ERL OPERATION OF S-DALINAC*

M. Arnold†, T. Bahlo, M. Dutine, R. Grewe, J. Hanten, L. Jürgensen, J. Pforr, N. Pietralla,
F. Schließmann, M. Steinhorst, S. Weih, Technische Universität Darmstadt, Darmstadt, Germany

Abstract

The S-DALINAC is a thrice-recirculating superconducting electron accelerator which can be either used in conventional accelerating operation or, since a major upgrade was installed in 2015/2016, as an energy recovery linac (ERL) alternatively. A once- or twice-recirculating ERL operation is possible due to the layout of the accelerator. During the commissioning phase the once-recirculating ERL operation was demonstrated in August 2017. Measurement data and an analytical model for the radio-frequency power behaviour due to changes in the beam loading are presented.

INTRODUCTION

The material discussed in this oral presentation is based upon the content of a scientific article which we have submitted on 4th of October 2019 to *Physical Review Accelerators and Beams*. Our present contribution to these conference proceedings, hence, contains descriptions of our work in the way which we were able to formulate them best.

S-DALINAC

The S-DALINAC is in operation since 1991 at TU Darmstadt [1]. A floorplan is shown in Fig. 1.

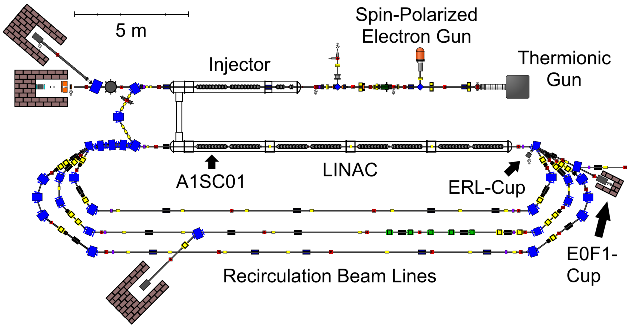


Figure 1: Floorplan of the S-DALINAC. The first main accelerator cavity A1SC01 and the two beam dumps being relevant for the measurement explained in section ”Once-Recirculating ERL Operation” are indicated.

The beam is either produced in a thermionic gun with a pre-acceleration of 250 keV or in a spin-polarized electron gun with a pre-acceleration of up to 125 keV. The beam is prepared for further acceleration with 3 GHz in the normal-conducting chopper-prebuncher section. The superconducting (sc) injector linac is able to accelerate the beam up to 10 MeV (7.6 MeV for recirculating operation). The beam is bent into the main accelerator, providing an energy gain of 30.4 MeV. The maximum design energy is 130 MeV at currents of 20 µA.

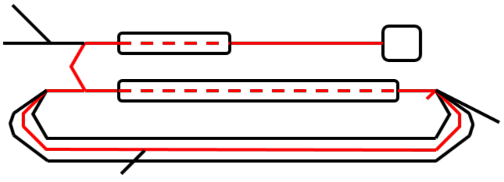
A New Recirculation Beam Line

In 2015/2016 a third recirculation beam line was installed, enabling higher end-energies and energy-recovery linac (ERL) operation due to a path-length adjustment system in the new beam line with a stroke of up to 360° [2,3]. The beam line elements have been aligned with a laser tracker [4], achieving a global 1D positioning precision in the order of 200 µm.

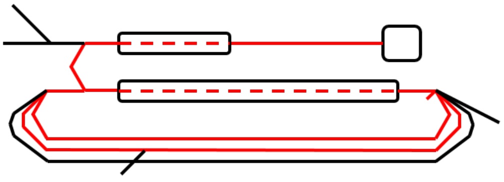
Operational Modes and Commissioning

The lattice of the S-DALINAC allows different operation schemes:

- Injector operation
- Single pass mode (one passage through the main linac)
- Once-recirculating mode (two passages through the main linac)
- Thrice-recirculating mode (four passages through the main linac)
- Once-recirculating ERL mode (one accelerating and one decelerating passage through the main linac, see Fig. 2(a))
- Twice-recirculating ERL mode (two accelerating and two decelerating passages through the main linac, see Fig. 2(b)), not demonstrated yet



(a) Once-recirculating ERL mode.



(b) Twice-recirculating ERL mode.

Figure 2: The S-DALINAC lattice is capable of a once- or twice-recirculating ERL operation. The 180° phase shift is done in the second recirculation beam line.

---

* Work supported by DFG through GRK 2128

† marnold@ikp.tu-darmstadt.de

63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2019, Berlin, Germany JACoW Publishing
ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOXBS03

STATUS OF NOVOSIBIRSK ERL

N. A. Vinokurov[†,1], Budker Institute of nuclear physics SB RAS, Novosibirsk, Russia
[1]also at Novosibirsk State University, Novosibirsk, Russia

Abstract

The Novosibirsk ERL is dedicated electron beam source for three free electron lasers operating in the wavelength range 8 – 240 micron at average power up to 0.5 kW and peak power about 1 MW. Radiation users works at 8 user stations performing biological, chemical, physical and medical research. The Novosibirsk ERL is the first and the only four-turn ERL in the world. Its peculiar features include the normal-conductive 180 MHz accelerating system, the DC electron gun with the grid thermionic cathode, three operation modes of the magnetic system, and a rather compact (6×40 m2) design. The facility has been operating for users of terahertz radiation since 2004. The status of the installation and plans are described.

INTRODUCTION

The Novosibirsk free electron laser (FEL) facility [1] has three FELs, installed on the first, second and fourth orbits of the dedicated energy recovery linac (ERL). The first FEL covers the wavelength range of 90 – 240 µm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 5.6 or 11.2 MHz and a peak power of up to 1 MW. The second FEL operates in the range of 40 - 80 µm at an average radiation power of up to 0.5 kW with a pulse repetition rate of 7.5 MHz and a peak power of about 1 MW. These two FELs are the world's most powerful (in terms of average power) sources of coherent narrow-band (less than 1%) radiation in their wavelength ranges. The third FEL was commissioned in 2015 to cover the wavelength range of 5 – 20 µm. The Novosibirsk ERL is the first and the only multiturn ERL in the world. Its peculiar features include the normal-conductive 180 MHz accelerating system, the DC electron gun with the grid thermionic cathode, three operation modes of the magnetic system, and a rather compact (6×40 m^2) design. The facility has been operating for users of terahertz radiation since 2004 [2].

ERL

All the FELs use the electron beam of the same electron accelerator, a multi-turn ERL. A simplified scheme of the four-turn ERL is shown in Fig. 1. Starting from low-energy injector 1, electrons pass four times through accelerating radio frequency (RF) structure 2. After that, they lose part of their energy in FEL undulator 4. The used electron beam is decelerated in the same RF structure, and the low-energy electrons are absorbed in beam dump 5.

The electron source is a 300-kV electrostatic gun with a grid cathode. It provides 1-ns bunches with a charge of up to 1.5 nC, a normalized emittance of about 20 µm, and a repetition rate of zero to 22.5 MHz. After the 180.4-MHz bunching cavity the bunches are compressed in the drift space (about 3 m length), accelerated in the two 180.4-MHz accelerating cavities up to 2 MeV, and injected by the injection beamline and the chicane into the main accelerating structure of the ERL (see Fig. 2).

The accelerating structure consists of 16 normal-conducting RF cavities, connected to two waveguides. The operation frequency is 180.4 MHz. Such a low frequency allows operation with long bunches and high currents.

The Novosibirsk ERL has three modes, one mode for operation of each of the three FELs. The first FEL is installed under the accelerating (RF) structure (see Figs. 2 and 3). Therefore, after the first passage through the RF structure, the electron beam with an energy of 11 MeV is turned by

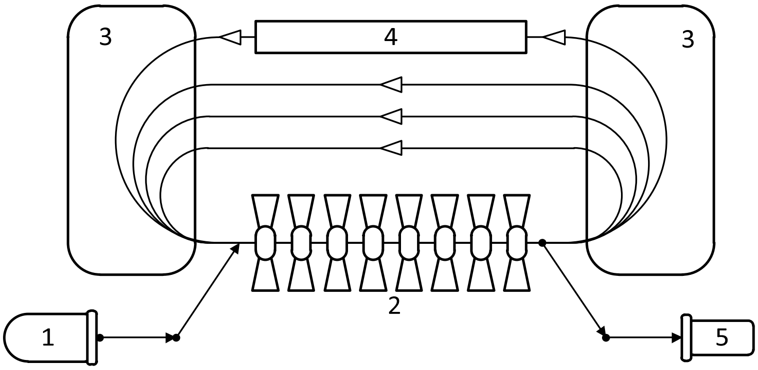


Figure 1: The simplified scheme of Novosibirsk ERL. 1 – injector, 2 – main accelerating structure, 3 – bending magnets, 4 – FEL, 5 – beam dump.

---

† vinokurov@inp.nsk.su

THE BERLIN ENERGY RECOVERY LINAC PROJECT bERLinPro – STATUS, PLANS AND FUTURE OPPORTUNITIES*

M. Abo-Bakr†, N. Al-Saokal, W. Anders, A. Büchel, K. Bürkmann-Gehrlein, A. Bundels, Y. Bergmann, P. Echevarria, A. Frahm, H.-W. Glock, F. Glöckner, F. Göbel, S. Heling, J.-G. Hwang, H. Huck, A. Jankowiak, C. Kalus, T. Kamps, G. Klemz, J. Knobloch, J. Kolbe, J. Kühn, B. Kuske, J. Kuszynski, A. Matveenko, M. McAteer, A. Meseck, S. Mistry, R. Müller, A. Neumann, N. Ohm-Krafft, K. Ott, L. Pichl, F. Pflocksch, J. Rahn, O. Schüler, M. Schuster, Y. Tamashevich, J. Ullrich, A. Ushakov, J. Völker,
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany.

Abstract

The Helmholtz-Zentrum Berlin is constructing the Energy Recovery Linac Project bERLinPro, a demonstration facility for the science and technology of ERLs for future light source applications. bERLinPro was designed to accelerate a high current (100 mA, 50 MeV), high brilliance (norm. emittance below 1 mm mrad) cw electron beam. Given the recent prioritization of the BESSY II light source upgrade to the BESSY VSR variable pulse length storage ring, HZB is forced to draw on resources originally allocated to bERLinPro so that the full project goals can no longer be reached within the current project period. As a result, bERLinPro had to be descoped within the present boundary conditions, with the goal to maximize its scientific impact . We report on the adjusted project goals, on the progress and status of the building, the warm and cold infrastructure and on the time line of the remaining project.

INTRODUCTION

bERLinPro [1] is an Energy Recovery Linac Project, currently under construction at the Helmholtz-Zentrum Berlin (HZB), Germany. Application of superconducting radio frequency (SRF) systems will allow cw operation of all RF systems and thus to accelerate high currents. The layout is shown in Fig. 1, the project's basic set of parameters is listed in Table 1.

The bERLinPro injector, consisting of an photo injector cavity (1.4 cell), followed by a Booster module containing three SRF cavities (2 cells), generates a high brilliant beam with an energy of 6.5 MeV.

The beam from the injector is merged into the linac section by means of a dogleg chicane. Two beams then pass the main linac to be accelerated and decelerated respectively. Through a racetrack magnetic lattice, the accelerated beam will be recirculated to demonstrate effective energy recovery, while the decelerated one is sent into the dump line with a high power (650 kW, designed for 100 mA operation) beam dump at its end.

Space in the return arc is provided to install future experiments or insertion devices to demonstrate the potential of ERLs for user applications. Various of these options have been discussed on a satellite workshop [2] of the ERL2019. Due to schedule, resources and budget reasons a major descope of the project became necessary. As one of the two major consequences, the high current gun, planned for up to 100 mA beam operation in a later phase of the project was canceled. Thus bERLinPro will be operated with a medium current gun only, expected to generate a maximum current of about 5 mA, limited by the installed TTF III RF power couplers. The second major project descope is the cancellation of the bERLinPro main linac, which will not be part of the project anymore. However, acceleration and energy recovery is still planned in bERLinPro, due to a collaboration with the Johann Gutenberg University Mainz. With the so called MESA option [3] the temporal test operation of one of the two MESA project [4] main linacs will give the chance to characterize the MESA module with beam and to accelerate the beam in bERLinPro to an energy of about 32 MeV and to demonstrate energy recovery.

Table 1: bERLinPro's main target parameters, initial project goals before descoping parenthesized.

parameter	value
maximum beam energy / MeV	32 (50)
maximum average current* / mA	5 (100)
RF freq. & max. rep. rate / GHz	1.3
reference bunch charge / pC	77
normalized emittance / μm rad	1.0
bunch length (standard mode) / ps	2.0
bunch length (short pulse mode**) / fs	100
maximum losses	$< 10^{-5}$

* limited by the gun maximum coupler power or to lower values by beam break up (BBU)
** at reduced bunch charge

The accelerator installation was planned in two stages, to subsequently commission the various SRF modules and machine parts. Stage-I, being the entire low energy beam path from the gun to the high power beam dump, is completed now: all girders and magnets as well as the vacuum system components including all the diagnostics hardware are placed and aligned, RF and cryogenic installations are finished. The only exception are the two SRF modules (gun

---

* Work supported by the German Bundesministerium für Bildung und Forschung, Land Berlin and grants of Helmholtz Association.
† Michael.Abo-Bakr@helmholtz-berlin.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOXBS05

STATUS OF THE MESA ERL-PROJECT*

F. Hug†, K. Aulenbacher[1], S. Friederich, P. Heil, R.G. Heine, R. Kempf, C. Matejcek, D. Simon
Johannes Gutenberg-Universität Mainz, Mainz, Germany
[1]also at Helmholtz Institut Mainz, Germany and
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Abstract

MESA is a recirculating superconducting accelerator under construction at Johannes Gutenberg-Universität Mainz. It can be operated in either external beam or ERL mode and will be used for high precision particle physics experiments. The operating cw beam current and energy in EB mode is 0.15 mA with polarized electrons at 155 MeV. In ERL mode a polarized beam of 1 mA at 105 MeV will be available. In a later construction stage of MESA the beam current in ERL-mode shall be upgraded to 10 mA (unpolarized). Civil construction and commissioning of components like electron gun, LEBT and SRF modules have been started already. We will give a project overview including the accelerator layout, the current status and an outlook to the next construction and commissioning steps.

INTRODUCTION

The Mainz Energy-recovering Superconducting Accelerator (MESA) (layout see Fig. 1) will be a low energy continuous wave (cw) recirculating electron linac for particle and nuclear physics experiments. In the first phase of operation it will serve mainly three experiments.

The main experiment of MESA, run in external beam (EB) mode, where the beam needs to be dumped after being used, will be the fixed target setup P2 [1], whose goal is the measurement of the weak mixing angle (Weinberg angle) by measuring parity violation asymmetry with highest accuracy. Required beam current for P2 is 150 µA with spin-polarized electrons at a maximum energy of 155 MeV.

Additionally, a so called beam-dump experiment (BDX) is planned to run in parallel to P2 [2]. This experiment will be located outside of the accelerator hall in line with the beam dump and is dedicated for searching dark particles, which might be generated dumping the beam of the P2 experiment, benefiting from the massive radiation shielding of the dump, which reduces background to a minimum. The third experimental setup will be the high resolution two-arm spectrometer facility MAGIX [3], which uses a gas jet target [4] and can be run in ERL mode.

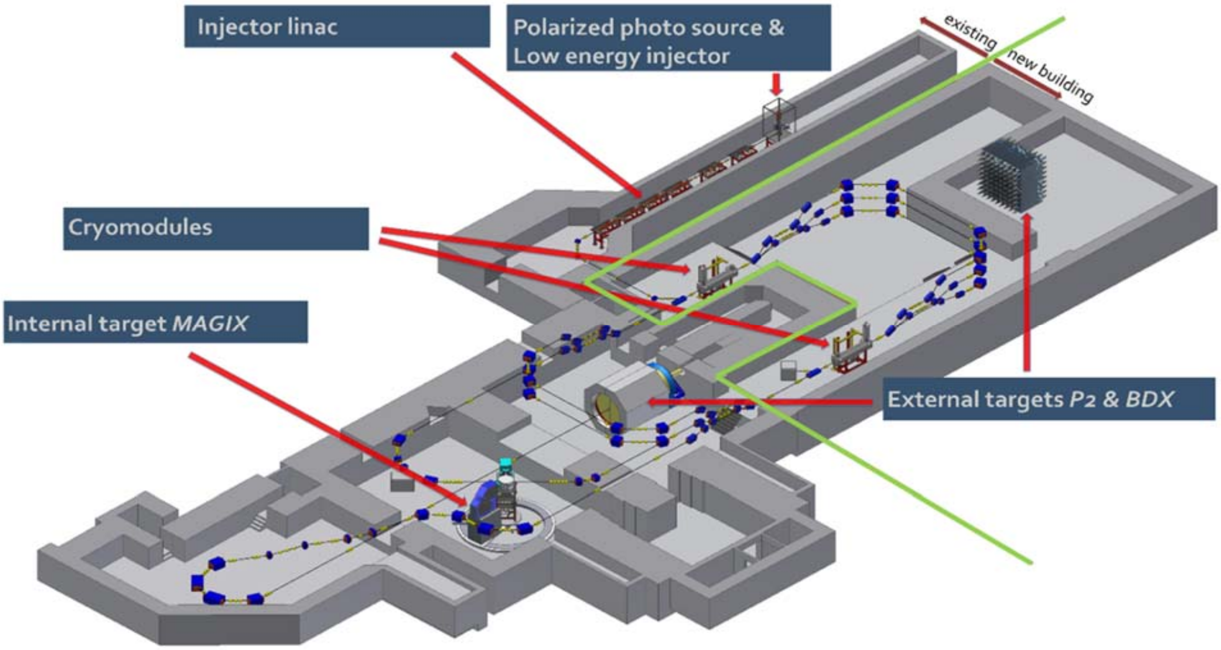


Figure 1: Layout of the MESA accelerator and the planned experimental setups. The accelerator will be located in existing and newly constructed underground halls. The boundary between the old and new parts of the building is marked by a green line. The injector will be constructed and commissioned first as it is located in an existing building part. Civil construction work for the new underground hall has started and will last until end 2021. Afterwards, construction of main linac and experiments will start as well (courtesy of drawing: D. Simon).

---

* This work has been supported by DFG through the PRISMA$^+$ cluster of excellence EXC 2118/2019 and by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

† flohug@uni-mainz.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-MOCOYBS04

ELECTRODISINTEGRATION OF ^{16}O AND THE RATE DETERMINATION OF THE RADIATIVE α CAPTURE ON ^{12}C AT STELLAR ENERGIES

I. Friščić *, T. W. Donnelly, R. G. Milner
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Abstract

For over five decades one of the most important goals of experimental nuclear astrophysics has been to reduce the uncertainty in the S-factor of radiative α capture on ^{12}C at stellar energies. We have developed a simple model, which relates the radiative capture reaction and the exclusive electrodisintegration reaction. We then show that by measuring the rate of electrodisintegration of ^{16}O in a high luminosity experiment using a state-of-the-art jet-target and a new generation of energy-recovery linear (ERL) electron accelerators under development, it is possible to significantly improve the statistical uncertainty of the radiative α capture on ^{12}C in terms of E1 and E2 S-factors in the astrophysically interesting region, which are the key inputs for any nucleosynthesis and stellar evolution models. The model needs to be validated experimentally, but, if successful, it can be used to improve the precision of other astrophysically-relevant, radiative capture reactions, thus opening a significant avenue of research that spans nuclear structure, astrophysics and high-power accelerator technology.

INTRODUCTION

During the stellar evolution, the helium burning stage is dominated by two reactions: radiative triple-α capture and radiative α capture on ^{12}C, *i.e.* ^{12}C$(\alpha,\gamma)^{16}$O. The values of the individual rates will determine the ^{12}C/^{16}O abundance at the end of the helium burning stage, which highly influences the subsequent nucleosynthesis [1]. The current uncertainty in triple-α capture at stellar energies is known with an uncertainty of ~10%, but for the ^{12}C$(\alpha,\gamma)^{16}$O rate the situation is much worse [2]. In the modeling of the stellar evolution, the large uncertainty of the measured ^{12}C$(\alpha,\gamma)^{16}$O rate translates into large range of rates and because of this models give different outcomes in terms of nuclei abundance inside a star of a given mass [1, 2]. Thus, for many decades, the goal of experimental nuclear physics was to improve the precision of measurements of the ^{12}C$(\alpha,\gamma)^{16}$O rate at stellar energies [3]. Attempts were made to constrain the ^{12}C$(\alpha,\gamma)^{16}$O rate using the models and the observed solar abundances [1], implicating that the experimental rate needs to be measured with an uncertainty ≤10% [4]. Such a level of precision has still not been achieved..

At typical helium burning temperature for massive stars $\sim 2 \cdot 10^{8}$ K, the equivalent Gamow energy E_g is ~300 keV and due to large Coulomb barrier the cross section of the ^{12}C$(\alpha,\gamma)^{16}$O reaction is extremely small $\sim 10^{-5}$ pb, making the direct measurements infeasible. The strategy is to measure the cross section, which is usually expressed in terms of the astrophysical S-factor as a function of α-particle center-of-mass (cm) kinetic energy E_α^{cm}:

$$S = \sigma E_\alpha^{cm} e^{2\pi\mu} \tag{1}$$

where μ is the Sommerfeld parameter, at several larger energies and then to extrapolate to stellar energies. The extrapolation is complicated due the structure of ^{16}O [5] and involves dealing with the interference of subthreshold and above threshold E1/E2 states.

In the past, many different experimental methods have been developed and used to measure the ^{12}C$(\alpha,\gamma)^{16}$O rate, including the direct reaction measurements [6–19], elastic scattering ^{12}C$(\alpha,\alpha)^{12}$C [20, 21], and $\beta-$delayed α-decay of ^{16}N [22–24]. Below $E_\alpha^{cm} < 2$ MeV the data points are increasingly dominated by the statistical uncertainties, due to rapidly falling of the cross section as it approaches the Gamow energy. Recently, researchers have started to investigate the inverse reaction induced by real photons (the photodisintegration of ^{16}O), in order to improve the statistics of low-energy data. One concept uses a bubble chamber [25, 26] and the other an optical time projection chamber [27]. More details about the specific experiments and the astrophysical implications of the ^{12}C$(\alpha,\gamma)^{16}$O rate can be found in the most recent review [2].

Contrary to photodisintegration, where the real photon beam is involved $|\vec{q}| = q = E_\gamma$, the electrodisintegration uses an electron beam with an exchange of a virtual photon $(\omega,\vec{q})$, for details see [28]. In the past, the potential astrophysical application of the electrodisintegration of ^{16}O was discussed in [29] and an storage ring based experiment was proposed in [30], but was never carried out. More recent discussions [31, 32] are motivated by development of a new generation of high intensity (≈ 10 mA) low-energy (≈ 100 MeV) energy-recovery linear (ERL) electron accelerators [33, 34] and which together with modern jet gas targets [35], can deliver luminosity $>10^{35}$ cm^{-2} s^{-1}. By measuring the final state of the scattered electron it is possible to define and fix the α+^{12}C excitation energy, but at the same time control the three-momentum of the virtual photon $\vec{q}$ either by selecting the electron scattering angle θ_e or the beam energy E_e, see Fig 1. The real photon result can be recovered by taking the limit $q/\omega \to 1$.

In this paper, we briefly present a new method to improve the precision of the ^{12}C$(\alpha,\gamma)^{16}$O reaction at stellar energies based on electrodisintegration of ^{16}O, *i.e.* ^{16}O$(e,e'\alpha)^{16}$C. The full description of this method can be found in [36].

---

* friscic@mit.edu

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-TUCOXBS01

BEAM HALO IN ENERGY RECOVERY LINACS

O. A. Tanaka[†], High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

The beam halo mitigation is a very important challenge for reliable and safe operation of a high energy machine. Since Energy Recovery Linacs (ERLs) are known to produce high energy electron beams of high virtual power and high density, the beam halo and related beam losses should be properly mitigated to avoid a direct damage of the equipment, an unacceptable increase in the vacuum pressure, a radiation activation of the accelerator components etc. To keep the operation stable, one needs to address all possible beam halo formation mechanisms, including those unique to each machine that can generate beam halo. Present report is dedicated to the beam halo related activities at the Compact ERL at KEK, and our operational experience with respect to the beam halo.

INTRODUCTION

Beam halo studies and halo mitigation schemes are of the great importance at each stage of accelerator R&D. For those machines that are at their design stage, beam halo studies are limited simply by the absence of the real equipment to perform some tests. Nevertheless, several halo formation mechanisms and processes impacting into the halo could be modeled and estimated prior the machine construction. Here are some of them:

- A space charge effect causes emittance blow-up and bunch lengthening that finally could lead to the formation of the beam halo and consequent beam losses. Examples of space charge effect studies for ERL machines could be found in [1] – [4].
- Effects of the CSR (Coherent Synchrotron Radiation). CSR related issues are in trend nowadays, and addressed in numerous studies (see, for example, [4] – [5]).
- Dark current from the electron gun and longitudinal bunch tails originated at the photocathode [6] – [7].

Other mechanisms could be studied only after the machine construction. One of the examples of the processes enhancing the halo that could not be investigated beforehand is a dark current from RF cavities. Recent results could be found in [8]. Another example is those halo formation mechanisms that are unique for each machine. Thus at the Compact ERL (cERL) at KEK such a unique process was detected and explained for the essential vertical beam halo observed in the end of the injector section and at several locations of the recirculation loop [9]. However, this study was done for the low bunch charge operation (1 pC/bunch, [10]), while the next step operational goal was to achieve a high bunch charge operation (60 pC/bunch, [11]).

Recent industrialization of the cERL beam line [12] imposed new requirements to the beam operation. During last run in June 2019, we optimized injector to the energy 4 MeV [13]. Design parameters dedicated to this run and achieved parameters are listed in the Table 1. Next operational step is to develop the method of beam tuning to control space charge effect. Thus, to be able to produce mid-infrared Free Electron Laser (IR-FEL) light in May 2020, we need to tune the machine for high charge CW operation, while the normalized rms emittance should be kept less than 3π mm mrad, bunch length should be of order of 4 ps, and the energy spread should be minimized to less than 0.062%. These considerations motivated several halo related activities at cERL.

IR-FEL upgrade requires a high bunch charge CW operation. Accordingly, the energy spread should be minimized to improve the FEL-light quality. The halo influence should be studied in this respect. Then, bunch length and beam emittance should be controlled, and we need to exclude the beam halo impact (or reduce as much as possible). Also a reasonable collimation is required to protect the beam line components from its unnecessary activation and to lower the overall beam losses. Collimators should be tested and approved towards the CW operation. Present report is dedicated to these activities and our operational experience with respect to the beam halo.

Table 1: Typical Parameters of CERL Run in June, 2019

Parameter	Design	In operation
Beam energy [MeV]:		
Injector	4	4.05
Recirculation loop	17.6	17.5
Bunch charge [pC]	60	60
Repetition rate [GHz]	1.3	1.3
Bunch length (rms) [ps]	4	4.5
Energy spread [%]	<0.06	0.12
Normalized emittance (rms) in injector [μm·rad]:		
Horizontal	< 3	2.89±0.09
Vertical	< 3	1.99±0.20

HALO TRACKING THROUGH THE INJECTOR

After the injector optics was updated for the energy of 4 MeV, a high bunch charge (60 pC/bunch) beam with a longitudinal bunch tail was tracked through it to compare with observed profiles. To introduce the longitudinal bunch tail into simulations, the initial longitudinal distribution of the bunch was generated in accordance with the curve shown in Figure 1. The core of the bunch is 50 ps FWHM flat-top Gaussian. The backward tail includes 20% of the core intensity. A small (1.5% of the core) forward tail was also added similarly to how it was done in previous beam halo studies [9]. The cutoff of the longitudinal distribution was set to 100 ps. The initial trans-

---

[†] olga@post.kek.jp.

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-TUCOXBS03

BEAM DYNAMICS LAYOUT OF THE MESA ERL*

F. Hug†, K. Aulenbacher[1], D. Simon, C.P. Stoll, S.D.W. Thomas
Johannes Gutenberg-Universität Mainz, Mainz, Germany
[1]also at Helmholtz Institut Mainz, Germany and
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Abstract

The MESA project is currently under construction at Johannes Gutenberg-Universität Mainz. It will be used for high precision particle physics experiments in two different operation modes: external beam (EB) mode (0.15 mA; 155 MeV) and energy recovery (ERL) mode (1 mA; 105 MeV). The recirculating main linac follows the concept of a double sided accelerator design with vertical stacking of return arcs. Up to three recirculations are possible. Acceleration is done by four TESLA/XFEL 9-cell SRF cavities located in two modified ELBE cryomodules. Within this contribution the recirculation optics for MESA will be presented. Main goals are achieving best energy spread at the experimental setups in recirculating ERL and non-ERL operation and providing small beta-functions within the cryomodules for minimizing HOM excitation at high beam currents.

INTRODUCTION

The Mainz Energy-recovering Superconducting Accelerator (MESA) is a low energy continuous wave (cw) recirculating electron linac for particle and nuclear physics experiments under construction at Johannes Gutenberg-Universität Mainz [1-3]. The first phase of operation foresees to serve mainly three experiments, two of them running in external beam mode (EB) and one in energy recovering mode (ERL). MESA construction was funded in 2012. The facility and its experiments [4-6] have undergone several design changes since then. The latest change of layout has been applied in spring 2019 and was presented already in [7]. Therefore, start to end tracking simulations for the complete machine [8] are still based on an older layout version and need to be repeated for the new one. Nevertheless, the main design of MESA has been kept up throughout the changes of accelerator layout. MESA will be constructed in a double sided accelerator layout with two superconducting linacs and vertically stacked return arcs. In EB mode, up to three linac passes are possible and maximum beam energy and current yield 155 MeV and 150 µA respectively. In ERL operation only two passes can be used for acceleration and after experimental use of the beam for deceleration again. The maximum beam energy reduces to 105 MeV but the maximum beam current is not limited by installed rf power anymore and can go up to 1 mA. In a later stage of MESA operation, the beam current shall be increased to the maximum available current from the injector linac (10 mA) [9].

All MESA experiments rely on excellent beam quality in order to perform precision experiments on nuclear and particle physics searching for dark particles and beyond standard model physics. Therefore, a relative energy spread of the beam of approx. 10^{-4} (RMS) or better is required for not being the main source of error in electron scattering experiments. In addition, beam quality needs to be kept stable for long time measurement runs. In particular, in ERL mode reaching these conditions can be quite challenging, as high beam intensities can deteriorate the bunches and decrease beam quality. Furthermore, instabilities due to high beam current like beam break-up (BBU) have to be considered when designing the MESA optics. In the following sections we will present the MESA optics layout and will discuss the possibility to achieve best energy spread by application of certain non-isochronous longitudinal working points.

MESA LAYOUT

General Layout

The MESA beam is produced at a polarized dc photogun on an extraction voltage of 100 kV [10]. The gun injects the beam into the low energy beam transport system (MELBA) [11]. Here, spin manipulation can be applied and a chopper-buncher section is used for longitudinal matching into the normal-conducting booster linac MAMBO. In the booster linac the electrons are further accelerated by four normalconducting injector cavities up to 5 MeV beam energy up to10 mA cw beam current [12,13]. The simulated transverse and longitudinal phase space from MAMBO has been used in simulations presented within this contribution [14]. The 5 MeV beam is transferred into the main linac through a 180° arc afterwards, which can also be used as bunch compressor in order to reach shortest possible bunches at the position of the first SRF cavity of the main linac [14,15]. The recirculating main linac is using a double sided accelerator design with two superconducting linac modules [16], each on either side, containing in total four SRF cavities and providing an energy gain of 25 MeV per turn. Recirculation arcs are stacked vertically. Figure 1 illustrates the MESA layout.

Vertical Spreaders and Combiners

The vertical spreader and combiner sections need to separate the beams of different energies to their return arcs. In addition, vertical dispersion needs to be cancelled out at the end of each spreading or combining section. Longitudinal dispersion, also known as momentum compaction, adding

---

* This work has been supported by DFG through the PRISMA$^+$ cluster of excellence EXC 2118/2019 and by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

† flohug@uni-mainz.de

63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2019, Berlin, Germany JACoW Publishing
ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-TUCOXBS04

THE LHeC ERL – OPTICS AND PERFORMANCE OPTIMIZATION*

S.A. Bogacz[†], Jefferson Lab, Newport News, VA, USA

Abstract

Unprecedently high luminosity of 10^{34} cm^{-2}s^{-1}, promised by the LHeC accelerator complex poses several beam dynamics and lattice design challenges [1]. Here we present beam dynamics driven approach to accelerator design, which in particular, addresses emittance dilution due to quantum excitations and beam breakup instability in a large scale, multi-pass Energy Recovery Linac (ERL) [2]. The use of ERL accelerator technology to provide improved beam quality and higher brightness continues to be the subject of active community interest and active accelerator development of future Electron Ion Colliders (EIC). Here, we employ current state of though for ERLs aiming at the energy frontier EIC. The main thrust of these studies was to enhance the collider performance, while limiting overall power consumption through exploring interplay between emittance preservation and efficiencies promised by the ERL technology [3].

ERL ARCHITECTURE

The ERL layout is sketched in Fig. 1. The machine is arranged in a racetrack configuration hosting two superconducting linacs in the parallel straights and three recirculating arcs on each side. The linacs are 1 km long and the arcs have 1 km radius, additional space is taken up by utilities like spreading, matching and compensating sections. The total length is 9 km: 1/3 of the LHC circumference. Each of the two linacs provides 10 GV accelerating field, therefore a 60 GeV energy is achieved in three turns. After the collision with the protons in the LHC, the beam is decelerated in the three subsequent turns. The injection and dump energy has been chosen at 500 MeV.

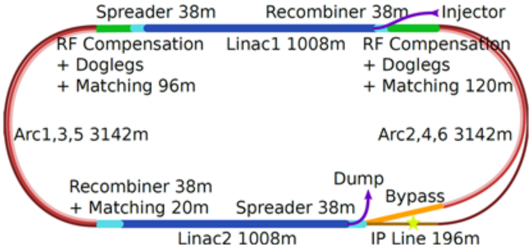


Figure 1: Scheme of the LHeC ERL layout.

Linac Design and Optimization

Each 1 km long linac hosts 72 cryo-modules, each containing 8 cavities for a total of 576 cavities per linac operating at 802 MHz. In the baseline design a quadrupole is placed every two cryomodules providing a FODO configuration. Note that the optics of a high gradient linac can be substantially perturbed by the additional focusing coming from the RF [4]. It is therefore important to make sure that it is properly modelled.

Energy recovery in a racetrack topology explicitly requires that both the accelerating and decelerating beams share the individual return arcs. This in turn, imposes specific requirements for TWISS function at the linacs ends: the TWISS functions have to be identical for both the accelerating and decelerating linac passes converging to the same energy and therefore entering the same arc.

To visualize beta functions for multiple accelerating and decelerating passes through a given linac, it is convenient to reverse the linac direction for all decelerating passes and string them together with the interleaved accelerating passes, as illustrated in Fig. 2. This way, the corresponding accelerating and decelerating passes are joined together at the arcs entrance/exit. Therefore, the matching conditions are automatically built into the resulting multi-pass linac beamline.

The optics of the two linacs are symmetric, the first being matched to the first accelerating passage and the second to the last decelerating one. In order to maximize the BBU threshold current, the optics is tuned so that the integral: is minimized. The resulting phase advance per cell is close to 130°. Non-linear strength profiles and more refined merit functions were tested, but they only brought negligible improvements.

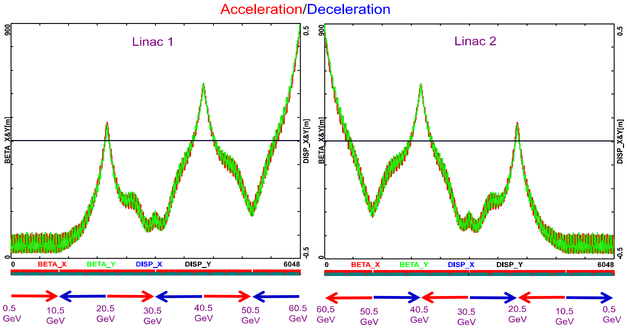


Figure 2: Beta function in the optimized LHeC Linacs during the acceleration. The linac contains 576 cavities.

Recirculating Arcs

All six arcs (three on each side) are accommodated in a tunnel of 1 km radius. Their lattice cell adopts a flexible momentum compaction layout that presents the very same footprint for each arc. This allows us to stack magnets on top of each other or to combine them in a single design. The dipole filling factor of the cell is 76%; therefore, the effective bending radius is 760 m.

The tuning of each arc takes into account the impact of synchrotron radiation at different energies. At the highest

---

* Work has been authored by Jefferson Science Associates, LLC under Contract No. DE-AC05-06OR23177 with the U.S. Department of Energy.

[†] bogacz@jlab.org

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-TUCOXBS05

BEAM TIMING AND CAVITY PHASING

R. Koscica[*], N. Banerjee, G. H. Hoffstaetter, W. Lou, G. Premawardhana
Cornell University (CLASSE), Ithaca, NY 14853, USA

Abstract

In a multi-pass Energy Recovery Linac (ERL), each cavity must regain all energy expended from beam acceleration during beam deceleration. The beam should also achieve specific energy targets during each loop that returns it to the linac. To satisfy the energy recovery and loop requirements, one must specify the phase and voltage of cavity fields, and one must control the beam flight times through the return loops. Adequate values for these parameters can be found by using a full scale numerical optimization program. If symmetry is imposed in beam time and energy during acceleration and deceleration, the number of parameters needed decreases, simplifying the optimization. As an example, symmetric models of the Cornell BNL ERL Test Accelerator (CBETA) are considered. Energy recovery results from recent CBETA single-turn tests are presented, as well as multi-turn solutions that satisfy CBETA optimization targets of loop energy and zero cavity loading.

INTRODUCTION

The Energy Recovery Linac (ERL) is designed to create high-quality, high-current beams at a lower energy cost than conventional linacs. Energy transferred to the beam during acceleration is later recovered by the system. In an ERL where the beam accelerates and decelerates through the same linac, full energy recovery is achieved when each radio-frequency (RF) cavity in the linac recovers the energy that it originally expended: a beam ideally causes zero net power load on the system. In multiturn ERLs, the beam enters the linac at different speeds during each accelerating or decelerating pass. As a result, the beam may experience phases slipped away from the ultrarelativistic case, and this phase slippage can result in incomplete energy recovery.

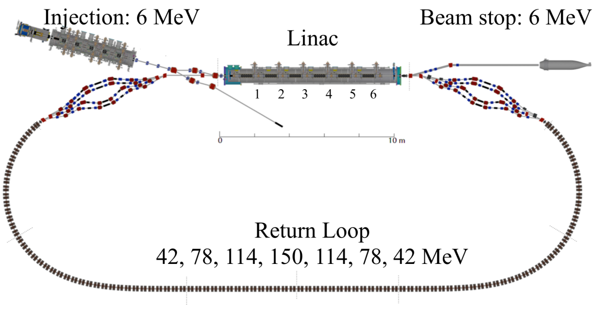


Figure 1: CBETA layout [1]. CBETA has a single linac with 6 RF cavities. The return loop has 4 independent beam paths shared by accelerating and decelerating beams of corresponding energy.

The Cornell BNL ERL Test Accelerator (CBETA) is a single-linac ERL with four independent loops that return the beam to the linac (Fig. 1). A 6 MeV beam accelerates to 150 MeV over four passes of the main linac, where it may be used for experiments. The beam then decelerates to 6 MeV over four more passes, using the same set of loops to return to the linac as during acceleration. The intended beam will have a current of 40 mA [1]. In Summer 2019, CBETA was tested in a 1-turn configuration. A beam of under 0.1 μA accelerated from 6 MeV to 42 MeV, then decelerated back to 6 MeV. Better than 99.8% energy recovery was achieved in each cavity.

CBETA has not yet been tested in multiturn operation, where energy recovery may be more challenging to achieve due to the increased complexity of the system. If a 4-turn CBETA model is simulated with RF phase and loop length settings that give energy recovery when $v = c$ everywhere, then a 40 mA beam of expected non-ultrarelativistic speed incurs up to 46 kW power load in a single cavity. However, the CBETA cavities only have 2 kW power allotted for beam acceleration; assuming a beam speed of $v = c$ would result in unfeasible power consumption.

Optimization of RF phase and loop timing is needed to reduce the simulated beam load during multi-turn operation. Direct optimization would require a large system of variables and constraints, but the system size can be greatly reduced if RF phases are chosen for a symmetric accelerating and decelerating energy configuration. The ERL symmetry strategy presented here is further discussed in [2] and [3].

OPTIMIZATION SYSTEM

Suppose a single-linac ERL with shared accelerating and decelerating return loops (*e.g.* CBETA) has M linac passes and N cavities. For CBETA, $M = 8$ and $N = 6$. The optimization system must have N constraints to minimize each cavity load. An additional $(M - 1 = 7)$ constraints are needed to ensure that the beam has the correct energy during return loops, such that the shared loops can direct both accelerating and decelerating beams identically, and the central loop can achieve the correct maximum energy for experiments. To achieve these goals, one can vary the length of the $\frac{M}{2} = 4$ independent return loops, or the RF phase and voltage of the N cavities. This optimization system will have a total of $(N + M - 1 = 13)$ constraints and $(2N + \frac{M}{2} = 16)$ possible variables.

If the ERL is made symmetric, then the accelerating time-energy profile of a single-particle ideal beam is experienced in exactly reverse order during deceleration. This mirrored energy profile causes the load on each pair of cavities equidistant from the linac center, *e.g.* the first and last, to be correlated: only $\frac{N}{2} = 3$ load constraints are needed. The symmet-

---

[*] rmk275@cornell.edu

A FERROELECTRIC FAST REACTIVE TUNER (FE-FRT) TO COMBAT MICROPHONICS*

N. Shipman, J. Bastard, M. Coly, F. Gerigk, A. Macpherson, N. Stapley,
CERN, Geneva, Switzerland
I. Ben-Zvi, Brookhaven National Laboratory, Upton NY, USA
C. Jing, A. Kanareykin, Euclid Techlabs LLC, Gaithersburg MD, USA
G. Burt, A. Castilla, Lancaster University, Lancaster, UK
E. Nenasheva, Ceramics Ltd, St.Petersburg, Russia

Abstract

FerroElectric Fast Reactive Tuners (FE-FRTs) are a novel type of tuner that may be able to achieve near perfect compensation of microphonics in the near future. This would eliminate the need to design over-coupled fundamental power couplers and thus significantly reduce RF power, particularly for low beam current applications.

The recently tested proof of principle FE-FRT is discussed and the theory and practice of FE-FRT operation are developed. These theoretical methods are then used to explore the potential benefits of using an FE-FRT with specific ERL proposals, which are seen as one of the major use cases. Specifically the ERLs considered are: eRHIC ERL, PERLE, LHeC ERL and the Cornell Light Source. Particular attention is given to the substantial peak and average RF power reductions which could be achieved; in many cases these are shown to be approximately an order of magnitude.

INTRODUCTION

Energy Recovery Linacs (ERLs) are designed to operate with virtually no beam loading. In principle, the only forward power that must be supplied to an ERL cavity is that needed to replace the power lost on the cavity walls. For super conducting cavities this is rather small.

Unfortunately, even with well designed cryomodules, frequency excursions caused by microphonics are typically orders of magnitude larger than the natural bandwidth of the cavity and as a result almost all of the supplied forward power is reflected and lost.

Significant effort has been made in recent years to design fast mechanical piezo-electric tuners to combat microphonics. Whilst important progress has been made in this direction[1–3], it is an extremely difficult challenge. Although piezo-electric crystals are intrinsically fast, the speed of a piezo-electric tuner is limited by how fast a deformation can be applied to the cavity wall. A cavity also has its own mechanical resonances which imply complicated transfer functions between piezo actuator input and cavity resonant frequency. In addition, any applied mechanical deformation will invariably excite additional unwanted mechanical vibrations which will themselves affect the frequency.

Recent progress in ferroelectric (FE) material properties[4–6] have now made an entirely new method of combatting microphonics viable. An FE-FRT is a device containing FE material which is coupled to the cavity via an antenna and transmission line. By applying a voltage to the FE, its permittivity and therefore the reactance coupled to the cavity is altered, which changes the cavity's resonant frequency.

FE-FRTs have no moving parts, do not act on the cavity mechanically and do not excite unwanted mechanical vibrations. They also operate outside of cryomodules avoiding the cryogenic cost of dissipating power in liquid helium.

For ERLs and low beam loading machines FE-FRTs could soon offer significant power and cost savings.

PROTOTYPE FE-FRT

A proof of principle (PoP) FE-FRT was designed by S. Kazakov, built by Euclid and successfully tested on an SRF cavity at CERN[7]. A photograph and 3D rendering are shown in Fig. 1. It connects to the cavity on the left via a co-axial cable and to a high voltage source on the right.

The PoP FE-FRT was tested with a superconducting cavity and preliminary results were presented in [7]. The (measurement limited) response of the cavity to the tuner was found to be $< 50\,\mu$s, the true response may be much faster as the FE material itself responds in $\sim$ 10s ns[8, 9].

Whilst the response time estimation was measurement limited, it is already possible to draw two key conclusions. Firstly the cavity response to an FE-FRT is not limited by the time constant of the cavity. Secondly the response time is certainly fast enough to easily correct for microphonics which are typically not significant above $\approx$ 1kHz [3, 10].

Predictions of PoP FE-FRT impedance as a function of frequency were made with a transmission line model (TLM), and compared to CST simulations[11] and VNA measurements in Fig. 2. Close agreement is seen around the intended operating frequency ($\approx$ 400 MHz), validating the TLM.

MECHANISM OF ACTION

Theory of an FE-FRT has already been presented in [7]. Here the most important results are reviewed and behaviour in anticipated paradigmatic scenarios is explored.

Theoretical Overview

The cavity is modelled as a conductance G_c, capacitance C_c and inductance L_c connected in parallel. The cavity-tuner or FE-FRT coupler is modelled as a lossless trans-

---

* This work was supported in part by the DOE SBIR grant: DE-SC0007630.

CHARACTERIZATION OF MICROPHONICS IN THE cERL MAIN LINAC SUPERCONDUCTING CAVITIES

F. Qiu[1,2,†], S. Michizono[1,2], T. Miura[1,2], T. Matsumoto[1,2], D. Arakawa[1], H. Katagiri[1], E. Kako[1,2],
H. Sakai[1,2], K. Umemori[1,2], T. Konomi[1,2], M. Egi[1,2]
[1]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
[2]The Graduate Univiersity for Advanced Studies (Sokendai), Hayama, Kanagawa 240-0193, Japan

Abstract

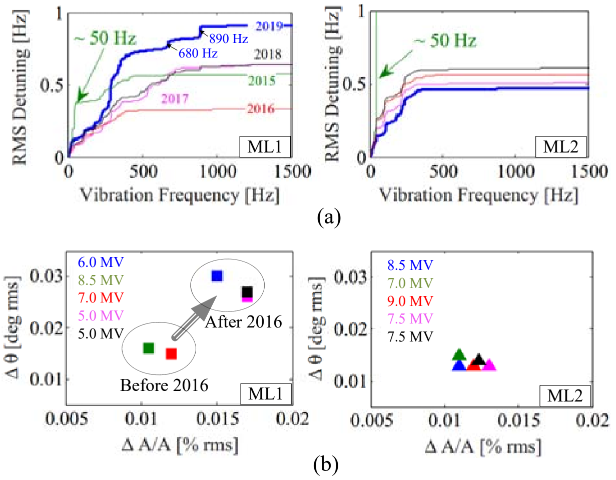
In the main linac (ML) of the KEK-cERL, two superconducting cavities with high loaded Q ($Q_L \approx 1\times10^7$) are operated in continuous wave (CW) mode. It is important to control and suppress the microphonics detuning owing to the low bandwidth of the cavities. We evaluated the background microphonics detuning by the low level radio frequency system during the beam operation. Interestingly, a "field level dependence microphonics" phenomenon was observed on one of the cavities in the ML. Several frequency components were suddenly excited if the cavity field is above a threshold field (~3 MV/m). We found that this threshold field is probably related with the cavity quench limits despite the unclear inherent physical mechanism. Furthermore, in order to optimize the cavity resonance control system for better microphonics rejection, we have measured the mechanical transfer function between the fast piezo tuner and cavity detuning. Finally, we validated this model by comparing the model response with actual system response.

INTRODUCTION

At KEK, a compact energy recovery linac (cERL) was constructed to study the feasibility of the future 3 GeV ERL based light source in 2009 [1]. It is a 1.3 GHz superconducting (SC) facility that operated in continuous-wave (CW) mode. In the main linac (ML) of the cERL, two nine-cell cavities (ML1 and ML2) were installed for energy recovery [2]. These two cavities have a high loaded Q (Q_L) of about 1×10^7, with the corresponding cavity half-bandwidth ($\omega_{0.5}$) of about 65 Hz. The lower bandwidth makes the cavity phase very sensitive to the microphonics detuning. A low level radio frequency (LLRF) system is usually required to reduce the microphonics effects.

Figure 1(a) compares the cumulative microphonics detuning as a function of the vibration frequency of the ML cavities in the past 5 years (indicated by different colors). In 2015, a 50 Hz component caused by scroll pumps was observed in both cavities (especially ML2). This components were disappeared after inserting a rubber sheet under the pumps. From 2016 to 2019, we have observed that the microphonics conditions gradually deteriorated in the ML1 cavity. Roughly, the RMS micrphonics detuning in 2019 (blue) is 2.5 times of the detuning in 2016 (red). On the other hand, such a phenomenon was not observed in the ML2 cavity. Figure 1(b) shows the corresponding RF stability (left: ML1, right: ML2) in the past 5 years. After 2016, according to Fig. 1(b), the RF stabilities for ML1 cavity were, unfortunately, getting worse due to the deteriorated microphonics conditions. Whereas the stabilities of ML2 cavity always performed well due to its similar microphonics conditions in the past five years.

In view of this situation, we have investigated the background microphonics of these two cavities carefully. Interestingly, a "field level dependence microphonics" phenomenon was observed in cavity ML1 [3]. We found that if the cavity field in the ML1 is larger than a threshold filed of 3 MV/m, several high frequency components were suddenly excited. This threshold field is probably related with quench limits according to the experimental results. Furthermore, in order to optimize the current resonance control, we measured the transfer function (TF) model between the piezo tuner and the cavity detuning, and then demonstrated the validation of the model in the beam commissioning. This paper will present our studies in 2019.



(a)

(b)

Figure 1: Five years comparison of (a) cumulative RMS detuning (in a function of vibration frequency) and (b) amplitude and phase stabilities (under feedback operation) of the ML1 (left) and ML2 (right). The cavity voltages in each operation are also marked in Fig. 1(b).

LLRF SYSTEM

Figure 2 shows the digital LLRF systems (indicated by red block) and frequency tuner system (indicated by blue block) of the ML cavities. The detailed information of these two systems can be found in [4-5] and [6], respectively. The phase differences ($\Delta\varphi$) between cavity pick-up and cavity incident (Pf) are calculated in both two systems. In LLRF system, this $\Delta\varphi$ will be further filtered

---

[†] qiufeng@post.kek.jp

LOW LEVEL RF ERL EXPERIENCE AT THE S-DALINAC*

M. Steinhorst†, M. Arnold, T. Bahlo, R. Grewe, L. Juergensen, J. Pforr, N. Pietralla,
F. Schließmann, S. Weih
Institut für Kernphysik, TU Darmstadt, Darmstadt, Germany

Abstract

In 2011 the present digital low-level RF (LLRF) control system was set into operation. The first successful one-turn ERL operation was set up in August 2017. The RF control performance was investigated during this new possible operation mode in comparison to other modes that were conventional already before at the S-DALINAC.
The efficiency of the ERL operation can be determined by measurement of the beam loading in the cavities. This could only be done for the first main accelerator cavity. Therefor, an alternative way to determine the ERL efficiency from the already done RF control stability measurements was done to have a good estimate for this measurement. To quantify the ERL efficiency via beam loading measurement an RF power measurement system was developed which is able to measure the RF powers and hence the beam loading for all cavities simultaneously.

RF STABILITY

Introduction

The recirculating superconducting Darmstadt linear accelerator S-DALINAC [1] is one of the main research instruments at the institute for nuclear physics at the TU Darmstadt. It is operating in cw mode at beam currents of up to 20 µA with energies of up to 130 MeV using a thrice recirculating scheme. The current in-house digital LLRF control system of the S-DALINAC was developed in 2011 [2]. Since 2017 the S-DALINAC can be used as an energy recovery linac (ERL). The ERL mode is adjusted by shifting the phase of the beam by 180° in the second recirculation beam line. A first succesful ERL operation was conducted in August 2017 with an injector energy of 2.5 MeV [3, 4]. To state if the current digital LLRF control system is sufficient for a stable ERL operation, it have to be tested in this operation mode and the results have to be compared with stabilities in other modes that are conventional at the S-DALINAC.

Measurement

The investigation of the stability of the current RF control system was done by measuring the residual amplitude and phase errors of all cavities in four different operation modes at a beam current of about 1 µA during an about two hours measurement run. Figure 1 shows an overview of the different operation modes. For RF stability investigation the amplitude error and phase error data of the RF signal was measured in the time domain using the RF control electronics [2, 5]. The data was then Fourier-transformed to the

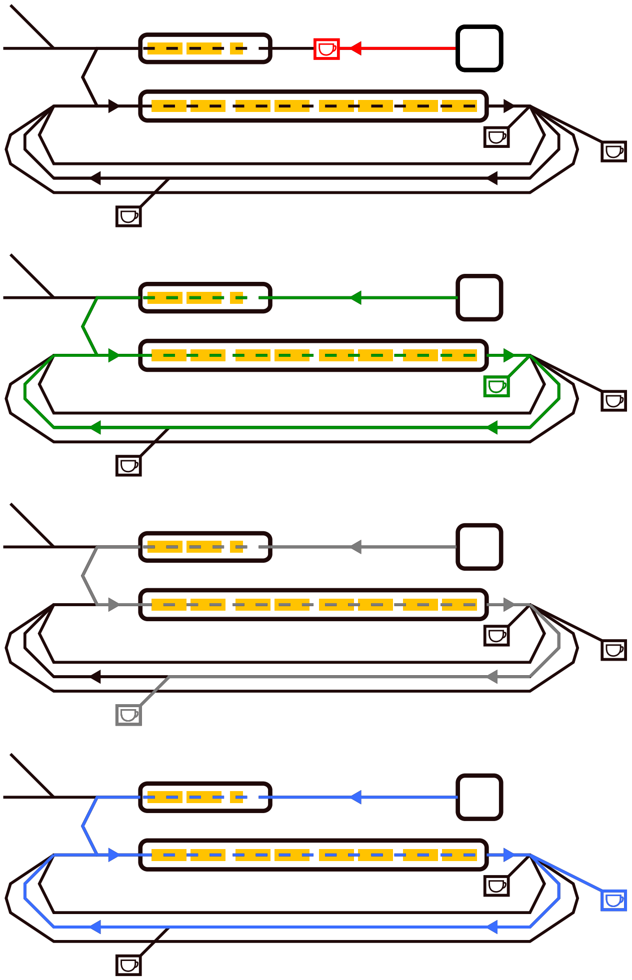


Figure 1: Schematic overview of the four different operation modes of the S-DALINAC during the ERL run. Top: Operation without beam. The beam was stopped at a Faraday cup in front of the injector (beam path indicated in red). Second: Once recirculated ERL operation. The beam was accelerated once in the main accelerator, decelerated in a second pass and dumped in a dedicated cup (green). Third: Once accelerated beam operation. After the first pass through the main accelerator the beam was dumped in a cup in the second recirculation beam line (grey). Fourth: Twice accelerated (once recirculated) beam operation. The beam was accelerated two times in the main accelerator (blue).

---

[*] Supported by DFG (GRK 2128)

[†] msteinhorst@ikp.tu-darmstadt.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-TUCOZBS06

CRYOMODULES FOR THE MAINZ ENERGY-RECOVERING SUPERCONDUCTING ACCELERATOR (MESA)*

T. Stengler†, K. Aulenbacher[1], F. Hug, D. Simon, C.P. Stoll, S.D.W. Thomas
Johannes Gutenberg-Universität Mainz, Mainz, Germany
[1]also at Helmholtz Institut Mainz, Germany and
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

Abstract

Two superconducting radio frequency acceleration cryomodules for the new multiturn ERL facility MESA (Mainz Energy Recovering Superconducting Accelerator) at Johannes Gutenberg-Universität Mainz have been fabricated by industry and are undergoing rf tests at the Helmholtz Institut Mainz (HIM) currently. The modules for MESA are modified versions of the ELBE modules at Helmholtz Center Dresden-Rossendorf. The design energy gain per module and turn is set to 25 MeV. Acceleration is done by in total four TESLA/XFEL cavities, which have been vertically tested at DESY, Hamburg, Germany before being integrated in the MESA modules. In order to validate the performance of the fully dressed cryomodules a test stand has been set up at HIM. Within this contribution we report on the necessary modifications of the modules for high current ERL operation as well as on vertical and horizontal rf test results.

INTRODUCTION

For the main linac of the Mainz Energy-Recovering Superconducting Accelerator MESA [1-3], currently under construction at Johannes Gutenberg Universtität Mainz, two ELBE/Rossendorf-type [4] cryomodules have been produced by industry in Germany [5]. Each module consists of two TESLA/XFEL cavities running on an operation frequency of 1.3 GHz in continuous wave (cw) mode. For electron acceleration a gradient of 12.5 MV/m in each cavity is required to suit the experimental needs of the MESA facility. The dynamic losses of the cavities are limited due to the maximum available cooling power of the cryo-plant. Therefore, the unloaded quality factor of each cavity running on the operating gradient of 12.5 MV/m needs to exceed a value of 10^{10} at the operating temperature of 1.8 K. If MESA is run in ERL mode, a beam current of up to 1 mA needs to be accelerated and decelerated two turns each, yielding to a total sum of 4 mA electron beam in cw inside the accelerating cavities. To suit these needs of MESA, modifications on the module needed to be applied. In particular, the cooling of the HOM antennas was optimized and a fast eigenfrequency tuner (XFEL/Saclay type) based on Piezo actuators for an optimized microphonics compensation has been integrated [6,7].

MESA CAVITIES

Specifications

The performance goals for the MESA cavities and cryomodules have been specified beforehand and the vendor guaranteed parameters for the total energy gain per cryomodule and the static and dynamic cryogenic losses. Table 1 gives an overview on the target values to be verified in the horizontal acceptance tests at HIM.

Table 1: Specifications of fully dressed cryomodule performance in horizontal test operated at 2 K [8]

Variable	Specified Value
Energy Gain	25 MeV
Static Losses	< 15 W
Dynamic Losses @ 25 MeV (cw)	< 25 W
$\propto Q_0$ @12.5 MV/m	$> 1.25{\cdot}10^{10}$

Vertical Test Results

After cavity production a XFEL standard treatment procedure has been applied to the cavities. To check the performance of each cavity after being welded into their Helium vessels, a vertical test at DESY has been carried out. Goals of this test have been the measurement of the quality factors at 2 K and 1.8 K and the determination of maximum gradients and performance limits. The test results have already been discussed in detail in [7,8]. Nevertheless, for giving the possibility to compare the results with the horizontal ones, the results will be presented briefly again. All cavities have achieved test results within specification at 2 K (see Fig. 1).

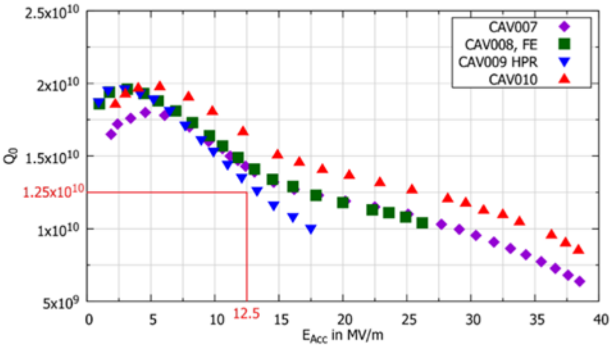


Figure 1: Vertical test results at 2 K operation for all MESA cavities. The measurements have been done at DESY AMTF. All cavities are above specification (red box). CAV 008 showed field emission above 26 MV/m [8].

---

* This work has been supported by DFG through the PRISMA⁺ cluster of excellence EXC 2118/2019.
† tstengle@uni-mainz.de

High Current Performance of Alkali Antimonide Photocathode in LEReC DC Gun *

M. Gaowei[†], E. Wang, J. Cen, A. Fedotov, D. Kayran, R. Lehn, C. J. Liaw,
T. Rao, J. Tuozzolo, J. Walsh
Brookhaven National Laboratory, Upton, NY 11973, U.S.A

Abstract

The bi-alkali antimonide photocathode are chosen as the electron source material for the Low Energy RHIC electron Cooling (LEReC) project at RHIC, BNL based on its requirement for high bunch charge and long-time beam operation. This report presents the design and operation of the cathode deposition and transportation systems for the LEReC photocathodes, the cathode performance under the high current operation in the LEReC DC gun, as well as the characterization of the damaged cathodes from the long-time operation. *In situ* x-ray characterization results for the growth recipe of the alkali antimonide photocathodes prepared for the LEReC is also presented and discussed.

INTRODUCTION

The bunched beam electron cooler (LEReC) at the Relativistic Heavy Ion Collider (RHIC) has been built to provide luminosity improvement for Beam Energy Scan II (BES-II) physics program BES-II at RHIC. The photocathode DC gun in the LEReC accelerator is designed to provide an average current of up to 100 mA, with a required quantum efficiency of 2% ~ 10% from the photocathode material. In the LEReC 2018 operation, the photocathode DC gun has generated an average current of 30 mA and operated non-stop for several hours, with cathode lifetime fitted to be ~ 100 hours. [1-4] In this paper we report the *in situ* x-ray characterization results for the growth recipe of the alkali antimonide photocathodes prepared for the LEReC operation. Cathode performance in the 9.3MHz CW operation of LEReC is also reported. Post operation characterization has been performed and results are discussed in the last section of this paper.

CATHODE DEPOSITION

The LEReC cathode deposition has been switched from the effusion cell deposition back to the sequential 3 step deposition using SEAS getter sources since 2018. The deposition procedure we used for the bi-alkali antimonide photocathode was well developed for the ERL and CeC projects. [5] Compared to the CeC system, the LEReC deposition chamber differs slightly in geometry and does not have an active cooling capacity for the substrate. Therefore, the growth procedure in the LEReC deposition chamber has been optimized for this specific application. The detailed design of the LEReC deposition chamber was described in [6].

As was described in [6], the recipe we decided to use for the LEReC cathode is the well-established sequential growth recipe where 10 nm of Sb was deposited onto the substrate at 80 ˚C, followed by K and subsequent Cs deposition. The K step was performed at 135 ˚C to 140 ˚C, while the Cs step is performed between 130 ˚C to 70 ˚C, while the sample heater is turned off and the substrate cools down. Photocurrent generated by green light was monitored for both the K and the Cs step.

The temperature profile of the substrate with respect to the QE evolution through the K and the Cs step are plotted in Fig. 1. The inset photocurrent during the K step has been shown in × 5 scale for better display and the Cs QE was scaled by post QE calibration with a green laser with known power from the characterization chamber. For the LEReC cathode, we decided to seize the K deposition at an early stage, shortly after the QE rise and before its maximum. The Cs growth is stopped after substrate temperature drops below 70 ˚C, which is the known temperature for maintaining the stable stoichiometry of K_2CsSb. [7]

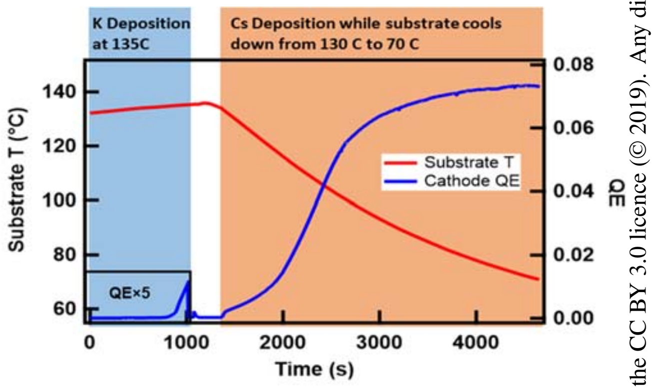


Figure 1: The temperature profile of the substrate with respect to the QE evolution in the Cs step.

The full deposition process takes ~ 2 hrs, while the whole deposition cycle for one cathode is typically 12 hrs, including the substrate heating cleaning, cathode cool down, QE mapping and puck exchange. The production rate for this deposition system is therefore 2 cathodes per day.

In 2018, we have produced 28 cathodes using this system. In 2019, the produced cathodes increased to 38, with an average deposition QE increased from 5.41% to 6.25%. Figure 2 and Table 1 listed all the as measured deposition QE from the LEReC cathodes in 2018 and 2019. The optimized deposition procedure for the LEReC deposition system has yielded ~ 1% higher average QE and an overall

---

*This work was carried out at Brookhaven Science Associates, LLC under contract DE-SC0012704 with the U.S. DOE.

[†] mgaowei@bnl.gov

63th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs ERL2019, Berlin, Germany JACoW Publishing
ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WECOXBS03

BENCH TEST RESULTS OF CW 100 mA ELECTRON RF GUN FOR NOVOSIBIRSK ERL BASED FEL *

V. N. Volkov †, V. Arbuzov, E. Kenzhebulatov, E. Kolobanov, A. Kondakov, E. Kozyrev, S. Krutikhin, I. Kuptsov, G. Kurkin, S. Motygin, A. Murasev, V. Ovchar, V.M. Petrov, A. Pilan, V. Repkov, M. Scheglov, I. Sedlyarov, S. Serednyakov, O. Shevchenko, S. Tararyshkin, A. Tribendis, N. Vinokurov, BINP SB RAS, Novosibirsk, Russia

Abstract

Continuous wave (CW) 100 mA electron rf gun for injecting the high-quality 300-400 keV electron beam in Novosibirsk Energy Recovery Linac (ERL) and driving Free Electron Laser (FEL) was developed, built, and commissioned at BINP SB RAS. The RF gun consists of normal conducting 90 MHz rf cavity with a gridded thermionic cathode unit. Bench tests of rf gun is confirmed good results in strict accordance with our numerical calculations. The gun was tested up to the design specifications at a test bench that includes a diagnostics beam line. The rf gun stand testing showed reliable work, unpretentious for vacuum conditions and stable in long-term operation. The design features of different components of the rf gun are presented. Preparation and commissioning experience is discussed. The latest bench test beam results are reported.

INTRODUCTION

Recent projects of advanced sources of electromagnetic radiation [1] are based on the new class of electron accelerators where the beam current is not limited by the power of rf system – energy recovery linacs (ERLs). Such accelerators require electron guns operating in continuous wave (cw) mode with high average current. The only solution is an rf gun, where the cathode is installed inside the rf cavity. There are no back bombardment ions in rf guns so there are no cathode degradation, and the vacuum condition does not critical there (see Table 1). The most powerful Novosibirsk FEL [2] can be more powerful by one order on magnitude with this rf gun [3-5].

RF GUN AND DIAGNOSTIC STAND

The rf gun and diagnostic stand are presented in Fig. 1.

The RF gun cavity is made on the base of standard bimetallic cavity of Novosibirsk ERL. Detailed information can be found in [3-5]. Only the insert with the thermionic cathode-grid unit is built into the cavity. The gridded thermionic dispenser cathode is driven by special modulator with GaN rf transistor. The modulator generates a launch pulse voltage of up to 150 V and the duration of about 1 ns in any series with repetition frequencies of 0.01 - 90 MHz.

The insert focusing electrode has a concave form to decrease the electric RF field at the grid surface down to 1 MV/m (by one order on magnitude). Due to this the fields before the grid and after it becomes equal to each other so the laminarity of the electron beam flow through the grid remains higher and beam emittance lower. Furthermore, the insert focusing electrode executes the strong rf focusing on the beam just near the cathode that ensures the beam emittance compensation at the relatively low electric field at the cathode. Also it ensures the absence of dark currents in the beam.

There are in the stand: 30 kW water cooled beam dump with 5 cm lead radiation shield, wideband Wall Current Monitor (WCM2) inserted into the replaceable target, Transition Radiation Sensor, the pair of standard WCM, three focusing solenoids, and the special testing cavity.

Table 1: Measured RF Gun Characteristics

Average beam current, mA	≤100
Cavity Frequency, MHz	90
Bunch energy, keV	100 ÷ 400
Bunch duration (FWHM), ns	0.06 ÷ 0.6
Bunch emittance, mm mrad	10
Bunch charge, nC	0.3 ÷ 1.12
Repetition frequency, MHz	0.01 ÷ 90
Radiation Doze Power, mR/h	100/2m
Operating pressure, Torr	$10^{-9} \ldots 10^{-7}$
Cavity RF loses, kW	20

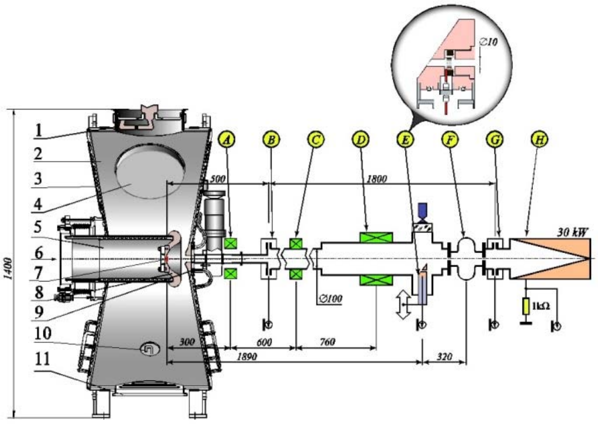


Figure 1: Rf gun and stand layout: 1-Power input coupler; 2- Cavity shell; 3-Cavity back wall; 4-Sliding tuner; 5-Insert; 6-Cathode injection/extraction channel; 7-Thermionic cathode-grid unit; 8-Concave focusing electrode; 9-Cone like nose; 10-Loop coupler; 11-Vacuum pumping port; A-Emittance compensation solenoid; B-First Wall Current Monitor (WCM); C, D - Solenoids ; E-Wideband WCM and transition radiation

---

* Work supported by Russian Science Found- n (project N 14-50-00080)
† v.n.volkov@inp.nsk.su

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC01

STATUS AND FUTURE PERSPECTIVE OF THE TRIUMF E-LINAC

S.D. Rädel*, M. Alcorta, F. Ames, E. Chapman, K. Fong, B. Humphries, O. Kester, D. Kishi,
S.R. Koscielniak, R.E. Laxdal, Y.Y. Ma, T. Planche, M. Rowe, V.A. Verzilov,
TRIUMF, Vancouver, Canada

Abstract

The currently installed configuration of TRIUMF's superconducting electron linac (e-linac) can produce an electron beam up to 30 MeV and 10 mA. Low beam power commissioning of the e-linac spanning the section from the electron gun to the high energy dump took place in summer 2018 and 2019 with an achieved beam energy of 30 MeV. As the driver of the Advanced Rare Isotope Laboratory (ARIEL[1]) project, the e-linac will deliver electrons to a photo-converter target station to produce neutron-rich rare isotope beams (RIB) via photo fission. The e-linac will have sufficient beam power to support the demands of other user community as well. This driver accelerator could serve as a production machine for high field THz radiation and as irradiation centre. A recirculation of the beam would be beneficial for RIB production at higher beam energy and would allow for high bunch compression to generate THz radiation. Such a system would also allow for the investigation of a high beam intensity energy recovery linac. To this end, TRIUMF is investigating the design of an alternate circulation path and the beam dynamics as a first step.

INTRODUCTION

TRIUMF's e-linac is a driver accelerator established within the ARIEL project which was proposed in 2008 [1]. The description of the scientific program can be found in [2, 3].

The layout of the e-linac is shown in Figure 1, including DC gun, bunch compressor and third cryomodule EACB. Currently still in the commissioning phase, the e-linac is operating in a continuous wave (cw) mode with 100 W beam power. This is limited by the present license for beam energies above 10 MeV.

With its final beam specification of 30 MeV and 10 mA the e-linac is an ideal test driver for a high power, high intensity THz photon source. Application for THz radiation are of high-field nonlinear spectroscopy, imaging (including microscopy), biology and medicine as well as in industrial applications.

The Canadian photon science community has a high demand and needs for light sources, therefore the e-linac is a potential drive for a high brilliance source for an IR-FEL. [4]

COMMISSIONING UPDATE

This year TRIUMF continued commissioning the e-linac. In 2018 the commissioning team achieved several milestones while guiding the beam from the source to the main high energy dump with a low power beam, see Figure 1. A detailed description of 2018 commissioning can be found in [5]. Also, during the commissioning the machine protection system (MPS) along the beamline has been commissioned step-by-step to the entrance of EACA.

Electron Gun

The e-linac uses a 300 kV RF-modulated thermionic electron source. The source has been commissioned and operating parameters have been verified. More detailed results can be found in [6, 7]. The origin of recent high voltage problems, which prevented operation above 270 kV, has been identified. They are caused by discharges along a high voltage cable, which connects the power supply to the source. An improvement of the design is being implemented.

Machine Protection System

The e-linac beam loss monitors (BLM) of the MPS are undergoing commissioning [8]. Currently the BLMs in the low and medium energy sections of the e-linac (300 keV and 10 MeV) have been commissioned with a combination of BGO scintillator coupled to a Photo-Multiplier Tube and long ionization chambers. The BLM commissioning in the high-energy section (300 MeV) is underway. Once the BLMs have been commissioned, the power will be slowly increased above 100 W to test the various components of the accelerator, including the 100 kW beam dump.

RF

After passing an injection cryo module that boost the electron beam energy to 10 MeV, the main acceleration happens in the main superconducting acceleration module equipped with two 1.3 GHz nine-cell radio frequency (rf) cavities. Both cavities are driven by one single klystron in a self-excited loop (SEL) in vector sum control [9]. During the 2018 commissioning both cavities were locked and successfully driven together. Instabilities seeded by microphonics and sustained by ponderomotive effects (internal electromagnetic pressure [5]) limited the beam acceleration to an energy of up to 25 MeV with a beam energy stability outside specification.

This year environmental vibration and consequent microphonic effects were reduced at most frequencies by passive means. This was accomplished by adding damping materials or modifying design of several systems including the LN2 cryogenic system and the interfaces to the rf waveguide

---

* sradel@triumf.ca

[1] ARIEL is funded by the Canada Foundation for Innovation, the Provinces AB, BC, MA, ON, QC, and TRIUMF. TRIUMF receives funding via a contribution agreement with the National Research Council of Canada.

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC08

DISPERSION MATCHING WITH SPACE CHARGE IN MESA

A. Khan*, O. Boine-Frankenheim, Technische Universität Darmstadt, Germany
K. Aulenbacher, Johannes Gutenberg-Universität Mainz, Germany

Abstract

For intense electron bunches traversing through bends, as for example the recirculation arcs of an Energy-Recovery Linac (ERL), dispersion matching with space charge of an arc into the subsequent radio-frequency (RF) structure is essential to maintain the beam quality. We show that beam envelopes and dispersion along the bends and recirculation arcs of an ERL, including space charge forces, can be matched to adjust the beam to the parameters of the subsequent section. The present study is focused on a small-scale, double-sided recirculating linac Mainz Energy-recovering Superconducting Accelerator (MESA). MESA is an under construction two pass ERL at the Johannes Gutenberg-Universität Mainz, which should deliver a continuous wave (CW) beam at 105 MeV for physics experiments with a pseudo-internal target. In this work, a coupled transverse-longitudinal beam matrix approach for matching with space charge in MESA is employed.

INTRODUCTION

For intense electron bunches at low to medium energy traversing through bends, it is essential to understand the details of space-charge-induced effects to maintain beam quality throughout the ERL operation [1]. Particularly, current dependent dispersion matching of an arc into the subsequent RF section has been found to be essential to preserve the beam quality. Dispersion matching with space charge has been discussed mostly in the context of high intensity beams in conventional synchrotrons [2]. For example, [3,4] outlined the concept of two different dispersion functions, one for the beam center, which is not affected by space charge, and one for the off-center particles. Experiments related to space charge and dispersion with low energy proton beams were performed in the CERN PS Booster, matching the beam from the linac into the synchrotron. Although the space charge was found to be relevant, it was sufficient to use the zero-intensity dispersion for the matching of the beam center, in order to improve the injection efficiency [5]. In this work, we show that the space-charge-modified dispersion plays a key role for the adjustment of the R_{56} required for both the isochronous and the non-isochronous recirculation mode of an ERL.

An important role of the recirculation arc in an ERL is to provide path length adjustment options to set the accurate required RF phase of 0° to 180° for acceleration and deceleration. Transverse space charge modifies the dispersion function along the arc and so the momentum compaction which is the transport matrix element R_{56} for the individual particles. In case the arc settings are chosen for zero-intensity, one would end up with a dispersion and bunch length different from the design values at a subsequent RF structure [6]. It is therefore necessary to understand the modification of dispersion due to space charge along the arc in order to do proper matching into the next lattice section. Longitudinal space charge also plays an important role, especially for short bunches and small momentum deviations. Longitudinal space-charge-induced variations in the bunch length or momentum deviation also affect the transverse space charge force by varying the local current density and the transverse beam size through the dispersion.

DISPERSION WITH SPACE CHARGE

In the presence of bending magnets, the horizontal displacement x of a particle from the reference particle is written as [6]

$$x\,(s) = x_\beta\,(s) + D_0\,(s)\,\delta, \tag{1}$$

where x_β is the betatron oscillation amplitude, $D_0 \equiv D_0(s)$ is the dispersion function, and $\delta = \Delta p/p_0$ is the fractional momentum deviation. The linear dispersion function without space charge $D_0(s)$ is the solution of the equation [2]:

$$D_0''(s) + \kappa_x(s)D_0(s) = \frac{1}{\rho(s)}, \tag{2}$$

which gives the local sensitivity of the particle trajectory to the fractional momentum deviation δ, and the prime denotes derivative with respect to distance s along the beamline. ρ is the bending radius and κ_x is the linearized horizontal external focusing gradient.

With space charge, we can write:

$$x_{\rm sc}\,(s) = x_{{\rm sc},\beta}\,(s) + D\delta, \tag{3}$$

where $D \equiv D\,(s)$ is the dispersion function with space charge.

Taking the average of Eq. (1) and Eq. (3) and subtracting them over the symmetrical phase space distribution, such that $\langle x_\beta \rangle = \langle x_{{\rm sc},\beta} \rangle = 0$, we obtain (see also [4]):

$$\langle x_{\rm sc} \rangle - \langle x \rangle = (D - D_0)\langle \delta \rangle. \tag{4}$$

For a beam with a momentum distribution centered at the design momentum the dispersion describing the position of the beam centroid is space charge independent. This also explains the experimental results obtained in the CERN PS Booster [5]. There the dispersion was measured and matched by changing the beam momentum and recording the displacement of the beam center.

To observe the effect of space charge on the individual particle dispersion, we have to compute the second moments of the beam distribution. Using the assumption that the momentum deviation is uncorrelated to the betatron oscillations,

---

* khan@temf.tu-darmstadt.de

INVESTIGATION ON THE ION CLEARING OF MULTI-PURPOSE ELECTRODES OF BERLINPRO

G. Pöplau*, Universität zu Lübeck, Lübeck, Germany
A. Meseck, HZB, Berlin, and Johannes Gutenberg-Universität, Mainz, Germany

Abstract

High-brightness electron beams provided by modern accelerators require several measures to preserve their high quality and to avoid instabilities. The mitigation of the impact of residual ions is one of these measures. It is particularly important if high bunch charges in combination with high repetition rates are aimed for. This is because ions can be trapped in the strong negative electrical potential of the electron beam causing emittance blow-up, increased beam halo and longitudinal and transverse instabilities. One ion-clearing strategy is the installation of clearing electrodes. Of particular interest in this context is the performance of multi-purpose electrodes, which are designed such that they allow for a simultaneous ion-clearing and beam-position monitoring. Such electrodes will be installed in the bERLinPro facility. In this contribution, we present numerical studies of the performance of multi-purpose clearing-electrodes planned for bERLinPro, i.e. we investigate the behavior of ions generated by electron bunches while passing through the field of the electrodes. Hereby, several ion species and configurations of electrodes are considered.

INTRODUCTION

The Energy Recovery Linac bERLinPro is currently being set up at the Helmholtz-Zentrum Berlin. Based on superconductive RF (SRF) technology, it aims to deliver high current, low emittance cw beams, and to demonstrate energy recovery at unprecedented parameters [1].

In general, Energy Recovery Linacs place very high demands on maintaining beam brightness and reducing beam losses. Ions in vicinity of the electrons have a ruinous impact on the brightness and stability of the beam. This also applies to bERLinPro. Hence counter measures such as clearing electrodes and their performance is of highest importance for the project. For bERLinPro multi-purpose electrodes, that enable simultaneous ion-clearing and beam position monitoring were developed and built at the HZB [2].

They consist of four rectangular electrode-plates, which can in principle be biased independently with a voltage up to 1000V resulting in different voltage-configurations. The different voltage-configurations naturally have different distributions of the electric field. In this paper, we evaluate the performance of the bERLinPro multi-purpose electrodes for four different voltage-configurations. We relate the difference in performance for different voltage-configurations to the motion of the ions within the corresponding clearing fields.

Table 1: Nominal Parameters of bERLinPro.

bERLinPro Bunch	
Nominal Beam Energy	50 MeV
Nominal Beam Charge Q	77 pC
Maximum Repetition Rate	1.3 GHz
Transv. RMS Bunch Size $\sigma_{x,y}$	300 μm
Bunch Length σ_t	2 ps
Vacuum Pressure	$5 \cdot 10^{-10}$mbar

SIMULATION SETUP AND SIMULATION TOOLS

In this section a short introduction to the simulation setup and the simulation tools are provided. Since the applied models and simulation tools coincide with those used for former studies, more details can be found in [2, 3]. The nominal parameters of bERLinPro that are relevant for the simulations are summarized in Table 1.

The Multi-Purpose Electrode

A description of the technical details of the bERLinPro multi-purpose electrode was given in [2]. Here we only provide the information relevant for the presented simulation studies. The multi-purpose electrodes are constructed of four rectangular stripes (electrode-plates) with a size of 10 mm x 38 mm. These stripes are placed pairwise in parallel with a distance of 24.72 mm along the elliptical beam pipe of bERLinPro (70 mm x 40 mm).

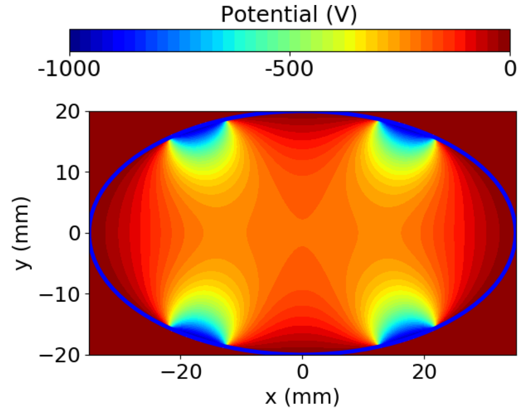


Figure 1: The potential of the bERLinPro multi-purpose electrode with a voltage of −1000 V supplied to all four electrode-plates.

Figure 1 shows the potential of the electrodes with the typical voltage-configuration, where a voltage of −1000 V is

---

[*] poeplau@math.uni-luebeck.de

X-RAY ICS SOURCE BASED ON MODIFIED PUSH-PULL ERLS

I. Drebot*, A. Bacci, A. Bosotti, F. Broggi, S. Cialdi, L. Faillace, D. Giannotti,
D. Giove, P. Michelato, L. Monaco, R. Paparella, F. Prelz, M. Rossetti Conti, A. R. Rossi, L. Serafini,
D. Sertore, M. Statera, V. Torri, INFN, Milano, Italy
V. Petrillo, Universitá degli Studi di Milano & INFN, Milano, Italy
G. Galzerano, E. Puppin, Politecnico di Milano, Milano, Italy
A. Esposito, A. Gallo, C. Vaccarezza, INFN/LNF, Frascati Roma, Italy
G. Mettivier, P. Russo, A. Sarno, Universitá di Napoli, Napoli, Italy
P. Cardarelli, M. Gambaccini, G. Paternó, A. Taibi, Universitá di Ferrare & INFN, Ferrara, Italy

Abstract

We present the conceptual designs of BriXS and BriXsinO (a minimal test-bench demonstrator of proof of principle) for a compact X-ray Source based on innovative push-pull ERLs. BriXS, the first stage of the Marix project, is a Compton X-ray source based on superconducting cavity technology with energy recirculation and on a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz, producing 20-180 keV radiation for medical applications. The energy recovery scheme based on a modified folded push-pull CW-SC twin Linac ensemble allows to sustain MW-class beam power with almost just one hundred kW active power dissipation/consumption.

INTRODUCTION

BriXS (Bright and compact X-ray Source) [1] is a twin Compton X-ray source based on superconductive cavities technology for the electron beam with energy recirculation and on a laser system in Fabry-Pérot cavity at a repetition rate of 100 MHz, producing 20-180 keV radiation.

It has been conceived as the first acceleration stage of the X-ray FEL MariX [2,3]. MariX is an X-ray FEL based on the innovative design of a two-pass two-way superconducting linear electron accelerator, equipped with an arc compressor to be operated in CW mode at 1 MHz.

The double Compton X-ray sources will operate at very high repetition rate 100 MHz, with 200 pC electron bunches that means very high average current 20 mA.

These Compton sources are designed to operate with an electron energy range of 30-100 MeV, which for a 20 mA of current means 2 MW. Such a high beam power cannot be dumped without deceleration, and together with the CW (Continuous Wave) regime, it justifies to foresee an ERL (Energy Recovery Linac) machine, like in the CBETA ERL projecct [4].

The focus on enabled applications by such an energy range and brilliance is on medical oriented research/investigations, mainly in the radio-diagnostics and radio-therapy fields [5,6], exploiting the unique features of monochromatic X-rays, as well as in micro-biological studies, and, within this mainstream, material studies, crystallography and museology for cultural heritage investigations. In this paper, the layout and the typical parameters of the BriXS X-ray source will be discussed.

MACHINE LAYOUT

The BriXS layout, shown in Figure 1, consists of two symmetric beam lines, fed by two independent photoinjectors, where two equal and coupled Energy Recovery Linacs (ERL) accelerate the electron beams. Electron trains are extracted from the photo-cathodes Inj1 and Inj2 at the left side of in Figure 1. The two ERLs (named ERL1 and ERL2 in the Figure) accelerate and decelerate the electron trains in an unconventional push-and-pull scheme. Bunches from Guns and travelling right away in the Figure are accelerated, those coming back from the interaction points (IPs) are decelerated during the energy recovery phase and brought simultaneously to a single beam-dump. Each Linac is therefore traversed by two counter-propagating trains of electron beams, both gaining and yielding energy. This push-and-pull coupled scheme permits to concurrently drive two Compton X-ray sources with the same degrees of freedom, in terms of energy and electron beam quality, as a Linac driven source, with the advantage that the coupled ERLs scheme, fed by two independent RF, systems is more stable. CW electron Guns, capable to produce such an average beam current, are not yet state of the art. Some of the most promising photo cathode Guns [7] as the Cornell DC Gun [8] and the RF-CW Apex Gun [9] have been therefore compared by simulations. Considering the simulations results was chosen the APEX one. Partial modifications of the beam lines to host additional Compton interaction points are under study. BriXs should be considered as a single folded ERL running two beams. This scheme is more compact than two independent ERLs, with the necessity of less magnetic elements and, therefore, a minor cost. An important advantage is that the present scheme provides two knobs for adjusting the phases at the entrance of the linacs in the recovery stage, thus circumventing the necessity of additional matching lines for running one single ERL at different energies.

INJECTOR

Two twin injectors are present in BriXS. The injector layout of the BriXS/MariX common acceleration beam-line, as sketched in Figure 2, is composed of the following accelerating and focusing elements: 1. The CW RF Gun; 2.

---

[*] illya.drebot@mi.infn.it

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC13

PRELIMINARY INVESTIGATIONS AND PRE-RESEARCH SCHEME OF HIGH AVERAGE CURRENT ELECTRON INJECTORS AT IMP

Q.T. Zhao[†], Z.M. Zhang, J.C. Yang, H.W. Zhao
Institute of modern physics, Chinese academy of sciences, Lanzhou, China

Abstract

High average current electron injectors are desired by high average beam power SRF linacs. With respect to the different linac applications, different beam qualities are required. Two kinds of the electron guns are planned for future projects at IMP, one is thermionic electron gun dedicated for high average current, and another one is photocathode gun for high average current and high beam quality or even with high polarization. Current status and development of the high average current electron sources are investigated and summarized. The thermionic gun studies are planned and the feasible types of guns for the future Electron ion collider of China (EicC) project are also proposed. The pre-research of these required electron injectors is schemed, which will be the start of high average current and high-quality electron source development at Institute of modern physics (IMP), Chinese academy of sciences (CAS).

INTRODUCTION

High repetition rate, high average current electron injectors are required by many high average power superconducting radio frequency (SRF) electron linacs. These high average power SRF linacs are dedicated for different applications, such as high average power free-electron lasers (FEL) [1], medical isotope production [2], industry application [3], electron ion collider (EIC) [4], electron cooling for high energy heavy ions [5] and so on. With respect to different applications mentioned above, the requirements of the beam quality are different. The final beam quality required in the interaction region can be traced back to the requirements on the electron bunches from the injector, the first stage of the SRF linac. The electron injector, beginning with a cathode, is the source of the electrons. The quality, bunch length, and timing of the electrons injected into the first linac cavities are critical to determining the properties of the final high energy electron bunch.

Electron injectors can use several different types of cathodes to generate the electrons. One approach is to use a thermionic cathode, which can produce high average currents, but its shortage is hard to generate short bunch length and high repetition rate electron bunches, and the beam quality is mediate. Another approach is to use a photocathode, which is very popular and the promising method to produce high quality electron bunches and can be used for applications with high quality beam, such as FEL, EIC and electron cooling. However, the thermal issues, short lifetime, and drive-laser average power requirements currently present limitations for high average current photocathode injectors. Another unique advantage of the photocathode injector is capable to generate the polarization electron beam which is required for EIC. The electron gun can be classified into three types by the gun cavities and field modes, high voltage DC type, normal conducting RF and SRF type [6]. Due to the critical thermal loads for the normal conducting RF gun, it is not efficient and suitable for high average current and high average power electron source. Another issue of its poor vacuum condition, the normal conducting RF gun is not suitable for polarization electron source. Therefore, here we mainly talk about the high voltage DC gun and SRF gun.

The SRF linac projects are planned in IMP, one is dedicated with high average power application for medical isotope production and others are planned for EicC project [7], which has two SRF linacs, one requires polarized electron injectors with high beam quality and high polarization rate and another one needs high repetition rate, high bunch charge, high beam quality electron injectors for e-cooling of the high energy heavy ions. Different electron injectors are scheduled for the above projects based on the properties of the different types of the electron injectors. In this paper, we discussed the designed and required injectors' parameters for different application and proposed the solution and study plans of the injectors.

RF MODULATED THERMIONIC CATHODE HIGH VOLTAGE ELECTRON GUN

Due to the ability to generate high average current, long lifetime, and good stability and reliability, the thermionic cathode gun is preferred for many high average powers with mediate beam quality applications, like IR-FEL [8] and medical isotope production [9]. Normally, the thermionic cathode high voltage gun generates the direct current, which should be manipulated to short bunch with chopper and buncher devices, in order to match the RF acceleration. This method is inefficient and costly. Another method is gated the thermionic cathode high voltage DC gun with RF voltage, the generated electron bunch repetition rate is same with the frequency of the RF voltage, which is very convenient to generate the high repetition rate electron bunches, as high as 1 GHz [10]. This kind of gun is also considered to be the possible electron source for energy recovery linacs (ERLs) [11], like ERL based IR-FEL, electron cooling [12].

[†] Email address: zhaoquantang@impcas.ac.cn

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC14

ELECTROMAGNETIC DESIGN OF A SUPERCONDUCTING DUAL AXIS SPOKE CAVITY*

Ya. V. Shashkov†, N. Yu. Samarokov
National Research Nuclear University MEPhI, Moscow, Russia
I.V. Konoplev, John Adams Institute, Department of Physics, University of Oxford, Oxford, UK

Abstract

Dual axis superconducting spoke cavity for Energy Recovery Linac application is proposed. Conceptual design of the cavity is shown and preliminary optimizations of the proposed structure have been carried out to minimize the ratio of the peak magnetic and electric fields to the accelerating voltage. The new design and future work are discussed.

INTRODUCTION

In order for the ERL based sources of coherent THz and X-ray radiation to be widely accepted a truly compact (10 m^3), high average current ERLs are required. The demand for the compactness and efficiency can be satisfied by superconducting RF Energy Recovery Linear accelerators (SRF ERL).

The application of two-axis cavity made of identical elliptical shaped RF superconducting accelerating cells for the ERLs applications was proposed by Noguchi and Kako in 2003 [1] and was revisited by Wang, Noonan, and Lewellen in 2007 [2, 3]. The advantage of the asymmetric dual axis system to localise HOMs was only recently realised [4-6] and it was suggested to use for a number of the ERL based applications.

The spoke cavity, originally invented for acceleration of ions and protons, can be used for electron acceleration and there is a growing interest in applications of the multispoke cavities [7]. In this paper, we present the conceptual design of the dual axis asymmetric spoke cavity, optimizations of the cavity shape and preliminary results of the cavity studies. The attractive features of RF superconducting spoke cavities include: 1) the operating frequency of the spoke cavity mainly depends on the spoke length; 2) high cavity stiffness reduces the fluctuation of the cavity resonant frequency due to microphonics; 3) the minimisation of the frequency fluctuations can decrease the required RF power and soften the tolerances required for the construction of the HP input coupler. The spoke cavity is compact as compared with conventional elliptical cavity and if the outer size of a spoke cavity is similar to that of the elliptical cavity, the operating frequency of the spoke cavity is nearly half of that the elliptical cavity. There are a number of advantages of using the low frequency including possibility of utilization of the solid-state power sources as well as operation at higher 4.2 K temperature. Cell coupling of the spoke cavity is stronger than that of elliptical cavity and higher coupling coefficient means robustness with respect to the manufacturing inaccuracy and higher mechanical stability. The fields on the outer surface of a spoke cavities can be relatively small allowing for both the fundamental power coupler and higher-order mode couplers to be located on the outer surface rather than on the beam line. This means better "packing" as couplers are on outer conductor. We note that the tuning of a spoke cavity is complex and demonstration of the ideal design is outside the scope of this work. The aim of this paper is to demonstrate conceptual design with the fields comparable to those observed for a single axis spoke cavity. We focus on a several concepts of the dual axis spoke cavity design and discussion of the advantages and disadvantages of the structures. The schematic diagrams showing merging of the two cavities into the dual axis spoke structure is presented on Fig. 1.

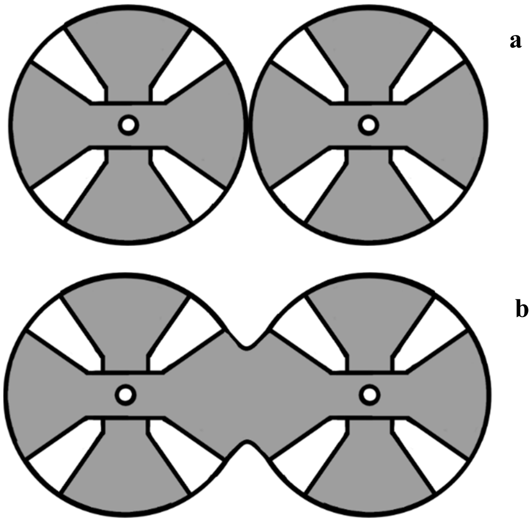


Figure 1: Schematic illustration of observing the dual axis spoke cavity via merging of two cavities (a) before merging and (b) after merging.

TUNING PROCESS

High surface fields in superconducting cavities are highly undesirable because of the detrimental effects on the cavity and ERL performance. At high surface magnetic fields, quenching can occur, and high surface electric fields can cause electron field emission and RF breakdown. As a result, when comparing the performance of the cavities, normalized surface fields are often discussed.

Spoke cavities have a large number of geometric parameters which often influence RF properties. The cavity optimization, therefore is multi-parametric process with a large parameter space to be explored. As a result, the tuning of the cavity to satisfy many parameters takes place in several stages.

---

* The reported study was funded by RFBR according to the research project 18-302-00990

ELECTRON OUTCOUPLING SYSTEM OF NOVOSIBIRSK FREE ELECTRON LASER FACILITY– BEAM DYNAMICS CALCULATION AND THE FIRST EXPERIMENTS

Y.V. Getmanov[1,2†], O.A. Shevchenko[1], N.A. Vinokurov[1,2], A.S. Matveev[1,2]
[1] Budker INP SB RAS, 11 ac. Lavrentiev prosp., Novosibirsk, Russia, 630090
2 Novosibirsk State University, 1 Pirogova St., Novosibirsk, Russia, 630090

Abstract

The radiation power of the FEL with optical cavity can be limited by the overheating of reflecting mirrors. In the electron outcoupling scheme electron beam radiates the main power at a slight angle to the optical axis. For this, it is necessary to divide undulator by dipole magnet at least for two parts – the first for the electron beam bunching in the field of the main optical mode, and the second for the power radiation by deflected beam.

Electron outcoupling system is installed on the third FEL based on the multiturn energy recovery linac of the Novosibirsk Free Electron Laser facility (NovoFEL). It consists of three undulators, dipole correctors and two quadrupole lenses assembled between them. There are two different configurations of the system since the electrons can be deflected in either the second or the third undulator.

The electron beam dynamics calculations and the results of the first experiments are presented.

INTRODUCTION

Free electron lasers (FELs) are the unique source of monochromatic electromagnetic radiation. Radiation is generated due to motion of relativistic electron bunches into the magnetic field of undulator. In contrast to types of lasers, FEL allows to receive radiation of any given wavelength in the operating range, and this wavelength can be relatively quickly tuned [1]. The efficiency of FEL is tenths of a percent of the electron beam average power therefore the use of the energy recovery linacs (ERLs) seems to be the most optimal. The maximum achievable power of an FEL with an optical cavity, aside from the parameters of the electron beam, can be limited by the overheating of reflecting mirrors. To prevent this effect there was proposed the electron outcoupling system [2,3]. Numerical calculations of the such configurations were carried out by various groups of researchers [4-7].

The main idea of the electron outcoupling scheme is to radiate the main part of the power into the small angle to the FEL optical axis, thereby avoiding mirrors overheating. The principle of operation of the schemee is the following (Fig. 1): the electron beam (1) is turned by the dipole magnet (2) into the undulator (3); bunched by interaction with electromagnetic field of the fundamental mode (6) and then deflected by small angle (5) direct to the next undulator (4); emits the main power of the radiation (8). This radiation transported (7) to the user stations. Then the used electron bunch (9) is removed from the system by magnet (2).

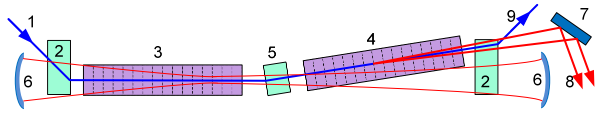


Figure 1: 1 – initial electron beam; 2 – bending magnets; 3 – bunching undulator; 4 – radiating undulator; 5 – beam rotation magnet; 6 – optical mirrors and fundamental mode; 7 – electron outcoupling mirror; 8 – main radiation power; 9 – used electron beam.

NOVOFEL FOUR-TRACK ERL

NovoFEL (Fig. 2) is the high-power terahertz and infrared radiation source [8]. Radiation can be generated by three different FELs using an electron beam of three different ERL configurations. The main parameters of the third FEL based on four-track ERL (Fig. 3) are presented in Table 1. The third FEL operates as user facility since 2015. It consists of three permanent magnet undulators with the variable gap (see Fig. 4) and an optical cavity. This undulator separation into three parts was made, in particular, for experiments with electron outcoupling system. For this purpose, the quadrupole lenses and additional dipole correctors are installed in the empty spaces between the undulators and at the ends of the undulators (Fig. 5). The feasibility study of using this scheme in the NovoFEL facility was described in [9].

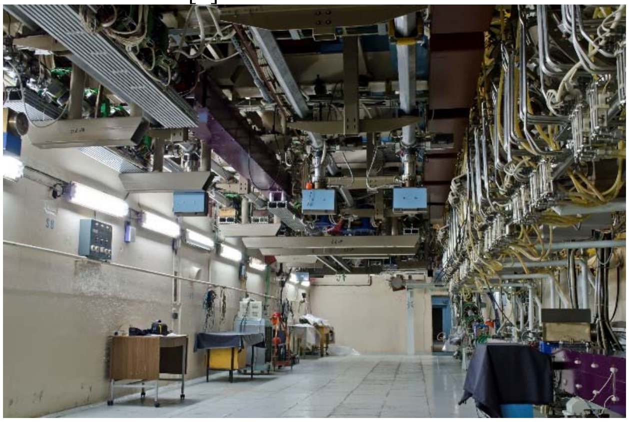


Figure 2: Accelerator hall and the tracks (on the ceiling) of the four-pass NovoFEL ERL.

---

† y_getmanov@mail.ru

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC17

PHOTOCATHODE R&D AT DARESBURY LABORATORY: NEW TRANSVERSE ENERGY SPREAD MEASUREMENTS AND THE DEVELOPMENT OF A MULTI–ALKALI PHOTOCATHODE PREPARATION FACILITY

L.B. Jones[1,3*], D.P. Juarez-Lopez[2,3], L.A.J. Soomary[2,3], B.L. Militsyn[1,3],
C.P. Welsch[2,3] & T.C.Q. Noakes[1,3]

[1] ASTeC[†], STFC Daresbury Laboratory, Warrington, WA4 4AD, United Kingdom
[2] Department of Physics, University of Liverpool, L69 7ZE, United Kingdom
[3] The Cockcroft Institute, Warrington, WA4 4AD, United Kingdom

Abstract

The minimum achievable emittance in an electron accelerator depends strongly on the intrinsic emittance of the photocathode electron source. This is measurable as the mean longitudinal and transverse energy spreads in the photoemitted electron beam from the cathode source.

ASTeC[†] constructed the Transverse Energy Spread Spectrometer (TESS) experimental facility to measure both the transverse and longitudinal electron energy spectra for III–V semiconductor, multi–alkali and metal photocathodes. Our R&D facilities also include in–vacuum quantum efficiency measurement, XPS, STM, plus ex–vacuum optical and STM microscopy for surface metrology.

Photocathode intrinsic emittance is strongly affected by surface roughness, and the development of techniques to manufacture the smoothest photocathode is a priority for the electron source community. Other factors such as crystal face, illumination wavelength and temperature have a significant effect on photocathode intrinsic emittance. We present an update on advances in our photocathode R&D capabilities and some preliminary results from new measurements.

INTRODUCTION

The intrinsic emittance of a photocathode is the combination of many physical attributes such as composition, crystal face, surface roughness, cleanliness, quantum efficiency (QE), work function (ϕ) and illumination wavelength (λ). Intrinsic emittance expressed in microns per mm of laser illumination spot diameter ($\mu m/mm$) defines the lower limit of emittance in a well–configured linear accelerator.

In the absence of space charge effects, the source emittance can be preserved throughout acceleration in machines of this class [1]. The impact of reducing intrinsic emittance is therefore significant, and can potentially reduce both the physical size and capital cost of a Free-Electron Laser (FEL) facility driven by such an accelerator [2] while also increasing the X–ray beam brightness and hence the FEL performance. This is the primary justification for our work in this area in support of the CLARA [3] linear accelerator project.

Our Transverse Energy Spread Spectrometer (TESS) [4] experimental facility measures the photocathode electron emission footprint for low–energy electrons (typically <100 eV) from which the transverse and longitudinal energy distribution curves (TEDC and LEDC respectively) can be extracted [5]. TESS is connected to our III–V Photocathode Preparation Facility (PPF) [6] which provides storage for up to 6 photocathode samples under XHV conditions and supports thermal and atomic hydrogen cleaning.

The factors which affect photocathode performance require a suite of diagnostic techniques so our R&D facilities also include XPS, LEED and AFM/STM in our SAPI (Surface Analysis, Preparation and Installation) system [7, 8], with ex–situ interferometric optical and AFM microscopes for surface roughness measurements. We have a range of laser and broadband light sources which permit QE measurements at various wavelengths on different cathode materials.

Recently the TESS experimental system has been further upgraded and we have constructed a vacuum suitcase system which facilitates the movement of up to 4 photocathode samples between our various experimental systems under UHV conditions. This vacuum suitcase can also be used to bring photocathodes from other laboratories for characterisation using our systems. Our photocathode manufacturing capabilities are also being expanded through the construction of a multi–alkali photocathode preparation facility.

TESS CRYOGENIC UPGRADE

The TESS detector was originally specified as a general–purpose instrument to image the photoemission footprint of semiconductor photocathodes under illumination by solid–state laser modules [4]. The detector combined 3 independent grid meshes with a microchannel plate (MCP) electron multiplier and a P43 ITO phosphor screen, using a sensitive camera to record the electron emission footprint.

The detector was recently upgraded and now uses a single demountable grid mesh which facilitates the same transverse and longitudinal energy spread measurements, but with increased sensitivity [9]. This upgrade included the installation of a broadband Energetiq EQ–99 laser plasma-driven light source coupled through nitrogen–purged off–

---

[*] lee.jones@stfc.ac.uk
[†] ASTeC: Accelerator Science and Technology Centre

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC19

OPTIMIZATION OF THE PERLE INJECTOR

B. Hounsell*[1, 2], M. Klein, C.P. Welsch[1], University of Liverpool, Liverpool, United Kingdom
W. Kaabi, Laboratoire de l'accélérateur Linéaire CNRS/IN2P3 Université Paris-Saclay, Orsay, France
B.L. Militsyn[1], UKRI STFC, Sci-Tech Daresbury, Warrington United Kingdom
[1]also at Cockcroft Institute, Warrington, United Kingdom
[2]also at Laboratoire de l'accélérateur Linéaire CNRS/IN2P3 Université Paris-Saclay, Orsay, France

Abstract

The injector for PERLE, a proposed electron Energy Recovery Linac (ERL) test facility for the LHeC and FCC-eh projects, is intended to deliver 500 pC bunches at a repetition rate of 40.1 MHz for a total beam current of 20 mA. These bunches must have a bunch length of 3 mm rms and an energy of 7 MeV at the entrance to the first linac pass while simultaneously achieving a transverse emittance of less than 6 mm·mrad. The injector is based around a DC photocathode electron gun, followed by a focusing and normal conducting bunching section, a booster with 5 independently controllable SRF cavities and a merger into the main ERL. A design for this injector from the photocathode to the exit of the booster is presented. This design was simulated using ASTRA for the beam dynamics simulations and optimized using the many objective optimization algorithm NSGAIII. The use of NSGAIII allows more than three beam parameters to be optimised simultaneously and the trade-offs between them to be explored.

INTRODUCTION

PERLE is a proposed three turn 500 MeV ERL intended as a test facility for the FCC-eh/LHeC projects [1]. The bunch repetition rate of PERLE is 40.1 MHz which means that to achieve an average beam current of 20 mA a bunch charge of 500 pC is required. The specification of PERLE requires also a transverse emittance of less than 6 mm·mrad at a bunch length of 3 mm to be delivered from the injector to the main ERL loop. The specifications of the PERLE injector are summarised in Table 1.

Table 1: A Summary of the Specification for the Bunch Properties Delivered from the PERLE Injector

Beam parameter	**Required value**
Bunch charge, pC	500
Bunch repetition rate, MHz	40.1
Average beam current, mA	20
RMS normalised transverse emittance mm·mrad	< 6
RMS bunch length, mm	3
Beam energy, MeV	7
Uncorrelated energy spread, keV	< 10
Operation mode	CW

The requirement of a CW operation mode and beam parameters of the injector means that there are three possible options for the electron source: a high voltage DC electron gun, an SRF CW gun or a VHF CW gun. The gun should operate with photocathode illuminated with laser light which is the only way of providing beams with the required time structure at the required quality.

The majority of pre-existing ERL projects have used DC gun based injectors. The possible operation mode with polarised electrons of PERLE would require a GaAs based photocathode. This kind of photocathode is extremely sensitive to the vacuum conditions and at the moment only DC guns are capable of achieving the vacuum quality required. Such a gun was used as electron source of ALICE ERL test facility at Daresbury Laboratory, UK [2]. In addition it has been experimentally demonstrated at Cornell University that DC gun based injectors can deliver bunches with bunch charges higher than the nominal value for PERLE and transverse emittances lower than required for the PERLE specification [3]. The history of successful use of DC electron guns on ERL projects, the possibilty of re-using the ALICE electron gun, the fact that they are the only technology which can provide polarised electron beams and their experimentally demonstrated performance at high bunch charges are all factors in why the injector for PERLE will be based on a DC electron gun.

INJECTOR LAYOUT

The PERLE injector follows the proven layout comprising of a 350 kV high voltage electron gun, focusing solenoid, a normal conducting buncher cavity, solenoid and then a superconducting booster linac. The booster linac consists of 5 SRF cavities with independently controllable phases and amplitudes. A sketch of the layout can been seen in Fig. 1.

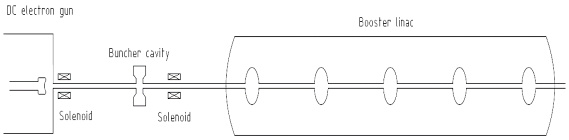


Figure 1: The layout of the PERLE injector.

The electron gun used for the PERLE injector will be an upgraded and modified ALICE electron gun operating with an antimonide based photocathode such as Cs_3Sb. The majority of the upgrade will be identical to that designed for ALICE itself [4]. However the electrode system has to

---

* ben.hounsell@cockcroft.ac.uk

Decoupling Cathode and Lattice Emittance Contributions from a 100 pC, 100 MeV Electron Injector System

N.P. Norvell*, SLAC National Accelerator Lab, Menlo Park and UC Santa Cruz, CA USA
M.B. Andorf, I.V. Bazarov, J.M. Maxson, C. Gulliford
Center for Bright Beams, Cornell University, Ithaca NY, USA

Abstract

We present simulation results to decouple the emittance contributions that are intrinsic from the injector lattice versus emittance contributions due to the quality of the cathode out of a 100 MeV electron injector system. Using ASTRA driven by the NSGA-II genetic algorithm, we optimized the LCLS-II injector system with a zero emittance cathode. We then imposed FEL specific energy constraints and show how the Pareto Front solution shifts. Lastly, we reoptimized at various cathode emittances to map out the dependence of cathode emittance versus final emittance out of the injector system. We then determined the cathode quality needed to hit a 0.1 mm mrad 95% rms transverse emittance specification out of the current LCLS-II injector system.

SIMULATION MOTIVATION

SLAC National Accelerator Lab is currently constructing a MHz repetition rate Free Electron Laser (FEL), the Linac Coherent Light Source II, to follow up the success of the 120 Hz LCLS. LCLS-II will initially run with a 4 GeV superconducting linac but plans are underway to upgrade the linac further to accelerate electrons to 8 GeV for LCLS-II HE (High Energy), increasing the maximum deliverable x-ray energy up to almost 15 keV[1]. Even after the upgrades to the LCLS-II facilities, FEL users would still like a higher photon range from the LCLS-II complex. At higher electron energies, the x-ray energy range becomes throttled by emittance if the number of undulator magnets are not increased[1]. Emittance directly determines how efficiently the electron beam microbunches, which is required to start the exponential growth of x-ray production in the undulators[2]. Currently, LCLS-II expects a transverse normalized emittance of 0.4 mm-mrad at the first undulator for a 100 pC electron beam. As shown in Fig. 1, simulations predict that decreasing the normalized emittance at the undulators from 0.4 to 0.1 mm-mrad with an 8 GeV electron beam would expand LCLS-II HE x-ray energy upper bound from 15 keV to 22 keV. The benefit from lower emittance is even more drastic for FELs driven with higher electron energies with a similar undulator hall.

The quality of the electron beams produced in an accelerator facility is inherently limited by the emittance of the beam produced in the injector system. We define the injector system as the beamline that takes the beam from a cathode to around 100 MeV, when space charge effects are no longer a concern. The current LCLS-II injector system simulations predict transverse emittances around 0.3 mm-mrad out of the injector, indicating that injector improvements are necessary and the correct place to start looking to improve the emittance [3]. In these proceedings, we investigate the emittance benefits for the LCLS-II injector we could expect from improving the cathode quality and determine how much we would have to improve the cathode by to deliver a beam with a 0.1 mm mrad 95% rms transverse emittance for the LCLS-II HE project.

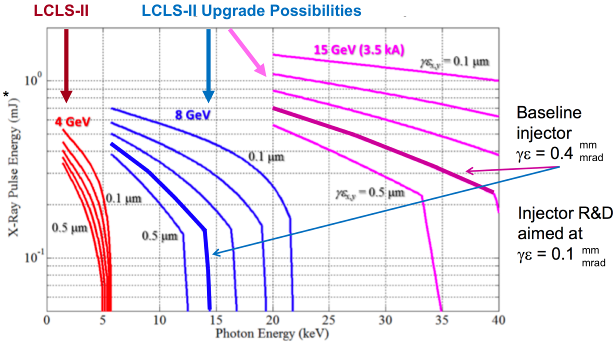


Figure 1: Expectations for how the emittance will effect the photon range for the LCLS-II and potential upgrades for various linac energies. The curves are predicted from the Ming Xie equations that numerically find the power gain length for x-ray generation[1].

OPTIMIZATION METHODOLOGY

We started with the optimization end point from the original LCLS-II optimization[4][5]. We used the particle tracking code ASTRA[6] driven by the multi-objective genetic algorithm NSGA-II [7] to compute and optimize two competing quantities, bunch length σ_z and the 95% rms horizontal emittance[8]. We get a set of solutions, called a Pareto Front, that visually documents the trade off between these two competing variables. We used a population size of 80 and ran all simulations with a bunch charge of 100 pC.

The first study documented the Pareto Front limit of an injector system. To isolate the lattice emittance contributions that are due to space charge, we turned off the cathode emittance by using ASTRA's generator program to create a radially uniform beam emerging from a zero longitudinal and transverse emittance source.

We imposed constraints to guide the optimizer to rea-

---

[*] nnorvell@slac.stanford.edu

BEAM IMPEDANCE STUDY ON A HARMONIC KICKER FOR THE CCR OF JLEIC

Gunn Tae Park, Jiquan Guo, Shaoheng Wang, Robert Rimmer,
Frank Marhauser, and Haipeng Wang
Thomas Jefferson National Laboratory, Newport News, VA 23606, USA

Abstract

The design of a high power prototype of the harmonic kicker cavity for the Circulator Cooler Ring (CCR) of Jefferson Lab's proposed Electron-Ion Collider (JLEIC) is complete and fabrication is underway. In this report we present some of the impedance studies assuming a high beam current of the JLEIC (~ 0.76 A average) to estimate the HOM power dissipation and RF power requirement.

INTRODUCTION

A harmonic kicker cavity has been developed as a device that rapidly injects/extracts electron bunches into/out of the CCR of JLEIC [1], [2]. The engineering design of a high power prototype cavity based on a quarter wave resonator (QWR) is complete (See Fig, 1) [3], [4]. The cavity optimization took into consideration the higher order mode (HOM) impedance spectrum so that the HOM power induced by passing electron bunches is relatively low. In this report, we demonstrate that the beam-induced power due to the HOM's is below ~ 15 W within a ± 10 mm transverse beam offset from the ideal orbit. Consequently, HOM dampers are not strictly needed. This analysis was carried out employing both analytical calculation with the knowledge of impedance of discrete eigenmodes and via a wake field simulation using CST-MWS and CST-PS respectively [5]. In addition, we estimated the required power from the RF source needed to maintain a constant kick voltage with five deflecting harmonic modes.

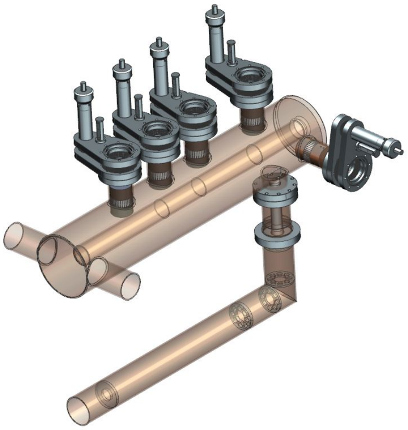


Figure 1: CAD model of the harmonic kicker cavity.

HOM POWER

The induced HOM power dissipated in the cavity can be evaluated in two ways. One is based on eigenmodes of the cavity computed numerically by the eigensolver of CST-MWS. Then the power associated with each eigenmode can be calculated analytically. The other is taking into account that the cavity modes are continuously fed by the beam bunch train. Therefore, the broadband coupling impedance spectrum (up to the first cutoff frequency of the beam pipe) has been evaluated using the wake field solver of the CST-PS, which allows to compute its power spectrum.

Time Structure of Beam Current in the CCR

The beam current in the CCR (for the parameters, see [6]) comes in a series of bunch trains with a gap (empty bucket) between the trains as shown in Fig. 2a. In addition to the periodicity of the bunch at a repetition rate of (f_b = 476.3 MHz), there is another periodicity arising from bunch train i.e., f_p = 1.4 MHz, which is very close to the CCR revolution frequency. The beam current can be expanded in a Fourier series, i.e.:

$$I(t) = \sum_m I_m e^{im\omega_p t} = c + id, \tag{1}$$

where

$$\begin{aligned} c(t) &= \sum_m I_m \cos(m\omega_p t), \\ d(t) &= \sum_m I_m \sin(m\omega_p t), \end{aligned}$$

where I_m and $m\omega_p$ with $\omega_p = 2\pi f_p$ are the amplitude and angular frequency of each mode of the current. The Fourier spectrum of the current is shown in Fig. 2b.

Power Evaluation via Eigenmodes

For each eigenmode, the induced voltage with beam current as given in the CCR can be written as

$$\begin{aligned} V_{b,n,\parallel}(t) &= \int_{-\infty}^{t} dt'\, I(t') \frac{\omega_n R_{n,\parallel}}{2Q_{n,0}} e^{(i\omega_n - 1/\tau_n)(t-t')} \\ &= \frac{R_{n,\parallel}}{Q_{n,0}} Q_{n,L} \Big(a + ib\Big), \end{aligned} \tag{2}$$

$$\begin{aligned} \text{where } a(t) &= \sum_m \frac{I_m}{\sqrt{1+\zeta_m^2}} \cos(m\omega_p t - \psi_m), \\ b(t) &= \sum_m \frac{I_m}{\sqrt{1+\zeta_m^2}} \sin(m\omega_p t - \psi_m), \\ \zeta_m &= 2Q_L\Big(\frac{m\omega_p}{\omega_n} - 1\Big), \quad \psi_m = \tan^{-1}\zeta_m. \end{aligned}$$

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-WEPNEC25

RESEARCH ON ALKALI ANTIMONIDE PHOTOCATHODE FABRICATION RECIPE AT PKU

D.M.Ouyang, X.K. Zhang, S. Zhao, H.M. Xie†, L.W. Feng, S. Huang, S.W. Quan, K.X. Liu,
Institute of Heavy Ion Physics & State Key Laboratory of Nuclear Physics and Technology Physics and Technology, Peking University, Beijing 100871, China

Abstract

Low emittance, high QE and long lifetime photocathode is widely studied for X-ray Free Electron Laser (XFEL) and Energy Recovery Linacs (ERL) applications. A deposition system for alkali antimonide photocathode (K_2CsSb, Cs_3Sb etc.) is being commissioned at Peking University. In this paper, we present our experimental results on alkali antimonide photocathode with this deposition system. We successfully fabricated Cs_3Sb photocathode on oxygen free copper, p-type Si (100) and Mo substrates with QE of 1.4%, 2.6% and 2.6% respectively.

INTRONDUCTION

XFEL, ERL and electron cooling demand low emittance, high QE and long lifetime photocathode. The alkali antimoide photocathode has high QE (4~10%) at green light, low intrinsic emittance (~0.5 μ m/mm) and long lifetime [1]. DC-SRF injector was stable operation to generating CW electron beams in 2014 at PKU [2]. Now, a low emittance DC-SRF photocathode injector (DC-SRF-II) is under construction for XFEL at PKU. In order to meet the requirement of the upgraded version of DC-SRF-II injector (bunch charge 100 pC, lower emittance < 1μm and repetition rate ~1MHz) [3-4], we choose the alkali antimonide photocathode.

In this paper we present our alkali antimonide photocathode deposition system and experimental results on fabricating Cs_3Sb photocathode at PKU. We also measured its spectral response and dark lifetime on the UHV system.

ALKALI ANTIMONIDE PHOTOCATHODE DEPOSITION SYSTEM

We have developed an alkali antimonide deposition system which consists of a deposition chamber, a transport chamber, a suitcase chamber, a spectral response measurement system, an intrinsic emittance measurement system (under construction based on LBNL design [5]), and four manipulators to transfer the sample. The substrate was initially kept in the suitcase chamber, and then transferred to the transport chamber by two manipulators. Utilizing another manipulator, the substrate can be moved to the deposition chamber. When the photocathode was prepared, it can be transported to injector by suitcase or though the transport chamber. Three sources, Cs, K and Sb were mounted on the deposition chamber and alkali sources were separated from each other and from the chamber by ultrahigh-vacuum (UHV) gate valves. A sputtering ion pump (400L/s) and SAES NEG pumps (3500L/s and 2000L/s) can provide pressure 10^{-9} Pa in deposition chamber and transport chamber. We employed a quartz crystal monitor to record the thickness of the film during evaporation and a residual gas analyser (RGA) was utilized to analyse the partial pressure of gases in the deposition chamber (see Fig. 1). The photocathode was irradiated by a 520 nm, power adjustable laser and we employed a Keithley 6485 picoammeter to monitor the photocurrent leaving the photocathode.

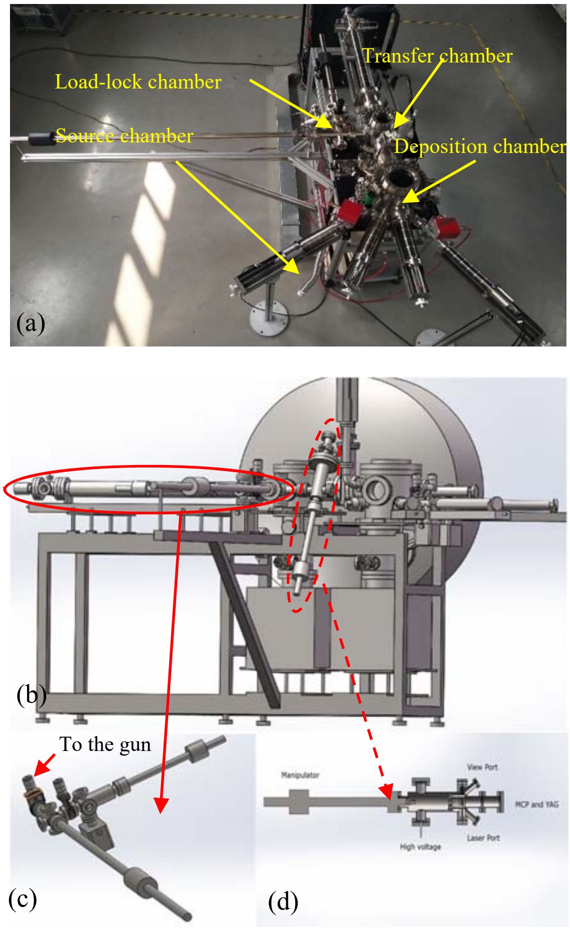


Figure 1: (a) Photograph and (b) schematic diagram of alkali antimonide photocathode deposition system. (c)Suitcase. (d)The intrinsic emittance measurement system.

---

† hmxie@pku.edu.cn

COMMISSIONING OF THE bERLinPro DIAGNOSTICS LINE USING MACHINE LEARNING TECHNIQUES*

B. Kuske†, Helmholtz-Zentrum für Materialien und Energie, Berlin, Germany,
A. Adelmann, Paul Scherrer Institut, Villigen, Switzerland

Abstract

bERLinPro is an Energy Recovery Linac (ERL) project currently being set up at HZB, Berlin. It is intended as an experiment in accelerator physics, to pioneer the production of high current, low emittance beams in a fully super-conducting accelerator, including SRF gun, booster and linac. RF-Commissioning of the gun is planned in mid 2020, [1]. HZB triggered and partially supported the development of release 2.0 of the particle tracking code OPAL [2]. OPAL is set up as an open source, highly parallel tracking code for the calculation of large accelerator systems and many particles. Thus, it is destined for serving attempts of applying machine learning approaches to beam dynamic studies, as demonstrated in [3]. OPAL is used to calculate hundreds of randomized machines close to the commissioning optics of bERLinPro. This data base is used to train a polynomial chaos expansion, as well as a neural network, to establish surrogate models of bERLinPro, much faster than any physical model including particle tracking. The setup of the sampler and the sensitivity analysis of the resulting data are presented, as well as the quality of the surrogate models. The ultimate goal of this work is to use machine learning techniques during the commissioning of bERLinPro.

INTRODUCTION

As any linear accelerator, an ERL is an initial value problem: without exact knowledge of the initial parameters of the beam, a later understanding and characterization of the beam parameters is difficult. Therefore, a thorough understanding of the gun is indispensable. Before the gun is assembled and tested, many ambiguities exist, starting from the actual energy of the beam, i.e. the gun field reachable with tolerable field emission, over the bunch parameters, to the system parameters leading to successful acceleration. As the system is heavily space charge dominated with bunch charges of 77 pC, tracking calculations including space charge take minutes to hours, depending on the size of the considered structure, the number of particles and the grid size, even with a highly parallized code like OPAL. It is tempting to try to replace the tracking calculations by surrogate models, that deliver answers very close to tracking results in much shorter time, in the order of milliseconds. That would enable 'online modeling' in the control room, where the surrogate model is fed by machine parameter read-backs and would deliver expectation results for beam measurements. The paper presents first steps in setting up surrogate models for the diagnostics line of bERLinPro, where the gun is characterized. It makes strong use of earlier work and experience, published in [3] and [4]. It is intended to use surrogate models to ease and to speed up commissioning.

DIAGNOSTICS LINE

The diagnostics line consists of the 1.3 GHz, 1.4 cell, single cavity SRF gun, providing up to 3 MeV electrons with a design bunch charge of 77 pC. The gun module also hosts two corrector coils (H/V) and a cold solenoid. The booster, hosting three two-cell cavities can boost the energy up to 6.5 MeV. The first cavity imprints a chirp on the bunch for velocity bunching, while the other two cavities are run on crest for acceleration. Further elements are 6 quadrupoles, a transverse deflecting cavity, a spectrometer followed by a 300 W Faraday cup, or, straight ahead, a 35 kW beam dump, Fig. 1. Optics were developed including the booster (6.5 MeV) and with three booster replacement quadrupoles (taken from the recirculator) and 2.7 MeV. Four beam position monitors (BPM) and two screens (FOM) are available for diagnostics.

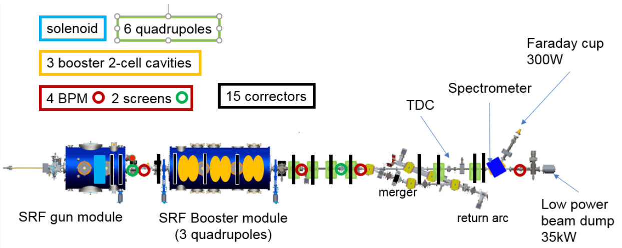


Figure 1: The diagnostics line is intended for the characterization of gun and booster and initial beam parameters.

Independent Modeling Parameters

The ambiguities in the gun parameters, prior to commissioning, are caused by:

- production uncertainties like cavity geometry and field flatness, i.e. the gun field
- changes during cool down of SRF structures (f.e. cathode retraction position)
- ambiguities before first use (f.e. achievable max. gun field amplitude).

In addition, the cathode laser pulse length, spot size and intensity, the solenoid strength, the phases and amplitudes of three booster cavities and the field of the six quadrupoles in the beam line will determine the bunch properties. The transverse beam size can be measured on the two screens and four BPMs. The transverse deflecting cavity (TDC) and the spectrometer in combination enable the measurement of

---

* Work supported by German Bundesministerium für Bildung und Forschung, Land Berlin and grants of the Helmholtz Association

† bettina.kuske@helmholtz-berlin.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-THCOWBS03

SYSTEM IDENTIFICATION PROCEDURES FOR RESONANCE FREQUENCY CONTROL OF SC CAVITIES*

S. Orth†, H. Klingbeil, Institut für Teilchenbeschleunigung und Elektromagnetische Felder,
Accelerator Technology Group, TU Darmstadt, Germany

Abstract

Energy Recovery Linacs promise superior beam quality—smaller emittance and higher intensity. To reach these goals, resonance frequency control of the superconducting RF cavities has to be optimized.

To ensure stability of the resonance frequency the helium pressure inside the cryomodules is measured and stabilized. In order to improve the performance of the applied controller, i. e. for optimizing its parameters, one has to obtain the system's transfer function by means of physical modelling or system identification techniques. In this work the latter approach is presented. Special constrictions are the necessity to run the system in closed-loop mode and using data obtained during normal machine operation.

The results of system identification procedures conducted at the helium-pressure stabilizing system of the S-DALINAC's cryomodules (Institute for Nuclear Physics, TU Darmstadt, Germany) and first results of a test with improved control parameters are shown.

MOTIVATION

Due to their narrow bandwidth SC cavities are very sensitive to changes in their geometry. A 1 mbar pressure change of the helium in the cryomodules for example can cause a change in the resonant frequency of 20 to 50 Hz. Resonance frequency control with e. g. piezo tuners can be used to counteract this [1]. Another approach can be eliminating the sources of some disturbances, like decoupling the cryomodules from mechanically vibrating components such as vacuum pumps. Nevertheless, if there is for example a sudden heat intake, maybe due to turning on the RF power delivery to the cavities (or vice versa, lesser heat intake if one has to turn them off), this can cause more helium to evaporate (or less, respectively) and thus resulting in fluctuations of the helium pressure that have to be damped by the controller by increasing (or decreasing) the pump's speed.

Figure 1 shows a typical measurement of the helium pressure when such a disturbance occurs. The system is operated in closed-loop mode so that the controller damps the disturbance to reach the steady state. At the S-DALINAC this process can take up to three hours, as on can see in Fig.1.

Although this is a rather slow process it causes drifts that have to be compensated by the piezo tuners. Since these feedback loops rely on the measurement of the RF phase, they can have problems detecting such slow changes and sometimes manual corrections to the RF phase are applied by the operators who recognize e. g. a drift in the beam energy. To improve long-term stability of the beam quality and to ease the operation of the machine, an improvement of the helium pressure stabilizing controller was desired.

There have been some tests modifying the controller's parameters—it's a standard PID controller with $P = 250,\ I = 3\,\mathrm{s},\ D = 0\,\mathrm{s}$:

$$U(t) = PE(t) + \frac{1}{I}\int_0^t E(t')\mathrm{d}t' + D\frac{\mathrm{d}E(t)}{\mathrm{d}t}. \quad (1)$$

Especially the D-component was slightly increased to speed up the system, but no results were found in the tested parameter range. To ensure stable operation this range was chosen very narrow.

With the model obtained from system identification an improved set of control parameters was suggested and successfully tested.

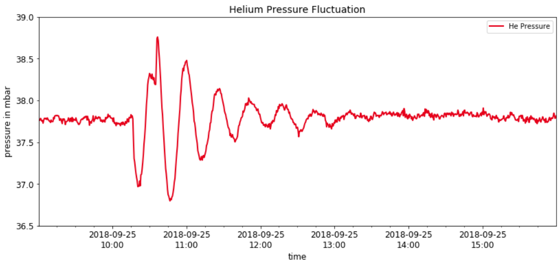


Figure 1: Helium pressure fluctuation in a cryomodule after a disturbance.

This system identification was also intended to serve as a prove of principle for closed-loop system identification procedures that are planned to be applied to other components as well. To make this transfer more convenient a generalized description of the system will be given in the next section followed by an overview over different closed-loop system identification techniques and a their advantages and disadvantages. Then, the results of such an identification process applied to the helium pressure stabilizing system and simulations with improved control parameters are shown. These predictions have been tested and first measurement results are presented.

BLOCK DIAGRAM AND SYSTEM EQUATIONS

The block diagram of a closed-loop system is depicted in Fig. 2. Note that for an open-loop system identification there is no feedback of the system's output y and in many cases the identification directly uses the system's input u. Also

---

* Work supported by DFG: GRK 2128 "AccelencE"

† orth@temf.tu-darmstadt.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-THCOWBS06

BEAM BREAKUP LIMIT ESTIMATIONS AND HIGHER ORDER MODE CHARACTERISATION FOR MESA*

C. P. Stoll†, F. Hug, Institut für Kernphysik der JGU Mainz, Germany

Abstract

MESA is a two pass energy recovery linac (ERL) currently under construction at the Johannes Gutenberg-University in Mainz. MESA uses two 1.3 GHz TESLA type cavities with 12.5 MV/m of accelerating gradient in a modified ELBE type cryomodule in c.w. operation. One potential limit to maximum beam current in ERLs is the transverse beam breakup (BBU) instability induced by dipole HOMs. These modes can be excited by bunches passing through the cavities off axis. Following bunches are then deflected by the HOMs, which results in even larger offsets for recirculated bunches. This feedback can even lead to beam loss. To measure the quality factors and frequencies for the dressed as well as undressed cavities improves the validity of any current limit estimation done.

MESA

The Mainz Energy-recovering Superconducting Accelerator (MESA) is a small-scale, multi-turn, double-sided recirculating linac with vertical stacking of the return arcs currently being built at the Johannes Gutenberg Universität Mainz [1]. The operation modes planned are a thrice recirculating external beam mode (EB) with 150 µA current and 155 MeV particle energy for precision measurements of the weak mixing angle at the P2 Experiment or a twice recirculating energy recovering mode (ER) with 1 mA and later 10 mA current at a beam energy of 105 MeV where 100 MeV of beam energy can be recovered from the beam and fed back into the cavities. A windowless gas target as part of the MAGIX experiment will enable electron scattering experiments with different atoms. An overview of the MESA facilities is given in fig. 1. The electron source (STEAM) provides up to 1 mA of polarized beam at 100 keV. It is followed by a spin manipulation system containing two Wien filters. A chopper system with a collimator and two buncher cavities prepares the longitudinal phase space of the bunches for the normal conducting milliampere booster (MAMBO), which accelerates them to 5 MeV. A 180° injection arc delivers the beam to the first cryomodule. Depending on the operation mode the beam is either twice or thrice recirculated. This paper focusses on the high current twice recirculating ERL operation, where the beam passes each cavity 4 times and is then dumped at 5 MeV in the ERL beam dump.

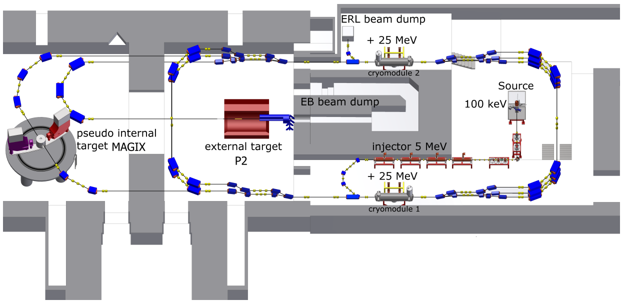


Figure 1: Overview of the MESA layout as used in this work.

SRF CAVITIES AND CRYOMODULES

For the MESA main accelerator two ELBE-type cryomodules were chosen [2] and modified for ERL operation [3]. Each module contains two 9-cell superconducting radio frequency (SRF) cavities of the TESLA-type. These cavities will provide a gradient of 12.5 MeV at $Q_0 = 1.25 \times 10^{10}$ while being operated at 1.8 K and 1.3 GHz. A CAD model of the full cavity string is provided in fig. 2. Besides the wanted accelerating π-mode, also unwanted HOMs with high quality factors exist in the cavity. As the TESLA-type cavities are elliptical cavities, dipole modes naturally occur in pairs of two with polarisations separated by approximately 90° and very small differences in frequency. For a simulation of the threshold current at least two HOMs have to be present in one cavity.

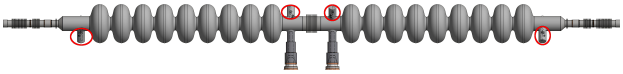


Figure 2: CAD Model of the MESA cavity string. In the bottom center the two HF power couplers can be seen, the four other ports (red circles) are the HOM couplers.

As can be seen in fig. 2 two HOM ports, which allow for the measurement of HOMs for each cavity, are present.

DIPOLE HIGHER ORDER MODES

In [4] a dedicated study of HOMs in TESLA type cavities including the effects of fundamental power couplers and higher order mode couplers was presented. A total of 86 dipole HOMs is presented. Each dipole HOM has a polarisation, a quality factor Q and a shunt impedance R/Q. In fig. 3 an example of the field distribution in a dipole HOM can be seen. As part of the quality control and site acceptance tests the HOM spectra were measured first in the vertical cold test, not yet tuned to the fundamental mode, and a second time for each cavity in the fully assembled string in the cold cryomodule tuned to the 1.3 GHz fundamental mode.

---

* This work has been supported by DFG through the PRISMA+ cluster of excellence EXC 2118/2019 and Research Training Group GRK 2128 and by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

† stollc@uni-mainz.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-THCOXBS02

DEVELOPMENT OF HOM COUPLER WITH C-SHAPED WAVEGUIDE FOR ERL OPERATION

M. Sawamura†, R. Hajima, QST, Tokai, Ibaraki 319-1195 Japan
Masato Egi, Kazuhiro Enami, Takaaki Furuya, Hiroshi Sakai, and Kensei Umemori,
KEK, Tsukuba, Ibaraki 305-0801 Japan

Abstract

We are developing the higher-order mode (HOM) attenuators for superconducting cavity for high current beam operation. We propose new type of HOM coupler using C-shaped wave guide (CSWG). The CSWG has good features of high-pass filter, easy cooling of the inner conductor, and compactness. The measured and calculated results of the CSWG type HOM coupler installed to TESLA type cavity model showed good properties of high external Q-value for the accelerating mode and low external Q-values for HOMs. Since CSWG becomes long to get high external Q-value for accelerating mode, bending CSWG type HOM coupler is practical considering the cryomodule design. The bent CSWG type HOM coupler showed similar properties to the straight CSWG.

INTRODUCTION

The superconducting accelerator projects such as International Linear Collider (ILC) or Energy-Recovery Linac (ERL) are pushed forward all over the world. The superconducting cavity has an advantage of high Q-value due to few wall losses. This leads to a disadvantage that beam acceleration easily grows up higher-order modes (HOMs). Since HOMs excited in a cavity increase with beam current and cause beam instability [1], the performance of HOM attenuators finally limits cavity performance.

Desirable properties of the HOM attenuators so as not to deteriorate the cavity performance are as follows.

i. Ability to install near the cavity not to decrease the effective accelerating field.
ii. Effective cooling to avoid the temperature rise leading to breaking superconductivity for high power of HOMs.
iii. Separation of RF absorbers such as ceramics and ferrites from the cavity vacuum which might be sources of outgas and dust.
iv. Compactness to reduce the cryomodule size.

We developed the C-shaped wave guide (CSWG) as shown in Figure 1 [2]. The CSWG has the cutoff frequency determined by an inner diameter, an outer diameter, and a connection plate thickness since the CSWG is topologically similar to the rectangle wave guide. Furthermore, since the inner conductor connected with the outer conductor through the connection plate, the CSWG has an advantage of easy cooling of the inner conductor. Applying the CSWG to the HOM coupler satisfies the above requests.

The present paper describes the measured and calculated results of the CSWG type HOM coupler properties.

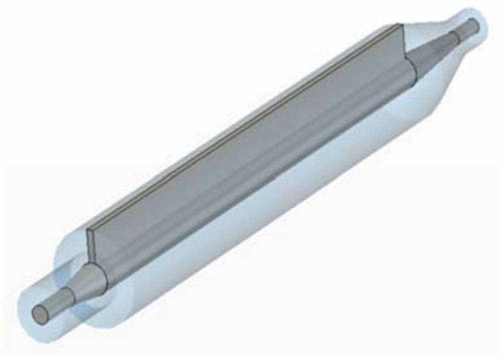


Figure 1: Schematic view of CSWG connected with coaxial lines at both ends.

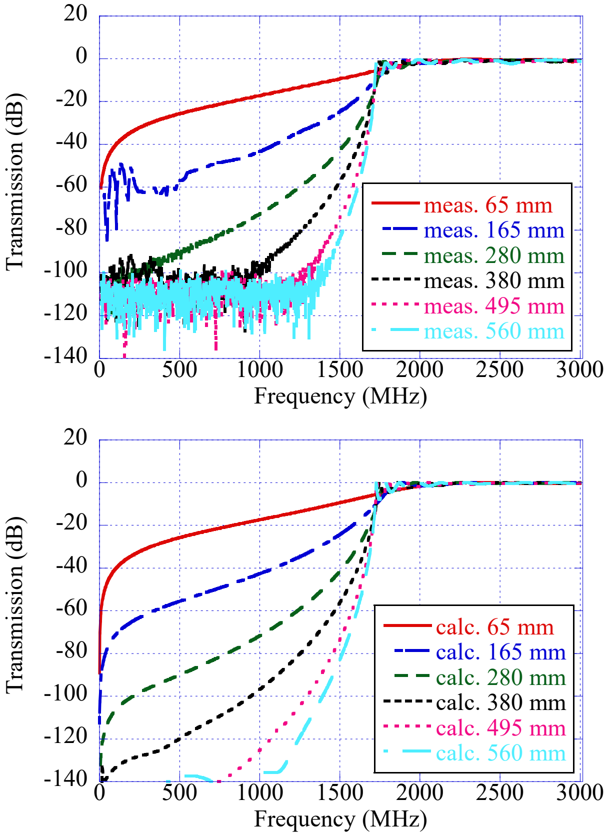


Figure 2: Measured (top) and calculated (bottom) transmission coefficients through CSWG for different CSWG length.

CSWG MODEL

The aluminium CSWG models were fabricated to measure the RF properties. The inner and outer diameters were 18 mm and 42 mm, respectively. The CSWG length can be varied from 65 mm to 560 mm. The coaxial-N

---

† email address: sawamura.masaru@qst.go.jp

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-THCOYBS01

METAL AND SEMICONDUCTOR PHOTOCATHODES IN HZDR SRF GUN

R. Xiang†, A. Arnold, P. Murcek, J. Teichert, HZDR, 01328 Dresden, Germany
J. Schaber, TU Dresden & HZDR, 01328 Dresden, Germany

Abstract

Quality of photocathode in a photoinjector is one of the critical issues for the stability and reliability of the whole accelerator facility. In April 2013, the IR FEL lasing was demonstrated for the first time with the electron beam from the SRF gun with Cs_2Te at HZDR [1]. Cs_2Te photocathode worked in SRF gun-I for more than one year without degradation. Currently, Mg photocathodes with QE up to 0.5% are applied in SRF Gun-II, generating CW beams with bunch charge up to 300 pC and sub-ps bunch length for the high power THz radiation. It is an excellent demonstration that SRF guns can work reliably in a high power user facility.

INTRODUCTION

As well known, the quality of photocathodes is a key part to improve the stability and reliability of the photoinjectors. For SRF guns at HZDR, metal cathodes (copper, magnesium) and semiconductor photocathode (Cs_2Te) are chosen as photocathode materials.

The design is shown in the Fig. 1. The metal plug (ϕ 10mm, 7 mm long) can be photoemission material or the substratum with a deposited photoemission layer. The copper stem is used to cool down the plug to LN2 temperature, which is realized by cotact the conus area to a liquid N2 reservoir. The bayonet and spring can fix the cathode body on to the cold reservoir. The whole cathode is isolated to the SRF cavity, so that a bias can be loaded on the cathode to suppress the multipacting around cathode stem or reduce the dark current from the cathode [2].

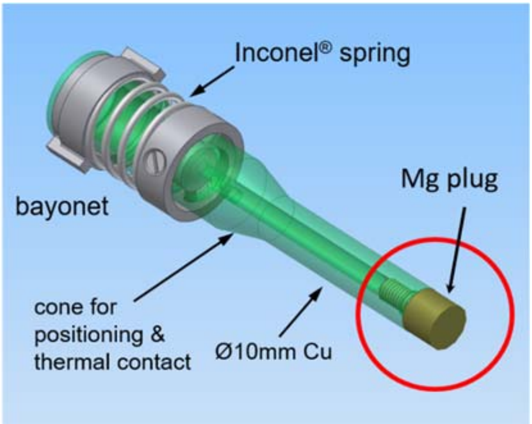


Figure 1: Design of photocathode in the SRF gun II.

Copper is used as commissioning cathode in SRF Gun-II. But the work function of Cu (4.6 eV) is rather high and its QE of 1×10^{-5} at 260 nm is too low for the regular beam production. Magnesium is a metal with low work function of 3.6 eV, and its QE can reach 0.5% after ps UV laser cleaning. Although it has lower QE than Cs_2Te, Mg has the advantage of long life time, reliable compatibility, good QE and little risk of contamination to niobium cavity.

Driven with UV laser Cs_2Te (with band gap 3.3 eV + electron affinity 0.2 eV) has shown good QE and long life time in the SRF gun-I. After we solve the problems of field emission and overheating during the last tests of Cs_2Te on Mo in SRF gun-II, it will be applied again with Cu substratum for the medium current generation.

CU CATHODE IN SRF GUN II

During the assembling of SRF gun cavity in the cleanroom, an oxygen free copper plug was installed in the cavity. The copper plug had been polished with diamond suspension, and then cleaned with alcohol in ultrasonic bath. Figure 2 is the photo of this copper cathode after use. The pattern on surface is believed from the flash during the rf commissioning.

Figure 2: The copper cathode after used in the SRF gun II. A radius of 0.3mm is used to reduce the field enhancement on the sharp edge. The pattern on surface is believed from the flash during the rf commissioning.

This Cu cathode helped to finish the successful commissioning for first beam [3]. There was no obvious multipacting problem with copper cathode. The maximum field on cathode surface is 14.6 MV/m, and the dark current from cathode was 53 nA. Difference parameters of SRF gun were measured with this cathode. A low transverse emittance of 0.4 mm·mrad for 1 pC bunch charge was achieved with this cathode.

Copper cathode is proved being safe for SRF gun. But the work function of Cu (4.6 eV) is rather high and its QE of 1×10^{-5} at 260 nm is too low for the regular beam production.

MG CATHODES IN SRF GUN II

As metallic photocathode, Mg is a safe choice for SRF gun. There have been several Mg photocathodes stably working in SRF Gun II since 2016. Figure 3 shows the QE measurement of the Mg #216 in the SRF gun II. A record

---

† email address: r.xiang@hzdr.de

HIGH CHARGE HIGH CURRENT BEAM FROM BNL 113 MHZ SRF GUN*

I. Pinayev†, I. Ben-Zvi, J.C. Brutus, M. Gaowei, T. Hayes, Y. Jing, V.N. Litvinenko[1], J. Ma, K. Mihara[1], G. Narayan, I. Petrushina[1], F. Severino, K. Shih[1], J. Skaritka, E. Wang, G. Wang, Y.H. Wu[1],
Brookhaven National Laboratory, Upton NY, U.S.A.
[1]also at Stony Brook University, Stony Brook NY, U.S.A.

Abstract

The 113 MHz superconducting gun is used an electron source for the coherent electron cooling experiment. The unique feature of the gun is that a photocathode is held at room temperature. It allowed to preserve the quantum efficiency of Cs_2KSb cathode which is adversely affected by cryogenic temperatures. Relatively low frequency permitted fully realize the accelerating field gradient what in turn helps to achieve 10 nC charge and 0.3 microns normalized emittance. We present the achieved performance and operational experience as well.

GUN DESIGN

The injector is an essential part of any accelerator, and the quality of the produced beams completely relies on its performance. Among the well-known electrostatic (DC) and normal-conducting (NC) RF photo-guns, the injectors based on an SRF cavity are rapidly gaining popularity in the generation of the high-brightness high-quality beams.

The idea of utilizing the SRF technology brings advantages and challenges [1, 2]. The biggest advantage is the reduced power losses (orders of magnitude lower compared to a NC cavity) which allow for reliable operation in continuous wave (CW) regime and generation of beams with high average current, providing a higher accelerating gradient. Another advantage is an excellent vacuum conditions inside the cavity which serves ad huge cryopump.

However, introduction of a photocathode into the SRF environment causes several complications: since the photocathode has to be replaced throughout the operation of the gun, the area around the cathode creates a condition for RF power leakage which has to be taken care of. To keep the power within the cavity, an RF choke filter has to be designed for this purpose.

Moreover, the cathodes are generally kept at room temperature creating an additional heat leak between the cold surface of the cavity and the warm cathode.

We utilized quarter-wave resonator (QWR) based geometry for our gun. The QWR cavities are specifically suitable for operation at low frequencies which allow for a generation of long bunches. This fact is beneficial for the reduction of the space charge effect in the initial stages of the beam generation, allowing to achieve higher charge per bunch. The accelerating gap in such a cavity is relatively short compared to the wavelength, which makes the field distribution in the gap close to constant. To a degree, such SRF guns are similar to DC guns but offer both high accelerating gradient and higher beam energy at the gun exit. The main RF parameters of the gun can be found in Table 1.

Table 1: RF Parameters of the Gun

Parameter	Value
Frequency, MHz	113
Quality factor w/o cathode	3.5×10^9
R/Q, Ω	126
Geometry factor, W	38.2
Operating temperature, K	4.2
Accelerating voltage, MV	1.25 (1.7)

The geometry of the SRF gun is shown in Fig. 1. The cavity body is made of bulk Nb, and, as all of the QWR geometries, has “outer conductor” and “inner conductor” parts due to the nature of this type of a cavity. The “inner conductor” is hollow and accommodates the system of the cathode insertion and extraction. The accelerating electric field is concentrated between the front wall of the cavity and the rounded part of the “inner conductor,” which we denote as the cavity “nose”. The inset in the Fig. 1 shows in detail the location of the cathode puck in the cavity nose.

The necessary half-wavelength RF choke for the reduction of the power leakage incorporates a hollow stainless-steel cathode stalk which allows insertion of a cathode puck [3, 4]. The cathode stalk is coated with layers of copper and gold to reduce heat emission into the 4 K system. It is kept at room temperature by circulating water in the channel soldered to the stalk.

The stalk does not have direct physical contact with the cold center conductor of the cavity, thus reducing the leakage of heat into the cavity only allowing the exchange of the radiated heat. The stalk is shorted at the far end to serve as a choke filter. The choke reduces the penetration of the RF field, and minimizes the voltage drop between the cathode and the cavity's center conductor. The gap between the stalk and the cavity nose at the entrance of the cavity is only 3.56 mm. The length of the stalk was shortened to account for the capacitance created by this small gap. The impedance transformer in the middle of the stalk is used to reduce the current through the short, which includes a coated bellow.

A pick-up antenna for measuring the RF voltage is located outside of the gun cryostat and is weakly coupled to the choke. The axial position of the stalk tip and, therefore, the photocathode surface with respect to the cavity nose can be manually adjusted. The latter provides us with an opportunity to optimize the initial focusing of the electron beam.

---

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
† pinayev@bnl.gov

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-FRCOWBS04

ESSENTIAL INSTRUMENTATION FOR CHARACTERIZATION OF ERL BEAMS*

N. Banerjee†, A. Bartnik, K. Deitrick, J. Dobbins, C. Gulliford, G. Hoffstaetter,
Cornell Laboratory for Accelerator-Based Sciences and Education, Ithaca, USA
J. S. Berg, S. Brooks, R. Michnoff,
Brookhaven National Laboratory, Upton, USA

Abstract

The typical requirement of Energy Recovery Linacs to produce beams with high repetition rate and high bunch charge presents unique demands on beam diagnostics. ERLs being quite sensitive to time of flight effects necessitate the use of beam arrival time monitors along with typical position detection. Being subjected to a plethora of dynamic effects, both longitudinal and transverse phase space monitoring of the beam becomes quite important. Additionally, beam halo plays an important role determining the overall transmission. Consequently, we also need to characterize halo both directly using sophisticated beam viewers and indirectly using radiation monitors. In this talk, I will describe the instrumentation essential to ERL operation using the Cornell-BNL ERL Test Accelerator (CBETA) as a pertinent example.

INTRODUCTION

The unique diagnostic requirements for beams produced in Energy Recovery Linacs (ERLs) stem from the hybrid nature of these accelerators which combine aspects of both Linacs and storage rings. Just like their Linac counterparts, ERLs produce very bright beams with typical normalized transverse emittance of a few microns. On the other hand, the requirements on longitudinal distribution of the beam depends on particular applications. A survey of beam parameters [1] of different ERL projects around the world reveals bunch lengths from less than a pico-second for light sources, up to 50 ps for the Coherent electron Cooler proposed for eRHIC. Just like storage rings, ERLs are CW high current machines with large beam power. However, beam is continuously produced in ERLs while rings can only hold a finite amount of charge inside. This difference is very important in the context of machine protection. Consequently, the list of diagnostics essential to ERL beam operations must include monitoring of all these aspects.

Apart from the distinguishing features of the beams, ERLs are sensitive to time of flight errors and losses. The time of flight of the beam in the return loop needs to be within the target value with narrow tolerances in order to ensure correct arrival phase in the accelerating cavities. This in turn establishes correct beam energies and zero average beam loading [2], which is crucial for sustaining high currents. In this way, ERLs are operationally time of flight spectrometers. [3] Further, ERLs are designed for high average beam power up to mega-watts, so even modest losses can result in large radiation and thermal load on machine components. Consequently halo characterization and bunch arrival time measurements are crucial for high current operations along with the usual measurement of the core and the transverse position of the beam.

The Cornell-BNL ERL Test Accelerator (CBETA) [4] is a 4-turn superconducting ERL which has been constructed under the collaboration of Cornell University and Brookhaven National Laboratories and is currently being commissioned. With a target injection current of 40 mA and the top energy of 150 MeV, the diagnostics used in this accelerator serves as a representative example of essential instrumentation crucial to ERL operation. In the next section, we describe how we measure the beam centroid in CBETA. Then we explain various methods of observing the phase space distribution of the core of the beam. After this, we list instrumentation to detect beam halo and loss, including the equipment protection system. Finally we describe other miscellaneous diagnostics.

BEAM CENTROID

Beam Position Monitors (BPMs) detect the position of the centroid of the bunch both in space and time. In terms of hardware, BPMs can be broadband devices such as button BPMs and striplines such as the ones used in CBETA, or they may work as resonant cavities which are narrowband. In the case of broadband monitors, the image charges induced by the bunches are electrically coupled to pickups and the relative amplitudes and phases of the detected impulses can be used to measure beam position. On the other hand cavity BPMs work by measuring the amplitudes and phases of specific resonant modes excited by the beam and can be used for very precise measurements. [5] ERLs pose an additional requirement on BPMs to be able to detect multiple beams at the same time, which is especially true in CBETA which has a Non Scaling Fixed Field Alternating (NS FFA) [6] return loop hosting 7 beams at the same time.

We use both time and frequency domain techniques for signal processing on broadband BPMs in CBETA. The time domain technique first uses a custom low pass filter with a cut off frequency at 800 MHz to broaden and smooth the incoming wideband signal from the buttons. Then after a programmable gain, we digitize the signal using a 400 MSPS ADC, after which a FPGA processes the data. We acquire

---

* This work was supported by the New York State Energy Research and Development Authority.

† nb522@cornell.edu

BEAM DYNAMICS SIMULATIONS FOR THE TWOFOLD ERL MODE AT THE S-DALINAC[*]

F. Schließmann[†], M. Arnold, M. Dutine, J. Pforr, N. Pietralla, M. Steinhorst
Institut für Kernphysik, Darmstadt, Germany

Abstract

The recirculating superconducting electron accelerator S-DALINAC at TU Darmstadt is capable to run as a onefold or twofold Energy Recovery Linac (ERL) with a maximum kinetic energy of approximately 34 or 68 MeV in ERL mode, respectively. The onefold ERL mode has already been demonstrated, the twofold ERL mode not yet. In conjunction with the first test phase of the twofold ERL mode, simulations have been performed to study the beam dynamics. Acceptance studies for individual beamline sections were carried out and the influence of phase slippage on the energy recovery efficiency during the entire acceleration/deceleration process was examined. The latter is crucial, since the maximum kinetic energy for the twofold ERL mode at injection is less than 8 MeV ($\beta < 0.9982$) while multi-cell cavities are used in the main accelerator that are designed for $\beta = 1$.

INTRODUCTION

The S-DALINAC at TU Darmstadt is a superconducting electron accelerator with a maximum energy gain of 130 MeV in conventional acceleration (CA) mode [1]. This energy gain is achieved by recirculating the beam three times in order to pass the main linac four times. The second of these recirculation beamlines houses a path length adjustment system (PLAS) that offers the possibility to change the phase of the beam relative to the accelerating cavities by up to 360° [2]. In this way, the S-DALINAC can be used as an Energy Recovery Linac (ERL) which requires a phase shift of roughly 180° [3]. By realizing such a phase shift, the electrons arrive at the cavities of the main linac at a time when a decelerating electric field is present. The electrons will then lose a part of their kinetic energy, which will be stored in the electromagnetic field in the cavities and can then be used to accelerate subsequent electrons. Due to the energy recovery, the acceleration process in the main linac exhibits a high power efficiency. In 2017, the onefold ERL mode was realized at the S-DALINAC [3, 4]. In this case, the electron beam was accelerated once, recirculated and decelerated. The next step is to realize the twofold ERL mode, i.e. accelerating the electrons, recirculating, accelerating again, recirculating, decelerating, recirculating and decelerating a second time. Figure 1 shows the floor plan of the S-DALINAC and schemes for the onefold and twofold ERL mode. The maximum energy gain in the onefold or twofold ERL mode is 34 MeV or 68 MeV, respectively, instead of 130 MeV as in the CA mode. Linked with the first test phase of the twofold ERL mode, beam dynamics simulations have been performed using the *elegant* tracking code [5]. An acceptance study of the recirculation beamlines provides the shape of the maximum phase space which can be guided through the individual beamlines. Furthermore, the negative impact of phase slippage on the ERL efficiency was investigated, if one optimizes on the first linac transit using an on-crest acceleration.

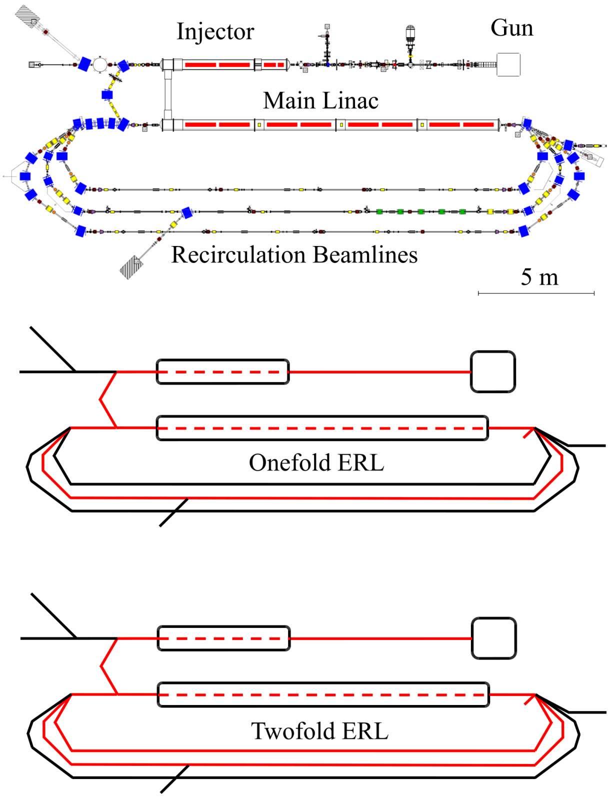


Figure 1: Floor plan of the S-DALINAC and schemes for the onefold and twofold ERL mode.

ACCEPTANCE STUDY OF THE FIRST RECIRCULATION BEAMLINE

In order to guide the beam without beam losses through the entire accelerator, it is important to know the acceptance of the beamlines. While an acceptance study of the entire accelerator is significantly influenced by the settings of all individual beam guiding devices, acceptance studies of several individual sections, which are examined independently, provide the necessary acceptance information to guide the

---

[*] Work supported by the BMBF through grant No. 05H18RDRB2 and by the DFG through GRK 2128.

[†] fschliessmann@ikp.tu-darmstadt.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-FRCOXBS04

STATUS OF THE CONTROL SYSTEM FOR THE ENERGY RECOVERY LINAC bERLinPro AT HZB*

Thomas Birke†, Pablo Echevarria, Dan Eichel, Roland Fleischhauer, Ji-Gwang Hwang,
Guido Klemz, Roland Müller, Christoph Schröder, Ervis Suljoti, Andriy Ushakov
Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin, Germany

Abstract

bERLinPro is an energy recovery linac (ERL) demonstrator project built at HZB. It features CW SRF technology for the low emittance, high brightness gun, the booster module and the recovery linac. Construction and civil engineering are mostly completed. Synchronized with device integration, the EPICS based control system is being set-up for testing, commissioning and finally operation. In the warm part of the accelerator, technology that is already operational at BESSY and MLS (e.g. CAN-bus and PLC/OPC UA) is used. New implementations like the machine protection system (MPS) and novel major subsystems (e.g. Low Level RF (LLRF), photo cathode laser) need to be integrated. The first RF transmitter has been tested and commissioned. For commissioning and operation of the facility the standard set of EPICS tools form the back-bone. A set of generic Python applications already developed at BESSY/MLS will be adapted to the specifics of bERLinPro. Scope and current project status are described in this paper.

INTRODUCTION

The goal of bERLinPro is the production of high current, high brightness, low emittance CW beams and to demonstrate energy recovery at unprecedented parameters [1]. The three stage acceleration consists of an SRF photo electron gun, an SRF booster linac with an extraction energy of 6.5 MeV and an SRF main linac module equipped with three 7-cell HOM damped cavities. All magnets and the vacuum system of the low energy injector and dump line are installed. Commissioning of the diagnostic line and the low energy part of the machine, i.e. gun / booster / linac replacement straight / dump line, the *banana* (see eponymous shape in Fig. 1) is planed for 2020,

bERLinPro is designed to show energy recovery for high current (100 mA) beams. The damping of higher order modes in the SRF linac is demanding and led to a new design of the HOM damping waveguids [2]. Availability of a proper linac module is critical.

The MESA project (Johannes Gutenberg Universität, Mainz, Germany) is planned for 1 % of the bERLinPro current, with a possible upgrade to 10 mA. For HOM-damping, the same technology as used at ELBE (HZDR) and XFEL (DESY) is in operation. Intermediate installation of the MESA linac module into bERLinPro allows to proceed towards recirculation with beam at 32 MeV and some mA at bERLinPro [3].

OPERATIONAL MODES

Unlike cERL and cBETA, bERLinPro features numerous different use cases. These comprise the photo-electron-source only, straight diagnostic beamline, *banana* path and recirculation with and without energy recovery (see Fig. 1). Available modes also differ in beam power, bunch charge, acceleration voltage and bunch train pattern as well as methods to increase beam current. All of these and the individual operation states of accelerating units, booster and linac modules will have immediate impact and consequences on a challenging set of soft- and hardware machine protection systems and set-ups.

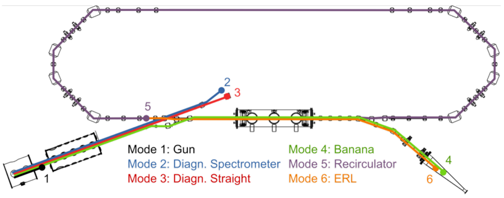


Figure 1: Basic bERLinPro layout and planned operation modes.

DEVICE INTEGRATION

The source part, consisting of an SRF photo electron gun, has already been set up in GunLab [4], where precision control of the laser guide system and the timing is presently in the works. With the beginning of installation in the bERLinPro bunker, integration of major functional blocks (e.g. laser) will be realized by remote control of 3rd party subsystems.

In March 2018 the first vacuum components for the *banana* path have been delivered, pumps and sensors are made available and are logged in the already running archiver [5] as they are installed. Similarly RF power conditioning and cryo system surveillance of cold compressors, warm vacuum pumps and the module feed boxes are well known and progress smoothly.

The various sub components of the booster and linac cryo modules are about to be addressed. At this point competing requirements for BESSY VSR [6] generate synergies, but also challenging working conditions.

IT-Infrastructure

Operator consoles as well as servers are strictly Linux-based. To be monitored and controlled, all relevant components need to be interfaced using an EPICS-I/O Controller (IOC) providing a Channel Access (CA) server.

---

* Work funded by BMBF and Land Berlin

† thomas.birke@helmholtz-berlin.de

ADJUSTING bERLinPro OPTICS TO COMMISSIONING NEEDS*

B. Kuske†, M. McAteer, Helmholtz-Zentrum für Materialien und Energie, Berlin, Germany

Abstract

bERLinPro is an Energy Recovery Linac (ERL) project being set up at HZB, Berlin. During the turn of the project, many adaptations of the optics to changing hardware realities and new challenges were necessary. Exemplary topics are chosen for each of the three different machine parts: the diagnostics line, the Banana and the recirculator. In the diagnostics line, the need to seek a quick understanding of the machine during commissioning and the low energy are the central concern. In the Banana, unwanted beam will dominate the performance. Commissioning of the recirculator will be realized with the super-conducting linac module fabricated for the Mainz ERL project MESA, as the bERLinPro linac is delayed. The Mainz linac will supply 60 % of the energy planned. While the adopted optics shows similar parameters as the original 50 MeV optics, studies of longitudinal space charge and coherent synchrotron radiation show that the lower energy leads to large emittance blow up due to micro bunching and CSR effects.

INTRODUCTION

bERLinPro is an Energy Recovery Linac project close to completion at HZB, Berlin, Germany, [1]. It is intended as an experiment in accelerator physics, to pioneer the production of high current, low emittance beams in a fully super-conducting accelerator, including SRF gun, booster and linac. The machine, with a length of roughly 80 m consists of three different independent sub-parts: the diagnostics line, straight forward from the SRF gun and booster; the low energy part, including injector, merger, linac straight, splitter and dump line. This is called the Banana. In presence of a linac module, the beam would run through the recirculator and be energy recovered before being led to the dump line, Fig. 1. Over the turn of the project different boundary conditions asked for optics adjustments and new challenges had to be met. The paper describes examples of this work for each machine part.

DIAGNOSTICS LINE

The diagnostics line consists of the 1.3 GHz, 1.4 cell, single cavity SRF gun, providing up to 3 MeV electrons with a design bunch charge of 77 pC. The gun module also hosts two corrector coils (H/V) and a cold solenoid. The booster, hosting three two-cell cavities can boost the energy up to 6.5 MeV. The first cavity imprints a chirp on the bunch for velocity bunching, while the other two cavities are run on crest for acceleration. Further elements are 6 quadrupoles, a transverse deflecting cavity, a spectrometer followed by a 300 W Faraday cup, or, straight ahead, a 35 kW beam dump, Fig. 2. Optics were developed including the booster (6.5 MeV) and with three booster replacement quadrupoles (taken from the recirculator) and 2.7 MeV. Four beam position monitors (BPM) and two screens (FOM) are available for diagnostics. Two laser systems are available: a 50 MHz laser providing single bunches at frequencies between 1 Hz and 100 kHz, corresponding to 77 pA to 8 µA, or up to 4 mA cw; and a 1.3 GHz laser providing macro pulses from 1 Hz to 1 kHz, 6 nA to 20 µA, or up to 100 mA cw.

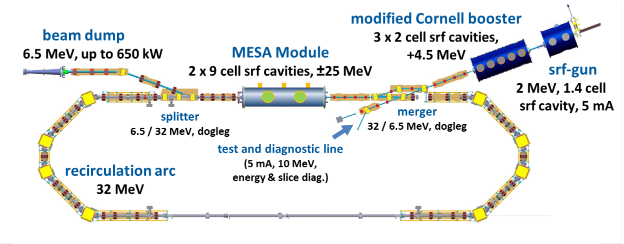


Figure 1: Layout of bERLinPro with the diagnostics line in straight continuation of the gun, the low energy part (Banana) from gun to dump, and the recirculator with the MESA module.

As any linear accelerator, an ERL is an initial value problem: without exact knowledge of the initial parameters of the beam, a later understanding and characterization of the beam parameters is difficult. Therefore, a thorough understanding of the gun is indispensable. The gun enables the low emittance and the stability of the complete machine due to the laser- and RF stability and the synchronization between the two. Most of the unwanted beam, from laser effects to field emission at 30 MV/m will originate in the gun and the machine up time is determined by the cathode life time. Finally, the goal of producing 100 mA is achieved in the gun (although with a second version, utilizing high power couplers).

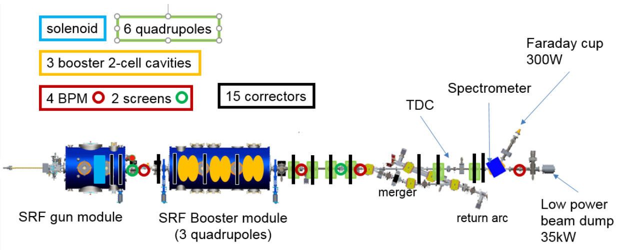


Figure 2: Diagnostics line: Intended for the characterization of gun and booster and initial beam parameters.

Before the gun is assembled and tested, many ambiguities arise, starting from the actual energy of the beam, over the bunch parameters, to the system parameters leading to successful acceleration. It is intended to use machine learning

---

* Work supported by German Bundesministerium für Bildung und Forschung, Land Berlin and grants of the Helmholtz Association
† bettina.kuske@helmholtz-berlin.de

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-FRCOYBS01

WORKING GROUP SUMMARY: ERL FACILITIES

Michael Abo-Bakr, Helmholtz-Zentrum Berlin, Berlin, Germany
Michaela Arnold, Technische Universität Darmstadt, Darmstadt, Germany

Abstract

The Workshop on Energy Recovery Linacs 2019 was held in September 2019 at Helmholtz Zentrum Berlin, Germany. Working Group 1 (WG1), named “ERL Facilities”, focused on ERLs around the world being in operation, under construction or in planning. In total seven invited oral presentations have been held and one poster contribution was presented. This report summarizes the main aspects of the presentations and introduces an overview on the ERL landscape.

INTRODUCTION

Fig. 1 shows a scattering plot of maximum beam energy vs beam current for of all ERL facilities around the world. Those are assigned into five categories: “operational ERL facilities” (purple), “past ERL facilities” (red), “planned ERL facilities” (green), “potential future ERL facilities” (blue) and “NC ERL facilities” (black). Diagonally running lines are added to the plot, representing “iso-lines” for selected virtual beam power values between 100 W and 10 GW.

All these facility data are collected in the “ERL facilities list”, an EXCEL file generated on the ERL workshop in 2017 and updated in 2019. An according version is available in the proceedings of both workshops [1,2]. The present version will be hosted and updated at HZB [3].

At present only four ERL facilities are in operation worldwide:

- Novosibirsk ERL at BINP in Russia (normalconducting)
- cERL at KEK in Japan (superconducting)
- S-DALINAC ERL at TU Darmstadt in Germany (superconducting)
- CBETA at Cornell in USA (superconducting)

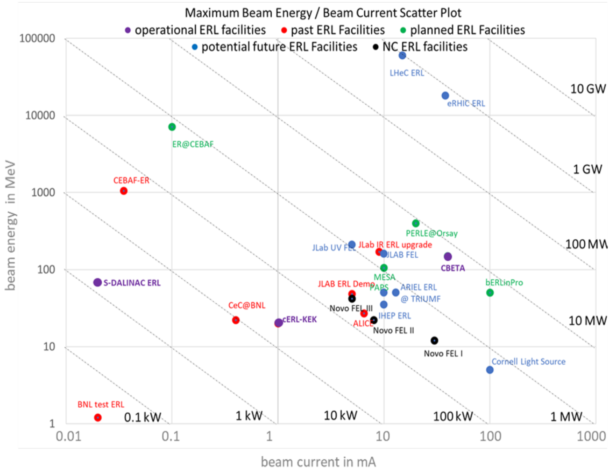


Figure 1: The ERL landscape is shown in maximum beam energy / beam current scatter plot. The status of the different facilities is indicated by colour code.

The Novosibirsk ERL is operated in multi-turn mode as the first multi-turn ERL world-wide. For the superconducting ERLs multi-turn ERL operation was not achieved up to now. CBETA (Cornell) and S-DALINAC (TU Darmstadt) are closest to success at the current time.

ERLS IN OPERATION

CBETA (Cornell)

As part of the development effort for a potential eRHIC design, the Cornell-BNL Energy recovery linac Test Accelerator (CBETA) [4], a 4-pass, 150 MeV SRF based ERL utilizing a Non-scaling Fixed Field Alternating-gradient (NS-FFA) permanent magnet return loop with large energy acceptance (factor ∼ 4), is currently under construction at Cornell University through the joint collaboration of Brookhaven National Lab (BNL) and the Cornell Laboratory for Accelerator based Sciences and Education (CLASSE).

In 2018 already the first beam was sent thorough the SRF chain, one separator and the first installed FFA unit. This spring, installation of the lowest energy splitter line after the linac and permanent magnet FFA loop was completed, allowing the beam to be passed nearly all the way back to the linac. In parallel to construction, beam commissioning was

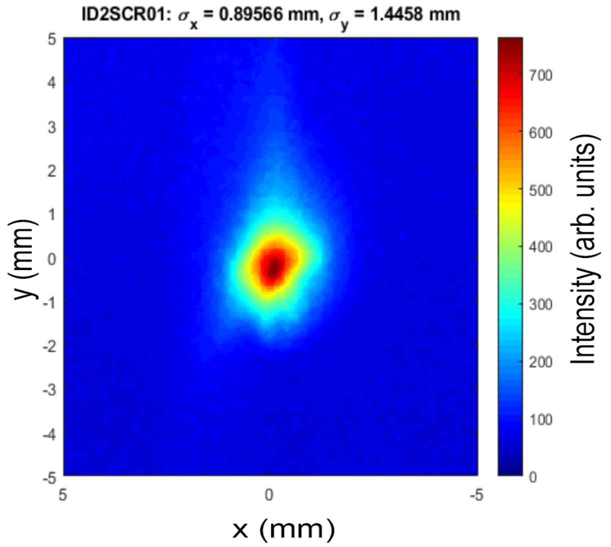


Figure 2: CBETA - recirculated beam on first view screen in the dump line ($E \approx 6.1$ MeV, $E_0 = 6.0$ MeV, $Q_b = 5$ pC).

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-FRCOYBS04

WORKING GROUP SUMMARY: SUPERCONDUCTING RF

F. Gerigk, CERN, Geneva, Switzerland
P. McIntosh, STFC, Daresbury, United Kingdom

Abstract

16 talks were presented in Working Group 4, which are divided into four main themes. These themes along with their talks will be listed and summarized in the following.

ERL SRF SYSTEMS SPECIFICATIONS, DEVELOPMENT, FABRICATION, COMMISSIONING AND PERFORMANCE

This theme includes 5 talks [1-5] reporting on 2 different cryomodules and on tests with 2 dual-axis cavities for ERL applications.

The MESA ERL at KPH Mainz employs 2 cryomodules, which were ordered as turn-key modules from industry. The performance goal of 12.5 MV/m at a Q_0 of 1.25 x 10^{10} was readily achieved in vertical tests at DESY. The first assembled module was accepted after a cold module test at Mainz, while the second module did not achieve specifications and will be sent back to the manufacturer. This failure was most likely caused by the undefined state of a valve during transport, which may have produced particles that travelled into the cavity volume. Nevertheless, this experience shows that vendors have accumulated enough technical know-how to deliver complete turn-key cryomodules. As the MESA facility is still under construction a collaboration with bERLinPro was created to make beam test with the qualified MESA module at bERLinPro. There, the construction is more advanced but funds are currently lacking for the procurement of a cryomodule. Beam tests are foreseen in 2021 at bERLinPro. The module will then be shipped back to Mainz and MESA plans first operation in 2022.

A report on operational experience with 2 ERL cryomodules came from cERL at KEK. The required phase and amplitude stability (< 0.01% and < 0.01 deg) was achieved by damping microphonics from rotary pumps with simple rubber feet. The modules suffer from increasing field emission during operation, which is probably related to contamination, but also to a high ratio of peak surface fields to accelerating fields of the particular cavities used. An unexplained vacuum burst event in 2017 further degraded performance of one module, which could so far not be recovered by high power pulsed processing.

Dual-axis cavities where already discussed at ERL 2017 [6] where a recommendation for was given for more R&D on this type of cavity. The cold test results reported by ODU [4] of a twin-axis cavity showed that the expected gradient of 15 MV/m could be surpassed, however only for one of the 2 cavities. Due to a welding defect Cavity 2 only reached 5 MV/m. Nevertheless, the suppression of multipacting by design was successful as well as the chemical treatment and processing.

Prototyping and warm tests of multi-cell dual axis cavities with bridge couplers were reported in [5] and showed good agreement between simulations and measurements.

HIGH LOADED Q CAVITY OPERATION (MICROPHONICS, LLRF, RF POWER SYSTEMS, TRANSIENT BEAM LOADING)

This theme comprised 6 talks [7-12] reporting on various types of RF control systems, encompassing both low-level and high-power technologies, as well as fundamental development of a HOM damped cavity solution.

Analysis of the microphonics characteristics of the two, cERL main linac cavities at KEK [7], has identified that the stability of the first cavity (ML1) has deteriorated over the past 5-years, whilst the second cavity (ML2) has remained stable. Further investigation has shown a cavity field-level dependency threshold of ~3MV/m for this limiting cavity, which is most likely related to a quench limit level. A transfer function characterisation has been developed for the cavity with its piezo tuner system, with future plans being made to optimise the cavity control more effectively utilising this analysis.

Three reports identified specific RF technology control processes employed for microphonics diagnostic and control for ERL operation. First single turn ERL operation was demonstrated at S-DALINAC in August 2017 with a new FPGA-based LLRF system [8], supporting a beam current of 1 µA to achieve up to 90% transmission efficiency for 6 out of 8 of the 20-cell S-band cavities. RF stability measurements showed a negligible phase control impact for beam currents <1 µA, however amplitude errors were much larger than expected and require further optimisation. A beam disturbance at 52 Hz was identified, which was assumed to originate from a gun-induced modulation, but this also requires further investigation to confirm. A new RF power measurement system has been developed and is ready for use with an optimization algorithm for improved RF Control.

Also at TU Darmstadt, system identification procedures for resonance frequency control of SRF cavities have been developed [9], driven by the primary motivation to overcome the impact of helium pressure transients and their effect on RF stability. By incorporating a 2-stage, least-square, close-loop transient analysis and integrating a suitable PID controller, optimised control parameters have been defined, which can effectively replicate the measured responses observed on the S-DALINAC accelerator. Reconfiguring the PID parameters with considerably increased differential gain has enabled the closed-loop re-