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WORKING GROUP SUMMARY: ERL FACILITIES

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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)

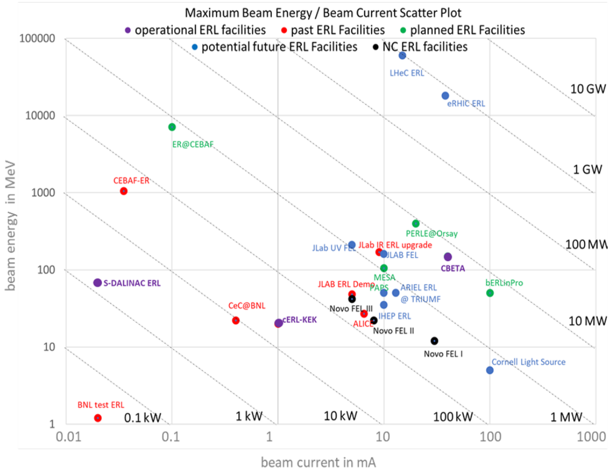

Figure 1: The ERL landscape is shown in maximum beam energy / beam current scatter plot. The status of the different facilities is indicated by colour code.

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

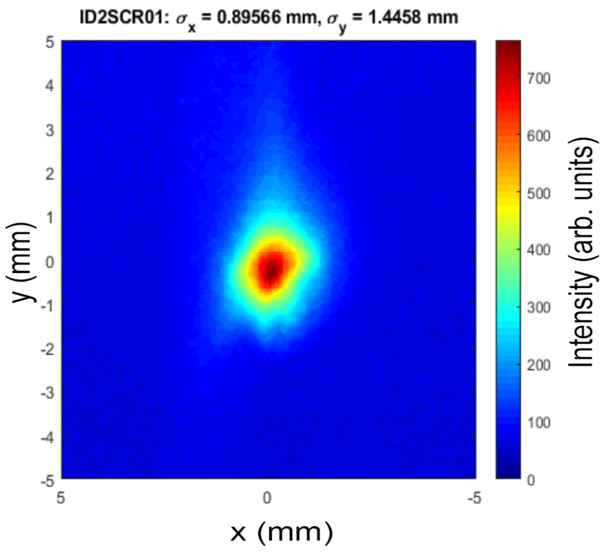

Figure 2: CBETA - recirculated beam on first view screen in the dump line ($E \approx 6.1$ MeV, $E_0 = 6.0$ MeV, $Q_b = 5$ pC).

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continued in March with the initial tune up of the injector for 5 pC bunches, as well as the recommissioning of the main linac, yielding a desired energy gain of 36 MeV.

In June 2019 the successful threading of the beam through the FFA permanent magnet return loop was achieved, with a very good transmission rate of 99.6% on the corrected orbit, see Fig. 2. By measuring the load deviation in the linac cavities the recovery efficiency was estimated to be larger than 99.8% at beam currents up to 8 μA.

Several important measurements of energy, emittance, tunes, orbit etc. have been performed accompanied by simulation to improve both the machine understanding and the virtual model.

The full 4-turn construction is underway now by installing the remaining higher energy spreader lines so that starting from 2020, CBETA will be available for R&D on high power beams. More details can be found in [5].

cERL (KEK)

The cERL is a superconducting linac based accelerator with a recirculation loop for the energy recovery at KEK [6]. It has been commissioned between 2013-15 with increasing currents up to 1 mA with cw operation and recovery. In 2016 the KEK future light source was decided to be based on a high-performance storage ring. However the importance of the R&D for industrial application based on ERL technologies has been pointed out, so that ERL activities were continued on a reduced level, now with the focus on potential industrial applications like ERL based EUV-FELs for lithography, high intense laser Compton Scattering sources, brilliant THz sources or rare isotope factories [7]. As these applications require a high bunch charge, high average current electron beam (target of cw current: 10 mA) with small emittance, pulses length and energy spread the operation of cERL could be restarted in 2017 with a high bunch charge operation phase (40 - 60 pC) to develop beam handling methods towards a high average current FEL.

In June 2018 an operation block followed, where once more stable 1 mA cw operation could be demonstrated, although the accelerating linac voltage had to be reduced to control field emission, see Fig. 3. The key to achieve stable cw operation was an optics fine tuning in order to reduce losses of beam halo and other sources of unwanted beam. Important tuning items were the transverse beam optics, R_{56}, the achromatic condition of the second arc as well as the deceleration and dump line tuning. Finally, the careful collimator setting was very important. In this machine setup emittances close to design values were measured and a 100% (within measurement accuracy) recovery efficiency was reached.

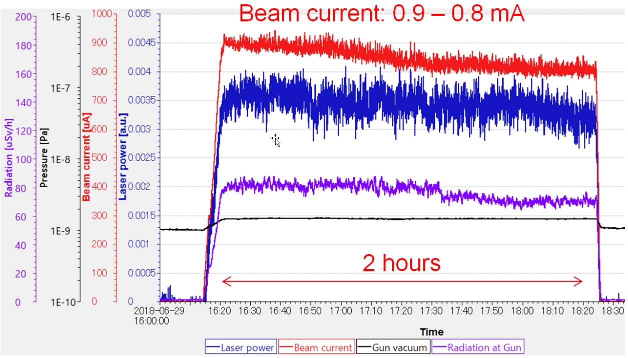

Figure 3: cERL - 1 mA beam operation with 2 hours of stable beam current, trajectory and radiation level, $V_{gun} = 500$ kV (DC), $E = 17.6$ MeV, $Q_b = 0.77$ pC).

Future planing go for a next test phase in 2020, aiming to reach stable 10 mA beam current operation. That run will give measurement opportunities to better understand the mechanisms of beam halo generation and mitigation, to study the wake fields caused by the collimators and to test the reproducibility of beam loss tuning and collimator setting. Also the observed cathode QE degradation of the GaAs photo-cathodes will be investigated. More details can be found in [8].

S-DALINAC ERL (TU Darmstadt)

The S-DALINAC, a 3 GHz superconducting electron linac, is in operation since 1991 at Technische Universität Darmstadt [9]. It was built as a recirculating linac. During a major upgrade in 2015/2016 a third recirculating beam line was installed [10]. This beam line houses a path length adjustment system being capable of a phase shift of up to 360° and thus the change to ERL operation. A commissioning phase followed the modification of the machine, where all six possible operation schemes have been or will be operated:

- 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)
- Twice-recirculating ERL mode (two accelerating and two decelerating passages through the main linac), not demonstrated yet

In August 2017 a once-recirculating ERL operation was demonstrated. The measurement is separated into four phases:

1. No beam in the main accelerator (red).
2. Single pass: one beam is accelerated in the main accelerator (grey).
3. Once-recirculating mode: two beams are accelerated in the main accelerator (blue).
4. ERL mode: one beam is accelerated, another beam is decelerated in the main accelerator (green).

Figure 4 summarizes the results. The change in forward (black curve) and reverse (orange curve) radio-frequency (RF) power of the first main accelerator cavity was monitored. During the ERL phase (green shading) the beam loading cancels nearly out. For one or two accelerated beams (grey and blue shading) the beam loading increases correspondingly. The beam current on the ERL beam dump (ERL-Cup, green curve) and on the extraction beam dump (E0F1-Cup, blue curve) was measured as further evidence of the operation mode.

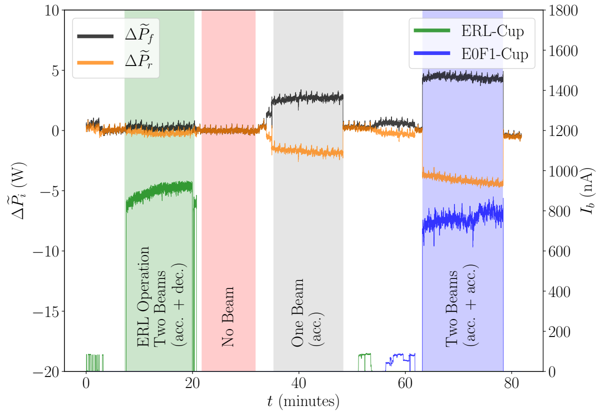

Figure 4: During four different settings (ERL: green, no beam: red, single pass: grey, twice accelerating: blue) the changes in forward (black curve) and reverse (orange curve) RF power of the first main accelerating cavity (A1SC01) have been monitored. The beam current on the corresponding faraday cups (ERL-Cup: green, E0F1-Cup: blue) was measured [11].

During this measurement the RF recovery effect for the first main accelerator cavity, the RF power gained back during deceleration, amounted to $(90.1 \pm 0.3)\%$. Additionally an analytical model was found for forward and reverse power. An analytical prediction of the reverse power was achieved after curve-fitting to the data of the forward power. More details can be found in [11, 12].

Novosibirsk ERL (BINP)

The Novosibirsk FEL Facility at Budker Institute for Nuclear Physics, based on a normal-conducting, 180 MHz accelerating system, has been the first multi-turn ERL in the world [13]. Since 2004 the facility has been operating for users of terahertz radiation. Constructed with a rather compact footprint of about (6 x 40) m^2 three modes of the magnetic system are now in operation, providing beams to drive three FELs in the wavelength range from 8 to 240 μm (see Fig. 5 and Table 1). 11 workstations are in operation and two more are currently under construction.

To further increase the FEL output power in addition to the existing DC electron gun with the grid thermionic cathode a high current, RF cw gun has been designed, constructed and also installed and commissioned in 2019 [14]. Also an option for user defined, fast changes of the average FEL power has been developed and is in operation now [15]. More details can be found in [16].

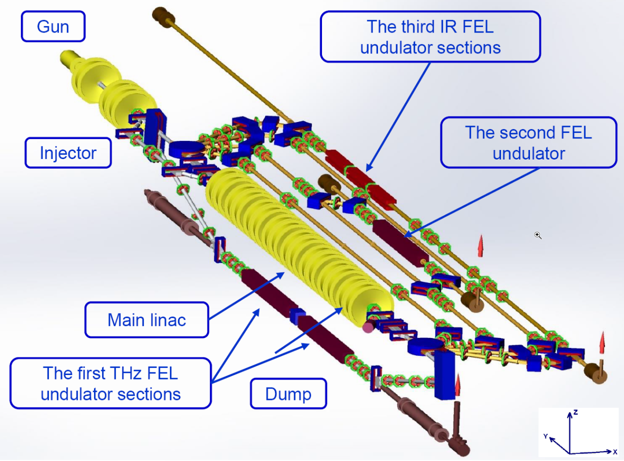

Figure 5: Footprint of the Novosibirsk ERL.

Table 1: NovoERL FEL modes. FEL 1 and FEL 2 are the world's most powerful (in terms of average power) sources of coherent narrow-band (less than 1%) radiation in their wavelength ranges.

	FEL 1	FEL 2	FEL 3
Energy / MeV	12	22	42
Current / mA	30	10	3
Wavelength / μm	90-240	37-80	8-11
Radiation power / kW	0.5	0.5	0.1
Pulse rep-rate / MHz	5.6 or 11.2	7.5	
Peak power / MW	1	1	

ERLS UNDER CONSTRUCTION

bERLinPro (HZB)

bERLinPro [17] is an Energy Recovery Linac Project, currently under construction at the Helmholtz-Zentrum Berlin (HZB), Germany. The layout is shown in Fig. 6.

The bERLinPro injector, consisting of an SRF photo injector cavity (1.4 cell), followed by a Booster module containing three Cornell design, 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 to be accelerated and is then send through a racetrack magnetic lattice to be recirculated in order to demonstrate effective energy recovery.

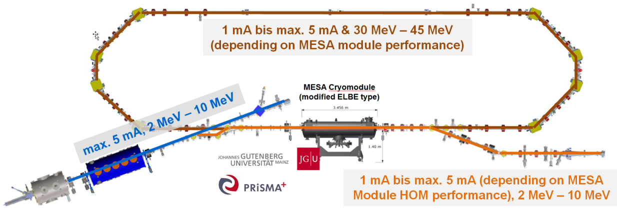

Figure 6: bERLinPro - with a MESA module as main linac.

After deceleration the beam is sent into the dump line with a high power beam stop 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.

Recently a major descope of the project became necessary. On the one hand, the high current gun, planned for up to SI100mA beam operation was canceled, so that bERLinPro will be operated with a medium current gun only, expected to generate a maximum current of about SI5mA, limited by the installed TTF III RF power couplers. On the other hand the main linac can not be purchased 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 the temporal test operation of one of the two MESA project 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 (compared to 50 MeV with the dedicated bERLinProlinac) and to demonstrate energy recovery.

Due to a variety of mostly externally caused delays the initially planned stage-wise installation is not longer possible within the remaining project time, running until the end of 2022. For that the installation of the whole machine including Gun, Booster & MESA module and the recirculator vacuum system will be firstly completed, before bERLinPro commissioning and beam operation will start in mid of 2021. More details can be found in [18].

MESA (JGU Mainz)

The MESA ERL Project [19] is a based on a double sided recirculation design with a normal-conducting injector and two superconducting main linacs running at different operation modes:

External beam operation (three recirculations): a polarized beam of up to 150 μA at 155 MeV will serve the P2/BDX experiment (weak mixing angle, dark sector searches),

ERL operation (two recirculations): a (un)polarized beam up to 1 (10) mA at 105 MeV will be provided for the MAGIX experiment (proton radius, dark photons, astrophysics, etc).

A footprint is shown in Fig. 7.

Construction of the extended MESA hall will run until 2021, afterwards the construction of accelerator and experiments will start. Many of the accelerator parts have been ordered or even built already. The electron source and first parts of the low energy beam transfer system are currently tested. First MESA beam was existing already (up to 150 keV) and a maximum beam current of 10 mA has been achieved.

The MAMBO linac parts are ordered and will be at Mainz in fall 2020. Afterwards setup and commissioning can start.

The cryo module tests started in June 2018. One module was accepted (April 2019), the second module is under re-treatment and will be tested again at the end of 2019. One module is planned to be tested with beam at HZB in 2021/2022. MESA operation with first beam to experiments is expected in 2023. More details can be found in [20].

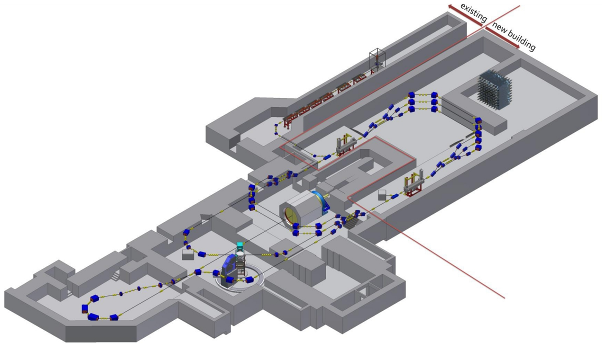

Figure 7: Footprint of MESA in the extended hall.

ERLS IN PREPARATION

PERLE (Orsay)

PERLE is a planned energy recovery linac facility to be hosted at Orsay-France, covering the 10 MW power regime [21]. It is planned as a compact multi pass ERL based on SRF technology, to serve as test bed for validation and testing a broad range of accelerator phenomena and technical choices for future projects, especially on SRF, for the Large Hadron Electron Collider (LHeC).

The PERLE main parameter are listed in Table 2, a footprint is shown in Fig. 8.

Table 2: PERLE Main Parameters

target parameter	value
injection energy / MeV	7
electron beam energy / MeV	500
normalised emittance $\varepsilon_{x,y}$ / mm mrad	6
average beam current / mA	20
bunch charge / pC	500
RF frequency / MHz	801.58

A DC photo-cathode gun will be used as electron source as it can produce the required high current as well as po-

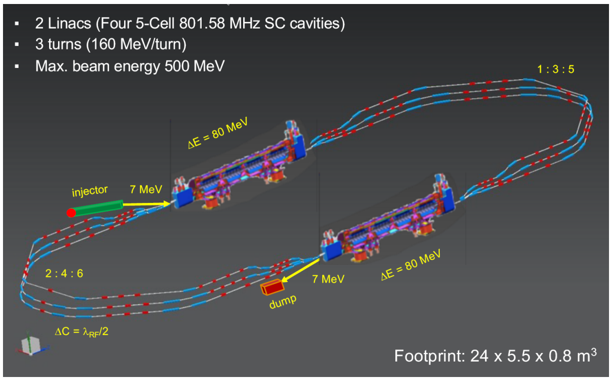

Figure 8: Schematics of the PERLE facility.

larised beams, needed for specific experiments. For that the design of the PERLE electron source will initially be based on the eXtra High Vacuum (XHV) DC photocathode gun previously used on the ALICE ERL / Daresbury and now transferred to Orsay. The significantly higher bunch charge of PERLE compared to ALICE requires a complete, ongoing re-optimisation of the gun electrode system.

For the linac the cryomodule layout developed by IPN Orsay and CERN for the Superconducting Proton Linac (SPL) with four 5-cell cavities has been choosen.

Cavity prototype and design activities to optimize a bare fine grain, high-RRR, 801.6 MHz five-cell Nb cavity design, to build a prototype and to validate the design in a vertical test at 2K helium temperature have been successfully completed at JLAB in 2018: an accelerating field slightly above 30 MV/m was reached with still $Q > 10^{10}$.

Beside the hardware activities mentioned, gun & injector optimization as well as magnet & lattice optimization of the recirculation have been performed. More details on the project can be found in [22].

CONCLUSION

The talks and discussions showed the current state on ERL facilities. Common goals are to achieve superconducting multi-turn operation and going to higher beam powers. This developments are important for potential future ERLs like LHeC ERL or eRHIC ERL.

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