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

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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

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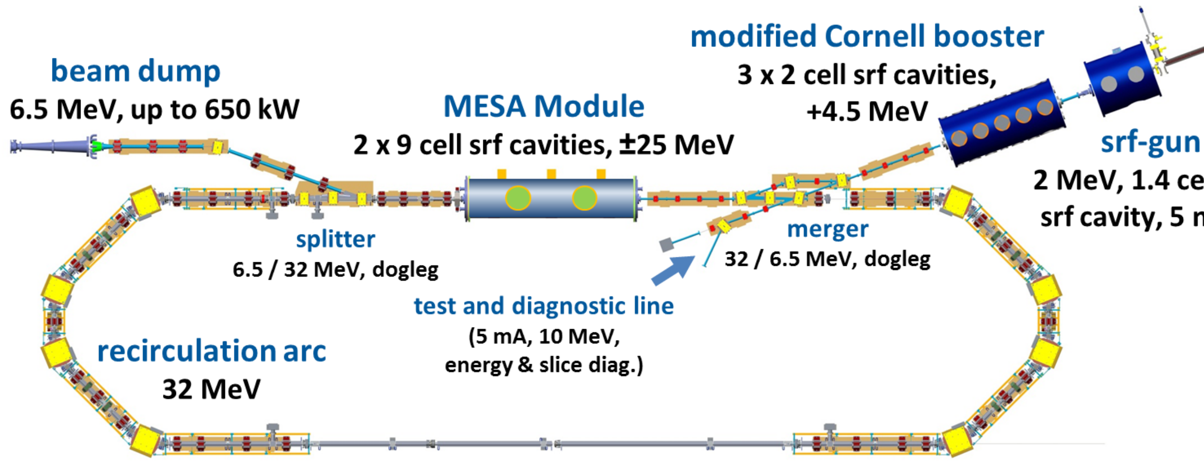

Figure 1: bERLinPro - with a MESA module as main linac.

& Booster), where still major components to start the cold string and module assembly are missing. Several production problems at the vendors, both with the gun cavity as well as with the Booster high power input couplers caused significant delivery delays. These directly determine the duration of Stage-I operation, since its end is set by the installation of the recirculator vacuum system, needed to start in October 2020 to hold the schedule for the remaining project phase, Stage II, running until the end of 2022 (with the MESA module at least until 6/2022). With the most recent delays, accumulated over the last year the Stage-I operation period shrunk to zero and will be not longer possible within the given time constraints. For that reason the installation of the whole machine for Stage II, including Gun, Booster & MESA module and the recirculator vacuum system will be completed, before bERLinPro commissioning and beam operation will start in mid of 2021.

BUILDING

The major construction of the building (Fig.: 2) was completed in 2016 so that machine component installation could begin. Two issues still need to be completed: first, the smoke exhaust system had to be modified to guarantee the requested volume flow, so far limited by under designed ventilation shafts. After installing a more powerful exhaust the incoming air flow was found to be insufficient. A solution has been

Figure 2: bERLinPro-Building in summer 2019

worked out and is awaiting its official authority permit from an external air conditioning expert. Second, after more than one year operating the cooling water system severe corrosion at welding seams were found in routine checks. After a full system inspection it became clear that the majority of seams had not been adequately welded. Moreover wrong types of steel (V2A instead of V4A) have been found, so that most of the pipes needed to be disassembled and have to be repaired or even replaced.
The work on both issues is ongoing and expected to be finished until the end of this year, so that the formal hand over of the building to the HZB may be expected in early 2020.

WARM MACHINE

All girders and magnets were delivered and installed in 2017 [5]. The Stage I magnets were precisely aligned after the installation of the vacuum chamber in the low energy machine part last year. The recirculator magnets will be reopened for vacuum chamber installation and heating by the end of next year, closed again and finally aligned. The dump has been installed also in 2017 - an additional lead block enclosure for local radiation protection has been erected this year.
The Stage I diagnostics components were installed together with the vacuum chamber. Cabling is ongoing and first hardware test have been started. The Control System is set up in its basic conception [6]. It is EPICS based and adopted from the other accelerator facilities operated at HZB, so that most solution for device communication and control as well as a variety of operation software is available.
The personal interlock system will become operational in the beginning of next year [7].

SRF COMPONENTS

A comprehensive overview on the status of the bERLinPro SRF Gun cavity can be found in [8], RF properties of all systems are shown in e.g. [9].

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RF and Cryo System

RF Systems: all three 270 kW amplifiers are installed now, four solid state 15 kW amplifiers are ordered. Also all circulators and wave guides were completely delivered and have been partly assembled already. The water cooled high power loads are partly delivered - one of them was already in use during the first 270 kW amplifier tests in full power operation (still before the loss of cooling water).

Cryogenics: Infrastructure: a L700-type, 4K Helium refrigerator was moved to bERLinPro accelerator hall. A 1.8 K cold compressor box, warm vacuum pumps, all cryogenic lines and three feedboxes for the cryomodules are delivered, installed and cabled. All leak tests have successfully been passed. The system is now awaiting commissioning, starting as soon as the cooling water is available again.

Electron Source

Two gun versions were initially planned: Gun1.0 (with TTF type couplers) for the first medium current project phase. In the second project stage a high power version - Gun 2.0 with KEK type couplers and capable to generate a 100 mA beam of up to 2.3 MeV energy - was planned to replace the first gun. With the descope of the project Gun2.0 had to be canceled, so that the maximum beam current will coupler limited remain at about 5 mA.

Cathode

A codeposition growth procedure has been developed at HZB to deliver high quantum efficiency (QE) Cs-K-Sb photo cathodes for bERLinPro [10]. Furthermore, upgrades have been made in the photo cathode laboratory to bring the production and analysis system (PAS) closer to a robust production system, namely with the installation of a new manipulator [11], see Fig. 3.

The thermal contact experiment (TCX, [12]) has been established to recreate the conditions inside the photo injector

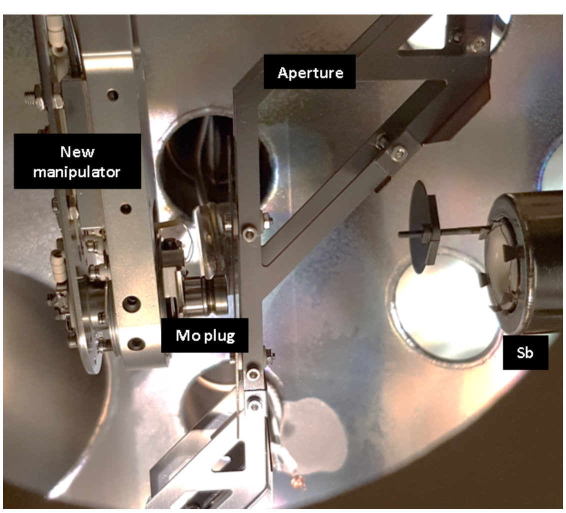

Figure 3: New manipulator in the cathode preparation chamber.

with respect to the cathode cooling system. Initial tests have been conducted using LN2 as a cooling medium. It was found, that a heat load of 30 W on the plug, would bring the plug up to room temperature. This could be reproduced in several cycles of assembling and disassembling the cathode plug to the holder. Further tests using He (g) have now begun which better simulate cooling in the gun.

Laser

Two lasers systems, running on 50 MHz and 1.3 GHz, are being developed and will be installed at the HZB by the Max Born Institute.

The 50 MHz laser in addition will deliver single bunches within a set of repetition rates in the Hz to 100 kHz range. It will be operational by the end of 2019. Starting in the NIR ($\lambda \approx 1\ \mu$m) after frequency doubling in a nonlinear conversion crystal the required wavelength in the green is generated. Synchronization with the RF system has been demonstrated down to the sub-picosecond level. The 1.3 GHz laser is under construction, expected to become operational in mid 2020.

The beam line from the laser hutch to the cathode in the gun module has a length of about 36 m. All optical components have been delivered. Due to the limited accessibility of major beam line parts (e.g. in the vicinity of the ceiling) some of the mirrors and lenses will be remotely adjustable. By operating about 24 m of the beam line under fine vacuum conditions ($p \sim 1$ mbar) degradation of the pointing stability of the laser spot on the cathode surface will be strongly reduced. The remaining distance needs to be accessible for alignment and diagnostic purposes and will be contained in tubes placed in air.

1.4 Cell Gun Cavity & Module

The SRF prototype gun cavity was an in-house development [13] in a collaboration with Thomas Jefferson Laboratory and Helmholtz Zentrum Dresden and used in a dedicated test facility called GunLab to demonstrate first beam generation with a high QE Cs-K-Sb photo cathode. The main idea was to fully characterize the photo injector's beam properties before installing it into bERLinPro. An overview of the limited beam program is presented in [14].

During assembly and testing of the SRF gun module in GunLab valuable experience was gained with the operation of this demanding technology in combination with a diagnostic beam-line and especially integrating a normal conducting, thermal-electrically isolated cathode into the cavity. By that, all surrounding vacuum systems have to maintain an ISO 5 cleanroom norm to avoid contamination and thus limitation of the SRF gun cavity. While the cavity's performance was maintained during the cleanroom assembly of the cold string, some level of contamination started to limit the usable field range by field emission once operating in the module. The reason might be caused by several obstacles, as a breaking of the first view-screen in the beam-line and some accidental venting of the SRF cavity via the cathode transfer system.

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Nevertheless, with the first transferred cathode made of solid Copper a limited beam program was performed, measuring QE maps, longitudinal phase-space of both, laser emitted electron beam and unwanted beam or dark current. Also, the cathode positing measurement system was commissioned and cross-checked, as the information of final cathode position with reference to the cathode cell's backplane is crucial for survival of this system. In the following, the holding system got damaged by over-heating and RF sputtering caused by a gap between Cu cathode plug and holder. This led finally to a loss of the next cathode of Cs-K-Sb type and the GunLab program was stopped.

In parallel a second cavity was manufactured, but before delivery to rebuild the gun module for bERLinPro got damaged on the inner RF surface at the vendor's site. Using both, the cavity operated at GunLab and the new one, a repair program was developed to mechanically remove the inner damages followed by chemical etching using standard buffered chemical polishing. This process is underway and the first cavity acts as a pilot in this refurbishment method, before it will be applied to the second cavity for bERLinPro. In case - this process is finalized in November this year, RF commissioning of the module can start autumn 2020. In the meantime, module assembly is being prepared in the accelerator hall.

Booster Module

The HZB Booster module is based on the Cornell design using three instead of five cavities and the first in zero-crossing operation for longitudinal phase space manipulation. Thus, for the two high power cavities new couplers had to be designed for up to 120 kW in cw regime to reach the envisaged voltage of 2.2 MV per cavity. For that also the coupling section of the cavities was modified. New fundamental power couplers were developed which are based on a design by KEK for their cERL project, but modified with respect to increased coupling and minimized coupler kick by a specially shaped antenna tip [15].

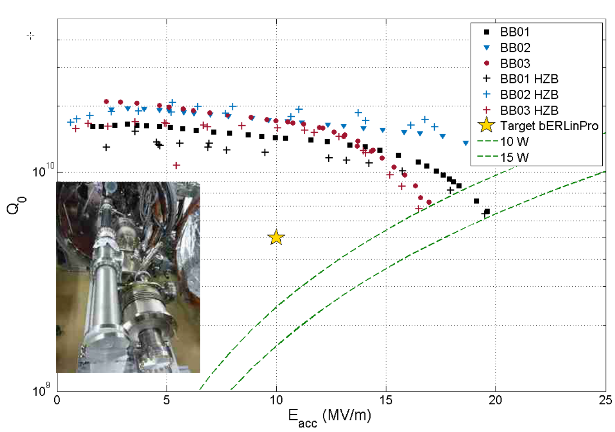

Figure 4: Quality factor versus accelerating field measurement reproducing the vertical test results from JLab at HZB in horizontal set up, see insert picture.

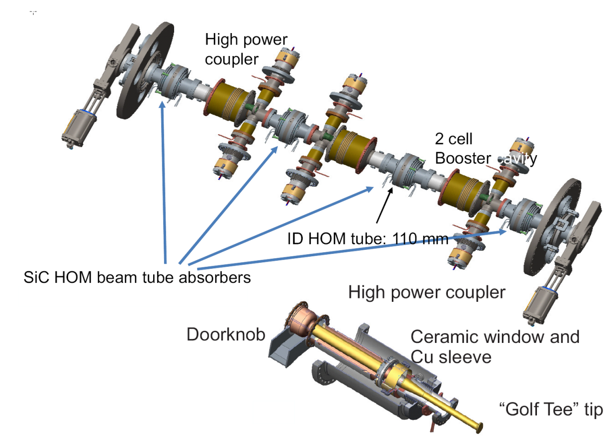

Figure 5: Scheme of the Booster module cold string and a cut-view of the fundamental power coupler.

Cavities

All cavities were retested at HZB and still fulfilled by far the specifications as shown in Fig. 4, similar to the post production tests done at JLab. Recently cavity one was retested with the blade tuner system installed and the results are unchanged, whereas the tuner system meets the required specifications.

Fig. 5 shows an overview of the Booster module cold string comprised of three 2-cell cavities with a Cornell style SiC higher oder mode absorber on both sides of each cavity. To limit the power load per coupler and reduce beam deterioration caused by coupler field distortions, each cavity is powered by a pair of opposite fundamental power couplers as shown in the sketch below the cold string.

Coupler

The modification of the KEK design to adapt it to the bERLinPro project requirements is described in detail in the following publications: [15–17].

Currently all eight coupler cold parts were received and also some pair of preliminary warm parts, so that assembly of the RF conditioning test stand was finished recently, see Fig. 6. Once radiation safety permit is issued and final installations are done, the conditioning will start about in Q1/2020, with the full power test envisaged around Q2/2020, when the final warm coupler parts are received. For the 5 mA operation regime, the fixed power coupling will be adjusted by spacers to increase external quality factor from $1.05{\cdot}10^5$ to about $1.8{\cdot}10^6$. Once full power operation is foreseen, those will be removed by reassembling the couplers. This reduces the required power from 60 kW to 13 kW at this beam current.

Module

In Fig. 7 a cut view of the module is shown. It will have a 80K Helium gas cooled thermal shielding and 2 layers of Cryoperm^{TM} magnetic shielding, whereas the first layer is between Helium tank and tuner of each cavity, the outer shielding is still locally around the cavity. That was done for

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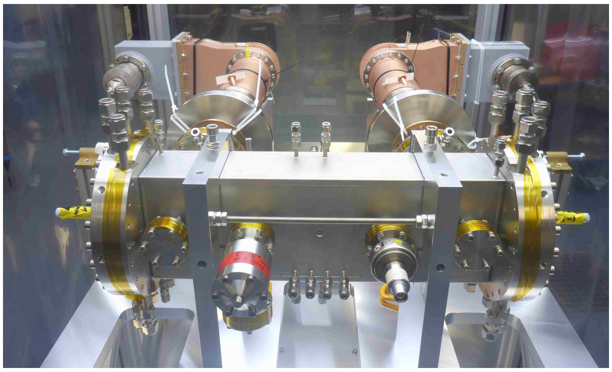

Figure 6: First pair of high power couplers installed for RF conditioning.

cost reasons, so that small vertical steering magnets are to be installed around the HOM absorbers to compensate for earth magnetic field which will act on the beam between the shielded areas via the normal conducting beam pipes.

Besides the HOM absorbers all cold string parts are in house, as well as magnetic shields, tuners, etc. The cryo-piping, thermal shielding and cryostat are currently being procured. It is planned to start string assembly after coupler conditioning around Q3/2020 and in the following complete the module. First cooldown and RF commissioning will thus happen within the bERLinPro's accelerator hall.

Linac Module / MESA Module

The revaluation of the project goals for now have stopped any further development of the bERLinPro main linac cavity and module. Still, for future upgrade the design is ready to being built [9, 18]. Currently all work is focused on integrating the MESA module into bERLinPro, see e.g. [3]. The main adjustments neccessary, are the adoption of the bERLinPro cryo-system to the pressure level and safety valve settings of the MESA linac module. Also a vacuum adapter with emphasis on particulate free assembly is designed which fits the bERLinPro vacuum system and beam pipe to the MESA module's geometry. Currently, a plan how to define acceptance tests to compare the performance of the module before and after operation with bERLinPro is being worked out. Anyhow, the MESA module will be the first linac to be operated with bERLinPro in ERL mode and eventually studies about beam break up can be performed [19].

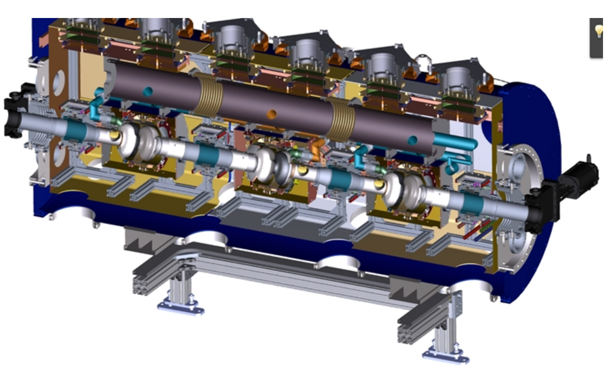

Figure 7: Cut view of the Booster module design.

OPTICS & THEORY

While the descoping of the project does not affect the injector design, the change of the main linac has some influence on the recirculator. The varied linac layout and the reduced accelerating gradients require moderate adjustments of the beam optics.

The change of strength and position of RF focusing in the main linac leads to modified matching conditions into the recirculator. With the reduced recirculation energy also the velocity decreases so that the path length had to be adjusted by about 5 mm. Also with the reduced recirculation energy the bump amplitude of the merger and splitter chicanes grows, but still will not limit the horizontal machine acceptance. However, a reduction of the injection energy remains possible though not favored. At reduced energy the beam becomes more sensitive to space charge (SC) and coherent synchrotron radiation (CSR) effects. Although of acceptable amount, an increased emittance dilution is seen in the simulation as well as indications for micro bunching [20]. After all recirculator adjustments also a re-tuning of the dump line including SC forces becomes necessary.

BBU threshold calculations using the measured MESA cavity HOM spectra with the updated bERLinPro lattice still have to be done. Beside these activities, commissioning planning is ongoing and tests of measurement routines have started.

TIMELINE

The proposed bERLinPro timeline for the remaining project time is summarized in Table 2. The operation period will start in mid of 2021 and includes all steps from commissioning to recirculation and energy recover. It is limited by the date, the MESA module needs to be returned to Mainz, currently assumed for the second half of 2022. VSR module tests in bERLinPro hall are delayed too and will most likely not happen during the foreseen operation period. The funding for a 2000 h/a operation of bERLinPro is secured until the end of 2022.

Table 2: bERLinPro - Present Project Planning

06/2020	Gun1 cool down and RF commissioning (no beam tests)
10/2020	start installation of recirculator vacuum (to be finished 03/2021)
12/2020	Booster module installed
01/2021	MESA module installed (collaboration JGU Mainz, 2 x 9 cell)
06/2021	First beam possible, with subsequent recirculation & recovery

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