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bERLinPro BECOMES SEALab: STATUS AND PERSPECTIVE OF THE ENERGY RECOVERY LINAC AT HZB*

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Abstract

Since end of the year 2020 the energy recovery linac (ERL) project bERLinPro of Helmholtz-Zentrum Berlin (HZB) has been officially completed. But what is the status of this facility, the next scientific goals in the framework of accelerator physics at HZB, what are the perspectives? To reflect the continuation of this endeavor and the broadening of applications of this machine from high current SRF based energy recovery concept up to an ultrafast electron diffraction (UED) facility producing shortest electron pulses, the facility is now named Sealab, Superconducting RF Electron Accelerator Laboratory. In this contribution, an overview of lessons learned so far, the status of the machine, the coming set up and commissioning steps with an outlook to midterm and future applications will be given. In summary, Sealab will expand, including the ERL application, and become a general accelerator physics and technology test machine to employ UED as a first study case and will also be an ideal testbed to investigate new control schemes based on digital twins or machine learning methods.

STATUS OF THE BERLINPRO PROJECT

In end of 2020 the ERL facility bERLinPro [1] accomplished the project phase by finalizing the building, setup of all technical infrastructure and installation of all major components of the warm machine. In summer 2021 also the final part of the beamline vacuum system with the recirculator was closed and assembled under ISO5 cleanroom conditons (see Fig. 1), as all of the machine to allow to preserve the high level particulate free environment for proper operation of the SRF cavity systems of photo-injector, booster module of the injector line and any future linac installation in the main recirculator. Currently, the facility is in its final assembly and commissioning phase for diagnostics, cryo-plant, SRF modules and photo-cathode laser system. Growing of high quantum-efficiency photo-cathodes and research in improved recipes is being continued and presented here [2]. After being operated in a dedicated laboratory [3, 4], the SRF photo-injector underwent a refurbishment program [5, 6] to recover the cavities and improve the installations and assembly routines. The focus is currently on finalizing the cryo-module and produce first beam from the photo-injector only, followed-up by the booster installation, for which the high power coupler processing is close to be accomplished [7]. Figure 2 displays an overview of the whole accelerator, whereas Table 1 summarizes the main parameters of the high current ERL and variable current injector setup implementing the two cathode laser systems at 50 and 1300 MHz [8].

Table 1: bERLinPro/SEALab Parameters

Parameter	ERL	Injector/UED
Beam energy (MeV)	50	6.5-10/2
I_{avg} (mA)	100	6-10/0.0025
Laser freq. (MHz)	1300	50, 1300
RF freq. (MHz)	1300	1300
ϵ_{norm} (mm mrad)	1 (0.6)	0.6/0.03
σ_t (ps)	2 (0.1)	0.02-2
Bunch charge (pC)	77	0.05-400

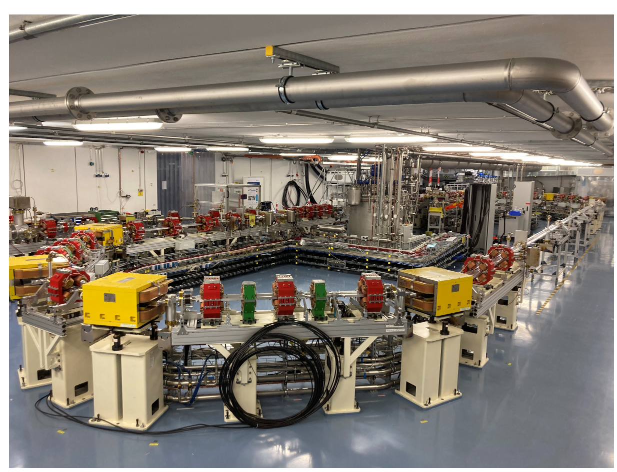

Figure 1: A view on the vacuum system of the bERLinPro accelerator.

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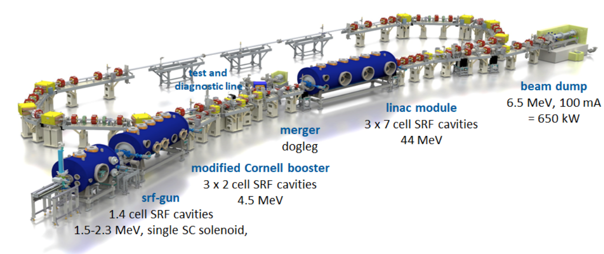

Figure 2: An overview of the bERLinPro/SEALab accelerator.

FROM bERLinPro TO SEALab

The bERLinPro project phase aimed at the setup and commissioning of a compact test accelerator for the energy-recovery linac mode. The goal was to demonstrate that the choice of systems enables generation, acceleration and recovery of a high brightness beam at high average current. These goals demand that the accelerator systems can be run with a very large range of beam parameters. For example during commissioning, first turns and setup of the electron optics is usually done at beam currents of several in the pA to nA range, with low charge bunches with 1 to 10 pC sent out at repetition rates from 1 Hz to 1 kHz. Already in this range all accelerator systems like the photoinjector [3] with drive laser and all necessary diagnostics tools must be able to run with these currents spanning three orders of magnitude. After establishment of first turns and the electron optics for transverse and longitudinal matching, the beam current will be increased up to the 10 to 100 mA regime, increasing by six orders of magnitude. This is done by increasing the bunch charge up 77 pC (design bunch charge) and by increasing the repetition rate from kHz to 1.3 GHz (design repetition rate) for the ERL mode. In this regime beam loss control and stability of the SRF controls is of paramount importance. Again the photoinjector and the diagnostics need to work in the regime. All in all, we have here an accelerator which is capable to run with a very broad range of beam parameters. This makes the accelerator very attractive not only for ERL related applications, but also for other relevant topics. One can imagine that the bERLinPro photoinjector serves as injector for an FEL class linear accelerator running in CW mode or stand-alone for electron scattering experiments. To map out the parameter space for these applications and to formulate a scientific program for the accelerator post-bERLinPro phase we organized a workshop to brainstorm, discuss and prioritize ideas [9]. The main themes discussed during this workshop were performance studies with the photoinjector, utilization as an accelerator test facility, CW SRF cavity/module tests and pilot experiments running the accelerator for multi-color radiation generation (IR/THz, Compton X-rays, ultrafast electron pulses).

Performance Studies of the Photoinjector

For performance studies with photoinjector the goal was to define some quick wins with the existing setup or with relatively minor modifications what can be impactful within five years. Previous attempts for ERLs approaching high beam power were often limited by the performance of the injector, mainly aspects related to beam halo generation, transport and associated losses, beam quality preservation in the merger section. Investigations into microbunching, related to mitigation and enhancement strategies, could also be undertaken with the photoinjector. With the transverse-deflecting RF structure [10] plus spectrometer magnet 6D phase space measurements could be possible in the straight line after the injector as well as in the post-merger linac axis line. With this setup the magnitude and evolution of microbunching can be studied as function of cathode material, drive laser pulse shape and longitudinal beam dynamics.

SRF Tests for Cavities and Modules

Multiple opportunities exist at bERLinPro/SEALab to test the performance of individual SRF cavities and complete SRF cavity modules. The first being on the main linac [11] axis following the merger, the second on the straight line in the return arc. Full module tests probing for beam break-up instability in case the SRF cavity operating frequency can be adjusted by the return arc for 180 deg of RF phase advance are possible. Parallel tests of a short cryomodule with single cell prototypes, even with more exotic concepts (like dual-axis cavities [12]), could be arranged in the straight line of the recirculation arc. Here also investigations into higher order modes (HOMs) at high beam current with variable bunch patterns are possible. As a test case a joint study has been undertaken to discover potential pitfalls and remedies for the integration of the MESA main linac module [13]

Multi-color Radiation Source

The setup of the accelerator allows the generation of electron pulses with a broad range of parameters, which could be transported to various locations in the electron beamline (see Fig. 3 for a footprint of bERLinPro/SEALab with options for radiation sources).

For example in the straight injection line beam energies from 1 to 6.5 MeV can be made available. In the recirculation loop, after acceleration with a main linac module, beam energies at a few 10 MeV could be reached. At repetition rates below 50 MHz, switching between pulse properties could even be done online, resulting in a continuous pulse train where high and low intensity pulses are interleaved. This opens up the possibility to run the facility in multi-color mode with tightly synchronized pulses at low and high energy. Let's consider an application which needs tightly locked pulses of different nature, like a pump/probe experiment. In this setup the material under investigation could be pumped with strong IR or THz pulses generated by high intensity electron pulses sent through an undulator or bending magnet in the recirculation line. Two kinds of THz sources could be imagined: A broadband, single or few cycle source (THz UHB) and a narrowband source with high peak power (THz HPP) [14]. The broadband and the narrowband IR/THZ sources could be operated simultaneously. For this,

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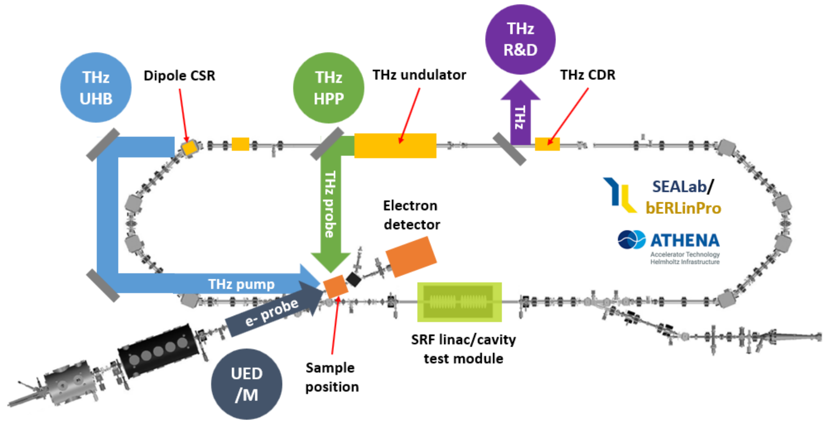

Figure 3: Footprint of the bERLinPro/SEALAb accelerator with overlays for multi-color radiation source opportunities.

the linac needs to accelerate e.g. 10 MHz bunch train for the undulator source with 1 MHz bunch train for the broadband dipole source. At the end of the first 180 deg arc, the beam can be split into two by means of the normal-conducting or SRF separator. This would allow independent longitudinal match (for bunch compression) for the two beams.

The material can be probed by ultra-short electron pulses from the straight injector line [15]. With this combination of IR/THz pump and electron probe pulse methods based on ultra-fast electron scattering like UED or UEM could be implemented at SEALab. The repetition rate needs to be flexible as condensed matter pump/probe experiments can be performed with kHz repetition rate while gas and liquid jet experiments can utilize MHz range. Energy-recovery can be included for the high intensity pulses enabling a sustainable operation mode for the facility.

The science case for a multi-color scheme with ultra-fast electron prove pulses has many applications in fields like materials science to understand coupling phenomena and energy flow in 2D materials and to perform in-operando studies of hetero-structures like solar cells. In chemistry to observe molecular dynamics in gas phase samples and for macro-molecular imaging in the liquid phase. Liquid phase experiments are also fundamental to biology applications, to study the DNA and RNA for early cancer marker and proteins.

ERL Aspects

Energy-recovery linac specific questions could be addressed already with the SRF photoinjector including investigations into halo formation, emittance preservation during initial acceleration and microbunching causes and mitigation strategies and also proving the high current related problems like beam driven wakefield interactions with the surrounding vacuum system and the required level of diagnostics and machine protection [16, 17]. These investigations are mandatory for the commissioning of any high average current, high brightness electron injector as e.g. for the PERLE project [18]. A detailed description of the European strategy for future accelerators and colliders also shines light on the potential application of ERLs as an efficient, even more sustainable large scale science driver, to which SEALab can potentially contribute with injector and linacs studies in both, the high brightness and high beam power regime. More information can be found here [19].

CONCLUSION

SEALab will offer a wide range of possible experiments for accelerator research and development and its potential applications covering a large range of beam parameter space to serve from short pulse-low charge UED measurements up to full high brightness, high current ERL studies and due to its flexibility nearly all combinations of parameters in between, e.g. as a FEL injector or a THz source. Currently, the refurbishing of the SRF photoinjector is ongoing, that first RF test and beam will be expected early 2023, followed-up by the booster module installation allowing also for the full UED pilot studies described in [15].

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