ACCELERATOR PHYSICS EXPERIMENTS AT THE VERSATILE SRF PHOTOINJECTOR OF SEALAB[*]

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Abstract

The superconducting radio-frequency photoelectron injector (SRF photoinjector), now under commissioning at the SEALAB accelerator test facility, has the potential to cover a fast area of beam parameters. Electron bunches from fs to ps length, with fC to nC charge can be accelerated to a couple of MeV beam energy. The legacy from the energy-recovery linac (ERL) test facility bERLinPro, the foundation of SEALab, allows us to operate the SRF photoinjector at very high repetition rate, with energy recovery (ERL), in a sustainable way for fundamental accelerator research into novel, energy-efficient electron accelerators. In this paper preparatory work for two applications is detailed. One is the use of the SRF photoinjector as a direct beam source for ultrafast scattering experiments with high 6D coherence, the other are experiments towards an ERL application for high-energy physics at high average current.

INTRODUCTION

The SRF photoinjector at SEALAB [1] was designed in the framework of the bERLinPro project [2–4]. The task of the photoinjector was to generate a low emittance (normalized emittance of 1 µmrad at 77 pC bunch charge) electron beam with 100 mA average current and to boost the beam energy to approximately 5 to 10 MeV. The bunch parameters and the average current specs were set to allow a radiation source application of an energy-recovery linac (ERL). The bunch length from the injector should be between 2 and 3 ps length to minimize non-linear RF contributions to the transverse beam quality. In the bERLinPro configuration, this beam energy is not recovered during the later deceleration phase because the relative energy spread produced by beam usage and in the bends will amplify during deceleration, thus preventing energy recovery down to near-zero energy. Consequently, the photoinjector must provide the full beam power (500 to 1000 kW at 100 mA). The voltage provided by each cavity is here limited by the average RF power that can be coupled to the beam, rather than the achievable peak field. From beam dynamics consideration, a split photoinjector configuration with separate gun and booster modules was chosen. Both modules contain SRF cavities operating at 1.3 GHz with continuous wave operation.

Given the short bunch length and low emittance target bunch parameters, linear and non-linear transverse and longitudinal space charge forces are the main reason of emittance degradation in the injector due to rather low injection energy. The injector beam energy was set to 6.5 MeV, a compromise between the requirements from space charge considerations and available RF power.

DESIGN RATIONALE

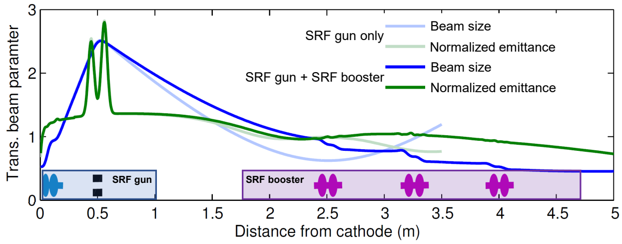

Figure 1: Example for one of the initial scenarios for the split photoinjector setup of SRF gun and SRF booster. Beam size and emittance were simualted for 77 pC scenario with a Gaussian pulse on cathode, see [5] for more details.

The initial idea was to setup the split photoinjector with separate SRF gun and SRF booster [6] (see Fig. 1) according to the Ferrario working point for effective emittance compensation [7] for bunches with slice parameter variations along the bunch. In an axially symmetric system, a solenoid is used to achieve emittance compensation at a certain point, usually starting with the first booster cavity. The solenoid is here located inside the SRF gun module directly after a 1.4 cell SRF gun cavity [8, 9]. For the SRF booster [10, 11], we considered 2 cell cavities as developed for the Cornell ERL booster [12, 13]. The beam can be accelerated off-crest in the gun cavity (beam dynamics of the emission process) and the first booster cavity (beam dynamics driven chirp required by the merger) and on-crest in two of the booster cavities resulting in a beam energy of 6.5 MeV which can be supplied to a beam with 100 mA average current. At lower current the beam energy maybe increased to an administrative limit of 9.5 MeV. The gun and booster section are axially symmetric, implementation of the emittance compensation scheme, finding a location for the fist booster cavity for a

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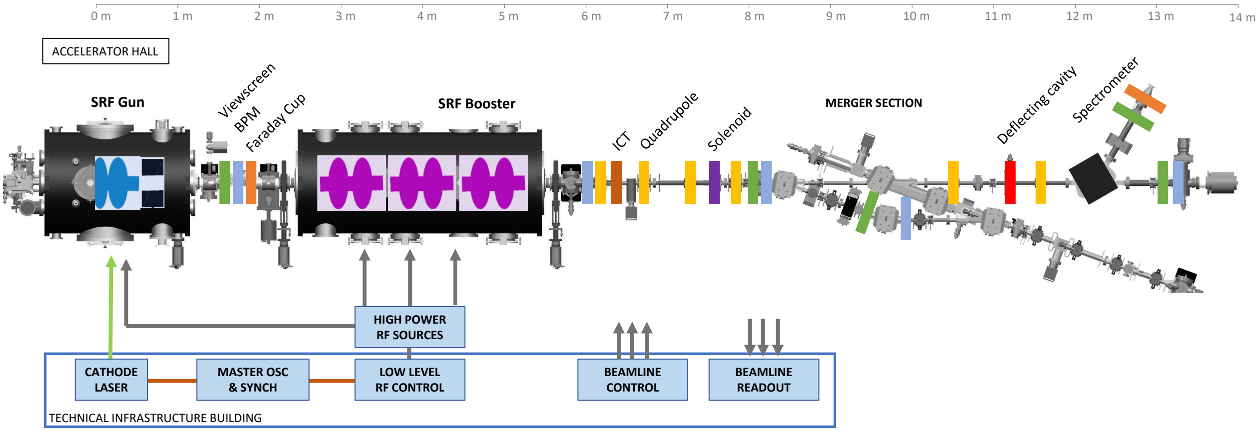

Figure 2: Footprint of the SRF photoinjector in SEALAB/bERLinPro installation.

given bunch length and charge distribution along the bunch, was done according to the Ferrario working point. After acceleration space charge forces due to the current profile are suppressed and all slices oscillate together and projected emittance growth stops. Estimations show, however, that the beam in the merger of bERLinPro is still space charge dominated; therefore, it is necessary to move the emittance compensation point further downstream to higher beam energy, into the linear accelerator. For a system without axial symmetry the 2D-emittance compensation technique was implemented to get both x- and y emittances minimal inside the linear accelerator [14, 15]. After some evolution steps of the SRF photoinjector beamline [16, 17], the design is now converging (see Fig.2 for a footprint).

The electron beamline of the photoinjector contains one cold solenoid [18] inside the SRF gun, six quadrupole magnets and one solenoid after the SRF booster to focus the electron beam. The first four quadrupoles after the SRF booster prepare the transverse beam dimensions for the merger and for 2D emittance compensation. In total 15 corrector coils are installed in the warm and cold section of the beamline for trajectory correction. For beam measurements, two viewscreen stations, four beam position monitors, two Faraday cups and one integrating current transformer (ICT) are installed in the beamline.

A short, dedicated diagnostics section is installed behind the merger. The purpose of the merger is to bend the incoming, fresh beam on the beam axis of the main linear accelerator while passing through the recirculated beam. In the diagnostics beamline two quadrupole magnets are located to match the beam into a dipole spectrometer and to prepare the transverse beam dimensions for the beam dump in straight direction. The bunch length can be measured here with a transverse deflecting RF cavity [19].

STATUS

We designed, built, and tested two SRF gun cavities with a superconducting Pb cathode (dubbed Gun 0.1 and Gun 0.2 [20–22]) in the preparatory phase of bERLinPro. After completion of that program, then within the bERLinPro project, a new SRF gun has been designed, built, and commissioned in the GunLab facility with a SRF gun cavity ready for normal-conducting, high QE photocathodes (dubbed Gun 1.1 [23]). First beam was generated from a metallic photocathode. After a technical failure of the photocathode handling mechanism the SRF gun has been repaired and is now setup in the SEALAB facility as the frontend of the SRF photoinjector beamline [24]. Setup of the SRF photoinjector nears completion in the accelerator hall of the SEALAB facility (see Fig.3 for a photo of the installation as of April 2023) [25].

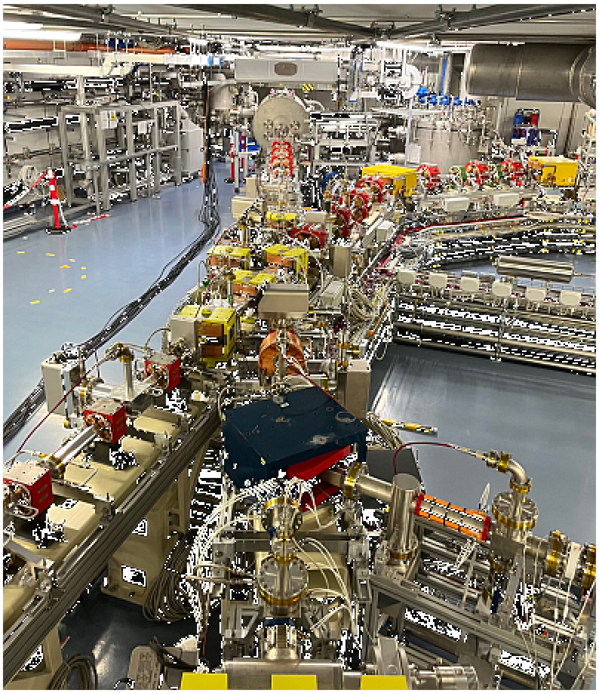

Figure 3: Photo of the SRF photoinjector as of April 2023.

The next step is setup and commissioning with beam [26]. After commissioning the goal is to map out the parameter space which can be reached with the photoinjector, for the ERL, lightsource application as well as other applications of the SRF photoinjector like ultrafast scattering (Ultrafast), and ERL for high energy physics (HEP).

FUTURE APPLICATIONS

The SRF photoinjector of SEALAB was designed produce intense electron beams of superior quality in 6-D phase space, the approach offers opportunities [27] for many applications beyond the baseline scientific case such as a multicolor lightsource [28], ultrafast electron scattering [29], and a testbeam for high-energy physics ERL applications. All of these applications can take direct benefit from the versatility of the photoinjector design. Table 1 core beam parameters for the bERLinPro and future applications are given.

Table 1: Core parameters (Beam energy E, bunch charge q_b, average current I_{avg}, normalized emittance ε_n, and rms bunch length σ_t) for the photoinjector: Initial bERLinPro specs and demonstrated parameter, plus specs for ERL for HEP and Ultrafast applications. Note that the demo parameters for bERLinPro have been observed with different SRF gun systems, and all without the SRF booster.

	bERLinPro		**Ultra fast**	**HEP ERL**
Parameter	**Specs**	**Demo**		
E (MeV)	6.5	2.5	3.5	7
q_b (pC)	77	0.1	0.1	77 to 500
I_{avg} (mA)	100	N/A	N/A	20 to 100
ε_{n} (μmrad)	<1	1.8	10^{-3}	1 to 6
σ_{t} (ps)	2 to 3	2	10^{-3}	2 to 10

Ultrafast Applications

Ultrafast scattering applications, in particular, can benefit from the photoinjector's ability to generate fs long electron bunches at several MeV beam energy, which opens the door to studying strongly correlated and quantum materials, heterostructures, and devices like solar cells or thin-film catalysts in a pump-probe configuration with the electron bunches of the SRF photoinjector acting as a probe. The photoemission process together with high field gradient during emission allows for the generation of a wide range of bunch charges, with very low source size and divergence. In total, four accelerating cavities can be used to compress the bunch to very short bunch length (fs regime) or to very low correlated energy spread [30]. The large number of transverse focusing elements, including two solenoids and six quadrupoles, allows for great flexibility in the photoinjector's operation. The larger number of elements is due to the more detailed nature of the 2D emittance compensation scheme. For ultrafast scattering, however, the large number of degrees of freedom provides versatility for very high performance operating with different modalities like diffraction and imaging [31], making this an innovative tool for materials research with high sensitivity in space, energy, and time [32].

HEP ERL Applications

The use of energy recovery in superconducting linac cavities offers a promising technique for increasing luminosity in high-energy physics (HEP) applications by one or more orders of magnitude, while keeping power consumption comparable to classic lower luminosity solutions [33]. This is an important step towards ensuring the future sustainability of HEP, as interaction cross-sections decrease at higher energy scales. SRF photoinjector of SEALAB can be used to generate high average current and complex temporal beam structure for HEP applications of ERLs.

R&D OPPORTUNITIES

The photocathode is a crucial piece in the SRF photoinjector. Ongoing research topics include understanding photocathode materials (in particular their electronic structure), epitaxial growth procedures, screening/encapsulation/protection of vacuum-sensitive materials, and investigation of the photoemission process for realistic material properties. Electron beam diagnostics systems play a crucial role in the success of ERLs, but they also pose unique challenges. These challenges stem from the combination of large dynamic range and non-equilibrium, non-Gaussian beam profiles with small transverse and longitudinal emittances. Furthermore, ERLs must operate with multiple beams of different energies transported in a single beamline, requiring a variety of beam modes for machine setup, average-current ramp-up, and high-power operation. The difference in average beam current between the tune-up and high-power modes can be up to five orders of magnitude, highlighting the need for large dynamic range beam measurements, especially demanding for the loss and arrival time monitoring. Local beam losses, which can reach 1W, are another issue that cannot be ignored.

Next to these another set of opportunities is linked to the SRF systems, like fast-reactive tuner development, efficient RF sources and high quality factor operation of the SRF cavities. This R&D avenue can be further followed by integration of a complete sustainable SRF linear accelerator module.

CONCLUSION

The SRF photoinjector at 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 ultrafast scattering up to full high brightness, high current ERL for HEP studies

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