STATUS OF THE B*ERL*inPro ENERGY RECOVERY LINAC PROJECT

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Abstract

In October 2010 HZB received funding to design and build the Berlin Energy Recovery Linac Project B*ERL*inPro. The goal of this compact ERL is to develop the accelerator physics and technology required to generate and accelerate a 100-mA, 1-mm mrad emittance beam. The B*ERL*inPro know-how can then be transferred to various ERL-based applications. Presently, B*ERL*inPro is in the design phase, the optics has been settled and first beam has been achieved with an SRF photoinjector— an important first step towards realizing a high-current CW injector.

INTRODUCTION

B*ERL*inPro's primary function is to demonstrate low-emittance, high-current operation so that the concepts and technology may later be employed for a wide variety of applications, including 4th generation X-ray and Compton sources, EUV lithography and nuclear physics. The focus of B*ERL*inPro therefore lies on developing a suitable electron source, the superconducting RF acceleration technology, the optics for beam transport and manipulation, appropriate diagnostics, and the control of beam loss.

Though originally designed as a 100 MeV machine, cost considerations forced a reduction to 50 MeV. As advised by the Machine Advisory Committee, the other primary parameters (Table 1) were left unchanged so that the physics and technology scope of B*ERL*inPro is not diminished.

OPTICS

B*ERL*inPro's layout is shown in Fig. 1. Its 6-MeV injection line consists of an SRF photoinjector and a three-cavity booster section. The beam is merged into the main linac via a dog-leg merger where it is accelerated by three SRF cavities to 50 MeV. Following recirculation the decelerated beam is dumped in a 600-kW beam dump at 6-MeV. Sufficient room is provided to include future "experiments" for users and multi-turn ERL operation.

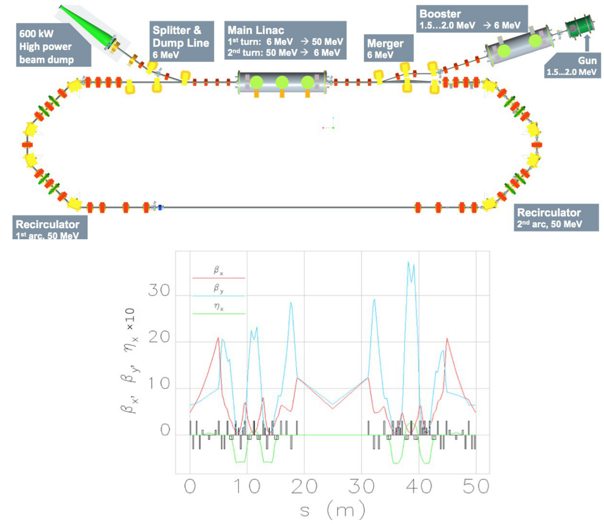

Figure 1: The B*ERL*inPro layout and the Twiss parameters in the ring (beta functions in [m], dispersion in [dm]).

Being a single-pass device, the ERL parameters, like the bunch repetition rate, charge, length or emittance can be adjusted within limits to address the demands of the users. This fact represents one of its inherent strengths. It also implies that there is no "standard" mode, but rather the application will determine the desired beam properties.

Since B*ERL*inPro is a "generic" demonstration facility, a parameter set suitable for future light-source operation has been adopted as "standard mode", as given in Table 1. The machine optics have been optimized to provide these values, as shown in Fig. 2 for the emittance. However, the design is sufficiently flexible to explore a wide range of other parameter, including short-pulse (140 fs) and low-energy-spread bunches.

Table 1: The "Standard" B*ERL*inPro Parameters

Parameter	Value	Unit
Beam energy	50	MeV
Beam current @ 1.3 GHz	100	mA
Bunch charge	77	pC
Bunch length	< 2	ps
Energy spread	0.5%	-
Emittance	< 1	mm mrad
Beam loss	$< 10^{-5}$	-

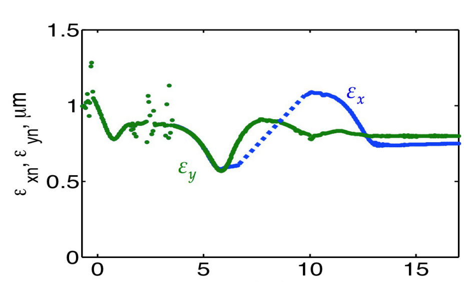

Figure 2: ASTRA simulations of the emittance evolution from the source through the main linac.

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Injection Line

An SRF cavity serves as a 1.8-MeV electron source. A SC solenoid refocusses the beam prior to acceleration in the 3-cavity booster. To reduce the number of costly RF-power transmitters, only the last two cavities accelerate while the first cavity operates near zero crossing to chirp the bunch for subsequent compression.

The merger is designed as a dogleg with quadrupoles mandatory for dispersion control. Sets of four quadrupoles behind the booster and in front of the linac provide emittance compensation and adjust the beta functions in the linac to satisfy BBU and matching conditions.

The final bunch properties are limited by those achievable in the injector. Also, the bunch compression depends on maintaining short bunches in the booster to limit RF curvature. This results in a number of layout restrictions:

- The solenoid must be as close as possible to the photoinjector cavity to minimize the transverse bunch size.
- The booster must be as close as possible to the cathode to minimze bunch lengthening due to velocity effects.
- The distance between the merger dipoles has to be short to maintain a small dispersion($R_{56} = 10$ cm).
- The drift space between the quadrupoles must be large to separate their functionality (40 cm each).

Recirculator

The 44-MeV linac consists of three 7-cell cavities. Three-dipole chicanes before the merger and splitter sections compensate the deflection of the merger and extraction dipoles on the accelerated beam. The arcs are composed of four 45° dipoles with a quadrupole in the center. It reduces the maximum dispersion and provides flexibility for vertical matching and choice of R_{56}, necessary to realize different operating modes. Sets of four individually powered quadrupoles are placed up- and downstream of the arcs to match the Twiss parameters. Their evolution in the ring for the standard mode is given in Fig. 1. Path-length adjustments are made by shifting the two central dipoles in beam direction with simultaneous transverse adjustment of the quadrupole to avoid steering. As a result, the recirculator layout provides:

- A large transverse and longitudinal acceptance to minimizing the loss rate.
- A tuneable R_{56} (-0.25 m $< R_{56} <$ 0.25 m) to adjust the bunch compression.
- Adjustable betatron phase advance to maximize the BBU limited.
- Sextupoles for non-linear corrections.
- Independent tuning of the arc and the straight sections.

Calculated BBU thresholds are significantly above 100 mA for a wide range of phase advances [1].

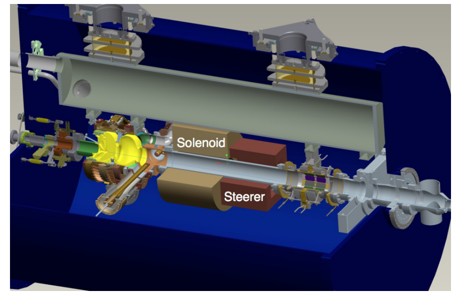

Figure 3: Layout of the SRF injector and SC solenoid.

SRF PHOTOINJECTOR

A 1.3-GHz SRF photoinjector equipped with a CsK_2Sb cathode is currently the baseline electron source. Given the many challenges the photoinjector must meet, its development is being staged. As a first step, an all-superconducting $1\frac{1}{2}$-cell system (including Pb cathode) was successfully commissioned in 2011 in the HoBiCaT facility [2, 3]. Two additional prototypes will follow, the first being in the planning stage. It will include a high-quantum efficiency CsK_2Sb photocathode to provide the full B*ERL*inPro bunch charge at average current < 5 mA. The second adds high-power couplers to handle the full 100-mA beam loading.

As shown in Fig. 3, the injector cavity developed at HZD-Rossendorf [4] is the starting point for developing a new design. The shape is being modified to find a compromize that satisfies beam-dynamics requirements, minimizes the peak surface and maximum cathode fields while providing for separation in phase/energy between the design beam and field-emission current. Both $\frac{1}{2}$-cell and $1\frac{1}{2}$-cell designs are being considered.

This cavity is being integrated in a module that adopts the "philosophy" of the Cornell booster system (see below). It includes an adjustable SC solenoid and steerers, as well as ferrite or ceramic beam-pipe absorbers to damp HOMs. The final version also requires two opposing fundamental power couplers to (a) compensate up to 200-kW beam loading and (b) symmetrize the coupler kicks. KEK-style ERL couplers [5] are planned to handle the 100 kW per coupler. So far they have demonstrated operation up to 40 kW CW [6] and are now being modified to provide additional cooling of the warm inner conductor. HZB is making modifications to permit horizontal coupler installation.

A dedicated beamline for 6-D phase-space beam characterization is included at HoBiCaT ("Gunlab") to permit off-line development work. Limited radiation shielding dictates that the average current not exceeds 50 μA at 2 MeV. A 25-Hz macro-pulse mode (54-MHz bunch repetition rate for 0.5 ms) will be implemented, with the SRF cavity operated CW. Full 5-mA (later 100-mA) CW operation will then be tested in the B*ERL*inPro building.

A cathode-preparation system, including in-situ analysis chamber, is under construction. It also permits the measurement of the quantum efficiency and the beam's energy distribution. The system can connect to BESSY II beamlines to use a multitude of characterization techniques.

BOOSTER SYSTEM

The booster consists of three 2-cell cavities. The module is based on the successful Cornell SRF system, whose demonstrated performance at $E_{\mathrm{acc}} = 12.5$ MV/m is sufficient for B*ERL*inPro [7]. One important modification is required: Since only two cavities (rather than Cornell's five) will provide acceleration, each must handle 230-kW beam loading, requiring the replacement of Cornell couplers by KEK-style couplers. As for the photoinjector, these are being modified for horizontal installation. While the general "philosophy" of the module is maintained, significant modifications are required to accommodate the new couplers.

Three 270-kW klystron-based RF transmitters will power the last two cavities as well as the photoinjector. The klystron tubes and power supplies have been ordered at CPI and FuG, respectively. The tranmitter is based on an existing system that HZB installed and operates at the Metrology Light Source [8]. Installation of the first system at HoBiCaT for coupler tests is planned in 2013.

The first booster cavity, operating near the zero-crossing for energy chirping, will be powered by a 15-kW solid-state transmitter. This will also serve as a prototype transmitter for the main linac cavities.

MAIN LINAC

The main linac features three 1.3-GHz 7-cell structures. Here HOM damping takes on a prominent role and plans call for water-cooled waveguide dampers similar to those developed at JLAB [9]. Their advantage lies in the fact that the fundamental mode is naturally rejected, they are broad band (if windowless) and HOM power can be dissipated at room temperature. The challenge lies in the thermal management with waveguide heat intercepts at 4.5 and 80 K.

Two different cell shapes were considered: The high-current JLAB 1.5-GHz waveguide-damped 5-cell cavity, scaled to 1.3 GHz [9], and the Cornell University 1.3-GHz 7-cell cavity [10]. The latter has an improved ratio of peak to accelerating electric field (2 rather than 2.4). In collaboration with Technische Universität Dortmund and Universität Rostock the two designs, combined with waveguide dampers, are currently being modified and used as the basis for BBU calculations [11]. Warm models are currently under construction for HOM measurements.

While the negligible beam loading relaxes the coupler design, the weak coupling ($Q_{\mathrm{ext}} \approx 5 \times 10^7$) yields a small bandwidth and microphonics dominate the RF-power requirement and achievable stability. Digital LLRF measurements have demonstrated that operation up to $Q_{\mathrm{ext}} \approx 2 \times 10^8$ is possible[12]. Still, electro-mechanical modeling of the cavity design takes on a prominent role. It is being carried out in collaboration with FZ-Jülich. 10 kW of RF power is budgeted for each cavity which will be supplied by individual 15-kW solid-state transmitters.

The design of the approximately 5.1-m-long linac module will start in 2013 once the final dimensions of the cavities are known.

RADIATION PROTECTION

The study and management of beam loss will be one of the key aspects of the B*ERL*inPro project to establish reliable values and techniques for future user facilities. Presently, the expected beam loss cannot be accurately estimated and the machine protection system will be designed to trigger at losses above 5 μA. However, the personnel protection must be designed for a worst-case loss scenario. An upper limit for CW electron losses is given by the 30-kW installed main-linac RF power, corresponding to losses of 0.6% at 100 mA. This places a heavy burden on the radiation shielding.

Annual dose calculations and activation estimates are based on 2000 h/a operation with beam loss occurring at six equally spaced points around the machine. New semi-analytical formulas for gamma and neutron radiation were developed for the B*ERL*inPro parameters [13]. The $13 \times 33 \times 3$ m^3 machine building will be placed underground for a considerable cost saving since the transverse radiation is three orders of magnitude lower than in the forward direction. The vertical shielding requirement is dominated by fast neutrons and demands a wall thickness equivalent to 20 cm of concrete + 3 m of sand to maintain general public access outside the building (dose $<$ 1 mSv/a).

Radiation measurement units consists of an ionization chamber and a neutron detector (BF3 proportional counter). To measure the complete neutron spectrum, the latter will be retrofitted with a 1-cm Pb cover to moderate neutrons. Calibration will take place at CERN in 2012.

The activation dose at the machine strongly depends on the choice of vacuum-chamber material. It has been estimated for Al, stainless steel and Cu [13]. Cu yields unacceptably high doses of order 1 Sv/h at 1 m. While the calculated activation for Al is about one order of magnitude lower than that of stainless steel, the latter is still favored due to cost considerations. Investigations are under way to determine whether parts of the arcs must be equipped with Al vacuum chambers.

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