THE INJECTOR LAYOUT OF B*ERL*INPRO*

B. Kuske #, M. Abo-Bakr, V. Dürr, A. Jankowiak, T. Kamps, J. Knobloch, P. Kuske, S. Wesch
Helmholtz-Zentrum für Materialien und Energie GmbH, Berlin, Germany

Abstract

B*ERL*inPro is an Energy Recovery Linac Project running since 2011 at the HZB in Berlin. A conceptual design report has been published in 2012 [1]. One of the key components of the project is the 100 mA superconducting RF photocathode gun under development at the HZB since 2010. Starting in 2016 the injector will go into operation, providing 6.6 MeV electrons with an emittance well below 1mm mrad and bunches shorter than 5 ps. In 2017 the 50 MeV-linac will be set up and full recirculation is planned for 2018. The injector design has been finalized and is described in detail in this paper. Emphasis is further laid on beam dynamics aspects and performance simulations of two different gun cavities.

INTRODUCTION

Ground breaking for the two new buildings for B*ERL*inPro is planned for April 2014. An industrial technique hall to host most of the technical equipment and a subterraneous accelerator hall will be set up close to the BESSY II accelerator complex. The installation within the accelerator hall is planned for 2015 and is initially limited to the injector (gun, booster, merger), a straight beam pipe to replace the linac and the dump line with a 650 kW beam dump, Fig. 1. Commissioning will start in 2016 with the cryogenic plant, followed by the RF commissioning. Most parts of the gun module have been ordered. The module assembly is planned for 2014 at the HZB. The module will be commissioned in a testing environment setup at HZB. The complete module will then be transferred into the accelerator hall, so that work can focus on the booster and on the beam dynamics in the merger. The booster module will be ordered this autumn. It is needed early, as a load for the commissioning of the cryo-plant. The call for tender for the magnets is close to being posted. The beam dump is an in house design, and has also been ordered.

HARDWARE

Layout

The gun is a 1.4-cell superconducting (SC) 1.3 GHz RF-gun with a CsK_2Sb cathode [2]. It provides 77 pC electron bunches at 2.3 MeV. The module also contains a SC solenoid. A short 0.7 m warm section between the gun module and the booster provides space for the laser port, diagnostics and steering coils. The booster module hosts three 2-cell cavities and raises the energy to 6.6 MeV. The merger is a dogleg merger, with three 20° parallel faced dipoles and two quadrupoles for dispersion compensation. The quadrupoles are positioned asymmetrically to provide space for a collimator in the dispersive section. Two further pairs of horizontal and vertical collimators are placed in front of and behind the merger. A total of eight quadrupoles are used for emittance compensation and the adjustment of the beta functions into the linac. The linac will consist of three 7-cell cavities. Two 20° dipoles and two solenoids guide the beam into the 650 kW beam dump. The dump is realised as a water-cooled copper cone.

Magnets

All magnets are being designed by BINP, Novosibirsk, Russia, and split into magnets for the high energy beam of 50 MeV and the injector magnets for <10 MeV. All injector/dump line dipoles are identical, 20°, rectangular H-magnets providing a large good field region of 80 mm to accommodate the large sagitta of the low energy beam and the path of the high energy beam in the same aperture (merger/splitter magnets). There will be no separate steering magnets; correction coils are included in the quadrupoles and dipoles. Further parameters are given in Table 1.

Table 1: Magnet Parameters of the B*ERL*inPro Injector

	No	Aperture	Max. field	L	Bend. radius
10 MeV		[mm]	[T]/[T/m]	[m]	[m]
Dipole	8	52	0.09	0.25	0.79
Dipole	1	82	0.09	0.25	0.79
Q-pole	10	52	0.50	0.15	-
Q-pole	6	82	1.70	0.15	-

Vacuum System

For the energy range of B*ERL*inPro the gamma dose rate of an aluminium chamber lies one order of magnitude below that of stainless steel and the activation rate after one year is two orders of magnitude lower [3]. Therefore, most of the vacuum system will be aluminium, despite the higher production costs. Only short inclusions like diagnostic or pumping ports will be made of stainless steel. For unification purposes the complete recirculator will have an aperture of 40x70 mm and will have cooling channels. The injector will mostly have a round chamber of 40 mm diameter; the aperture in the dump line is 70 mm. The pressure of at most $5\cdot10^{-9}$ mbar is achieved by coating the Al-chambers. NEG coating is an option

---

*Work supported by German Bundesministerium für Bildung und Forschung, Land Berlin, and grants of Helmholtz Association

#bettina.kuske@helmholtz-berlin.de

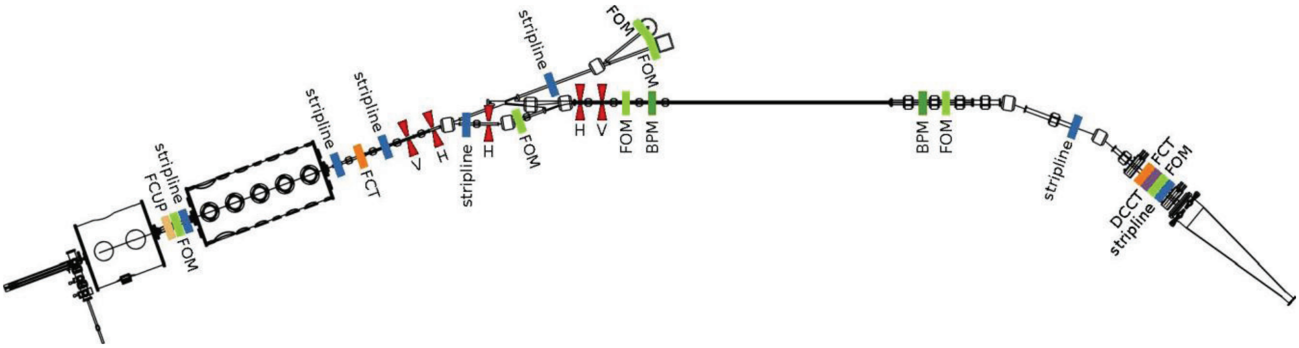


Figure 1: The setup of B*ERL*inPro will start with the injector, the linac straight and the dump line in 2015.

that would allow reaching the 10^{-11} mbar range after activation, when compatible with the SRF cavities.

Diagnostics

The diagnostics foreseen in the injector, Fig. 1, takes into account that the gun module has been characterized prior to the installation in the accelerator hall. For the beam diagnostics of the 6.6 MeV beam, a diagnostic line is set up in straight continuation of the booster; a second diagnostic line is planned in continuation of the linac (not shown). Collimators are placed in front of and behind the merger (H and V) and between the first and second merger dipole in the dispersive section (only H).

OPTICS

Gun Cavity

It has been decided to start with a 1.4-cell gun cavity instead of the original 0.6-cell cavity. The additional cell lowers the necessary peak field by 25% to 30 MV/m, strongly reducing the risk of field emission from the cathode. The particle energy rises from 1.7 to 2.3 MeV.

For the optics the main difference between the two cavities lies in the accelerating voltage during emission. In the 0.6-cell cavity, the phase for maximal energy gain lies close to the zero crossing of the RF field. This leads to a large relative energy spread and a longitudinal compression of the bunch during emission (particles emitted later see higher field). Consequently, longitudinal space charge and velocity de-bunching play a major role. In a 1.4-cell cavity the phase for maximal acceleration lies around 45°. During emission the field is almost doubled, leading to a reduced relative field variation. As a result, the energy spread behind the gun is smaller and there is almost no bunch lengthening. At ~1 m behind the cathode the bunch length is similar in both cases, σ_L = 1.5 mm, but the relative energy spread is 0.0015, compared to 0.01 for the 0.6-cell cavity, see Fig. 2.

Also the transverse bunch properties profit from the lower energy spread in the 1.4-cell cavity: The average sliced emittance decreases during acceleration and remains around 0.5 mm mrad. With the 0.6-cell cavity the sliced emittance increases during acceleration to 0.73 mm mrad and the dispersive effects in the merger increase the projected emittance to ~1 mm mrad.

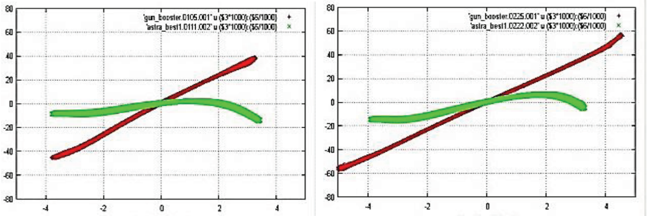


Figure 2: Longitudinal phase space [keV / mm] at 1.1 m (left) and 2.2 m (right) behind the cathode; red: 0.6-cell cavity, green: 1.4-cell cavity. The expansion due to the larger energy spread is clearly visible.

Emittance Compensation

The compensation of the degrading effects of space charge on the emittance in the injector has been calculated by two different methods. One is based on an analytical approach the other uses massive parallel computation and a self-defined goal function for optimization (swarm calculations) based on the ASTRA code [4]. In both cases, the longitudinal phase space, i.e. the pulse length of the cathode laser, the RF phases and the size of the energy chirp of the bunch were fixed.

The swarm calculations [5] were set up to optimize the projected emittance behind the linac, the free parameters were the laser spot size on the cathode, the solenoid and the quadrupole strengths. In the horizontal plane the longitudinal space charge due to the dispersion in the merger plays an additional role, which is automatically included in the optimization. The result is shown in Fig. 3 (top) for the horizontal phase space.

The projected emittance behind the merger is small, ε_x=0.82, ε_y=0.66 mm mrad. But the ellipses are not well aligned; the average sliced emittance of 0.5 mm mrad is much smaller than the projected value.

In the analytic approach [6] the bunch is regarded as a sequence of independent slices. The rotation of each slice in the transverse phase spaces depends on the slice charge and can be described in a linear approximation. The gradients of the quadrupoles can be optimized to align the phase space ellipses at a specific location in the lattice and thus reduce the projected emittance. The values of the laser spot size and the solenoid were taken from the swarm calculations.

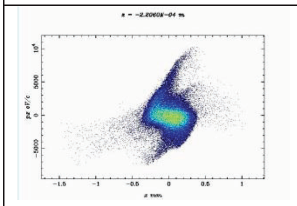
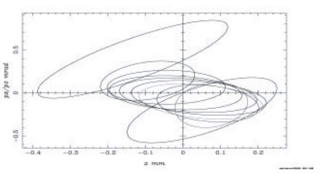
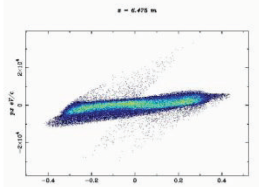
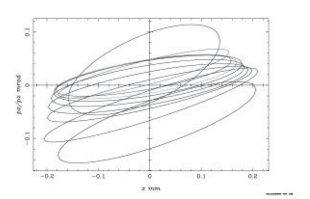
Horizontal Phase Space	Phase Space Ellipses for 10 Bunch Slices
swarm optimization	
	
ε_x=0.82, ε_y=0.66	slice average: ε_x=0.5, ε_y=0.5
analytic approach	
	
ε_x=0.96, ε_y=0.95	slice aver.: ε_x=0.64, ε_y=0.59

Figure 3: Horizontal phase space behind the linac and its decomposition to 10 longitudinal bunch slices for the swarm result (top) the analytic result (bottom).

Longitudinal space charge is neglected in this approach. The result is shown in Fig. 3 (bottom). The ellipses are well aligned, but the sliced emittance is ~20% larger and the projected emittance is ε_x=0.96, ε_y=0.95 mm mrad.

Best results were achieved by using the analytic values as start values for the swarm run. Table 2 lists the main beam parameters achieved behind the linac.

Table 2: Beam Parameters Behind the Linac

	unit	value
Bunch length	mm	1.49
Emittance x,y	mm mrad	0.76 / 0.61
Sliced emittance	mm mrad	0.49 / 0.50
Uncorr. energy spread	keV	3

Unwanted Beam

Unwanted beam includes halo, i.e. particles travelling with the beam at large amplitudes and dark current which are particles emitted from the cavity walls or the cathode itself around the peak of the RF field. Dark current will usually have an offset in time and energy to the beam. Halo particles are expected at the nominal energy but at large amplitudes. The energy acceptance of the merger with a round aperture of 40 mm and 20° dipoles is ~6% or 0.4 MeV. The energy gain of the beam in the first half-cell of the gun is ~1 MeV. Therefore, only particles that experience acceleration starting close to the cathode are liable to have enough energy to pass the merger and most of the unwanted beam will be lost in the aperture before.

Halo due to Coulomb scattering at residual gas is estimated to be ~1.5 10^{-7} in the injector and dominates Touschek scattering (10^{-9}). Halo due to stray light of the cathode laser originates mostly from, or close to, the cathode plug. Tracking has been performed for particles with amplitudes of 1-5 mm with the beam's time structure. The beta functions of these halo particles differ strongly from those of the main beam, due to the lack of space charge and the large amplitudes. They are over-focussed by the solenoid and reach up to 10 mm amplitude inside the booster module, but disappear in the beam at the location of the first collimators. Setting the collimator in the merger to +/-4 mm, 46% of these particles would be stopped (60% for +/-3 mm); another 34% (30%) can be scrapped off vertically in front of the linac. 10-20% of these particles will travel together with the beam.

Dark Current (DC) from the cathode has been simulated using the Fowler-Nordheim formulas with a work function of 1.9 eV, β = 200, E_{max}= 30 MeV and a uniform distribution of 3 mm radius (size of the cathode). The phase difference between the bunch and the peak of the DC is ~50°. Still, due to the long duration of the DC pulse, the front flank of the distribution overlaps with the bunch. 58% of the simulated DC gets lost before the merger. The transmission behind the merger is ~14%. Using the collimators, this value can be further reduced.

The interlock system for the injector will trigger at losses of 25 µA behind the booster. This limit includes the losses discussed, as well as the complete DC from the booster. The balance between the different sources of unwanted beam is unknown; still the expected transmitted current can be estimated to less than a few 10^{-5}.

REFERENCES

[1] Conceptual Design Report B*ERL*inPro, 2012, B. Kuske, N. Paulick, A. Jankowiak, J. Knobloch (editors).

[2] A. Neumann, W. Anders, A. Burrill, T. Kamps, J. Knobloch, O. Kugeler, „SRF Photoinjector Cavity for B*ERL*inPro“, IPAC 2013, Shanghai, China, these proceedings.

[3] M. Helmecke, K. Ott, "Activation Calculations with FLUKA for the B*ERL*inPro Vacuum System", RadSynch13, 2013, Brookhaven, USA.

[4] K. Flöttmann, ASTRA - A Space Charge Tracking Algorithm, Version 3.0,http://www.desy.de/~mpyflo/

[5] M. Abo-Bakr, B. Kuske, "ASTRA Based Swarm Optimizations of the B*ERL*inPro Injector", ICAP 2012, Rostock, Germany, pp. 281.

[6] A. Bondarenko, A. Matveenko, "Emittance Compensation Scheme for the BERLinPro Injector", Proc. IPAC 2011, San Sebastián, Spain, pp.1497.