DIAGNOSTICS BEAMLINE FOR THE SRF GUN PROJECT †

T. Kamps‡, V. Dürr, K. Goldammer , D. Krämer, P. Kuske, J. Kuszynski, D. Lipka,
F. Marhauser, T. Quast, D. Richter, BESSY, D-12489 Berlin, Germany
U. Lehnert, P. Michel, J. Teichert, FZ Rossendorf, D-01314 Dresden, Germany
P. Evtushenko, Jefferson Lab, Newport News, VA 23606, USA
I. Will, Max Born Institut, D-12489 Berlin, Germany

Abstract

A superconducting radio-frequency photo electron injector (SRF gun) is currently under construction by a collaboration of BESSY, DESY, FZR and MBI. The project aims at the design and setup of a CW SRF gun including a diagnostics beamline for the ELBE FEL and to address R&D issues on low emittance injectors for future light sources such as the BESSY FEL. Of critical importance for the injector performance is the control of the electron beam parameters. For this reason a compact diagnostics beamline is under development serving a multitude of operation settings ranging from low-charge (77pC), low-emittance (1 mm mrad) mode to high-charge (2.5nC) operation of the gun. For these operation modes beam dynamics simulations are resulting in boundary conditions for the beam instrumentation. Proven and mature technology is projected wherever possible, for example for current and beam position monitoring. The layout of the beam profile and emittance measurement systems is described. For the bunch length, which varies between 5 ps and 50 ps, two schemes using electro-optical sampling and Cherenkov radiation are detailed. The beam energy and energy spread is measured with a 180^o spectrometer.

MOTIVATION

Radio-frequency (RF) photoinjectors offer excellent performance characteristics for application at Free Electron Lasers (FEL). Strong RF accelerating fields together with emittance compensating solenoidal fields deliver high bunch charges in the order of 1 nC at low normalized emittances close to 1 mm mrad.

Future FEL light sources such as the proposed BESSY FEL [1] operate with superconducting RF (SRF) for electron acceleration to enable continuous wave operation to generate flexible bunch patterns to meet the user demands. Current photoinjectors work with normal conducting RF in a pulsed mode. Using SRF for the injector as well allows one to fully exploit the benefits of SRF technology. There are however issues with the application of SRF technology at electron gun cavities related to the high gradients and solenoidal fields. The emittance compensation scheme, which makes use of the solenoidal field in normal conducting RF guns cannot be used in a SRF gun without modifications. When superconducting material is placed in direct vicinity of strong magnetic fields, magnetic flux lines might be trapped. In case of a SRF gun this leads to a vast enlargement of the surface resistance, thus beating down the quality factor and impeding operation at the desired accelerating gradients. The SRF gun under development within the framework of this project utilizes a modified TESLA [2]-based design for a three and a half cell gun cavity made of Nb with a RF frequency of 1.3 GHz [5]. The axis peak field of the accelerating mode is 50 MV/m. In order to work with high gradients the quality factor has to be in the region of 10^{10}. To avoid degradation of the quality factor due to additional surface resistance the contribution from the solenoid magnetic flux has to be kept below 3.5 μT [3].

Furthermore the application of photo-cathodes at low temperatures and the compatibility with the SRF cavity have to be addressed. The SRF gun collaboration of BESSY, DESY, FZR and MBI sets out to tackle these issues. The target of the collaboration is to setup a SRF photoinjector [4] together with a diagnostics beamline serving as a test facility for future SRF injectors. The injector will be able to work in three different operation modes with beam parameters as listed in Tab. 1. All operation modes have been simulated using ASTRA [6] for emittance and bunch length performance to draw up a list of boundary conditions for the diagnostics elements. In Fig. 1 the modified emittance compensation scheme using a solenoid magnet positioned directly after the gun cryostat is shown for the ELBE mode. Here a solution with a working point at 2.66 m after the cathode surface was found.

Table 1: Beam parameters of the injector operation modes ELBE, High charge (HC) for neutron experiments and energy recovery linac R&D, and BESSY FEL (BFEL).

Mode	**ELBE**	**HC**	**BFEL**
Repetition Rate	13 MHz	1 MHz	1 kHz
Bunch Charge	77 pC	1 nC	2.5 nC
Bunch Length	5 ps	20 ps	50 ps
Transverse Emittance	1.5 μm	2.5 μm	3.0 μm

The diagnostics beamline task is to control all relevant beam parameters for all operation modes. Two different operation regimes can be clearly identified. One is the low charge regime with bunch charge between 10 pC and

† Work supported by the Bundesministerium für Bildung und Forschung
‡ kamps@bessy.de

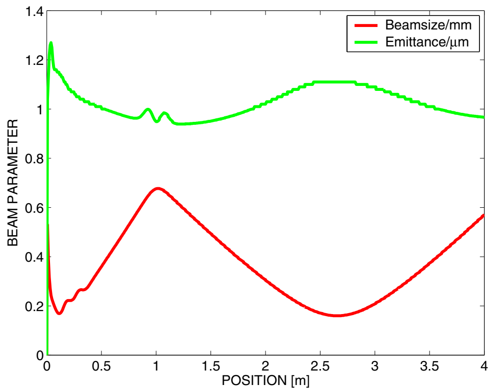

Figure 1: Propagation of beamsize and emittance for the ELBE mode with the modified emittance compensation scheme with input parameters like bunch length of 5 ps fwhm and with thermal emittance of 0.7 μm. The peak magnetic flux density is 230 mT at 1.0 m distance from the cathode. Clearly visible the working point at 2.66 m.

100 pC and the high charge regime between 1 nC and 2.5 nC. All elements therefore need excellent resolution combined with a large dynamic range. The expected beam sizes vary between several 100 μm and a few mm for the low charge regime and are by at least a factor of five larger for the high charge regime. Furthermore the diagnostics need to have high single bunch resolution.

DIAGNOSTICS OVERVIEW

The diagnostics beamline enables the measurement of the transverse emittance, energy spread and bunch length beside beam position, mean momentum and charge. A schematic overview of the beamline is shown in Fig. 2. It consists of beam position monitors (BPM), integrated current transformers (ICT), profile monitors based on YAG-screens, an emittance measurement system (EMS), a spectrometer dipole, a Cherenkov radiator, electro-optical sampling system (EOS) and Faraday cups (FCup). In addition the beam can be focused with a quadrupole triplet, guided to the ELBE beamline with a dipole magnet and the beam position will be corrected with steerer coils. In the following diagnostic elements to measure selected beam properties are described in more detail.

CHARGE AND BEAM POSITION

The task for the beam current and charge measurement is to verify that the charge produced at the cathode is completely transported along the whole beamline to the beam dumps. Furthermore dark current measurements directly at the cryostat exit are necessary to observe aging processes at the cathode and for machine protection reasons. The charge of individual bunches and the charge distribution in the beam pulse will be measured using ICTs and Faraday Cups. The beam dumps will be build as Faraday cups, there the beam is absorbed and the captured charge is monitored. The requirement for the accuracy is for all charge regimes $dQ/Q = 0.10$ which is met by state-of-the-art systems. In addition the sum signal of a BPM depends linearly on the bunch charge.

The requirements for the beam position measurement are a resolution of better than 100 μm for single bunches, for beam offsets as far as 5 mm. The readout electronics has to cope with all operation modes. For orbit control it is planned to use stripline BPMs as implemented at the ELBE accelerator [7]. The striplines have a length of 1/4 λ (which is the wavelength of the accelerating RF frequency of 1.3 GHz) and are mounted in a compact package as shown in Fig. 3. The readout electronics utilizes a logarithmic detector for direct RF to DC conversion and a logarithmic amplifier with a large linear dynamic range of 60 dB. The sensitivity is 0.8 dBm/mm.

Figure 3: Short stripline BPM. The BPM is 85 mm long, the inner diameter of the beam pipe clearance is 40 mm.

EMITTANCE AND PROFILE

For the foreseen operation regimes the emittance of the electron beam will cover the large interval between 0.5 mm mrad and 5 mm mrad. The required resolution is $d\epsilon/\epsilon = 0.20$ for all regimes. The beam is in all nominal operation modes space-charge dominated rendering emittance measurement techniques impossible which assume linear beam optics. For this reason a slit-based phase space sampling method (see for example [8]) is considered, where a narrow slit is moved perpendicular across the beam. The slit collimates the beam into emittance dominated beamlets, whose divergence is measured at screen stations following the slit mask. From these data the divergence of the beam in front of the slit mask can be reconstructed. Together with a transverse profile measurement at the slit mask plane the emittance can be calculated.

The purpose of the slit is to collimate the beam with respect to beamsize, peak current and emittance resulting in emittance dominated beamlets. The contribution of the slit

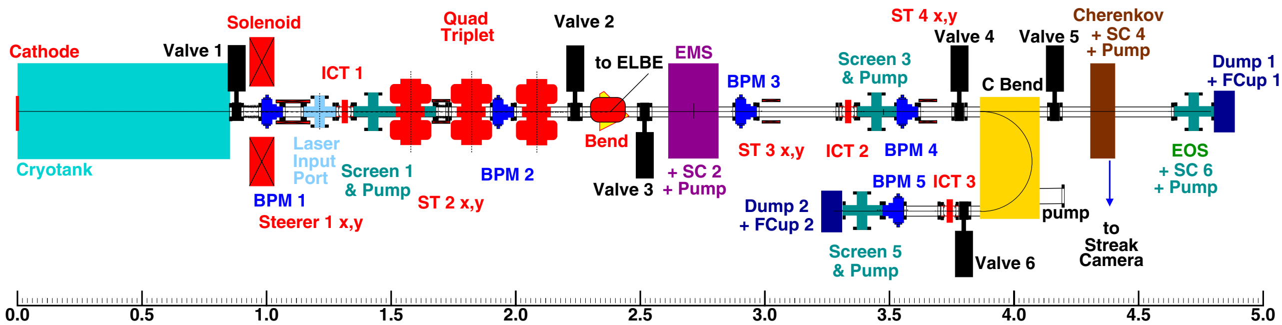

Figure 2: Diagnostics beamline overview including dipole magnet for the transfer to ELBE.

width towards the beamlet size should be small, but it must also be large enough to supply the beamlets with sufficient charge for a good signal to noise ratio. In order to meet the requirements from the various operation modes a single-slit mask with two slits of 100 μm and 50 μm width is under construction. The beamlets will be measured with three high resolution viewscreen stations downstream in the diagnostics beamline. The stations are located 0.6 m, 1.6 m and 2.0 m after the slit mask. The beamlet sizes at these stations vary between 60 μm and 250 μm. The mask itself is made of 1.5 mm thick tungsten, being an optimum between acceptance and background due to Coulomb scattering. Tungsten was chosen due to the high Z of the material. The emittance measurement station (EMS) itself will be positioned at the location of the working point for the ELBE mode 2.66 m behind the cathode surface.

The transverse charge distribution and the size of the beamlets created by the EMS will be measured with viewscreen stations. In total six such stations are planned for the diagnostics beamline. With all screen stations the transverse phase space charge distribution is projected on the horizontal and vertical beam coordinate. This is done by inserting a suitable screen into the beam path of the electrons. The beam image is then projected with a lens onto the sensitive area of a CCD camera. For the screen material several options have been considered. Powder Ce:YAG screens as used elsewhere in normal conducting injectors are not suitable because of poor vacuum compatibility. This leaves crystal Ce:YAG screens for this particular application. For the high charge regime optical transition radiation (OTR) based screens are foreseen.

BUNCH LENGTH

A precise measurement of the bunch length is essential as the transverse emittance is directly linked to the longitudinal charge distributions. The required resolution will be in the order of $d\sigma_z/\sigma_z = 0.10$ which is challenging for the low charge regime with a bunch length of 5 ps. The measurement technique must be robust in order to provide the required resolution for various correlation measurements, where the bunch length is measured versus bunch charge, drive laser phase and pulse length, RF gradient and beam energy. Therefore two systems with overlapping working range are selected. Both methods rely on the conversion of the electron intensity distribution into a corresponding light pulse. One uses the partial conversion of the energy of the electron bunch via Cherenkov radiation into a flux of photons with the same time properties as the electron bunch [9]. These light pulses are then measured with a streak camera which is placed at some distance to the injector. To obtain a good time resolution high light yield in a small opening angle is required. The opening angle of the Cherenkov radiation and the light yield depend on the refractive index of the material. A high refractive index results in high light yield but poor time resolution. Fused silica and aerogel have been considered for this task. The resolution achievable due to material properties is below 0.5 ps. The photon yield of aerogel is by four orders of magnitude higher while the vacuum compatibility of fused silica is preferred. Aerogel has the disadvantage that the material needs to be enclosed in a container inside the vacuum beam pipe. The beam has then to cross the boundary of this container adding to the resolution of the setup. A practical design with thin Al windows was conceived making the use of aerogel possible. The setup is shown in Fig. 4 The light path from the injector to the streak camera adds to this resolution resulting in a combined resolution for the radiator plus beam path to 0.7 ps which is dominated by effects due to multiple scattering in the finite material thickness of the aerogel. Two streak cameras are available: a

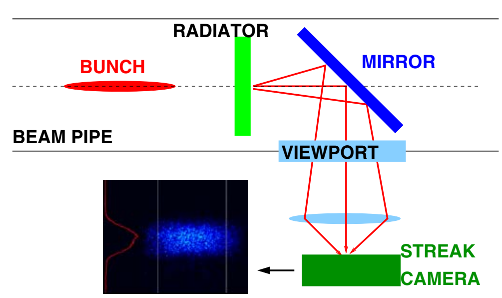

Figure 4: Setup of the bunch length monitor system with the Cherenkov radiator aerogel, the thickness of aerogel is 6 mm resulting in a time resolution of 0.4 ps.

synchroscan streak camera which can be setup to integrate over several consecutive weak pulses with 2 ps resolution.

Alternatively a model with 200 fs can be used for single shot measurements for the high charge regime.

The second method is based on electro-optical sampling [10] by sampling the birefringence induced by the electro-magnetic field of a relativistic electron bunch in a ZnTe crystal with ultrashort laser pulses. The resolution of this technique is determined by the width of the laser pulse, the relative time jitter between the laser pulse and electron bunch and the dispersion of the field pulse in the optical crystal. Furthermore the signal-to-noise ration depends on the distance between the ZnTe crystal and the electron bunch. Here a laser pulse with 100 fs length and linear polarization produced with a TiSa oscillator is transported to the ZnTe crystal (see Fig. 5). In presence of the electron beam electro-magnetic field the polarization becomes elliptically. The ellipticity can be analyzed with a quarter wave plate and a Glan Taylor prism. The task of the quarter wave plate is an online zero adjustment. The measurement will be done with a balanced detector. The expected resolution is dominated by the synchronization accuracy of the laser pulse to the electron bunch and in the order of 1 ps.

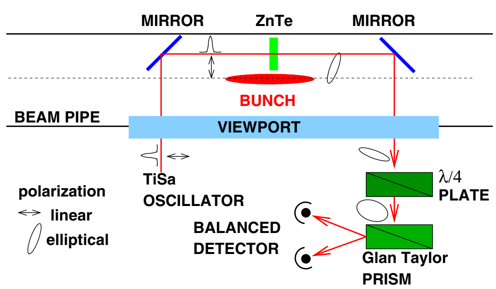

Figure 5: Setup of the bunch length monitor system with Electro-Optical Sampling. The arrows and ellipses indicate the orientation of the polarization when the electron beam moves in the vicinity of the crystal.

ENERGY AND ENERGY SPREAD

The required resolution for the energy measurement is in the order of 5 keV at 10 MeV. The energy and energy spread will be measured using a 180^o dipole spectrometer. The setup with additional diagnostics is sketched in Fig. 6. The resolution of the system depends mainly on the amplitude of the Twiss betafunction on screen SC5 in the dispersive arm. Using the quadrupole triplet in front of the dipole a waist can be achieved on screen SC4. After switching on the dipole magnet the waist is imaged on screen SC5, where the dispersive beam size will be measured. With this setup a granularity of 6 keV with at 2.5 nC bunch charge and 10 MeV mean energy is achieved.

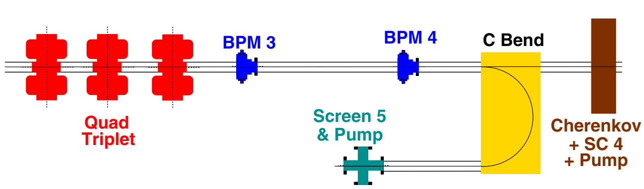

Figure 6: Setup of the energy and energy spread measurement.

SUMMARY AND OUTLOOK

The diagnostics beamline currently under construction will play a vital role in the commissioning and successful running of the SRF gun project. Proven and mature technology will be implemented in order to observe beam parameters at a multitude of operation modes. Critical observables will be addressed by two complementary monitor types. The conceptual design phase of the diagnostics beamline runs until mid 2005, after which procurement and construction of parts will begin. Shipment of components from BESSY to FZR will start mid 2006 so beam operation can start end of 2006. The commissioning and beam dynamics studies phase are planned in 2007 after which the injector will be handed over to ELBE.

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