INSTRUMENTATION NEEDS AND SOLUTIONS FOR THE DEVELOPMENT OF AN SRF PHOTOELECTRON INJECTOR AT THE ENERGY-RECOVERY LINAC BERLinPro

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Abstract

BERLinPro is an energy-recovery linac for an electron beam with 1 mm mrad normalized emittance and 100 mA average current. The initial beam parameters are determined by the performance of the electron source, an SRF photo-electron injector. Development of this source is a major part of the BERLinPro programme. The instrumentation for the first stage of the programme serves the purpose to have robust and reliable monitors for fundamental beam parameters like emittance, bunch charge, energy and energy spread. The critical issue of the second stage is the generation of an electron beam with 100 mA average current and a normalized emittance of 1 mm mrad. Therefore we plan to setup a dedicated instrumentation beam line with a compact DC gun to measure thermal emittance, current and beam lifetime. In parallel an SRF gun with dedicated diagnostics will be build focused on ERL specific aspects like emittance compensation with low energy beams and reliability of high current operation. This paper collects requirements for each development stage and discusses solutions to specific measurement problems.

CHALLENGES OF BERLINPRO

BERLinPro [1] should provide an electron beam with an average current of 100 mA and a normalized emittance of 1 mm mrad. High average current in the ERL requires a CW operation. The electron beam will be produced in a SRF photogun [2] operating at 1.3 GHz repetition rate.

One of the main goals of BERLinPro is a demonstration of a high brightness electron beam. The beam emittance is basically defined by the SRF photogun. A SRF gun with 100 mA average current and an emittance of 1 mm mrad has never been demonstrated. Therefore we plan to realize the gun in a staged approach (Table 1), where we especially focus on two parameters: current and emittance. In the first stage we want to demonstrate a beam from the SRF gun with a superconducting cathode and measure fundamental beam parameters like emittance, bunch charge and energy. The electrons from the SRF gun in Stage A are generated with a superconducting Pb film which is deposited on the back wall of the gun cavity. In Stage B a normal conducting cathode is introduced to the gun cavity with a quantum efficiency of about three orders of magnitude higher. Beam instrumentation for this stage will be focused on the slice diagnostics, which is relevant for the beam emittance compensation. In the third stage we should demonstrate an operation of the production gun at 100 mA.

Table 1: Expected Beam Parameters

Parameter	Stage A	Stage B
Goal	Beam demonstrator	Brightness R&D gun
Cathode	Pb	CsK_2Sb
Laser wavelength	258 nm	526 nm
Thermal emittance in terms of laser spot	0.8 μm/mm	0.4 μm/mm
Repetition rate	1...15 kHz	52 MHz
Laser pulse length	2 ps	<20 ps
Laser pulse shape	Gaussian	Flat-top
Bunch charge	16 pC	77 pC
Average beam current	$\sim$1 μA	$\sim$4 mA

STAGE A

The goals of the first stage are beam demonstration from the SRF photogun and understanding the cavity performance. A thin layer of lead with a diameter of 5 mm was deposited on the back wall of the superconducting cavity as a photocathode [3]. Lead has a work function of about 4 eV and a quantum efficiency of about $5{\cdot}10^{-4}$ at 266 nm, which can be achieved through laser cleaning [4]. The Pb photocathode is irradiated by a UV laser operating at 258 nm with 2 ps pulses delivered at (1-15) kHz with a laser power of $\sim$10 mW, so that the expected average beam current is about 1 μA.

Solutions of Stage A

A schematic overview of the diagnostics beam line is shown in Fig. 1. An electron beam current can be measured with a movable Faraday Cup located approximately 1.5 m downstream from the cavity exit or with an integrating current transformer (ICT). Three stations with a cerium-doped YAG view screen are used for the beam visualization (Fig. 2) and beam profile measurement. The transverse beam emittance can be investigated using the solenoid scan method with a superconducting solenoid placed in the cryovessel and a crystal YAG:Ce scintillation screen imaged by a CCD camera. The beam energy and the energy spread

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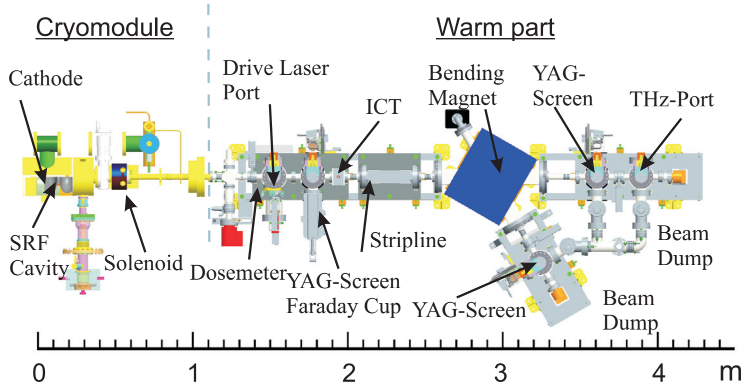

Figure 1: Schematic view of the diagnostics beam line for Stage A.

can be measured with a dipole spectrometer magnet. A relative bunch length can be determined by analyzing the coherent THz radiation. At the end of the straight section of the beam line and at the end of the dispersive arm, the electron beam is dumped into the isolated copper beam dump.

Measurement within Stage A

Dark current is an important issue for SRF guns, especially if the photocathode has a low quantum efficiency, like lead. Figure 2 shows the dark current image on the first YAG: Ce screen focused by the solenoid. The dark current was observed on both the YAG:Ce scintillation screen and proportional counter tube starting from a peak field of about 12 MV/m. The dark current increases exponentially with increasing field gradient and reaches ∼28 nA at 16.4 MV/m (Fig. 3).

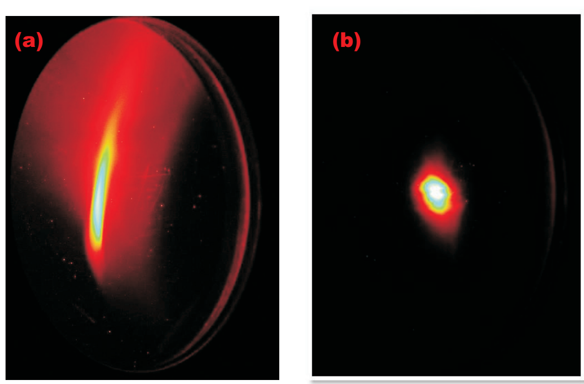

Figure 2: Dark current image on the YAG:Ce screen at 15.9 MV/m (a) and electron beam image (b).

One of the possible sources of the field emission could be the non-uniformity of the lead film. For our test a lead film was arc-deposited onto optical polished niobium substrates at the Andrzej Soltan Institute for Nuclear Studies. The preparation procedure was the same as for the lead cathode deposited on the wall of the cavity. To analyze the surface morphology and composition SEM/EDX measurements (SEM: Hitachi S-4800, EDX: EDAX Genesis V6.10) were performed. Figure 4 shows the inhomogeneity of the lead coating. Due to the preparation process droplets of several μm are found on the surface, which can act as a field emitter and cause dark current in the SRF gun. Surface contaminations produce local variation of the work function and influence the distribution of the quantum efficiency over the cathode area. We plan to perform laser cleaning of the emission surface to enhance the quantum efficiency and its homogeneity and compare beam parameters and dark current before and after laser cleaning, especially thermal emittance of the lead photocathode.

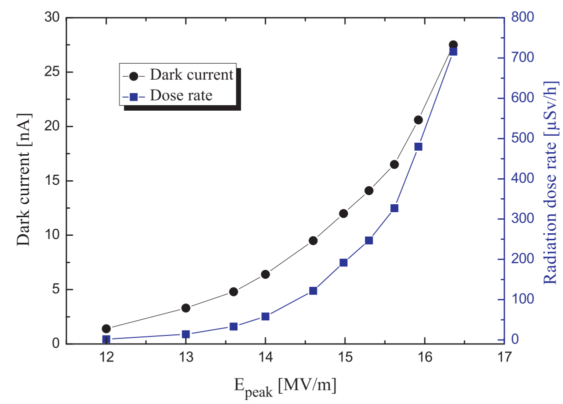

Figure 3: Dark current measured with the Faraday Cup and proportional counting tube versus electric field gradient.

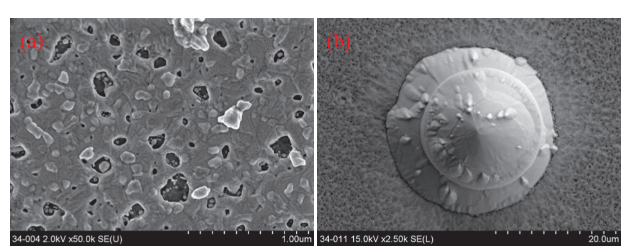

Figure 4: SEM pictures of lead deposited on optical polished niobium substrate with average roughness of 8-10 nm; 1 μm scale (a) and 20 μm scale (b).

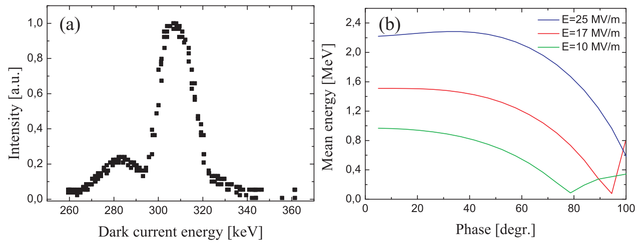

Figure 5: Dark current energy spectrum (a) and beam energy as a function of phase (b).

The energy spectrum of the emitted dark current measured with the dipole spectrometer magnet at a field gradient of 17 MV/m has two maxima at 283 and 308 keV (Fig. 5). Simulation with ASTRA confirms that electrons emitted at 90^0 and E = 17 MV/m have an energy of ∼290 keV at the exit of the gun.

STAGE B

The goal of the second stage is to build a SRF gun with a sufficient cathode lifetime, which is able to operate with 77 pC bunch charge, normalized emittance of 1 mm mrad and average current of several mA. The maximum allowed average current in the existing assembly hall is limited to 50 μA because of radiation safety reasons. As a consequence we plan to operate the photogun with 400 μs long macropulses separated by 40 ms. Within the macropulse the bunch repetition rate is 52 MHz at a bunch charge of 77 pC giving an average current in the macropulse of ∼4 mA, see Table 1.

As mentioned above the superconducting metal cathodes have a high work function and allow a maximum average current of several 100 μA only. Furthermore, a change of the cathodes, which are deposited on the wall of the cavity is nearly impossible. For production of a beam with high average current with the present state-of-the-art laser system, semiconductors with high quantum efficiency in the green part of the light spectrum are more suitable. Green light is more appropriate than UV light because more laser power is available at this wavelength. The materials in the gun cavity have a work function higher than the laser photon energy, which can reduce the dark current substantially. In order to investigate the dark current more detailed we plan to measure the bremsstrahlung spectra which is produced when the field emitted electrons impinge on the niobium cavity or stainless steel flanges.

For the second stage it is intended to produce longer bunches with higher bunch charges up to 77 pC and the emittance compensation scheme to reach low transverse emittance. The laser pulse illuminating the cathode will be flat-top with less than 2 ps rise time and at least 15 ps length on the plateau. Beam dynamics gets in turn more complicated as space charge and time dependent effects from the RF curvature must be taken into account. For this reason slice diagnostics is required. A transverse deflecting cavity with a linear polarized TM_{110} mode at 1.3 GHz is under development for this purpose. The cavity, following a design for the Cornell ERL test facility [5], is single cell of pill-box shape with nose cones located at the gap, where the beam passes through the cavity. The shape of the cavity is further optimized to supply sufficient deflecting voltage for 250 W power coming from the RF source. This can be achieved with a shunt impedance of 5.8 MΩ and a quality factor of Q∼10000. The voltage in the deflecting mode should allow bunch length measurements with a resolution of better than 1 ps at beam energies below 2 MeV.

Photocathode Research

The thermal emittance of the photocathode is an important issue because it defines a lower limit on the beam emittance that can be reached. The transverse beam emittance in SRF guns is dominated by space charge, RF fields and emission properties in the photocathode, so that in this way it is difficult to investigate the emittance and understand, what cathode parameters drives the emittance. For better understanding of the photoemission processes, which affect the beam parameters we plan to construct a 60 keV photoemission gun with an accelerating gradient at the photocathode surface of about 1.8 MV/m. We plan to measure the transverse thermal emittance in DC mode at a few μA current, to avoid space charge effects. The beam emittance can be investigated using the solenoid scan and the pepper-pot method. Cathode response time, cathode emission uniformity, which limits beam brightness and linearity of the quantum efficiency at high laser intensity could be measured at this DC-Setup, too.

ACKNOWLEDGEMENTS

Work funded by the Bundesministerium für Bildung und Forschung, Land Berlin and BMBF under contract number 05K10PEA. We thank G. Weinberg (FHI Berlin) for the performance of the SEM measurements.

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