SETUP AND STATUS OF AN SRF PHOTOINJECTOR FOR ENERGY-RECOVERY LINAC APPLICATION

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Abstract

The Superconducting RF (SRF) photoinjector programme for the energy-recovery linac (ERL) test facility bERLinPro sets out to push the brightness and average current limits for ERL electron sources by tackling the main challenges related to operation of SRF photoinjectors, the beam dynamics, the incorporation of high quantum efficiency (QE) photocathodes, and suppression of unwanted beam generation. The paper details the experimental layout and presents the status of the SRF photoinjector and the gun test facility GunLab at Helmholtz-Zentrum Berlin.

MOTIVATION

The ultimate brightness of an ERL depends on the performance of the electron gun delivering bunches of low emittance with short pulse length at highest average current. In the context of bERLinPro [1] at HZB, a hybrid Nb/Pb SRF gun (Gun0) has been setup and operated in two runs from 2010 to 2012 with two different gun cavities [2,3]. Currently planned for 2017 is the commissioning of GunLab and the first SRF gun with an insert allowing incorporation of a high QE photocathode (Gun1). The goal of the first run of Gun1 in GunLab is to commission the new SRF gun, achieve RF fields as required for low emittance performance and to demonstrate beam operation with electrons generated first from metal and then from multi-alkali photocathodes. The focus of the programme at GunLab is then on single bunch beam dynamics. After completion of the run in GunLab the SRF gun Gun1 will be relocated to the bERLinPro accelerator to tackle medium current (5 mA) operation. The next stage will be Gun2, with high power capable RF input couplers, reaching for higher average current.

BEAM DYNAMICS

The primary goals for the SRF gun are low emittance ($\varepsilon_n < 1$ mm mrad at 77 pC bunch charge) and short pulse length ($\sigma_t < 6$ ps). These can be achieved with large electric field amplitude during emission of the electron bunches, a photocathode workfunction and drive laser energy combination generating electrons with low excess energy, and avoidance of aberrations in the electron beam transport. Correlated effects caused by space-charge forces result in projected emittance growth. The emittance compensation technique allows aligning of the individual bunch slices at some points of the trajectory. At these points the projected emittance will be minimal. Beam dynamics investigations into 1D (axis-symmetric) emittance compensation indicate that the emittance oscillations can be damped [4], but that the electron bunches are still space-charge dominated: therefore it is necessary to place the emittance compensation point further downstream in the main linear accelerator. For this a 2D scheme was studied analytically and numerically utilizing the solenoid close to the cathode and quadrupole magnets between gun and main accelerator [5]. For the complete modelling of the SRF gun a multi-objective genetic algorithm (MOGA) optimization tool was implemented [6]. The tool allows to study the impact of design changes and variation of set parameters from drive laser and the SRF cavity on the beam dynamics. See Fig. 1 for an example with trade-off curves for the performance of the Gun1 system at different values for the peak electric RF field in the cavity.

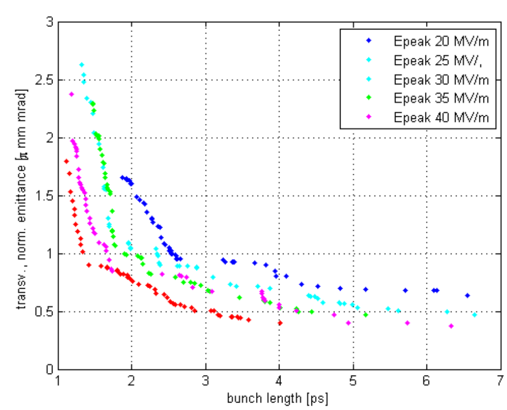

Figure 1: Pareto-optimum curves from MOGA runs with Gun1 at five different peak electric RF field values.

SRF GUN 1 (GUN1)

The SRF gun for bERLinPro is one of the most critical systems of the ERL and in order to mitigate the risk, it is developed in stages. The focus is now on Gun1, with a beam dynamics optimized cavity design and cathode insert mechanism allowing the use and exchange of high quantum efficiency normal-conducting photocathodes inside the SRF cavity. A 1.4 cell 1.3 GHz SRF gun cavity was built and tested inside the HoBiCaT facility [7] and is presently due to first cooldown and first operation with RF and beam [8].

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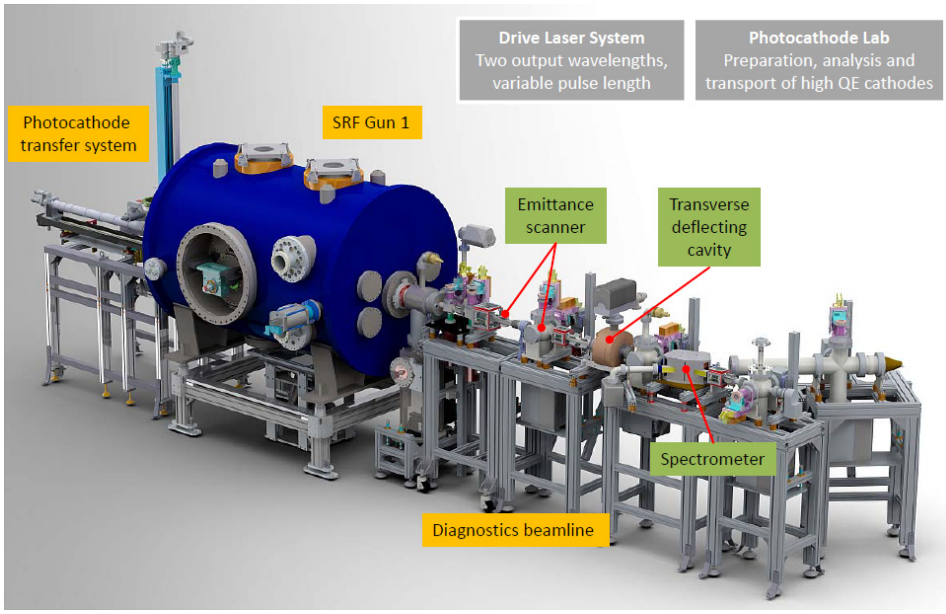

Figure 2: Gun1 cryomodule, photocathode transfer system, and GunLab diagnostics beamline.

GUNLAB FACILITY

The GunLab facility consists of several systems enabling the operation and characterization of advanced SRF and other gun systems: a photocathode drive laser with two output wavelengths, a photocathode preparation setup for the growth and treatment of metallic and multi-alkali photocathodes, and an electron beam diagnostics beamline allowing the 6D phase space characterization of space-charge dominated electron beams for beam energies up to several MeV. Figure 2 shows GunLab together with Gun1.

Drive Laser

The specifications for the driver laser system reflect the wish to operate the SRF gun with high flexibility with regards to the specific photocathode and the beam parameters. For a Cu photocathode laser pulses in the ultraviolet (UV) are required, for multi-alkali photocathodes pulses in the visible range of the optical spectrum (VIS).

The drive laser system consists of a diode-pumped mode-locked Yb:YAG oscillator with a diode-pumped regenerative amplifier. The infra-red (IR) output of the amplifier is converted in a two stage harmonic generator first to VIS at 515 nm and finally to UV at 258 nm. The single pulse repetition rate can be set to six fixed values between 10 Hz and 12 kHz. The laser can be synchronized to an external reference clock with a jitter of $\Delta t \leq 2\,ps$. The pulse length can be varied with a movable grating pulse-stretcher between $\tau = 2.2 \dots 29$ ps FWHM, which can measured with an integrated autocorrelator for the VIS output channel. The pulse length in the UV is fixed and between $\tau = 3 \dots 4$ ps FWHM, slightly longer than the VIS pulses due to the second conversion stage after the laser amplifier. The average output power (measured at 12 kHz repetition rate) is $P_{\mathrm{VIS}} = 0.27$ W at 515 nm and $P_{\mathrm{UV}} = 8.7$ mW at 258 nm. For radiation safety reasons the power in the VIS has to be attenuated by 30 dB. The laser power reaching the cathode can be further controlled remotely with an optical attenuator. The laser pulses are transported from the laser room to the gun with cascaded achromatic relay imaging telescopes. The drive laser beamline is 33 m long with 14 mirrors and nine lenses and contains a variable beam expander close to the laser exit and a transverse pulse shaping aperture close to the cathode. The transmission efficiency of the laser beam transport with baseline aperture opening is $\eta \simeq 50\%$.

The photocathode drive laser for GunLab was developed by the Max-Born-Institute in collaboration with HZB.

Photocathode Preparation

The photocathode and the photocathode substrate, operated inside the SRF gun cavity, should have a smooth surface (to avoid transverse emittance growth and unwanted field-emission), and should be chemically stable to avoid contamination of the SRF cavity surface. The use of CsK2Sb photocathodes with several percent level QE in the VIS allows to drive the photoinjector with a wavelength of around 500 nm (2nd harmonic from an IR oscillator), thus relaxing the requirements on the drive laser systems.

The preparation of CsK2Sb photocathodes is performed in a dedicated growth and analysis system [9]. For the initial commissioning of the SRF gun a Cu plug without cathode film will be prepared.

The multi-alkali photocathode film is deposited on a ultra-smooth, polycrystalline Mo cathode plug which will be inserted in the back wall of the SRF gun cavity. Up to four cathode plugs can be transferred between the growth chamber and the SRF gun under UHV conditions with a load-lock system [10]. The growth system is equipped with in-situ surface analysis tools to the study the influence of growth parameters on the composition of the materials and to find correlations with electronic structure and emission properties [11]. Several CsK2Sb cathodes with QE exceeding $QE_{VIS} \geq 5\%$ have been prepared, the highest QE was $QE_{VIS} = 10\%$.

During operation in the SRF gun the cathode plug and film will be heated by the wall currents flowing through the cathode plug and the laser beam intensity. The plug is cooled indirectly by gaseous He at 80 K. Experiments with a cathode heater and liquid N2 as coolant indicate that the operational temperature of the cathode film can be vary between -180 °C and room temperature, depending on the exact running conditions: retraction of the cathode, amplitude of the RF electric field and incoming laser power. Above 100 °C Cs rapidly dissipates and the 1/e lifetime of cathode will drop to values around 10 hrs.

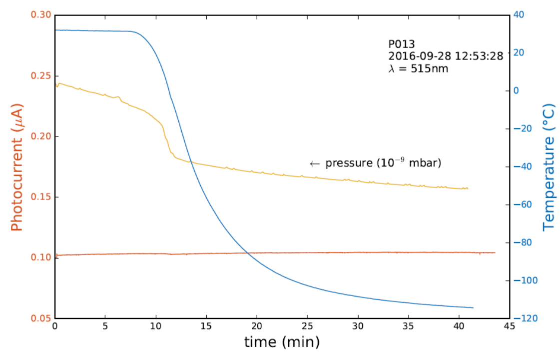

Figure 3: Data of photo-current measured at cathode P013 during cooldown from room temperature to -120 °C. Shown are photocurrent, temperature and base pressure inside the growth chamber.

Figure 3 shows data from cooldown experiments in the growth system. After preparation the cathode is cooled down to a temperature of -120 °C with liquid N2 over the course of 30 min. Before, during and after cooldown the photocurrent generated by a monochromatic light source at 515 nm on the cathode was recorded. No significant change in the photocurrent signal was observed. The same behaviour was observed after warming up the cathode to room temperature.

For the initial commissioning of the SRF gun an ultra-smooth, polycrystalline Cu plug will be used as photocathode. The Cu photocathode will be introduced particle-free into the UHV system of the growth and analysis chamber. The surface will be cleaned by Ar-sputtering and characterized by X-ray photoelectron spectroscopy (XPS). After an oxide-free surface has been achieved, at least two Cu photocathode plugs will be transferred under particle-free UHV conditions into the SRF gun.

Diagnostics Beamline

The GunLab diagnostics beamline allows commissioning of SRF gun systems and complete 6D phase space measurements [12]. The transverse emittance is measured at the first emittance compensation point as derived from MOGA optimization runs. At this location a viewscreen and transverse slit can be inserted in the beam path. In front of the slit, two steering coils can move the beam over the slit. After passing through the slit the beamlet will drift and are measured for the transverse size in another viewscreen station giving the divergence of the beam. A second method will be based on a quadrupole doublet scan method.

The bunch length will be measured with a normal-conducting transverse-deflecting RF cavity operating TM110 mode at 1.3 GHz. The streaked bunches can also be directed into a dipole spectrometer [13] for longitudinally resolved (sliced) energy and energy spread measurements.

The goal is to perform fast phase space measurements and compare the results with the trade-off curves derived from the MOGA runs.

The measurement of beam halo, generated by stray laser light or by field emission, will be performed with a viewscreen utilizing a beam core masking scheme. The scheme is implemented with a digital micro-mirror device in the optical beam path between viewscreen and optical readout camera. This technique increases the sensitivity of the optical readout channel by two orders of magnitude [12]. For beam loss monitoring a ring of charge sensitive diodes is placed around the beam chamber. The beam position will be detected with two stripline BPMs designed for 1.3 GHz readout. The beam current will be measured with a water-cooled Faraday cup insert and in the beam dumps.

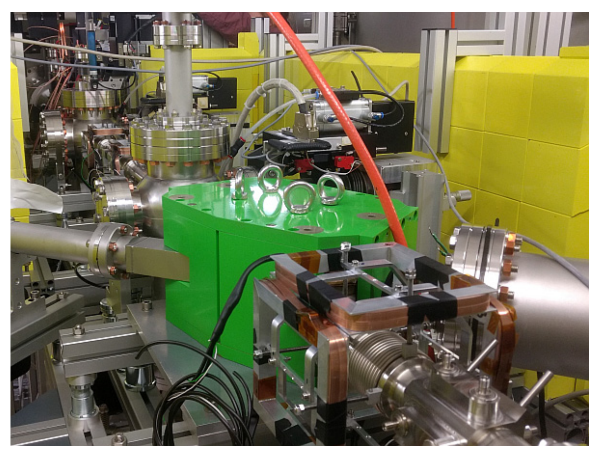

Figure 4: Diagnostics beamline of GunLab.

The beamline was assembled under particle-free UHV conditions. It is now (May 2017) ready for operation and awaits first beam (see Fig. 4).

STATUS AND OUTLOOK

In the last four years the novel SRF photoinjector Gun1 and GunLab, a facility to study electron sources under beam conditions, have been developed and setup. We are now (May 2017) awaiting first beam operation. In parallel design work on the high current Gun2 will be carried out, setup of a working device in GunLab is expected for 2020.

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