PROGRESS OF SRF GUN DEVELOPMENT AND OPERATION AT THE ELBE ACCELERATOR

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Abstract

Superconducting RF photo guns are suitable candidates for electron injectors in future free-electron lasers and energy recovery linacs. For the radiation source ELBE an SRF gun was build and put into operation. During long-term tests, the operation of normal-conducting photocathodes in the superconducting cavity has been successfully demonstrated. At moderate average currents of some hundreds of µA the Cs_2Te photocathodes possess long lifetime. The acceleration gradient is the key parameters for emittance and the maximum achievable bunch charge of the gun. Therefore two new cavities with higher performance were developed, built and treated. The final tests of these cavities are ongoing. An upgraded cryomodule with an integrated superconducting solenoid was built.

ELBE SRF PHOTO GUN

The superconducting radio-frequency photoelectron gun (SRF gun) has been developed for the injection of a high-brightness, medium average current (about 1 mA), and continuous wave (CW) beam into the ELBE linac. Due to its potential advantages, consisting in the combination of high-brightness and CW operation, this electron gun type is suitable for future use in energy recovery linacs and next-generation light sources. At ELBE the SRF gun will deliver beam in two operation modes: (a) the FEL mode with 13 MHz repetition rate and up to 80 pC bunch charge, and (b) the high-charge mode with 500 kHz repetition rate and up to 1 nC bunch charge.

The superconducting cavity, the main part of the SRF gun, consists of three TESLA cells and one optimized half-cell. The gun uses normal-conducting Cs_2Te photo cathodes with high quantum efficiency, illuminated with a picosecond ultraviolet laser. The cathode is placed in the cavity half-cell isolated by a 1 mm vacuum gap and cooled with liquid nitrogen. Additionally, a resonant superconducting choke filter surrounds the cathode and serves to prevent RF leakage through the coaxial vacuum gap. Details of the SRF gun design have been published earlier [1].

At ELBE the SRF gun is installed in parallel to the thermionic injector, which is used as injector for user operation most of the time. An extra diagnostic beamline connected to the SRF gun serves for characterization of the electron beam. Furthermore a dogleg-like beamline section with two 45°-bending magnets allows for injection of the SRF gun beam into ELBE (see Fig. 1).

SRF GUN OPERATION

With the present niobium cavity, produced by the company ACCEL (now RI) and surface-treated at DESY, the SRF gun has been in operation since 2007. It turned out that the usual cleaning procedures applied for TESLA cells are hampered for the SRF gun cavity, mainly due to the narrow cathode channel and the presence of the choke filter cell. For that reason, the processing attempts were not as successful as expected. The achieved peak field in the vertical test was limited by field emission to peak field of 23 MV/m at a $Q_0 = 1\times10^{10}$. Details are published in [2]. After commissioning the Q_0 inside the cryomodule revealed an intrinsic quality factor one order of magnitude lower. The achievable peak field is again limited by strong field emission and He consumption. In the following period, various measurements, done under different conditions, have shown that the performance keeps unchanged independent of whether the cathode is inserted or not. The gradient could be improved by applying high power pulsed RF processing To this day, a stable CW operation up to peak field of 18 MV/m is routinely established.

In order to reach higher gradients with the present cavity and simultaneously keep the low load to the liquid helium system, the input RF power can be pulsed. The typical repetition rate varies from 1 Hz to 10 Hz, and the pulse length can be adjusted from 5 to 20 ms. Recently, operation with 22 MV/m peak field was performed in the RF-pulsed mode. Compared with the CW mode, the beam energy reaches higher values up to 4 MeV and the beam emittance becomes also better.

The intrinsic quality factor versus gradient has been regularly measured in the past. Fig. 2 shows the curves measured from the years 2007 until 2013. The practical limitation for the peak field value of the acceleration field in the present cavity is the Q0 decrease and the corresponding increase of the RF heat loss in the cavity surface. For higher fields the source is the strong field emission. The acceptable heat loss is about 30 W.

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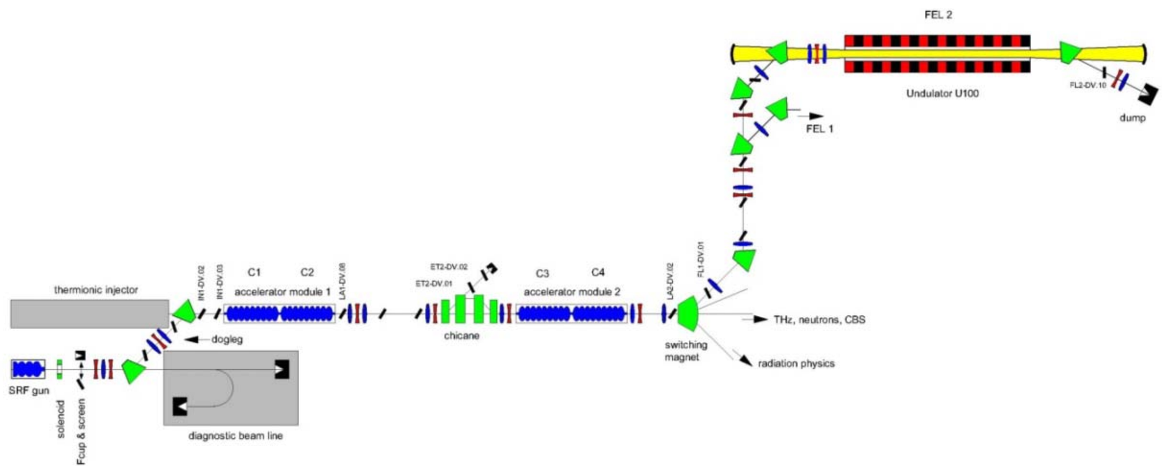

Figure 1: Layout of the ELBE linear accelerator with SRF gun and diagnostic beam line. In detail the figure shows the beam path from the SRF gun to the infrared free-electron laser FEL2: SRF gun, dogleg section, accelerator module 1, chicane section, accelerator module 2, S-shaped beamline section, FEL2. The beamlines to the other user stations are not shown in this figure.

From 2007 until 2011 the values for the peak fields were 16 M/m in CW and 21.5 MV/m for pulsed RF. (3 MeV and 4 MeV kinetic energy, respectively.) A temporary increase was obtained by high power processing (HPP) of the cavity. In autumn 2011 a number of photocathodes where exchanged within a short time for testing new designs and materials, as well as vacuum repair work was carried out at the beamline near the SRF gun. The measurement carried out afterwards (December 2011) showed a performance decrease of 12 %. But no further deterioration has been observed up to the present. Our experience is that the photocathode operation does not lower the gun cavity performance, but the cathode exchange is a critical issue.

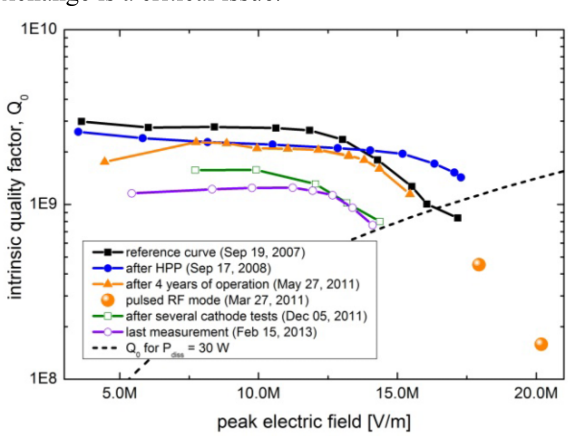

Figure 2: Summary of the SRF gun cavity performance measurements from 2007 to 2011.

Another problem for the high gradient is the dark current which increases rapidly to µA level in the macro pulse. Moreover, the dark current beam has nearly the same energy as the photocurrent. The main source of the dark current is believed to be the field emission from the rear wall of the cavity half-cell.

LASER

In 2012 a new UV driver laser for the SRF gun was delivered and commissioned. The laser had been developed by the Max-Born-Institut in Berlin and is called a two-channel laser system because it can deliver both laser pulses at 13 MHz with 3 ps FWHM and at 500 kHz (optionally 250 or 100 kHz) with 14 ps FWHM. These two channels support the two planned operation modes of the SRF gun. Both channels produce temporally Gaussian shaped pulses, and the average power at 258 nm is about 1 W. The laser consists of a Nd:glass oscillator at 52 MHz, a pulse picker generating the 13 MHz with an electro-optical modulator, a fiber-laser preamplifier for the 13-MHz-channel, a regenerative preamplifier for the 500-kHz-channel, a multipass final amplifier for both channels, and a frequency conversion stage with lithium triborate (LBO) and beta-barium borate (BBO) crystals.

PHOTOCATHODES

Because of its good quantum efficiency (QE) and robustness in RF fields Cs_2Te has been chosen as the standard photocathode for the SRF gun. From 2007 on, eleven Cs_2Te photocathodes have served for the SRF gun beam production. The photocathodes are prepared in a separate photocathode lab and then transported to the gun. The QE of the fresh photocathodes is between 8-15%. The cathodes are stored and transported in the chamber with vacuum in the order of 1×10-9 mbar. But the cathode QEs drop down quickly to 1-2% because of the material degradation and also the vacuum variation during transportation. Once the cathode is installed in the gun cavity, no obvious QE degradation has been found during the beam production. For example, cathode #170412Mo worked in SRF gun for more than one year, providing totally beam time of over 600 hours and 265 C charge.

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Operating the SRF gun in CW with 13 MHz repetition rate, the typical electron current was 0.3 mA and maximum average current achieved was 0.5 mA up to now.

ELBE INJECTION

Beam Characterization

In the past years the electron beam injected into ELBE was mainly used to perform beam characterization studies. The combination of the first acceleration module in ELBE and the Browne Buechner (BB) spectrometer allow for measurements of the longitudinal phase space [3] and of the bunch slice emittance [4].

The method for determination of the longitudinal beam parameters is the measurement of the energy spread after the first accelerator module as a function of the cavity phase. The electrons from the gun are guided through the achromatic dogleg into the first accelerator module. Then the RF phase of one cavity is varied and energy and energy spread are measured. The rms bunch length is presented in Fig. 3. The bunch length is between 3 and 4 ps, shorter than the rms laser pulse length of 6.2 ps. The minimum bunch length appears at the gun laser phase of 5°-10°. The results are closer to the ASTRA simulation results than the measurement with Cherenkov radiation and a streak camera performed in former times.

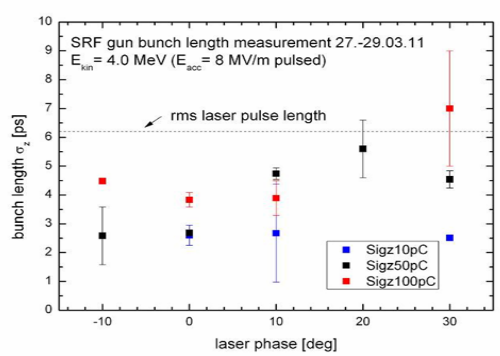

Figure 3: Results of bunch length measurements.

The method delivers the longitudinal phase space ellipse, as it is shown in Fig. 4. In this measurement the phase of cavity C2 was varied and therefore the picture shows the phase space after cavity C1. The phase space correlation is positive, i.e. the bunch head has higher energy. The energy width as well as the longitudinal emittance increase with laser phase.

For the slice emittance measurement the zero-phasing technique is applied which in a similar way converts the longitudinal distribution into a transverse distribution. The phase of cavity C2 is set to a value far from crest to produce a suitable energy chirp. Thus the horizontal position on the screen after the BB spectrometer characterizes the position in the bunch and a split in slices is possible. For these slices a quad-scan is carried out to obtain the vertical transverse emittances of the bunch slices using one of the quadrupoles between cavity C2 and BB spectrometer.

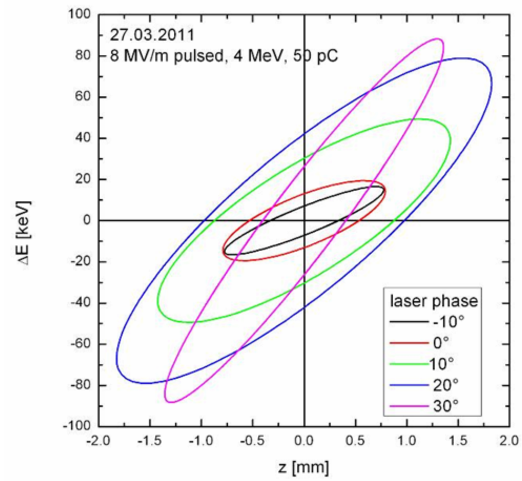

Figure 4: Longitudinal phase space measurement results for different laser phases.

In the measurement the bunch has been split into five slices. The transverse phase space ellipses measured for the five slices are shown in Fig. 5. For this measurement the beam of the gun had a kinetic energy of 3 MeV, bunch charge was 10 pC and the laser phase was 0°. The corresponding normalized emittances and the intensity distribution along the bunch are shown in Fig. 6. The slice emittance is an important quantity for characterization and optimization of the emittance compensation in RF photo guns. The present results confirm that the zero-phasing technique is applicable for further studies on this topic.

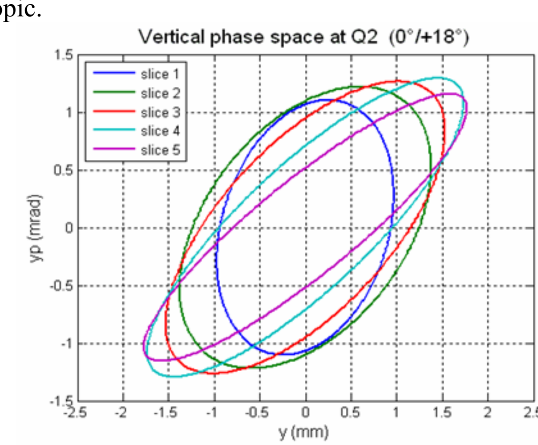

Figure 5: Measured transverse phase space ellipses of the five bunch slices.

Recently, another sophisticated beam diagnostics was tested. This method is described in Ref. [5] and allows a direct measurement of the longitudinal electron bunch profile. In principle, the longitudinal phase space is rotated by 90° so that the momentum distribution, measured finally with a spectrometer, delivers a one-to-one image of the initial longitudinal of the electron bunch.

The method uses a magnetic chicane and following zero-phasing RF acceleration. At ELBE both components, chicane and accelerator module 2, are available and the following dipole was used as spectrometer (see Fig. 1).

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One result is presented in Fig. 7 which shows in the lower part the temporal bunch distribution with an rms bunch length of 1.6 ps.

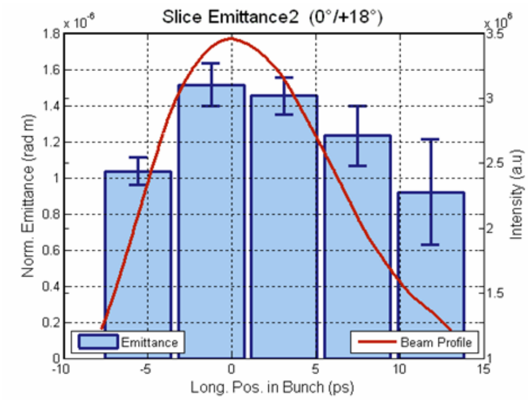

Figure 6: Measured normalized slice emittance values and bunch charge distribution.

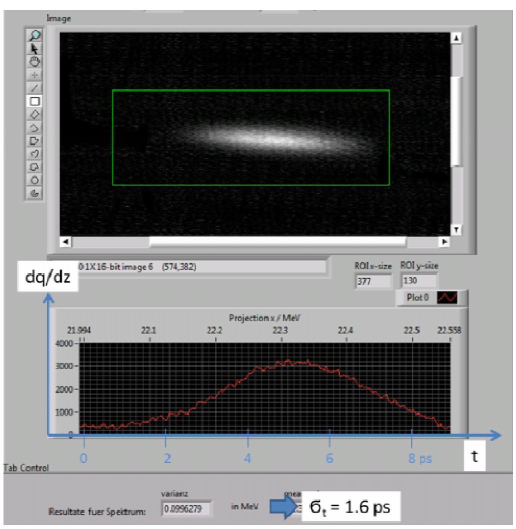

Figure 7: Bunch profile measurement with the method proposed by Crosson [5] for 13 MHz and 2 μA beam. The initial longitudinal laser distribution is a Gaussian with 2 ps rms.

Compton Backscattering

A first sophisticated experiment towards user application of the SRF gun was carried out in collaboration with the high-power laser group at HZDR in fall 2011. The electron beam was transported through the dogleg, accelerated in the two ELBE modules to 24 MeV and then guided to an interaction chamber with a permanent magnet quadrupole triplet to form the final focus. The pulse repetition rate was reduced to 10 Hz in order to adopt it to the DRACO laser. In a head-on collision with the 150 TW laser pulse, Compton-backscattered x-rays of 13 keV were produced and detected with an x-ray camera. The experiment confirmed the synchronization and electron beam stability of the SRF gun. Troublesome for the background and the beam alignment was the dark current from the SRF gun.

Far-infrared FEL

With the new UV laser system the SRF gun is able to produce beam with 13 MHz pulse repetition rate. That allows driving the free-electron lasers of ELBE with the SRF gun. A first successful attempt was carried out in spring 2013 using the far-infrared FEL 2. The beamline layout is shown in Fig. 1. For this first lasing the SRF gun was operated in pulsed mode. The acceleration gradient was 6.6 MV/m which corresponds to a peak field of 18 MV/m and yields 3.3 MeV kinetic energy. The beam current was 260 μA (20 pC bunch charge) within the macro pulse. After passing the dogleg section, the electrons were accelerated to 16 MeV in the first ELBE module (cavities C1 and C2) and up to the final energy of 27.9 MeV in the second ELBE module (cavities C3 and C4). A loss-free and achromatic beam transport in the dogleg section was essential for the success. After achieving that, the phases of the linac cavities were matched and the final energy adjusted. Finally, the steering and focusing in the S-bend and undulator section were carried out.

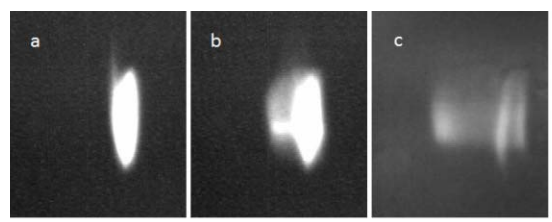

Figure 8: Screenshots with the electron beam in the dispersive section behind the FEL: (a) before lasing, (b) first lasing, (c) lasing with optimized beam transport in the undulator.

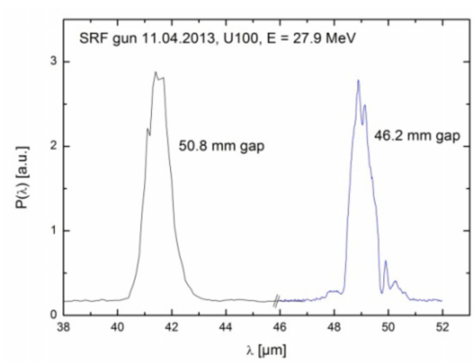

Figure 9: First measured FEL infrared spectra for undulator gaps of 50.8 and 46.2 mm.

An indicator for successful lasing is the increased energy spread behind the FEL which has been observed on an OTR screen behind the dipole (see Fig. 1). The images are presented in Fig. 8. The infrared radiation produced by the FEL was guided into a diagnostic room. As a measurement example, the spectra of the radiation for two undulator gaps are shown in Fig. 9.

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The operation of a FEL requires a comparably high level of beam quality with respect to all kinds of stabilities like beam energy, bunch charge, transverse position, phase jitter etc. Thus, successful lasing with the SRF gun represents an important milestone and confirms the design concept for this gun and the applicability in accelerator facilities.

FUTURE PLANS

To overcome the low-gradient problem with the existing SRF gun at ELBE, in a collaboration with JLab two new 1.3-GHz, 3.5-cell photo-injector cavities (one made of polycrystalline niobium, and one of large grain niobium) were fabricated. The design of the new cavities is slightly different in order to make the half-cell more rigid and simplify assembly in the clean-room. After time-consuming surface treatment and cleaning, for the small-grain cavity a very good performance has been obtained. After welding the cavity into the He tank, a peak field of 43 MV/m and a Q_0 of 2×10^{10} were obtained. Fig. 10 shows a photograph of the cavity prepared for the vertical test at Jlab.

Figure 10: Photograph of the small-grain SRF gun cavity within the He tank at Jlab.

The cavity will be installed in a new cryomodule with an upgraded design. The main difference to the existing one is the integration of a superconducting solenoid. The solenoid was designed and built by Niowave Inc. and has a similar design as the NPS SRF gun solenoid [6]. In our cryomodule the solenoid is positioned on a remote-controlled x-y table. A design drawing is shown in Fig. 8. The x-y table allows beam based alignment of the horizontal and vertical solenoid position with respect to the cavity´s electrical axis. The solenoid is directly cooled with liquid He via tubes connected to the He vessel of the cavity. The two step-motors are cooled with liquid nitrogen in order to hold the heat input into the He bath low.

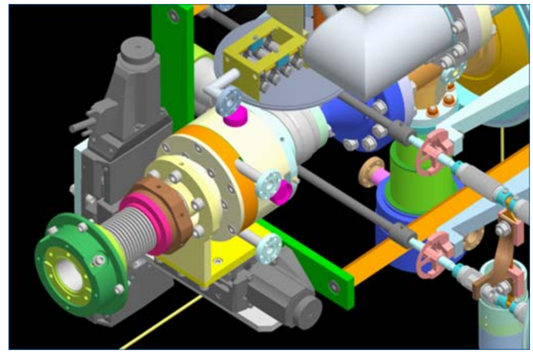

Figure 11: Design of the SC solenoid with x-y table in the new SRF gun cryomodule.

SUMMARY

Here, we have reported the operational status of the 3½-cell SRF gun at the ELBE accelerator of HZDR. Although the design value of the acceleration gradient could not be achieved, the gun is in operation as a unique test bench. Furthermore, the electron beam has been injected into the ELBE accelerator for beam parameter measurements and in order to check future user operation.

The low Q-value of the present gun cavity limits the beam quality. In cooperation with JLab two new cavities have been fabricated and tested. One of them, made of polycrystalline niobium, has shown a very promising performance in the vertical test bench. This cavity will be installed in a new improved cryomodule with a SC solenoid and will replace the present SRF gun at ELBE.

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