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SIMULATION OF ELECTRON BEAMS FROM THE ELBE SUPERCONDUCTING RF GUN FOR ULTRAFAST ELECTRON DIFFRACTION EXPERIMENTS

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Abstract

Moving towards beam energies around 2-6 MeV in ultrafast electron diffraction (UED) experiments allows achievement of larger coherence length for better *k*-space resolution, while the temporal resolution is improved when shorter electron bunches are generated and the velocity mismatch between the optical pump and UED probe vanishes. At Helmholtz-Zentrum Dresden-Rossendorf (HZDR), a series of superconducting CW RF (SRF) guns has been designed, built, and tested, with the latest version currently in routine operation as one of the electron sources for the ELBE Center for High Power Radiation. This SRF photoinjector produces bunches with few-MeV energies at up to MHz repetition rates, making it a suitable electron source also for MeV-UED experiments. The high repetition rate provides a significant advantage for the characterization of samples with low scattering cross-sections such as liquids and gases. In this paper, we showcase the beam quality achieved in first simulations of the ELBE SRF gun operating at low bunch charge as an electron source for diffraction experiments.

INTRODUCTION

Understanding the structure and reaction dynamics of matter are crucial for advances in the fields of chemistry, biology, physics, and material science [1,2]. For decades synchrotron light sources and later also x-ray free-electron lasers (FELs) were the sources of brilliant x-rays for the determination of the structure of matter. However, the size and cost of these facilities is large compared to that of electron diffraction setups, which are an alternative tool for the analysis of the structure of matter. Moreover, x-rays have a smaller scattering cross-section than relativistic electrons, typically a longer wavelength, and are only sensitive to a samples electron distribution, while electron diffraction is sensitive to both the nuclei and the electrons. Electron diffraction is typically done at keV beam energies, where little radiation shielding is required, and systems with table-top footprint are commercially available. Moving towards MeV electron beams allows for higher beam brightness and, thus, better transverse beam coherence, and allows for stronger bunch compression, leading to shorter electron pulses and better time resolution. Also, the electrons propagate at the speed of light at MeV energies, leading to a vanishing velocity mismatch between optical pump and electron probe in thick samples during pump-probe experiments.

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As stated previously, x-ray FELs are a source of brilliant x-rays. The construction of x-ray FEL facilities drove the development of electron sources with small transverse emittance and ps bunch length at MeV energies, which now provide well-suitable sources for electron diffraction, as shown e.g. in Ref. [3]. As of now, an SRF gun was used to perform MeV diffraction experiments, allowing for MHz repetition rates [4]. A normal-conducting gun was used in an optimized setup for electron scattering [5, 6], the detector sensitivity improved to allow for detection of a minimal bunch charge of 10^5 electrons, i.e. 16 fC, in a single shot [7]. MeV diffraction experiments were carried out with liquid-phase samples [8, 9], and a minimal total time resolution of 50 fs (FWHM) was shown [10].

At the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) plans exist to construct an MeV electron diffraction instrument with MHz repetition rates using a superconducting RF (SRF) gun [11]. This contribution gives an overview of the SRF gun in operation at ELBE [12] and shows the beam parameters achieved in simulations done in preparation for a first static test electron diffraction experiment.

ELBE SRF GUN AND DIAGNOSTICS BEAMLINE

The electron beam generated by the first SRF gun installed at ELBE was injected into the ELBE LINAC for the first time in 2010 [13], and subsequently utilized to support the CW user operation at ELBE. A sketch of the currently installed SRF gun II is depicted in Fig. 1. It consists of a

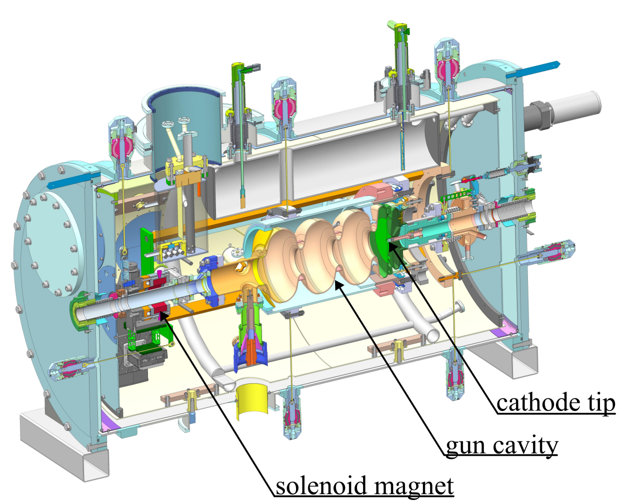

Figure 1: Sketch of the SRF gun II used at ELBE.

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3.5-cell niobium cavity, operating at a resonance frequency of 1.3 GHz. The cavity is submerged in a bath of liquid Helium to achieve and maintain superconductivity during operation. The helium vessel is surrounded by magnetic field shields, isolation vacuum, and a liquid nitrogen bath to minimize the heat dissipation from the room-temperature environment to the cavity. A superconducting solenoid magnet is also located in the cryostat, 0.7 m downstream the cavity half-cell back wall.

The photo cathode is inserted via a load-lock-mechanism into the cavity, so that the cathode surface is located near the back wall of the half-cell. The cathode plug itself is made from copper and kept at liquid nitrogen temperature and can be retracted by up to 4 mm from the back wall of the half-cell. A DC bias voltage of 5 kV is applied, corresponding to 1 MV/m of additional accelerating field on the cathode in order to suppress multipacting. As active cathode materials Cs_2Te and Mg are used [13, 14], achieving a quantum efficiency of typ. 1 % and 0.2 %, respectively, under illumination with the UV photocathode laser. The laser system operates at up to 13 MHz and the laser pulses have a pulse length of 2.5 ps (rms). The SRF gun is operated at a peak gradient of 20.5 MV/m, which corresponds to a maximal cathode surface RF gradient of 14.5 MV/m, allowing a beam energy of 4 MeV after the gun. The RF fields in the gun achieve an amplitude stability of $2 \cdot 10^{-4}$ (rms), and a phase stability of 0.01° (rms), corresponding to a timing jitter of 21 fs [15]. With this injector settings a few hundred pC can be emitted in a single bunch.

Downstream the gun a quadrupole magnet triplet is located. After the triplet a dipole magnet is installed, which guides the electron beam via a dogleg into the ELBE LINAC. Alternatively, the beam can be guided through this dipole magnet into a straight section which is equipped with a spectrometer dipole magnet to measure the beam energy and energy spread, as well as several screen stations. A slit station allows measurement of the projected emittance; however, it is designed to measure the emittance only at bunch charges well above 1 pC [16]. For the first electron scattering experiments it is planned to install the sample at $z = 2.41$ m and observe the diffraction pattern at $z = 5.41$ m.

SIMULATION

In order to test the SRF gun for the use as electron source for electron diffraction application a static diffraction experiment on a known sample is planned. This allows to measure the transverse beam emittance [17] and, in turn, benchmark the measurement against simulation results.

As the exchange of the photo cathode inside the SRF gun is time-consuming and a Cs_2Te inside the gun is required to support the user operation at ELBE with bunch charges on the order of 200 pC the use of Cs_2Te as cathode material is foreseen for the first UED experiment. The transverse momentum spread of 1.1 µm/mm of the Cs_2Te will contribute to a larger projected beam emittance, and thus to a smaller coherence compared to a metal cathode. We assume a transverse flattop laser profile on the cathode with a diameter of 100 µm. The photocathode laser has a temporal Gaussian shape with a length of 2.5 ps (rms). The SRF gun is set to a peak gradient of 20.5 MV/m, yielding a beam momentum of $p = 4.1$ MeV/c, corresponding to an electron wavelength of 0.3 pm. In this simulation a bunch charge of 100 fC is assumed. The simulation is carried out using ASTRA [18].

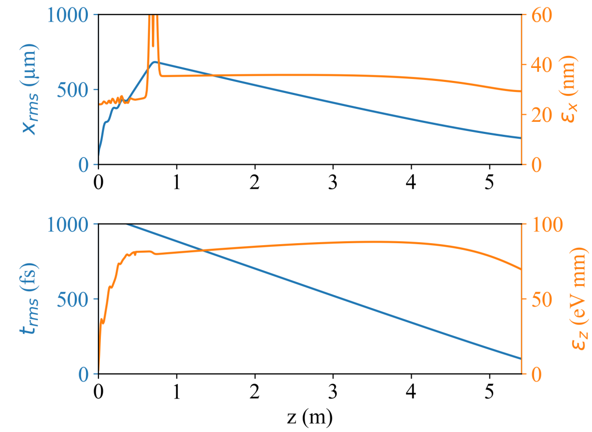

Figure 2: Beam properties along beamline. The sample will be positioned at $z = 2.41$ m, while the diffraction pattern will be recorded on a screen at $z = 5.41$ m.

Figure 2 shows the development of the rms beam size x_{rms}, transverse emittance ϵ_x, rms electron bunch length t_{rms}, and longitudinal emittance ϵ_z along the electron beamline. To decouple the optimization of the SRF gun setting and the beam transport, only the solenoid magnet is used to establish the beam optics for the diffraction in this simulation. The beam is focused onto the detector screen at $z = 5.41$ m to achieve good spatial resolution. The relatively large beam size at the sample position is acceptable during static diffraction measurements in stroboscopic mode. The SRF gun is set to an off-crest phase, leading to bunch compression in the gun and the beamline. This is done to estimate the bunching capability of this setup, even though a short bunch length is not required in a static diffraction experiment. Figure 2 shows that at this low charge, the bunch length reduces almost linearly after leaving the cavity towards the minimal bunch length of 100 fs (rms). While overall a strong compression could be achieved by operating the gun at off-crest phase, it was not possible to achieve the shortest bunch length closer to the gun. For a pump-probe experiment a laser system with a laser pulse length on the order of several tens to few hundred of fs should be considered.

The Figs. 3 and 4 show the transverse and longitudinal phase space at the sample position, respectively. In simulation, a transverse emittance of 36 nm and a transverse beam size of 480 µm (rms) is achieved at the sample position. The linearity of both phase spaces points out, that stronger compression of the transverse beam size and bunch length is possible, as only moderate higher-order contributions are present, which could limit the compression.

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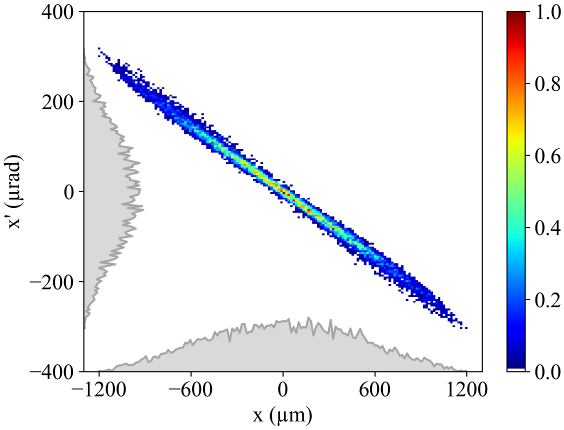

Figure 3: Transverse phase space at the sample position $z = 2.41$ m.

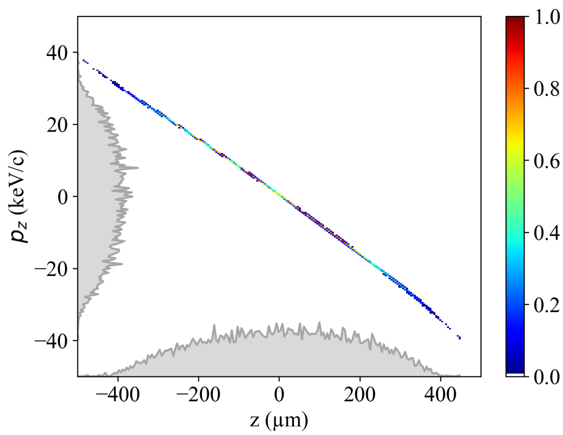

Figure 4: Longitudinal phase space at the sample position $z = 2.41$ m.

CONCLUSION

The HZDR prepares the construction of DALI: the Dresden Advanced Light Infrastructure [11]. An MeV UED instrument allows to probe the structural dynamics of matter and will become an integral component of this facility. The CW SRF gun is considered as electron source for the UED instrument to maintain parity with the MHz repetition rates of the THz sources at DALI.

This contribution showcases a simulation of the ELBE SRF gun for UED application. A first static UED experiment is planned to benchmark simulations with experimental results, and to develop and test instrumentation and diagnostics at ELBE for such beams.

Even though the first tests will be constraint in parameter space by the demands of the user operation at ELBE, a static diffraction experiment is feasible. Especially the transverse laser spot size on the cathode and the thermal emittance from the semiconductor cathode form choke points for the tests, while the photocathode laser pulses with ps duration relaxes the experiment, as the lower bunch charge density yields less beam degradation due to reduced space charge forces. In an experiment, quadrupole magnets in the diagnostics beamline will be used to achieve an improved beam transport, i.e. smaller beam size at the sample position and smallest beam size at the detector position. Preparations for the first static UED experiments are in progress.

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