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EXPERIENCES WITH THE SRF GUN II FOR USER OPERATION AT THE ELBE RADIATION SOURCE

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Abstract

The second version of the superconducting RF photoinjector (SRF Gun II) was successfully commissioned at the ELBE radiation source in 2014. The gun features an improved 3.5-cell niobium cavity combined with a superconducting solenoid integrated in the cryostat. With a Mg photocathode the SRF Gun II is able to generate bunches with up to 200 pC and with sub-ps length in CW mode with 100 kHz pulse frequency for the THz radiation facility at ELBE. In the ELBE linac, the beam is accelerated, gets a proper correlated energy spread, and is compressed in a magnetic chicane. Sub-ps pulses are obtained producing coherent diffraction radiation and superradiant undulator radiation.

INTRODUCTION

The superconducting linear accelerator of the Radiation Source ELBE has two electron injectors. The first one is a DC electron gun equipped with a grid-pulsed thermionic cathode. This electron gun delivers beam for user operation of ELBE most of the time. The second gun is the superconducting RF photoinjector (SRF Gun II), which is the second version of this gun with an improved 3.5 cell niobium cavity and a superconducting solenoid situated in short distance to the cavity inside the gun cryomodule. The gun was installed at the ELBE accelerator in 2014 followed by a commissioning phase [1,2]. Further improvements and optimization of gun components as well as the progress in operational experience have increased the performance and reliability on a level that the SRF Gun is now applied for user operation. ELBE is producing a variety of electromagnetic radiation and particle beams for different user experiments and applications, like far infrared FEL radiation, gamma rays, positrons and neutrons. As part of an upgrade of ELBE, a high-field high-repetition rate Terahertz facility (TELBE) was founded only a few years ago [3,4]. The benefit of the SRF gun for THz radiation production is the higher bunch charge. For 2018 the goal is to produce electron bunches at a charge of 200 pC, which is significantly higher than 80 pC delivered up to now by the thermionic injectors.

In the TELBE facility the coherent THz radiation is created by relativistic (sub-ps) electron bunches pathing through a dipole and through an undulator. At an aperture broad-band coherent synchrotron radiation (CDR) and in the undulator small-band coherent undulator radiation (CUR), also called super-radiant undulator radiation, are produced. For coherent radiation, that means that the longitudinal bunch length is shorter than the wavelength, the intensity grows with the square of the number of electrons. Therefore the spectral angular distribution can be written as

$$\left.\frac{d^2I}{d\omega d\Omega}\right|_{bunch} = N\{1+(N-1)F(\omega)\}\left.\frac{d^2I}{d\omega d\Omega}\right|_{single\ e}. \quad (1)$$

Here N denotes the number of electrons in the bunch. The form factor $F(\omega)$ of the normalized charge distribution $\rho(\boldsymbol{x})$ is given by

$$F(\omega) = \left|\int \rho(\boldsymbol{x}) e^{i\omega\hat{\boldsymbol{n}}\cdot\boldsymbol{r}/c} d^3x\right|^2 \quad (2)$$

and has a value between zero and one. As can be seen in Eq. (1), the spectral power splits into an incoherent and a coherent part. For the coherent part the quadratic increase with bunch charge sustains as long as the form factor does not decrease. Consequently the higher bunch charge with the SRF gun needs successful bunch compression.

EXPERIMENTAL LAYOUT

Figure 1 shows the beamline layout in use for the THz radiation production with the SRF gun injection. The Nb cavity in the SRF gun operates at an RF frequency of 1.3 GHz with an acceleration gradient of 7 MV/m (18.5 MV/m on-axis peak field). Thereby the RF heat dissipation into the 2 K helium bath is about 10 W. The photocathode consists of bulk magnesium with a quantum efficiency of 0.3 %. A picosecond laser system with Nd:glass oscillator, regenerative and final multi-pass amplifier, as well as fourth harmonic generation produces pulses at 263 nm wave length. At the cathode, a laser pulse energy of about 0.6 µJ is needed to produce the 200 pC pulses. At the photocathode the laser spot size is about 4 mm in diameter. The temporal profile is Gaussian with an rms pulse length of about 2 ps. After focusing with a superconducting solenoid the beam leaves the gun with a kinetic energy of 3.5 MeV and passes through a matching quadrupole triplet and the achromatic dogleg structure. In the first accelerator module with the SRF cavities C1 and C2 the beam is accelerated on-crest to an energy of 15.5 MeV. Further acceleration happens in the second module with cavities C3 and C4. Here the acceleration is off-crest with a phase of about 45° in order to produce the needed energy chirp of the bunch. The final beam energy amounts to 25.8 MeV. In the magnetic bunch compressor

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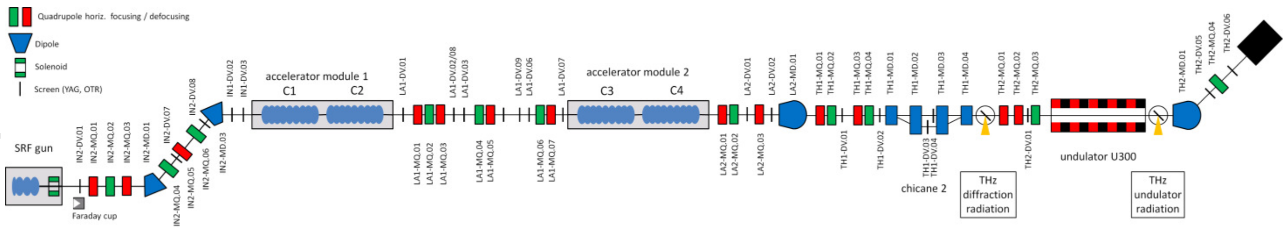

Figure 1: ELBE accelerator beamlines for THz radiation production with the SRF Gun II.

(chicane 2) the bunch is compressed to its sub-ps length. Since the bunch is already short in the last chicane magnet, this dipole is served as CSR source. The mirror downstream sends the radiation towards the THz laboratory whereas the electron beam passes through a centred hole towards the undulator U300. In this electromagnetic undulator with 8 periods and a period length of 300 mm the super-radiant undulator radiation is produced with a designated range between 0.1 and 3 THz. It follows a second hole-punched THz mirror, a bending magnet and the dump for the electron beam. Near the beamline a broad-band power meter allows for CUR measurements and with an insertable screen the bunch length can be determined from coherent transition radiation in a Martin-Puplett interferometer [5]. Further sophisticated terahertz radiation diagnostics can be done in the TELBE THz laboratory [4].

Table 1: SRF Gun and Beam Parameter Values

Parameter	Value
Laser size at cathode (rms)	1 mm
Laser pulse length (rms)	2 ps
Repetition rate	100 kHz
Bunch charge	200 pC
Kinetic energy gun	3.5 MeV
Final beam energy	25.8 MeV

THz PRODUCTION AND OPTIMIZATION

The photo injector was operated at 100 kHz micro pulse frequency in three different operation modes: diagnostics mode with short pulse trains (typically 0.2 ms at 5 Hz) setting up the beam and optimization, long pulse trains (5 ms at 25 Hz) for THz optimization and beam loss reduction, and continuous wave (CW) for THz production and measurement.

Starting with standard SRF gun operational parameters, i.a. a laser phase of 59° where the gun's beam energy spread has its minimum, a linac module 2 off-crest phase of 40°, a chicane deflection angle of 21°, and the undulator tuned to 0.5 THz, the beam was guided through the whole beamline. The transmission was checked by bunch charge measurements using the insertable Faraday cup downstream the gun, and ICTs after linac module1 and before the beam dump. With fixed chicane magnet parameters the chirp phase of linac module 2 was varied to minimize the bunch length by measuring directly the THz radiation with the power meter. The final bunch length is defined by the uncorrelated energy spread and phase space nonlinearities. In simulations it turned out that the major effect is the quadratic contribution produced by the first acceleration module. It can be reduced if the bunch length at module 1 is as short as possible. This can be achieved with a short laser pulse and a large laser spot at the photo cathode. Furthermore, the longitudinal space charge prolongation during the beam transport from the gun to linac module 1 can be counteracted by a suitable correlated energy spread. This optimization was carried out by properly decreasing the SRF gun laser phase to a value of 52° resulting in further significant increase of THz radiation power.

RESULTS

Figure 2 presents the measured THz power as function of bunch charge for beam parameters optimized for 200 pC and fixed in the measurement. According to Eq. 1 a quadratic dependency is expected as long as the space charge effect does not influences the longitudinal bunch shape.

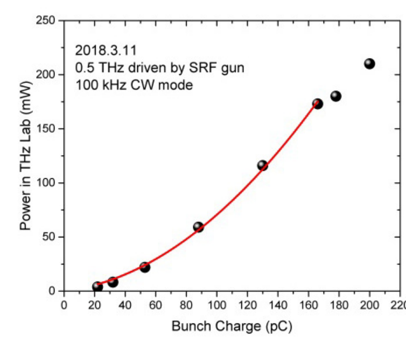

Figure 2: Measured THz power vs. bunch charge.

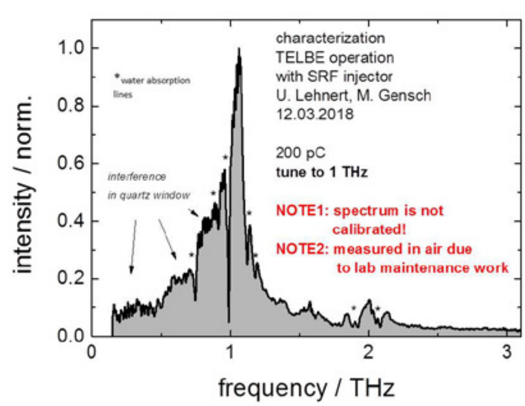

Figure 3: THz spectrum for 1 THz tuning.

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A Fourier transform spectrometer result for 1.0 THz fundamental frequency is shown in Fig. 3. Due to the decreasing form factor the higher harmonics contribution is rather small. Two stability measurements are presented in Fig. 4 and Fig. 5. The intensity fluctuation, here shown for the undulator radiation at 0.3 GHz, is mainly dominated by the electron injector stability.

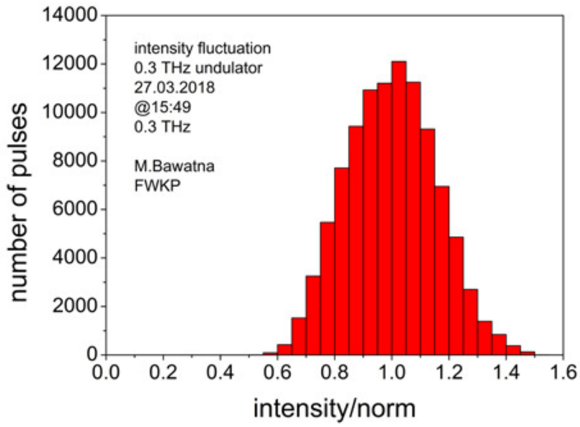

Figure 4: Measured intensity fluctuations of the THz pulse energy for 0.3 THz.

During the beam time in March, this amplitude stability was at least a factor of two better than that of the thermionic injector. The timing jitter measured to about 1 ps rms is mainly coursed by the RF phase stability of the accelerator and therefore rather independent of the injector used.

Table 2 present a summary of the obtained THz radiation power measured with 20 µA CW electron beam.

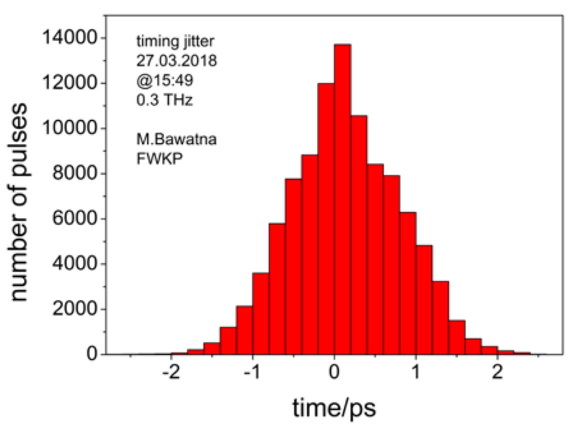

Figure 5: Measured timing jitter of the THz pulses.

CONCLUSION

Applying the SRF gun with a bunch charge of 200 pC, convincing results for THz production could be obtained. The SRF gun operated stably for a number of subsequent shifts without any shutoffs. For frequencies up to 1 THz the rise in THz power was according to the increase in the square of bunch charge compared to the thermionic injector. That means, the bunching concept worked and the form factor was near to one. Consequently, higher THz power together with better stability could be delivered to user experiments.

Table 2: Obtained THz power in CW operation for three undulator parameter values measured with 20% band pass filter for fundamental freq uency and higher harmonics, as well as total power (without filter and power meter without calibration).

THz Power	0.3 THz tuning	0.5 THz tuning	1.0 THz tuning
0.5 THz		215 mW	-
1.0 THz		89 mW	150 mW
1.4 THz		29 mW	14 mW
1.95 THz		7 mW	25 mW
total power	480 mW	375 mW	320 mW

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