BEAM TRANSPORT OPTIMIZATION FOR APPLYING AN SRF GUN AT THE ELBE CENTER

P. Lu, H. Vennekate, HZDR & TU Dresden, Germany
A. Arnold, P. Murcek, J. Teichert, R. Xiang, HZDR, Germany

Abstract

An SRF gun at the ELBE center has been operated with a magnesium cathode. Electron beams were produced with a maximum bunch charge of 200 pC and an emittance of 7.7 μm. Simulations have been conducted with ASTRA and Elegant for applying the SRF gun to ELBE user experiments, including neutron beam generation, positron beam generation, THz radiation and Compton backscattering experiment. Beam transport has been optimized to solve the best beam performance for these user stations at the bunch charge of 200 pC. Simulation results indicate that the SRF gun is potential to benefit the high bunch charge applications at ELBE.

INTRODUCTION

The ELBE (superconducting Electron Linac for beams with high Brilliance and low Emittance) accelerator is a high-power radiation sources open for users all over the world. The main radiation is an SRF linac based, CW operating electron beam with the maximum energy of 40 MeV and the maximum current of 1.6 mA [1]. The routinely used electron injector at ELBE is a DC (Direct Current) gun with a grid-pulsed thermionic cathode [2]. It provides a pulsed electron beam with a kinetic energy of 250 keV, a maximum bunch charge of 77 pC and a normalized transverse emittance of 13 μm. The second injector is an SRF (Superconducting Radio Frequency) gun which features a 3.5 cell SRF cavity and a normal conducting photocathode [3]. The SRF gun was commissioned with Cu cathodes. Before 2014, Cs_2Te cathodes were mainly used for all operations. In 2015, a serious contamination happened in the process of cathode exchanging. The Cs_2Te cathode was polluted as well as the cavity. From then on, magnesium cathodes were also prepared as a safer replacement to produce several hundreds of pC electron bunches.

The entire layout of the ELBE accelerator is shown in Figure 1. The electron beams from injectors are accelerated by two SRF linacs. Each linac contains two 9-cell Nb TESLA cavities working with 1.3 GHz standing wave. Two chicanes are installed for bunch compression. One is located between the two linacs and the other is after the second linac. Each chicane consists of 4 dipoles, arranged in a D-shape.

The direct use of the electron beam includes radiobiology research and the interaction with ultra-intense lasers for CBS (Compton backscattering) experiments. In addition, the electron bunches are also used to generate secondary user beams of two FELs operating in the IR/THz regime; a fast neutron beam (nELBE); a Bremsstrahlung gamma-ray beam; a low-energy positron beam (pELBE), patented single-electron test beams and THz radiation [1].

SIMULATIONS

The emission of the electron bunch and its acceleration in the gun cavity are simulated with ASTRA [4].The following beam transport is simulated with Elegant [5]. In ASTRA, the space charge effect is included for calculations of low energy beams. In Elegant, LSC (Longitudinal Space Charge) effect, CSR (Coherent Synchrotron Radiation) effect and Wake effect are considered besides the 3rd order matrix calculation of the beamline. The simulation methods are carefully analysed in Reference [6]. In the following of this section, only the critical requirements of user stations and the optimized results will be presented.

pELBE and nELBE

At ELBE, a monoenergetic positron beam is created by pair production from the primary electron beam at a multi-layer tungsten target. The positron experiment station is

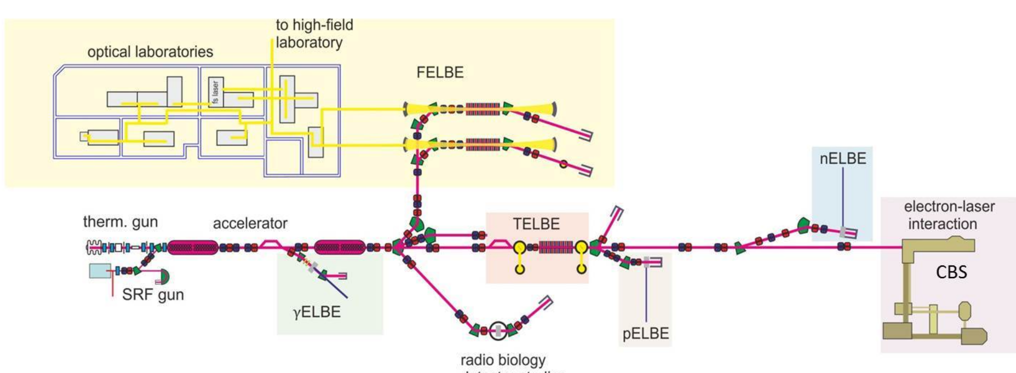

Figure 1: The layout of ELBE accelerator.

referred to as pELBE. The energy of the positron beam is adjustable in the range from 0.5 to 15 keV. The positron flux is 10^6/s and the time structure inherits that from the electron beam.

A very compact neutron ToF (Time-of-Flight) system has also been built at ELBE, named nELBE [7]. Electron beams are injected into a liquid-lead neutron radiator to produce neutrons with a continuous range of energies, together with the bremsstrahlung by the interaction of electrons and lead nucleus. The locations of pELBE and nELBE are shown in Figure 1.

At both pELBE and nELBE, a beryllium window is installed in front of the target, isolating the vacuum of the beamline. The beryllium window scatters the electron beam, and by the theory of multiple scattering through small angles [8] the rms scattering angle θ_0 is inverse-promotional to the energy of the incident beam. The "acceptance" is defined in the transverse phase space that in this region, electrons scattered with the angle of θ_0 can hit the target. Figure 2 illustrates the scattering of the window and the definition of the acceptance.

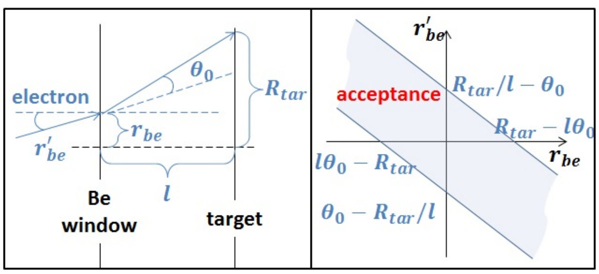

Figure 2: Geometries of the scattered electron beam on the beryllium window and the target (left). The area of acceptance in the transverse phase space (right).

Using the SRF gun and setting the bunch charge to 200 pC, the final energy of the electron beam is 38.8 MeV in simulation, while the linacs are set to the practical maximum value. For pELBE, all electrons can be transported into the acceptance region. For nELBE, where the acceptance is smaller due to a larger distance (190 mm) from the target to the beryllium window compared to pELBE (140 mm), only 70% of electrons out of the 200 pC can be transported into the acceptance, as shown in Figure 2. However, such a performance is still better than applying the thermionic gun which provides a beam with an energy lower than 35 MeV and as a result the area of acceptance is zero (Fig. 3).

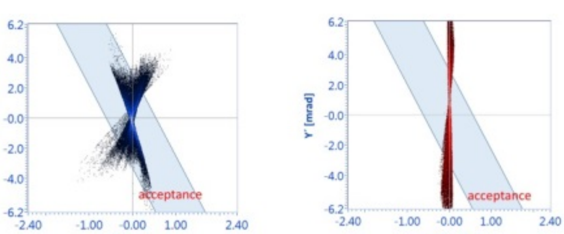

Figure 3: Optimized transverse phase space for nELBE. 70% of 200 pC electrons are inside the acceptance of the window.

TELBE

The high-field high-repetition-rate THz user facility TELBE has been built up and commissioned recently [9]. An undulator and a silicon mirror are installed as two radiators at TELBE. The undulator generates 8 cycle radiations with the frequency tuneable from 100 GHz to 3 THz. The silicon mirror generates single cycle of CTR (Coherent Transition Radiation) or CDR (Coherent Diffraction Radiation). Radiations generated by both the undulator and the silicon mirror are intrinsically synchronized to each other, as they originate from the same electron beam. The location of TELBE is shown in Figure 1.

A small temporal length of the electron bunch is desired which increases the intensity of the coherent radiation. Three bunch compression methods are tested in simulation with the bunch charge of 200 pC, as shown in Figure 4.

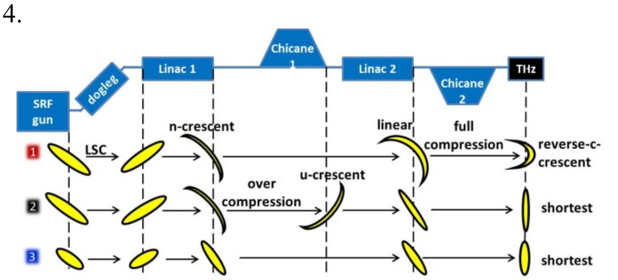

Figure 4: Different bunch compression methods for TELBE. Yellow shapes represent longitudinal phase spaces with the head of the bunch at the right side.

In Method 1, the bunch is directly compressed in chicanes. The nonlinearity obtained from linacs results in a "reverse-c-crescent" in the longitudinal phase space (Figure 4), which can be alleviated to make the bunch even shorter. In Method 2, the first chicane is used to over-compress the bunch where the "n-crescent" is turned to "u-crescent". Afterwards this u-crescent compensates the nonlinearity from the second linac and a linear distribution in longitudinal phase space can be achieved. Method 3 uses a shorter electron bunch from the SRF gun, which sacrifices the transverse beam quality due to stronger space charge effects in the shorter bunch. On one hand, shorter bunch reduces the nonlinearity from linacs, on the other hand, the dogleg tends to generate an "u-crescent" which is negligible for long bunches but more obvious for short bunches [6]. These two effects compensate each other and a quasi-linear longitudinal phase space can be expected after the second linac.

Detailed analysis of Method 2 and 3 can be found in Reference [6]. In general, all three methods are optimized in simulation that the transverse beam size and emittance satisfy the limitations of the entire beamline. The longitudinal phase space of the beam, which is of more concern for TELBE, is compared in Figure 5. In Method 1, the expected "reverse-c-crescent" is seen in simulation, where only 14% of electrons out of 200 pC are included in the FWHM (Full Width Half Maximum) bunch length of 0.06 ps. In Method 2, the over compression provides a more linear bunch in the longitudinal phase space but the bunch still has a long head. In this case, 44% of electrons stays

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in the FWHM bunch length of 0.15 ps. Method 3 provides the best result where 71% of electrons are focused into the FWHM bunch length of 0.21 ps and the peak current is almost doubled compared to Method 1.

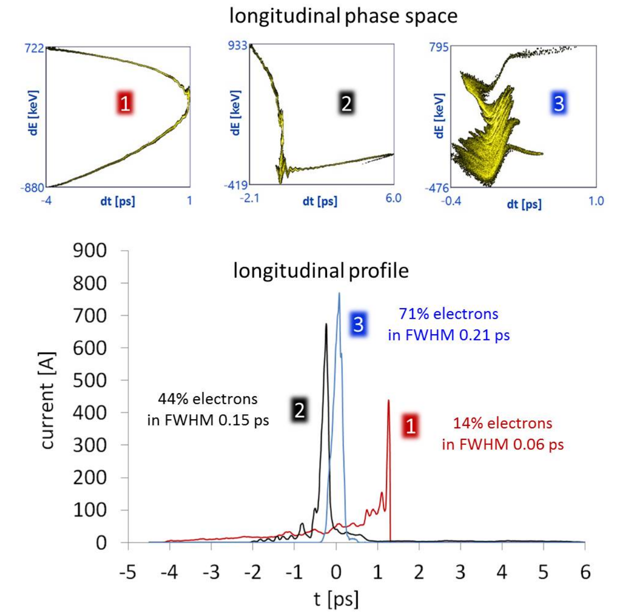

Figure 5: Longitudinal phase spaces and beam profiles of the three bunch compression methods.

Taking simulation results of Method 3 to represent the best possible performance of the beam from the SRF gun, we have 200 pC bunches with the bunch length of 0.21 ps. Compared to the thermionic gun which provides 77 pC (maximum 100 pC) bunches with the bunch length of 1.2 ps, the SRF is potential to enhance the THz radiations at TELBE.

CBS (Compton backscattering)

Compton backscattering is one of the most effective methods of gaining energy for photons [10], producing intense pulses tuneable from hard X-rays to γ rays with finite bandwidth [11,12]. The mechanism of Compton scattering is also referred to as Thomson scattering when the recoil of electrons is negligible [13], which is the case at ELBE.

The longest beamline of ELBE delivers the electron beam to perform the CBS experiments with a 150 TW laser — DRACO (DResden lAser aCceleration sOurce) [14,15]. The electric field of the laser pulse acts on electron bunches like a traditional undulator, but with a much smaller spatial period, which is the laser wavelength. The DRACO laser spot can be expanded to a maximum FWHM diameter of 35 µm, which is a quite small dimension for electron beams.

As shown in Figure 1, the CBS station is located after a long drift of about 47 m from the second chicane. In this long drift, the accumulated longitudinal space charge effect is strong enough to compensate the necessary energy chirp for bunch compression. As a result, the energy spread can be minimized before the interaction point of CBS.

The transverse emittance is minimized along the beamline using the implanted simplex optimization method [5,6]. The transverse size of the electron beam is focused from mms to µms using a FFS (final focusing system) [16]. the optimized phase space projections of a 200 pC beam at the interaction point is shown in Figure 6. The energy is 23 MeV (limited by the photon detector), the energy spread is 0.16%, The FWHM bunch length is 0.48 ps, the horizontal and longitudinal FWHM bunch size is 17 µm and 36 µm, respectively. Compared to the formal experiments using the thermionic gun with the bunch charge of 77 pC and the beam size over 100 µm, the simulation results indicate a possible progress for CBS experiments applying the SRF gun.

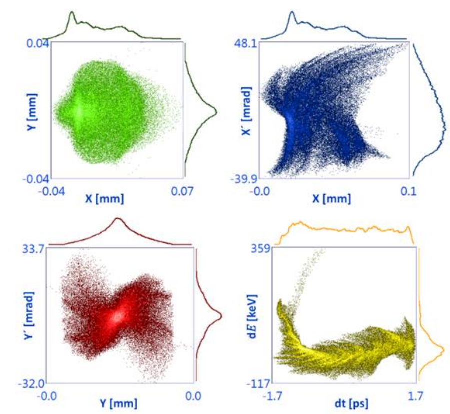

Figure 6: Optimized phase space of a 200 pC beam for Compton backscattering experiments. The bunch is generated from an SRF gun.

SUMMARY

The current performance of the SRF gun at ELBE (bunch charge of 200 pC, emittance of 7.7 µm) has already exceeded that of the routinely used thermionic injector at ELBE (77pC, 13 µm). Simulations of beams with 200 pC bunch charge from the photocathode to the user stations have shown positive results, that applying the SRF gun, the pELBE and nELBE station will receive more electrons on the target; a higher peak current in the electron bunch can be expected for TELBE and more electrons can be effectively interacted with the DRACO laser for CBS experiments. ELBE user time with the SRF gun have been scheduled in near future.

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