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HOLLOW ELECTRON BEAMS IN A PHOTOINJECTOR

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Abstract

Photoinjectors have demonstrated the capability of electron beam transverse tailoring, enabled by microlens array (MLA) setups. For instance, electron beams, transversely segmented into periodic beamlet formations, were successfully produced in several experiments at Argonne Wakefield Accelerator (AWA). In this proceeding, we discuss the necessary steps to demonstrate the hollow electron beam generation, with an arbitrary diameter and width with MLAs. We also present beam dynamics simulations and highlight key features of the hollow beam transport in LCLS copper linac.

INTRODUCTION

Hollow electron beams have been well known since 1960s, but due to multiple instabilities pointed out by early researchers [1–12] they have been largely forgotten. Nowadays, the most promising application of the hollow electron beams is proton beam collimation. This novel technique is soon to be implemented at Fermilab Accelerator Science and Technology (FAST) facility and later on at the Large Hadron Collider (LHC) [13–17]. The required hollow electron beams are generated in a special low energy source, mostly incompatible with a conventional accelerator. In this proceeding, we are exploring a different approach. We consider a nominal photoinjector configuration, e.g., the LCLS copper linac photoinjector, and modify the UV laser transverse profile employing spatial shaping techniques [18, 19]. Typically, transverse shaping is performed at some point upstream of the photocathode, which is then imaged onto the photocathode surface with a transport lens system. With the MLA shaping, for instance, one can apply a circular intensity mask at the homogenization point of the MLA, thus controlling parameters of the hollow beam. Other possibilities include the use of digital micromirror devices, axicon lenses, and more exotic Laguerre-Gaussian (LG_{0i}) modes of the laser.

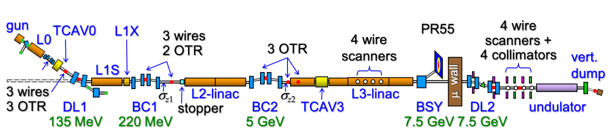

Figure 1: LCLS copper linac hard X-ray beamline.

LCLS PHOTOINJECTOR AND COPPER LINAC SIMULATION

In this section we provide the results of numerical beam dynamics simulations of the entire LCLS copper linac hard X-ray (HXR) beamline, starting at the photocathode, and up to the HXR undulator entrance. LCLS copper linac photoinjector is a 135 MeV machine that comprises of 1.6 cell S-band RF gun with copper cathode and is operating at 120 Hz repetition rate. It is followed by multiple normal conducting travelling wave S-band accelerating structures. For a detailed description of the machine see Ref. [20]. Currently the primary purpose of the LCLS copper linac photoinjector is to produce electron beams for LCLS XFEL operations. The 135 MeV electron beam is then further accelerated in 1 km long linac with the total maximum energy of 14 GeV. We performed our hollow beam numerical study in the LCLS copper linac at a 7.5 GeV beam energy. We note that in the photoinjector the beam is matched into the copper linac via a quadrupole lattice, yielding several betatron oscillations in both vertical and horizontal planes. According to previous studies, such oscillations, in combination with space-charge forces, often lead to a hollow beam break up. An overall layout of the beamline is reported in Fig. 1 and a typical beam envelope evolution in the LCLS photoinjector is presented in Fig. 2. We point out that the nature of instability, destroying the hollow shape, is similar to the one observed in recent coherent electron cooling studies (CeC) at Brookhaven National Laboratory [21]. For our studies we utilized conventional IMPACT-T beam physics code [22]. A detailed description of IMPACT-T 3D space-charge algorithm and it's comparison to other codes is available in Refs. [23–25]. As a guidance for initial simulation, the bunch charge was defined as

$$Q = 9\ \text{pC} \cdot \eta \frac{E_z}{\text{MV/m}} \frac{A}{\text{mm}^2} \quad (1)$$

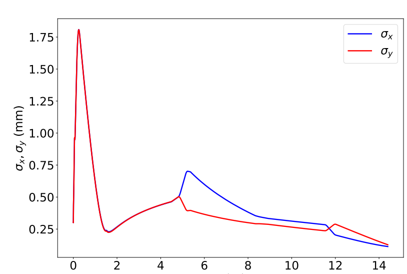

Figure 2: A typical electron beam size evolution in LCLS copper linac photoinjector.

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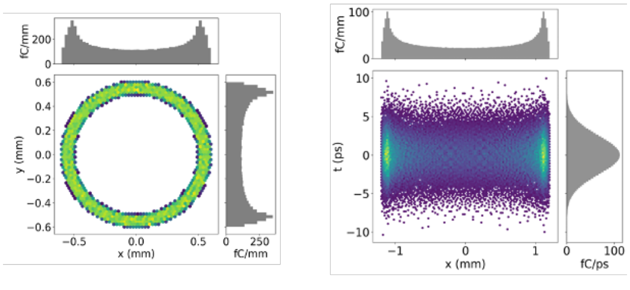

Figure 3: Transverse and longitudinal phase-space of the hollow UV laser beam at LCLS photocathode.

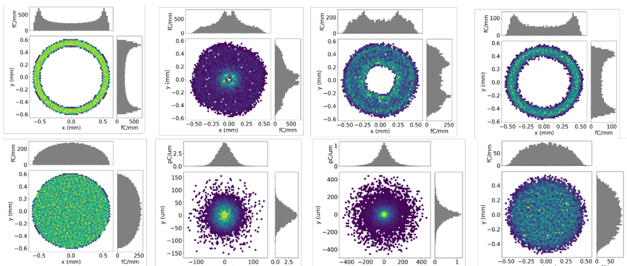

Figure 4: Hollow beam shown in Fig. 3, propagated to the injector exit with the fixed lattice parameters as a function of charge and comparison to a uniform beam of the same charge.

where E_z is the accelerating gradient in the gun, A is the illuminated area on the photocathode, and η is the efficiency parameter [26]. An example of a simulated hollow beam profile is displayed in Fig. 3. The outer radius of the hollow is 0.6 mm, and the thickness is 0.1 mm. We specified the Twiss parameters required for matched beam orbit in the LCLS copper linac and propagated hollow beams of various charges. We established, via numerical simulations, the value of a hollow beam charge, where it becomes free of space-charge instabilities to be about 3 pC. The results are summarized in Fig. 4. Interestingly, the final transverse distribution is almost identical to the one on the cathode.

It is important to point out that throughout the injector, the hollow beam transverse shape changes from round to elliptical and back to round, according to the lattice beta functions; see Figs. 2–5. During this process, the transverse charge density fluctuates along the hollow beam, until it becomes uniform again at the copper linac injection point.

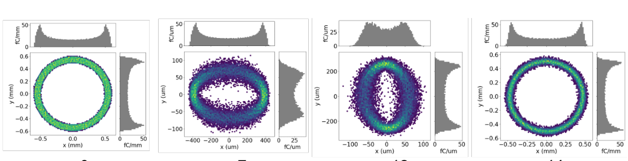

Figure 5: Evolution of the Q = 3 pC charge as a function of distance in the LCLS copper linac injector.

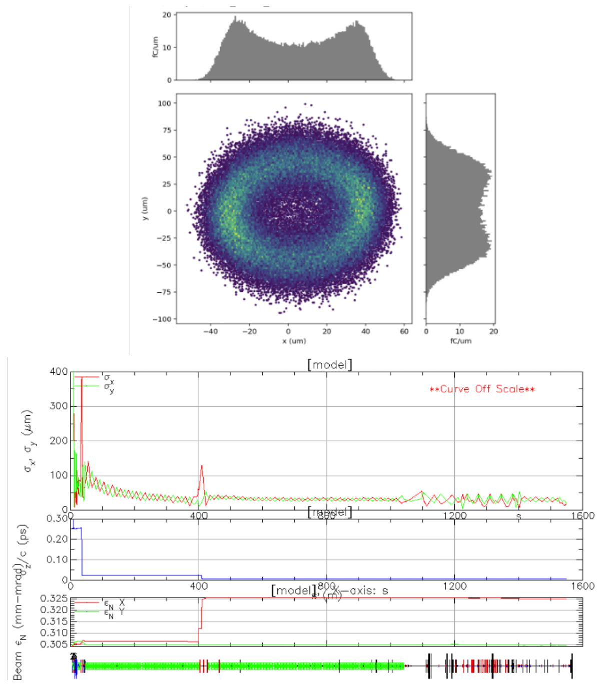

Figure 6: Matched 7.5 GeV hollow beam in the LCLS copper linac propagated up to HXR undulator entrance. The simulation was done in ELEGANT [27] and *Bmad* [28] and yielded almost identical results.

Finally, we sent the injector-made hollow beam into a nominal LCLS copper linac lattice. To gain confidence in the simulation, we used two codes: ELEGANT [27] and *Bmad* [28] with identical lattices, including Coherent Synchrotron Radiation (CSR) and wakefield effects, yeilding almost identical results. The resulting beam envelope and transverse charge density distribution at HXR undulator entrance are presented in Fig. 6. The hollow beam size is effectively demagnified by a factor of 10 compared to the initial laser profile at the cathode. The latter finding is quite remarkable but expected, because the space-charge forces are significantly suppressed at high beam energies.

LUME-IMPACT BEAM DYNAMICS PACKAGE

In order to rapidly prototype and optimize hollow beam simulations for LCLS copper linac photoinjector, we have utilized LUME-IMPACT package [29]. This software includes a collection of helper functions to the conventional PIC code IMPACT-T, that allows easy modification of initial particle distribution, gun and linac phase optimization, and fast beam trajectory matching. In combination with the precision and accuracy of IMPACT-T, we quickly established the range of accelerator parameters, allowing for a hollow beam to be propagated downstream of the injector distortion-free. We have also used initial particle distribution generator DISTGEN package [30] to probe different distributions, and the OPENPMD-BEAMPHYSICS package [31] for handling and plotting simulation results.

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SUMMARY

We have presented the results of numerical beam dynamics simulation of a hollow electron beam in LCLS copper linac beamline, generated with a transverse UV laser mask. The simulation shows that the beam is only stable at the very low charge values, where the beam becomes emittance-dominated. This however makes hollow electron beams a perfect candidate for beam-based studies. We will report the results of the practical hollow beam applications elsewhere in the near future.

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