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BUBBLE-BEAM ACCELERATORS: BREAKING THE PARADIGM

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Abstract

Most particle accelerators utilise beams with a charge density concentrated in the centre of the bunch in real 3-dimensional space and the 6-dimensional phase space. In this work, by enhancing the space-charge forces in a photocathode injector of the CERN Linear Electron Accelerator for Research (CLEAR) at CERN, we produce electron bunches with a "bubble-like" shape with a charge density mostly concentrated on the outside shell. We demonstrate that the dynamics of such beams can be tailored to achieve stable uniformity in the coordinate and momentum transverse planes simultaneously. This would allow for a uniform dose distribution without a severe loss of particles, which is of great interest to the irradiation community.

INTRODUCTION

The majority of particle accelerators for use in colliders, light sources, and irradiation facilities employ beams with a particle distribution concentrated in the core of the bunch. The transverse profiles of such bunches are often close to the Gaussian distribution. The longitudinal (or temporal) profile of these bunches has either a Gaussian or a flat-top distribution, which in the case of photoinjectors is usually achieved with a corresponding temporal laser profile.

Irradiation facilities can significantly benefit from utilising beams with a transversely uniform profile, allowing the delivery of a uniform dose across the target, minimising the effects of the orbit jitters. There are several methods which can produce uniform distributions of electron beams. More complex methods require transverse shaping of the ultra-short laser pulses in the photoinjectors to enhance the space-charge (SC) forces [1–3]. Therefore, they can not be easily employed at existing irradiation facilities without substantial modifications. Simpler methods can be used that are based on scanning techniques with pencil beams or collimating large beams. Employing sophisticated scattering systems can produce beams with good uniformity [4], but these suffer from major beam losses and as a result reduce the dose delivered to the target. Both methods are very limited in delivering ultra-high dose rate (UHDR) electron beams.

Previously, we have shown, in simulation [5, 6] and experimentally at CLEAR [7], that uniform transverse profiles can be produced by enhancing the SC forces in the photoinjector by balancing them with the magnetic field of the solenoid magnet. Furthermore, we showed that two uniformity points can be produced and that their location can be tuned to reach a desired position in the injector.

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In this work, we extend the previous results by demonstrating the regime in which uniformity is reached simultaneously in the coordinate and momentum space. In this regime, uniformity, once reached, is preserved during free-space propagation. Moreover, we show that bunches in such a regime have a unique "bubble"shape with most of the charge density concentrated on an outer shell. We also show that the "pyramid"formations, seen previously in and beyond the second uniformity point, correspond to the formation of additional high-density regions within the bubble.

CLEAR LAYOUT

The CLEAR facility is a descendent of the Compact Linear Collider (CLIC) Test facility (CTF3) at CERN, based around the CTF3 probe beamline [8, 9]. The CLEAR photoinjector consists of an S-Band (3 GHz) 2.5-cell RF gun with a peak on-axis electric field of up to 80 MV/m [10]. Beams are produced by a pulsed UV laser with rms pulse length of 2 ps [11]. The Gaussian transverse profile of the laser can be adjusted from a few hundred µm to a few mm rms spot size. A focusing solenoid is located immediately after the cathode to focus the beam and minimise the emittance growth. A de-focusing solenoid is used to compensate for the field strength on the cathode. A phosphor scintillator screen (BTV215) is located at 1.8 m from the cathode. The injector is followed by the S-Band accelerating cavities of the linac starting at 2.4 m from the cathode. The beam aperture in the injector part is limited by 50 mm radius of a vacuum beam pipe and additionally by the laser mirror placed at 1.5 from the cathode reducing the horizontal beam aperture in the negative direction to ~ 14 mm.

SIMULATION RESULTS

As described in [7], the first or second uniformity points can be reached at BTV215 for specific injector settings. In the first uniformity point the beam has a completely uniform transverse profile and in the second it has a small pyramid feature in the centre formed by to SC interactions as the beam evolves through a hollow distribution region. As before, we quantify the uniformity of the transverse distribution with its kurtosis [12]. We use the particle tracking code RF-Track to simulate the beam, applying the SC interaction between particles [13, 14].

The evolution of kurtosis with distance from the cathode, for beams simulated with different solenoid fields and gun phases, are shown in Fig. 1 (a). All beams start with a Gaussian distribution (kurtosis $k_{x,y} = 3$) at the cathode 0 m. For a magnetic field of B=0.1785 T and the gun phase

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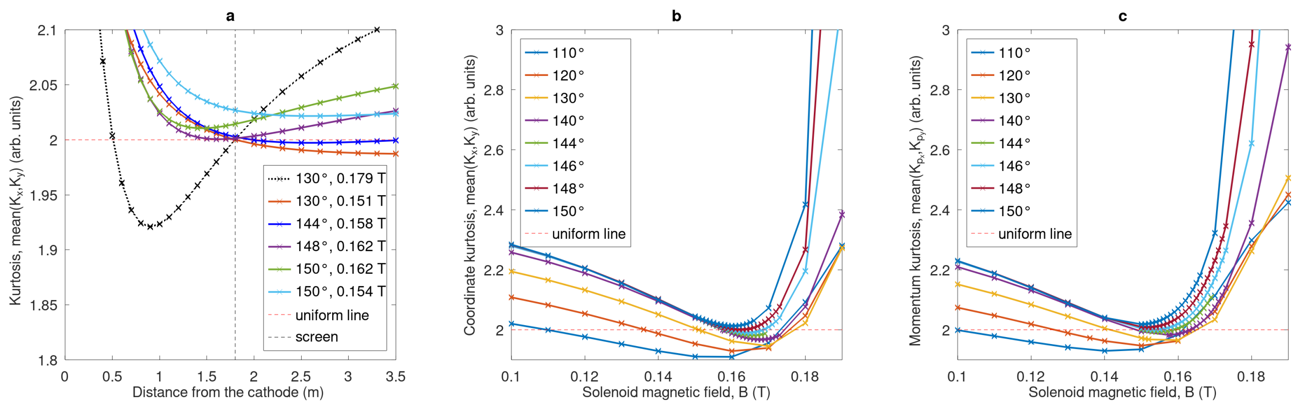

Figure 1: Simulation results with 10,000 particles for electron beams of 300 pC bunch charge, 2 ps rms laser pulse length and 1 mm rms spot size in both planes and a gun gradient of 70 MV/m: (a) Coordinate kurtosis evolution along the injector; Coordinate (b) and Momentum (c) kurtosis dependence at the injector screen location (1.8 m) from the solenoid magnetic field. At 144° gun phase and $B = 0.158$ T the electron beam enters a stable uniform regime at 1.8 m.

for the maximum energy, 130°, there are two uniformity points ($k_{x,y} = 2$), at 0.5 m and at BTV215 (1.8 m), and a hollow distribution ($k_{x,y} < 2$) in between. Downstream of the screen location the pyramid feature grows resulting in $k > 2$. The dependence of the coordinate, $k(B_{x,y})$, and momentum, $k(B_{p_x,p_y})$, kurtosis at the location of BTV215, on the magnetic field for different gun phases are depicted in Fig. 1 (b) and (c) respectively. At a phase of 110°, the coordinate kurtosis curve features two intersections with the uniformity line ($k_{x,y} = 2$) corresponding to the first and second uniformity points at the screen. Increasing the phase of the gun allows the control of the minimum value of kurtosis between the two uniformity points and the separation between them in terms of magnetic field values. At phases $> 148°$, $k(B_{x,y})$ does not reach uniformity at 1.8 m. At a phase of 148°, $k(B_{x,y})$ features a single uniformity point at B=0.162 T. The corresponding momentum kurtosis at this setting is slightly larger than 2 resulting in the coordinate kurtosis to slightly grow downstream the screen location, with the beam becoming less uniform transversely. Close to this setting, at 144° and B=0.158 T, the uniformity is simultaneously reached in the coordinate and momentum space: $k_{x,y,p_x,p_y} = 2$ at BTV215. As a result, the evolution of the Kurtosis downstream of the screen, shown in Fig. 1 (a), is minimal and the bunch remains transversely uniform. We refer to these settings as a "golden point".

The location of the stable uniformity region can be shifted closer to the cathode by adjusting the phase and magnetic field settings. It is typically close to the setting with a single overlap of $k(B)-$curve with $k_{x,y} = 2$ at a desired location. These adjustments allow the control of the transverse beam size at a given location. Its minimisation can be additionally achieved by tuning the transverse spot size of the laser and the pulse duration since both affect the charge density distribution. A small transverse beam size can be of great importance, particularly if higher frequency linac structures (e.g. X-band CLIC structures) with smaller apertures are foreseen downstream of the injector.

Understanding the formation of SC produced transverse uniformity and pyramid feature is difficult in terms of 2D or 4D dynamics. By taking longitudinal slices along the bunch and analysing the kurtosis values and corresponding transverse distributions of these slices it is evident that a transversely uniform bunch has slices with $k_{x,y} < 2$ close to the core of the bunch and slice of $k_{x,y} > 2$ in the tail regions. This fact and the fact that the SC forces in the injector region act in 3D, suggest looking into the 3D charge-density distribution along the injector. Figure 2 (a) depicts the evolution of the 3D charge density with distance from the cathode for injector settings that produce a golden point. The initially Gaussian distribution transforms to a bubble beam by repulsing the electrons from the core of the bunch to the outside region. For comparison, the corresponding 3D distributions for injector settings producing a severe pyramid in the transverse distribution are shown in Fig. 2 (b). The pyramid clearly corresponds to the formation of additional high charge density regions in the tails of the bunch. Although not shown here, as the pyramid bunch propagates further downstream, with growing kurtosis, an additional region of high charge density is formed.

EXPERIMENTAL RESULTS

Experimentally measuring the hollow 3D charge density distribution would require a variable polarisation transverse deflector with a series of upstream and downstream quadrupole magnets and a complex reconstruction algorithm based on the simulations of measurements or/and multidimensional tomography methods. Furthermore, justifying the "golden point"dynamics along the injector could be accomplished by the series of the transverse screens or/and a

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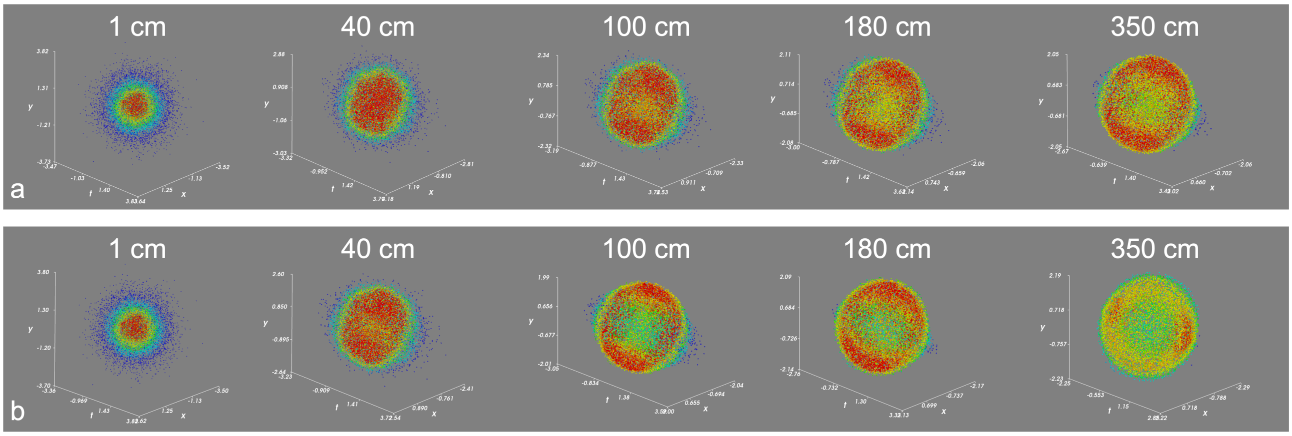

Figure 2: Evolution of the 3D charge density distribution along the injector (coordinates and time are normalized by the corresponding rms values): (a) beam evolving to the stable uniform regime starting at 180 cm; (b) beam evolving through the 2nd uniformity point at 180 cm featuring an additional high density regions in the tails of the bunch.

movable transverse screen. These techniques are currently out of reach for the existing CLEAR injector layout. However, performing solenoid scans for various gun phase settings and different laser spot sizes is possible with present hardware. The full comparison of these scans with the simulation data will be reported in future. Due to the limited volume of these proceedings, here we report on a highlight of our recent measurement campaign advancing on the results presented in [7].

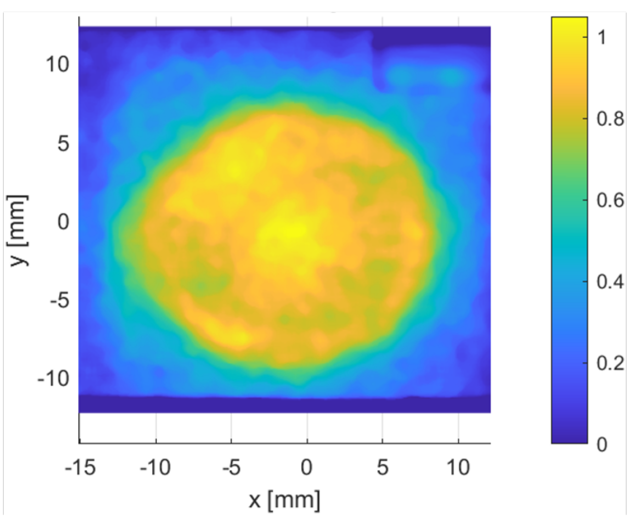

Figure 3: Experimentally measured particle distributions at BTV215 for the train of four bunches with a total charge of 180 pC.

Figure 3 depicts the transverse distribution measured at BTV215, of a beam comprised of four bunches with a total charge of 180 pC. The measured rms beam size in horizontal and vertical planes are 6.4 mm and 5.3 mm respectively. The asymmetry is caused by a slightly elliptical laser spot on the cathode. The beam has a quite uniform profile with kurtosis calculated to be 2.14, likely an overestimation due to noise on the screen. Despite some imperfections in the flatness of the distribution, fluctuations in the density distribution in the centre of the beam profile are < 25%, substantially less than the severe pyramid, ~ 40% higher than the rest of the profile, reported in [7].

CONCLUSION

In this paper, we demonstrate that beams with a simultaneous uniform distribution in the coordinate and momentum planes can be reached by utilising and tailoring the space-charge forces in photo-cathode injectors. This allows spacial uniformity to be propagated stably through free space, not just locally as shown in [7]. Moreover, we extend our understanding of the space-charge interaction in the injector region by analysing the 3-dimensional charge density distributions and finding a "bubble-like"beam distribution. Such a bubble beam breaks the paradigm of existing accelerators, which predominately operate with Gaussian beams with most of the charge density concentrated in the core of the bunch. The methods demonstrated here are shown in the example of the CLEAR photoinjector but can be easily applied to most existing photoinjector facilities. On top of the immediate impact of the proposed method for reaching a uniform dose for the irradiation facilities, investigating the potential benefits of bubble-like beams across several accelerator pillars, such as for light sources, advanced acceleration technologies, and particle colliders can be of great interest to the accelerator community.

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