GENERATION OF TRANSVERSELY UNIFORM BUNCHES FROM A GAUSSIAN LASER SPOT IN A PHOTOINJECTOR FOR IRRADIATION EXPERIMENTS

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Abstract

Beams of uniform transverse beam profile are desirable for a variety of applications such as irradiation experiments. The generation of beams with such profiles has previously been investigated as a method of reducing emittance growth. These methods, however, often use complicated optics setups or short, femtosecond laser pulse lengths. In this paper, we demonstrate that if ultra low emittance is not the target of the photoinjector, it is possible to produce transversely uniform beam profiles using a simple Gaussian laser, with a bunch length of a few picoseconds, utilising space-charge effects only.

INTRODUCTION

Irradiation facilities [1] around the world are used to investigate the effect of high-energy particle beams on electronics [2–4], to study the makeup of historical objects and art [5], and for medical applications, notably radiotherapy [6, 7]. Electron beams are used at several of these facilities, including the CLEAR user facility at CERN [8, 9]. Electron irradiation facilities typically consist of accelerators that produce beams with Gaussian beam profiles and direct them onto a target. Non-uniform transverse beam profiles can lead to uncertainty in the dose that is incident on the target. To increase the uniformity of the dose, the beam size is often increased to a significantly larger size than the target and often collimated, which reduces the total dose incident on the target and the maximum dose rate. If it was possible to generate an entirely uniform beam profile in the irradiation facility, then the total dose and dose rate could be increased.

Photoinjectors used in free electron lasers (FEL) are often designed to produce electron bunches that have 2D uniform beam profiles or have 3D uniform ellipsoid beam profiles in order to reduce the emittance of the beam and increase brightness [10]. 3D-uniform ellipsoids also have the added advantage in that the space-charge forces inside the bunch are linear. However, these photoinjectors commonly use extremely short laser pulses, often less than 100 fs, or laser pulses that are shaped in 3D [11, 12]. Such systems are complicated to set up and require regular maintenance, thus are not feasible for use in an irradiation facility. The ability to produce electron beams with uniform transverse beam profiles with Gaussian lasers with bunch lengths of a few picoseconds could potentially be useful in an irradiation facility and should, therefore, be investigated.

GENERATING UNIFORM BEAMS

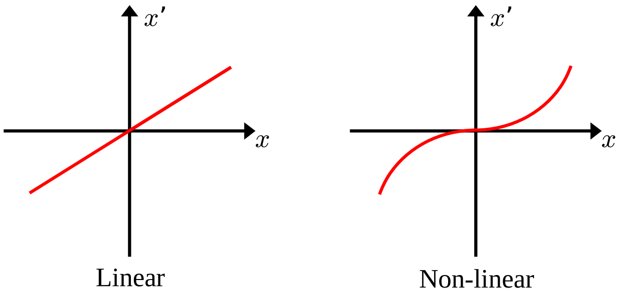

Figure 1: Transverse phase-space of a beam under the influence of linear and non-linear focusing forces.

Bunches produced in photoinjectors tend to exist in the space-charge regime, such that the interactions of particles within a bunch are dominated by the self field of the bunch. In the space-charge regime, non-linear space-charge forces cause the phase-space of the bunch to distort in the manner illustrated in Fig. 1. These space-charge forces cause bunches created in non-equilibrium to evolve towards stable states with a potential energy that is minimised. If a bunch is initially created with a Gaussian distribution then the space-charge forces will cause particles in the core to move towards the tails. If the space-charge forces present in the photoinjector are low, the beam will continue to have a transverse beam profile similar to a Gaussian. If the space-charge forces are increased, then the tails of the Gaussian begin to become more populated and the bunch will have a more uniform transverse beam profile. When the space-charge forces are too high, the beam becomes highly peaked around its centre, with a diffuse surrounding halo. In a photoinjector the evolution of the space-charge forces are determined by the bunch charge, the laser spot size, the laser pulse length, the strength of the RF field, the phase of the RF field, and the strength of solenoid field. It is, therefore, possible to control the space-charge driven evolution of the phase-space of a bunch by changing these parameters.

The photoinjector used at the CLEAR facility consists of a 2.5 cell RF gun operating at a frequency of 3 GHz. Electron bunches are produced by a UV laser with a Gaussian laser profile and 4.7 ps pulse length, incident upon a Cs_2Te photocathode [13]. The gun is surrounded by two solenoid magnets, one to focus the outgoing electron beam, and one to reduce the solenoid field to zero on the photocathode. By simulating a modified version of the CLEAR gun using

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the ASTRA particle tracking code [14, 15], it is possible to demonstrate how the gun can be used to produce beams with uniform transverse beam profiles. In these initial simulations a bunch of charge 0.4 nC was produced from a laser pulse of length 1 ps and Gaussian transverse shape of size 1.6 mm, and accelerated at the peak accelerating phase in the gun with an RF field of 110 MV/m. The strength of the solenoid magnet was varied showing how it could be used to control the uniformity of the transverse beam profile.

The evolution of three bunches focused by different solenoid fields are shown in Fig. 2. Each magnetic field strength shown illustrates a separate space-charge evolution leading to three different transverse beam profiles. Slices of the transverse beam profile of each field at a distance of 1.5 m from the photocathode are shown in Fig. 3. In each case the space-charge forces present in the gun are not strong enough to produce uniform beam profiles at the exit of the gun. For a solenoid of strength 0.21 T, the beam is constantly diverging following the gun, resulting in a significant drop in space-charge forces with distance. The beam profile, therefore, remains Gaussian. The bunch that is focused by a solenoid field of 0.26 T is only diverging a small amount during the drift. Therefore, the space-charge forces are almost constant during the drift causing the beam core to diffuse outwards creating a uniform beam profile at 1.5 m. For a solenoid field strength of 0.29 T the beam is converging as it leaves the gun towards a beam waist at 0.9 m from the photocathode. In this simulation, the beam profile profile changes from Gaussian towards uniform at the waist to a core-halo profile at 1.5 m. By only adjusting the strength of the solenoid it is possible to adjust the distance at which the beam has a uniform transverse beam profile.

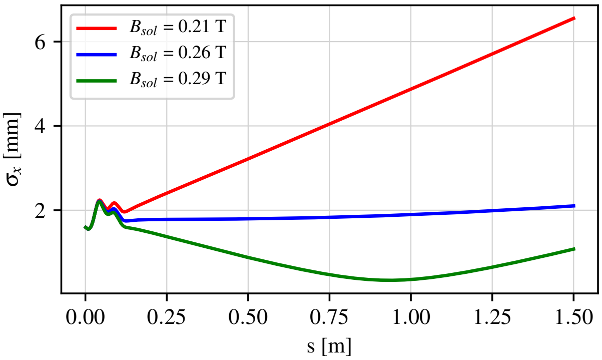

Figure 2: Beam size vs distance from the photocathode with different solenoid magnetic field strengths.

As the space-charge forces drop significantly with increased energy, it is proposed that by rapidly accelerating the bunches following the photoinjector it would be possible to quickly reduce the space-charge forces, thus fixing an angle in phase-space of uniform beam profile. There would be some phase-space rotation as the bunch is accelerated, however, it would be possible to use magnetic elements following the accelerating cavities to rotate it back to a uniform profile in x - y.

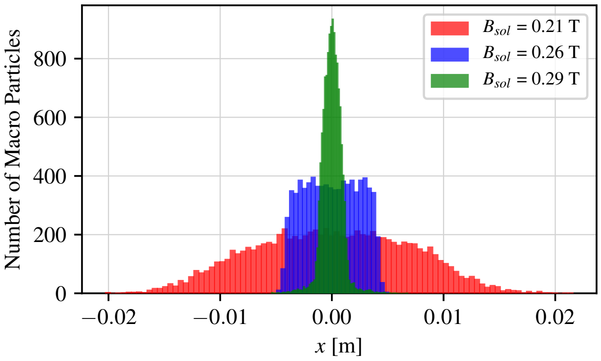

Figure 3: Particle distributions in x across a slice in y of width $\pm\sigma_y/4$.

PROPOSED LINEAR ACCELERATOR

To demonstrate the feasibility of producing electron beams with a uniform beam profile for use in an irradiation facility, a compact linear accelerator was proposed. The linac consists of the CLEAR photoinjector followed by 8, X-band RF cavities similar to those used in the Compact Linear Collider (CLIC). Each cavity is 500 mm long, and operates with a maximum field gradient of 35 MV/m. The total energy of the bunch at the end of the linac was 100 MeV. As the electron beam exits the RF gun at an energy of ∼ 5 - 10 MeV, the high-gradient of the X-band cavity produces a strong RF focusing effect. The RF focusing leads to a rapid reduction in bunch size and an increase in space-charge forces which cause the emittance to grow and phase-space to move to a core-halo profile which leads to beam losses. To counteract the RF focusing it was necessary to produce a beam that is diverging at the entrance to the first cavity. As the CLIC type structures have an aperture of less than 4 mm radius it was necessary to keep to the beam smaller than 4 mm upon entrance to the cavity to avoid beam losses. To produce a diverging beam with a small beam size it was preferable to have the cavity as close to the gun as possible. A minimum length of 1.2 m was chosen as a common length of modern, compact photoinjectors such as the new CLEAR electron source. As the CLIC cavities have a frequency of 12 GHz, it was necessary to keep the bunch length less than 1 ps to reduce the energy spread at the exit of the linac.

A bunch of charge 0.4 nC was generated from Gaussian laser spot of size 0.8 mm with a pulse length of 1 ps in ASTRA. It was then tracked in ASTRA to the beginning of the first X-band cavity. The bunch was then tracked to the end of the final accelerating structure using the RF-Track code [16, 17]. To qualify the uniformity of the beam profile the kurtosis was calculated. The kurtosis describes the relative population of the tails of a distribution relative to the core [18]. The kurtosis of a distribution in x, with a mean μ and standard deviation σ, is defined as,

$$K_x = \frac{\langle (x-\mu)^4 \rangle}{\sigma^4}. \quad (1)$$

With this definition, the kurtosis of a Gaussian distribution would be 3. Distributions with a higher density in the core have a higher kurtosis, and distributions with a higher density in the tails, a lower kurtosis. The kurtosis through one plane of a 2D uniform distribution is 2. An optimisation of the gun RF field strength, RF phase, and solenoid strength, as well as the linac RF field strength and phase was undertaken for a bunch of 2000 macro particles. The target of the optimisation was for a kurtosis of 2 to be achieved in both x - y at the entrance to the linac, to minimise losses in the linac, and for the bunch to a kurtosis of 2 at a projected angle in phase-space at the end of the linac. Following the optimisation of beamline parameters, a bunch with 50,000 macro particles was tracked through the linac and the results verified.

In the optimisation, the RF field of the gun was set to 110 MV/m and the strength of the gun solenoid magnet set to 0.277 T. The phase-space of the bunch at the entrance to the X-band linac is shown in Fig. 4. The beam profile is uniform in x -y and has a maximum radius of 3.1 mm. The effect of the space-charge forces in rotating the position-momentum phase-space is clear. The beam is symmetric between x and y. As the beam is uniform at this location, a beam television screen could be inserted here to verify the beam set up experimentally.

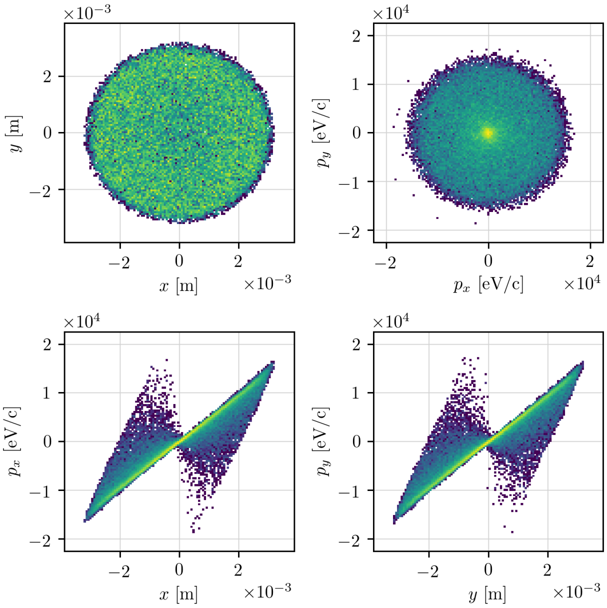

Figure 4: Transverse phase-space of a 0.4 nC bunch 1.2 m from the photocathode, generated from a laser spot of 0.8 mm.

When tracked through the linac there were no losses in simulation. The transverse beam profile is shown in Fig. 5 and is not uniform. Superficially the beam looks similar to a core-halo distribution. However, there exists an angle in phase-space in which the beam has a kurtosis of 2. A rotation of the phase space of the beam by this angle is also shown in Fig. 5. By placing an optical matching section after the linac it is possible to recreate a beam with a uniform beam profile.

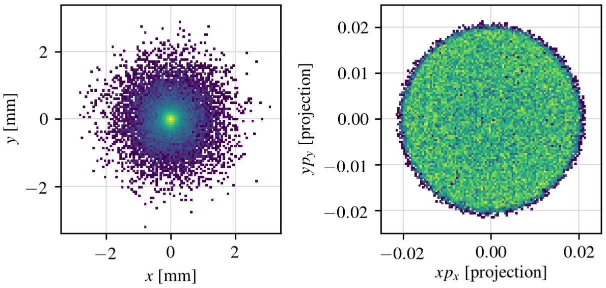

Figure 5: **Left:** Transverse beam profile measured at the linac exit. **Right:** Projected beam profile at an angle of phase-space giving $K_x = 2$ at the linac exit.

As non-linear space-charge forces are used to generate the uniform beam profile it was important to check whether the beam quality and uniformity is reduced by the typical jitters present in a photoinjector. Therefore, scans of photoinjector parameters were performed to the tolerances experienced at CLEAR. The RF phase was scanned by ±1°, the RF gradient in the gun by ±1 %, the bunch charge ±2 %, the laser spot size by ±5 %, the laser pulse length by ±10 %, and the position of the laser spot by ±100 µm. A small linear response to these jitters was seen at both the entrance to the linac and the exit of the linac on emittance, energy spread, beam size and kurtosis. Furthermore, the effects of cathode non-uniformities were also investigated demonstrating that they did not significantly effect the uniformity of the final beam profile.

CONCLUSION

Generating electron beams with uniform beam profiles would be useful in irradiation facilities. It has been shown in this paper that using a modified version of the CLEAR photoinjector it is possible produce beams that have a uniform beam profile following the gun. The level of uniformity could be controlled by altering the parameters of the photoinjector. In particular, the distance at which a uniform profile can be obtained is able to be changed by only altering the strength of the solenoid field around the gun. It has also been shown that by rapidly accelerating this uniform beam, the phase-space can be locked and a uniform beam profile achieved at higher energies. Further analysis of these dynamics should be undertaken to fully detail the effects taking place in order to fine tune the parameters in a real facility. The design of a matching section should be investigated in order to produce uniform distributions of different sizes.

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