ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL119

EXPERIMENTAL GENERATION OF TRANSVERSELY UNIFORM ELECTRON BUNCHES AT THE CLEAR FACILITY AT CERN

A. Malyzhenkov*, L. A. Dyks, R. Corsini, W. Farabolini, A. Latina, CERN, Geneva, Switzerland
P. N. Burrows, P. Korysko[1], C. Robertson[1], JAI, University of Oxford, Oxford, UK
A. Aksoy[1], Ankara University, Ankara, Turkey
[1]also at CERN, Geneva, Switzerland

Abstract

Electron beams with a flat-top transverse distribution are highly desired for uniform dose delivery in irradiation applications, like studies of radiation damage to electronics and radiotherapy, as well as for potential applications in the improvement of light sources. In this work, we report on the optimisation of the electron photocathode injector parameters which allow such uniform distributions to be reached. This can be achieved starting from a standard Gaussian transverse distribution of the laser, by tailoring the space charge forces and the magnetic field of the solenoid. We report on the first experimental demonstration of this method at the CLEAR facility at CERN.

INTRODUCTION

Irradiation facilities [1] are powerful tools to study the effects of high-energy particle beams on materials [2] and electronics [3,4], to test detector components for high-energy physics [5], and medical applications such as radiotherapy [6, 7]. Different users require beams with different particle types and different beam parameters. One of the key beam parameters in these facilities is for the delivered beam to have a uniform dose profile across the user's experiment, which can reduce uncertainties in dose deposition.

Electron beams are used at several irradiation facilities, including the CLEAR user facility at CERN [8, 9]. The beams in primary electron irradiation facilities are typically produced with Gaussian beam profiles using thermionic sources or photoinjectors, then accelerated and directed to a target. Typically the uniformity of the beams can be reached by either enlarging the beam size to a larger size than the target and then collimating it, or by scanning a pencil beam across the target. Both these methods reduce the total dose incident on the target and the maximum dose rate that can be achieved.

It has previously been shown that electron beams with uniform bunch profiles can be created in the photoinjectors used in free electron lasers (FEL) in order to create beams of ultra-low emittance to increase brightness [10]. These photoinjectors use extremely short (<100 fs), often transversely shaped, laser pulses to induce high space-charge (SC) forces which shape the bunch profile [11, 12]. Such laser systems are unsuitable for an irradiation facility as they are complicated to set up and maintain.

* alexander.malyzhenkov@cern.ch

Ultra-low emittance beams are not necessarily desirable in an irradiation facility which often needs to irradiate large targets. Simulations have been performed, suggesting that by relaxing the requirement to minimise beam emittance and optimising the parameters of the photoinjector for uniformity only, it could be possible to use SC forces to produce transversely uniform beam profiles using a simple Gaussian laser, with a bunch length of a few picoseconds [13, 14]. Furthermore, simulations suggest that the uniform beam produced in the photoinjector could be accelerated to higher energies at which the SC forces are negligible while maintaining the uniform profile.

In this paper, the initial simulations of this effect are expanded upon. In particular, we show that a uniform beam can be generated at the end of the injector within the existing CLEAR layout and measured at the first available beam profile monitor. Additionally, the first experimental efforts to produce SC-induced uniform beams at the CLEAR irradiation facility are presented.

CLEAR INJECTOR

The photoinjector used at CLEAR consists of a 3 GHz, 2.5-cell RF gun with a peak on-axis electric field of up to 80 MV/m [15]. The gun is surrounded by two solenoid magnets, a focusing solenoid to focus the beam and a defocusing solenoid to ensure the field strength on the cathode is zero, typically used to minimise emittance. The maximum focusing strength seen by the beam is 0.235 T, limited by the existing current supply. Electron bunches are produced by a pulsed UV laser incident upon a Cs_2Te photocathode [16]. Each laser pulse has a pulse length of 2 ps rms and a Gaussian transverse profile with adjustable spot size. Three 3 GHz accelerating cavities from the LEP injector linac [17] are located after the photoinjector, with the entrance of the first 2.4 m from the cathode. A phosphor scintillator screen (BTV) is located 1.8 m from the cathode, BTV215. There are two corrector magnets between the gun and the cavities, one placed after the gun and one after the BTV screen. From the exit of the RF Gun (0.25 m) to the location of BTV215, the aperture is limited to 50 mm radius by a vacuum beam pipe. Additionally, a UV-laser mirror is installed 1.5 m from the cathode, limiting the horizontal beam in the negative direction to ~ 14 mm at its location.

SIMULATION RESULTS

For nominal CLEAR operation with Gaussian beams, the solenoid field is usually adjusted to minimise the transverse

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL119

emittance. In this work, however, following the concept described in [13, 14], we adjust the magnetic field of the solenoid to reach a uniform transverse profile for a given bunch charge and target the uniformity at the BTV215 location. To investigate whether this is possible at CLEAR, we use the particle tracking code RF-Track to simulate the beam accounting for the SC interaction between particles [18, 19]. One million macro-particles represent each bunch balancing the speed of the simulations whilst minimising the statistical noise across the results. We quantify the uniformity of the distribution with its kurtosis [20]. The characteristic values for 2D Gaussian and 2D uniform beams along each axis are $k_{x,y} = 3.0$ and $k = 2.0$ respectively. A hollow distribution is quantified with $k < 2.0$. For $k > 3.0$ the beam becomes sharper than a Gaussian. The kurtosis values for the simulated distributions are noted in the figure captions. Comparing kurtosis values enables changes in uniformity due to the photoinjector parameters to be quantified.

We assume a bunch charge of 285 pC, a gun gradient of 80 MV/m, a phase of 139.7°, and a Gaussian laser spot size with $\sigma_x = 0.74$ mm and $\sigma_y = 0.88$ mm. This represents the asymmetry of the CLEAR UV laser due to the phase-matching walk-off issues in the harmonic conversion crystals. All used parameters should be easily achievable experimentally. Figure 1 shows a simulation of the transversely uniform beam distribution obtained at BTV215 with a solenoid field of 0.17 T. Variations in the normalised density across the beam are predominantly due to statistical noise. As it moves along the injector (Fig. 2), the profile of the bunch flattens from a Gaussian distribution at the cathode to a first uniformity point at 180 cm (BTV215).

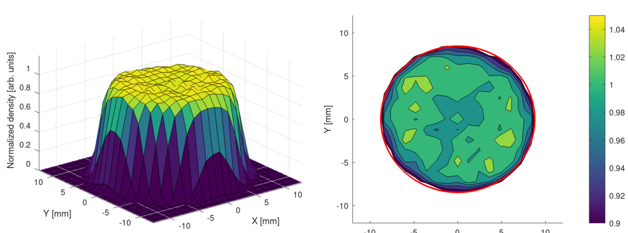

Figure 1: Simulated uniform distribution at 1.8 m from the cathode for 0.17 T magnetic field: (left) histogram of the particle distribution and (right) colour map representation. Corresponding kurtosis values are k_x=2.027 and k_y=2.022.

Varying the solenoid field by ~ 6% noticeably affects the uniformity as shown in Fig. 3. A smaller magnetic field of 0.16 T shifts the first uniformity point upstream of BTV215, while a stronger magnetic field of 0.18 T results in the shift of the first uniformity point towards the cathode and results in a slightly hollow beam at BTV215.

Using a magnetic field of 0.2 T generates a second uniformity point at BTV215 (Fig. 4). This pushes the first uniformity point to 50 cm from the cathode. Between the first and second uniformity points, the beam evolves through a hollow distribution. Due to this, there is a small "pyramid" in the middle of the second uniformity point, which

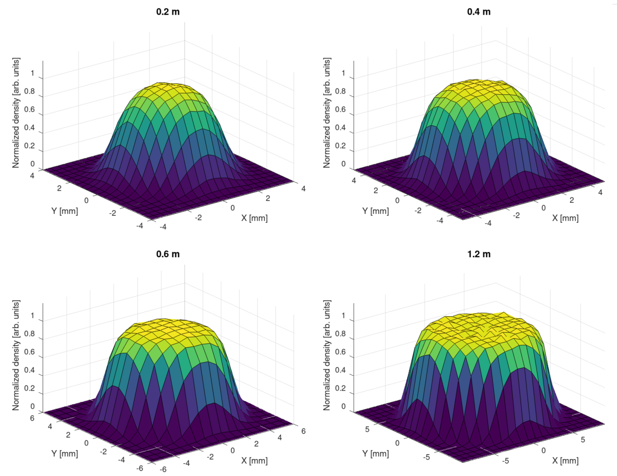

Figure 2: Evolution of the transverse beam distribution along the injector from a Gaussian distribution at the cathode. Corresponding kurtosis values are $k_{x,y}$=2.36 / 2.34 at 0.2 m, $k_{x,y}$=2.20 / 2.22 at 0.4 m, $k_{x,y}$=2.13 / 2.15 at 0.6 m, and $k_{x,y}$=2.05 / 2.05 at 1.2 m.

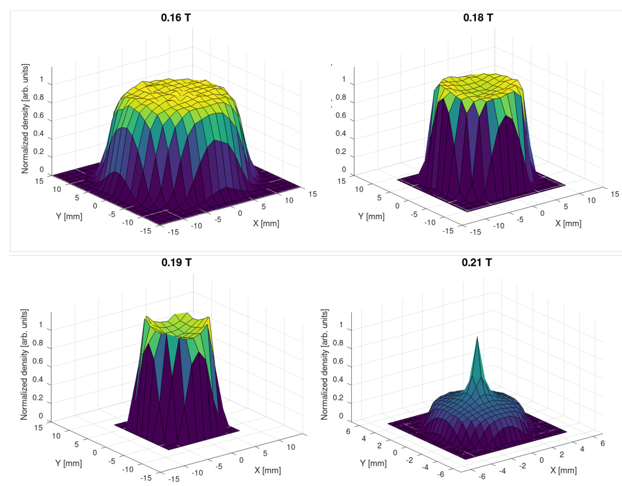

Figure 3: Effect of the magnetic field variations near the first and second uniformity points at 180 cm. Corresponding kurtosis values are $k_{x,y}$=2.07 for B=0.16 T, k_x=1.98, k_y=2.00 for B=0.18 T, k_x=1.99, k_y=1.95 for B=0.19 T, and k_x=2.19, k_y=2.21 for B=0.21 T.

becomes more pronounced downstream. Apart from this small region, good uniformity is reached across the beam. An advantage of the second uniformity point over the first is a smaller transverse size of the beam along the injector, which would minimise losses and ease transmission. The energy spread for the 0.2 T set point is 0.96%, slightly larger than 0.81% for the 0.17 T set point, while the bunch duration is 2.2 ps and the beam energy is 5.84 MeV for both cases.

The drawbacks of the second uniformity set point are caused by stronger solenoid focusing. It results in a more rapid kurtosis evolution along the injector, enhancing the asymmetry effects in the initial laser distribution. Additionally, this set point is more sensitive to the fluctuations of the

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL119

beam parameters and hardware settings. The effects of the magnetic field variations are compared in Fig. 3.

We note that more simulation results for different bunch charge and laser spot sizes at the cathode (not shown) can result in a more hollow beam (with smaller kurtosis) in between the two uniformity points, which in turn would lead to an appearance of a more severe "pyramid" in the second and following uniformity points.

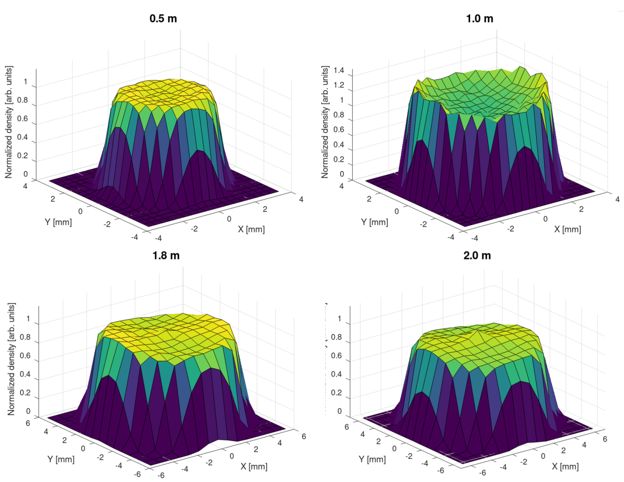

Figure 4: Simulation results for the magnetic field of 0.2 T optimised to reach the second uniformity point at 180 cm. Corresponding kurtosis values are $k_{x,y}$=2.04 / 2.04 at 1.0 m, $k_{x,y}$=1.93 / 1.97 at 1.0 m, $k_{x,y}$=1.99 / 2.03 at 1.8m, and $k_{x,y}$=2.0 / 2.05 at 2.0 m.

EXPERIMENTAL RESULTS

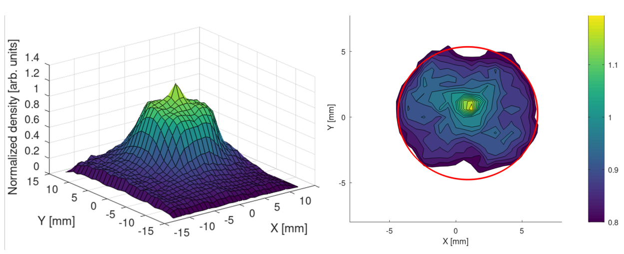

Figure 5: Experimentally measured particle distribution for a solenoid field of 0.153 T at BTV215: (left) histogram of the particle distribution and (right) colour map representation

Uniform beam distributions with a presence of a "pyramid" feature have been observed experimentally as shown in Fig. 5. For this, the laser spot size was set to $\sigma_{x,y}$= 0.97 / 0.9 mm and the bunch charge to 200 pC. The gun gradient was limited by the available klystron power. It was set to 65 MV/m corresponding to the average beam energy of 4.7 MeV at the exit of the gun. We measured the beam energy with a corrector magnet and cross-checked the results with a phase scan. The uniformity point was found by scanning the front coil (FC) and the back coil (BC) simultaneously such that the resulting field at the cathode surface is compensated [21]. The current values delivering the closest to uniform distribution are 210 A for the FC and for 177 A for the BC corresponding to a solenoid field of 0.153 T. The non-zero background at the edges of the beam on the measurement screen can be explained by the severe dark current which was present during the measurements. For some shots, we measured up to 70 pC dark current, which is distributed over the whole RF pulse in a distribution that increased linearly across the screen. The dark current background and median camera noise outside of the screen edges were subtracted across the results.

Distributions at the neighbouring solenoid settings are illustrated in Fig. 6 for comparison. The presence of the pyramid suggests that these settings correspond to the second (or later) uniformity point. Reduction of the magnetic field decreases the relative size of the pyramid but results in a severe increase of the beam size such that it covers the entire screen and the edges of the beam are hard to detect, making the measurements inconclusive. Increasing the gun gradient would decrease the size of the beam at BTV215. The systematic setup and solenoid scans for different laser spot sizes were rather limited and are to be studied in further experiments with the aim to locate the first and second uniformity points at BTV215 within a single parameter scan.

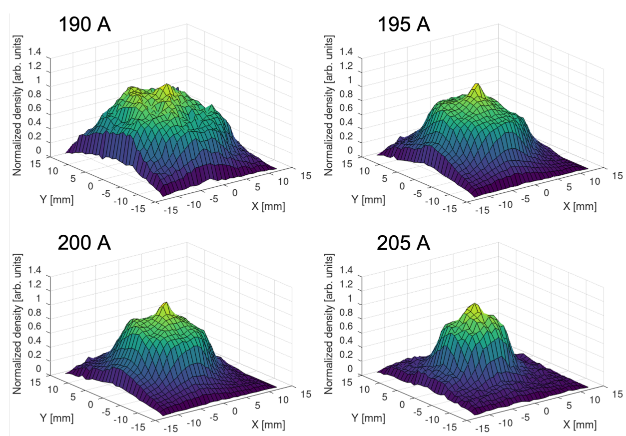

Figure 6: Experimentally measured particle distributions at BTV215 for different current settings in the FC: 190 A, 195A, 200 A, and 205 A. The BC current was adjusted accordingly to keep the zero magnetic field at the cathode. The corresponding peak solenoid field is varied within 0.14-0.153 T.

CONCLUSION

Generating electron beams with uniform beam profiles using SC forces would be useful in irradiation facilities. This paper shows the first simulations and experimental analysis of this technique at CLEAR. The simulations suggest that it should be possible to see both uniformity points using the present CLEAR setup. The initial experimental results appear to be close to the second uniformity point. However, these results are only preliminary and a further, more systematic experimental study should be undertaken in order to demonstrate both uniformity points.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL119

REFERENCES

[1] CERN Facilities DB https://irradiation-facilities.web.cern.ch/

[2] N. Charitonidis *et al.*, "Radiological assessment of the Collimator Materials tests at HiRadMat in 2012", CERN, Geneva, 2012. https://infoscience.epfl.ch/record/178219

[3] M. Tali *et al.*, "Mechanisms of Electron-Induced Single-Event Upsets in Medical and Experimental Linacs," *IEEE Trans. Nucl. Sci.*, vol. 65, no. 8, pp. 1715–1723, Aug. 2018.

[4] M. Tali *et al.*, "Mechanisms of Electron-Induced Single-Event Latchup," *IEEE Trans. on Nucl. Sci.*, vol. 66, no. 1, pp. 437–443, Jan. 2019.

[5] J. Bernhard *et al.*, "CERN Proton Synchrotron East Area Facility: Upgrades and renovation during Long Shutdown 2," CERN, Geneva, Switzerland, Rep. CERN-2021-004, Dec. 2021. doi:10.23731/CYRM-2021-004

[6] R. Corsini, L. A. Dyks, W. Farabolini, A. Gilardi, P. Korysko, and K. N. Sjobak, "Status of VHEE Radiotherapy Related Studies at the CLEAR User Facility at CERN", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2704–2707. doi:10.18429/JACoW-IPAC2021-WEPAB044

[7] V. Rieker, J. J. Bateman, R. Corsini, L. A. Dyks, W. Farabolini, and P. Korysko, "VHEE High Dose Rate Dosimetry Studies in CLEAR", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 3026–3029. doi:10.18429/JACoW-IPAC2022-THPOMS031

[8] D. Gamba *et al.*, "The CLEAR user facility at CERN," *Nucl. Instrum. Meth. Phys. Res. A*, Dec. 2017.

[9] R. Corsini *et al.*, "First Experiments at the CLEAR User Facility", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4066–4069. doi:10.18429/JACoW-IPAC2018-THPMF014

[10] L. Serafini, "The short bunch blow-out regime in RF photoinjectors," in *Proc. Workshop on single pass, high gain FELs starting from noise, aiming at coherent x-rays*, Garda Lake, Italy, 1997. doi:10.1063/1.54425

[11] J.B. Rosenzweig *et al.*, "Optimum Beam Creation In Photoinjectors Using Space-Charge Expansion", in *Proc. FEL'06*, Berlin, Germany, Aug.-Sep. 2006, paper THPPH070, pp. 752–755.

[12] M. Khojoyan *et al.*, "Beam Dynamics Optimization for the High Brightness PITZ Photo Injector Using 3D Ellipsoidal Cathode Laser Pulses", in *Proc. FEL'13*, New York, NY, USA, Aug. 2013, paper TUPSO36, pp. 298–302.

[13] L.A. Dyks *et al.*, "Generation of Transversely Uniform Bunches from a Gaussian Laser Spot in a Photoinjector for Irradiation Experiments", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2483–2486. doi:10.18429/JACoW-IPAC2022-THPOST019

[14] L.A. Dyks, "Studies for upgrading and optimising the CLEAR beamline, and generating uniform electron-beam profiles for irradiation experiments", Ph. D thesis, University of Oxford, 2022, https://ora.ox.ac.uk/objects/uuid:43d90b95-bcf5-4b20-ac27-6c6e47ce9c0c

[15] J. Brossard, M. Desmons, B. M. Mercier, C. P. Prevost, and R. Roux, "Construction of the Probe Beam Photo-injector of CTF3", in *Proc. EPAC'06*, Edinburgh, UK, Jun. 2006, paper MOPLS114, pp. 828–830.

[16] E. Granados *et al*, "Capabilities and performance of the CLEAR facility photo-injector laser". Rep. CERN-OPEN-2020-002, Sep. 2019. https://cds.cern.ch/record/2705786

[17] R. Belbeoch *et al.*, "Rapport d'etudes sur le projet des linacs injecteur de LEP (LIL)", Rep. LAL-PI-82-01-T, 1982. https://cds.cern.ch/record/136636

[18] A. Latina, "Update of the Tracking Code RF-Track", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 4180–4182. doi:10.18429/JACoW-IPAC2021-THPAB203

[19] A. Latina, RF-Track Reference Manual https://zenodo.org/record/3887085

[20] P.H. Westfall, "Kurtosis as Peakedness, 1905–2014. R.I.P.", *The American Statistician*, vol. 68 no. 3, pp. 191-195, 2014, doi:10.1080/00031305.2014.917055

[21] H. Purwar, C. Bruni, A. Gamelin, H. Guler, L. Garolfi, C. Vallerand, A. Gonnin and B. Mercier, "Optimization of CLEAR beam optics: preliminary experimental simulation results," *Internal report*, Oct. 2017 (available upon request).