PERFORMANCE OF THE TU/E 2.6 CELL RF-PHOTOGUN IN THE 'PANCAKE' REGIME

S.B. van der Geer*, M.J. de Loos, O.J. Luiten, G.J.H. Brussaard, M.J. van der Wiel
Eindhoven University of Technology, The Netherlands
G. Pöplau, Rostock University, Germany

Abstract

Controlled plasma acceleration requires electron bunches to be injected into the plasma channel with a length of a fraction of the plasma wavelength. Taking into account parameters of a realistic plasma channel, this sets the requirements for the bunch at the entrance of the channel to a transverse size of about 30 micrometer and a duration in the order of 100 femtoseconds. The production of such bunches requires state-of-the art accelerator technology. In this paper we present GPT simulation results of the 2.6 cell rf-photogun currently in operation at Eindhoven University of Technology. Calculations are presented in the low-charge short-pulse regime with emphasis on bunch lengthening due to path length differences and space-charge effects. The numerical challenge is tackled using high-precision field-maps and the newly developed 3D mesh-based space-charge model of GPT. It is shown that with the present injector bunches can be produced that are suitable for injection into the planned experiment for controlled acceleration in a plasma-wakefield accelerator.

INTRODUCTION

Controlled plasma wakefield acceleration holds the promise of acceleration gradients of well over 1 GV/m [1], surpassing state-of-the-art rf-technologies by at least one and possibly several orders of magnitude. These fields have been proven experimentally, but so far only resulting in an accelerated bunch with an unacceptably large energy spread. The most straightforward option to reduce this energy spread is to inject a bunch with a length much shorter than the plasma wavelength. For realistic plasma channel parameters [2], this means that we require a bunch with a transverse size of about 30 micrometer and a duration in the order of 100 femtoseconds.

The 2.6 cell rf-photogun currently in operation at Eindhoven University of Technology [3] has been designed as a booster for a 2 MeV semi-DC accelerator with a field of 1 GV/m [4, 5]. Despite the advantages of a combined approach, the technological difficulty of operating both DC and RF makes it worthwhile to investigate both schemes as independent injectors for the purpose of controlled plasma acceleration. In this paper we present detailed simulation results of the General Particle Tracer (GPT) code [6, 7] of the existing TU/e gun, operated without the pre-accelerator, in the low-charge short-pulse regime.

* sgeer@pulsar.nl

SET-UP

The set-up under investigation consists of the existing 2.6 cell TU/e rf-cavity and a number of focusing elements. A solenoid is used to focus the bunch tightly into the plasma channel, but the simulation does not include the plasma acceleration process itself. The layout is shown schematically in Figure 1.

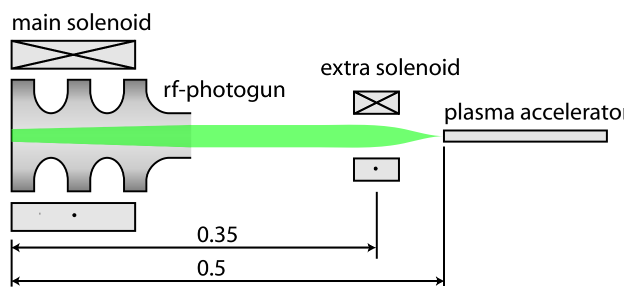

Figure 1: Schematic layout of the set-up.

Rf-cavity

The TU/e 2.6 cell rf-photogun [3, 4, 5] is a state-of-the-art S-band standing wave cavity with axial power coupler. A total of 10 MW dissipated power in the rf-cavity results in a maximum on-axis acceleration field of 105 MV/m, as shown in Figure 2. A higher field is obviously desirable, but not easily attainable due to breakdown problems. The rf-phase is set to the maximum output energy of 7.45 MeV, because RF bunch compression is not possible at 3 GHz for a bunch of only 30 micron length.

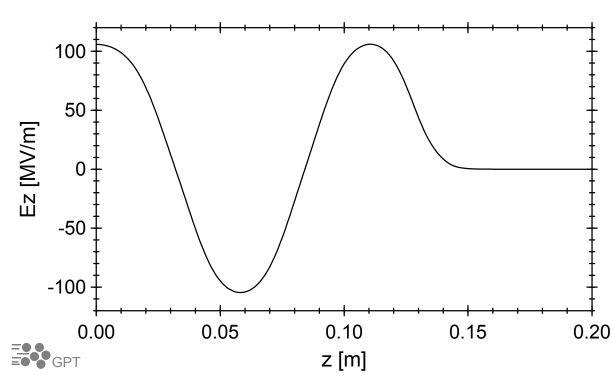

Figure 2: Electric field-profile on–axis.

The GPT tracking simulations use a dense 2D field-map for the rf-cavity to accurately calculate non-linear effects.

Magnetic focusing field

The magnetic focusing field is created by three solenoids. The solenoid around the cavity is set to a peak field of about 0.2 T, required to produce a parallel beam. A small bucking coil is used to zero the field on the cathode plane to maximize the focusing properties of the bunch. The strength 0.7 T for the additional focusing solenoid is chosen such that the bunch goes through a waist at the entrance of the plasma channel. The maximum distance between the additional solenoid and the entrance of the plasma channel is set by the beam radius times the required spot size divided by the emittance. A smaller distance is possible, but experimentally not desirable.

The combined on-axis magnetic field-profile is shown in Figure 3. The optimal strength and shape of the magnetic field is a weak function of bunch charge, but to ease interpretation of the results we chose to use a fixed profile in this paper.

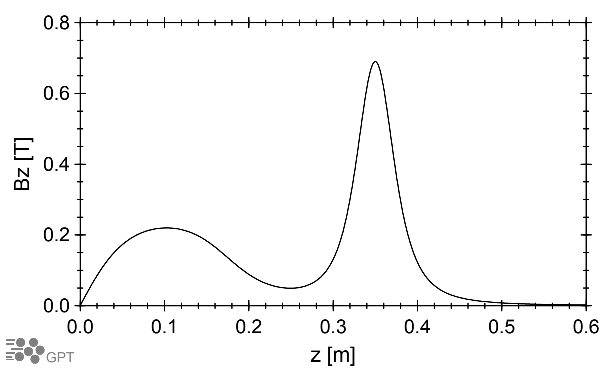

Figure 3: Magnetic field profile on-axis.

Initial particle distribution

The initial temporal particle distribution is chosen to have a 30 fs FWHM gaussian profile, which is the minimum pulse duration achievable with the present laser system. The transverse initial profile is a uniform (flat-top) distribution with a radius of 1.0 mm and initial thermal emittance of 0.45 μm. The initial radius is the best compromise for a charge of 10 pC. A larger radius obviously reduces space-charge effects, but increases path-length differences induced by the rf (de)focusing irises and the focusing elements. For a target bunch-length of 100 fs FWHM, a radius of 1 mm already results in an additional lengthening of over 50 fs in the present set-up.

GPT SIMULATION RESULTS

The General Particle Tracer (GPT) code [6, 7] is a well-established simulation tool for the design of charged particle accelerators and beam lines. GPT is based on full 3D particle tracking techniques, providing a solid basis for the study of all 3D and non-linear effects of charged particles dynamics in electromagnetic fields. An embedded fifth order Runge-Kutta driver with adaptive stepsize control ensures accuracy while computation time is kept to a minimum. GPT provides various space-charge models, ranging from 1D interaction to full 3D point-to-point calculations. Version 2.7 of the GPT code, used for all simulation results presented in this section, incorporates a 3D mesh-based space-charge model tailor made for bunches with extreme aspect-ratios [8].

Transverse dynamics

Figure 4 shows the evolution of the FWHM transverse bunch size as function of longitudinal position for various bunch charges. Because the solenoid strengths are not changed as function of charge, the longitudinal position of the focal plane varies slightly. From the detailed (bottom) plot it is clear that it is possible to focus down to 30 μm for the presented charges.

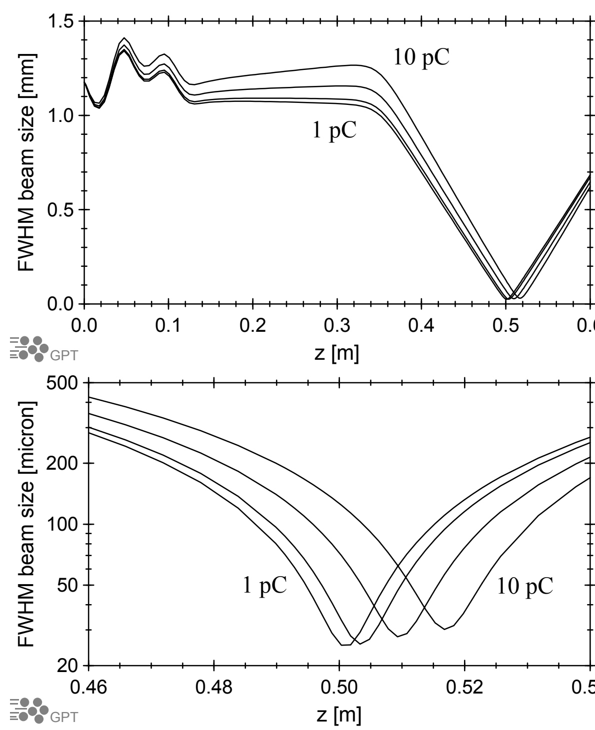

Figure 4: Transverse FWHM beam size as function of position for 1, 2, 5 and 10 pC charge. The bottom plot is a detail of the focal area on a logarithmic scale.

The RMS emittance in the focal plane is not a strong function of charge and in all cases below 0.6 μm. This is compatible with the most demanding applications such as SASE-FELs and colliders [9].

Longitudinal dynamics

Arguably the most interesting result of the simulation is the bunch length calculation, as shown in Figure 5. The bunch with 5 pC total charge has a length of about

100 fs FWHM in the focal plane at z=0.5 m, marginally meeting the target parameters.

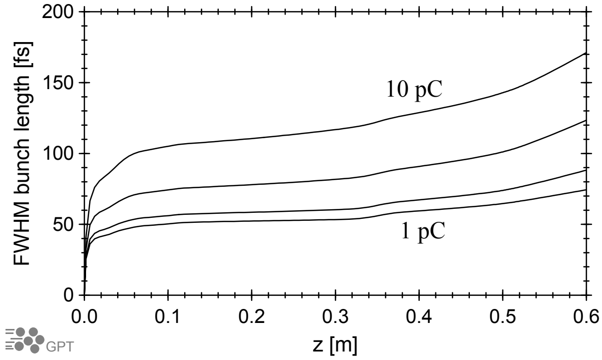

Figure 5: FWHM bunch length as function of position for a total charge of 1, 2, 5 and 10 pC.

The system is designed such that path-length differences and space-charge effects are well balanced. Increasing the initial radius will decrease undesired space-charge effects at the cost of an increase in path-length differences, and vice versa. Path-length differences during the focus into the plasma channel have a significant contribution to the final bunch-length. Obviously, a more shallow focus would reduce this contribution, but unfortunately this is not an option given the criteria for the transverse spot-size in the focal plane.

Figure 6 shows the evolution of the RMS energy spread. Space-charge effects in the region just before the plasma accelerator cause a sharp rise in energy spread. Fortunately, the additional energy spread has little effect on the final bunch-length, as there is not enough time to evolve in a positional spread due to the sharp focus.

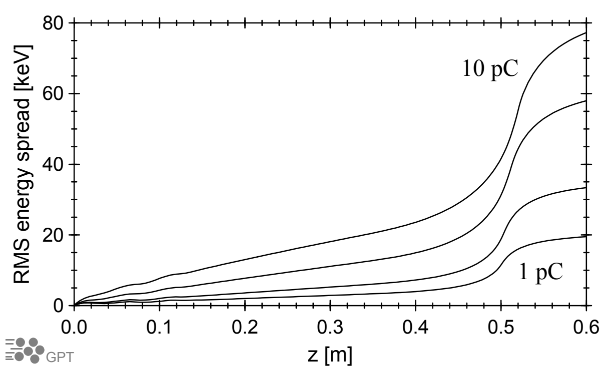

Figure 6: RMS energy spread as function of position for 1, 2, 5 and 10 pC.

Detailed phase-space in focus for 10 pC bunch

Detailed longitudinal and transverse phase-space projections in the focal plane at the entrance of the plasma-channel are shown in Figure 7 for a 10 pC bunch. The results are obtained with 500,000 sample particles and the mesh-based space-charge model of GPT [8].

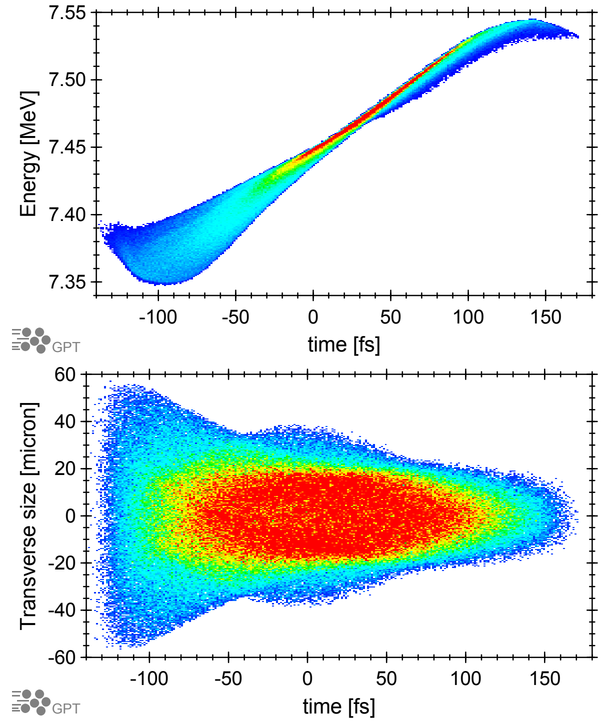

Figure 7: Detailed phase-space plots in the focal plane for a 10 pC bunch. The top figure shows the energy distribution as function of longitudinal position and the bottom figure shows the transverse distribution.

CONCLUSION

The existing 2.6 cell rf-photogun of Eindhoven University is a suitable injector for a controlled plasma wakefield experiment if the charge is lowered to 5 pC. In that case, detailed GPT simulations predict a transverse FWHM size of 30 micrometer with a FWHM bunch length of 100 femtoseconds in a realistic set-up.

REFERENCES

[1] E. Esarey et al., *IEEE Trans. Plasma Sci.*, Vol. 24, p. 252 (1996).

[2] A. Butler, D.J. Spence, and S.M. Hooker, *Phys. Rev. Lett.* **89**, 185003 (2002).

[3] F.B. Kiewiet, Ph.D. Thesis, Eindhoven University of Technology, 2003.

[4] M.J. de Loos et al., *Proc. European Part. Accel. Conf. 2002, Paris, France*, p. 1831.

[5] S.B. van der Geer and M.J. de Loos, Ph.D. Thesis, Eindhoven University of Technology, 2001.

[6] S.B. van der Geer, M.J. de Loos, *Proc. European Part. Accel. Conf. 1998, Stockholm, Sweden*, p. 1245.

[7] GPT User Manual, Pulsar Physics, Soest, The Netherlands, http://www.pulsar.nl.

[8] G. Pöplau et al., *IEEE Trans. Magn.* **40**, 714 (2004).

[9] M.J. van der Wiel, in *The Physics of High-brightness Beams*, edited by J. Rosenzweig and L. Serafini, p. 3, World Scientific (Singapore), 2000.