A DC/RF GUN FOR GENERATING ULTRA-SHORT HIGH-BRIGHTNESS ELECTRON BUNCHES*

F.B. KIEWIET, O.J. LUITEN, G.J.H. BRUSSAARD, J.I.M. BOTMAN, and M.J. VAN DER WIEL,
Department of Applied Physics, Eindhoven University of Technology, the Netherlands

Abstract

We are developing a source for ultra-short, high-brightness electron bunches. Our aim is a 100 pC, 100 fs (i.e. 1 kA), 10 MeV electron bunch with a normalized emittance better than 1 π mm mrad, which is suitable for plasma wakefield acceleration and (after further acceleration) as input for SASE-FELs. Our approach is to create a short bunch and keep it short during acceleration, thus avoiding the potential problems of magnetic compression afterwards. A mode-locked Ti:Sapphire laser will be used to photo-emit the electrons from a metal cathode. This bunch has to be accelerated to relativistic velocities within the shortest possible distance to avoid blowing up the bunch due to space charge. This will be accomplished in a novel two-step acceleration scheme: pulsed DC acceleration to 2 MeV in a field of 1 GV/m, followed by RF acceleration to 10 MeV in a 100 MV/m, $2\frac{1}{2}$ cell, S-band standing wave cavity.

1 INTRODUCTION

Until now the main route to ultra-short, i.e. sub-ps, bunches has been to start with rather long bunches and use magnetic compression after acceleration to higher energies. The main advantage of this method is that space-charge induced emittance growth, which is particularly severe at low energies, is avoided. However, it is not yet clear what the effect of coherent synchrotron radiation and space charge forces in bending magnets is on the emittance [1, 2]. An alternative to magnetic compression is to start with short bunches and keep them short during acceleration, thus avoiding the need of compression. Very short laser pulses can be used to make the short bunches. They have to be accelerated to high energies within very short distances both to keep them short and to limit the space charge induced emittance growth. For the above mentioned beam characteristics acceleration fields of at least 500 MV/m are required [3], far beyond the maximum attainable fields in state-of-the-art RF accelerators. However, studies on vacuum breakdown indicate that metals can withstand voltage gradients of a few GV/m if the duration of the field is in the order of ns [4]. Measurements at BNL [5] confirmed that it is possible to apply a field of 1.5 GV/m during 2 ns. The highest voltages that nowadays can be switched on this time scale are in the order of a MV. This is not enough to freeze the electron bunch so a second acceleration stage is needed to boost the energy to the 10 MeV level. As most of the beam blow-up will occur at low velocities the requirements on the acceleration field in this second stage are less severe. Therefore it can be a state-of-the-art high field RF booster capable of maintaining the high brightness of the bunch.

* Work supported by the Foundation for Fundamental Research on Matter

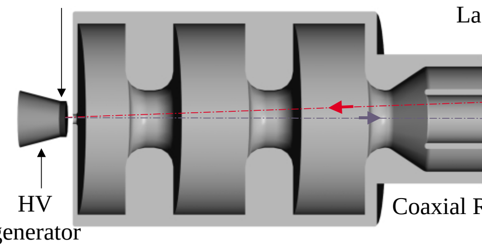

Figure 1: Schematic of the DC/RF gun

At Eindhoven University of Technology a project has been started to build such a combined DC/RF accelerator. The goal of this project is to make electron bunches with a brightness which is at least an order of magnitude higher than achievable with current state-of-the-art RF electron guns. This paper describes the progress on the experimental setup. In particular the design and the experimental characterization of the RF cavity will be presented.

2 ACCELERATOR SETUP

The experimental setup is schematically depicted in figure 1. The HV generator applies a 2 MV, 1 ns flat top voltage pulse between the photocathode and the back plane of the RF cavity. The gap between the cavity and the cathode is 2 mm, creating a field of 1 GV/m. A short laser pulse, synchronized with the HV generator, photo-emits the electrons from the cathode. Since the transition time for the 2 mm gap ($<$ 10 ps) is much shorter than the HV pulse length, the electrons are essentially accelerated in a DC field. After having been accelerated to 2 MeV, the electron bunch enters the RF cavity through a small hole and is accelerated further to a final energy of 10 MeV.

2.1 Photocathode

Ideally the photocathode should have femtosecond response time and low intrinsic emittance. Although semiconductor based photocathodes like $CsTe_2$ have a high quantum efficiency and a low work function they will almost certainly be not fast enough. We therefore opted for a metal cathode. However, the high work function of metals requires UV wavelengths (i.e. the work function of copper is 4.65 eV requiring 267 nm photons) which is accomplished by taking the third harmonic of the 800 nm Ti:Sapphire laser. The photo-emission process may be facilitated by the Schottky effect associated with the 1 GV/m field. Estimates indicate a reduction of the work function by 2 eV [6]. So the second harmonic (400 nm) can probably be used. In first instance a copper cathode will be tried. With a conservative estimate for the quantum efficiency of 10^{-5} [5] and without the Schottky effect 50 μJ of laser energy (266 nm) should be more than sufficient to photo-emit 100 pC of charge.

2.2 Ti:Sapphire laser

The laser illuminating the photocathode is a mode locked Ti:Sapphire laser synchronized to the RF oscillator and the HV generator (rms jitter < 50 fs, to be published). It operates at a wavelength of 800 nm and has an output energy of 1 mJ in 25 fs [Femtolasers GmbH, Vienna]. Second and third harmonic generation is used to convert to 400 nm (300 μJ) and 266 nm (90 μJ).

2.3 HV generator

The HV generator, being built by the Efremov institute in St. Petersburg, Russia, will deliver a 2 MV voltage pulse with 150 ps risetime and 150 ps falltime and an adjustable flat top of 0.3–1 ns. It consists of three main parts: a resonant transformer (Tesla coil), which converts the primary voltage of 50 kV to 2 MV, a laser-triggered spark gap to synchronize the HV generator with the photo-emission laser, and a coaxial pulse shaping line. To synchronize the HV pulser and the laser it is essential that the jitter on the laser triggered spark gap is less than 0.5 ns.

2.4 RF cavity

The RF accelerator is a $2\frac{1}{2}$ cell disc-loaded S-band standing wave structure operating in π-mode. It is based on the widely used BNL $1\frac{1}{2}$ cell structure [7], with an additional cell to reach a final energy of 10 Mev. To focus the electrons a solenoid with a maximum field of 0.5 T will be used. A bucking coil behind the cathode cancels the field on the cathode. RF power, delivered by a 10 MW klystron (Thomson, TH2157), is coaxially coupled to the cavity through a so-called door-knob coupler (figure 2). Its design is based on DESY's L-band TTF FEL gun coupler [8]. The door-knob transforms the TE_{10} mode in the rectangular wave guide to the TEM mode in the rigid coax. Matching of the rectangular wave guide to the coax is adjusted with a movable short. Optimal matching of the coax to the cavity has been achieved by carefully designing the entrance iris. In addition, the matching can be fine-tuned by slightly changing the length of the inner conductor. Because the RF power is coupled coaxially instead of sideways the cavity has complete cylindrical symmetry. This has a number of advantages. Firstly, it enables extremely high design precision (resonance frequencies, field profile and coupling), since 2d-codes like Superfish can be used. Secondly, the emittance compensation and focusing coil can be placed in the optimum position not hindered by the RF coupling. Finally, the possible emittance growth due to multipole components in the E_z field is avoided [9].

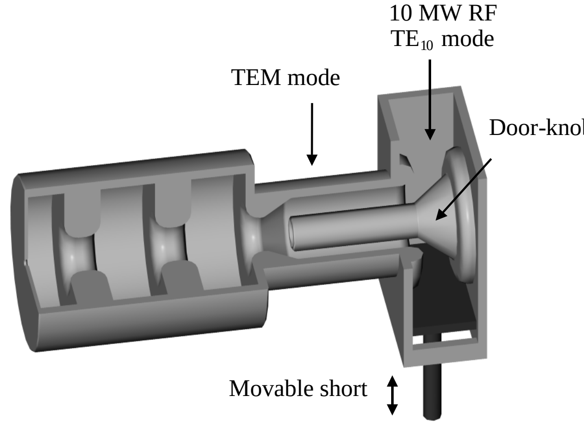

Figure 2: Door-knob transition

3 EXPERIMENTAL RESULTS

Superfish was used to design the $2\frac{1}{2}$ cell cavity. To preserve cylindrical symmetry it was decided not to use tuning plungers. Since there is no way to alter the frequency or optimize the field profile afterwards the cavity had to be made with very tight tolerances. It was made out of high purity OFHC copper (Outokumpu, ASTM C10100) on a single diamond turning machine with an accuracy of 1 μm. The three cells were made separately and brazed. Figure 3 shows a photograph of the middle cell. The holes in the circumference are used to clamp the cells before brazing. The cavity has been characterized with an HP8753c network analyzer by measuring the reflected signal (*S11*) as function of frequency, as shown in figure 4. Fine-tuning of the length of the inner conductor has been used to obtain critical coupling with less than -30 dB reflection. As expected

Figure 3: Photograph of middle cell

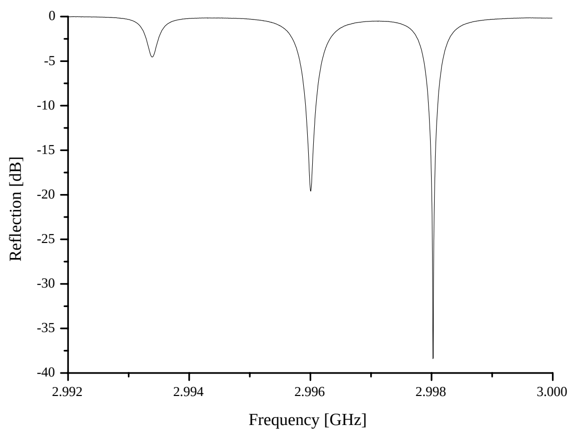

Figure 4: Resonance frequencies of the cavity

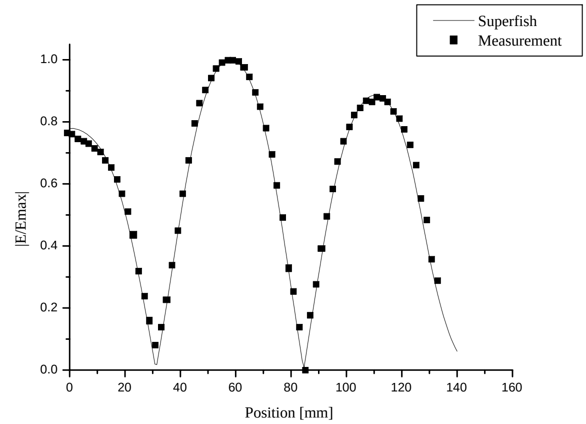

Figure 5: Measurement and Superfish simulation of the on axis field profile in the cavity

the cavity has three, nicely separated, modes, corresponding to the 0-mode, an intermediate mode, and the π-mode. The Superfish code predicted a resonance frequency for the π-mode of 2998.5 MHz, in excellent agreement with the measured frequency, 2998.03 MHz (less than 0.02% error). A Lorentzian profile fitted to the π-mode resonance curve yielded a loaded Q of 6540 ± 50 corresponding to an unloaded Q of 13080 ± 100. To match the resonant frequency of the cavity to the center frequency of the klystron (2998.5 MHz) the cavity has to be operated at a temperature of approximately 30 °C. Table 1 summarizes the measured and calculated cavity characteristics. Field profile measurements have been done with the bead-on-wire method [10] using a 4 mm dielectric bead. The measured and calculated field profiles, clearly π-mode, are plotted in figure 5. The height of the maximum in the first $\frac{1}{2}$ cell is 78% compared to 100% and 88% in the second and third cell. A Superfish simulation with the measured dimensions gives a good fit. Originally the cavity was designed with a better field balance (90%, 100% 100%). During machining, however, a systematic error of 4 μm was made in the diameter of the first half cell which caused the additional field imbalance . This will be improved in the next version.

Table 1: Measured and calculated cavity parameters (In air at 20 °C)

Cavity Parameters	Superfish	Measured
Quality factor	13600	13080
Resonances: [MHz]		
π-mode	2998.5	2998.03
Intermediate mode	2996.4	2996.01
0-mode	2993.8	2993.39
Transition Time factor	0.78	
Eff. shunt impedance	41 MΩ/m	
Coupling	VSWR $<$1.05	VSWR $<$1.05

4 CONCLUSIONS

A combined DC/RF gun promises to be a simple, low cost and (almost) table top accelerator for generating high brightness electron bunches. As a first step a 3 GHz RF gun with full cylindrical symmetry has been designed and built. The resonance frequencies and the on-axis field have been measured and are in excellent agreement with Superfish simulations. First acceleration experiments are underway.

5 REFERENCES

[1] B. Carlsten and T. Raubenheimer, “Emittance growth of bunched beams in bends,” *Phys. Rev.*, vol. E51:1453, 1995.

[2] Y. Derbenev, J. Rossbach, E. Saldin, and V. Shiltsev, “Microbunch radiative tail-head interaction,” *(DESY) TESLA-FEL 95-05*, 1995.

[3] M. de Loos, S. van der Geer, J. Botman, O. Luiten, and M. van der Wiel, “Production of ultra-short, high charge, low emittance electron bunches using a 1 GV/m DC gun,” *Proc. of the 1999 Part. Accel, Conf.*, p. 3266, 1999.

[4] G. Mesyats and D. Proskurovsky, “Pulsed electrical discharge in vacuum,” *Springler-verlag Berlin Heidelberg*, 1989.

[5] K. Batchelor *et al.*, “A high current, high gradient, laser excited, pulsed electron gun,” *Proc. Europ. Part. Acc. Conf.*, pp. 791–793, 1998.

[6] T. Srinivasan-Rao, J. Fisher, and T. Tsang *J. Opt. Soc. Am.*, vol. B8, p. 294, 1991.

[7] K. Batchelor *et al.*, “Development of a high brightness electron gun for the accelerator test facility at Brookhaven National Laboratory,” *Proc. of the Europ. Part. Acc. Conf.*, pp. 954–957, 1988.

[8] K. Floettmann DESY TTF FEL, private communication.

[9] D. Palmer *et al.*, “Microwave measurements of the BNL/SLAC/UCLA 1.6 cell photocathode rf gun,” *Proc. of 1993 Part. Accel. Conf.*, 1995.

[10] L. Maier and J. Slater, “Field strength measurements in resonant cavities,” *J. Appl. Phys.*, vol. 23, p. 68, 1952.