The Eindhoven High-Brightness Electron Programme

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Abstract

The Eindhoven High-Brightness programme is aimed at producing ultra-short intense electron bunches from compact accelerators. The RF electron gun is capable of producing 100 fs electron bunches at 7.5 MeV and 10 pC bunch charge. The DC/RF hybrid gun under development will produce bunches < 75 fs at 9.5 MeV, 10 pC. These bunches are suitable for injection into a Laser Wakefield Accelerator (LWA). Injection of electron bunches from the RF photogun into a 1 cm capillary discharge channel with $2\times10^{18}\,\text{cm}^{-3}$ electron density and a 2 TW drive laser allows acceleration of the electrons to $50\pm20\,\text{MeV}$. This combination of hardware will be employed to demonstrate controlled laser wakefield acceleration. If the plasma channel can be adapted to work at lower pressures, around $2\times10^{17}\,\text{cm}^{-3}$, a 5 cm channel, in combination with the DC/RF gun will produce bunches with energies of $50\pm5\,\text{MeV}$.

Introduction

The overall research theme of the group ‘Physics and Applications of Accelerators’ at Eindhoven University of Technology is the *generation of ultra-high brightness electron bunches from table-top accelerators* and their application in generating short-pulse coherent radiation. Within that framework, Laser Wakefield Acceleration (LWA) holds the promise of the ultimate compact accelerator, capable of accelerating electron bunches to hundreds of MeV in only a few cm. The most successful concept to date is the self modulated or forced wakefield acceleration [1], in which a 10-100 TW laser is focused into a gas-jet. Electrons with energies up to 200 MeV have been detected, but since injection of electrons into the wakefield relies on instabilities, the distribution is Maxwellian-like. To obtain a better energy distribution we will use a high-brightness electron gun to inject pre-accelerated electrons into a plasma wave guide. The main challenge in this concept is to accelerate electrons to 5-10 MeV in a bunch, shorter than the plasma wavelength (order 100 fs for plasma densities of 10^{17}-10^{18} cm^{-3}). In this note, we will discuss the possibilities to generate such an electron bunch with the existing RF photogun and the DC-RF gun under development in our group.

Femtosecond Photocathode Electron Guns

In most conventional schemes aimed at producing ultra-short electron bunches a relatively long (10 ps) electron bunch is compressed after acceleration. In order to avoid collective effects, such as coherent synchrotron radiation and to keep the electron gun compact, we have chosen a different strategy, which avoids the need of magnetic compression. In our scheme, a 30 fs UV laser pulse is used to create an electron bunch at a metal (copper) photocathode. To minimize the effects of space charge the challenge now becomes the acceleration of this bunch to relativistic energies over as short a distance as possible. For this purpose an improved RF-photogun was designed and realized which allows field strengths up to 120 MV/m, slightly higher than existing RF guns. In a later stage, a 2 MV, 1 ns pulse will be applied to the photocathode, which is place 2 mm in front of the RF accelerator. The electrons will initially be accelerated in a 1 GV/m field, further limiting space charge effects.

The Eindhoven RF photogun is a 2½-cell, 3 GHz resonant cavity (see figure 1). One of the unique features of this gun is the absence of tuning capabilities of the individual cells. The accelerator was designed and manufactured in-house to 1 µm precision, to balance the cells. Overall tuning is possible by controlling the temperature of the whole cavity. This design,

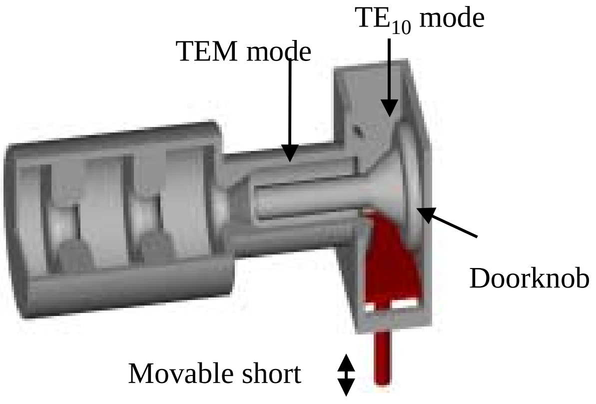


***figure 1**: The 3 GHzRF gun*

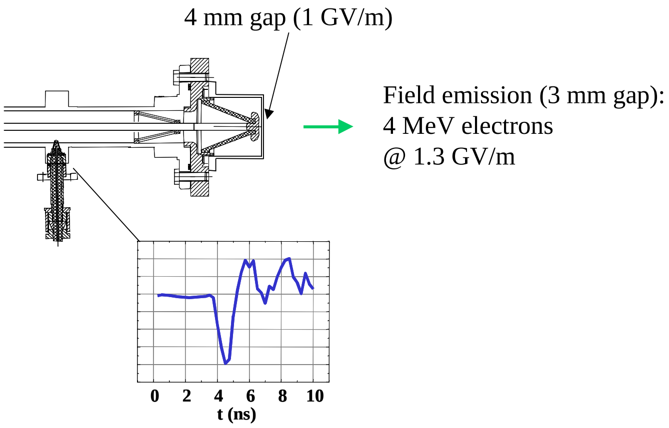
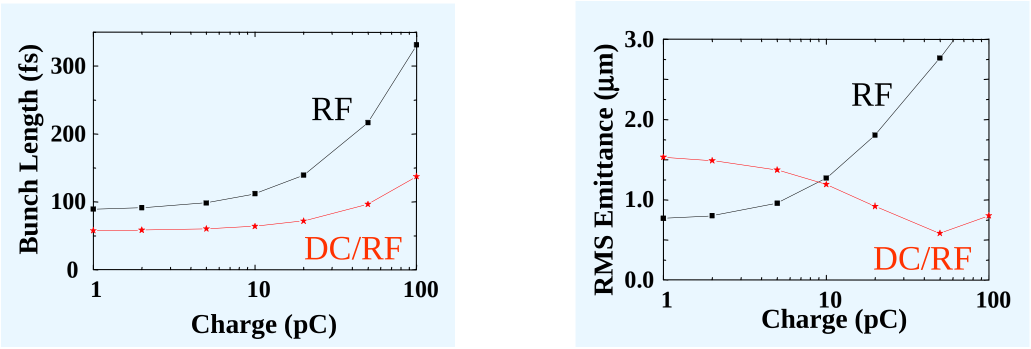


***figure 2**: The pulsed DC gun*



(a) (b)

***figure 3**: Bunch length (a) and Emittance (b) as a function of bunch charge for RF and DC-RF*

together with an adapted version of the coaxial coupler (originally developed at DESY) provides a perfectly cylindrically symmetrical field. The RF gun is driven by a 10 MW klystron allowing acceleration to 7.5 MeV. The properties of the electron bunch after acceleration were simulated using the GPT code [2]. The results are shown in figure 3.

To be able to inject electrons into the proper phase of a laser wakefield, synchronization of the electron bunch with the drive laser is of prime importance. We have developed a synchronization scheme in which the 75 MHz Ti:Sapphire oscillator acts as the master clock for the RF and provides the seed for a terawatt amplifier. With this scheme we were able to reduce the phase jitter between the laser and the RF to 0.4° RMS, which results in 80 fs jitter after the accelerator [3]. With a slightly different cavity (this cavity was designed to be used after the 2 MV DC pulse), and an improvement of the klystron stability from 0.1% to 0.05%, the jitter can be reduced to 10 fs.

The DC pulser consists of a Tesla transformer, followed by a pulse-forming line (PFL). The transformer delivers a 2.5 MV pulse of approximately 100 ns duration, which is transferred to a coaxial, pulse forming line through a laser triggered spark gap. In the PFL, the pulse is shortened to 1 ns (see figure 2). The line ends in a simple diode configuration with a 3 mm gap. Field emitted electrons were measured with energies up to 4 MeV. Incoupling of the UV laser is being installed and photoemission measurements will be possible in the near future. Results of simulations of the electrons after acceleration in the DC-RF hybrid gun are shown in figure 3.

Controlled Laser Wakefield Acceleration

The most promising plasma channel for controlled wakefield acceleration is the capillary discharge channel developed by Butler et al. [4]. They have shown guiding of high power ($>10^{17}$ W/cm^2) over distances up to 5 cm. An identical plasma channel is available to us through the FOM Institute for Plasma Physics ‘Rijnhuizen’, The Netherlands, which is a partner in our LWA program. The best results were obtained by Hooker et al. with on-axis electron densities around 2×10^{18} cm^{-3}. The matched spot-size for guiding of the drive laser in that case is 35-40 μm. We plan to use a *modest* 2 TW laser to drive the wakefield (0.4 TW is now available, and the upgrade to 2 TW is underway).

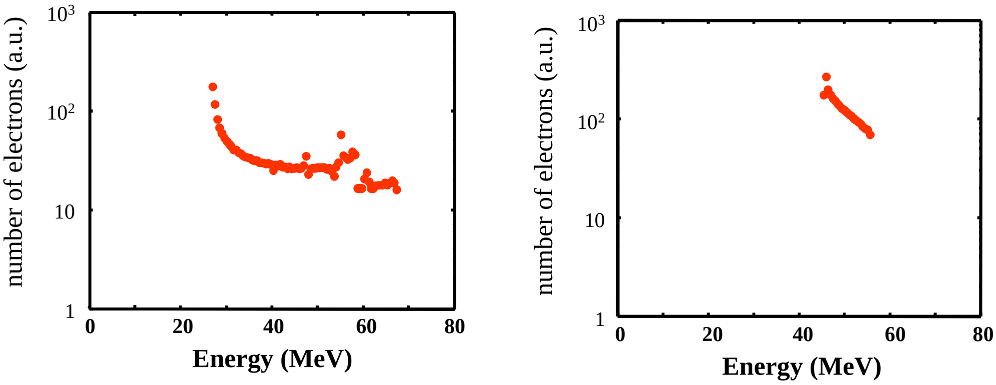


***figure 4**: 1D simulations of the Electron Energy Distribution after LWA, with available components (a) and short-term improvements (b).*

To estimate the energy distribution of the electrons after acceleration in LWA we have performed 1D calculations (the parameters are summarized in Table I). Figure 4(a) shows the results using the components that are currently available to us, i.e. the RF photogun and a 1 cm long plasma channel at 2×10^{18} cm^{-3}. In this plasma the wavelength ($\lambda_p = 24$ µm, or 80 fs) is still shorter than the electron bunches produced by the RF photogun. Therefore the electrons are injected into all phases of the plasma wave and the energy distribution is more or less flat between 30 and 70 MeV. This is already a significant improvement compared with Self-Modulated LWA, because, although the injection *phase* of the electrons cannot be controlled, the acceleration *distance* is essentially equal for the entire electron bunch.

To control the injection phase of the electron bunch we need to reduce the bunch length and/or increase the plasma wavelength. Both developments are in progress. With the DC-RF hybrid gun the bunch length can be reduced to less than 75 fs at 10 pC bunch charge (see figure 3). If the plasma can be adapted to work at lower pressures, the plasma density could be decreased to (a few times) 10^{17} cm^{-3}. Results of the 1D calculations for a plasma channel of 5 cm are shown in figure 4(b). These improvements would produce electron energies of 50 ± 5 MeV.

Table I: Parameters for controlled laser wakefield acceleration

	Available	Foreseeable improvements
High Brightness Injector	**100 fs, 10 pC 7.5 MeV**	**75 fs, 10 pC 9.5 MeV**
Plasma Waveguide	**2×10^{18} cm^{-3}**	**2×10^{17} cm^{-3}**
Drive Laser	**2 TW**	**2 TW**
Expected Results	**50±20 MeV**	**50±5 MeV**

Conclusions

Controlled Laser Wakefield Acceleration is feasible using the state-of-the-art 2½-cell RF gun. Injection in a 1 cm capillary discharge channel with $2\times10^{18}\,\mathrm{cm}^{-3}$ electron density and a 2 TW drive laser allows acceleration of the electrons to $50\pm20\,\mathrm{MeV}$. This combination of hardware will be employed to demonstrate controlled laser wakefield acceleration at Eindhoven University.

Development of a DC-RF hybrid photogun as well as a plasma channel with a lower density ($2\times10^{17}\,\mathrm{cm}^{-3}$) will lead to better energy control ($50\pm5\,\mathrm{MeV}$) in the foreseeable future.

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