

# DESIGN OF THE PRODUCTION AND MEASUREMENT OF ULTRA-SHORT ELECTRON BUNCHES FROM AN S-BAND RF PHOTOINJECTOR

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## Abstract

The Electron Beam Test Facility (EBTF) is planned for installation in late 2012 at Daresbury Laboratory. An S-band RF photoinjector provides ultrashort, low emittance electron bunches up to 6 MeV. A suite of diagnostics has been designed to fully characterise the bunches. A particular focus has been on producing and measuring bunch lengths less than 100 fs. This can be achieved with a multi-cell standing wave S-band transverse deflecting cavity. Operating such a cavity with low energy electrons provides certain challenges which are discussed in this paper with respect to beam dynamic simulations.

## EBTF



Figure 1: The beam diagnostics section of EBTF.

The Electron Beam Test Facility (EBTF) is a 6 MeV electron accelerator designed to provide low emittance, short pulse beams to two user stations [1,2]. It will also act as the front end for the proposed CLARA accelerator [3]. Initially, the beam for EBTF will be delivered by a 2.5 cell S-band normal conducting RF gun (Fig. 2) originally designed for the ALPHA-X project [4].



Figure 2: The ALPHA-X S-band RF gun.

The front end of EBTF (Fig. 1) has been designed as a photoinjector diagnostics suite to fully characterise the bunches in 6D phase space. A variety of YAG screens, slits and pepperpots will be used to characterise the beam transversely. Characterising the beam longitudinally is

more challenging. A dipole and YAG screen can be used as a simple energy spectrometer. Bunch length can be measured by using a transverse deflecting cavity (TDC) to streak the longitudinal position of the particles onto the transverse plane, thus making it viewable on the YAG screen. Furthermore, if the streak is performed in the vertical plane, then passing the beam around the horizontal spectrometer dipole will make the longitudinal phase-space directly viewable on the screen. Combining the TDC with the transverse beam diagnostics will allow time-sliced emittance measurements to be made.

## SHORT BUNCHES

The shortest bunch that can be delivered from the photoinjector is determined by the laser pulse length, cathode response time, and space charge. For EBTF, the laser pulse length has been specified to have a minimum of 40 fs rms with a Gaussian temporal profile. Copper photocathodes have a very fast response time so this has been neglected in the simulations. Space charge effects can be reduced by operating at low bunch charge and by operating at the proper choice laser spot size on the photocathode for each bunch charge.

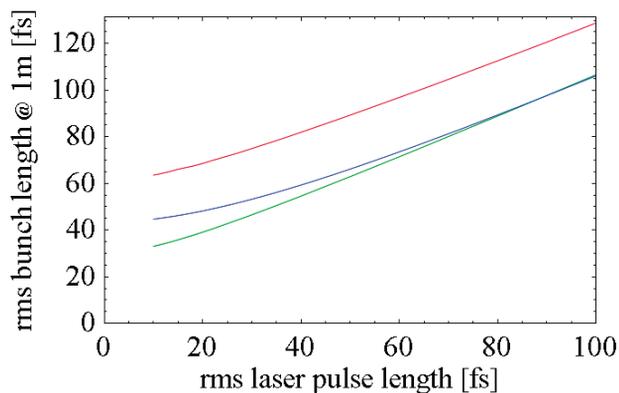


Figure 3: Electron bunch length as a function of laser pulse length for a 1 pC bunch with laser spot diameters of 0.5 mm (red), 1 mm (green), and 2 mm (blue).

The bunch expands due to space charge and also if there is a time-energy chirp from the gun. The phase of the RF gun can be used to control the time-energy correlation of the beam emerging from the gun, but the space charge expansion still occurs. This effect is stronger for a shorter beam as can be seen in Fig. 3. Simulations performed using GPT, use a 1 pC bunch as an example, in order to minimise the space charge effect, with a 40 fs rms laser pulse length and 1 mm diameter.

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### TRANSVERSE DEFLECTING CAVITY

An RF cavity excited with a transverse dipole mode will give a time-varying transverse kick to a bunch passing through it if it is set at the correct phase. Such a cavity can be seen in Fig. 4, see [5] for the design details. This cavity is a standing wave structure comprising of 9-cells to maximise the total transverse voltage applied to the beam, allowing it to be re-used for CLARA in the low energy regime. The frequency of the dipole mode,  $f$ , has been chosen to be equal to the operational frequency of the gun. The other transverse mode has been suppressed by coupling slots in the iris walls.

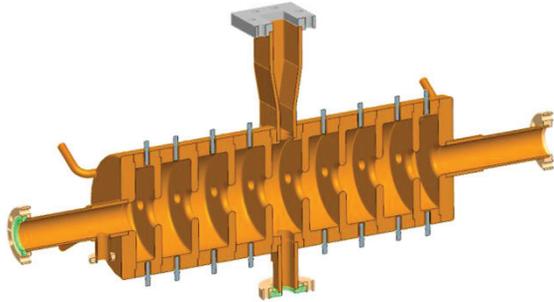


Figure 4: 9-cell transverse deflecting cavity.

The transverse magnetic and electric,  $V_t$ , fields both provide a kick to the beam in the same plane. On-axis, the longitudinal electric field,  $V_z$ , is zero, however, they scale with distance,  $a$ , from the axis as follows

$$V_z = \frac{2\pi f a}{c} V_t \quad (1)$$

At higher beam energies the influence of these fields may be neglected but at low energy their contribution is very significant.

### BEAM DYNAMICS ISSUES

The EBTF diagnostics beamline was designed around the transverse deflecting cavity. Following the gun are four quadrupoles to control the transverse beam size through the cavity. In the straight ahead branch after the cavity there is a long drift to a large diameter YAG screen. The beam pipe aperture expands to allow for maximum vertical beam size. A dipole leading to another long drift followed by a large YAG screen will be used for the energy spread and longitudinal phase-space measurements.

Two quadrupoles are placed post-transverse deflecting cavity in both branches in order to maximise the effect of the kick on the beam by the cavity on the screens. The size,  $\sigma_y$ , of the deflected beam on the screen is determined by [6]

$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_z^2 \beta_d \beta_s \left( \frac{2\pi e V_0}{\lambda p c} \sin \Delta \psi \cos \phi \right)^2}$$

where  $\sigma_{y0}$  is the beam size on the screen in the absence of the deflecting voltage,  $\beta_d$  and  $\beta_s$  are the optical functions at the TDC and screen,  $\Delta \psi$  is the betatron phase advance from TDC to screen,  $\phi$  the RF phase of TDC at

wavelength  $\lambda$ ,  $\sigma_z$  the rms bunch length and beam momentum  $p$ .

This suggests that a large vertical beam size within the cavity is advantageous. However, from Eq. 1, a beam with a large vertical beam size will be influenced by differing longitudinal electric fields and thus an energy spread will be imparted on the beam. Fig. 5 shows the case where the four quadrupoles (the first at 1.2 m from the gun) before the TDC have been set to allow a small vertical beamsizes throughout the cavity to minimise this energy spread increase.

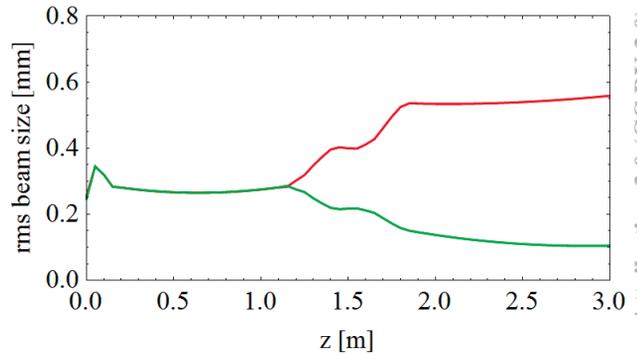


Figure 5: Vertical (green) and horizontal (red) beam sizes through the TDC.

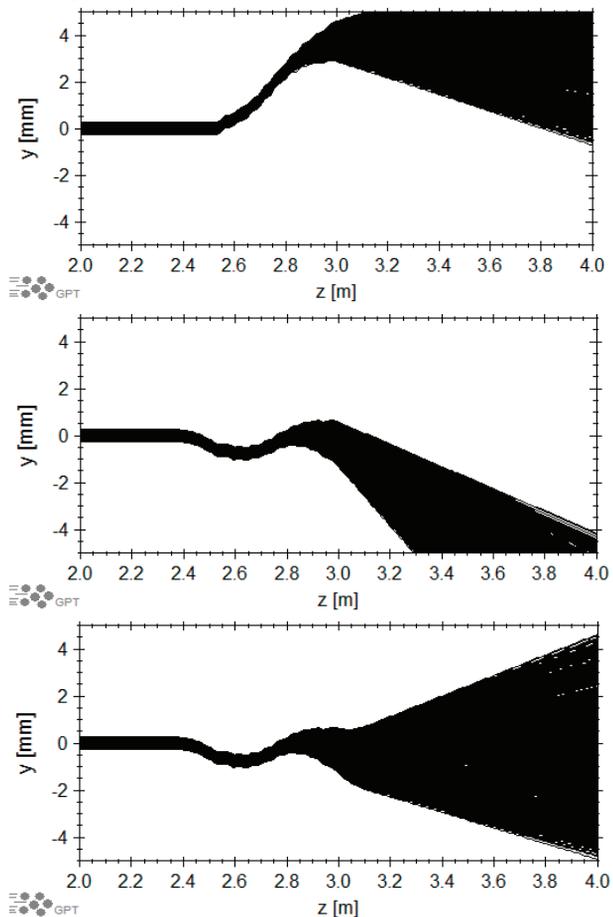


Figure 6: Vertical trajectories through the TDC; without correctors (top), with the entrance corrector (middle) and with both entrance and exit correctors (bottom).

The cavity has been designed so that the total offset to the beam is reduced whilst the streak is maximised. However, whilst operating at a low beam energy and high deflecting voltage, the offset given to the beam can still be large, as shown in Fig. 6, where  $V_t$  is set to 3.5 MV. This transverse offset means the beam sees longitudinal fields as given by Eq. 1 which gives a net change in energy to the beam, as well as an increase in the energy spread due to the non-zero vertical beamsize, as shown in Fig. 7.

This effect can be compensated with a steering magnet placed just before the entrance to the TDC. This trajectory correction does not negatively affect the amount of streak, as shown in Fig. 6. A second steering magnet, at the exit of the cavity, corrects the final trajectory back along the axis.

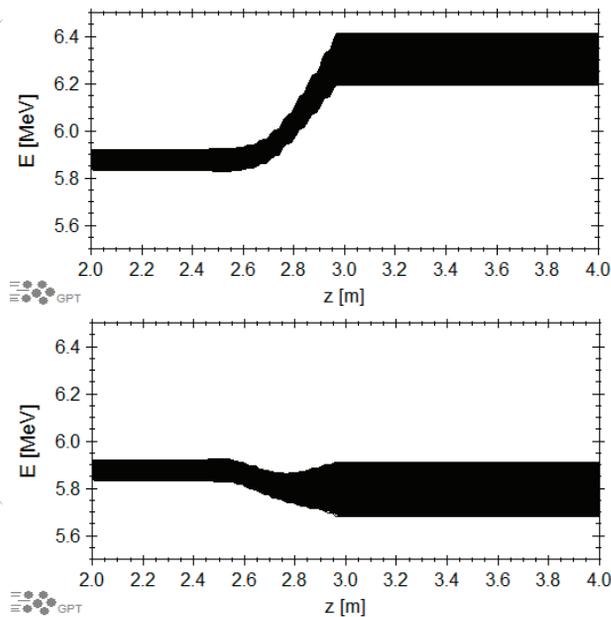


Figure 7: Energy distributions through the TDC; without correctors (top) and with correctors (bottom).

By having a zero net offset through the cavity, the net energy gain is now corrected, as shown in Fig. 7, with no significant effect on the increase in energy spread as the beamsize remains about the same. This increase in energy spread can wash out the original energy spread from the gun, which will make direct longitudinal phase space measurements on the screen after the dipole difficult. Fig. 8 shows the beam on the screens for the straight path and the dispersive path.

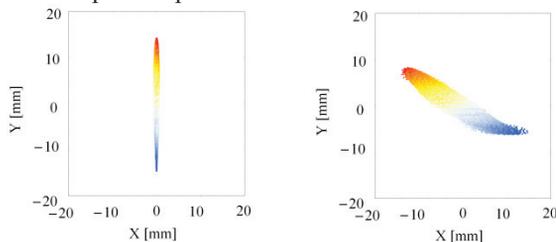


Figure 8: Beam on the straight path screen (left) and the dispersive path screen (right). Blue to red relates to low to high particle energies.

To check that the TDC is performing the required mapping of the bunch length on to the vertical beamsize, we can plot the longitudinal position (pre-TDC) against vertical beamsize (on the screen), as shown in Fig. 9. For the straight path we can see a clear correlation, however, in the dispersive path, this correlation is reduced (and inverted) due to dipole focussing. The two quadrupoles after the dipole can be used to restore the correlation.

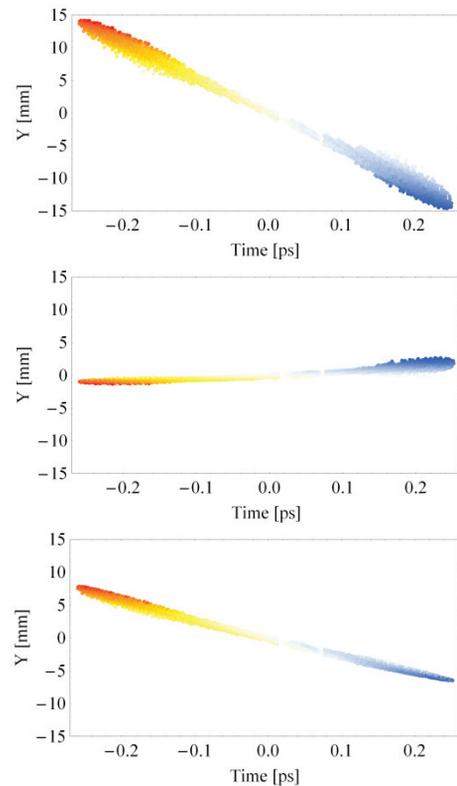


Figure 9: Correlation of longitudinal position pre-TDC against vertical beamsize on the screen for the straight path (top), dispersive path (middle), and the dispersive path with post-dipole quadrupoles (bottom).

## CONCLUSIONS

Simulations have shown that EBTF has the potential to create sub-100 fs electron bunches which can be measured using a transverse deflecting cavity if care has to be taken to minimise adverse beam dynamics effects.

## ACKNOWLEDGMENTS

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