HIGH REPETITION RATE S-BAND PHOTOINJECTOR DESIGN FOR THE CLARA FEL

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Abstract

We present the design of a 1.5cell S-band photoinjector RF gun intended to be operated at repetition rates up to 400 Hz in single bunch mode. This gun is intended for use at the proposed CLARA (Compact Linear Accelerator for Research and Applications) FEL test facility at Daresbury Laboratory in the UK and will first be tested and characterised on VELA (Versatile Electron Linear Accelerator) in 2015. The final cavity design is presented including optimisation for CLARA beam dynamics, and choice of a novel coaxial H-shaped coupler.

INTRODUCTION

CLARA (Compact Linear Accelerator for Research and Applications) is a proposed 250 MeV, 100-400 nm FEL test facility at Daresbury Laboratory in the UK [1]. The electron source for CLARA needs to be able to operate in various regimes to meet the different FEL operational modes. In single bunch modes it needs to deliver bunch charges up to 250 pC at repetition rates of up to 400 Hz. In multi-bunch mode it needs to deliver 16 x 25 pC bunches with a bunch separation of 100 ns.

To meet this requirement, a 1.5 cell, 2.9985 GHz photocathode RF gun, shown in Fig. 1, has been designed. The gun is intended to operate with a peak field of 120 MV/m for the 100 Hz modes, which will be reduced to 100 MV/m for the 400 Hz modes to moderate the average power in the gun and thus heat loads. The gun will initially be tested on VELA [2] which contains a suite of diagnostics to fully characterise the 6D phase space of the emitted electron beam.

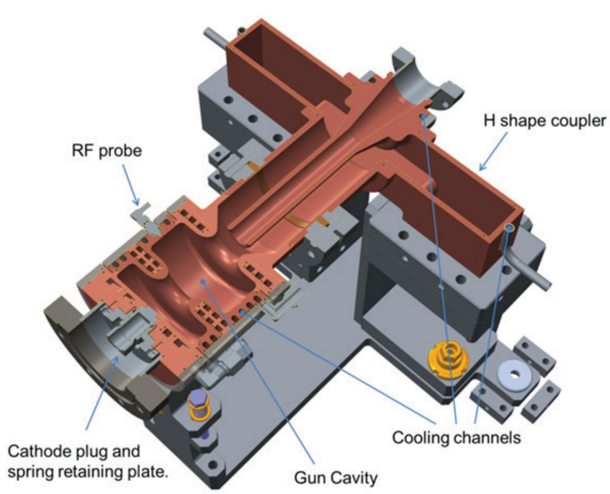

Figure 1: Overview of the gun design.

OVERVIEW AND COOLING

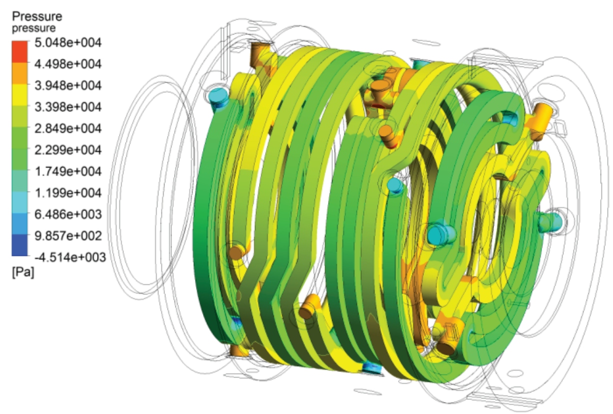

Figure 2: Pressure profiles at the surface of the cooling channels.

A 1.5 cell gun was chosen over 2.5 cells as, although this reduces the final energy of the electron bunch, it reduces the power requirements to the gun. Power fed into the gun manifests as heat deposited into the cavity walls and needs to be extracted by the cooling system. The expected average power for a 2.5 cell gun is almost double that of a 1.5 cell cavity, and for 100 MV/m at 400 Hz was estimated to be 6.8 kW for the 1.5 cell case.

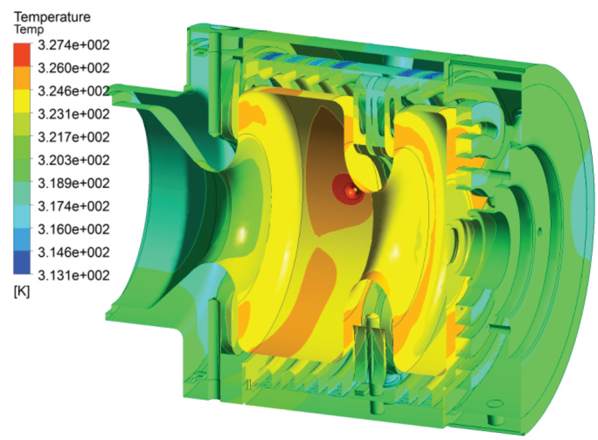

Figure 3: Temperature profile with the proposed cooling system with the gun operating at 100 MV/m at a 400 Hz repetition rate.

The magnetic field distribution of the cavity was converted into a heat flux and computational fluid dynamics simulations carried out in ANSYS. This showed that the proposed cooling, shown in Fig. 2,

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consisting of nine channels cut into the bulk of the cavity, was sufficient to extract this power. More details of the cooling can be found in [3] and the temperature profile of the gun can be seen in Fig. 3.

To provide feedback, which is particularly needed for the multi-bunch operation mode, an RF probe is included in the second cell to monitor the fields, as shown in Fig. 1. A dimple is placed opposite for symmetry reasons. Although the probe aperture is blended, this local distortion to the magnetic fields causes it to be the area with the largest temperature increase, as shown in Fig. 3.

The gun will be equipped with a photocathode exchange system to accept 10 mm plugs of the INFN/DESY type [4]. The cathode is inserted through a plug in the back-plate of the first cell. Such a system allows for cathode changeover without breaking the cavity vacuum, and enables different metal and alkali photocathodes to be tested.

The gun cavity will be surrounded by a solenoid for emittance compensation and transverse focussing, and a bucking coil behind the cavity to cancel the magnetic field on the cathode plane. A coaxial coupler was chosen over side-coupling in order to preserve symmetry of the fields in the cavity and to minimise the effects of the dipole mode. This also allows the main solenoid to be placed around the cavity itself, rather than after, which is desirable from a beam dynamics standpoint.

More details on the overall gun design can be found in [5].

CAVITY DESIGN

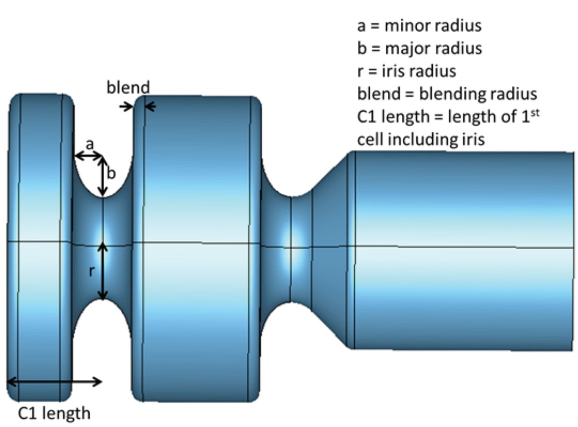

Figure 4: Parameterised 2D gun cavity model.

The cells are cylindrical with rounded edges to allow for a better distribution of the magnetic field and, as result, heat load. For the purpose of RF and beam dynamics optimisation, the cavity was parameterised as shown in Fig. 4 and modelled in Superfish via a custom Mathematica interface. This allowed each parameter to be varied individually, and a script automatically adjusted the radii of both cells to compensate for any changes in frequency or field flatness. Overall frequency will be set with operational water temperature with a scale factor of 50 kHz/°C, typical for S-band cavities. Tuning range is therefore limited by reasonable temperature ranges of about 10 K, leading to a 500 kHz tolerance in frequency.

The iris radius, r, was chosen as a trade-off between geometrical quality factor, R/Q, and mode separation. The iris profile was chosen to be elliptical to minimise the maximum surface electric field. The ellipse minor radius, a, was fixed to 8 mm to give room for the cooling channels the ellipse major radius, b, and iris radius, r, optimised to give maximum R/Q for a minimum mode separation of 20 MHz.

FIRST CELL LENGTH OPTIMISATION

The parameter which has the largest effect on the beam dynamics is the first cell length. For optimisation the cell length was varied in Superfish and on-axis electric field distribution exported into ASTRA to simulate the beam dynamics. The beam, generated with a 76 fs rms laser pulse, as is currently used on the VELA photoinjector, was tracked from the photocathode through to the exit of the first linac module of CLARA as detailed in [1] and the beamline components optimised to give the minimum transverse emittance for each case.

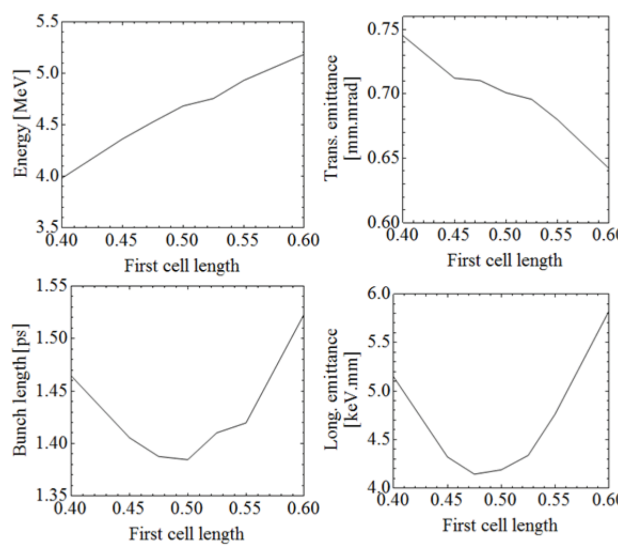

Figure 5: Beam parameters at the exit of the CLARA first linac for different gun first cell lengths for a 250 pC bunch and a gun peak field of 120 MV/m.

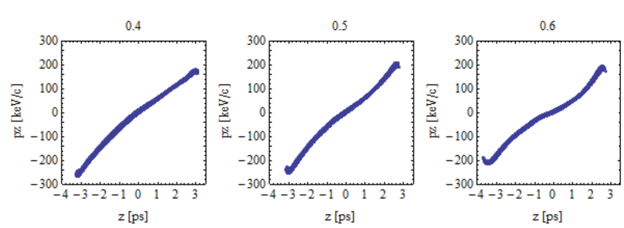

Figure 6: Longitudinal phase space of a 250 pC bunch at the exit of the CLARA first linac for gun first cell lengths marked above, for a gun peak field of 120 MV/m.

Operating with such a short laser pulse means that essentially the gun is operating in the "blow-out" regime [6] where the longitudinal beam distribution, instead of being determined by the laser pulse shape, is determined

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by the space-charge, which forces the beam to expand longitudinally very rapidly after emission. The resulting beam is thus highly depending on the bunch charge, and the initial acceleration. Thus the electric fields in the first cell are critical for obtaining the best beam properties.

The first linac in CLARA will operate in two modes – firstly near crest in the modes where the beam will be compressed via a magnetic chicane downstream, and secondly, near the zero-crossing which uses velocity bunching to compress the bunch longitudinally. The simulations in this paper show only the case on the near-crest acceleration mode.

Figure 5 shows the results of the cell length scan for a 250 pC bunch with a peak on-axis electric field of each cavity of 120 MV/m. The first cell length is given as a fraction of the full cell length, which is set to half a wavelength. Increasing the cell length increases the final energy of the gun and reduces the transverse emittance.

However, looking at the longitudinal properties, there is an optimum cell length for minimising bunch length and longitudinal emittance. Figure 6 shows that for longer cell lengths there is more curvature in the longitudinal phase space of the beam – this makes the beam more difficult to manipulate downstream to provide the required bunch length for the FEL. Given that there is no requirement for higher gun energy and the transverse emittance in all cases meets the requirements of less than 1 mm.mrad for the FEL, a first cell length of 0.5 times that of the full cell provides optimum longitudinal beam properties.

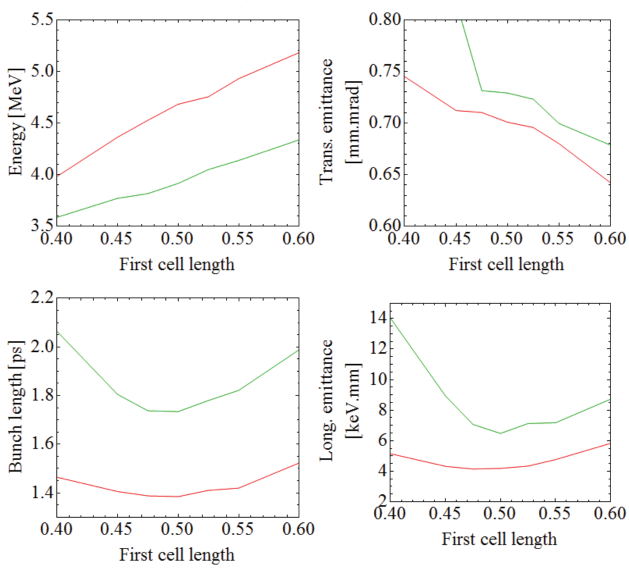

Figure 7: Beam parameters at the exit of the CLARA first linac for different gun first cell lengths for a 250 pC bunch and a gun peak field of 120 MV/m (red) and 100 MV/m (green).

The cell length scan was also carried out for a gun peak field of 100 MV/m and the results shown in Figs. 7 and 8. As can be seen, this lower gun gradient reduces the quality of the beam in all respects but the trends are the same. It is still apparent that a first cell length of 0.5 times that of the full cell gives good longitudinal properties. A shorter cell has clear first order curvature in the longitudinal phase space, whilst a longer cell gives rise to higher order curvature.

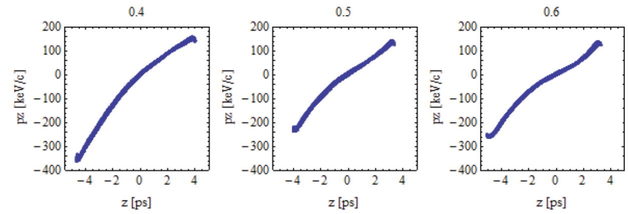

Figure 8: Longitudinal phase space of a 250 pC bunch at the exit of the CLARA first linac for gun first cell lengths marked above, for a gun peak field of 100 MV/m.

The cell length scan was also repeated for the 120 MV/m case at reduced bunch charges of 100 pC and 25 pC. The 100 pC case is shown in Figs. 9 and 10. It can be seen that the minimums for longitudinal emittance and bunch length are not for the same cell length as in the 250 pC cases. However, both of these parameters are much lower over all cell lengths due to the vastly reduced space-charge influence. Figure 9 also shows that the longitudinal phase-space doesn’t vary as much as the high charge regime.

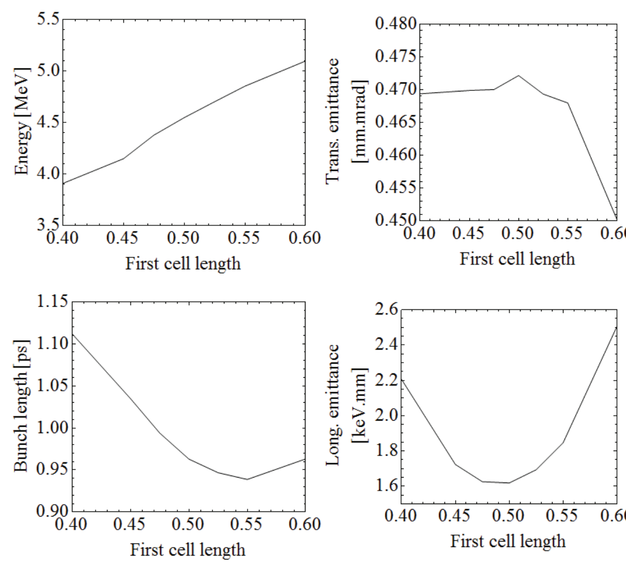

Figure 9: Beam parameters at the exit of the CLARA first linac for different gun first cell lengths for a 100 pC bunch and a gun peak field of 120 MV/m.

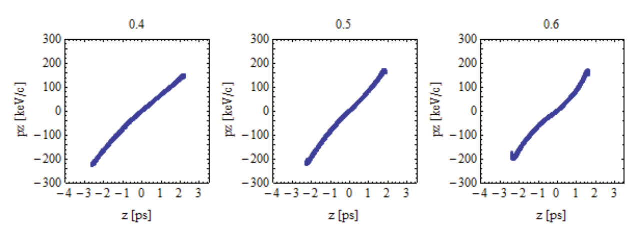

Figure 10: Longitudinal phase space of a 100 pC bunch at the exit of the CLARA first linac for gun first cell lengths marked above, for a gun peak field of 120 MV/m.

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For the nominal case of 120 MV/m and 250 pC, the evolution of beam properties for CLARA is shown in Fig.11.

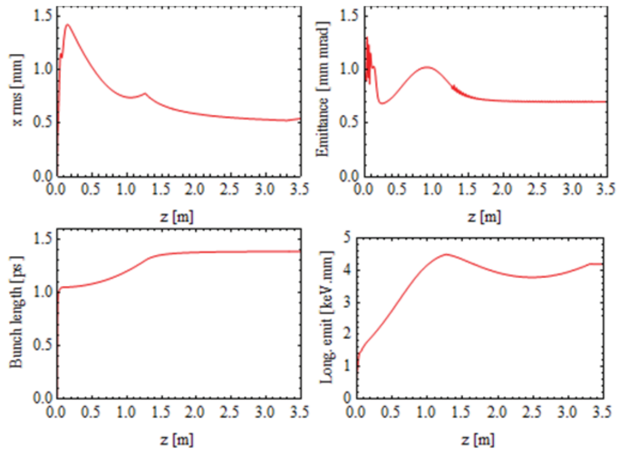

Figure 11: Evolution of parameters of a 250 pC bunchthrough linac 1 for the nominal case of 120 MV/m.

COUPLER DESIGN

Studies carried out on single-feed asymmetric designs show that they lead to a TE11 dipole mode that can propagate to the cavity, as shown in Fig. 12. Due to the aperture size required for the laser, the cut-off frequency of the TE11 mode in the coax section was below 3 GHz, resulting in up to 16% of the input power being transmitted to the TE11 mode at the doorknob. While the coaxial length can be modified to cancel this out it still leads to a standing wave in the coupler which could cause a 50 kV transverse kick to the beam and cause asymmetric coupler and cavity heating, coupler mismatch and multipactor conditions. In order to allay that risk, it was decided to use a dual-feed system whereby the RF arrives to the cavity symmetrically.

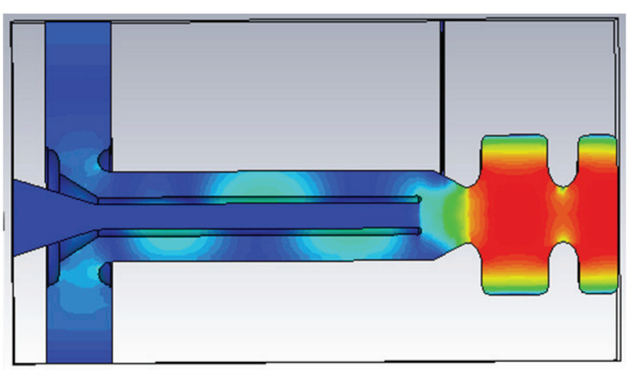

Figure 12: Dipole mode in the coaxial coupler of a single-feed asymmetric design.

A capacitive match at the doorknob is the solution commonly chosen for similar designs. However, it is a major risk in terms of multipactor and breakdown due to its geometry. An inductive iris would allow matching while removing the additional vulnerabilities presented by the capacitive coupling. The inductive iris is, however, not tuneable, and reduces vacuum conductivity of the gun.

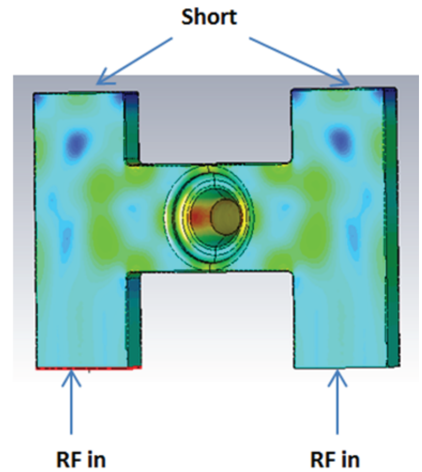

Figure 13: Electrical fields in the H-feed coupler.

In order to allow the coupler to be tuned to achieve the best possible match, we propose an alternative H-feed design, shown in Fig. 13. Movable shorts allow fine tuning of each arm separately, allowing the best possible compensation of phase errors in the two arms as well as the overall match of the transition. The shorts also give good access for pumping should this be required.

CONCLUSIONS

A 1.5 cell S-band RF gun cavity equipped with a novel H-feed coaxial coupler has been designed with cavity properties optimised to provide beam for the CLARA FEL test facility and operate at repetition rates up to 400 Hz.

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