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DELIVERABLE 5.3: STATUS REPORT OF A HIGH AVERAGE CURRENT SRF GUN

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1.0 Abstract

A 100 mA 10 MeV continuous wave electron injector is required to delivery high brightness electron bunches for many proposed Free Electron Laser (FEL) based facilities. A possible solution to provide such high brilliance sources might be a Superconductive RF (SRF) gun. In order to match into the accelerator, the gun has to be operational at L-band frequencies (1.3GHz or 1.5GHz) or a harmonic of this frequency. The development of a high current RF gun based on the TESLA type technology (1.3 GHz) has been carried out. This report details the current status of the design including beam tracking confirming the performance achieved.

2.0 Introduction

Exploration in the fields of high energy particle physics, material and life sciences is made possible using large facility particle accelerators such as linear accelerators (linacs) linear colliders along with synchrotrons and free electron lasers based X-ray sources. These devices make the incredible structures of matter visible and give us a glimpse at the construction and operation of matter that was previously invisible and misunderstood. Intense electron sources are required to provide the necessary beam quality for successful experimental results to be achieved.

Advances in RF subsystems have finally provided the justification to develop a world leading high brightness electron source desirable for the 4GLS High Average Current Loop [1]. In addition to their traditional role in fundamental particle and nuclear physics research, high brightness injectors can utilise the advanced electron beam transport of SRF technology and have become the essential instrument for much of the front line scientific investigations in the life and material sciences. The demand for ever increasing injector specifications has required rapid evolution of the underpinning technologies and the key items are the high power RF delivery system and cold cathode based technology.

Table 1: Required parameters of the HACL injector.

	Design Goal
Gun frequency	1.3 GHz
Bunch repetition rate	1.3 GHz
Average beam current	100 mA
Beam energy	10 MeV
Sliced emittance	1 π·mm·mrad
Bunch length	20 ps
RMS energy spread	0.1%
Bunch charge	77 pC

Due to the user requirements for 4GLS, the parameters are required from the injector operation are highlighted in Table 1.

3.0 Conceptual Design

One of the most advanced SRF guns in development is currently underway at Forschungzsentrum Dresden (FZD), where they are developing a 10 MeV 1 mA 3½ cell gun operating at 1.3 GHz [2]. A number of reasons do not allow the operation of this gun at 100 mA. Due to trapped High Order Modes (HOM) and availability of RF power [3], namely 1 MW CW, and high power RF couplers a bespoke gun design is required that can utilise available RF sources and minimises disruption to the beam from unwanted HOMs.

A 1½ cell design coupled onto a 2 cell cavity is being developed, that will contain fewer trapped HOMs and allow additional power couplers to be inserted that can handle the peak RF power already available in RF sources. Figure 1 illustrates the conceptual design of the gun cavity being proposed for the HACL injector.

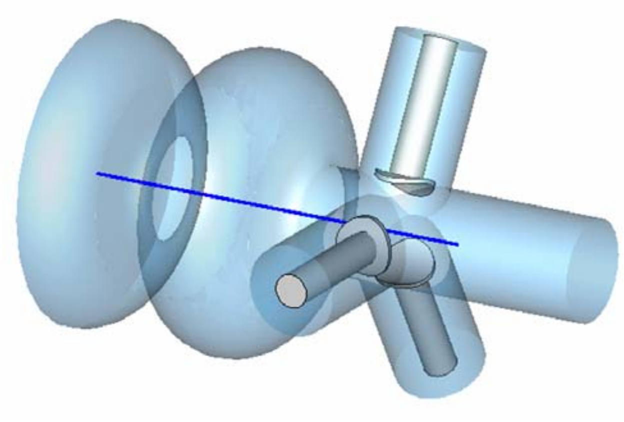


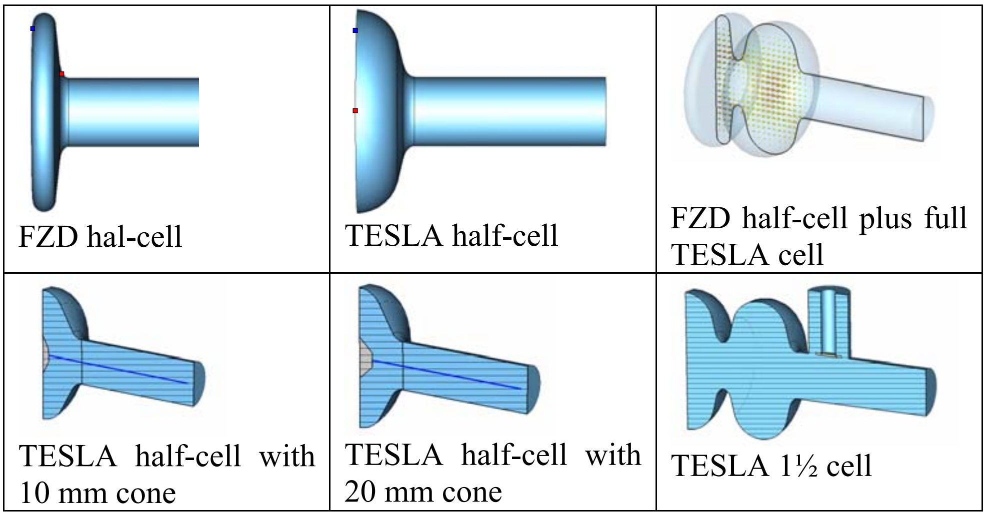
Figure 1: Conceptual design of 1½ cell gun cavity with fundamental power couplers located at 120º

The optimisation criteria for the gun was carried out assessing the final beam energy that the gun is capable of against projected bunch length, transverse emittance and longitudinal emittance. The RF design was carried out using CST's MAFIA and Microwave Studio [4], whilst the beam tracking simulations were carried out using the ASTRA code [5].

3.1 RF cavity Design

Initially a simple TESLA [6] half-cell and the first half-cell of the FZD SRF gun design were adopted. To enhance the acceleration fields inside the cavity a protruding cathode design was employed and, finally, a re-entrant shape of the cavity also investigated.

A cone was introduced onto the rear wall of the gun to enhance the field on the cathode surface keeping the cell shape unchanged. This should produce a much improved beam quality for an equivalent RF power.The majority of the gun shapes investigated is visualised in the Figure 2.



FZD hal-cell

TESLA half-cell

FZD half-cell plus full TESLA cell

TESLA half-cell with 10 mm cone

TESLA half-cell with 20 mm cone

TESLA 1½ cell

Figure 2: RF design of the first ½ cell and complete cavities that have been assessed

The cone on the cavity back wall increases the peak fields on the cathode surface; however this is only advantageous if the particle is emitted from the cavity axis. Any electrons emitted away from the axis will have stronger de-focussing fields immediately from the cathode surface causing increased divergence of the beam. An additional focussing can be applied by proper selection of the cone shape to minimise this divergence at the cost of the peak fields on the cathode. This is a parameter that will be investigated and optimized further during the course of the project.

For each cavity shape proposed the distribution of E_{pk}, B_{pk}, and E_{acc}, were calculated to ensure safe operation of the design prior to using the longitudinal electric field for beam tracking. Optimisation of the first half-cell was carried out to determine the projected benefits from cathode shaping and how cavity shapes benefited the performance for the gun.

The RF parameters for the different cavity shapes investigated are summarised in Table 2.

Table 2: Comparison of RF parameters for the launch cell

	R/Q	E_{pk}/E_{acc}	cB_{pk}/E_{acc}
FZD ½ cell	114.4	1.91	1.25
TESLA ½ cell	186.2	1.059	0.76
TESLA ½ cell & 5 mm cone	205.531	1.55	0.81
TESLA ½ cell & 10 mm cone	218.492	1.86	0.73
TESLA ½ cell & 15 mm cone	188.977	2.47	0.71
TESLA ½ cell & 20 mm cone	187.162	2.75	0.75

3.2 Coupler Design

An anticipated 450 kW CW RF power required for the gun operation is transmitted through three separate couplers which should provide high level of coupling (Q_{ext} of 10^5). The field asymmetry introduced by the couplers is minimised in two ways: firstly, the couplers are placed equidistant radially around the beam pipe (see Figure 1); secondly, to minimise the couplers penetration into the beam pipe, a "pringle" shaped antenna has been adopted.

At the moment no coaxial coupler exists at 1.3 GHz capable of handling 150 kW CW RF power, therefore it is anticipated that a rescaling of a Tristan type RF window will be integrated into the RF final design.

Figure 3 shows a plot of the transverse electrical fields in the coupler region calculated for a single coupler and for two couplers installed at 180º. As may be seen, there is still a small asymmetric kick that may potentially lead to some emittance dilution. It's influence on the beam dynamics will be studied in the future with a 3D code.

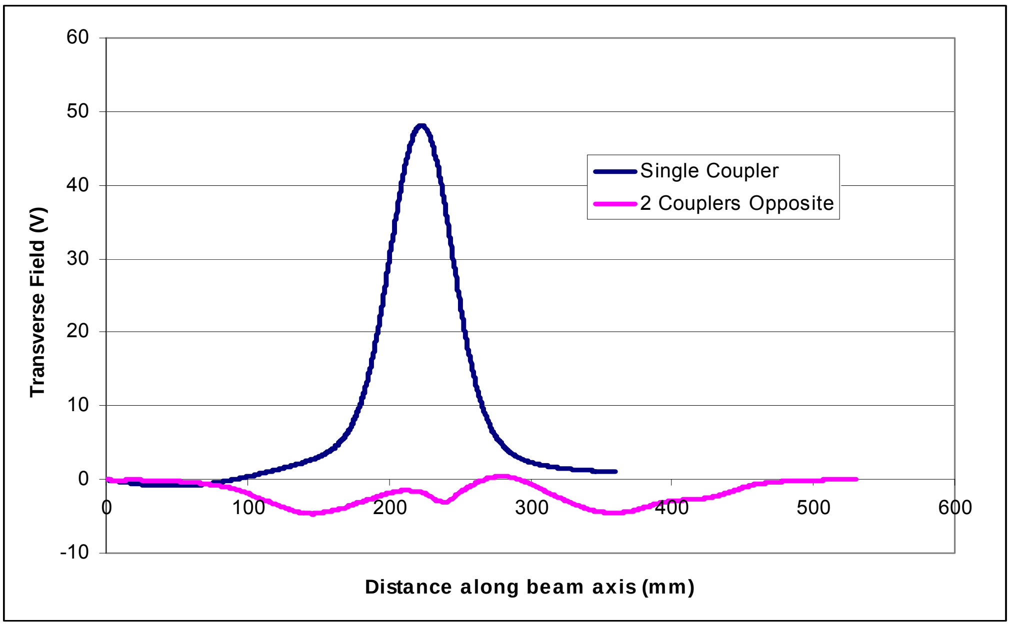


Figure 3: Transverse electric fields in the coupler's region

3.3 Power Requirements

At optimum coupling the required RF power to generate the accelerating field is equivalent to the power transferred to the beam. Therefore, $P=V_{acc}I_b$, since we require >7 MV acceleration for up to 100 mA, that equates to 700 kW, assuming 3 couplers per cavity, that equates to 116 kW delivered through each coupler.

Assuming on-crest acceleration, the required Q is calculated using the following formula.

$$Q_{opt} = \frac{V_{acc}}{\frac{R}{Q} I_b \cos \phi_b}$$

For an acceleration of 3.5 MeV per cavity, this gives an optimum coupling of 1.75 x 10^5.

4.0 Beam Tracking

The most optimum RF cavity design with regards to R/Q, cryogenic losses etc, may not necessarily provide the most desirable beam qualities, particularly at non-relativistic case as the beam is far more susceptible to transverse fields. As part of the design process it is necessary to evaluate each cell of the RF structure and to compare with the same equivalent accelerating field.

In order to make the comparison of each half-cell cavity geometry fair, the beam properties have been recorded at a distance of 1 m away from the cathode, where the RF fields decayed close to zero. It was assumed also identical accelerating field in the cavities. For each beam parameter the RF phase has to be swept to find the optimum operating point. Once this is complete, it is then necessary to determine the best operating phase as a compromise between the different beam parameters.

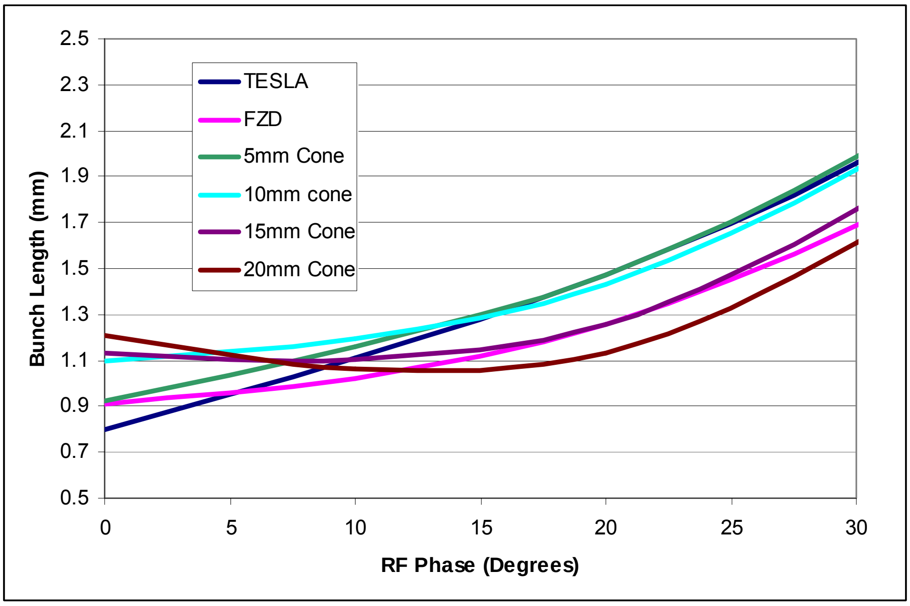


Figure 4: Comparison of bunch length for half-cell cavities

As it is evident in Figure 4, at the optimum phase of the RF to provide the minimum bunch length, there is little gain with small variations in the cavity shape. The same can also be deduced for the rms transverse emittance. Although the parameters show little difference between cavity shapes, there is a fairly obvious optimum RF phase to provide the minimum bunch length, and this phase has to be evaluated with the other monitored characteristics to ensure operation within the design tolerances.

The most significant advantage is observed when monitoring the energy of the beam (Figure 5). Here the TESLA cavity half cell provides the greatest acceleration for the same accelerating gradient. Modifications to the cathode region such as including the cone did not show any signs of improvement in acceleration.

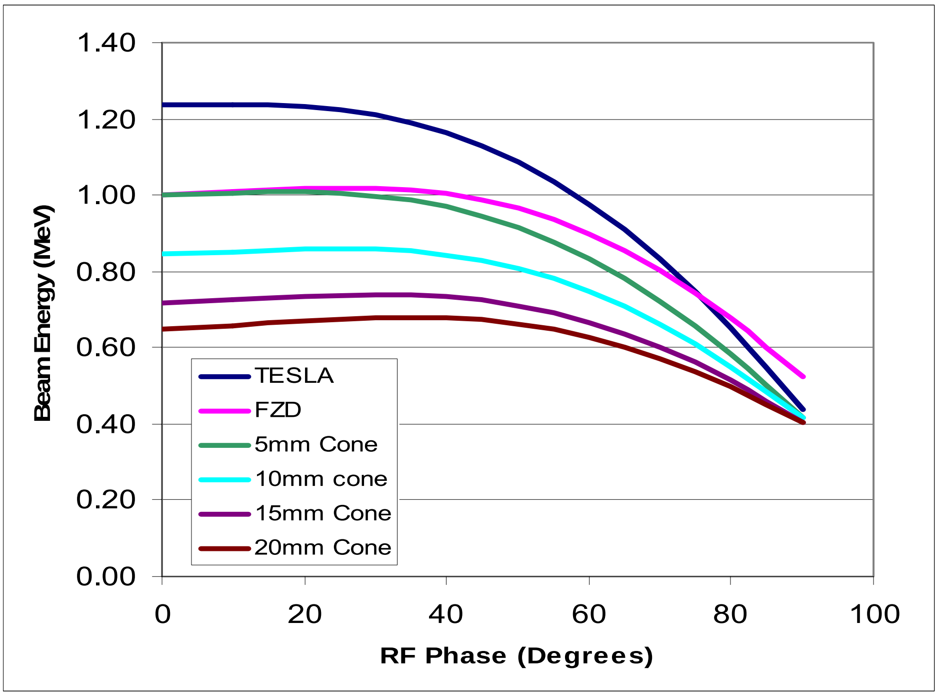


Figure 5: Beam Energy as a function of RF phase for each cavity assessed

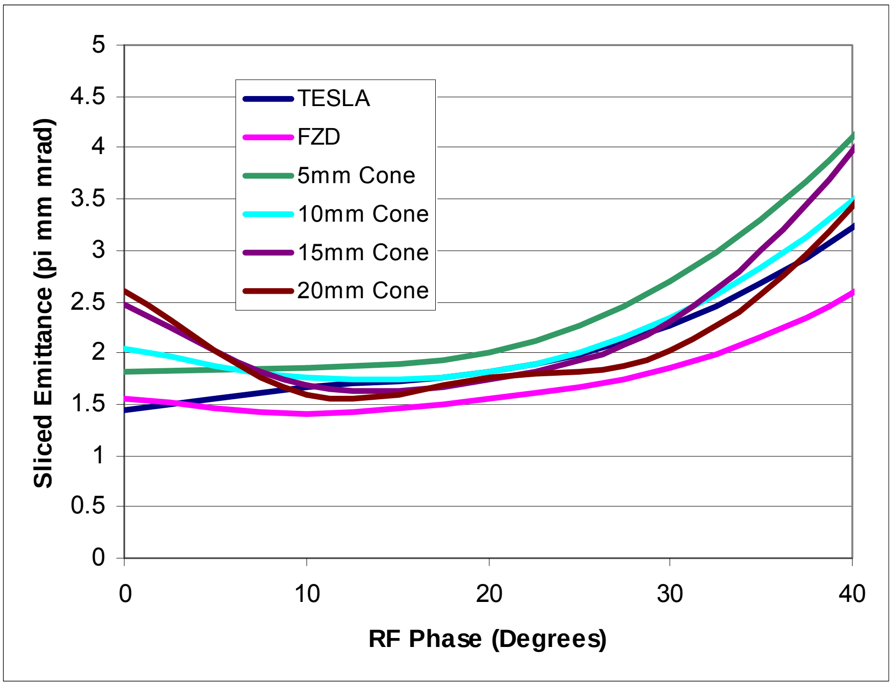
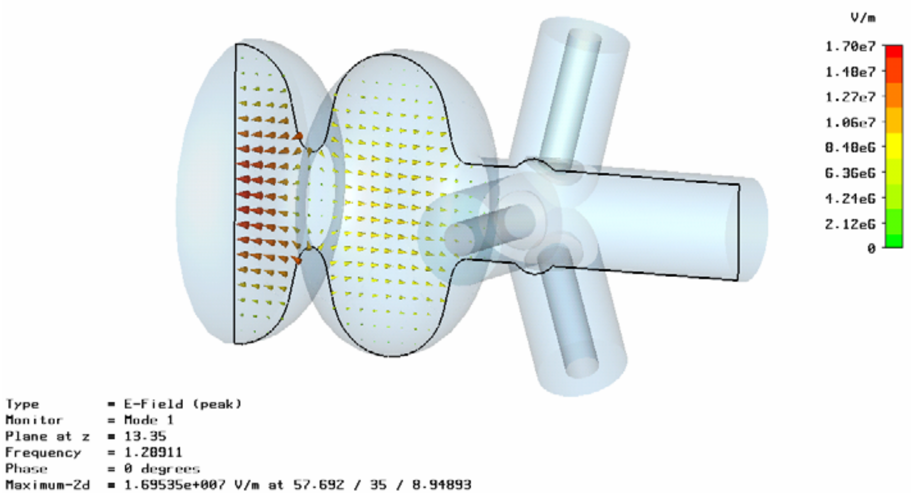


Figure 6: Sliced emittance as a function of RF phase for each cavity assessed

As can be seen with the assessments presented, many of the beam parameters are insensitive to the cavity field profile, instead they are influenced more so by the achievable field amplitude. To develop the cavity shape further an assessment of a 1½ cell cavity is required.

5.0 1½ Cell Cavity Assessment

From the information gathered on the single half-cell, an additional TESLA cell was added to the FZD and TESLA half-cell, and the same cavity and beam parameters evaluated.



```
Type         = E-Field (peak)
Monitor      = Mode 1
Plane at z   = 13.35
Frequency    = 1.28911
Phase        = 0 degrees
Maximum-2d   = 1.69535e+007 V/m at 57.692 / 35 / 8.94893
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Figure 7: Electric field contours in a TESLA 1½ cell cavity

Here, the RF phase has more impact on the minimum beam emittance and energy spread, however the difference between the two types of cavities assessed, there was little benefit found for either cavity. Each gave a similar transverse and longitudinal emittance (Figure 8), whilst the TESLA type shape, again gave a slightly larger acceleration, see Figure 9.

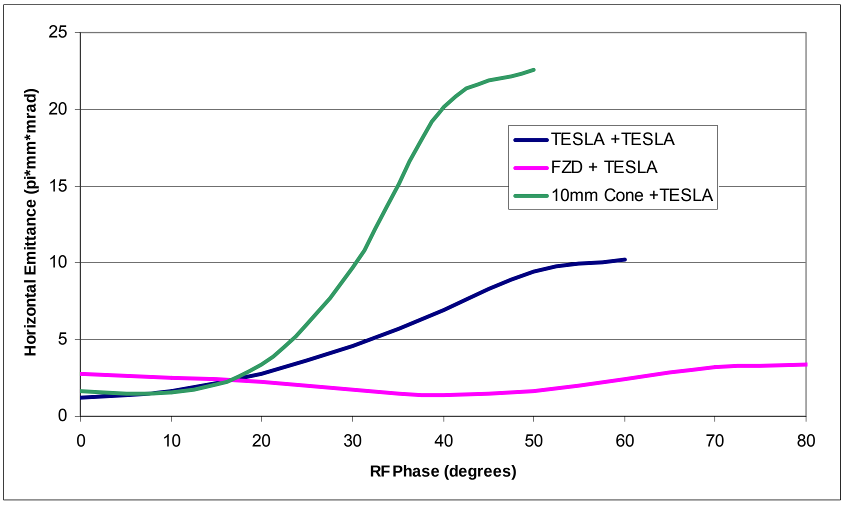

Figure 8: RMS transverse emittance as a function of RF phase

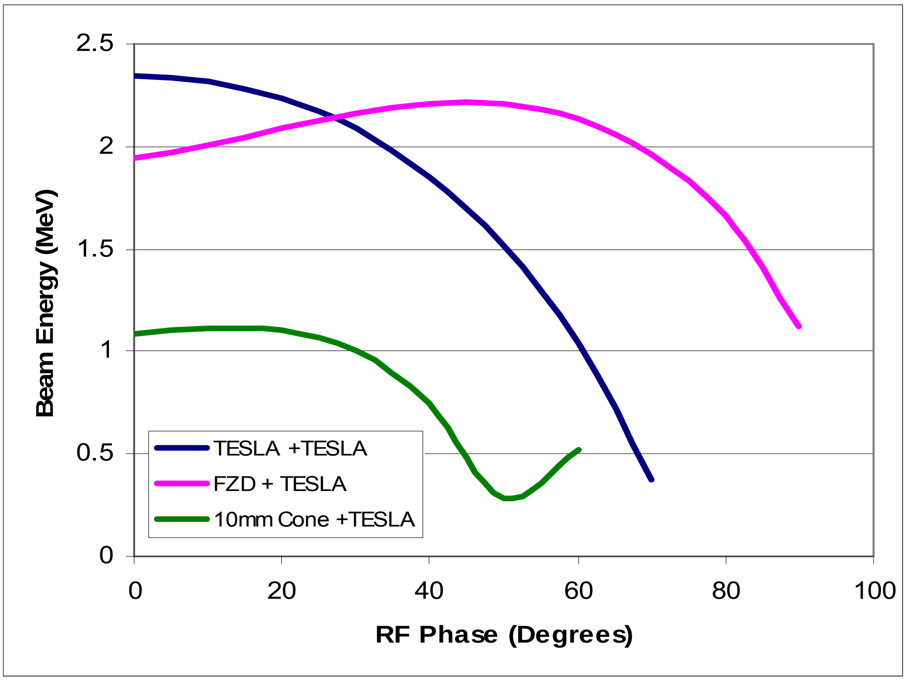

Figure 9: Beam energy as a function of RF phase

It is also observed that the phase of maximum acceleration is within a few degrees of the point of minimum transverse emittance. Since the electrons are accelerated faster, the influence of space charge is less significant, highlighting the major advantage of RF guns in general.

6.0 High order mode Analysis

Clearly with increase of the number of cells in the cavity, the number of excited modes and the likelihood of their trapping is also enhanced. HOM power dissipated in the 2K liquid helium is proportional to the beam current, therefore will increase with the increase of the beam current and trap additional modes. The trapped HOMs will also perturb the beam affecting the quality of the transmitted beam

In order to assess the improvement of the 1½ cell cavity, an assessment of the HOMs compared with the FZD 3½ cell gun has been made. The results are shown in Figure 10. The mode analysis has shown significant reduction of the number of trapped HOMs in 1½ cell cavity compare to 3½ cell, however it is still desirable to remove the HOMs with the large R/Q values, as should the beam excite these modes excessive RF power will be deposited in the 2K liquid helium.

HOM damping is therefore required to reduce the impedance of these modes and to reduce the chance of coupling them to the beam.

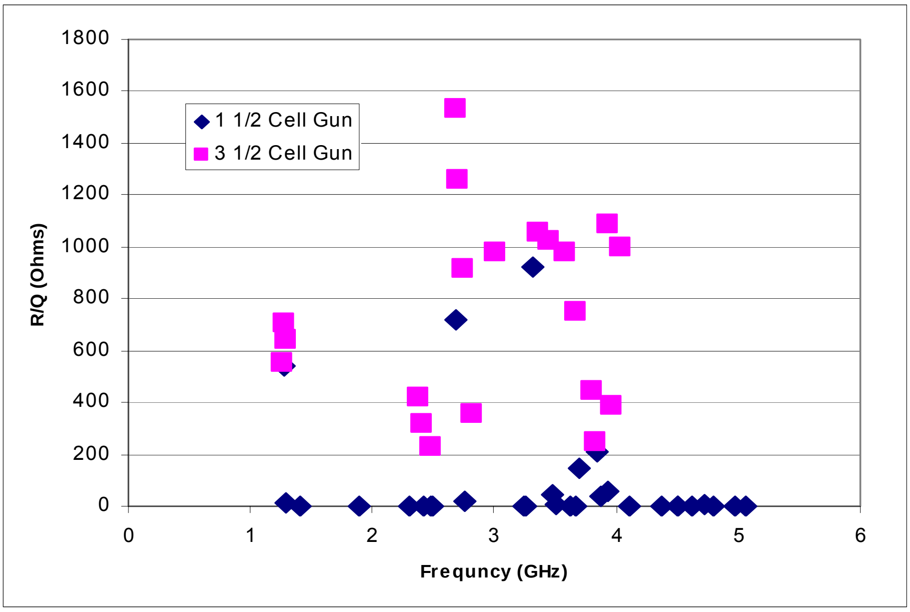

Figure 10: A comparison of the R/Q value for the first 30 modes of the 1½ cell and 3½ cell structures

Increasing the beam pipe diameter will assist in the propagation of the strong HOMs out of the superconductive cavity and will need to be assessed.

7.0 Additional Booster Cavity

In order to gain the additional acceleration, a booster cavity is required. A booster cavity based on the Cornell ERL injector module [7], however modifications have been made to increase the power handling capacity of the couplers and the number of couplers used. Since fixed coupling is considered it reduces the complexity of the coupler by removing the requirement for bellows, and therefore increases the power handling capable with the coaxial type couplers.

In order to optimise the gun cavity and booster cavity together, both the RF phase with respect to each other as a function of longitudinal distance between the cavities has to be made, then due to the drift space, additional solenoid focussing has been investigated.

The additional solenoid focussing has so far yet to be optimised as the longitudinal centre, phase and field strength all have to be optimised with the cavity phases in order to benefit the most. Without solenoid focussing, the system developed meets most the required specifications, albeit slightly lower in energy (see figure 11).

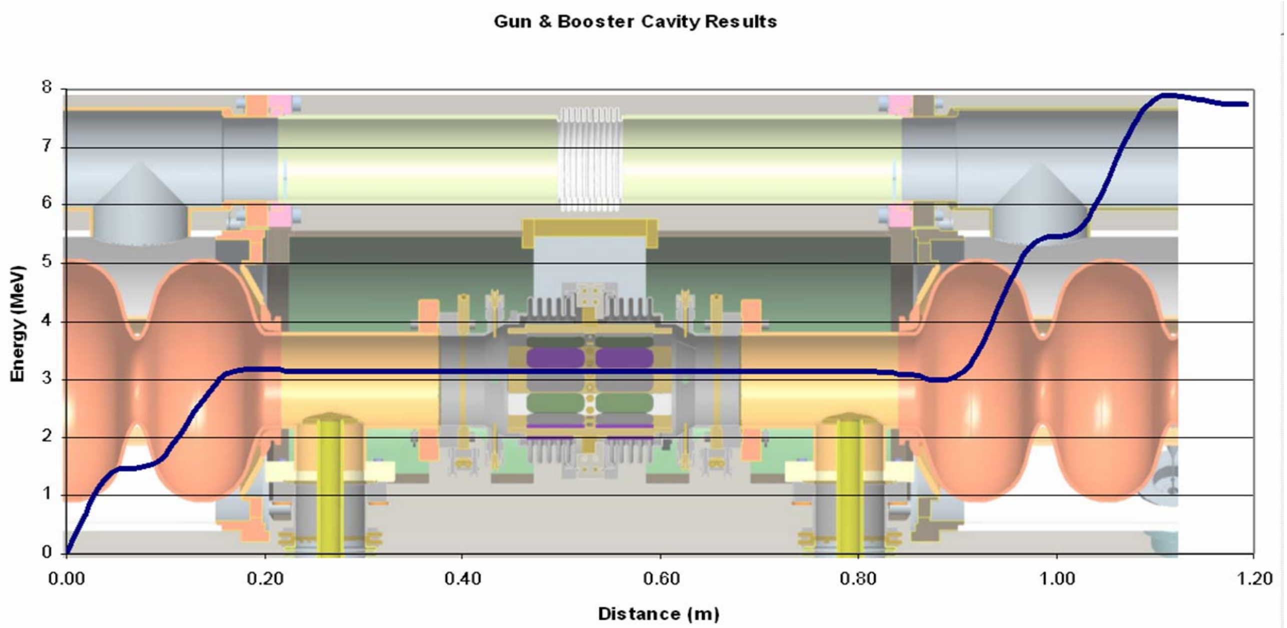

Figure 11: Beam Energy as a function of distance through the cryomodule

With respect to the beam dynamic properties, there is a trade off between the longitudinal emittance and the transverse emittance. As the RF phases are adjusted and solenoid focussing is introduced, one parameter is improved at the expense of the other. Here without solenoid focussing and operating on crest, the transverse emittance has been optimised, with the longitudinal emittance twice the desired level.

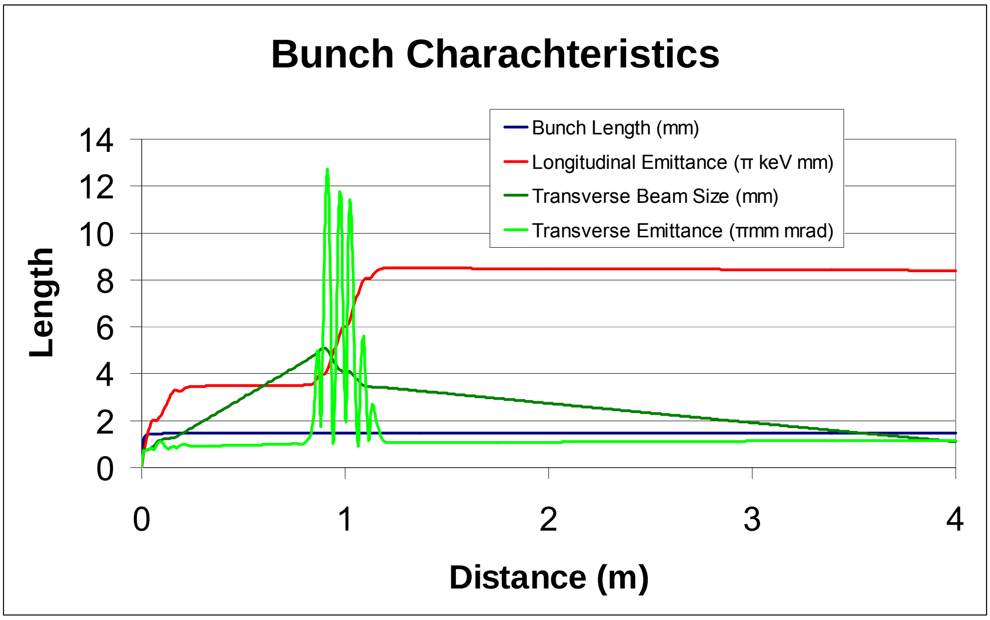

Figure 12: Beam Dynamic Properties through the cavity

8.0 Conclusions

The conceptual deign of the SRF gun is progressing. Optimisation of the launch cell provided a clear understanding as to the sensitivity of the cell design against its beam properties, and how the beam energy affects the transverse and longitudinal emittance. Whilst investigations into the use of re-entrant type cavities and protruding cathodes had the desired effect of improving the peak fields on the surface of the cavity or maximising the field on the cathode respectively, neither showed much improvement in the beam dynamics.

At high average currents it has been highly desirable to maximise the cavity and cryomodules design to minimise the generation of HOMs, improve the damping of the HOMs and to substantially increase the power delivery in the cryomodules.

By carrying out these studies, a gun design has been developed that meets closely with the specification of a number of proposed accelerators. Further work will be carried out with the aim of finalising the design, including the RF power couplers and HOM beam dynamic assessment to validate the design.

9.0 Work Outstanding

Work is on-going to develop a suitable coupler design capable of handling the higher cw powers required. This is based on the Tristan type RF window scaled to 1.3 GHz. RF, thermal and structural simulations will be used to confirm the power handling capability for this coupler.

Additional work to optimise the focussing in the drift space between the two cavities in the module. Due to the number of parameters that can vary, no definite parameter set has been identified.

Further assessment of the HOMs with the broader beam pipe diameter is on-going, whilst adjusting the coupler position to maintain the desired level of coupling.

10.0 Acknowledgement

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I would also like to take the opportunity to thank Rama Calaga from Brookhaven National Laboratory for his helpful advice.

11.0 References

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