CONCEPTUAL DESIGN OF A HIGH AVERAGE CURRENT SRF GUN

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Abstract

Up to a 100 mA 10 MeV continuous wave electron injector may be required to deliver high brightness electron bunches for future light sources. One of the possible solutions would be the use of Superconducting RF (SRF) cavities due to the high RF power and vacuum requirements. The development of a suitable acceleration scheme has been identified, including the design of the RF Cavities. In this paper, the injector design and performance as well as the associated challenges are presented.

INTRODUCTION

Normal conducting RF photoinjectors are the state-of-the-art in injector development since they have demonstrated very high brightness electrons on a number of accelerators. By design, they provide immediate acceleration from the surface of the cathode to the orders of a few MeV, whilst preserving a very low beam emittance. As the duty factor of such injectors is pushed higher and higher, the required level of RF power prohibits the use of normal conducting cavities since the ohmic losses become unmanageable. By exploiting SRF technology, the RF losses are removed and permit much higher average power to be delivered. Due to their nature, SRF injectors have a vastly improved vacuum due to cryogenic pumping, increasing the selection of cathode materials. Whilst the system sounds simplistic, there are a number of challenges introduced by adopting SRF technology that are to be discussed here.

The development of a high average current (HAC) injector has commenced as a possible solution for the New Light Source [1] project in the UK. Indications from the scientific community suggest the requirement of a high repetition rate light source, hence the need for an equivalently high repetition rate injector.

Table 1: Design goals for a HAC 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

The final rep rate will determine whether a normal conducting or SRF gun is required. However, research is required immediately to ensure both options exist. The maximum anticipated operating parameters for this injector are listed in Table 1.

As part of the EuroFEL design study, a 100 mA CW gun was studied [2] and therefore these parameters have been chosen as the upper limit for the injector design, since the likely operational parameters for the New Light Source will not be as demanding, the injector design could work well within the machine requirements.

MODULE DESIGN

Studies of the SRF gun cavity were carried out in [2] and the final design utilised the TESLA shape for most of the structure. This design achieved the design goals with regards to the particle tracking studies, however further assessment of the geometry was carried out to evaluate the higher order mode (HOM) extraction.

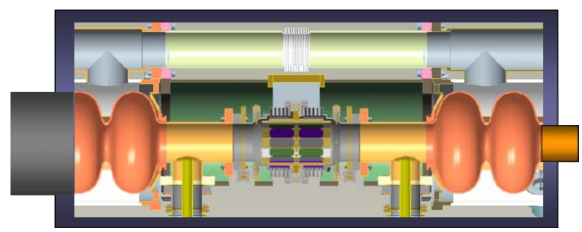

Figure 1: Layout of the injector

As well as the launch cavity, a second cavity for acceleration completes the injector, and for this an adapted Cornell, 2-cell cavity shape [3] has been studied. This should be sufficient to provide the necessary acceleration.

The beam pipe diameters have been widened to allow the HOMs to propagate. The HOMs are then absorbed by a broad band absorber [4] located in the space between these two cavities. The absorber consists of a series of ferrite and ceramic plates used to absorb over 200 Watts of RF power over a frequency range of 1 to 40 GHz.

The layout for the module will utilise experience gained from the development of a high duty factor accelerator module [5] currently under construction at Daresbury Laboratory.

HOM EXTRACTION

In order to improve the propagation of the HOMs, a study of the iris geometry was carried out. Trapped HOMs will interact with the beam causing unwanted emittance growth. By increasing the iris diameter, the power of the HOM trapped in the cavity is significantly reduced, thereby lessening the interaction with the beam. The implication of broadening of the beam pipe has the undesirable effect of reducing the efficiency of the

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fundamental accelerating mode, by reducing its R/Q. A compromise between maintaining the high efficiency and minimising the emittance growth has to be evaluated. Three extreme cases were studied. Figure 2 shows the cavity shape. Option 1 is the original TESLA cavity shape, with a beam pipe radius of 39 mm. Option 2 includes an end Iris, opening to 53mm, whilst option 3 broadens straight out to the 53mm beam pipe.

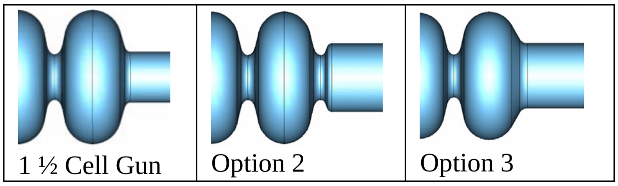

Figure 2: End cell optimisation

For each cavity geometry, an assessment of the R/Q for the fundamental and HOMs was carried out. The R/Q for each cavity mode is displayed in Figure 3. Option 3 yields only a 7% drop in the R/Q for the fundamental mode compared to option 1, whilst The R/Q for the strongest HOMs are 40% less. Therefore the increase in power required to generate the RF voltage is easily outweighed by the drop in HOM power trapped in the cavity.

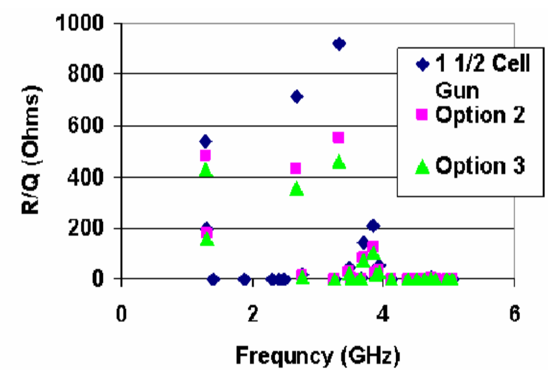

Figure 3: HOM Assessment

RF POWER DELIVERY

RF power is delivered to the cavity via a number of fundamental power couplers (FPC). Geometrical restraints restrict any more than 3 couplers per cavity, see Figure 4. Each FPC is fed by an individual RF source. At 1.3 GHz, the peak CW RF power per transmitter available is around 160 kW from a Klystron. Due to losses in the transmission line (20%) and overhead required for the LLRF control system (10%), only 110 kW of power is available for acceleration.

Assuming 3 FPCs per cavity, the peak RF power that can be delivered to the injector module limits the total acceleration to approximately 6.5 MeV. For 100 mA average beam current, 3 FPCs per cavity will be required. To minimise the asymmetries in the EM fields, and therefore minimise the coupler kicks, each FPC is placed equidistant around the circumference of the beam pipe.

To further reduce any asymmetric kick to the beam, it is recommended to avoid the coupler penetrating into the beam pipe. The Cornell coupler “pringle” shaped antenna has high levels of coupling, without penetrating into the beam pipe, even for critical coupling.

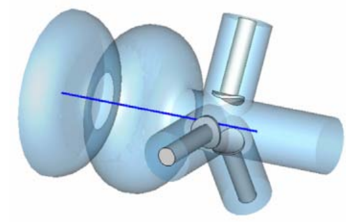

Figure 4: Location of couplers on gun cavity

For optimum coupling, the required RF power to generate the accelerating field is equivalent to the power transferred to the beam. Therefore, $P=V_{acc}I_b$. and the operational Q_{ext} optimum for the cavity is calculated from equation 1.

$$Q_{opt} = \frac{V_{acc}}{\frac{R}{Q} I_b \cos\phi_b} \qquad (1)$$

For <650 MHz repetition rate it is assumed that a modified Cornell coupler could be used, as this has been tested to levels 50 kW CW. This coupler has the ability to adjust the Q_{ext} by adjusting the length of the inner conductor. This requires the use of bellows and limits the coupler to 50 kW. It is proposed that removing the bellows may improve the power handling capability of this coupler even further. Assuming that over 100 kW CW is possible with the modified coupler, it may then be possible to use only two FPCs per cavity.

For lower average current, only 1 FPC may be required. RF simulations demonstrate an order of magnitude increase in the transverse fields compared to 2 FPCs situated in opposition, for an equivalent accelerating voltage. Figure 5 is a plot of the transverse voltage along the beam pipe axis in the region of the couplers.

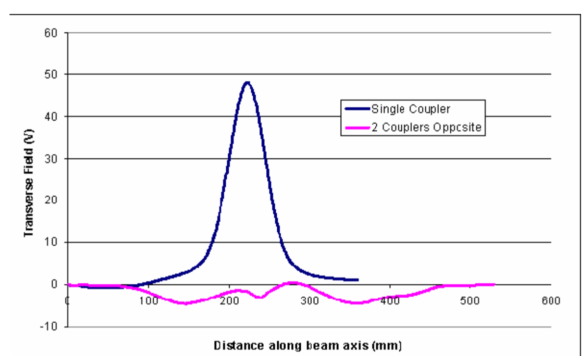

Figure 5: Asymmetric fields in near coupler

In the injector, the electrons are non relativistic, and the fields are low in comparison with the TESLA accelerating cavity, therefore asymmetric fields are highly influential. The kick is proportional to the transverse field and inversely proportional to the accelerating voltage, see equation 2 below.

$$kick = \frac{V_t}{V_{acc}} = \frac{\int (E_y + cB_x) dx}{\int E_z dz} \quad (2)$$

Where V_t is the transverse voltage and V_{acc} is the accelerating voltage. Since the accelerating voltage is fixed for the injector, there is a large advantage in minimising the transverse voltages to preserve the highest possible emittance. For this reason a dual FPC scheme mounted opposite is being considered over a single FPC, even for lower power options.

CATHODE AND LASER ISSUES

The choice of cathode material will strongly affect the engineering design of the injector. Since the cathode is mounted on or very close to the SRF cavity surface, the preference would be to use the cavity surface as the cathode. Studies have been carried out to utilise the niobium surface, however for CW operation, the laser power required to produce sufficient current would destroy the superconducting surface.

Table 2: Cathode material options

Type	QE	Lifetime	Work Function	Examples
Metals	$\approx 10^{-4}$	Months	≈ 4 eV	Copper, Lead, Niobium,
Semi-conductor	$\approx 10^{-2}$	Hours	≈ 2 eV	GaAs, Ce2Te

For different operating regimes of an SRF injector it is clear to see when a metal or semiconductor cathode can be used. Assuming a quantum efficiency (QE) of 5 x 10^{-5} requires 100 μJ of Laser energy to generate 1nC of photocurrent. Operating at 100 Hz, equates to 10 mW of laser power required, or 100 W at 1 MHz. In this regime a metal cathode is possible.

In terms of the operating requirement for this injector, at a rep rate of 1.3 GHz, requires 7.7 μJ of laser energy to generate the 77 pC bunches. For a metal cathode at 1.3 GHz, this equates to 10 kW and for a semiconductor cathode at 1.3 GHz, this equates to 100 W of laser power. Clearly this rules out the use of a metal cathode, and therefore there is a requirement to engineer a method for mounting the cathode that is both thermally and electrically isolated from the SRF cavity. Semiconductor cathodes have the disadvantage that they require extreme vacuum conditions to provide a useable lifetime, and therefore the enhanced vacuum conditions achieved from cryogenic pumping provides an additional advantage for adopting SRF technology.

The main concern when adopting a semiconductor cathode would be the lifetime. This would require regular changes or in-situ replenishment of the cathode. The simplest technique would be to allow for fast exchange of cathode barrel in a vacuum environment behind the cathode mounting. This is a must for continuous long term operation of a user facility.

FINAL INJECTOR PEFORMANCE

Figure 6 displays the final beam properties for the RF design and highlights how the goals for the beam properties have been met. The energy gain has not reached the design goal of 10 MeV, due to limitations of the RF power delivery and to avoid breakdown in the cavities. The conceptual RF deign of the injector has progressed enough to begin addressing the mechanical design issues.

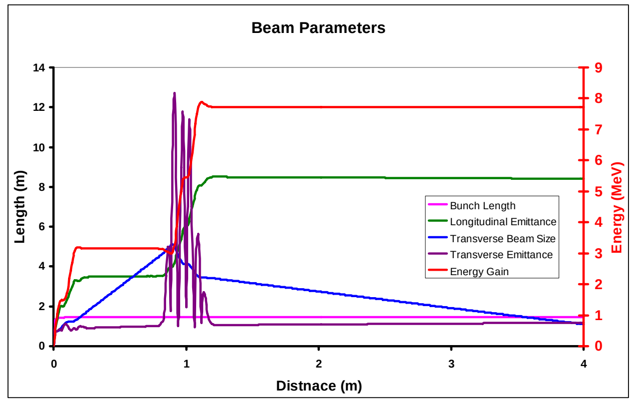

Figure 6: Final beam characteristics

CONCLUDING REMARKS

The design study for the high average current injector has been completed in terms of the physics design and the ability to meet the specification defined. A SRF gun would be the only viable option for large duty factors (>1MHz up to CW), therefore further research into cathode materials and cathode housing will be required.

The optimisation of the cavity shape will also require verification, to ensure a high efficiency is maintained, simultaneously reducing the HOM power excited.

REFERENCES

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