NORMAL-CONDUCTING HIGH CURRENT RF PHOTOINJECTOR FOR HIGH POWER CW FEL*

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Abstract

An RF photoinjector capable of producing high average current with low emittance and energy spread is a key enabling technology for high power CW FEL. The design of a 2.5-cell, π-mode, 700-MHz normal-conducting RF photoinjector cavity with magnetic emittance compensation is completed. With average gradients of 7, 7, and 5 MV/m in its three accelerating cells, the photoinjector will produce a 2.5-MeV electron beam with 3-nC charge per bunch and transverse rms emittance below 7 mm-mrad. Electromagnetic modeling has been used extensively to optimize ridge-loaded tapered waveguides and RF couplers, and led to a new, improved coupler iris design. The results, combined with a thermal and stress analysis, show that the challenging problem of cavity cooling can be successfully solved. Fabrication of a demo 100-mA (at 35 MHz bunch repetition rate) photoinjector is underway. The design is scalable to higher average currents by increasing the electron bunch repetition rate, and provides a path to a MW-class FEL. This paper presents the cavity design and details of RF coupler modeling.

INTRODUCTION

The design of a demo 700-MHz CW RF photoinjector (PI) accelerating a 100-mA electron beam (3 nC bunches at 35-MHz repetition rate) was discussed in [1]. A normal-conducting 2.5-cell RF cavity with gradient E_0=7 MV/m in all three cells brings the beam to 2.7 MeV. The solenoidal focusing keeps the transverse rms emittance below 7 mm-mrad at the wiggler. The challenging problem of the cavity thermal management can be solved with water cooling, but the power density near the RF coupler irises was very high, above 220 W/cm^2.

To reduce the maximal power density, and therefore to simplify iris cooling and reduce stresses, the RF cavity was modified. In its new design, the 2.5-cell cavity has the electric field gradients of 7, 7, and 5 MV/m in the three subsequent cells. We call it the “775” design. Due to lower RF fields in the third cell, and because of a new RF coupler [2], the highest power density near the coupler irises was reduced almost two times, down to 120 W/cm^2. At the same time, this design satisfies all beam dynamics requirements. The only noticeable change is the beam exit energy of 2.54 MeV. It can be easily compensated in the injector booster cavity, if needed, see [1].

RF CAVITY DESIGN

Similar to the previous (777) design, the new RF cavity of the high-current CW photoinjector consists of 2.5 cells plus a vacuum plenum. The cells are on-axis electrically coupled through large beam apertures. The layout is illustrated in Fig. 1. The first half-length cell, where a photocathode is housed, is followed by two full-length cells and a vacuum plenum with pump ports. Cooling water pipes, as well as two tapered ridge-loaded waveguides for RF input, connected to the third cell, are also shown.

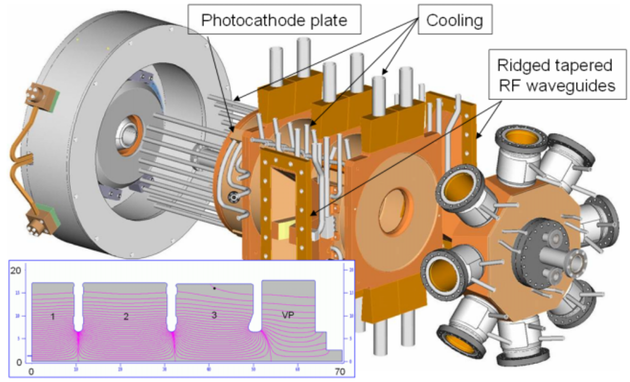

Figure 1: Photoinjector RF cavity with vacuum plenum (VP, right) and emittance-compensating magnets (left).

The basic 2-D design of the photoinjector RF cavity was performed using the Poisson/Superfish (SF) and Parmela [3] beam dynamics simulations. The insert in Fig. 1 shows the electric field lines calculated by SF; dimensions are in cm. The final cavity design is a result of iterations with SF and MicroWave Studio (MWS) [4] eigensolver, followed by thermal analysis. MWS eigenmode computations give frequency shifts due to 3-D details of the cavity (vacuum pump ports, coupler irises). They are taken into account, so that the working-mode frequency will be 700 MHz with 3-D effects included. The surface-current distribution inside the copper PI cavity for the 775 design is plotted in Fig. 2. Compared to the 777 design, the fields in the third cell are lower, which reduces the power density on the coupler irises.

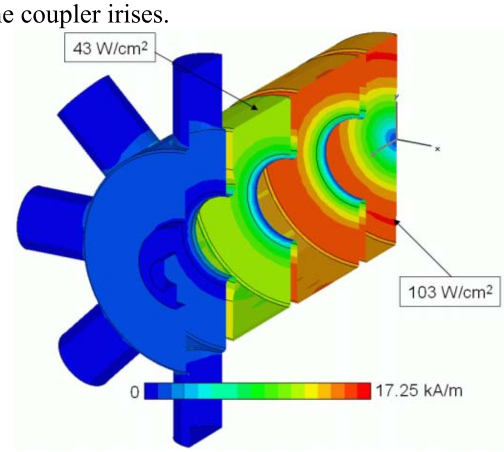

Figure 2: Surface current distribution of the π-mode in the 2.5-cell RF cavity for 775 design (MWS eigensolver).

* Supported by the DoD High Energy Laser Joint Technology Office through a contract from NAVSEA.

The wall power loss density is about 43 W/cm^2 at the location where the RF coupler iris will be attached; for the 777 it was 75 W/cm^2. The highest power density in the cavity without RF couplers is on the cell septa and on the first half-cell end wall – slightly above 100 W/cm^2.

Some 775 PI parameters are summarized in Tab. 1. The wall power loss is either calculated by Superfish/MWS for copper surface at 20° C (SF), or found by the thermal analysis (TA), where the resistivity was considered at the surface temperature with the cooling taken into account.

Table 1: Parameters of demo 100-mA CW photoinjector

Parameter	Value
Exit beam energy, MeV	2.54
Total beam power, kW	254
Wall power loss, kW (SF | TA)	668 | 728
Max loss power density, W/cm^2 (SF | TA)	103 | 114

NEW RF COUPLERS

For 100-mA operation of the normal-conducting CW PI, more than 900 kW of RF power is required, cf. Tab. 1. The power is fed into the cavity through two ridge-loaded tapered waveguides (RLWG). Their design is based on experience from the LEDA RFQ and SNS. The matching ridge was made narrow to minimize a possibility of multipacting. The ridge reduces reflections of input RF power due to waveguide tapering. Its profile was designed using 2-D SF calculations for multiple cross sections. 3-D MWS S-parameter computations confirmed that the reflections in RLWG were indeed small at 700 MHz.

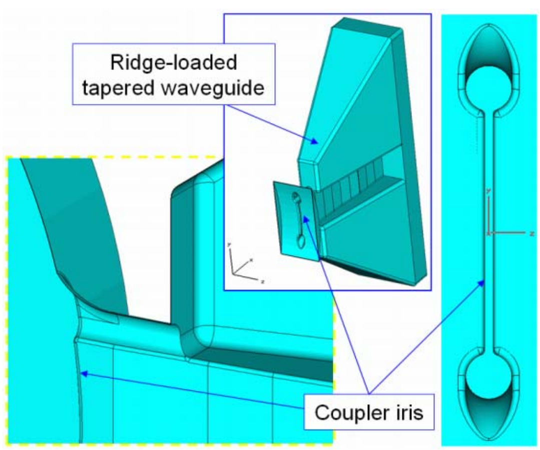

Figure 3: Coupler iris: cut-out view through the middle of the iris gap (left); view from inside the cavity (right).

RLWGs are connected to the third cell via “dog-bone” shaped RF coupler irises in the thick wall, not shown in Fig. 3-4. Cooling channels are embedded in the wall. The iris consists of a 2″-long narrow slot with two holes near its ends. Compared to the earlier design [5,1], the iris holes are larger (radius 4.75 mm instead of 2.5 mm) and have a smooth blending into the cavity. The wall thickness is increased from 0.5″ to 1.2″ in the place of RLWG connection to the cavity. The narrow iris slot produces only small perturbations of the cavity RF fields. The coupling is adjusted by changing the radius of the iris holes.

Time-domain MWS simulations have been applied to design the RF couplers [2,5] using a model shown in Fig. 4: a short pill-box cavity with two tapered RLWGs. This cavity is a slice cut out of the third cell of the PI cavity; it has the same radius, 169.24 mm. The frequency of the TM_{010}-like mode in the pill-box without couplers is adjusted to 700 MHz by choosing the axial length of the on-axis cylindrical extension.

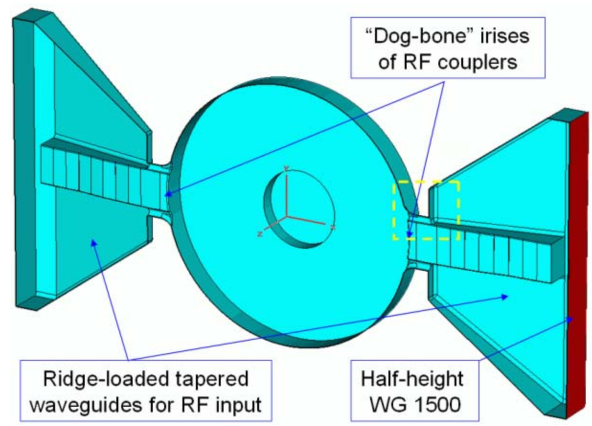

Figure 4: MWS model of RF couplers: a cut-out view through the iris mid-plane, cf. blow-up in Fig. 3 (left).

The required waveguide-cavity coupling for the 2.5-cell PI cavity with 100-mA current is $\beta_c=(P_w+P_b)/P_w\approx1.38$, where P_w=668 kW is the wall power loss, and P_b=254 kW is the beam power at the cavity exit, cf. Tab. 1. When the same couplers are connected to the model pill-box cavity, the coupling is $\beta_{pb}=\beta_c(W_c/W_{pb})(H_{pb}/H_c)^2$. Here W_i, H_i, Q_i – the stored energy, magnetic field at the coupler location (without coupler), and unloaded quality factor – are easily calculated with eigensolvers. Then the required value of the external quality factor for our pill-box model is Q_e= $Q_c/\beta_c(W_{pb}/W_c)(H_c/H_{pb})^2$ = 1933. We use direct MWS time-domain calculations to find the external quality factor of the model [2]. The structure is excited with a short RF pulse, and the fields decay due to radiation through the coupler irises. Since all metal surfaces are perfectly conducting, the field decay constant is directly related to Q_e. For the iris with the slot width 1.788 mm and the blend radius inside the cavity 19 mm, the correct coupling is achieved for the hole diameter equal to 9.5 mm.

Another MWS time-domain simulation gives the field distributions [2]. An RF input signal at the model cavity resonance frequency (with RLWGs), f_{res}= 698.727 MHz, has the amplitude that gradually increases and then remains constant. Figure 5 shows the input and output signals at the WG port. With a constant waveguide input, the output decreases reaching a point (t=685 ns) where it vanishes, and increases again after that. This is due to a destructive interference of the wave reflected from the coupler iris, and that radiated into WG from inside the cavity. The reflected-wave amplitude remains constant when the input is constant, while the radiated-wave amplitude increases as the cavity field increases. These two waves are always in opposite phases, and at the moment when they cancel each other, the reflected power vanishes. It corre-

0-7803-8859-3/05/$20.00

sponds to an exact match; snapshots give us field distributions for the matched 100-mA case. Another interesting point in Fig. 5 is where the output amplitude reaches 16% of the RF input amplitude (t=850 ns). It corresponds to the thermal-test situation, when the PI cavity is tested running with the nominal field gradients but without beam. In that case, due to a mismatch, the power reflected back into the waveguides is equal to 2.5% of the input RF power [2].

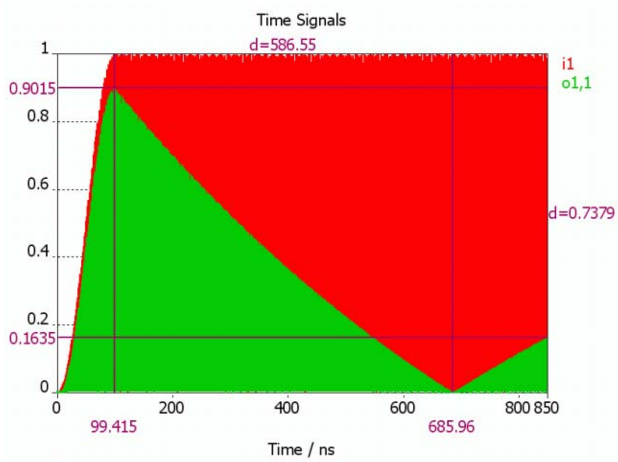

Figure 5: Waveguide input (red) and output (green) signals from MWS time-domain calculations.

A surface-current snapshot at the match (t=685 ns) is shown in Fig. 6. The max field values are near the ends of the coupler irises. The field scaling is for 0.5 W of average power per WG, while it should be 461 kW per WG for the matched 100-mA case. This gives us the scaling factor of 960 for the fields at the match, in Fig. 6. The max power density near the iris ends is about 120 W/cm^2, assuming copper surfaces. The regions of high power density are small and well localized, which makes easier their cooling with dedicated cooling channels. For the thermal-test point (t=850 ns) the field picture is similar. The field is higher than in Fig. 6, but its scaling factor is lower (827), since the total RF power without beam, but with 2.5% reflection is 342 kW per WG. The max power density on the iris, 120 W/cm^2, is the same as for the 100-mA match, confirming that the cavity thermal management can be validated without beam. The power loss density in the tapered RLWG is relatively low. Since the field structure inside the cavity is similar to that of the cavity eigenmode, we used eigensolvers to cross-check the max field values near the irises [2]. Such calculations give incorrect fields in waveguides, but are much faster than in time domain, even with fine meshes. This approach gives the max power density near the iris ends 118 W/cm^2.

Based on the above results, the maximal power density on the coupler irises for the 775 design is 120 W/cm^2. The power density on the smooth walls at the iris location is 43 W/cm^2, Fig. 2. The ratio is 2.79, i.e. the magnetic field enhancement due to the iris presence is only by a factor of $\sqrt{2.79} = 1.67$. For comparison, in the LEDA RFQ couplers such a power ratio was about 10, with the maximal power density near the iris ends around 150 W/cm^2.

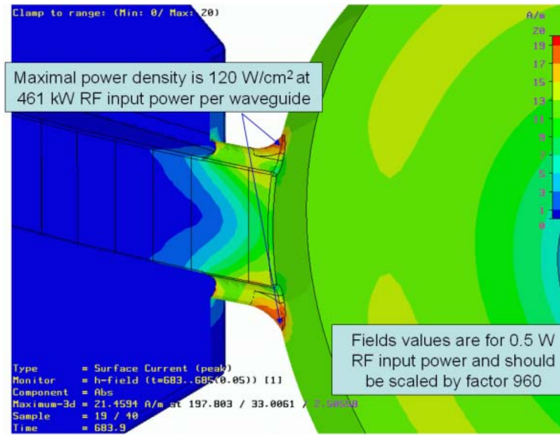

Figure 6: Surface-current distribution near the coupler iris for the matched case. Note the field scale.

Another useful comparison is with the 777 design. The max power density on the irises was above 220 W/cm^2 [1], mainly due to the higher smooth-wall power density, 75 W/cm^2. The ratio was still below 3, but the max density was higher than what has already been successfully demonstrated in the LEDA CW operation. This fact was the main reason for changing to the 775 PI cavity design.

CONCLUSIONS

The presented design surpasses the required beam parameters while addressing the key issue for a high-current normal-conducting CW RF photoinjector (PI), namely, an effective structure cooling. It provides a path forward to a very high power amplifier FEL. Upgrading the RF cavity for currents up to 1 A is straightforward [2].

A 100-mA CW operation of the normal-conducting RF PI cavity requires almost 1 MW of 700-MHz RF power. The RF couplers are optimized to reduce the max power density on the irises down to 120 W/cm^2, only about 15% higher than the max power density in the smooth cavity without couplers, 103 W/cm^2. These values are well below those for the coupler irises in the LEDA RFQ.

The full-power prototype photoinjector RF cavity is being fabricated by AES. Our plan is to install the prototype in the existing facilities at LANL and to perform its RF and thermal testing without beam in early 2006.

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