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

Los Alamos NATIONAL LABORATORY

Systems, Energy Advanced

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ABSTRACT

An RF photoinjector capable of producing high continuous 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 the electric field gradients of 7, 7, and 5 MV/m in the three cells, the photoinjector will produce a 2.5-MeV electron beam with 3-nC charge per bunch and 7 mm-mrad transverse rms emittance. Electromagnetic modeling was used extensively to optimize ridge-loaded tapered waveguides and RF couplers, which led to a new improved coupler-iris design. The results, combined with a thermal/stress analysis, show that the challenging problem of cavity cooling can be successfully solved. A demo 100-mA (at 35-MHz bunch-repetition rate) photoinjector is being manufactured. The design is scalable to higher power levels by increasing the bunch repetition rate, and provides a path to a MW-class amplifier FEL. The cavity design and details of RF coupler modeling are presented.

INTRODUCTION

The design of a demo 700-MHz CW RF photoinjector (PI) that accelerates a 100-mA electron beam (3 nC per bunch at 35-MHz repetition rate) was discussed in Ref. [1]. In that design, 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 resolved with water cooling [1]. However, the power density near the RF coupler irises was very high, above 220 W/cm².

To reduce the maximal power density, and therefore to simplify iris cooling and reduce stresses, the RF cavity was modified. In its new, more conservative, design, the 2.5-cell RF 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, as well as because of a new RF coupler [2], the highest power density near the coupler irises was reduced almost two times, down to 120 W/cm². At the same time, the 775 design of the RF cavity satisfies all the beam dynamics requirements. The only noticeable change is the beam exit energy of 2.54 MeV; this 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 consists of 2.5 cells plus a vacuum plenum. The cells are on-axis electrically coupled through large beam apertures. The layout (Fig. 1) includes emittance-compensating magnets: a solenoid and a bucking coil. After the first half-length cell, where a photocathode will be housed, there are two full-length cells, followed by a vacuum plenum with eight vacuum-pump ports. Figure 1 shows cooling water pipes, as well as two ridge-loaded tapered waveguides for RF input, which are connected to the third cell.

The basic 2-D design of the photoinjector RF cavity was performed using Poisson/Superfish (SF) codes [3] and Parmela [4] for beam dynamics. Fig. 2 shows the electric field lines found by SF. One can see tuning rings on the separators, i.e. on the cavity walls separating cells 1 & 2, as well as 2 & 3.

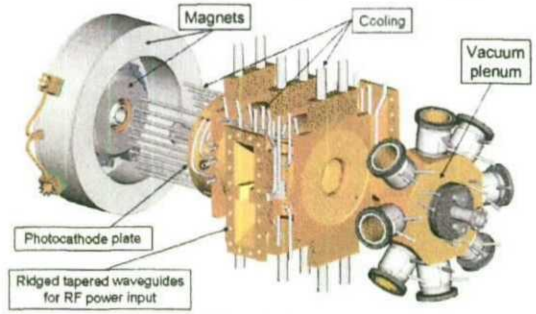

Figure 1: Photoinjector RF cavity with vacuum plenum and magnets.

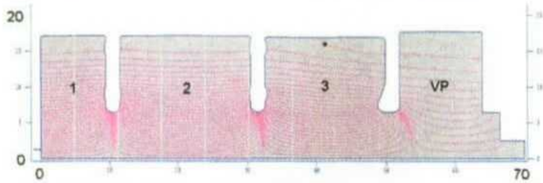

Figure 2: Electric field lines in 2.5-cell RF cavity (dimensions are in cm).

The final cavity design is a result of iterations made with SF and MicroWave Studio (MWS) [5] eigensolver, followed by thermal analysis. MWS eigenmode computations included frequency shifts due to 3-D details of the cavity (vacuum pump ports, coupler irises) [6], which have been taken into account in the SF design. Compared to the 777 design, the fields in the third cell are reduced. This does not have an adverse effect on the beam emittance, because the beam energy is already high enough after the first two cells, but allows reducing the power density on the coupler irises in the third cell. The surface-current distribution inside the copper PI cavity for the 775 design is plotted in Fig. 3. The reduced gradient in the third cell leads to lower values of the wall power loss density, compared to the first two cells. It is about 43 W/cm² at the location where the RF coupler iris will be attached. The same density for the 777 design was 75 W/cm². The highest power density in the cavity without RF couplers is slightly above 100 W/cm².

Some parameters of the photoinjector are summarized in Tab. 1. The values of the wall power loss are either calculated by Superfish or MWS for copper surface at 20° C, or found by thermal analysis, where the resistivity was considered at the surface temperature with cooling taken into account.

*Supported by the DoD High Energy Laser JTO through a contract from NAVSEA

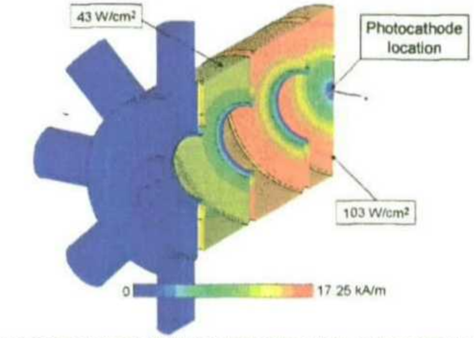

Figure 3: Surface current distribution in the 2.5-cell RF cavity for 775 design.

Table 1: Parameters of demo 100-mA CW RF photoinjector cavity.

Parameter	Value
Exit beam energy, MeV	2.54
Total beam power, kW	254
Wall power loss from Superfish, kW	668
Wall power loss from thermal analysis, kW	728
Max wall loss power density (Superfish), W/cm²	103
Max wall loss power density (thermal analysis), W/cm²	114

NEW RF COUPLERS

For 100-mA operation of the normal-conducting CW photoinjector, more than 900 kW of RF power is required. This power will be fed into the cavity through two ridge-loaded tapered waveguides (RLWG). Figure 1 shows only the tapered ridge-loaded section of the RF input WG; its larger cross section is equal to a half-height WR1500. This section is connected to another transition, from the half-height to a standard full-height WR1500. The RLWG 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. The ridge profile was designed using 2-D SF calculations for multiple cross sections. 3-D S-parameter computations with the MWS have confirmed that the input signal reflections in RLWG are indeed small at 700 MHz.

The RLWGs are connected to the third cell of the cavity via "dog-bone" shaped RF coupler irises in the thick cavity wall. Time-domain MWS simulations have been used to design and optimize the RF couplers [2]. The procedure was described in [7]. The iris consists of a 2"-long narrow slot with two cylindrical holes near its ends. Compared to the earlier version [7, 1], the coupler design is significantly modified. The iris holes are now larger (radius 4.75 mm instead of 2.5 mm) and have a smooth, large-radius blending into the cavity. The wall thickness is increased from 0.5" to 1.2" in the place where the RLWG is connected to the cavity.

Details of the new coupler are in Figs. 4-5. Only the vacuum (inner) parts of the cavity and coupler are shown; they are surrounded by metal walls with embedded cooling channels. The iris slot (gap) is very narrow, so the coupler irises introduce only small perturbations to the cavity RF fields. The coupling is adjusted by changing the radius of the iris holes.

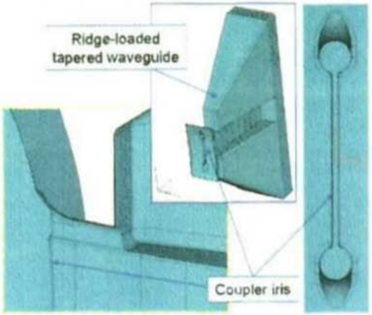

Figure 4: Coupler iris: cut-out view through the middle of the iris gap (left); view from inside the cavity (right).

For MWS time-domain calculations we use a model of Fig. 5: a pill-box cavity with two attached tapered ridge-loaded waveguides. The cavity is essentially a slice cut out of the third cell of the PI cavity; it has the same radius as the third cell, 169.24 mm. The frequency of the TM_{010}-like mode in the pill-box without couplers is adjusted to be 700 MHz by choosing the axial length of the on-axis cylindrical extension.

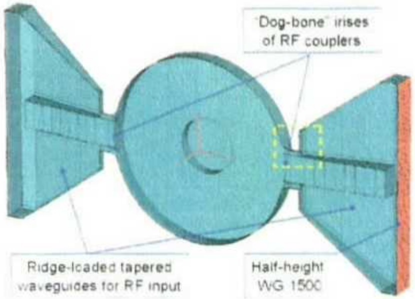

Figure 5: MWS model of RF couplers: a cut-out view through the iris mid-plane, cf. blow-up in Fig. 4 (left).

The required waveguide-cavity coupling for the 2.5-cell PI cavity with 100-mA current is $\beta_c=(P_w+P_b)/P_w=1.38$, cf. Tab. 1. When the same couplers are connected to the pill-box cavity in our model, the coupling will be different. It can be related to the external quality factor of the pill-box cavity. We use direct MWS time-domain calculations to calculate the external quality factor in the model and to adjust the coupling [2]. First, the structure is fed with a short RF pulse through the waveguide port (red). The fields excited in the pill-box then decay due to radiation through the coupler irises into WG. The field decay constant is directly related to the cavity external quality factor. For the iris in Figs. 4-5, 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 9.5 mm.

Another MWS time-domain simulation is performed to find the field distributions. The RF input signal at the model cavity resonance frequency (with RLWGs), f_{res}= 698.727 MHz, gradually increases and then remains constant. Fig. 6 shows the input and output signals at the waveguide port. With the constant waveguide input, the output decreases reaching a point (t=685 ns) where it vanishes, and increases again after that. The output decrease is due to a destructive interference of two waves: one is reflected from the coupler iris, and the other is radiated into the waveguides 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 certain moment they cancel each other, so that the reflected power vanishes. This corresponds to an exact match; snapshots at that moment give us field distributions for the matched (to 100 mA) case. Another interesting point in Fig. 6 is where the output amplitude is 16% of the input (t=850 ns). It corresponds to the thermal-test situation, when the cavity will be tested running with the nominal field gradients but without beam. The power reflected back into the WG is 2.5% of the input RF power, see [2].

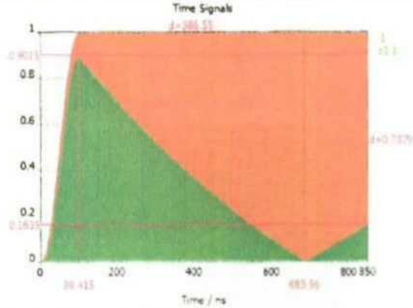

Figure 6: Waveguide input (red) and output (green) signals.

A snapshot of the surface currents in the MWS model taken at the match (t=685 ns) is shown in Fig. 7. The maximal field values are near the ends of the coupler irises. The max power density near the iris ends is about 120 W/cm², assuming that the cavity surface is copper. The regions of high power density are small and well localized, which makes their cooling easier with dedicated cooling channels.

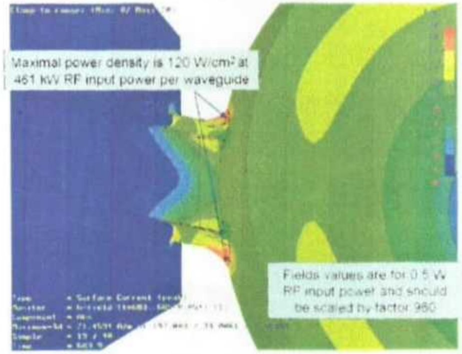

Figure 7: Surface-current distribution near the coupler iris for the matched case.

For the thermal-test point (t=850 ns) the field picture is similar to Fig. 7. With total RF power (without beam, but with 2.5% reflection) $1.025P_w$ = 684.7 kW (342 kW per WG), the max power density on the iris, 120 W/cm², is the same as for the 100-mA matched case. This result confirms that the cavity thermal management can be validated without beam. It shows also that the hottest spots are defined by the fields inside the cavity, not by the amount of the RF power fed through waveguides. One can see from Fig. 7 that the power loss density in the tapered RLWG is relatively low.

Because the field structure inside the cavity is similar to that of the cavity eigenmode, we can use eigensolvers to cross-check the maximal field values near the irises [2]. Such calculations do not give correct fields in waveguides (due to boundary conditions), but they are much faster than in time domain, even with rather fine meshes. This approach gives the max power density near the iris ends 118 W/cm², close to the time-domain results.

Based on the above results, the maximal power density on the coupler irises for the 775 design is 120 W/cm². It should be compared to the power density on the smooth walls at the iris location, 43 W/cm², cf. Fig. 3. The ratio is 2.79, which means that 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, while the maximal power density near the iris ends was around 150 W/cm². In our design, the coupler irises create much smaller distortions of the cavity magnetic field, so the maximal power density is below that in the LEDA RFQ couplers, even though the average smooth-wall power density is almost three times higher.

Another useful comparison is with the 777 design. The maximal power density on the irises was above 220 W/cm² [1], mainly due to the higher smooth-wall power density, 75 W/cm². The ratio was still below 3, but the maximal density was higher than what has already been 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), 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, see in [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 maximal power density on the irises. As the result, the magnetic field enhancement due to the coupler irises is only 67% above the field on the smooth cavity wall in the same cavity cross section. For the 775 design of the PI cavity, the maximal power density near the irises is 120 W/cm², only 15% higher than the maximal global power density in the smooth cavity without couplers, 103 W/cm². These values are well below the maximal power density on the coupler irises in the LEDA RFQ, which was successfully operated in CW with 100 mA of the proton beam current.

The full-power prototype RF cavity is being manufactured, see [8]. Our plan is to install the prototype in the existing facilities at LANL and to perform RF and thermal testing without beam in 2005.

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