MITIGATION OF ELECTRIC BREAKDOWN IN AN RF PHOTOINJECTOR BY REMOVAL OF TUNING RODS IN HIGH-FIELD REGIONS[*]

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Abstract

The π-mode resonant frequency of the 1.6 cell SLAC/BNL/UCLA style RF photoinjector electron gun is conventionally tuned using cylindrical copper tuning pieces that extend into the full-cell cavity through holes in the side of the gun. This design begins to fail in many versions of this popular gun design at higher voltage levels, when the cavity undergoes electric breakdown in the vicinity of the tuners. In order to remove the tuners from the region of high electric field, mitigating this problem, the full cell geometry must be changed significantly. We report on a method of accomplishing this, in which we use a mechanical device of custom design to stretch the cavity structure of an existing photoinjector in order to tune the resonant frequency up by over 2 MHz. We present results of testing the modified photoinjector in an RF test bed with both copper and magnesium cathodes, succeeding in putting approximately 8 - 10 MW of RF power into the gun. This is an improvement over the 4 MW routinely achieved in a similar gun using conventional tuning methods installed at the UCLA Neptune laboratory.

INTRODUCTION

The 1.6-cell S-band RF photoinjector design is currently used in many high-brightness electron beam laboratories [1, 2, 3]. This electron beam source consists of a cylindrical copper cavity divided by an iris into a full-cell, $\lambda/2$ in length, and a half-cell, $0.6\lambda/2$ in length. RF power is generated by a klystron and fed into the full-cell through a copper waveguide, driving a two-mode standing wave in the multi-cell structure via cell-to-cell coupling [4].

A circular cathode plate making up one end of the half-cell produces electrons when illuminated by a drive laser. These electrons are accelerated by the RF electric field along the axis of the cavity through both cells and out of the beam port. The accelerating π-mode resonates at an S-band frequency of 2856 MHz, with the fields in the cell centers oscillating at π radians out of phase with each other. This means that the longitudinal on-axis electric fields in each cell point in opposite directions, with a node of the standing wave at the center of the coupling iris. If the electrons are injected at the proper RF phase, field oscillations will be such that the electrons always see an accelerating field as they pass between the cells. Thus the voltage experienced by the electrons across the gun is the sum of the voltages across each cell.

Prior to beam operation the photoinjector needs to be tuned in order to precisely match the π-mode frequency of the structure with the frequency of the input RF power. Viewing the cavity as two capacitively-coupled LC circuits, tuning is accomplished by adjusting the inductances or capacitances of each circuit. The half-cell is tuned capacitively by forcefully deforming the cathode plate using a bolt threaded through a flange and into the back of the cathode. The full-cell is conventionally tuned inductively by inserting cylindrical copper tuning pieces into the cell. Finally, the π-mode position is adjusted *in situ* by changing the ambient temperature.

BREAKDOWN ISSUES

Gun Performance Limits

It is a somewhat common problem that the limit on achievable cavity voltage levels in such photoinjectors is much lower than expected, resulting in disappointing beam production. In these cases the cavity often performs normally during initial RF conditioning, accommodating satisfactory input power levels of 7 MW or more. At some point arcing occurs, apparently causing catastrophic damage, and thereafter the cavity is limited to much lower power levels. Some examples are the 1.6-cell RF guns at the UCLA Neptune and LLNL PLEIADES laboratories, with post-damage upper input power limits of 4.5 MW and less than 4 MW respectively [5].

There is *in situ* evidence pointing to the tuning rods in the full-cell as the cause of these crippling electric breakdown problems. The tuning rods are cylindrical copper pieces that extend into the full-cell from outside of the gun through holes in the cavity wall. They are mounted on mechanical actuators that allow adjustment. A metal spring encircles the tuning rod several millimeters from its end in order to maintain contact between the copper piece and the wall of the hole it sits in, providing an electrical seal. Darkening and roughening of the copper appear on the tuning piece after continued use, indicating that much arcing has taken place there.

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[*] Work supported by the United States Department of Energy

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Multipactoring and Gap Fields

Arcing in RF structures is often caused by multipactoring [6]. This is a phenomenon in which an electron strikes a metal surface, causing the emission of secondary electrons which then strike another surface, and so on in a chain reaction until there is a significant amount of charge involved.

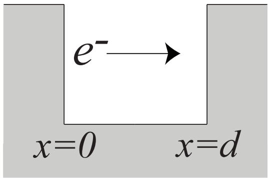

Figure 1: Diagram for calculation of multipactoring threshold field in tuner gap. Illustration represents the gap between the tuning piece and the hole wall, with the lower conducting boundary representing the spring encircling the tuning piece.

To verify that it is reasonable to suspect arcing in the tuner gap, we will make a simple calculation of the electric field amplitude ideal for multipactoring in this geometry and compare it with an estimation of the field present in the gap. Referring to the diagram in Figure 1, consider an electron born on one side of the gap between the tuning piece and the hole wall, at position $x = 0$ with velocity $\dot{x} = 0$. The non-relativistic one-dimensional equation of motion for this electron in a sinusoidally-varying electric field is

$$m\ddot{x} = eE\sin\omega t\,. \tag{1}$$

Integrating twice and applying initial conditions yields the solution

$$x = \frac{eE}{m\omega^2}(\omega t - \sin\omega t)\,. \tag{2}$$

Conditions are ideal for multipactoring if the applied electric field reverses direction at the moment the electron strikes the wall and secondary electrons are emitted, so that they are accelerated back toward the other side of the gap. This situation corresponds to $\omega t = \pi$ and $x = d$. Making these substitutions in Eq. (2) gives

$$eE_{\text{mp}} = mc^2\frac{4\pi d}{\lambda^2}\,. \tag{3}$$

Solving for E_{mp} and making the substitutions $\lambda = 10.49$ cm (S-band wavelength) and $mc^2 = 0.511$ MeV, we get

$$E_{\text{mp}} = 0.58\ \text{MV/m} \times d\ \text{(in mm)} \tag{4}$$

for the electric field amplitude ideal for multipactoring in terms of the gap width d in millimeters. In our case d is on the order of 1 mm, so we would expect to see multipactoring occur when a field of around $E = 0.58$ MV/m is present in the gap.

A simple estimation based on transmission line analysis shows that the electric field present in the tuner gap has a magnitude of $\sim$ 9.9 MV/m at the top of the gap and decreases sinusoidally to zero at the bottom of the gap. This indicates that at some point near the gap bottom, the field value is equal to the ideal multipactoring field, and the location of this field value moves up and down the gap as the field oscillates with time. Thus it is reasonable to expect significant amounts of multipactoring in the tuner gap.

Mitigating Breakdown

If multipactoring in the tuner gaps is indeed the cause of problematic breakdown, operating the photoinjector with tuners fully retracted may provide some improvement in the performance. Measurements indicate that retraction of the tuners decreases the π-mode frequency by over 2 MHz in this particular photoinjector. This frequency difference is far too large to compensate for with temperature tuning, which provides only 44 kHz of tuning per degree Celsius. The solution we chose in this study was to physically deform the full-cell structure in order to regain the 2 MHz lost by removal of the tuners. The frequency-domain analysis code SUPERFISH [8] indicates that a 150 μm displacement of the downstream full-cell wall produces the desired results.

It is not immediately clear that having the tuning pieces pulled out of the tuning holes will be an improvement, because the empty holes in the side of the full-cell remain. Studies of the effects of defects in conducting planes on surface currents [7] show that the cases of a right circular cylindrical hole (empty tuner hole) and a circular annular hole (tuner hole with tuning piece present) are equivalent in terms of perturbations to surface currents on the surrounding conducting plane. In both instances, the surface fields on the surrounding plane are unperturbed. The difference in arcing behavior then lies in the effective gap width in which multipactoring takes place. In the filled hole case the gap width is small, $\leq$ 1 mm, which was the basis for our estimation of E_{mp} above. In the empty hole case the distance across the gap is considerably larger, meaning an increase in the field required for multipactoring to occur.

HARDWARE DESIGN

The full-cell was stretched using a custom mechanical device designed and fabricated at UCLA. The device consists of three metal plates separated by stainless steel rods, and a large steel threaded bolt to apply the stretching force. Figure 2 shows a photograph of the stretcher device installed on the gun, illustrating the assembly. The stretcher device itself is artificially highlighted to appear very bright in the photograph so it can be easily visually distinguished from the body of the gun. The gun is clamped between two plates with the beam port extending through the upper plate. A third plate is raised above the beam port. A threaded rod extends through the third plate and is threaded through a flange bolted on to the beam port, with a nut tightened on the rod so it cannot move with respect to the beam port flange.

Stretching is accomplished by turning a nut located on the threaded rod above the third plate, tight against the

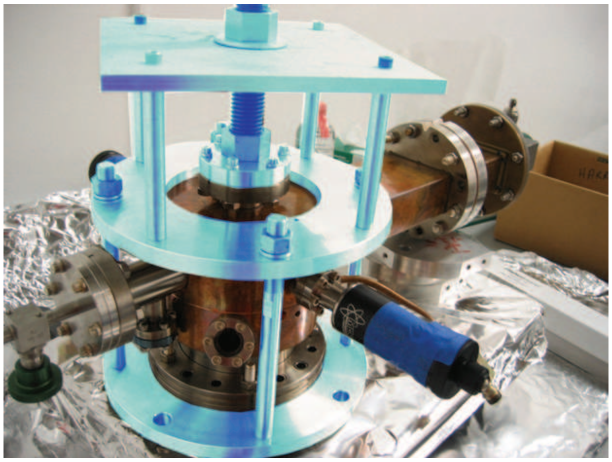

Figure 2: Stretcher device installed on photoinjector. Stretcher is artificially highlighted in photograph for clarity.

plate. The force of the pull is solely on the beam port flange, such that the downstream wall of the full-cell is moved during stretching. The π-mode frequency is monitored on a network analyzer connected through a waveguide coupler during stretching. An iterative process of stretching past the desired frequency and then releasing the bolt tension so that the full-cell relaxes is performed until the cell relaxes to the correct frequency under no tension.

RESULTS

Following stretching, RF measurements were made to verify the effect of the deformation. A bead-drop measurement of the field balance showed a $\sim$40 kHz difference between the frequency perturbations in the two cells, a discrepancy that was expected due to the presence of the dielectric wire attached to the metal bead. A measurement of the cell coupling yielded a good value of $\beta = 1.007$. These measurements served as indication that the structural distortion was not significant enough to damage the RF performance of the cavity.

The photoinjector was subsequently conditioned at high power with an unpolished copper cathode installed. RF power was delivered to the cavity as it would be during beam operation, and increased slowly until a high operating level was reached. As mentioned previously, that operating level is around 4.5 MW in a similar gun operating in the UCLA Neptune laboratory, with the tuning pieces in use. Removal of the tuners in our test gun allowed a level of 8.4 MW to be reached, a marked improvement. Conditioning was repeated using a polished magnesium cathode with similar success, reaching a level of approximately 9 – 10 MW. This improvement over the copper cathode case is most likely due to the polishing. In both cases the gun responded extremely well to conditioning. This gun is currently in use in an ultrafast electron beam laboratory at UCLA and is performing quite well [9].

SUMMARY

The 1.6 cell SLAC/BNL/UCLA style RF photoinjector electron gun is capable of operating at significantly higher levels of input RF power when the full-cell tuning pieces are removed from the cavity. Simple calculations and *in situ* evidence suggest that arcing occurs in the vicinity of the tuners when they are not fully retracted. This is supported by the increase in power accomodated by the gun after removal of the tuners.

An RF gun no longer in use in a linac system and known to have an unreasonably low RF power capacity was used as a test-bed for this study. After using a mechanical device to deform the cavity geometry so that frequency tuning could be accomplished without use of the full-cell tuning pieces, the cavity was conditioned at high voltage, accommodating up to 10 MW of forward power. This is a drastic improvements over previously achievable power levels of 4 – 4.5 MW. More recent photoinjectors are being designed to be used with the tuners completely retracted, an attribute that allows operation at much higher power levels, approximatley 15 MW in the case of ORION at SLAC. The results of this study are a successful verification that full-cell tuning rods negatively affect RF photoinjector performance.

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