PLANAR-FOCUSING CATHODES*

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Abstract

Conventional π-mode rf photoinjectors typically use magnetic solenoids for emittance compensation. This provides independent focusing strength but can complicate rf power feed placement, introduce asymmetries (due to coil crossovers), and greatly increase the cost of the photoinjector.

Cathode-region focusing can also provide for a form of emittance compensation. Typically this method strongly couples focusing strength to the field gradient on the cathode, however, and usually requires altering the longitudinal position of the cathode to change the focusing.

We propose a new method for achieving cathode-region variable-strength focusing for emittance compensation. The new method reduces the coupling to the gradient on the cathode and does not require a change in the longitudinal position of the cathode. Expected performance for an S-band system is similar to conventional solenoid-based designs. This paper presents the results of rf cavity and beam dynamics simulations of the new design.

INTRODUCTION

The standard SLAC/BNL/UCLA-type π-mode photoinjector physics design (see Figure 1) [1] has proven to be remarkably flexible and robust. Variations have been designed to operate over a frequency range from 700 MHz [2] to 17 GHz [3]. Improvement to rf field quality, first from port symmetrization [1] and later from improved rf power feed schemes (including on-axis power feeds [4] and a redesign of the side-wall power coupling scheme and full-cell geometry [5]) have resulted in considerably better engineering designs. Alternate cavity geometries have been devised to emulate the basic performance whil improving field balance stability [6]. Second-generation emittance compensation schemes, for instance the "new working point" method proposed by M. Ferrario [7], have led to better injector-region beamline designs. As a result of these improvements, many of these guns are starting to reach the performance predicted by various simulation codes.

There are a few features of the basic design which, even with these recent improvements, remain somewhat undesirable. One such feature arises from engineering practicalities, the other, from the basic physics. Both involve the solenoid focusing method used to implement emittance compensation.

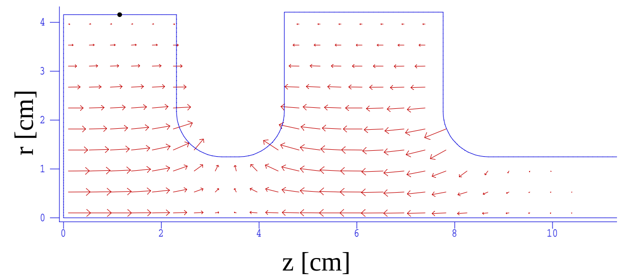

Figure 1: Geometry of basic BNL-type S-band gun. Arrows indicate electric field strength.

Most physical solenoid designs will have crossovers; that is, at some point, there must be a component of current flow parallel to the axis of the solenoid. In many designs the global axial current flow is zero, but local axial currents still must exist. These introduce non-zero transverse magnetic fields on the axis of the solenoid and can be expressed as a sum of dipole, quadrupole, etc., fields. These fields can impact the emittance compensation process, as well as x/y plane symmetry of the electron beam. A good solenoid design will minimize these effects, but to some level they will always be present.

The emittance compensation process is well-documented and described in many places. In general, the process involves allowing an electron beam to evolve, using a solenoid lens to provide a focusing kick based on the differential evolution of the various portions of the beam, and then using a capture linac section to accelerate and "freeze" the beam when it oscillates through a minimum-emittance point due to the solenoid kick. The main difficulty with this method is the oscillation itself; it is still important, even with second-generation schemes, to get the oscillation "just right" to generate and preserve the low emittance.

The use of a magnetic mode in an rf cavity to perform emittance compensation has been proposed [8]. This addresses the question of crossover effects (and introduces other, similar concerns relating to field quality in the cell), but the emittance oscillation effects still occur.

Alternate methods of emittance compensation have been contemplated, most often in the context of superconducting rf guns using cathode-region focusing [9]. The main difficulty with these schemes is that they usually operate by recessing and / or curving the cathode, reducing the field on the cathode surface relative to the maximum on-axis field (see Figure 2). Since the radial field is proportional to $-dE_z/dz$, this results in net focusing; to some extent, any cathode-region field-focusing scheme must make use of this principle.

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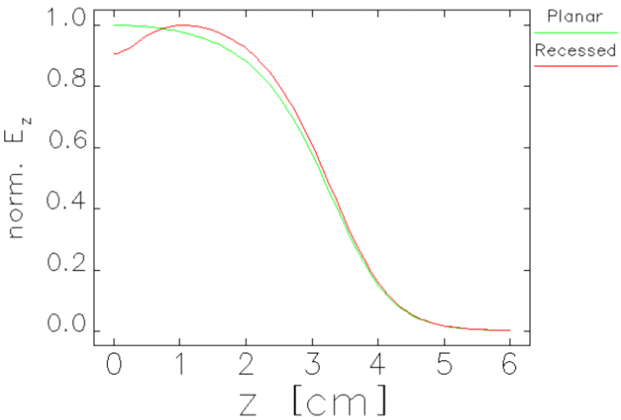

Figure 2: On-axis fields for a single-cell gun with a planar cathode surface (green) and a cathode recessed by 1 mm for a radius of 5 mm (green). Fields have been normalized to the on-axis peak.

Generally, in such a scheme, the focusing geometry is either fixed, or the focusing strength (normalized to the peak on-axis field) is altered by moving the cathode longitudinally. Although the latter approach provides some tunability, doing so can significantly alter the magnitude of the axial field on the cathode, as well as requiring a change in the cathode's physical position. There is also a subtlety here regarding where the focusing is applied. If the cathode surface is metallic and planar, no focusing is provided immediately at the cathode because the field will be normal to the surface. All focusing is provided as the beam travels from the cathode to the point of maximum on-axis field. Concave cathodes provide immediate radial focusing but require a drive laser pulse with a wavefront curved to match the cathode if the beam is not to have a concave leading edge and a convex trailing edge.

PLANAR-FOCUSING CATHODES

Ideally, one would like an emittance compensation scheme with the following properties:

- no azimuthal variation of the fields used to perform emittance compensation;
- independent control of accelerating gradient and "compensation" field strength (either at the cathode or downstream);
- planar cathode surface (for ease of laser preparation, off-axis injection, etc.);
- fixed position cathode emission surface;
- minimal variation of emittance from emission at the cathode to capture in the linac; and, of course,
- no reduction in the actual beam quality generated, compared to an alternate method.

We have a design for a cathode that meets most of these criteria. A 1.6-cell-equivalent S-band higher-order-mode gun design [10] has been used for all modeling and simulation presented in the remainder of the paper, due to the stability of the field balance in the presence of local perturbations. A standard BNL-type geometry could also have been used but would have required more extensive retuning during the initial optimization phases of the work.

rf and cavity design

The basic layout of the planar focusing cathode design is shown in Figure 3.

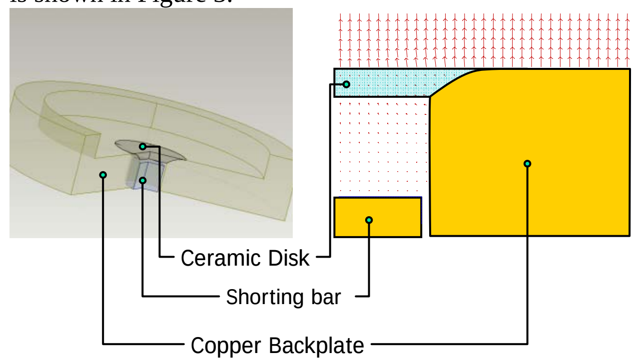

Figure 3: Layout of the planar focusing cathode geometry.

The copper backplate is simply the back wall of the cathode cell. A ceramic disk is positioned over a hole in the center of the backplate. The cavity field can penetrate the ceramic, and a radial component to the cavity field can exist at the surface of the ceramic. The magnitude of the radial field, relative to the on-axis field at the cathode center, can be adjusted by moving the shorting bar longitudinally. The electrons are emitted from the surface of the ceramic disk. For our simulations, we assume A-35 ceramic, with dielectric properties (including losses) as given in [11]. The radius of the hole in the backplate is 0.5 cm, and the ceramic thickness is 2 mm.

By changing the position of the shorting bar, the effective focusing strength may be changed from slightly *de*focusing (bar almost touching the back of the ceramic) to maximum focusing (bar recessed to beyond cutoff). A plot of the normalized radial focusing term as a function of shorting bar position is shown in Figure 4; negative numbers indicate focusing.

Changing the shorting bar position, especially between -0.2 and -0.4 cm, where the change in focusing is greatest per unit displacement, will also impact the cavity frequency, as shown in Figure 5. The fractional frequency shift is fairly small (on the order of $3.5{\cdot}10^{-5}$ at most), and we are considering methods to negate the frequency shifts, e.g., with a concentric-plunger tuning system.

Beam dynamics calculations

The beam dynamics code PARMELA [12] was used to simulate the performance of an HOM gun fitted with a planar-focusing cathode, with the beam injected into a standard 3-m SLAC-type TWCG linac section. The evolution of the transverse emittance and spot size for a 1 nC bunch is shown in Figure 6, as a function of distance from the cathode. The absence of a focusing solenoid allows the linac tank to be placed closer to the gun than is the case with the typical installation, at about 40 cm from the cathode in these simulations. Thermal emittance is not included in the simulation.

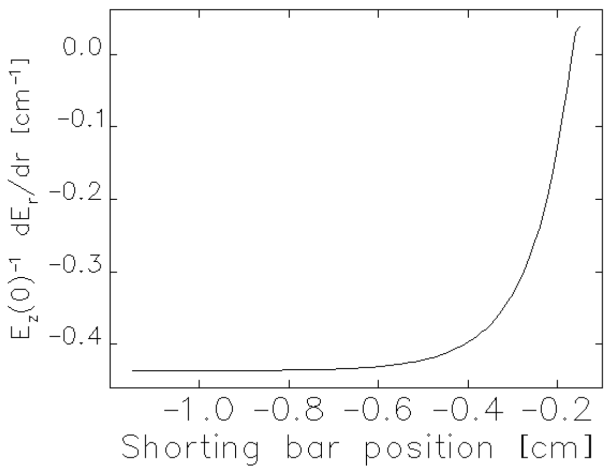

Figure 4: Radial focusing strength (normalized to the axial field at the cathode surface) as a function of shorting bar position relative to cathode backplate.

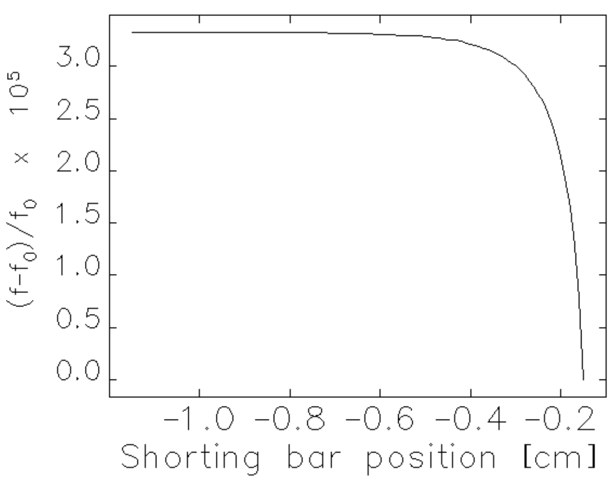

Figure 5: Fractional frequency shift with shorting bar position.

The cavity fields, at 90º past the zero-crossing, are shown in Figure 7. As this is a higher-mode gun design, the on-axis fields in the full-cell region are about 1.4 times higher than what they would be in an equivalent BNL-style gun. In this case, with a peak on-axis field approaching 200 MV/m, the peak surface field is approximately 250 MV/m. This is considerably higher than one would expect in a comparable BNL-type gun; however, some measures can be taken to reduce the ratio, including changing the profile of the exit aperture. The most important region is near the cathode, where peak fields are similar to conventional S-band BNL-type gun operating points.

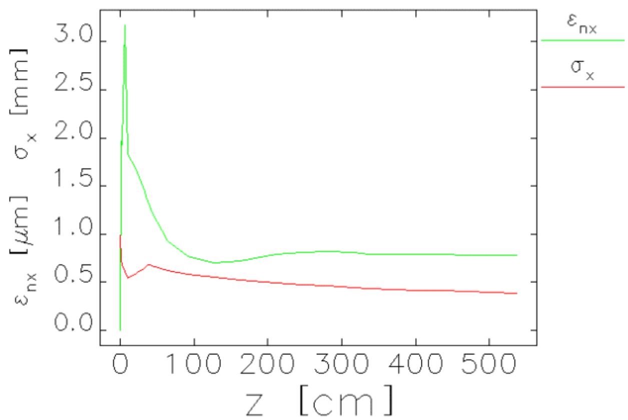

Figure 6: Transverse normalized emittance (green) and spot size (red) for a 1 nC beam, as a function of distance from the cathode.

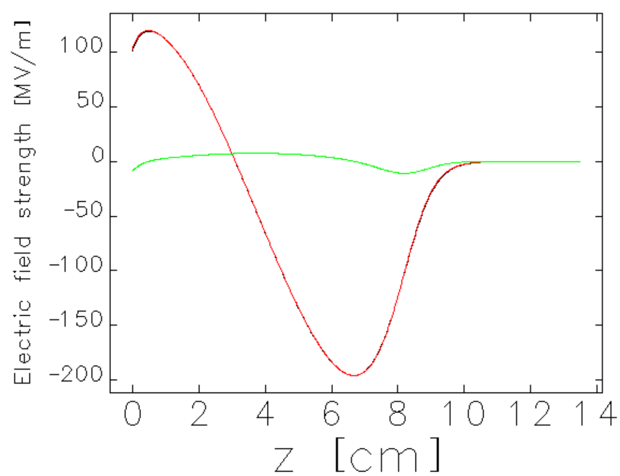

Figure 7: Cavity fields for HOM gun with planar focusing cathode. Black curve: E_z at r=0 mm; Red curve: E_z at r=2 mm; Green curve: E_r at r=2 mm.

Comparison with conventional techniques

A plot of emittance vs. distance is shown in Figure 8 for a conventional configuration (BNL-type gun with solenoid), fixed-focusing recessed-cathode configuration, and the planar recessed cathode. All three were run using PARMELA and assumed the same bunch charge (1 nC). None of the simulations include thermal emittance, so as to directly compare the basic performance of the emittance compensation technique. The performance of all three techniques is approximately the same in terms of ultimate emittance achieved.

PRACTICAL CONSIDERATIONS

Cathode heating at operating gradients

The 2-d cavity code SUPERFISH [13] was used to calculate the fields for these simulations; one parameter generated by SUPERFISH is the CW loss in dielectrics for a given field strength. Scaling from this level to operation at

100 MV/m on the cathode center, with a 2 μs rf pulse and a 30 Hz pulse repetition rate, an average power of approximately 110 W will be dissipated in the cathode ceramic. This should be within our ability to cool; the use of lower loss ceramics would also reduce the power loss. Some lossiness is desirable, however, to prevent charge buildup on the ceramic.

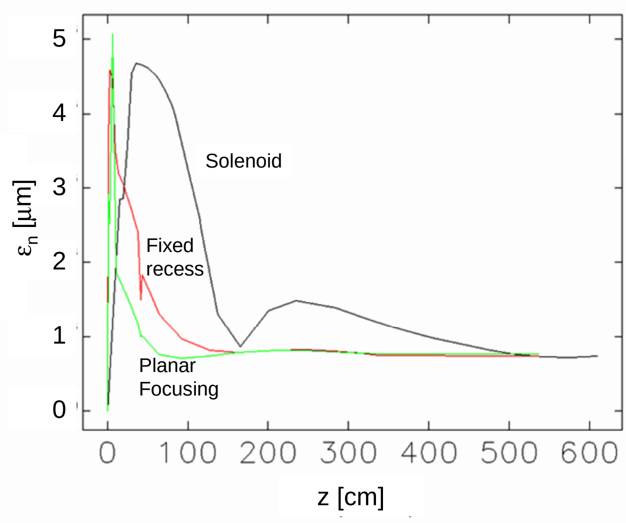

Figure 8: Transverse normalized emittance for (black) conventional solenoid-based injector, (red) injector with a fixed, recessed cathode, and (green) a planar focusing cathode.

Required gradients

As mentioned, the fields required to achieve this performance via the HOM-type gun are quite high in the full-cell equivalent. In practice, however, the planar focusing cathode could be adapted to a standard BNL-type gun with appropriate additional tuning provisions, so as to not perturb the field balance too significantly. Alternately, separate cavities could be used for the cathode and full cells, thereby allowing independent adjustment of the gradient and phase. This approach offers several other advantages, including the ability to reduce the energy spread of the electron beam via appropriate phasing of the full cell.

Spot size and cathode selection

The planar focusing cathode technique requires a somewhat larger laser spot size on the cathode, approximately 2 mm radius, as compared to approximately 1 mm in the conventional design. All else being equal, this would double the thermal emittance; however, the authors were unable to find a relevant comparison for the ceramic used in the simulations. The question of whether the ceramic would make an acceptable photocathode is also open, although conversations with several experts [14,15] lead us to believe that several acceptable choices, such as diamond, may exist.

CONCLUSIONS

We have proposed a method for performing emittance compensation using a cathode-region focusing scheme. This technique allows the focusing strength to be adjusted somewhat independently of the on-axis field strength. Beam dynamics calculations indicate performance should be comparable to presently in-use emittance compensation schemes, with a simpler configuration and fewer possibilities for emittance degradation due to the focusing optics.

There are several potential difficulties with this approach, including cathode material selection, cathode heating, and peak fields in the gun. We hope to begin experimenting with a cathode of this type in the near future, and several possibilities exist for reducing the peak gradients to more acceptable levels.

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