Grid-focused diodes for radiography*

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Abstract

Simulations with the TRAK ray-tracing code have shown that grid-focused diodes might be a simple alternative to gas/plasma cell focusing for moderate-energy radiography machines. Multi-grid focusing has advantages over single grid focusing, especially in circumventing neutralization from gases evolved from the heated target. The practical technology for grid focusing was established many years ago in an extensive series of experiments.

I. INTRODUCTION

For several years diodes with gas cells for space-charge neutralized focusing of the electron beam have been used for radiography [1,2]. Extensive experimentation varying gas-cell pressure, type, length, and number of cells has resulted in radiographic spot sizes as small as 3-4 mm. More recently experiments have started use pre-ionized plasma filled cells [2]. In this paper we describe an alternative approach using wire grids to focus the beam instead of gas cells. This approach has several attractive features including operational simplicity and ease of tuning for minimum spot size.

The simulations in this paper were done for beam parameters similar to those proposed for new IVA-powered radiographic diodes at the Atomic Weapons Establishment (AWE) in Great Britain. We modeled a 14-MV diode and set the AK gap to produce a 43-kA beam, which is close to the 40 kA expected for the new AWE diode after accounting for magnetically-insulated transmission-line (MITL) losses [2,3].

Our simulations used the TRAK ray tracing code [4]. The TRAK code package includes mesh generation, electric and magnetic field solvers, and particle orbit tracking with self-consistent effects of beam fields. TRAK uses finite-element methods on conformal meshes, which yields accurate simulations of space-charge and field emission. TRAK is especially suited for simulations of gas- or grid-focused diodes, in which there can be extensive orbit crossing. Assignment of currents on the conformal mesh preserves zero divergence and unambiguously defines the sense of axial current. This is necessary to model the complex reflex orbits in a pinched beam.

II. GAS-CELL FOCUSING

There is a well-known range of gas pressures for stable propagation of electron beams [5-11]. In the absence of external focusing fields, a beam propagating in vacuum is dominated by the defocusing space-charge electric field, which slightly exceeds the focusing magnetic field of the beam current. Beam-electron impact ionization of low-density background gas partially cancels the space-charge field. At low pressures, secondary electrons are ejected from the ionized channel by the beam space charge. In this low-pressure, ion-focused propagation regime the beam can be disrupted by the ion-hose instability. At somewhat higher pressures the beam is entirely space charge neutralized, and secondaries remain in the channel to contribute to an induced return current that partially magnetically neutralizes the beam. This regime is susceptible to the two-stream instability, which is damped by collisions as the pressure is further increased, allowing the beam to propagate in equilibrium. The stable propagation regime is cut off at higher pressures by the appearance of the resistive hose instability.

In principle, the proper choice of gas pressure or plasma density can result in cancellation of both the magnetic and electric forces, resulting in ballistic propagation of the beam with a constant convergence defined by the entrance angle at the anode. This is the "paraxial" diode described in [1].

In this ideal case the spot size is limited by the emittance, which can easily be dominated by foil scattering by the cell input window and scattering in the gas. We did not model these effects in our simulations, so

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the "intrinsic beam spot size" reported here is only limited by that part of emittance intrinsic to the beam dynamics.

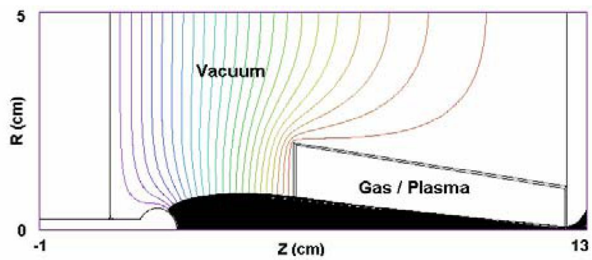

Figure 1. Ideal ballistically-focused diode 14-MeV diode with force-free, ballistic electron trajectories (f_e=1, f_m=1) and optimum gas cell length.

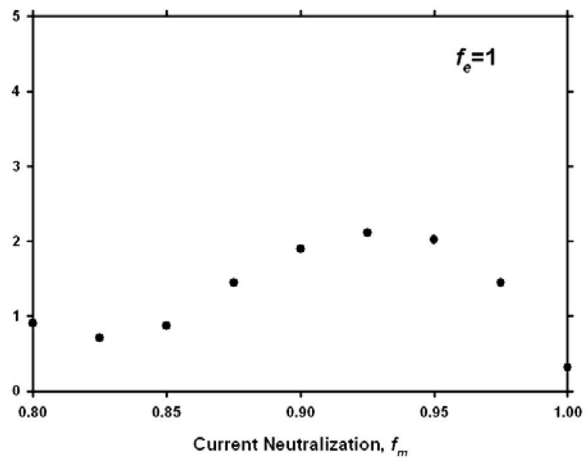

Figure 2. The ballistically-focused diode beam intrinsic spot size at optimally positioned converter as a function of current neutralization for fully space-charge neutralized beam (f_e=1).

Our TRAK simulations of a gas/plasma cell modeled space-charge neutralization by adjusting the permittivity of a fictitious dielectric that reduces the electric fields to the equivalent of space-charge neutralization, f_e, in the range 0 to 1. TRAK was modified to include an option for reducing the beam magnetic fields in order to model return-current magnetic neutralization, f_m, in the range of 0 to 1.

In these simulations the AK gap spacing and knob position were adjusted to produce a 43-kA beam from the 14-MV cathode, which is close to the 40-kA predicted by PIC code simulations that included the full MITL and current losses [2,3]. This was achieved with a 3.0-cm AK gap for the 1-cm diameter ball cathode, which had space-charge limited emission over the front surface within a 120° included angle.

Fig. 1 shows the result of simulating an ideal ballistically-focused paraxial diode with force-free electron trajectories. This is achieved when a completely space-charge neutralized beam (f_e=1) is also fully current neutralized (f_m=1). In this simulation we optimized the cell length from input anode foil to converter target to minimize the beam size at the converter.

The ideal full return-current neutralization is not immediately induced in the ionized gas or plasma. Figure 2 shows the sensitivity of the spot size to the degree of magnetic neutralization, which will clearly increase the time integrated spot size.

III. GRID FOCUSING

The practical difficulties associated with gas or plasma cells can be avoided through the use of grid focused transport. Moreover, a smaller spot size is possible with this technique. In this approach, highly transparent wire grids are placed transverse to the beam to short out the beam space-charge fields [12-20]. Two different types of grid transport have been demonstrated in beam experiments. The first is to use grids as periodic focusing elements, based on the well-known focusing properties of a grounded plane [15-19]. An alternate method is to place the grids close together, separated by less than a betatron wavelength [20]. Used in this fashion they effectively neutralize the beam space charge throughout the transport cell; acting as an "artificial ionized gas".

A. Single-grid focusing

A simple geometry using a single highly-transparent grid to locally short out the space charge and focus the beam onto the converter target is shown in Fig. 3. The basic diode dimensions used in these simulations are the same as those for Fig. 1, but the converter target has been relocated to the focal point of the anode grid. In practice, one would also replace the anode foil with a highly transparent grid, such as was used in the grid transport experiments [16-20]. Those experiments used grids that were 98% transparent and higher transparency grids can be fabricated if they are not expected to survive for more than a single shot. The use of a grid instead of a foil will greatly reduce the beam emittance from scattering, and thus also reduce the practical spot size, which is proportional to the emittance divided by the final beam convergence.

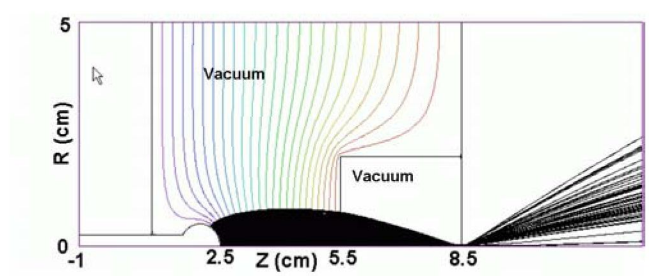

Figure 3. 14-MeV beam focused using only the anode grid. The entire diode volume, including the cell, is in vacuum.

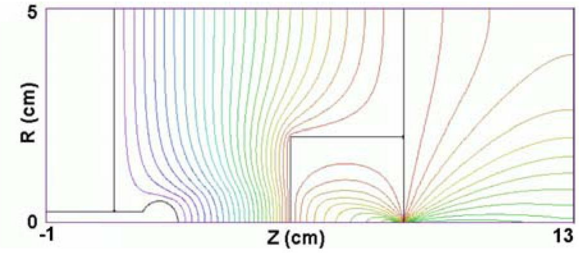

Figure 4. Equipotential contours including space charge for the grid-focus cell shown in Fig. 3.

Since the single-grid focusing cell has a large space charge throughout the cell (Fig. 4), we anticipate that neutralization from gas desorbed from target heating would be a problem with this concept. For the beam current density on target in the simulations, the rate of heating of a W or Ta target would be in excess of 200C/ns, so within a few nanoseconds the target would exceed the 400 degree temperature rise. This has been shown to be the threshold temperature for gas desorption, which is then ionized by the electron beam and neutralizes the space charge [21]. Although it has been demonstrated that target heating effects can be mitigated through laser cleaning of the target [22], a simpler approach would be the use of multigrid focusing discussed below.

B. Multiple-grid focusing

A straightforward approach to eliminating the target heating problem is the use of a multigrid focusing cell. In this geometry multiple grids are placed close enough together (spacing much less than a betatron wavelength) that the space charge field is almost completely cancelled out in the transport volume [20]. As shown in Fig. 5, this can be done by adding two more grids. The grids serve as an artificial gas or plasma to neutralize the beam, without the complications of either. The reduction in space charge in the multi-grid diode can be seen by comparing Fig. 6 with Fig. 4. The immunity of a multi-grid cell to defocusing from target heating is shown in Fig. 11, where we modeled space-charge neutralization by adsorbed gas as described in Sec. II.

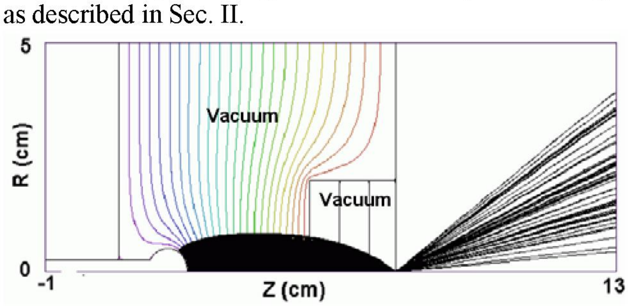

Figure 5. 14-MeV beam focused by anode foil, with additional grids to short out the residual space-charge fields.

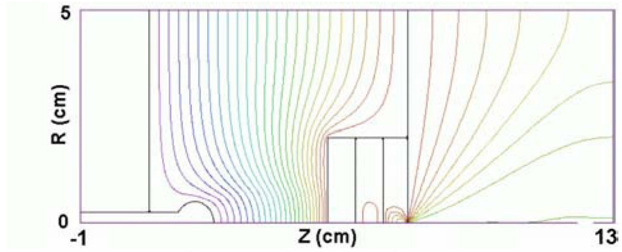

Figure 6. Equipotential contours including space charge for the multi-grid focus cell shown in Fig. 5.

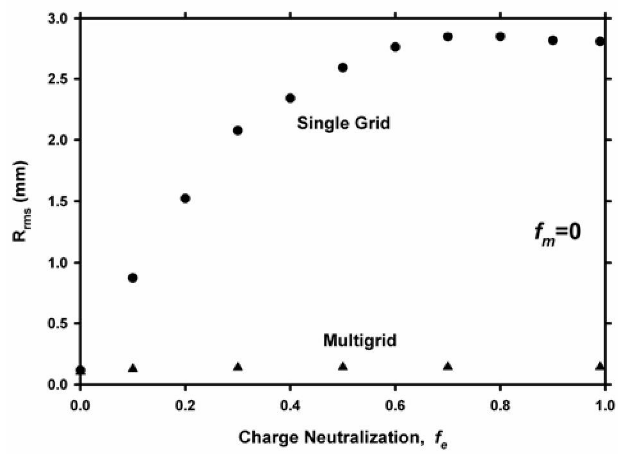

Figure 7. Effect of neutralization by gas desorbed from heated target on the intrinsic spot size of grid focus cells. (Circles) Single grid cell. (Triangles) Multigrid cell. .

IV. CONCLUSIONS

Table I summarizes the simulation results for the three configurations considered in this study. The major advantage of grid focusing over the ballistically focused paraxial diode is that it frees one from the complexity of time-dependant gas ionization, plasma physics, and beam-gas/plasma dynamics.

Table I. Parameters of the simulations.

	Ballistic (Paraxial)	Single-grid	Multi-grid
Cell Length	7.0 cm	2.90 cm	2.05 cm
Intrinsic spot size	0.32 mm	0.12 mm	0.14 mm
Envelope Convergence	5.3°	17°	31°
Relative dose	1.00	0.64	0.38

Grid focusing also results in a smaller intrinsic spot size, because of the higher beam convergence at the target. However, this higher convergence will also reduce the radiographic dose on axis for grid focusing compared to the ideal ballistic focus. We estimated the reduction in dose from Monte-Carlo calculations of bremsstrahlung from half range tantalum targets for beams of varying envelope convergence. As shown in Table I, the dose for the multigrid focus is only 38% of the paraxial dose. Although the single grid cell has less reduction of dose on axis, the multigrid geometry is preferred because of its immunity to uncontrolled gas neutralization from heating the bremsstrahlung converter.

We also investigated the sensitivity of these diodes to voltage variation, because this will result in a larger time-integrated spot size due to the pulse shape. We found that there is little difference in this sensitivity for the three configurations studied.

In practice, experimental results can be expected to be somewhat different than simulated because the emittance may be dominated by scattering. This is especially true for the ballistic focus cell, which requires a solid entrance foil, and also has gas scattering to contend with. Scattering should not be as significant for the grid or multigrid cells, because they use highly transparent grids. All of the trends predicted by these simulations should be put to the test with appropriate experiments.

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