USING THE ORBIT TRACKING CODE Z3CYCLONE TO PREDICT THE BEAM PRODUCED BY A COLD CATHODE PIG ION SOURCE FOR CYCLOTRONS UNDER DC EXTRACTION *

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Abstract

Experimental measurements of the emittance and luminosity of beams produced by a cold-cathode Phillips Ionization Gauge (PIG) source under dc extraction are presented. (The source being studied is of the same style as ones used in a series of K250 proton cyclotrons for cancer therapy.) The effect of source aperture shape, and plasma arc current on luminosity are discussed. The concepts of 'plasma boundary' and 'plasma temperature' are developed as a useful set of parameters for describing the initial conditions used in computational orbit tracking. Experimental results for r-pr and z-pz emittance are compared to predictions from the orbit tracking code Z3CYCLONE with results indicating that the code is able to predict the beam produced by these ion sources with adequate accuracy such that construction of actual cyclotrons based on these measurements can proceed with reasonably prudent confidence that the cyclotron will perform as predicted.

COLD CATHODE ION SOURCE FOR CYCLOTRONS

The class of internal ion sources studied in this report uses a Penning Ion Gauge (PIG) Discharge [1] to produce the ion beam. The ion source is modeled very closely after the source used in the Harper Hospital Medical Cyclotron [2] except for the detail of being optimized for protons rather than deuterons.

ION SOURCE TEST STAND

The ion source test stand at the National Superconducting Cyclotron Laboratory (NSCL) uses a (13.875 inch pole radius) room temperature electromagnet which produces magnetic fields of about 10 KG using a 100 ampere coil current. Two 700 liter/second turbo pumps are used to bring the vacuum chamber to the 10^{-7} torr range when the source gas is turned off or the 10^{-5} torr range when hydrogen is flowing to the source at 2.5 cc/min.

An isolated high voltage "dee" holds the puller electrode and the slit and wire probes (Figure 1) that are used to measure the emittance of the beam. Data collection on the ion source test stand is computer controlled. The positions of the probes are set with servo motors and read from potentiometers. The current on the slit probe and the current on the wire are read by standard NSCL beam current monitors.

EXPERIMENTAL RESULTS

Radial and axial emittance measurements were made for two different source apertures each 5.0 mm tall differing only in width. For each chimney, measurements were made will several different arc currents. Maximum arc current was limited by the stability of the plasma for the 0.25 mm wide source aperture and by the cooling of the probes for the 0.50 mm wide source aperture. Emittance and Luminosity shown in table 1 represent the area needed to contain 90% of the beam.

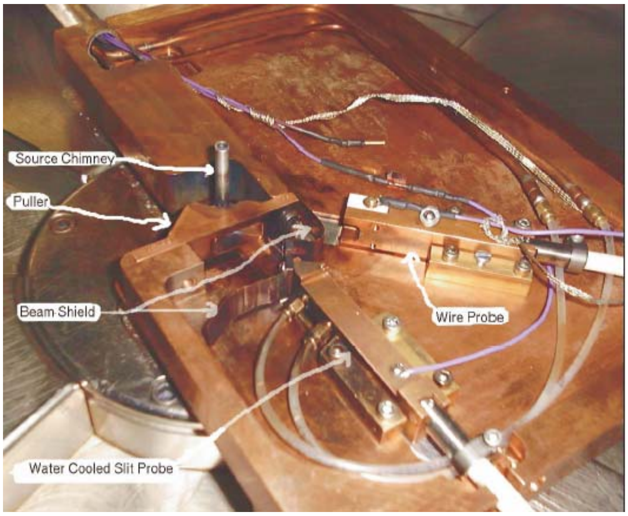

Figure 1: The "slit" and "wire" probes used for radial profile measurements are seen inside the high voltage dee along with water cooling lines. The beam shield prevents any beam from hitting the water cooling lines or passing in front of the slit probe and hitting the

Aperture Width (mm)	Arc Current (mA)	Beam Current (µA)	ε_r (mm-mrad)	ε_z (mm-mrad)	Luminosity $\left(\frac{A}{cm^2 - sr}\right)$
0.25	250	165	25.5	141	4.6
0.25	350	195	23.5	121	6.9
0.25	450	227	25.0	127	7.1
0.50	100	401	57.9	206	3.4
0.50	150	590	64.9	239	3.8

Table 1: Experimental Results

Z3CYCLONE ORBIT TRACKING CODE

The NSCL code Z3CYCLONE was designed for tracking orbits from the ion source slit all the way to extraction in a cyclotron neglecting forces generated by other particles i.e. a "single particle" calculation. Numerical maps of the electric field and of the magnetic field and the initial conditions for the ions (location, energy, and initial direction of motion) are required as input. (Z3CYCLONE has been modified for this study to allow tracking of orbits in a DC electric field.)

PARAMETERIZAION OF INITIAL CONDITIONS

While Z3CYCLONE has proved to be a reliable orbit tracking program, orbit calculation is only as accurate as the initial conditions given, and the selection of accurate initial conditions can be complicated in a cyclotron with an internal ion source.

To obtain the initial conditions used for the orbit calculations presented in this paper we have used a technique taken from the doctoral dissertation of J. R. Schubert "Extending the Feasibility Boundary of the Isochronous Cyclotron." [3] Schubert's work showed that changes as small as several thousandths of an inch (hundredths of a mm) in the shape of the plasma boundary (the surface with electric potential equal to that of the chimney of the ion source) can have a large effect on beam trajectories.

Our challenge is to produce an algorithm based on simple parameters (plasma boundary shape and plasma temperature) that generates a collection of initial conditions such that Z3CYCLONE's calculated orbits match the experimental beam produced by our ion source.

Plasma Boundary

Calculations of the electric field between the source chimney and the dc "puller" were made with the three dimensional Laplace equation solver Relax 3d.

For the electric field calculations, along with electrodes representing the chimney and the puller, a cylindrical "image electrode" with an arbitrary positive voltage is placed on the axis of the chimney. This electrode does not represent any physical object, but is used to provide a continuous electric field derivative at the plasma boundary. This is important for the electric field interpolation done in Z3CYCLONE. Putting voltages of varying levels on the image electrode has the additional effect of changing the shape of the plasma boundary thus exploring the effect of possible different plasma pressures.

Figure 3 shows different plasma boundaries which are the result of different voltages for the image electrode along with plan views of the tracked orbits, radial emittance plots, and axial emittance plots which result from these plasma boundaries. Since any of these beam profiles can reasonably be expected from the chimney-puller geometry, only an experiment can determine which best corresponds to the actual beam.

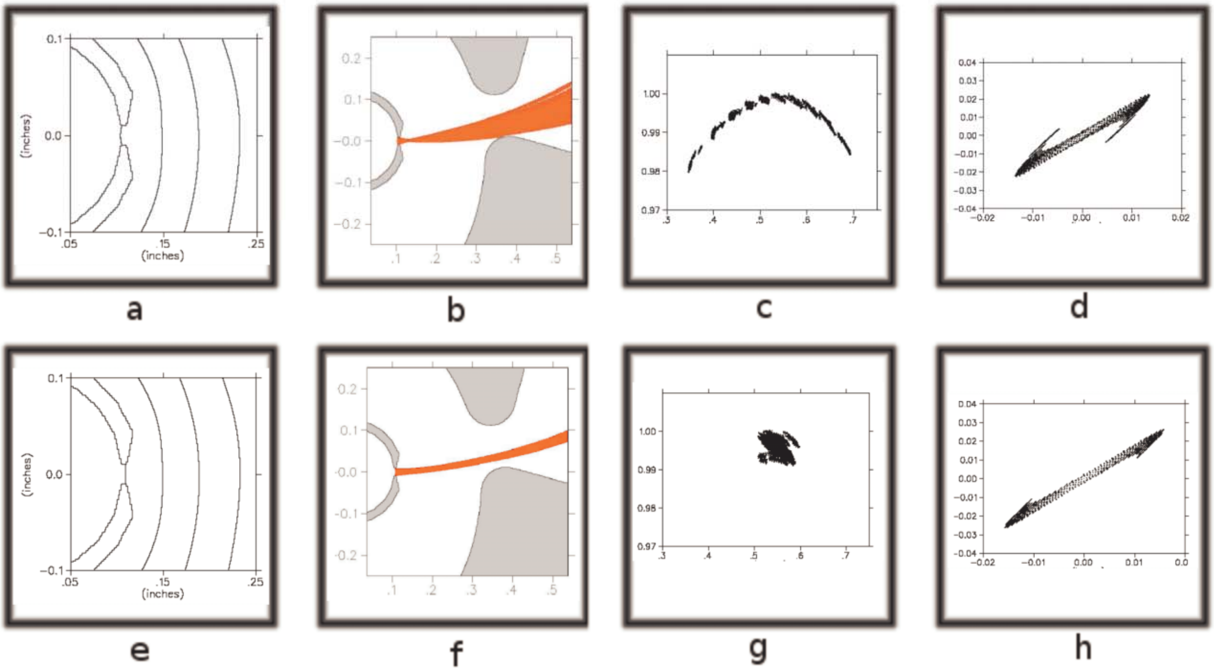

Figure 3: Shown are the electric field calculations with two different potentials assigned to the image electrode. The first results in a concave plasma boundary (a), while the second results in a slightly convex plasma boundary (e). The resulting calculated orbits are displayed for each electric field in plan view (b and f), radial emittance (c and g) and axial emittance (d and h). (All emittance plots in this paper are in arbitrary units having to do with the locations of the two probes; area in these plots is directly proportional to emittance.) The shape of the plasma boundary has a strong effect of the shape of the radial emittance plot and the size of the tails in the axial emittance plot of the calculated beam.

Plasma Temperature

Figure 4 shows how the starting energy of the tracked orbits affects the radial and axial emittance of calculated beam. (When creating a collection of tracked orbits to match the experimental beam, we select a distribution of starting energies by fitting five discrete energy values to a Maxwell-Boltzman distribution representing a characteristic plasma temperature.)

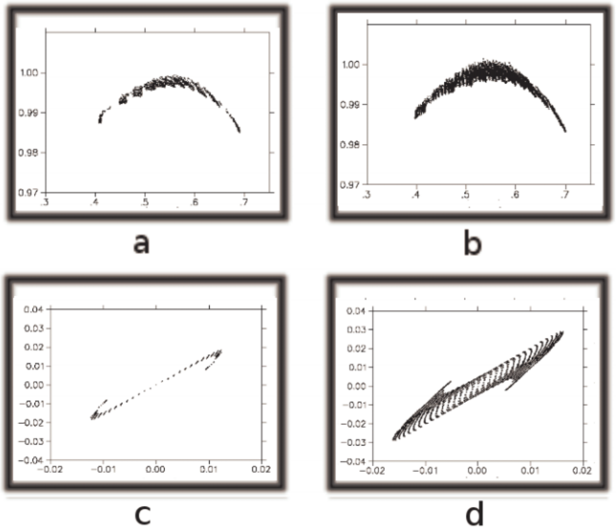

Figure 4: Show are radial (a) and axial (c) emittance plots for a 1 eV starting energy and radial (b) and axial (d) emittance plots for a 10 eV starting energy. (Single starting energies were tracked rather than a distribution of energies to emphasize their effect on calculated orbits.)

The Ensemble of Tracked Orbits

All orbits are started on the plasma boundary. For the calculations presented in this paper, 403 starting locations are used (31 unique z positions at each of 13 unique horizontal locations within the chimney opening.) For each starting location, 49 different starting angles were tracked, 7 angles in the median plane and 7 angles vertically. For each combination of starting position and starting angle 20 different rays were tracked, namely: five different starting energies and four different accelerating potentials (to account for variations in the dee voltage on the ion source test stand), i.e. 349,940 rays for each source aperture geometry.

COMPARISON OF CALCULATED RAYS TO EXPERIMENTAL BEAMS

Figure 5 shows a comparison of the calculated orbits and an experimental beam. These plots are for experiments and calculations with the 0.25 mm wide source aperture. The initial conditions for the collection of tracked rays were generated using a plasma temperature of 35,000 K, and a plasma boundary that was slightly convex.

The computed orbits are an excellent match for the radial emittance of the experimental beam, namely they produce a plot with the same size, same curvature, and the same orientation. The computed orbits match the axial emittance of the experimental beam to a lesser extent in that they produce a beam with the same area. However, the shape of the beam matches less well. Designing a cyclotron with an aperture adequate to accept the calculated beam represents a conservative approach.

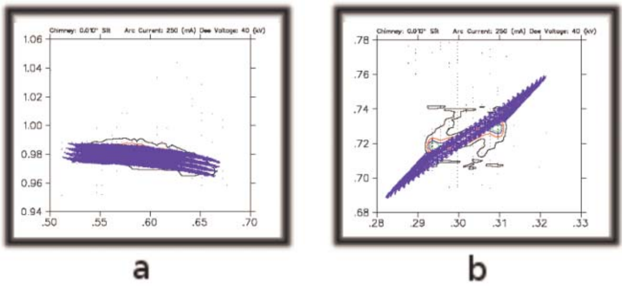

Figure 5: Shown are the radial (a) and axial (b) emittance of the collection of calculated orbits (in blue) plotted on top of the emittance of the experimental beam (contours).

CONCLUSIONS

To the best of our knowledge, these are the first measurements of emittance and luminosity of a cold cathode internal ion source. The expected general trend of increasing luminosity with increased arc current was observed.

With appropriate initial conditions, the orbit tracking code Z3CYCLONE is able to predict to good accuracy the beam produced by the cold cathode (PIG) ion source.

REFERENCES

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[2] Blosser, H. G. et al. Compact Superconducting Cyclotron for Neutron Therapy, IEEE Transaction on Nuclear Science, NS-32, No. 5 3287 (1985).

[3] Schubert, Jeffery R. *Extending the Feasibility Boundary of the Isochronous Cyclotron*, Ph.D. Dissertation, Michigan State University, 1997.

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