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Rutgers 12-Inch Cyclotron Ion Source Studies: Part II (Ion Source Simulations and Measurements)

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ABSTRACT. Since the publication of the first Ion Source Studies document there have been improvements in both the understanding and implementation of the ion source system.[1] The understanding has been greatly assisted by the 3-dimensional E&M particle tracking code SIMION. Several experiments in the adjustment of the ions' initial condition have benchmarked our 3D model as well as identified the source of the large initial ion launch angle. From these results an electrically symmetric chimney has been machined and installed. Additionally, to enhance the peak field near the ion source aperture, pullers have been mounted to the face of the DEE. These improvements have resulted in an hundred fold increase in proton beam intensity at the target and further improvements are anticipated

VERTICAL MOTION. An earlier document "Observation of Betatron Motion in the 12-Inch Cyclotron" concluded by inquiring as to what the source of the large observed betatron amplitude was – the answer lies in the ions initial conditions.[2] Since the ion source aperture is located in the median plane, an initial vertical displacement can not be the culprit, thus an initial launch angle must be to blame. Evidence to back up the accusation presented itself when, after a particularly long beam run, a spiraled discoloration appeared on the copper chimney. The discoloration began at the aperture and wrapped in the direction of the beam rotation and with downward pitch as shown in figure 1. The discoloration is taken to be tracks of ions launched during the early portion of the RF phase that were not energetic enough to clear the chimney. It was suspected that the slight vertical asymmetrical geometry of the ion source chimney was the cause of the vertical electric field. In obtaining the order of magnitude of the vertical field a slope of 4.3 degrees was calculated from the spiral track.

A right-handed coordinate system is used, the ion source aperture points in the direction of the x-axis, the DEE-Dummy DEE gap is parallel to the y-axis, and the vertical axis is parallel to the vertical magnetic field. The vertical electric field was estimated from the measured slope. If one calculates that in one half of an RF cycle, the ion vertically declines 0.032 inches in height the effective integrated electric field is simply calculated from:

$$z = \frac{1}{2}at^2$$

$$F_z = ma_z = qE_z$$

$$a_z = \frac{qE_z}{m}$$

$$z = \frac{qE_z}{2m}t^2$$

$$E_y = \frac{2dm}{qt^2}$$

$$E_y = \frac{(2)(0.00081m)(1.6x10^{-27}kg)}{(1.6x10^{-19})(40nS)^2} = 100\frac{V}{cm}$$

When the ions have struck the chimney at this point they have a vertical energy of about 10eV.

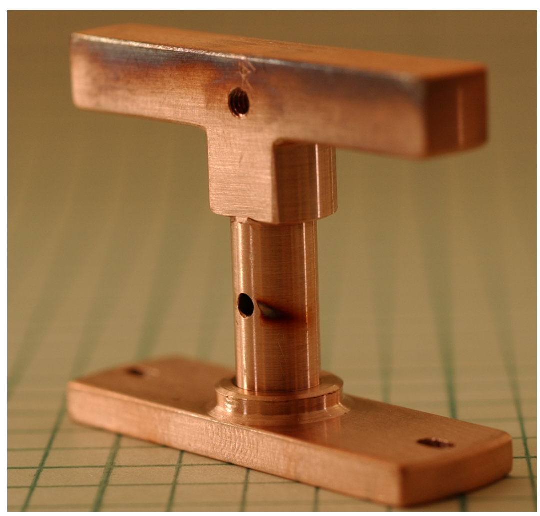

Fig. 1. Chimney discoloration shows launch angle.

To support these findings, the vertical two-dimensional DEE and Chimney silhouette geometry was entered into Poisson-Superfish (PSF) and solved as a 2D electrostatic problem.

[3] Obviously the 2D model was severely limited due to complex 3D geometry, but the model was at least valid in the X-Z plane from the symmetry about that plane, and confirmed a vertical electric field of order estimated above. Taking this calculation further required a full 3D code.

Want of a 3D E&M modeling code with the ability to fly and track ions prompted the purchase of SIMION - a full 3D E&M particle tracking code.[4] A 2-dimensional (X-Z plane) PSF magnetic field file describing the cyclotron's magnet field was imported into SIMION. SIMION then azimuthally rotated the 2D field about the z-axis creating the complete full 3-D volume. The chamber lids, dummy DEE, and ion source chimney were drawn as a single 3D solid in AutoCAD, again imported into SIMION. Finally, because of the simplicity of the DEE geometry, it was drawn in the SIMION graphics editor. The compilation resulted in the SIMION *workbench* shown in figure 2. The magnetic field, DEE voltage, and angular frequency were set to nominal 12-inch cyclotron settings. Ions, of unity mass and charge (i.e. protons) were launched with zero kinetic energy at the position of the aperture.

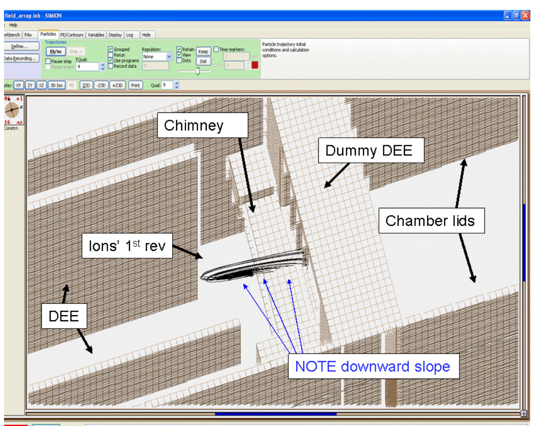

Fig. 2 SIMION showing declination of 1st turn

SIMION indeed confirmed our observation of a vertical deflection. After this benchmark, SIMION has led to further clarifications. For instance, the placement of the radially adjustable florescent screen at its present azimuthal location was dictated by practical limitations. By happenstance this position was very close to the azimuthal location of the maximum radial betatron amplitude (turn-to-turn spacing is at its greatest), thus providing the ability to discern the axial betatron motion.

THREE HOLE EXPERIMENT. Since a vertical electric field was identified to be the source of the initial launch angle, a simple experiment was performed in an attempt to further understand the ions' initial conditions. A chimney with three identical apertures was machined, one aperture was in the median plane as is typical of the normal ion source, and an aperture placed 2.5 mm above and below the median plane aperture. In addition to experiencing the vertical electric field the off-plane apertures gave the ions initial betatron amplitudes. The cyclotron was brought up to typical operating values – this time three stacked purple glows appeared fanning into the face of the DEE (figure 3). The intensity of the three apertures declined as they moved away from the filament, as plotted in figure 4. The off-plane sources intensity varied only +/- 7% from the median plane aperture. A typical 15 second digital exposure of the fluorescent screen was made. Two (not three) sinusoidal patterns, slightly shifted in phase appeared. The third beam was lost to the DEE lid owning to the additive effects of large launch angle and betatron amplitude.

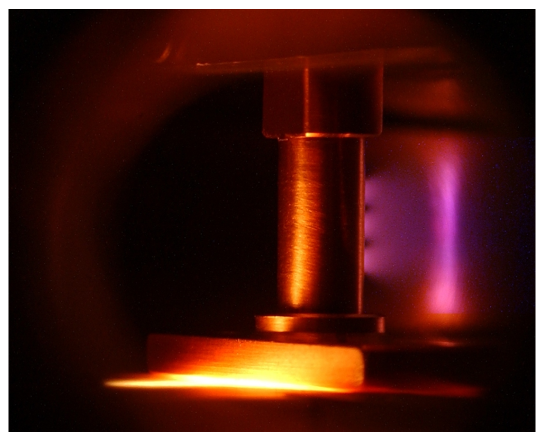
Fig. 3 Three-hole Chimney in operation.

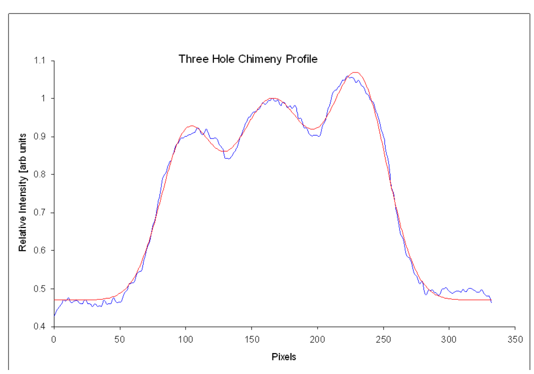

Fig. 4 Three-hole Chimney intensity profile

Although the florescent screen intensity increases as the ions gain energy; the reduction in the turn to turn spacing, as well as the damping of the betatron oscillation, the viewer quickly losses the ability to distinguish the two different betatron paths. For a region of about 1.5 betatron periods (between 185 keV and 325 keV) the fluorescent screen intensity and turn to turn spacing were sufficient to capture an image useful for analysis. Calibration of the horizontal pixels indicates that the horizontal spacing of the two prominent betatron waveforms corresponds to a phase difference of 47 degrees.

Using the SIMION model, ions were launched at three heights from the face of the chimney - corresponding to the three apertures of the chimney. The SIMION output matched the measured findings, including the third beam being lost to the DEE early on.

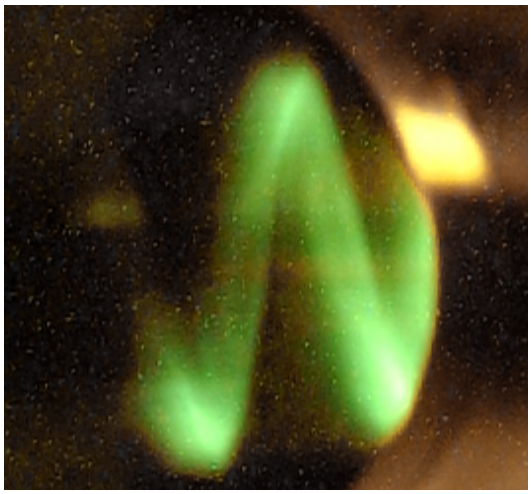

Fig.5 Two betatron curves seen with 3-hole

Operation was at 600 watts at 14.90 MHz with a magnetic field of 0.977 Tesla. Plugging this data into the SIMION model we were able to reproduce the following plot (figure 6).

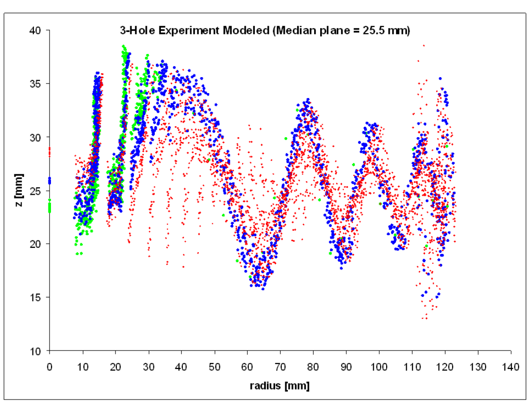

Fig. 6 Three hole chimney SIMION simulation.

Peak vertical displacement from the median plane was approximately 9 mm in both measurement and simulation. From figure 6 we see that ions starting above the median plane (Z > 25.5 mm) were more likely to succeed to target. Ions that started at the lower aperture were very quickly lost. This analysis was pushed further to locate the optimal height from which to launch the ions from in this given geometry. From figure 9 it is seen that a height of 34 mm is the optimal location for a point source to launch from. This is 8 mm above the median plane.

EFFECT OF DEE VOLTAGE. As the RF power is increased the intensity of the beam increases. Presently, the practical amount of RF power that can be safely used for prolonged operation is about 500 watts. Operating with power levels on the order of 1kW have been tried, but only for very brief periods (30 seconds). The following image is an overlay of two photographs operating at two different power levels. Only the RF power level was varied, all other parameters were held fixed. The first betatron image (left sinusoidal pattern) is of 500 watts and the second (right sinusoidal pattern) was with 600 watts of RF power. The RF power of 500 watts corresponded to approximately 10 kVp-p and 600 watts corresponded to approximately 11 kVp-p. A SIMION calculation displayed similar results, figure 8.

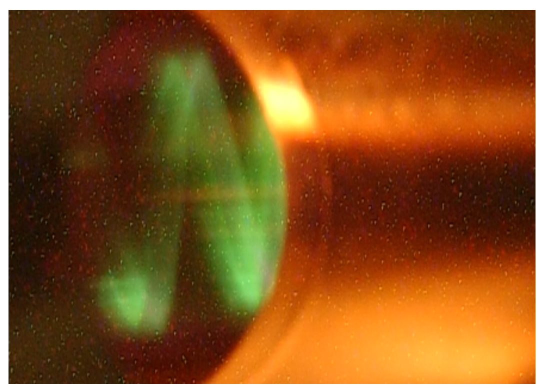

Fig.7 Composite of betatron traces at two RF power levels.

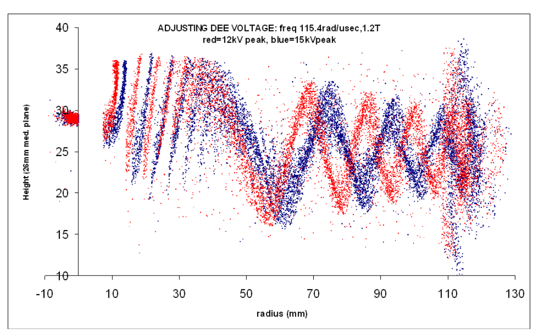

Fig. 8 SIMION differing DEE voltages

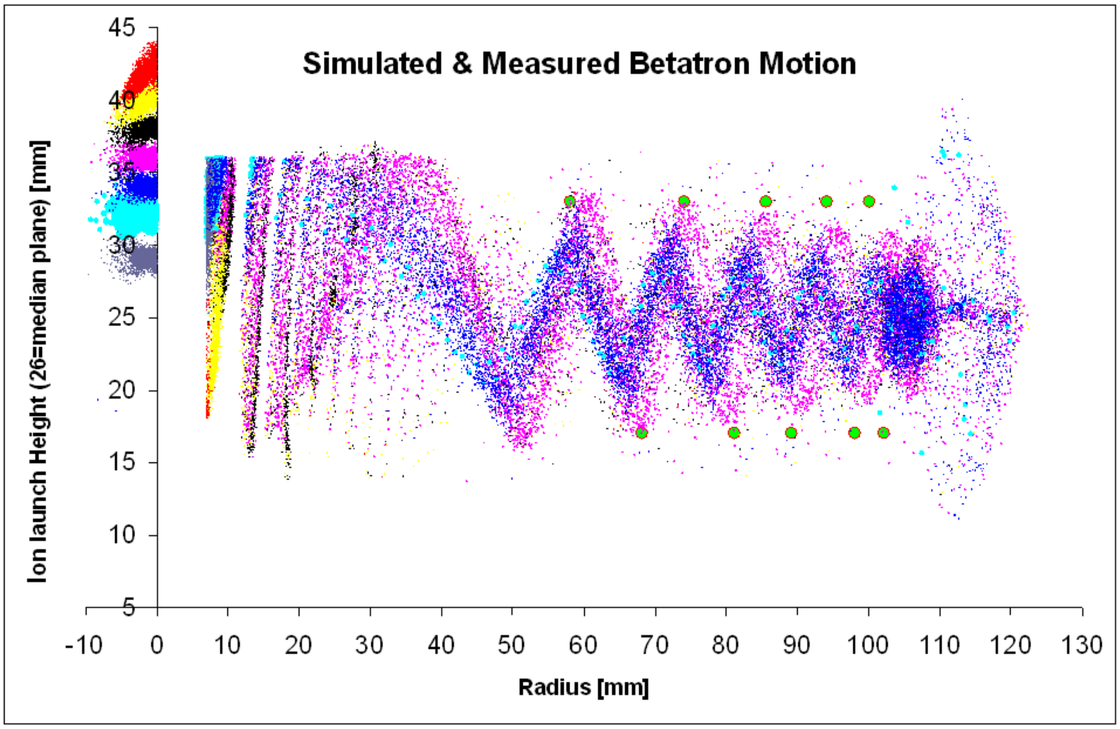

Fig. 9 Differing ion launch heights simulated in SIMION, green dots are location of measured peaks and valleys (dots heights are not representative of data height). Note height of DEE lid is at 36 mm. Also note beam blow up at r = 110 mm, this is where n = 0.2 resonance resides, see reference [2].

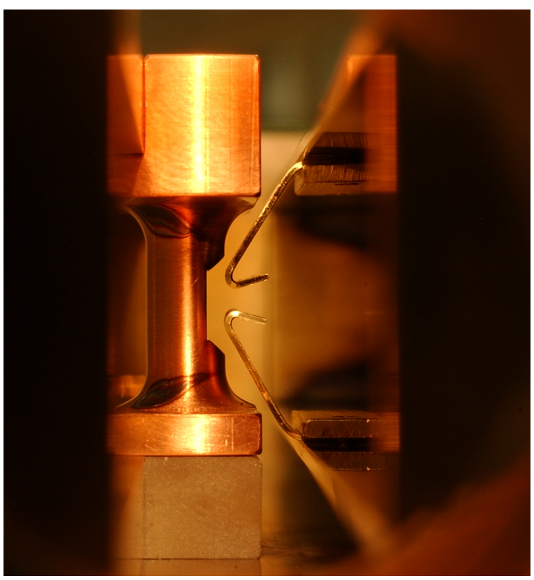

Fig. 10 Symmetrical chimney and pullers

ION SOURCE IMPROVEMENTS. From these simulations and experiences several improvements were made to the ion source chimney. The most obvious was to make the ion source geometry symmetrical about the median plane. To this end even the Macor boat was sputtered with platinum to produce an electrical contiguous surface from top lid to bottom lid. The new chimney's wall was thinned near the aperture to increase the amount of field that penetrates into the plasma column. To further take increase the local electric field, angled brass plates were mounted on the face of the DEE near the ion source aperture. The plates were named "pullers" for their obvious role in ion extraction. A simple PSF model showed that the field at the plasma sheath increased by a factor of 760. According to the Langmuir-Childs' (LC) law a 130 fold increase in the *peak* emitted ion source should result.[5] Already measurements show approximately two orders of magnitude increase, and significantly more is expected once better initial steering is accomplished (discussed later).

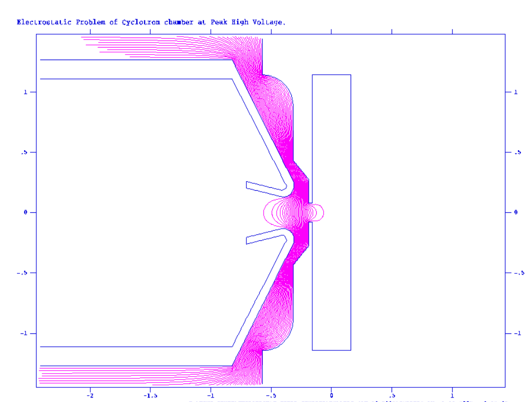

Fig. 11 Pullers enhance field near aperture.

Running the cyclotron with supplemental pumping, the hydrogen gas flow was increased to the point where the primary beam can be visibly seen via recombination.

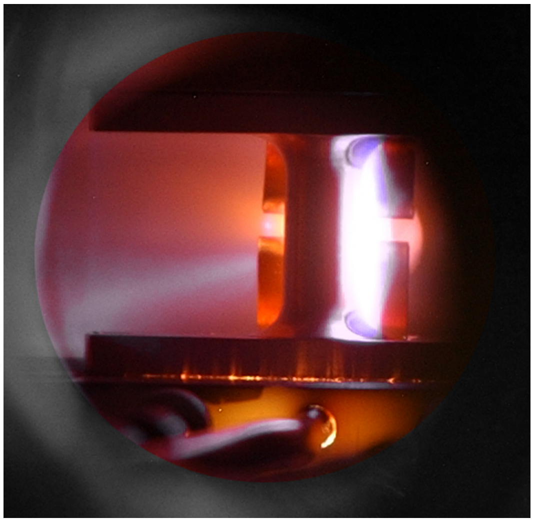

Fig. 12 1st revolution seen spiraling downward.

Figure 12 shows an intense beam spiraling to the left and downward while operating at 600 Watts. The beam is terminating at the leftmost portion of the chimney base. Secondary electron emission can be noted by vertical striations observed emanating from the ion beam's impact location.

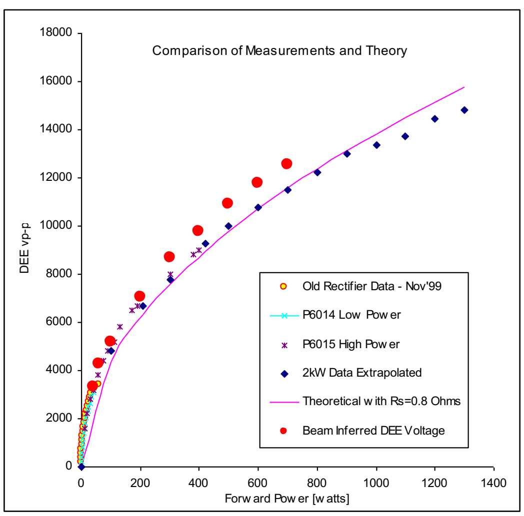

Fig. 13 Calculated and Measured DEE Voltages.

A series of images were taken at differing RF input power levels. The ion beam's radius was calculated by using a calibration of the images pixels against the 0.25 inch diameter of the chimney. The initial energy of the ions (protons in this case) was determined from the calculated radius, magnetic field and the mass; and was then plotted as a function of input power. Twice the energy data was plotted against previously quoted peak-to-peak DEE voltages.[6] There is strong agreement with the older data; a slight increase in DEE voltage for a given power is seen – this is attributed to improvement in the Q from reworking the RF matching box.

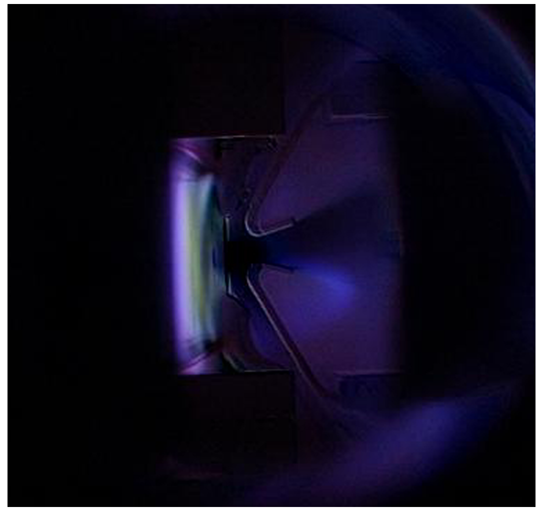

Fig. 14 1st revolution viewed from 90º port.

Figure 14 shows the ion source in operation from the same point of view as Figure 10, a background image was subtracted to remove the saturated pixels, thus accentuating the beam image. It is clear from these views (figures 10 and 14) that the pullers are vertically offset; measurement shows they are 0.32mm high. As a result, the ions are introduced closer to the bottom puller, where the non-zero, off-plane, vertical gradient strongly pulled the beam down. A PSF model in which the DEE and pullers are raised by 0.32 mm illustrates the experienced vertical field; see figure 15.

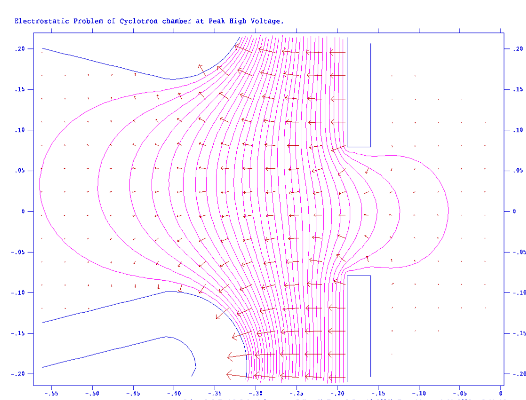

Fig. 15 Vertical field from offset pullers impart initial launch angle.

Optimization of the puller placement and vertical gap needs further investigation. Livingston found that for a 0.0625 inch diameter aperture that pullers with a vertical ¼ inch gap residing ¼ inch away from the aperture yielded best results. [7] This parameter space for our cyclotron has not yet been explored. It is clear from figure 12 that the ions initial radius is very large, thus the pair of pullers plates could be replaced with by a single solid plate with just an aperture in it.

FUTURE IMPROVEMENTS. There are several planned improvements to further increase the beam on target intensity. Again a large downward launch angle exists; this time due to a slight vertical misalignment of the pullers. This signifies that initial conditions are very sensitive to the puller-chimney alignment and that adjustability is a necessity. A bellows 4-axis (yaw, pitch, roll, and gap spacing) adjuster is being designed. Its implementation will permit adjustment while running. To further increase ion production and to protect the bottom of the Macor boat, a small circular piece of metal, such as tungsten will be placed beneath the filament and sit at the filament bias voltage. Additionally, spiraling the filament should localize the heat generation as well as substantially increase the electron emitting surface. Finally, installation of a constant current bias supply is planned.

Not directly pertaining to ion production, but worth mentioning is the installation of a reset-able minutes meter to track filament lifetime. Filament lifetime is presently the limitation in operating time. Optimization of filament lifetime will greatly decrease downtime.

CONCLUSIONS. Improvements to the ion source have greatly increased the beam on target current. Presently proton beam currents of order 20µAmps can be focused onto the collector. The increased beam power has been duly noted; it is now sufficiently high to damage the Radeline fluorescent screen. The screen has blistered and no longer fluoresces near the median plane, rather glowing embers can be seen. This circumstance will only be exacerbated once the initial beam can be steered for maximum capture efficiency. Further, noticeable RF beam loading is anticipated, and adjustable RF power coupling will become necessary.

ACKNOWLEDGEMENTS. The authors thank Prof. M. Kalelkar for arranging the needed funding to make this work possible.

REFERENCES

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[2]http://www.physics.rutgers.edu/cyclotron/papers/Betatron_Studies.pdf

[3]http://laacg.lanl.gov/laac/services/serv_access.phtml

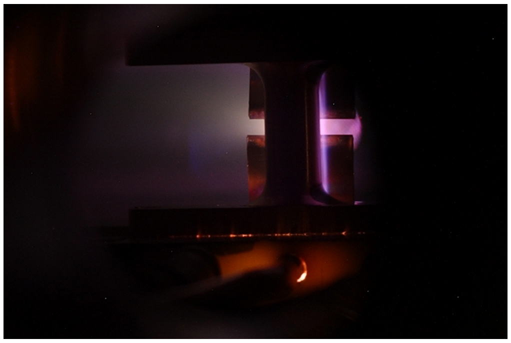
[4] www.simion.com

[5] *Theory and Design of Charged Particle Beams*, M. Reiser, John Wiley and Sons, Inc 1994

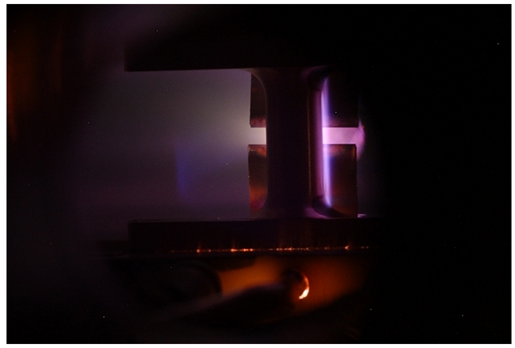
[6]www.physics.rutgers.edu/cyclotron/papers/12inch_dee_voltage.pdf

[7] *A Capillary Ion Source for the Cyclotron*, M.S. Livingston, M.G. Holloway, and C.P. Baker, Rev. Sci. Inst. 10, 63 (1939)

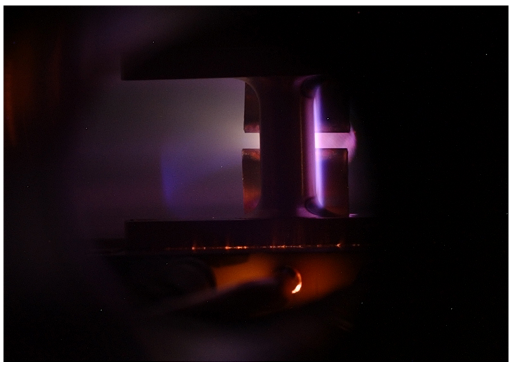
Selected Images of Initial Ion Beam Revolution at Differing Power Levels.



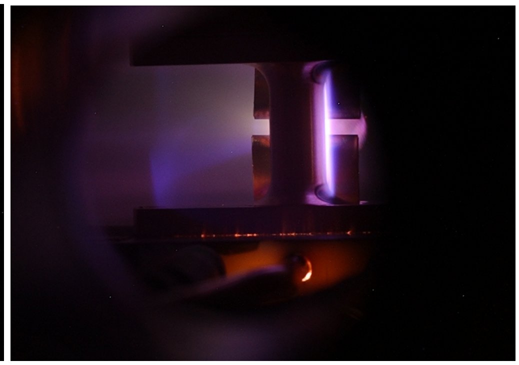
40 Watts



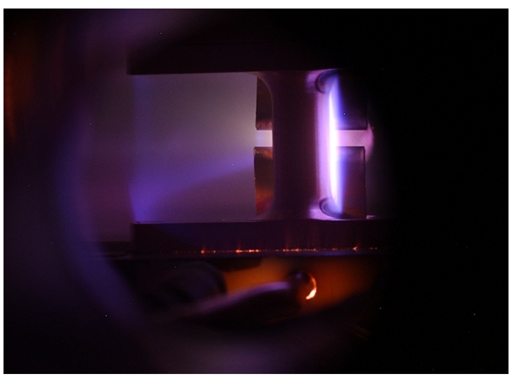
60 watts



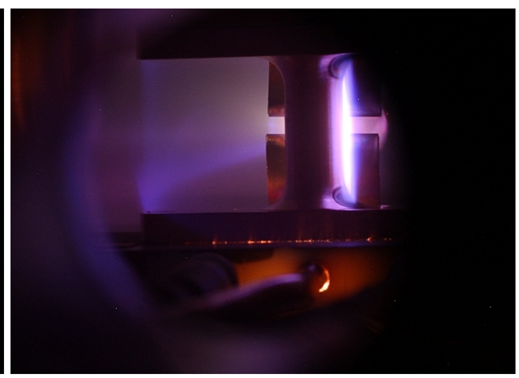
100 Watts



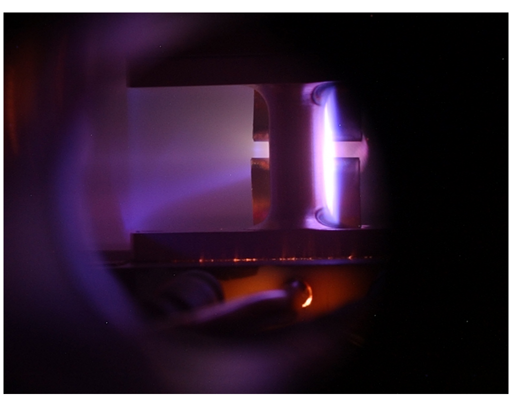
200 Watts



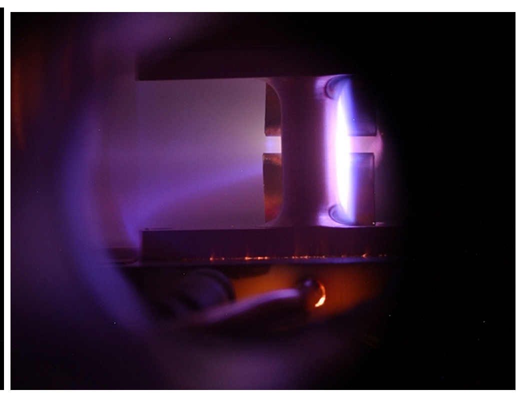
300 Watts



400 Watts



500 Watts



600 Watts