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Rutgers 12 Inch Cyclotron Ion Source Studies: Part I

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ABSTRACT: The Rutgers 12-Inch Cyclotron is a small research grade cyclotron dedicated to accelerator instruction in the Physics Departments senior level lab course. Ever since its first beam in September 1999, the cyclotron has been very limited in its production of ion beam current, less than 10nA. Multiple plans of attack have either been attempted or are presently ongoing to increase the beam current with a goal of 1μA set. It may even be possible to achieve an order of magnitude more. This document intends to record the design of a chimney placed on top of the existing ions source to promote ion production in the optimal region and RF phase.

INTRODUCTION: After several attempts to increase beam intensity without success, the ion source is being investigated. Initially, new pole tips were designed and installed to introduce a very slight decrease in the vertical B-field with increasing radius. This field promotes focusing in both the vertical and radial directions. There is an ongoing student based measurement program to characterize the magnetic field in the full 2-D median plane to ensure azimuthal symmetry. Still without a significant increase in beam current, a larger RF power supply was installed with the hopes of increasing beam current by reducing the number of total revolutions required. This has not been sufficiently tested, but it believed to only marginally increase existing beam current. The issue of ion source generation is under study, more over ion generation at the appropriate time.

In a personal communication with Dr. Peter Miller of MSU NSCL, head of operations, in November 2005, a good point was brought up that has thus far eluded close inspection by me. As the ion progresses radially outward in the cyclotron, gaining energy with each revolution, the turn spacing of each successive revolution becomes smaller and smaller. Our existing Ion Collector has a rather thick shield on the tip which relies on the ion turn spacing to be greater than 0.06inches.

Quantitatively, some quick math will show that with a DEE Vp-p of 10kV (an increase in 10keV in energy per revolution), the ion revolution turn spacing near r = 4 inches, in a B-field of 1.0T will be just 0.04 inches, which is smaller than the 0.06 inch RF shield of the tip of the ion collector we have been using thus far. Dr. Miller suggested that I try an exposed Cu block, grooved near the region of the ion impact as to utilize the B-field and metallic walls of the groove to suppress erroneous readings from secondary electrons. As I explained to Dr. Miller the original purpose of the shield was to prevent RF from coupling to the pickup and disrupting the reading or even damaging the Electrometer. We agreed a large series inductance (an RF Choke) should mitigate this concern.

From a personal communication with Dr. Uve Kirchner, December 2005, of the UKE Zyklotron at DESY, I have learned one should be suspicious of the ion source if the measured beam current is very low in the region close to the ion source, i.e. the regime of large turn spacing. After describing to Dr. Kirchner that we have invested in more RF power to obtain higher DEE voltage, thus requiring fewer ion revolutions before achieving ultimate ion energy; as well as our efforts to produce weak focusing pole tips and the associated field measurement program that is ongoing, Dr. Kirchner felt that all indications pointed to meager ion production.

While visiting DESY in June 2005, I located a paper written by R.R. Wilson in 1939, which describes the type of ion source we have had employed up to now, its characteristic behavior (which I have also observed during operation), and some of the theory that describes the plethora of activity during operation.. On a personal note, I feel it is remarkable what this pioneer was able to do without the use of computer assisted modeling. With that said, I will introduce my efforts to understand the problem with the aid of LANL's Poisson Superfish FEA code.

MODELING: To begin with the existing cyclotron geometry was entered into LANL's Poisson Superfish finite element code. Because Superfish is a 2D based code, the cyclotron was diametrically "sliced" through the DEE center.

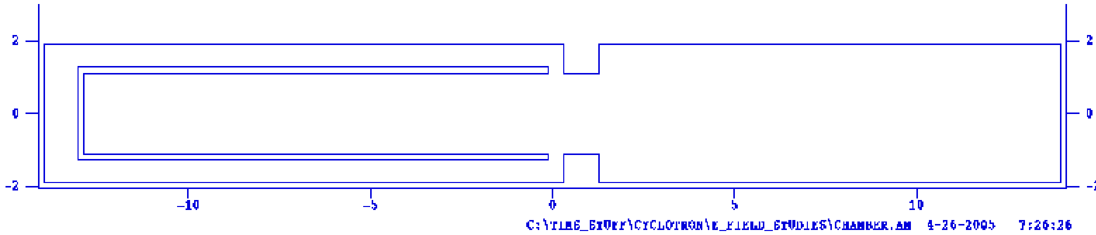


Fig. 1 The Cyclotron geometry was entered into the Electrostatic Solver.

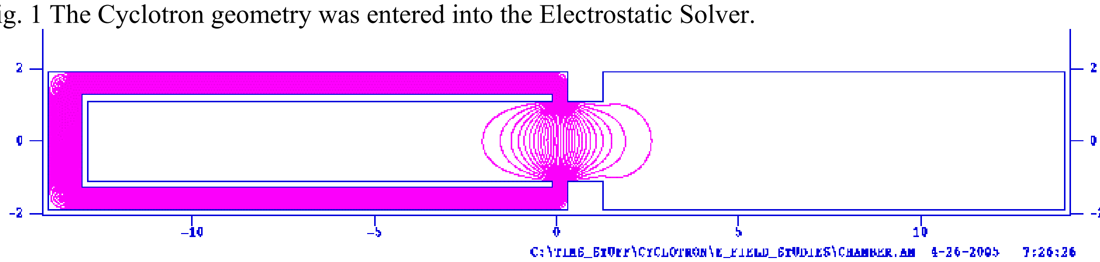


Fig. 2 Superfish's Electrostatic Solver's output, displaying lines of constant potential.

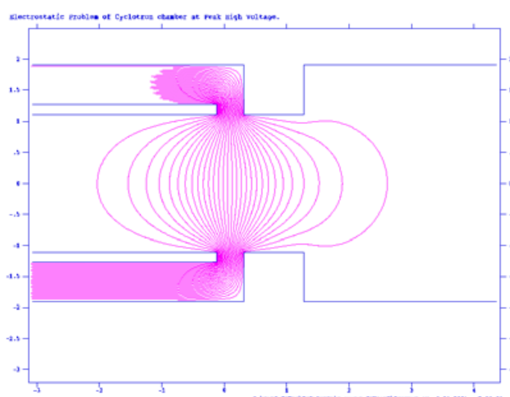
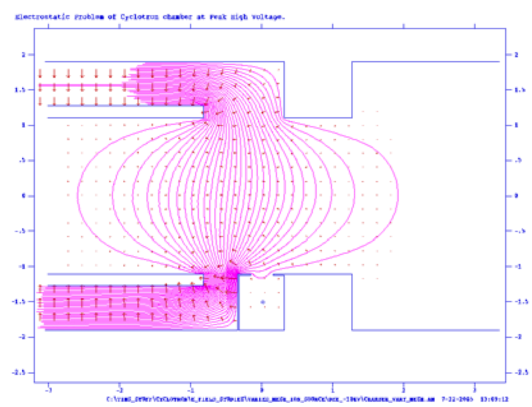


Fig. 3 PSF model of DEE-Dummy DEE



Fix.5 PSF model showing suppression of e-.

A peak DEE voltage of 10kV was chosen. First the ion source was not included as to see the distortion in the field lines due to the DEE-Dummy DEE asymmetry. The distortion is satisfactorily low with a dummy DEE of 3/8-inch thickness. Next we incorporate the geometry of the existing ion source.

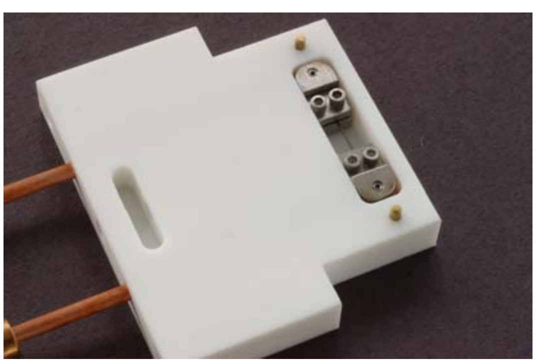


Fig. 4 Original Ion Source (less metallic shield)

It becomes immediately clear from the PSF simulation that while the DEE is going highly negative, the electron emission is suppressed, and emitted electrons are returned to the filament. Observation of increased filament emission with application of RF is consistent with this model: electrons returned to the filament causes the filament to heat even further thereby emitting more while DEE is positive.

CHIMNEY: The inclusion of a chimney placed on top of the existing design will permit the thermionic electrons to travel to the median plane, thereby generating ions in the entire column. A small aperture, 1/16 of an inch in diameter, opening towards the DEE permits ions to be drawn into the accelerating field. Initially, the aperture will be taken as the ions origin (as opposed to presume the ion leaving the chimney with significant velocity). Naively, the aperture of the first test chimney is directly point at the

DEE; two blank chimneys are also being manufactured for the purpose of investigating other launch angles. A PSF simulation which includes the chimney's geometry shows the natural matching of field lines to the ions initial desired trajectory. With validation from this computer simulation, a practical chimney was designed and manufactured by the Rutgers Physics & Chemistry machine shop.

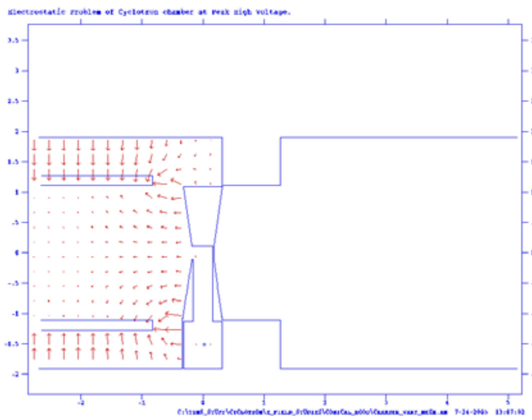


Fig.6 Plot of E-field vectors near ion aperture.

During a holiday visit to Rutgers, I took the opportunity to operate the ion source with the chimney installed. Unfortunately, the RF power at available was only 50 watts from the ENI350L located at the Control Rack. At best, the DEE Vp-p was 3500, so the first ions could only attain 1.750keV, mapping out a trajectory inadequately small to clear the body of the chimney.

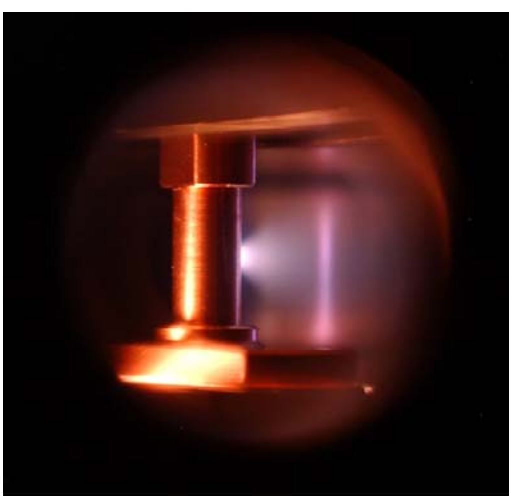


Fig. 7 Chimney in operation.

ION PATHS: The question remains as to how much RF power is required to ensure that the ions clear the chimney? Using a RHS let us consider the equations of motion for an ion traveling in the median plane. A magnetic field, B, is normal to the plane causing the particle to experience an orthogonal force dependant on the tangential velocity in the other axis. We assume that the accelerating electric field, of peak magnitude of E, is purely parallel to the *x* axis. Take the origin at the aperture of the chimney. With these assumptions, we can write down the force equations:

$$\ddot{x} = \frac{-qE}{m} + \frac{qB\dot{y}}{mc} = -\frac{qE_m}{m}\cos(\omega t) - \omega\dot{y}$$

$$\ddot{y} = \frac{-qB\dot{x}}{mc} = -\omega\dot{x}$$

After solving the above and substituting with the cyclotron frequency:

$$\omega = \frac{qB}{m}$$

we can write the solutions to the above equations which give the particles position at "any" subsequent time:

$$x = -\frac{qE_m}{2m\omega^2}\{-\sin(\omega t_0)\sin(\omega t) + \omega t\sin(\omega t + \omega t_0)\}$$

$$y = \frac{qE_m}{2m\omega^2}\{-\cos(\omega t_0)\sin(\omega t) + 2\sin(\omega t_0)[1-\cos(\omega t)] + \omega t\cos(\omega t + \omega t_0)\}$$

It remains to be determined what E is. I reference a document, previously written by the author, which studied the peak DEE voltage as a function of input RF power. In summary, the peak DEE voltage can be determined by:

$$V_{peak} = \sqrt{\frac{2PL}{R_s C}}$$

Where P is power in watts; R_s is the AC resistance – determined to be 0.8Ω; L is the cyclotron tank inductance - set to 1.1μH; and C is the DEE capacitance measured at 78pF. We take the electric field as the peak DEE voltage divided by the DEE-Dummy DEE gap. The DEE-Dummy DEE gap is taken at 0.50 inches. With this final assumption we can plot the first revolution of an ion at differing peak E fields. Further more, we can consider ions originating at different times in a single RF period.

The following page contains six plots of differing power levels. 1000 watts is considered the practical upper limit of available RF power. Each plot considers nine ion paths, each originating at later phases – equally delayed by 1/9 of an RF cycle.

Ion Paths at Different RF Power Levels

March 7, 2006. Assumes DEE-DEE Gap Distance of 0.50 Inches & R_{AC} of 0.80Ω

Fig. 8 50 Watts:

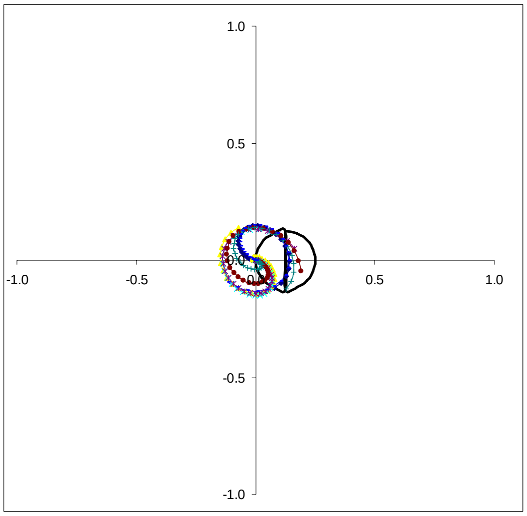


Fig. 9 100 Watts:

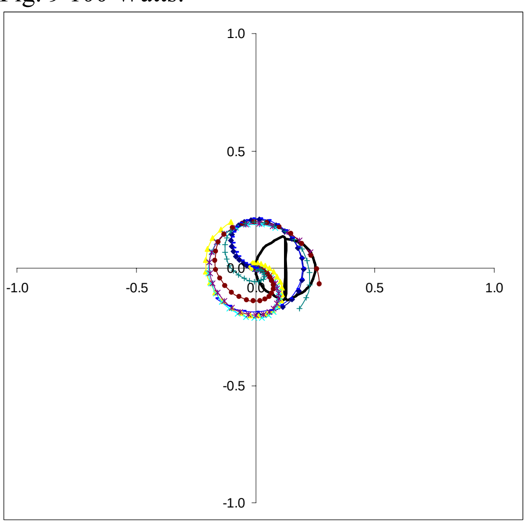


Fig. 10 175 Watts:

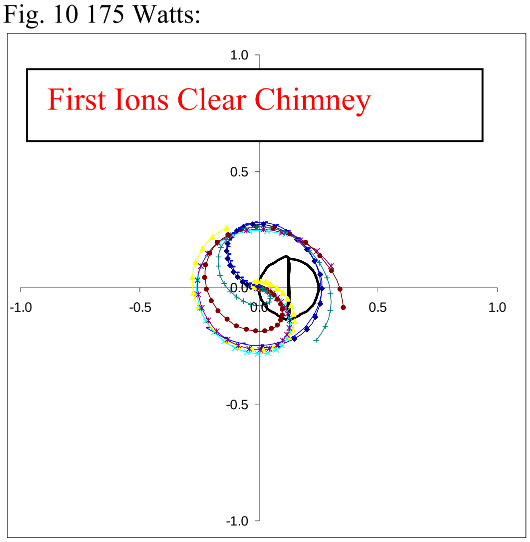


Fig. 11 200Watts:

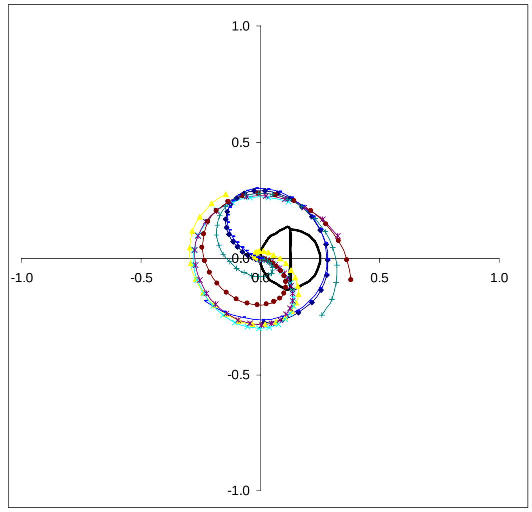


Fig. 12 400 Watts:

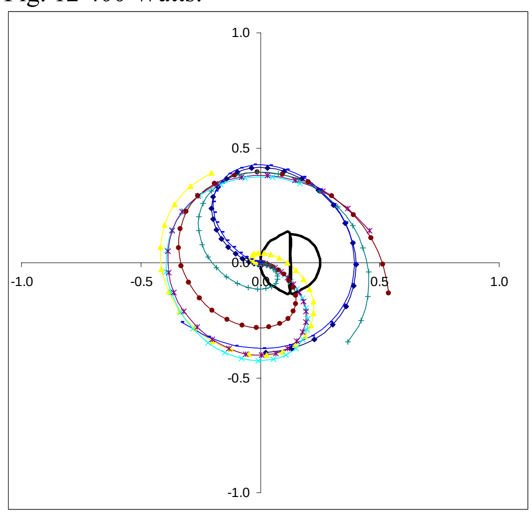
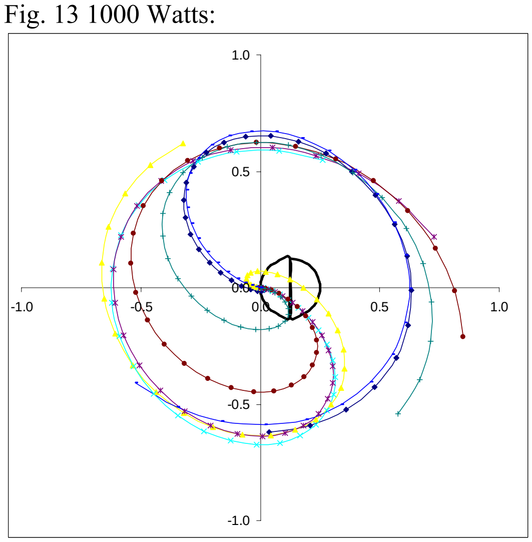


Fig. 13 1000 Watts:



This model does not take into account the transit time factor. It is seen that an input RF power level of 50 watts is too low, and 500 watts should be sufficient. The first ions are expected to clear the chimney at approximately 200 watts.

FUTURE: At the time of writing this documents version, the experiment of increasing RF power above 50 watts has not been performed. It is the hope that a pair of “cyclotron students” can perform this experiment in the near future. Otherwise the author anticipates an opportunity to perform the experiment this summer.

Additionally, it would be interesting to operate the new ion source with the RF off and with the DEE sitting at a negative potential to collect and measure the ion current from the source. Comparison of the ion current at the source and target will give a measure of the focusing effectiveness.

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REFERENCES:

Poisson-Superfish can be downloaded from: http://laacg.lanl.gov/laac/services/serv_access.phtml

J.J. Livingood, “Principles of Cyclic Particle Accelerators” D. Van Nostrand, 1961

Livingston and Blewett “Particle Accelerators” McGraw-Hill, 1962

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

Formation of Ion in the Cyclotron, R.R.Wilson Phys. Rev. Vol. 56 September 1939. pp.459

The Ionization of Hydrogen by Single Electron Impact ,W. Bleakney, Phys. Rev. 35, 1180 (1930)

http://www.physics.rutgers.edu/cyclotron/papers/12_inch_dee_voltage.pdf