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Alternate RF Systems for Synchrocyclotrons (February 2015)

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***Abstract*—Synchrocyclotrons are a useful adaptation on cyclotron accelerators that allow protons to reach relativistic energies without slipping out of phase with the RF system. They work by modulating the RF frequency with time to suit how relativistic particles are at certain times and radii. However, current implementations of synchrocyclotrons typically involve large, unwieldy, and delicate mechanical capacitors that rapidly rotate to change the capacitance and frequency of an LC circuit. The present study derived a function for frequency modulation with time using Mathematica, designed pole tips for the Rutgers 12" Cyclotron to simulate and scale the relativistic action of the Berkeley 184", and tested the frequency function and pole tips in Simion. Finally, the function was driven onto the dees at a lower-than normal frequency to increase bandwidth. The goal of this study was to provide a proof of concept for a new design technique that could make synchrocyclotrons more accessible and affordable for medical and experimental usage.**

I. Introduction

The synchrocyclotron is a useful adaptation on the classical cyclotron that compensates for the phase slippage at higher radii and energies. It allows accelerated particles to reach higher energies than they would in a cyclotron, because it compensates for the relativistic mass increase with an appropriate decrease in frequency to keep the beam in phase with the RF [1]. It is preferable for such uses as proton radiation therapy, a cancer treatment, because overcoming the energy limitations of relativistic phase slippage is necessary to reach energies for treatment of deeper tumors [2]. Obviously, then, creating a cheaper and more maintainable synchrocyclotron is of interest to the medical community, so that proton radiation therapy can be more accessible to all cancer patients. This study tests a new design for the RF system that could be very helpful in efforts to make synchrocyclotrons more accessible and affordable for medical use.

II. Background

Because particles in a constant magnetic field have the same frequency of oscillation no matter their energy, a cyclotron can be tuned to the frequency $f = \frac{qB}{2\pi m}$, where q and m are the charge and rest mass, respectively, of the particle being accelerated, and B is the magnitude of the magnetic field [3]. However, particles being accelerated are not at rest, so their rest mass is a less and less accurate estimate of effective mass as energy increases. This estimate entirely fails around 15-20 MeV, when protons in a cyclotron will become syncopated with the RF system and decelerate back into the center [4]. Once protons have reached these relativistic energies, one must either change the magnetic field or the frequency with radius to adapt to the effective mass increase. Isochronous cyclotrons strengthen the magnetic field as a function of radius to compensate for particles being less responsive to forces at higher masses [5], but this is limited by the amount that the gap between pole tips can be changed while still having both room for the dees and a decent field at the center. Synchrocyclotrons, on the other hand, allow much higher energies but sacrifice beam current. A synchrocyclotron modulates its frequency with time, adapting with a small "bullet" of particles' relativistic factor as they move out of the accelerator, and then bringing the frequency back up

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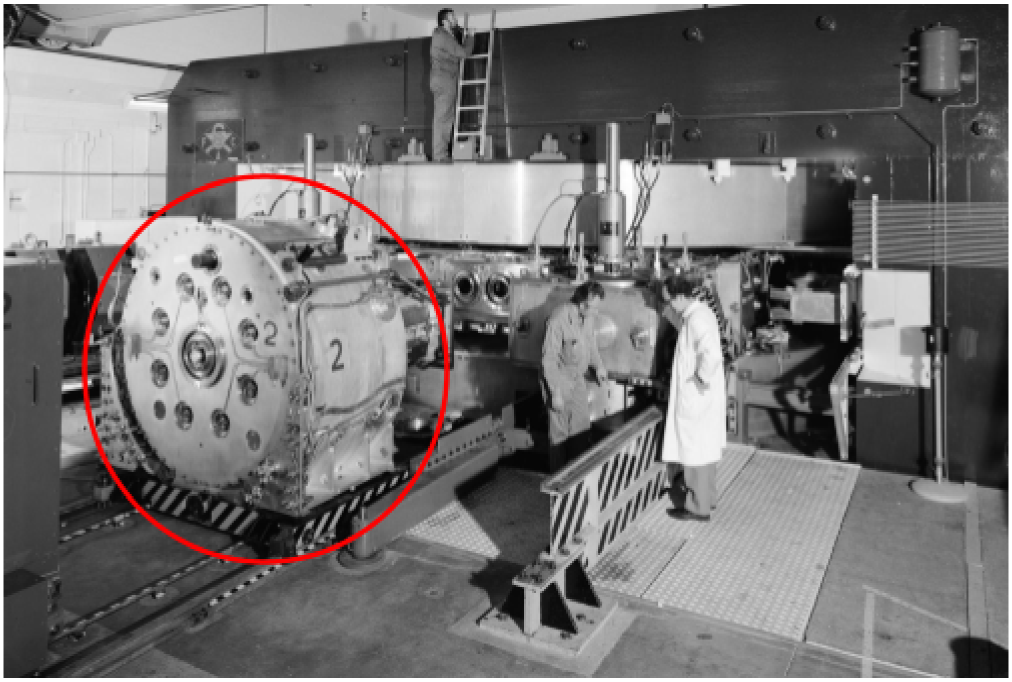
once they exit to start accelerating a new “bullet” [6]. In the past, synchrocyclotrons have used large mechanical capacitors in parallel with the dees to modulate the frequency of the LC resonant circuit with time [7]. As visible in the image below, these capacitors are the size of oil drums, and because they have large rotating parts at frequencies up to 200 Hz, they can end up tearing themselves apart with centripetal force.

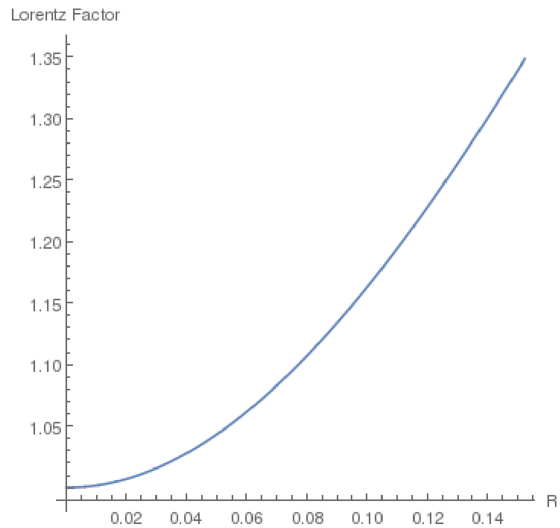


The rotary capacitor of the CERN 600 MeV Synchrocyclotron, circled [8]

This design is difficult to maintain, has many breakable mechanical parts, and is quite large and expensive. A better design might involve components that do not move, and thus are easier to maintain or repair.

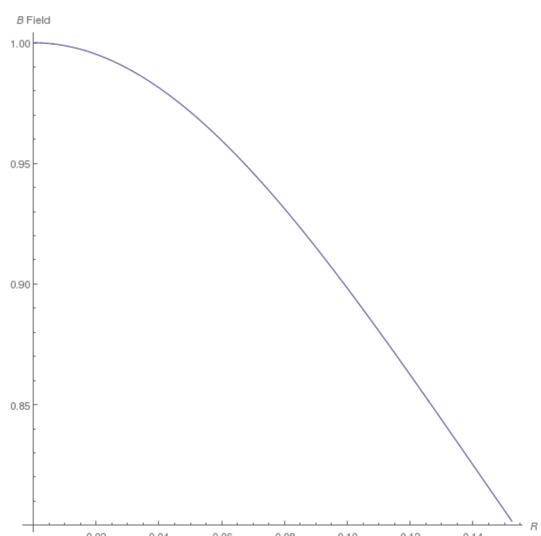
III. Methodology

Because, unfortunately, the authors did not have access to a cyclotron with the radius or magnetic field to hit energies with a noticeable relativistic effect, it was necessary to manufacture the relativistic effects by weakening the magnetic field with radius. First, the value of gamma at each radius on the Berkeley 184” was calculated using energies, and then scaled to the Rutgers 12”. For any cyclotron, the equation for the usual relativistic factor as a function of radius comes out to $\gamma(r) = \frac{\sqrt{m^2c^2+B^2q^2r^2}}{mc}$, and this is plotted below, after being mapped by radius to the 12”. All Mathematica-produced graphs were created with an assumed 1T field, but ended up scaling accurately to other field strengths.



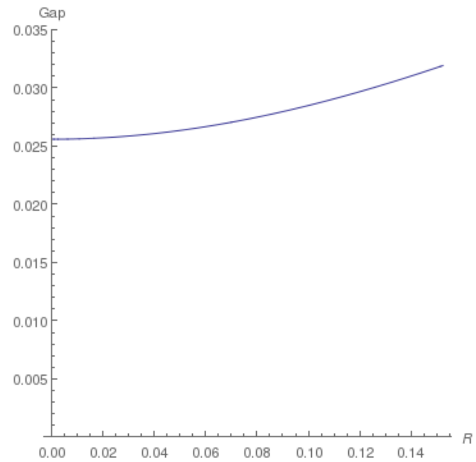
Simulated lorentz factor as a function of Rutgers 12” radius

Next, under the estimation that the protons in the 12” would not experience any noticeable relativistic effects, the relativistic effects were worked into the magnetic field magnitude. Since particles whose masses increase are less responsive to forces, if the masses are constant and the magnetic field decreases, the particles will move in the same fashion. In mathematical terms, if we determine that $f = \frac{qB}{2\pi\gamma m}$, the B field by radius can be set at $B(r) = \frac{B_0}{\gamma(r)}$. This field is plotted below, again scaled for the Rutgers 12”.



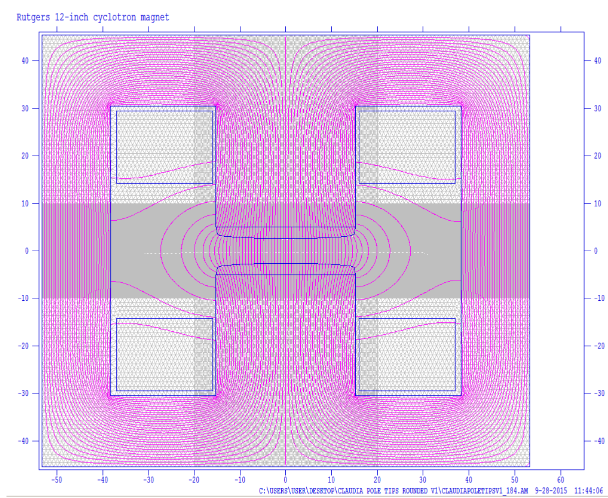
B field for simulation as function of Rutgers 12” radius

To actually construct pole tips for this field, the traditional estimate of the field being inversely proportional to the gap was used. Below is a plot of the estimated gap versus radius, in meters.



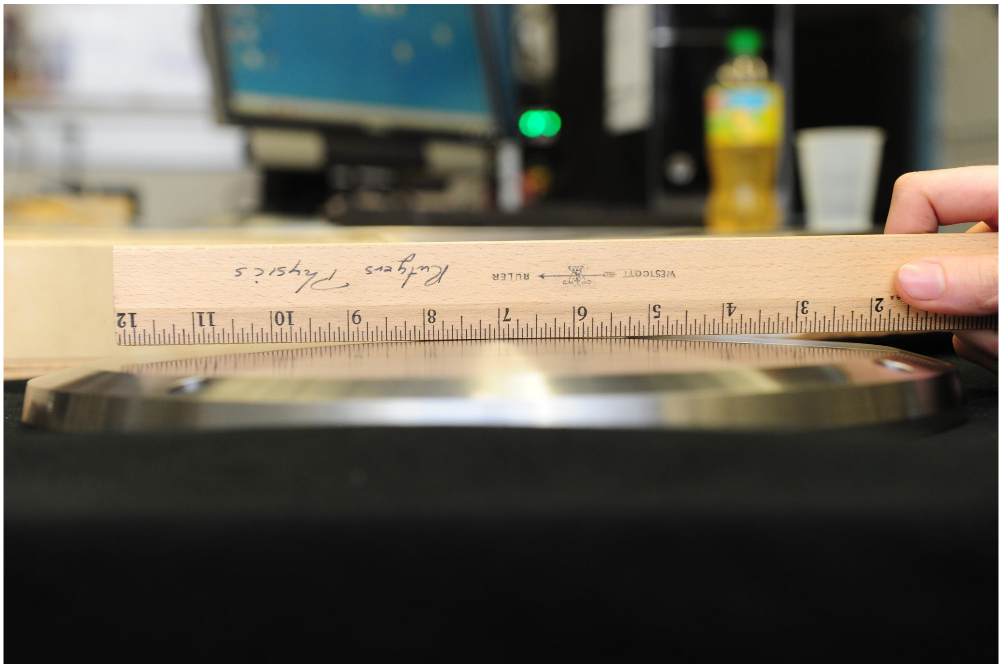
Estimate of needed magnet gap

This was transformed into coordinates for use with Poisson Superfish, from LANL. This program plotted the pole tips, then calculated their field with a set magnet current. The output with field lines is shown below.



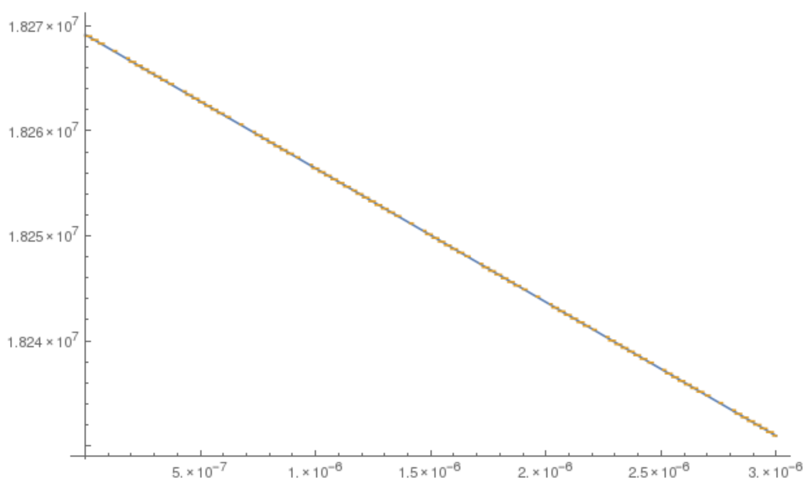
PSF output for relativistic simulation pole tips

Analysis of the midline field showed that the pole tips created the intended magnetic field drop-off, so the pole tips were plotted in AutoCAD and sent to the Rutgers machine shop to be created.



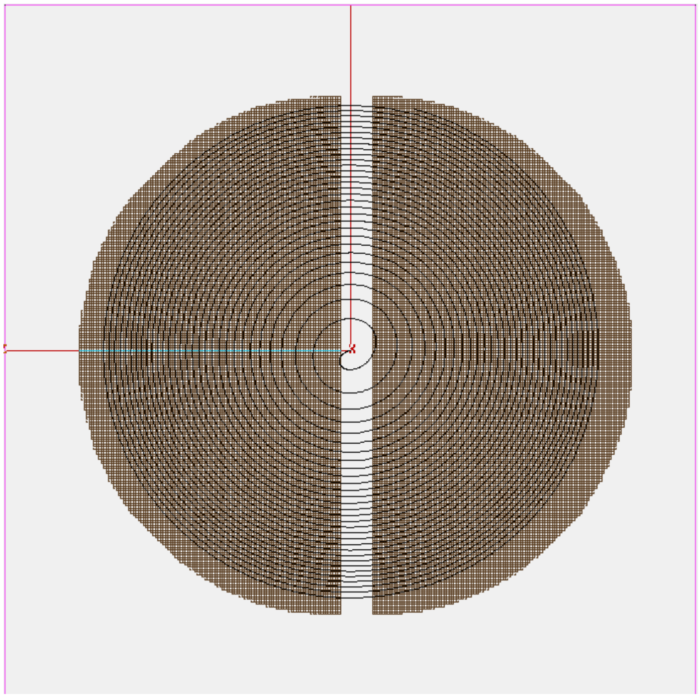
Magnet pole tips

The next step was to figure out how the frequency would be modulated with time. Frequency as a function of radius was trivial, but calculating versus time required an iterative function that added up the time spent traveling around each radius, and how much its radius increased with every pass across the gap. Using Mathematica, a collection of timestamps when the particle was halfway through each dee could be plotted. Surprisingly, it came out to be almost perfectly linear. A curve fit revealed a function for how the frequency should drop off with time, dependent on voltage and magnetic field strength.



Curve fit for frequency of time function

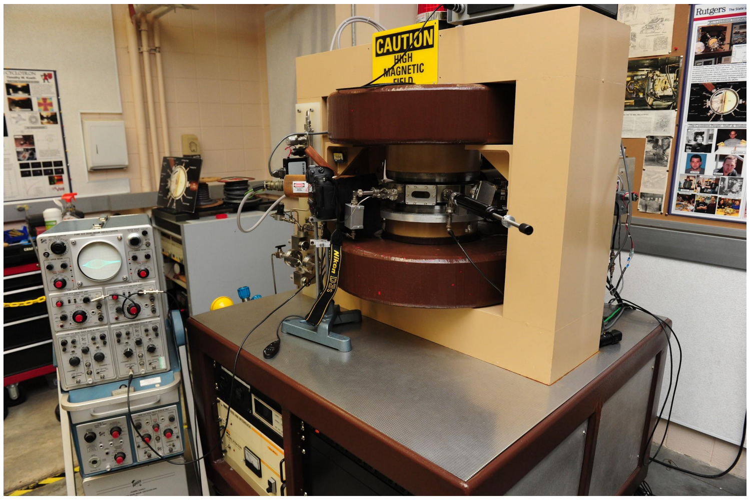
Next was to simulate the action that these modified frequency functions and B field have on a particle beam. With Simion, the PSF fields could be imported into a simulation of the Rutgers 12”, and then from there it was easy to code in a frequency function. With adjustment of the frequency function, it is possible to get a weak beam in the simulation at voltages as low as 6kV, but operates very well around 10kV.



A 10kV simulation run in Simion, with Relativistic pole tips and RF.

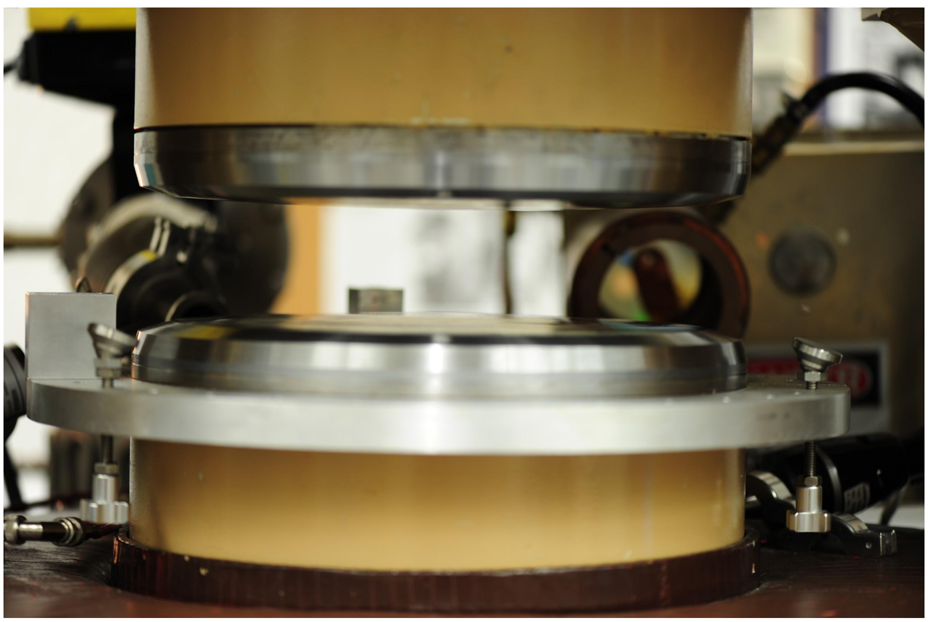
This RF signal visually has very little phase slippage, and is found to be stable for a wide range of particles' initial conditions. The fact that this frequency modulated signal is responsible for getting beam becomes even more evident when running the relativistic simulation field with a constant RF frequency appropriate for the center field (equivalent to running a large synchrocyclotron at constant field). It takes upwards of 26kV of dee voltage to allow even a slight beam to escape. Obviously, synchrocyclotrons have huge energy advantages over classical cyclotrons for producing high-energy particles.

The next step, of course, was figuring out how to get this function onto the dees. At normal operating frequency, the LC resonator of the RC circuit will only operate at a very small range of frequencies without a massive voltage drop-off. However, at a lower frequency, the bandwidth is much larger [9], and the frequency can be swung through a few hundred kHz with minimal change in voltage. For these tests, the former calculations were adapted to be run around 7.16 MHz, with a much lower field strength. The magnet was running a little under 0.48 T at center field, judged by testing the center field at various currents without the chamber inside, and confirmed by getting beam at certain magnet currents. The machine was first tested with constant frequency and weak-focusing pole tips to ensure that it was functioning properly.

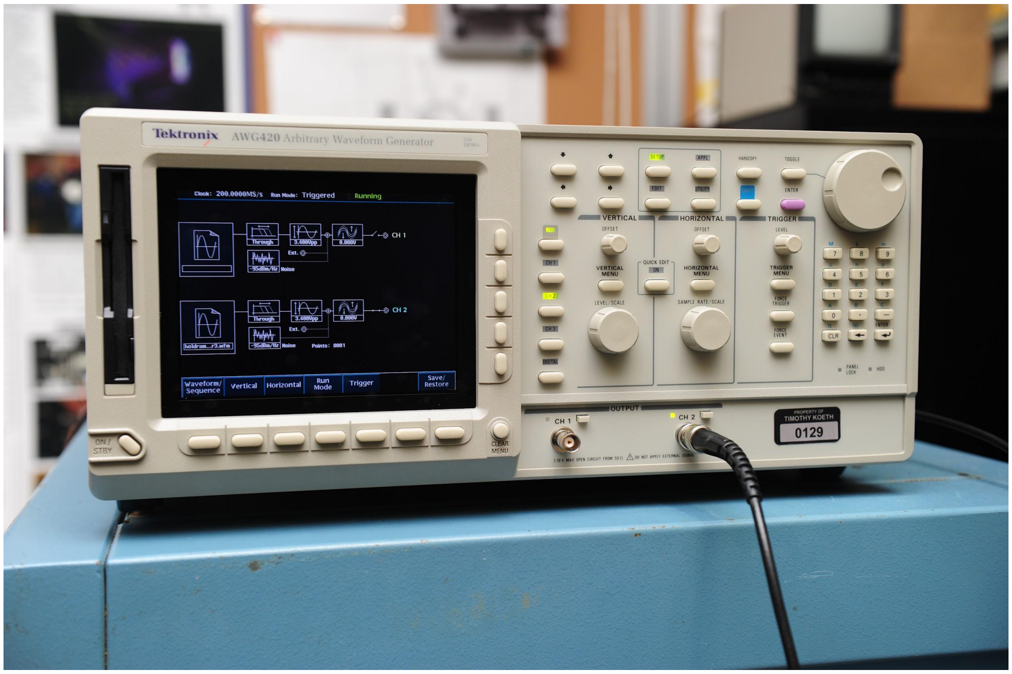


Rutgers 12” cyclotron

Next, the synchrocyclotron pole tips and a function generator with the calculated frequency modulated function were put onto the machine.



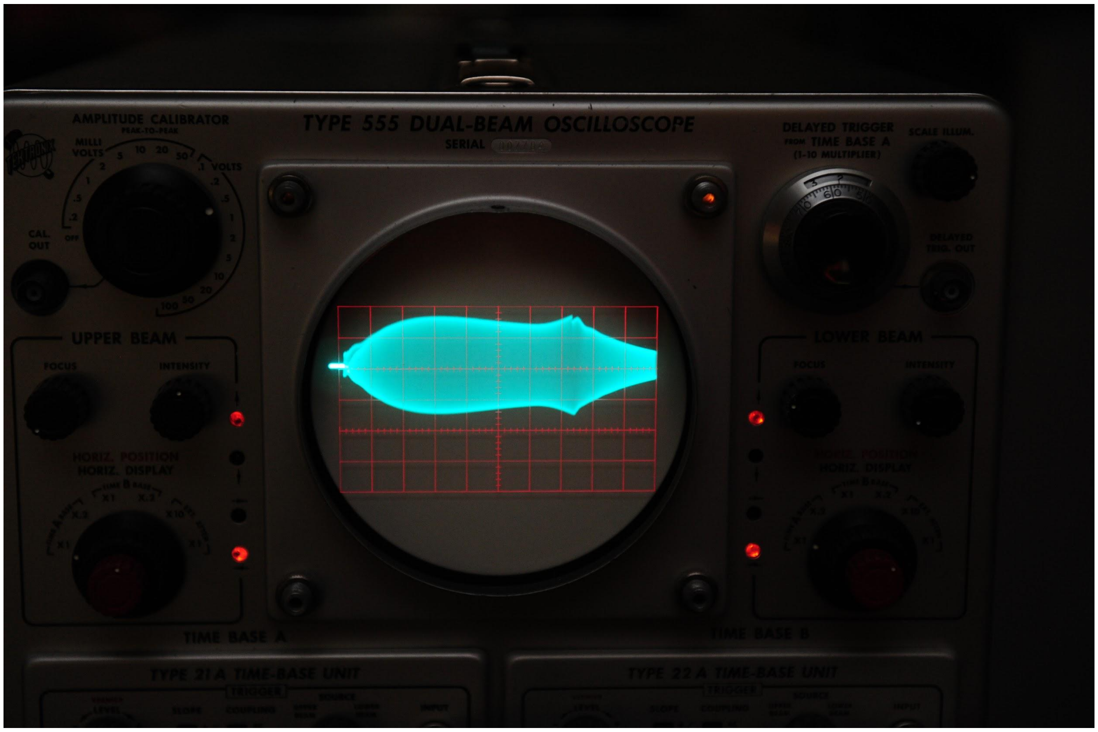
Relativistic pole tips on the Rutgers 12”



Tektronix AWG420, running the frequency-ramped function at a 1kHz rate

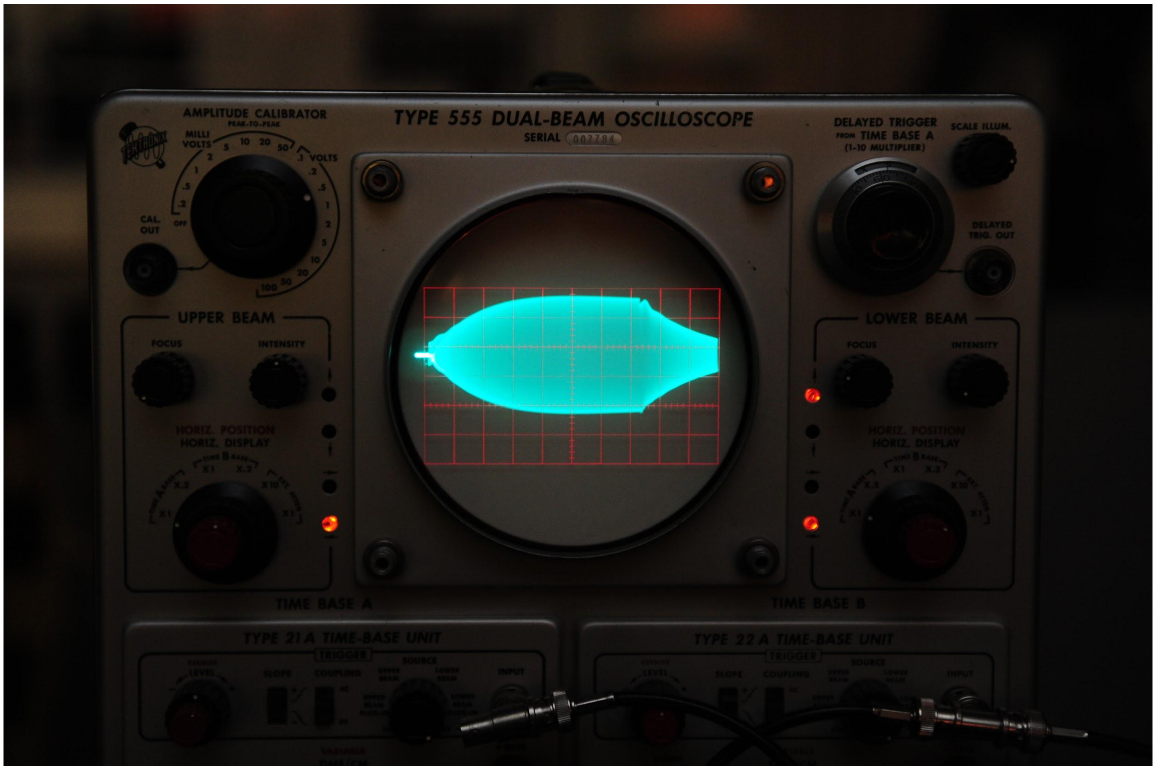
A camera was set up at the viewport, as shown in the photo of the cyclotron above, for the deflector to take long-exposure photos of the beam exiting and determine its current relative to other setups.

Next, before starting, the amplitude of the dee voltage function had to be calibrated to stay nearly constant through the frequency ramp. There were two problems to solve with this. First, the frequency sweep can end up departing either side of the bandwidth. To fix this, the resonant frequency of the tank circuit can be adjusted by means of a mechanically adjustable capacitor in parallel with the dee, to center the ramp as well as possible around the resonant frequency. A bad setup with a noticeable irregularity in dee amplitude is shown below.



A setup using frequencies outside the bandwidth of the tank circuit

Second, the time for the beam to exit the accelerator was about 7 μs, during which time the frequency would fall off as the beam exited. However, the time that it took for the tank circuit to ring up to an equilibrium energy and stay at a constant voltage was about 30 μs, and the FM function was being pulsed at 1 kHz, so the RF circuit had to ring up each time particles were accelerated. A solution to this was to program the AWG to sit at the ramp's start frequency for 30 μs before actually performing 7 μs ramp. As shown in the picture, by the time the function hits the frequency increase, the dee has been holding its voltage for a few microseconds, and holds a constant voltage amplitude until it rings down.

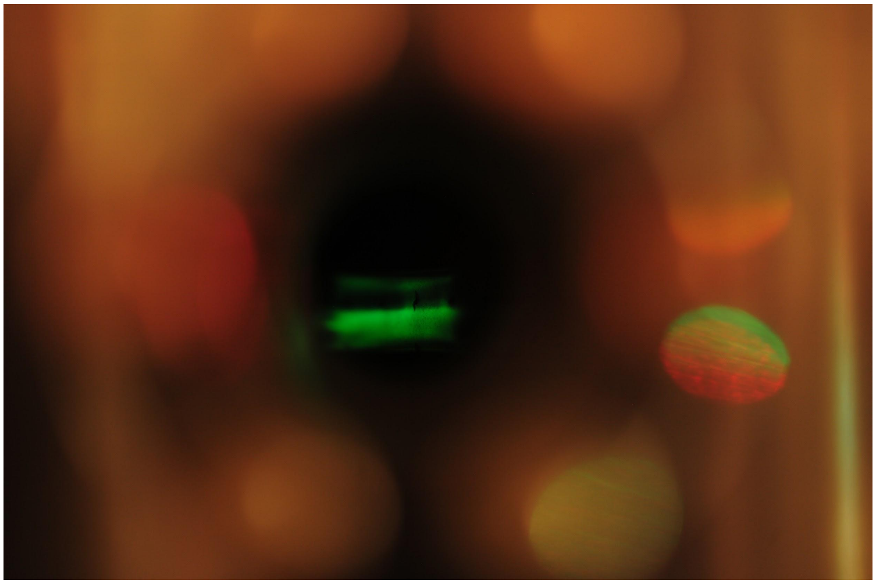


The final calibration of the RF system

Finally, the cyclotron was ready to test the frequency function.

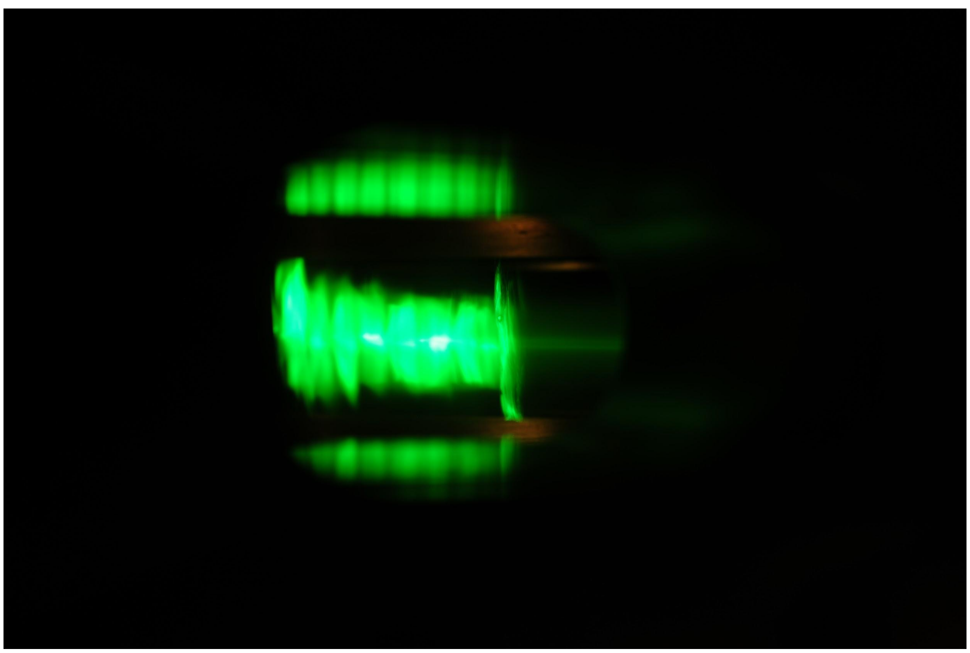
IV. Results

Initially, the frequency function calculated with Mathematica was tested against a constant frequency. Neither hit the deflector, so the insertable phosphor screen was used to intercept the beam at its highest radius. As it turned out, the original function calculated with Mathematica provided an insignificant change in maximum radius over the constant frequency. This soon turned out to be because significant parts of that code were designed for a machine operating at 1T and double the frequency. After adjusting the final frequency to be much lower, the beam was making it almost all the way out. Then, after a few more adjustments to the magnet, RF strength, frequency of pulses, and deflector voltage, beam appeared solidly in the detector. To compensate for factors not accounted for in simulation, multiple final frequencies were tested, and a ramp of about 7.16 MHz to 6.8 MHz over 7.3 μs at a 1 kHz pulse rate provided the highest current in the deflector with how the rest of the cyclotron was set up. The beam, as shown by the detector, is pictured below.



Beam from the frequency-modulated function, in the deflector

The pole tips were also used with a constant-frequency pulse of the same duration, to test the improvement from the new frequency function. The beam didn't make it to the deflector with constant frequency pulses, so instead, the beam was depicted by sliding the phosphor screen in and out of the beam while a camera took a 10-second exposure.



The beam phase-slipping about 3 in. out as it also hits a resonance

V. Conclusions and Future Work

In conclusion, this experiment was very successful. The Rutgers 12" was successfully converted into a synchrocyclotron, using a new set of pole tips that times particle arrival as if the particles are in the Berkeley 184" cyclotron. Using the expanded bandwidth of a lower frequency, it was possible to make a large sweep in frequencies with a near-constant voltage amplitude through the entire sweep. In larger machines or at higher frequencies, though it would take more power to drive the tank circuit harder, it would be possible to get more bandwidth by adding a resistor and lowering the Q of the circuit.

The next step will be to completely replace the RF tank circuit with an amplification system bridging the AWG through a series of vacuum tubes and a transformer to induce the voltage in the see. This system will be much less lossy at higher frequencies and larger machines, because it will not be necessary to lower the Q of a tank circuit by adding a resistor or otherwise experiencing voltage loss. It will provide much more flexibility in the range of frequencies that can be reached at constant voltage amplitude, without as much power consumption. Hopefully, the synchrocyclotron modifications to the Rutgers 12" will also inspire others to try experiments with improvements on synchrocyclotron RF systems.

References

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