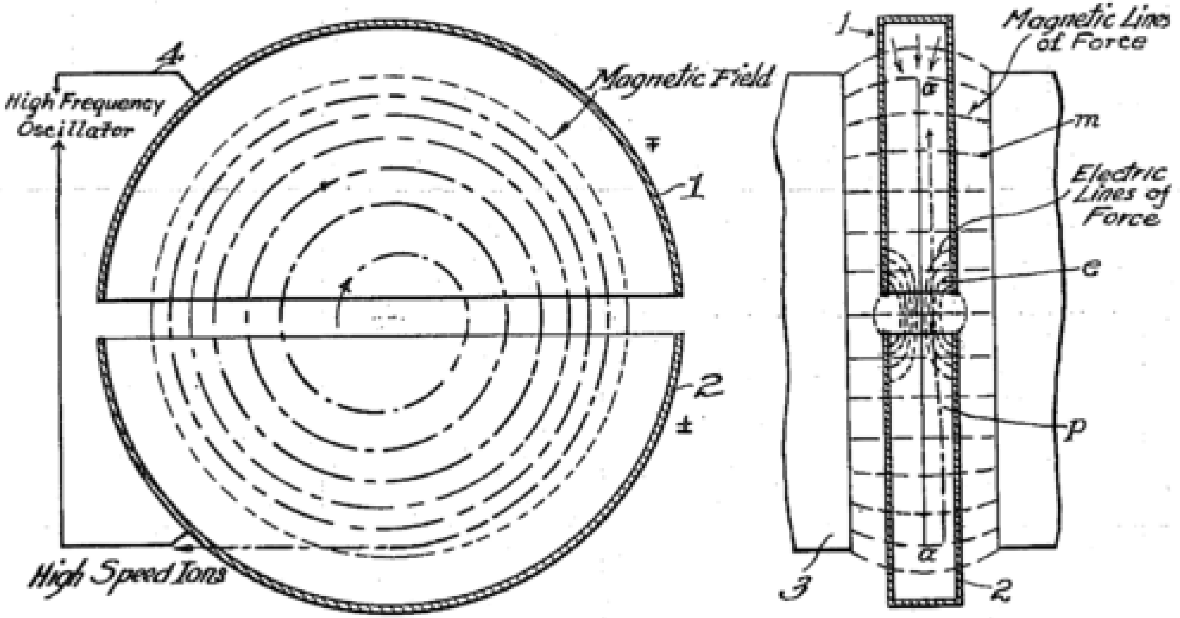
NSCL Cyclotron Basics

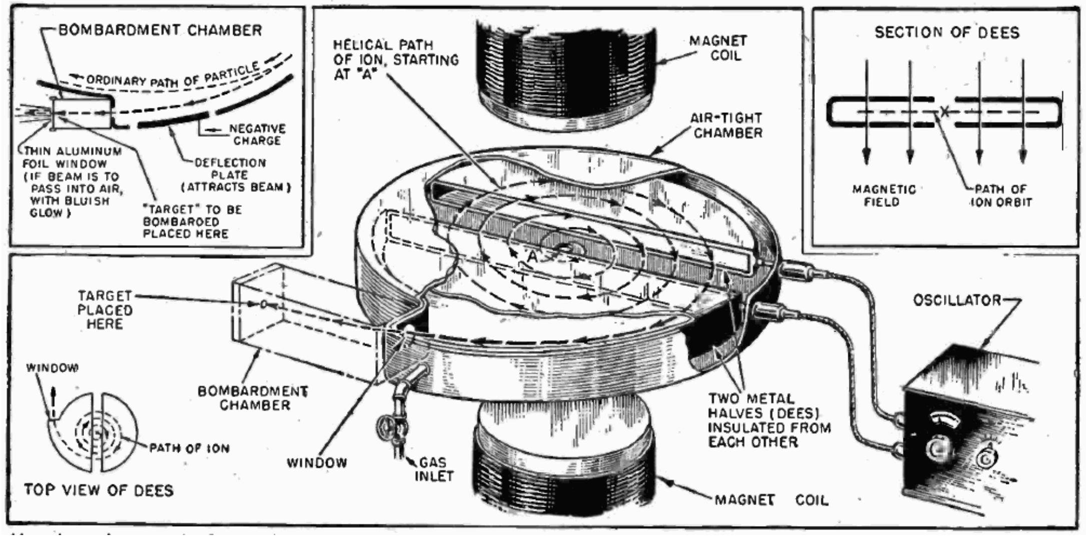
An overview of the cyclotrons at the CCF

David R. Poe   2015

One is no doubt familiar with the description of the cyclotron as found in physics texts. There is a magnetic field which serves to cause charged particles to orbit in circular orbits, and two Dees inside the magnets which have opposite, alternating voltages. The particles gain kinetic energy when crossing the gaps between the Dees, all happening inside of a vacuum chamber. The drawings are from the Wikipedia article on the cyclotron.

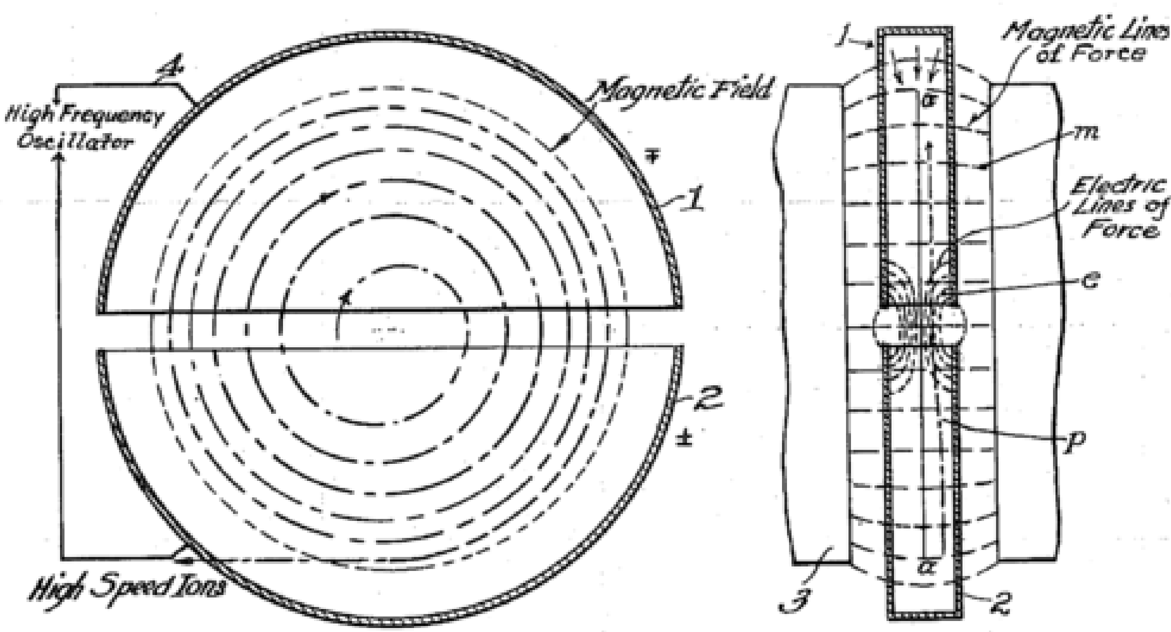


The diagram above is of cyclotron operation from Lawrence's 1934 patent. (Lawrence is Earnest Lawrence of Berkeley, California, winner of the 1939 Nobel Prize in Physics for his invention of the cyclotron.) The "D" shaped electrodes, called “Dees”, are enclosed in a flat vacuum chamber, which is installed in a narrow gap between the two poles of a large magnet.



One of the two Dees in the diagram may be grounded without loss of functionality, so it is called a one Dee cyclotron. The machines we use at the NSCL have three Dees with the hills performing the function of grounded, dummy Dees.

The basic requirements come from the fact that a magnetic field provides a force perpendicular to the direction of the magnetic field and to the velocity. The force F is the cross product $\vec{F}=q\,\vec{v} \times \vec{B}$ where F, velocity v and magnetic field B are vectors, and q is the electric charge. Setting the centripetal force, mv^2/r, equal to magnetic force qvB and rearranging, $\omega = \frac{v}{r} = qB/m$. From this comes the relation that the particle frequency, and hence the RF frequency, is $f=\frac{qB}{2\pi m}$. Different ions with the same ratio of q/m will run at the same frequency in the same magnetic field. Ions with the same ratio of missing electrons to atomic mass are usually separated in frequency due to small differences in atomic mass. These are so-called analog beams.



Simple classical approximation:
Energy E is proportional to turn number.
Radius r of turn n is proportional to velocity v, so r is proportional to $\sqrt{E}$. Number of turns $\propto$ to r^2. Turn separation proportional to $\frac{1}{r}$.

The cyclotrons at the NSCL produce their magnetic fields by means of superconducting coils, allowing for approximately ten times the beam energy than would be possible from a conventional machine of the same size. The "k" value comes from the equation $E/_A = k(\frac{q}{A})^2$, where E/A is in MeV/u, q is the charge state and A is the atomic mass. Labels such as k50 and k500 refer to the strongest magnetic fields we can run. For a cyclotron accelerating protons, q=A=1=q/A, and k is simply the energy of the protons in MeV. The k value thus represents the energy of a proton beam that could be accelerated in the same field.

Every beam that we run has its own particular k value that may be found from k=$(\frac{E}{A})/(\frac{q}{A})^2$. For example, for 140 MeV/u 48 Ca 20+:

k=$140/(\frac{20}{48})^2$ or k=806.4.

Kerst-Serber Equations

Define n =$-\frac{r}{B}\frac{dB}{dr}$ or n= $-\frac{dB/B}{dr/r}$ n = $-\frac{\text{fractional change in B}}{\text{fractional change in r}}$

It can be shown that, for small radial and axial displacements x=(r-R) and z, respectively, (where R is centered orbit):

$$\frac{d^2x}{dt^2} + (1-n)\omega^2 = 0$$

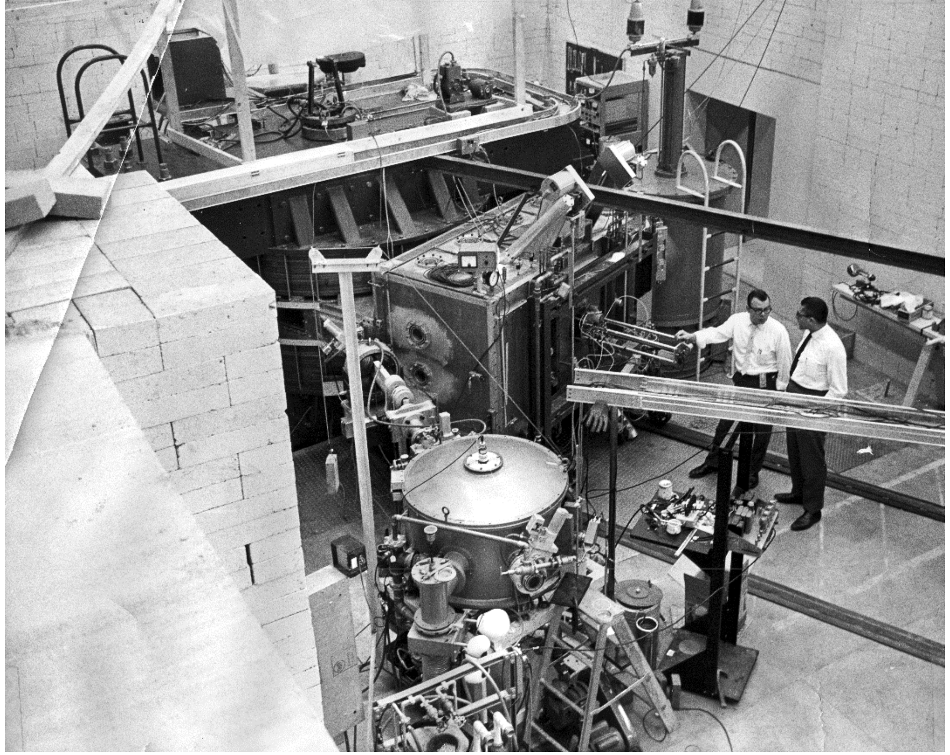
$$\frac{d^2z}{dt^2} + n\omega^2 = 0$$

The solutions are x= $x_m \sin(1-n)^{1/2}\,\omega t$

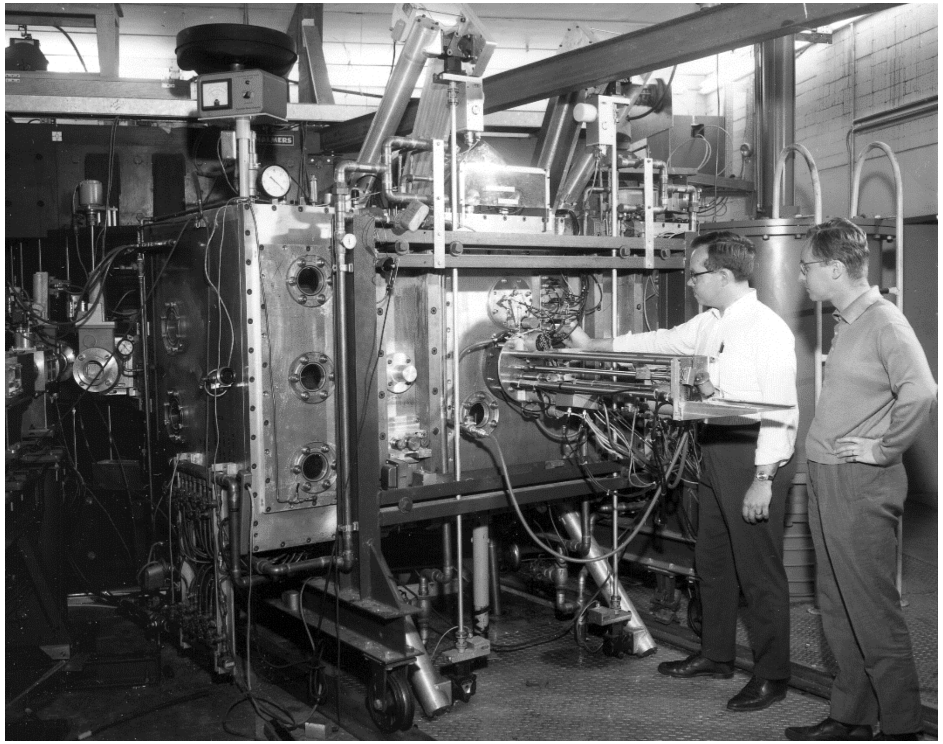
And z=$z_m \sin(n)^{1/2}\omega t$

So for focusing in both r and z to occur, 0 < n < 1, a field decreasing with radius.

nu-R = $\frac{\omega_r}{\omega} = \sqrt{(1-n)}$ nu-z = $\frac{\omega_z}{\omega} = \sqrt{n}$

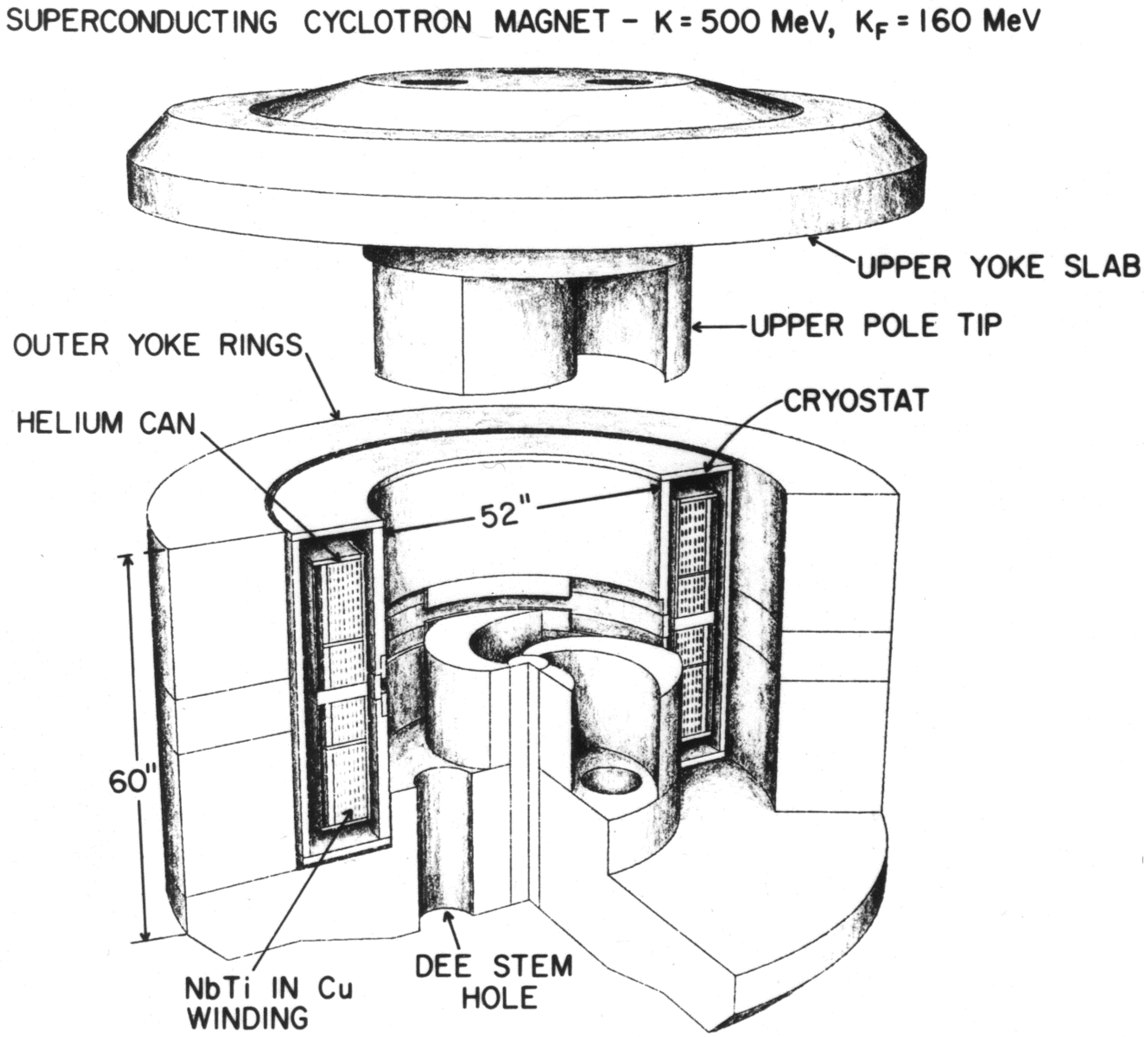


K50 and neutron chamber. Dick Dickinson and Aaron Galonsky.



K50, Sam Austin, and Pierre Locard.

Although no longer in existence, it is of historical interest to note that the first cyclotron here at MSU was the k50, first producing beam in 1965. It was “conventional”, that is, not superconducting, and had an extraction radius similar to that of the k500. Its location was just inside what is now the transfer hall. The present transfer hall north door is seen behind the machine, and the vault, as well as the building itself, ended at the wall to the left of the door.



Left is a drawing showing the construction of the NSCL k500 cyclotron magnet, from the MSU cyclotron annual report of 1974-1976, article "Superconducting Cyclotron General Description", H. Blosser, et. al.

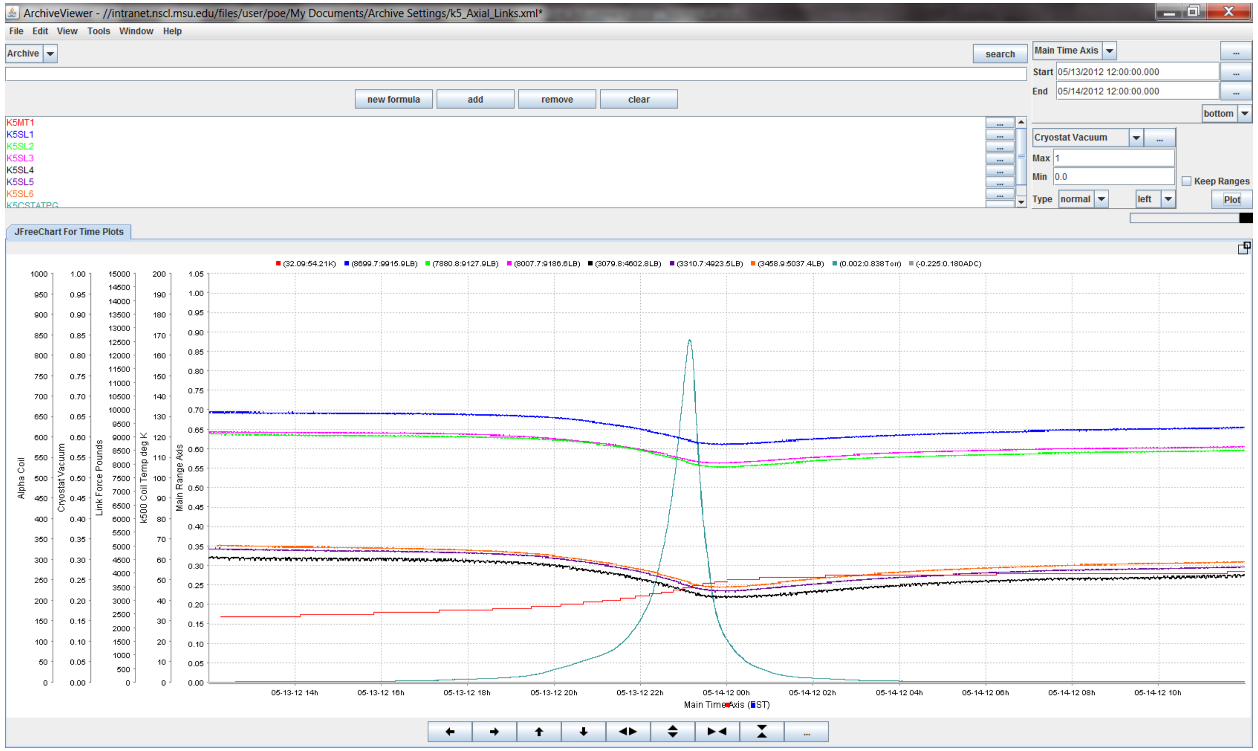
Note the part labelled "cryostat". This is a vacuum vessel inside of which lies a "Helium Can". The superconducting wire is wound on four forms in this can, and wired such that it forms four coils, as described below.

Each cyclotron magnet contains four coils, two above the median plane and two below. In each cyclotron, the two closest to the median plane are wired in series and are called the alpha coil, while the two farthest from the median plane are also in series and are called the beta coil. The purpose of having the two coils is that it allows us to have a magnetic field that increases with radius so as to maintain a constant orbital frequency for the particles in spite of relativistic effects. The condition is B=$\boldsymbol{B_0/\sqrt{1-\frac{V^2}{C^2}}}$ or B=$\boldsymbol{B_0\gamma}$. The higher the beam energy the greater is the difference between the alpha and beta coil currents. The two coils cannot exactly match the required conditions, so we must have trim coils as well. During operation, use is made of the so-called "epsilon" function, which allows the operator to make slight shifts of the main magnetic field of a few parts per million. It is a software function run through the magnet control app that changes the currents in both coils in such a way that isochronism is maintained, and changes the field by the number of parts per million that the operator has specified.

The coils are wound onto bobbins, which are vacuum tight. Liquid helium fills the spaces around the coils inside the bobbins. Spacers were installed at the time of construction to allow helium to flow between the wires. The cryostat must stay under vacuum to provide thermal insulation for the liquid helium, and there are thermal shields cooled by liquid nitrogen between the bobbins and the outside world. The bobbins are suspended in vacuum inside the cryostat by means of the support links, which are epoxy glass laminate bands under tension. If the coil is not properly centered in the iron the coil will move as the field is increased and a link may break. For this reason the links have strain bolts incorporated, and the measured strains must stay within bounds while operating the magnets. An additional constraint is that the links must not be allowed to become slack.

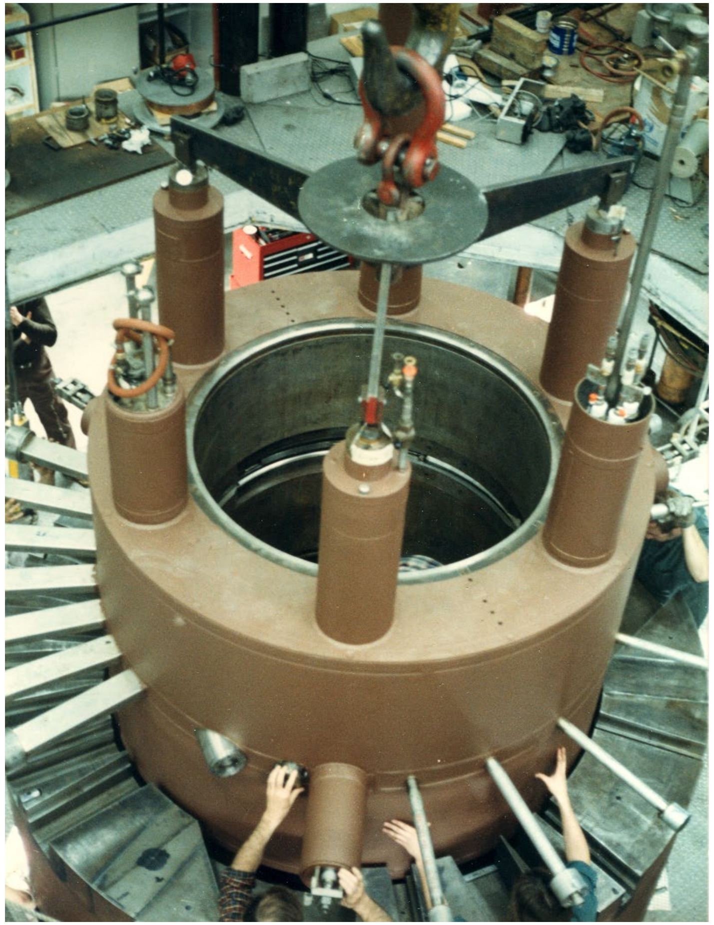
The bobbins of both cyclotrons are each suspended by nine support links, which are epoxy glass laminate bands under tension. When the bobbins are emptied of liquid helium and allowed to warm up, the tension in the support links lessens. The strain in the links is measured by means of strain bolts built into the system, and in the case of the k500 care must be taken that the lower links not become completely loose. During periods of cryostat warm-ups, the strain links must be periodically tightened so that the lower links do not drop below 1,000 pounds of tension. There is a guideline to be followed at these times.

Small air leaks into the cryostat lead to a build up of frozen air on the surfaces of the bobbin, which tends to act as an enormous cryo-panel. When the temperature in the cryostat becomes high enough, the frozen oxygen and nitrogen will be released from the surfaces and be pumped out by the vacuum pump.

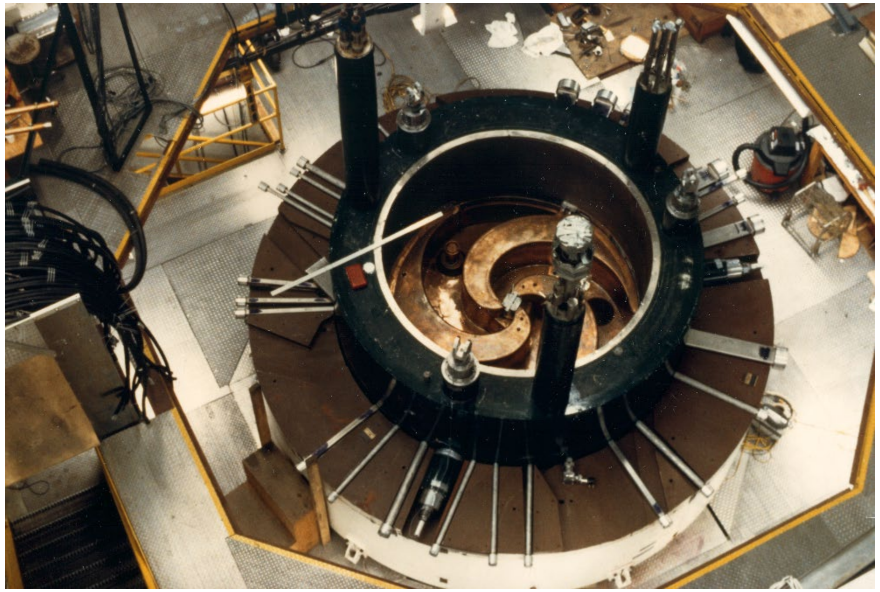


During this time the link forces will drop precipitously as the outer walls of the cryostat are cooled due to the poor vacuum, then they will rise again as the walls warm up after the vacuum improves.

The above chart shows an Archiver plot of the k500 strain links as the cryostat vacuum went through such a peak in May of 2012. The temperature took a step upwards.



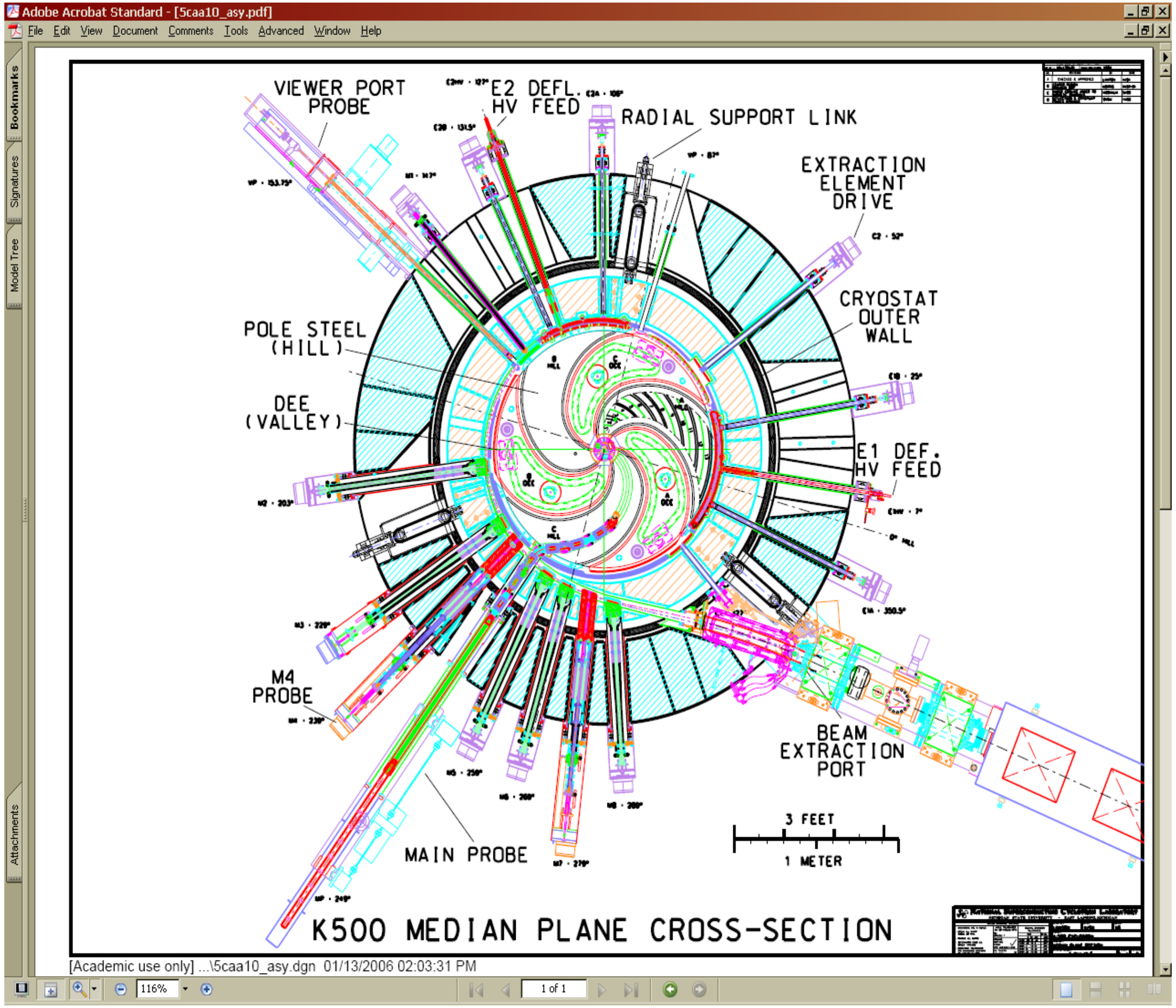
K500 iron yoke being subsequently lowered into place. Merritt Mallory, Bernie Waldman, David Poe and Ron Zarobinski.



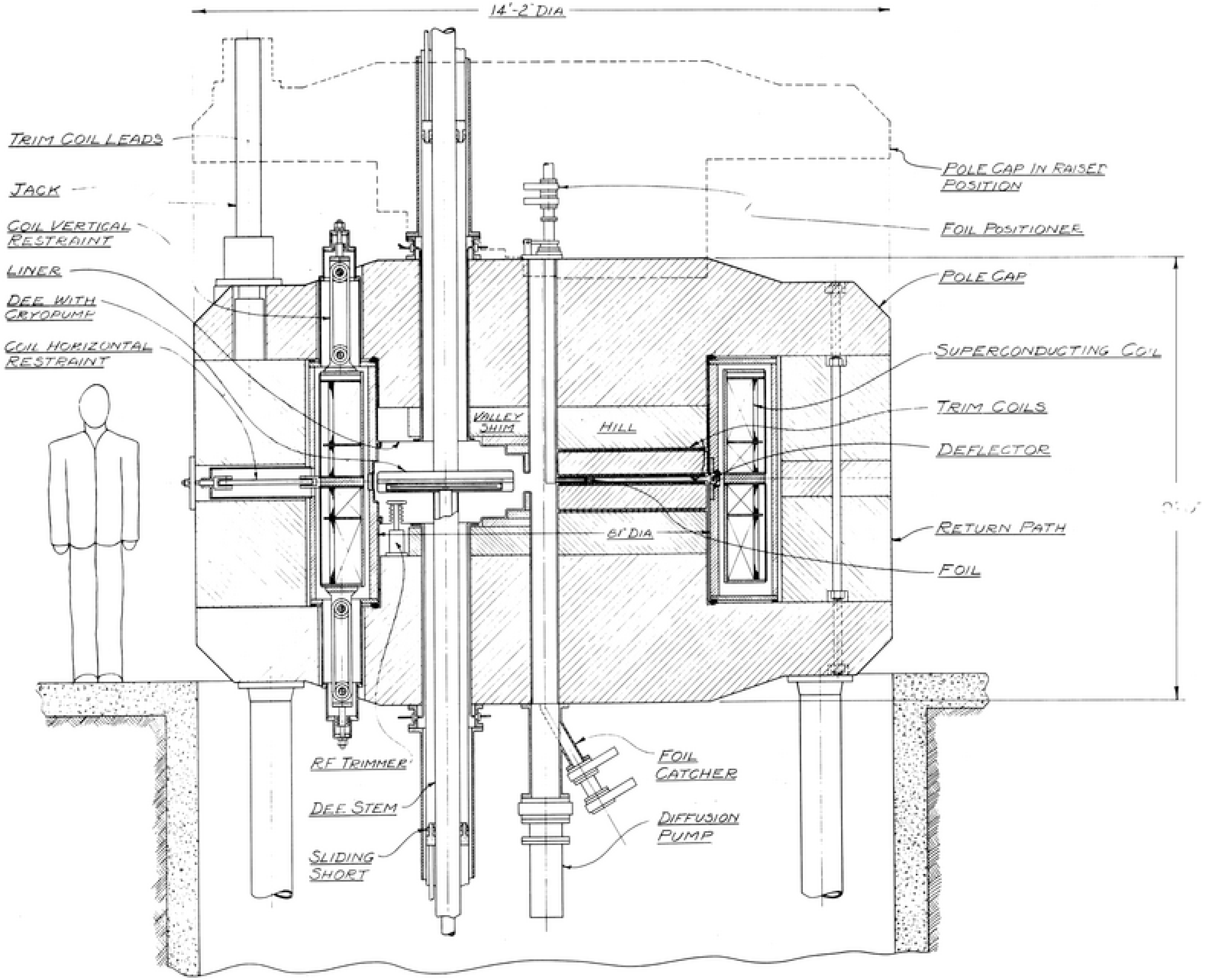
K1200 cryostat in place. Lower liner is installed over pole tips.

K500 cryostat being lowered into place. Note the median plane penetration elements.

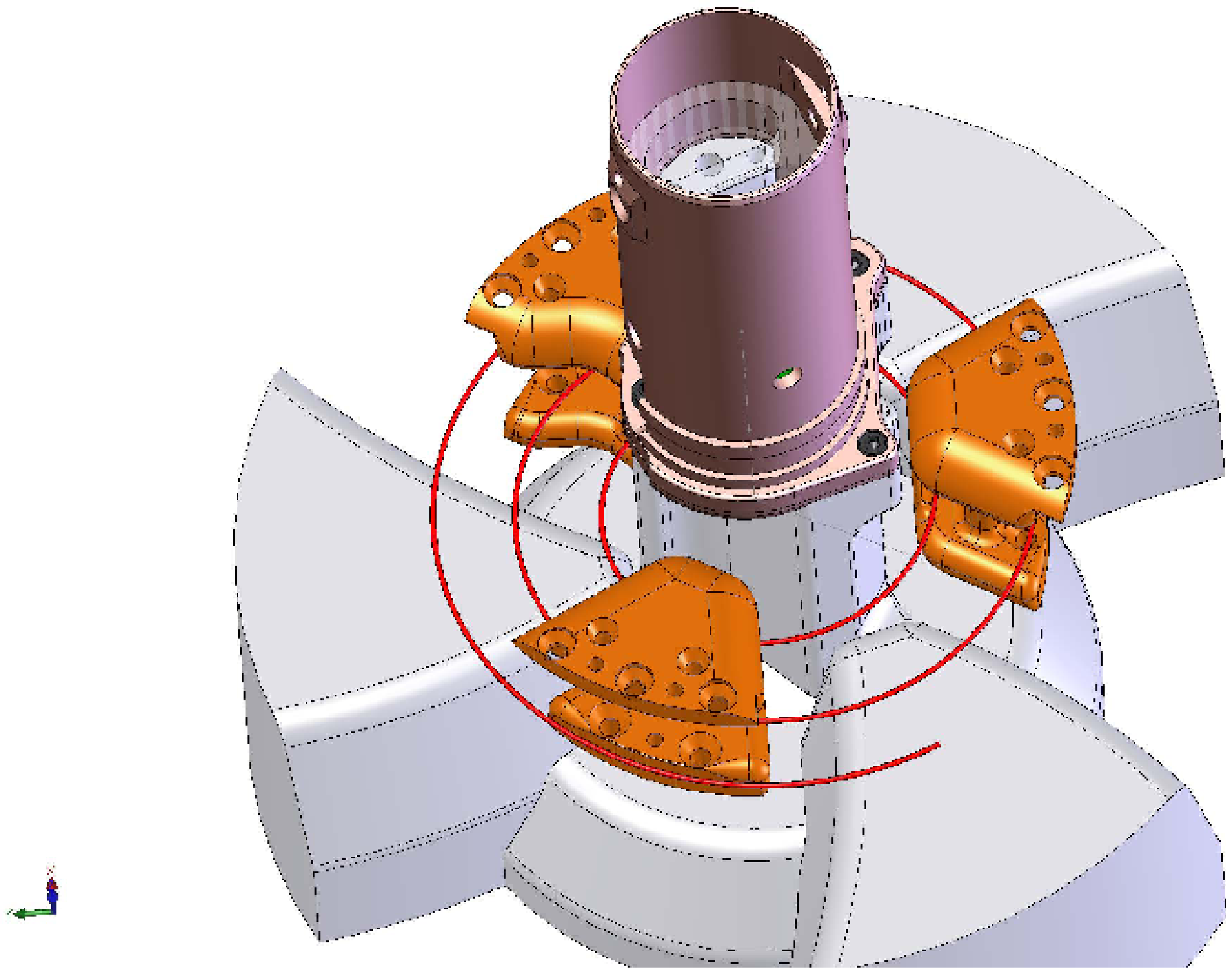
So as to clarify the nature of the machines, here are a few photos showing the construction phases of both cyclotrons, at the times of mating up the cryostats with the entire assemblies.



To the left is a drawing of the NSCL k500 cyclotron, which is somewhat more complex than the Lawrence drawing. The innermost circular area represents the beam chamber, where the ions are accelerated. The ring outside of that is the region of the cryostat, containing the main coils and vacuum, then an iron ring is outside of that. There is an inflector mounted in the center of the machine, where the particles are introduced. The particles then spiral outward in a counter clockwise direction as they gain energy, making approximately 250 turns before being extracted. For extraction, they must be guided into the entrance of the E1 deflector where they begin their journey through the extraction channel.



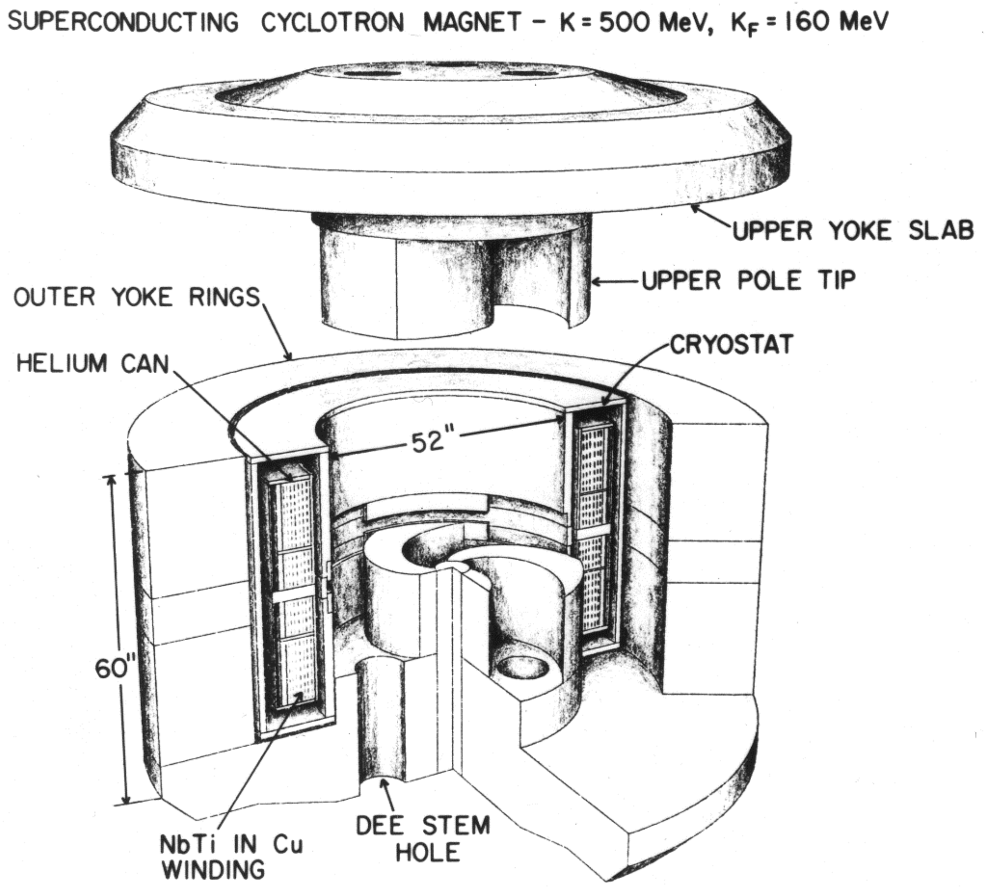
Side view drawing of k500 cyclotron.



Beam from the ECR ion source is injected into the k500 through the spiral inflector, exiting through a hole that faces the "A" Dee tip, where it begins its journey through the central region and the cyclotron. It is basically a cathode and anode producing an electric field so as to bend the beam from vertical to horizontal. The spiral shape is necessary because of the magnetic field.

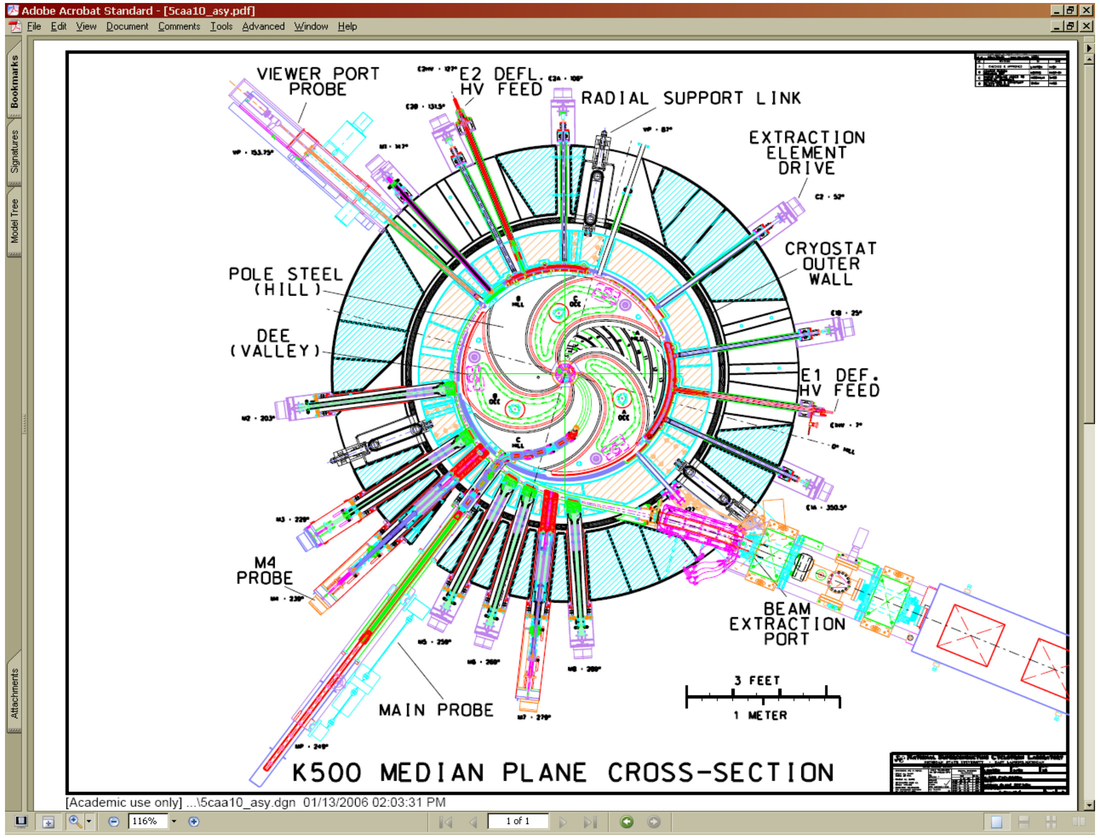
Note the presence of three “hills” in the drawing at right. Their purpose is to provide much needed vertical focusing to the beam, since a magnetic field that increases with radius will otherwise defocus it. The shape of the magnetic field lines in the region above and below the median plane provides for a net focusing effect, and it is enhanced by the spiral shape. The “valleys” are between the hills and are where the Dees reside. Note the large hole in the bottom of one valley in the drawing, which is where the Dee-stem penetrates into the chamber.

With the presence of the magnetic field established, one may accelerate particles by means of Dees. Each of our machines has three Dees, and acceleration occurs six times during each orbit as the particles traverse the gaps between the hills and the valleys. The entire inside of the beam chamber is covered by a copper liner, so when the particles are over a hill they are in a field free region and the hills act as dummy Dees. A particle leaving a hill will be attracted to the Dee, which will have a negative potential at that time, then the polarity of the Dee potential will change while the particle is inside it so that when traversing the gap from the Dee to the next hill the particle is repelled.



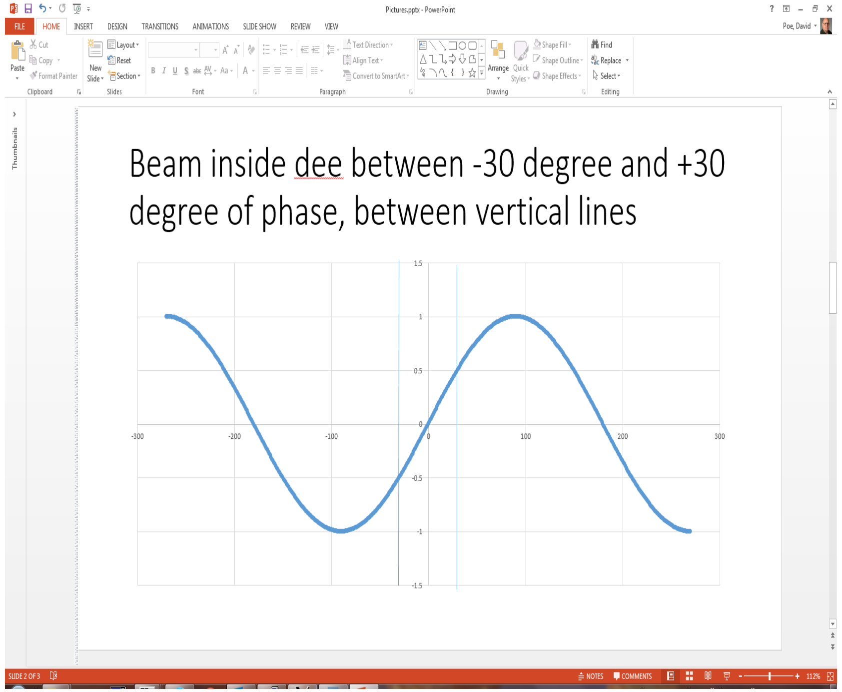
Left, the K1200 under construction. One can see the installed lower pole-tips with the trim coils mounted. The lower liner and cryostat can be seen as well.

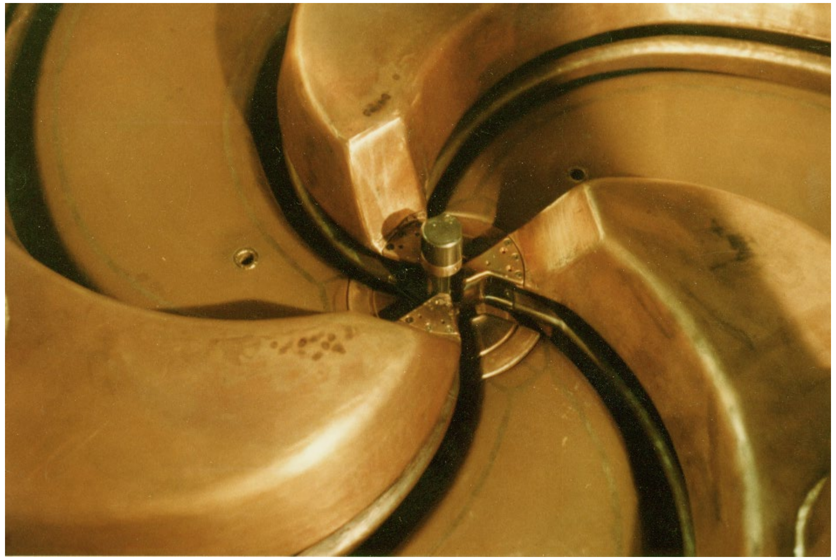
For contrast, the above picture shows the pole-tips for the original k50 cyclotron. Picture was no doubt taken sometime before k50 operations began in 1965.



The three Dees are seen between the hills, and the hill between the A and the C Dees shows the liner removed, showing the trim coils. The main probe consists of a series of wheeled carts with a beam current reading probe at the end, and is seen on a curved track that goes down the center of a hill. There is a “viewer probe” with a scintillator that moves radially immediately downstream of the E2 deflector. The radial support links may be seen extending from the outer wall of the cryostat in to the coil tank. The many penetrations are for driving extraction elements; deflectors, magnetic channels and compensating bars. Deflectors provide an electric field that pushes the beam outward. Magnetic channels, or focusing bars, provide radial focusing to compensate for radial defocusing caused by the decreasing magnetic field. The compensating bars attempt to maintain the desired three fold symmetry of the magnetic field that the magnetic channels would otherwise destroy by their presence.

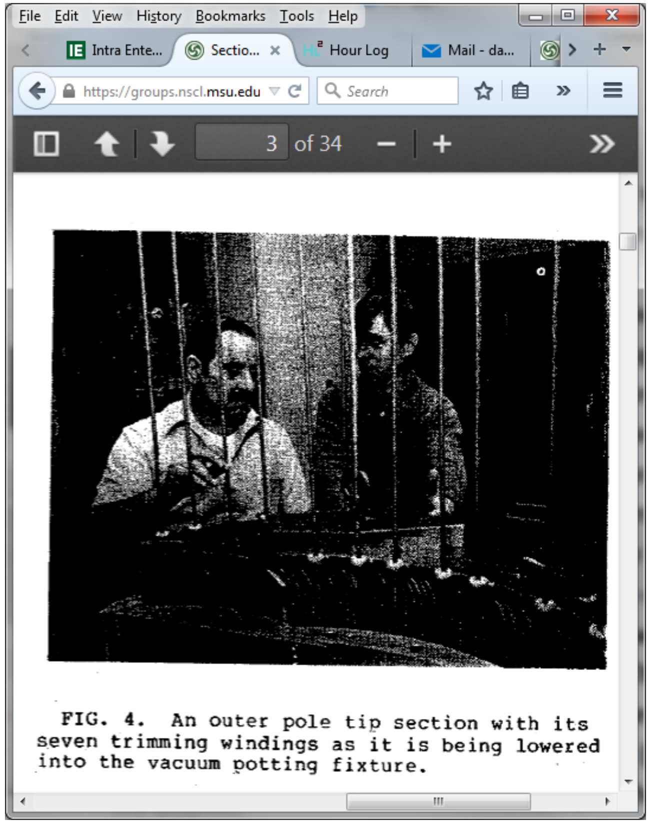
Both cyclotrons are divided neatly into segments of 1/6. Each hill is 60 degrees wide, as is each valley with its associated Dee. Consider a beam running in first harmonic. The acceleration of the beam only occurs when crossing a gap between a hill and a Dee, either entering or leaving a Dee, since inside the Dee or over a hill the particles are in a nearly electric field free region. There are therefore six acceleration periods during each orbit, when entering or leaving a Dee. In first harmonic the beam frequency equals the RF frequency, so one may picture the particles riding in lockstep with the RF voltage, “surfing” if you will. In order to be accelerated, a particle must approach the entrance of a Dee while the Dee is at a negative potential so as to attract the positively charged particle, then the Dee must change to positive polarity while the particle is inside of it. Since a Dee is 60 degrees in width, the particle will travel 1/6 of an orbit while inside of the Dee. This means that the RF will go through 60 degrees, or 1/6, of an oscillation during this time, so the particle will enter and leave 30 degrees from the voltage zero crossing, when the voltage is at ½ of the peak voltage (Sin(30 degrees) = ½). During second harmonic operation, such as in the current k500 configuration, the particles cross the gaps at 60 degrees giving .866 times full Dee voltage at the crossing. K500 Dees and hills shown at lower right.





The trim coils are wound around each of the hills, then the equivalent coils on each of the six hills are wired in series to form one trim coil. There are 13 such coils in the k500 and 21 in the k1200, not counting the trim coil zero coils, which are on the center plugs. There is something of an exception in that the coils used for the bumps have independent supplies on each top/bottom pair, but are run under software control so as to act as one trim coil.

Left, the k500 lower pole with trim coils on the hills.



Left

Dan Magistro and Guenter Stork, preparing a segment of pole-tip for potting its trim coils in place.

Picture from 1979-80 NSCL Annual Report.

The “bumps” are trim coils wired as described above. They are used to move the beam orbit center, both to center it at low radius, then to de-center it at extraction to provide a gap between turns, with the entrance to the first deflector placed in that gap. The bump trim coils are numbers one and twelve in the k500, and numbers one, five and twenty one in the k1200. In stand- alone operation, trim coil 1 is used for centering in the k1200, not 5, but in coupled mode trim coil 1 is not used and trim coil 5 is used to correct for off-centeredness of beam immediately after stripping.

K500 Pole Tips

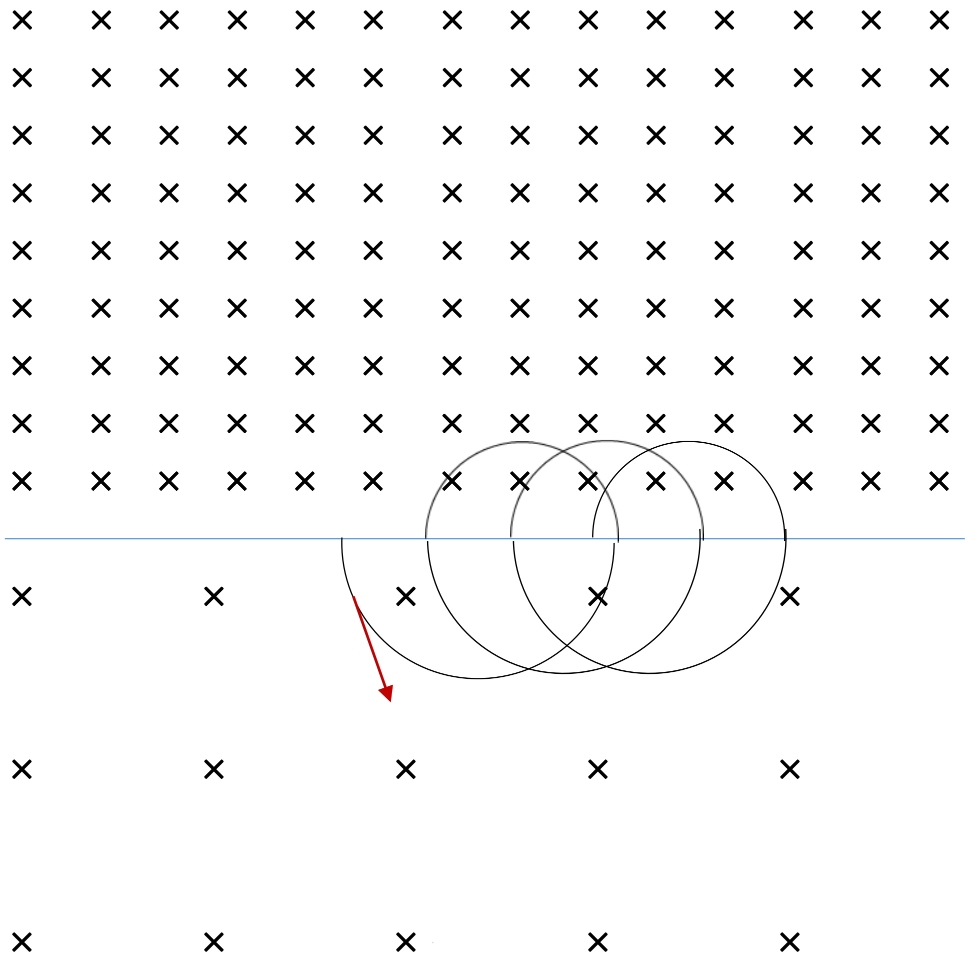
Guenter Stork & K500 trim coils (1980)

Dallas Cole fitting K1200 trim coils (August 1985)

K500 Trim Coils

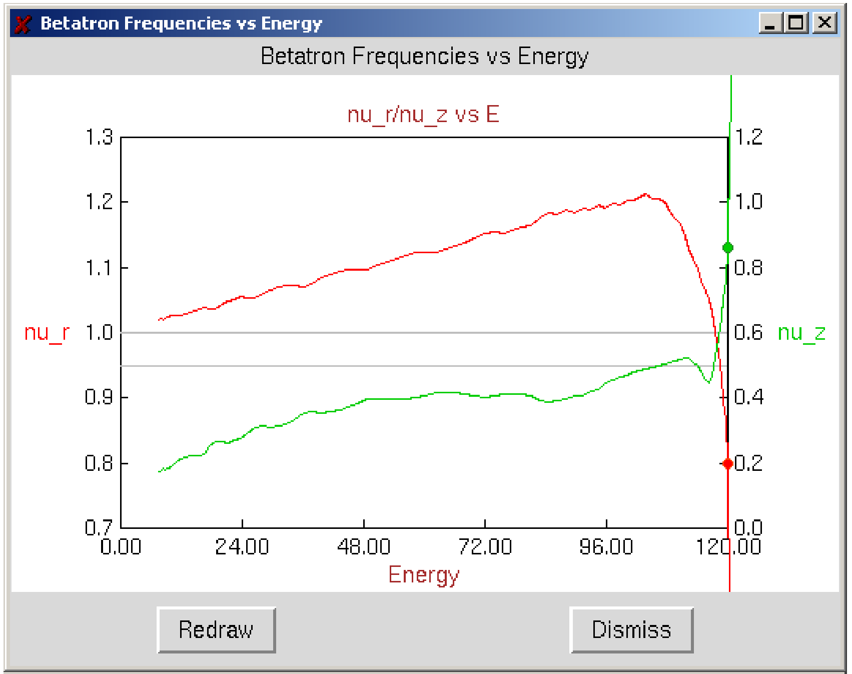
A simple way to picture the action of a bump is to imagine a beam of particles circulating in a uniform magnetic field, moving in a circle. Then imagine a line bisecting the circle, with the magnetic field stronger above the line than the below. The orbit will now be a semi-circle of one size on the stronger side of the line, and a semi-circle of a larger size on the weaker field side. The particle orbit center will then move in a direction along the line.

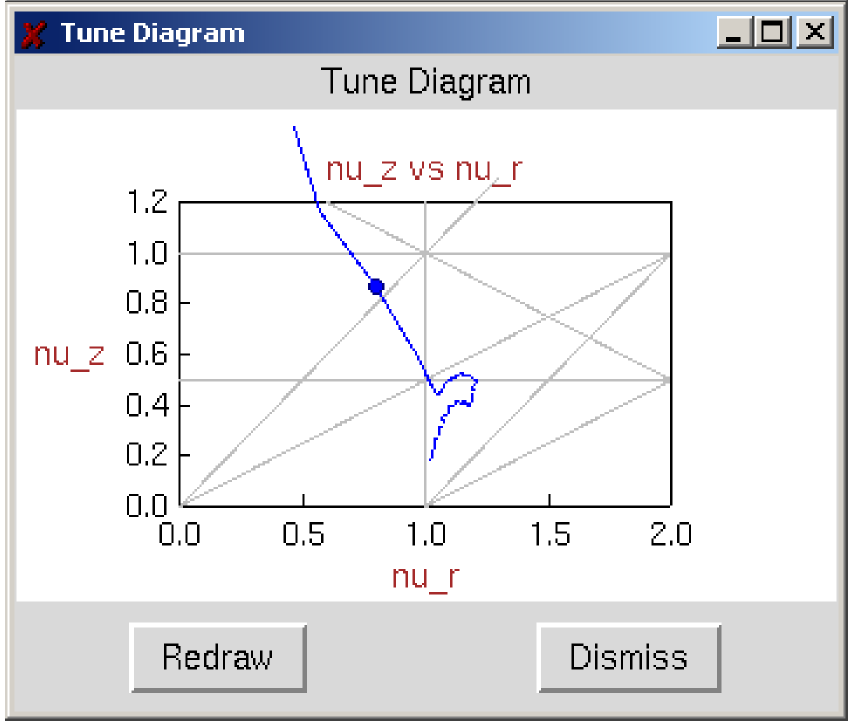
No such step function of magnetic field exists in the cyclotrons; a bump in the cyclotron produces an increased field on one side of an orbit with a decreased field on the other, approximately sinusoidal with azimuth, at the radius of the bump coil. It works best where the magnetic field is nearly flat; dB/dR=0 and nu-R=1. Both machines have such a region near the center and another just before extraction.

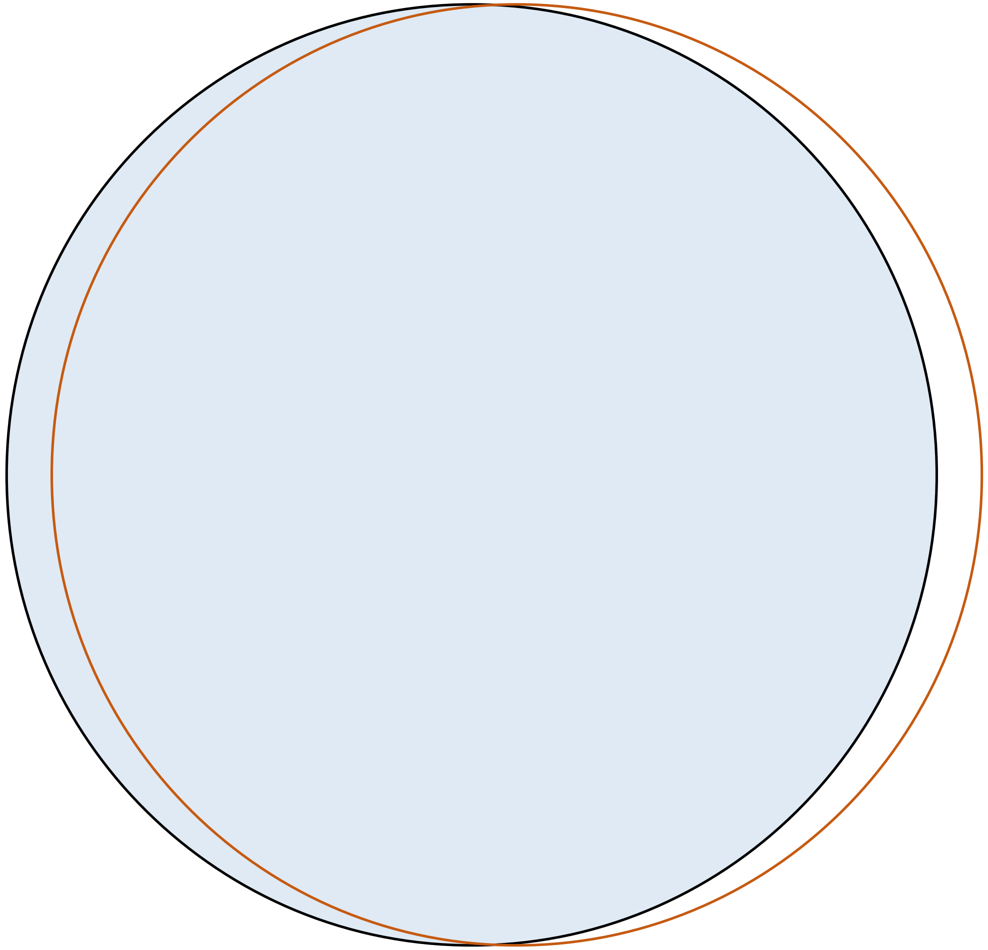


Orbit center drifts to the right in above illustration. Stronger B field in the upper portion.

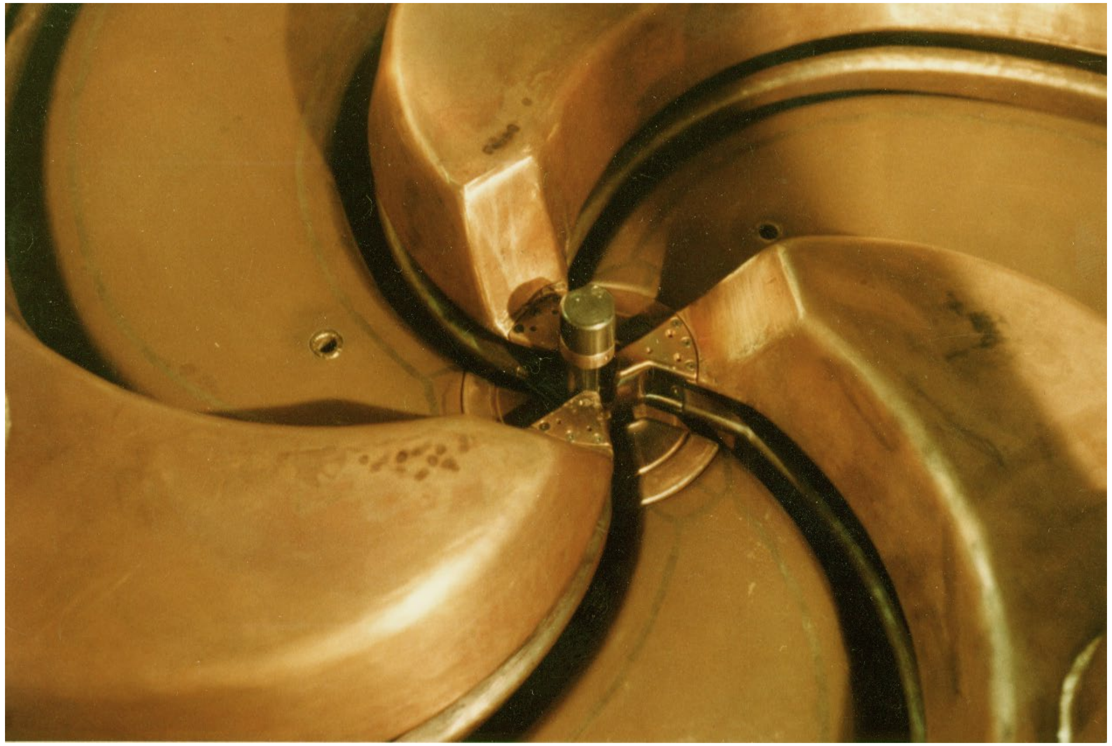
One will often see reference to “nu-R” and “nu-Z”. These are the radial and vertical frequencies of oscillation for a particle displaced from the “ideal” orbit. (As are all real particles.) The numbers are normalized to the oscillation frequency and are therefore close to 1, rather than in mega-hertz. It is a dimensionless number. To make an analogy with a mass on a spring, the frequency of an oscillation is an indication of the spring constant, so the value gives an indication of the vertical or radial focusing “spring constant”. Many beams in the k500, especially high magnetic field cases, have problems with inadequate vertical focusing at low radius, indicated by a low nu-z. (Less than 0.1 is problematic, less than 0.08 means work should be done on the problem.) Beam with a value of nu-Z close to 0.5 for an extended time tend to blow up vertically since any top/bottom asymmetry will kick the particles away from the median plane. Certain combinations will give rise to troublesome resonances, such as nu-R= 2*nu-Z, which changes radial oscillations due to poor centering into vertical oscillations. Nu-R + 2*nu-Z = 3 is a deadly resonance which in fact sets the low field limit over much of the operating diagram.







In a uniform magnetic field, there is no preferred center, and a charged particle will move in a circle. The drawing at the left shows a circular orbit (black), and a second orbit slightly to the right. Imagine that the black circle is centered at the center of the cyclotron, then the red circle is performing a radial oscillation about the "ideal, centered" orbit. Since it orbits at the same frequency as the centered particle it is seen to perform one radial oscillation per turn, so that it has a nu-R value of one. Regions where nu-R=1 are regions where there is no restoring force pushing a particle towards a centered orbit. A bump will therefore have a centering/decentering effect at these regions. The centering and extraction bumps are produced by trim coils whose influence is relatively great in regions where nu-R goes through one. Since our magnetic field increases with radius so as to maintain isochronism, it goes through a peak shortly before extraction before it begins to decrease, causing a nu-R close to 1 region, and the extraction bump is effective at this peak. There is also a nu-R of one region at low radius.

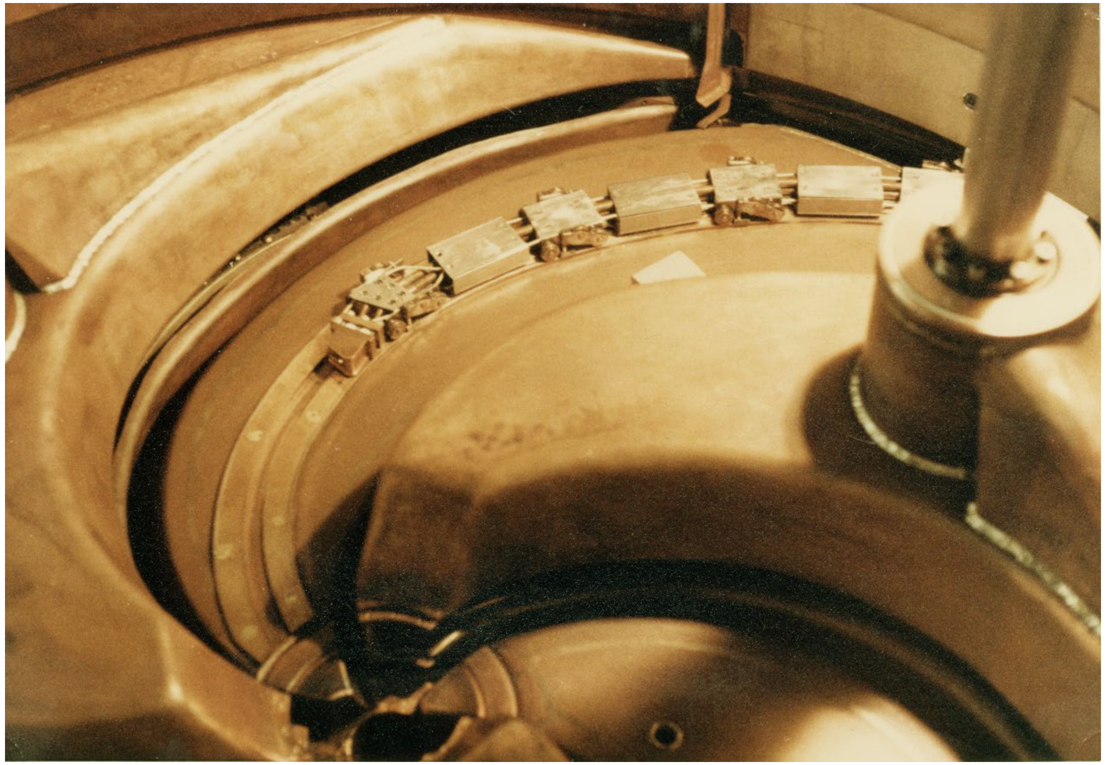


Interior of k500 cyclotron. The particles are accelerated only when crossing the gaps between the hills and the Dees. In the center is an old style PIG (Penning Ion Gauge) ion source.

In the k500 cyclotron the beam makes approximately 250 turns running, as we do, in second harmonic. The k1200 runs in first harmonic and the beam makes around 600 to 800 turns after the stripper foil, depending on the beam. In first harmonic the RF system runs at the same frequency as the beam, while in second it runs at twice the frequency as the beam. In second harmonic, the Dee phases must be reversed. Think of it as the particles moving 1/3 of the circumference of an orbit while the Dee voltage rotates in the opposite direction 2/3 of the circumference, so that Dee voltage is correct at the time a particle approaches a Dee gap. This means that the k500 has two “wedges” of beam existing simultaneously, 180 degrees apart. Each wedge will supply a pulse of beam so that there will be one pulse going into the k1200 on each of its RF cycles.

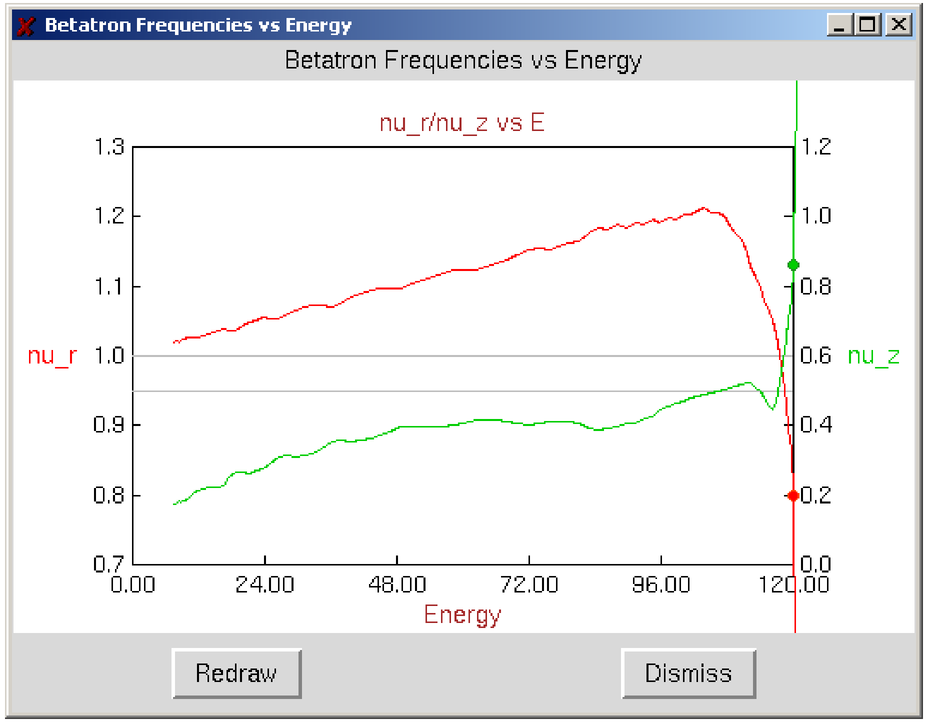
When the beam has reached full radius, it is ready to extract. “Full radius” means the maximum radius of the internal beam, which is not the same for every beam. The radius for extraction is determined by the decrease in the magnetic field and, since we run beams of different energies and field strengths, the radius varies somewhat. Values are given for each beam on the calculation sheet such as VP_Max and MP_Max which show the expected outermost radius of the internal beam at the azimuth of the associated probe. The extraction bump is used to provide a significant gap, usually 0.15 inches, between the last internal turn and the extracted turn. The septum of the E1 deflector is (theoretically) placed half way between these turns.

The state of the beam may be monitored by means of a beam probe. The k500 main probe is shown in the picture. The control system allows one to produce a plot of beam current versus radius as the probe is moved.



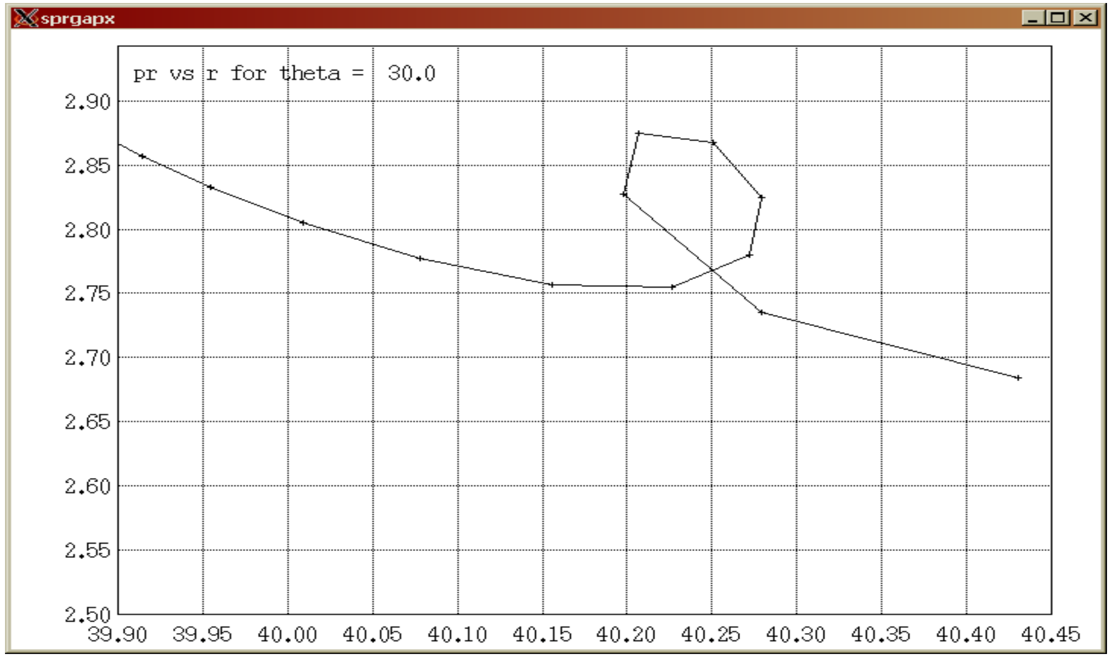
The k500 cyclotron main probe runs on a track between the A and B Dees. One must be able to accelerate beam out to MP_Max in order to extract it. By running down the center of a hill, it is in an electric field free region.

At what radius do we extract? The designers considered this problem, and the answer is that we want to extract as far out as we can without the beam blowing up radially. At large radius the magnetic field begins to decrease, so the vertical focusing increases and the radial focusing decreases. If we extract too far out the beam will be too wide to properly fit through the extraction elements. It was found by computer simulations that extracting at the radius where nu-R =0.8 would be about right, and that is how we set up the machines. Nu-R is red line below.



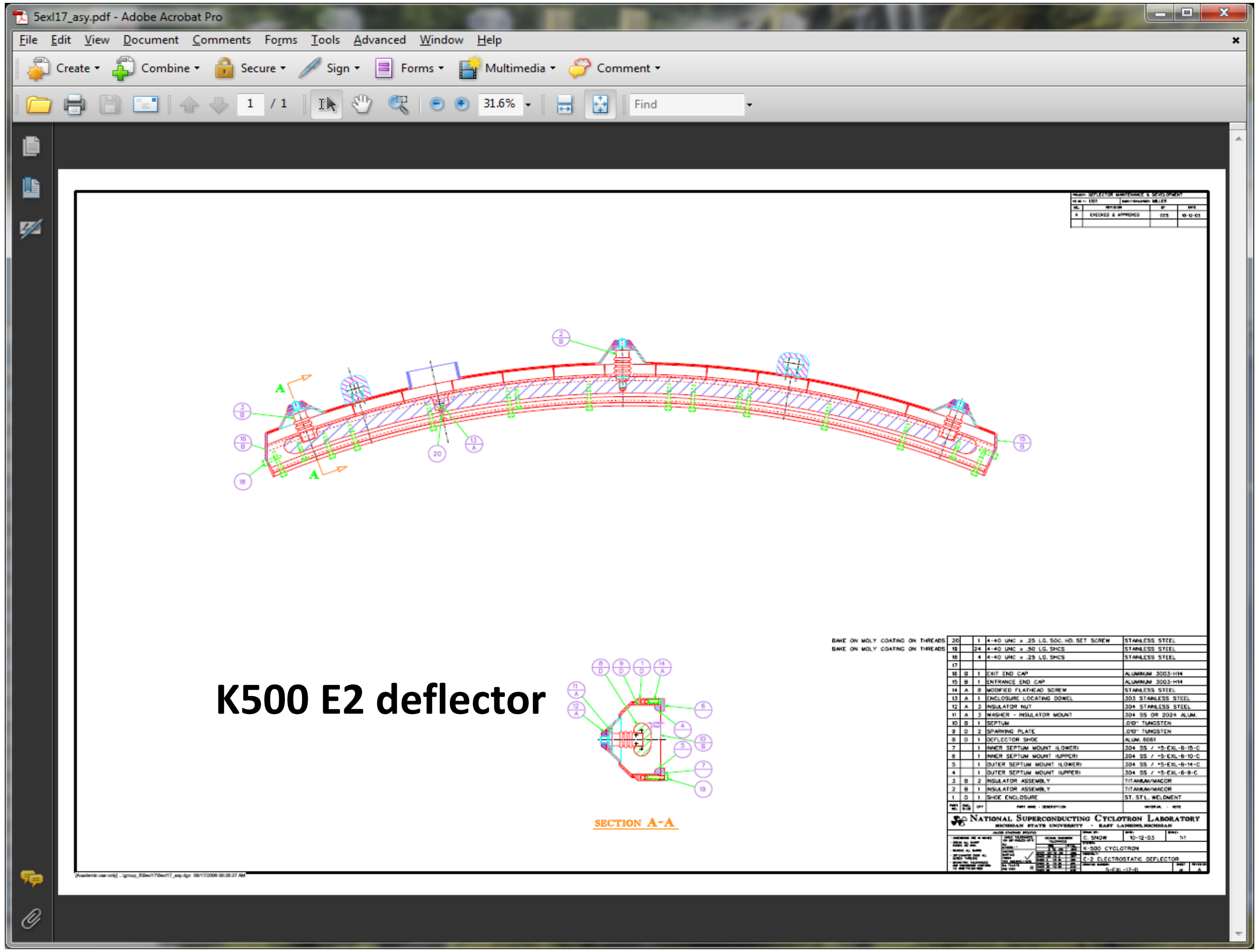
The effect of the extraction bump is to cause a radial oscillation at extraction so that there is adequate space between turns to allow efficient extraction. Like a child's swing, the particles experience an increasingly large radial oscillation, until there is a significant gap between turns. The turn spacing without the bump would be approximately 0.055 inches in the k500 and 0.025 inches in the k1200, but by use of the extraction bump it can be made to be approximately 0.15 inches in both machines.

The entrance of the first deflector, called E1 in both machines, is placed by design so that the septum is halfway between the last internal orbit and the extracted orbit. Note that this does not place the beam in the center of the deflector channel, as one might expect.

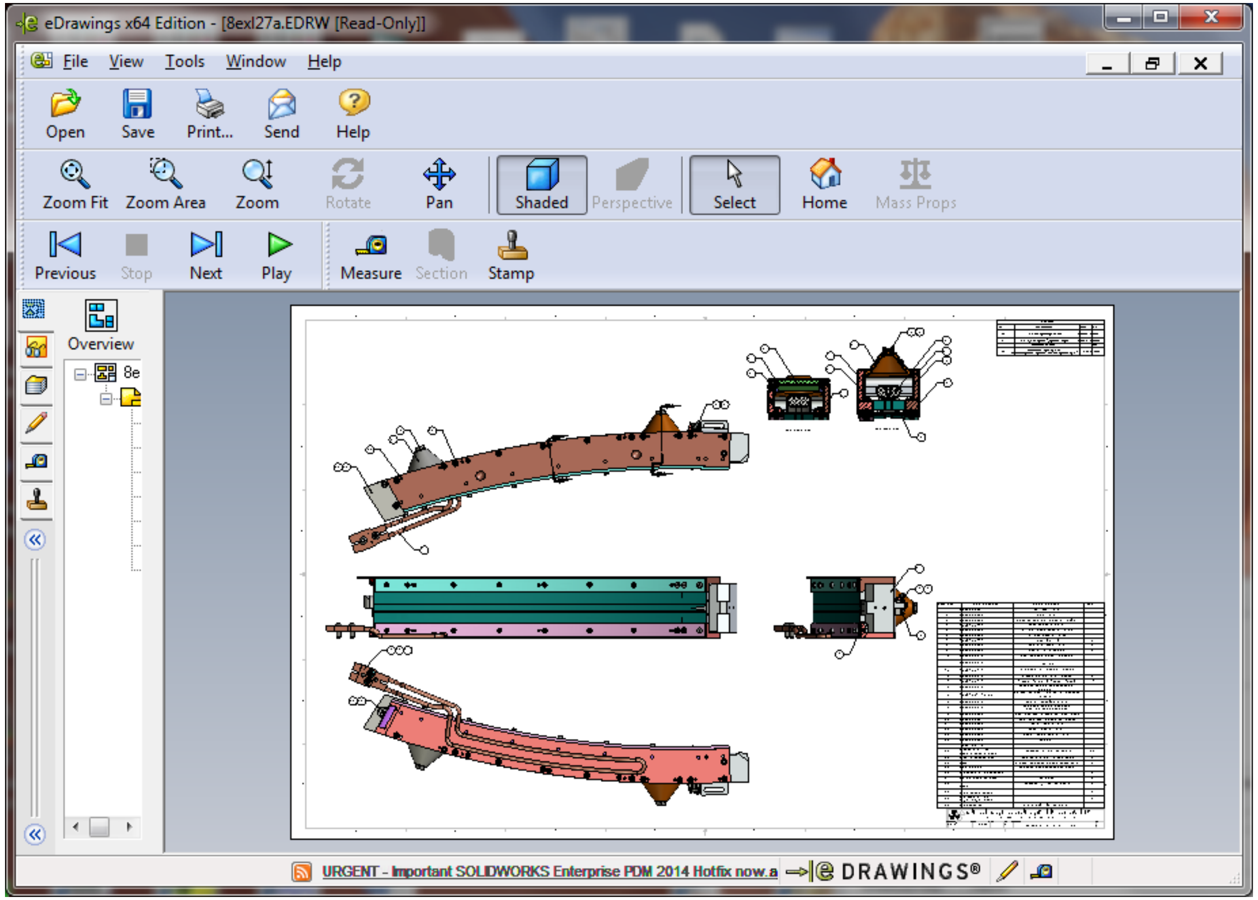


Above, the last thirteen turns in the k1200 for our standard case for a beam of 140 MeV/u 48 Ca 20+, at the azimuth of the E1 deflector entrance. The plot shows pr versus R, where pr is a canonical unit for the radial component of momentum. It gives an indication of the angle of the beam, as a high pr means it is angling outward. Due to the induced radial oscillation, the particles "pile up" and form a loop, then give a separation of 0.15 inch between the last two turns. The E1 septum should be placed half way between them, at roughly 40.35 inches.

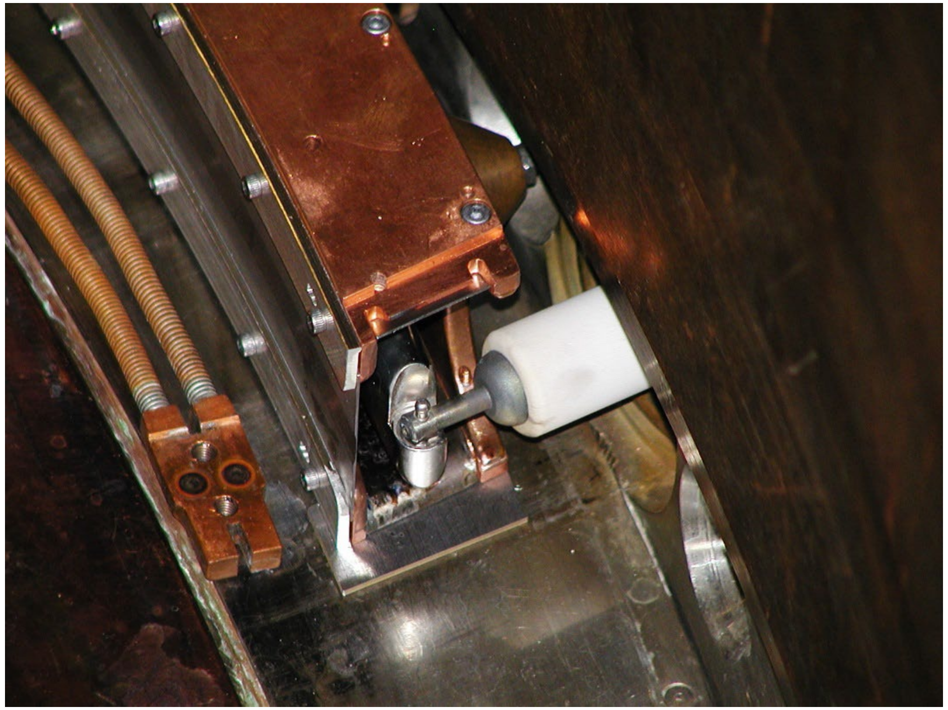
Each cyclotron has two deflectors, named E1 and E2 in each. A deflector is a device used in extracting the beam, and basically provides a region of space containing a DC electric field which accelerates the particles radially outward. It consists of an enclosing housing at ground potential inside of which is an electrode that extends the length of the deflector, and is maintained at a high negative potential. A high voltage is supplied through a feed-through from the outside by a high voltage power supply. Voltages for operational beams range from a low of perhaps 40 kV in the k500 to a high of perhaps 75 kV in the k1200. Actual k1200 deflector electric field values are usually about 110 kV/cm for most operational beams. There is a thin metal sheet that forms the inner edge of the deflector, called the septum. The septums consist of 0.025 in thick tungsten that has been ground down to 0.010 in thickness in the central region, except for the k500 E2, which uses 0.010 inch molybdenum.



The k1200 E1 deflector consists of three segments, called E1A, E1B and E1C, with E1A being the most upstream. They connect together so as to form one single deflector approximately one meter in length, or 1/6 of the cyclotron circumference at extraction radius. The segmented construction allows for the altering of the radius of curvature, and allows the operator to tune the four drives to match any particular beam path.



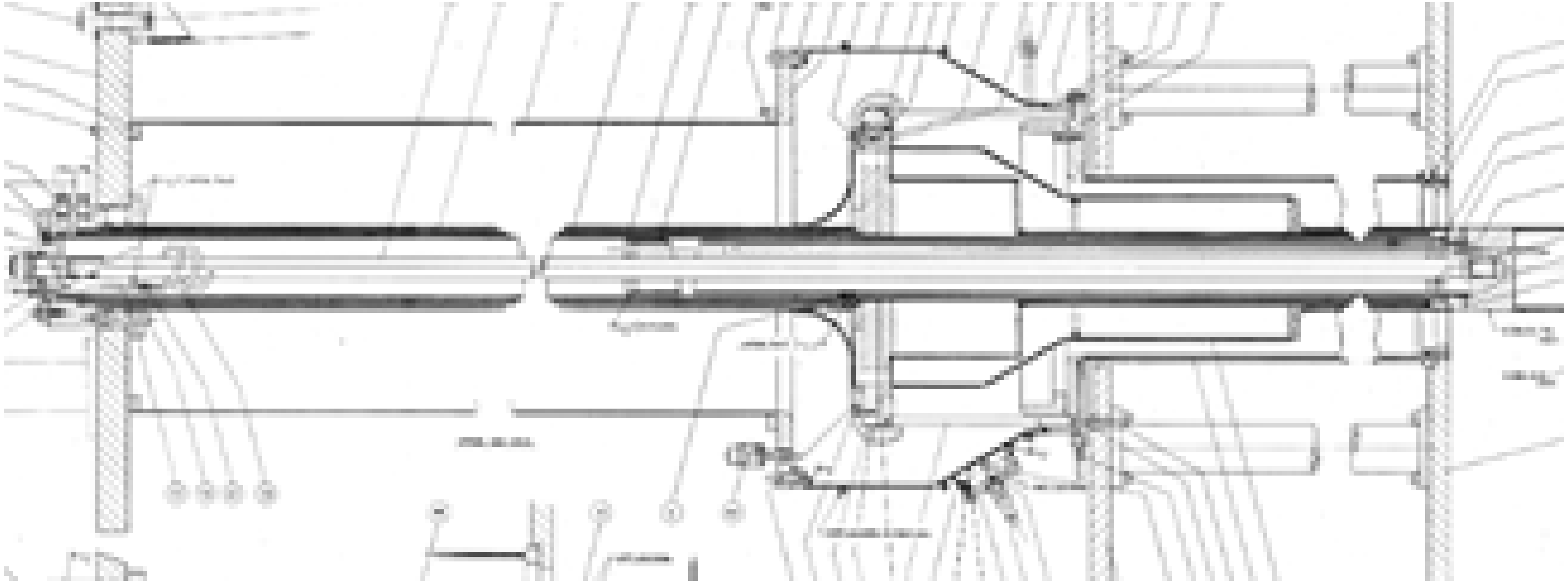
K1200 E1A deflector segment. Note the water-cooling lines.

The above left picture shows an installed k1200 E1 deflector. The picture on the right shows the front of the E1B segment with the high voltage feed-through attached to the high voltage electrode, or "shoe". Note the thin tungsten septum at the inner edge. It is 0.025 inches thick, ground down to 0.010 inches in the median plane. The E1A segment is then installed after E1B, with its shoe connecting on top of the feed-through. The water-cooling flexible manifold is seen in front of E1B, and the E1A water connection will attach to the rectangular copper block.

K500 old style dee-stem
Tim Antaya, Dallas Cole

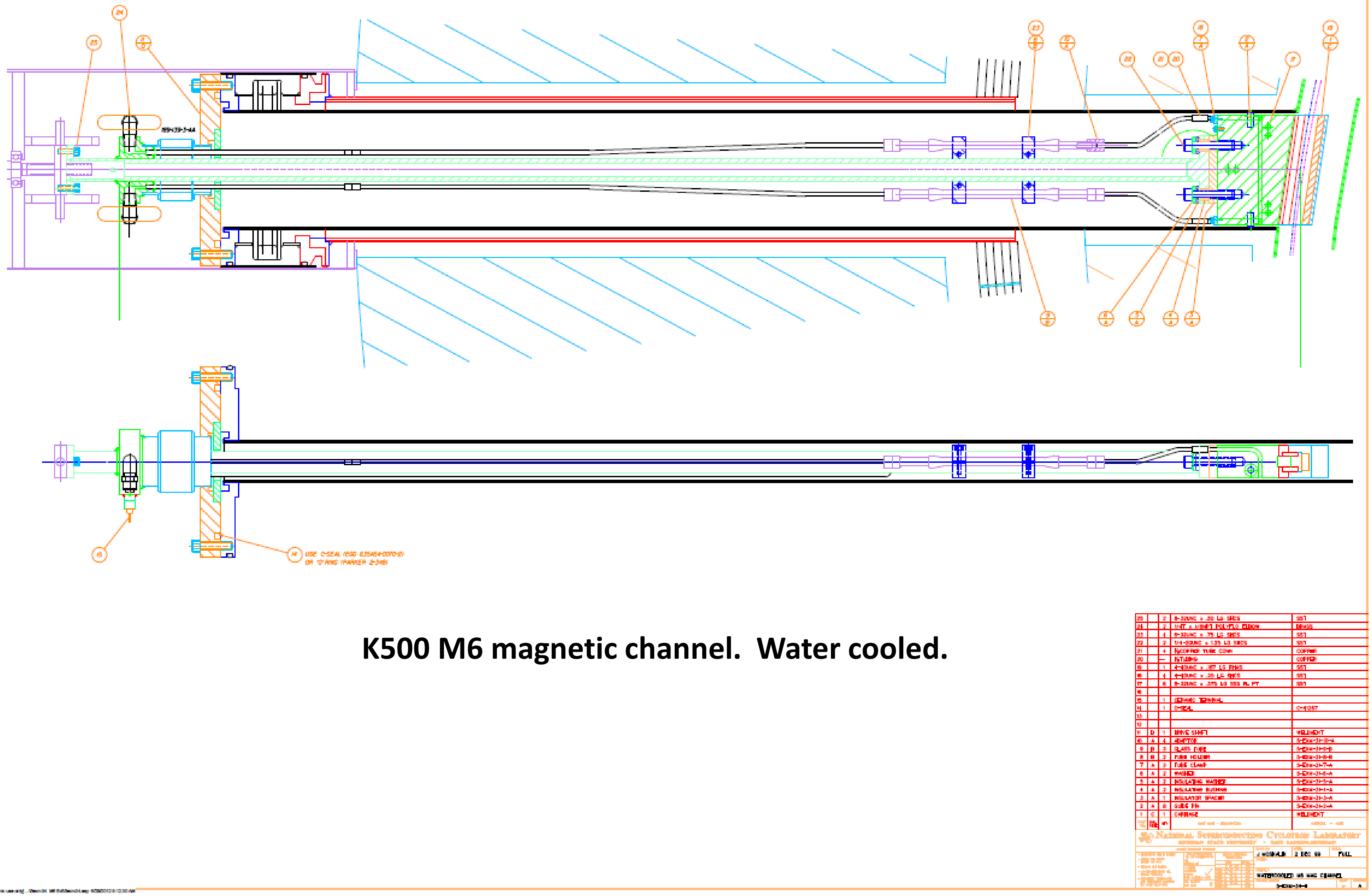
The Dees are mounted on the ends of Dee-stems, which extend out through the vacuum into the outside world. The idea is to create a resonant cavity so that the Dee will oscillate at the desired voltage and frequency. A Dee-stem is basically an inner and outer conductor with a sliding short between them on the far end (outside of the machine) and with the Dee on the other end. A ¼ wavelength standing wave is induced into the Dee-stem through the input coupler, which penetrates through the lower cap and excites, but does not contact, the Dee, thereby resonating the Dee-stem. The Dee is at a voltage node and current anti-node, while the sliding short is at a current node and voltage anti-node. An upper and a lower Dee-stem together may be thought of as a ½ wavelength resonator with a voltage node at the center. (This leads to a potential problem in that the system will remain resonant as long as the top to bottom distance is ½ wavelength, which can happen if both upper and lower sliding shorts are displaced vertically an equal amount. This will lead to large RF currents crossing between upper and lower Dees through the Dee tips and edge strips, not to mention vertical components in the electric field at the Dee gaps. This has in fact happened, and is not idle speculation.) A k500 Dee-stem is shown to the left.



Dee-stem

K500 Dee-stems - Tim Antaya, Henry Blosser, Don May

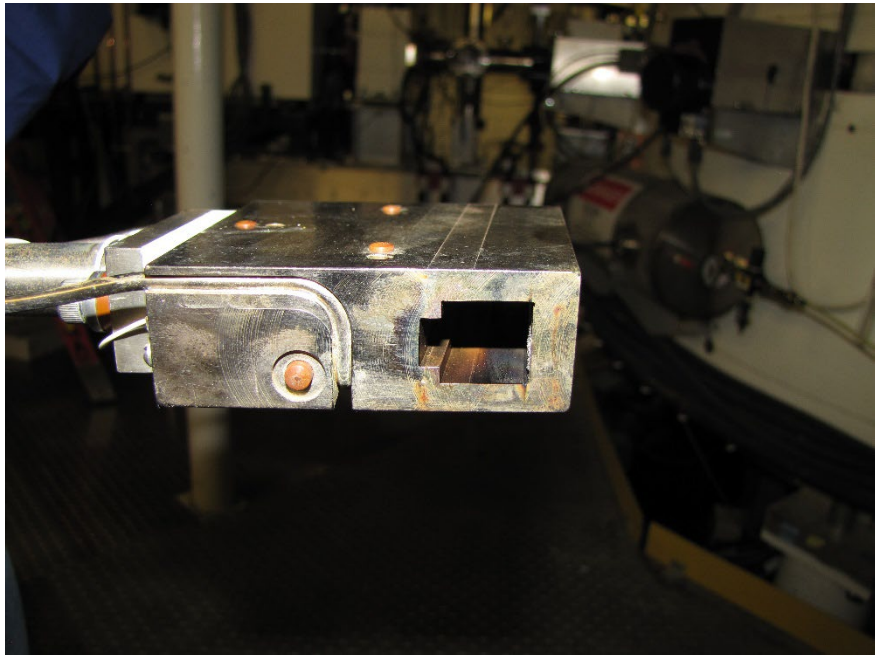
Inner Conductor - The white insulator provides the vacuum break



K500 M6 magnetic channel. Water cooled.

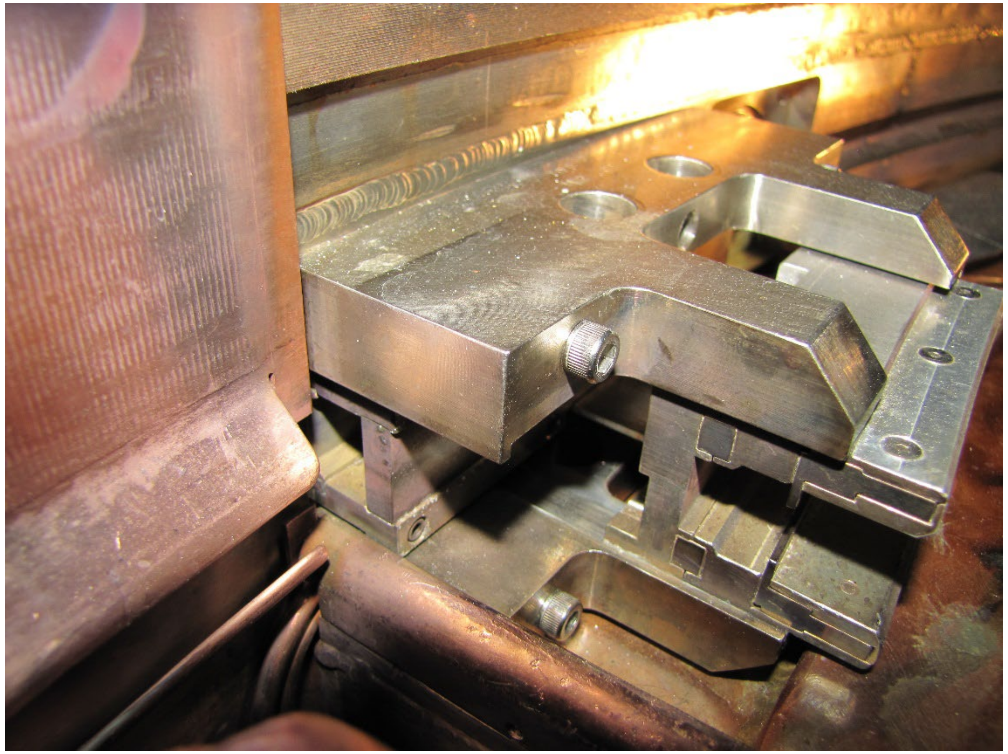
On the previous page is a drawing of a magnetic channel, specifically M6 from the k500. The reason we have magnetic channels is that the magnetic field is dropping precipitously at extraction radius, focusing the beam vertically but de-focusing it radially. Without the magnetic channels beam exiting the cyclotrons would be very short but very wide.

Magnetic channels do not have any active magnets in them, they are simply mixtures of magnetic and non-magnetic materials. The head includes a passage through which the beam may pass, and inside the passage the magnetic field increases rather than decreases with radius, reversing some of the radial de-focusing. It will therefore steer the beam, so moving the channel will move the beam downstream. They are water-cooled.

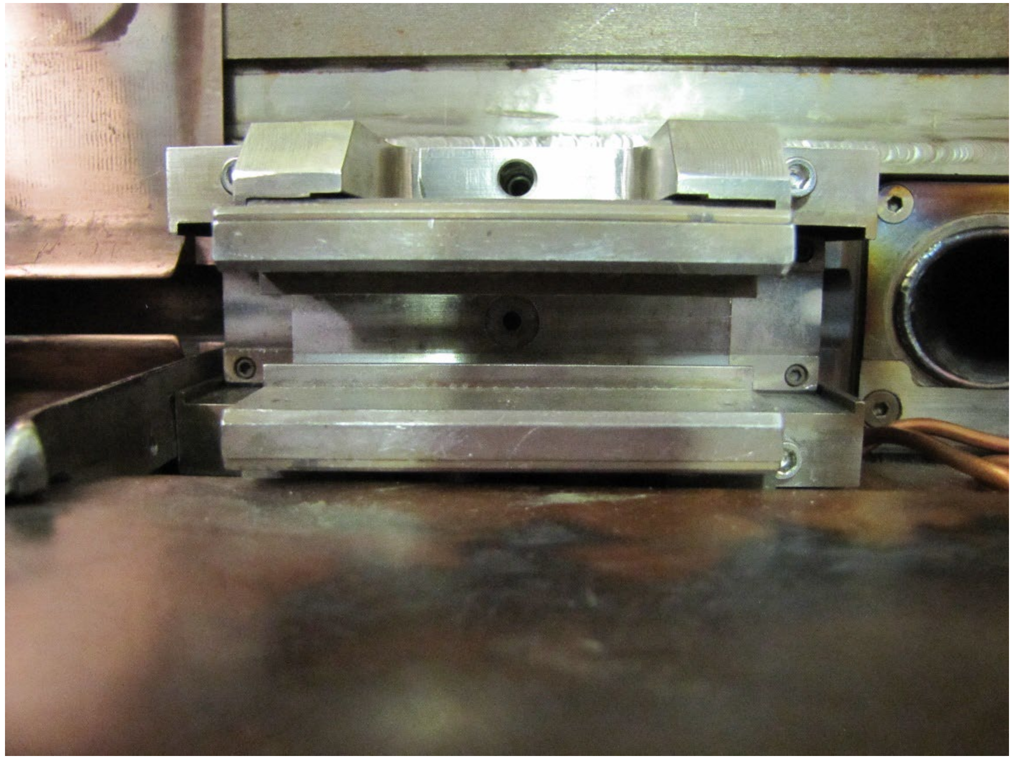


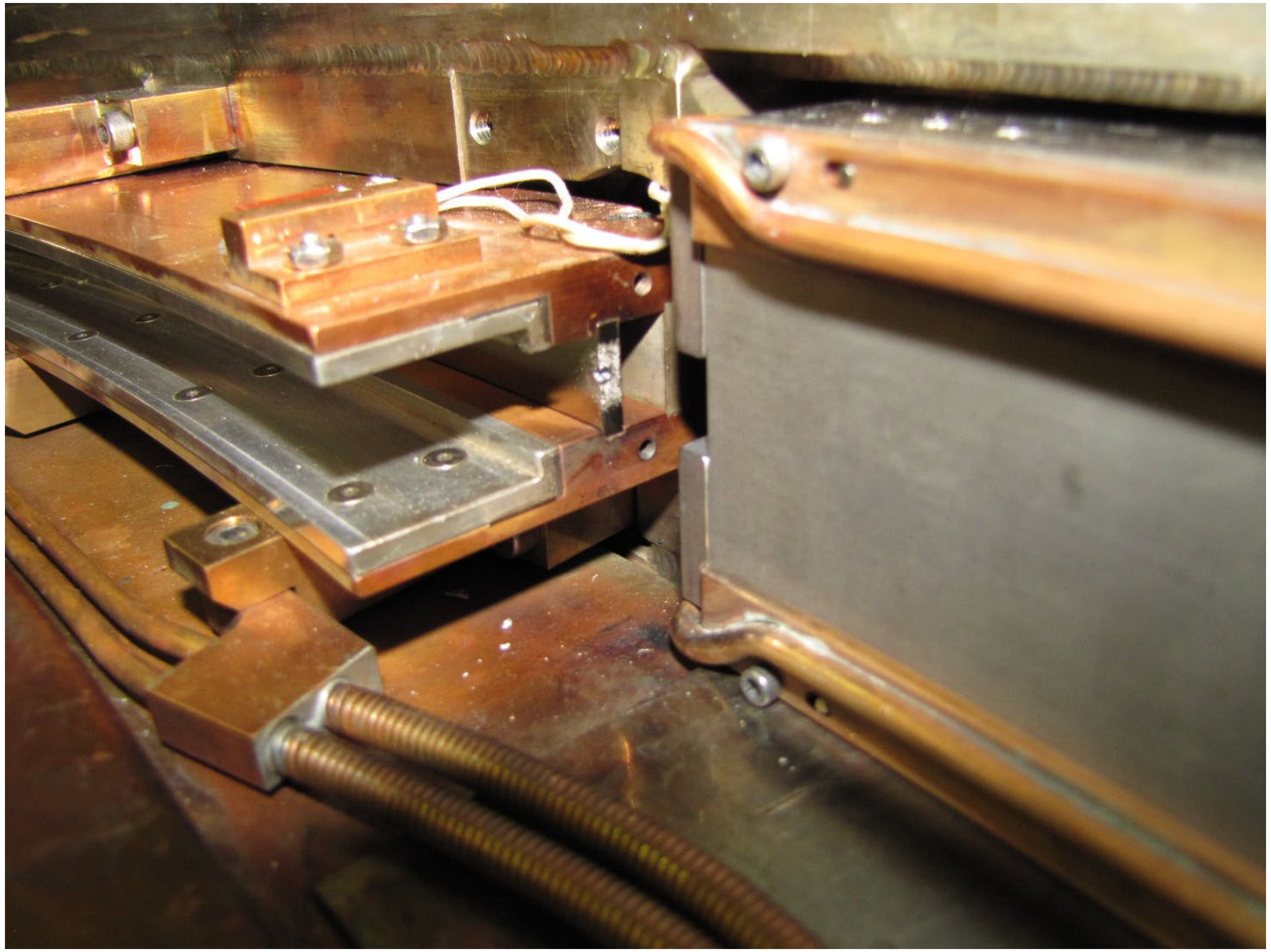
Compensating bars are devices used to approximately maintain three fold symmetry in the magnetic field at large radius. Without the compensators, the various extraction elements would disrupt the symmetry of the field, and the beam would be subject to distortions, especially when passing through the nu-R=1 region, where it is easily moved. When doing extraction calculations, they are automatically moved in concert with their respective extraction elements.

In the k1200, C1 and C2 compensate B1, C3 and C4 compensate M1, and C5 and C6 compensate M2. There used to be a C7 but it was removed to make room for N062. C8 is a free parameter used to try to minimize excessive unwanted first harmonic.



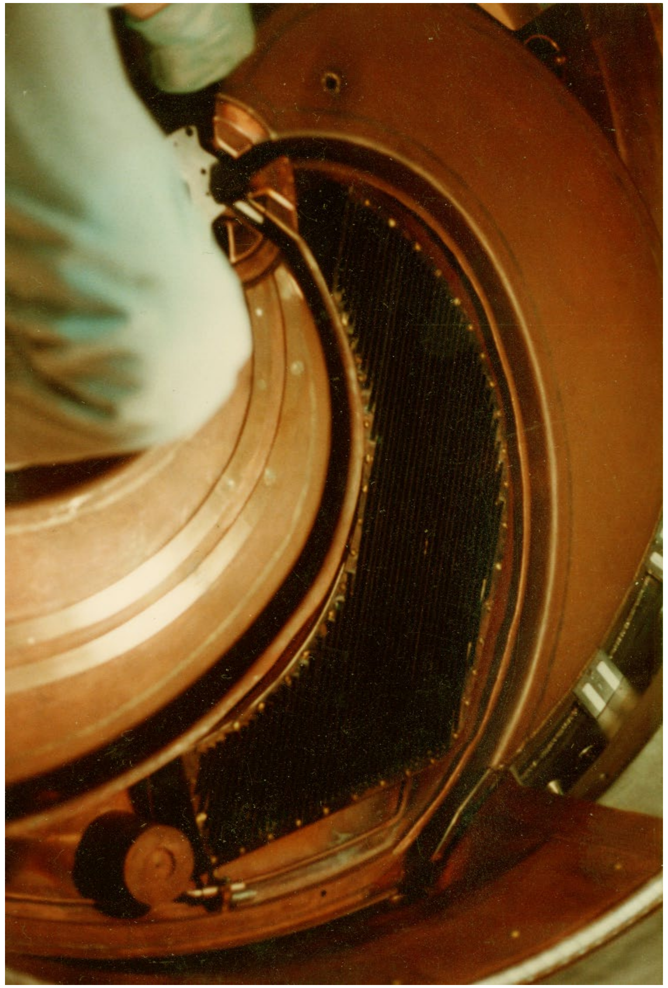
Two views of k1200 C3 compensator.





The photo at the left is of the k1200 B1 extraction element. B1 is in the extraction channel immediately following the E2 deflector, which is seen in the right hand part of the picture. B1 acts as a sort of magnetic deflector, simply providing a region of space in which the magnetic field is somewhat lower than it would be otherwise. B1 does not focus or steer the beam, which means it is often not moved by operators since it has little effect unless it is moved radically. C1 and C2 are compensators for B1, and both have two drives so that the they may match the angle of B1 as well as the radius.

It would be nice to dispense with deflectors and replace them with magnetic elements similar to B1, but a magnetic field cannot be made to end as abruptly as can an electric field at a septum.



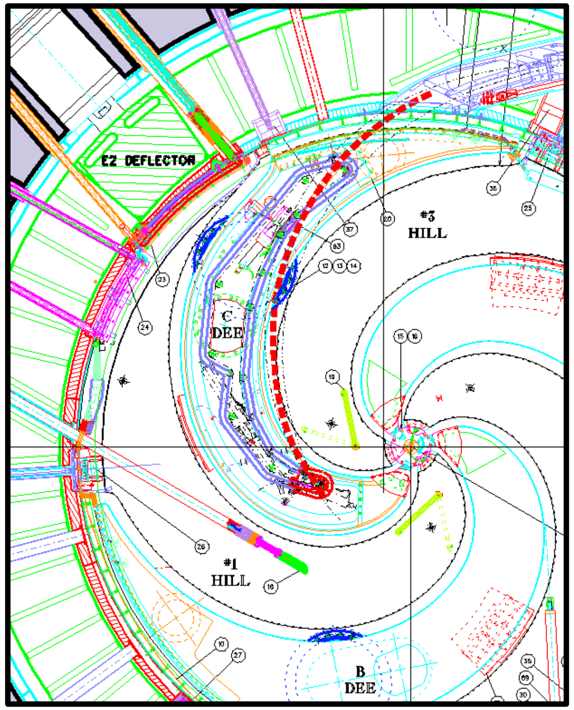
Older style helium cooled k500 Cryo-panel. It resides inside of One of the Dees.

Vacuum in the cyclotron beam chambers is accomplished by a combination of turbo-molecular pumps and cryo-pumps. The turbo-pumps are on tall pipes called silos to get away from the strong magnetic field of the cap, but they still must be surrounded by iron boxes to further lower the field. The turbo pumps are themselves pumped by mechanical vacuum pumps.

The cryo-panels are situated inside of the Dees, and consist of an interior panel, as seen in the picture to the left, which is surrounded by an outer box. The inner panel is cooled by liquid helium delivered through a transfer line inside of the hollow inner core of the Dee-stem, and is called the helium cryo-panel. The outer box is similarly cooled by liquid nitrogen, and is called the nitrogen cryo-panel.

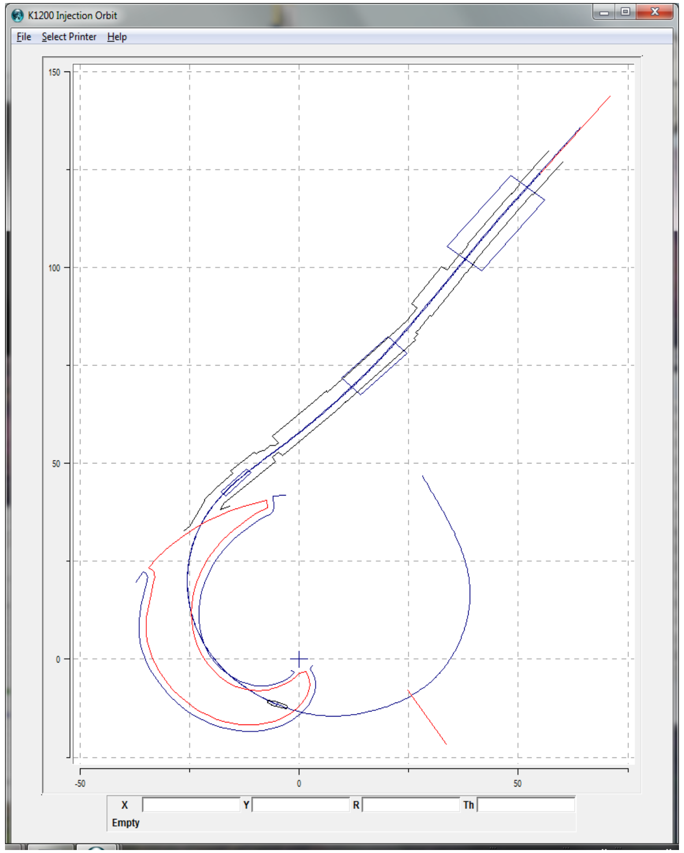
The transfer lines that deliver the cryogens to the cryo-panels consist of a series of concentric stainless-steel tubes, with vacuum spaces alternating with supply and return lines.

In addition to the beam chamber, there are vacuum systems for the liners, guard branches and the cryostat vacuums.



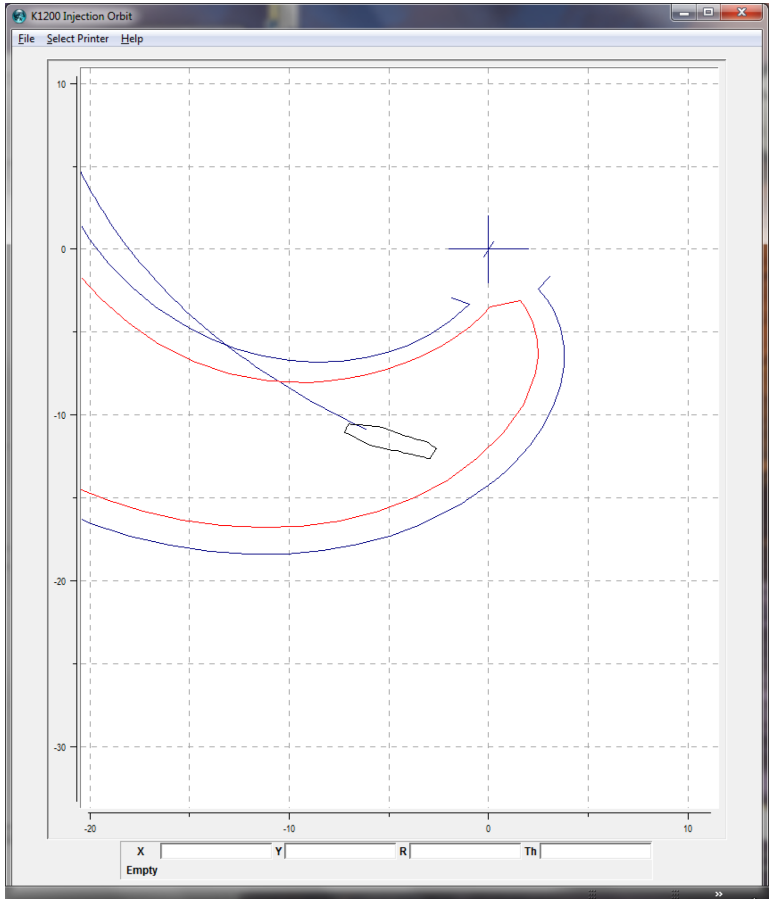
Upon exiting from the k500, beam traverses the coupling line and enters the k1200. The k1200 derives much of its effectiveness from the fact that a beam from the k500 will have sufficient energy to be stripped to high charge states at high intensity.

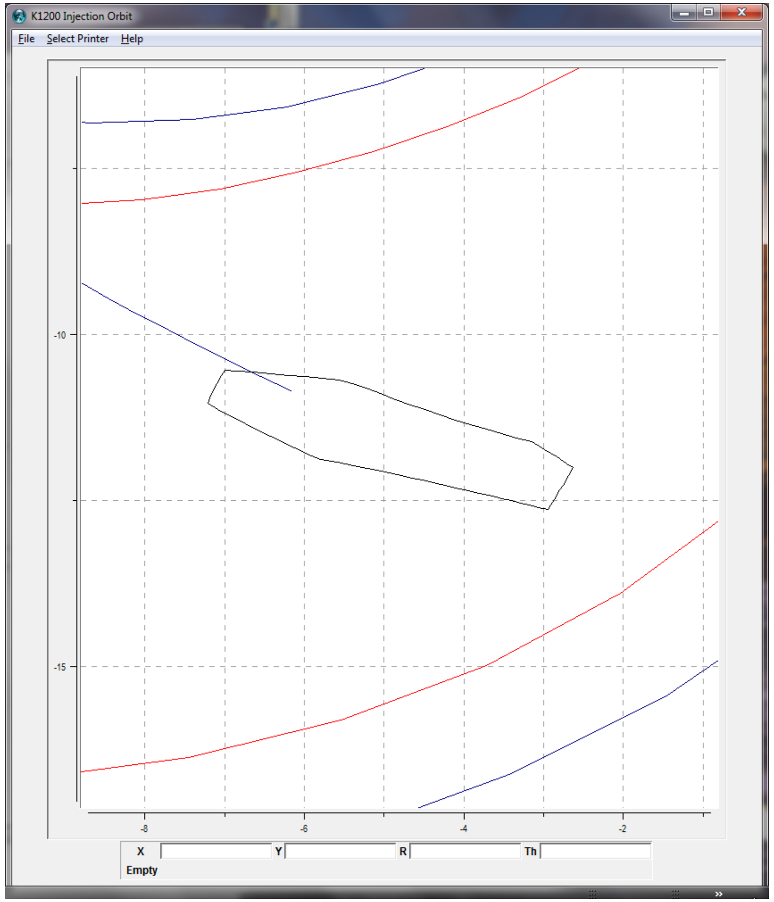
The beam is guided onto a stripper foil inside the k1200 C dee, the foil being made of thin Carbon. The foil is at a position such that the particles, upon losing many more of their electrons, will be in a centered orbit.



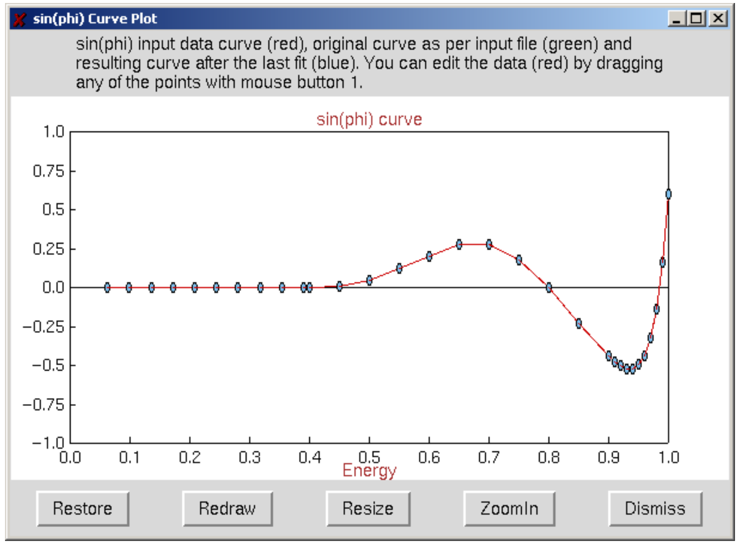
In order for a successful injection and acceleration to occur, the cyclotrons must be set so that the charge state in the k1200 is between approximately 2.3 and 2.7 times that of the k500 beam. If not, the beam will be bent either too much or too little while traversing the k1200 on its way to the stripper foil.

The stripper foil mechanism hold 31 foils. Most of them are carbon foils of density 600 micro-grams per square centimeter. All of the foils except the one in use lie flat so as not to intersect the beam. They are all attached by a bicycle like chain that moves new foils into the upright position. The position of the in use foil may be adjusted by moving the "platter", on which the entire assembly is mounted. This is necessary so that the stripped beam, upon leaving the foil, is in a properly centered orbit. The space in which the foil may move is displayed in the Injorb output, and is seen below.

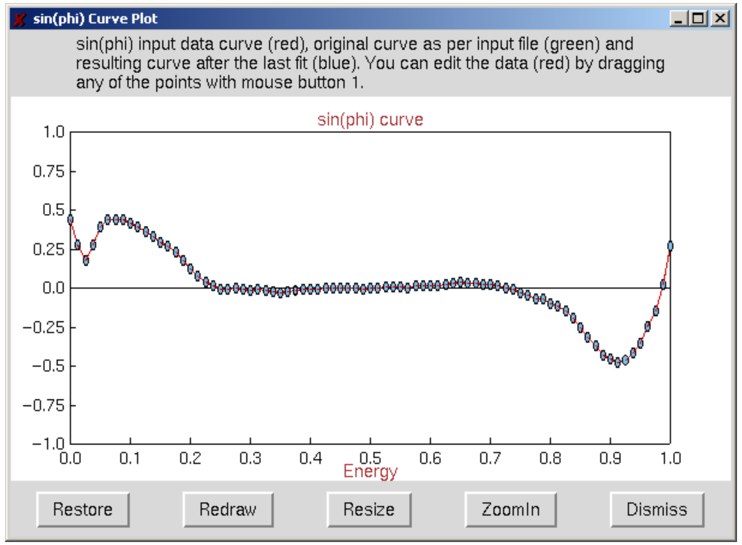




Some attention must be give to the subject of “phase curves”. A phase curve is simply a graph showing the angle between an ideal particle and the RF phase that provides for maximum acceleration. Graphs of the phase curve generally display the sine of the phase versus fraction of total energy, with the phase angle being the RF phase minus the particle phase. One will note that the phase curves in the binders for each beam show a rising curve at the outside edge where the beam is extracted and the field is dropping, allowing the particle to lag behind the RF. Beams are extracted at differing phase angles depending on the beam, usually between 20 and 40 degrees in the k1200 and lower, usually in the 10 to 30 degrees range in the k500. (Differences in the k500 extraction phase add directly to differences in the k5-k12 phase between machines.) To the left below is the standard k1200 phase curve used in the k1200. It is really just a file of pairs of numbers. To the right below is k500 phase curve called Sin Phi L.

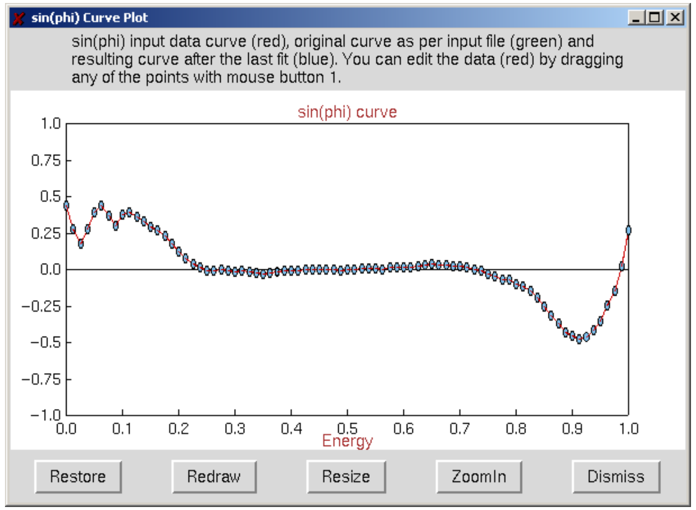


These curves are “input” curves, used by the calculation software. A resultant curve will be produced in the calculation.

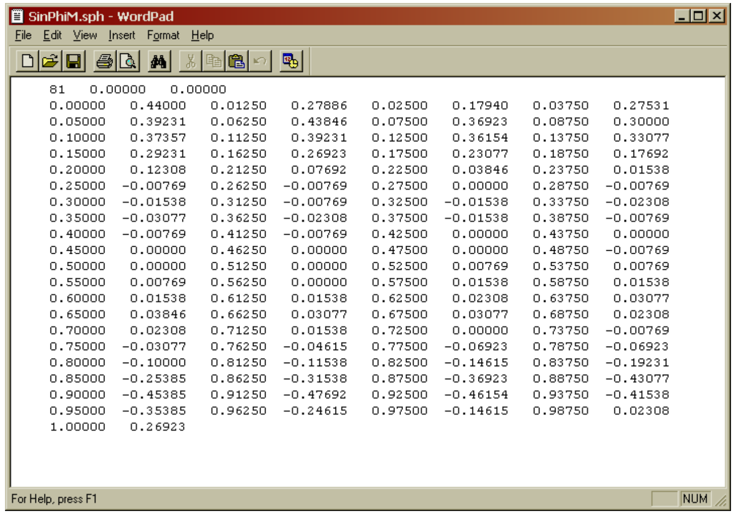


In order to minimize energy spread in the extracted beam, it is important that the total area under the phase curve be close to zero. The phase curves are often modified to help avoid resonances or to increase (usually) vertical focusing. Since resonances are expressed by relations between vertical and horizontal oscillation frequencies, and the frequencies are related to the focusing force, ($\omega = \sqrt{\frac{k}{m}}$), one may try to improve the resonance situation by changing the focusing. A positive second derivative in the phase curve will increase nu-Z.

The cyclotrons rely on the "flutter" produced by the hills and valleys to produce vertical focusing, but at low radius this effect goes away. Both machines therefore have "cones", meaning a slightly increased field at the center, giving a decreasing field, and hence vertical focusing. In high field cases in the k500 vertical focusing becomes too low and we use a modified phase curve, Sin Phi M, to correct it.



K500 Sin Phi M in graphical form on the left, and the set of numbers that constitute the actual file on the right.



SinPhiM.sph - WordPad

File Edit View Insert Format Help

81 0.00000 0.00000

0.00000	0.44000	0.01250	0.27886	0.02500	0.17940	0.03750	0.27531
0.05000	0.39231	0.06250	0.43846	0.07500	0.36923	0.08750	0.30000
0.10000	0.37357	0.11250	0.39231	0.12500	0.36154	0.13750	0.33077
0.15000	0.29231	0.16250	0.26923	0.17500	0.23077	0.18750	0.17692
0.20000	0.12308	0.21250	0.07692	0.22500	0.03846	0.23750	0.01538
0.25000	-0.00769	0.26250	-0.00769	0.27500	0.00000	0.28750	-0.00769
0.30000	-0.01538	0.31250	-0.00769	0.32500	-0.01538	0.33750	-0.02308
0.35000	-0.03077	0.36250	-0.02308	0.37500	-0.01538	0.38750	-0.00769
0.40000	-0.00769	0.41250	-0.00769	0.42500	0.00000	0.43750	0.00000
0.45000	0.00000	0.46250	0.00000	0.47500	0.00000	0.48750	-0.00769
0.50000	0.00000	0.51250	0.00000	0.52500	0.00769	0.53750	0.00769
0.55000	0.00769	0.56250	0.00000	0.57500	0.01538	0.58750	0.01538
0.60000	0.01538	0.61250	0.01538	0.62500	0.02308	0.63750	0.03077
0.65000	0.03846	0.66250	0.03077	0.67500	0.03077	0.68750	0.02308
0.70000	0.02308	0.71250	0.01538	0.72500	0.00000	0.73750	-0.00769
0.75000	-0.03077	0.76250	-0.04615	0.77500	-0.06923	0.78750	-0.06923
0.80000	-0.10000	0.81250	-0.11538	0.82500	-0.14615	0.83750	-0.19231
0.85000	-0.25385	0.86250	-0.31538	0.87500	-0.36923	0.88750	-0.43077
0.90000	-0.45385	0.91250	-0.47692	0.92500	-0.46154	0.93750	-0.41538
0.95000	-0.35385	0.96250	-0.24615	0.97500	-0.14615	0.98750	0.02308
1.00000	0.26923						

For Help, press F1 NUM

In spite of all of the cyclotron complexity, not to mention that of the beam-lines, ions sources, experimental equipment, water-cooling system and et-cetera, the cyclotron system does in fact produce an accelerated and extracted beam, and run fairly reliably. Over a period of years, the cyclotron lab staff used a plethora of ordinary materials and carefully arranged them into a configuration that would cause a deluge of atoms to cascade down a pipe at very great speed. It shows what can be done with enough time, money, manpower, intelligence and imagination.

I hope this short look into the aforesaid complexities leads to a greater understanding and appreciation thereof.