STUDY AND REDESIGN OF THE NSCL K500 CENTRAL REGION*

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Abstract

The proposed K500-K1200 cyclotron coupling project calls for a redesign of both the inflector and central region of the K500. An increased injection voltage will be needed to reduce space charge effects in the higher intensity beam. In order to obtain stripping injection matching with the K1200, the K500 will operate in the second harmonic rf mode. To meet the requirements of this higher energy beam (and new rf mode) a new spiral inflector and central region geometry were designed. Results of beam orbit calculations and experimental data concerning phase selection and central region acceptance will be presented.

I. Introduction

The NSCL presently operates the K1200 superconducting cyclotron with support from the NSF for nuclear physics research. With the purpose of increasing the intensity of low mass ions (A < 40) and the energy of heavy ions (up to uranium) a proposal to couple the K500 to the K1200 cyclotron has been presented [1]. The ions are produced in an external ECR ion source and axially injected in the K500 cyclotron. After extraction the beam is transported and injected in the K1200 where it is stripped and accelerated to higher energies (5 Tm).

To decrease the deleterious effects of a more intense injected beam, the energy of the ECR produced beam has been increased. In the stand-alone configuration the K500 was used in first harmonic mode to obtain the maximum possible energy (80 MeV/u for ions with Q/A=0.5). In the coupled mode the maximum energy needed is only 16.6 MeV/u for ions with Q/A=3/16. A maximum ECR voltage of 30 kV was selected, this voltage being considered as within easy reach of the present ECR configuration. These parameters define a total energy of 5.6keV for the O^{+3} ion. This higher energy, higher intensity beam requires the design of a new inflector. Additionally, the new 2^{nd} harmonic central region limits the radial extent of the inflector to 2.0 cm and requires flexibility in the positioning of the orbit center of emerging ions. A spiral inflector was therefore studied based on the inflector presently used in the K1200.

II. Inflector Design

An increase in the axial height (for ease in construction) and gap size (for improved acceptance) over the present inflector was studied and comparisons of the two inflectors made. Acceptances in initially uncoupled x,v_x and y,v_y phase spaces were calculated as were the effects of changing the axial field by way of a solenoid along the injection route. The spiral inflector equations described by Belmont and Pabot [2] can be used to determine an appropriate electric field and inflector shape to best match the required machine parameters. An inflector field of 20kV/cm was chosen to maximize the final radius in a 4.6 Tesla central field. This results in a 1.96 cm final (inflector exit) central ray radius and an inflector height of 3.00 cm. The final inflector outline is shown in figure 1 along with the reference orbit as the inflector will sit in the 2^{nd} harmonic central region. The figure was used as input to a RELAX3D [3] run with grid dimensions Δx=Δy=.0254cm and Δz=.127cm. The vertical grid size is clearly visible as steps in the hill shape.

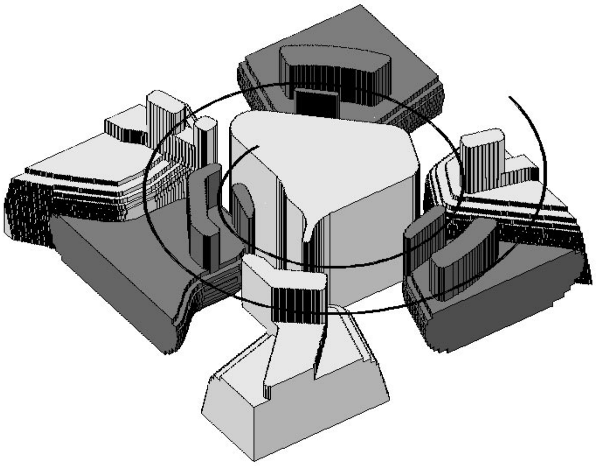

Figure. 1. The 2^{nd} harmonic central region design. The view show a cutaway of the central region electrodes below the magnetic median plane. The dark structures are the dee tips while the large object in the center is the inflector housing. The other light structures are the ground potential hills. The first turn phase slit can be seen in the upper left corner. Also shown is the path of the central ray.

A. Acceptance Calculations

To estimate the acceptance of this inflector design, ions were tracked from 3m below the cyclotron median plane through the inflector. This was accomplished using two ray tracing codes MYAXIAL and INFLECTOR [4] which integrate the equations of motion for ions passing through the axis of the cyclotron magnetic field and the inflector electrodes, respectively.

All ions were started 3m below the median plane and passed through a solenoid field centered at 2.227m below the median plane, the K500 magnet yoke field, a circular aperture at the entrance to the inflector centered on the magnet axis with a diameter equal to the electrode spacing, the inflector and finally an exit aperture centered on the reference ray. The inflector voltage and position were set by requiring the central (axial) ray to emerge with $v_z = z = 0$. Initially uncoupled x, v_x and y, v_y phase spaces were started in order to avoid the complications inherent in dealing with an initially coupled, 4d space. The normalized acceptances for the new inflector are compared to those for the

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Table I

Normalized Acceptance (mm-mrad)

Inflector Gap	$\beta\gamma$	x, v_x	y, v_y
6 mm	.0035	5.77	7.80
4 mm	.0030	5.42	3.66

old K500 inflector in table I. Clearly the new 6mm aperture inflector will have a much greater acceptance, as expected.

III. Central Region Design

Once an inflector shape was determined a second harmonic central region was designed. All electrode shapes and positions had to accommodate the new, larger inflector housing and guide the beam through the central region leaving it reasonably well centered. The dee voltage chosen for the O^{+3} test case was 70kV (well below the 80kV which can be reliably achieved) with a chosen minimum electrode separation of 8mm. With these considerations in mind a central region was designed that produced a well centered beam with good vertical focusing properties. Figure 1 shows the central region so obtained as well as the path of the central ray. This figure also shows the first turn phase selection slit (located at θ=110°) which will be used to limit the phase width of the beam.

A. Central Region Acceptance and Phase Selection

In order to determine the acceptance of the new 2^{nd} harmonic central region and inflector system, a set of ions were tracked from 3.0m below the median plane of the K500, up the magnet axis, through a 1^{st}+2^{nd} harmonic buncher, the spiral inflector and out through the first 23cm of the K500. The ion paths up to the exit of the inflector was accomplished using the aforementioned MYAXIAL and INFLECTOR codes , while the motion through the central region of the K500 used a modified version of the Z3CYCLONE [5] orbit code. This modified version extends the number of electric fields from two to three and removes ions whose paths intersect with electrode or dee structures. In addition this new version saves the particle's r and ϕ values at the locations of both the central region slit and the phase selection pins (located at r=17.88cm).

In order to calculate the percentage of the input DC beam which maps into the final 3° bandwidth required by the K500-K1200 coupling project, a range of emittances were tracked up the machine axis and through the spiral inflector. Each set of starting conditions consisted of a uniform circular distribution of points (one point per mm-mrad) spanning the emittance area in x,p_x and y,p_y. Each point in x,p_x space corresponded to a complete set in y,p_y which spanned the entire emittance area. In this way a spatially coupled set of starting conditions was obtained. To simulate the time structure of the incoming beam a series of coupled x,p_x/y,p_y sets were started each separated by 2° RF. This now complete set of starting conditions was then passed through the K500 axis elements (a single solenoid and buncher), through the inflector and out past the K500 phase selection pins.

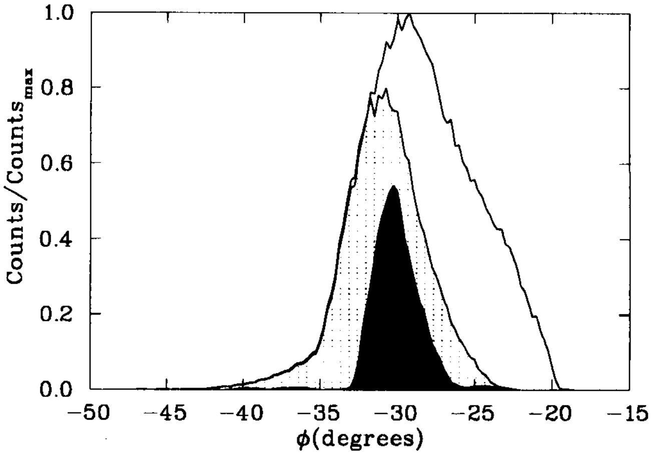

Figure. 2. Timing spectra at r=22.0cm. The three spectra are (white) before the first turn slit, (dotted) after the first turn slit, and (filled) after the 18cm phase selection pins. The peak has been reduced from 10° FWHM to one of only 3°.

Extraction requirements restrict the timing spectra coming out of the central region to 3° FWHM. In order to obtain this, a scheme is necessary to select only those particles whose final phases fit this range. Utilizing the radius dependence on the phase radial slits have been used to select only those ions with the proper phase [7]. Presently, the K500 is equipped with two phase pins located on the 0° and 120° hills at a radius of 18cm. These pins consist of two movable tungsten blades that are used to intersect the beam [6]. As mentioned above, there is a third slit, consisting of a fixed aperture window, located on the first turn. Thus there are three apertures which may be used in phase selection.

To model the effect of these slits a program was used which simulates the effect of various slit combinations. This program accepts r,ϕ orbit data at specified slit positions and a set of final ϕ data. At each slit position a separate pin (labeled A,B, and C) can be inserted. The position of each pin can be adjusted, it can be inserted or removed, and the width of the pin can be set. In this way any combination of pins, pin positions and pin width can be achieved. The program then identifies which ion orbits (if any) intersect with each pin and removes these from consideration. The final collection of surviving ions is then binned according to final phase and a beam timing spectra is produced. Additionally, a variable width, first turn, window slit can be inserted to further reduce the final timing spectra. By using the r,ϕ output of the central region orbit code a measure of the acceptance of the cyclotron into a 3° FWHM timing region which can be expressed as a percentage of the input DC beam (at z=-3.0m) surviving for various starting emittances and buncher modes.

IV. Acceptance Results

A variety of starting emittances were calculated in order to determine the performance of the injection plus central region design. Starting emittances of 25, 50 and 75π mm-mrad in each of the coupled x,p_x/y,p_y phase spaces were tracked through the phase selection process. Additionally, in order to determine the relative gain of the 1^{st}+2^{nd} harmonic buncher system, these

Table II

Percentage of DC Beam in 3° FWHM Peak

Buncher Harmonics	Initial Emittance (mm-mrad)		
	25π	50π	75π
1^{st} Harmonic Only	11.0%	5.8%	2.9%
1^{st} and 2^{nd} Harmonics	16.7%	9.5%	5.5%

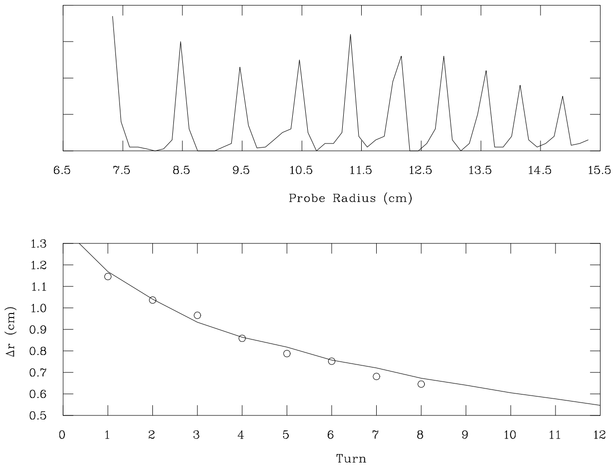

Figure. 3. Top: Differential wire probe trace in the K500. Bottom: Δr vs. turn for the same. Circles represent probe data while the curve was calculated by computer orbit tracking.

starting emittances were run in both buncher modes and the various parameters of the phase selecting slit system were adjusted to give a 3° FWHM peak containing the maximum number of surviving ions. Figure 2 shows the timing spectra before the first turn slit, just after this fixed window, and then the final 3° peak obtained by using the outer phase pins for a 75π mm-mrad emittance using the 1^{st}+2^{nd} harmonic buncher mode. Table II shows the percentage of the injected DC beam which survives in the appropriate bandwidth for a range of buncher modes and initial emittances. As can be seen, using the 1^{st}+2^{nd} harmonic buncher mode provides a 50 to 90 percent increase in the surviving beam.

V. Experimental Results

The new K500 central region and inflector have been built and are currently being commissioned. Early results from runs of 15MeV O^{+4} show dee voltages higher than the design levels. This is due to errors in the placement of the dees in the central region. The planned upgrade calls for a correction of this effect. As a check on the reliability of the orbit code calculations measurements of radius gain per turn were made on the O^{+4} beam. Figure 3 shows a differential probe trace and a comparison of measured values with those obtained from computer runs. By varying starting time of the calculated central ray good agreement between the two can be reached. Measurements of the internal bunch length have been made using both the first turn slit and phase selection pins. A 3° FWHM bunch length has been observed for the internal beam.

VI. Conclusions

A new inflector and 2^{nd} harmonic central region have been designed to meet the specification of the K500-K1200 coupling project. Beam orbit calculations show that a 3° FWHM bunch length, with good transmission properties can be achieved. The new design has been installed and early results support the design's calculated properties.

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