AXIAL INJECTION AND PHASE SELECTION STUDIES OF THE MSU K1200 CYCLOTRON*

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Abstract

Axial injection into a cyclotron through its iron yoke, a spiral inflector, and the central region electrodes couples the transverse coordinates of motion together, as well as with the longitudinal coordinates. The phase slits in the K1200 cyclotron use the $r-\phi$ correlations inherent in acceleration of ions in a cyclotron. Computer simulations of injection into and acceleration within the K1200 cyclotron encompassing the four transverse dimensions together with time were used to determine beam matching requirements for injection and phase selection in the K1200 cyclotron. The simulations were compared with measurements using an external timing detector.

I. INTRODUCTION

Simulation of the function of the phase slits, which have been installed in the K1200 cyclotron at MSU[1], requires an accurate understanding of the injected beam. The ion source for the cyclotron can be any one of three external ECR sources. A 90° analyzing magnet selects ions with a specific Q/M, which are then brought into the K1200 vault 3 m below the median plane of the cyclotron. Figure 1 shows the portion of the injection line which is inside the cyclotron vault. A bending magnet guides the beam up the axis of the cyclotron, where a solenoid focuses it for inflection into the cyclotron. There is also a buncher in the injection beam pipe, which is used to increase transmission into the cyclotron. A spiral inflector brings the beam onto the median plane of the cyclotron, where it is defined by, and guided about the machine center by the central region electrodes.

While this is an idealized picture of the injection process, it serves as a start for the injection calculations. Starting the beam at the exit of the vertical bending magnet, these calculations ray trace the ions up the yoke of the cyclotron and through the spiral inflector with modifications of the programs MYAXIAL, where bunching has been added, and INFLECTOR[2]. The ray tracing then continues through the central region and out into the cyclotron with Z3CYCLONE[3]. Ions which strike electrodes are removed from the calculation, and the radius and phase of the surviving ions are saved each time they pass by the active area of the slits. A third program was written to sort through the final output, rapidly displaying the number of particles versus phase of the beam which passed the phase slits. This allows an interactive tuning of the simulated phase slits.

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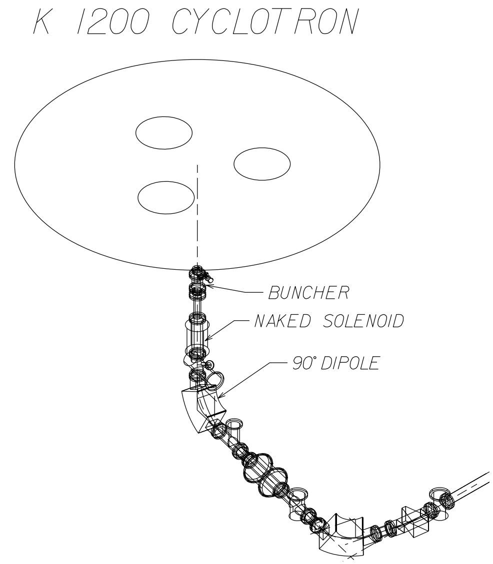

Figure. 1. K1200 Axial Injection Line. Depicted are the buncher, focussing solenoid, and 90° bending magnet. The axial portion is used in the injection studies.

II. CONTINUOUS (DC) BEAM INJECTION

The injection study began with a two dimensional study of the initial coordinate system. Phase space ellipses were followed to the inflector exit. The resulting ellipses were coupled in the transverse coordinates, with distortions existing in both. The solenoid strength, and the initial ellipse shape were varied, and both could reduce but not eliminate this distortion. The radial spot became smaller and more distorted as the solenoid field was increased, while at the same time, the axial dimension was losing its distortions. The point where the solenoid was tuned to inject the largest area in phase space was also a happy compromise between beam quality in the two coordinates. The optimum initial phase space also varied with solenoid strength.

The two dimensional ellipses were changed to a four dimensional lattice, covering 100π mm·mrad in each transverse dimension, so that the couplings could be observed. The solenoid was found to increase transmission by focussing the beam into the entrance aperture of the inflector. Matching the initial phase space ellipse served to minimize distortions caused by traversal of areas in the yoke where the iron suddenly narrowed. Both this, and the solenoid, minimized the divergence of the beam entering the inflector.

Following the beam through the inflector and central region the smaller beam produced by the solenoid, has now become the larger beam in both spot size and divergence. Clear couplings

Table I

K1200 Cyclotron DC Acceptance. Injection efficiencies are presented for four 4–D DC acceptance studies. Transmission are given in percent at the entrance and exit of the inflector, and after the central region of the cyclotron.

Case 1:	I_{infl}	=	60.5%	I_{start}
$B_{sol} = 0.0kG$	I_{exit}	=	89.1%	I_{infl}
circular	I_{CR}	=	11.9%	I_{exit}
ellipses		=	10.6%	I_{infl}
		=	6.4%	I_{start}
Case 3:	I_{infl}	=	99.5%	I_{start}
$B_{sol} = 2.65kG$	I_{exit}	=	100.0%	I_{infl}
circular	I_{CR}	=	12.0%	I_{exit}
ellipses		=	12.0%	I_{infl}
matched		=	11.9%	I_{start}
Case 5:	I_{infl}	=	76.0%	I_{start}
$B_{sol} = 0.0kG$	I_{exit}	=	95.4%	I_{infl}
elongated	I_{CR}	=	12.3%	I_{exit}
ellipses		=	11.7%	I_{infl}
matched		=	8.9%	I_{start}
Case 6:	I_{infl}	=	100.0%	I_{start}
$B_{sol} = 2.65kG$	I_{exit}	=	96.7%	I_{infl}
elongated	I_{CR}	=	11.4%	I_{exit}
ellipses		=	11.0%	I_{infl}
		=	11.0%	I_{start}

have also been found between r and z and r and p_z as well as the expected $E-\phi$ correlations. The transmission of four cases is presented in Table 1.

III. BUNCHED BEAM INJECTION

The time spread of the 4–D pulse was also examined as functions of the solenoid focussing and injection matching of the initial phase space. Matching the beam for traversal up the yoke minimized the spreading of that pulse in time. Focusing with the solenoid made small improvements in the time spread for both matched and unmatched cases. Transmission through the inflector also spread the beam in time, with the final results shown in Figure 2. It rounded off the peaks of the matched cases, and extended all of the bases, but the FWHM's were essentially unchanged. This debunching sets a limit on how tightly the buncher can bunch the beam into the cyclotron. The 4–D studies were extended in time to include the buncher. Figure 3 shows the two extremes of the best and worst calculated bunching.

One final note on bunching: the buncher added a 1% variation in the kinetic energy of the injected beam which is correlated with time. The spiral inflector is electrostatic, bending the less energetic ions more than, and the more energetic ions less than the reference particle, which is bent onto the median plane. Thus all the particles starting at the buncher at any specific time, will be shifted axially, inducing an oscillation about the median plane.

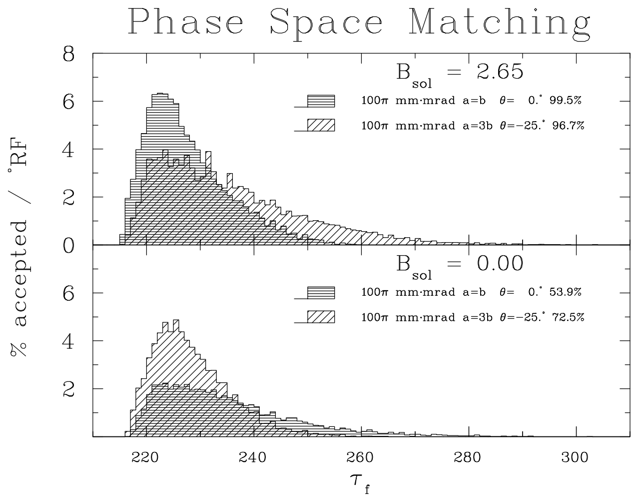

Figure. 2. Debunching Produced by the Yoke and the Inflector. Matching the initial phase space for injection up the yoke will minimize the straggling of the beam.

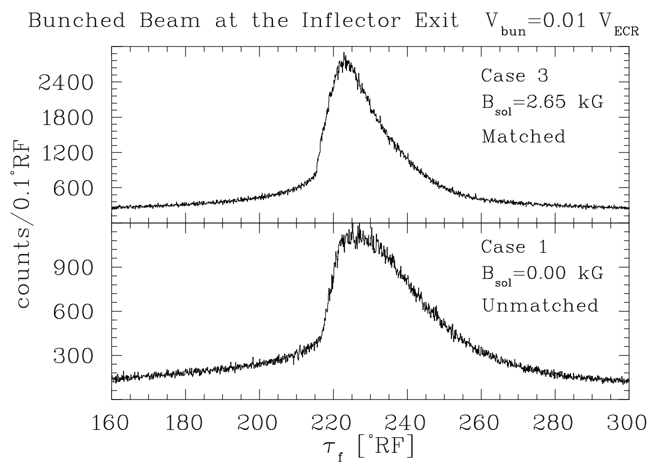

Figure. 3. Bunched Beam at the Inflector Exit. The improvement possible in the bunching efficiency by matching the injected phase space of the beam is depicted above.

IV. PHASE SELECTION

The phase slits are two posts which are inserted axially into the beam at a radius of 7 in, and in the center of two hills. These posts can be shifted over a small radial range, which encompasses about three turns. Each beam pulse takes several turns to clear a post, which cuts out a piece of the beam each pass. A correlation between E and ϕ has built up at this point, turning the radial cuts into time cuts. Figure 4 shows a simulation of this process made on the beam from the 5–D starting lattice, which has survived the injection process. The buncher has been tuned to one side, and the two slits have been tuned to remove as much of the beam outside of the main peak as possible, with beam not cut by one slit being cut by the other. The multi turn process is clearly evident, handicapping the use of the slits to define a clean and narrow phase cut.

Figure 5 shows a measurement made using an internal timing detector[4], and performed under similar conditions as the above calculation. The multi turn cutting of the beam by the phase

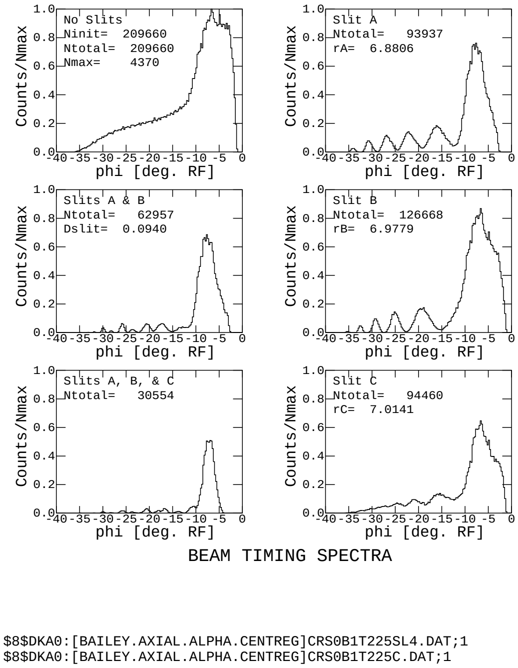

Figure. 4. Calculation of Phase Cuts Made with the Buncher Tuned to One Side. The upper left is the uncut phase spectra, with the upper and middle right being the phase cuts produced by the individual slits. The two slits combined are on the middle left, with the lower two showing the effect of a hypothetical third slit.

slit is evident, though the calculation over predicted the phase width and hence the number of phase cuts made. The use of the buncher almost made this a clean phase cut.

The injection into the K1200 has been studied, resulting in a good understanding of the phase selection process being used at the present time. Better phase selection can be achieved by restricting the emittance of the injected beam, and matching its initial phase space. This would allow cleaner bunching of the beam. Clean phase selection will require an initial central region phase cut, eliminating the overlap of turns at the phase slits.

References

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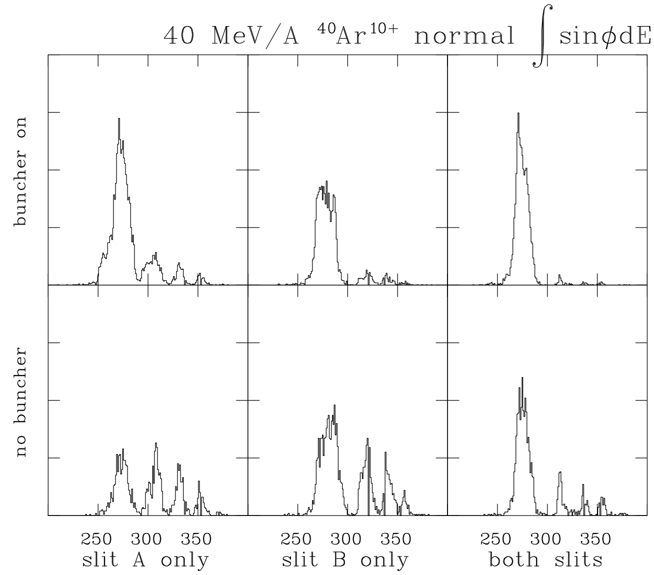

Figure. 5. Measurement of Phase Cuts Made with the Buncher Tuned to One Side. This measurement shows that the calculations, while slightly pessimistic, simulate the actual conditions of the beam at the phase slits.