DESIGN OF THE INJECTION CHANNEL MAGNETS FOR THE K1200 CYCLOTRON

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1 Introduction

The basic requirement for the K1200 cyclotron stripping injection is to transport the required ion beams from the K500-to-K1200 coupling line matching point to the K1200 equilibrium orbit where a carbon stripping foil is positioned, and match the injected beam transverse phase spaces to the eigen-ellipse of the K1200 accelerated beam. Due to the small aperture of the K1200 injection channel and strong magnetic field gradients along the injection path, which lead to strong radial defocusing and vertical overfocusing, proper transverse beam focusing has to be provided to ensure the efficient injection into the K1200 cyclotron. Early studies of the K1200 injection beam dynamics in 1995[1] shown that a single active combined-function K1200 injection channel magnet placed at the return path of the K1200 yoke did not provide adequate radial focusing for the injected beams. As a result, a new movable, passive K1200 injection focusing bar was introduced into the injection channel to provide additional radial focusing for the injected beams. A wide range of ion beams is required for the coupled cyclotron facility at the NSCL to support the proposed nuclear physics research programs and they will have different beam trajectories and transverse behaviours through the injection channel. Table 1 shows the six test beams used in our studies ranging from low energy, heavy ions to high energy, light ions. The stripping angles are given in the K1200 cyclotron coordinate system.

Table 1: Beam characteristics for the six test beams

Field Case	Ion	Q/A	Stripping Energy (MeV)	Stripping Angle (degree)
20206	$^{238}U^{+20}$	0.08402	2.10	243.60
100381	$^{84}Kr^{+13}$	0.15494	9.43	245.00
100425	$^{40}Ar^{+7}$	0.17518	9.43	245.50
2005	$^{16}O^{+3}$	0.18750	16.66	238.40
40218	$^{238}U^{+22}$	0.09242	4.09	250.00
9531	$^{238}U^{+32}$	0.13445	9.04	256.00

2 K1200 injection magnets

2.1 K1200 injection focusing bar

The K1200 injection focusing bar consists of 3 curved bars symmetric with respect to the K1200 cyclotron mid-plane to match the injected beam trajectories and reduce the possible beam loss. The bar configuration is shown in Figure 1 and was designed not only to provide uniform magnetic field gradient but also to be able to fit into the limited space in the K1200 injection channel. In addition, a special driving mechanism was designed to move the focusing bar in order to position the required injected beam on the corresponding K1200 equilibrium orbit and hit the stripping foil. Only a single drive is required to move the K1200 injection focusing bar origin along an R=46.77 inch radial track. Two beam current monitors were positioned at the entrance of the focusing bar not only to monitor the beam loss but also used as a beam diagnostic tool in the beam injection tuning process.

The magnetic field of the bars was calculated using TOSCA[2] and the field contours are shown in Figure 2. Since the bars are almost fully saturated by the K1200 main cyclotron magnet, the same bar field could be used for all six test beams studies. After the focusing bar was installed in the K1200 cyclotron, its magnetic field gradient was measured with different K1200 main fields. The comparison with the TOSCA model shows they match very well. Figure 3 shows measured field gradient of the focusing bar with three K1200 main fields and the TOSCA calculation result.

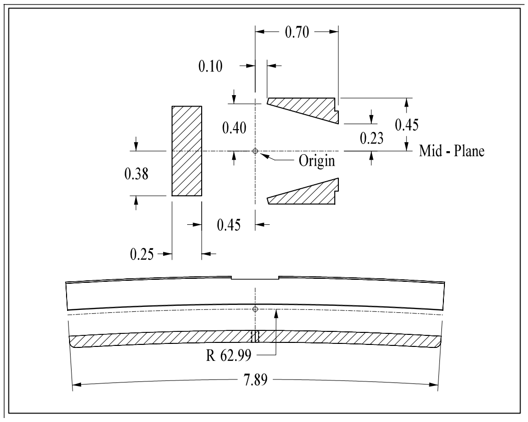

Figure 1: The K1200 injection focusing bar configuration.

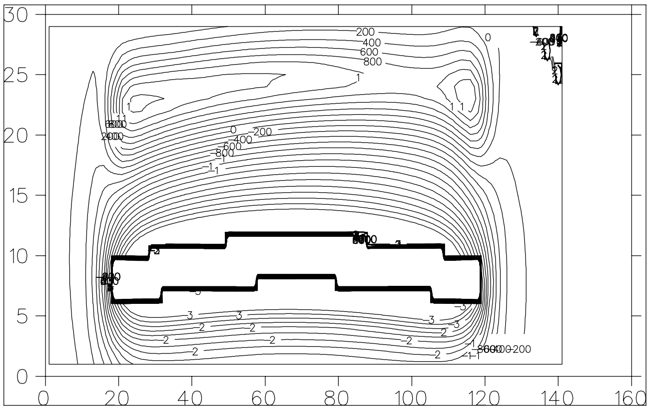

Figure 2: The magnetic field contours of the K1200 injection focusing bar.

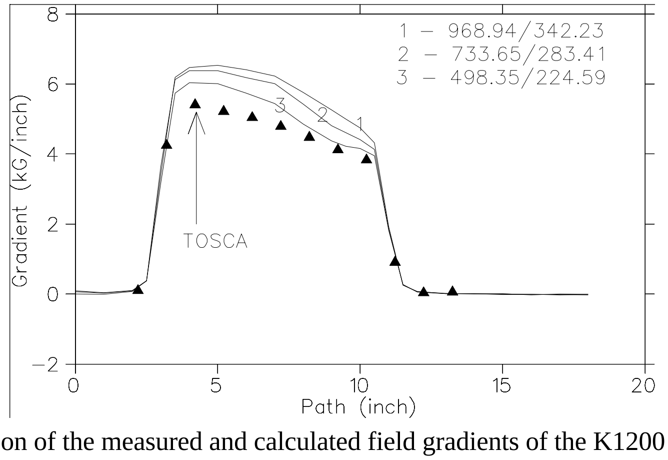

Figure 3: The comparison of the measured and calculated field gradients of the K1200 injection focusing bar.

2.2 K1200 Injection Channel Magnet

The K1200 injection channel magnet is located in the return path yoke of the K1200 cyclotron magnet. It is an active, combined-function magnet to provide both deflecting and radial focusing for the injected beams. The magnet pole has a volume of 2.5 l (each) and the pole face was chosen to provide uniform magnetic field gradient in the aperture. Four double pancake coils of 4.76 mm square water-cooled copper conductor wrap around each pole, and there are total 72 turns for each coil. Figure 3 shows the injection channel magnet configuration with the beam vacuum chamber in place.

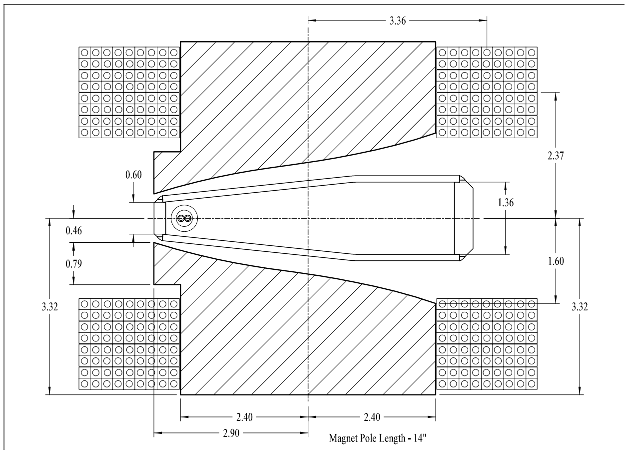

Figure 4: The K1200 injection channel magnet configuration.

The K1200 injection channel magnetic fields for different test beams in early studies were also calculated using TOSCA. After the channel magnet installation into the K1200 cyclotron, a K1200 injection channel magnet mapper using a Hall probe was constructed and extensive field mapping[3] was done to better understand the magnetic field in this region and its impact on the injected beams. The magnetic field in this region depends not only on the K1200 main magnet coil current, but also on the K1200 injection channel magnet coil current which has a range of ± 220 A. The field mapping process consists of two parts. One is the measurement of the magnetic field and gradient at the center of the injection channel magnet, and the other is the detailed field mapping covering the whole region. To cover the K1200 operating diagram, a total of 21 sets of K1200 main magnet coil currents were used for central magnetic field and gradient measurement, and a total of 6 sets of K1200 main coil currents were used for detailed two-dimensional field mapping.

The K1200 injection channel magnetic field map for the six test beams in our studies were obtained by interpolating from the field mapping data, and were used in the K1200 injection beam dynamics studies. Figure 4 shows the resultant magnetic field and the gradient in the centre of the K1200 injection channel magnet for a test beam field (20206).

3 K1200 injection beam dynamics

The K1200 injection calculations were performed using the K1200 injection focusing bar and the active injection channel magnet discussed in this paper for the six test beams. The beam trajectories were calculated backward from the position of the equilibrium orbit at the stripping angle inside K1200 cyclotron, through injection channel using INJORB5 code developed by D. Johnson. The K1200 injection focusing bar position and the injection channel magnet current were adjusted so the beam central trajectory reaches the coupling line matching point at $R= 120$ inch and $\theta=68°$ in the K1200 cyclotron coordinate system, where a bending magnet is located. The K1200 beam eigen-ellipses were also tracked from the stripping angle to the matching point resulting in the beam envelopes along the injection path and the required beam transverse phase space parameters from coupling line. Figure 5 shows beam radial trajectories, the K1200 injection channel, the focusing bar and the channel magnet, and the transverse beam envelope for $^{16}O^{3+}$ (2005) beam. The injected beam emittance was assumed to be 2.5π mm-mrad in both planes. Similar results were obtained for the other test beams as well. The resultant beam parameters at the matching point required from the coupling line are show in Table 2 and used in the coupling matching calculations.

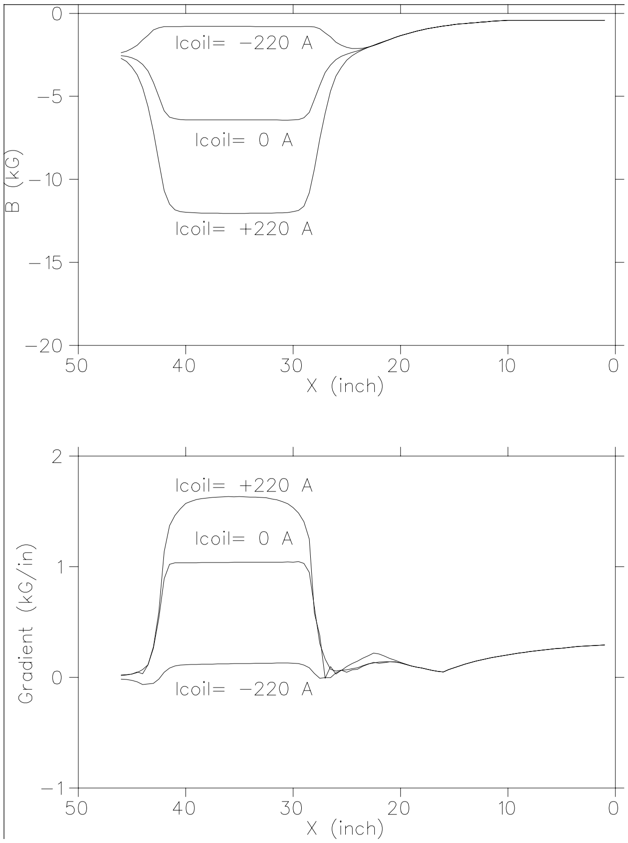

Figure 5: The measured magnetic field and gradient at the center of the K1200 injection channel magnet for a test beam field (20206).

Table 2: Required beam transverse phase space parameters at the matching point for the coupling line.

Field	β_x (m)	α_x	β_y (m)	α_y
20206	7.6445	10.7486	145.3411	78.3587
100381	19.6088	-9.7317	43.2385	22.9362
100425	13.8895	-9.3557	55.4113	28.9072
2005	50.0288	-4.5368	35.6475	16.8039
40218	25.0704	-3.9192	18.2099	9.6251
9531	19.8228	1.6566	11.8225	7.4730

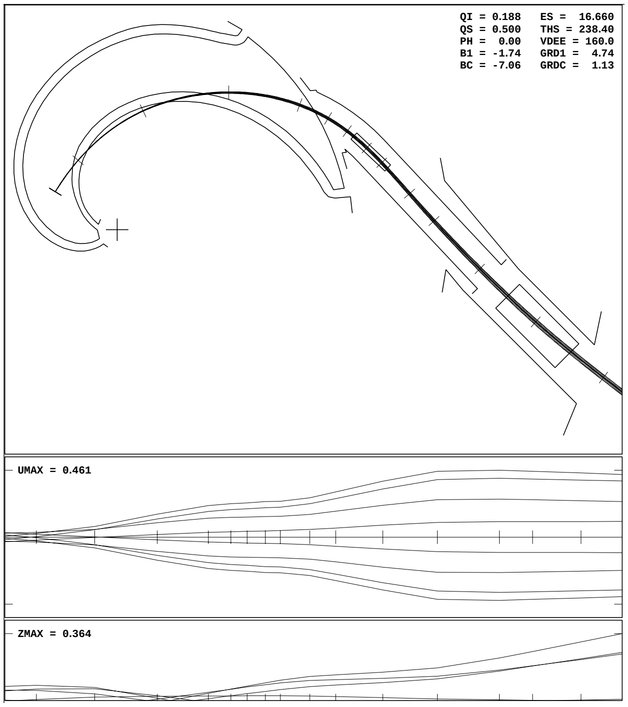

Figure 6: The injected beam trajectories and the transverse envelopes for test beam of $^{16}O^{3+}$ (2005).

4 Summary

Two magnetic elements were included in the K1200 injection channel to ensure the efficient radial stripping beam injection into the K1200 cyclotron. The magnetic field measurement and mapping for these elements were done after the installation, and the results match very well with the TOSCA model. The K1200 injection calculations were performed from stripping foil to the coupling line matching points through the injection channel. The results show the magnetic channel elements provide the proper focusing and beam matching for all six test beams covering the K1200 operating diagram. The predicted setting for the stripping foil position, injection channel elements settings and the beam transverse space spaces at the matching point for the coupling line were used in the commissioning of the coupled cyclotron facility at the NSCL since 2000, and shown to be extremely accurate. In 2001, the injection code INJORB5 were upgraded using Tcl-Tk interface and became an essential tool for the CCP commissioning and future operation.

References

[1] D. A. Johnson and F. Marti, “Survey of Injected Beam Parameters at the K1200 Cyclotron”, NSCL-CCP6-1995, Michigan State University, 1995.

[2] VECTOR FIELDS, Inc., Oxford.

[3] X. Wu, T. Grimm and F. Marti, “K1200 Cyclotron Injection Channel Magnetic Field Mapping and Interpolation”, NSCL-CCP21-2000, January 2000.