NuMI Extraction Comparison for Two and Three Kickers

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I have compared a couple of options for a two and three kicker solution. I wanted to make sure that I could replicate the proposed orbits and offsets and understand the difference between the apertures in each scenerio. The requirements on each system need to be understood to determine if the aperture requirements showed that two kickers failed to meet requirements and three kickers were required or if two kickers would work and meet requirements but didn't give much breathing room. First, the beam properties and the aperture requirements (for misalignments and steering) need to be understood and documented.

- What will be the beam emittance in each plane? What kind of distribution is assumed? What will the tails look like? What is the intensity these assumptions are made for? What representation should be used to encompase 100% of the beam, including tails? I think we have to assume that any "halo" would be removed?

- Will there be collimators in the MI or will the beam be shaped at injection or up the ramp?

- For these assumptions, are there any locations in the ring that will present problems or need to be upgraded? For example is there enough circulating aperture at other kicker and Lambertson loactions at injection and top energy?

- What is the tolerable loss at locations around the ring, kickers and lambertsons, including the MI60 extraction Lambertsons for circulating and extracted beam?

- What is the aperture requirement for steering through the extraction regions?

- What is the minimum distance from the edge of the beam ellipse (as defined earlier) to any steel for circulating and extracted beam.

I think these assumptions need to be addressed before any decision can be made on the separation requirement of the extracted and circulating beam at the entrance to the Lambertsons.

For the current comparison, I assumed a gaussian beam with a Fermilab 95% normalized emittance of 40 π-mm-mr in both planes. Currently, at the 4.5E12 /batch level , the measured horizontal and vertical emittances, I believe, are on the order 22 and 15 π-mm-mr , respectively . However, I calculate a sigma based upon

$$\sigma_{95} = \text{sqrt}\,[\varepsilon_{95}\beta \,/\, 6\pi(\gamma\beta)]$$

Then 95% of the beam is contained within +/- 2.45 σ_{95} . To include the contribution due to any beam tails, I assume that 100 % of the beam is contained in an ellipse of +/- 4 σ_{95} . I use this defintion at all energies and both planes. I assume a coupled machine with the same emittances in both planes. I believe this is an over estimate in the vertical plane based upon observations in the MI (typically the vertical is smaller). In this definition, I cannot determine loss rate except by looking at how much of the ellipse intersects steel so I determine a hard limit for no losses by the separation of the edge of the ellipse with any steel aperture.

At 120 GeV/c, the MI correctors can move the beam 1 mm/amp horizontally and 0.44 mm/amp vertically considering a beta of 56 meters. The power supply operating current is limited to about 15A. Some fraction of this current is used for closed orbit correction at high field. I think on the average, about half of the available current is used, with some locations actually running out of current at high field. This means that we should allow about half of this current for closed orbit control at extraction. This should give us about 7 A to use for orbit control. This implies that we have on the order of 7mm horizontal control and 3 mm of vertical control.

Current Configuration (3 kickers)

I used the current proposal layout exactly (well almost) with respect to the quad displacements Lambertson excitations, off-sets and rolls. I still am using 2 kickers downstream of the quad 602 instead of three. This should make only minor differences so I will ignore slight differences in position and angle at the Lambertsons. To be more explicit:

Quad Displacements

Q602	1.582 mm
Q606	-1.964 mm
Q610	-1.708 mm
Q612	0.0588 mm
Q614	1.54 mm

Lambertson/KickerGeometry

Magnet	Delta x	Delta y	roll	angle
LAM60A	3.2 mm	-4 mm	.115 mr	3.0 mr
LAM60B	4.0 mm	-1 mm	.115 mr	7.54 mr
LAM60C	2.0 mm	2.0 mm	.115 mr	7.54 mr
V100	28-31 mm	30-80 mm	0	8.4 mr
K602	0	0	0	900ur

Figure 1 shows the closed and extraction orbit for these conditions. The circulating beam trajectory is about – 7 mm at Q604 and about 18 mm at Q608. One of the first things I noticed is that having the orbit cross zero at about 610, the circulating aperture through the lambertsons is smaller than it need be (see proposal in 2 kicker option). The small closed orbit bump at Q604 produces a large extracted orbit excursion of about 37 mm at Q604 vacuum valve. Including a 4 σ beam envelope this uses up about 44 out of the 50 mm aperture. Reducing this should help aperture thru the valve.

Additionally, the beam trajectory out of the c-magnet rs rather large at about 1 mr toward the outside. If the first dipole in the beamline is10 meters down stream then the central trajectory moves roughly 10 mm farther to the outside from about 30 mm to about 40 mm outside the MI centerline. This need to be confirmed that there are no MI inteferences.

Figure 2 shows the beam ellipse at the entrance and exit of the first Lambertson.Here the separation of the beam centroids at the entrance is about 37 mm and about 44 mm at the exit. Assuming a 4 mm septa thickness the and the beams centered there should be about 16.5 mm clearance between the centroid and the steel. The beam at the entrance has the larger vertical extent. It looks like the circulating beam is significantly closer to the septa than the extracted beam. This should be better centered. Also the vertical alignment of the Lambertson places the circulating beam closer to the top edge of the notch. This vertical offset should be reduced. By measuring the opening angle on Sasha's plots, it looks like the opening angle is substancially less than the 78 degrees it should be. This could be that what he is plotting is the effective aperture due to the vertical offsets.

Figure 3 shows the beam entering and exiting the quad 608 along with the quad aperture and all three Lambertson apertures. If the vertical trajectory through this region is on the centerline this vertical arrangement significantly reduces the vertical aperture. Here the first Lambertson had a 3 mr bend which places the exiting bean at about x = 27 mm and y = 17 mm.

Figures 4 – 6 show the beam through the last two Lambertsons and the c-magnet. The separation between the extracted beam and the steel at the downstream of the last two lambertsons is reduced due to the roll of the Lambertsons. If this roll angle is reduced the separation would remain nearly constant.

Figure 6 shows the c-magnet installed with the center of the c-magnet flange at 120 mm above the MI centerline. The beam enter the c-magnet flange at 90 mm and the c-magnet steel at 94 mm above the MI centerline. This puts the beam about 26 mm below the centerline. The lambertson pitch shown is about 15 mr such that the beam exits about 5 mm above the c-magnet flange centerline. With this geometry, the beam elevation into the Q1 is about 218 mm (if its ~1.5 m downstream of the c-magnet) close to the elevation required by the "new style" 3Q60 quad at this location

<u>Otion 1 (2 kickers)</u>

I also calculated a 2 kicker option to the 3 kicker solution. I will say that this is not optimized and has no connection at this time with the beamline, but the general features should be apparent. For this option I used the same Lambertson angles with different rolls and offsets. I also generated a different closed orbit. Here, I used correctors, but this could easily be generated (at least in part) by quad moves. I reduced the kicker strength by about 25% from 900 ur to 680 ur total kick. The bottom line is that the close orbit is more symmetrical; the separation between the circulating and extracted beam at the entrance to the first Lambertson is smaller (i.e. 28 mm as compared to almost 38 mm); the circulating beam has increased vertical and horizontal aperture; and the horizontal trajectory exiting the c-magnet is more nearly parallel to the MI centerline. I used a kicker strength of 1.36 kG-m per kicker which translates to about 680 ur total kick (about 75% of the 3 kicker solution). This strength corresponds to about 55 kV setting (about 53 kV reading A/D) on the kickers. The next two tables list the parameters used for this option.

Beam Position for fitting

HP604	X = -15 mm
HP608	X = 18 mm
HP610	X = 18 mm
HP612	X = 0 mm
HP612	X' = 0 mr

Lambertson/KickerGeometry

Magnet	Delta x	Delta y	roll	angle
LAM60A	0->2 mm	0 mm	.104 mr	3.0 mr
LAM60B	0.0 mm	0 mm	.045 mr	7.54 mr
LAM60C	0.0 mm	00 mm	.045 mr	7.54 mr
V100	17 mm	30-90 mm	0	8.4 mr
K602	0	0	0	680ur

Figures 7 thru 12 show the beam envelope and same cross section for the 2 kicker option as the first six figures show for the 3 kicker option. Looking at Figure 7, the first observation is that the the closed orbit and extraction orbit through the 604 region is smaller and more symmetrical such that the vacuum valve aperture should not be a problem. The other observation is the reduction is separation at the entrance to Lambertsons and the reduction of the angles at the exit of the Lambertsons.

Looking at figure 7 the Lambertson has a horizontal offset at the upstream end of 2 mm (solid line) and 0 mm at the downstream end (dashed). The larger vertical ellipse is the upstream beam. This could better optimized.

Figure 8 shows the beam at the entrance and exit of the quad. The extracted beam has a 8 mm clearance from the edge of the 4 σ ellipse where as the 3 kicker solution had a 12.6 mm clearance. How critical is this additional 4.6 mm?

Conslusion

Depending on the free aperture requirements, the two kicker solution should work. The three kicker solution provides additional beam separation margin of safety if needed. If three kickers are used, the closed orbit, Lambertson paramenters, and kicker strengths need to be revised to produce a better closed orbit and extraction trajectory. Again the downstream beamline trajectories and installation needs to be addressed.

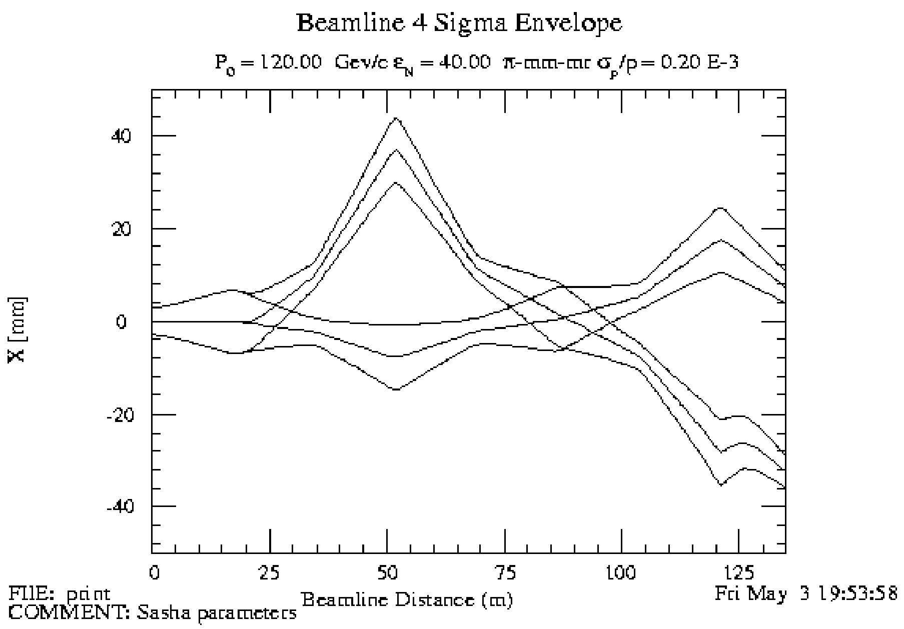


Figure 1 : Beam envelope for 3 kicker solution

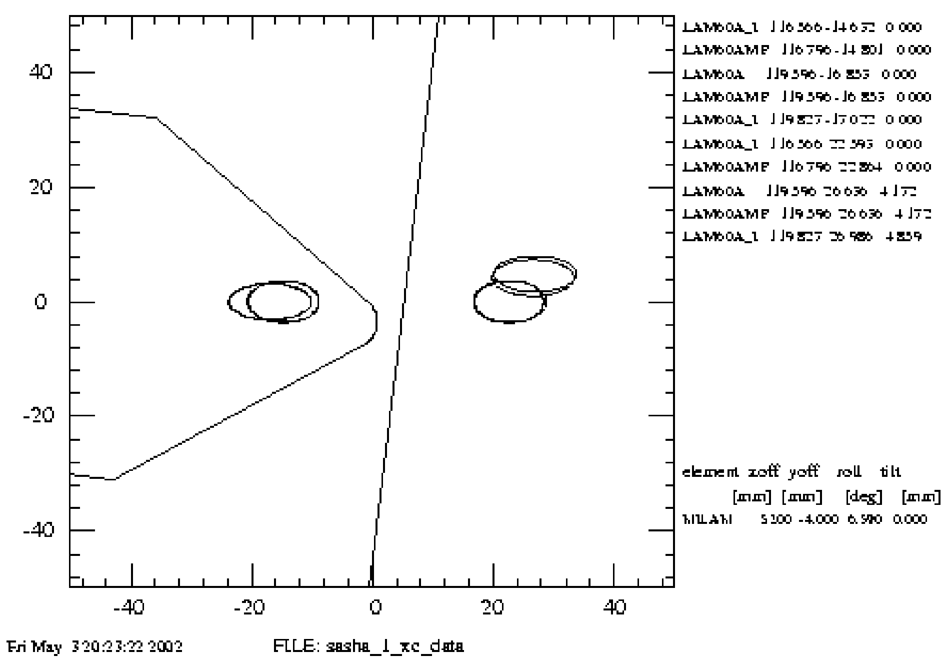


Figure 2 : Lambertson LAM60A cross section for 3 kicker solution

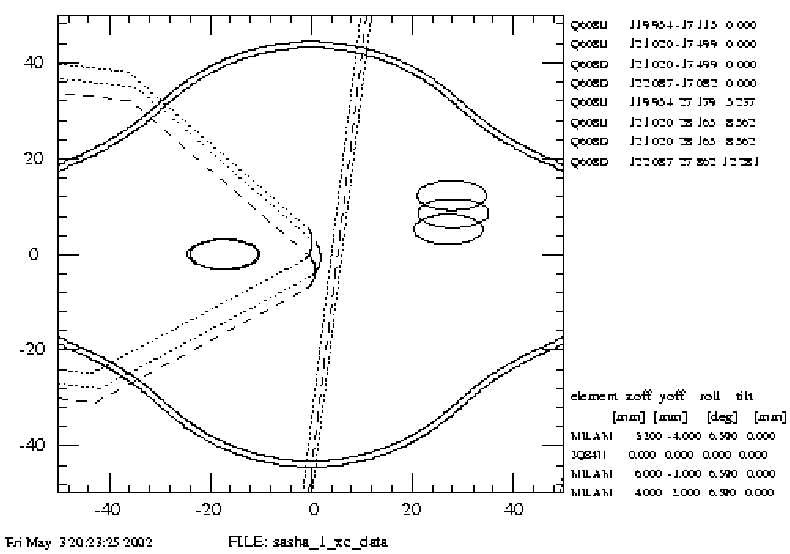


Figure 3 : Beam trajectories through the quad 608 and Lambertson cross sections for 3 kicker solution

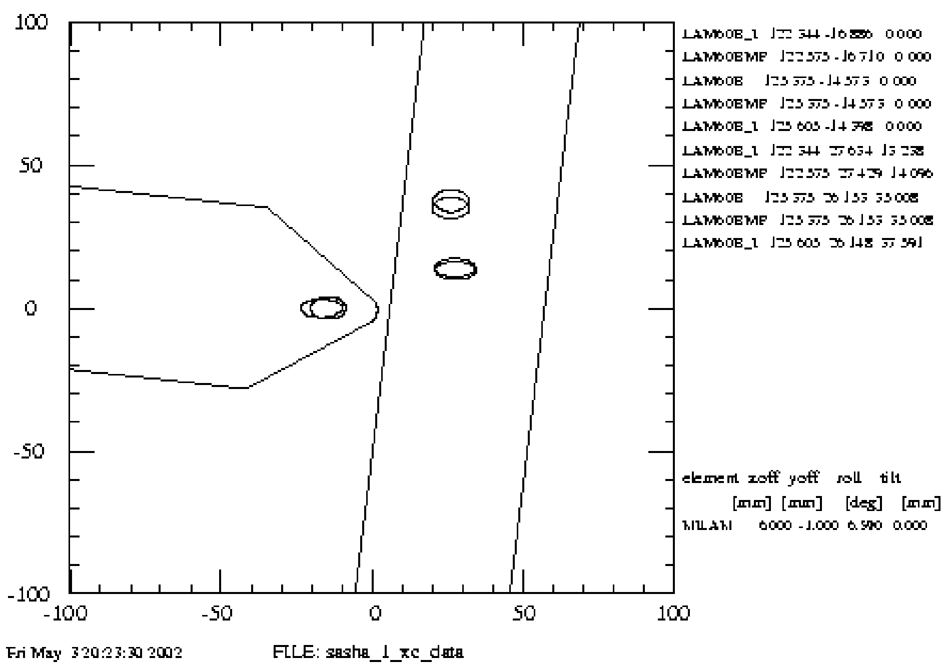
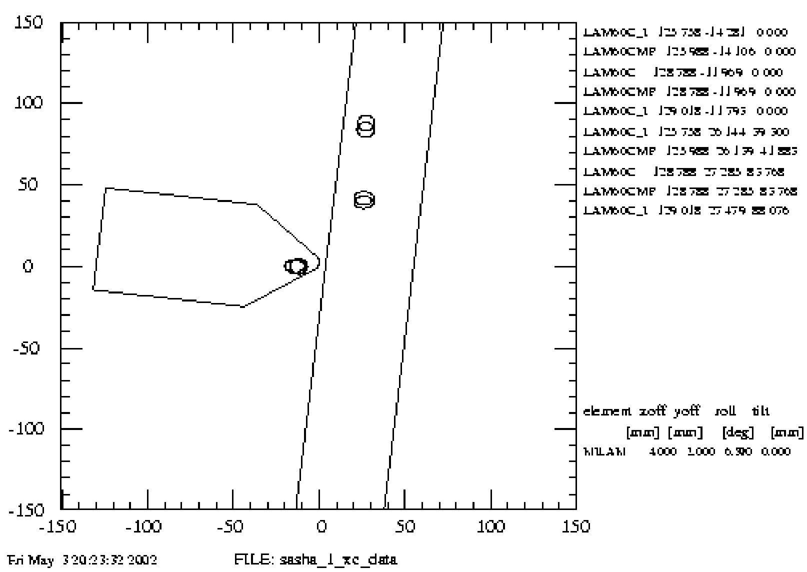


Figure 4 : LAM60B cross section for 3 kicker solution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LAM60CMP 125.988 26.139 41.883
LAM60C 128.788 27.285 83.768
LAM60CMP 128.788 27.285 83.768
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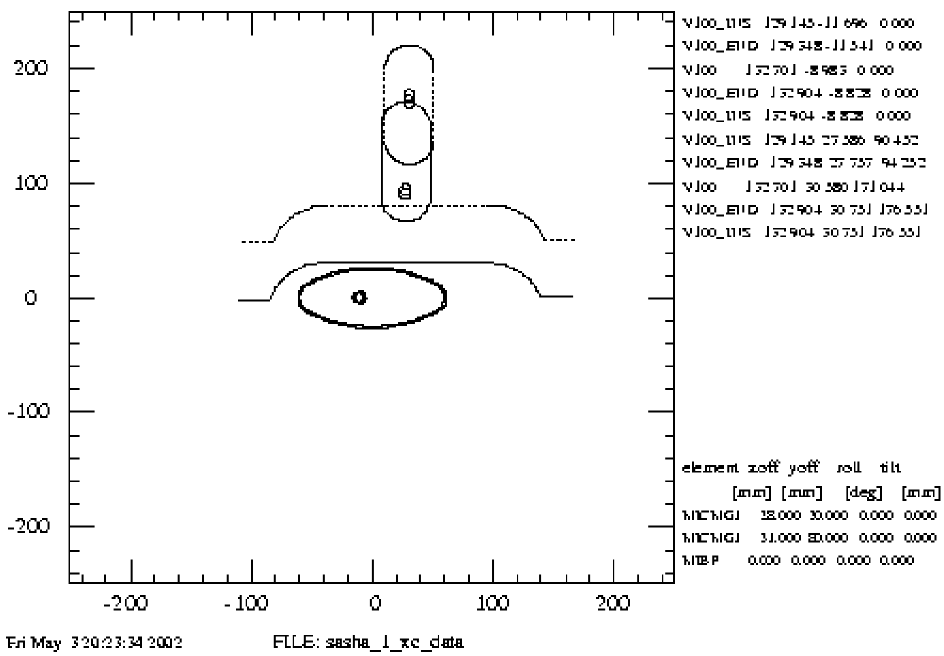


Figure 5: LAM60C cross section for 3 kicker solution

Figure 6 C-magnet cross section for 3 kicker option

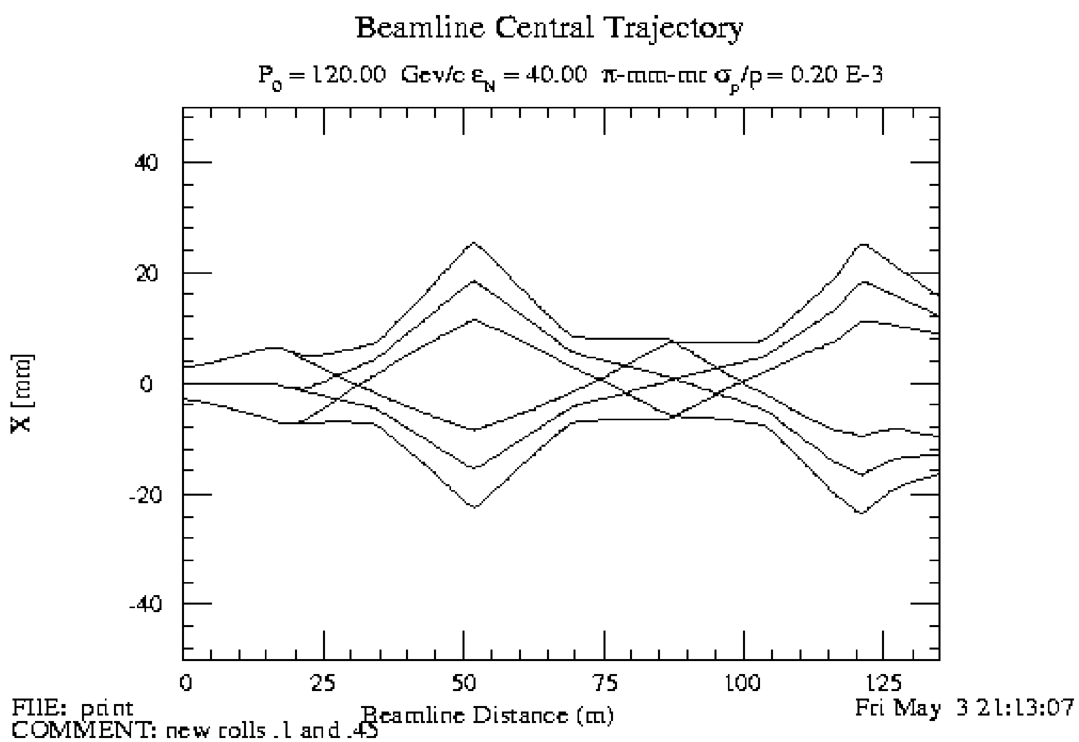


Figure 7 Beam envelop for circulating and extracted beam in the 2 kicker option

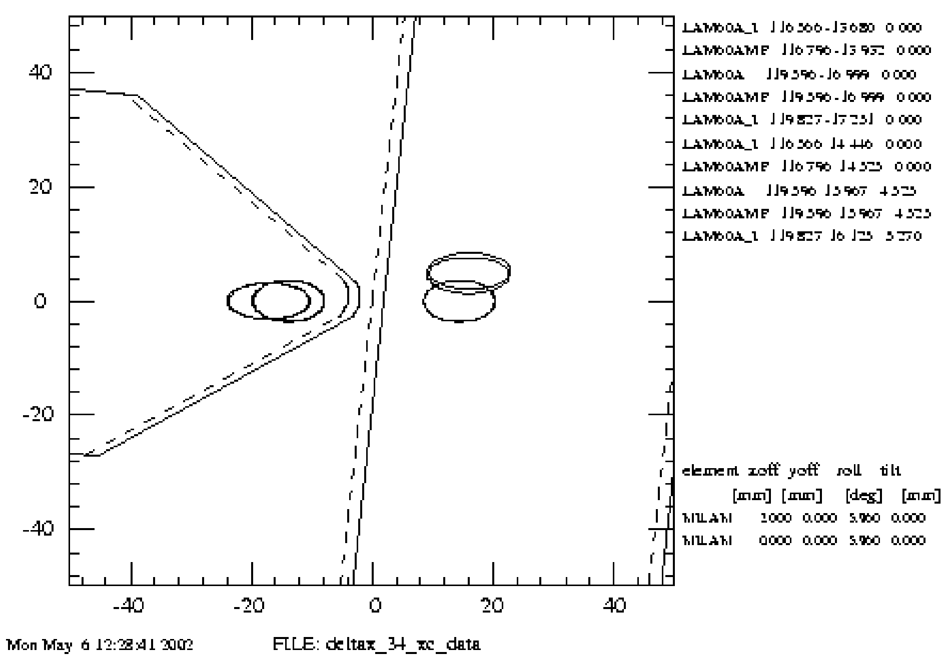


Figure 8 LAM60A cross section for the 2 kicker option

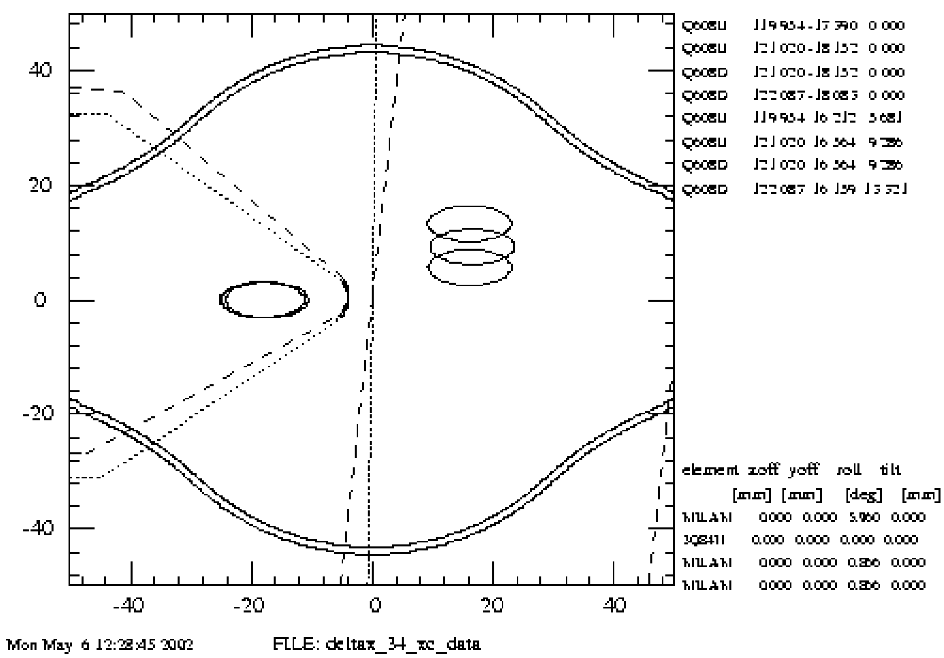
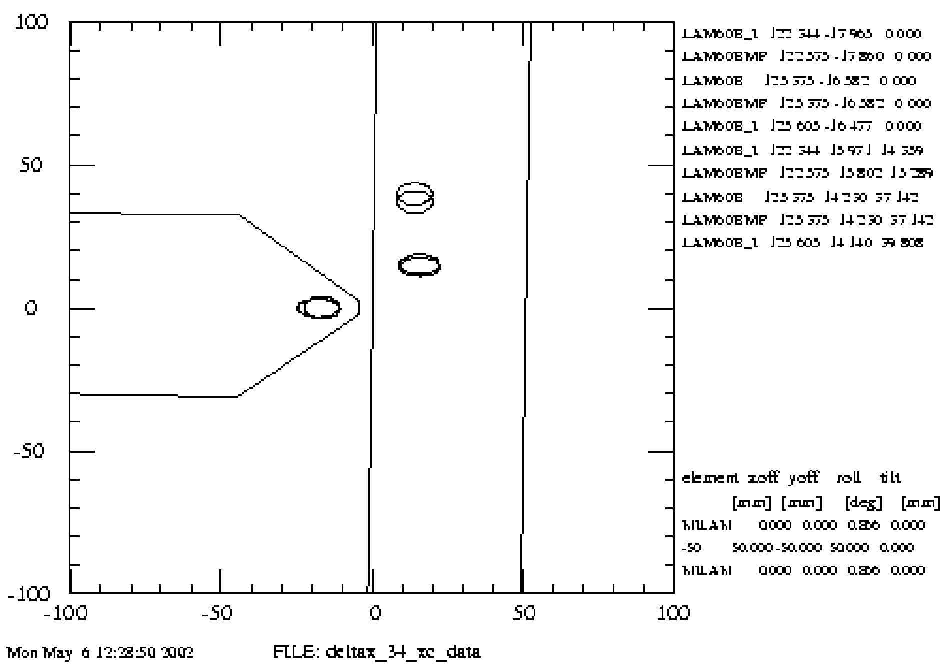


Figure 9: Q608 cross section for the 2 kicker option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LAM60BMP 122.575 15.802 15.289
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-50 50.000 -50.000 50.000 0.000
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Figure 10: LAM60B cross section for the 2 kicker solution

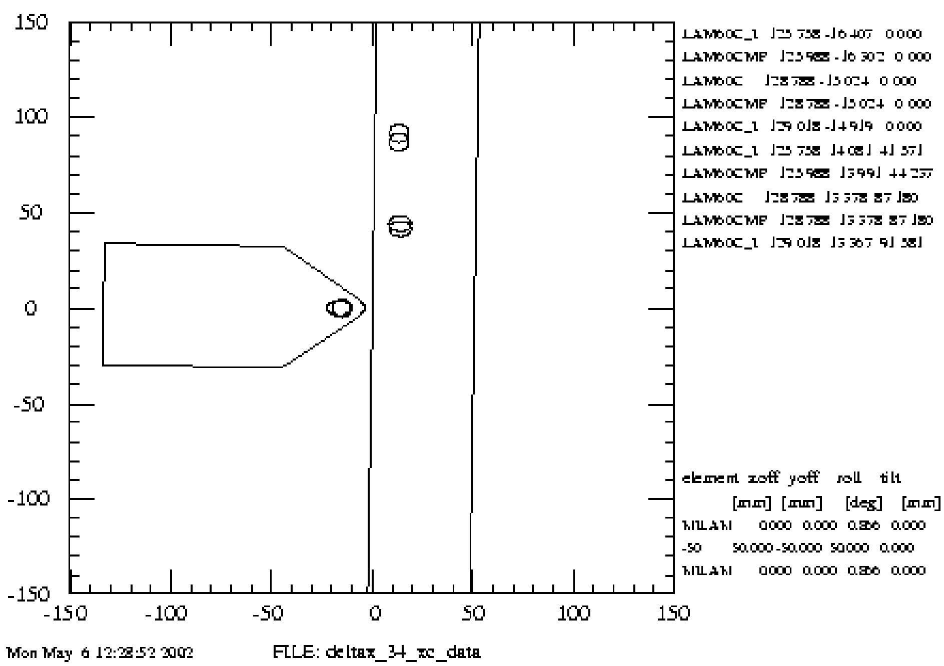

Figure 11: LAM60C cross section for the 2 kicker solution

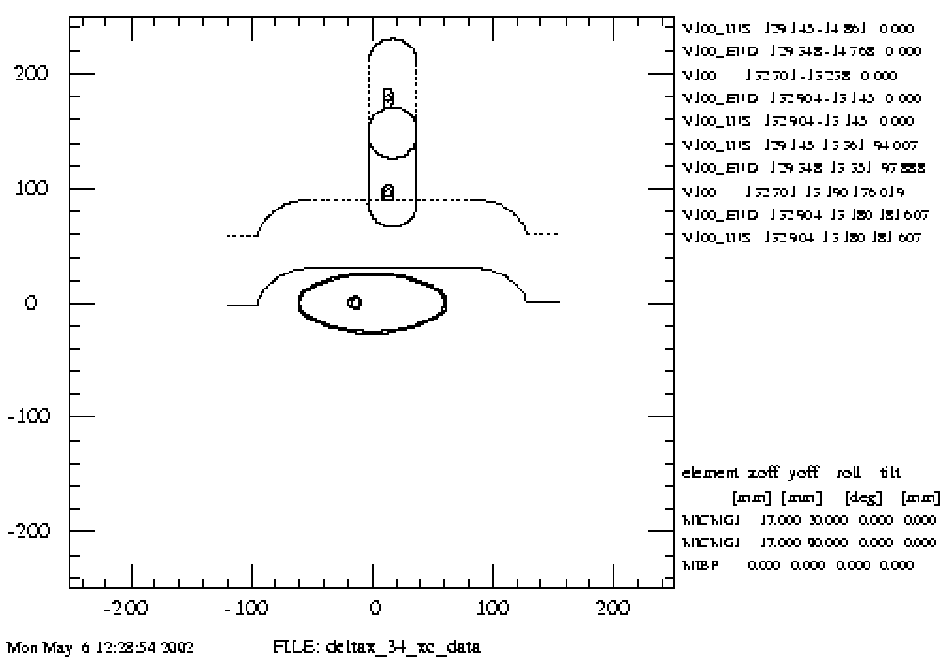

Figure 12: C-magnet cross section for the 2 kicker solution