MI_15 Kicker Specifications

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1 Introduction

This note describes the specifications for the injection and extraction kickers for the Main Injector. The basic criteria for the choice of kickers includes: location (available slot length and phase advance to the lambertson); field (the maximum kG, accuracy, and stability); aperture (does it represent an aperture restriction, can it be made to achieve the specified field uniformly across the gap); timing (rise time, fill time, pulse duration, fall time, repetition rate); availability of kicker modules and/or power supply.

At this time, all kickers in the Main Injector are assumed to be horizontal.

The proton abort kicker is not discussed. The conceptual design of the abort line and the requirements for the abort kicker were described in the latest CDR(page 18).

The Tevatron injection kickers are also not discussed in this note. The current injection design utilizes vertical injection kickers in the Tevatron which will require a larger gap than the current Tevatron injection kickers. Since the MI project will follow the 36x36 bunch operation, and new faster pbar injection kickers must be designed for use with the Main Ring, it would be prudent to design these faster kickers with the aperture that will be required when the Main Injector comes on line.

2 Kicker Locations

The kicker locations in the Main Injector are shown in Figure 1. The horizontal phase advance between all kicker locations and lambertsons is approximately 90 degrees. The proton extraction, pbar extraction and pbar injection kickers are located in the missing dipole slot (closest to the straight section) of the first half cell either upstream or downstream of the straight section. An enlarged view of the straight section MI-60, for the proton extraction and pbar injection transfers, is shown in Figure 2. The slot length between the dipole and the QF quad is 6.1399 m. A distance of .375 meters from either end is subtracted for connections. Another 2 meters is subtracted between the kickers and the QF quad for the proton extraction kickers for placement of correction elements. [Note: The correction element package placement has not yet been determined.] This leaves 3.39 meters flange-flange for the placement of the proton extraction kicker and the pbar extraction kicker. The slot between the QF and Q00 quads in MI-60 has been reserved for the proton slow extraction septa.

The kicker/lambertson orientation for 150 Gev pbar extraction in straight section MI-80 is identical to that of MI-60. The slot labled "X0" is free in MI-80, so the extraction kicker could go there (for a little better phase advance) if need be.

The proton injection straight section layout is slightly modified from that shown in figure 2. First, the injection lambertson has moved about 6 meters toward the center of the straight section. The location of the lambertson was determined by using the maximum bend (of the lambertson) to calculate its distance from the inner quad, QI, such that the beamline clears the QI quad and leave room for beamline magnets over the MI magnets. The minimum elevation for the beamline above the MI, to allow an SQA quad to be placed directly over a MI dipole with no clearence, is 25.2". The current elevation is set to approximately 31 1/2". The kicker was moved into the slot between QF and Q00 to get closer to a 90 degree horizontal phase advance (it's approximately 85 degrees).

Table 1 summarizes the kicker locations, slot length, required field, and position and angle at the lambertsons. It is assumed that any of these residiual horizontal angles at the lambertsons can be removed by rolling the lambertsons.

3 Aperture Considerations

The generally stated aperture requirement for the Main Injector has been that the MI should have an admittance of 40π-mm-mr. The largest vertical beta in the ring (β_y=78) occurs in the defocussing outer quad, Q0, of the doublets used in the straight section insertion. The lattice functions around the straight section are shown in Figure 2b. The approximate position of the elements shown in figure 2 are displayed between the dispersion and beta function curves. The vertical beta in the first dipole (inside beam pipe diameter of 1.9") after the quad ranges from about 78 meters down to 55 meters. If one uses the definition of admittance as $\pi\frac{a^2}{\beta}(\gamma\beta)$, where a is the half aperture; then the admittance of this dipole and the MI would be about 71π-mm-mr. A "reduced" admittance may be defined by subtracting ±5 mm from the available physical aperture for orbit (or steering) errors (i.e. the effective aperture is reduced from a^2 to $(a-5)^2$), then the admittance is "reduced" to 44π [from here on, the mm-mr unit is assumed]; still within the stated specifications.

With the Linac upgrade the Booster is expected to routinely produce proton beams with a transverse emittance of 30π at its highest intensities. It might not be entirely unreasonable to expect beam with an emittance of 40π sometime in the future, although the typical emittance will probable be in the range of 15 to 25π. It then would be prudent to design the kicker/lambertson apertures that would allow the maximum potential emittance of the Booster (for protons) and the Accumulator (for pbars). So, considering 40π normalized emittance beams, the required minimum separation at the proton injection lambertsons is approximately 53 mm, if a maximum of 30π beams are expected this separation could be reduced by the six times the difference

8 and 150 Gev pbars. The dashed line in the figure represents the gap of the current F17 lambertson laminations. The solid line represents a 2" gap that has been displaced up by 1" from the notch. This had to be shifted to accomodate the trajectory of the injected 8 Gev pbars. Once again the minimum separation for 40π beams is approximately 58 mm.

The inner quad,QI, is only 0.4 meters from the lambertson. Figure 6 shows the best orientation of the lambertson in the MI aperture while maintaining the 5 mm distance of the injected beam from the outer quad aperture. This shows the 8 Gev circulating beam approximately 25 mm to the inside and the lambertson notch approximately 10 mm outside from the center of the quad. This quickly reduces the physical aperture of the quad. The position of the lambertson must also be consistent with the 120 Gev slow extraction solution of the beam position and size at the lambertson. Figure 6b shows the orientation for 15π beams.

The separation is quickly reduced in passing through the outer quad Q0. However, due to the large vertical beta, the injected beam could be moved outside by only 5 to 10 mm. Figure 7 shows 40π injected circulating beam positions through the outer quad, QO, of the straight section.

A comparison of the 48.3 mm physical aperture of the dipole (1.9" id. beam pipe) with the 6σ beam size at the dipole shows that for an ϵ_N of 30π the 6σ beam size is 38.5 mm which gives $\pm$5mm for orbit errors. For an ϵ_N of 40π , the vertical height of the beam is 44.5 mm which is only $\pm$2.1 mm remaining aperture for any orbit errors. Figure 8 shows the separation of the injected and circulating beams through the nearest dipole to the straight section. The 6σ beam envelope for a 40π beam is shown in the aperture.

Figures 9 and 10 show the location and beam sizes for 150 Gev (40π) protons, through the pbar injection lambertsons and the inner quad. The 17 mr bend of the lambertson produces a 75 mm displacement at the end of the lambertson, too large to fit in the existing F17 lambertson.

The ideal aperture specifications for the kickers would be that they would have the same 4" by 2" aperture as the dipole magnets (inside beampipe dimensions are 3.9" by 1.9") so as not to produce an aperture restriction. **This 4X2 inch requirement on the aperture eliminates the possibility of the reuse of any existing kicker magnets.** If the aperture were chosen to be 3 3/8" by 1 1/2"(85.75mm X 38.1mm) then some of the existing kicker magnets could be reused.

In comparison with the aperture of the bending magnet above, the lattice functions at the locations of the kickers range from 54 to 30 meters horizontally and 12 to 23 meters vertically. For a 1 1/2" vertical aperture and a beta of 23 meters, the vertical admittance (including the ±5mm for errors) would be 81 π-mm-mr. These lattice functions produce a 6σ beam size of 38mm (h) by 24mm (v) for a normalized emittance of 40 π-mm-mr. If this beam size is compared to the existing kicker aperture, there will be ±7mm in the vertical plane and ±24mm in the horizontal plane for steering errors. This will produce less of a vertical aperture restriction than the 78 meter vertical beta in the first dipole next to the straight section.

4 Timing considerations

The kicker timing specifications for injection and extraction are based upon the following assumptions:

- The harmonic number of the MI is 588 (i.e. 7 times 84 for Booster).
- The Rf frequency will range from 52.8 Mhz at injection to 53.1 at 150 Gev.
- A maximum of 6 Booster batches will be accelerated in fixed target mode.
- The Main Injector will accelerate "short batches" (to be defined later) for injection into the Tevatron in the Collider mode.

From these assumptions we get:

- **a bucket length of 19 ns.,**
- **a batch length of 1.6 μs,**

- **a revolution frequency of 90.3 kHz,**
- **and a revolution period of 11 μs.**

The timing requirements for the proton injection kicker are the most stringent. They are similar to the requirements of the present Main Ring. Assume each of six batches are loaded in boxcar fashion, that is one after another. The current Booster extraction kickers have a rise time of approximately 50 ns. and extract up to 83 out of 84 bunches. If an 85 RFC bucket delay is used for each injection, this will produce a two bucket separation between batches. This would require the proton injection kicker to have a 2 bucket (38 ns) rise and fall time. The flattop time would be the length of the batch (1.6 μs). This would produce a 78 bucket (1.48 μs) gap between the bunches.

The proton extraction kicker is required to transfer a full MI ring of 6 batches to the Tevatron for fixed target and single bunches for Collider operation. The 6 batch extraction provides the timing constraints for the proton extraction kicker. It must have a rise time of less than 1.48 μs corresponding to the gap between the first and last batch. It must have a flattop time of greater than 9.7 μs (6*85*1.9 μs) to extract all batches. The fall time is not important in this case.

If the last batch injected was delayed by 750 ns., it would be placed in the middle of the abort gap. There would now be a single batch in the middle of the gap and 750 ns. on either side. The timing specifications of the proton extraction kicker would become more stringent. This would require a rise and fall time of 700 ns with a variable flattop time from 8 μs to 9.7 μs to extract 5 or 6 batches. This would allow the extraction of a single batch [for pbar production] during slow spill cycles. [Note: This would have implication on the required rise time for the proton abort kicker.] The minimum required specifications do not reflect this option, but this should not be ruled out if possible.

The pbar injection kicker will be required to inject only single "short " batches from the Accumulator. The the sum of the rise and fall time must be less than 9.6 μs with a flattop time of 1.6 μs. The number of pbar bunches in this single short batch is determined by the Accumulator extraction RF harmonic number. In the past the Accumulator has unstacked and extracted a single bunch per Main Ring cycle using the h=2 suppressed bucket RF. When the h=4 harmonic is implemented in the pbar source, then up to 4 bunches spaced by 21 buckets could be extracted from the Accumulator. This would represent a 1.6 μs beam pluse. This would reduce the pbar filling time of the Tevatron by requiring only 9 fillings to achieve 36 pbar bunches in the Tevatron.

The timing requirements for the pbar extraction kicker are much less stringent than those of the proton extraction kicker. Only single batches will be extracted which dictates the rise time for the kicker will be less than 9.6 μs. It must have a flattop time of at least the length of a single batch (1.6 μs).

The repetition rate for the proton injection and extraction kickers is driven by the 1.5 sec. (minimum) cycle time for the 120 Gev pbar production cycles. The repetition rate for the pbar injection and extraction kickers is driven by the minimum unstacking/transfer time required by the Accumulator. This is currently taken to be on the order of 20 sec.

The kicker timing requirements are summarized in Table 3.

5 Tolerances

To estimate the tolerance and pulse-to-pulse variation specifications, the effect of a position and angle error on the extracted and injected beams must be calculated.

For the injected beams, the emittance growth due to a steering error is given by [1,2]

$$\Delta\epsilon = 3(\gamma\beta)\frac{\Delta x_{eq}^2}{\beta}\pi. \tag{1}$$

where the value Δx_{eq} is defined as the equivalent position error and defines

[1] M. Syphers, "An Improved 8 Gev Beam Transport System...", TM-1456

[2] R. Gerig, "A Dispersion Mismatch Criteria ...",MI-0001

the maximum excursion from the closed orbit and is given by[2]

$$\Delta x_{eq} = [\Delta x^2 + (\beta\Delta x' + \alpha\Delta x)^2]^{1/2} \tag{2}$$

where Δx and Δx' are the position and angle errors through the kickers. If a BPM were located at the kicker, the maximum amplitude of the betatron oscillations on successive turns (Turn By Turn) is given by $\pm\Delta x_{eq}$. For a BPM located elsewhere the ring the maximum amplitude would be given by $\sqrt{\frac{\beta_{bpm}}{\beta_{kick}}}\Delta x_{eq}$. For example, at a QF quad the β_x=55 meters, so Δx_{eq} at the quad would be 1.131 times the value at the kicker.

At the proton injection kicker $\beta_x = 43$ meters and $\alpha_x = 2$. The kicker has a 1.2 mr kick. If there is a field error of 1/2% this would correspond to a 6μr error and produce Δx_{eq} of 0.26 mm (which would be a ±0.26 mm excursion on a TBT display located at the kicker). At 8 Gev this gives an emittance growth of 0.04π. An error in the pbar injection field would produce the same growth.

A position error of 1.0 mm through the kicker, with the proper kick, will produce a Δx_{eq} of 2.24 mm at the kicker. The TBT would show ±2.24 mm at the kicker or ±2.53 mm excursion at any QF quad in the ring.This would produce an emittance growth of 3.3π!! This means the injection line must be stable enough to keep the position at the kicker to within ±0.55 mm to keep the emittance growth down to 1π. For comparison, using the Main Ring lattice functions at MK90 (β_y=85 meters and α_y=0.2), a 1 mm position error through the kickers in the Main Ring would produce a Δy_{eq} of 1.02 mm and an emittance growth of 0.35π; a factor 10 less sensitive. The TBT at the kicker would show a ±1.02 mm excuesion.

Therefore, the location of the injection kickers make the position through the kicker very critical and sensitive. If one puts a maximum limit of 1π emittance growth for injection position errors due to kicker field errors, the ripple and pulse-to-pulse variation must be kept within 2.4%.

A 1/2% error in the 150 Gev extraction kicker field would produce a horizontal displacement error of 0.13 mm at the extraction lambertson. The angle at the lambertson (to within a μr)would not be changed. If no other magnetic beamline element were changed, this offset would be translated to a position offset in the Tevatron injection kickers. Calculation of Δx_{eq} at the proton and pbar kickers gives 0.184 mm and 0.13 mm. These correspond to an emittance growth of 0.34π and 0.29π, respectively. If a maximum emittance growth of 1π, due to a position error generated by the extraction kicker field error, is acceptable, the ripple and pulse-to-pulse variation must be kept within 1%.

6 Hardware

The hardware design and specifications need to be done to meet the requirements described here, summarized in Tables 2 and 3. A few comments about the selection of magnets should be made. First, many of the existing kicker magnets have the 3 3/8" horizontal and 1 1/2"vertical aperture. This appears to be sufficient for some existing magnets to be reused. Looking at Terry Asher's Operation Bulletin on Kickers, several kicker magnets appear to have potential for reuse. However, a detailed design must be done.

- Proton injection: The requirements are not to different than the existing MK90 or MKS01. A new magnet would probably need to be built with the larger aperture (3 3/8" hor X 1 1/2" ver).
- Proton extraction: A single 2.1 meter D48 magnet can produce 1.25 kG. This would need a new power supply. This kicker and the pbar injection kicker share the same straight section. It's not clear if these kickers could be the same magnet with two power supplies or whether two independent kicker magnets are required.
- Pbar injection: If a second kicker magnet is required, (different from the proton extraction kicker), a shortened E17-1 kicker might be a potential candidate.
- Pbar extraction: Here a D48 kicker magnet with a new power supply is a candidate.

7 Summary and Comments

The location, field, aperture, timing, and tolerances for the kickers in the Main Injector have been specified assuming all horizontal kickers. The next step would be to do a detailed design of the magnets and power supplies to see what existing equipment could be reused. Below are a few comments regarding the kickers and the Main Injector.

- A detailed design of the proton abort line including kicker and lambertson should be done.
- Both proton and pbar injection kickers for the Tevatron need to be designed. The required fields have been specified for vertical kickers in MI-0010 and timing requirements are summarized in TM-1637.
- High field correctors should be considered to control the beam position around the injection and extraction straight sections.
- The pbar injection/proton extraction lambertson needs to be designed.
- Investigate the design of a larger aperture quad for use around the straight sections. For example, use the Tev II LQA laminations with a different coil (i.e. fewer turns) to verify it will achieve the required field and maintain a reasonable temperature.
- Investigate vertical injection for proton injection line.

Table 1: Main Injector injection/extraction kicker locations.

kicker	location	slot [m]	Bdl [kG-m]	Δx [mm]	Δx'[mr]
proton inj.	MI-10	5.35	.4	60	-.029
pbar inj.	MI-60	3.35	.382	60	-.220
proton ext.	MI-60	3.35	2.625	24	-.089
pbar ext.	MI-80	5.35	2.625	24	-.089

Table 2: 8 Gev beam sizes in Main Injector magnets between the injection lambertson and kickers.

magnet	β_x / β_y	σ(8 Gev)[mm]	$\pm 3\sigma$[mm]	separation [mm]
lambertson	55	6.2	18.6	60
	25	4.2	12.6	
QI	55 - 47	6.2 - 5.8	18.6 - 17.4	60-55
	30 - 40	4.6 - 5.3	13.8 - 15.9	
Q0	26 - 19	4.3 - 3.7	12.9 - 11.1	40 - 33
	70 - 79	7.0 - 7.5	21.0 - 22.5	
B2	19 - 18	3.7 - 3.6	11.1 - 10.8	33 - 26
	77 - 55	7.4 - 6.2	22.2 - 18.6	
kicker	54 - 30	6.2 - 4.6	18.6 - 13.8	
	12 - 23	2.9 - 4.0	8.7 - 12.0	

Table 3: Main Injector kicker timing requirements.

kicker	rise time	duration	fall time	rep. rate
proton inj.	38 ns.	1.6 μs.	38 ns.	1.5 sec.
pbar inj.	note 1	1.6 μs.	note 1	approx. 20-30 sec.
proton ext.	$<$ 1.48 μs.	$>$9.6 μs.	NA	1.5 sec.
pbar ext.	$<$ 9.6 μs.	1.6 μs.	NA	approx. 20-30 sec.

note 1: The sum of the rise and fall time must be less than 9.6 μs.
note 2: The rep. rate for the pbar injection and extraction kicker is dependent on how fast the Accumulator can unstack.

WINDOW PARAMETERES, XLO, XHI, YLO, YHI,

7-FEB-90 12
window # 2

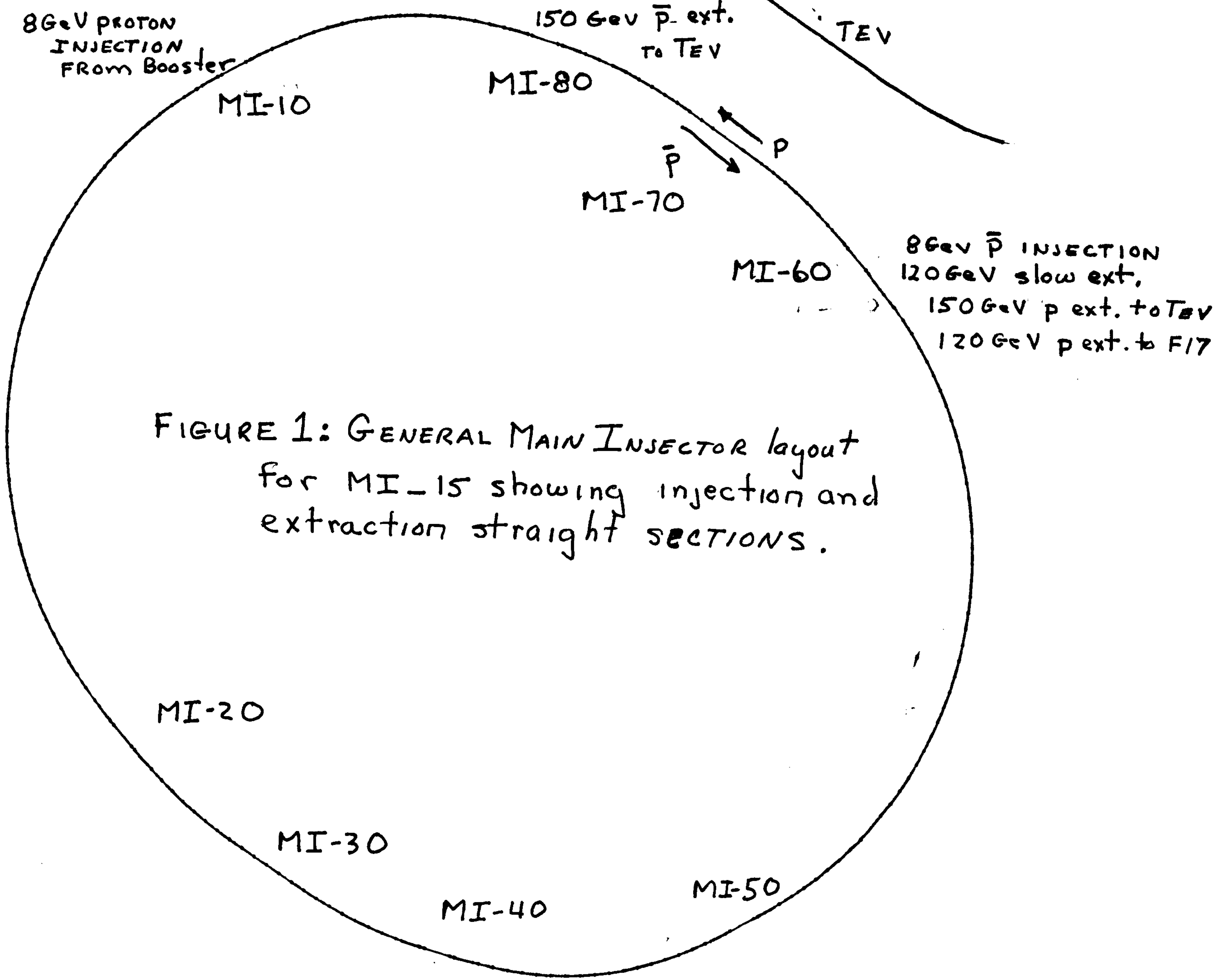


FIGURE 1: GENERAL MAIN INJECTOR layout for MI_15 showing injection and extraction straight SECTIONS.

WINDOW PARAMETERES, XLO, XHI, YLO, YHI,

29-MAR-90 12:
window # 2

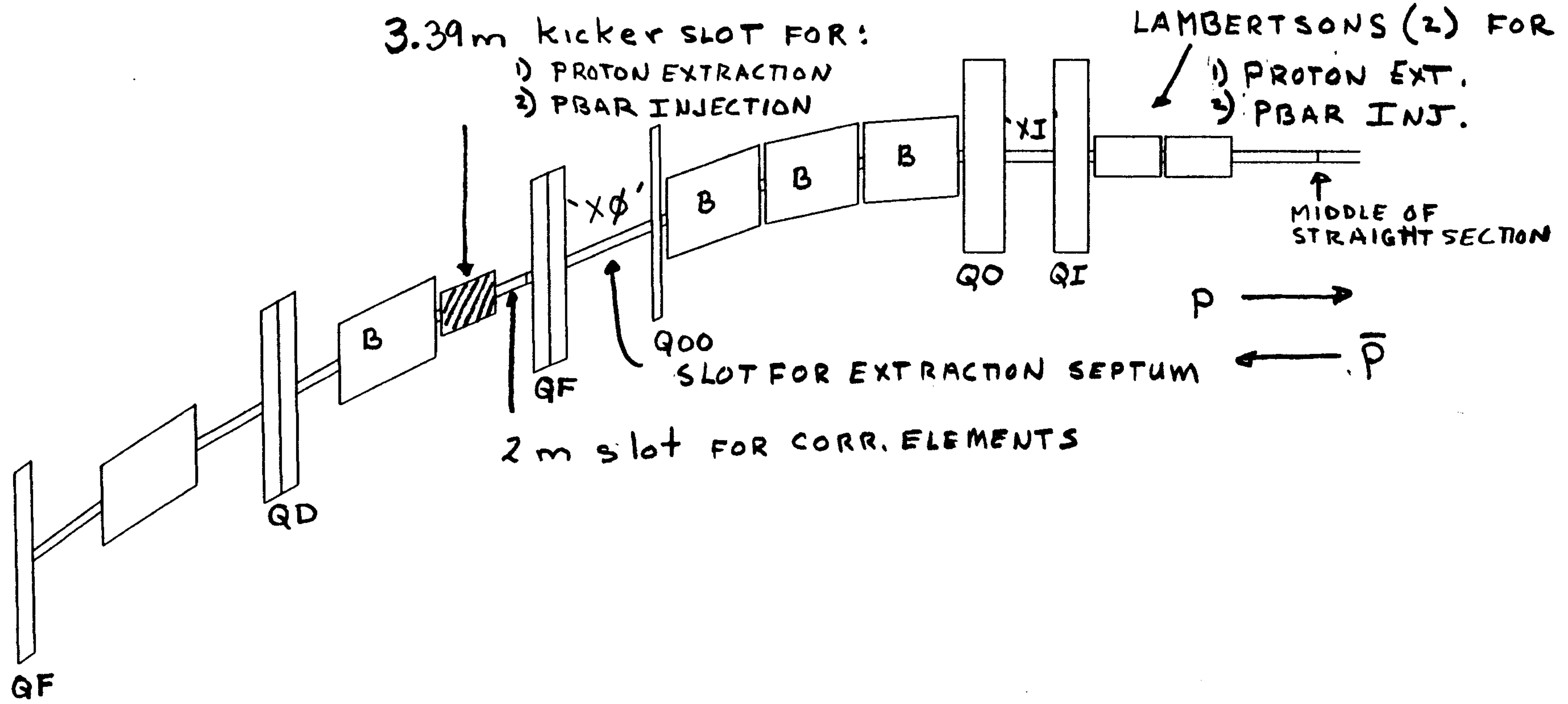


Figure 2: Configuration of straight section MI-60

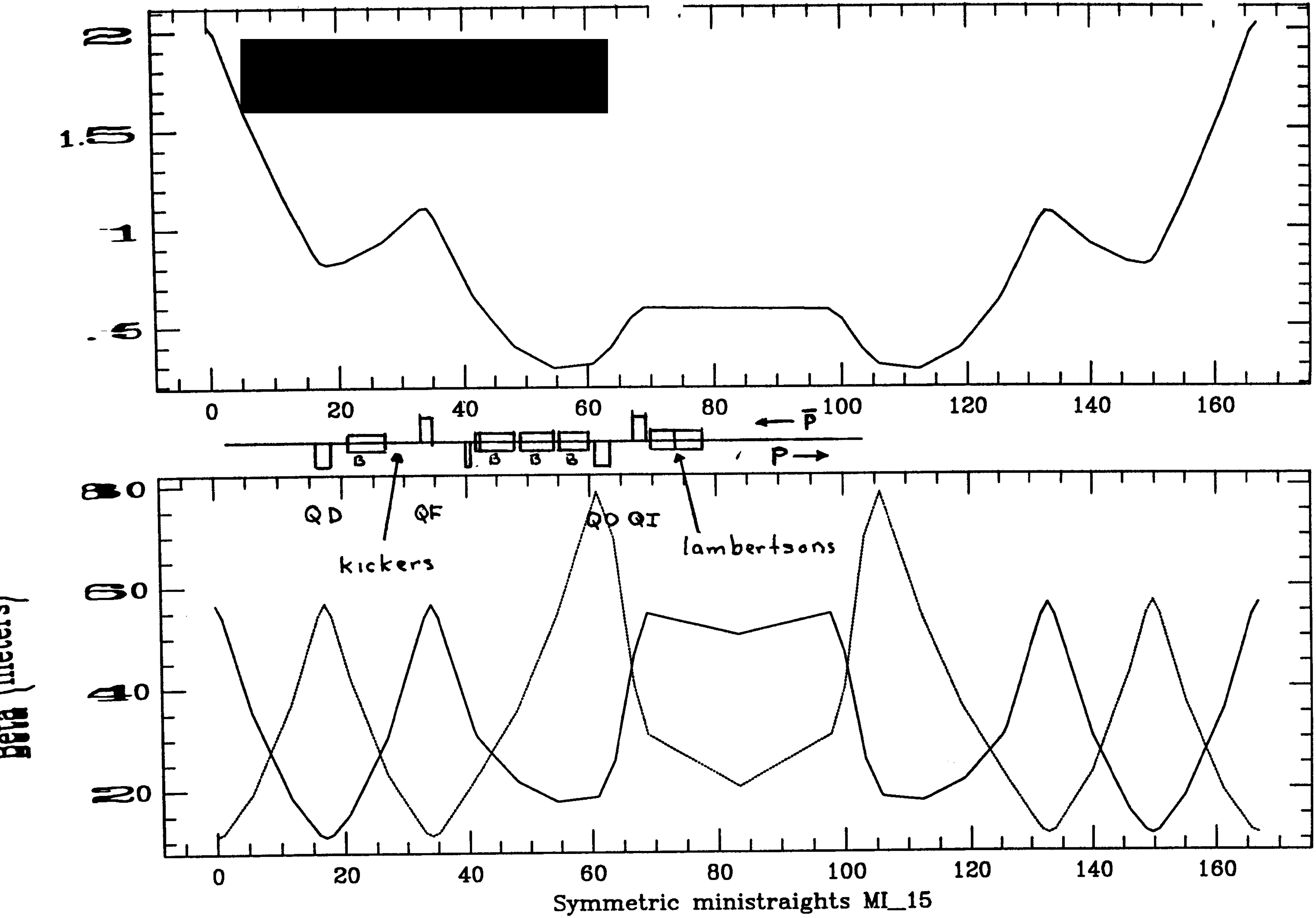


Figure 2b: Lattice functions for straight section.

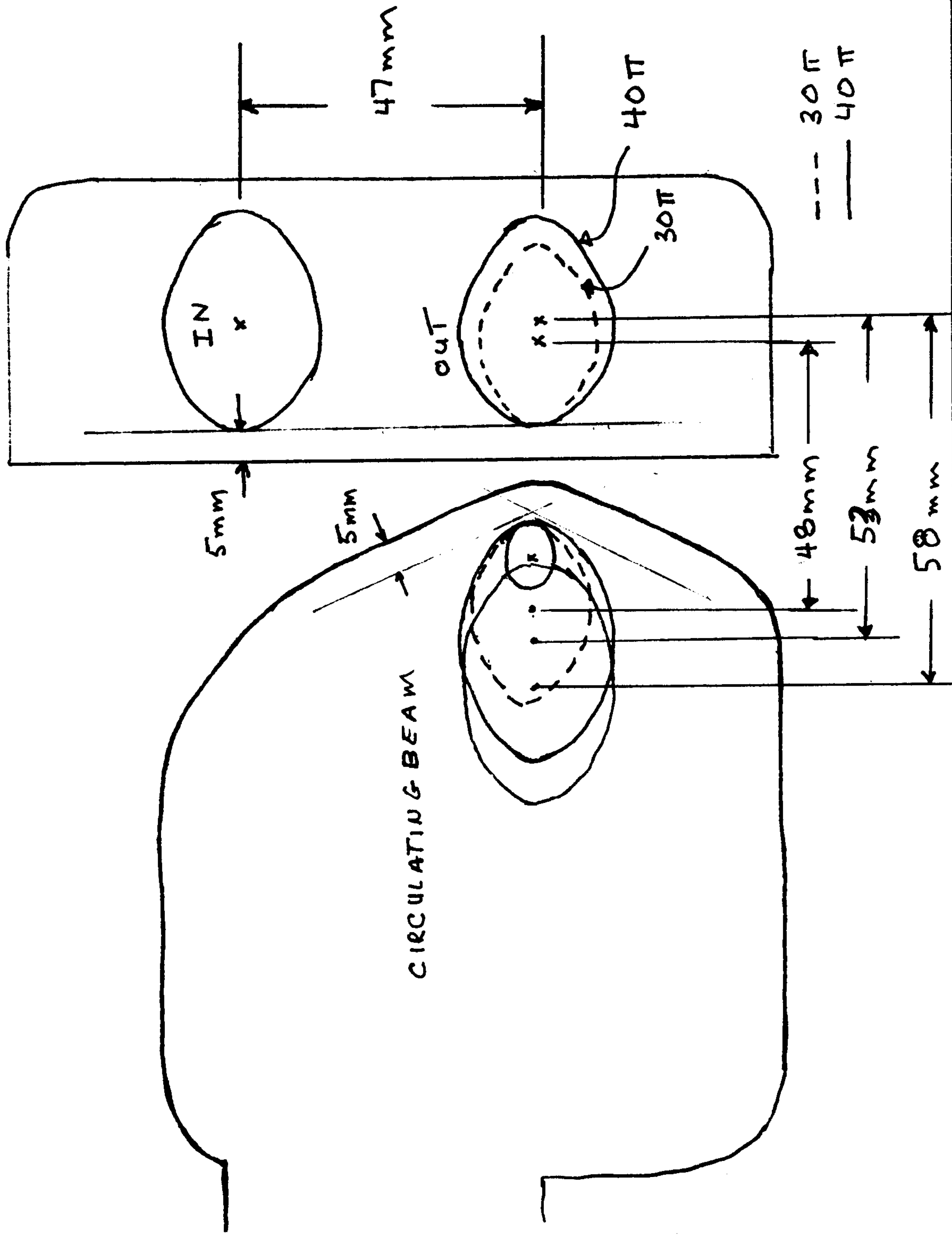
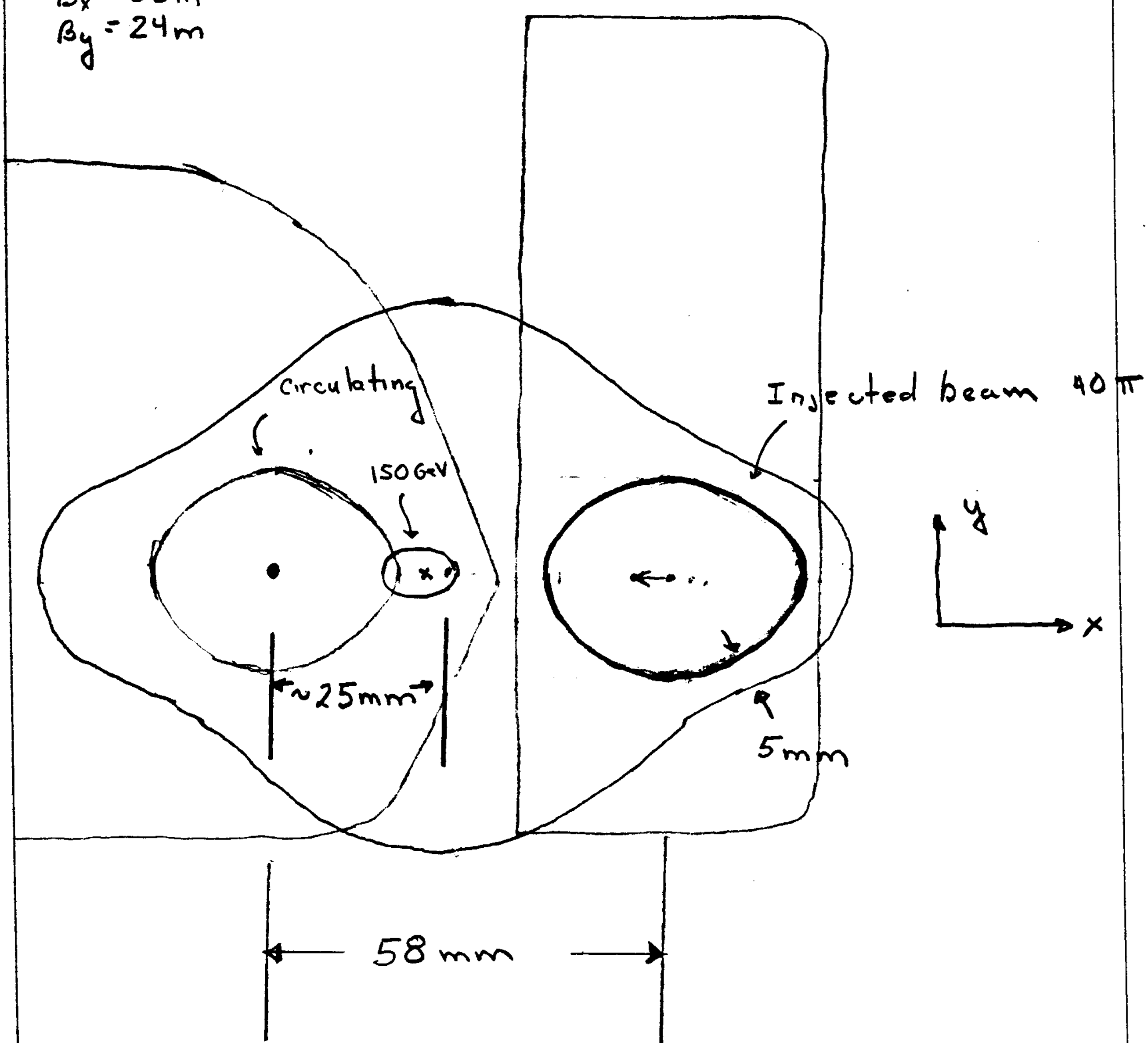


FIGURE 3 : 8 GeV PROTON INJECTION LAMBERTSON (EXISTING MR AØ 8 GeV LAMBERTSON

$\epsilon_N = 40\pi$
$\beta_x = 55m$
$\beta_y = 24m$



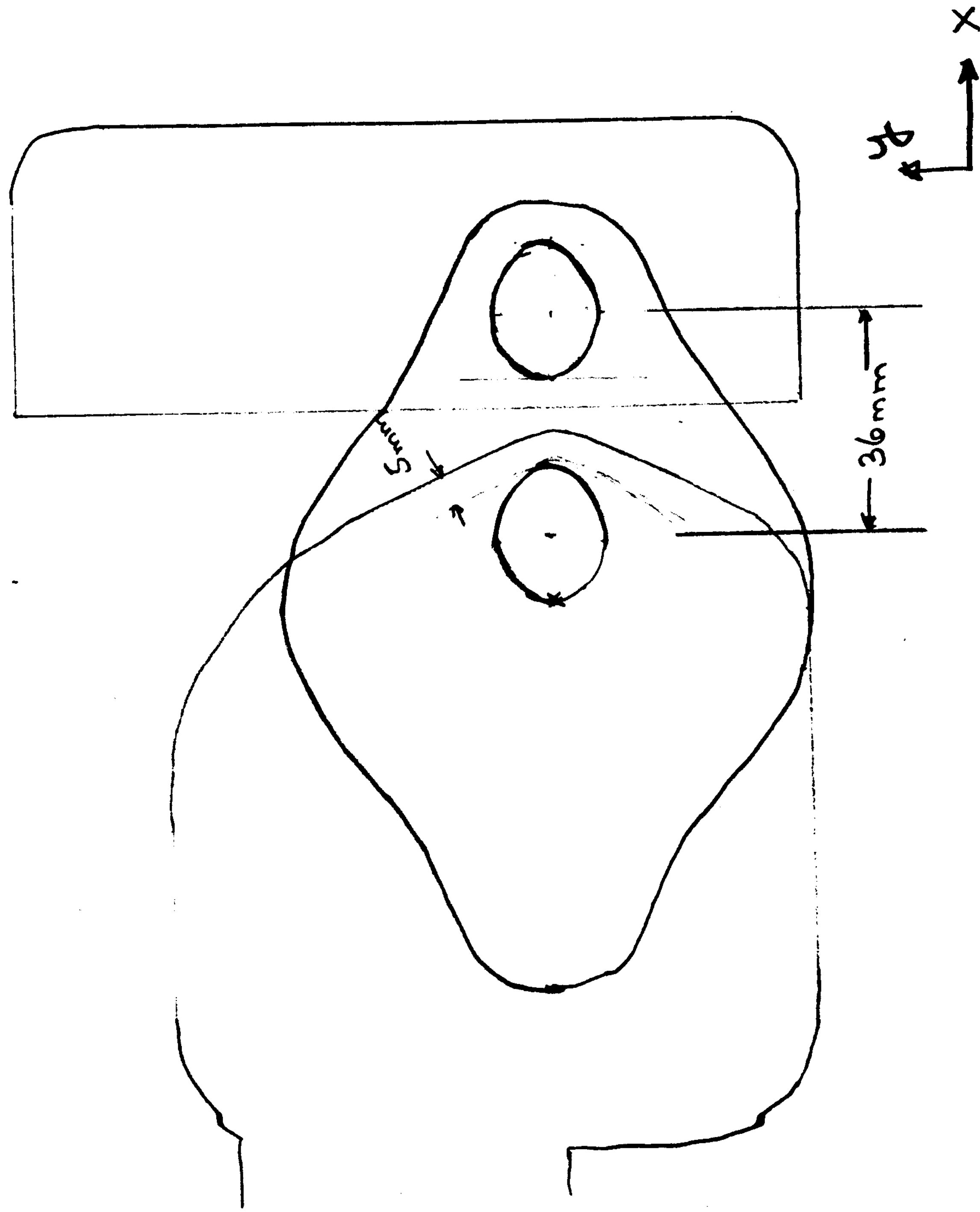


Figure 4b: First quod downstream

$\epsilon_N = 15\pi$