Fermilab

FERMILAB-UPC-157

The Tevatron Injection System

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We shall endeavour in this report to bring up to date the description of the forward beam transfer system first outlined in the 1979 Design Report. Since that time a more detailed design has been completed (and partially implemented) which produced several changes from the initial scheme, the overall philosophy however remained surprisingly intact. The forward injection line located in the E0 long straight section is designed to be compatible with a similar system running in the opposite direction for antiproton injection.

Basic Scheme

Forward injection involves a single turn transfer between the Main Ring and the Tevatron with the beam kicked horizontally across magnetic septa (Lambertson magnets) in the Main Ring at the upstream end of E0 using the existing extraction kicker magnet at C48. This then initiates the vertically downward bend (16.6 mrad) towards the superconducting string at E11, 25.5" below the Main Ring. The vertical dog-leg is completed by two more Lambertson magnets at the downstream end of the long straight which brings the beam back into the horizontal plane. The beam is then placed onto the horizontal closed orbit by another fast rise time kicker magnet located at the warm E17 ministraight in the Tevatron. While the basic lattice structure of the Main Ring and the Tevatron is similar, a transverse emittance dilution of ~30% would be expected without any attempt to match the beam shape. A quadrupole in the injection line is used to provide both horizontal and vertical matching. Horizontal beam steering is accomplished in the Main Ring and the injection line by a series of bump magnets; the correction coil dipoles provide the corresponding function in the Tevatron.

Injection Orbits

The major change in beam dynamics between the design report and the current scheme is the absence of a relative momentum offset between the two rings. At the cost of removing the colliding beam option between the Main Ring and the Tevatron, the circumferences of both machines have been made identical. This fact allows us to make an essentially free choice between injecting beam to the radially inside or outside of both rings as the injection dymanics become symmetric about the closed orbit. The choice of injecting the beam to the inside of the long straight section was made to avoid changing the polarity of the C48 Main Ring kicker which is also used to extract protons at F17 for antiproton production. The use of the C48 kicker to inject beam at EØ creates the possibility of introducing uncomfortably large amplitude oscillations through D sector of the Main Ring. In order to reduce the size of these oscillations, where possible, we have installed in the Main Ring three bump magnets at C22, C32 and D38. These three magnets can be excited so as to produce a closed orbit 180^{o} out of phase with the kicked beam and thus reduce the effective orbit excursions by a factor of 2 throughout most of the sector. Precise control of the beam position in the Main Ring across the long straight, essential to ensure loss free injection, is provided by another set of bump magnets at D46 and E17. Powered in series these magnets generate an orbit bump similar to that currently used in the Main Ring for extraction. A hypothetical closed orbit suitable for injection is shown in Figure 1 (the actual orbits used for injection will undoubtedly be determined empirically but ought to be similar to those shown in this report). The orbit excursions between C22 and D38, D46 and E17 are apparent. Figure 2 shows the same closed orbit modified by firing the kicker which produces the orbit cusp at C48. The orbit amplitude remains approximately constant up to D38 after which the amplitude increases to a maximum offset of 48 mms at D48. The horizontal orbits across the long straight

Fig 1. MAIN RING CLOSED ORBIT PRIOR TO INJECTION

TUNE 19.420
MAX. OFFSET((CMS) 2.34
HORIZONTAL PROJECTION

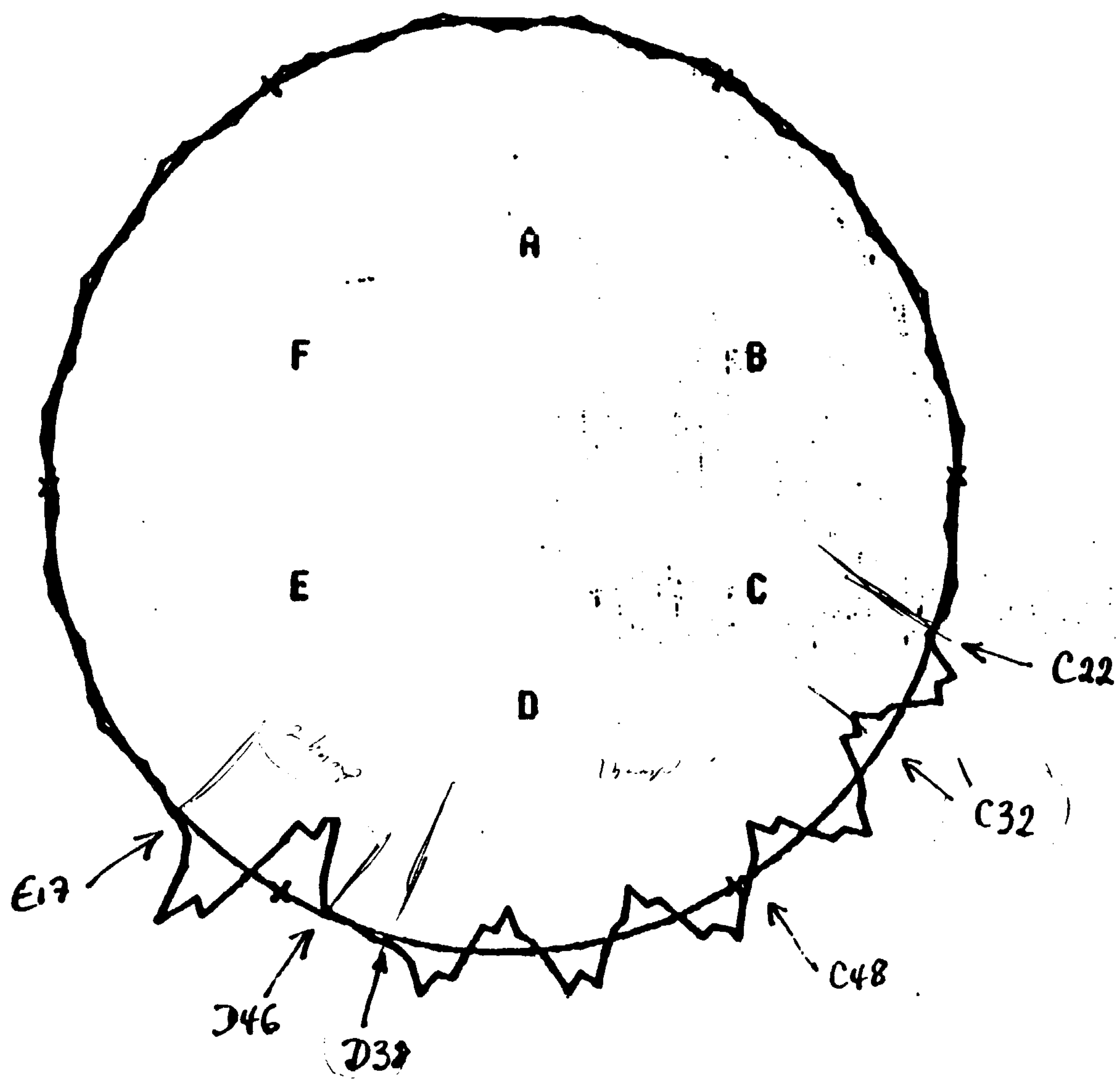


Fig. 2. Main Ring injection orbit

TUNE 19.420
MAX. OFFSET((CMS) -4.82
HORIZONTAL PROJECTION

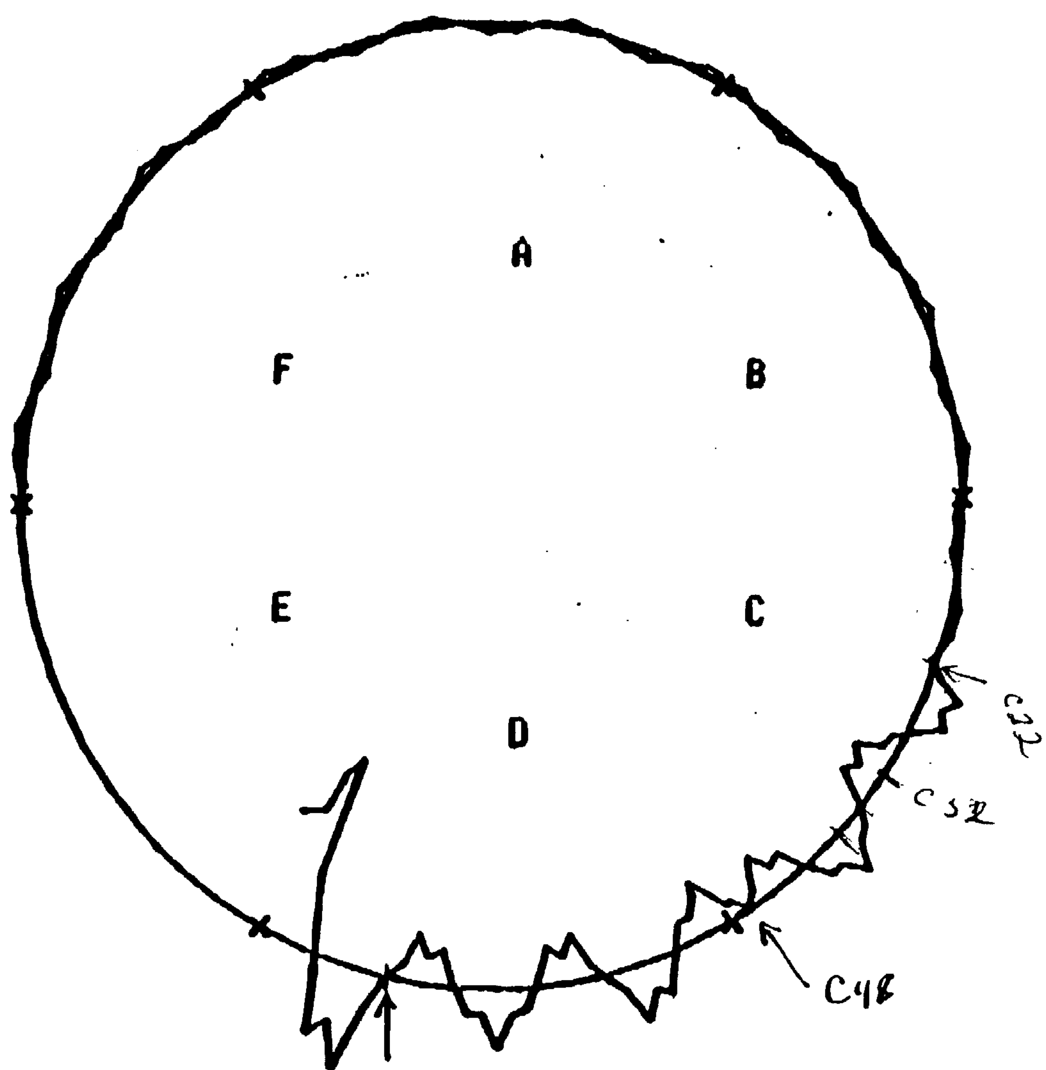


Fig 2

section are shown in more detail in Figure 3, the error bars on the Main Ring orbits give the expected beam size (±4 mm) at the Lambertson septum. With these particular injection parameters one can see an intra-beam separation of ~7 mms with the septum offset at 25 mms. The corresponding Tevatron orbits are shown in Figure 3B. The closed orbit bump between E11 and E17 is generated by the correction coil dipoles at E11, E13, E15 and E17 and serves to reduce orbit excursions within the restricted aperture of the Tevatron as well as decrease the integrated field strength required from the kicker magnet at E17.

Injection Energy and Beam Emittances

The upper limit to the injection energy is dictated by the fields achievable in the septum magnets and fast kickers. The lower limit is set by the field quality of the superconducting magnets. At 500 A (113 GeV/c) the relative sextupole component of the dipole is 50% larger than at higher currents, above 1000 A the field quality is essentially independent of the excitation current (See Figure 4). Based on these criteria we have chosen 150 GeV/c as the nominal transfer momentum. Recent measurements on the Lambertson septa show acceptable field quality at a 200 GeV/c current. Calculations on the requisite field strength of the E17 kicker are not quite so straightforward as the excitation changes with the injection orbit which is in turn influenced by many other factors, for the orbit shown in Figure 3B. The magnets are running at 60% of nominal 150 GeV maximum.

Current Main Ring measurements at 8 GeV/c give a measured beam emittance of 10 ~ 12 π mm-mrad for an intensity of 2.5×10^{12} per booster batch. Assuming no phase space dilution from mismatching and non-linear fields then the beam emittance is expected to scale inversely with momentum which leads to a value of 0.07 π mm-mrad at 150 GeV/c. We have assumed a relatively pessimistic 0.15 π mm-mrad (90%) for the design. The longitudinal emittance of the beam does not affect the injection dynamics directly and by transferring the beam into stationary rf buckets with constant magnetic field we would not expect

→ $\frac{\varepsilon_8}{\varepsilon_{150}} = \frac{P_{150}}{P_8}$: $\frac{10}{\varepsilon} = \frac{150}{8}$ ↳ if $\dot{B} \neq 0$, mismatching a problem?

$\varepsilon = .55$

INJECTION ORBITS ① Eφ

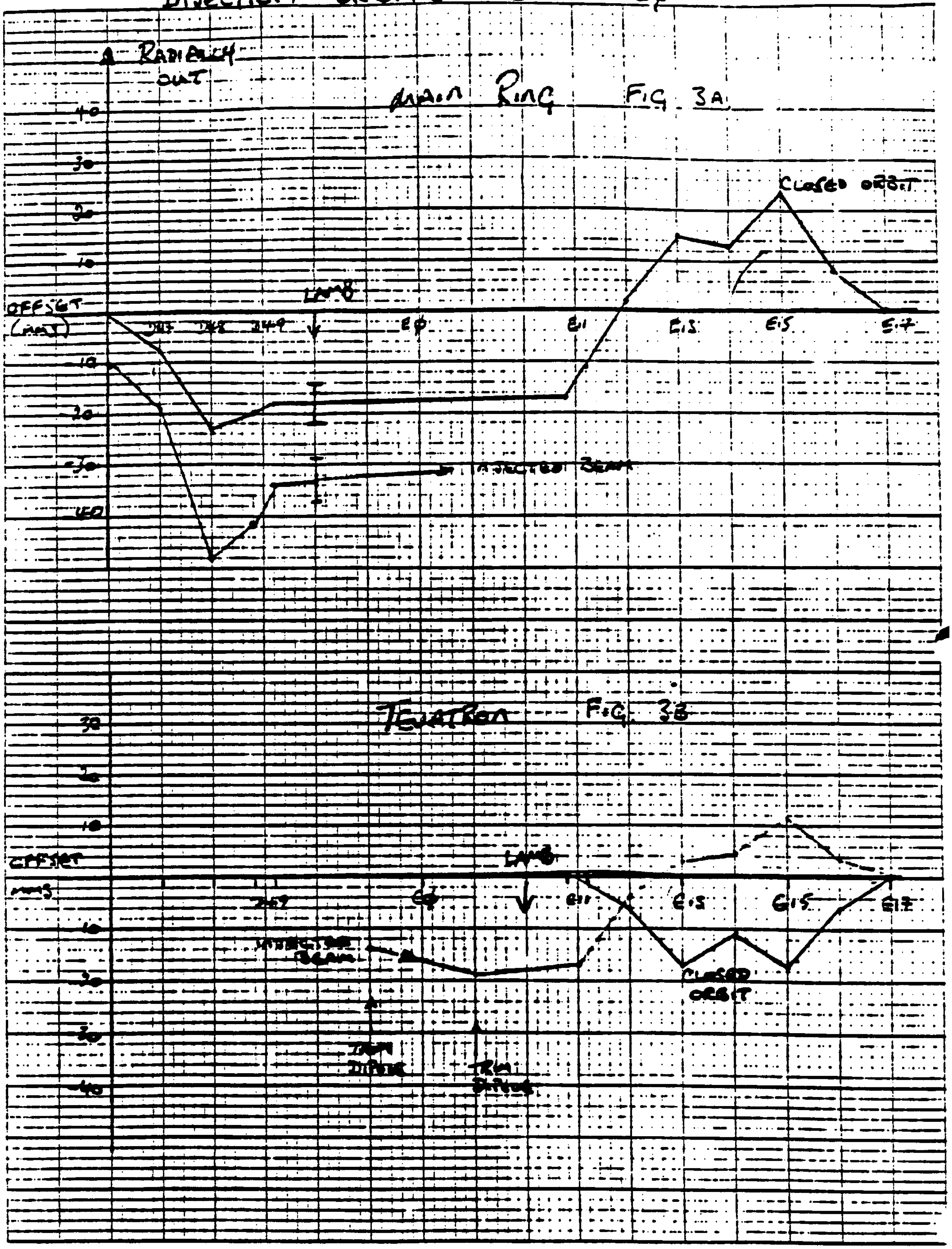
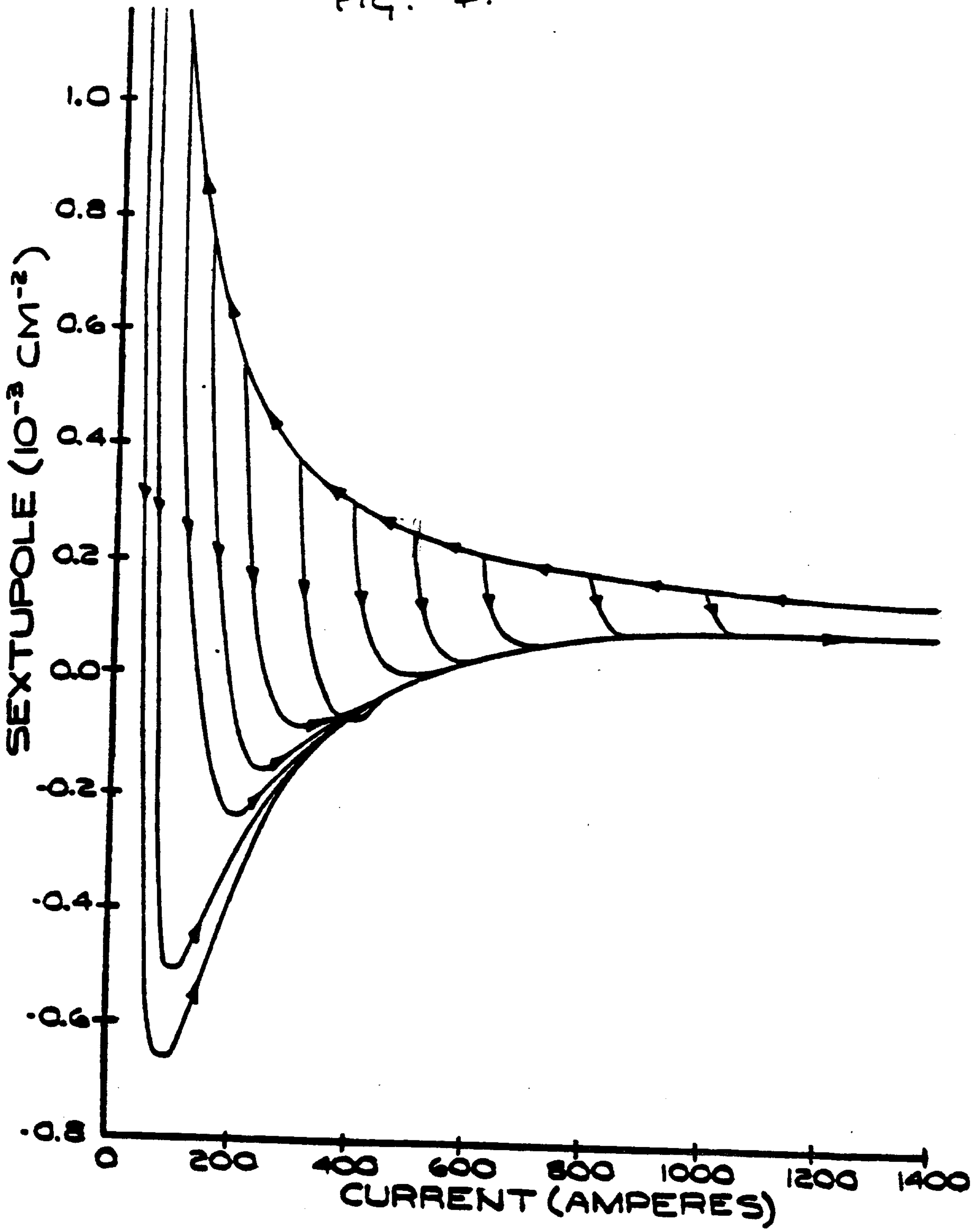


Fig. 4.



Hysteresis behavior of the sextupole component in a dipole magnet.

any significant mismatching. Using a longitudinal emittance value of 0.25 eV-S and an rf voltage of 1 MV/turn a momentum spread of the $\pm 0.25\times10^{-3}$ is expected which in turn gives dispersive contribution to the beam size in the long straight of less than ±1 mm.

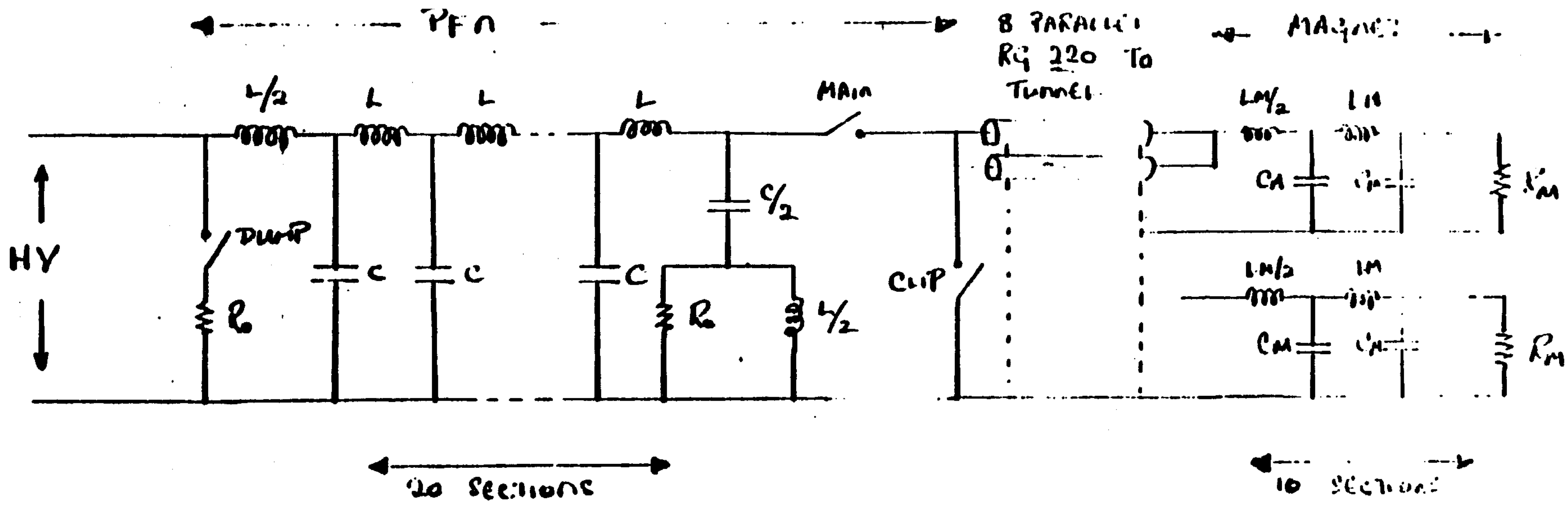
Fast Kickers

The operation of the injection kickers that we shall consider here is that of fixed target running and not the colliding beam mode. For this type of operation 12/13 of the Main Ring will be filled with protons and then transferred to the Tevatron in a single turn. The missing portion of the beam is to allow the relatively slow abort kickers sufficient rise time to enable loss free beam aborts; it does however also provide a 1.6 μsec beam window for the injection kickers too. With this somewhat generous time allowance it ought to be possible to keep the kicker ripple to within the ±1.5% range. The Main Ring C48 kicker consists of a lumped delay line pulse forming network (PFN) together with an inductive-resistive load. A system of this type permits a very fast rise time magnetic field (360 ns) but very large fall-time reflections (25%). As the beam has already left the machine when these reflections occur they have no effect. The E17 Tevatron kicker has the beam circulating in the aperture after the firing of the magnet and therefore requires fall time reflections to be kept to a minimum. A system with this kind of performance is shown schematically in Figure 5. The 6.25 Ω lumped delay line PFN is discharged via the main switch into 2 lumped delay line ferrite kicker magnets each of which has a 12.5 Ω impedance. The rise time on the current pulse is expected to be ~250 nsec with a ~300 nsec propagation time down the magnets resulting in a ~550 nsec rise time for the integrated field. A fast fall time for the magnets is made by firing the clip switch then permitting the field to decay in a time similar to the rise time. Oscillations in the circuit can be minimized by adjusting the front end cell of the PFN; possibly more important however is the

1 μsec gap for reflections to die down before the beam sees the magnets again. The PFN has a nominal maximum voltage rating of 75 kV which corresponds to 3000 A in each magnet. With this current the magnetic field is some 650 G which gives a total maximum integrated field strength for the system of 2.6 kG-m. The magnet modules are C-style magnets, 2 m long, with a 56 mm gap. The characteristic impedance is achieved by using the natural inductance of the magnet together with capacitors distributed along the magnet length.

Magnet Septa

The injection Lambertson magnets are similar in design to the current Main Ring extraction devices. The magnets have 12 turns of water cooled 0.46" square copper giving a useful dipole field aperture of 3.5"x0.9". The nominal operational current of 1575 A produces a ~9 kG field. The maximum useable field is defined by the saturation of the steel (Republic Steel LoCore 'B') and is ~12 kG. The septum is 2" thick and is formed with a half angle of 45°. The magnets are self-supporting and are straight to within $\frac{1}{2}$ mm over the full length of 4.25 ms. In order to achieve a good operational vacuum the vacuum skin does not encase the whole magnet but only that $\frac{1}{4}$ of the magnet covering the field free region and the dipole field. To allow this,the magnet is made up of two different types of laminations; an outer U-shaped lamination which ensures mechanical rigidity and an inner lamination which is completely enclosed by the vacuum skim and is inserted into the outer laminations. The inner laminations are vacuum degassed at 1400°F prior to stacking and the complete magnet is able to be baked in place up to 250°F. Ion pumps connected to the field-free region are distributed along the magnet. Using these techniques we measure operational vacuum levels of ~5×10^{-9}Torr with three 30 liter ion pumps. The inner lamination stack is also extended 2½" beyond the outer to reduce the effect of dipole fringe fields at the end of the magnet from entering the field free region. For a 150 GeV/c injection energy the total integrated field in the field



$R_0 = 6.25\ \Omega$
$L = 3.125\ \mu H$
$C = 0.08\ \mu F$
$\tau = 0.5\ \mu sec$

TOTAL PULSE LENGTH ~ 20 μs

$R_m = 12.5\ \Omega$
$L_m = 0.375\ \mu H$
$C_m = 0.0024\ \mu F$
$\tau_m = 30\ ns$

[illegible] TRAVEL [illegible]
TIME ~ 300 [illegible]

free region is ~4 kG-in. The detailed Lambertson specifications are shown in Figure 6.

Beam Diagnostics and Synchronization

In theory the injection system is a loss free one with the missing booster batch allowing the rise and fall of the kickers to take place in the absence of beam. To ensure this is indeed the case we have installed Tevatron style loss monitors on each element of the injection line (two on the first downstream Lambertson).

The beam position is measured at both the upstream and downstream end of the injection line, horizontally and vertically, using "warm" versions of the Tevatron position detectors. The read-in electronics will be partially standard Tevatron (RF module) and partially customized for the injection line to allow the position of individual batches to be recorded. The major elements of the injection line are shown schematically in Figure 7.

Synchronizing the kicker magnets with respect to the circulating beam hole will be provided by a 47 kHz master strobe and a system of digital delays. This setup will also provide the appropriate start-stop pulses for the position detection and loss monitor electronics.

Horizontal positional injection errors caused primarily by flat top ripple on the injection kickers will inevitably be present at some level. A kicker mismatch of ±3% will produce beam oscillations of up to ±1½ mm, which, if left undamped would blow-up the beam by ~40% in a few hundred turns. This form of beam blow-up can be avoided by using a medium speed beam damper (5 MHz bandwidth) the basic properties of which have already been outlined (UPC 152).

Table 1 gives a list of the injection elements and their nominal settings for 150 GeV/c injection.

NATIONAL ACCELERATOR LABORATORY

ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE

SUBJECT: TEVATRON INJECTION LAMBERTSON 150 GEV RAMPED (30% DUTY CYCLE)

NAME

DATE

REVISION DATE

MAGNETIC FIELD:

Central Field * 9.16 KG

Uniformity across 4.0" gap < 5G

POWER:

DC Power * 5.0 KW

Current * 1555 A max (500 A D.C.)

Voltage * 31 V max (10 V D.C.)

Copper Temp. Ave. * 68 °F

Resist @ Temp. * 0.02 Ω

Inductance 1.5 mH

COOLING:

Water Temp. Rise * 16 °F

Total Flow * 2.2 GPM

Pressure Drop * 100 PSI

COIL DATA:

Conductor O.D. * 0.46" * 0.46"

Hole Diameter * 0.25"

Turns 12

Water Paths 2

Ave. Turn Length 180.0"

WEIGHTS:

Coil & Insul. 246 lb.

Core

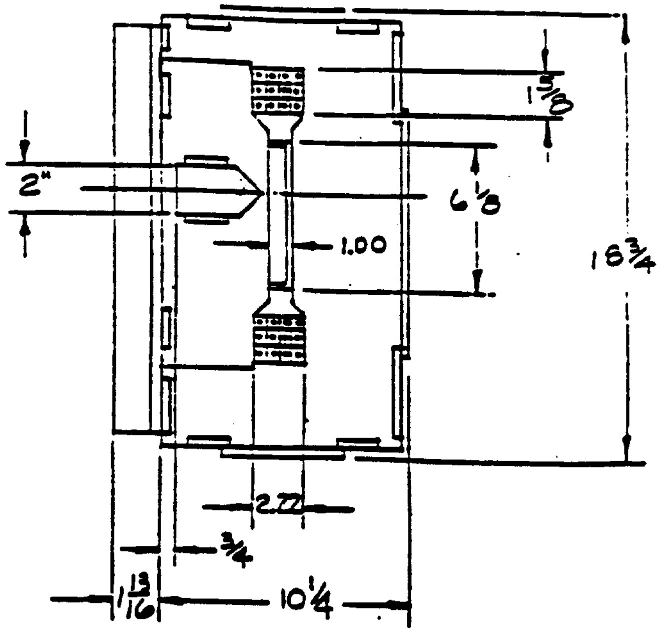
Support

Total Magnet Assembly

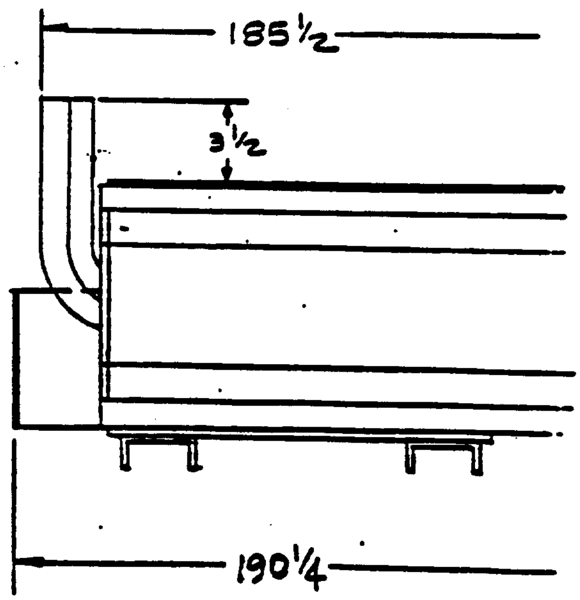
CALCULATION CONSTANTS:

Fig 6.

OUTLINE DIMENSIONS



SECTION VIEW

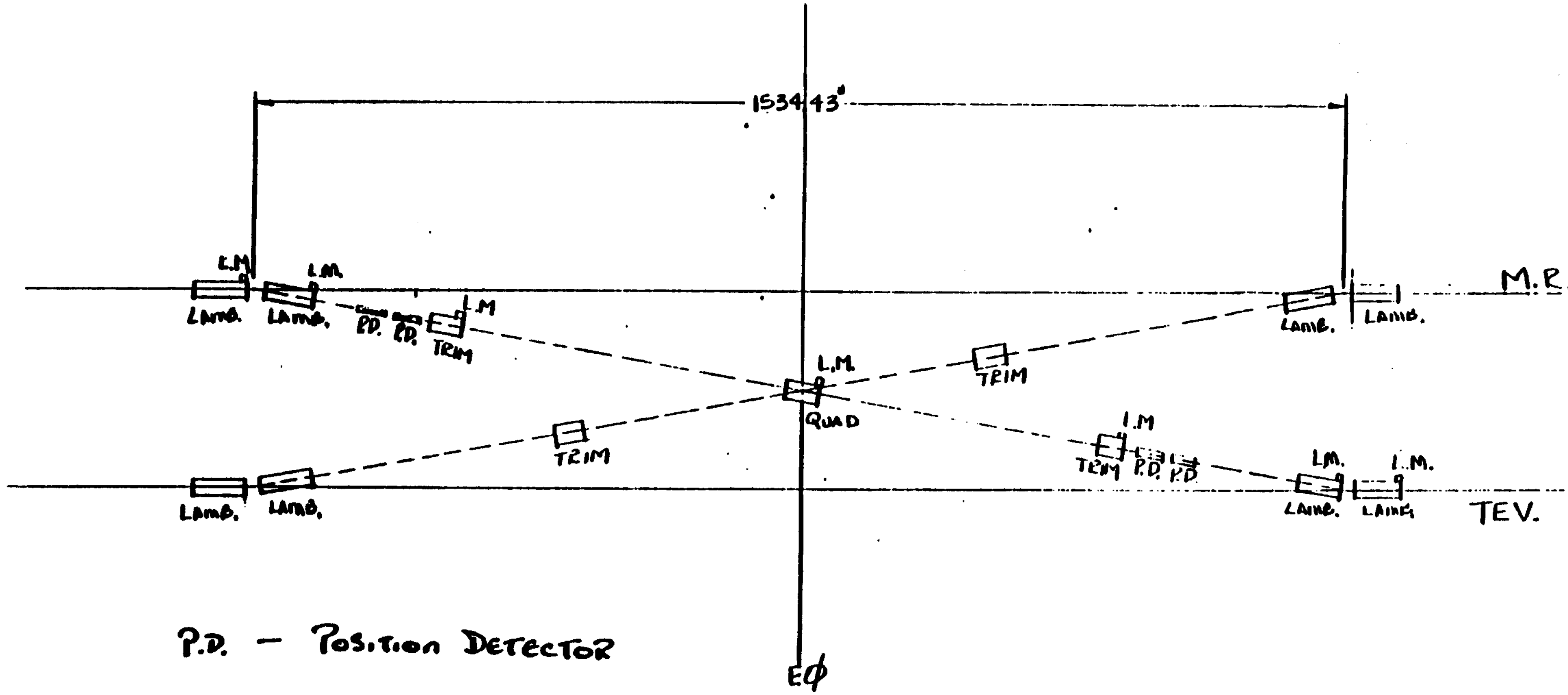


PLAN VIEW

Table 1 Injection Elements 150 GeV Nominal Setting

Element	Type	Current (Amps)	Bend Angle (mrad)	Maximum Current (Amps)
C22 Bump Main Ring (C24)	40" Dipole	10	-0.125	70
C32 Bump Main Ring	40" Dipole	4	-0.05	50
D38 Bump Main Ring	40" Dipole	10	— 0.125	50
D46 - E17 Bump Main Ring	40" Dipoles	20	-0.25, +0.25	50
EØ Injection Lambertsons	183" Dipoles	1570	16.67	~2100
EØ Upstream Trim	60" Dipole	12	- 0.22	100
EØ Downstream Trim	60" Dipole	18	0.33	100
EØ Lattice Matching Quad	34" Quad	20	---	50
C48 Kicker Main Ring	6 m Ferrite Dipole	28 kV	-0.25	70 kV
E17 Kicker Tevatron	4 m Ferrite Dipole	43 kV	0.33	70 kV
E11 Bump Tevatron	Correction Coil Dipole	12	-0.2	50
E13 Bump Tevatron	Correction Coil Dipole	3.6	-0.06	50
E15 Bump Tevatron	Correction Coil Dipole	3.6	-0.06	50
E17 Bump Tevatron	Correction Coil Dipole	12	-0.2	50

FIG 7 INJECTION LINE SCHEMATIC (VERTICAL)



P.D. — POSITION DETECTOR

L.M. — LOSS MONITOR

Acknowledgements

The design of the injection system involved the work of many people, with the most honorable mention awards going to Sho Ohnuma and Helen Edwards.