ii. Equipment

AGS extracted beam bunches pass through a transfer line in moving from AGS to RHIC, a layout of which appears as Fig. 5-1. The transfer line is called the ATR (AGS To RHIC) line, and begins downstream of AGS extraction which comprises the G10 Extraction Kicker and the H10 Extraction Septum. Before exiting the AGS vault, the beam undergoes a 4.25^o bend through two dipole magnets accompanied by three quadrupoles. The bunches then traverse a spur called the "U" line, which had been in operation for many years for the AGS neutrino program. The old "U" line has been dismantled, and all components have been either re-furbished or replaced for ATR operation.

An 8^o dispersion free bend comprised of four gradient dipoles connected in a modified triplet (FDDF) configuration is found in the "U" line. Prior to the 8° bend, a stripping station is located where the last two electrons are removed from the as yet not fully stripped heaviest species. The stripper can be retracted when it is not needed. Transport optics are designed to form a double waist at the foil to minimize the dilution in phase space of the beam caused by scattering in the foil and to compensate for the associated changes in emittance shape. This first section of the ATR will be shared, at least for the next few years of operation, with the g-2 AGS experiment, and optic components were chosen to accommodate the differing transport requirements. A pair of g-2 deflection magnets (VD3 and VD4) are located just upstream of the 8^o bend. Activation of the deflection magnet pair will direct beams to the g-2 target for the AGS experimental program; deactivation allows RHIC injection. Changeover from high intensity protons for g-2 to RHIC beams should be on the order of 1/2 hour for the beamline retuning. Six quadrupoles preceeding and four following the 8^o bend allow tuning capability to prepare the bunches for acceptance into the subsequent "W" line spur.

This next section of the beam transfer line, the "W" line, deflects the beam both horizontally and vertically, such that its axis at the entrance to the ring selector runs along the intersection of a horizontal plane, approximately 52 mm above RHIC's median plane, and the vertical plane through the machine center and the crossing point at 6 o'clock. This vertical plane is a plane of reflection symmetry: reflecting one ring and its beam transfer branch in it yields the other.

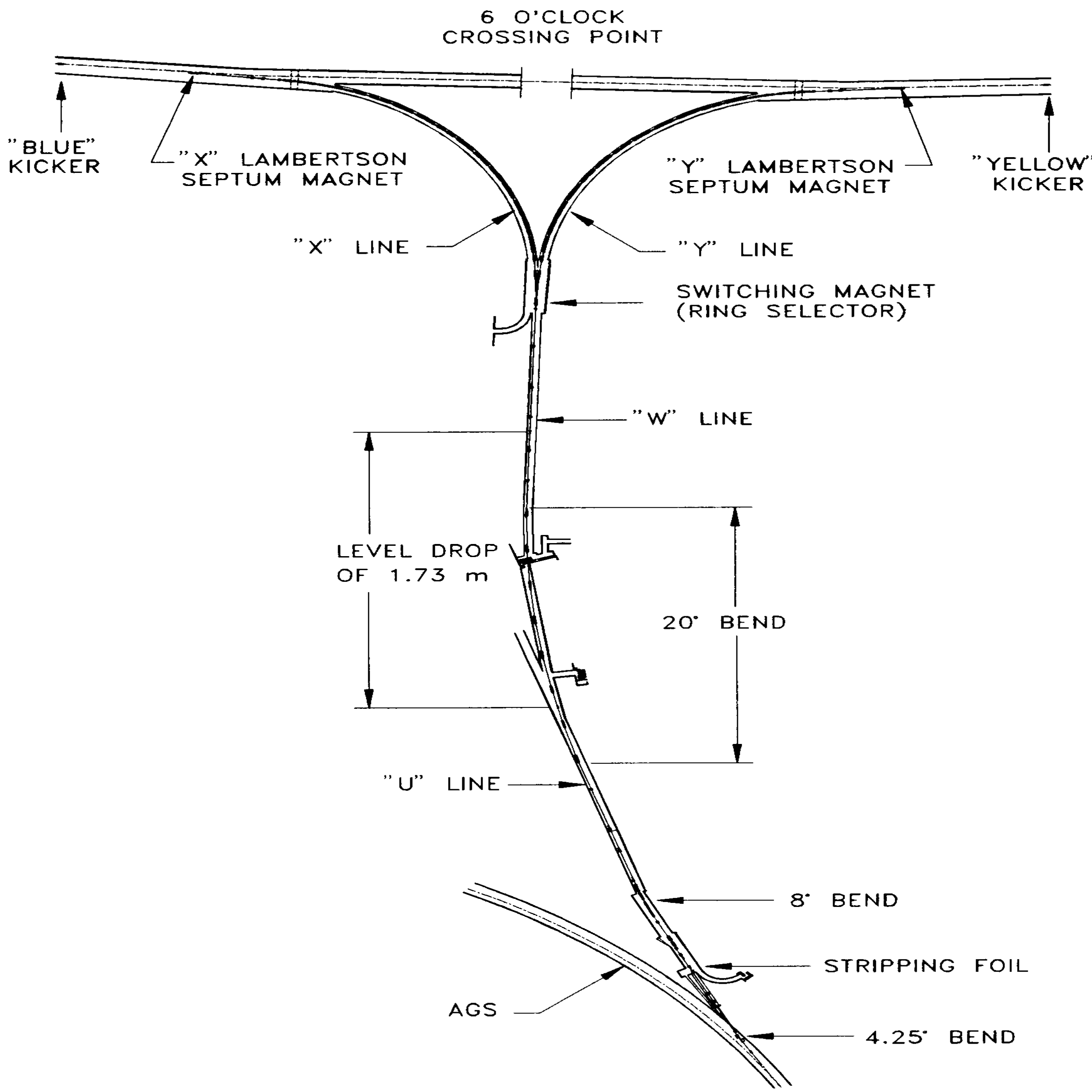

Fig. 5-1. Schematic layout of the AGS to RHIC (ATR) transfer line.

The horizontal deflection in this section is 20^o in an arc with an average radius of 405.82 m, the change in vertical level is approximately 1.73 m. The horizontal deflection and the change in level are entwined: the former is performed by a string of 8 gradient magnets in an AG focusing arrangement, the latter by a pair of vertical pitching dipoles, the first one of which is located between the second and third horizontal deflectors. The gradient magnets are each about 3.66 m long with field strength of about 1.19 T. They are separated from each other by drift spaces of 14.05 m. The second pitching dipole is placed between the second and third quadrupole of a string of six between the last horizontal deflector and the switching magnet (ring selector). These, together with the upstream quadrupoles in the "U" line, provide for flexibility in the choice of focusing parameters at the entrance of the ring selector. Between the second pitching magnet and the switching magnet, the beam line can be nominally free of horizontal and vertical dispersion ($X_p = X_{p'} = 0$ and $Y_p = Y_{p'} = 0$), thus ensuring reflection-symmetric behavior of the beam in the subsequent beam transfer branches into the two rings. The final drop in beam level over about 52 mm in the injection region leaves a small residual vertical dispersion in the circulating beam, thus increasing the vertical emittance by a small amount. This increase can be avoided altogether by resetting the system to compensate for that dispersion.

The next sections consist of the two reflection-symmetric branches, which begin at the entrance to the switching magnet and end in the injection halls. The switching magnet guides the beam via a dispersion match into one of these two "big bend" strings of 25 long plus 1 short gradient magnets, which carry the beam along arcs with average radii of 96.333 m and deflection angles of 48.15 mrad in each long gradient magnet. The gradient magnets in each big bend are arranged in a OFoFOODoDO pattern with horizontal and vertical betatron phase advances of about π/2 rad per cell.

Each big bend ends in its associated injection hall in the 6 o'clock insertion as shown in Fig. 5-2. There it is followed by a matching section, a string of four horizontally deflecting gradient magnets, one horizontally deflecting dipole, and six quadrupoles, which are excited to match the betatron functions and the dispersion functions of the transfer line to those of the RHIC lattice upstream of the RHIC quadrupole Q8O. The five bending magnets are each about 2.95 m long, and together deflect the beam through about 198 mrad. Three of the six quadrupoles for adjustment of the match between big bend and RHIC are imbedded into this string, the other three form a triplet at the end of the string.

Table 5-1. Injection Magnet Parameters

	Kicker	Septum
Deflection (mrad)	1.86	38
Strength (T·m) @ $B\rho$ = 100 T·m	0.186	3.8
Field (T)	0.044	0.95
Length (m)	4×1.12	4.0
Beam tube aperture, i.d. (mm), circulating beam	41.2	67.4
H×V (mm), incoming beam		63.5×26.1
Risetime (1 - 99%) (nsec)	95	
Flat top (nsec)	20	
Flat top tolerance	±1%	
Fall time (nsec)	800	

Injection occurs downstream of the last transfer line triplet, YQ4, YQ5 and YQ6 in Fig. 5-2. The injected beam lies in a plane vertically about 52 mm above the collider ring midplane. A vertical deflection (~3 mrad) is provided by the pitching dipole magnet (YP1), upstream of the septum, to direct the incident beam downward through the RHIC quadrupoles Q8O and Q9O, so that it will cross the RHIC reference orbit in the center of the injection kicker magnet located downstream of Q9O. The arrangement of the injection magnets is shown in Fig. 5-3 and their principal parameters are listed in Table 5-1.

An iron septum (Lambertson) magnet, bending 38 mrad horizontally, brings the incident beam axis into coincidence, horizontally, with the reference orbit in the outer arc. The iron septum of the Lambertson magnet separates the incident beam from the circulating one. In the region of the circulating beam, the stray field from the septum is held to less than 0.2 G by means of a soft-iron beam pipe, acting as a magnetic shield. The insertion CQS assemblies Q8O and Q7O will be shortened in this region by omitting the blank sextupole correctors, in order to allow sufficient space for the incoming beam to clear the ring components.

Leaving the septum the beam passes off-axis through the aperture of the vertically defocusing ring quadrupole Q8O, and the vertically focusing Q9O, and is finally bent into the median plane by injection kickers KI1 - KI4. The four injection kicker modules provide a vertical deflection of 1.86 mrad, depositing the beam onto the RHIC orbit.

The Septum Magnet

The Iron Septum (Lambertson) Magnets are designed to horizontally deflect the injected beam onto a path parallel to the circulating beam. Two such magnets are used, each one injecting into one of the counter-circulating beams of the RHIC machine. The two magnets are identical magnetically, but are physically mirror images of each other. The Septum Magnet is the last element in the ATR beam transfer line and is electrically in series with the transfer line dipoles, thus saving the cost of a separate large power supply; a separate trim power supply is connected in parallel across the septum magnet to allow fine adjustment of the injection angle.

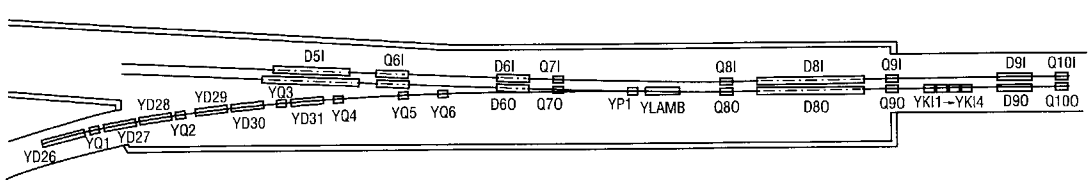

Fig. 5-2. Six o'clock insertion with location of yellow ring injection equipment.

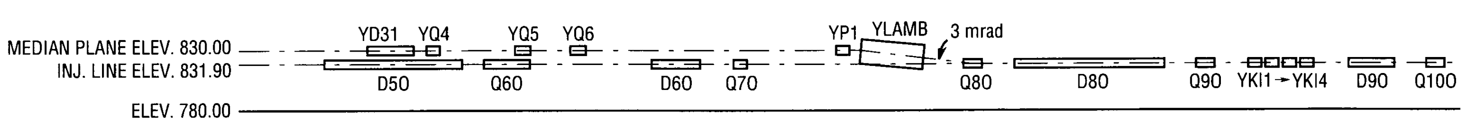

Fig. 5-3. Injection component layout/(elevation).

Table 5-2. Septum Magnet Parameters

Bend angle	38	mrad
Length	4	m
Magnetic field @ injected beam	9.5	kG
Field uniformity @ injected beam	$< 6\times10^{-4}$	
Stray fields @ circulating beam	< 0.2	G
H/V aperture @ injected beam	63.5×26.1	mm^2
Wall thickness @ injected beam tube	0.8	mm
Beam tube i.d. @ circulating beam	67.4	mm
Wall thickness @ circulating beam tube	1.3	mm
Septum thickness	10.8	mm
Vacuum requirement	$< 1\times10^{-10}$	mbar

The magnets are designed to achieve field uniformity of $\Delta B/B < 6\times10^{-4}$ over the width of the incident beam path and stray fields in RHIC's circulating beam pipe of less than 0.2 G at $B_o = 9.5$ kG transverse to the beam direction. In addition, the magnet is ultra-high vacuum compatible in that only the insides of the beam tubes are exposed to the vacuum and the entire assembly is bakeable in situ to 300 ^{o}C. The principal design parameters are listed in Table 5-2.

The relative location of the magnet with respect to the straight section Q7O - Q8O of the RHIC ring is shown in Fig. 5-4a (top view), 5-4b (side view), and 5-4c (view looking upstream). Figure 5-4a shows the injected beam at the entrance of the magnet, which will bend by ~38 mrad and will then continue at the exit of the magnet on the same vertical plane as the RHIC circulating beam.

The geometry of the magnet changes along the beam axis; one of the cross sections of the magnet is shown in Fig. 5-5 and corresponds to the middle of the magnet. A dimensioned view of the "Y" line injection area, indicating the Lambertson and ancillary devices, is presented in Fig. 5-6.

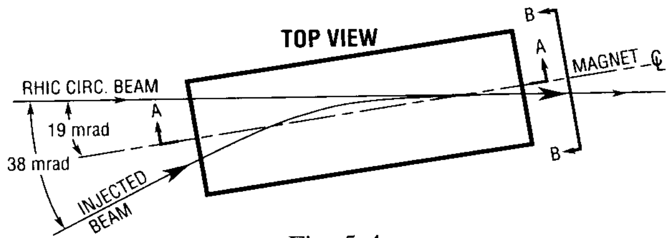

Fig. 5-4a.

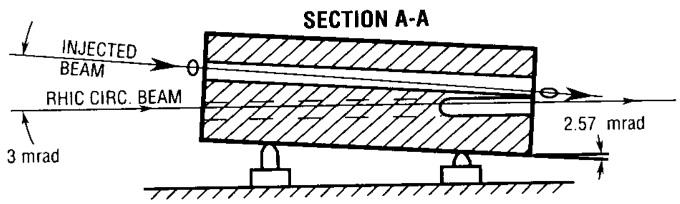

Fig. 5-4b.

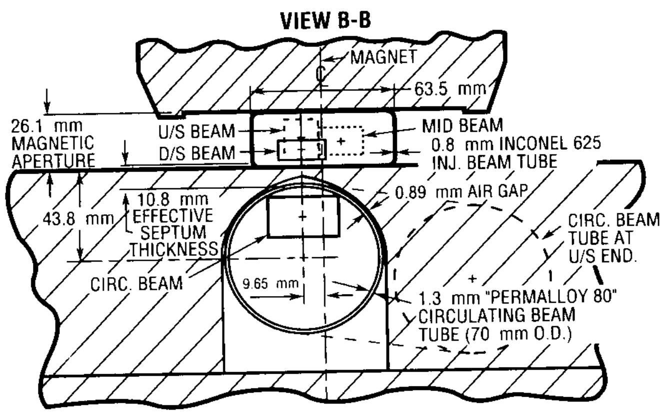

Fig. 5-4c.

Fig. 5-4. Septum Magnet.

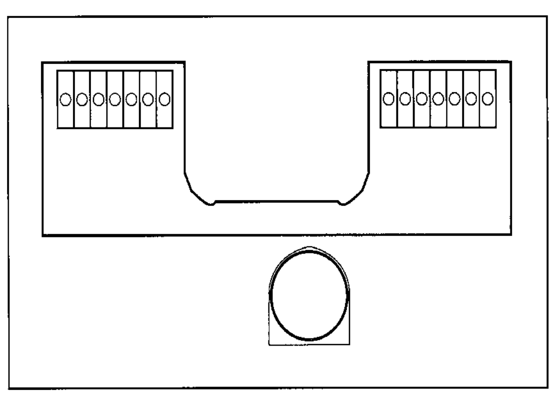

Fig. 5-5. Septum Magnet Cross Section.

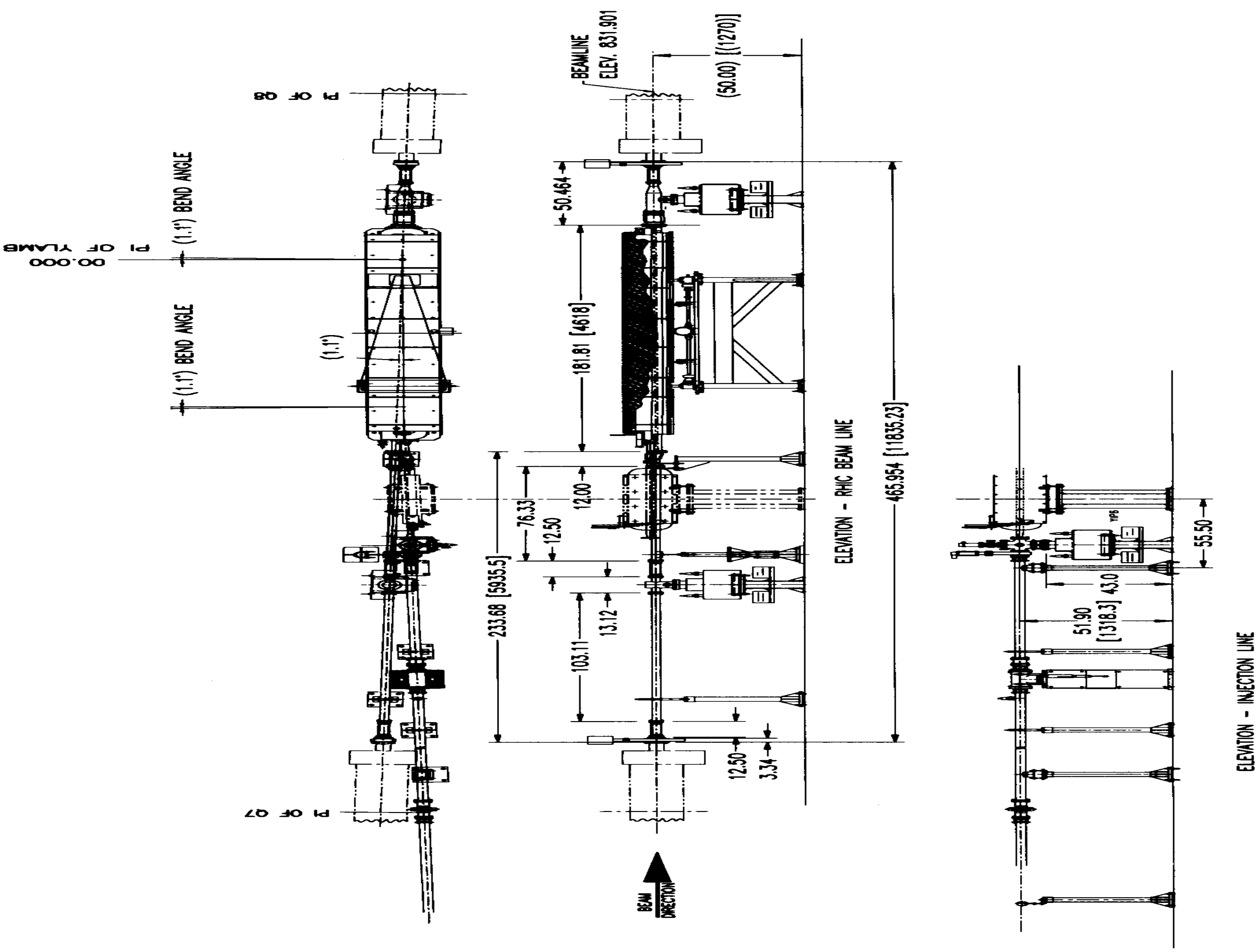

Fig. 5-6. "Y" line Lambertson injection area. (Brackets show dimensions in mm)

Steel Characteristics. Two and three-dimensional computer modeling showed that the design parameters could be met and exceeded by fabricating the magnet body out of an ultra-low carbon (< 0.005%) steel in the unannealed condition. The material (called "INTRAK") is available in large slabs and can be machined without significantly altering the magnetic properties.

Beam tube Materials. The material for the circulating beam tube is critical as it serves a number of functions. First, it must be ultra-high vacuum compatible, which means prefiring at a temperature of at least 950 ^{o}C in a vacuum of at least 1×10^{-5} mbar and should be corrosion-free like stainless steel. In addition, it serves a vital magnetic shielding function. The tube is spaced from the surrounding ultra-low carbon steel by a 1 mm air gap and intercepts leakage fields. For this function, it must have high permeability at low field levels. It must also have sufficient physical strength to resist the vacuum loads with a relatively thin wall. Finally, it helps if the thermal coefficient of expansion is close to that of the magnet body. A material called "Permalloy 80" meets all these conditions. To reach the required annealed condition, it must be heated to 1150 ^{o}C after fabrication. This also serves as the vacuum firing.

The injection tube material selected is Inconel 625. It is completely non-magnetic, has good vacuum and thermal expansion properties, and has high stiffness and yield strength to resist vacuum loading. Both the beam tubes are welded into the common stainless steel downstream chamber (see Fig. 5-7).

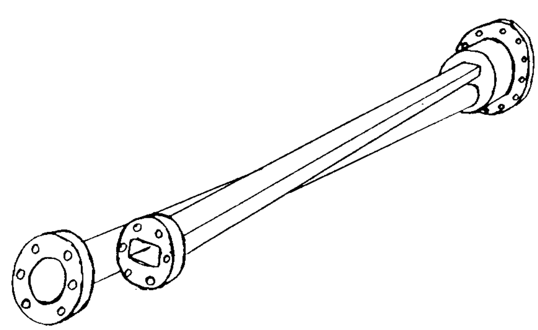

Fig. 5-7. Septum Magnet Vacuum Chamber.

Bakeout. Because of the difficulty of trying to heat the injection tube (which is in intimate contact with the poles) independently of the magnet, it was decided to heat the entire magnet. The coil is thermally insulated from the core and is water cooled during bakeout. A covering heater blanket of 20 kW heats the assembly to 250 °C in 12 hours.

Injection Kicker System

The purpose of the injection kicker is to provide the ultimate deflection to the incoming beam from the AGS into RHIC. The beam is kicked in the vertical direction to place it on the equilibrium orbit of RHIC. Each bunch in the AGS is transferred separately and stacked boxcar fashion in the appropriate RHIC rf bucket. In order to achieve the required deflection angle, four magnets powered by four pulsers will be used for each ring of RHIC. When the bunches are stacked in RHIC, the last few rf buckets are left unfilled in order to provide a gap in the beam to facilitate the ejection or beam abort process. This also means there is not a severe constraint on the fall-time of the injection kicker. The performance specifications for the kicker are given in Table 5-1. The performance is achieved using four Blumlein pulsers each connected to a magnet forming a matched transmission system. The pulsers will be located outside the RHIC tunnel and will be connected to the magnets by about 75 m of high voltage cable. An overview of the injection kicker system is shown in Fig. 5-8.

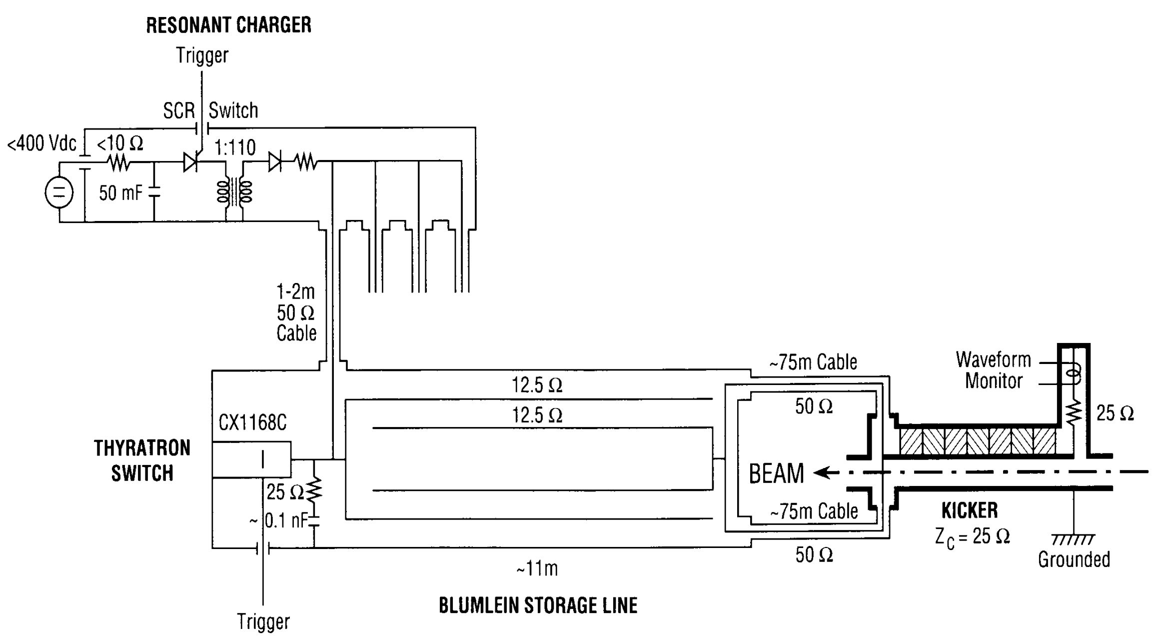

Fig. 5-8. Overview of the injection kicker system.

The Kicker Magnet. The magnet consists of a "C" cross section formed of ferrite bricks that approximates a transmission line as shown in Fig. 5-9. If properly oriented with respect to the beam, both the electric and magnetic fields can contribute additively to the deflecting force, although by far the largest contribution is made by the magnetic field. The characteristics are given in Table 5-3.

The injection kicker is constructed in two functional components, the core and the frame. The core represents and determines the magnet properties and the frame supports the magnet and provides the connection to the terminating resistor and the pulsed power supply. This concept was chosen to allow rapid replacement of damaged cores.

The magnet core is a structure of ferrite blocks and buss bar, solidly held together with epoxy. The ferrite blocks are produced to 50 μm accuracy. Prior to their incorporation into the core, the top ferrite blocks are high voltage tested for 2 ms to 50 kV and the side blocks to 40 kV. The blocks are Al_2O_3 bead blasted to roughen the surface for better epoxy adhesion and cleaned with ethanol and Zero-Tri. The sides of the blocks are primed with Conap-Primer AD1147 and baked to 70°C for 30 min. When ready for assembly, a 0.1 mm thick indium layer is attached with 3M Repositionable Adhesive 75 on the surface, which will contact the buss bar. Proper spacing of blocks is achieved by ~1mm thick, 2 mm ∅, insulating spacers, which are attached with a minimal amount of Loctite 454 Superglue.

The blocks are assembled together with the bus bar in a fixture and impregnated with epoxy. The high voltage capabilities depend completely on full contact between epoxy and ferrite surface and greatest care during the preparatory stages is mandatory. To assure separation of core and core-casting fixture, the latter is prepared by covering it with a thin layer of beeswax at 75°C. The core is formed with the epoxy, Conap RN-1000 and EA-87 hardener in a 100:37 ratio by weight. RN1000 has low viscosity, a long pot life below 22 ^{o}C and only 0.8% shrinkage during cure. The thoroughly mixed epoxy is slowly transferred into the fixture under vacuum, better than 1 Torr, to avoid the formation of bubbles. A gap of 0.7 mm between the bricks can be inspected during and after the pour to ensure no voids exist. After allowing the escape of gases formed during the solidification of epoxy, the fixture is pressurized and remains at 10 psi, typically till the next day.

Surface epoxy and other irregularities are ground off using diamond wheels on a flat milling machine. Prior to the final assembly of the core into the frame, a 0.1 mm thick indium layer is put on the top of the core. Good contact with the frame in order to avoid gaps and local field enhancements is achieved by assembly under mechanical pressure and voids are filled with Dow-Corning Sylgard Silicone elastomere 184 mixed with hardener in a 10:1 ratio.

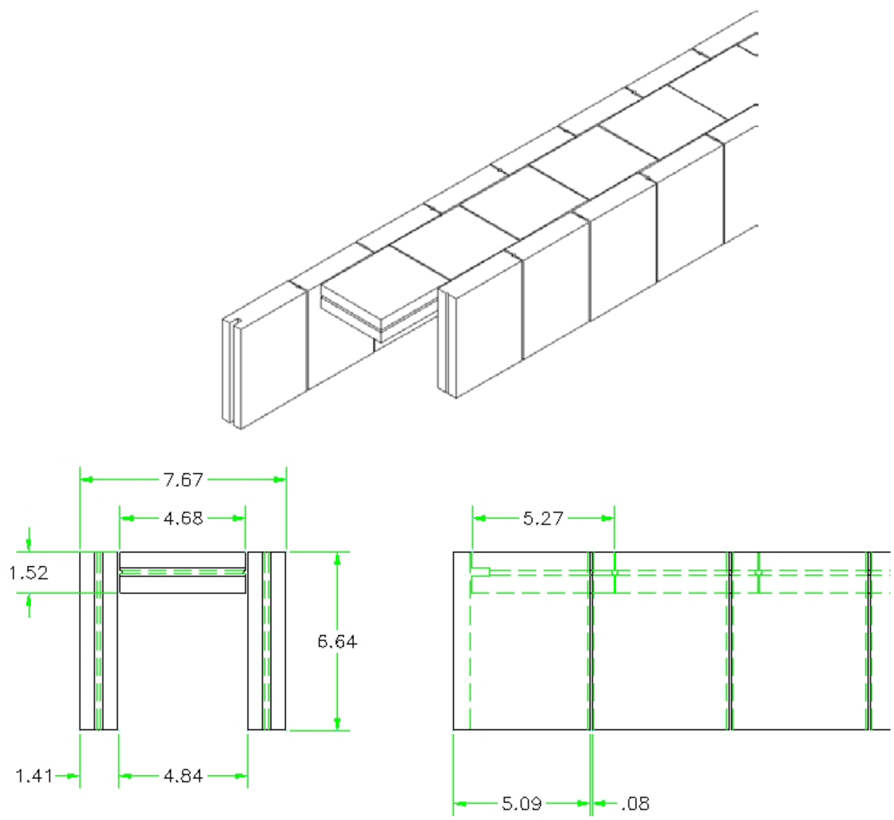

Fig. 5-9. All-ferrite core of RHIC injection kickers (dimensions in cm)

Table 5-3. Injection Kicker Magnet Characteristics (each)

Strength at 2000 A	0.0465	Tm
Number per ring	4	
Propagation time	45	ns
Impedance	~ 50	Ω
High frequency cut off	~ 25	MHz
Magnet aperture, width × height	48.4 mm × 51.2	mm
Magnet length	1.12	m
H field deflection	~94%	
E field deflection	~ 6%	
Ceramic beam tube, circular aperture wall thickness	41.3 3.2	mm mm
Min repetition period	33	ms
Life time	10^6	shots
Core material-ferrite, 29 sections	Ceramic magnetic CMD 5005 50 mm long × 13.9 mm thick	
Bus bar/return frame	Aluminum 6061-T6	
Epoxy potting material	Conap Inc RN1000	

The magnet is designed to permit high temperature bakeout of the ceramic beam tube. For this procedure, the bottom plate shown in Fig. 5-10 is removed and the magnet elevated above the beam tube. The finite elements comprising the magnet result in a frequency cut off in the 25 MHz range: This increases the effective current risetime to about 40 ns. The combination of risetime and propagation time results in an integrated field risetime of about 95 ns.

The pulser. The Blumlein pulser consists of rigid, oil filled transmission lines in a folded, triaxial configuration of the type developed at SLAC. The major dimensions of the storage lines are given in Table 5-4. The triaxial delay line pipes are insulated with Teflon spacers and filled with Calumet Caltran 60-15 oil under slight positive pressure. The dielectric constant is 2.35. The delay lines are assembled from sections each about 2.4 m in length. The combination provides two delay lines of 12.5 Ω impedance, which feed a 25 Ω load, formed by the connecting cables (2×50 Ω in parallel), the magnet and a 25 Ω oil-filled hockey puck resistor assembly. The electrical properties of the Blumlein are shown in Table 5-4. The pulser is switched by a two-gap deuterium thyratron designed for high dI/dt applications (EEV type CX 1168C). An R-C network in parallel with the switch tube provides a small amount of overshoot in the current waveform, this improves the field risetime by a few nanoseconds.

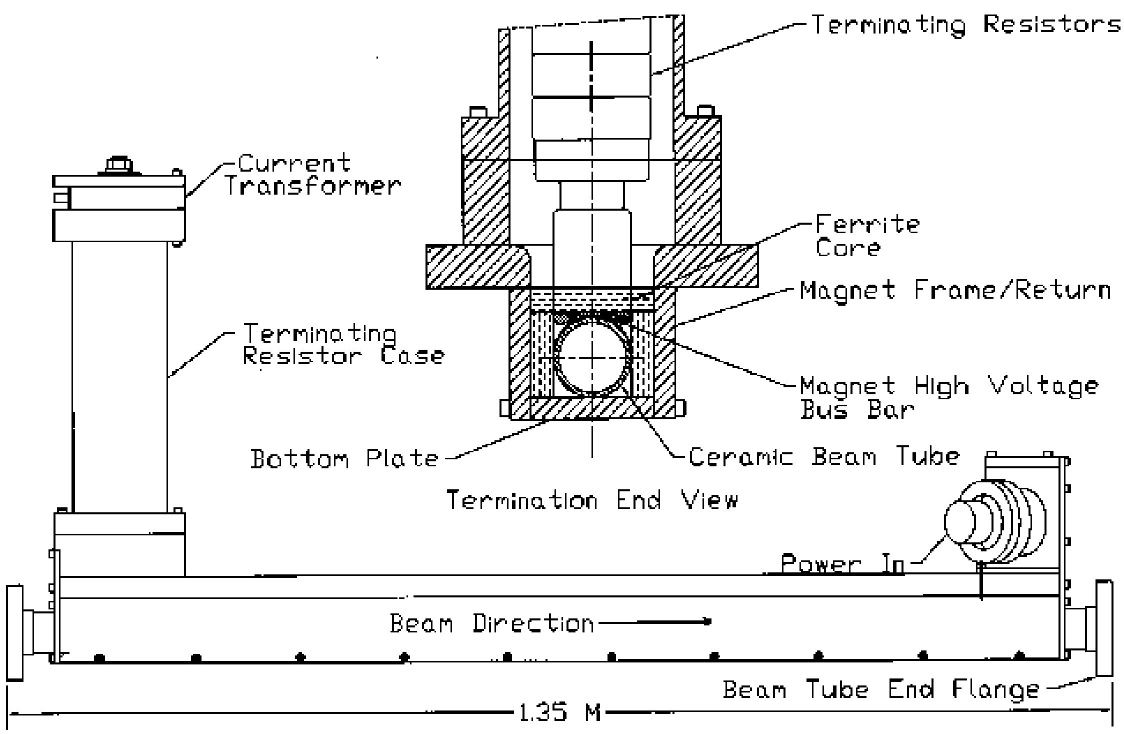

Fig. 5-10. General assembly of transmission line magnet.

Table 5-4. Blumlein Pulser Parameters

	Blumlein Dimensions	
Outer coaxial line	134.5 mm o.d.×98.0 mm i.d. ±0.1	mm
Inner coaxial line	76.2 o.d.×55.5 mm i.d. ± 0.1	mm
Length	10.95	m
Material	Aluminum 6061 - T6	
Insulating oil	Caltran 60-15	
Insulating Standoffs	PTFE Teflon	
	Blumlein Pulser Characteristics	
Load impedance	25	Ω
Two-way propagation time	110	ns
Operating voltage	50	kV
Operating load current	2000	A
Max voltage	60	kV
Current risetime	30	ns
Storage line capacitance	10	nF