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INJECTION BEAM TRANSPORT AND INFLECTOR FOR THE CORNELL 10 GEV SYNCHROTRON

I. OPTICAL DESIGN

A. Introduction

A Varian S-band electron linac having the following properties was chosen as the injector for the Cornell 10 GeV electron synchrotron.

Maximum energy, at zero current	226 MeV
Beam current at 150 MeV	100 mA, pulse
Energy spread	1%
Pulse length	2.32μsec
Maximum repetition rate	60 pps
Emittance (horizontal or vertical)	1.6 mrad-mm

Some of the parameters of the synchrotron ring which are relevant to the problem of injection are:

Magnet pole width	10 cm
Gap height	2.6 cm, 3.9 cm
Horizontal acceptance, at $\Delta p/p=0$	10 mrad-cm
Vertical acceptance	5 mrad-cm
Momentum tolerance	±.89%
Orbit revolution time	2.521μsec
Magnetic field at 150 MeV/c	50 Gauss

For economy of building construction the linac was located inside the synchrotron ring. The linac axis intersects the ring at the ninth magnet (M9) downstream from the L0 long straight section at an angle of about 26°. Figure 1 shows the layout of the injection system. The linac beam is bent through 25.48° by an achromatic beam transport system of two bending magnets JB2 and JB3 and a quadrupole JQ3. Momentum selection is made by slits at JQ3. The second bending magnet is close to the short straight section between ring magnets M9 and M10. M10 has its inside return yoke extended so that the linac beam can pass inside. At the next straight section the injected beam is bent again by a septum magnet placed as close as possible to the nominal synchrotron orbit. Finally in the straight section between M11 and M12 the injected beam intersects the synchrotron orbit and is inflected into the right direction by a pulsed coil.

B. Transport System

The sector magnet plus quadrupole plus sector magnet beam transport system is the simplest solution to the following requirements: (1) Bend the linac beam by about 25° so that it is nearly parallel to the synchrotron orbit, (2) focus the beam on a slit with enough dispersion to allow a 1% momentum selection, and (3) deliver the analyzed beam at the exit of the system almost parallel and with very little dispersion. Figure 2 shows some representative particle trajectories. The first magnet JB2, a uniform-field sector magnet of angle $\Theta = 12.74°$ and radius of curvature $R=58.6$cm, brings an initially parallel linac beam to a horizontal focus at a distance downstream $L = R/\sin\Theta = 263$ cm with a momentum dispersion $p_0(\partial x/\partial p) = R = 5.9$ mm per percent momentum deviation. The momentum limiting slit is placed at this focus (actually a little upstream) and the movable jaws are normally set for about 1% full width. A horizontally focusing quadrupole JQ3 immediately downstream of the focus reverses the slopes (relative to the center line) of the off-momentum trajectories that pass through the slit, so that all trajectories in the second half of the system are symmetric about the focus. That is, the particles emerging from the second bending

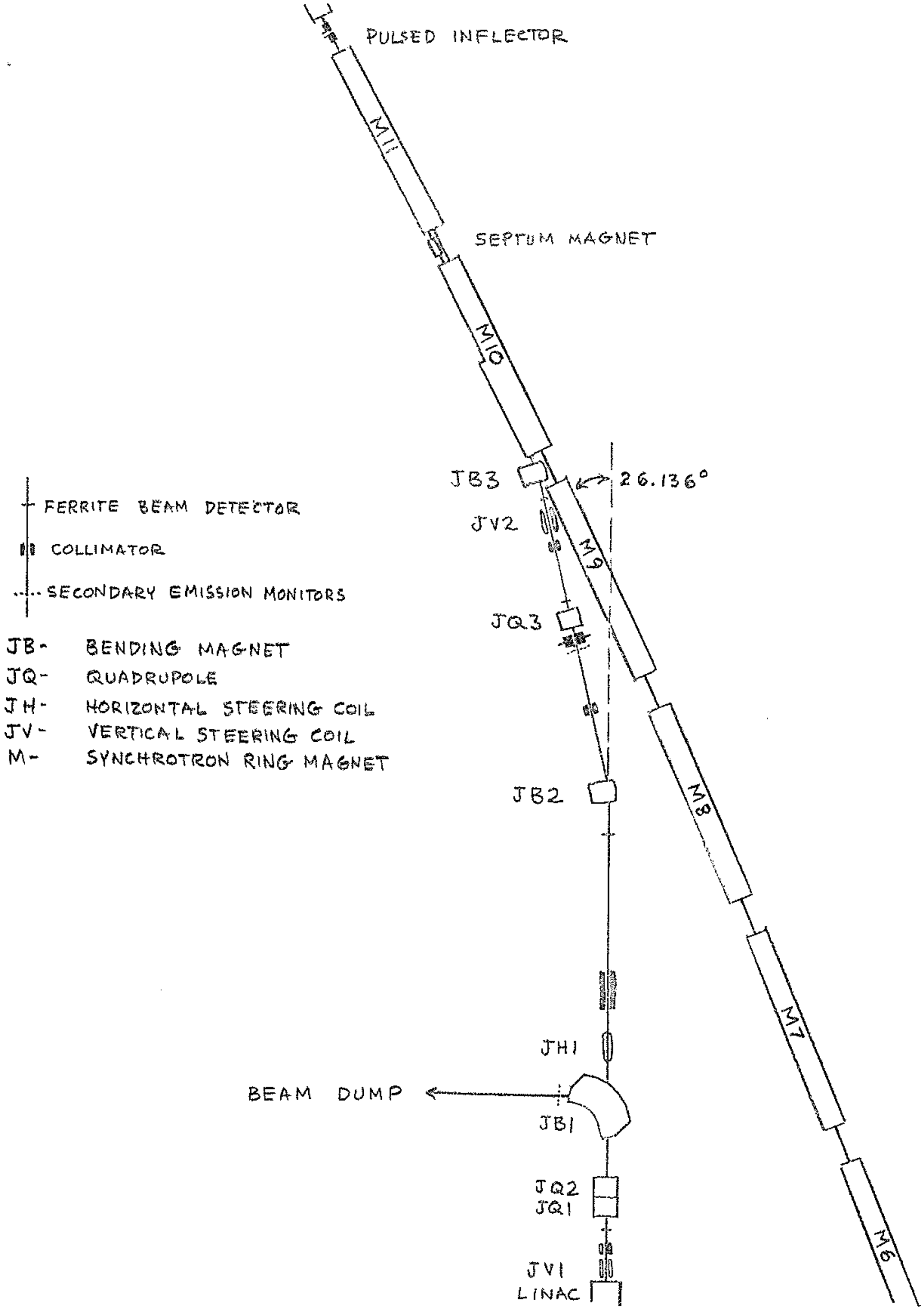


Fig. 1 Schematic diagram of the injection transport system, not to scale.

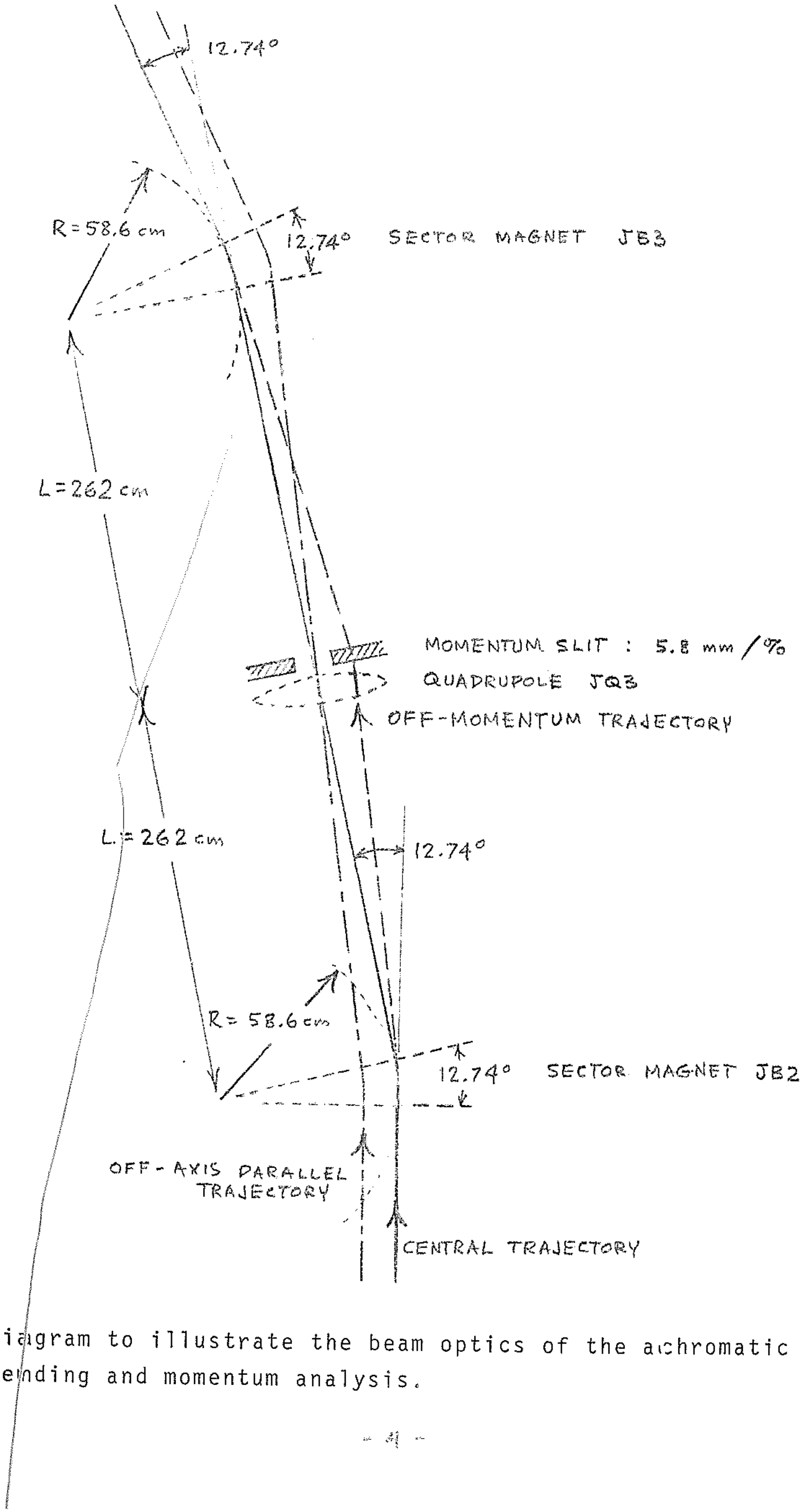


Fig. 2 Diagram to illustrate the beam optics of the achromatic bending and momentum analysis.

magnet JB3 located a distance L downstream from the focus form a parallel beam again with no momentum dispersion. To achieve this the focal length of JQ3 is L/2 and JB3 is identical to JB2. The overall first-order horizontal transfer matrix (displacements, slopes and fractional momentum deviations) from JB2 to JB3 is:

$$\begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

That is, the exit beam cross section is identical to that of the entering beam, except that the extreme momenta have been removed, the central trajectory has been deflected by 25.48°, and the displacements and slopes are inverted (left to right and vice versa - - of no consequence, assuming a symmetric beam).

At the linac exit is a quadrupole doublet, JQ1 and JQ2, to keep the linac beam parallel in the horizontal plane and to counteract the vertically diverging effect of JQ3. Horizontal and vertical steering coils (see Fig. 1) are placed here and there throughout the system to provide for empirical steering corrections. Upstream of each major magnet there is a 9.6 mm diameter water-cooled copper collimator to protect the magnet coil insulation from deterioration by stray radiation and to define the beam direction well enough to make the momentum analysis meaningful. Downstream from each collimator the beam passes through a ferrite core with a secondary winding to monitor the beam current pulse.

An auxiliary analyzing magnet JB1, called the dump magnet, allows one to divert the linac beam by an angle of 86.7° through a vacuum tank into a shielded cave for linac tunup and energy analysis without injecting into the synchrotron. A movable collimator, called the shutter, immediately downstream serves to protect personnel in the synchrotron tunnel from accidental irradiation while the dump is in use. When the linac beam is being injected into the synchrotron, the dump magnet field is turned off and the shutter is opened.

C. Septum and Inflector

In general, a multiturn inflection system has the advantage of permitting beam injection over a longer duration and thus getting more particles into the synchrotron. One pays for this by not being able to put all of the particles into stable synchrotron orbits. In our case multiturn injection loses its advantage because the linac beam pulse duration does not exceed the orbit period. Consequently a single-turn (in the pulse-length sense) center-line pulsed inflector is the obvious choice.

The second sector magnet JB3 fits into the 25 cm straight section between ring magnets M9 and M10 so that the incoming linac beam just misses the yoke of M9. The yoke of M10 is extended (see Fig. 3) in the beam plane to allow the injected beam to enter the synchrotron vacuum. At the center of the M9-M10 straight section the injected beam is 14.0cm from the nominal synchrotron orbit. If the pulsed inflector were placed at the next straight section, it would have to deflect the injected beam through an angle of about 1.5° in order to put it on the central orbit. Since a fast pulsed magnet for 150 MeV/c particles with the required geometry (angle, length and operture) is not easy to construct, we have chosen to minimize the problem by putting a DC septum magnet as close as possible to the synchrotron central orbit in the M10-M11 straight section so that in the following straight section where the injected beam finally intersects the nominal synchrotron orbit, the required inflection angle is only .7° (12.2 mrad).

The choice of bending angles for the sector magnet, septum magnet, and pulsed inflector, and the choice of clearance between the injected and circulating beams at the septum were determined by comparing trajectories (computed by W. Evanco) through the synchrotron field (including fringing) for various assumptions of inflection angle. An inflection angle of .7°, implying a septum deflection of 1.28° (22.5 mrad) and a separation of 4.9 cm at the septum, was chosen as a reasonable compromise between low inflector field and large septum clearance.

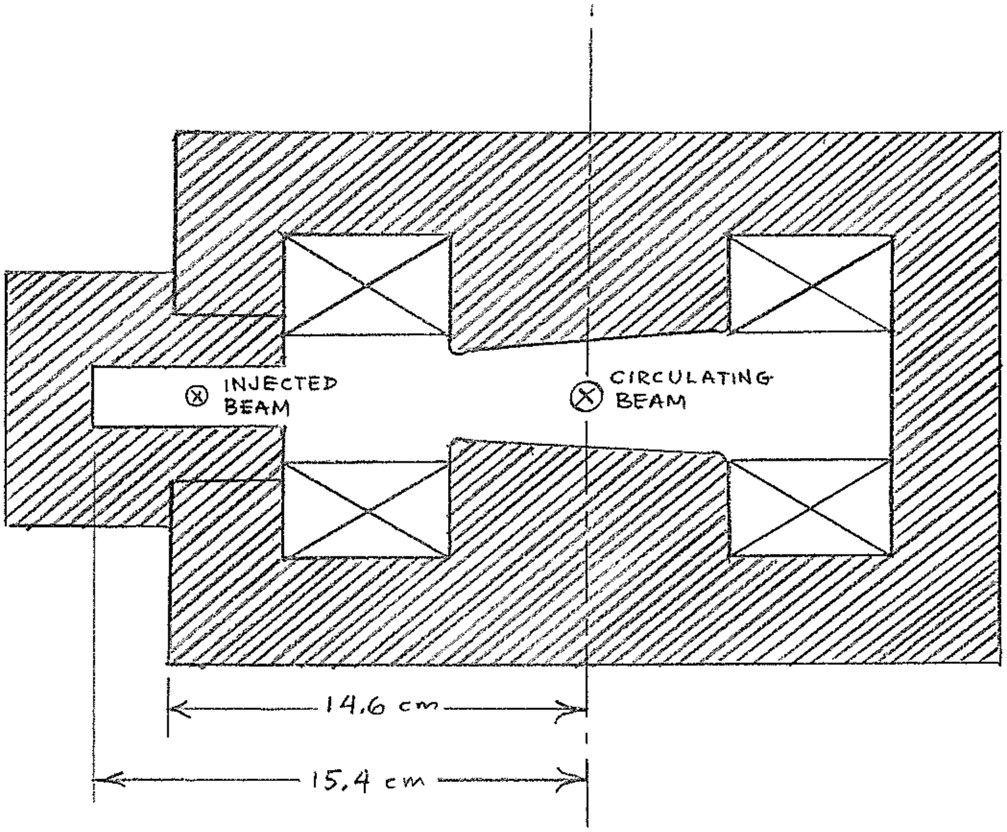


Fig. 3 End view of the upstream face of synchrotron magnet M10, showing the modification of the yoke to accommodate the injected beam.

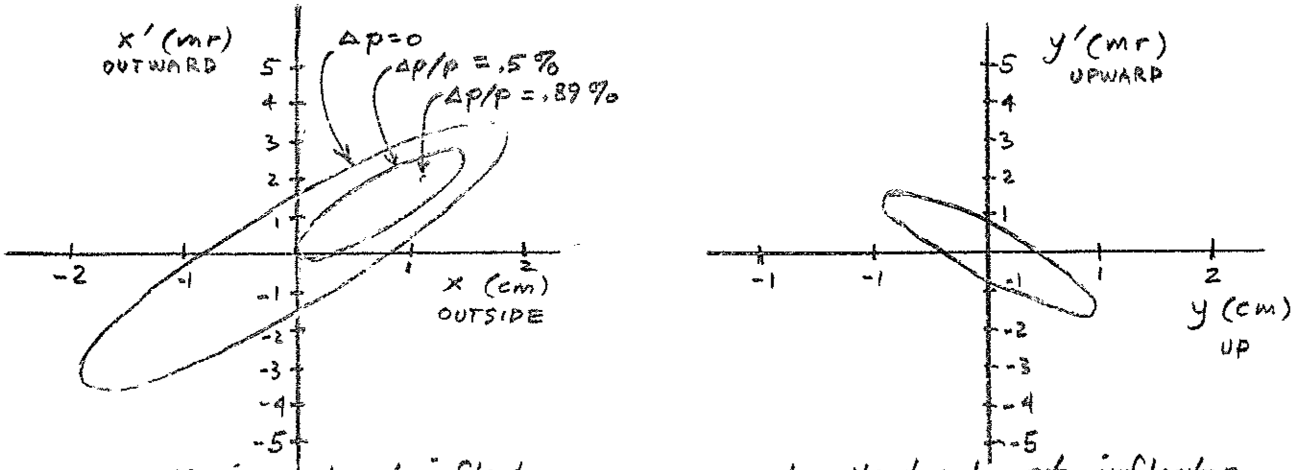
The horizontal and vertical acceptance ellipses for stable synchrotron orbits starting at the inflector straight section (Fig. 4a,b) were propagated backward through the inflector and the M11 field along the injectron trajectory to the septum straight section (Fig. 4c,d), and then through the septum magnet and the M10 fringe field to the sector magnet straight section (Fig. 4e,f). The phase voume corresponding to trajectories which lead to stable synchrotron orbits is very much larger than the phase volume (emittance) of the linac beam delivered to the synchrotron, so that precise matching is not necessary. This means that the injection efficiency should not be very sensitive to error or uncertainty in the details of the magnetic field plots or to misalignment, higher-order focusing and defocusing effects, or space charge. Empirical optimization of the beam monitor signals using the various steering and focusing elements in the system can compensate for almost any defect in the beam optics.

II BEAM TRANSPORT MAGNETS

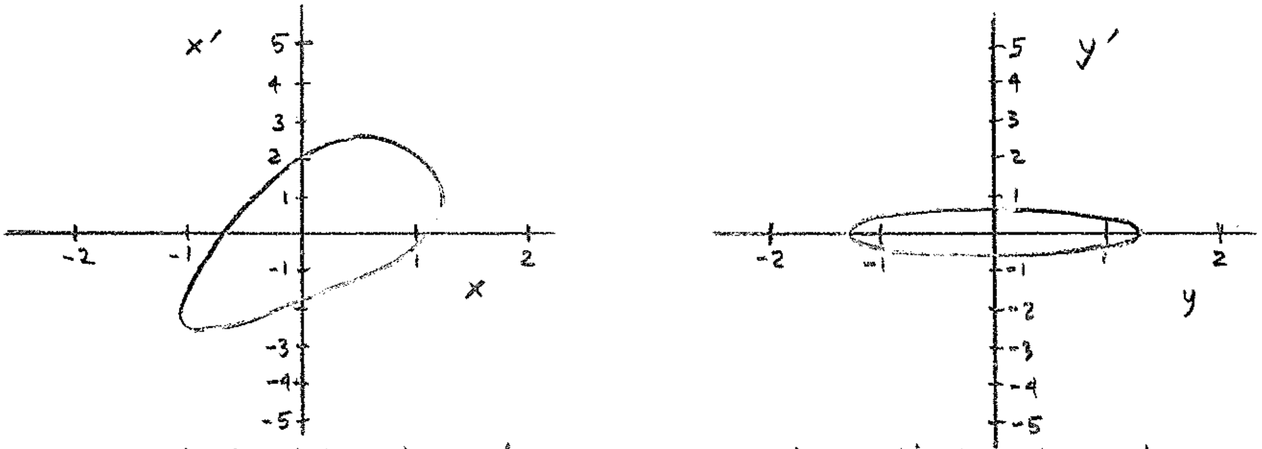
Bending Magnets

These are two identical uniform-field C magnets. The poles are cut so that a trajectory of radius 58.6 cm intersects the entrance and exit pole edges at right angles and the angle of deflection is 12.74°. There is a shield plate just outside the gap so that the fringing field of JB3 (.2% of the gap field 13 cm away from the beam line) will not perturb the circulating synchrotron beam. The first magnet JB2 is known as the Analyzing Magnet; the second JB3 is called the Trimmed Magnet. They are powered in series by one supply; the second magnet has an extra smaller supply, the "trim", which can add to the main current. The magnets and supplies were designed and manufactured to Cornell specifications by ARCO, Walnut Creek, California. Some of the important parameters are listed below:

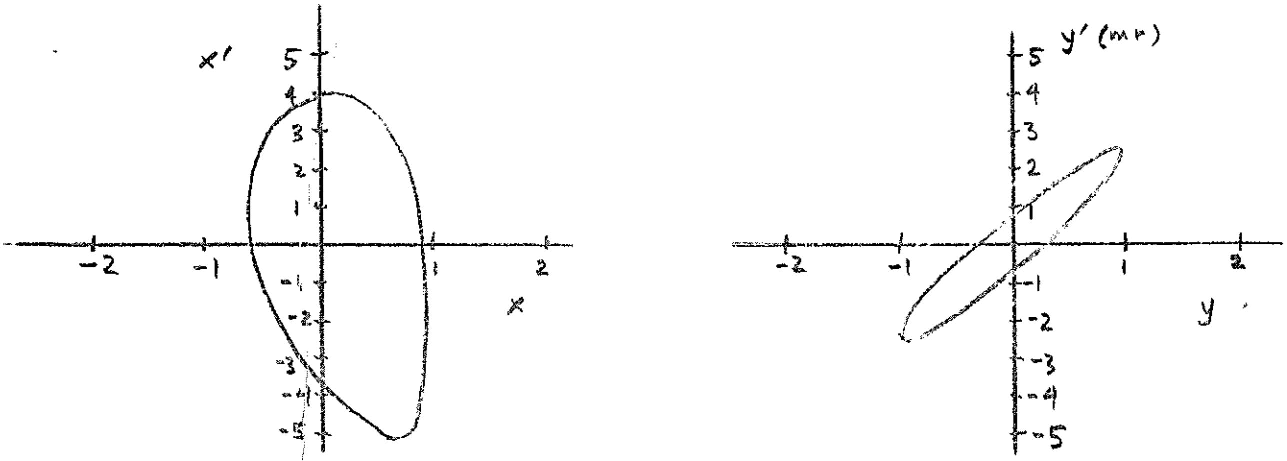
Bend angle	12.74°
Bend radius	58.6 cm



a - Horizontal, at inflector b - Vertical, at inflector



c - Horizontal, at septum d - Vertical, at septum



e - Horizontal, at JB3 f - Vertical, at JB3

Fig. 4 Synchrotron acceptance ellipses. A particle displaced from the nominal central trajectory by displacements x and y and slopes x' and y' whose values lie within the closed curves will be captured in a stable orbit. These curves were computed by W. Evanco by tracing trojectories through the design synchrotron fields.

Arc length	12.4 cm
Gap height	2.22 cm
Cooling	water: approx. 3 gpm @ 25 psig
Interlocks	water flow, temperature
Maximum current	32 A
Resistance (both coils of one magnet)	1.25 Ω
Maximum field	11.8 kG

For the required bending angle the relation between magnet current, magnet field, and particle momentum is plotted in Figure 5.

Power Supplies:

Maximum output current	30 A (series), 4 A (trim)
Maximum output voltage	150v " 75v "
Current regulation	.1% (each)
Current programing constant	12.3 Ω/A, 130 Ω/A
Remote programing resistor	0-500Ω, 2 1/2 w (each)
Metering shunt	50mV @ 30 A (each)
Input	208v, 3ϕ, 5kW (total)

Sources of more Information:

Specifications for Cornell Injection Magnets and Supplies SPEC:KB-1.

Proposal for an Injection Magnet Assembly AR-1008, ARCO.

Test Results and Power Supply Instructions, ARCO.

ARCO drawings: Magnets-BH-2734, BH-7114
Supplies-BG-0084A, BG-0074C,
BG-0133, BF-9303, BF-9313,
BG-9524, BG-9534, BH-2264,
BH-2253.

Quadrupole Magnets

The quadrupoles JB1, JB2, and JB3 are identical, except that the first two are joined together to make a doublet with a common yoke and an effective separation distance of 25.4 cm. They were manufactured

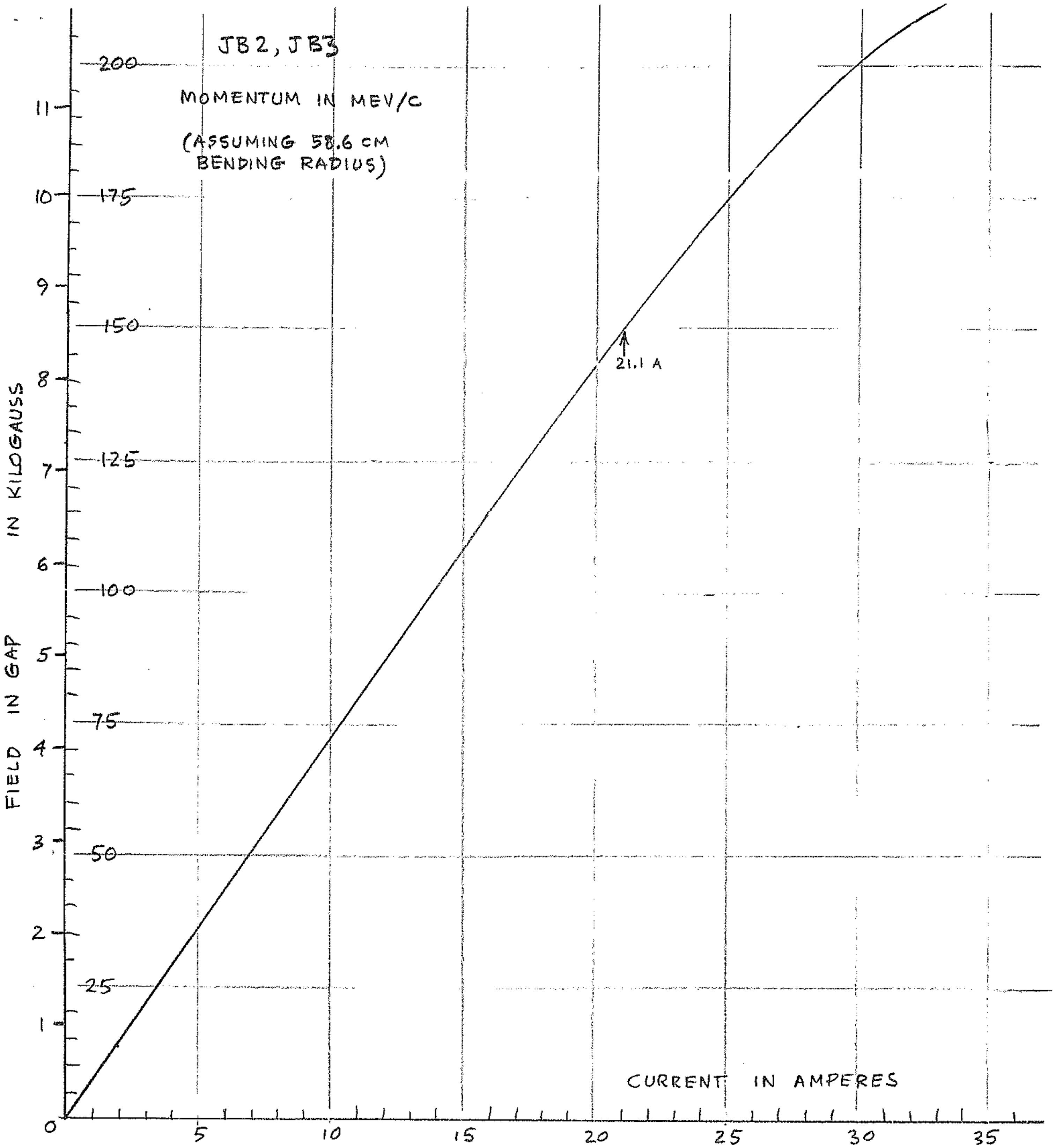


Fig. 5 Nominal calibration curve for the momentum analysis magnets of the beam transport system, obtained from field measurements made by the manufacturer, ARCO.

by Spectromagnetic Division, Hayward, California (catalog numbers 1006 and 1050).

Inscribed diameter	5.08 cm
Effective length	12.7 cm
Cooling	convection
JQ3 current at 150 MeV (nominal)	3.66 A
Maximum current	12A
Resistance (all coils of one quad)	1.1Ω
Maximum gradient	1.0 kG/cm
Minimum focal length at 150 Mev/c	40 cm

Each quadrupole is powered by a Harrison Lab #6427A supply with the following specifications:

Maximum output current	15 A
Maximum output voltage	18 v
Current regulation	1%
Current programing constant	1 5 Ω/A
Remote programing resistor	0-200Ω, 2 1/2 w
Metering shunt	50 mV @ 15A
Input	120v AC, 450 w

Sources of more information:

Specifications for Cornell Injection Magnets and Supplies SPEC:KB-1.

Spectromagnetic Magnetic Quadrupole Lenses: Spectromagnetic advertising bulletin.

Spectromagnetic drawings A35887-1A, A35886-1A

Operating and Service Manual Model 6427A DC Power Supply, Harrison Laboratories.

C. Dump Magnet

The dump magnet JB1, a uniform-field edge-focusing C magnet, was adapted from one of the quadrant magnets of the Cornell storage ring project by widening the gap and drilling a hole through the yoke for the undeflected linac beam. It was manufactured by P.E.M., Oakland, California.

Bend angle	86.7°
Orbit radius	47.8 cm
Gap height	1.59 cm
Cooling	water: 7.5 gpm @ 60 psi
Interlocks	water flow, temperature
Maximum current	800 A
Resistance (both coils)	.056 Ω
Maximum field	15.6 kG

For the nominal bending radius the relation between magnet current, magnetic field, and particle momentum is plotted in Fig. 6.

The magnet is powered by two Sorenson DCR 40-500 A supplies wired in parallel. Each supply has the following specifications.

Maximum output current	500 A
Maximum output voltage	45 v
Current regulation	1%
Current programing constant	.3 Ω/A
Remote programing resistor	0-100Ω, 5 w
Metering shunt (both supplies in parallel)	50 mV @ 800 A
Input	480 v, 3ϕ, 26 kW

Sources of more information:

Zero Gradient Magnet Test Data and Instruction Manual, P.E.M.

Drawings DH 3220, CM 1227 B.

Specifications for 10 GeV Synchrotron 800 Amp. Magnet Supply, SPEC:KB-2.

Instruction Manual for Model DCR 40-500 A, Sorenson.

D. Steering Magnets

Two vertical steering magnets are located at the extreme ends of the transport system, JV1 near the linac exit and JV2 near the synchrotron entrance. A horizontal steering magnet JH1 is located near the

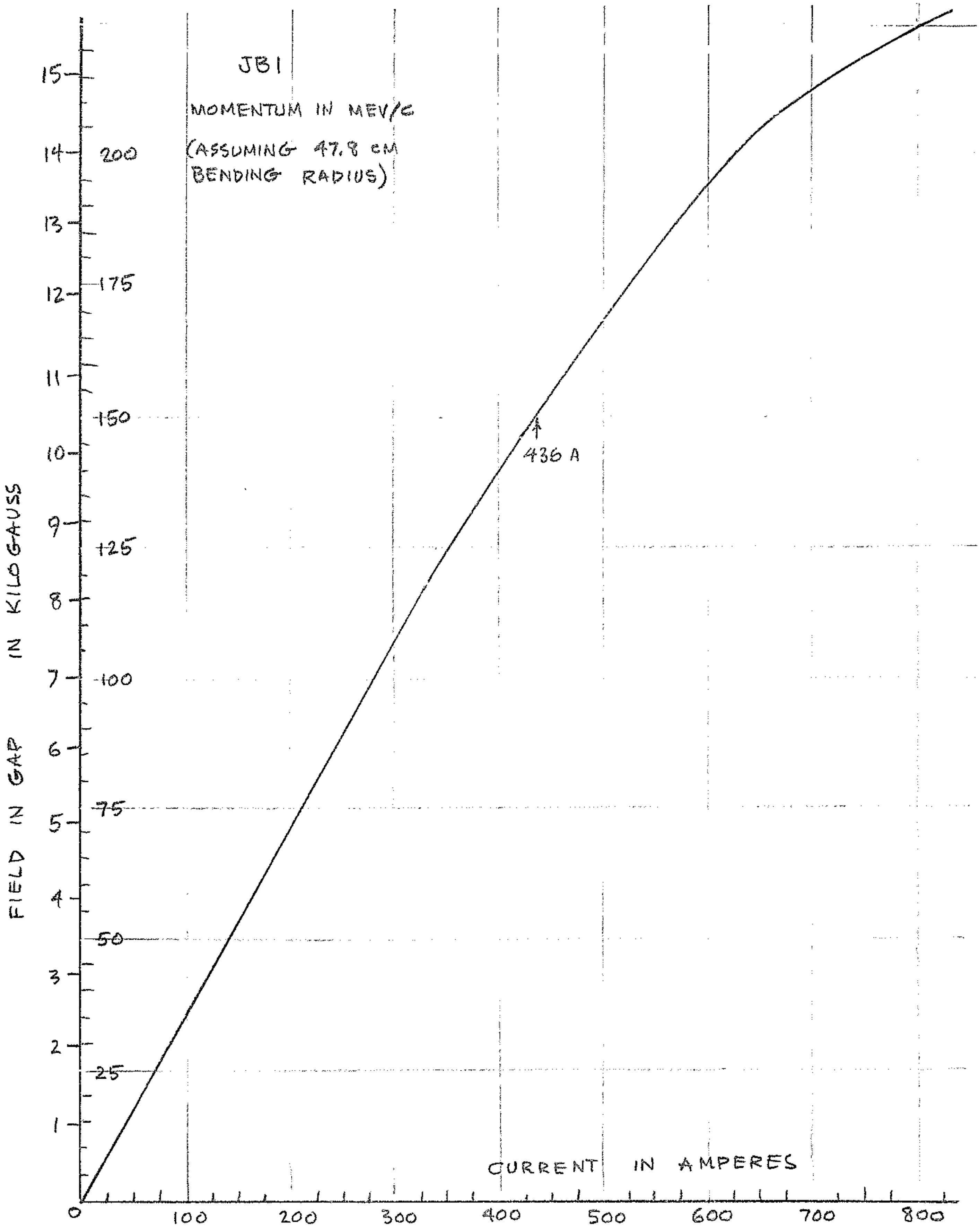


Fig. 6 Nominal calibration curve for the dump magnet, obtained from field measurements made by the manufacturer, P.E.M., corrected for the increase in gap height from 9.53 mm to 15.88 mm. The correction was made by assuming that the current for a given field was increased by 5/3.

dump magnet. These three magnets plus the trim current in JB2 are used to optimize the beam centering. Each steering magnet consists of a pair of coils wrapped close to the 3.8 cm diameter beam pipe, about 28 cm long. Each coil is 120 turns of #18 varnished wire potted in epoxy and wrapped with glass fiber tape.

Maximum current (pair of coils in series)	6 A
Resistance	3.8 Ω
Maximum field	165 Gauss
Maximum bend angle at 150 MeV/c	9 mrad = .5°

Each of the three steering magnets is powered by a Lambda LH 122S DC supply with the following specifcations:

Maximum output current at 30° C	5.7 A
Maximum output voltage	20 v
Current regulation	<1%
Current programing constant	about 20 Ω/A
Remote programing resistor	100Ω, 2 1/2 W
Metering shunt	50 mV @ 5A
Input	120v AC, 300w

For more information see the Lambda instruction manual.

III. BEAM PIPE

A. Vacuum System

The beam pipe is made of stainless steel tubing, 3.8 cm outer diameter, 1.6 mm wall. Sections are flanged together with conoseal flanges, manufactured by Aeroquip Corp., Los Angeles: female flange 55291-150S, male flange 55292-150S, copper gasket 55666-150EC, coupling 50773H150. The layout is given on drawing DH 3249, which has references to detailed drawings of the individual parts. The bending magnets JB1, JB2, JB3 require special vacuum chambers which fit between the poles.

There is a fast-acting pneumatically-controlled metal-gasketed gate valve at the linac exit, and near the synchrotron entrance there is a gate valve of the same type as used in the synchrotron ring. Between these valves the beam pipe is evacuated by two pumps: a 50 ℓ/s Varian vacion pump near the linac end and an oil diffusion pump (as in the synchrotron ring) near the synchrotron end. Upstream of the diffusion pump is a cold trap which the beam passes through. The trap is cooled by a compressed-air operated mechanical refrigerator (Welch series 3150 cryorefrigerator). Since the pumping speed through the beam pipe is very low, the vacuum at the linac end can be considerably better than the synchrotron vacuum.

The tables which support the beam pipe and the components of the transport system are surveyed into position so that the beam center line is 20.3 cm (8.00") above the top surface of the tables. The alignment of all components is made with respect to a line scribed along the top surface of the tables.

B. Collimators and Slits

Collimators and slits are used at various points along the beam pipe to limit the lateral extent of the beam, in order to define its position, direction, and momentum accurately, and to protect the various components from the deteriorating effects of stray radiation. Their dimensions are tabulated below and their locations are given in Fig. 1:

DESIGNATION	LENGTH	HOLE	DRAWING
Linac exit	10.2 cm	9.5 mm I.D.	CH 3131
Shutter	30.5 cm	9.5 mm I.D.	CH 3221, DH 3300
JB2 exit	10.2 cm	9.5 mm high x 25.4 mm wide	CH 3135
Mom. Slit	10.2 cm	9.5 mm high x 0-19.0mm wide	BH 3188
Synch. entrance	10.2 cm	9.5 mm I.D.	CH 3131

The linac exit, JB2 exit, and synchrotron entrance collimators are fixed in position and brazed to the beam pipe at the ends. The shutter is similar except the beam pipe has bellows in it so that the shutter can be rotated to block the beam line. The momentum slit has two movable jaws mounted in a vacuum box. They connect to drive motors and the cooling water supply through bellows in the sides of the box. All the collimators are made of copper and are water cooled. The jaws of the momentum slits have water channels drilled in them; the others have copper tubing soldered to the outside of the 7.6 cm diameter body of the collimator. Each collimator is surrounded by lead shielding.

C. Beam Detectors

Immediately downstream from each collimator (except JB2 exit), is a ferrite beam monitor. The steel beam pipe is interrupted by a short ceramic pipe section around which is placed an inductive beam current pickup similar to those used in the synchrotron ring: a ferrite core with secondary windings (the beam is the primary). The sensitivity is of the order of 10 mA of beam current per volt of signal.

On the upstream face of each of the jaws of the momentum slit is a set of three secondary emission monitors. Each monitor consists of six 50μ stainless foils alternately connected to about 1kV. The monitors are spaced about 1% apart in momentum, and provide a continuous indication of the intensity and momentum distribution of the part of the linac beam which does not pass through the slits. The sensitivity is of the order of 1mA of beam current per mV of signal.

At the exit of the dump magnet is a similar set of six secondary emission monitors so that the linac beam can be analized in momentum without injecting into the synchrotron. The detectors are spaced by 1.5% in momentum, except that the low momentum detector covers about 4%. The central trajectory to which the magnet calibration applies is the fourth detector.

IV SEPTUM

A. Septum Magnet

Although in principle the septum magnet could be run DC, the current is actually pulsed to simplify the cooling. To prevent eddy currents in the iron it is made of .22 mm silicon steel laminations (see drawing BH3112) punched from the steel salvaged from the flux bars of the old Cornell 300 MeV synchrotron. The magnet is excited by eight turns of #16 wire (1.29 mm diam.). The insulation, which must survive the full intensity of the linac beam for arbitrarily long periods, consists of tubes of AlSiMag ceramic, 1.40 mm I.D. and .14 mm wall. Because the ceramic is very brittle the coil is made up in straight sections and soldered together. Sheets of stainless steel hold the finished coil in place in the magnet. The magnet is mounted in an oversize version (drawing DH3160) of the standard synchrotron pump box. The edge of the iron is located 2.04 cm (.800") from the line passing through the centers of the vacuum flanges. The magnet parameters are listed below.

Gap height	12.7 mm
Gap width	27.4 mm
Septum coil thickness	2.67mm
Length of laminations	13.43cm
Inductance	25μH
Maximum peak current	165 A
Nominal bending angle	1.28° = 22.5 mrad
Current for 150 MeV/c	90 A
Field - current ratio	about 10 Gauss/A

B. Septum Current Supply

Figure 7 shows a diagram of the current pulsing circuit. At the start of a cycle neither SCR is conducting and point A is at a negative voltage. When an "on" trigger is received, SCR_1 fires discharging C through the septum magnet L_1 . A current oscillation in the L_1C loop starts but is extinguished after half a cycle because the current through SCR_1 cannot reverse. This leaves C oppositely charged. Soon a "recharge" trigger turns on SCR_2 and C begins to discharge through L_2 starting another half cycle of oscillation, which this time leaves point A at a negative voltage. Now the circuit is ready for another "on" trigger.

A careful analysis of the circuit shows that the voltage swing at A and the peak current through the septum magnet L_1 are limited only by the losses in the circuit, mainly in the effective septum magnet resistance R.

$$V_{A\,max} \approx - V_{A\,min} \approx V(4Q-\pi)/\pi, \text{ where } Q = L^{1/2}\,C^{-1/2}\,R^{-1}$$

$$I_{pk} \approx 4\ V/\pi R$$

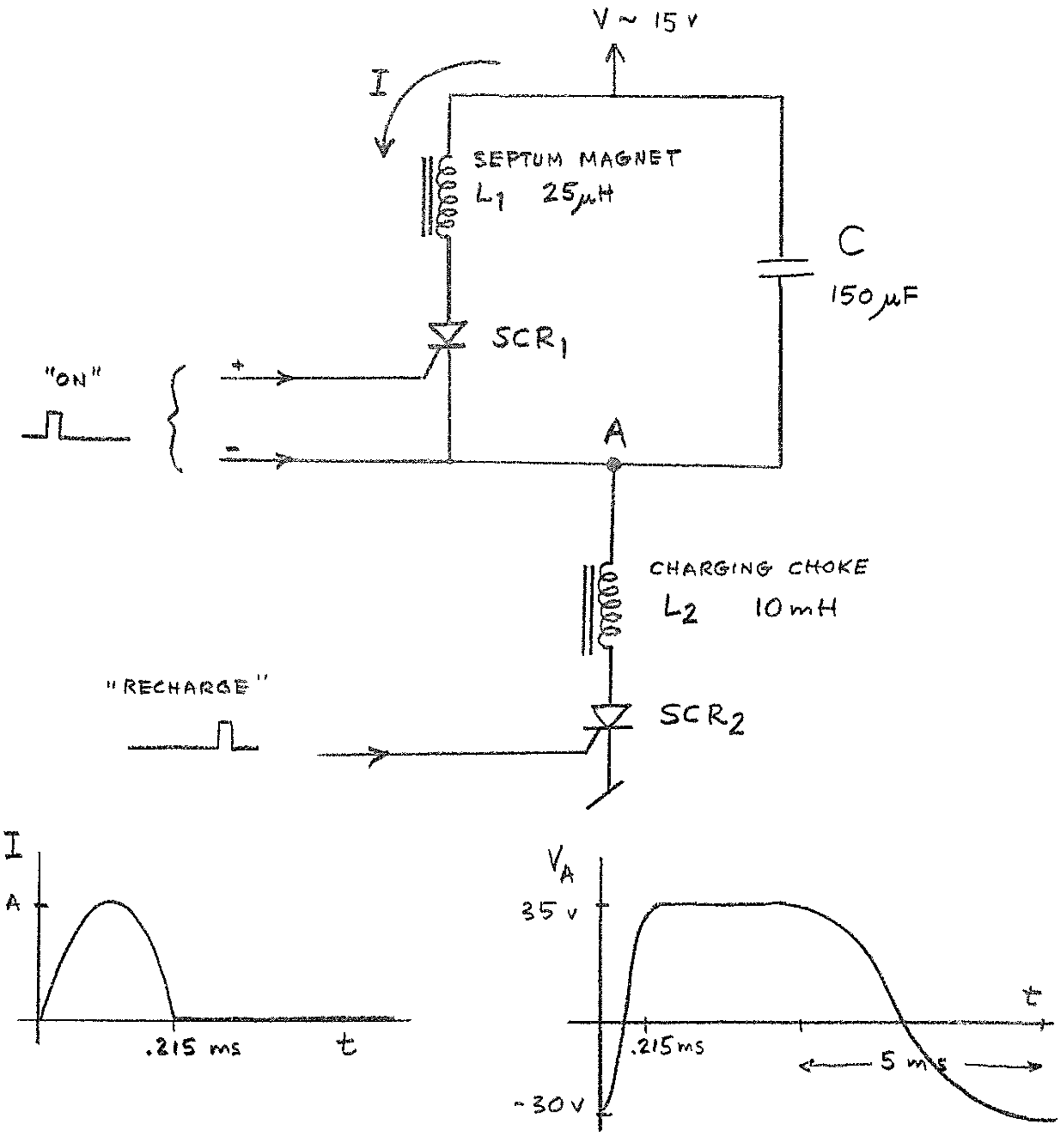


Fig. 7 Simplified schematic diagram of the septum magnet pulsing circuit, showing the important waveforms.

The circuit parameters and waveforms are shown in Fig. 7. For a bend of 1.28° at 150 MeV/c a supply voltage of about V=17v is required. This is provided by a Technipower L-40.0-6.0 voltage regulated supply. The "on" and "recharge" pulses come from the Septum Trigger Circuit, which is triggered by a standard timing pulse.

V INFLECTOR

A. Inflector Coil

The inflector and its pulsing circuit are similar to those used in the early days of operation of the Cornell 2 GeV synchrotron - now replaced by a multiturn inflector system. The injected beam intersects the normal synchrotron orbit at an angle of about 12 mrad and is deflected by a pulsed magnetic field so that it emerges on the central orbit. Since the same electrons pass through the inflector again on their second time around 2.52 μ sec later, the magnetic field must be shut off in a time which is a small fraction of 2.52 μ sec so that they will not be deflected out of the synchrotron. A magnet which can be turned off rapidly must have low inductance, which means that to get a large enough field, the current must be large; and rapid switching of large currents requires high voltage.

The "magnet" is a four-turn coil of #7 wire (drawing DH3334) mounted in a standard 8.9 cm diameter (3 1/2") pipe between synchrotron magnets M11 and M12. The dimensions, 24 cm long by 4.5 cm wide by 3.2 cm high, are determined by the available space in the straight section and the required beam aperture (see Fig. 4). The inductance is 2.5μH. The field and current for a 12 mrad deflection of a 150 MeV/c particle are 230 Gauss and 700 A, respectively.

The coil is supported by ceramic spacers. A retractable secondary emission probe (drawing DH3336) can be inserted into the center of the coil to help in centering the beam before turning on the inflector pulser.

B. Inflector Pulsing Circuit

The current supply for the inflector must provide around 1,000A and turn off in a fraction of a microsecond. The tolerance on the current before and after turnoff, however, is not very severe since we only have to bend the beam by 12 mrad, and since the horizontal aperture of the synchrotron is about ±1 mrad (Fig. 4a), we can allow the top of the pulse to deviate from flatness perhaps by as much as ±5% and we can tolerate a comparable current remaining after turnoff. The pulsing circuit is therefore rather simple (Fig. 8). A lumped-constant delay line of 8 sections (two spare sections are also available) with a characteristic impedence of R_d=12.5Ω and a delay of about 1.2 μsec is charged to double the supply voltage V through a choke and a high-voltage semiconductor diode stack. The other end of the line is connected to the anode of a EGG HY-32 hydrogen thyratron by four RG-217/U 50Ω cables in parallel. When the thyratron (located near the inflector) is pulsed into conduction the line discharges to ground through the inflector L and the terminating resistor R_t, a 8.33Ω , 4.5 kW bank of six resistors in parallel. The discharge current rises in a time of the order of L/R_d to a plateau $I=2V/2R_d$. After a time equal to twice the delay time of the line, the leading edge of the current pulse is reflected and the current falls to zero again approximately symmetrically. The rise and fall times are slightly lengthened because of the high-frequency cutoff of the lumped-constant line. The line alone would limit the rise time to no less than .14μ sec.

The actual value of the terminating resistance is adjustable in steps and is determined from an empirical optimization of the current pulse shape. The 1-4μ H inductors in the line (drawing CH3158) are also tuned empirically. The pulse length was chosen to be equal to the synchrotron orbit frequency so that the periodic reflections in the inflector current would perturb the synchrotron orbit only when the empty portion of the beam orbit, corresponding to the turnoff time, passes the inflector. In practice the inflector pulse is flat within ±5% for about 90% of its length, the turnoff time is about .7 μ sec, and except for the harmless reflections, the current after turnoff is less than 10% of the peak current. At the time of this writing

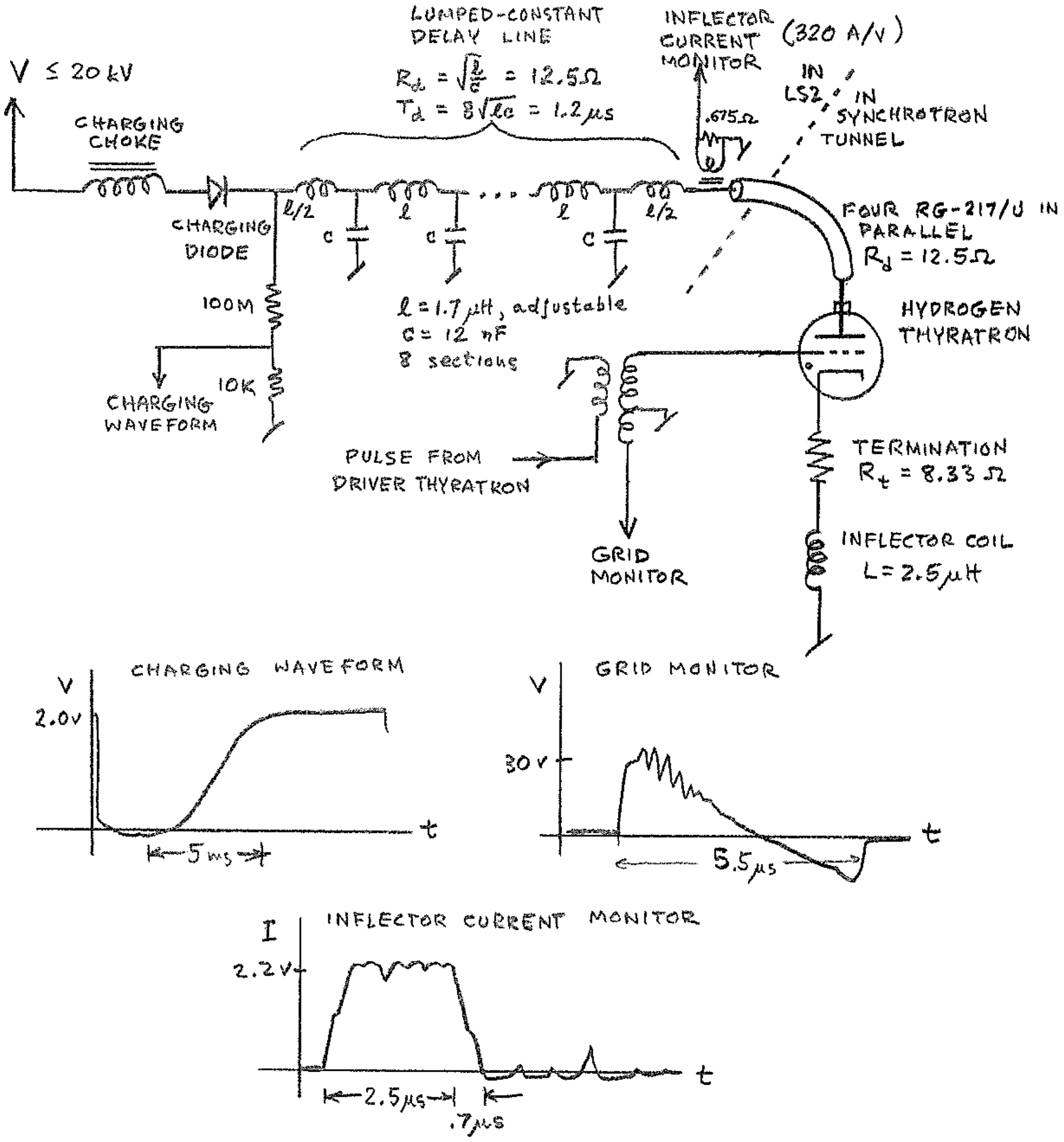


Fig. 8 Simplified schematic diagram of the inflector pulsing circuit, showing the important waveforms. For more details see drawing CH3800.

there is a plan to replace the lumped-constant delay line with a continuous coaxial cable line in order to improve the shape of the current pulse.

The DC charging voltage comes from a 20 kV, 300 mA unregulated supply manufactured by Del Electronics (Model PS 20-300-1, see operating Instruction Manual for details). The three-phase input comes from a 208 v, 3ϕ autotransformer which can be used to vary the inflector current. The AC input is regulated. The current can be monitored by the DC supply voltage or by a signal obtained from a current transformer at the output of the charging line (320 Amps per Volt of signal). The trigger source for the HY-32 thyratron is a 4C35 hydrogen thyratron (called the "driver" and located near the inflector, drawing AM 1258A), which is driven by a vacuum tube pulser. The pulse waveform at the grid of the HY-32 is available for trouble diagnosis.