BEAM EXTRACTION FOCUSING COILS FOR THE BEVATRON*

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Abstract

A nested quadrupole and sextupole coil system to enhance proton beam extraction from the Bevatron is discussed. The integrated quadrupole field, nominally 50 kG-in./in., is obtained with four current sheets, approximated with 32 conductors. Internal to the quadrupole coil, a six-conductor coil produces the sextupole field. A clear beam aperture of 3.5 in. by 3.0 in. is provided with good field in the 2.5 in. by 1.5 in. central region.

The coil system, housed in a stainless steel support structure, is located in the gap of the main guide field magnet and in the Bevatron's main vacuum system just upstream of the accelerator beam exit port. Remote positioning of the coil system is accomplished with motor driven screw drives for different extraction beam orbits. Focusing coils and positioning equipment were installed in June, 1972, and have operated successfully during tests.

Background

Beam losses have existed within the Bevatron in transporting all the reasonantly extracted internal proton beam to the external proton beam first focus. The problem has been due primarily to the fact that the extracted beam must pass through the Bevatron's outer fringe field which acts as a strong horizontally-defocussing quadrupole with an integrated gradient of 100 kG-in./in., for the highest energy beam (6.6 Gev/c). Consequently, just downstream from the fringe field some of the extracted beam is lost to the vacuum tank of the Bevatron, causing highly undesirable radiation damage. Currently a new 50 Mev injector for the Bevatron is being installed. The anticipated increased beam intensity and vertical emittance will aggravate this radiation problem. Also, focussing elements downstream from the fringe field are too far away to efficiently cancel the fringe field defocussing.[1]

How can these difficulties be overcome? One solution to this beam transport problem would be to move the focussing elements upstream and enlarge the vacuum tank of the Bevatron, where beam interference exists. This solution was considered, but would be very costly, both in dollar cost and in shutdown time of the Bevatron.

A more realistic solution was pursued, namely, by placing focussing elements in the Bevatron's outer fringe field to partially cancel the defocussing effect of the fringe field. With orbit calculations, a scheme was worked out with a focussing coil of about 46 kG-in./in. integrated gradient for a 6.6 Gev/c beam. This coil placed in the gap of the main guide field magnet, outside the internally circulating beam envelope, and just upstream from the accelerator beam exit port, would allow all the extracted beam to be transported to the external proton beam first focus using existing elements and apertures. Further, it was found that the non-linear Bevatron fringe field makes it desirable to also insert a sextupole coil into this outer fringe field regim to enhance the beam phase space.[1]

Requirements

From beam analysis work, two beam extraction focussing elements were specified, a quadrupole coil and a sextupole coil, with design requirements given in Table No. 1.[2]

Although the coils had to be located in the gap of the Bevatron main guide field magnet, they could not interfere with beam injection and beam acceleration in the Bevatron. These considerations placed further limitations on the design as follows:

1. The coil system had to be contained in an approximate volume of $7\frac{1}{2}$" x 50" retangular horizontal area and 12" vertical height.

2. The coil system had to be placed in the 10^{-7} torr Bevatron main vacuum system.

3. The use of any magnetic material was precluded because magnetic material in the gap of the main guide field magnet would perturb the accelerating guide field.

4. Pulsed operation of the coils so that the injected beam would not be lost during low energy beam acceleration.

5. A 50 gauss-in. eddy current field limitation produced in the coil and support structure by the accelerator guide field to minimize loss of the injected beam.

6. A strong coil support structure to contain the coil forces.

7. A reasonably radiation resistant coil insulation system.

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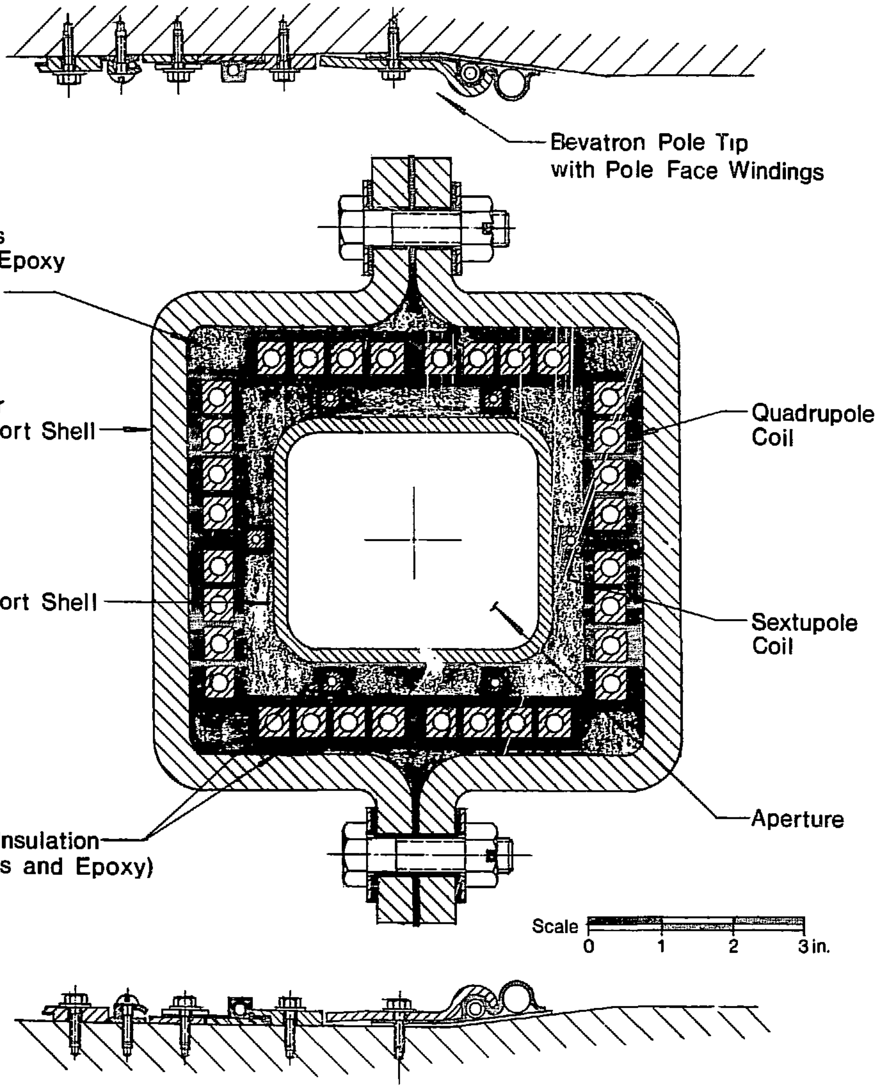

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Fig. 1. Cross-Sectional View of the Beam Extraction Focussing Coils

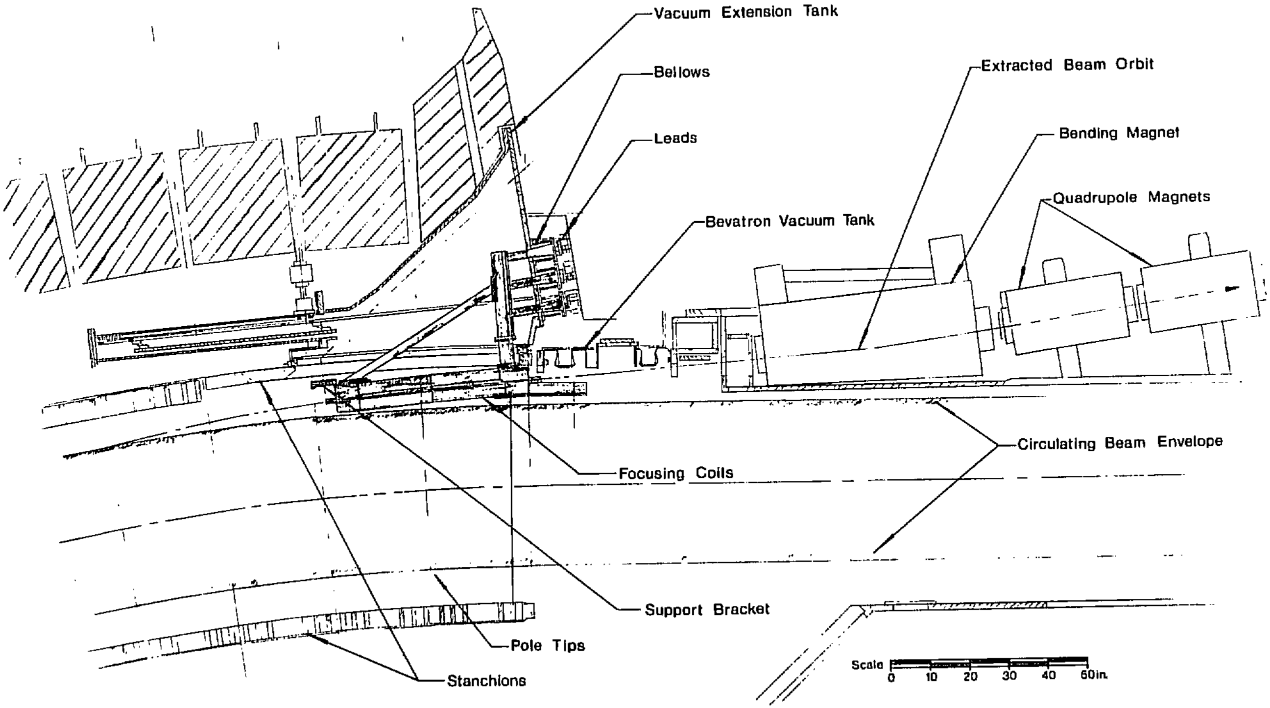

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Fig. 2. Sectional Plan View of Bevatron Showing Focussing Coils

TABLE I. Specified Design Requirements for the Beam Extraction Focussing Coils

Requirement	Quadrupole Coil	Sextupole Coil
Aperture	3.5" horizontal ($X=\pm1.75"$) by 3.0" vertical ($y=\pm1.50"$) clear aperture	Same as quadrupole coil
Field Strengths	Gradient - Effective Length product (integrated gradient) $K_Q \cdot l_{effQ} = 50$kG-in./in. where $B'_{yQ} = K_Q$ and $B_{yQ} = K_Q X$	Sextupole Coefficient - effective length product $K_S\ l_{effS} = 2.25\ \frac{kg\text{-}in.}{in^2}$ where $B_{yS} = K_S\ (X^2 - Y^2)$
Field Accuracy	A combined error, $\frac{\Delta (B_{yQ} \cdot l_{effQ}) + \Delta (B_{yS} \cdot l_{effS})}{B_{yQ} \cdot l_{effQ} + B_{yS} \cdot l_{effS}}$ within a few percent in the central portion of the aperture; $-1.25 \leq X \leq 1.25$ and $-0.75 \leq Y \leq 0.75$	

8. Minimum internal modification of the Bevatron because of the awkward working areas and somewhat radioactive exit beam port area.

Also, for different energy extracted beams, the beam orbits are different through the fringe field, which fact requires remote positioning of the focussing coils.

Design

A nested quadrupole and sextupole coil system was developed with the aid of computer programs QCOIL and POISSON[3] for the beam extraction focussing coils. The integrated quadrupole field, nominally 50 kG-in./in., is obtained with four current sheets, approximated with 32 conductors. Inside the quadrupole, a six conductor coil produces the sextupole field. These are shown in cross sectional view of the coils, Figure No. 1[2]. A plan view of the beam exit area of the Bevatron with the focussing coils is shown in Figure No. 2.

Fields

For the coil configuration shown, two dimensional coil fields were calculated considering the shaped Bevatron pole tips infinitely permeable, saturated at their highest operating field, and with the pole tips removed. A little variation in the fields in the central portion of the aperture was noted considering these three conditions.

The quadrupole gradient was found to be about 1% higher with the pole tips considered infinitely permeable as compared to the pole tips removed which seemed reasonable.

With the quadrupole coil, it was necessary to make two coil sections longer than the other two which introduced a dipole field at the ends of the coil. The total calculated integrated dipole field of 7.9 kg-in. was found acceptable.

Field error calculations, for the case where the Bevatron pole tips were saturated, indicated a quadrupole coil maximum vertical field deviation from a linear gradient of about 3% at the extremities of the central aperture ($X\pm1.25"$). Considering that the magnitude of the calculated sextupole field errors was insignificant when compared to the magnitude of the quadrupole field errors, the 3% represented the combined error and was deemed acceptable.

Parameters

Calculated design parameters, based on the design requirements from Table No. 1, for these two coils are given in detail in Table No. 2[2].

TABLE II. Calculated Design Parameters for the Beam Extraction Focussing Coils

Parameter	Quadrupole Coil	Sextupole Coil
1. Magnetic		
1.1 Effective length (l_{eff})	39.5" (measured 42.2")	46.2" (measured 48.7")
1.2 Gradient (K_Q)	1.269 kG/in.	-----
1.3 Sextupole Coefficient (K_S)	-----	0.0488 kG/in^2
1.4 Integrated dipole field	7.9 kG-in. (measured 9.1 kG-in.)	-----
1.5 Current	5815 Amps	1114 Amps
1.6 Stored Energy	670.6 J	1.66 J
2. Physical		
2.1 Total turns per coil	16	3
2.2 Number of coil sections	4	1
2.3 Number of turns per coil section	4	3
2.4 Conductor	0.467" Sq. x 0.275" ID Hollow copper	0.255" Sq. x 0.125 ID Hollow copper
2.5 Coil length per section	36.6 ft	29.6 ft
2.6 Total coil length	146.4 ft	29.6 ft
3. Electrical		
3.1 Design current(105% of 1.4)	6100 Amps	1170 Amps
3.2 Peak current density	38,900 A/in^2	22,500 A/in^2
3.3 Rms current density	15,300 A/in^2	8,830 A/in^2
3.4 Coil Resistance @ 40 C.	8.36×10^{-3} Ω	5.09×10^{-3} Ω
3.5 Coil D.C. voltage	51.0 volts	5.7 volts
3.6 Power duty factor(based on a 1 sec. flat pulse with a 0.1 sec. linear rise and fall every 6.9 sec.)	0.155	0.155
3.7 Coil power	48.1 kW	1.08 kW
3.8 Coil inductance	39.7×10^{-6} H	2.67×10^{-6} H
3.9 Coil electrical time constant	4.75×10^{-3} sec.	0.525×10^{-3} sec.
3.10 Mutual inductance	-1.5×10^{-8} H	-1.5×10^{-8} H
3.11 Coil inductive voltage	2.31 volts	0.029 volts

Parameter	Quadrupole Coil	Sextupole Coil
4. Cooling		
4.1 Design water temperature differential	20°C	20°C
4.2 Total water flowrate	9.14 gpm	0.21 gpm
4.3 Number of water circuits	4	1
4.4 Water flowrate per circuit	2.28 gpm	0.21 gpm
4.5 Circuit water pressure drop	53.9 psi	27.1 psi
4.6 Coil thermal time constant	3.1°C/sec.	1.1°C/sec.

Fabrication

Coil Winding

Figure No. 3 shows the details of the quadrupole winding. The coil was wound in four sections. Each section consists of four turns each, wound from about 40' of 0.467" sq. by 0.275" diameter hollow copper, with the leads exiting from the Bevatron vacuum tank. For a reasonably compact end configuration and ease in fabrication, two of the coil sections are somewhat longer than the other two. This introduces a small vertical dipole field component at the ends of the quadrupole coil. The coil also has a $1\frac{1}{2}$ degree bend in the middle of its length which gives the coil an approximate fit to the extracted beam orbit curve.

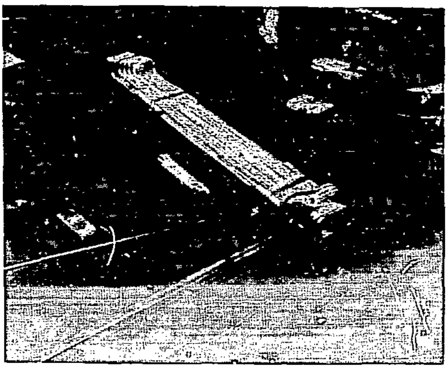

Fig. 3. Bare Wound Quadrupole Coil.

The bare wound sextupole coil wound from 0.255" sq. x 0.125 diameter hollow copper, is shown in Figure No. 4. Note the matching $1\frac{1}{2}$ degree bend which matches the quadrupole coil.

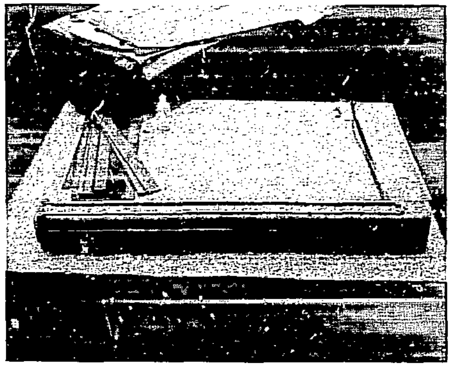

Fig. 4. Bare Wound Sextupole Coil.

Coil Insulation

Two insulation systems were considered for insulating and vacuum potting the coil. One was to use a mineral filled epoxy resin formulation with little glass (little glass is used so the filler will not be strained out) to obtain a resonably radiation resistant coil insulation. Unfortunately, the mineral filled epoxy formulations have some limitations; namely they result in a very brittle material and they do not lend themselves to a void free impregnation. The other approach is to cram as much glass and Nema G-10 into the voids of the coil and then impregnate with a non-filled epoxy resin formulation known to be comparitively radiation resistant, tough, and capable of void free impregnation. Since the coils had to be placed in the main Bevatron vacuum system where voids are very undesirable and would be subjected to pulsing forces, the non-filled epoxy formulation was used.

Figure No. 5 shows some of the glass insulation. All conductors were covered with either two layers of 14 mil. thick braided tight-weave fiberglass sleeving or with 1.0" wide by 7 mil. thick standard weave tape. The minimum insulation thickness between conductors was 45 mils.

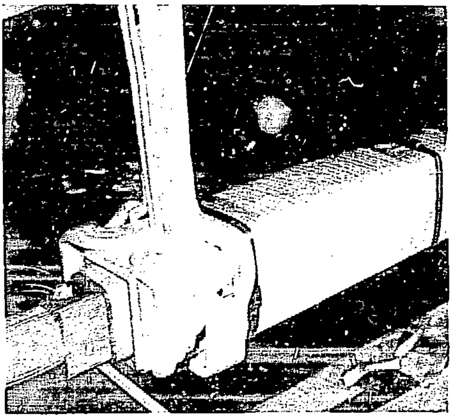

Fig. 5. Fiberglass Insulation Detail.

The coils were vacuum impregnated with a unmodified low viscosity epoxy resin (EPON 826), Polyglycol diepoxide resin (DER 736) and an aromatic amine harderner (TONOX) formulation per LBL Specification M20C[4].

Coil Support Structure

A metallic support was built to contain the coil and coil forces, up to 360 lb/in.[2].[5] This was done instead of relying on the questionable strength of the epoxy fiberglass insulation after radiation by the extracted Bevatron beam. Annealed 304 stainless steel was selected for the support structure material because of its comparatively high elastic modules and high electrical resistivity and acceptable magnetic permeability of less than 1.02.

Basically, the support structure consists of three parts as shown in Figure No. 1. The inner shell is a 0.188" thick pipe that has been squashed into a rectangular shape which provides the clear aperture of 3.5" by 3.0". The two outer shells are fabricated from $\frac{1}{2}$" plate and welded at the ends. To achieve welds that were crack free and non-magnetic, a permeability of less than 1.02, Kromarc 55 (a Westinghouse trademark) welding rod was used. Bolting at the top and bottom was selected primarily to keep the support structure horizontal radial dimensions small. This allows for a maximum length coil. Also, with the small horizontal radial dimension the eddy currents induced by the Bevatron vertical guide field are less. All the sections of the support structure are insulated from one another to minimize eddy currents and grounded through resistors. Calculations showed the eddy currents to be less than 50 gauss-in. at the outer edge of the beam envelope. The support structure is shown in Figure No. 6 and also functioned as the potting mold for the coils.

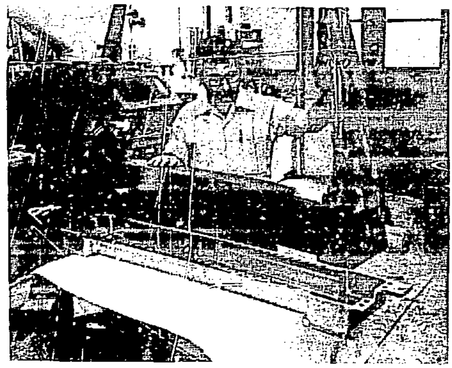

Fig. 6. Support Structure and Coils After First Potting.

Coil Fabrication

Fabrication of the coils followed the following basic steps.

1. Coil winding.

2. Coil insulating with fiberglass sleeving, tape, and Nema G-10, and assembling coil sections with the coil support structure.

3. First vacuum impregnation of the coil.

4. Removal of outer coil support structure and repair of casting.

5. Coil lead forming.

6. Coil lead insulating with fiberglass sleeving, tape, and Nema G-10, reinstallation of

the lead support structure.

7. Final vacuum impregnation of the coils and leads. The final impregnation also included the coil which allowed the coil shrinkage voids from the first impregnation to be filled.

Figure No. 7 shows the completed coil and leads. The strange configuration for the leads was a design restriction imposed by the Bevatron vacuum extension tank where it was convenient to bring the utilities to the coil.

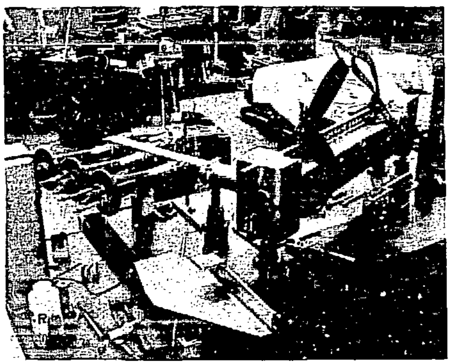

Fig. 7. Focussing Coils and Support Structure

Electrical tests were performed at various stages of fabrication. After the first impregnation, the quadrupole coil was successfully impulse tested to 1600 volts with its outer support shell removed. After final potting, DC high-pot tests to 3 KV were successful between the two coils and from each coil to ground.[6]

Hydraulic tests were also done on the coils. Flowrates were recorded through the various circuits at 40, 60, & 80 psi pressures and found to be satisfactory.

Drive Units

The support structure assembly positioned in the gap of the Bevatron main guide field is movable in the radial direction and restrained in the vertical and azimuthal positions.

Radial positioning of the coil is accomplished with two independent drives, an upstream and a downstream drive unit. Each unit has a stainless steel screw turning in a naval broze nut, lubricated with Apiezon H vacuum grease, which gives radial movement. The screws in turn are driven with Slo-Syn motors through chain drives. The upstream and downstream positions are read with counters. The upstream drive unit has a 1.9 in. normal travel range and the downstream end a 0.6 in. normal travel range. The travel range limits are set by micro-switches. If these fail, positive stops prevent the threads from locking.

The assembly is restrained vertically at each end, three points total, with polished stainless brackets, attached to the coil support structure, which slide between surfaces of Teflon impregnated bronze Glacier DU bearing material. Azimuthally the coil structure is restrained by the upstream drive unit which has a trunion nut to allow for horizontal rotation.

Fortunately, the net pulsing coil forces are small, 70 lbs. azimuthally and 54 lbs. radial. The major loading on the coil is due to the vacuum loading where the coil leads come through the Bevatron vacuum extension tank. Bellows are required with the leads to allow for the necessary coil motion.[5]

Magnetic Measurements

Magnetic measurements were made on the focussing coils prior to installation into the Bevatron because:

1. Precise measurements were not needed.

2. It is very difficult to work in the Bevatron in the area where the coils are located.

3. The area is also somewhat radioactive.

Vertical field integral measurements were taken for both the quadrupole coil at 1800 amperes and the sextupole coil at 420 amperes, in air and also in a flat pole iron gap which approximated Bevatron geometry. Measurements were made with two search coil, each 66 inches long mounted side by side with a $1\frac{1}{2}$ degree bend in the middle corresponding to the centerline axis of the coils, two X-Y stages which positioned the coils and two integrators with a digital voltmeter. Voltage was induced in the search coil by turning the magnet power supply on and off.

The measurements substantiated the field calculations except that the assumed calculated effective lengths of the coils were less than those measured which is good. A 1% increase in the gradient of the quadrupole with the coil measured in the iron gap was seen when compared to the coil measured in air which was expected.

For the quadrupole coil measured in the flat pole iron gap, in the central aperture, $-1.25 \leq x \leq 1.25$ and $-.75 \leq y \leq .75$, maximum deviation of the vertical field integral from a fitted linear curve through the data points was $1\frac{1}{2}\%$ at the aperture extremities($X=\pm1.25$). The measurement uncertainty was about ±1%. The calculated field error for this geometry was 1% at the aperture extremities which indicates that the field measurements substantiate the calculations. From the above, one should expect to obtain the calculated 3% field deviation from a linear gradient for the actual Bevatron geometry which satisfies the design requirements. The sextupole coil vertical field measurements gave expected results with the magnitude of the errors being less than the quadrupole coil field errors.[8]

In the central aperture, the vertical field integrals measured in the iron gap, as a function of current are given by[8]:

Quadrupole Coil

$$(\int B_y \cdot dl)_{QI}\ (\text{kG-in.}) = (1.568 + 9.277\ X\ (\text{in.}))\cdot 10^{-3} I\ (\text{amp})$$

Sextupole Coil

$$(\int B_y \cdot dl)_{SI}(\text{kG-in.}) = 2.133 \cdot 10^{-3}(X^2(\text{in}^2) - Y^2 (\text{in}^2)) \cdot I\ (\text{amp})$$

Installation and Operation

The focussing coils and positioning equipment were installed during a five day vacuum shutdown in the later part of June 1972. Figures No. 8 and No. 9 show the upstream and downstream sections of the focussing coils during installation.

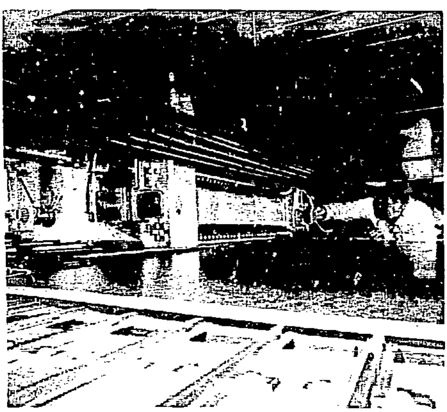

Fig. 8. Upstream End of Focussing Coil During Installation.

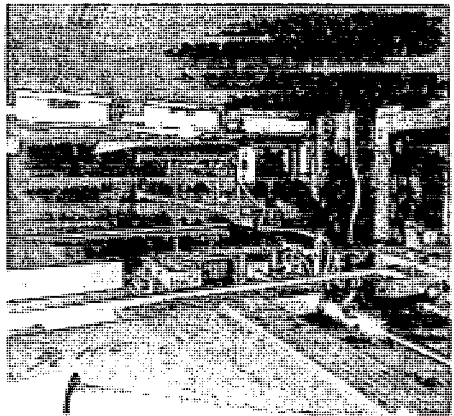

Fig. 9. Downstream End of Focussing Coil During Installation.

Note that space is at a premium and that the support structure fills the entire gap. In Figure No. 8., the clear bore aperture can be seen. The upstream threaded drive shaft and trunion nut are behind the round disc which is the outer stop. Figure No. 9 shows the downstream drive shaft counter, and support bracket.

The focussing coils have operated successfully with the Bevatron proton beam during test and are currently undergoing beam development tests.

Acknowledgement

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