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EXTRACTION AND TRANSFER OF HIGH-QUALITY BEAMS FROM SYNCHROTRONS OF THE FOOFDOD TYPE WITH APPLICATION TO THE OMNITRON*

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ABSTRACT

Acceleration of ions of low charge-to-mass ratio in the Omnitron is accomplished in two acceleration cycles with the beam transferred between the synchrotron and the concentric storage ring between cycles. Successful tandem acceleration requires that the beam quality be maintained through each ring-to-ring transfer. The extraction method here described provides a ring-to-ring match in both betatron phase planes, including dispersion. Maximum efficiency is obtained from the deflecting magnets as a consequence of both kicking and extracting at the point of maximum radial betatron amplitude. The beam path and focusing are chosen to minimize the aberrations due to passing through the extreme fringing magnet in the accelerator gradient magnets. This requires a special focusing magnet in the accelerator extraction line and the shimming of two storage ring gradient magnets.

I. INTRODUCTION

The quality of the extraction line elements is more important in the Omnitron than most accelerators because 3-4 traversals of these elements are necessary to obtain the high-energy heavy-ion beams for biomedical research. In this process, ions of low charge state are accelerated to the maximum magnetic rigidity, extracted, and stored in a concentric storage ring while the synchrotron magnetic field returns to its injection value. The ions are then stripped to a high charge state and reinjected into the synchrotron for acceleration to a much higher energy.[1]

During the extraction and reinjection process, the beam must pass through four ferrite kicking magnets. Because of the rapid rise (or decay) required in the kicker magnets, current regulation will be difficult to achieve, and the ringing and noise will randomly deflect portions of the beam in the radial plane, degrading the quality of the beam. The phase space of the beam will be uniformly further diluted by Coulomb scattering upon passage through the stripping medium.

The object of the design of the extraction and reinjection transport systems is to match the beam in transverse phase space, as well as the dispersion, and to minimize degradation of beam quality due to uncompensated aberrations along the beam path. Damping of betatron amplitudes occur over the first acceleration cycle. The maximum dilution of transverse phase space due to the above mentioned processes that can be tolerated, brings the emittance back to its original injection value upon commencing the second acceleration cycle.

II. GEOMETRY OF EXTRACTION COMPONENTS

The displacement of the beam at some azimuthal point B due to a radial kick at a point A of magnitude $\Delta r'_A$ is

$$\Delta r_B = \Delta r'_A \sin \mu \sqrt{\beta_A \beta_B}$$

where β is the Courant-Snyder amplitude function and μ is the betatron phase advance between A and B. The maximum amplitude, for a given deflection, occurs when the deflector magnet and the extraction septum are located at points of maximum (radial) betatron amplitude and separated by $\pi/2$, $3\pi/2$, in phase angle.

The required displacement is at least equal to the sum of the width of the beam at the extraction septum location and the width of the septum. The septum must be clear of the portion of the vacuum tank occupied by the beam during injection. If the useful width of the magnetic field at full energy is be less than that at injection, an additional amplutide will be required to clear the region between the radial extent of the useful field at extraction and the septum. Assuming a fixed septum width, a smaller kick is required for a septum located where the radial betatron amplitude is maximized than elsewhere.

In the FOOFDOD design β_z attains a relative minimum value in the OO straight section (between pairs of F magnets) where β_x attains a, relative maximum value. Placing the extraction components in these straight sections results in minimum magnet gaps as well as optium efficiency. This and other considerations dictated the choice of the FOOFDOD configuration for the Omnitron.

The deflection required of the ferrite kicker magnets is substantially reduced when a thin septum magnet is added to the extraction system. Extracting with a septum magnet in one straight section requires a deflection of about 150 mrad, which is excessive for a thin septum. Using a much smaller deflection (16 mrad) brings the beam out through the fringing field of the following cell, emerging from the ring in the next FF straight section. An additional benefit of locating the thin septum between pairs of F magnets is that in this case flux leakage beyond the thin septum is minimized. If slow extraction were ever required from the accelerator the thin septum magnet will serve the function of deflecting both the fast and slow extracted beams from the synchrotron through the same channel.

III. GRADIENT MAGNET FIELD PROFILE

The magnetic field profile of the Omnitron gradient magnets[2] is shown in Fig. 1; that of the storage ring is similar. Extracting in the F-F drift space means the beam must pass through the final F magnet in the vicinity of the "knee" beyond the constant gradient region toward the narrow gap of the magnet. It is not economically feasible to increase the width of the constant gradient portion of the aperture on the high field side of the (rapid cycling) synchrotron magnet.

Unlike the (constant field) storage ring magnet, it is not feasible to shim the synchrotron magnet to provide a separate constant gradient region along the path of the extracted beam as is shown in Fig. 1 for the storage ring magnet DM. This is because of the magnetic nonlinearities in this region and the requirement for extraction over a wide range of ion energies (The ring-to-ring transfer system must also serve to provide extracted beam direct from the synchrotron to the experimental areas).

The solution is to bring the beam throgh the last F magnet close to the return leg, well beyond the very nonlinear knee region. It is possible to design the gradient magnets so the field in this region, along the revised extracted beam path, is close to a pure sextupole field[2] with effects which can be corrected in the beam transport system. The deflection required to bring the beam through this region of the F magnet is still less than that required to extract in a comparable FOFDOOD design.

The effect of the large defocusing field beyond the knee, as well as the aberrations induced in this region, can be minimized by introducing additional radial focusing ahead of the last F magnet as shown in Fig. 2. In the Omnitron the optimum location for this focusing is just ahead of the F magnet; it is provided by a 20 cm septum quadrupole with a 3.7 kG/cm gradient as shown. If it could be built, a higher gradient would be desirable to minimize the width of the beam through the F magnet.

IV. TRANSFER TO AND FROM THE STORAGE RING

Transfer to the storage ring poses different problems because of the inside location of the transfer lines. The discussion here refers to extraction (reinjected beam), but injection is just the mirror image.

In extracting from the inside of the storage ring, a septum magnet (SB, Fig. 4), placed in a long straight section, deflects the beam 16 mrad radially inward. At the next short straight section, the beam is beyond the normal aperture, and a thicker septum magnet M3 deflects the beam 37 mrad. The beam is now directed so that, as it enters the next magnet DM, the field is falling rapidly. The beam cannot now simply be allowed to traverse the fringe fields of DM and FM as it will not then leave the ring. This is because the extraction orbit in this case receives much less bending than the reference orbit and thus bends sharply towards the outside of the ring. This orbit is shown in Fig. 3. This is avoided by shimming the fields of DM and FM to maintain them as high as possible. With shimming, as shown in Fig. 1, the orbit shown as a heavy line in Fig. 3 results.

This shimming is accomplished by placing additional iron in the fringe field region as was done for the CERN PS extracted beam.[3] After emerging from the ring magnet FM, the beam is nearly parallel to the reference orbit, but it has been displaced about 16 cm. This leaves ample room for the return yoke of magnet M1 which bends the beam 4.5°.

V. MATCHING

To minimize excursions in the storage ring, and subsequently in the second cycle in the main ring, the transfer section must provide an envelope match in both planes and also to provide a perfect match in angle and displacement from the off-energy equilibrium orbit in the synchrotron to the equilibrium orbit of corresponding energy in the storage ring. A perfect match is one where the beam widths, divergences, and dispersive displacement and relative slope at the end of the transfer system, including the shimmed first cell of the storage ring, are equal to a matched storage ring beam of equal emittance at that location. The radial dispersion is completely specified whereas one degree of freedom remains in both the radial and vertical transfer matrices.

The parameter adjustment was performed using the IBM 7094 digital computer code 4P which can meet up to 20 conditions on the beam simultaneously.[4] The code uses one of two algorithms in achieving parameter optimization: (1) minimize the maximum weighted error in meeting the set of conditions, or (2) minimize the weighted sum of errors in meeting these conditions. The linear programming method used in 4P automatically incorporates constraints upon the minimum and maximum values of adjusted parameters, restricting solutions to physically realizable parameters.

In the problem here considered weighting of individual beam conditions was chosen so that equivalent weighted errors represented equally bad mismatches. All quadrupole gradients and drift spaces were adjusted, subject to the additional constraints that the bending magnets in the transfer line were not to be moved. In the absence of constraints, one would expect to obtain a perfect (six condition) match with the adjusting of six physical parameters. Ideally six quadrupoles with suitable spacing would be used, but physical limitations due to the short transfer line (Fig. 4) make this impractical.

It is characteristic of the linear programming algorithm that several of the parameters will have as optimum values, the maximum value permitted. This is, of course, correct for a problem in which the objective function to be minimized and the constraints are truly linear functions of the parameters being optimized. If the initial values of the parameters are "close" to the optimum values, the actual nonlinear problem will be solved in a few iterations. Adequate "closeness" is defined as having the initial and optimum parameter points being in the same "valley" in the n+1 dimension space whose coordinates are the values of the n parameters being'varied and the objective function being minimized.

Solution convergence is generally enhanced by adding more conditions and constraints to the problem, even through these additional quantities are actually redundant. Adding them serves to eliminate "valleys" in the n+1 dimension space that do not contain the solution. This is necessary if the initial values of the parameters lie far from the optimum values.

Thus the problem presented to 4P specified all of the envelope conditions at the center of the long straight section in the storage ring and, in addition, most of the envelope requirements entering the magnet FM plus the additional specifications that the envelope width must not exceed a set value anywhere within the transport system. Several good solutions to this problem were obtained. Cathode ray tube envelope plots of two of them are shown in Fig. 5 (five quadrupole match) and Fig. 6 (two quadrupole match). These show the beam as it leaves the last F magnet of the synchrotron to where it enters the magnet FM of the storage ring. The first curve above the axis represents an ion with momentum error $\Delta p/p=0.5\%$. The five quadrupole match has a residual relative error of 5% in x envelope, 44% in the y envelope, and 6 % in the dispersion. The two quadrupole match has residual errors of 20%, 97%, and 32%. As the energy spread is expected to be quite small in the Omnitron, the match in the y plane can be improved at the expense of the match in dispersion, if desired. The transport system will also include sextupole magnets to correct residual aberrations occuring in the fringe fields.

VI. REFERENCES

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

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2. K. Halbach, private communication.
3. A. Asner, P. Bossard and C. Iselin, Proceedings of the International Conference on Magnet Technology, Standard, 1965, p. 126
4. P. Meads, Nucl. Instru. and Meth. 40 (1966), p.166.

FIGURE CAPTIONS

Fig. 1. Field profile of gradient magnets. Shimming required for magnets at the point of entry to the storage ring is also shown.

Fig. 2. Extraction orbit in last half-cell of accelerator.

Fig. 3. Reinjection orbit, showing extraction from last half-cell of storage ring.

Fig. 4. Plan showing elements of transfer line between accelerator and storage ring.

Fig. 5. Beam envelopes for a 5-quadrupole match. Locations of elements are as shown in Fig. 4 except for Q1 and the adjacent M1, which have been moved.

Fig. 6. Beam envelopes for a 2-quadrupole match. Q4 has the position shown in Fig. 4, but Q5 is moved closer to Q4.

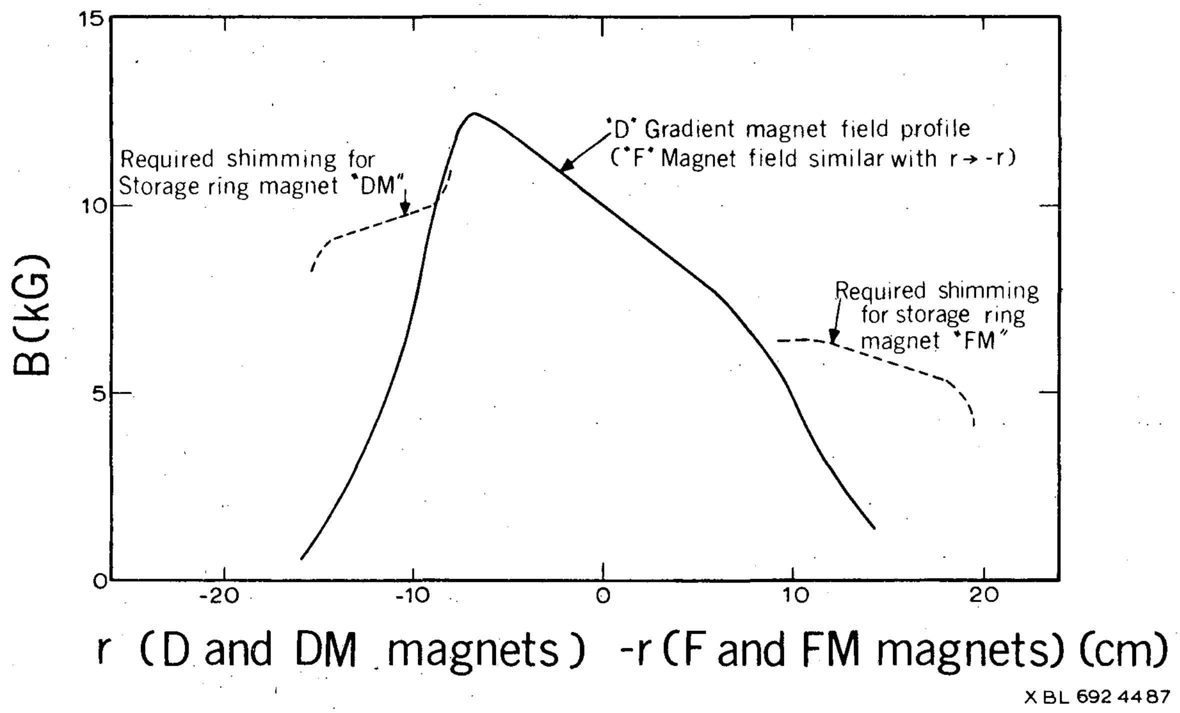
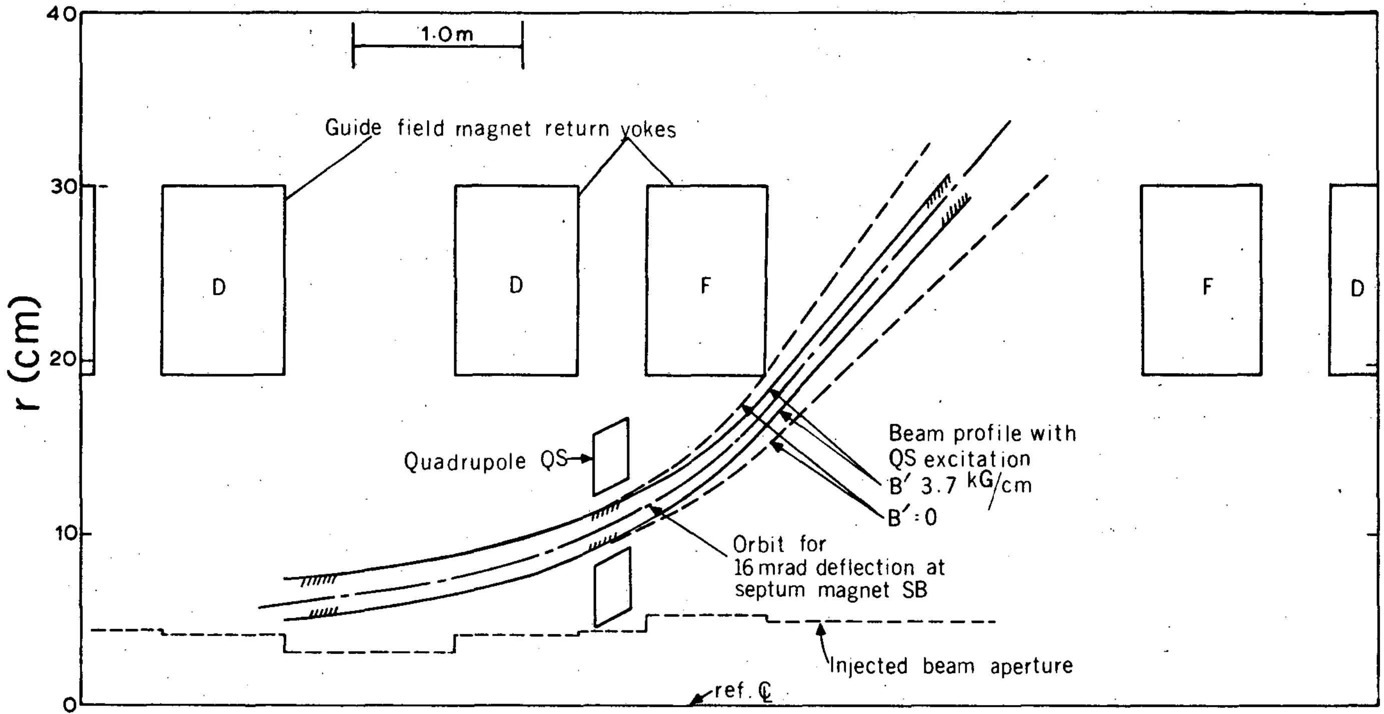

15
10
5
0
B(kG)
-20
-10
0
10
20
r (D and DM magnets) -r(F and FM magnets) (cm)
'D' Gradient magnet field profile
('F' Magnet field similar with r → -r)
Required shimming for
Storage ring magnet 'DM"
Required shimming
for storage ring
magnet 'FM"
XBL 692 4487

Fig. 1



XBL 6924488

Fig. 2

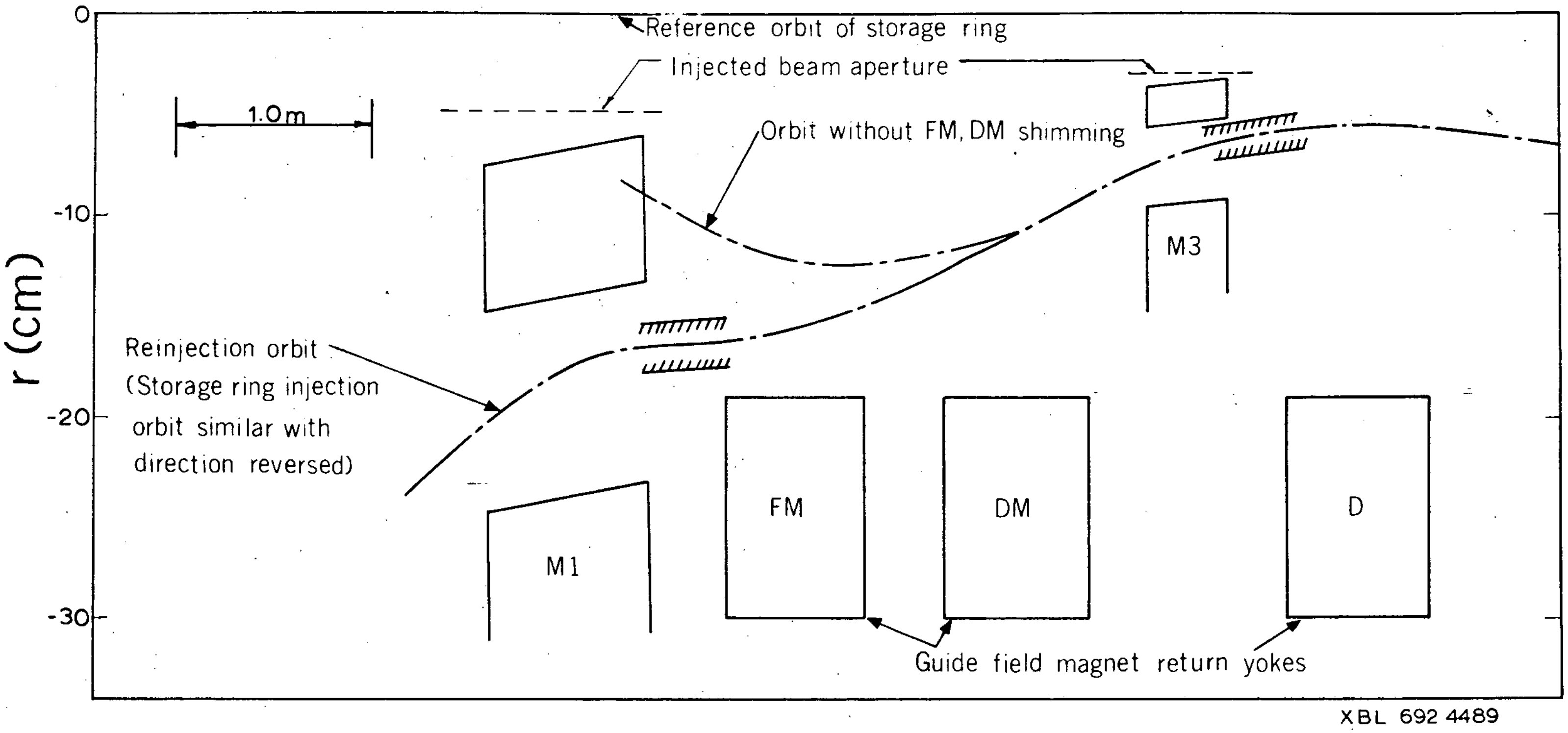
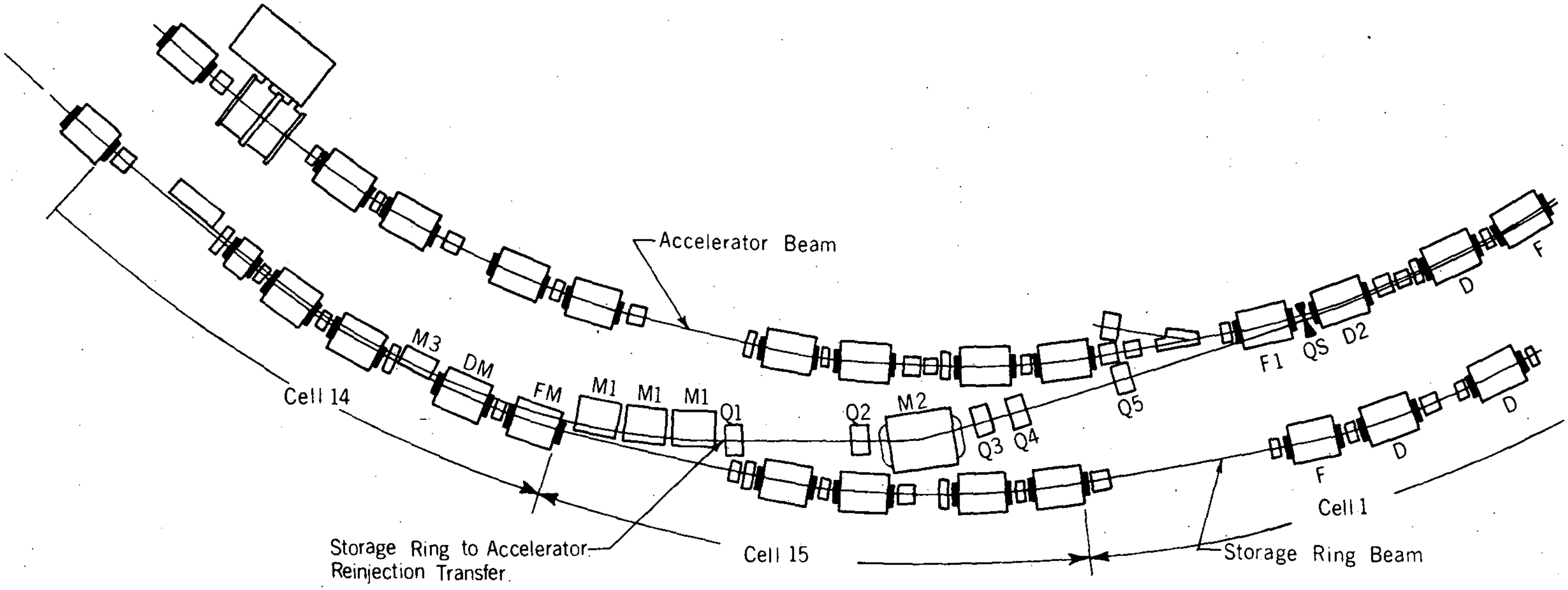

0
-10
-20
-30
r (cm)
1.0m
Reference orbit of storage ring
Injected beam aperture
Orbit without FM, DM shimming
Reinjection orbit
(Storage ring injection
orbit similar with
direction reversed)
M1
M3
FM
DM
D
Guide field magnet return yokes
XBL 692 4489

Fig. 3



XBL 692 4495

Fig. 4

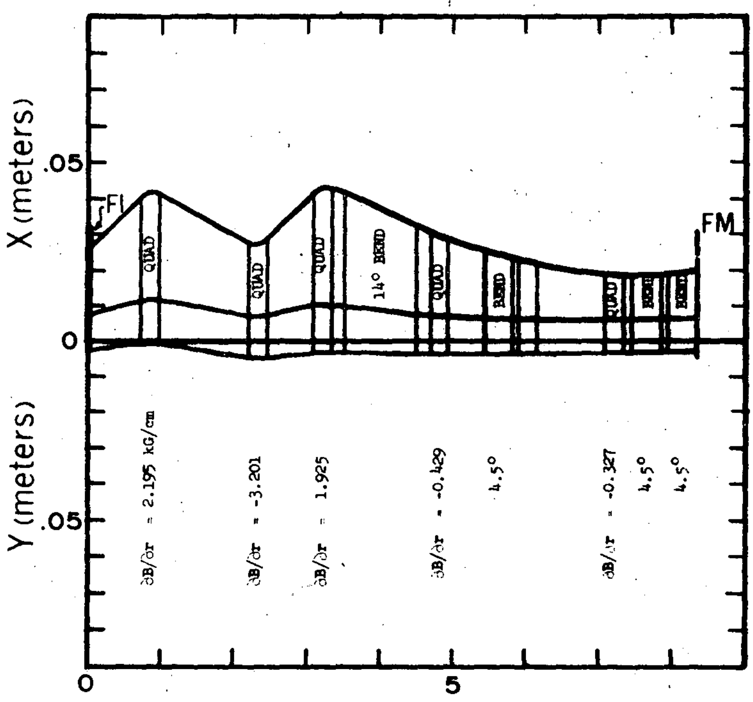

X (meters)
Y (meters)
.05
0
.05
0
5
FI
FM
QUAD
QUAD
QUAD
14° BEND
QUAD
BEND
QUAD
BEND
BEND
∂B/∂r = 2.195 kG/cm
∂B/∂r = -3.201
∂B/∂r = 1.925
∂B/∂r = -0.429
4.5°
∂B/∂r = -0.327
4.5°
4.5°

Fig. 5

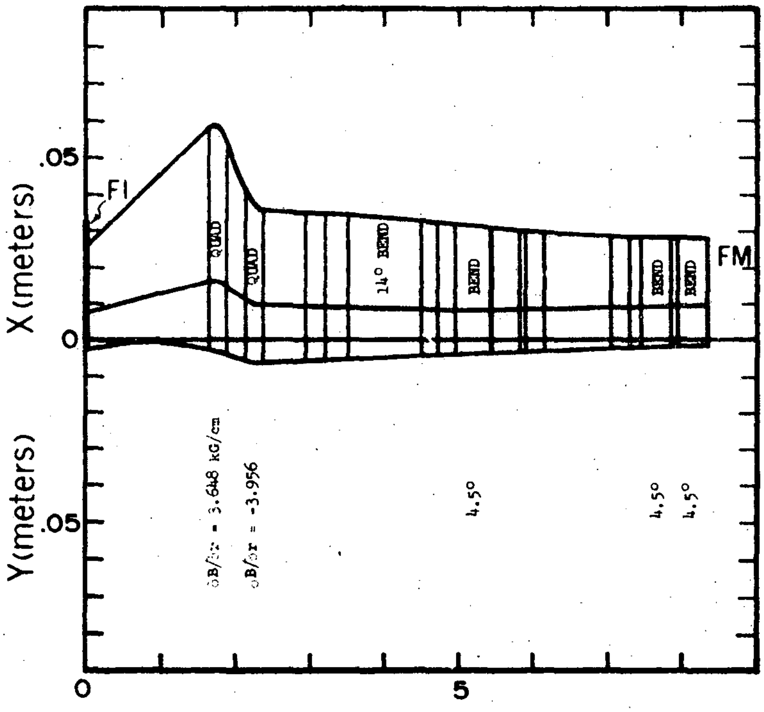

X(meters)
Y(meters)
.05
0
.05
FI
FM
QUAD
QUAD
14° BEND
BEND
BEND
BEND
∂B/∂r = 3.648 kG/cm
∂B/∂r = -3.956
4.5°
4.5°
4.5°
0
5

Fig. 6

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