ACCELERATOR MAGNET DEVELOPMENT AT CRNL

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The proposed proton beam current in the linear accelerator for Atomic Energy of Canada's Intense Neutron Generator is 65mA. Since this is some orders of magnitude higher than in any other existing or proposed accelerator, there are two unique requirements for the ING magnets: they must be of high quality, to spill as small a fraction of this current as possible; and they must be able to withstand a higher radiation dose from the particles which are spilled than magnets in other accelerator installations. We require 100% duty factor, but do have the advantage of fixed energy, and so constant excitation.

Figure 1 shows a preliminary estimate of the dose rates in different sections of the accelerator(1). These dose rates are arrived at by using the allowable spill rate which results in an acceptable radiation field at machine components 10 hours after shut-down: it is accepted that local dose rates could be 100 times higher than those shown, and the uncertainty is large; as yet there has been no analytical prediction of lateral beam spill. Conventional epoxy-fibreglass insulation has a life, generally set by mechanical failure, of about 6 x 10^3 MRad. This, together with the requirement of brazing or welding the drift-tube quadrupoles into their housing, has led to an investigation of ceramic and oxide insulation system for our magnet windings, to achieve adequate life in their radiation environment. These offer the prospect of withstanding doses of 10^5-10^6 MRad, and will be used where the configuration allows.

However, we feel it is necessary to estimate the spill rate which will be achieved, and, since the data are not readily available from other installations, we are proposing an experiment to measure beam spill in our own 25 MeV tandem Van de Graaf accelerator, as shown in Figure 2. Here, the emittance of the 15μA proton beam from the accelerator is controlled by two sets of slits in X and Y planes. The beam then passes through a carefully mapped quadrupole doublet, and downstream a search is made for particles outside the expected boundary. For this we will use a Li-drifted silicon detector, which has enough sensitivity to sense individual protons. The intention here is to determine experimentally the quality of magnetic focusing fields which will be required to achieve the low beam spill which is necessary. Prediction of the beam spot dimensions at the detector plane is shown in Fig. 3, for perfect thick quadrupoles.

Now, to turn to the magnet requirements of the accelerator proper:

Table 1

ALVAREZ SECTION

DRIFT-TUBE QUADRUPOLES:

	Gradient	Dimensions	
1st Tank	5 kG/cm	1.5 cm ID	10 cm OD
(2 βλ)	2 kG/cm	1.5 cm ID	10 cm OD
Others	4 kG/cm	1.5 cm ID	10 cm OD
(1 βλ)	1 kG/cm	3 cm ID	8.5 cm OD

REEL WINDING: INSULATION POLYIMIDE FILM
DOSE 10^3-10^4 M Rad

TUBE WINDING: INSULATION CERAMIC ENAMEL
DOSE 10^4-10^5 M Rad

Table 1 shows the current design of the Alvarez section with 43 cells each requiring a quadrupole, in a 2 βλ first tank, and from 66 to 28 cells per tank in the remaining 8 βλ tanks, requiring a quadrupole in alternate cells, or 155 magnets. To provide the high gradients of the first two tanks, where, in addition, the drift tubes are short (from 8.2 to 19 cm, leaving end-winding space of only 1 to 3 cm), we are proposing to use the reel winding developed by Main, Haughian and Meuser at LRL(2). Figure 4 shows the winding assembled on the yoke and pole structure.

The requirements of tanks 3 to 9, ranging from 2.6 kG/cm at 1.5 cm ID to 1 kG/cm at 3 cm ID, can, we feel, be met by a hollow conductor winding, even with our 100% duty factor. We propose using a square-section conductor, multi-layer coils, and fired ceramic enamel insulation (on the poles and yoke for ground insulation, and on the conductor for inter-turn insulation)(3). Our current tests are directed to making the brazed connections between coils, and to the leads coming up the drift-tube stem. These leads we plan to make from a dual-concentric copper tube, insulated with magnesium oxide, as this type of construction not only has high resistance to radiation damage, but also permits considerable deformation without affecting the insulation quality: this makes bending and flattening of the leads, where required, much easier.

Table 2

COUPLED CAVITY SECTION

	Gradient	Dimensions
DOUBLETS	3.25 kG/cm	5 cm ID
	2.5 kG/cm	5 cm ID
ELECTRO-MAGNETS	1) Al Coils, Anodized Strip 2) Cu Coils, Al_2O_3 or ZrO_2 Foil Insul.	
SINGLETS	900 G/cm	5 cm ID
	450 G/cm	5 cm ID
PERMANENT MAGNETS:	Oriented Barium Ferrite	

Table 2 gives the magnet requirements for the coupled-cavity section of the accelerator; focusing occurs between each of the 322 tanks, and doublets and singlets are used, their strength decreasing as the proton energy increases. The field required at the pole tips of the doublets--6.2 to 8.2 kG--requires these to be electro-magnets, and in addition to trying to make the coil insulation radiation-resistant, as we indicate here, we intend making provision to replace defective magnets by having them open, clam-shell fashion, as shown in Figure 5. The winding proposed initially is an anodized aluminum strip 7/8 in. wide x 0.060 in. thick, with each coil consisting of three pancakes. The whole magnet, on its support structure, can be moved laterally for replacement; quick electrical disconnects are used for the magnet separation, and for connecting it to its base. The coils are air-cooled. Table 2 shows that the gradient requirements for the singlets are much less (they are 20 cm long, compared to 10 cm per section for the doublets). It is hoped that most of these quadrupoles can be permanent magnets; to date, gradients of 630 G/cm have been reached with an arrangement as shown in Fig. 6. Figure 7 is a photograph of the assembled magnet. This quadrupole is also removable from the beam tube by hinging one half, but in this case, it is not only for easy replacement that the magnet splits; the initial separating force on these magnets is 1700 lbs, and assembly is decidedly tricky without the cam-and-hinge arrangement. Fig. 8 shows the magnet in its open position.

Now a few words about the design of quadrupole magnet pole tips. Because of our concern about the field quality required to minimize the beam loss, we have attempted to design our magnets on an analytical basis. Fig. 9 is an outline, ψ is the magnetic potential and B the flux density. This approach was used by Lari and Ballendir of ANL(4), who applied it to circular arc pole tips with good agreement with measurement. The flat-face pole concept was tried by Danby and Jackson of BNL(5); they, like Wolfe and Blackstein at Chalk River, found that changing the ratio of slot width to aperture, Fig. 10, permits minimizing one of the harmonics, say the 6th, but not several simultaneously. To obtain more degrees of freedom, Keech at Chalk River has developed a pole-tip shape, Fig. 11, in which the angles α and θ can be varied to give simultaneous minima of 6th, 10th and 14th harmonics. This design at present does not take the variation of potential at the coil into account.

Only 6th, 10th and 14th harmonics are considered, since the strong radial dependence of the higher harmonics ($\left(\frac{R}{R_o}\right)^{16}$ for the 18th, for example) makes them negligible over most of the magnet aperture; the usable aperture is defined by the beam tube. Good agreement has been found between the measured harmonics in a (poor) quadrupole, and those derived from the magnetostatic program TRIM(6).

	m=2	m=6	m=10	m=14
Measured:	100	3.33	2.89	1.24
TRIM :	100	3.37	2.44	1.26

These values are in scalar potential, at full bore.

This covers most of the aspects of magnet development currently under way at CRNL: there are also closely related programs of precision magnetic measurements and alignment.

References

1. I.M. Thorson, AECL, Private Communication.
2. R.M. Main, J.M. Haughian and R.B. Meuser, "High Gradient Drift-Tube Quadrupole Magnets", UCRL-17156, September, 1966.
3. E.D. Bush, Jr., "Mechanical Design of Drift tubes and Quadrupole Magnets for the Alvarez Linac "Proc. of the 1966 Linear Accelerator Conf., LA-3609, p. 157.
4. R.S. Lari and G.J. Bellandir, "Calculation of the Harmonic Content of Asymmetrical Quadrupole Magnets", ANL report RSL/GJB-2.
5. G.T. Danby and J.W. Jackson, "Magnetic Measurements of AGS Experimental Beam Quadrupoles", BNL Internal Report, 1963.
6. J.S. Colonias and J.H. Dorst, "Magnet Design Applications of the Magnetostatic Program Called TRIM", Proc. of Int. Symposium on Magnet Technology, 1965.

DISCUSSION

(A. Harvey)

VOICE: Did you try aluminum oxide as an insulator and what was the result?

HARVEY, AECL: We were not the first people to try this. In the 1930's the Swedes were winding generator rotors with anodized aluminum strip conductors. We discovered this because a manufacturer received one of these to repair after it had been in service for 30 years. If we can do this we would be quite happy. Our problem nowadays is to get aluminum with the anodized coating on it. The aluminum is preferably in strip form and passed continuously through an anodizing bath. We have set up a prototype of such a bath in Canada. We have a manufacturer who has produced samples of anodized foil for us. I believe there are sources in the U.S.

POLK, BNL: What is the thickness of the oxide coating?

HARVEY, AECL: Since we have only got our first samples of foil, we have wound no coils and have set no specifications for the thickness. You can get very good voltage breakdown characteristics with a coating thickness of 0.0001 to 0.0002 inches.

BLEWETT, BNL: From the first picture you showed of a high field quadrupole, it wasn't clear to me what was the geometry of the winding, or how it was put together.

HARVEY, AECL: The next paper deals with the construction of these high-gradient drift-tube quadrupoles.

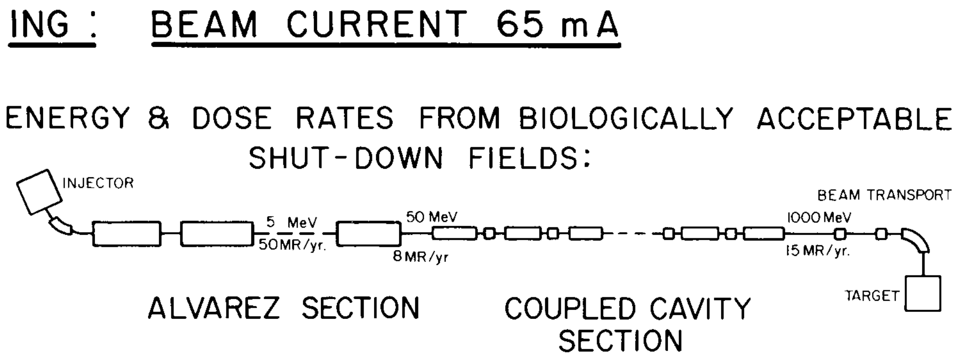


Figure 1 Energy and Dose Rates in ING

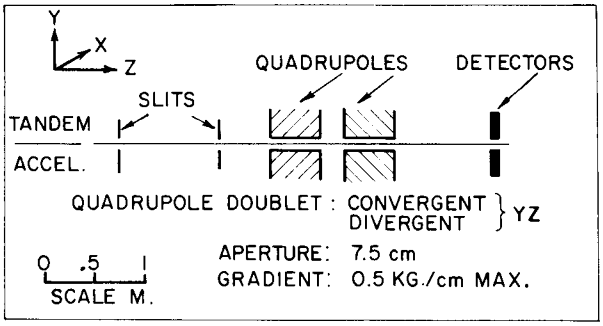


Figure 2 Beam Spill Experiment, Ion-optical system

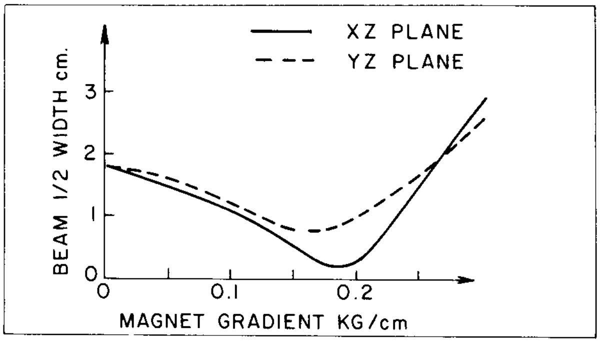


Figure 3 Beam Size vs. Magnet Excitation

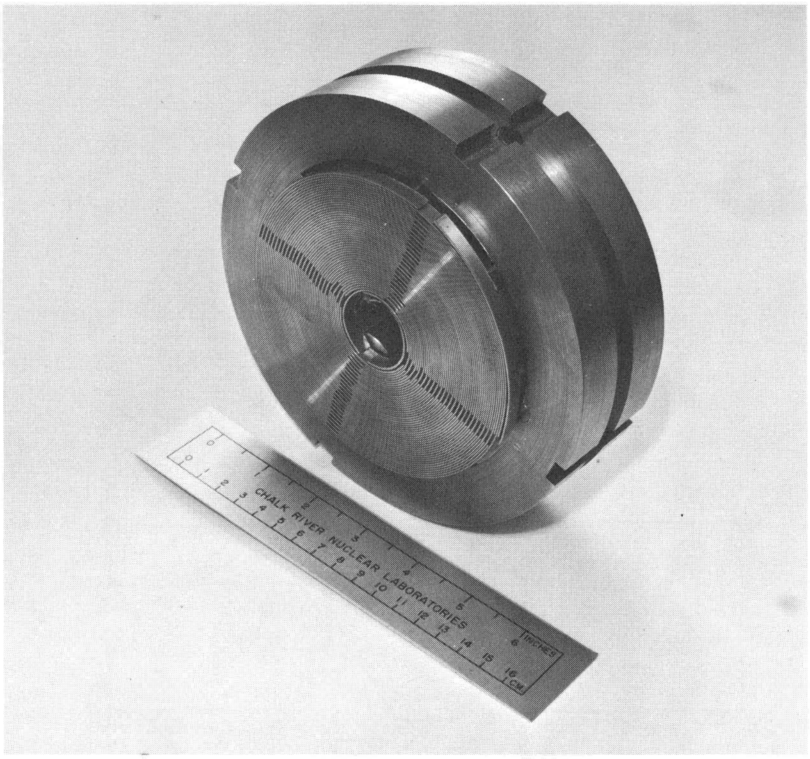


Figure 4 Reel-wound Alvarez Quadrupole

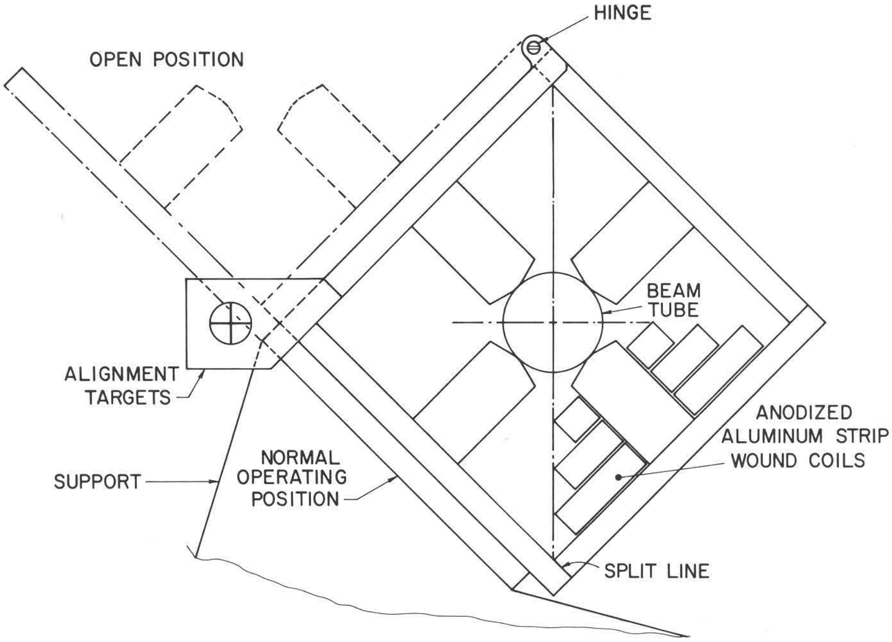


Figure 5 "Clam Shell" Quadrupole

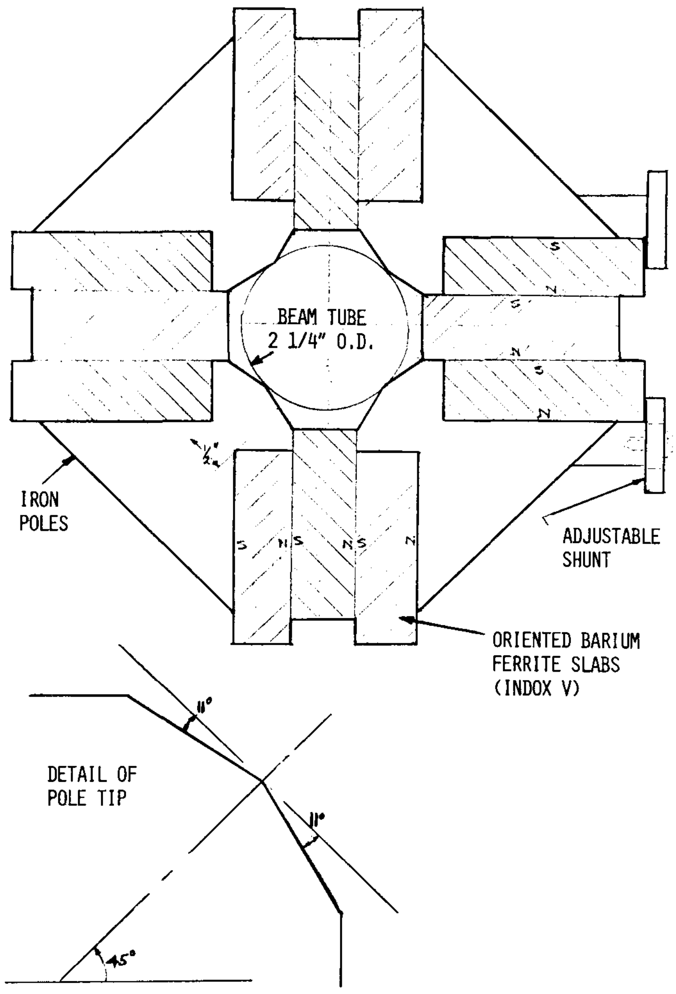


Figure 6 Permanent Magnet Quadrupole

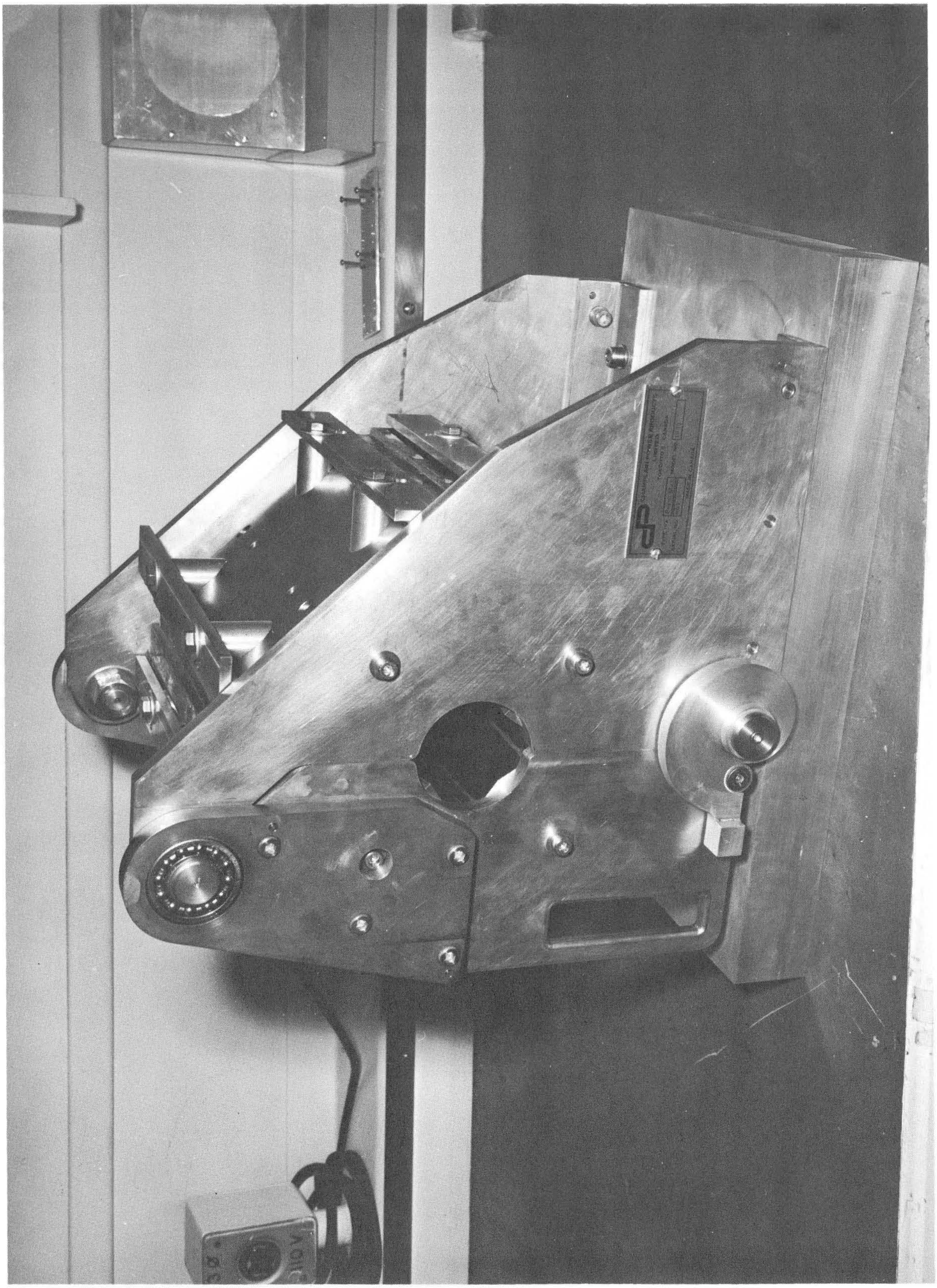


Figure 7 Permanent magnet quadrupole assembled

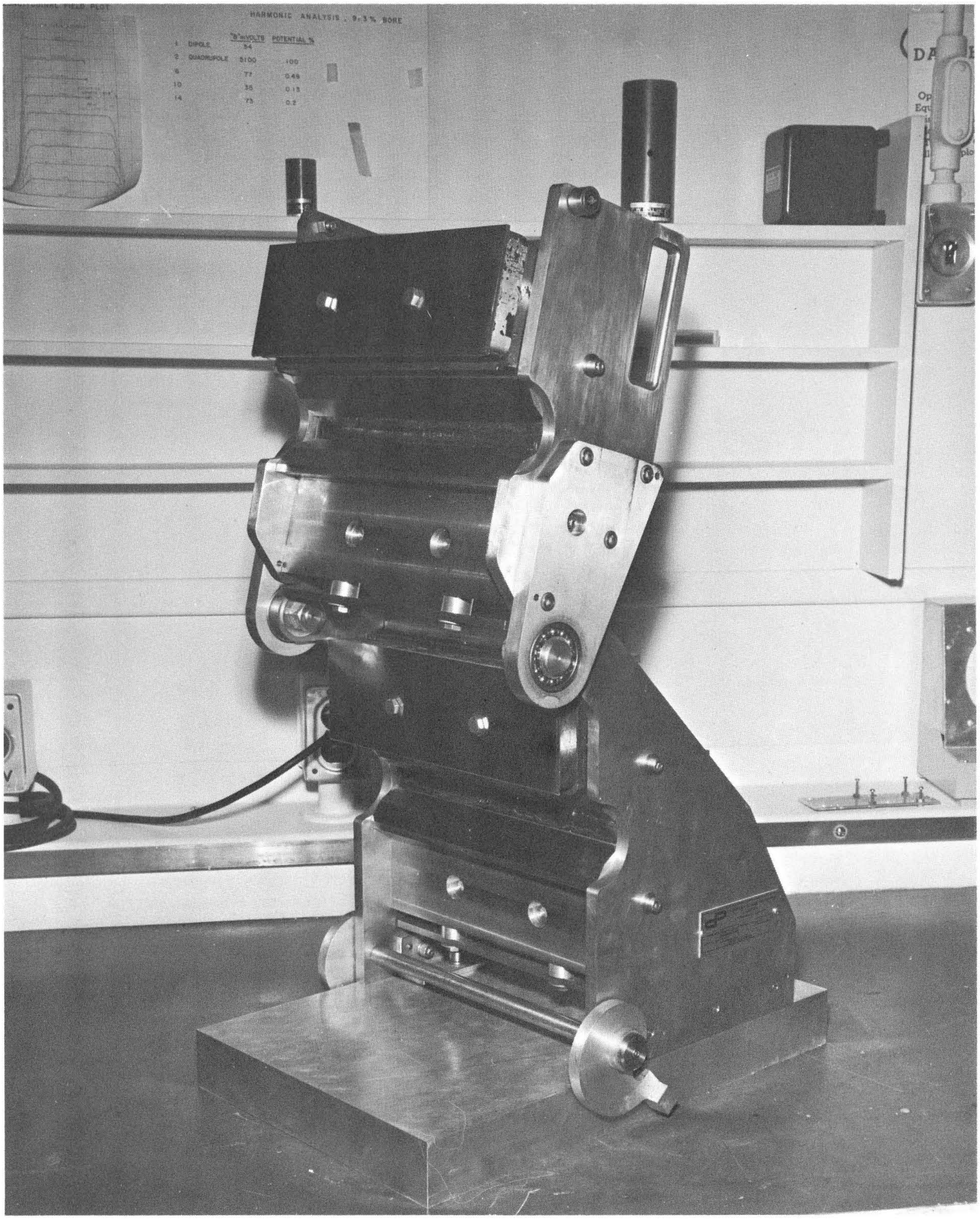


Figure 8   Permanent magnet quadrupole open

POLE-FACE DESIGN

$$\nabla^2\psi = 0 \qquad B = \nabla\psi$$

$$\psi = \sum_{n=1}^{\infty}\{(A_n r^n + B_n r^{-n})\sin n\theta + (C_n r^n + D_n r^{-n})\cos n\theta\}$$

$B_n = D_n = 0$ since region encloses origin, eliminating r^{-n} terms.

WITH PERFECT QUADRUPOLE SYMMETRY

$$\psi(r,\theta) = -\psi(r,\theta+\tfrac{\pi}{2})$$

$$\psi(r,\theta) = \psi(r,\tfrac{\pi}{2}-\theta)$$

$$\psi = \sum_{n=0}^{\infty} A_m r^m \sin m\theta, \qquad m = 2(2n+1)$$

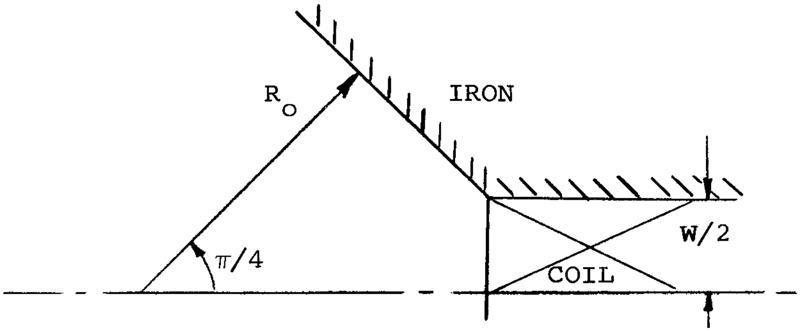


Figure 9 Quadrupole quality

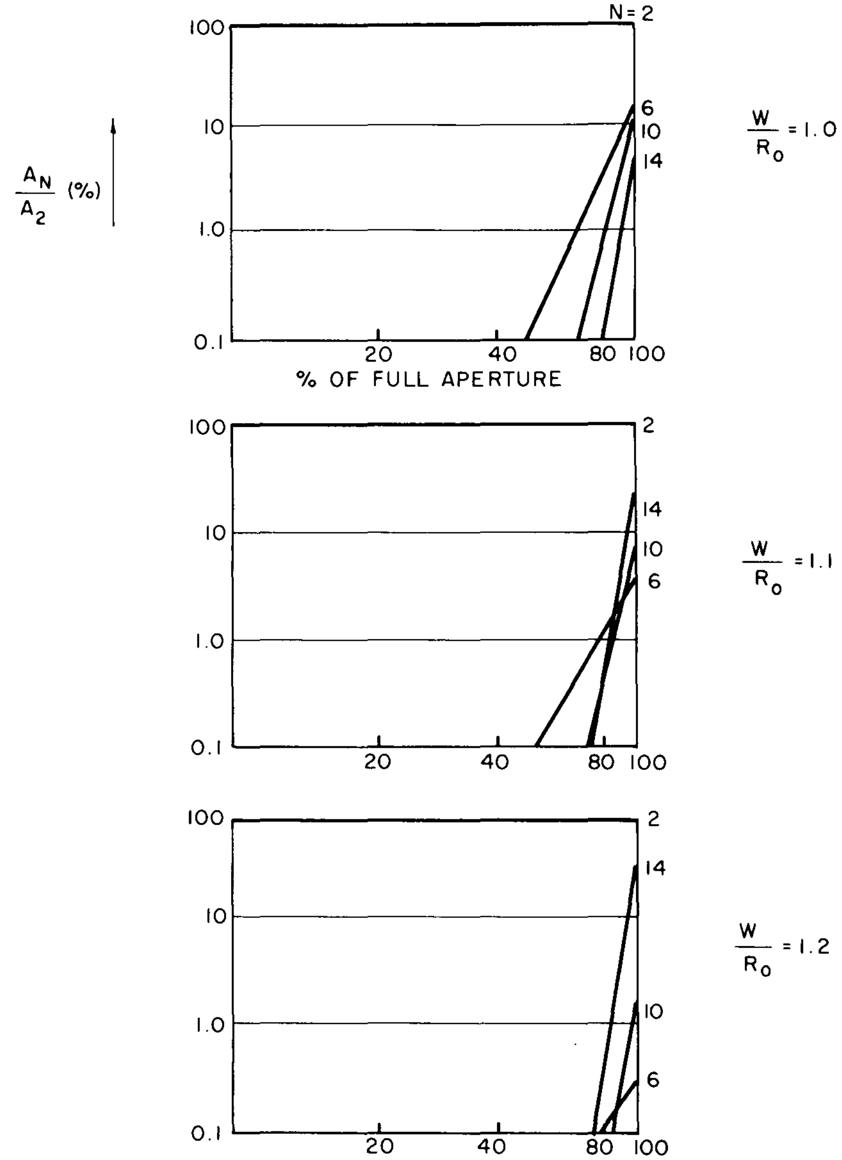
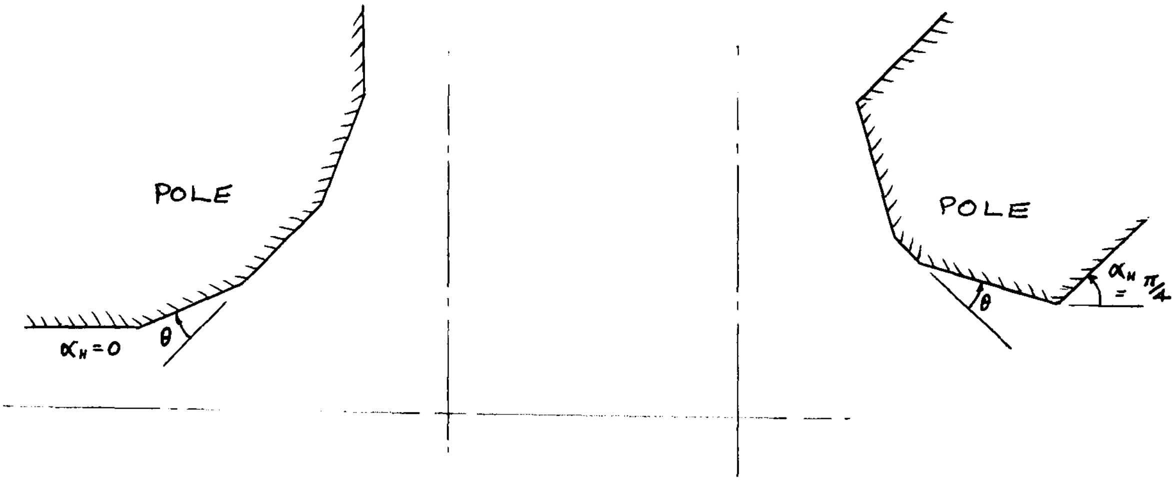


Figure 10 Magnitude of Harmonic Coefficients vs. % Aperture



FIELD $B = C_1 r + C_5 r^5 + C_9 r^9 + C_{13} r^{13} + \cdots$

$C_5 = C_9 = 0.$

θ (π units)	C_{13}
0.07	-0.0214
0.08	-0.008
0.09	0.004
0.10	0.016

θ (π units)	C_{13}
0.07	-0.0293
0.08	-0.013
0.09	0.002
0.10	0.015

Figure 11 Keech Pole Design