WINDOW FRAME OR "SUPERFERRIC" MAGNET DESIGN FOR LOW B(< 3T) HEAVY ION STORAGE RING STUDY*

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Abstract Double magnets share common laminations without magnetic coupling. Single layer coils of rectangular conductor are dry wound on extruded bore tubes. Magnet construction requires no molding or prestress. Absence of superconducting (SC) magnetization fields in the aperture results in very large dynamic range. The coil is wound continuously across the midplane to give unusually large dynamic aperture. Above ~2.2 T saturation is corrected by simple sextupole windings with no inductive coupling to the dipole. Ultrastable design requires no internal quench protection. A quadrupole pair of novel design gives excellent field quality to B > 2 T without corrections, with no SC magnetization. Experience shows magnets are accurate enough for the assembly to take place at its final location. No training is required. Test procedures (measurements with search coils or with the beam) and cooldown properties are discussed.

Window Frame Magnet Unique Features

- Parallel plane, dry-wound, single layer, current sheets of monolithic, rectangular conductor.
- Field quality is determined by the iron boundaries: the coil construction of continuous layers across the horizontal midplane makes conductor location uncritical.
- No SC magnetization: dynamic range > 100 to 1.
- Cross coupling of fields is negligible.
- Outward forces are low (~500 psi); no prestress.
- Rapid quench propagation, excellent thermal stability assured by pure aluminum backing sheets.
- Curvature is only two dimensional since the magnet cross section is rectangular.
- No extensive magnet R&D program based on feedback from tests is necessary as for cos θ designs.

Previous Experience

Two 2 meter long window frame magnets were operated in series at 4 Tesla in an AGS 30 GeV/c extracted beam up to 10^{13} protons per pulse for ten years. Radiation heating experiments showed they could absorb far more energy than other comparable designs, approaching 1 kJ per pulse before quenching and requiring no added quench protection. Measurements of the magnets (constructed without a modeling program) are plotted in Fig. 1, demonstrating the construction accuracy achieved for window frame magnets.[1]

Another window frame magnet,[2] an R&D prototype for the CBA, with a 6-layer main dipole coil, eventually reached a peak field of 6.8T (short sample). With no quench protection, the maximum quench temperature reached was ~90°K. The 6.8 T magnet integrated field error terms were measured at 70% ρ_{sc},ρ_{sc}=4.1cm. Iron saturation plays no part in these terms. As predicted, these terms (a_1 = -1.49×10^{-4}; a_2 = $+1.45 \times 10^{-4}$; all others $<10^{-4}$) were acceptable, verifying that these magnets could be built as designed without R&D. The allowed terms were also in agreement with the values computed for the design--$\Delta B/B$ was $\leqslant 1 \times 10^{-4}$. This high field design was considerably more complex than the Heavy Ion Storage Ring (HISR) design.

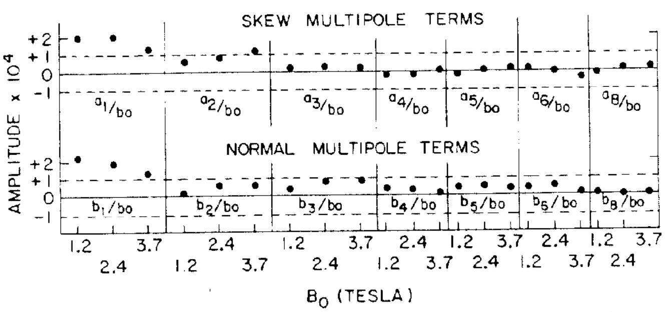

Fig. 1. Relative difference of ∫Bds for the two 4T magnets. The measurements were made at full beam aperture (70% ρ_{sc}) using simultaneous long coil signals from the two series powered magnets.

The Design for a HISR - Dipole and Quadrupole

The dipolar current sheets terminate at iron pole faces perpendicular to the current sheets. (Figs. 2 and 3.) Image currents in the iron effectively extend the sheets to infinity, giving very pure dipole fields. Excitation above saturation (B~2T) produces only sextupole aberration, no other harmonics. The sextupole correcting pole-face windings are independently excited above 2.2T (80 GeV Au/amu).

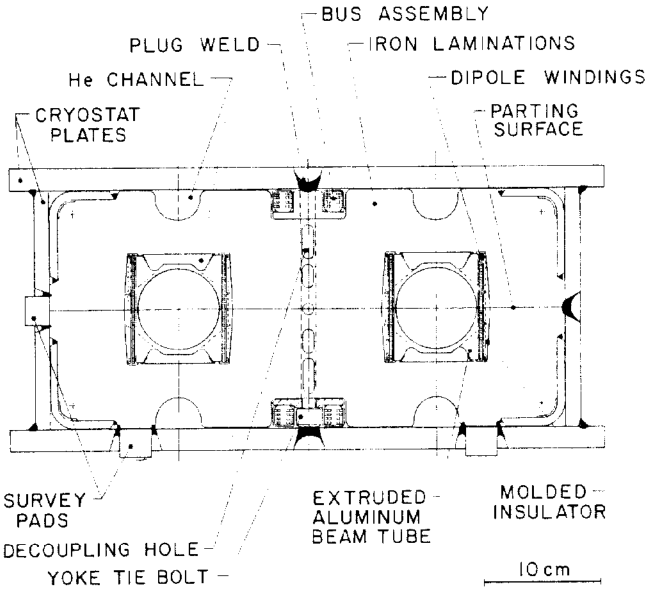

Fig. 2. Window frame dipole cross section.

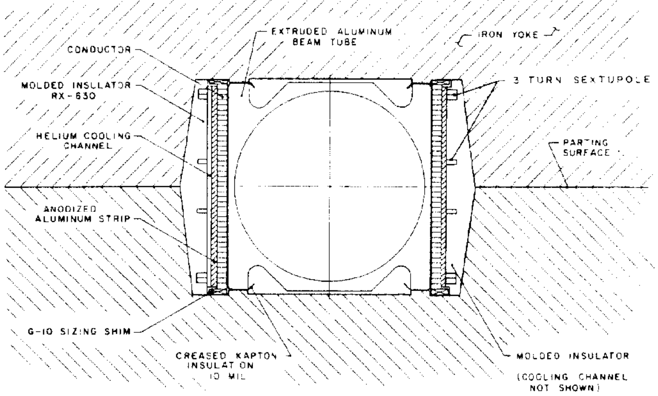

Fig. 3. Dipole coil assembly cross section.

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SC magnetization currents are similarily imaged to infinity. Thus no magnetization fields occur in the aperture. They are contained within the SC current sheets and the surrounding iron. The absence of magnetization problems at low fields means that the magnets are much less sensitive to temperature variations than cos θ magnets.

Table 1. Calculated Window Frame Dipole Harmonics

B_o (T)	< 1.9	2.18	2.72
GeV/amu (Au)	<70	80	100
x (mm)	25.4	25.4	12.7
$b_2 \times 10^4$	0	0*	0*
$b_4 \times 10^4$	- 0.08	- 0.68	- 0.38
$b_6 \times 10^4$	0.08	0.38	0.06
$b_8 \times 10^4$	0.02	0.08	0.003
$b_{10} \times 10^4$ etc.(all 0)	0	- 0.01	0
x "good field" (mm)	≤25.4	<25.4	12.7

* Sextupole cancelled by "pole face" windings for B_o >2.2T; $b_2=15\times10^{-4}$ uncorrected at B_o=2.72T-See Fig.4.

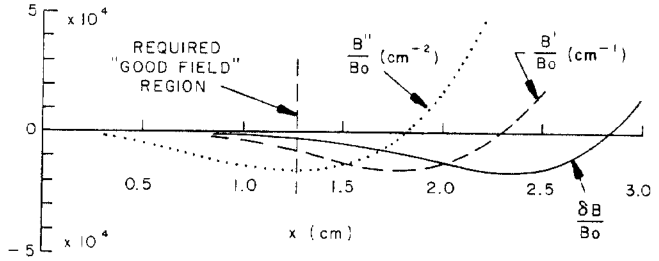

Fig. 4. Window frame dipole field and derivatives' variation with x at 2.72T, 100 GeV/amu(Au),ρ_{sc}=3.5cm.

The design meets and in some cases exceeds the desired HISR specifications: beam tube i.d. 66 mm, "good field" aperture 50 mm at injection and 25 mm at 100 GeV/amu, dynamic range of 100/1, unlimited momentum imbalance between the colliding beams, and ramp time less than 30 seconds (>0.09T/sec). Short sample field is at ~130 GeV/amu. JxB at 2.7T is a very conservative 56% of short sample.

Table 2: Dipole Operating and Quench Parameters

Operating Current 100 GeV/amu(AU)	3.86 kA
Operating Field 7 cm ID of SC	2.7 T
Operating Current/Copper Area	0.82 kA/mm²
Stored Energy per Aperture	240 kJ
Inductance per Aperture	32 mH
Quench Current	> 5 kA
Quench Field	3.6 T
Quench Current/Superconductor Area	2.40 kA/mm²

The 12 m dipole magnet with ρ_{sc}=35mm has a single layer of monolithic rectangular conductor (1.68 mm x 4.06 mm) (Fig. 3), with Cu/SC = 1.7. The dipole is curved after assembly with a radius of 275 m and a sagitta of 60 mm.

Cross coupling of fields between beam apertures is negligible, $<1 \times 10^{-4}$ of pure quadrupole (Fig. 5). The two dipoles are assembled in common iron laminations for economy and precise alignment, but the flux returns in separate paths.

The very precise, iron dominated field depends on the conductor turns being aligned as a single conducting current sheet. Only light mechanical preload (~50 psi) is applied, sufficient to tighten the coil assembly both vertically and horizontally. The magnetic pressure at 100 GeV/amu(Au) is only ~500 psi outward on the coil sheet, but it assures registration against a sheet of anodized pure Al which in turn is accurately supported by a molded insulator (RX-630) backed by the iron. Exact radial location of the current sheet is not critical; coherent outward motion of a few mils has no effect on the field. The turns are insulated with ~0.04mm layers of Formvar. The coil has no high stress plastic support structure. The coil layer is drywound on the extruded aluminum beam tube, without impregnation and curing, and transferred into the iron yoke with the precise register characteristics of punched laminations. The dipole yoke consists of two laminated half cores which envelop the bore tube and coil assembly of both magnets and accurately establish the beam tube centerline.

High purity aluminum backing sheets and a profusion of helium cooling channels yield uniquely high level heat exchange from the coil package to a large volume of helium. Much more energy is required to initiate a quench than with other comparably high current density designs. Any quench propagates so rapidly throughout the coil that overheating does not occur.

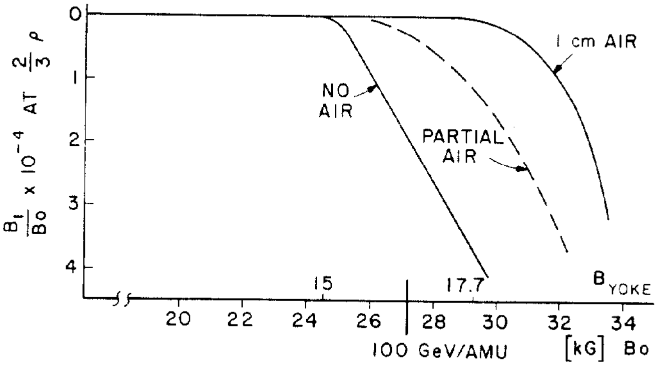

Fig. 5. Computed double dipole coupling-quadrupole term only significant.

The quadrupole magnet utilizes a single layer current sheet in each of the four coil slots. The four piece laminated iron yoke, split radially at the pole centers, was chosen to provide maximum symmetry and precision. A precision honed outer iron cylinder is shrunk fit around the four yoke segments, with positive interference to capture the coils accurately ensuring four-fold symmetry (Fig. 6). The 1.56 m quadrupole is compact: outer diameter is 17 cm, gradient 59 T/m, B_{Tip}(peak) 2.22 T. The coil is dry wound directly on the extrusion tube using rectangular monolithic conductor, Cu/SC = 1.25. Windings are continuous across the midplanes between the poles. Field shape is precisely determined by the accurately located iron boundaries. The quadrupole requires no correction coil for Δμ ≤ 120° with $B_{Tip} \leq 2.2$ T.

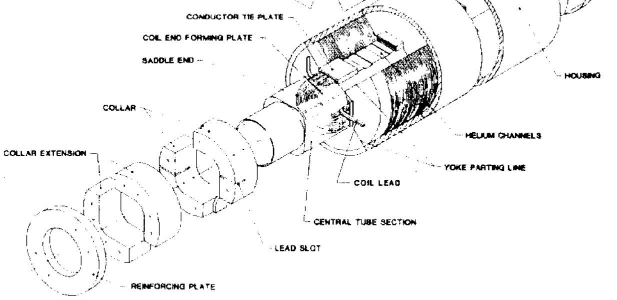

Fig. 6. HISR 2 - Coil Quadrupole

Table 3. Calculated Quadrupole Harmonics

Pole Tip Field (T)	< 1.8	2.22
GeV/amu(AU)	<80	100
x(mm)	25.4	12.7
$b_5/b_1 \times 10^4$	-0.59	1.22
$b_9/b_1 \times 10^4$	-0.10	0.001
$b_{13}/b_1 \times 10^4$	-0.04	0
x "good field" (mm)	≤ 25.4	12.7

The quadrupoles (smaller than dipoles) are supported by extra dipole laminations stamped with two locating holes at the correct spacing inside the tight fitting cryostat.

The F and D quadrupoles are bussed separately, each string with nominally one-half of the current used in the dipole. This permits easy tune control along and orthogonal to the principle diagonal.

Correction Magnet Features and Specifications

Two 0.15 m long sextupoles are located at each end of all quadrupoles powered in series to produce an "achromatic quadrupole." Their iron dominated, compact design (Fig. 7), similar to the quadrupole, produces pure sextupole field. The single layer windings contain only 3 hand-wound turns of rectangular, monolithic conductor.

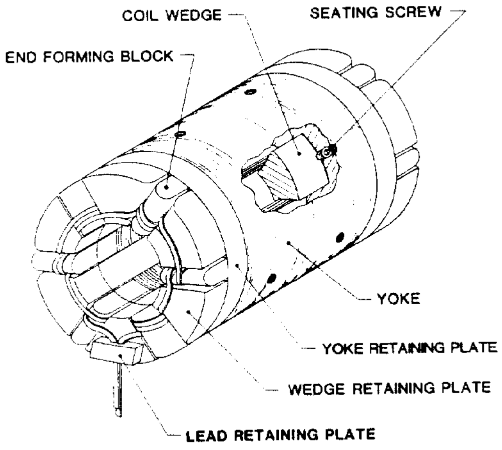

Fig. 7. Sextupole assembly.

Dipole saturation produces sextupole above 80 GeV, where the required good field aperture is one half that at low energies. A simple planar 3-turn sextupole correction coil is adequate (Fig. 3). Wound as a partial second layer on the outside of the dipole current sheet, it produces sextupole field with the dipolar component approximately cancelled to minimize inductive coupling.

The 10 cm orbit correcting magnet (Fig. 8) (a_0, b_0 and a_1) has locally powered (60A max.) feedback capability. Observation of beam position and on-line computer orbit analysis and feedback keeps the beam at the center of the aperture with high precision, eliminating horizontal to vertical coupling. Internal self-alignment of magnets in the unicell is estimated to be ±1/4 mm requiring only 25% of the correction capacity.

"Unicell Assembly"

The pairs of dipole, quadrupole, sextupole and orbit correcting magnets and the pickup electrodes are all assembled in one cryostat (the "unicell"). The unicell has been designed for fast cooldown or warm up. Fast flowing He gas, heat exchanged with liquid N_2, can flood through the system designed to have excellent longitudinal and transverse heat transfer properties without twisting.

During a short R&D phase dedicated to producing two unicells, extensive magnetic measurements would be carried out at liquid He temperature using multisection integrated long coil techniques. Detailed magnetic testing would be done for the first 10% of magnets of each type during production, and for about 10% of the remaining production magnets for quality control. The balance would be simply tested at room temperature since no quenching should occur. The window frame magnets constructed to date have had field precision equal to the best designed water cooled accelerator magnets, and well within the range of control of the machine corrections. Given the simplicity of the window frame magnet geometry, and the experience to date, individual testing of all units in helium prior to assembly in the ring should prove to be unnecessary.

The main requirement on the dipoles and quadrupoles is that their position be stable. Location and orientation errors can be compensated. The refined "survey" can be done with the beam.

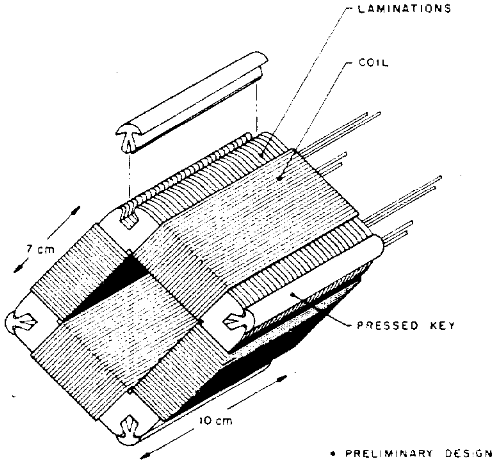

Fig. 8. Orbit correction magnet.

References

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2. G. Danby, et al., 1983 Particle Accelerator Conf., 3/21-3/23/83, Sante Fe, BNL 32806.