# A LARGE BORE PULSED QUADRUPOLE MAGNET FOR TRANSPORT OF HIGH CURRENT BEAMS AT LOW ENERGIES*

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## *Abstract*

We present the design of a large bore pulsed quadrupole magnet for transport of a high current, space charge-dominated heavy ion beam in a neutralized beam focussing experiment using four magnets. The design is current dominated, with solid circular cross-section insulated copper conductors located within a circular laminated iron core. The design produces a field of 0.96T at the maximum beam envelope of 12cm. The magnet has a short length relative to its bore, and a small number of turns in order to minimize inductance, thus allowing high currents at modest voltage. Conductor diameter is chosen to minimize the combination of resistive and eddy current losses in the magnet coils, within limits of existing fabrication equipment. Higher order multipole field components sum to 0.06%$B_2$ @10cm radius. Coils are fabricated using a wind/stretch technique to produce straight and accurately located conductor runs while preserving the integrity of the polymer insulation. Coils are wound in a "single layer/double pancake" style to place all conductor runs at the same radius, yet avoid "stranded" conductors at the poles. The beamtube is a separate composite stainless steel/fiberglass epoxy beam tube for the entire magnetic transport line. This minimizes eddy current losses in the vacuum system, both in the midsection of the magnets and at the magnet ends, where thick flanges would normally be present.


## 1 MAGNETIC DESIGN

The pulsed quadrupole magnet is a high voltage, low inductance, current dominated design, with conductors arranged around a circular iron boundary. Figure 1 shows the octant cross section. Design parameters are shown in Table 1. Pulse width is chosen to give adequate current flat top uniformity during the beam transit time, while maintaining a sufficiently low voltage for reliability. The number of turns is minimized to keep inductance and resistance low. The minimum number of turns is limited primarily by field quality requirements, and secondarily, in this case, by the ease of fabrication. Reducing number of turns requires increasing conductor cross-section. A circular cross section conductor is chosen to minimize electrical stress on conductor insulation.

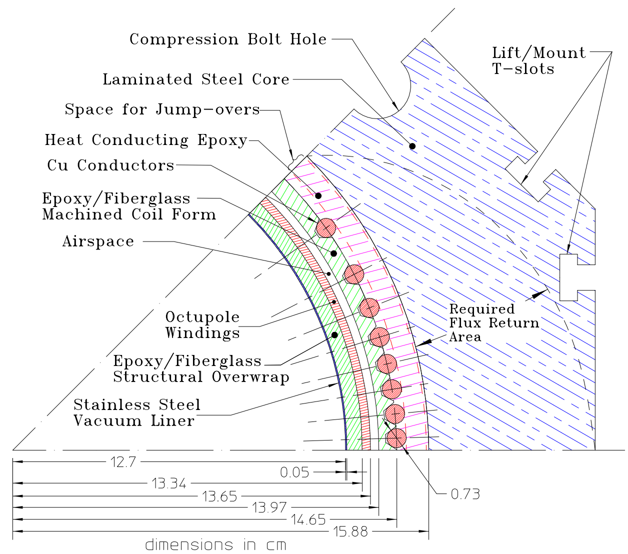


**Fig. 1 Octant Cross-Section**

| | | |
|---|---|---|
| Beam Aperture Radius, R | 12.7 | cm |
| Magnet Winding Radius, R | 14.65 | cm |
| Mag., Total Lengths, L , L | 40, 46 | cm |
| Magnet to magnet spacing | 60 | cm (ctr.-ctr.) |
| Field Gradient, B' | 8 | T/m |
| Maximum Field, B | 0.96 | T, @12cm |
| Number of turns, N | 8 | Turns/coil |
| 2D Field Coefficients, B (Σn\|A \|/2A , n=6,10,…,26) | $6x10^{-4}$ | T/T @10cm |
| Conductor diameter, r | 7.3 | mm |
| Magnet Current, I - I | 2.3- 9.2 | kA |
| Magnet Resistance, R | .014 | Ω |
| Magnet Inductance, L | 202 | μH |
| Pulse length (full half sine), t | 1.6 | ms |
| Magnet Voltage, max., V | 3.7 | kV |
| Pulse energy/magnet, max., U | 9.2 | kJ |
| Energy loss/magnet, max., Q | 1.7 | kJ |
| Max., Operating Pulse Rates | 1, 0.1 | Hz |
| Temp. Rise, max., steady state | 27 | °C, (1Hz P.R) |

**Table 1 Magnet Parameters**

For a given number of turns, N, of a circular cross section conductor of radius $r_c$, pulse width (half sine) t, coil eddy current losses scale to the fourth power of conductor diameter:

work supported by the Director, Office Of Fusion Energy, U.S. Doe, under Contract No. DE-AC03-76SF00098
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$$q_e = \frac{\pi}{8} t r_c^4 \dot{B}^2 \sigma \quad \text{(per unit length conductor)}$$

where:

$$\dot{B} = \max.\, dB/dt \textit{ through conductor}$$

$$\sigma = \textit{conductor conductivity}$$

and:

$$Q_e = 4K^2 q_e N\bar{l} \quad \text{(magnet coils total)}$$

where:

$$\bar{l} = \textit{avg. turn length},$$

$$K = \textit{avg. cond. field factor} (\sim 5/8 B\max.)$$

while total coil resistive losses fall as the square of the conductor diameter:

$$Q_r = \tfrac{1}{2} I^2 \frac{4N\bar{l}}{\sigma\pi r_c^2} t$$

An optimum conductor diameter, $r_{co}$ can be found which produces a minimum total loss $Q_t = Q_e + Q_r$:

$$r_{co} = \sqrt[6]{\frac{t^2 R_w^2}{2K^2\pi^3\mu_o^2 N^2\sigma^2}} \quad ; R_w = \textit{winding radius}$$

This minimum occurs when total resistive losses are twice the total eddy current loss (this is a more accurate way to calculate $r_{co}$). For this design, a conductor diameter of 9.4mm is indicated to minimize losses. This is too large for our winding/stretching machine, and thus a 7.3mm diameter conductor is chosen (AWS #1; largest size readily available with the desired insulation). As such, coil losses are primarily resistive at the given pulse width. The magnet ends are made square (in θ-Z space) to both maximize the effective length of the 2D cross section and to facilitate forming into circular arcs. The magnet is short enough that "self-compensated ends" typically featuring semi-circular or elliptical ends have little advantage over this "body-end" compensated design. Such ends cannot easily be formed circular in the XY plane by pressing on a circular form. Fabricating a solid conductor magnet with self compensated ends would require a substantially more complex winding method and associated machinery.

Conductor location in the 2D design was found by computing a generalized cos nθ current distribution and dividing this into 8 equal areas, then finding the centroid for each area in cylindrical coordinates. Compensation for individual conductor lengths is provided (body-end compensation). Results from the 2D analysis code PANDIRA[1] were used to provide "feedback" higher order multipoles, which were then corrected for in subsequent iterations. The motivation behind this method, rather than the more usual one of performing optimization analyses on limited sets of parameters to optimize limited sets of criteria, is to allow the possibility of maximizing good field radius in current dominated designs with both circular and noncircular boundaries. Maximizing good field radius near magnet windings requires more consideration of higher order harmonics which are usually not as significant in more conventional designs where good field radius is typically no more than 2⁄3 the inner radius of the windings. This technique should allow any conductor pattern that can be expressed analytically to be "relaxed" iteratively to the limit of its ability to produce a desired field quality.

## 2 COIL DESIGN

The magnet's short pulse length of 1.6ms (full half sine wave), requires a high voltage design, with 3.7kV between the leads. Copper wire was purchased with a high grade NEMA 35C (polyester-polyamide/imide) insulation coating 0.05mm thick which tests to 10-15 kV for crossed conductors in a hi-pot test, even after significant bending.

The magnet's main coil package consists of 4 "single-layer, double-pancake" coils, of 8 turns per coil, 4 turns per "pancake" (fig. 2). It is wound in typical double pancake style, with an inward spiralling layer changing to an outward spiralling layer, to bring both ends to the coil periphery. The coil is then "collapsed" into a single layer at one winding radius, with turns interleaved. This is made possible by the fact that conductor diameter is small enough to allow all conductors to lie on a single radius. It is accomplished by making "jump-over" bends where the conductors of the outwardly spiralling layer jump over the conductors of the inwardly spiralling layer where they cross.

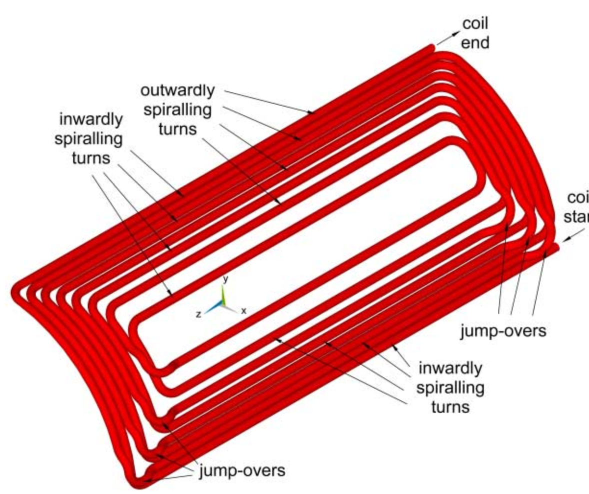


**Fig. 2 Single Layer/Double Pancake Coil Design**

Coils are wound "flat" (in a plane) on a single axis winder; both the inward and outward spiralling layers wound in one continuous operation with no splices. The individual turns are wound in an ascending spiral fashion between two multiple-grooved plastic dies, one of which is fixed, and the other connected to a movable hydraulic ram. Thus each wire turn is wound into a separate groove, instead of on top of the previous turn, as is normally done. After winding under low tension, the wire ends are clamped off and the coil layer is stretched axially to the point of yield. This removes initial wire curvature and kinks, with negligible reduction in wire diameter or damage to insulation. After winding and stretching, the coil collapses under its own weight into a flat, planar coil layer, with the exception of the jump-overs, which interfere. S-bends are made in the legs of those conductors that must jump over the underlying conductor. Extra conductor length is provided in the winding dies for these bends.

The coils are then placed on a circular plastic die and pressed to form the circular curvature on the ends, taking care not to apply force on the jump-overs.

The coils are then assembled onto machined fiberglass (G-10) coil forms, connected together with leads, and epoxy potted into the laminated iron cores with heat conducting epoxy. The magnet coil casting carries all magnetic forces and heat generation directly into the steel cores.

Cooling is by conduction through the epoxy to the iron core, which is convectively cooled to ambient temperature on its periphery. A .025mm stainless steel foil wrap may be added to the casting to provide a smooth ground layer on the outer diameter (to shield conductors from the sharp edges of the laminations). An alternative method is to cast the coils in epoxy using a smooth cylindrical mold, paint a resistive coating over this casting to form a smooth ground, then bond the casting into the core with a thin flowing epoxy. A resistive coating on the magnet ID will reduce static charge build-up and provide a uniform ground.

## 3 BEAM TUBE DESIGN

To minimize eddy current losses, a stainless steel thin wall tube 0.05mm thick is utilized for a beam tube. This tube is externally stiffened and strengthened to withstand vacuum by filament winding epoxy/fiberglass over it to a total wall thickness of 6.3mm. It is a separate structure from the magnets and a 6.3mm annular gap exists between it and the coil form inner radius. Eddy currents are calculated to be 5% of the main field, with a decay time constant of ~30 μs[2]. The beam tube is O-ring sealed on the ID by an internal flange, as the beam size is relatively small at the entrance and exit of the transport line. A further reason for separating the beam tube from the main magnet is to allow its removal for installation of thin windings for higher order multipole correction. These would be used to investigate the feasibility of using octupole magnets to correct for the inherent pseudo-octupole aberrations found at the ends of the magnet. They would likely be fabricated from flexible printed circuit material and wrapped around the beam tube. The annular gap between the beam tube OD and the magnet ID provides for these corrector magnets.

## 4 CORE DESIGN

The flux return core is laminated M36 magnetic steel, .025” thick, with C5 insulation. Eddy currents are calculated to be negligible for this thickness. The core extends axially only to the end of the coil, eliminating the usual overhang. This is to maintain sufficient separation between successive magnets, which operate at substantially different currents. The core will be assembled and held together with insulated stainless steel bolts. Steel endplates 6.3mm thick provide uniform compression for the core laminations, and feature a full radius on the edges where coil conductors are located, to reduce electrical stress on conductor insulation. Bolt holes are located at the poles, where flux return requires the least amount of radial thickness. Mounting T-slots are located on all eight outer edges to allow flipping of laminations to minimize straightness deviation occurring from thickness variations. Method of fabrication will be laser cutting, which is accurate and inexpensive, with minimal burr.

## 5 ACCELERATOR INTERFACE DESIGN

The single beamtube eliminates all intermagnet flanges and bellows, reducing weight and cost. It is supported only by the end flanges, and has minimal sag. This allows tighter magnet to magnet spacing. Magnets are moveable on a common rail along the beam direction to allow beam optics reconfiguration. Vacuum pumping will be provided immediately upstream and downstream of the beamtube at large multiple port vacuum chambers. Beam diagnostics will be inserted axially upstream on the end of a cantilevered beam, as no intermediate ports are available. Pulsers are +/-2kV SCR switched capacitive discharge type, to minimize voltage to ground. Each magnet has its own pulser to provide a modular system with experimental flexibility.

## 6 REFERENCES

[1] Halbach, K., Holsinger, R. SUPERFISH …, LANL rpt. LA UR-96-1834, 1987

[2] Kilpatrick, R. LBNL, Engineering Note M4435, 1971