MAGNETIC DESIGN OF SUPERCONDUCTING QUADRUPOLES FOR A SC LINAC FOR APT

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Abstract

This paper describes the magnetic design for superconducting quadrupoles to be used in the superconducting option of the proton linac for the Accelerator Production of Tritium (APT) project. The quadrupole magnets provide the focusing for a singlet FODO lattice used in the linac. The magnets have a 16 cm (13 cm) aperture in the hi-β (medium-β) section of the linac. The proposed design is a coil dominated magnet with an iron yoke at a larger radius to shield the magnetic field from other parts of the accelerator. The field performance, field quality, peak field and forces on the conductor are discussed.

1 INTRODUCTION

The proton linac for the APT project is likely to have superconducting RF cavities for the medium energy, $\beta = 0.64$, and high energy, $\beta = 0.82$, regions of the machine. Two options have been considered for the quadrupole focusing in the linac. One is to position a single superconducting quadrupole (either focusing or defocusing) between each of the SC RF cavities. The magnets would be placed in the same cryostat as the RF cavities. Each medium-β (high-β) cryostat would contain 3(4) RF cavities and 4(5) SC quadrupoles. There are 30 medium-β and 78 high-β cryostats in the linac. The other option is to place only the RF cavities into the cryostat and use a room temperature quadrupole doublet (one focusing and one defocusing) between each of the cryostats. The SC quadrupole in the singlet lattice design provides a higher gradient and shorter period length than the room temperature doublet design. The singlet linac with the SC quadrupoles would reduce the beam size by about half in each of the transverse dimensions. The Conceptual Design Report for the APT project [1] uses the singlet design with the SC quadrupoles. The APT project is now favoring SCRF design with the separate room temperture quadrupole doublet. This report discusses the superconducting singlet design with SC quadrupoles.

Certain requirements for the SC quadrupoles are dictated by the linac design. These are summarized in Table 1 . Because of the large beam current in the accelerator a large aperture is chosen to keep the number of particles hitting the beam pipe to a minimum so that hands on maintainance will be possible. The gradient requirements for the quadrupoles are modest for a superconducting magnet. This allows conservative operation at about half of the quench current. Since the APT accelerator is intended to be operated with an uptime efficiency of 85%, good quadrupole reliability is essential. Another design concern is that the field from the quadrupole should not interfere with the proper operation of the RF cavity. The requirement is stated that the field from the quadrupole must be less than 1 gauss at the RF cavity wall. This requirement is easily met.

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Table 1: Superconducting Quadrupole Parameters.

Parameter	Medium-β section	High-β section
Aperture radius (cm)	6.5	8.0
Lattice half period (m)	1.70	2.03
Quadrupole length (m)	0.305	0.459
Effective length (m)	0.294	0.338
Integrated gradient (T)	3.30	3.26
Nominal gradient (T/m)	11.2	9.6
Operating temperature (K)	4.3	4.3
Number of quadrupoles	120	390

2 MAGNET DESIGN

The proposed quadrupole is coil dominated with the iron yoke at approximately twice the coil radius so that most of the magnetic flux is returned in the space between the coil and yoke. The iron yoke remains essentially unsaturated for optimum shielding. Fig. 1 and Fig. 2 show the transverse and axial views of the quadrupole cold mass. The iron yoke surrounds stainless steel laminations which register the coil position and support transverse components of the coil forces. A stainless steel shell exterior to the yoke along with the bore tube contains the helium.

The coil is of a planar racetrack design and is wound with 460 (264) turns for the medium-β (high-β) design. The construction technique for the coil is the same as used for the sextupole and trim quadrupole magnets for the RHIC project at BNL. [2] The coil consists of alternate layers of insulated wire and epoxy-impregnated fiberglass wound in a rectangular form. The wire is a 25.5-mil diameter NbTi superconducting strand, and is the same as that used in the the outer cable of the Superconducting Supercollider dipole magnets. The wire has a copper to superconductor ratio of 1.8 to provide conductor stability. The coils are conservatively designed to operate at one half the quench current. The magnet should be self-protecting and will not be damaged by overheating during a quench, because of its fast normal-zone propagation velocity and the short coil length. The peak field at the coil limits the current that a wire can carry. The field at the coil is calculated using the 3D mag-

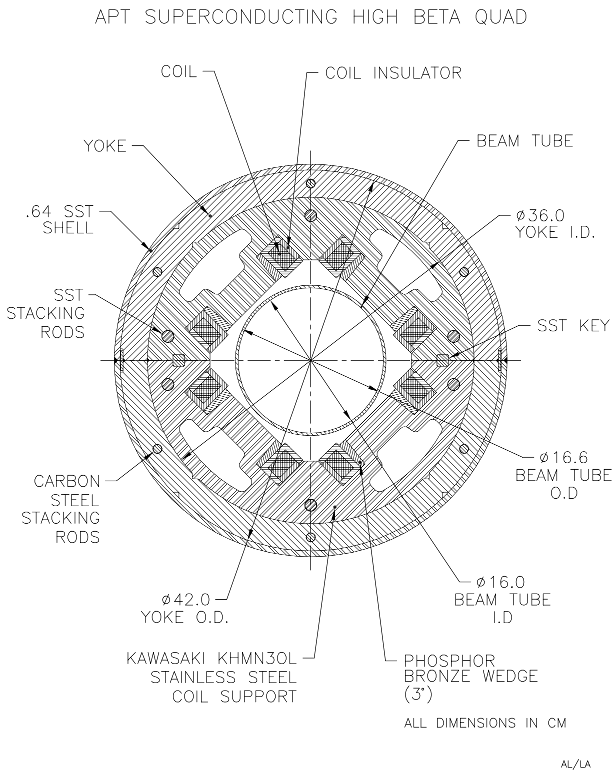

Figure 1: Cross section of the high-β quadrupole.

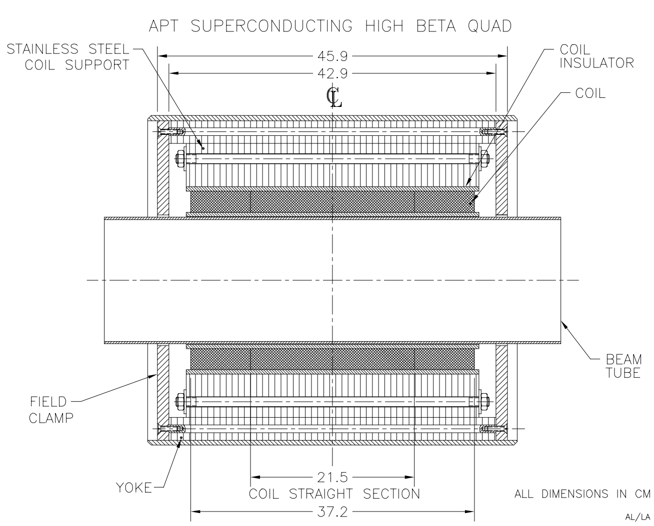

Figure 2: Longitudinal section of the high-β quadrupole.

Table 2: Coil Parameters for the Superconducting Quadrupoles.

	Medium-β	High-β
$B_{peak\ coil}$, T	3.0	2.0
Amp-turns	111578	82650
I_{wire}, Amp	243	314
N_{turns}	334	264
Inductance,H	0.126	0.133

netic field finite element program TOSCA. [3] Table 2 lists the design parameters of the coil. The RF cavities will operate at 1.9K with superfluid He. There would be a 50% increased quench margin if the magnets were operated at the same conditions. However without increased refrigeration, the helium surrounding the magnets would be just above the superfluid state, which is an unstable operating point. 4.3K is the likely operating temperature at this point. Skew and normal trim dipole coil windings for beam steering can be mounted in the magnet poles.

3 FIELD PERFORMANCE

The SC quadrupoles should exhibit good field quality for the linac. Deviations from perfect field quality can come from systematic design errors, random construction errors and magnet alignment errors. The largest contributor to the field error is likely to come from the magnet-to-magnet variation of the integral gradient, $G \cdot L$. The first harmonic allowed in magnets built with perfect quadrupole (2θ) symmetry is the duodecupole (6θ) term. The azimuthal angle subtended by the coil can be chosen to make the 6θ term negligible. A conductor placement accuracy of 4 mils (100 μm) gives non-allowed harmonics that are less than 0.0004 of the integrated gradient at $R_{ref} = 5$ cm.

Table 3 summarizes the estimates of the various contributions to the field quality that can be expected. The harmonics are calculated at a reference radius of 5 cm. The table indicates that a good field radius of 5 cm where $\frac{\Delta B}{B} < 0.001$ is achievable. These estimates are based on construction and placement errors obtained with the RHIC accelerator magnets. The alignment errors in Table 3 are estimated from RHIC magnet field measurements relative to external markers on the magnets. They do not include the additional contribution from magnet installation errors.

One of the major design concerns for the SC quadrupoles that share the same cryostat with the SCRF cavities is whether the magnetic field from the magnets will interfere in any way with the operation of the cavities. The field from the SC quadrupoles at the cavity wall is estimated to be less than 50 mG with the magnets operating. This estimate is without the use of μ-metal shielding which will be present to shield the cavities from the earth's magnetic field.

Table 3: Estimates of contributions to RMS field errors. For the evaluations of the field harmonics a reference radius of 5 cm is chosen.

Contribution	Error
$\frac{\Delta GL}{GL}$	0.003
$\frac{C(6\theta)}{GL}$	$< 10^{-4}$
Random Harmonics	$< 4 \times 10^{-4}$
Angular Alignment	0.6 mrad
Center Alignment	75 μm

Table 4: Calculated Lorentz Forces for the APT Linac quadrupoles. Side forces are *lbs per inch* and the end force is given in *lbs*.

Forces	Medium-β	High-β
Side Forces in plane	367	220
Side Forces out of plane	4	4
Total End Forces	5957	4638

4 MECHANICAL ISSUES

Because of the intense beam, the large aperture of the beam pipe is necessary to keep the number of particles hitting the pipe to a minimum so that hands on maintainance will be possible. Large aperture magnets typically have a large Lorentz force acting on the coils. The end forces in particular are proportional to the stored energy which has a radial dependance, $F_{ends} \sim r^4_{bore}$. However the gradient requirements of the APT linac quadrupoles are low enough that the stress in the NbTi is less than that in other magnets of similar construction. Table 4 summarizes the side and end forces that are expected to be seen in the quadrupoles. The side forces are separated into the component in the coil plane and perpendicular to it. The perpendicular component measures the interaction of the coil with the other coils and with the iron yoke. It tends to be small when the magnet is not iron dominated. The total end force is summed over all four coils. The side forces are supported by the stainless steel laminations holding the coils. Whether to support the coil ends has not been decided. The force per wire in the coil end is modest enough that end support may not be needed. Table 5 shows the axial force per wire and tensile stress on NbTi. Since the Lorentz forces elongate the wires and since NbTi is stiffer than copper, it is assumed the entire force strains the NbTi and that limits the performance.

The reliability of the SC magnets inside the same cryostat as the RF cavities is of great concern since the APT is expected to operate with minimal downtime in production. The APT is also expected to function for 40 years. Estimates of the reliability of these magnets can be made using the operational experience of the Fermilab Tevatron and DESY HERA accelerators. The correction magnets in both facilities are similar in construction to these quadrupoles. Each of these accelerators has more corrector magnets than are needed for APT. The Tevatron corrector magnets, which have been in operation for 13 years, have an average mean time between failure (MTBF) of 3×10^6 hours. The MTBF for the Tevatron correctors is increasing with time. The HERA correctors, which have been in operation for six years, have an a MTBF of 3×10^7 hours. Cold testing 100% of the superconducting magnets would remove the infant mortality failures. SC quadrupole failures should not limit the APT availability.

Table 5: End force per wire and stress on NbTi for the APT linac quadrupoles and other magnets of similar construction. *Field Level* indicates whether the forces are at the operating value or at conductor limit. Force and stress are in *lbs* and *Kpsi* respectively.

Magnet	Field Level	Axial Force per wire	NbTi Stress
Medium β	Operating	4.6	12.0
High β	Operating	4.4	12.2
RHIC trim quad	Operating	1.1	3.5
RHIC trim quad	Current Limit	4.5	14.2

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] Accelerator Production of Tritium Conceptual Design Report, 1997 Los Alamos Document LA-UR96-4847, APT-Doc-005.

[2] P. Thompson et al., Superconducting Sectupoles and Trim Quadrupoles for RHIC, Proceedings of the 1996 Particle Accelerator Conference, Dallas, p 1396 (1995).

[3] TOSCA is a computer code marketed by Vector Fields, Inc.