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DESIGNS OF THE LOW ENERGY INTERTANK QUADRUPOLE MAGNETS FOR APT*

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Abstract

The 700-MHz room temperature Low Energy (LE) Linac for the Accelerator Production of Tritium (APT) facility employs three different types of Coupled Cavity Drift Tube Linac (CCDTL) structures to accelerate a 100 mA cw proton beam from 6.7 MeV to 96.9 MeV and two different types of side Coupled Cavity Linac (CCL) structures to accelerate the beam from 96.7 MeV to 211 MeV [1,2,3]. Focusing of the beam is done with quadrupole electromagnets located between the segments of the accelerating structures in a FODO lattice. Since the longitudinal space available for the magnets is severely limited, the ratio of the magnet core length to the bore diameter varies over the range from 0.9 to 1.4. The pole tips have been designed with 3-D finite element modeling to keep total field harmonics less than 1% of the quadrupole component within ¾ of the beam tube aperture. In this paper, we present the physics parameters, detailed design, and some magnetic measurements of the prototypes for the two of the quadrupole magnet designs.

1 INTRODUCTION

There are 11 modules in the LE Linac; 6 CCDTL structures and 5 CCL structures. The beam tube diameter increase gradually from 2.0 cm to 6.0 cm in six stages. Four quadrupole magnet designs have been developed for these six beam tube sizes. These magnets are identified as CCDTL-1, CCDTL-2, CCL-1 and CCL-2 although magnet CCDTL-2 is also used in the first sections of the CCL. Table 1 presents the magnet requirements and quantities for the LE Linac.

The quadrupole magnets are located between the segments of the accelerating structures in a FODO lattice. The physical envelope of the quadrupoles and the integrated strength, i.e. the gradient-length product (GL) was determined by the beam optics design and by constrains of available insertion length, interface with vacuum chambers and flanges, and the vertical space envelope defined by the coupling cells between accelerating cavities. The severely limited longitudinal space envelope between the cavities prevents the use of dedicated steering magnets. The apertures of the quadrupoles are designed to allow sufficient radial clearance with respect to the vacuum beam tube to allow translation of the magnets horizontally and vertically which provides beam steering. This approach was chosen both to avoid dipole windings, which introduce significant sextupole fields, and to obtain the maximum cross-sectional area for the quadrupole windings.

Table 1: Magnet Requirements for LE Linac Modules

Module	Magnet	Quantity	GL_{max}(T)	GL_{min}(T)
1	CCDTL-1	49	2.625	2.344
2	CCDTL-1	57	2.332	2.332
3	CCDTL-1 CCDTL-2	32 11	2.332 2.055	2.063 1.985
4	CCDTL-2	32	1.978	1.795
5	CCDTL-2	34	1.790	1.639
6	CCDTL-2	28	1.635	1.538
7	CCDTL-2	18	1.538	1.538
8	CCDTL-2	19	1.538	1.499
9	CCDTL-2 CCL-1	3 18	1.496 1.486	1.489 1.434
10	CCL-1 CCL-2	7 14	1.431 1.410	1.413 1.373
11	CCL-2	20	1.370	1.200

2 DESIGN AND ANALYSIS

The very short length of the iron quadrupole core compared to the required pole tip diameter, especially for the CCL-1 and CCL-2 quadrupoles, where the iron length is less than the aperture size, makes it challenging to meet specified field uniformity requirements. The vertical dimensions are also restricted limiting the flux return yoke area in the middle of vertical plane. The transverse dimensions of all LE intertank magnets are 40 cm wide and 20 cm high with the overall insertion length of the CCDTL-1, CCDTL-2 and CCL1 restricted to 7.0 cm and the CCL-2 restricted to 9.0 cm.

Electromagnetic analyses were performed using Vector Fields [4] and Mermaid [5] 3D finite element software. The pole tip geometry was optimized to minimize the multipole harmonics by gradually flattening a hyperbolic

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profile. Earlier designs of the CCDTL-1 prototype were developed with a narrow pole tip and correction bumps on the corners to minimize the higher harmonics. A picture of this magnet is shown in Figure 1. The prototype CCL-1 magnet is shown in Figure 2.

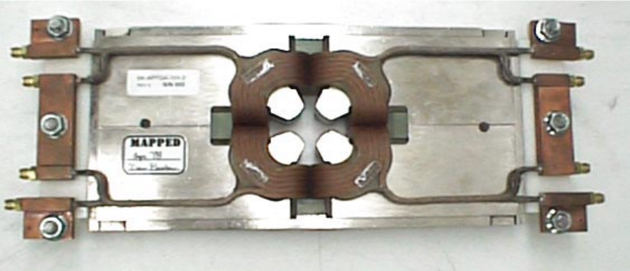

Figure 1: Prototype CCDTL-1 Quadrupole Assembly

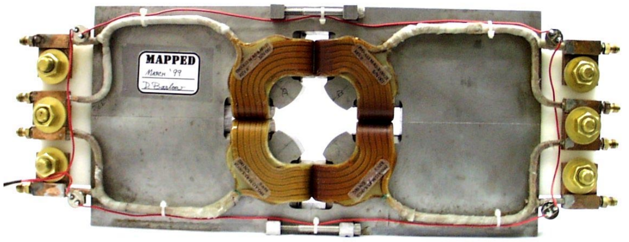

Figure 2: Prototype CCL-1 Quadrupole Assembly

2.1 Field Errors and Harmonics

Field errors are evaluated by obtaining the Fourier series of integrated quadrupole field at a given reference radius R and azimuth angles θ:

$$\int_0^Z B_x(R,\theta)\cdot dz \text{ and } \int_0^Z B_y(R,\theta)\cdot dz$$

B_x and B_y are horizontal and vertical components of the Field *B*. The field components B_y and B_x were integrated along the longitudinal axes “z” from the center of magnet out to z = 4 aperture diameters (in air) from the edge of the pole. Thus, values of integrated quadrupole field at the fixed arc of radius R represent a function $F(\theta)$ in the interval $[-\pi < \theta < \pi]$. The azimuth angle $\theta = 0$ lies along the positive “x” axis. Fourier series generated by this function $F(\theta)$ is represented by:

$$F(\theta) = \frac{a_0}{2} + \sum_{k=1}^{\infty}\left(a_k \cdot \cos k\theta + b_k \cdot \sin k\theta\right)$$

The harmonics of B_y are evaluated by the ratios of A_n/A_2, where $A_n = a_{k+1}$, and A_2 is the amplitude of the quadrupole field. Optimization of the pole tip geometry is achieved by minimizing A_6. The calculated 3D harmonics that are allowed by symmetry are presented in Table 2 for each of the four magnet designs. The harmonics are presented a 75% of the beam tube radius. Figure 3 shows a plot of the 2D-field distribution for one quadrant of the CCL-1 magnet. The difference between the vertical and horizontal flux return yokes is evident in this figure.

Table 2: Harmonics of LE Intertank Quadrupoles

	3D HARMONIC CONTENT	
	CCDTL-1	CCDTL-2
A_n/A_2	At R=1cm	At R=1.31cm
A_6/A_2	0.018%	-0.25%
A_{10}/A_2	-0.007%	-0.013%
A_{14}/A_2	-0.008%	0.005%
	CCL-1	CCL-2
	At R = 1.5 cm	At R = 2.25 cm
A_6/A_2	-0.15%	-0.18%
A_{10}/A_2	-0.053%	-0.025%
A_{14}/A_2	-0.006%	-0.008%

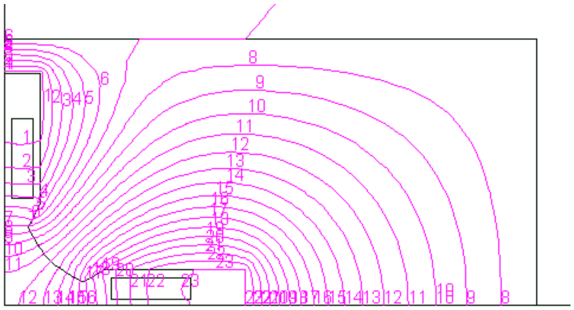

Figure 3: Field Plot of CCL-1 Quadrupole at the Center of the Magnet

The results of magnetic measurements of the CCDTL-1 and CCL-1 prototypes are presented in Table 3. The measurements are presented at an excitation corresponding to the maximum field given in Table 1. The measurements show that these designs will meet the specified requirements. The measurements for CCDTL-1 are for the narrow pole design. A wider pole design is presently in the final stages of assembly. This magnet will be measured and the best magnet will be adopted for the final design.

Table 3: Prototype Measurements

	CCDTL-1	CCL-1
A_n/A_2	At R = 1 cm	At R = 1.5 cm
A_3/A_2	-0.09%	-0.053%
A_4/A_2	-0.05%	-0.02%
A_5/A_2	0.01%	0.018%
A_6/A_2	0.08%	0.135%
A_{10}/A_2	-0.01%	-0.044%

2.2 Magnet Core and Windings

The magnet cores are constructed in quadrants machined from 1006 Low Carbon Steel. The quadrants are keyed and fastened in mid-planes in such a way that each quadrant is always in the same position with respect to geometrical center after assembly or reassembly. Quadrants are made out of prefabricated blanks, fastened together as a unit, and the pole tip profile is wire EDM machined on all four pole tips. The prefabricated blanks are identical for the CCDTL-1, CCDTL-2 and CCL-1 magnets. Thus, upon disassembly and installation of the vacuum beam pipe or the coil windings, the geometrical and magnetic centers do not move. The keys and fastening components are fiducials, and the four quadrants are kept as a set for a particular magnet. Thus, all assembly tolerances are kept to the minimum.

The magnet and its support stand will be precision aligned and fiducialized with a taught wire system on a bench using an identical mounting system to that used in the beam line. The mounting rails will be pre-aligned to tolerances of better than 0.002”.

Magnet windings are epoxy-impregnated structures are tightly fit around each quadrant. Electrical and water cooling connections are connected on both horizontal sides of the core due to the limited space available.

3. POWER SUPPLIES AND CONTROLS

The power supply requirements were based on the following constraints:

- The first four magnets will be independently powered to match the RFQ beam to the CCDTL lattice.
- Power supplies will be sized to energize multiple magnets using shunts to provide adjustment between magnets.
- Power supplies will not power magnets in more than one Linac section.
- The last two magnets will be independently powered to help match the LE Linac beam to the HE Linac lattice.

In addition to the above constraints the following assumptions were made:

- An even number of magnets will be powered by each supply whenever possible.
- In cases where the magnet excitation is the identical for many sequential magnets within a given Linac section, shunts will be provided for tuning an even number of magnets (typically 4).

In general, the quadrupole magnets will be powered in series from a single 40 KW dc supplies. There will typically be eight magnets connected to each supply with a by-pass shunt across each magnet. The shunts will provide a 5% tuning range in the magnet current and minimizes the number of cable runs between the power supply gallery and the tunnel.

4 REFERENCES

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