

# APT HIGH ENERGY LINAC INTERTANK ASSEMBLY DESIGN\*

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## Abstract

The 700-MHz superconducting High Energy (HE) Linac in the Accelerator for the Production of Tritium (APT) accelerates a 100 mA continuous wave (cw) proton beam from 211 MeV to a final energy of up to 1.79 GeV [1,2,3]. The design of the 700 MHz radio frequency (rf) cavities has been optimized for two beam velocity intervals,  $\beta=0.64$  and  $\beta=0.82$ . Two intertank designs, medium- $\beta$  and high- $\beta$ , have been developed for these two velocity intervals. Three cryomodule designs have been developed corresponding to three different lattice periods in the APT HE Linac. Room temperature quadrupole doublet magnets placed in the intertank assemblies between the cryomodules focus the beam. Each quadrupole magnet contains additional dipole steering windings to correct for small beam misalignments. The intertank assembly between cryomodules also includes beam diagnostic instrumentation, the interconnecting beam pipe, flanges, and the vacuum interface. This paper presents the physics parameters, the results of 3-D magnetic field calculations, and the detailed design of the quadrupoles and the associated intertank assemblies for the medium- $\beta$  and high- $\beta$  sections of the HE Linac.

## 1 INTRODUCTION

The HE intertank focusing (QF) and defocusing (QD) quadrupoles in the high- $\beta$  and medium- $\beta$  sections are designed to satisfy the following requirements:

- To fit into the “warm section” between cryomodules with the same beam tube ID as the cryomodules;
- To be mounted as a unit, QF and QD, as a doublet;
- To provide for transverse and longitudinal beam centroid diagnostics (beam position and beam phase monitors);
- To allow space for “special” diagnostics and other instrumentation (e.g. beam profile monitors);
- To have the Steering Dipole Correction Coils in horizontal and vertical planes.

The conceptual design of the APT utilized a FODO lattice throughout the accelerator with superconducting quadrupoles located within the cryomodules [4,5]. The HE Linac was changed to a doublet lattice, and the quadrupoles were moved to the warm sections between

cryomodules to streamline the design and minimize alignment problems. The intertank parameters for the four sections of the HE Linac are presented in Tables 1 and 2. The distinction between the two high- $\beta$  sections is that for a lower production rate facility, Section 4 would not be built. The large aperture of the beam pipe is the same as the cavities and is necessary to keep beam losses to a minimum and permit hands-on maintenance.

Ninety of the high- $\beta$  magnets are used in the High Energy Beam Transport line to the target/blanket.

Table 1: Medium- $\beta$  Intertank Parameters

Section	1 ( $\beta=0.64$ )	2 ( $\beta=0.64$ )
Cryomodules	6	30
Period Length (m)	4.876	6.18
Quadrupoles	12	60
Intertank Length (m)	1.606	1.609
Output Energy (MeV)	241.6	471
Quadrupole Effective Length (m)	0.35	0.35
Beam Tube ID (cm)	13	13
Quadrupole Spacing (m)	0.34	0.34
Quadrupole Gradient (T/m)	5.6 – 5.1	5.5 – 6.05

Table 2: High- $\beta$  Intertank Parameters

Section	3 ( $\beta=0.82$ )	4 ( $\beta=0.82$ )
Cryomodules	35	42
Period Length (m)	8.54	8.54
Quadrupoles	70	84
Intertank Length (m)	1.9	1.9
Output Energy (MeV)	1030	1700
Quadrupole Effective Length (m)	0.45	0.45
Beam Tube ID (cm)	16	16
Quadrupole Spacing (m)	0.34	0.34
Quadrupole Gradient (T/m)	5.0 – 7.25	7.25 – 9.76

## 2 DESIGN AND ANALYSIS

Electromagnetic simulations of the quadrupole field and steering dipole field were performed using the Vector Fields [6] and Mermaid [7] finite element modeling

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software. The ratio of the magnet core length to the bore diameter is 2.26 for the high-β quadrupole and 2 for the medium-β quadrupole. The pole tip profile has been designed to minimize field harmonics of the integrated quadrupole field within ¾ of the aperture. The optimization of pole tip geometry is achieved by gradually flattening the pole tip from a hyperbolic profile and iterating it with radial arcs and corner radii, the so-called “harmonic bump”.

### 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 angle θ:

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

B<sub>x</sub> and B<sub>y</sub> are the horizontal and vertical components of the field B. The azimuth angle θ = 0 on the “x” axis. The field components B<sub>y</sub> and B<sub>x</sub> were integrated along the longitudinal axis “z” from the center of quadrupole out to 75 cm from the center, which is 3.33 aperture diameters (in air) from the edge of the pole for the high-β quadrupole, and 4.4 aperture diameters for the medium-β quadrupole. Thus, values of integrated quadrupole field at the fixed arc of radius R represent a function F(θ) in the interval [-π < θ < π]. The Fourier series generated by this function F(θ) is represented by:

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

The harmonics of B<sub>y</sub> are evaluated by the ratios of A<sub>n</sub>/A<sub>2</sub>, where A<sub>n</sub> = a<sub>k+1</sub>, and A<sub>2</sub> is the amplitude of the quadrupole field. Optimization of the pole tip geometry is achieved by minimizing A<sub>6</sub>. The significant harmonics are summarized in Tables 3 and 4.

### 2.2 Intertank Design

The HE Intertank module consists of the following major components:

- Horizontal focusing quadrupole magnet (QF),
- Vertical focusing quadrupole magnet (QD),
- Diagnostic beam box,
- Beam position and phase detectors,
- Vacuum system,
- Support stand.

The intertank layout and assembly, shown in Figures 1 and 2, is located between gate valves that are part of the adjacent cryomodule assemblies. The intertank is assembled as a unit, and the quadrupole magnets are precision aligned with a taut wire in the lab prior to installation in the tunnel. Each doublet will use quadrupoles with matched excitation functions powered in series by a single power supply. The QF (QD) quadrupoles will be configured for horizontal (vertical)

steering fields. All quadrupoles will be constructed with steering windings although only about 40% need be energised based on misalignment and steering simulations.

Table 3: 2-D Harmonic Content of Quadrupole Magnets

2-D HARMONIC CONTENT		
	Medium-β (r=5 cm)	High-β (r=6 cm)
A <sub>6</sub> /A <sub>2</sub>	0.041 %	0.010 %
A <sub>10</sub> /A <sub>2</sub>	-0.058 %	-0.137 %
A <sub>14</sub> /A <sub>2</sub>	-0.007 %	0.005 %
A <sub>1</sub> /A <sub>2</sub> *	2.154%	1.579%
A <sub>3</sub> /A <sub>2</sub> *	0.896%	0.631%

\* Calculated for dipole field of 100 Gauss

Table 4: 3-D Harmonic Content of Quadrupole Magnets

	Mermaid 3-D	Vector Fields 3-D
	Medium-β (r=5 cm)	
A <sub>6</sub> /A <sub>2</sub>	-0.260%	-0.255%
A <sub>10</sub> /A <sub>2</sub>	-0.063%	-0.046%
A <sub>14</sub> /A <sub>2</sub>	0.008%	-0.006%
High-β (r=6 cm)		
A <sub>6</sub> /A <sub>2</sub>	-0.310%	-0.284%
A <sub>10</sub> /A <sub>2</sub>	-0.120%	-0.193%
A <sub>14</sub> /A <sub>2</sub>	0.004%	0.073%

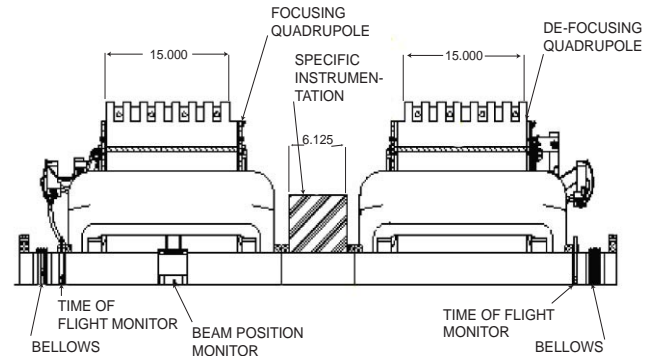


Figure 1: High-β Intertank Layout

The support stand utilizes a modified 6-point support scheme using 3 vertical struts and a floating plate that is positioned with respect to the stand with 2 additional horizontal struts and one axial strut. This allows for accurate, independent positioning of the magnet through all 6 degrees-of-freedom.

### 2.3 Magnet Electro-Mechanical Design

The electrical and mechanical parameters for the HE intertank quadrupole magnets are summarized in Table 5.

The magnetic circuit consists of four quadrants. Each quadrant is constructed of precision punched laminations (1008 low carbon steel - 1/16” thickness) sandwiched between ½-inch end plates adding to a 15-inch (38.1-cm) core assembly. The end plates will be chamfered as

needed to improve field uniformity on the basis of prototype magnetic measurements.

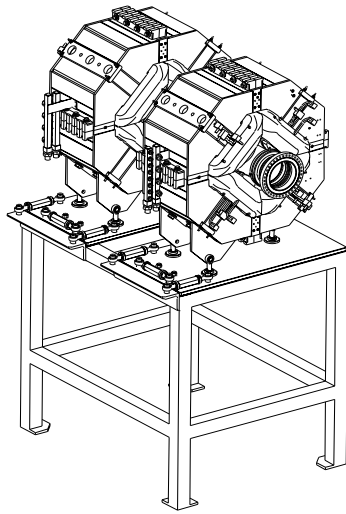


Figure 2: Intertank Assembly

Table 5: Parameters for the HE Intertank Magnets

PARAMETER	Quadrupole Parameters	
	Medium- $\beta$	High- $\beta$
Integrated Strength	2.12 T	4.39 T
Aperture	13.8 cm	16.8 cm
Effective Length	0.35 m	0.45 m
Core Length	28.1 cm	38.1 cm
Gradient	6.05 T/m	9.76 T/m
Current	290 A	420 A
Conductor	3/8" x 3/16" $\varnothing$	3/8" x 3/16" $\varnothing$
Turns/Pole	N = 40	N = 66
Resistance	0.037 $\Omega$	0.087 $\Omega$
Voltage	10.7 V	36.6 V
Power	3.11 kW	15.4 kW
Water Flow	2.34 gpm	4.16 gpm
Temperature Rise	5.1°C	14.0°C
Steering Dipole Parameters		
Dipole Field (Max.)	$\pm 100$ Gauss	$\pm 100$ Gauss
Current	15.6 A	15.0 A
Conductor	AWG8 wire	AWG8 wire
Turns/Pole	32	40
Resistance	0.038 $\Omega$	0.05 $\Omega$
Voltage	0.6 V	0.75 V
Power	9.25W	11.3 W

The electrical windings for the main quadrupole coil and the dipole steering correction coil are epoxied/potted in one structure as shown in Figure 3. The water-cooled 3/8-inch square hollow copper conductor is used for the main quadrupole coils. The steering dipole correction coils use round AWG8 copper wire and are cooled via conduction from the water-cooled quadrupole coils. Terminals have been provided for the connection of temperature sensors on all cooling water outlets. The high- $\beta$  coils are constructed with two parallel cooling circuits per pole, and the medium- $\beta$  has a single cooling circuit per pole.

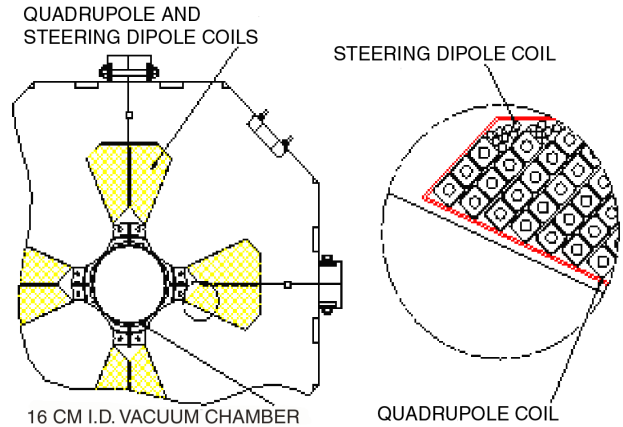


Figure 3: Cross-section, High- $\beta$  Quadrupole

### 3 REFERENCES

- [1] P. Lisowski, The Accelerator Production of Tritium Project, Proceedings of the 1997 Particle Accelerator Conference, Vancouver BC, p. 3780 (1997).
- [2] G. P. Lawrence and T. P. Wangler, Integrated Normal-Conducting/Superconducting High-Power Proton Linac for the APT Project, Proceedings of the 1997 Particle Accelerator Conference, Vancouver BC, p. 1156 (1997).
- [3] J. Tooker & G. Lawrence, Overview of the APT Accelerator Design, these proceedings.
- [4] Accelerator Production of Tritium Conceptual Design Report, 1997, LA-UR96-4847, APT-Doc-005.
- [5] S. Kahn and P. Wanderer, Magnetic Design of Superconducting Quadrupoles for the SC Linac for APT, Proceedings of the 1997 Particle Accelerator Conference, Vancouver BC, p. 3350 (1997).
- [6] VECTOR FIELDS Ltd, Oxford, England, "Software for Electromagnetics", 1997.
- [7] Mermaid for DOS, SIM Ltd, 630058 Novosibirsk, Russia.