DESIGN STATUS OF THE CRYOMODULES FOR THE APT LINAC[1]

B.M. Campbell, K.C. Chan, D.E. Daney, M.A. Daugherty,
R. Gentzlinger, B. Rusnak, J.A. Waynert
Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

The SRF part of the Accelerator Production of Tritium (APT) linac is over 1-km long and comprises more than 80% of the linac, the first part being water-cooled. The SRF cavity's design peak field, accelerating gradient, and Q_0 correspond to the current state-of-the art [1]. The cavities are cooled in a bath of 2-K helium II, which is used in several other operating cryomodules. What sets this cryomodule apart is the high RF power required to accelerate the 100-mA proton beam. Although nearly 100% of the power is delivered to the beam, the losses in the cavities and power couplers still place a substantial load on the central helium liquifier. The design of the power coupler cooling must be carefully optimized to minimize this load. This paper will describe the cryomodule conceptual design and some of the analytical methods that were applied.

INTRODUCTION

The cryomodules, cavities, and power couplers are being designed concurrently at Los Alamos. The relatively short schedule to go from conceptual design to a functional cryomodule in about two years dictates that, where applicable, we adopt proven technology developed on existing cryomodules.

The SRF part of the APT linac is divided into a medium energy section that use cavities of different beta and different length cryomodules. Table 1 summarizes these two linac sections.

Table 1. Summary of the APT SRF Linac

	Medium Energy Section	**High Energy Section**
Energy	217 MeV to 469 MeV	469 MeV to 1700 MeV
Cavity design β	β=0.64	β=0.82
RF power	280 KW per cavity	480 KW per cavity
Number of cavities	2 per cryomodule	4 per cryomodule
Number of cryomodules	51	77

The design described in the April Conceptual Design Report [1], uses superconducting quadurpoles in a singlet, FODO lattice to focus the beam. This met APT performance requirements, however the SC magnets located between each cavity made the cryomodule design complex. We are currently developing an alternate design that uses resistive quadrupoles in a doublet lattice located in the warm space between the cryomodules [2]. Stronger transverse focusing is required at medium energy so the cryomodules for that section contain only two cavities, while the cryomodules for the high energy section contain four cavities.

The APT cryomodules are being designed to become part of a plant used for industrial production. The accelerator is being designed for a 40-year life and availability during scheduled operations of greater than 85%. Beam loss is low enough to allow hands-on maintenance, and not require the use of radiation-hard materials. We are currently designing a β=0.64 cryomodule, shown in Figure 1, for the Engineering Development and Demonstration (ED&D) program.

[1] Work support by the US Department of Energy

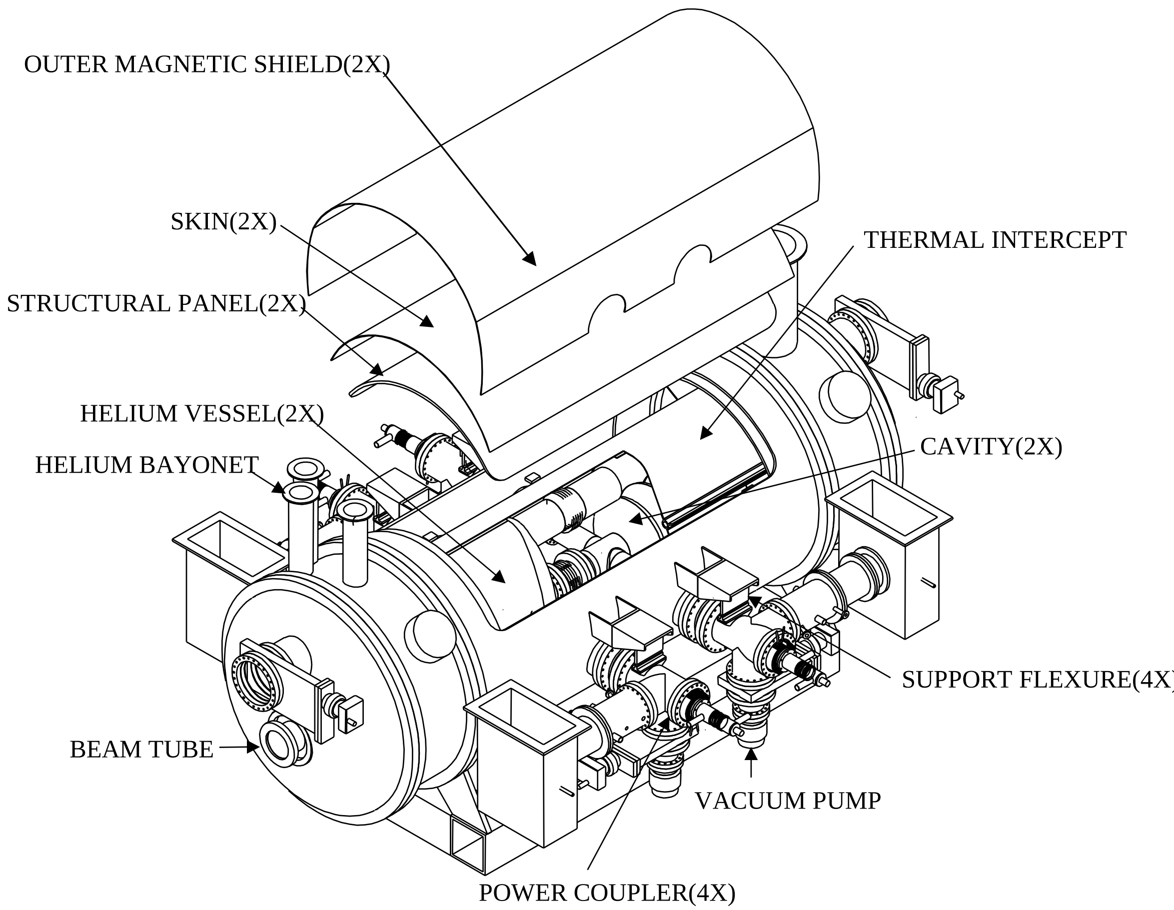

Figure 1. β=0.64 Cryomodule with the thermal intercept and helium vessel cut away.

CAVITY, TUNER, AND HELIUM VESSEL

Table 2 gives a summary of the cavity design. The cavities are made from niobium with a RRR of 250 that is formed and welded following well established cavity fabrication methods. The thickness of the niobium sheet is 3-mm for the β=0.82 cavity and 4-mm for the β=0.64 cavity. After fabrication the cavities are chemically etched and high pressure water rinsed using state-of-the art procedures. To avoid possible residual magnetic fields, the helium vessel is made from unalloyed titanium as used for the Tesla Test Facility (TTF) helium vessels.

Table 2. Cavity design summary.

	b=0.64	**b=0.82**
Aperture Radius	65 mm	80 mm
Cavity Radius	194 mm	200 mm
Wall slope	10°	10°
Number of cells	5	5
Frequency	700 MHz	700 MHz
Peak surface field	15 to 17 MV/m	14 to 17 MV/m
Accelerating gradient	4.7 to 5.0 MV/m	Constant 5.5 MV/m
Cavity losses $Q_0 = 5 \times 10^9$	15.4 W	24.1 W

A cavity inside its helium vessel is shown in Figure 2. In the cryomodule the helium vessels are connected by an upper 15-cm vapor duct and a lower 1-cm liquid transfer line. The liquid helium level at 2-K is 7-cm above the cavity. To recover from a fault in the central helium liquifier, it is sometimes necessary to raise the sub-atmospheric pressure, which causes the 2-K helium to warm to 4.5-K and expand. Sufficient ullage space is provided in the helium vessel to keep the liquid level below the vapor return duct to permit vapor flow when sub atmospheric pumping resumes and thus reduce recovery time.

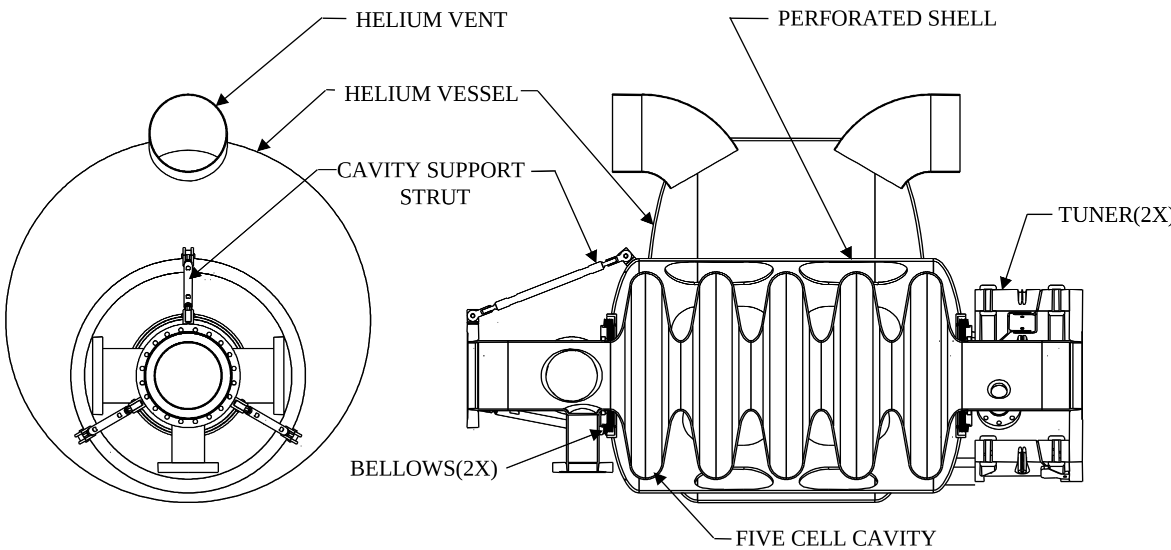

Figure 2. β=0.64 cavity and helium vessel assembly

The function of the tuner is to tune the cavity to 700 MHz or to detune an unpowered cavity so that the beam does not excite cavity fields that would decelerate subsequent particle bunches. The tuner elastically deforms the cavity to change the iris gaps, which changes the resonant frequency. The tuner can be divided into 3 parts: a linear actuator outside the vacuum vessel, a lever, and a mechanism that increases the leverage and moves the end of the cavity, shown in Figure 3. This mechanism was invented for the Los Alamos Pion Linac cavity, then further developed for the Cornell B-Factory cavity, and most recently used for the CESR cavity. For APT, we improved the lever support to reduce stresses in the flexures. Advantages of this tuner are: no sliding or rolling contacts that can gall inside the vacuum, minimal mechanical backlash, and an easily repaired linear actuator located outside the vacuum vessel.

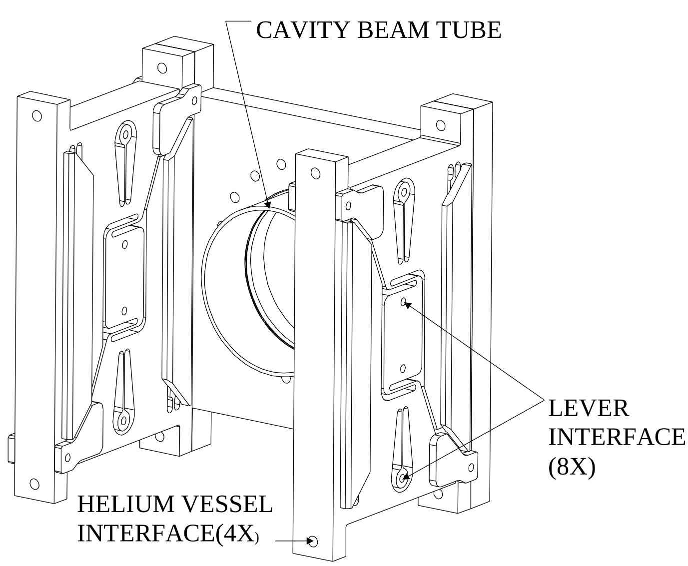

Figure 3. Cavity frequency tuner

POWER COUPLER

Each cavity is powered by 2 coaxial couplers [1], rated at 210 kW for the β=0.82 and 140 kW for the β=0.64 cavities. Two characteristics of the power coupler design influence the cryomodule design: warm windows located outside the vacuum tank and a noncompliant outer conductor. Design choices made to accommodate these characteristics are described later.

The losses from the high RF power transmitted by the coupler can result in large heat loads on the refrigeration plant. The power coupler cooling must be carefully designed to minimize these loads which in early designs were more than 10 W to 2-K per coupler. A finite difference thermal model is used to calculate the heat transferred to the helium bath, to the outer and inner conductor cooling stream.

The thermal model considers the following:

- Temperature dependent thermal conductivity
- Temperature dependent surface resistance
- Thermal conductivity of superconducting niobium
- Surface resistance of superconducting niobium
- Geometry dependent RF losses
- Radiation from 300-K and the center conductor

A design that looks promising for reducing the heat loads is described as follows:

- RRR 40 niobium beam tube and attached outer conductor, Figure 2
- Stainless steel outer conductor with 15-μm thick copper plating
- Cooling tube spiral-wrapped around the outer conductor
- Inner conductor cooled with 200-K helium

In the improved design, the outer conductor cooling functions somewhat like gas cooled leads for a superconducting magnet. It is also similar to the approach that CERN uses for the LHC couplers. The helium enters the spiral wrap at 2.3-K near the niobium tube and flows toward the warm end where it exits at 300-K. In addition to removing the heat from RF losses in the copper plating, the temperature of the niobium tubes must be maintained below 9-K to be superconducting. The heat load to the bath and the 2.3-K stream for this design is less than 3-W compared to 10-W for the earlier design.

THERMAL INTERCEPT AND MAGNETIC SHIELDING

The purpose of the thermal intercept is to reduce refrigerator work. The function is to attenuate thermal radiation to the 2-K helium and divert heat conducted from 300-K. The thermal intercept is made of an aluminum cylinder that is assembled from an upper and lower half. Each half is cooled with a single tube trace located at 12 and 6 o'clock. The tube is attached by welding to tabs formed by slotting the panel similar to the Tesla Test Facility cryomodule. This design provides predictable thermal contact and provides compliance for thermal displacements that occur during cool down.

Although the thermodynamic efficiency of the cryomodule changes with intercept temperature and can be optimized, the intercept temperature will be selected based on design constraints on the central helium liquifier. Blankets of multi-layer insulation (MLI) made of aluminized mylar are placed on both sides of the aluminum cylinder. Spokes, end beam tubes, tuner actuators, and instrumentation leads are thermally connected with straps to the aluminum panel. The location of the connection is calculated to minimize the total refrigeration work and depends only on the thermal conductivity of the item and the temperature of the intercept; if the cross section is uniform.

The function of the magnetic shield is to attenuate the earth's magnetic field that would reach the cavity. For cavities made of sheet niobium, as opposed to sputtered niobium on copper, residual magnetic fields are trapped when the niobium becomes superconducting which greatly reduces the cavity Q. The requirement of less than 10 mGauss will be met with 2 passive layers of Conetic or Cryoperm. Helmholtz coils will also be assessed on the cryomodule mockup for attenuating the axial magnetic fields.

VACUUM VESSEL

The vacuum vessel, shown in Figure 1, has large access openings top and bottom designed like the CERN LEP vacuum vessel. The material is 304 stainless steel plate. It is made in several sections: a center section with large openings top and bottom that goes into the clean room, two end extensions for the cryogenic helium plumbing, and elliptical end closures. The openings are closed with a recessed structural panel that carries the hoop stresses from external pressure and then covered with a skin that seals on an o-ring around the opening. When open in the clean room, the vertical laminar flow of air is not disturbed so that particulate contamination does not enter the cavities when the power couplers are installed. To make the center section easier to clean, we will make it from plate purchased with a ground surface and use full penetration welds that will be ground smooth.

CAVITY AND POWER COUPLER SUPPORT

The function of the cavity support is to maintain the cavity alignment, and stabilize the cavity from vibration that could lead to microphonic instability. The design must accommodate large thermally induced displacements. As mentioned before, the cavity and two power couplers form a single structural unit that must be supported. A flexure attached to each power coupler outside the vacuum vessel, Figure 1, constrains the coupler-cavity unit in five degrees of freedom. The transverse direction is left free on the power couplers to permit contraction during cool down. The unit is fully constrained by four spokes attached to the side helium vessel. During cool down the position of the power couplers is fixed and the cavity contracts toward the couplers. This increases the tension in the four spokes, but stresses are less than the design margin of 2. The heat leak to 2-K is 12 mW for all six spokes.

INTEGRATED THERMAL MODEL

Because the components in the cryomodule interact thermally, a complete, integrated, finite-difference model is used to calculate refrigeration power, temperatures, and flow rates, so that we can thermodynamically optimize the design [4]. Figure 4 is a diagram of the model for the β=0.64 cryomodule that shows the components modeled, coolant flow loops, and the output points for calculated values.

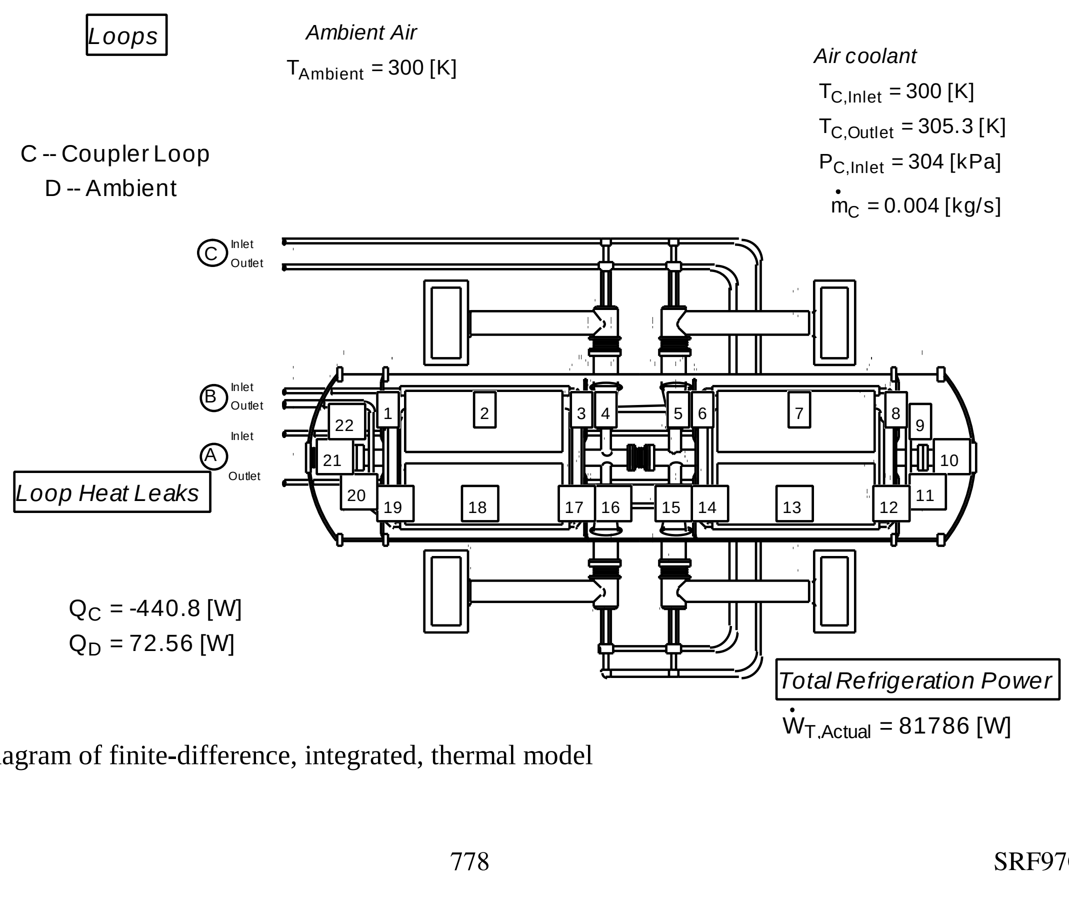

Figure 4. Diagram of finite-difference, integrated, thermal model

CRYOGENIC HELIUM SYSTEM AND FAULT HANDLING

The cavities are submerged in a 2-K bath of liquid helium II. Table 2 shows the cavity losses that must be removed by the phase change to helium II vapor at the surface of the bath. Supercritical helium is supplied at 2.2-K and 3 atm and expanded through a Joule-Thompson valve to 0.031 atm forming the 2-phase helium II that is then separated with a phase separator. A 15-cm duct connects the helium vessels and returns the helium vapor to the refrigeration plant.

A separate helium stream at 60-K and 3 atm is used to remove heat from the thermal intercept. A third stream to cool the power coupler outer conductor is under consideration and is described in the power coupler section.

With a loss of vacuum, the liquid helium in the helium vessels will boil and rapidly evolve helium that must be vented to prevent over pressurizing the helium vessels and cavities. Four separate venting systems are required to handle the various fault scenarios and these are summarized in Table 3. The worst case shown in Table 3 is venting the helium vessel following a breached beam tube outside the cryomodule. Air rushes into the 2-K cavity and condenses on the cavity wall depositing heat with a flux of 3.8 W/cm^2 into the helium bath. The evolved helium is vented through the 15-cm duct to pressure relief devices that vent into the tunnel or possibly into the vacuum vessel.

Table 3. Summary of the vent systems for a β=0.82 cryomodule

Venting System	**Relief Device**	**Set Pressure**	**Size**
Helium vessel	Resealable + burst disk	1.9 atm	15 cm
Vacuum vessel	Low pressure single action	1.1 atm	10 cm
Cryomodule beam tube	Burst disk	2 atm	4.2 cm
Warm beam tube	Burst disk	1.2 atm	10 cm

CRYOMODULE HEAT LOADS

Table 4 summarizes the various heat loads, both static and dynamic, that the cryomodule components place on the cryogenic helium. The heat loads from HOMs shown in the table are maximum values for each section and decrease at lower beam energy. The power coupler heat loads will probably be reduced by the improved cooling method described in the power coupler section.

Table 4. Comparison of heat loads for individual components in the cryomodule.

	b = 0.64 Cryomodule		**b = 0.82 Cryomodule**	
	2-K (W)	**45-K (W)**	**2-K (W)**	**45-K (W)**
Cavity (each)	24.1	0	15.4	0
Power Coupler (each)	5	22	3.5	15
HOMs (per cavity)	0.6	0	1.7	0
End Beam Tubes (2)	1.64	23.5	1.84	24
Radiation - MLI	0.92	9.1	2.2	19.4
Other	1.44	15.3	1.96	21.6

CRYOMODULE ASSEMBLY

The couplers and cavities are assembled and hermetically sealed in a class 100 clean room. The center section of the vacuum vessel must go into the clean room because the power coupler windows are located outside the vacuum vessel. This approach follows the procedure at CERN and only requires that the center section be designed to be easily cleaned. The beam tubes are sealed with a special valve that maintains a seal with part of its body and actuator removed. The thermal intercept, cryogenic plumbing, and remaining components are installed outside the clean room. Finally, the end of the vacuum vessel is slipped over the special valve and the panels and skin installed to close the vacuum vessel.

CAVITY MICROPHONICS

Cavity vibration and its effect on the RF frequency will be measured on the prototype 5-cell β=0.64 cavity that is currently being fabricated. The cavity will be installed in its inner perforated shell, shown in Figure 2, but without the outer helium vessel. This permits access to the cavity for installing accelerometers and also for adding cavity supports if needed. The RF control system has been extensively modeled [5] and this model will be used with the measured data to assess microphonic instability.

The next phase will be testing the cavity in the ED&D cryomodule at 2-K. A wire position monitor will be used to measure helium vessel vibration. Effect on the RF frequency will again be measured and the RF control system assessed.

FULL-SCALE MOCKUP

We are currently building a complete full-scale mockup of the β=0.64 cryomodule. The purpose is to assess the assembly procedure, assembly clearances, and to measure the magnetic field reaching the cavity. We will assess Helmholtz coils and different ways of applying the passive magnetic shields.

CONCLUSIONS

The industrial application of the APT cryomodules and the high RF power with its attendant heat load on the central helium liquifier cause a shift in the design priorities from other cryomodules. However, appropriate proven technology can and will be applied where possible to meet the very ambitious development schedule.

REFERENCES

[1] APT Conceptual Design Report, Pages 5-92 to 5-109, Los Alamos Report LA-UR-97, April 15, 1997

[2] G.P. Lawrence, T.P. Wangler, “Integrated Normal Conducting / Superconducting High-Power Proton Linac for the APT Project”, 1997 Particle Accelerator Conference, Vancouver, May 1997.

[3] B. Rusnak, et al., “Power Coupler Design”, Proc. Eighth Workshop on RF Superconductivity, Abano Terme (Padova), Italy, October 1997.

[4] J. Waynert, et al., “APT Preliminary Cryomodule and Power Coupler Thermal Modeling: History and Status”, Los Alamos Memo ESA-EPE: 98-001, October 1997.

[5] A. Regan, “APT LLRF Control System Model Results”, 1997 Particle Accelerator Conference, Vancouver, May 1997.