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Spallation Neutron Source (SNS) Coupled-Cavity Linac Hot Model

Report of the SNS Linac R&D Program

SNS 101020000-TR0001 – R00

Work supported by the Office of Science of the U.S. Department of Energy.

Compiled and edited by Robert Hardekopf

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John Bernardin
Jim Billen
Stan Brown
Nathan Bultman
Will Fox
Tom Hardek
Robert Hardekopf
Steve Hopkins
Subrata Nath
Don Rej
Paul Tallerico
Lloyd Young

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LIST OF ACRONYMS

List of Acronyms

AC	alternating current
AMU	atomic mass units
BC	bridge coupler
CCDTL	coupled-cavity drift-tube linac
CCL	coupled-cavity linac
CDR	Conceptual Design Review
CW	continuous wave
DC	direct current
DTL	drift-tube linac
EMQ	electromagnetic quadrupole
EPICS	Experimental Physics and Industrial Control System
FODO	focus-drift-defocus-drift
FFODDO	focus-focus-drift-defocus-defocus-drift
HCP	Hazard Control Plan
HPRF	high-power radio frequency
HVCM	high-voltage converter-modulator
I&Q	in-phase and quadrature
JLab	Jefferson Laboratory
kW	kilowatt
LAMPF	(Clinton P. Anderson) Los Alamos Meson Physics Facility
LEDA	Low-Energy Demonstration Accelerator for Production of Tritium project
linac	linear accelerator
LIR	Laboratory Implementation Requirement
LANL	Los Alamos National Laboratory
LANSC	Los Alamos Neutron Science Center
LLRF	low-level radio frequency

MEBT	medium-energy beam transport
MHz	megahertz
MW	megawatt
NEG	Non-evaporable getter
NG	Northrup-Grumman
OFE	oxygen-free electrolytic
OFHC	oxygen-free, high-conductivity
ORNL	Oak Ridge National Laboratory
P&ID	pipng and instrumentation diagram
PID	proportional integral differential
R&D	research and development
RCS	resonance control system
RCT	radiation control technician
RF	radio frequency
RFQ	radio-frequency quadrupole
RGA	residual gas analyzer
RTD	resistance temperature device
SCC	side-coupling cell
SCL	superconducting linac
SNS	Spallation Neutron Source
SRF	superconducting radio frequency
TLD	thermo-luminescence detector
VSWR	voltage-standing wave ratio
WBS	work-breakdown structure

SPALLATION NEUTRON SOURCE (SNS) COUPLED-CAVITY LINAC HOT MODEL

ABSTRACT

The Spallation Neutron Source (SNS) is a major research facility being constructed at Oak Ridge National Laboratory by a collaboration of six national laboratories. The coupled-cavity linac (CCL) is part of the accelerating chain that provides the beam power to the neutron-producing target. As part of the SNS R&D program, the CCL physics and engineering designs were validated with a copper hot model, consisting of two full segments coupled by a radio frequency (RF)-powered bridge coupler. The RF tuning procedures worked as expected. The hot model operated up to 480-kW peak power at a full 7.2% RF duty factor with an accelerating field of 4.08 MV/m. The peak and average powers were 17% higher than maximum design values. Measured cavity field flatness, field stability, Q, iris coupling, and stop band agreed closely with calculated performance. In addition to validating manufacturing, assembly, and handling procedures, the CCL hot model successfully tested the temperature and resonant-tracking control, amplitude and frequency algorithms, hardware and personnel-protect interlocks, vacuum conditioning procedure and time, vacuum-system performance (pressure, contaminants), and dark-current x-ray levels.

1

SNS-LINAC R&D AND CCL HOT-MODEL OVERVIEW**1.1 INTRODUCTION**

The Spallation Neutron Source (SNS) is an accelerator facility being built by the US Department of Energy's Department of Science. The SNS will employ neutrons as a research tool in a variety of disciplines including biology, material science, superconductivity, and chemistry. The neutrons are produced by bombarding a heavy metal target with a high-energy proton beam, accelerated with a linear particle accelerator or linac. The SNS, which will be located at Oak Ridge National Laboratory (ORNL), is being built in collaboration between six national laboratories (see Figure 1-1).

The linac consists of four accelerating elements—a radio-frequency quadrupole (RFQ) that accelerates the beam from an ion source to 2.5 MeV, a drift-tube linac (DTL) that accelerates the beam from 2.5 to 87 MeV, a coupled-cavity linac (CCL) that accelerates the beam from 87 to 185 MeV, and a superconducting radio frequency linac (SRF linac or SCL) that accelerates the beam from 185 to 1,000 MeV. The CCL is a multi-cell copper structure comprised of four modules, each made up of twelve segments. Each segment contains eight accelerator cavities or cells (see Figure 1-2). Between each segment is a copper bridge-coupler cavity that provides electrical continuity between the adjoining

Figure 1-1. Layout of the SNS facility showing national laboratory responsibilities

segments. RF power is fed into the accelerator cavities through the bridge couplers to provide high-gradient electrical fields that accelerate the ion beam. Additional design details on accelerator structures can be found in Wangler [1] and Chao and Tigner [2].

1.2 HOT-MODEL PLANNING

A “hot model” is a powered section of a linac structure that is usually constructed as a prototype model before major funds are committed for full construction. The CCL hot model was an integral part of SNS linac planning from the beginning of the project. In the SNS Conceptual Design Review (CDR) report of July 1997 [3], the R&D required for various RF structures was specified, including in Section 3.7.1 the following text:

“ . . . A CCL hot model will be constructed and tested with the power supplies available.”

The CDR review committee strongly endorsed this program and recommended that linac R&D funding be increased to provide both coupled-cavity drift-tube linac (CCDTL) and CCL hot models. In the summer of 1997, the baseline funding for SNS included \$6.3 M in the work-breakdown structure (WBS) 1.1.2.2 for R&D for design and engineering of both the CCDTL and CCL structures. When the SNS project was modified in the fall of 1999 to eliminate the 4-MW upgrade option (which required a funnel at 20 MeV), the CCDTL structure was dropped and the CCL modeling effort was confirmed as necessary and re-estimated. Figure 1-3 is a schematic of

Figure 1-2. Coupled-cavity linac (CCL) arrangement

the proposed hot-model layout after the CCDTL was eliminated.

1.3 SCOPE AND PURPOSE OF WORK

The system scope for WBS 1.1.2.2 was defined in the January 2000 SNS-linac baseline review as follows:

- 1) *CCL cold models:* Design and fabricate test models for RF properties;
- 2) *CCL hot model:* Design, fabricate, assemble, tune, and test a two-segment CCL hot model structure;
- 3) *Vacuum system for hot model:* Design, fabricate, assemble, and test the hot-model vacuum system;
- 4) *Water system for hot model:* Design, fabricate, assemble, and test resonance-control water-cooling system; and
- 5) *Facility operation for hot model:* Complete facility design, experimental and safety plans; obtain approval, and oversee operation.

The CCL hot model has multiple purposes, as defined in the following outline from the same baseline review.

- 1) Verification of the resonance-control system, which encompasses
 - a. Water cooling,
 - b. Low-level radio frequency(LLRF) controls, and
 - c. High-power radio frequency (HPRF) drive.

Figure 1-3. Hot-model assembly showing two CCL segments with powered bridge coupler

- 2) Confirmation of the mechanical design and manufacturing of the CCL including
 - a. Vacuum system verification, and
 - b. Alignment.
- 3) Qualification of vendors for the procurement of CCL components.
- 4) Examination of operational issues such as cold start, multipactoring, cavity conditioning, RF-field distribution under power, and thermal distribution.

1.4. BUDGET

Following a project change request in the spring of 2000, the final budget for WBS 1.1.2.2, CCL Engineering Models, was established as shown in Table 1-1.

In addition to this budget, WBS 1.1.2.7, RF Power, was funded to buy prototype klystrons and to develop the RF test stand for

component testing and for powering the CCL hot model.

1.5 HOT-MODEL PHOTOGRAPHS

Figures 1-4, 1-5, and 1-6 show the completed CCL hot model, the cavities during fabrication, and the support stand and vacuum manifold. More detailed descriptions and photographs are in the chapters that follow.

Table 1-1. Final Budget for the CCL Engineering Models R&D Program

WBS	Name	Cost (FY00 \$)
1.1.2.2.1	Cold Models	675,787
1.1.2.2.2	Hot-model RF structure	790,863
1.1.2.2.3	Hot-model support structure	56,790
1.1.2.2.4	Hot-model vacuum system	162,049
1.1.2.2.5	Hot-model water-cooling & resonance control system	233,583
1.1.2.2.6	Hot-model assembly and testing	1,110,277
Total		3,029,349

Figure 1-4. CCL hot model assembled in test position.

Figure 1-5. Copper CCL hot-model half-cells at energy of beta 0.403

Figure 1-6. Vacuum manifold installed on CCL hot-model support structure

1.6 DISPOSITION

Since the CCL hot model is a long-lived stand-alone unit, the costs associated with its construction were moved to the capital construction budget in 2001. Following initial tests at Los Alamos, the hot model will be used as a dynamic RF-power load for testing SNS RF-power systems. It could also be used for this purpose and possibly to test new thermal-control algorithms and to train physicists and operators in cavity conditioning, RF power systems, and resonance-control systems. It may be shipped to ORNL as the project installation phase evolves. At the present time (July 2002) the CCL hot model is in storage at the LANSCE Area A in Los Alamos.

2

LINAC DESIGN ISSUES AFFECTING THE CCL

2.1 LINAC LAYOUT

The SNS linac design is a combination of RF-structures consisting of both normal and superconducting accelerating cavities. A sectional sketch of the entire linac is shown in Figure 2-1 below. A 402.5-MHz RFQ accelerates an H^- ion beam from the injection energy of 65 keV to 2.5 MeV. A six-tank DTL, also at 402.5 MHz, accelerates the beam to 86.5 MeV. The next accelerator section is an 805-MHz coupled-cavity linac (CCL) of side-coupled type that accelerates the beam to an energy of 186 MeV. Each of its four RF-modules contains 96 accelerating cells. Each module is an assembly of 12 eight-cell segments resonantly coupled together with three-cell bridge couplers. Each module is excited through waveguide irises located in two of the eleven bridge couplers. The RF

power from a single 5-MW klystron splits once to drive each module, as indicated in Figure 2-1.

2.2 DTL-CCL TRANSITION

The transition energy between different accelerating structures is usually a compromise between accelerating efficiency and cost for each type of accelerating structure. Accelerating efficiency is inherently dependent on the cavity type of the structure, e.g. DTL, CCDTL, or CCL, and the shunt impedance ZT^2 that in turn depends on the bore radius of the cavity and the cell geometry specifics. Cost is dependent on the cavity type and the structure frequency. To maintain relatively high real-estate accelerating efficiency, the transition energy between the DTL and CCL was chosen on the basis of

Figure 2-1. Layout diagram of the SNS linac

effective shunt impedance ZT^2 . The crossing point between the falling DTL (402.5-MHz) ZT^2 curve and the rising CCL (805-MHz) ZT^2 curve is about 90 MeV, as shown in Figure 2-2. In Figure 2-2, the bore radii were 1.25 cm for the DTL and 1.5 cm for the CCL. These radii were chosen to maintain a relatively high-shunt impedance and yet provide a large enough clearance for the beam, considering expected input emittance and errors.

2.3 CCL-SRF TRANSITION

Beam dynamics issues dominate the decision on the transition energy from CCL to SRF structure. From cost and beam-loss risk considerations, the sooner an SRF structure can be started the better. But lowering the transition energy to around 100 MeV would necessitate a third low-geometrical beta ($\beta=0.48$) SRF elliptical-cavity group. Furthermore, fabrication of such a low- β elliptical cavity, as well as associated operational issues in a pulsed-mode, would

need significant R&D. More importantly, space-charge effects tend to become more important as energy decreases and the CCL has more focusing strength per unit length to counteract such effects. A beam energy of about 200 MeV seems to satisfy both of these issues. The energy of 186 MeV was chosen as an appropriate cut-off point to end the CCL structure, considering a workable power-partitioning scheme and allowed maximum number of cavities in a module.

2.4 CCL FOCUSING LATTICE

The CCL contains a total of 48 quadrupole magnets located between the segments in a focus-drift-defocus-drift (FODO) lattice of $13 \beta\lambda_{805}$. The quads in the DTL linac are arranged in a focus-focus-drift-defocus-defocus-drift (FFODDO) lattice period of $6 \beta\lambda_{402.5}$. The near equal length of the transverse focusing lattices in the DTL and the CCL helps to achieve a smooth and nearly current-independent match across the DTL to CCL transitions. Furthermore, since the

Figure 2-2. Effective shunt impedance ZT^2 for DTL and CCL structures

SRF-linac section has comparatively weaker transverse focusing (because of increased lattice period), the quadrupole gradients starting at the DTL are gradually ramped down to finally match the beam in the SRF lattice. Care is taken to make the average transverse focusing strength per unit length (k_{ot}) across the DTL to CCL and CCL to SRF transitions as smooth as possible. Likewise, the cavity phase and amplitude are ramped in the first and last CCL modules to match the k_{lo} (longitudinal focusing strength per unit length) of the DTL and SRF linacs, respectively. This matching is necessary done to avoid halo and emittance growth caused by mismatch.

2.5 PHASE ADVANCE

Zero-current transverse and longitudinal phase advance per meter across the linac are shown in Figure 2-3. The blue and red curves represent the k_{ot} and k_{ol} values, respectively. While the values across the transitions are very nearly equal, the first-derivatives are not. The longitudinal and transverse phase advance per period cross each other for only a single

period at the end of the CCL (figure not shown), thus avoiding onset of a second-order (weak) parametric resonance.

2.6 RESONANCE MODES

Other sources of potential halo and emittance growth are resonant modes that can develop in the beam itself. Figure 2-4 is a theoretical resonance chart calculated for nominal SNS-linac design parameters, which include a 52 mA beam current and an average emittance ratio of 1.2. The contoured peaks identify potential beam resonances. The shaded areas of decreasing intensity around the peaks give expected rates of emittance growth with 5% being the lowest value plotted. The beam tune trajectories across the linac superimposed on this plot correspond to a 52 mA beam. The tune trajectories in different sections of the linac are all in the lightest shaded areas. The two peaks on the left of the plot are weak resonances and take a long time to develop. The peak at tune ratio σ_1 / σ_1 of 1.00 is a third-order resonance and takes 20–30 betatron periods to develop.

Figure 2-3. Zero-current transverse and longitudinal phase advance per meter; k_{ot} and k_{ol} across the linac

Figure 2-4. Tune trajectories across the entire linac superimposed on a theoretical resonance chart

At the 38-mA baseline beam current, the tune depression is less severe, causing the tune trajectories to move upwards. Thus we expect no emittance growth as a result of resonance conditions in any of the linac structures.

2.7 EMITTANCE GROWTH

In Figure 2-5 we show the emittance profiles for the rms, normalized transverse and longitudinal emittance values, across the entire linac as a function of energy. We used an input distribution to the RFQ of a one hundred thousand particle 4-D waterbag distribution, which is then transported through the medium-energy beam transport (MEBT) to

Figure 2-5. Beam emittance profile along the entire linac for reference beam

the input of the DTL. There are no scrapers to remove halo particles transversely, nor are there any energy filters to eliminate the low-energy particles at the output of the RFQ. The anomalous initial rise in the longitudinal emittance at approximately 2–4 MeV is because of the presence of these low-energy particles in the beam. Eventually, at approximately 4 MeV, these particles get lost radially in the first tank of the DTL. A standard set of linac errors is included in this simulation. An emittance growth of about 25% and 35% is observed in the transverse and longitudinal phase-spaces, respectively, at the end of the CCL linac.

3

PHYSICS DESIGN OF THE CCL CAVITIES

3.1 CAVITY LAYOUT

This chapter describes the CCL RF-cavities physics design. The CCL consists of 384 accelerating cavities arranged in 48 segments of 8 cavities each. All cavities within a segment are identical, and the segment length gradually increases to match the average velocity of the particles in the beam. The length of an accelerating cavity is $\beta\gamma/2$, where βc is the design particle velocity for the segment and $\beta\gamma$ is the distance traveled by the design particle in one RF period at 805 MHz. The space between segments has a length of $5\beta\gamma/2$. We further subdivide the 48 segments into 4 RF modules of 12 segments each. Within a module, three-cell bridge couplers span the space between segments. A module contains a total of 213 cavities: 96 accelerating cavities, 84 internal coupling cavities, 22 larger coupling cavities in the bridge couplers, and 11 center bridge cavities, of which two have waveguide feeds.

3.2 PHYSICS DESIGN PROCEDURE

To carry out the beam-dynamics design for the CCL, we interpolate cavity parameters from a list of several representative CCL accelerating cells. We use the *Superfish* code to design the shapes of the accelerating cavities and coupling cavities and to compute surface fields and RF-power losses. The data required for the beam-dynamics effort are the transit-time factors for each cell. For a total power estimate, we also need the shunt impedance, ZT^2 . After completing the beam-dynamics design, we then repeated the runs of

the cavity design codes to determine properties of each CCL accelerating cavity. In parallel, we designed two types of coupling cavities and the bridge coupler cavity, which spans the space between two segments of the CCL structure. One coupling cavity type connects two accelerating cavities and the other connects an accelerating cavity to the bridge-coupler center cavity. We tested several aluminum low-power models of both the CCL structure and the bridge coupler, and we built and tested at full RF power a two-segment copper hot model.

3.3 ACCELERATING-CAVITY SHAPE

The CCL accelerating cavity is cylindrical-symmetric about the beam axis. The program *CCLfish* sets up the geometry for symmetric CCL cells and runs *Superfish* repetitively, varying the cavity geometry to tune each cavity to the desired frequency. The *Superfish* codes *Automesh*, *Fish*, and *SFO* are included as subroutines within the main tuning program. The coupling slot between accelerating cavities and coupling cavities is a three-dimensional effect that, of course, is not included in the axially symmetric design codes. We discuss the coupling slot separately below.

Figure 3-1 shows a cross section of the right half of a CCL cell. The symmetry plane is in the gap center between the two noses. The lower left corner is the center of the cell. Figure 3-2 shows more detail near the nose, and Figure 3-3 shows a tuning ring feature that does not appear in Figure 3-1. The full

Figure 3-1. Half cell showing geometrical parameters in a CCL accelerating cavity

Figure 3-2. Detail of the CCL cell near the nose

gap is g , and the full cell length is L . R_b is the bore radius. The full cavity diameter is D and the outer-corner radius is R_{co} . There are three circular arcs on the nose profile. R_{ci} is the inner corner radius, which connects the vertical surface at the septum of thickness s to the cone-angle segment. The cone angle is α_c . R_o is the outer-nose radius, which connects the cone-angle segment to an optional vertical flat segment of length F , and R_i is the inner-nose radius, which connects the vertical flat segment to bore. The latter two arcs are tangent if $F=0$.

Figure 3-3. Detail showing the tuning ring feature in the CCL cavity

The tuning ring provides a few MHz of tuning range, which is sufficient to compensate for the frequency effects of machining tolerances and for uncertainties in frequency estimates of 3-D effects such as coupling slots. We machine these rings after frequency measurements on a full segment stack before brazing the segment.

Figure 3-4 shows the electric field lines calculated by *Superfish* for representative CCL cavities.

3.4 ACCELERATING-CAVITY PARAMETERS

Table 3-1 lists the CCL design and geometrical parameters common to all accelerating cavities. The 402.5-MHz DTL delivers the input beam with an initial beam energy 87.8 MeV, which corresponds to velocity $\beta=0.4045$ for H^- ions. The CCL output beam energy is 185.6 MeV, or $\beta=0.5502$. For the peak surface electric field, we set a conservative limit of 33.9 MV/m,

Figure 3.4. Superfish fields for CCL accelerating cells for $(=0.40)$ (left) and $(=0.56)$ (right)

which corresponds to about 1.3 times the Kilpatrick criterion at 805 MHz. Power considerations required that the accelerating field E_0 not exceed 3.77 MV/m.

3.5 DESIGN CHOICES

In the early days of the SNS project, when the entire linac following the DTL was to be a room-temperature machine, we investigated a number of bore radii and varied other parameters to optimize the CCL shunt impedance ZT^2 . When the room-temperature CCL scope changed to a much shorter ~ 100 -MeV linac section, we fixed several parameters to reduce cost and ease manufacturing. The final single bore radius listed in Table 3-1 resulted in a slight reduction in ZT^2 . We also chose not to use the

Table 3-1. Accelerating-cavity Design Parameters

Parameter	Symbol	Value
Resonant frequency	f	805.0 MHz
Initial energy	W_i	87.8 MeV
Final energy	W_f	185.6 MeV
Maximum surface electric field	E_{Peak}	33.9 MV/m
Bore radius	R_b	1.5 cm
Accelerating field	E_0	3.77 MV/m
Cavity diameter	D	24.9580 cm
Septum thickness	s	1.0 cm
Cone angle	α_c	10 degrees
Outer corner radius	R_{co}	2.74 cm
Inner nose radius	R_i	0.085 cm
Outer nose radius	R_o	0.26 cm
Nose flat length	F	0.0 cm
Tuning-ring frequency effect	Δf_{Ring}	2.5 MHz
Tuning-ring width	W_{Ring}	3.0 cm
Tuning-ring thickness	T_{Ring}	0.24–0.30 cm
Tuning-ring offset	Δy_{Ring}	0.0 cm
Tuning-ring angle	α_{Ring}	20 degrees
Frequency tolerance	δf	0.002 MHz
Smallest mesh size	δx	0.028 cm

optional flat section on the nose ($F=0$ in Figure 3-2). The small cone angle improves shunt impedance by increasing the transit-time factor, but it also increases the peak surface electric field. Included in Table 3-1 are the frequency tolerance δf used by *CCLfish* as a termination criterion and the smallest mesh size δx in the *Superfish* problem geometry. We use a fine mesh in the regions where we are interested in the surface fields and a coarser mesh in other regions. Figure 3-5 shows a detail of the mesh for the $\beta=0.40$ cell. The smallest mesh triangles are near the end of the nose.

3.6 CELL TUNING

We tuned the 17 cells corresponding to $\beta=0.40$ – 0.56 in 0.01 steps by adjusting the gap between noses. The cavity length for a CCL cell is always $\beta\lambda/2$. The inner corner radius varies with β to improve shunt impedance. Table 3-2 lists some of the cavity parameters. The peak power density and cell power

Figure 3-5. Expanded view of the $\beta=0.40$ cavity showing mesh near the nose

columns in Table 3-2 correspond to a 7% RF duty factor. The cell power and shunt impedance columns include an additional 15% of RF power dissipated near the coupling slots. Although the code runs used symmetric half cells, the cell power in the last column corresponds to a full cavity.

Table 3-2. Data for Representative CCL Accelerating Cavities

Velocity β	Gap $g/\beta\lambda$	R_{ci} (cm)	ZT^2 ($M\Omega/m$)	Cavity Q	E_{Peak} (MV/m)	Peak P/A (W/cm ²)	Power (kW)
0.40	0.126	0.84	33.3	15,900	33.9	3.01	4.66
0.41	0.130	0.86	34.2	16,200	32.5	3.01	4.78
0.42	0.133	0.88	35.0	16,500	32.2	3.00	4.90
0.43	0.136	0.90	35.9	16,700	31.9	3.00	5.02
0.44	0.139	0.92	36.6	17,000	32.6	3.01	5.13
0.45	0.142	0.94	37.4	17,300	32.0	3.01	5.24
0.46	0.145	0.96	38.1	17,500	32.1	3.02	5.34
0.47	0.148	0.98	38.8	17,800	32.0	3.03	5.44
0.48	0.151	1.00	39.5	18,000	31.5	3.04	5.53
0.49	0.154	1.02	40.2	18,300	30.5	3.05	5.62
0.50	0.157	1.04	40.8	18,500	31.1	3.06	5.71
0.51	0.160	1.06	41.4	18,700	31.2	3.08	5.79
0.52	0.162	1.08	41.9	18,900	30.1	3.10	5.87
0.53	0.165	1.10	42.5	19,100	30.0	3.11	5.95
0.54	0.167	1.12	43.0	19,300	30.7	3.13	6.02
0.55	0.170	1.14	43.5	19,500	29.8	3.16	6.09
0.56	0.172	1.16	43.9	19,700	29.7	3.18	6.15

Table 3-3 lists the transit-time factor integrals for the CCL representative cells. For definitions of these integrals, refer to the Poisson Superfish documentation [1].

3.7. COUPLING CAVITIES AND COUPLING SLOTS

The CCL has two types of coupling cavities shown in Figure 3-6. The field contours shown for the TM_{010} mode are lines of constant magnetic field H . These contours are parallel to the electric field direction. An internal coupling cavity connects two accelerating cavities within a segment. The figure shows half of a symmetric cavity. These cavities attach above or below the accelerating cells, alternating from top to bottom. Because all accelerating cavities have the same outer corner radius and septum thickness, all the internal coupling cavities are identical to one another.

Figure 3.6. Coupling cavities used between accelerating cavities (left) and between an end accelerating cavity and the center bridge cavity (right)

Table 3-3. Transit-time Factor Results for the Representative Ccels

β	T	TP	S	SP
0.40	0.887244	0.033823	0.360501	0.048387
0.41	0.888527	0.033466	0.359065	0.048322
0.42	0.889664	0.033152	0.357883	0.048283
0.43	0.890661	0.032878	0.356950	0.048268
0.44	0.891521	0.032644	0.356252	0.048277
0.45	0.892241	0.032450	0.355802	0.048311
0.46	0.892844	0.032291	0.355557	0.048366
0.47	0.893378	0.032151	0.355380	0.048425
0.48	0.893767	0.032054	0.355514	0.048517
0.49	0.894063	0.031983	0.355808	0.048626
0.50	0.894268	0.031939	0.356257	0.048750
0.51	0.894372	0.031925	0.356878	0.048890
0.52	0.894414	0.031928	0.357591	0.049040
0.53	0.894364	0.031958	0.358476	0.049207
0.54	0.894257	0.032005	0.359442	0.049381
0.55	0.894067	0.032076	0.360554	0.049569
0.56	0.893821	0.032163	0.361743	0.049765

Table 3-4 lists the geometric parameters for the internal coupling cavities. The coupling slot between accelerating cavity and coupling cavity starts as the intersection of the cavity corner radii machined from both sides of a copper plate. To ensure a consistent coupling factor within each segment, one of the final machining steps mills the edge of the slot to specified dimensions. The nominal coupling factor is 5%. Because of the increasing volume of the accelerating cells with particle velocity, the actual coupling varies from 5.45% in Segment 1 to 4.45% in Segment 48.

External coupling cavities (shown on the right in Figure 3-6) connect the last accelerating cavity of a segment to the center bridge cavity. These cavities are longer than internal coupling cavities, and they are not longitudinally symmetric. The overall length of the external coupling cavity is 7.37 cm, and the nose length (on flat) is 2.64 cm. Except for the longer nose, the accelerating-cell side of the cavity has the same profile as an internal coupling cavity. On the side opposite the accelerating cavity (between the external coupling cavity and the center bridge cavity), the cavity diameter steps down from 17.45 cm to 16.0 cm. This feature helps move the center bridge cavity farther from the accelerator

beam axis leaving more room for the quadrupole magnets. The coupling slot on the bridge-cavity side is an arc near the cavity outer radius. For an arc subtending an angle of $\sim 120^\circ$, the resulting coupling to the center bridge cavity is about 7%. We use the angular extent of these slots in the two external coupling cavities of a bridge coupler to set the ratio of accelerating field in the adjacent segments. In the first eight segments of Module 1, the design calls for a $\sim 2.5\%$ increase in E_0 from segment to segment. To achieve this ramp, the upstream coupling slot in the first seven bridge couplers will be about one degree smaller in extent than the downstream slot. The coupling slot is a feature that one could include in computer computations by using a 3-D electromagnetic code. However, we have found that such 3-D calculations are often unnecessary. Instead, we prefer to estimate the frequency effects of the coupling slot using a Slater-perturbation approach, adjust the cavity dimensions to compensate for the frequency effect, and then build and test a low-power aluminum model of the structure. The Slater-perturbation analysis follows a procedure described by J. Gao [2] and requires only the geometrical properties of the slot and data computed by the *Superfish* code for the accelerating cavity and coupling cavity. The *Superfish* data needed are the stored energies and the fields E and H at the location of the coupling slot.

We have taken this approach for coupling slots in all the cavity types in the CCL. For the accelerating cells, the slots lower the cavity frequency by about 24 MHz for Segment 1 and by about 17 MHz for Segment 48. To correct for this effect, we reduced the outer radius of the cavities. The tuning rings provide enough range in frequency adjustment to tune the cavities to their pre-braze

Table 3-4. Coupling Cavity Geometry

Geometrical Parameter	Dimension
Cavity length	4.46 cm
Cavity diameter at equator	17.45 cm
Length of 17.45-cm diameter segment	0.829 cm
Cavity diameter maximum	18.55 cm
Outer corner radius	0.9525 cm
Inner corner radius	0.3175 cm
Nose diameter	8.725 cm
Nose length (on flat)	2.48 cm
Nose corner radius	0.3175 cm
Nose face an	3.0 degrees

target frequency as discussed in the tuning plan. For the internal coupling cavities, the slots lower the frequency by about 35 MHz. Shortening the noses corrects the frequency. In the larger external coupling cavities, the combined effect of the two coupling slots is about 60 MHz. Again, we compensate for the effect by shortening the noses.

3.8 BRIDGE-COUPLER CAVITY

Figure 3-7 shows line drawings of the bridge-coupler cavity and portions of the two adjacent external coupling cavities. This portion of the coupling cavity corresponds to the profile at the far right in Figure 3-6. The bridge-cavity axis is offset by 4.93 cm from the axis of the coupling cavities.

Figure 3-7. Bridge coupler isometric view (top), end view (left), and cross section (right).

Table 3-5 lists the geometric parameters for the bridge cavities. The $5\beta\lambda/2$ -long space between segments contains the two external coupling cavities, which all have the same length, and the central bridge cavity, which increases in length. As the length of the bridge cavity changes, the nose length changes to keep the cavity tuned to 805 MHz. From the four nose lengths that appear in Table 3-5 (two at each end of the linac for cavities, with and without a drive iris), we linearly interpolate according to β the nose length in all other bridge cavities. Only the third and ninth bridge couplers in each module include a drive iris.

3.9 BRIDGE-CAVITY FEATURES

The bridge cavity includes a large slug tuner with a range of about 12 MHz. To tune each bridge cavity, we insert the bridge coupler into the center of a five-cell tuning

fixture for a series of measurements described in the tuning plan. At the end of the tuning procedure, both end cavities have the same frequency (when measured individually), the $\pi/2$ -mode frequency of the five-cell structure equals the target value, and no significant RF power can be observed in the two coupling cavities. When these conditions have been achieved using an adjustable-length slug tuner, we then machine the water-cooled copper slug to the required length. Another feature in the bridge cavity is the TE-mode tuner, which is a solid copper rod welded to the top of the cavity. The large coupling slots on the ends of the cavity split the degeneracy between the two orthogonal TE_{111} modes. One of these modes couples strongly to the adjacent coupling cavity's TM_{010} magnetic field in the slot and would interfere with the proper behavior of the coupled chain of resonators. The vertical TE-mode tuner lowers the frequency of the offending TE_{111} mode to

Table 3-5. Bridge-coupler Cavity Geometry

Geometrical Parameter	Dimension
Overall length (segments 1-2, $\beta=0.4054$)	33.80 cm
Overall length (segments 47-48, $\beta=0.5475$)	47.03 cm
Cavity length (segments 1-2, $\beta=0.4054$)	22.37 cm
Cavity length (segments 47-48, $\beta=0.5475$)	35.61 cm
Cavity diameter	26.50 cm
Nose diameter	13.00 cm
Nose length in $\beta=0.4054$ cavity with iris	1.51 cm
Nose length in $\beta=0.4054$ cavity without iris	2.06 cm
Nose length in $\beta=0.5475$ cavity with iris	1.39 cm
Nose length in $\beta=0.5475$ cavity without iris	1.90 cm
Nose corner radius	0.16 cm
Nose face angle	3.0 degrees
Outer corner radius	0.0 cm
Inner corner radius	0.16 cm
Slug tuner diameter	10.16 cm
TE-mode tuner length	17.56 cm
TE-mode tuner diameter	0.95 cm

below 690 MHz, which is several full widths of the TM_{010} passband below 805 MHz. The RF magnetic field near the TE-mode tuner is low enough that conduction cooling of the rod is sufficient. The slug tuner incorporates a second TE-mode tuner perpendicular to the vertical rod. As the length of the successive bridge cavities increases, the mode frequency of the other TE_{111} mode (the one that does not couple to fields in the slots) moves through the TM_{010} passband. While the bridge coupler is installed in the five-cell tuning fixture, we adjust the TE-mode tuner on the slug-tuner axis to move this TE_{111} mode to a “safe” location. Since it does not couple to the fields, we are only moving it a few 10s of MHz away from the operating mode.

3.10 CCL MODULES

The CCL will be built in four RF modules, each module consisting of twelve eight-cavity segments and eleven bridge couplers. Each module receives RF power from a single 5-MW klystron connected to two of the bridge couplers. Table 3-6 lists parameters for the four CCL modules needed in the RF control system design. The energy gain ΔW and

synchronous phase ϕ_s comes from the *Parmila* design. The phase values for Modules 3 and 4 are average values. These modules actually have phase ramps. The values of $E_0 T$ are averages for the module derived from the energy-gain equation $\Delta W = qE_0 TL \cos \phi_s$, where L is the module length including all intersegment spaces, and ϕ_s is the value reported in the table. Beam power P_B assumes an average beam current of 34 mA (65% of 52 mA). The stored energy U , unloaded quality factor Q_0 , and cavity power $P_C (= \omega U / Q_0)$ are from *Superfish*, which includes an empirical estimate of the power increase in each segment caused by coupling slots. The total cavity power has been increased by an additional 3% to account for expected losses in the bridge couplers. Parameter β in Table 3-6 is the cavity-to-waveguide coupling factor that results in zero reflected power at 100% of the design current. This value is given by $\beta = 1 + P_B / P_C$. The coupling factor for each of the two drive irises will be half of the β value listed for a module. External Q and loaded Q are given by $Q_{Ext} = Q_0 / \beta$, and $Q_L = Q_0 / (1 + \beta)$. The detuning angle ψ (for full beam current) is given by $\tan \psi = [(\beta - 1) / (\beta + 1)] \tan \phi_s$.

Table 3-6. CCL Module Parameters

Module	ΔW (MeV)	P_B (MW)	ϕ_s (deg)	$E_0 T$ (MV/m)	U (J)	Q_0	P_C (MW)	β	Q_{Ext}	Q_L	ψ (deg)
1	20.334	0.691	-30.0	1.983	6.86	16,310	2.127	1.325	12,309	7,015	-4.6
2	23.979	0.815	-30.0	2.139	8.49	17,418	2.465	1.331	13,089	7,473	-4.7
3	26.074	0.887	-29.5	2.140	9.09	18,432	2.493	1.356	13,597	7,825	-4.9
4	28.412	0.966	-28.0	2.146	9.66	19,311	2.530	1.382	13,975	8,108	-4.9

4

CCL COLD-MODEL MEASUREMENTS AND RESULTS

4.1 INTRODUCTION

The function of a cold model is to establish the geometry required for successful operation of the RF structure as a resonant system and to give information about various system sensitivities to slight geometric variations. In order to establish and verify the geometry for the SNS CCL, several cold models were constructed for both the low-energy end ($\beta=0.404$) and the high-energy end ($\beta=0.549$) of the CCL structure. There were several modifications to the mechanical design approach that occurred during the cold-model construction and testing as the RF performance and interrelated cavity influences were studied and understood.

4.2 BRIDGE COUPLER

Early in the design process, a large-diameter 3-cell bridge coupler was envisioned to provide coupling between CCL segments. Several of these coupling cells were to be powered, i.e., the RF power would be supplied through waveguides to these cells. Figures 4-1 and 4-2 below show the full engineering design and the cold-model version that was constructed to test the parameters of this type of coupler.

The aluminum model that was built to test the bridge coupler is shown in Figure 4-3. Initially, the ends were capped with blank off flanges during solo tests of the bridge coupler.

Later, four aluminum accelerating cells (half of an 8-cell segment) were added to each end to measure the coupling parameters through the assembly. The final arrangement is shown in Figure 4-4, which also shows the bead-pull apparatus used for the measurements.

Figure 4-1. Engineering drawing of powered bridge coupler

Figure 4-2. Cold model of powered bridge coupler

Figure 4-3. High-energy bridge coupler assembled for Initial frequency tests

Figure 4-4. Assembled bridge coupler and accelerating cells with bead-pull apparatus

4.3 INITIAL TESTS AND MODIFICATIONS

During testing of the system shown in Figure 4-4, we discovered that the stored energy in the large-diameter end cells of the coupler was too great to allow sufficient coupling between the segments and the center bridge cell. A coupling of about 5% is required for proper power flow through the module, and we were measuring less than half that flow. To address the problem, we made the decision to reduce the size of the bridge-coupler end cells but to leave the large-diameter center cell unchanged.

The impact of this modification on the segments was to reduce the offset spacing between the end coupling cell (a half cell that mates to the bridge) and the beam centerline. In order to maintain the same offset of the center bridge cell and provide adequate space for the electromagnetic quadrupole (EMQ) magnet assemblies, we needed to modify the bridge coupler and make the center and end cells non-coaxial. This additional complexity in the bridge coupler was required to allow proper packaging of all the required hardware in the intersegment regions surrounding the EMQ magnets.

4.4 MODIFIED BRIDGE COUPLER

The revised design is shown in Figure 4-5. For mechanical stability reasons, the unit is on its side. In use, the waveguide feed in the center of the photograph is oriented in the horizontal direction and the space between the segments is oriented upward. Note the coupling-cell offset geometry as discussed above. A photograph of an internal plate of the bridge coupler is shown in Figure 4-6. The coupling slot between the bridge center cell and the end cell is the crescent-shaped opening in the plate. By varying slightly the length of the coupling slots between the end cells and the center cell of the bridge,

Figure 4-5. Revised cold-model hardware with modified bridge coupler

Figure 4-6. Coupling slot between bridge center and end cells

the field ramp required in CCL Module 1 could be achieved.

4.5 ADDITIONAL MEASUREMENTS

In addition to the coupled segment and bridge models, we made cold-model arrangements of individual segments as shown in Figure 4-7. Measurements were made to determine the final shape and orientation of the coupling slots internal to the segments, shown in Figure 4-8. For these measurements, both half segments (as shown in Figure 4-5) were joined to form a full-length (8-cell) segment to achieve the proper stored-energy reference point. This procedure was used to determine the required offsets between the target value of the average-cell tune and the desired final accelerating mode frequency (805 MHz). The two frequencies are different because of the substantial direct coupling between adjacent accelerating cells within the segment group (so called next-nearest-neighbor coupling). This target value must be known for each segment to allow final tuning of the segment.

Figure 4-7. Full 8-cell cold-model assembly of CCL segment 1

Figure 4-8. Internal segment coupling slot

5

ENGINEERING DESIGN OF THE CCL RF STRUCTURES

5.1 INTRODUCTION

We decided early in the conceptual design process for the SNS linac that a full-scale powered test model was essential to an adequate understanding of the performance of the mechanical design of the CCL linac. To that end, a number of different possible CCL hot-model configurations were examined prior to selection of the final design concept. As mentioned earlier, there was an initial intention to include a hot model of the CCDTL structure on the same test stand to minimize duplication of support services and the size of the required test cell. When the CCDTL was eliminated from the baseline design for SNS, the design of the hot model was configured to include two full CCL 8-cell accelerating segments and the common bridge coupler between [1]. The basic rationale was that while more components, especially additional bridge couplers, could provide some information about field ramping techniques and multi-segment stability, there was neither time nor budget for such an endeavor. Answers to the most important questions could be obtained with the selected configuration.

- 1) Could the structure be reliably and successfully fabricated and tuned using the techniques and suppliers selected?
- 2) Was the thermal management system properly designed in terms of water distribution and resonance control logic?
- 3) Was the vacuum system sized properly, and did it perform well during conditioning?

- 4) Was the RF conditioning of the structure easily accomplished, especially the window region, and did it operate stably under power?

As detailed in the following pages, the hot-model tests did answer these questions. These tests provided the basis for our claim at the final design review for the CCL system that the mechanical design, the proposed manufacturing techniques, and the basic operational characteristics would meet the system requirements.

5.2 MECHANICAL DESIGN CONSIDERATIONS

The objective for the mechanical design was to utilize the CCL baseline design drawings for both hot-model and production components unless revisions were required based on the hot-model experience. The hot model constructed represents a small section of the baseline CCL. The baseline design of the CCL requires relatively short accelerating sections (segments) compared to some previous CCL installations, such as at LAMPF and Fermilab. This CCL design allows the frequent magnetic focusing required for high-current linacs, but it requires resonant coupling (bridge couplers) between a large number of segments for efficient use of RF power. The shorter segments allow for easier handling during the final stages of manufacture, but the large RF klystrons in the baseline design (5 MW) leads to physically long groups of coupled segments, referred to as a module. The length of the modules

(about 50 ft) has implications on maintaining uniform field distribution during operation with beam. It also affects installation and handling during final assembly in the linac tunnel. For the energy range selected for the CCL structure, an 8-cell segment configuration with 12 segments per module provided a good match to both the required magnetic focusing lattice and efficient use of the RF power.

5.3 HOT-MODEL LAYOUT

To fully test the manufacturing aspects of the CCL during construction of the hot model, we selected a design with full-length segments (all 8 cells in each) and a bridge coupler with an RF-drive feed. This arrangement allowed us to fully characterize the machining, handling, shipping, and brazing fixtures required for full-scale production. The segments are of the “internal type,” having a bridge-coupler flange on each end terminated by a simple cover plate (see Figure 5-1). The entire assembly is mounted on a welded-steel tubing support structure with adjustable transverse segment supports. The electromagnet quadrupole that will be included between segments on the actual CCL module was not included in the hot model, since no beam was to be accelerated.

Figure 5.1. Layout of the CCL hot model

5.4 SEGMENT DESIGN

The segments are composed of machined copper plates that are joined using multiple steps of furnace brazing and machining to form the RF cavities of the segments. The length of the segments is $4\beta\lambda$ (see Chapter 3). Two types of RF cavities are formed: the eight accelerating cells located on the beam axis, and the side-coupling cells located off-axis and alternating side-to-side in the segment assembly. Water-cooling passages are machined into the walls (septa) separating the individual cells within the segments (see Figure 5-2).

Figure 5.2. Accelerating and coupling-cell septa showing cooling passages

The water passages remove heat from the copper and allow the resonant frequency of the cells to be controlled by the temperature of the water. The resonance control system (RCS), including the water pumps, piping, and computer hardware and software, maintains a frequency match between the RF amplifiers and the copper cavities (see Chapter 8). Figure 5-3 shows an example of flanged ports provided in the side coupling cells and the bridge center cell for vacuum pumping to maintain the required high-vacuum environment during operation (see Chapter 7).

Figure 5-3. Vacuum port on the coupling cell

5.5 ACCELERATING CAVITY AND SIDE-CELL DESIGN

Both the physics design and the mechanical engineering of the accelerating cells and side coupling cells were done to provide simplicity in the machining and tooling requirements. All cells within a segment are identical, using an average cell length for the group. A constant shape was selected for all side coupling cells throughout the linac regardless of beam energy. In addition, several parameters were held constant for all accelerating cells (see Figures 3-1 and 3-2), including the cell diameter, the outer corner radius, the shape of the coupling

slot opening between the cells, and the details of the shape of the cavity nose, including tip radii and nose angle. In order to tune the cells with increasing cell length along the linac, the gap width is varied by slightly changing the nose length, and the inner corner radius is varied slightly to match the requirements of the segment nose length. These simplifications greatly reduce the number of different cell parameters and thus the machining complexity required to manufacture the segments. Figure 5-4 shows isometric views of these cells.

Figure 5-4. Accelerating cavity (left) and side-cell (right)

5.6 BRIDGE-COUPLER REQUIREMENT

Bridge couplers are resonant RF cavities that allow power to flow between segments. The bore of the accelerating cavities is so small (3 cm) that no power is transferred by coupling along the beam axis. The bridge couplers are all $2.5\text{-}\beta\lambda$ long and consist of three cells. The end cells are nominally unexcited and dissipate very little power. However the center cell is excited on all

bridge couplers in the CCL, and this cell provides a convenient location to interface the RF waveguide feed on some of the bridge couplers. For the hot model, the bridge coupler was the length required for inter-segment 1—the location between Segments 1 and 2. (In the final CCL, power feeds are required at the one-quarter and three-quarter points of each module; that is Coupler 3 and Coupler 9 in Module 1. The hot-model bridge coupler was a slightly special element in terms

of tuning because Coupler 1 would normally not be powered.) Figure 5-5 (identical to Figure 3-7) shows the design of the hot-model bridge coupler.

5.7 BRIDGE-COUPLER DESIGN

The bridge-coupler center cell is connected to the two end cells by slots. The length of the slots controls the amount of coupling and also affects the frequency of all

Figure 5-5. Bridge coupler isometric view (top), end view (left), and cross section (right).

three cells, as well as the end cell of each adjacent segment. The length of these slots is accounted for in the cavity design and set precisely in the tuning process. Since the center cell in the coupler is excited, water-cooling is provided in the cylinder wall to allow frequency control of the cells. As mentioned above, two couplers per module have a waveguide attachment flange with a slot coupling the waveguide feed port to the coupler. The center cell also has a direct connection to the vacuum manifold on each unit. During RF conditioning, the ceramic in the RF window evolves gas from its surface. It is desirable to pump this gas load locally; therefore, on the couplers with waveguide feeds we add auxiliary non-evaporable getter (NEG) pumps to increase pumping in the RF-window region.

During low-power testing of a full-scale aluminum model of the bridge coupler, several undesirable modes were observed. We added a mode-separation post to the center cavity, protruding into the cavity from the top surface of the cylinder, as shown in Figure 5-5. This post moves the unwanted modes away from the main coupling mode so that tuning of the module is not compromised. A slug tuner on the side of the cylinder is used for fine adjustment of the resonant frequency during final tuning of the modules. Power dissipation on the tuning post is very low and is simply conducted into the cooled wall of the coupler. The slug tuner has slightly more power loss because of its width and location, so it has water -cooling for thermal control

5.8 SEGMENT MECHANICAL SUPPORT AND VACUUM SYSTEMS

The segments are supported by adjustable cross members mounted on top of a welded steel-frame assembly. The steel-frame uses square tubing for rigidity and low cost. The cross members allow for vertical and transverse alignment of the segments and for longitudinal sliding to accommodate the thermal expansion of the segments and bridge couplers during operation. The cross members attach to the steel frame with vertical adjusters. The segments mount to the cross members with a three-point contact; two contacting points in the front cross member and one on the rear (see Figure 5-6). Resting beneath the segments and nested in the steel-frame assembly is the full-length vacuum manifold that provides distributed pumping to the side coupling cells (bottom sides only) and to the bridge-coupler central cell. The upper side coupling cells are not actively pumped. This configuration results in the indirect pumping of each accelerating cell and the beam tube region between segments through the side coupling cells. Both calculations and measurements showed that conductance through the coupling cells was sufficient to provide good quality vacuum in the accelerating cells.

Figure 5-6. CCL segment mechanical support

6

FABRICATION AND ASSEMBLY OF THE CCL HOT-MODEL RF STRUCTURES**6.1 INITIAL MACHINING OF THE SEGMENTS**

The CCL segment fabrication process involves a series of sequential machining and brazing steps starting with the OFE (oxygen-free electrolytic) copper plate material. The copper stock material is purchased in rectangular plates, formed in the hot-rolled condition, and cut to size with minimum excess material. The plate in the hot-rolled form does not require further annealing before machining. In the initial machining phase the plates are surfaced flat on both sides, and the coupling cell and the cooling channels for the septum are milled to finished size (see Figure 6-1). The parts are then transferred to a lathe where the final contour of the coupling cell is turned, followed by a complete facing operation across the entire brazed surface to ensure flatness of the septum surfaces that will be joined by brazing.

Figure 6-1. Facing of the brazing surfaces on lathe

6.2 INITIAL FURNACE BRAZE

The next phase is the furnace braze using a copper-gold alloy at about 1,000°C to join the plates together in pairs at the prepared surfaces. Each segment has 14 internal plates joined to form pairs and two end plates that have an external copper cover plate brazed at this step (see Figure 6-2).

The cover plate for the end cell covers the water channels machined in the septum wall and also provides stiffening to the septum that is only 5-mm-thick without the cover. The stiffening strengthens the wall and limits the amount of deflection caused by external atmospheric pressure when the accelerator is operating and under internal vacuum. Any wall deflection would result in a change in the spacing between the noses in the end cell of the segment, which would change the resonant frequency of the cell and the segment.

6.3 CAVITY MACHINING

Following the first braze step, the plate pairs (now called half-cell assemblies) and the end walls are returned to the machine shop for machining of the accelerator cavity shape. At this point a milling operation removes most of the bulk material from the cell on each side of the half-cell assembly, and a lathe-turning operation provides the final precision contour of the RF cavity (see Figure 6-3).

Both sides of the half-cell assembly and one side of the endplates are machined to a specified contour that is based on the overall

Figure 6-2. CCL cell internal plates joined to form pairs

Figure 6-3. Lathe turning provides the final precision contour of the RF cavity

length of the cell. Cell lengths change with each segment, so each group of plates associated with a specific segment has the same accelerating-cell contour geometry. As shown in the Figure 6-4, the cell contour includes a circumferential ring, or raised area, on the cavity side of the septum that is specifically provided to allow for tuning of each cell.

By machining a portion of the ring away, the resonant frequency of a cell can be lowered but not raised. Therefore, the cell frequency in the final-machined cells is designed to be slightly higher than required.

Figure 6-4. Circumferential ring or raised area on the cavity side of the septum that is provided to allow for tuning of each cell

The calculations specify a ring height that will nominally be half removed during the tuning process, if the cavity contour were otherwise perfect. Since the cavity contour is never perfect, the ring allows for some error in either direction. Since the accelerating cells are formed as the region between two adjacent half-cell assemblies when they are joined at the surface, each cell contains two noses and two tuning rings. The interface surface is called the cell equator surface. It has a series of specific groove features for placement of the brazing alloy wire for the second braze which will produce a complete segment (see Figure 6-5).

Figure 6.5. Electron-beam welding of a cover strip over a water channel and wire grooves for the brazing alloy

6.4 COUPLING-SLOT MACHINING

After the accelerating cavity is complete the overlap regions between the side-coupling cells and the accelerating cells on each side of the half-cell assemblies have now formed an opening between the cells—called the coupling slot—that is roughly elliptical in shape with sharp edges. These edges must be removed to avoid thermal problems and to provide a precise shape that is consistent for each opening, since this controls the power flow and the coupling between cells in the segment. A machining operation is performed on each side of each half-cell assembly by a milling cutter with the plate presenting at a 45-degree angle. Therefore, the path is a simple two-dimensional curve with the edge of the milling cutter removing material to produce a roughly 2-mm-thick flat around the perimeter of the coupling slot (see Figure 6-6).

Figure 6-6. Side coupling cell showing coupling slot (left) and expanded view of the coupling-slot region (right)

6.5 VACUUM PORT AND STACKING

After each plate assembly is milled, a second milling operation on the end of the assembly produces an opening to receive a stainless-steel tube for attachment of the vacuum manifold. After this vacuum port and the coupling slot are completed, the half-cell assemblies and the endplate are assembled together (stacked) with the aid of a fixture shown in Figure 6-7 below.

Figure 6-7. Cell assemblies and the endplate are assembled together (stacked) with the aid of a fixture

6.6 FREQUENCY ADJUSTMENT

At this point, the resonant frequency of each cell and the frequency of the accelerating mode ($\pi/2$ mode) are measured. Based on the measurement, a calculation is made to determine how much material must be machined from the tuning ring to produce uniform frequencies in all cells—slightly below the desired final frequency. This low-side offset allows for the opportunity to raise the cell frequencies and $\pi/2$ mode frequency after final brazing for precise tuning of the segment. The machining is performed, and the segment assembly is cleaned with a detergent and water solution and thoroughly rinsed with distilled water (see Figure 6-8).

Figure 6-8. Finish machining is performed for precise tuning of the segment

The segment is then placed into the shipping fixture shown below for transport to the furnace brazing facility (see Figure 6-9).

Figure 6-9. Segment in shipping fixture for transport to the furnace brazing facility

6.7 PREPARATION FOR BRAZING

At the brazing facility the segments are unpacked and all individual components are again cleaned with water and detergent followed by a thorough rinse with distilled water. This rinsing is followed by wiping the segment with a mild acetic acid solution, rinsing with water, and a final drying with boil-off nitrogen gas. The components are then assembled on a brazing fixture with the brazing alloy placed into the joints (see Figure 6-10A, B, and C).

The entire segment and fixture are then loaded into the furnace and the brazing process initiated. The furnace loading is shown in Figure 6-11.

6.8 FINAL BRAZING AND LEAK TESTING

The brazing cycle is tailored for the *Cusil* alloy used, and the cycle time is about 12 hr from initial pump-down to furnace-open after the cycle. After the cycle was complete and the assembly was cool enough to handle, all internal passages were leak-tested with a helium leak detector to insure vacuum integrity of the segment (see Figure 6-12).

During the leak-testing, we took great care not to touch the brazed assembly with bare hands so as not to contaminate the external surface. The objective was to prevent migration of organic contaminants from the external surface of the segment into the interior of the unit during handling and tuning. After completion of the leak-testing, we repackaged the segments in the shipping fixtures and returned them to the machine shop for vacuum-flange welding. Following this weld, the segment was re-tested for vacuum integrity.

Figure 6-10. Showing the assembly with the brazing fixture and alloy in place. (a) cleaning with detergent, (b) rinsing after acid cleaning, and (c) braze alloy wire placed in grooves

6.9 BRIDGE COUPLER FABRICATION

The bridge coupler was designed to utilize electron beam welding as the primary joining method (in preference to furnace brazing). During the design process, discussions with brazing personnel indicated that some development would be required to ensure

Figure 6-11. Segment and fixture being loaded into the furnace for initiation of the brazing process

Figure 6-12. Leak-testing internal passages with a helium leak detector to insure vacuum integrity of the segment unit

against deformation of the end walls during brazing. Any deformation could result in an installation problem because the flatness of the flange fit to the segments could not be assured. Metal O-ring seals were planned for these flange joints, and these seals require a precise mating condition to exist for proper sealing. In addition a welding approach would allow for simple repair if any leaks were to occur in the process and a time advantage in the schedule was realized by using a resource separate from the brazing activities. Therefore, the bridge-coupler components were manufactured, packaged, shipped, and welded in a straightforward

manner. Figure 6-13 shows the complete complement of components prior to shipment for welding.

Additional activities for the bridge couplers include pre-preparation of the stainless steel fittings to include a copper base (done in a copper-gold braze cycle) so that the fittings could be directly welded into the body with a copper-to-copper weld joint. After completion of the welding, the assembly was helium leak-tested for vacuum integrity. No leaks were found and no repairs were required. The completed coupler was shipped to LANL for assembly into the hot-model test stand.

6.10 SEGMENT TUNING

During the tuning phase at LANL, the segments were individually tuned starting with the side coupling cells. A special tool was used to spread the noses slightly on the coupling cells to raise their frequency to the desired value. The accelerating cells were then tuned using the dimpling ports provided (see Figure 6-14). A detailed description of the tuning is given in Chapter 12.

Figure 6-14. Accelerating cells have their frequencies raised by a special dimpling tool

6.11 ASSEMBLY AND FINAL TUNING

After the segments were tuned individually, the bridge coupler was installed between the segments, and a field measurement was made through the segment cells. This measurement insured proper tuning of all cells and proper coupling between the three components (see Figures 6-15 and 6-16). After tuning was completed, the components were moved into final position, and the vacuum, water, and RF power systems were connected.

Figure 6-13. Complete complement of components prior to shipment for welding

Figure 6-15. Bridge coupler installed between CCL hot-model segments

Figure 6-16. Final frequency check of assembled hot model

7

THE CCL HOT-MODEL VACUUM SYSTEM**7.1 REQUIREMENTS**

To effectively accelerate the protons along the beam line, the CCL requires an internal vacuum environment with a base pressure of 9.0×10^{-8} Torr averaged over the beam line. This high vacuum provides an acceptable environment for the high-gradient electrical fields that are established within the CCL's proton accelerating cavities. In addition, the high vacuum minimizes the undesired stripping and scattering of the proton beam [1]. To provide a satisfactory safety margin in the design of the CCL vacuum system, a design goal of 5.0×10^{-8} Torr was sought as the average operating vacuum base pressure along the CCL beam line. To achieve this vacuum, we have to consider the pumping speed, surface material and geometry, conductance paths, and gas loads. In addition to achieving the base vacuum pressure, the gas composition must be carefully controlled. For example, low molecular-weight gas molecules such as H_2 , H_2O , N_2 , O_2 , and CO can be acceptable for proton scattering, whereas heavy hydrocarbon molecules are generally undesirable [1]. The CCL cavity surface material, surface finish, and cleanliness are critical in defining the gas load and composition in the CCL vacuum system. In addition, the gas load and composition is significantly influenced by the amount of time the CCL cavities are vacuum and RF conditioned. Both of these conditioning activities tend to lower the vacuum pressure by enhancing the removal of adsorbed gas species on the vacuum surfaces [2].

7.2 HOT-MODEL VACUUM SYSTEM

To determine the vacuum compatibility of the CCL manufacturing, assembly, and cleaning processes, assess the adequacy of the vacuum system design and numerical modeling techniques, and develop an understanding of the vacuum and RF conditioning processes, a prototype CCL vacuum system was fabricated, assembled, and tested on the CCL hot model. This chapter discusses the design and performance of the vacuum system. First, the design and layout of the prototype vacuum system, including the selection of vacuum pumps, hardware, and instrumentation is presented. Next, the development of a numerical vacuum model, including the model geometry, conductance formulas, and mass conservation equations is discussed. The use of the numerical model in sizing the vacuum pumps and hardware, as well as predicting the pressure distribution and average surface outgassing rates, is discussed. Finally, empirical ion-gauge and residual gas analyzer (RGA)-pressure data from the hot-model vacuum tests are used to assess vacuum-system performance and numerical modeling accuracy, as well as to characterize the vacuum conditioning of the CCL environment. The vacuum-environment characterization is presented with plots of the gas composition and surface outgassing histories of the vacuum environment over a 1,000-hr vacuum and RF conditioning period.

7.3 VACUUM-SYSTEM LAYOUT

Figures 7-1 and 7-2 show a schematic of the CCL hot model with vacuum-system components highlighted and a photograph with several vacuum-system interfaces.

7.4 VACUUM ENVIRONMENT

The vacuum environment for the CCL hot model can essentially be divided into three main regions. The first and largest vacuum region is comprised of the interconnecting volumes of the CCL cavities and side coupling cells (SCCs). These volumes, shown in the cross-section of Figure 7-3, make up the majority of the vacuum environment and contribute the greatest amount of gas from surface outgassing. The second vacuum region is the bridge coupler, a large cylindrical vessel that connects the two segments. The third and final

vacuum region lies within a waveguide transition piece that joins the RF window to the bridge coupler. The RF window has the potential to be a large gas load, as it is porous and traps a large number of gas molecules that are only released when excited by applied

Figure 7-1. CCL hot-model schematic with vacuum systems and interfaces highlighted

Figure 7-2. CCL hot model showing vacuum-system interfaces

RF energy. At the waveguide connection to the bridge coupler is an iris, which is a narrow slit in the bridge coupler wall. Because of its low conductance, little pumping speed occurs through the iris. Consequently, the waveguide transition housing between the RF window and the bridge coupler, forms a vacuum region that is nearly independent of the other CCL vacuum regions. The cross-section view shows the complex geometry and interconnections of the accelerator cavities and side coupling cells within each segment.

7.5 PIPING AND INSTRUMENTATION

Figure 7-4 displays the piping and instrumentation diagram (P&ID) of the prototype CCL vacuum system. The center feature of the vacuum system is an electro-polished 304 stainless steel vacuum manifold with an internal diameter of 20.32 cm (8.0 in.) and a length of 355 cm (140 in.). The vacuum manifold was connected to the CCL segments and bridge coupler by seven 6.35-cm (2.5-in.) internal diameter formed bellows. The majority of vacuum pumping on the manifold was performed by two 550 L/s Varian V550 turbo pumps, each backed by an oil-free, 300 L/min, Varian PTS 300 scroll pump. This pump combination was chosen because of its

ability to pump all gases and evacuate the vacuum environment from atmospheric pressure down to the required operating pressure in the 10^{-8} Torr region. A 300 L/s Varian VacIon Plus 300 Diode ion pump was also selected to gather performance data needed for the design of the SNS facility-based linac vacuum systems. Also connected to the vacuum manifold was a nitrogen-gas purge system equipped with pressure regulators, a flow throttling device, and isolation, vent, and pressure relief valves. The vacuum pump speeds were determined with the numerical model discussed in the Section 7.9. The RF window waveguide transition region was evacuated by a 1300 L/s SAES CapaciTorr-B 1300-2 NEG pump. The NEG pump was chosen because of its large pumping speed, light weight, and small spatial envelope. A 70 L/s Varian V70 turbo pump was used for NEG pump activation and regeneration purposes. Manual gate valves were used for all pump isolation connections. The vacuum system configuration utilized design concepts found in previous particle accelerator vacuum systems ([2], [3], and [4]). More details on the present vacuum system design and hardware selection process can be found in Bernardin [5].

Figure 7-3. Details of the CCL cavities showing vacuum regions

Figure 7-4. Piping and instrumentation diagram of CCL vacuum system

7.6 VACUUM MEASUREMENT

Vacuum pressures were measured with a *Granville-Phillips* 370 Stabil-Ion Vacuum Measurement System. Thermal conductivity gauges were used to monitor vacuum levels between 10^{-4} and 760 Torr, while hot filament ion gauges (Stail-Ion 370120) were used to monitor high vacuum levels in the 10^{-9} to 10^{-3} range. The positions of these gauges on the prototype CCL vacuum system are shown in Figure 7-4. Each *Granville-Phillips* 370 controller/ion gauge combination is calibrated to an accuracy of 4% over a pressure range of 10^{-9} to 10^{-3} Torr for pure nitrogen [7]. The measurement accuracy is degraded if the vacuum gas is made up of gas species other than nitrogen. To acquire an accurate pressure

measurement, P_{act} , from a vacuum environment containing gases other than nitrogen, the ion gauge pressure reading, P_{meas} , must be corrected according to the following equation [8]

$$P_{act} = \frac{P_{meas}}{\sum_i Se_i \times \frac{P_i}{P_{total}}}, \quad (1)$$

where Se_i is the sensitivity of the ion gauge to gas species i , P_i is the partial pressure of gas species i , and P_{total} is the sum of the partial pressures of all the gas species. The gas-dependent sensitivity values for the *Granville-Phillips* ion gauges are given in Table 7-1.

RGA scans, to be presented with the

experimental results, reveal that approximately 20% of the gas mixture is made up of nitrogen, with the remainder of the vacuum gas mixture made up of other atmospheric gases. RGA data collected during this study, and ion gauge sensitivity parameters provided by *Granville-Phillips*, were used to estimate the uncorrected accuracy of the ion gauge readings as 10% for the gas mixtures encountered in this study.

Table 7.1. Ion-gauge Pressure Sensitivity Factors for the *Granville-Phillips* 370 Stabil Ion-Gauge Controller [7]

Gas Species	Sensitivity Factor, S_e
He	0.18
H ₂	0.46
H ₂ O	1.12
O ₂	1.01
N ₂ and CO	1.00
Ar	1.29
CO ₂	1.42

7.7 RESIDUAL GAS ANALYSIS

To monitor the gas composition of the vacuum environment and obtain the partial and total pressures needed in Equation (1), *Inficon Transpector-2* RGAs were mounted on the vacuum manifold and RF window assembly. Each RGA was equipped with a C100M sensor head with a microchannel-plate electron multiplier and Faraday cup. For all tests reported here, the electron multiplier was turned off. The C100M sensor head is capable of monitoring between 0 and 100 Atomic Mass Units (AMU), or mass-to-charge ratio, with a resolution (peak width at 10% of peak height) of 0.9 AMU and a sensitivity of 10^{-4} Amps/Torr for N₂. The *Transpector-2* RGA analyzes gases by ionizing the gas molecules in an ion source, separating the ions by mass in a mass filter, and measuring the quantity of

ions at each mass in a Faraday Cup detector. The magnitudes of these signals are displayed on a remote computer in the form of ion current (amps) versus AMU (mass to charge ratio). Before an ion current can be converted to a partial pressure, the operational characteristics and nuances of the RGA's ion source, mass filter, and detector must be understood and accounted for. For example, during the ionization process, free electrons may or may not ionize a gas molecule. In addition, the free electron may strip one or more electrons from a gas molecule. Other factors influencing the ion current conversion include the transmissivity of the mass filter as well as the gain and sensitivity of the detector ([8] and [9]). Equation (2) shows the relationship between the partial pressure of substance i , and the ion current, I_{ib} , of substance i at an AMU b , and accounts for the instrument and physical factors discussed above.

$$P_i = \frac{I_{ib} \times FF_{N28}}{FF_{ib} \times XF_{ib} \times TF_b \times S}, \quad (2)$$

where FF_{ib} is the fragmentation factor, or fraction of total ion current from substance i having an AMU b , FF_{N28} is the fragmentation factor for N₂⁺ ions at 28 AMU from N₂ (0.9), XF_i is the ionization probability of substance i relative to N₂, TF_b is the transmission factor or the fraction of total ions at AMU b which pass through the mass filter relative to ions at an AMU of 28, and S is the sensitivity of the instrument to nitrogen or the ion current at 28 AMU per unit of nitrogen partial pressure (10^{-4} Amps/Torr) [7]. Table 7-2 provides the values of FF_{ib} , XF_i , and TF_b for various gas species and the *Transpector-2* RGA.

Table 7-2. Ion Current-to-Partial Pressure Conversion Factors for the *Transpector-2* RGA and C100M Sensor Head [9]

Gas Species	b	FF_{ib}	XF_i	TF_b
H ₂	2	1.00	0.44	14.0
He	4	1.00	0.14	7.0
H ₂ O	18	0.75	1.00	1.6
N ₂ & CO	28	0.90	1.00	0.9
O ₂	32	0.95	1.03	1.0
Ar	40	0.83	1.20	0.7
CO ₂	44	0.70	1.40	0.6

7.8 OPERATION

The vacuum pressures and RGA data were collected with a *Hewlett Packard* 34970A data acquisition system run on a PC loaded with *Labview* 5.0® software. To minimize electrical noise and interference, all instrumentation and communication cables were shielded and electrically grounded. The prototype CCL vacuum system experiment was initiated by opening the vacuum pump isolation valves, turning on the vacuum gauge controllers, and turning on the scroll pumps to allow the entire vacuum environment to reach a pressure of approximately 10 milli Torr. At this point, the two turbo pumps on the vacuum manifold and the single turbo pump on the RF window assembly were switched on. Twenty hours of turbo pump operation were required to bring the system base pressure down below 10^{-6} Torr. At this point, a *Balzers* HLT270 helium leak detector connected to the vacuum manifold was used to leak check the entire system. The leak detector had a minimal detectable helium leak rate of 3.8×10^{-12} Torr L/s and was calibrated with a known leak rate of $4.2(\pm 0.2) \times 10^{-7}$ Torr L/s. All detectable leaks were sealed prior to continuing the vacuum testing. After 100 hr of vacuum conditioning and obtaining a vacuum pressure in the 10^{-7} Torr region, the NEG pump was activated and the RGAs and ion pump were turned on.

Following an initial vacuum conditioning period of 180 hr, RF power at various amplitudes, frequencies, and pulse lengths was applied intermittently to the prototype CCL over the next 800 hr. More details on the RF conditioning are presented in Figure 7-9 and in Section 7.13. The RF energy, along with the vacuum pumping, served to clean the vacuum surfaces and allow the vacuum pressure to continuously decrease. The vacuum and RF testing of the prototype CCL took place over a period of 950 hr, during which the RGA and ion gauge data was periodically recorded.

7.9 NUMERICAL MODEL

To accurately size the vacuum pumps and hardware to achieve desired operating pressures, optimize instrumentation locations, and assess the performance of the CCL vacuum system, a representative numerical vacuum model of the prototype CCL vacuum environment was constructed. The numerical model used a nodal network approach by representing the volumes, complex surfaces, and tortuous paths of the CCL vacuum environment, as a series of equivalent sub-volumes or nodes, joined by conductance paths. Figure 7-5 displays this transformation for a portion of a CCL segment.

Figure 7-6 displays the complete and simplified model representation of the prototype CCL vacuum system. Because the conductance between neighboring cavities and between the innermost cavities and the bridge coupler were so small (<40 L/s), some of these flow paths were neglected in the simplified numerical model.

Figure 7-5. Transformation of CCL segment vacuum geometry to a simplified numerical model representation

Figure 7-6. Numerical model representation of the prototype CCL vacuum environment

Figure 7-7 summarizes the simplified geometry of the various vacuum areas within the CCL segments.

The RF window vacuum environment was not included in this model because the coupling conductance through the iris in the bridge coupler was less than 20 L/s. This approach required a separate vacuum analysis for the RF window environment [6].

The steady-state pressure distribution within the CCL vacuum environment was obtained by solving the following mass conservation equation for each of the j sub-volumes in the model

$$\sum_{i=1}^n C_{i \rightarrow j} (P_i - P_j) + Q_{j, leak} + Q_{j, outgas} - S_{eff} P_j = 0, \quad (3)$$

where the $C_{i \rightarrow j} (P_i - P_j)$ is the gas conducted into volume j from volume i , n is the number of volumes connected to volume j , $Q_{j, leak}$ is the total-gas leak load into volume j , $Q_{j, outgas}$ is the total surface outgassing load into volume j , and $S_{eff} P_j$ is the gas load removed from volume j by vacuum pumps with an effective speed of S_{eff} . In the high-vacuum region, all of the conductance paths in the vacuum model could be represented as molecular flow of nitrogen (@ 298 K) through a short tube, C_{st} ,

Figure 7-7. Numerical model geometries and dimensions

$$C_{st} = 12.11 \times \frac{D^3}{(L + 1.33D)}, \quad (4)$$

or through an aperture, C_{app} .

$$C_{app} = 11.58 \times A, \quad (5)$$

where the units on conductance are L/s, D is the tube diameter in cm, L is the tube length in cm, and A is the aperture area in cm² [10]. Table 7-3 summarizes the conductance values of the paths connecting the various sub-volumes in Figure 7-6.

Table 7-3. Summary of the Conductance Values used in the Numerical Model of the CCL Vacuum System

Conductance Path Symbol	Conductance Model	Conductance Value (L/s)
C0	Aperture	528
C1	Aperture	631
C2	Short Tube	118
C3	Short Tube	37
C4	Short Tube	1470

7.10 GAS COMPOSITION

The numerical model used in this study represented the gas composition as pure nitrogen. RGA data, to be presented in the next section, indicate that over 90% of the gas mixture in the CCL prototype was comprised of H₂, N₂, H₂O, CO, O₂, and CO₂. Turbo pumping speeds as well as tube and aperture conductance for these gas species, with the exception of H₂, are within 15% of one another, and hence the pure nitrogen assumption is reasonable. A more detailed transient model that accounts for gas species-dependent outgassing, pumping speed, and conductance is under development.

The system of simultaneous equations resulting from the implementation of Equations (3) through (5) with the vacuum model of Figure 7-6, were solved using Mathematica 3.0 run on a PC [11]. While the current vacuum model can only be used for quasi steady-state analyses, it does provide the valuable design information for sizing the vacuum pumps and hardware to achieve the desired operating pressures, optimizing instrumentation locations, and assessing the performance of the prototype CCL vacuum system. As mentioned previously, a more detailed model that accounts for gas species-dependent conductance and pump speeds, as well as transient surface outgassing rates, is currently under development.

7.11 NUMERICAL MODELING PREDICTIONS

This section describes numerical predictions associated with the performance of the CCL vacuum system. The unknowns that were investigated include total pump speed, vacuum pressure distribution, and total surface outgassing rate. Figure 7-8 displays total vacuum pump speed as a function of the manifold pressure and average surface outgassing rate, as predicted with the numerical model.

The mathematical expression that relates the total pump speed, S_{tot} , (L/s) to manifold pressure, P_{man} (Torr), and surface outgassing rate, Q_{outgas} , (Torr L/s/cm²) is given as

$$S_{tot} = \frac{81,266 \times Q_{outgas}}{P_{man} - 55.3 \times Q_{outgas}}. \quad (6)$$

The relationships between pressures at various locations and the manifold pressure, as well as the surface outgassing rate, are displayed in Table 7-4. The manifold pressure was chosen as the independent pressure variable because it

Figure 7-8. Total vacuum pump speed as a function of manifold pressure and surface outgassing Rate as predicted with the prototype CCL vacuum-system numerical model

Table 7.4. Numerically Predicted Pressures in the CCL Vacuum System as a Function of the Manifold Pressure, P_{man} , and Average Surface Outgassing Rate, Q_{outgas} .

Pressure Location	Pressure Relationship (Torr) Units: Q_{outgas} (Torr L/s/cm ²) and P_{man} (Torr)
Top coupling cell port at end of segment	$P_{cpte} = 163 * Q_{outgas} + P_{man}$ (7)
Top coupling cell port in middle of segment	$P_{cptm} = 115 * Q_{outgas} + P_{man}$ (8)
Accelerator cavity at end of segment	$P_{ace} = 161 * Q_{outgas} + P_{man}$ (9)
Accelerator cavity in middle of segment	$P_{acm} = 113 * Q_{outgas} + P_{man}$ (10)
Average over beam-line	$P_{beamline} = 138 * Q_{outgas} + P_{man}$ (11)

corresponds to a pressure measurement location on the prototype CCL vacuum system. Thus, by measuring the manifold pressure and knowing the total pumping speed, we could assess the pressure distribution within the prototype CCL as well as the surface outgassing rate.

Equation (6) was used to size the vacuum pumps for the steady-state operation of the prototype CCL vacuum system. To solve the equation, reasonable values for the manifold pressure and average surface outgassing rate were needed. As discussed previously, the CCL vacuum pressure design goal of 5.0×10^{-8} Torr corresponds to the region along the beam line. Inserting this value in Equation (11), along with a surface outgassing rate of 2×10^{-10} Torr Liter/s/cm², ([10] and [12]) results in a manifold pressure of 2.24×10^{-8} Torr. Using this pressure and the surface outgassing rate given above, Equation (6) predicts a required total vacuum pumping speed of 1,433 Liters/s. To satisfy this vacuum pumping requirement, the prototype CCL vacuum system manifold was equipped with two 550 L/s turbo pumps and one 300 L/s ion pump.

Note that the average surface outgassing rate of 2×10^{-10} Torr Liter/s/cm² that was chosen to represent the conditions at or near steady-state corresponds to an extremely clean and polished copper or stainless steel surface that has received chemical cleaning and possibly some vacuum conditioning. Initial outgassing rates during the first several hundred hours of vacuum conditioning would be expected to be much higher than this rate.

7.12 EXPERIMENTAL RESULTS

The four main goals of the vacuum experiments on the prototype CCL were as follows:

- 1) Determine if the vacuum system design could satisfy the vacuum pressure requirement,
- 2) Observe the gas composition or cleanliness of the vacuum environment,
- 3) Obtain empirical pressure data to benchmark the numerical vacuum model, and
- 4) Characterize the vacuum conditioning process by quantifying the time-dependent composition of the vacuum environment and estimating the surface outgassing rate histories of the various gas species present in the system.

7.13 ION-GAUGE MEASUREMENTS

The ion gauge pressure measurements taken during the course of the experiment are shown in Figure 7-9(a). These pressure measurements were taken during a period when no RF power was applied and the vacuum system was fully recovered from any previous RF conditioning. When the RF power was active, the vacuum pressures tended to fluctuate erratically as absorbed gases were stimulated by the RF energy and forced to desorb or outgas from the vacuum surfaces. Figure 7-9(b) displays the fluctuating pressures as recorded during a one hour RF conditioning period.

The pressure data shown in Figure 7-9 correspond to the exact measurements recorded from the *Granville-Phillips* instruments and were not corrected with Equation (1) for a mixed gas environment.

Figure 7-9. Vacuum system ion gauge pressure histories. In plot (a), the discrete pressure data points correspond to instances during which the RF power was shut off, while in plot (b), the continuous pressure readings correspond to a period during which RF power was applied.

Plotted are the vacuum pressures measured at the vacuum manifold, the RF window, the beam tube between the segments, and at a top SCC port on Segment 1. Note that the ion gauge for the top SCC port was not turned on until 300 hr into the experiment. The boxes at the top of Figure 7-9(a) provide summary details on four major RF-conditioning periods during which the amplitude, frequency, and pulse width of the RF energy were varied. The average RF power was continuously increased in magnitude throughout the experiment, as the CCL RF structure design physicists and engineers tested the accelerator structure's electrical performance. Referring to Figure 7-9(a), the vacuum and RF conditioning of the prototype CCL served to continuously clean the vacuum surfaces, as indicated by the decrease in system pressure over the 950 hr duration of the experiment. During the first 350 hr, all of the vacuum pressures continually decreased. During the next 300 hr, the pressures in the coupling cell

port and RF window began to increase. These pressure rises were caused by the gradual saturation and corresponding reduction in pumping speed of the NEG pump. To correct this situation, the NEG pump was regenerated, which required heating the getter material to drive off adsorbed hydrogen gas. This hydrogen was removed from the vacuum environment by the turbo and ion pumps. Following regeneration of the NEG pump, the pressures in the coupling cell port and RF window assembly dropped considerably. Referring to the beam tube pressure history in Figure 7-9(a), it can be seen that the average beam line pressure design requirement of 9×10^{-8} Torr, and the design goal of 5×10^{-8} Torr were both met. The pressure readings at the beam tube ceased after 650 hr of testing, after that particular ion gauge was damaged. The vacuum manifold pressure decreased continuously during the experiment, reaching a nearly steady-state pressure of 1.8×10^{-8} Torr.

Gas Composition

Gas Species	Partial Pressure (Torr)	% Total Gas Composition
H ₂	7.74e-09	1.5
He	0.0	0.0
H ₂ O	3.98e-07	78.7
N ₂ or CO	5.60e-08	11.1
O ₂	1.20e-08	2.4
Ar	1.77e-09	0.3
CO ₂	1.16e-08	2.3
Other	1.90e-09	3.7
Total RGA	5.06e-07	100.0
Ion Gauge	9.22e-08	

Gas Composition

Gas Species	Partial Pressure (Torr)	% Total Gas Composition
H ₂	1.91e-09	7.0
He	9.18e-10	0.0
H ₂ O	1.15e-08	41.7
N ₂ or CO	7.02e-09	25.5
O ₂	1.88e-09	6.8
Ar	2.56e-10	0.9
CO ₂	2.32e-09	8.4
Other	2.60e-09	9.7
Total RGA	2.75e-08	100.0
Ion Gauge	2.39e-08	

Gas Composition

Gas Species	Partial Pressure (Torr)	% Total Gas Composition
H ₂	9.24e-10	6.8
He	0.0	0.0
H ₂ O	5.40e-09	38.4
N ₂ or CO	3.73e-09	26.5
O ₂	1.16e-09	8.3
Ar	9.49e-10	0.7
CO ₂	1.49e-09	10.6
Other	1.24e-09	8.7
Total RGA	1.41e-08	100
Ion Gauge	1.74e-08	

Figure 7-10. RGA scans and partial pressures for the CCL prototype vacuum system (a) before, (b) during, and (c) after RF and vacuum conditioning

7.14 RGA MEASUREMENTS

Figure 7-10 displays three RGA scans (ion current versus AMU) taken at the CCL vacuum manifold during the course of the vacuum experiment. The ion currents were converted to partial pressures using Equation (2) and the conversion constants listed in Table 7-2. The partial pressures for the primary gas constituents of each RGA scan, along with the composition percentages of these gas species, are listed in the tables beside each RGA scan in Figure 7-10. The RGA scans reveal relatively little hydrocarbon contamination, with the majority of the vacuum environment comprised of H_2 , H_2O , N_2 , CO , O_2 , Ar , and CO_2 . The partial pressures of each of these gas species is seen to decrease during the course of the experiment, which is consistent with the ion gauge pressure data shown previously in Figure 7-9. The composition of the vacuum gas is dominated with water vapor during the early stages of vacuum conditioning. As the experiment progressed, the vacuum surfaces continued to clean up and the system pressure continuously decreased. The H_2O species was dominant throughout much of the beginning of the experiment, but became less dominant as the experiment progressed. H_2 , CO , N_2 , O_2 , and CO_2 made up the majority of the remaining gas composition. The presence of the atmospheric gases is a result of a combination of de-sorption, permeation, and seal leakage. The trace of Ar is most likely an artifact of the CCL brazing process that was performed in an argon furnace. The third RGA scan in Figure 7-10, taken near the end of the 1,000-hr experiment, reveals a very clean vacuum environment and a low-system pressure consistent with the needs of the high-energy RF fields and the accelerating proton beam. Both the ion gauge and RGA data suggest that the vacuum system was adequately designed and that cleanliness

controls were correctly implemented to obtain the desired vacuum environment for operation of the CCL.

7.15 NUMERICAL MODEL VALIDATION

Validation of the numerical model was achieved by comparing numerically predicted pressures to experimentally measured values. As discussed previously, the numerical vacuum model was developed for steady-state analysis in the molecular flow regime. Validation of the model required using quasi steady-state empirical pressure data. Although the vacuum pressures in the experimental apparatus varied with respect to time, they did so in a relatively slow manner. Consequently, the empirical measurements could be treated as quasi steady-state data needed for benchmarking the model. Benchmarking the numerical model began by setting the numerically predicted manifold pressure value equal to the experimentally measured value at a particular instant in time. Using this manifold pressure and the defined total pumping speed of 1,400 L/s, the average surface outgassing rate was determined from Equation (6). Next, Equations (7) and (9) were solved for the pressures in the top coupling cell port and end-most accelerator cavity, respectively. This entire process was repeated multiple times to generate the numerically predicted pressure histories shown in Figure 7-11. This figure also shows the experimentally measured pressures for the top coupling cell port and the beam tube. The differences that exist between the model predictions and empirical data can be attributed to attributes of the numerical model, including its geometric simplification, the use of N_2 rather than multiple gas species to calculate conductance and pump speeds, the exclusion of the RF window area and NEG pump, and the assumption of uniform surface

Figure 7-11. Comparison of numerically predicted and experimentally measured pressure histories within the prototype CCL vacuum environment

outgassing. Even so, the numerical model does well to estimate the pressure distribution within the CCL vacuum environment.

7.16 PARTIAL-PRESSURE AND OUTGASSING-RATE HISTORIES

The numerically predicted pressure distribution in the CCL agrees reasonably well with that measured experimentally. Consequently, the average surface outgassing rates predicted with the model (Eqn. 6) should be representative of that which existed in the prototype CCL vacuum environment. Figure 7-12 displays the predicted average surface outgassing rate that would have existed during the course of the experiment, using the defined pumping speed of 1,400 L/s and the measured manifold pressure values with Eqn. 6. As Figure 7-12 indicates, the surface outgassing rate continued to decrease,

reaching a final value of 1.5×10^{-10} Torr L/s/cm² after 950 hr of vacuum and RF conditioning. This surface outgassing rate is in agreement with that reported by [10] and [12] for clean, polished, OFHC copper. In addition, [13] presented a similar surface outgassing rate curve that was obtained experimentally from a prototype linac structure.

7.17 PARTIAL PRESSURES

Multiple RGA scans, taken at the vacuum manifold during the course of the experiment, were used to construct partial pressure histories of the primary gas constituents making up the CCL vacuum environment. Figure 7-13(a) displays the partial pressure histories for the dominant gas species, as well as the sum of the partial pressures measured with the RGA, and the total pressure measured with the vacuum manifold ion gauge and

Figure 7-12. Average surface outgassing rate history as predicted by the numerical model

corrected with Equation (1). Note that the RGA data between 200 and 550 hr after starting the experiment was lost because of data acquisition malfunctions. The partial pressure histories displayed in Figure 7-13(a), show a continual decrease as the vacuum surfaces are cleaned during the vacuum and RF conditioning processes, which is consistent with the vacuum manifold pressure data of Figure 7-9. Note that the partial pressures obtained with the RGA do not show the increase in pressure as the NEG pump saturated (as in Figure 7-9), because they were measured at the vacuum manifold.

In reference to Figure 7-13(a), the sum of the partial pressures obtained with the RGA is in excellent agreement with the ion-gauge pressure measurements for pressures below 5×10^{-8} Torr. However, the agreement begins to decay as the pressure gets above this value. There are several factors that account for the

disagreement. First, the sum of the RGA partial pressures does not include gas species present in small amounts. In addition, many of the conversion factors of Tables 7-1 and 7-2, used to correct the RGA and ion-gauge measurements, are not as accurate at higher pressure values. In any case, the RGA data do give a good representation of the gas species composition history during the course of the experiment.

The partial pressure values presented in Figure 7-13(a) were used as input to the numerical model of the prototype CCL vacuum system to estimate the surface outgassing histories of the primary gas constituents. This also required incorporation of the gas species dependent pump speeds and conductances. The results of this effort are shown in Figure 7-13(b). As the plots reveal, the trends of the surface outgassing rates are quite similar. However, the magnitudes of

Figure 7-13. Gas species (a) partial pressures and (b) surface outgassing rates versus time within the prototype CCL vacuum environment

the rates are highly species-dependent. Water vapor has the highest surface outgassing rate, followed by N₂ and CO, H₂, O₂, CO₂, and Ar. The total surface outgassing rate, obtained through a summation of the individual gas specie rates, is also displayed in Figure 7-13(b).

7.18 CONCLUSIONS

This study focused on the design, analysis, and testing of a vacuum system for a prototype CCL. As part of this study, a numerical vacuum model was developed and benchmarked with empirical pressure data collected from a prototype CCL vacuum system. From the numerical analysis and experimental results, the following key conclusions can be drawn.

- 1) The vacuum system design, aided with pump sizing information from the numerical model, provided sufficient vacuum pumping to meet the pressure requirement of the CCL.
- 2) Empirical RGA and ion gauge data revealed that cleanliness controls were correctly implemented to obtain the desired vacuum environment for operation of the CCL.
- 3) The simplified numerical vacuum model possessed sufficient accuracy to size the vacuum pumps, predict the pressure distribution within the CCL vacuum environment, and provide an estimate of the average surface outgassing rate.
- 4) Partial pressure and outgassing rate histories were generated for each of the dominant gas species in the vacuum environment.

8

THE CCL HOT-MODEL WATER-COOLING AND RESONANCE-CONTROL SYSTEM

8.1 INTRODUCTION

This chapter discusses the design, analysis, and testing of a water-cooling system for the CCL hot model. First, the design concept and method of water temperature control is discussed. Second, the layout of the prototype water-cooling system, including the selection of plumbing components, instrumentation, as well as controller hardware and software is presented. Next, the development of a numerical network model used to size the pump, heat exchanger, and plumbing equipment is discussed. Finally, empirical pressure, flow rate, and temperature data from the prototype CCL water-cooling tests are used to assess water-cooling system performance and numerical modeling accuracy.

8.2 COOLING-SYSTEM REQUIREMENTS

RF power is fed into the accelerator cavities through the bridge couplers to provide high-gradient electrical fields to accelerate the beam. Approximately 60–80% of this power is dissipated in the CCL's copper structure. To maintain an acceptable operating temperature, as well as to minimize thermal stresses and maintain desired contours of the accelerator cavities, the heat must be removed from the structure. This removal is done using forced convection cooling to water-cooling passages within the copper structure. The internal cavity and CCL water-cooling passages are displayed in Figure 8-1.

Figure 8-1. A CCL Segment showing exploded view of the cooling passages

The bridge coupler cooling passages consist of copper coils that are brazed to the outer cylindrical surface, as displayed in Figure 8-2.

Figure 8-2. Bridge coupler showing cooling coils

More details on these cooling passages, as well as the finite element and computational fluid dynamics numerical models employed to optimize their designs and the water flow rates, can be found in Bernardin [1]. Table 8-1 summarizes the heat loads and required water-cooling flow rates and temperatures for the various CCL components.

8.3 COOLING-SYSTEM LAYOUT

Cooling water is supplied to the CCL cooling passages by a closed-loop water-cooling and temperature-control system, similar to those used on other linacs [2, 3]. A highly simplified flow diagram of such a closed-loop temperature control system is shown in Figure 8-3.

In this loop, water is pumped at a constant flow rate to the CCL, where it picks up heat. On the return leg, a 3-way valve directs a portion of the flow through a liquid-to-liquid heat exchanger to dump heat to a chilled water source, while the remainder of the water is diverted through a bypass line. These two flows then recombine before entering the pump for circulation back to the CCL.

Figure 8-3. Simplified flow diagram of water-cooling system

8.4 TEMPERATURE CONTROL

In this closed-loop circuit, water temperature control is achieved by manipulating the hot side (CCL side) heat-exchanger water flow rate while holding the cold-side water inlet temperature and flow rate constant. By changing the hot-side water flow rate, the overall heat transfer coefficient

Table 8-1. Summary of the Heat Loads and Required Water-cooling Flow Rates and Temperatures for the CCL Hot Model.

Component	Heat Load [W]	Water Flow Rate [Lpm] (gpm)	Water Inlet Temp. and Range [°C]
Individual Cavity	1,073	9.5 (2.5)	25.0 ±7.5
Individual SCC	119	0.95 (0.25)	25.0 ±7.5
Bridge Coupler	500	3.8 (1.0)	25.0 ±7.5
Segment of 8 Cavities	9,545	83.6 (22.0)	25.0 ±7.5
Entire CCL Prototype	19,590	171 (45.0)	25.0 ±7.5

of the heat exchanger is varied. Since the heat removal rate must effectively remain constant for a quasi-steady-state condition, the heat exchanger's hot-side water temperature must change inversely to the overall heat transfer coefficient to achieve a new and balanced operating condition. Consequently, increasing the water flow through the heat exchanger results in an increase in the overall heat transfer coefficient, and an associated decrease in the mean outlet water temperature. And conversely, decreasing the water flow through the heat exchanger results in a decrease in the overall heat transfer coefficient, and an associated increase in the mean outlet water temperature. The outlet water temperature dependence on the heat exchanger hot-side flow rate is depicted in Figure 8-4. More detailed descriptions of the cooling system are provided in Section 8.5.

Heat Exchanger Hot Side Water Flow Rate

Figure 8-4. Outlet water temperature dependence on heat-exchanger flow rate

8.5 PIPING AND INSTRUMENTATION

Figure 8-5 displays the piping and instrumentation diagram of the prototype CCL water-cooling system. The heart of the water-cooling system is the water skid, or the components that lie within the dashed outline of Figure 8-5. The water skid is a self-contained unit with all of the necessary plumbing, water-purification hardware, instrumentation, pumping, and heat-transfer equipment required for delivering

Figure 8-5. Piping and instrumentation diagram (P&ID) for the CCL hot model

water at a desired flow rate, purity, and temperature to the CCL RF structure.

8.6 WATER SKID

The prototype water skid fabricated for this study is displayed in Figure 8-6. A small capacity tank served as a water reservoir and allowed for expansion and contraction of the water associated with temperature changes. The tank was equipped with a Nitrogen gas source for controlling system pressure and reducing the presence of dissolved oxygen in the water. A pressure relief valve, vent valve, and a liquid low-level indicator were added to the tank for safety purposes. The water reservoir fed the main water line on the suction side of the pump through a manual valve. The reservoir tank capacity was kept below 38 Liters (10 gal) to minimize the effect of its thermal mass on the time response of the water loop's temperature control system.

Figure 8-6. Prototype CCL cooling-system water skid

A high-capacity, variable-speed centrifugal pump (R.S. Corcoran Co., Series 4000, Model DVL-FAB (AA)), rated at 380 Lpm @ 455 kPa (100 gpm @ 65 psig), with a maximum dead head pressure of 630 kPa (90 psig), was selected to supply a constant water flow rate to the RF structure. To provide for heating of the water loop, a 34-kW inline electrical water heater was placed downstream of the pump. A manual ball valve, plumbed in parallel with the heater, was used to direct all of the water flow through the heater when it was in use. To remove the waste heat from the cooling loop and maintain the desired water temperature, a stainless steel counter-flowing heat exchanger (Flat Plate Inc., FP10*20-60) was incorporated. The cold side of the heat exchanger was supplied with refrigerated water from a water chiller (Cooling Technology, Inc., Model CPCW-35) possessing a maximum flow capacity of 570 Lpm @ 307 kPa (150 gpm @ 44 psig), and a rated heat removal capacity of 115 kW @ 10° C delivery temperature. The chiller's waste heat was dumped to a facility-supplied, evaporative cooling water circuit.

8.7 TEMPERATURE CONTROL

The water temperature in the flow loop was manipulated by adjusting the distribution of water flow between the heat exchanger and the heat exchanger by-pass line (see Figure 8-5). This distribution was achieved using a proportional 3-way valve (A-T Controls Inc., Series 30, Model 30-F1-150/TED2-XX-T) upstream of the heat exchanger. The 3-way valve split the water flow between the heat exchanger and a by-pass line. The water skid delivered cooling water to a main supply manifold, which distributed the water to the CCL cavities, side coupling cells, and bridge coupler by way of multiple distribution lines, as shown in the piping and instrumentation diagram of Figure 8-5.

A corresponding set of water lines served to transfer the cooling water back to the water skid upon exiting the CCL. Globe valves on the supply lines and flow meters on the return lines were used to accurately meter the correct amount of water to each set of CCL components. The majority of the plumbing was fabricated from copper pipe and fittings, as well as flexible Buna-N hoses. The valves, strainers, and other components were comprised of 316 stainless steel.

8.8 WATER PURIFICATION

A water purification system was included in the design of the water skid to minimize the formation of deposits, scale buildup, biological growth, corrosion, and radionuclide activation. This system consisted of 5×10^{-6} m and a 1×10^{-6} m filter for removal of debris, a carbon bed for extraction of hydrocarbons, several ion exchange resins for the removal of salts and minerals, an oxygen scavenger to remove dissolved oxygen, and an ultraviolet lamp to kill bacteria. The water treatment hardware was placed in a small side loop through which approximately 3% of the total flow was circulated. Electrical resistivity, pH, and dissolved oxygen sensors were used to monitor the water purification system performance. A sampling port was provided to monitor particulates, total organic carbon, bacteria counts, and trace elements. More specific details concerning the criteria, design, and performance of the water purification system can be found in Bernardin [1] and Katonak [4].

8.9 INSTRUMENTATION

A variety of transducers, shown in Figure 8-5, were strategically placed on the water skid and on the CCL supply and return lines to record water temperature, pressure, and flow rate. Platinum wire wound RTDs (100 Ohm, 3 lead, European calibration) with a calibrated accuracy of $\pm 0.1^\circ\text{C}$, were used to measure water temperatures. System pressures were measured with transducers with a 0–699 kPag (0–100 psig) full-scale range and an accuracy of 2.8 kPa (0.4 psi). Paddlewheel flow meters, with an accuracy of ± 6.1 cm/s (± 0.2 ft/sec) were used to monitor flow rates in water lines with internal diameters of 2.54 cm (1 in.) and larger. Turbine flow meters, with an accuracy of 1%, were used on water lines with an internal diameter of 0.95 cm (0.375 in.). To minimize electrical noise and interference, all instrumentation and communication cables were shielded and electrically grounded. Several of the transducers were used for flow and temperature control purposes during operation, while the remainder was employed for system monitoring as well as energy balance and pressure drop calculations. All transducers, as well as the 3-way control valve, were connected to a Fieldpoint distributed input/output and data acquisition system, which was supervised with a PC running *Labview* 5.0 software. The *Labview* 5.0 software acquired all of the water purity, temperature, pressure, and flow rate data at a periodic rate defined by the operator. Water temperature control was achieved with a *Labview* PID control algorithm to manipulate the position of the 3-way valve. The PID algorithm employed a user-supplied water temperature set point and a user-defined RTD temperature reading as the feedback variable. Specific details on the design and operation of the temperature control system software can be found in Chapter 14 [5].

8.10 SYSTEM OPERATION

Before the prototype CCL water-cooling system tests could be conducted, the correct flow distribution had to be established. We achieved this distribution by circulating water through the entire system and manually adjusting the globe valves on the CCL water inlet lines, the water purification loop, and the pump by-pass loop. Flow rates were continuously monitored throughout the system to obtain the necessary valve settings. Next, the water chiller was turned on and the water supply temperature and flow rate were set. The two electrical water heaters were turned on to supply a steady-state heat load to the system. Finally, the water temperature control system was activated and the desired CCL water inlet temperature set point was programmed into the control system software. At this point, the *Labview* PID algorithm maintained the desired water temperature through control of the 3-way valve position, and the data-acquisition system continuously logged the system's water temperatures, pressures, and flow rates. Once the water-cooling system was functioning properly, the performance testing of the CCL hot model and its water-cooling and temperature-control

system was initiated. During these tests, RF power at various amplitudes, frequencies, and pulse lengths was applied intermittently to the hot model. The total average RF power was gradually increased to the design level of 19.59 kW for the hot model. Throughout the tests, the temperature, pressure and flow rate data from the water-cooling system, as well as the RF parameters, were periodically recorded.

8.11 NUMERICAL MODELING

To support the design and optimization of the water-cooling system, a representative numerical model of the prototype CCL water-cooling system was developed using the software package *Sinda/Fluint* [6]. This model aided in the sizing of the water-cooling system components so that the cooling parameters listed in Table 8-1 could be met. *Sinda/Fluint* uses a nodal network modeling approach to represent a complex flow system as a series of lumps, where pressure and temperature are calculated, connected by path lines, where flow resistance is defined and flow rate is calculated. Figure 8-7 illustrates the *Sinda/Fluint* representation of a basic flow loop.

Figure 8-7. *Sinda/Fluint* representation of flow loop

Lumps may be described by a tank, T-10, where energy and mass can change with time, or they may be represented by a simple junction, J, which is a tank of zero volume. Path lines can be made up of one of many different elements including tubes, T, of a given length and diameter, a valve, CT, with a variable flow resistance, a pressure loss, L, to account for a fitting or pipe bend, a constant volume pump, VF, etc. A *Sinda/Fluint* model may also employ a “Tie” element that is used to join fluid sub models with thermal sub models, such as those required in a heat exchanger calculation. More specific *Sinda/Fluint* modeling capabilities can be found in *Sinda/Fluint* [6]. Two separate *Sinda/Fluint* models were built for this study. The first, termed the CCL segment and Bridge Coupler model, was used to represent the water lines and cooling passages between the supply and return manifolds on the CCL. This highly detailed model was used to determine the pressure drops across the CCL cooling passages and water supply and return lines. The second model, termed the Water Skid and Flow Loop Model, characterized the entire CCL flow loop, with an emphasis on the water-skid components including the pump, heater, and control valve. This model was used to determine the entire system pressure drop and calculate the CCL water supply temperature as a function of the heat exchanger hot side flow rate. More specific features of these two models are discussed below.

8.12 CCL SEGMENT AND BRIDGE-COUPLER MODEL

The *Sinda/Fluint* model of the 8-cavity CCL segment and bridge coupler is shown in Figure 8.8 alongside an equivalent 3-D representation and flow diagram. The model consists of three main cooling circuits, one for the bridge coupler (BC), one for the SCCs, and one for the accelerator cavities. Each cooling circuit within the model is made up of a number of tube, loss, and valve elements to account for the lines, fittings, bends, cooling passages and valves shown in Figure 8.8.

The *Sinda/Fluint* input for a tube includes a length and a diameter dimension, and the output consists of the pressure drop corresponding to a defined flow rate. The modeling input for a valve, CT, and a loss, L, consists of the flow passage cross sectional area and a dimensionless “K” or loss coefficient, defined in Idelchik [7] as

$$K = 2 DP / (r v^2), \quad (1)$$

where, DP is the pressure loss across the segment, r is the fluid density, and v is the mean fluid velocity. The numerical values for the various tube, loss, and valve elements shown in Figure 8-8 are summarized in Table 8-2. Note that the loss factors for the valves were left as floating variables that were adjusted in the numerical model to obtain the desired flow rates in the cavities, SCCs, and BC. The valve loss factors that provided the desired flow distribution are listed in Table 8.2. The majority of the loss factors listed in the table are summations of multiple loss factors corresponding to the many fittings and bends that make up the CCL water lines. More detailed information concerning the precise geometry and make-up of the CCL’s internal cooling passages and water lines, as well as the associated loss coefficients, can be found in Bernardin [1].

Figure 8-8. (a) CCL 8-cavity segment and bridge coupler model 3-D representation and flow diagram, and (b) corresponding Sinda/Fluint model.

8.13 WATER-SKID AND FLOW-LOOP MODEL

The Sinda/Fluint model of a simplified water skid and flow loop is shown in Figure 8-9 alongside an equivalent flow diagram. To reduce the complexity of the modeling process, the water purification and pump by-pass loops were left out of the water skid model since they would not significantly influence the overall system pressure drop or temperature control predictions.

The numerical model consists of a number of tube, loss, and valve elements to account for the lines, fittings, bends, and valves. An equivalent loss element, L2, was used to represent the water lines and cooling passages

of the CCL RF structure. The equivalent loss factor for L2 was determined from the CCL segment model shown previously in Figure 8-8. Using a pressure drop of 65.7 kPa (9.4 psi), a flow rate of 171 Lpm (45 gpm) through the CCL RF structure, and a hydraulic diameter of 5.08 cm (2.0 in.) for the simulated RF structure loss element resulted in a loss factor of 64.7. All of the tube and loss factor values for the water-skid and flow-loop model are summarized in Table 8-3. A more detailed breakdown of the water skid component's loss coefficients is given in Bernardin [1]. A heat-input element, used to represent the heat dissipation from the RF structures and water heater, was placed immediately downstream of the RF structure loss element.

Table 8-2. Tube, Loss, and Valve Parameters for the CCL 8-cavity Segment Model

Symbol & Description	Tube or hydraulic dia. [cm]	Length [cm]	K factor
T1: Outer cooling circuit line	7.6	30.5	0.0
T2: BC supply line	1.0	58.4	0.0
T3: BC body cooling lines	0.3	88.9	12.5
T4: BC slug tuner cooling lines	1.0	88.9	4.8
T5: BC return line	1.0	101.6	0.0
T6: SCC main supply line	1.0	27.9	0.0
T7: SCC top grouping supply line	1.0	55.9	0.0
T8: SCC bottom grouping supply line	1.0	27.9	0.0
T9: SCC supply & return sub-manifold run length between SCC ports	1.0	10.2	0.0
T10: Individual SCC supply line	1.0	25.4	0.0
T11: SCC cooling passage	0.3	53.3	0.0
T12: Individual SCC return line	1.0	10.2	0.0
T13: SCC top grouping return line	1.0	12.7	0.0
T14: SCC bottom grouping return line	1.0	40.6	0.0
T15: SCC main return line	1.0	175.3	0.0
T16: Cavity main supply line	2.5	66.0	0.0
T17: Cavity top grouping supply line	2.5	7.6	0.0
T18: Cavity bottom group supply line	2.5	165.1	0.0
T19: Cavity internal headers	2.5	6.4	0.0
T20: Cavity top grouping return line	2.5	154.9	0.0
T21: Cavity bottom group return line	2.5	15.2	0.0
T22: Cavity main return line	2.5	55.9	0.0
L1: BC supply line losses	1.0	N/A	3.6
L2: BC body cooling channel losses	0.3	N/A	4.1
L3: BC slug tuner channel losses	1.0	N/A	8.9
L4: BC return line losses	1.0	N/A	3.57
L5: SCC main supply line losses	1.0	N/A	3.64
L6: SCC top group supply line losses	1.0	N/A	2.06
L7: SCC bottom group supply line loss	1.0	N/A	1.86
L8: Individual SCC supply line losses	1.0	N/A	3.69
L9: SCC cooling passage losses	0.3	N/A	1.00
L10: Individual SCC return line losses	1.0	N/A	3.69
L11: SCC top group return line losses	1.0	N/A	1.82
L12: SCC bottom group return line loss	1.0	N/A	2.06
L13: SCC main return line losses	1.0	N/A	4.00
L14: Cavity main supply line losses	2.5	N/A	3.76
L15: Cavity top group supply line loss	2.5	N/A	0.86
L16: Cavity bottom group supply loss	2.5	N/A	2.40
L17: Cavity cooling passage losses	1.3	N/A	75.0
L18: Cavity top group return line losses	2.5	N/A	3.00
L19: Cavity bottom group return loss	2.5	N/A	0.86
L20: Cavity main return line losses	2.5	N/A	5.86
CT1: BC valve	1.0	N/A	142.2
CT2: SCC valve	1.0	N/A	24.4
CT3: Cavity valve	2.5	N/A	0.7

Figure 8-9. (a) Flow diagram of the prototype CCL water-flow loop, and (b) corresponding Sinda/Fluint model.

Table 8-3. Tube, Loss, and Valve Parameters for Water-skid Model.

Symbol & Description	Tube or hydraulic dia. [cm]	Length [cm]	K factor
T1: Water skid outlet line	3.8	309.9	0.0
T2: RF structure supply transfer line	5.1	365.8	0.0
T3: RF structure return transfer line	5.1	365.8	0.0
T4: Water skid inlet line	5.1	50.8	0.0
T5: Heat exchanger inlet line	3.8	38.1	0.0
T6: Heat exchanger line	3.8	2.5	0.7
T7: Heat exchanger outlet line	3.8	144.8	0.0
T8: Heat exchanger by-pass line	3.8	22.9	0.0
T9: Pump inlet line	3.8	132.1	0.0
L1: Water skid outlet line losses	3.8	N/A	12.2
L2: Equiv. CCL RF structure loss	5.1	N/A	64.7
L3: Water skid inlet line losses	3.8	N/A	2.1
L4: Heat exchanger inlet line losses	3.8	N/A	1.5
L5: Heat exchanger outlet line losses	3.8	N/A	6.7
L6: By-pass line manual valve loss	3.8	N/A	1.8
L7: Pump inlet line losses	3.8	N/A	1.1
CT1: 2-way control valve	3.8	N/A	Vary

A constant flow rate pump element, VF, was used to represent the performance of a centrifugal pump. *Sinda/Fluint* was not capable of modeling a 3-way control valve. Therefore, a 2-way proportional valve was modeled in the heat exchanger by-pass line. This valve configuration closely emulated the flow conditions encountered with the 3-way valve over the majority of its operational range. However, the use of the 2-way valve did not allow for the modeling condition where all of the water was by-passed around the heat exchanger.

8.14 HEAT EXCHANGER MODEL

Finally, a thermal sub-model of the heat exchanger was included in the water skid model. The development of this thermal sub-model first required the sizing of a commercially available flat plate heat exchanger to meet the temperature, heat load, and flow rate requirements listed in Table 8-1, while providing reasonable pressure drops. Once the heat exchanger was selected, its thermal performance was incorporated in the

numerical model in the form of a correlation that related the heat exchanger's overall heat transfer coefficient, UA , to the hot side water flow rate, Q_h , for a constant cold side flow rate.

$$UA = (25.3Q_h + 65.7)/(Q_h + 8) \text{ for } Q_c = 72.2 \text{ Lpm}, \quad (2)$$

$$UA = (63.3Q_h + 164.3)/(Q_h + 17) \text{ for } Q_c = 551 \text{ Lpm}, \quad (3)$$

where the units for UA are $W/^\circ C$ and for Q_h are Lpm.

8.15 PRESSURE-DROP PREDICTIONS VERSUS MEASUREMENTS

Table 8-4 provides a comparison between the numerically predicted and the experimentally measured pressure drops across the CCL RF structural components, as well as the entire RF structure and the water skid's pump. Note that while the flow rates were specified in the numerical model prior to the experiments, they had to be manually

Table 8-4. Comparison of Predicted and Measured Pressure Drops within the CCL RF Structure and Water Skid.

Component	Sinda/Fluint Model Prediction		Experimental Measurement	
	Flow Rate [Lpm] (gpm)	Pressure Drop [kPa] (psi)	Flow Rate [Lpm] (gpm)	Pressure Drop [kPa] (psi)
Upper Cavities	30.8 (8.1)	39.2 (5.6)	33.1 ±1.9 (8.7 ±0.5)	42.7 ±2.8 (6.1 ±0.4)
Lower Cavities	38.4 (10.1)	38.5 (5.5)	39.1 ±1.9 (10.3 ±0.5)	39.9 ±2.8 (5.7 ±0.4)
Upper SCCs	3.0 (0.8)	12.6 (1.8)	3.4 ±0.04 (0.9 ±0.01)	7.7 ±2.8 (1.1 ±0.4)
Lower SCCs	3.8 (1.0)	12.6 (1.8)	3.4 ±0.04 (0.9 ±0.01)	7.7 ±2.8 (1.1 ±0.4)
BC	4.2 (1.1)	5.6 (0.8)	4.2 ±0.04 (1.1 ±0.01)	9.8 ±2.8 (1.4 ±0.4)
RF Structure	364.8 (96.0)	142.5 (20.4)	358.3 ±4.2 (94.3±1.1)	138.3 ±2.8 (19.8±0.4)
Pump	364.8 (96.0)	593.1 (84.9)	358.3 ±4.2 (94.3±1.1)	569.4 ±2.8 (81.5±0.3)

adjusted with proportional valves in the experimental set-up. Consequently, there are some minor discrepancies between the numerical and experimental flow rates. The error ranges for the empirical flow rate and pressure drop measurements, correspond to the accuracy limitations of the respective transducers. As Table 8-4 indicates, the numerical model did quite well to predict the pressure drops across the CCL cavities and bridge coupler. In each case, the numerically predicted pressure drop is within, or just outside, the empirical accuracy range of the corresponding measured value. The discrepancies can be attributed primarily to the flow rate differences between the model and experiment.

8.16 WATER TEMPERATURE PREDICTIONS VERSUS MEASUREMENTS

In addition to the pressure drop assessments, an equally important task of the numerical modeling was to predict the CCL RF structure water supply temperature, using the temperature control methodology discussed previously. Figure 8-10 displays numerical predictions of the CCL water inlet temperature as a function of the heat exchanger's hot side water flow rate for different heat loads, q , as well as various heat exchanger cold-side flow rates, Q_c , and cold side water inlet temperatures, T_{ci} . Also plotted in Figure 8-10 are experimental measurements of the CCL water supply temperature for

Figure 8-10. CCL inlet water temperature as a function of the heat-exchanger hot-side flow rate for various heat loads, q , as well as heat-exchanger cold-side water inlet temperatures, T_{ci} , and flow rates, Q_c .

various conditions. The experimental data corresponds quite well with the numerical predictions, displaying agreement with both the absolute temperature values and the trends. More importantly, the experimental data indicates that the water-cooling system provided both the necessary cooling of the RF structure and the required water temperature control.

8.17. CONCLUSIONS

This chapter focused on the design, analysis, and testing of a water-cooling and temperature-control system for the CCL hot model. As part of this study, two numerical flow network models were developed for the CCL RF structure and water-cooling skid and benchmarked with empirical water flow-rate, pressure, and temperature data collected from a prototype CCL water-cooling system. From the numerical analysis and experimental measurements, the following key conclusions can be drawn.

- 1) The water-cooling and temperature control system design, aided with the pump and heat exchanger sizing information from the numerical model, adequately met the heat removal and temperature regulation requirements of the CCL.
- 2) The numerical flow network models possessed sufficient accuracy to predict pressure drops within the CCL RF structure and water-cooling skid. In addition, the numerical water skid model accurately predicted the CCL RF structure water supply temperature, using the temperature control methodology outlined in this study.
- 3) The accuracy of the modeling results demonstrates that flow network modeling, including the selection of flow loss coefficients and modeling of heat exchangers, can be successfully employed in designing a complex water cooling system.

9

PROCUREMENT OF THE 2.5-MW, 805-MHz R&D KLYSTRONS**9.1 INTRODUCTION**

The 805-MHz RF system for the SNS linac was initially designed with 2.5-MW peak power klystrons that had modulating anodes and isolated collectors. The intent was to award two contracts as part of the linac R&D program and to place the order for the majority of the production klystrons with the more successful of the two vendors. The contracts were awarded by a combination of technical factors and price. The original specification was completed on October 10, 1997, and it was revised on March 3 1998 after discussions with the vendors. The main elements of the specification [1] are listed in Table 9-1

The two successful bidders were *CPI* and *Litton Industries*, both California firms. Two non-US bidders were weaker technically and had higher costs. Both contracts were awarded in 1998 with 14-month specified delivery dates.

9.2 CPI CONTRACT

The following dates document the timeline for the *CPI* contract.

- Contract award: May 4, 1998
- Preliminary design review: July 30 1998
- Final design review: November 3, 1998
- Contracted delivery date: July 4, 1999
- Klystron acceptance: September 24, 1999

The vendor reviews contain proprietary information, so they are not included in this report. *CPI* had just invested in a new solid-state modulator, and this modulator was used for the factory acceptance tests. The new modulator worked fairly well even though one of its modules did fail. It was very difficult to find out which module failed. The vendor has

Table 9-1 Specifications for 805-Mhz R&D Klystron Bbid

Quantity	Value	Units
Frequency	805	MHz
Peak Output Power	2.5	MW
Average Output Power	250	kW
DC to RF Conversion Efficiency	55	%, Minimum
Operating Voltage	120	kV Maximum
Power Gain	45	dB, Minimum
Focus Solenoid Current	40	A, Maximum
VSWR Tolerance	1.5:1	Minimum, stability
Power Transfer Linearity	+/- 100	kW with output power from 600 to 2100 kW
Saturated Bandwidth	+/- 0.7	MHz, -1dB
24-hr Heat Run Peak Power	2.75	MW at 12% duty
Harmonic Power	-27	dB relative to carrier

since incorporated failure identifying circuits, so this problem has now been eliminated. Figure 9-1 is a photograph of the “bare” klystron (without magnet) taken at the vendor test facility.

9.3 CPI KLYSTRON TESTS

The *CPI* klystron exceeded the specifications when it was first tested at the factory. No adjustments were required except the focus current, which had to be increased because the bandwidth was too small and the efficiency too high. This klystron produces excessive gas at saturation for the highest-impedance phase of the 1.5:1 mismatch, but we are unlikely to operate the klystron in this state for significant time periods. A major innovation was the use of an air-cooled, aluminum-foil-wound, focus solenoid, which

Figure 9-1 *CPI* klystron (without magnet) at vendor test facility

ran fairly hot during the factory tests in California. With the dry, thinner air at Los Alamos, the focus solenoid initially shut itself down from an over-temperature fault after a few hours of operation. The cure was to install a water-cooled plate in the solenoid; the klystron could then operate continuously. Our conclusion is that air cooling of a few kW at 7,300 ft altitude is difficult, so subsequent klystron orders specified water-cooled solenoids. Aside from this overheating problem, this klystron has operated flawlessly. Figure 9-2 shows the factory test data. At 113 kV the klystron current was 41.5 A and the output power was 2.605 MW peak [2].

Figure 9-2 also shows the power transfer curve and the most important operating parameters. The efficiency was 55.4% and the amplitude nonlinearity was 100 kW. The phase nonlinearity was 0.5 degree. All of these values just meet the specification. A brief summary of the factory tests was presented at the 2002 International Vacuum Electronics Conference [3]. The heater-hum measurement specified was not done. This klystron was run for many hundreds of hours at Los Alamos and performed without faults during the hot-model experiments described in this report.

9.4 LITTON CONTRACT

The following dates depict the timeline for the *Litton* contract.

- Contract award: June 9, 1998
- Schedule review: February 4, 1999
- Final design review: July 10, 1999
- Contracted delivery date: August 9, 1999
- Klystron acceptance: November 9, 2001 (conditional)

Figure 9-2 Factory test data for CPI 850-MHz, 2.5-MW klystron showing peak power output vs. peak RF-input drive power

The *Litton* design was based on the L-5859, the 12-MW peak power, 805-MHz, 100- μ s pulse-length klystron built for Fermilab. The *Litton* klystron was subject to several experimental and fabrication problems. The first problem arose because an Air Force purchase order had higher priority for use of *Litton*'s single test stand. Los Alamos mitigated this problem by loaning the Air Force eleven klystrons that could be used in their application (a large radar station). However, *Litton* still had to deliver all the Air Force klystrons before they could test our klystron. A lesser complication was the delivery and testing of a Fermilab klystron in this same time period. When the SNS klystron was finally tested, the modulator was marginal for reliable operation at the high voltage and

average power required. In addition, the SNS klystron failed at least three times at the factory: once for a cracked window, once for a cracked gun ceramic, and once for very low beam current. After each failure, the klystron was taken apart and rebuilt. However, no design changes were required, and when the klystron came close to meeting its design objectives in November 2002 (27 months late on the 14-month contract date specified), we decided to take delivery. This klystron, now called the *Northrup-Grumman* (NG) L-6048, was conditionally accepted by Los Alamos at a reduced price since it did not fully meet contract specifications. (NG acquired *Litton* Industries during the course of this contract.) A condensed version of the factory tests was presented at the 2001 Vacuum Electronics

Device Conference [4], and some of the design considerations were also presented earlier in [5]. The factory test data are very high quality, having been collected with a sophisticated computer-controlled data collection and analysis system. The *Litton* klystron has not been operated at Los Alamos, but it is stored as a spare for use in the test stand if needed. The vacuum on the klystron is good and is checked every couple of months. Figure 9-3 is a photograph of this klystron taken by the vendor.

Figure 9-3 Photograph of *Litton* klystron

9.5 LITTON KLYSTRON TESTS

The *Litton* klystron has achieved over 60% efficiency but not while it is tuned to pass the 1% linearity tests. We believe the problems were the result of not enough attention to design and operational details and not because of basic flaws in the design. We discuss these failures below in some detail to apply the lessons learned.

- 1) When the electron-gun ceramic was broken, the vendor found a very small water leak on the klystron body, which may have been the cause of the arc that cracked the ceramic. There is a spark-gap crowbar on the factory test stand that was designed in the 1950's to prevent damage to a klystron when it arcs, but this crowbar did not function adequately for this arc. At Los Alamos we either use a backup fuse in series with the spark gaps, or, in more modern designs, ignitron crowbars, which are much more reliable than the spark gap variety. (For the SNS system, the converter-modulator protects the klystrons without requiring any crowbar.)
- 2) When the window cracked, the klystron was producing 50-kW average with 500-kW peak power. At this power, calculations showed the klystron would not need air cooling, so the window air cooling was not on. All subsequent testing was done with the window cooling installed. In fact, on the SNS RF system the klystron cannot be turned on until the window air is flowing. Additionally, arc detectors are used to shut down the klystron within a few microseconds of when an arc starts.

- 3) The possible cause of the emission failure was either a gross contamination problem or a serious assembly problem. Both can be controlled by attention to detail.

Each of the three rebuilds took about four months to complete. The rule of thumb is that rebuilds cost between 50 and 75% of the cost of a new klystron. These costs were borne by the vendor because of our fixed-price contract.

The remaining problem came from an incorrectly dimensioned part that caused an aperture just before the collector to be too small. (This component was correctly dimensioned on the assembly drawing, but incorrectly dimensioned on the component drawing.) The electron beam hits this component when the RF output power is large and this limits the average power that the klystron can make. The component could only be replaced with another costly rebuild, which

the manufacturer did not want to do. To minimize the heating of this part, the focus magnet current must be doubled over the design value, which makes the beam smaller in the output region. This current doubling made the focus current over twice as high as the specification. It also reduces the efficiency below the 55% specification because the reduced radius beam interacts less with the fields in the output cavity. The optimum operating parameters from the factory acceptance tests are shown in Table 9-2.

The linearity test results are also shown in Figure 9-4.

The efficiency barely passed the 55% minimum and the linearity was very close to the specification. The magnet currents were too high and the klystron had too much body power, so the klystron was never tested to the full heat-run requirements [6].

Table 9-2 Typical Operating Parameters for *Litton* Klystron

Parameter	Specification	Test Setting
Focus Coil #1 Current, Voltage	$I < 40 \text{ A}, V < 300 \text{ VDC}$	63 A, 29 V
Focus Coil #2 Current, Voltage	$I < 40 \text{ A}, V < 300 \text{ VDC}$	52 A, 31 V
Focus Coil #3-4 Current, Voltage	$I < 40 \text{ A}, V < 300 \text{ VDC}$	37.5 A, 39 V
Focus Coil #5 Current, Voltage	$I < 40 \text{ A}, V < 300 \text{ VDC}$	17.5 A, 5 V
Focus Coil #6 Current, Voltage	$I < 40 \text{ A}, V < 300 \text{ VDC}$	0 A, 0 V
Heater Current	$I_f < 30 \text{ A}$	25.8 A
Heater Voltage	$E_f < 30 \text{ VAC}$	27.1 V
Electron Beam Voltage	120 kV maximum	107.0 kV
Mod-Anode Voltage (ON)	$20\% E_k \leq eM-A \leq 80\% E_k$	78% (83.4 kV)
Cathode current	55 Amp maximum	43.1 A
Mod-Anode Current	$-2 \text{ mA} \leq IM-A \leq 4 \text{ mA}$	2 mA
RF Frequency	805 MHz	805 MHz
Power Output(Peak)	2.5 MW minimum	2.55 MW
RF Efficiency	$\eta \geq 55\%$	55.20%
Power Input(Peak)	79 W maximum	33.6 W
RF Power Gain	$G \geq 45 \text{ dB}$	48.8 dB

Figure 9-4 Northrop Grumman, (Litton) L-6048 output peak power vs. input power

9.6 SPECIFICATION EVOLUTION

The two R&D klystrons described above were specified to operate with the CCL baseline design at the time the contracts were placed. Since they were intended for use without circulators, they were specified to have a 1.5:1 voltage standing-wave ratio (VSWR) tolerance and they both met this requirement. In early 2001, the SNS baseline was changed to use 5-MW peak power klystrons for the CCL as a cost savings measure. Klystrons were sent out for bids again, this time without the modulating anodes and without the isolated collectors. Elimination of the modulating anode saved capital costs, but some operational flexibility was lost since each klystron's beam current can no longer be independently adjusted. Also, circulators were required because of the higher power, so the VSWR tolerance of the SNS production klystrons was reduced to 1.2:1 instead of the 1.5:1 for the R&D klystrons. Other changes in specifications for the SNS production klystrons were made to

take advantage of the newly developed high-voltage converter-modulator [7] and to realize further cost savings.

9.7 CONCLUSIONS

The *CPI* klystron exceeds all the specifications that have been measured, and it produces 2.5 MW within a few minutes of when it is turned on. It performed flawlessly during the hot-model tests. It has also been used extensively for SNS window and circulator tests, and is the mainstay of the Los Alamos RF test stand and the SNS component test program. The *Litton* klystron is a viable spare, which could be used up to the 2-MW level. Both Los Alamos and the klystron vendors learned some important lessons and many of these lessons were applied to the SNS production klystrons. Both klystron developments were successful, although the delivery delays in the *Litton* case were severe. Several extra trips to *Litton* were required to help find the cause of each problem and to generate solutions and recovery plans. Having a fixed-price contract proved advantageous for the Department of Energy in this case.

10

ASSEMBLY AND OPERATION OF THE HOT-MODEL RF-POWER SYSTEM

10.1 INTRODUCTION

The hot-model cavity configuration consists of two shortened sections of SNS accelerating cavity linked with a bridge-coupling unit. An RF-drive orifice is inserted in the bridge section and is provided with a vacuum flange that matches the RF-window flanges used throughout the LAMPF 805-MHz accelerating section. (Since the SNS-designed window was not yet available, we used a spare RF vacuum window from LAMPF for the hot-model tests.) Figure 10-1 shows the two cavity segments and the bridge coupler with the RF window flange.

The following photograph (Figure 10-2), taken from the side opposite the RF-window connecting flange, shows the cavity assembly being installed prior to testing.

Figures 10-3 and 10-4 show a LAMPF RF vacuum window and the completed hot-model waveguide connection.

10.2 SHIELDING AND INTERLOCKS

The hot model was surrounded with portable lead-shielding panels for x-ray shielding, and several x-ray detectors were located around the general area.

Figure 10-1. Hot-model assembly showing RF-window flange

Figure 10-2. Photograph of the cavity being installed.

Figure 10-4. WR975 waveguide connection to the hot model

Figure 10-3. LAMPF 805-MHz vacuum window

Figure 10-5 shows the approximate locations of these shielding panels and detectors.

The shielding panels were assembled from a sheet of eighth-inch lead sandwiched between a pair of quarter-inch aluminum sheets. The assembly was mounted on a wheeled stand to allow the panels to be moved around during maintenance and to achieve optimum radiation shielding during operation. During the experiment additional shielding, in the form of lead-shot-filled blankets, was added directly around the model to fill gaps in the movable-panel shields. Figures 10-6 and 10-7 show some of these panels in use.

Three x-ray detectors were hard-wired into the RF-transmitter interlock chain to give an automatic trip for x-ray radiation detected outside the shielded enclosure. During the highest-power operation sequences, we observed x-ray radiation outside the enclosure in excess of our 5-mrem/hr limit, but we were able to control this radiation by adding additional lead blankets. Three “emergency-off” buttons were also wired into the hardware interlock chain and one is visible in Figure 10-7. An overall block diagram of the RF-interlock system is shown in Figure 10-8.

Figure 10-5. Approximate locations of the hot-model shielding panels, x-ray detectors, and “emergency off” buttons

Figure 10-6. Part of the x-ray-shielding enclosure, including lead blankets added on the left moveable panel and one of the “emergency off” buttons

Figure 10-7. Another View of the Shielding Panels

Figure 10-8. RF-power hardware interlock chain

10.3 LOW-LEVEL RF SYSTEM

A low-level RF (LLRF) control system was installed in a control room located adjacent to the hot model, and power-monitoring directional couplers were cabled into the control room. This system was a rudimentary version of the final SNS system, but it had the capability of demonstrating full RF frequency and amplitude control of the hot model. Included as part of the LLRF system was an arc detector. This chassis provided an RF-drive interrupt function based on a vacuum threshold input. In addition to the vacuum trip function, the chassis also performed its main function of interrupting RF drive during an actual window arc. Both the air side and vacuum side of the window were monitored.

10.4 WAVEGUIDE RUN

Since the klystron was located at a considerable distance from the hot-model test pad area, a WR-975 waveguide was used to connect the klystron to the hot model. Figure 10-9 shows a schematic of this waveguide run. At the time of the hot-model testing, other RF hardware was located adjacent to the model and we switched waveguides between hot model testing and other components.

A circulator (as will be used on SNS) was not available for the hot-model testing, but the klystron is capable of withstanding large amounts of reflected power. However, power reflected towards the klystron will be re-reflected and appear back at the hot model cavities. If the phases of the re-reflected power and the initial drive power happen to

Figure 10-9. Outline of the waveguide run used to power the hot model

add, the power applied to the model increases during the period in which the model is detuned. We observed this undesirable condition at the start of hot-model testing. To correct this condition, the total length of the waveguide run was increased one-half wavelength by using a segment of the waveguide run near the klystron. Figure 10-10 is a photograph of this section of the waveguide run.

10.5 SECOND RF SOURCE

An external signal generator was added to the low-level klystron drive path to provide the capability of exciting other cavity modes while allowing the normal cavity mode to heat the structure. The two nearest cavity modes are of most interest. As the structure heats up, these modes may move the resonant frequency, and knowledge of this frequency shift is important to the overall cavity design.

Figure 10-10. The waveguide section used to change the phase of RF-power reflected to the cavities

The added RF source was gated on just after the normal excitation and its frequency was adjusted to excite the desired mode. Power splitters were used as adders to allow both RF sources to feed the klystron input. Figure 10-11 shows this connection.

Figure 10-11. Power splitters allowing second RF source to feed the klystron

10.6 KLYSTRON

As discussed in Chapter 9, the klystron used for hot-model operation was a 2.5-MW *CPI* klystron—the first of two early klystrons purchased for the SNS R&D program. It has a modulating anode for use with conventional modulator designs. We had been utilizing this klystron for high-power RF component testing, primarily with a DC power supply and conventional modulator. With the addition of an anode bias divider, the klystron will also operate from a pulsed cathode supply such as the SNS converter-modulator.

10.7 MODULATOR

At the beginning of the hot-model program, we utilized a DC power supply that was limited to about 1-MW average power. The *CPI* klystron has poor efficiency when operated at the reduced peak power levels desired for hot-model work. Consequently,

the power-supply and klystron system would provide full peak power to the hot model, but we were limited in average power to about 25 kilowatts. Later, we were able to reconfigure the modulator to allow operation with the SNS prototype high-voltage converter-modulator (HVCN), and in this configuration we could provide full repetition rate and full average power to the hot model. However, since much of the hot-model testing did not require full average power, a majority of the hot-model testing was conducted with the DC supply. Near the end of the hot-model run period, we did utilize the HVCN to test temperature control and cavity frequency control systems under full average power conditions. Figure 10-12 shows the RF test stand layout.

Figure 10-12. Layout of the RF test stand used for the hot-model tests

10.8 RF PROTECTION

An optical arc detector aimed at the output RF window monitors the klystron. This detector interrupts the klystron drive by inhibiting a gate pulse fed to the intermediate power drive amplifier. The amplifier includes a pin-diode switch as part of its normal complement of hardware, which is used to provide gating of the klystron drive power when a continuous wave RF input signal is being used. For the hot-model operation, the LLRF system provided the desired RF gating pattern, but the driver amplifier was used as backup protection to prevent an operator from selecting an excessively long RF burst and to ensure that the klystron was not driven during klystron rise or fall times. A reflected power sample, blanked during cavity fill and decay times, was utilized to remove RF drive if the reflected power reached dangerous levels. The nominal setting for this trip level was about 40 kW and the inhibit circuitry had to be reset manually if the trip condition occurred. Two additional optical arc detectors were installed to observe the vacuum and air sides of the hot-model RF window. These detectors interrupt the low-level signal input to the klystron intermediate drive amplifier. The drive is only interrupted for a period long enough to allow a window arc to clear. In the hot-model case, we set the interrupt time to one second. A trip indication was provided from the hot-model vacuum system. When the vacuum exceeded $1\text{E-}6$ Torr, the LLRF drive was interrupted by the same circuitry used for window arc protection. In practice, the vacuum takes some time to recover and the RF remains gated off during this time.

10.9 RF-POWER MONITORING

For the high-power RF component-testing program, we utilize a directional coupler installed in the waveguide near the klystron as a rough output-power monitor. The RF-power meter readout from this monitor is available in the control-room area and this readout provides our primary power reading. For the hot model, a directional coupler was also installed in the vertical waveguide run just ahead of the last waveguide bend—a section with several feet of straight waveguide on either side. This local monitor was split several ways to provide hot-model data logging, feedback to the LLRF system, and control-room monitoring. Using this monitor, the data-logging system kept a running record of hot-model input power. On initial turn-on of the hot model, however, we observed an appreciable discrepancy between the klystron monitor and this local monitor. Because of time constraints we adjusted the klystron monitor to agree with the local monitor, waiting until after the tests to calibrate the monitors.

10.10 RF-POWER CALIBRATION

After the hot-model tests were completed, we worked to determine the source of the calibration discrepancy between the klystron monitor and the local monitors. We also individually calibrated attenuators, filters, cables, and power splitters with a network analyzer. Figure 10-13 is a line diagram including all the components used in the forward-power monitor path. We discovered calibration errors in several components, indicated in the figure. We originally used an offset value of 76.48 dB for the total loss encountered in the forward-power Boonton metering path. The correct value of 74.81 dB was later obtained both by measuring the total loss of the combined metering path and by

adding the individual losses. Converting the offset error of 1.67 dB to a correction factor yields a 0.68 factor that was applied to the data.

10.11 INDEPENDENT VERIFICATION

In addition to the component calibration, we also have data from a JLab SRF power-coupler test that relates the local power-meter readings to a calorimetric measurement. This test was conducted just after the bulk of our hot-model operation period but before the concluding hot-model extended continuous power run. The data include power readings from the klystron power monitor in addition to the local power meters. Figure 10-14 gives a graphical representation of these data. Klystron output data are plotted as independent data points on this curve with the 0.68 correction factor applied. The curves show reasonable agreement with the calorimetric data from the SRF power-coupler tests.

Power calibration data obtained during a load test prior to the hot-model operation is displayed in Figure 10-15. These data show that the local power monitor was reasonably

accurate during this measurement sequence. There is a 3.3% disagreement between thermal data and the local directional-coupler-derived power data. We observed that the klystron monitor was indicating a bit high during this measurement, though no actual data were recorded. For the hot-model tests we increased

Figure 10-13. RF-power monitoring block diagram

the klystron power meter offset by 1 dB instead of the expected 1.8 dB. Since the klystron monitor was already indicating high one might assume the difference is reasonable.

Figure 10-16 displays data from an operating period on October 17, several months after the hot-model tests. The klystron monitor offset had not been altered from its hot-model setting until we adjusted the klystron output power meter to agree with the local monitor readout prior to this session. We had to lower the klystron monitor attenuation setting from 70.5 dB to 68.8 dB to get agreement with the local monitor. This difference of 1.7 dB agrees favorably with the offset error of 1.8 dB determined from component loss measurements. These data show good agreement between thermal data and the local monitor. We believe we now understand the differences observed between

the klystron monitor and the local monitor during the hot-model operating period and can properly correct the power readings as discussed above.

Since we ran an independent data-acquisition system throughout the hot-model test period, we have recorded files of the entire operation. Figure 10-17 is an example of one of these files that shows the initial power applied to the hot model with the calibration applied.

Figure 10-14: Calibration data from SRF power-coupler tests just prior to final hot-model power run

Figure 10-15. Data from a component testing session just prior to the hot-model operation

Figure 10-16. Calibration data from JLAB SRF power-coupler testing conducted just after the hot-model test

Figure 10-17. Calibrated power levels supplied to the hot model during the initial start-up period

11

HOT MODEL TEST STAND OPERATION AND SAFETY

11.1 PROJECT SAFETY REQUIREMENTS

LANL maintains strict administrative requirements regarding workplace safety. Before any new project can commence operation, it is a LANL requirement that key project personnel perform a thorough assessment of the potential hazards and develop a written Hazard Control Plan (HCP). LANL's standard five-step process was used to develop the HCP for operation of the CCL hot-model test stand. The five steps of this process are as follows:

- 1) Define the nature and scope of the work to be performed.
- 2) Identify and evaluate the specific hazards associated with the work.
- 3) Develop and implement appropriate controls for each of the hazards.
- 4) Perform the work in accordance with the HCP.
- 5) Evaluate the effectiveness of the HCP and revise as necessary.

11.2 HAZARD CONTROL PLAN

We developed the HCP entitled *CCL Hot Model Test Facility* in accordance with Los Alamos National Laboratory administrative guidelines outlined in LIR 300-00-01, *Safe Work Practices*, and LIR 402-700-01, *Occupational Radiation Protection Requirements*. The HCP package consists of five separate documents tied together by a sixth document (number 1) [1-6], as follows:

- 1) HCP-SNS-3-005, *Operation of the CCL Hot-Model Test Facility*.

- 2) SNS-101020200-PN0001, *Coupled-Cavity Linac Hot-Model Conditioning and Operations Test Plan*.
- 3) HCP-SNS-3-004, *Coupled-Cavity Linac Hot-Model Water-Cooling and Resonance-Control System Conditioning and Operations*.
- 4) HCP-SNS-3-003, *Coupled-Cavity Linac Hot-Model Vacuum System Conditioning and Operations*.
- 5) LANSCE-5/SNS-2 HCP: 00-014, *MPF-18 RF Transmitter/Modulator for Klystron and RF-Powered Accelerating Structures (Hot Models) Testing*.
- 6) LANSCE-5/SNS-2 HCP: 00-013, *120 kV DC Supply/Capacitor Room, MPF 18*.

The scope and purpose of each of these documents is explained in the following sections.

11.3 HCP-SNS-3-005, OPERATION OF THE CCL HOT-MODEL TEST FACILITY

This document serves as the primary HCP for ensuring overall safe operation of the hot model. It identifies all of the significant hazards and risks associated with the operation of the experiments, HCPs, procedures, and controls that will be adhered to during operation of the hot model. A hierarchical matrix of the potential hazards identified in the other HCPs is used to determine the initial risk level and the residual risk level after implementation of the hazard controls. The document also describes the

various subsystems (i.e. water, vacuum, RF) and the designated point-of-contact for technical and/or safety issues pertaining to each of the subsystems. It also identifies the individual responsible for overall supervision during the process of conditioning and testing the hot-model RF structures.

11.4 SNS-101020200-PN0001, HOT-MODEL CONDITIONING AND OPERATIONS TEST PLAN

This document describes the process of tuning, conditioning, and testing the hot-model RF structures and subsystems. It explains the process of conditioning the RF structures with high-power RF (HPRF) in terms of power levels and duty factors to be used during each step of the conditioning process. It also provides an estimate of the expected electron impact energies that are produced at various RF power levels. We used the information contained in this document to estimate the maximum x-ray energies that would be produced in the vicinity of the RF structures during testing. We then used these estimates to determine the shielding requirements and radiation hazard controls that would be used during testing operations.

11.5 HCP-SNS-3-004, WATER-COOLING AND RESONANCE-CONTROL SYSTEM

This document describes the general operating principles and the potential hazards associated with the operation and maintenance of the water-cooling system in the hot-model facility. It also describes the potential hazards that could develop in the event of a malfunction or improper operation of the water-cooling system.

11.6 HCP-SNS-3-003, VACUUM-SYSTEM CONDITIONING AND OPERATIONS

This document describes the general operating principles and the potential hazards associated with the operation and maintenance of the high vacuum system in the hot-model facility. It also describes the potential hazards that could develop in the event of a malfunction or improper operation of the vacuum system.

11.7 LANSCE-5/SNS-2 HCP: 00-014, MPF 18 RF TRANSMITTER/ MODULATOR FOR KLYSTRON AND RF POWERED ACCELERATING STRUCTURES (HOT MODELS) TESTING

This document describes the hazards associated with normal operation of the HPRF klystron modulator test stand. It explains the design and operating principles of the various subsystems and the hazards and hazard controls associated with those systems. The document also provides detailed operating procedures for normal and off-normal operating conditions, as well as emergency shutdown procedures.

11.8 LANSCE-5/SNS-2 HCP: 00-013, 120 KV DC SUPPLY/CAPACITOR ROOM, MPF 18

This document describes the hazards associated with normal operation of the HPRF power supply and associated capacitor room. It explains the design and operating principles of the various systems and the hazards and hazard controls associated with those systems. The document also provides detailed operating procedures for normal and off-normal operating conditions, as well as emergency shutdown procedures.

11.9 RADIATION HAZARDS

During the development of the HCPs for the hot-model project, it was determined that the greatest hazard associated with the experimental activities would be the radiation hazard associated with the production of x-rays in the vicinity of the RF structures during conditioning and full power testing. Preliminary calculations were performed to determine the amount of shielding that would be required around the test stand. Additionally, radiation monitoring equipment was installed outside the shielding enclosure and interlocked to the HPRF system to provide a means of shutting off RF power in the event of radiation dose levels exceeding acceptable levels. Radiation control technicians (RCTs) performed radiation surveys around the shielding enclosure each time the HPRF power levels were increased during the conditioning process.

11.10 OPERATIONAL SAFETY RESULTS

No reportable injuries or radiation exposures occurred during the assembly and operation of the hot-model test facility.

12

LOW-POWER TUNING OF THE HOT-MODEL CAVITIES

12.1 INTRODUCTION

The CCL hot model consists of two segments of CCL structure—each having eight accelerating cavities and seven internal coupling cavities, plus a three-cell bridge coupler connecting the two segments. Low-power tuning of the cavities followed the procedures set forth in the document SNS Coupled Cavity Accelerator RF Cavity Tuning Requirements. This tuning plan [1] is part of the procurement package for the CCL equipment specification number SNS-104040200-EQ0003-R01. After low-power tuning, the structure's p/2-mode frequency was 805.108 MHz (scaled to 70°F, under vacuum). The target is 805.11 MHz, where the extra 110 kHz anticipates the expected frequency shift between no-power and power conditions.

12.2 BEAD-PULL MEASUREMENT

An axial bead-perturbation measurement showed a constant value of E_0 to within $\pm 0.4\%$ rms.

The Segment 2 average field was 0.42% higher than the Segment 1 average. Since the beam-dynamics error budget includes $\pm 1\%$ segment-to-segment field amplitude errors, the measured field distribution meets the requirements. We also measured the tilt sensitivity (or stability of the fields against frequency perturbations) by deliberately introducing end-cell perturbations. We raised the Cell-1 frequency 160 kHz by pulling the end wall and lowered the Cell-16 frequency 160 kHz by inserting a metal tube in the bore. A plot of the percentage difference in field between perturbed and unperturbed measurements showed the expected slope caused by the stop band of $\sim +50$ kHz. (See Figure 12-1.)

Figure 12-1 Bead pull measurement on hot-model cavity

Figure 12-2 shows the bead-pull apparatus set up on the CCL hot model.

Figure 12-2 Photograph of the bead-pull measurements being performed on the CCL hot model

12.3 CAVITY Q

The calculated Q of the hot-model structure is 16,140. This Q assumes that the bridge center cell has 45% of the stored energy of the accelerating cells and that 3% additional power is dissipated for each 1% of coupling. The measured Q was $16,055 \pm 85$, which is 99.5% of the calculated Q.

12.4 STOP-BAND GAP

We left a positive stop-band gap of ~50 kHz to ensure that the stop-band gap would remain positive under operating conditions. Figure 12-3 shows the measured dispersion curve for Segment 1. The results for Segment 2 are indistinguishable from Segment 1.

Figure 12-3 Measured dispersion curve for segment 1

13

HIGH-POWER TESTING OF THE CCL HOT MODEL**13.1 RF CONDITIONING**

Because low-level RF control was unavailable when we started RF-power conditioning and the klystron frequency was 805.000 MHz, we heated the water to about 85°F in order to operate at 805.000 MHz with low RF power. Table 13-1 lists different power levels relevant to the cavity conditioning. The peak power column corresponds to the total hot-model power that corresponds to the field levels listed in the next column. The Segment-1 design power level is low because of the field ramp from Segments 1–9.

Conditioning started on Friday, August 3, 2001, using 1.05-ms pulses at a repetition rate of 20 Hz. Vacuum interlocks inhibited the RF power if pressure reached as high as 10^{-6} Torr. Below 20-kW peak power, cavity pressure was usually the limiting factor in speed of conditioning. Above 20 kW, pressure at the 30-year-old LAMPF RF window was the limiting factor. Conditioning proceeded while controlling either the water or copper temperature. It took 6 hr to reach 20 kW, 21 hr to reach 270 kW, and 15 hr (42 total hr) to reach 480 kW.

13.2 OPERATION AT POWER

Using the original power supply on the 805-MHz klystron restricted operation to a 40-Hz repetition rate (~4.5% duty). Later, when the new converter-modulator became available we were able to run at the design duty factor of 7%. Without low-level RF control, we held the cavity on resonance at 805 MHz by controlling either the water temperature or the copper temperature. This method worked very well, but it did require changing the set point when we made significant changes in average RF power. We found it helpful to run the cavity slightly warmer than the temperature that produced minimum reflected power. When a vacuum trip occurred, the cavity would cool, which reduced reflected power and make recovery easier.

Table 13-1. Hot Model Power Levels.

Cavity operating condition	Peak power (kW)	Axial Field E_0 (MV/m)	Surface Field (Kilpatrick)
Segment 1 design:	270	3.06	1.05
Segments 9-48 design:	410	3.77	1.29
Conditioned to:	480	4.08	1.40

13.3 RADIATION LEVELS

Typically, while operating at the maximum power allowed by the vacuum trip point, we saw some significant radiation outside the lead shield walls. For a time we had to restrict access around the south end of the hot model because of x-rays in line with the cavity bore tube. Placing lead “pillows” over the boreholes reduced this radiation from over 5 mR/hr to less than 0.2 mR/hr. Reducing power slightly virtually eliminated the radiation outside the lead enclosure.

13.4 LOW-LEVEL-RF FREQUENCY CONTROL.

Eventually, we had the ability to track the resonant frequency using the low-level RF control system developed for the Low-Energy Demonstration Accelerator (LEDA). Before amplitude control was available, we automatically tracked the cavities’ resonant frequency while the water system controlled the copper cavity surface temperature. Using this scheme, reflected power was typically 2 or 3 kW at 450-kW forward power. With the window and cavity still showing signs of RF conditioning, the system would recover immediately after a vacuum trip. We could run the power level up to any value below 450 kW without much response of the vacuum pressure.

13.5 LOW-LEVEL RF AMPLITUDE CONTROL

By August 15, 2001, we added amplitude control to the low-level RF system and, as a result, we accomplished several of our goals for testing the hot model. The water system received the RF error signal from the LLRF and adjusted the water temperature to keep the cavity resonant frequency within the narrow frequency range where the LLRF remains

locked (at 805.000 Mhz). The LEDA LLRF system was developed for a CW (continuous wave) accelerator so some changes were required for the pulsed system. First, we added an independent pulser to establish a timing signal for the RF pulse. This addition allowed us to run the LLRF control board in CW mode and avoided “double pulsing” the klystron when the board switched modes (e.g. from open loop to RF tracking or from RF tracking to I&Q control). Previously, the double pulsing was tripping off the high voltage to the klystron. Second, with the system running we were able to tune the gain settings on the water system’s PID control loop to seek and maintain a particular set point on the RF error signal. We also had to experiment with digital and analog, gain and phase settings and other settings on the I&Q controls. Once we found the correct settings, the system was very stable. When we abruptly changed power levels between 425 kW and 35 kW, the control system maintained the set point amplitude and resonant frequency without ever losing lock. We repeated this test several times, allowing the temperature to stabilize for a few minutes at each new amplitude set point.

13.6 STOP-BAND MEASUREMENT UNDER POWER

An important goal of the hot model testing was to measure the stop-band gap at full RF-power operating conditions. The change in the stop-band gap that occurs when RF power is applied is an important piece of design information that we had no other way of obtaining. Up to 250-kHz stop-band gap is easily tolerated on the two-segment, 33-cell hot model. The modes nearest the $\pi/2$ mode are ~ 2 MHz away. On a 12-segment structure, the nearest modes will be only ~ 300 kHz from the $\pi/2$ mode, making tighter demands on the tuning. To measure the stop band, we used the last 50 ms of the pulse to switch in a different

RF generator whose frequency we could control. By observing the reflected power during this part of the pulse, we measured the frequencies of the two nearest modes to the $\pi/2$ mode that are observable. These are actually the second nearest modes on each side because the nearest modes have almost no field in the drive cavity. Table 13-2 lists the frequencies we found at several power levels.

The stop band was slightly more positive at high power than at low power. The fact that these modes remain at very nearly the same frequency at these different power levels indicates that the cooling of the coupling cavities is well balanced with the cooling of the accelerating cavities and that the stop band in the dispersion curve is not sensitive to the power level.

13.7 DARK-CURRENT X-RAY MEASUREMENTS

Thermo-luminescence detectors (TLDs) were used to take measurements of the dark-current x-rays at a nominal power level during a 1-hr run. The (uncalibrated) power level read from the RF-power meter at the klystron was 410 kW (7 % duty factor at 60 Hz, 1 ms). Applying the RF-meter calibration factor of 0.68 (see Chapter 10), this was a nominal power of about 280 kW. The TLDs were placed directly above the viton O-ring, on the flange joining the accelerating cavities to the powered bridge coupler. The readings ranged from 1.3–3.0 rad/hr. For an estimated SNS 40-yr operating life, using 24-hr/day and 300 days/yr, the highest reading of 3 rad/hr is equivalent to 0.9 megarad accumulated dose. Since viton O-rings have been estimated to have a radiation tolerance of at least 20 megarad, these measurements indicate that SNS should have no trouble with this use of O-rings.

Table 13-2. Stop-band Measurements Under Power

Peak Power (kW)	Average power (kW)	" $\pi/2 - 2$ " mode	" $\pi/2 - 2$ " mode	" $\pi/2 - 2$ " mode	Stop-band change (kHz)
35	2.5	800.923	805.000	809.625	–
340	24.5	800.933	805.001	809.636	+10 $\pm$ 3
450	32.4	800.934	805.001	809.635	+9 $\pm$ 3
500	36.0	800.934	805.000	809.633	+8 $\pm$ 3

14

COMPUTER CONTROLS FOR THE CCL HOT MODEL

14.1 INTRODUCTION

The proper operation of the CCL is based on full-power acceleration by each cavity. This acceleration, in turn, is based on each cavity being in resonance with the input RF-power frequency. Since the resonant frequency of a cavity is a function of its size, control of the cavity size controls the cavity's resonant frequency. In a normal-conducting cavity, much of the RF power is absorbed in the cavity walls, so control of the cavity size is really a matter of removal of the proper amount of heat generated by the absorbed power. The heat removal is accomplished by flowing cooling water through the passages in the cavity's walls. Controlling the temperature of this cooling water controls the temperature of the cavity and thus the resonant frequency.

14.2 CAVITY COOLING SYSTEM CONTROLS

The system that supplies the cooling water is equipped, among other things, with a pump for producing coolant flow, a heater to heat the cooling water and increase the cavity temperature when desired, a heat exchanger to cool the water and decrease the cavity temperature when desired, and a three-way valve to divert some of the water returning from the cavities through the heat exchanger while allowing the rest to recirculate. In that way the temperature of the cooling water, and consequently of the cavities, can be manipulated. Although the water system is equipped with many manual valves that are

used to balance flow in the various areas of the hot-model system, the only computer manipulated item is the three-way valve. The pump is run as a constant flow pump, and the flow rate into the cold side of the heat exchanger is also held constant. Many points, including surface temperatures, water temperatures, flow rates, the three-way valve position, forward and reflected RF power, as well as the RF error signal, are instrumented and can be read and displayed by the control system.

14.3 MAIN OPERATOR SCREEN

Figure 14-1 shows the main operator screen, which appears on the left side of the monitor. As the operator selects other displays, they appear on the right side of the monitor. All monitored data is written to a file at an update rate that is specified on this panel. The operating mode, i.e., "manual," "auto temperature," or "auto RF" is selected under *Control Mode*. If auto temperature mode is selected, the particular temperature variable as well as the set point can be selected. In auto RF mode, the set point for the RF error is set internally at 5.9 volts. The operator can select variables to be monitored and visually displayed by clicking on the "select signals" boxes on the left of the display areas. On the far right of the display is a button that provides for shutdown of the hot-model control system. An additional button is provided that will cause an immediate data update without waiting for the selected time for another update.

Figure 14-1 Main operator display for hot-model control system

14.4 RF-INTERLOCK DISPLAY

Secondary displays can be viewed by moving the pointer in the display box to the desired display. These displays appear to the right of the main operator display. Figure 14-2 shows the “RF-interlock” display. This display shows the out-of-tolerance signals as well as providing for a means of selecting other variables to be monitored, allowing for a manual override, and displaying a “lighted” button when RF is enabled. This enabled button appears black in the figure.

14.5 CONTROL-VALVE DISPLAY

Figure 14-3 shows the “control-valve” display. This display shows the mode of control, a plot of the error between the set point of the particular variable being used,

the actual value of that variable, and a plot of the set point itself along with the actual value. It also displays a meter showing the position of the valve from no water passing through the heat exchanger (current position of the needle indicating all the way to the hot side or 0% open) to all the water passing through the heat exchanger (100% open or all the way to the cold side). It displays the process variable being used if in the automatic temperature mode. In addition to the plot, the values of the set point and the process variable are displayed in numbers. Also displayed and provided for adjustment are three sets of PID gain values. This display is mainly used for tuning the PID parameters.

Figure 14-2. RF-interlock display

Figure 14-3 Control-valve display

14.6 COOLANT-PASSAGE DIAGRAM.

Figure 14-4 shows a mimic diagram of the coolant passages in the hot model itself. This displays all of the flow rates, water pressures, and water temperatures, as well as the approximate locations for each within the hot model. Also shown are inlet and outlet flow rates, water pressures, and water temperatures. The RF error, forward power, and reflected power, as well as all of the surface temperatures, are displayed in tabular form at the bottom of the diagram.

14.7 WATER-CART DIAGRAM

Figure 14-5 displays another mimic diagram. This diagram is of the water cart. All of the components of the water cart are shown including the water conditioning system, the pump, the heat exchanger and the water chiller, and all of the valves including the three-way valve. Actually, this display shows an automated open-close valve on the heat exchanger bypass leg. This display was taken from an earlier design. If this valve were moved to the right of the intersection of the bypass leg and the leg coming from the heat exchanger and replaced with a three-way valve, a proper configuration description would be in place. Various flow meters and pressure meters are displayed in their approximate locations. Data from the water purification system is also displayed.

Figure 14-4 Mimic of the hot-model coolant passages

Figure 14-5 Mimic of the water cart

A meter, similar to the one displayed in Figure 14-3, is also displayed above the bypass leg. Below the mimic diagram are two knob displays. The one to the right is a control knob for manually adjusting the three-way valve. In this diagram it is grayed, indicating that it can't be used for control. When manual mode is picked on the main operator display, the graying is removed and the knob can be used. The knob to the right of this one is a display-only knob and is provided for a graphical readback of the valve position. The numbers under these knobs also provide for a display of the command being sent to the valve and the actual valve position. Below the knobs, several alarm indicators are displayed.

These displays provide the necessary functionality for full operation of the water cart system and the resonance control of the hot model. During the week or so that the experiment ran, several operators with various degrees of familiarity with the water system and with the displays themselves used these displays and obtained the desired operation from RF conditioning of the two cavities to full-power operation of the system that actually exceeded the design limits.

14.8 ARCHIVING OF DATA

The control system archived all of the data that was instrumented. Each day of operation was saved in a separate file. Figure 14-6 shows a plot of the RF error, the RF-cavity power, and the RF set point. As noted, the RF set point is set internally to 5.9 volts and is just put on this plot as a straight line. The data chosen for this plot were taken during a period when the hot model was run in automatic RF mode, so the RF error signal being returned from the low-level RF system was used as the process variable in the PID algorithm. As the RF error increases from zero after the system was turned on, one can see the corresponding increase in the RF-cavity power. Actually, the system is manipulating the temperature of the cavity and, as the cavity size changes, the cavity approaches resonance. As the cavity

approaches resonance less power is being reflected and more power is seen as cavity power. When the RF error signal is driven to the set point, as seen at about 19,900 s on the time axis, the cavity power is running at about 430 kW. Occasionally, the power trips off for some reason (see the power level a short time after 19,900 s). When the power comes back on the control algorithm reacts, attempting again to drive the RF error to 5.9 volts.

When the RF system is stable and not tripping, one can see that the system provides good control, keeping the RF power fairly stable in the cavity.

Figure 14-6 Plot of RF data vs. time

14.9 OFF-NORMAL OPERATION OF THE HOT MODEL.

Many challenges were present during the execution of the hot-model experiment. The water chiller that supplied cold water to the heat exchanger had a capacity that was much too large for the heat load. Consequently, the chilled water temperature fluctuated several tenths of a degree in a several second cycle. The design called for constant temperature for the chilled water. The three-way valve seemed to stick and had only 100 steps from one extreme to the other. This problem could be demonstrated by selecting the valve position in one of the display panels on the main operator display. The display showed quantized values in the valve position. Although the pump was connected to an accurate flow meter, the control of the pump speed was so complicated that, in the minimal amount of time that was available to execute the experiment, it was decided to run the pump open loop and control the flow by manual operation of the valve. Consequently, as the control valve changed position, the flow through the system varied. As indicated previously, the design called for constant flow. However, even with these off-normal conditions, the system still operated well within specifications. Actually, the positive side of this is that this problem provided a good test with off-normal conditions.

15 CONCLUSIONS

15.1 INTRODUCTION

The design, fabrication, and testing of the CCL hot model represented a significant investment of resources and funding for the SNS project. Was this investment warranted and did we learn what we needed to from the hot model to successfully construct the CCL for the SNS project? The simple answer is yes. The CCL hot model was very successful, but to explain this more thoroughly it is necessary to review the goals we had for the hot model. The design and operation of a bridge-coupled CCL of this type had not been done before. There were many unanswered questions associated with manufacturing, tunability, and stability of this particular type of RF structure.

15.2 GOALS

We had three major goals for the CCL hot model.

- 1) Demonstrate that the bridge-coupled CCL RF structure was stable under high-power operation,
- 2) Develop a scheme to tune the structure that could be transferred to industry, and
- 3) Design and fabricate the RF structure to demonstrate a cost-effective approach to large-scale production that could be accomplished by industry.

Additionally, we wanted to use the hot model as an opportunity to integrate and test as much of the SNS hardware as possible. The accomplishment of these goals turned out to be a considerable challenge.

15.3 REQUIREMENTS

First we had to build a prototype bridge-coupled CCL structure using manufacturing techniques available to industry. This structure would require over 500 kW of peak high-power RF at 805 MHz during full-power testing. We wanted to use one of the prototype 2.5-MW klystrons to test the hot model, but at reduced operating power the klystron would have reduced efficiency. It would require the use of the prototype HVCM that was being developed for SNS to achieve the necessary power input to the klystron. This modulator in turn required modifications to the test-facility building to provide necessary AC power. The SNS LLRF system was not sufficiently developed at this time to support the test, so we adapted a similar system developed for the LEDA project developed for testing the hot model. We built and used a prototype SNS water-cooling system, incorporating resonance-control capability to cool the hot model and demonstrate the ability to use cooling-water temperature control to stabilize the cavity frequency. We also built and used a prototype SNS vacuum system, capable of maintaining vacuum in the cavity in the 10^{-8} -Torr range during operation to maintain the cavity vacuum. We developed and used a computer-controlled data-acquisition system, representative of the SNS Experimental Physics and Industrial Control System (EPICS), to test the resonance-control algorithms planned for the SNS CCL and provide protection for equipment and personnel during operations.

Finally, we developed and implemented a test plan, including a hazard-control plan, to adequately control operations during testing and protect personnel from x-rays and other hazards that could be encountered.

15.4 SCHEDULE

The construction and integration of this equipment proved to be challenging on the time scale available to conduct the test. The time available to design, build, and conduct the testing of the hot model was driven by the need to finish the CCL design and place an order for its construction early enough to allow the vendor adequate time to build it. Additionally, the hot-model RF system was the only system available to the project to conduct testing of other high-power RF hardware such as the couplers and windows for the super-conducting cavities that JLab was building for SNS. Therefore, the time for preparation and testing of the hot model had to be inserted between the times for these other tests, since both were essential to the SNS schedule. The design of the bridge-coupler cavity turned out to be problematic. Cold-model testing revealed structure problems that required further cold modeling before final machining of the hot model could be completed. Following machining of the hot-model cells, they would have to be brazed together in a large stack using a fairly complex brazing operation. Given the complexity of this brazing operation and the irreversibility of a failed stack braze, a practice stack braze was originally planned. However, so much time was consumed working through the cold-model structure issues that no time was left for the practice stack braze if we were to meet the project schedule. It was decided to proceed directly to the final stack braze without a practice braze, and fortunately we were successful the first time.

15.5 TUNING

Upon completion of the cavity fabrication, tuning of the structure began. This tuning proceeded rapidly and successfully, including development of specialized hardware to simplify the tuning process. A key measurement to be made during tuning of the cavity was measurement of the stop band. We desired a small, slightly positive stop band to ensure stability of the fields in the structure. A stop band of +50 kHz was achieved, and it is believed that this will provide excellent field stability under high-power operation. The final assembly, tuning, and integration of the test hardware were accomplished in the relatively short time frame of about three weeks. This accomplishment was a result of good planning by the technical staff involved in the testing, and that the staff had a great deal of experience with accelerator hardware and had worked together before to integrate an accelerator system.

15.6 TESTING

The testing of the hot model went extremely well and was conducted over a period of about two weeks. The initial conditioning of the structure proceeded rapidly, and peak-power operation at 480 kW was achieved after only 42 hr of conditioning. Initial operation at peak power was limited to 4.5% duty factor because the SNS prototype HVCM was unavailable at this time. Prior to the completion of testing, however, the HVCM came on line to power the klystron, and full peak-power operation at 480 kW and 7% duty factor, with an average power of 33.6 kW, was achieved. During the testing of the hot model, we demonstrated that the resonance-control system worked extremely well. We demonstrated the ability to maintain the resonant frequency at 805.000 MHz with a reflected power of only 3 kW and with

450 kW of forward power. We controlled the resonant frequency and field amplitude over a peak-power range from 35 kW to 425 kW. Abrupt changes in power were introduced into the hot model over this range to determine the ability of the LLRF and resonance-control system to respond to these changes. The system responded extremely well and never lost lock on the set-point control. We measured the stop band under high-power operation. This stop band was a key measurement because significant changes in the stop band could cause field tilts and result in an unstable RF structure. This measurement also indicated how well the cooling was balanced between the accelerating and coupling cavities. The stop band proved to be very stable under high-power operation, increasing by only 10 kHz over the entire operating power range. This slight increase meant that we had designed and produced a stable RF structure and that we were cooling it uniformly.

15.7 POWER MEASUREMENT

The tight schedule for testing precluded us from carefully calibrating the RF-power measurements until after the tests were completed. Two power couplers were used to measure RF power—one was located at the klystron, and the other was installed just upstream of the hot model. Analysis of the test data revealed a discrepancy between the measurement made by the RF coupler closest to the hot model and calorimetric data obtained by the water-cooling system. Subsequent calibration of the RF coupler yielded a correction factor of 0.68, which was applied to all RF measurements made by that coupler. When this correction was made, we achieved excellent agreement between measurement techniques and were thus able to demonstrate that the hot model had successfully exceeded its design specifications.

15.8 RESULTS

The CCL hot model was an extremely successful endeavor. We met or exceeded our principal goals of demonstrating that we had designed a structure that could be tuned and operated in a stable manner at the required power levels. We developed a manufacturing process and built the hot model using commercial vendors, demonstrating that it is possible for industry to build the entire CCL. Subsequent procurement of the SNS CCL from industry demonstrated that a substantial cost saving in CCL construction was achieved by having industry build the RF structure. We developed a comprehensive tuning plan that could be used by industry to tune the CCL structure. We determined that we had in fact designed a stable RF structure that would condition rapidly and that would operate over a broad range of operating parameters. We had the opportunity to test much of the SNS prototype hardware in an integrated test, including the water-cooling and resonance-control system, the vacuum system, the HVCM, the 2.5-MW prototype klystron, and the bridge-coupled CCL structure. We had the opportunity to integrate much of this hardware, test it as a system, and work through problems associated with RF-power measurements and interfaces between various systems. This experience has allowed us to anticipate some of the problems that LANL and ORNL will face as we test and commission the CCL at ORNL.

15.9 LESSONS LEARNED

The hot model was a very successful test; however, in retrospect there were a few things we could have done that would have made it even more successful. The time frame for testing the hot model was highly constrained because of the availability of only one high-power RF test stand for the entire SNS project at the time of these tests. Had we built JLab's RF test stand earlier to conduct the testing of the super-conducting couplers and windows, more time would have been available to test the hot model and characterize its performance at higher RF-power operating levels and over a longer time period. It would also have been desirable to test a prototype of the SNS LLRF control system, had it been available, and work through some of the system integration issues earlier rather than later. It would have been desirable to have ORNL personnel participate in the tuning and testing of the hot model so that they would be better prepared for commissioning the CCL. We clearly needed closer collaboration in this area. Hindsight is 20-20, but perhaps this report can help influence planning in future accelerator construction projects so they may benefit from our experience.

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