LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T970148-00 - E** 8/7/97

Beam Tube Bakeout Preliminary Design

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1 INTRODUCTION

1.1. Purpose and Scope

The purpose of this document is to outline the preliminary design for the thermal insulation, heating power and control, pumping, instrumentation, and data acquisition and logging equipment to be used for the bakeout of the LIGO Beam Tube Modules. The preliminary design is intended to be sufficiently developed to permit critical evaluation of all aspects of the design approach, even though certain details (such as specific locations of all temperature sensors) may be incomplete. The design must meet the requirements defined in the draft Beam Tube Bakeout Design Requirements Document (LIGO-E960123-03-E). During the final design/implementation phase, blocks of the design (such as the location list of temperature sensors) will be subjected to final scrutiny in a focused mini-review. As each block of the design is completed and approved, the equipment will be acquired, installed and tested by Hanford on-site LIGO staff, who will subsequently perform the bakeout.

1.2. Acronyms

AC	Alternating Current
AP	Blanked Port for Auxiliary Turbo Pump
BT	Beam Tube
BTE	Beam Tube Enclosure
CBI	Chicago Bridge and Iron, Inc. (Beam Tube fabrication and installation contractor)
CC	Cold Cathode Gauge
CH_4	Methane
CL	Blanked Port for Calibrated Leaks
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAS	Data Acquisition System
DC	Direct Current
DRD	Design Requirements Document
L	Variable Leak Valve
LIGO	Laser Interferometer Gravitational-Wave Observatory
LN_2	Liquid Nitrogen Trap
M	Metal Sealed Valve
P	Pirani Gauge
PSI	Process Systems International
RGA	Residual Gas Analyzer
RP	Blanked Port for Roots and Turbo Pumps
TBS	To Be Supplied
V	Viton Sealed Valve

1.3. Applicable Documents

1.3.1. LIGO Documents

M950001	Project Management Plan, latest revision
E950018	Science Requirements Document, latest revision
E950020	Beam Tube Module Requirements-Fabrication & Installation Contract, latest revision
E960123	Beam Tube Bakeout Design Requirements Document, latest revision
E940002	Vacuum Equipment Specification, latest revision
E94xxxx	Beam Tube Module Specification (formerly Specification No. 1100004)
E94xxxx	Process Specification for Low Hydrogen, Type 304L Stainless Steel Vacuum Products (formerly Specification No. 1100007)
M950046	Project System Safety Plan, latest revision
E950089	Interface Control Document (ICD): Beam Tube (BT) - Civil Construction (CC), latest revision
D950027	Beam Tube Pump Port Hardware, latest revision
T960178-01-E	Beam Tube Bakeout Conceptual Design (predecessor to this document)

1.3.2. Non-LIGO Documents

ASTM-C-795	Standard Specification for Thermal Insulation for Use in Contact with Austenitic Stainless Steel
TBD	CBI Beam Tube Configuration Drawings

2 OVERVIEW

The salient features of the LIGO beam tubes which affect the design of the bakeout are summarized here. The beam tube will be baked out in increments of 2 kilometer modules. The LIGO beam tube modules are stainless steel vacuum vessels, 1.2 m diameter by 2 km long. There are four such modules at each of two sites (8 total). Each vessel consists of 50 sections of stainless steel thin-wall (3 mm wall thickness) tubing, each 40 m long, separated by a stainless steel expansion joint designed to accommodate the thermal expansion of the 40 m sections during a bakeout. The tube sections are supported by structures designed to accommodate the thermal expansion and to minimize heat loss through the mechanical connections. The tube sections and expansion joints are welded together to form a continuous leak-tight tube. The ends of the 2 km long modules are terminated by 114/122 cm gate valves. There are nine 250 mm diameter pumping ports distributed at 250 m intervals along the module. The beam tube is enclosed in a concrete protective cover with access doors at each pump port location (there are also emergency accesses between the pump ports).

The beam tube bakeout design must meet the requirements given in the Beam Tube Bakeout Design Requirements Document, LIGO-E960123. The basic plan is to heat each beam tube module to ~150 °C under high vacuum for ~30 days, with sufficient pumping speed to remove adsorbed water and contaminants. The key elements of the design are illustrated in schematic form in Figure 1 (here, to aid visualization, the beam tube is regarded simply as a vacuum vessel, stripped of its unusual geometry). The eight beam tube modules are baked sequentially, with equipment moved from one module to the next.[1] The elements are:

- **Insulation**, which reduces heat loss during bakeout from the hot vacuum vessel to an economical level and increases the thermal time constant of the vacuum vessel, reducing temperature dependence (both during bake and afterwards) on the ambient environment. Insulation will be wrapped around the entire length, ends and ports of a beam tube module.
- A **heater,** which dissipates energy from the local power company to raise the temperature of the vacuum vessel. The proposed bakeout system will heat the beam tube module with direct current flowing through the shell of the beam tube. Heating is by power loss in the resistance of the stainless steel shell (I^2R).
- The **heater power source**, which consists of the local power company which provides the electrical energy, AC transformers and wiring to deliver the power to DC power supplies which in turn convert the power to voltages and currents suitable for the heater, and attendant electrical wiring.
- A **heater controller**, which receives a signal from the **control temperature sensor** and adjusts the power delivered to the heater to maintain a constant temperature of the vacuum vessel.
- The **bake pumps**, which remove gases evolved during the bakeout and maintain a vacuum in the vacuum vessel.
- A **residual gas analyzer (RGA)**, a mass spectrometer which measures the partial pressures of residual gas in the vacuum vessel.

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[1] Currently it is assumed that it is most economical to leave the insulation and temperature sensors in place on each beam tube module, but this assumption is not crucial to the design.

- A **monitor system** which includes sensors (temperature of vacuum vessel, power supply currents and voltages, environmental parameters such as outside temperature and wind speed, and other engineering parameters as needed), data acquisition and display, and data recording. Data display and recording for the RGA will be separate from the monitor system, since these features can be purchased as options with the RGA controller, and data can be merged after-the-fact.

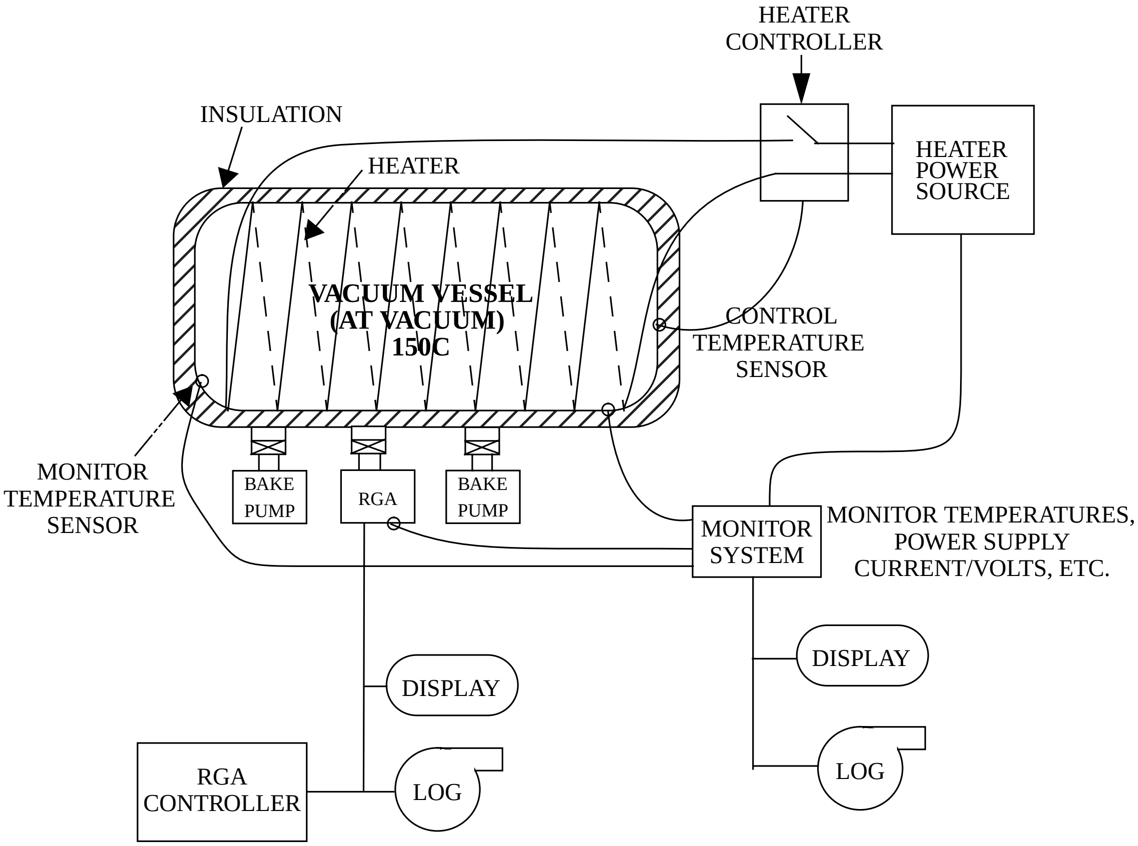


Figure 1: Schematic diagram of equipment during bakeout and cooldown

After the beam tube has been baked sufficiently, it is allowed to cool down (by shutting down the heater power) while continuing to pump. The heating equipment (heater power source and controller) can be immediately moved to the next beam tube module to be baked. After reaching ambient temperature, measurements are made of the residual gases in the beam tube to verify the success of the bakeout and to determine with maximum sensitivity whether any air leaks are present. The pumping speed needed is much lower than during the bake, and the RGA sensitivity needed is higher. The plan is to remove the pumps used during the bakeout and install them on the next beam tube module to be baked. A pump and RGA dedicated to post-bake measurements are then installed.

3 TECHNICAL DESCRIPTION

3.1. INSULATION

3.1.1. Tube Walls

The insulation consists of two layers of thermal insulation materials (see Figure 2). The first (inner) blanket layer is a 12 kg/m^3 (0.75 lb/ft^3), 0.075 m (3 inch) thick inorganic glass fiber blanket material bonded together by a high-temperature thermosetting resin. It is rated for 343 °C. It complies with the requirements of ASTM-C-795 for controlling stress corrosion of stainless steel. We have chosen Knauf Type KN-75, a material mainly used as thermal and acoustic insulation in both industrial equipment and marine applications. The second (outer) layer is a 12 kg/m^3 (0.75 lb/ft^3), 0.075 m (3 inch) thick inorganic glass fiber material with a moisture-barrier facing, rated for 120 °C. We have chosen Knauf Duct Wrap, the material used in an earlier beam tube bakeout demonstration.

The inside layer will be installed in wraps which match the stiffener ring spacing (~0.75 m (30 inch) wide) and secured in place with aluminum bands on 0.3 m (12 inch) centers. The outer layer will be installed over the inner layer with staggered seams, and also secured by bands on 0.3 m (12 inch) centers. The outer layer has an aluminum-foil/scrim/kraft-paper (FSK) facing on the outside to block moisture penetration and reduce conduction and radiation losses; the FSK facing includes a .05 m (2 inch) flange along one edge to overlap the FSK facing of the adjacent wrap of insulation. The flanged facing joints will be sealed with aluminum foil/scrim adhesive tape.

The two layers, a total of 0.15 m (6 inch) thick, provide a combined heat loss of 5.5 mW/cm^2 of beam tube surface area (220 W/m of beam tube length) at a beam tube temperature of 150 °C. The insulation provides a thermal time constant of about 9 hours.

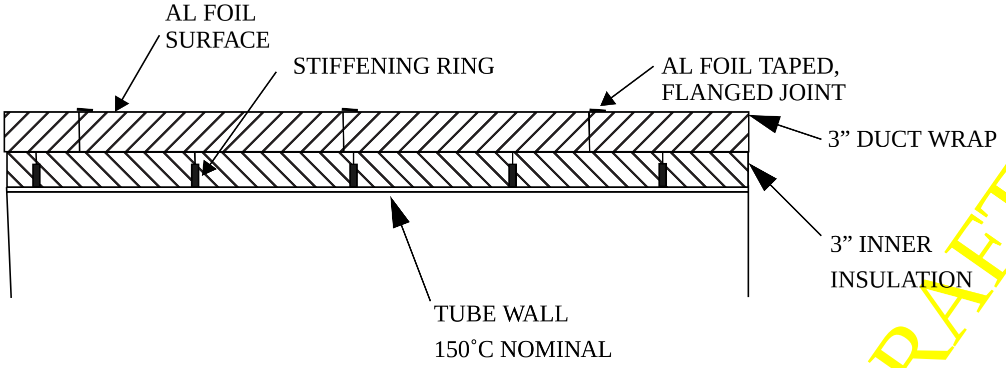


Figure 2: Tube wall insulation (section view)

3.1.2. Bellows and Guided Supports

The bellows convolutions and thinner (2.7 mm) wall thickness lead to increased heat loss per unit length. To compensate for the higher heat dissipation per unit length, the insulation thickness at the bellows will be reduced by omitting the inner 0.075 m (3 inch) layer and replacing the outer layer with a 0.025 m (1 inch) layer of Knauf Pipe and Tank (P&T) insulation with FSK facing (rated for 454 °C), which results in an estimated bellows temperature between 200 °C and 250 °C (Figure 3). The locally increased temperature compensates for the added losses through the adjacent guided support cables, so that no additional insulation is required at those penetrations. The P&T insulation is loosely installed to accommodate up to 0.025 m (1 inch) stretching in this region when the beam tube is cold.

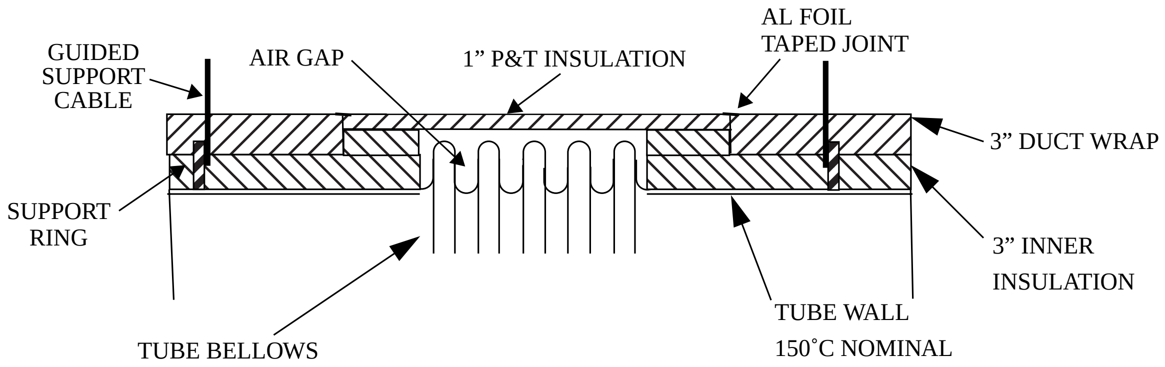


Figure 3: Bellows insulation (section view)

3.1.3. Fixed Supports

The beam tube is attached to the fixed supports at special stiffening rings, through Micarta insulating mounts. An additional 0.75 m (30 inch) wide wrap of the inner insulation material will be installed on each side of the fixed support stiffening rings, embedding the support attachments (see Figure 4), to partially compensate for increased conductive losses.

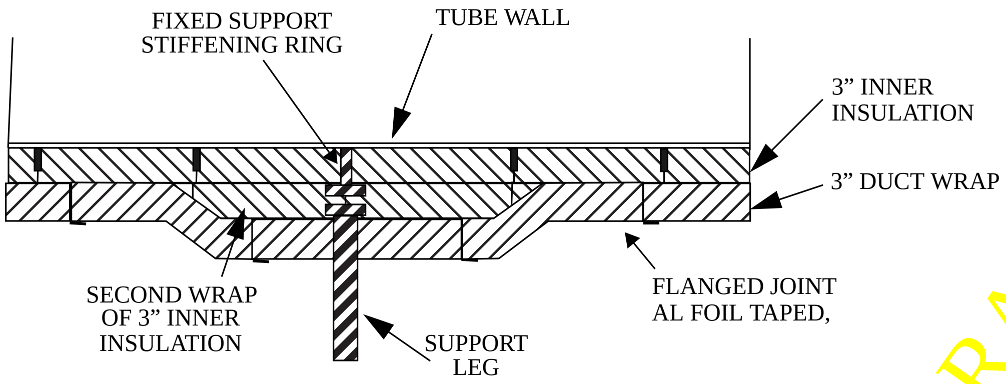


Figure 4: Support insulation (section view)

3.1.4. Ends and Pump Ports

The ends of the beam tube module are connected to the 114/122 cm gate valves. The 114/122 cm gate valves and the nine pump ports will be insulated with custom fitted thermal heater jackets similar to those designed by PSI for the bakeout of the LIGO Vacuum Equipment. The thermal jackets will be purchased directly by LIGO for the beam tube bakeout. Thermal jackets will also be installed around the Vacuum Equipment spool pieces connecting the long LN2 coaxial pumps to the 114/122 cm gate valves, for a distance of about 1 m, to radiatively heat the valve gate. PSI estimates that this approach will yield a gate temperature of about 140 °C.

3.2. Heating Power and Control

3.2.1. AC Source/Distribution

The power to be used for the bakeout will be supplied by the 13.8 kV (WA, 13.2 kV in LA) AC power available along the beam tube every 250m and provided by the local site public utility. The 13.8 kV power line is housed in subsurface electrical vaults along the arms and across the service road from the beam tube service entrances.

The 13.8 kV power will be converted down to end-use voltages and brought to the beam tube module stub-ups near the service entrances by the local public utility (Figures 5 and 6). Power transformers for the high power DC heating will be provided at two locations along the beam tube module (see Figure 5). These transformers will be moved with the DC power supplies to each beam tube module. Separate transformers and power distribution panels provide 208VAC, 3Ø and 120VAC, 1Ø power for thermal jackets, pumps, instrumentation and smaller equipment. These will be supplied and installed at seven locations along the beam tube module (see Figure 6). Power for equipment at the module ends is obtained from inside the buildings (except at the LA midpoint, where temporary power must also be provided). Two complete sets of transformers are provided so that a module can be set up for bakeout during the bake, cool down and post-bake evaluation of another module.

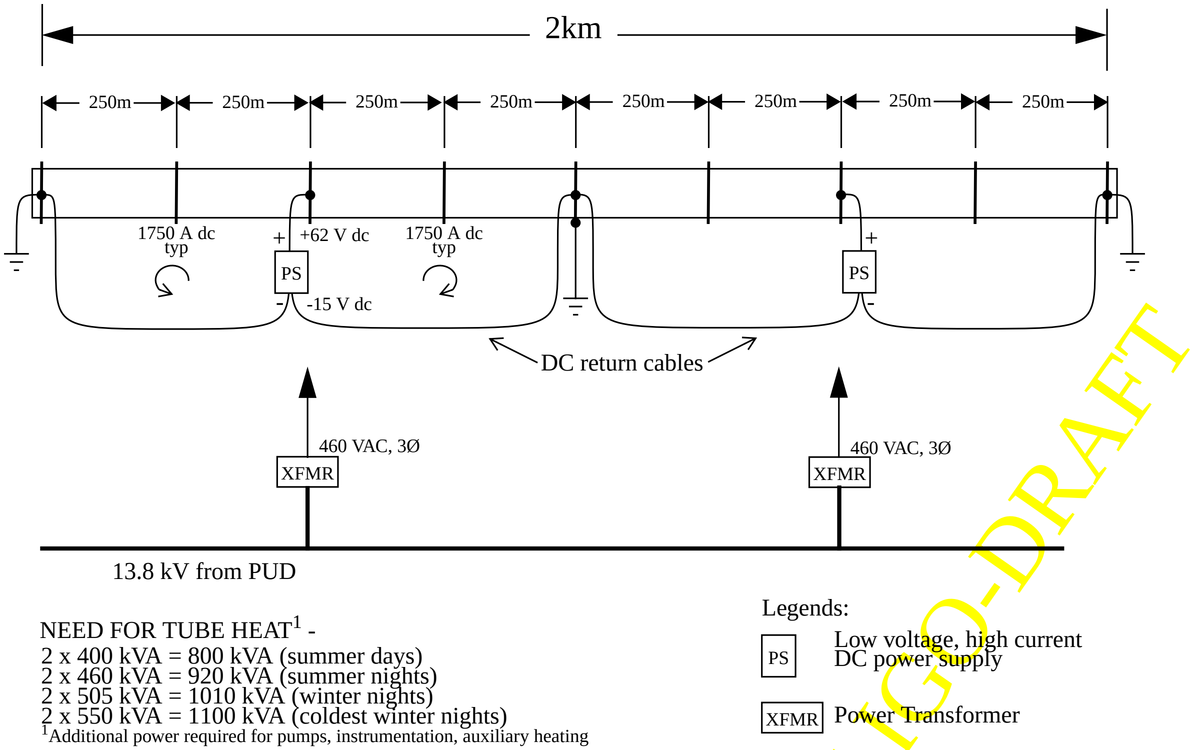


Figure 5: Heating power source layout

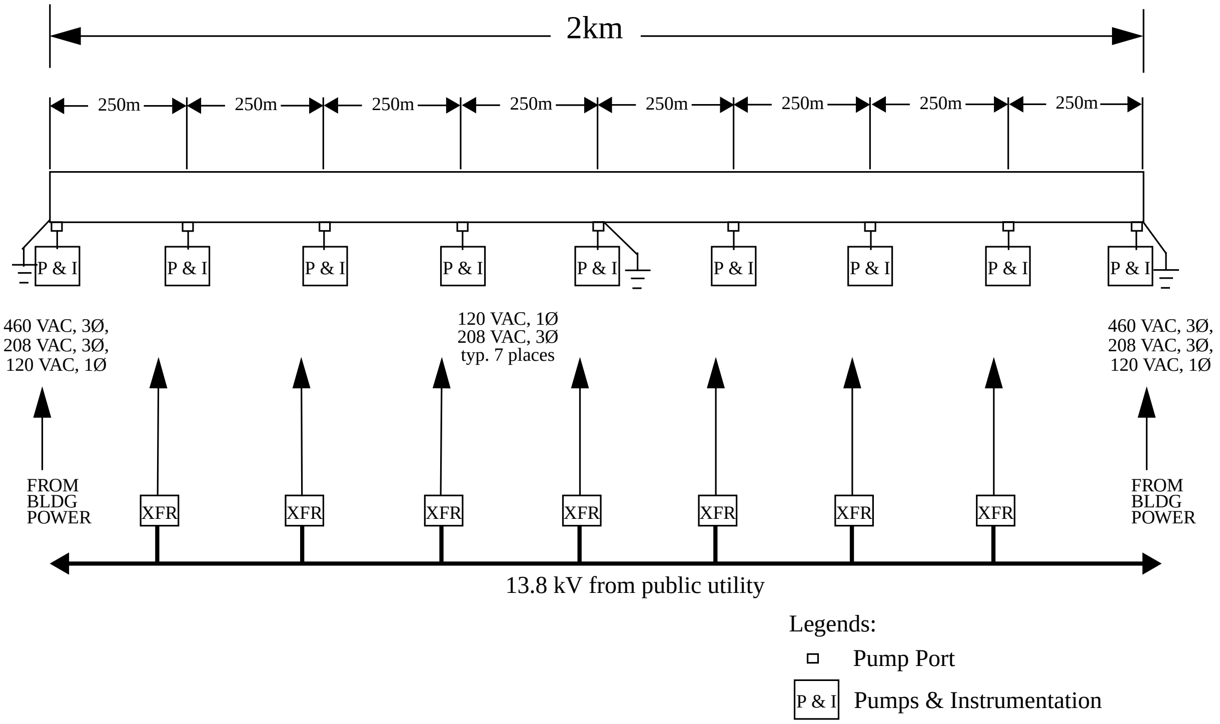


Figure 6: Power distribution for heater jackets, pumps and instrumentation

3.2.2. DC Power Supplies

Power for heating the beam tube will be provided by two 100V/5000A DC power supplies (Figures 5 and 7). The power supplies will be positioned at two locations along the beam tube module. The beam tube module is grounded at both ends and at the midpoint, and the supplies are connect to the tube midway between these grounded points. Copper return cables are connected at the grounded points to return the heating current to the power supplies. The DC power supplies will be operating nominally at 77 V and at 3500 A. Each DC power supply will be controlled using temperature feedback (see Figure 7).

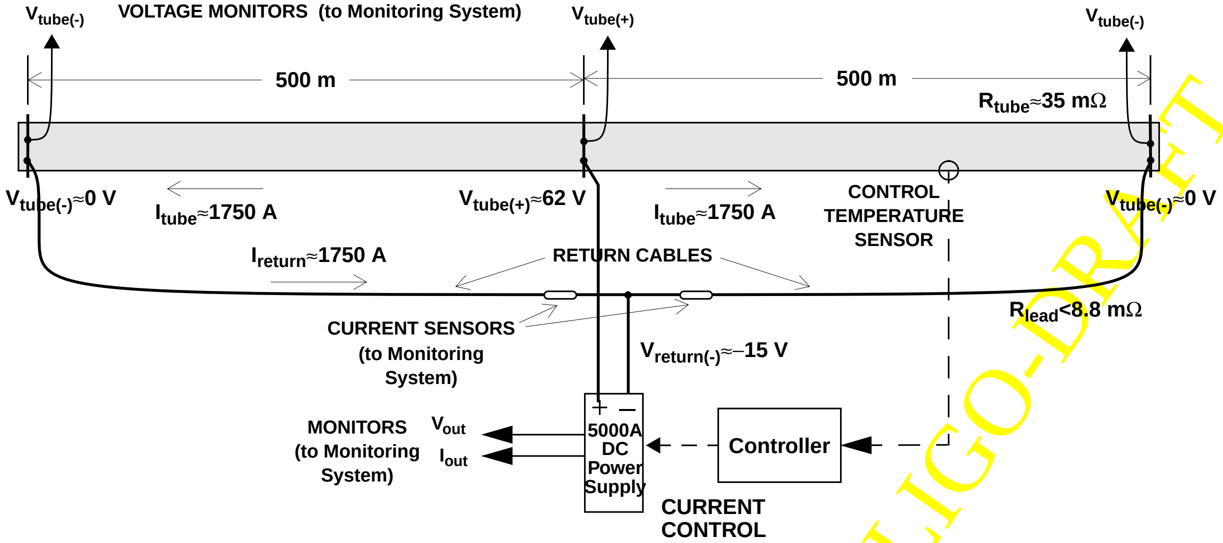


Figure 7: DC power supply control and connections to beam tube

The 5000 A DC power supplies to be used for the beam tube module heating will be Transrex 500 kW DC magnet power supplies. These power supplies have adequate output, current regulation and control characteristics, and will be operated at about half rated output power. They have already been burned in and will be borrowed from Fermi National Accelerator Laboratory (Fermilab) for the duration of the bakeout activities. These supplies will be housed in temporary, ventilated enclosures to provide weather protection and furnished with local, dedicated water-cooling equipment.

A model was developed to predict power supply currents required to maintain the beam tube at 150 °C under varying ambient conditions at the two sites. Results are summarized in Figure 8, which also shows the current predicted by the model for the beam tube qualification test (point labeled “TQTR”); actual current during the test averaged 2475 A.

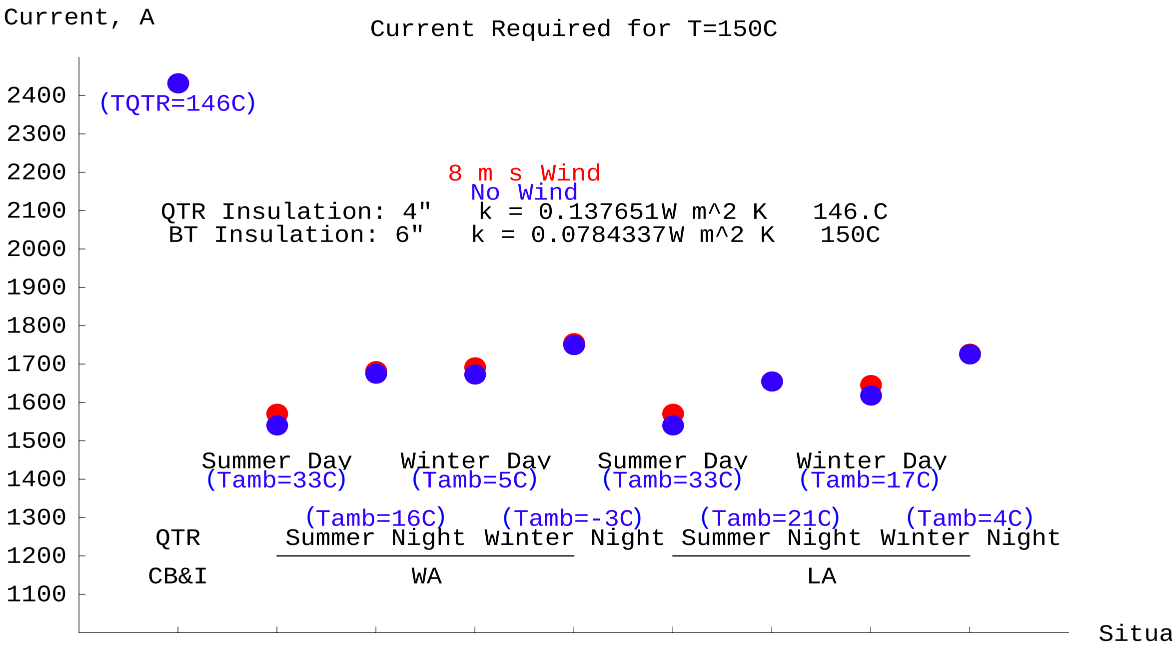


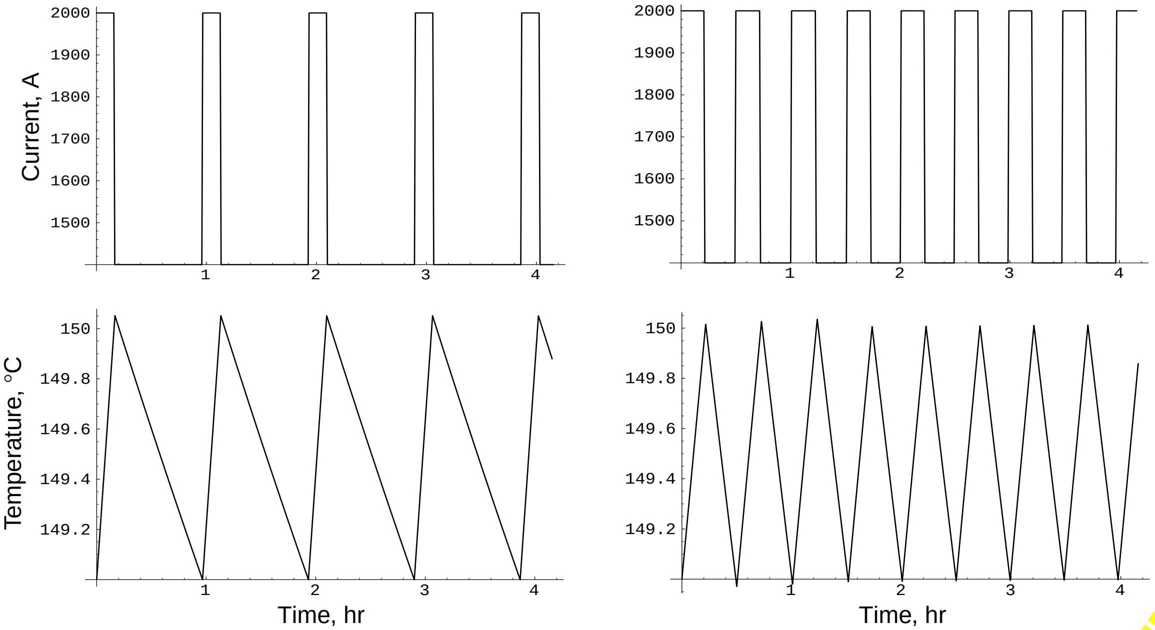
Figure 8: Current to maintain a bakeout temperature of 150 °C under varying ambient conditions; model includes ambient temperature, solar illumination and wind effects

3.2.3. Temperature Control of Tube Wall

The beam tube bakeout temperatures will be ramped up in 10 °C steps to a nominal bakeout temperature of 150 °C by manually setting the power supply currents. The monitoring system (Section 3.4) will permit determination of thermal gradients. During the bake, the temperature is controlled by switching the current output of the DC power supplies between two values set by the operator (the power supply currents are controlled by two I/O modules located at the power supply clusters, connected to the monitoring system I/O bus - see Section 3.4; the control function will be implemented in the monitoring system computer, a PC running a commercial data acquisition and control software program). Temperature feedback information from designated beam tube temperature sensors will be used to switch the currents independently in each pair of 500 m loops to maintain a temperature set by the operator. Figure 9 illustrates the beam tube temperature and power supply current vs. time for an example controller described in Table 1, calculated using the thermal model mentioned above.

Table 1: Example control algorithm

Condition		Controller response
Temperatures	**Current**	
$T_{tube}<T_{set}-{}^{1}/_{2}T_{deadband}$	don’t care	Set $I=I_{high}$
$T_{tube}<T_{set}+{}^{1}/_{2}T_{deadband}$	$I=I_{high}$	Set $I=I_{high}$ (no change)
$T_{tube}>T_{set}+{}^{1}/_{2}T_{deadband}$	don’t care	Set $I=I_{low}$
$T_{tube}>T_{set}-{}^{1}/_{2}T_{deadband}$	$I=I_{low}$	Set $I=I_{low}$ (no change)



a. Hanford site, summer days (no wind)

b. Hanford site, summer nights (no wind)

Figure 9: Controller example: behavior for Hanford site, summer days (a) and nights (b) with I_{high}=2000 A, I_{low}=1400 A, $T_{setpoint}$=149.5 °C, $T_{deadband}$=1 °C

3.2.4. Heating and Temperature Control of Ends/Ports

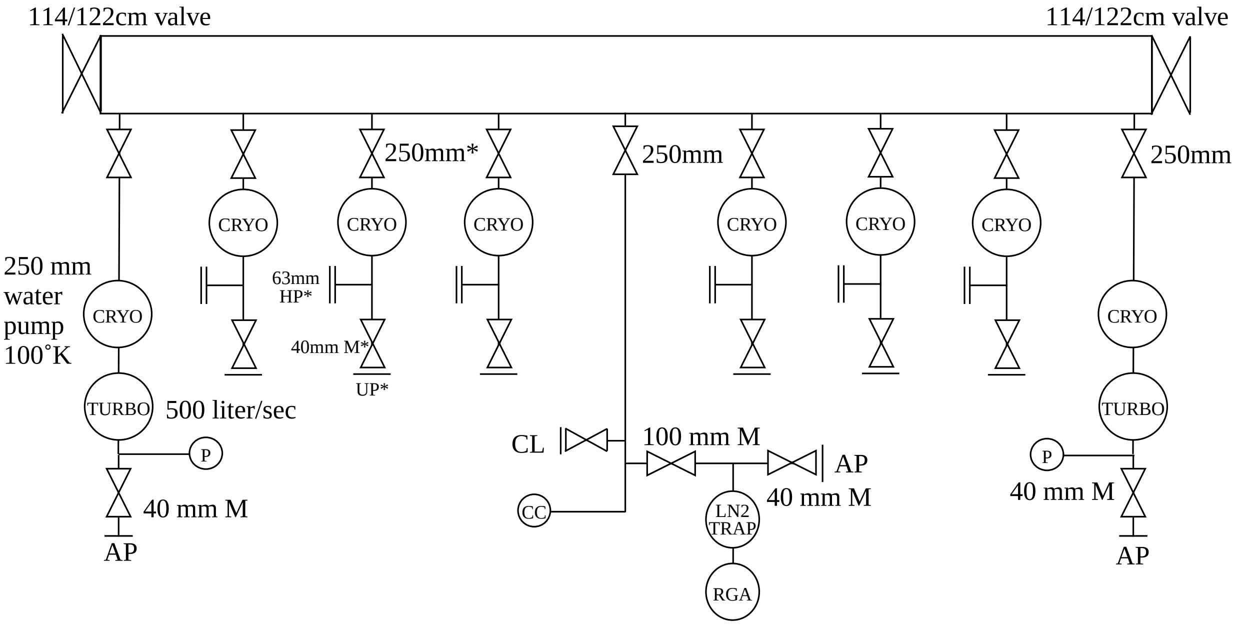
The gate valves at the ends of the module and the pump port hardware along the module will be heated to bake temperature with custom thermal heater jackets fit tightly over the gate valves, termination anchor supports and pump inlets. The jacketed elements will be maintained at the bake temperature with standalone, manually operated temperature controllers and dedicated temperature sensors, separate from the monitoring system. Power for the gate valve and pump port hardware bakeout heaters and controllers will be provided from the power distribution panels.

3.3. VACUUM PUMPS AND VACUUM INSTRUMENTATION

3.3.1. Vacuum Pumping and Monitoring During Bakeout

Pumping during bakeout will be provided by two 2000 liter/second (l/s) turbomolecular pump for pumping H_2, CO_2 and other non-condensable gases and eight 10 inch He cryo (refrigerating) pumps for pumping of H_2O and other condensable gases. The arrangement of shown schematically in Figure 10. The cryo pumps will be commercially available single stage refrigeration units, cooled by refrigeration compressors located near the pump ports. The pumping surface temperature is adjustable and will be set to 100 K. The cryo pumps will provide about 2,500 l/s pumping speed for H_2O at each port, which yields the same pump speed per unit of beam tube surface area as used during the earlier beam tube qualification test (QT). Power for the vacuum pump hardware will be provided from the power distribution panels.

Partial pressures will be monitored during the bakeout and cool down by a single RGA located at the module mid-point (see Figure 10). The RGA output will be displayed and recorded remotely at the location of the monitoring system display and operator's controls for the bake temperature. A cold cathode gauge to measure total pressure and Pirani gauges to measure turbo pump back-pressures will be connected to the monitoring system (Section 3.4).



LEGEND:

AP	Port for auxiliary turbo pump	M	Metal sealed valve
BP	250mm blank off plate	P	Pirani gauge
CC	Cold Cathode gauge	RP	Port for roughing
CL	Port for calibration leaks	UP	Port for utility purposes
HP	Port for RGA head installation	*	Type H Pump Port Hardware furnished by CBI

Figure 10: Schematic of vacuum pumps and RGA during bakeout

3.3.2. Vacuum Pumping and Measurement After Bakeout

Pumping during post-bake measurements will be provided by a single 2000 l/s turbo pump. After the beam tube module has cooled to ambient temperature, the 250 mm gate valves will be closed and the bakeout pumps will be removed. A separate, clean turbo pump will be installed, along with a clean, pre-baked, high-sensitivity RGA. The RGAs and gauges will have only local control and display. The equipment arrangement is shown in Figure 11. The expected partial pressures are shown in Table 2. A portable calibration module (Figure 12) will be used to verify RGA partial pressure measurements.

Table 2: Estimated Partial Pressures at 23 °C After Bakeout

	Mid-point Pressure (torr)
H_2	$< 7 \times 10^{-9}$
CO	$< 8 \times 10^{-11}$
CO_2	$< 3 \times 10^{-11}$
H_2O	$< 1.4 \times 10^{-12}$
Hydrocarbons	Σ 41,43,55,57 $< 1.8 \times 10^{-12}$

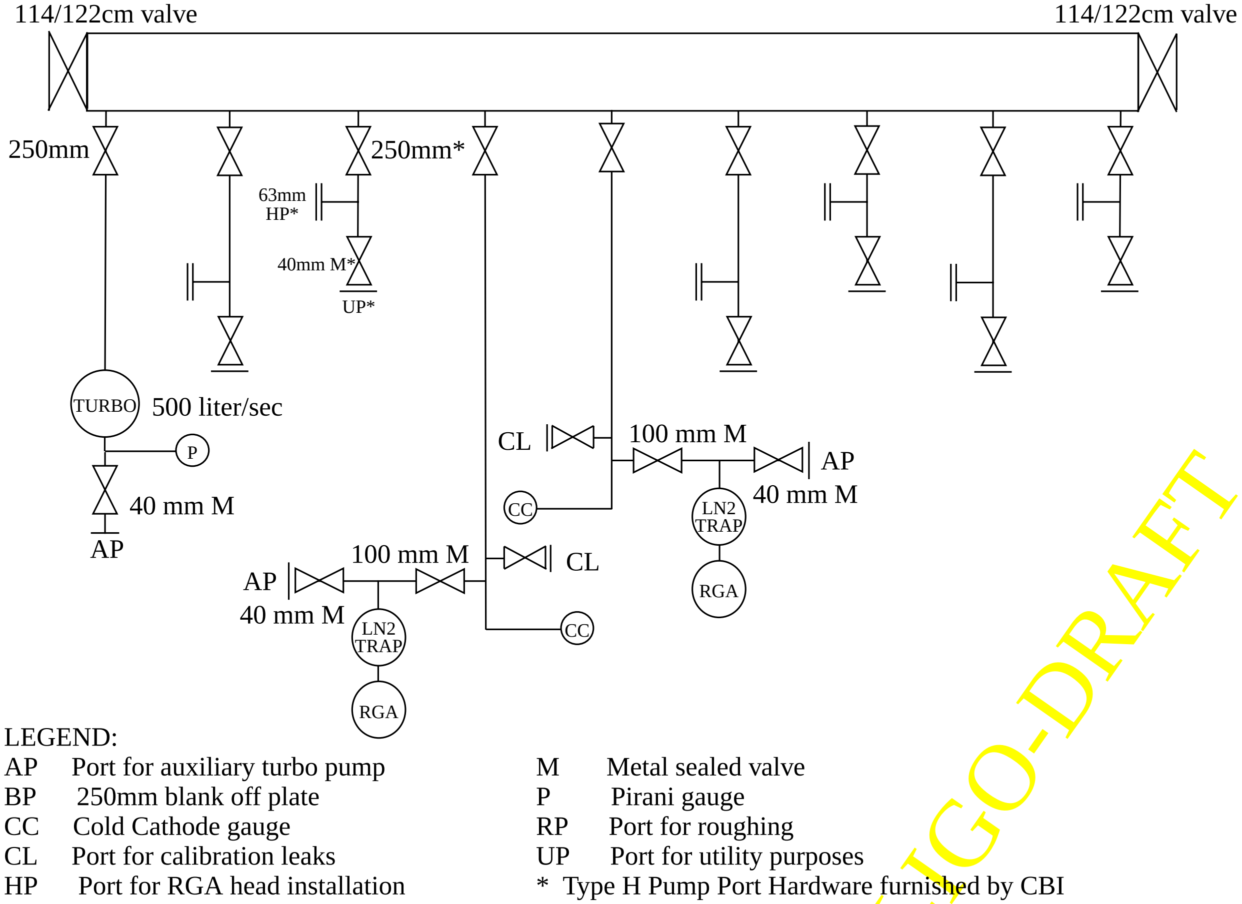


Figure 11: Post-bake test configuration

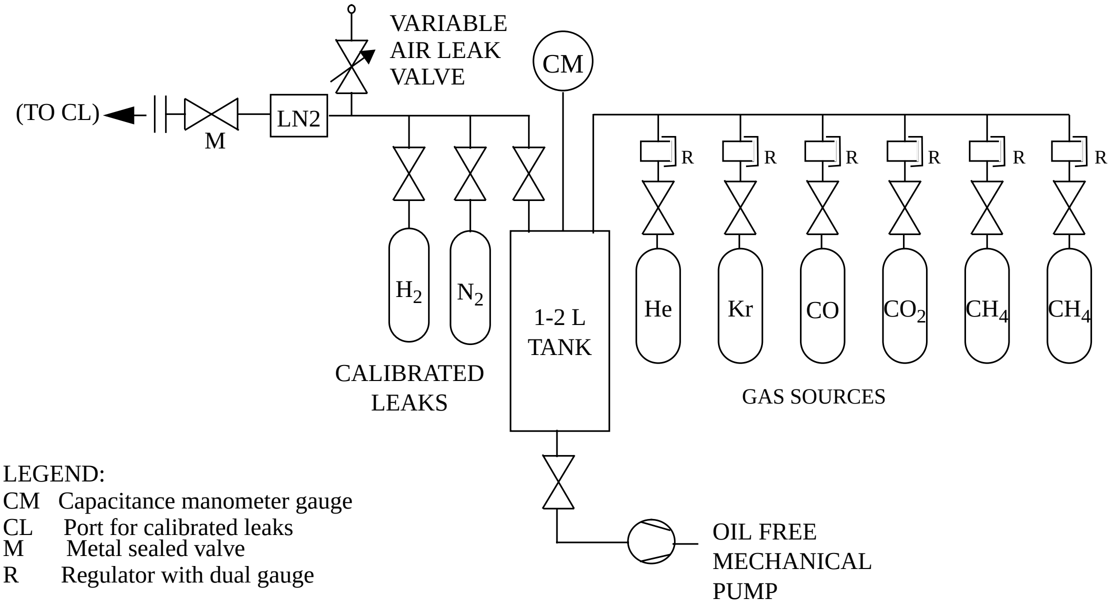


Figure 12: Portable Calibration Module

3.4. MONITORING SYSTEM

The monitoring system will consist of a standard PC computer running a commercial data acquisition and control software program. Commercially available I/O modules operating on a proprietary I/O bus with a range of 2,300 m (7,500 ft) will be distributed along the beam tube module to measure temperatures, power supply electrical parameters, pressures, and equipment status and provide analog outputs to control the DC power supplies. The layout is shown schematically in Figure 13.

Table 3 provides a sample list of measurement channels. Temperature measurements will be taken at representative locations, mostly concentrated around the tube ends and near pump ports, to ensure that the temperature behavior of the entire beam tube module is understood. Selected temperature channels will be used for temperature control as described in Sec. 3.2.3. Other measurements include strain at fixed supports,

From the computer operator interface terminal, the operator will be able to access, record and alarm all DC current and voltage data and all temperature data. A complete sample of all data (< 256 channels) will take about 1 Kbyte, so if samples are logged once per minute, a 30 day bakeout will need about 50 Mbyte, which can easily fit onto the PC's hard disk drive. An ethernet connection to the corner station's networking facilities will allow the data to be downloaded over the Internet for permanent archiving and remote analysis.

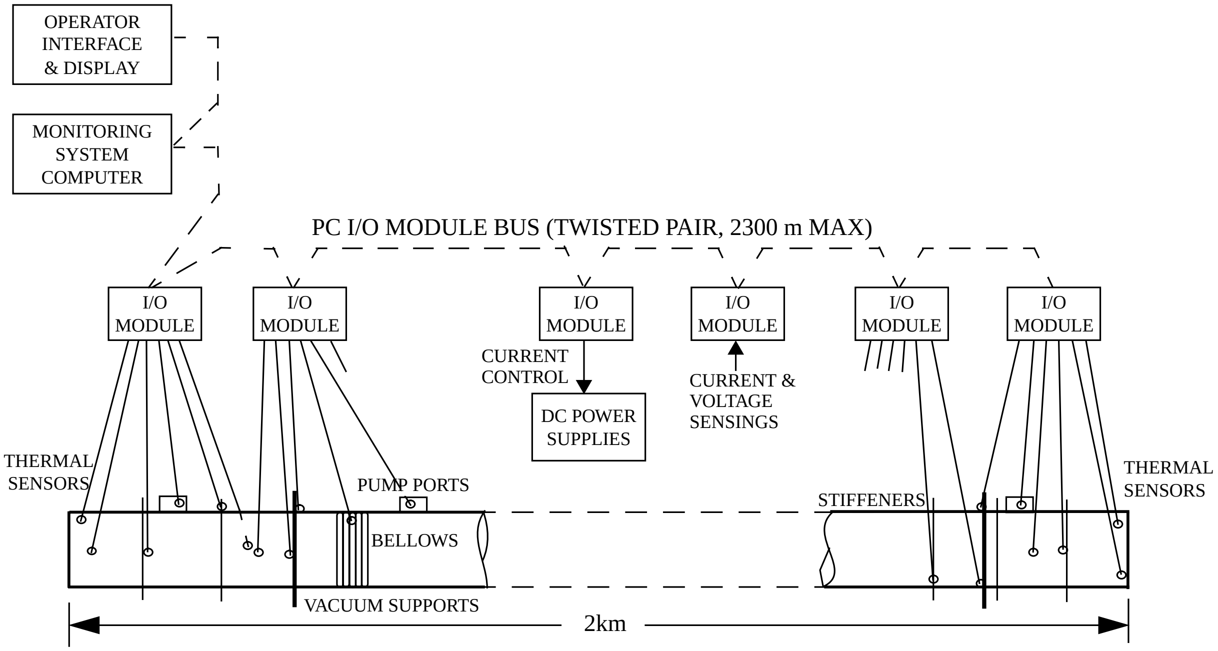


Figure 13: Monitoring system layout

Table 3: Monitoring System Channels

Signal Name	Measurement location		Description	
	Station (m)	Clock angle (hr)		
Temperatures:				
T1-T60			Temperatures at near end of beam tube, at gate valve, pump port, anchor, fixed supports, bellows and guided supports, and tube wall in representative locations along the first 60 m of beam tube	
T61-T102			Six representative temperatures at each pump port location (7 places)	
T103-T120			Temperatures at far end of beam tube, at gate valve, pump port, anchor and representative tube wall locations	
T121			Ambient air temperature (outside)	
T122-T126			Ambient air temperatures inside enclosure	
Bakeout power supply electrical:				
V1-V5			Voltages on tube at power supply connection points	
V6-V9			Voltages at + and - outputs of power supplies	

Table 3: Monitoring System Channels

V10-V11			Power supply voltage monitor outputs	
I1-I4			Currents in power supply return cable legs	
I5-I6			Power supply current monitor outputs	
Vacuum gauges:				
P1-P3			Pressures at cold cathode, Pirani and capacitance manometer (Calibration Module) gauges	
RGA1			RGA analog output	
Miscellaneous channels and status indicators:				
F1-F4			Strain gage information at fixed support N	
F5-F8			Strain gage information at fixed support M	
CR1-CR9			ON/OFF status of cryo pumps	
WP1-WP4			Water pressure and flow for power supply cooling	
CT1-CT9			Cryopump cold plate temperatures	
TP1-TP2			Status of turbo pumps	
LN1			Status of LN_2 trap at RGA	
W1			Digital output from weather station (wind speed, temperature, humidity)	
ETC1			Etc.	
Output channels:				
PS1-PS2			Set output currents of the 2 DC power supplies for heating	

APPENDIX A

INFORMATION FOR THE BAKEOUT DESIGN

The follow is a collection of relevant data and constants collected by R. Weiss and forwarded to me in August 1996. With Rai’s permission, I’m including it here so that the information is conveniently accessible to others.

- **CONTENTS**

1) Outgassing gas load during bake based on CB&I Qualification Test
2) Pressure during bake with end pumping only
3) Waterbake model curves for water outgassing rate, pressure, water loading on traps
4) Beam Tube Physical, Mechanical and Thermal Parameters
5) Model results for heating power and enclosure temperature as a function of insulation thickness

1) GAS LOADS DURING BAKE

ESTIMATES BASED ON CB&I QUALIFICATION TEST

Parameter values used for estimate:

T_{bake} = 150C = 423K maximum bake temperature, + - 10 K

L = 2km = 2 x 10^5 cm module length

V = 2.4 x 10^6 liters volume of module

A = 7.8 x 10^7 cm^2 surface area of module

Water outgassing parameters for waterbake model

T_0 = 9000 K binding temperature

R = 0.7 readsorption parameter

σ = 45 monolayers at t = 0

these parameters are consistent with a 296K water outgassing rate measured

$$J_{water}(296K) = \frac{1.2\times10^{-8}}{t(\text{hrs})} \quad \text{torr liters/sec cm}^2$$

Condensible gases

Table 4: Outgassing rate at 150C in torr liters/sec cm^2 measured in CB&I QT

molecule	beginning of bake	end of bake
	torr liters/sec cm2	torr liters/sec cm2
H_2	8.3 x 10^{-11}	8.3 x 10^{-11}
CH_4		
CO	4.6 x 10^{-12}	9.3 x 10^{-13}
CO_2	1.0 x 10^{-11}	2.6 x 10^{-12}

Methane data needs to be pulled out of the data files. Methane outgassing is comparable to CO

2) PRESSURE IN BEAM TUBE DURING BAKE WITH END PUMPING ONLY FOR NON CONDENSIBLE GASES

Parabolic profile with only end pumping

$$P(x) = J\left(\frac{\pi L a}{F} + \frac{L^2}{v a^2}\left(\frac{3}{8} - \frac{3}{2}x^2\right)\right).$$

$$0 \le x \le 0.5$$

x = normalized distance from the middle of the module = 0.5 at pumps

P(x) = pressure in torr

J = outgassing rate in torr cc/sec cm^2

L = module length in cm

a = radius of tube = 62 cm

v = molecular speed at temperature = 4.22 x 10^4 $\sqrt{\frac{28}{\text{amu}}}\sqrt{\frac{T}{296K}}$ cm/sec

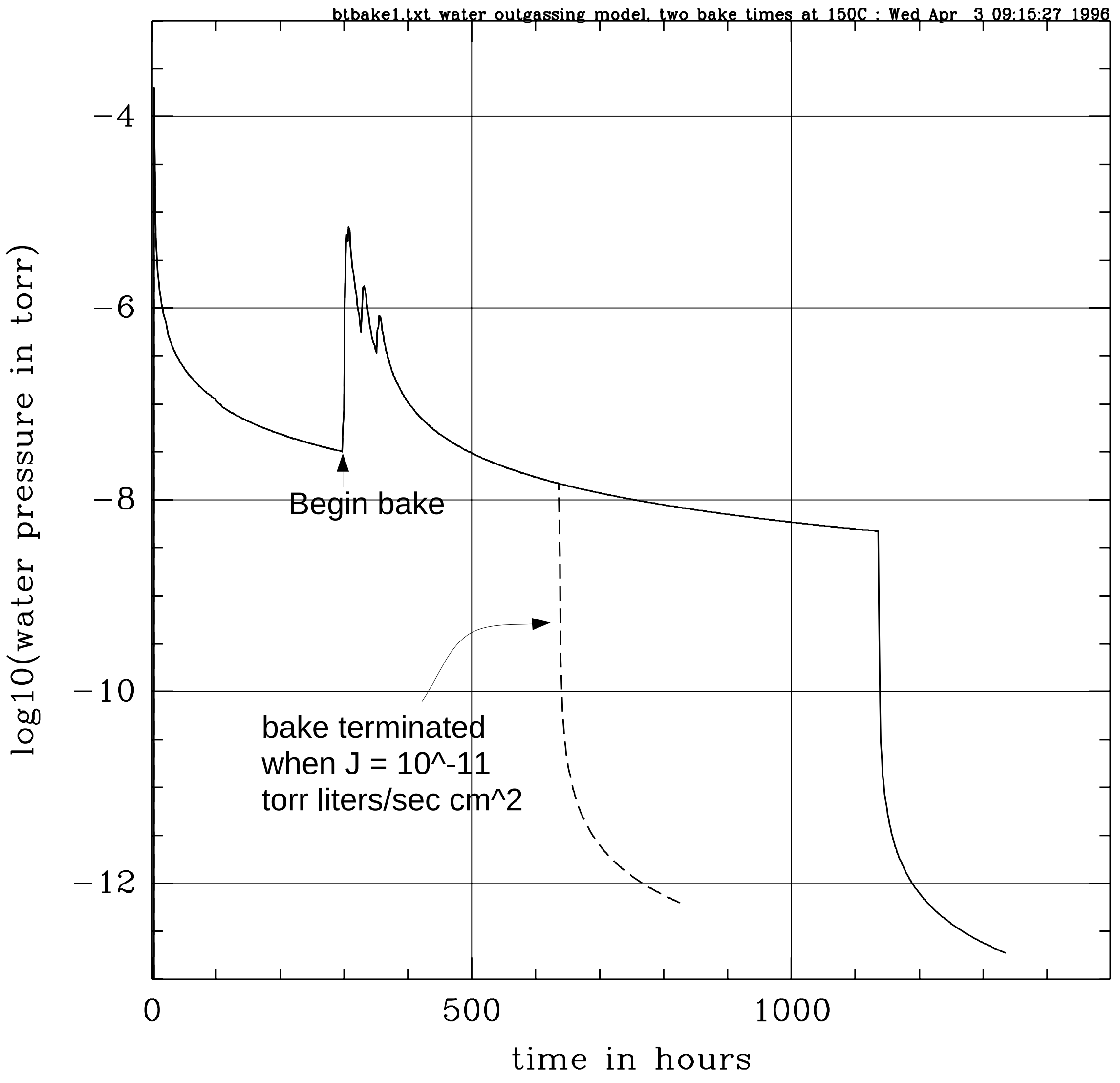
F = end pumping speed in cc/ sec

Table 5: Pressure for various pumping speeds at ends

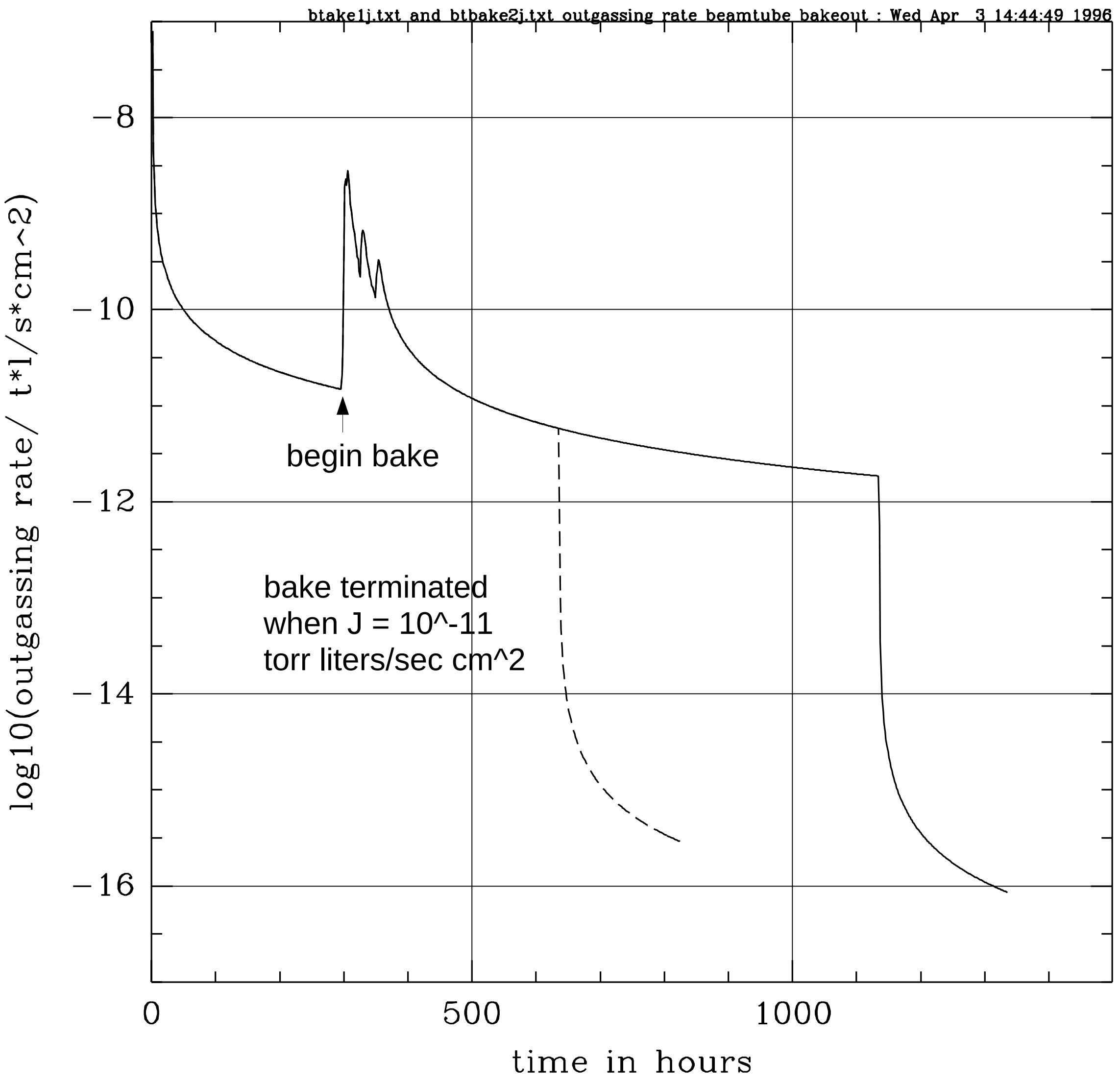
molecule	pumping speed at end	P(end)	P(midpt)
	liters/sec	torr	torr
H_2	300	1.1 x 10^{-5}	1.3 x 10^{-5}
	1000	3.3 x 10^{-6}	5.1 x 10^{-6}
CH_4	300		
	1000		
CO	300	6 x 10^{-7}	1.0 x 10^{-6}
	1000	1.8 x 10^{-7}	5.4 x 10^{-7}
CO_2	traps	10^{-7}	10^{-7}
	traps	10^{-7}	10^{-7}

Methane will have lower pressure than CO

3) WATERBAKE MODEL CURVES FOR WATER OUTGASSING AT 150C



waterbake.f model for beamtube bake at 150C. Liquid Nitrogen traps at the 10 inch ports every 250 meters., F = 2500 liters/sec/port
Model parameters: T0 = 9000K, R = 0.7, σ = 45 monolayers at t = 0



waterbake.f model for beamtube bake at 150C.
Model parameters: T0 = 9000K, R = 0.7, σ = 45 monolayers at t=0

The outgassing rate is almost independent of the pumping speed at 150C since the readsorption is not important at the bake temperature. It becomes a major factor on cooling and the resulting ultimate water pressure.

Water accumulation on traps

Total water removed from surface per module during evacuation = 105 cc

Water removed during bake :

surface loading goes from 5 to 1 monolayers

water removed = 9.3 cc

surface load on single trap (9 traps, 1000 cm^2 /trap) = 10μ

Note: A trade off here on the trap consumption and surface loading. Trap emissivity grows above 0.1micron surface loading. May want to make a special design to move water to a holding surface within the trap after warm up to avoid additional pumps or use cryo pumps as suggested by Sibley

4) Beam Tube Physical Parameters

Y = Young's modulus = 1.9×10^{12} dynes/cm^2 = 2.8×10^4 kpsi

S = yield stress = 3.4×10^9 dynes/cm^2 = 5×10^1 kpsi

ρ = density = 8 gm/cm^3

k_{ss} = thermal conductivity = 1.6×10^{-1} watts/cm K

c_{ss} = heat capacity = 4.8×10^{-1} joules/gm K

ε_{ss} = far - infrared emissivity when oxidized = 2.6×10^{-1}

α_{solar} = solar absobtivity oxidized = 8×10^{-1}

α_{ss} = thermal expansion coefficient = $1.6 \times 10^{-5} + 1.6 \times 10^{-8}(T - 300K)$ 1/K

ρ_{ss} = electrical resistivity = $7.52 \times 10^{-5} + 8.65 \times 10^{-8} (T - 300K)$ ohm cm (Lab meas.)

$= 8.07 \times 10^{-5} + 6.07 \times 10^{-8} (T - 300K)$ (QT meas.)

Beam Tube Mechanical Parameters

w = wall thickness = 3.23×10^{-1} cm

a = inside radius = 62 cm

l_1 = long section length = 1.981×10^3 cm

l_2 = short section length = 1.90×10^3 cm

s = stiffening ring spacing = 7.6×10^1 cm

t = stiffening ring width = 4.76×10^{-1} cm

h = stiffening ring height = 4.45 cm

Expansion joints

w_b = wall thickness = 2.67×10^{-1} cm

l_b = total length for 9 convolutions = 7.37×10^{1} cm

k_{ax} = axial spring rate = 1.5×10^{9} dynes/cm = 8.24×10^{3} lbs/in

k_{trans} = transverse spring rate = 1.75×10^{10} dynes/cm = 1.0×10^{5} lbs/in

Insulation properties (Knauf duct wrap**)**

k_{ins} = thermal conductivity = $4.0 \times 10^{-4} + 3.1 \times 10^{-6}$ (T - 300K) watt/cm K

ρ_{ins} = density 1.6×10^{-2} = gm/cm^3

c_{ins} = heat capacity = 7.0×10^{-1} joules/gm K

Air

ρ_{air} = density = $1.25 \times 10^{-3} \left(\frac{300}{T}\right)$ gm/cm^3

η_{air} = viscosity = $1.8 \times 10^{-4} \sqrt{\frac{T}{300}}$ gm/cm sec

k_{air} = thermal conductivity = $2.2 \times 10^{-4} \sqrt{\frac{T}{300}}$ watts/cm K

c_{air} = heat capacity at constant pressure = 1.1 joules/gm K

P_{air} = Prandtl number = $\frac{\eta c}{k}$ = 1.1

G_{air} = Grashof number = $\frac{g \Delta T \rho^2 l^3}{T \eta^2}$ where l = typical convection cell dimension

k_{conv} = effective convective conductivity = 0.11 k_{air} $(GP)^{0.29}$

k_{wind} = thermal conductivity due to wind u = $\sqrt{\rho_{air} k_{air} r c_{air} u}$ watts/cm K

Concrete

ρ_{conc} = density = 2.2 gm/cm^3

k_{conc} = thermal conductivity = 1.8 x 10^{-2} watts/cm K

c_{conc} = heat capacity = 8 x 10^{-1} joules/gm K

ε_{conc} = total emissivity = 9 x 10^{-1}

r_c = enclosure (nominal) inner radius = 2.4 x 10^2 cm

w_c = enclosure wall thickness = 15 cm

Paints Zinc or Titanium Oxide

α_{solar} = solar absorbtivity = 2.5 x 10^{-1}

ε_{ir} = far-infrared emissivity = 8.5 x 10^{-1}

Environment

J_{sun} = peak solar intensity at ground in June (WA, LA) = 1.2 x 10^{-1} watts/cm^2

u_{wind} = mean surface wind speed in June (WA) = 2 x 10^2 cm/sec

u_{wind} = mean surface wind speed in June (LA) = 1 x 10^2 cm/sec

T_{air} = mean air temperature in June (WA) = 21 C

T_{air} = mean air temperature in June (LA) = 26.6 C

5) MODEL RESULTS FOR HEATING POWER AND ENCLOSURE TEMPERATURE AS A FUNCTION OF INSULATION THICKNESS

Elements of model

Assume cylindrical coaxial geometry with four temperatures

Tt = 423K at Rt = 62 cm : the temperature and radius of the tube

T1 = ? at R1 = Rt + th :temp. and radius at the surface of the insulation of thickness th

Te = ? at Re = 240 cm : temp. and radius at the inner surface of the concrete cover

T0 = 300K at R0 = 255 cm : ambient temperature outside the concrete cover

Thermal transport

$Rt \le R \le R1$ conduction and radiation through insulation

$R1 \le R \le Re$ convection

$Re \le R \le R0$ conduction through concrete

```
 tube temp =    4.230E+02  outside temp =    3.000E+02   tube resistance (ohms) =1.402E-01
insul. thickness        power          volts            current      T outside insul      T inside cover
        cm                  W              V                  A                 K                   K
t =  5.00E+00 p =  8.96E+05 v =  3.54E+02 a =  2.53E+03 T1 =  3.39E+02 Te =  3.02E+02
t =  7.50E+00 p =  6.92E+05 v =  3.11E+02 a =  2.22E+03 T1 =  3.31E+02 Te =  3.02E+02
t =  1.00E+01 p =  5.70E+05 v =  2.83E+02 a =  2.02E+03 T1 =  3.26E+02 Te =  3.01E+02
t =  1.25E+01 p =  4.87E+05 v =  2.61E+02 a =  1.86E+03 T1 =  3.23E+02 Te =  3.01E+02
t =  1.50E+01 p =  4.28E+05 v =  2.45E+02 a =  1.75E+03 T1 =  3.20E+02 Te =  3.01E+02
t =  1.75E+01 p =  3.84E+05 v =  2.32E+02 a =  1.65E+03 T1 =  3.18E+02 Te =  3.01E+02
t =  2.00E+01 p =  3.48E+05 v =  2.21E+02 a =  1.58E+03 T1 =  3.17E+02 Te =  3.01E+02
t =  2.25E+01 p =  3.20E+05 v =  2.12E+02 a =  1.51E+03 T1 =  3.16E+02 Te =  3.01E+02
t =  2.50E+01 p =  2.97E+05 v =  2.04E+02 a =  1.46E+03 T1 =  3.14E+02 Te =  3.01E+02
t =  2.75E+01 p =  2.77E+05 v =  1.97E+02 a =  1.41E+03 T1 =  3.13E+02 Te =  3.01E+02
t =  3.00E+01 p =  2.61E+05 v =  1.91E+02 a =  1.36E+03 T1 =  3.13E+02 Te =  3.01E+02
t =  3.25E+01 p =  2.46E+05 v =  1.86E+02 a =  1.33E+03 T1 =  3.12E+02 Te =  3.01E+02
t =  3.50E+01 p =  2.34E+05 v =  1.81E+02 a =  1.29E+03 T1 =  3.11E+02 Te =  3.01E+02
t =  3.75E+01 p =  2.23E+05 v =  1.77E+02 a =  1.26E+03 T1 =  3.11E+02 Te =  3.01E+02
t =  4.00E+01 p =  2.13E+05 v =  1.73E+02 a =  1.23E+03 T1 =  3.10E+02 Te =  3.01E+02
```

From FORTRAN program ~weiss/cbi/bake/baketemp.f