Magnet and RF Cavity Test Stand Design

Tom Peterson, SLAC

USPAS

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Outline

- Test dewars and test stands
  - Saturated bath test dewars
  - Double bath test dewars
  - SRF test cryostats
  - SRF cryomodule test stands
  - Horizontal magnet test stands
- Procurement and assembly

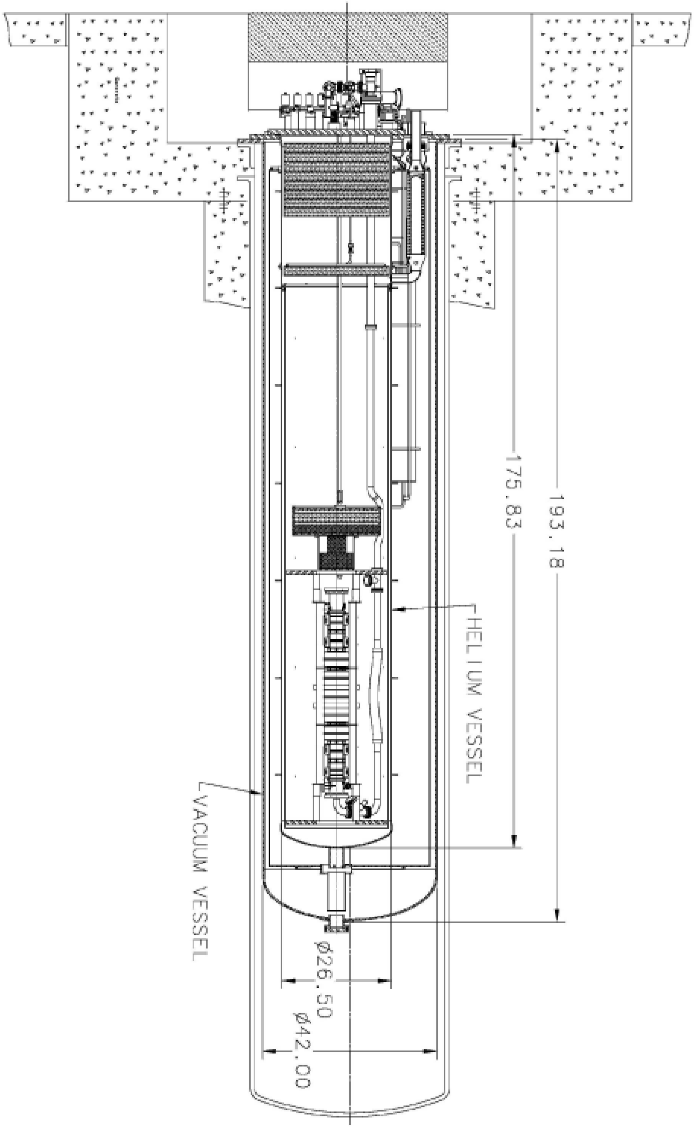
Saturated bath vs. subcooled

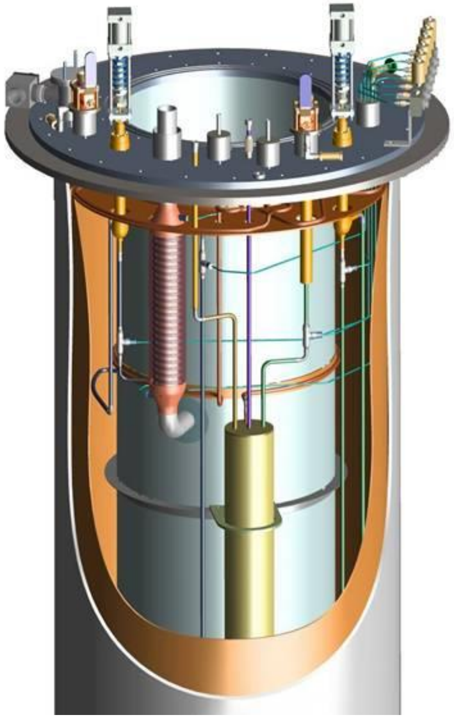
- Accelerator magnets are often cooled with subcooled liquid
  - Typically working near the limit of the superconductor with large stored energy
  - Ensure complete liquid coverage and penetration
- Superconducting RF cavities are generally cooled with a saturated bath
  - Large surface heat transfer in pool boiling for local "hot spots"
  - Very stable pressures, avoid impact pressure variation on cavity tune

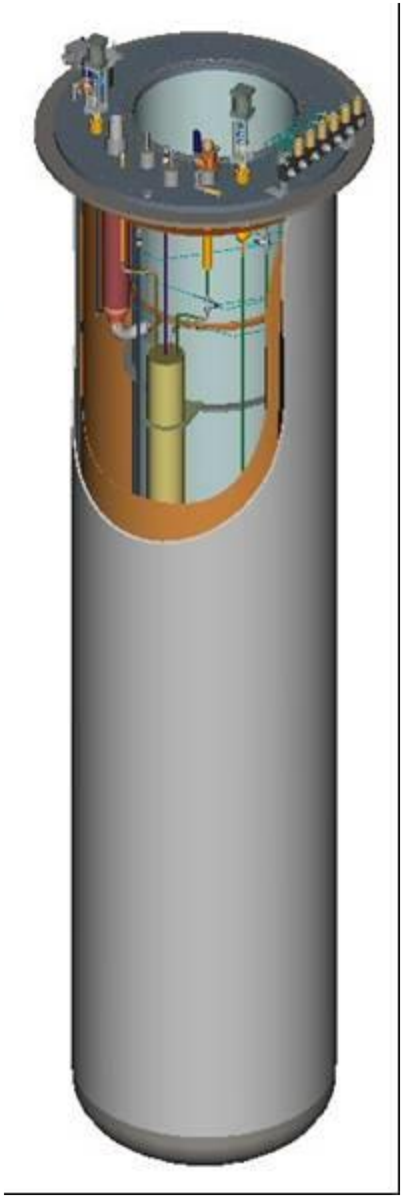
Saturated bath dewar

- Simple, in principle
  - Essentially a “bucket” of liquid helium
- Entirely at saturation pressure
- Very stable pressure and temperature
- Low heat load due to simple “hanging” construction of inner vessel

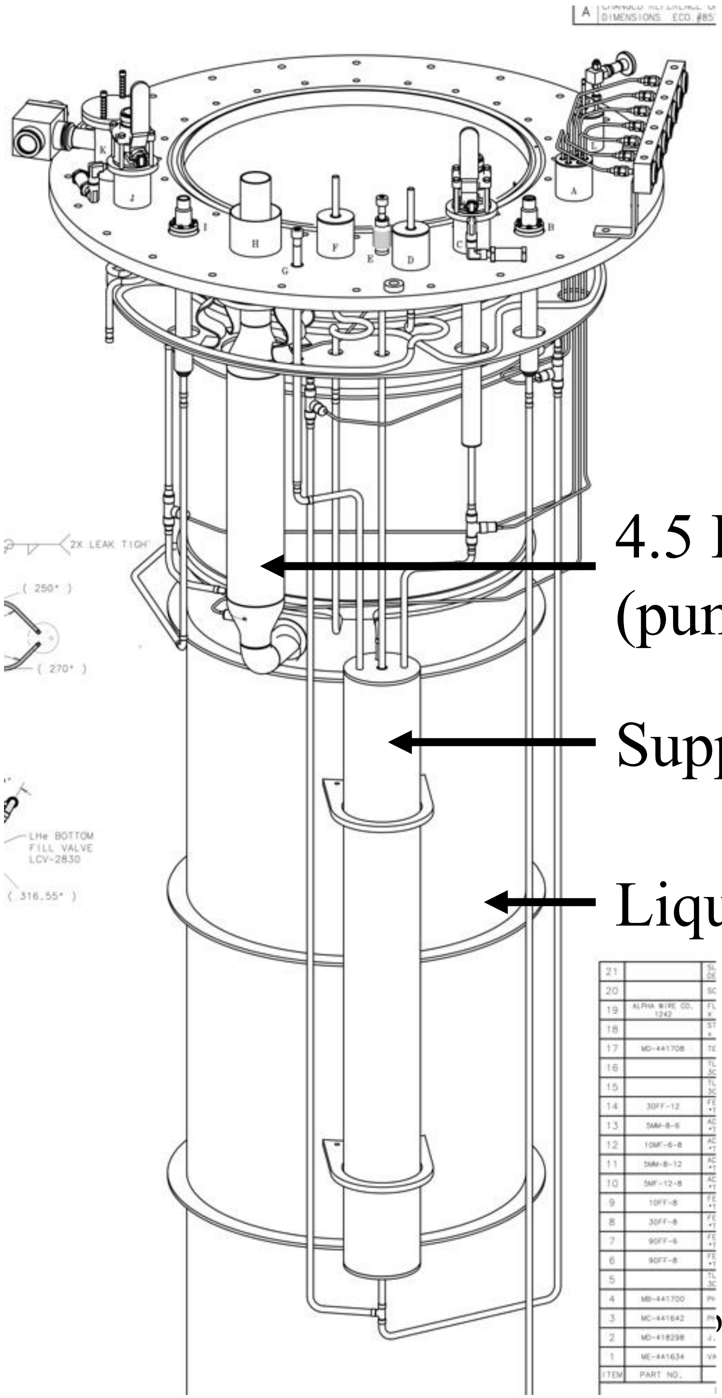
Saturated bath dewar







Saturated bath RF cavity test dewar

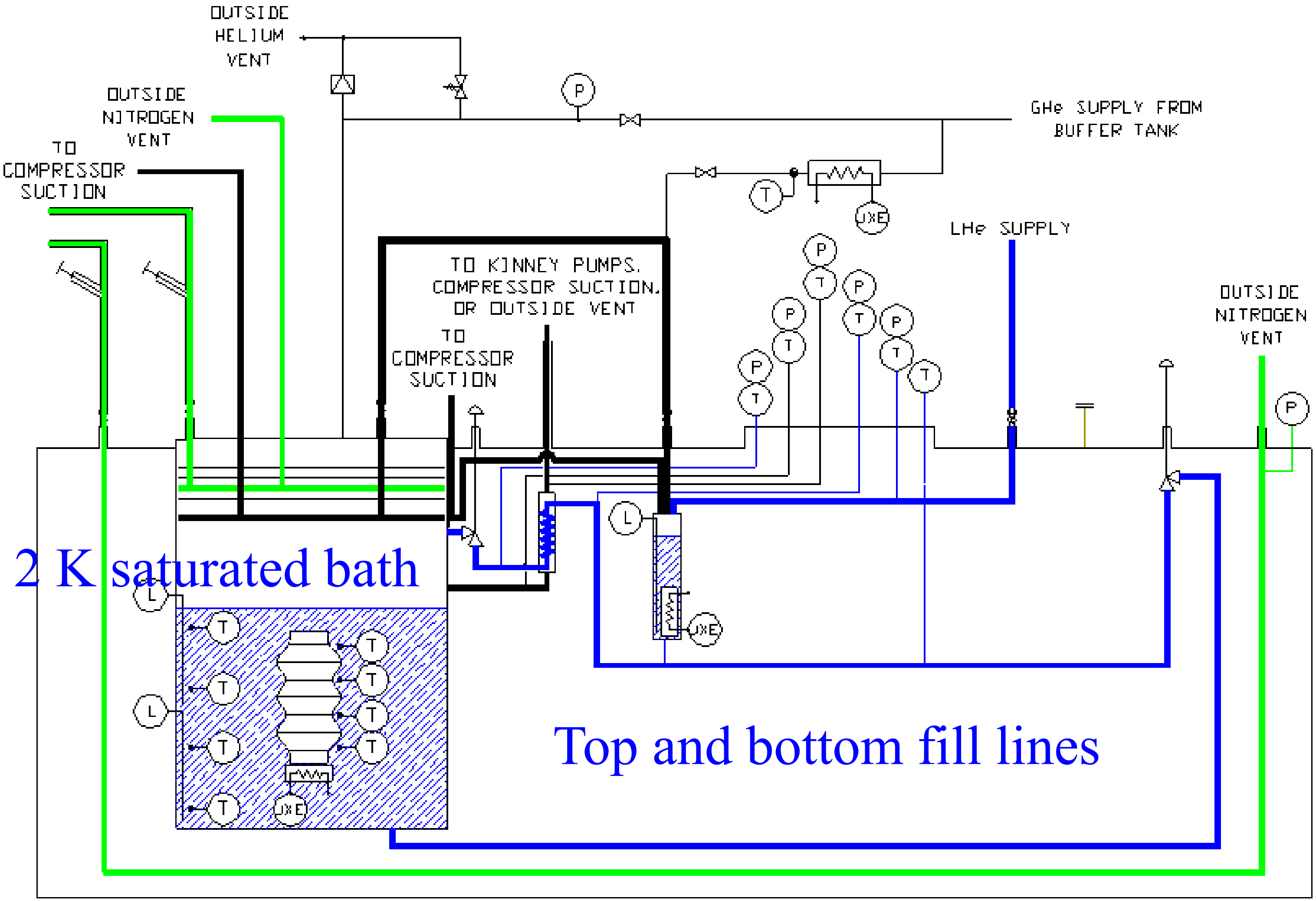


4.5 K to 2 K heat exchanger
(pumped flow precooling supply)

Supply helium phase separator

Liquid helium space with RF cavity

Saturated bath dewar schematic



2 K saturated bath

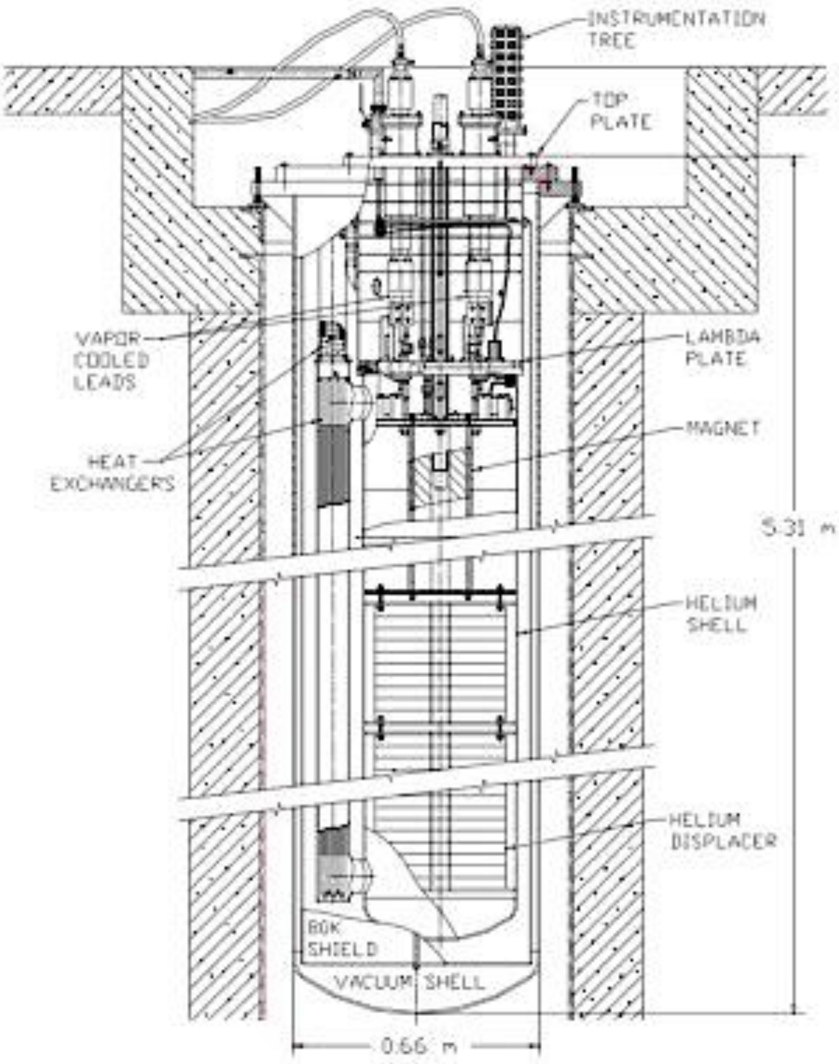
Top and bottom fill lines

Saturated bath dewar issues

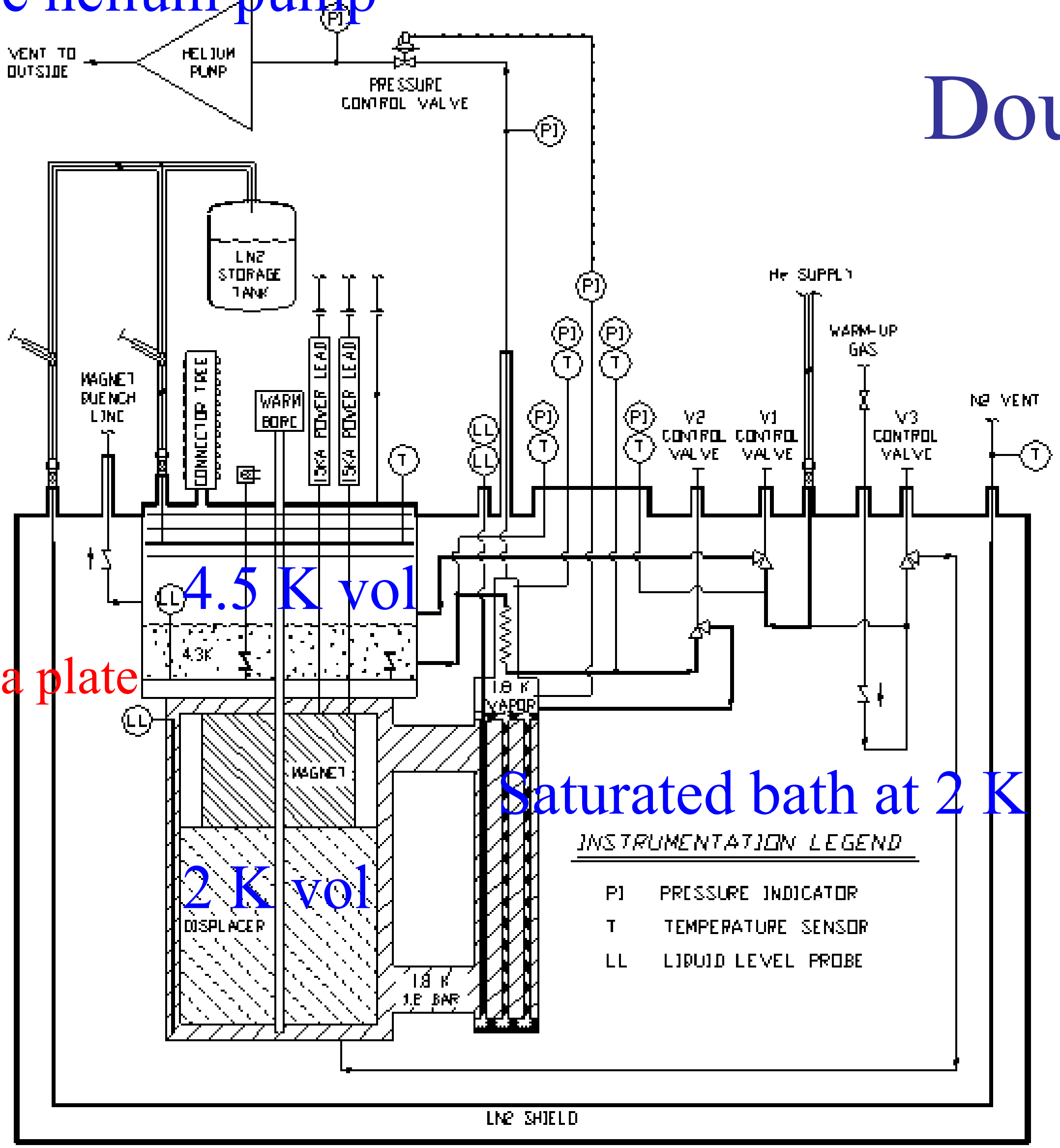
- Subatmospheric if less than 4.2 K
  - Many potential air inleaks if < 4.2 K
  - Air inleak may appear as operational problem without a clear cause
    - For example, low pump-down or cool-down rate
- Large volume of liquid presents venting problem with loss of insulating vacuum to air
  - As much as 4 W/sq.cm. heat deposition on bare surface
  - Venting may be a design challenge for a low pressure vessel (large pipes, etc.)
  - We use MLI even under a thermal shield in order to reduce venting flow rate with loss of vacuum

Double-bath dewar

- 4.4 K liquid above 1.2 bar, 2 K liquid
- So 2 K liquid is subcooled, single phase liquid
- 4.4 K above is saturated
- Separated by a "lambda plate"
- Also low heat load



Double-bath flow schematic


Large helium pump

4.5 K vol

Lambda plate

Saturated bath at 2 K

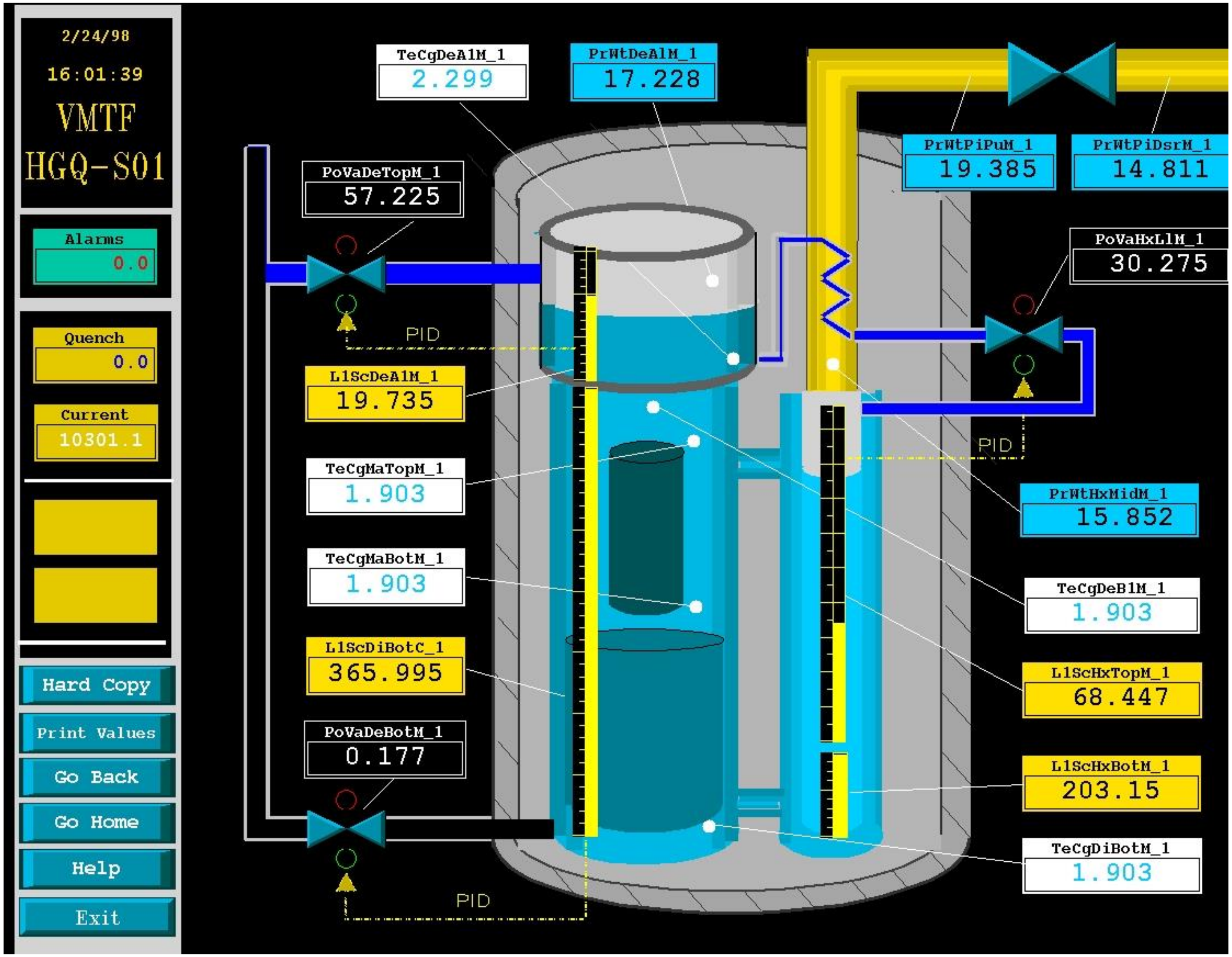
2 K vol

- Large, vertically oriented heat exchanger between saturated bath and pressurized helium permits operation with normal, subcooled helium as well as superfluid

Double-bath dewar

- Mostly positive pressure
  - Provides subcooled liquid
- Seal between 4.3 K and sub-lambda regions is a heat transfer barrier
  - Need not be hermetically tight
  - Key feature is to provide long, thin path for heat transport, so leaks should be long
  - Flat seal rather than "knife-edge"

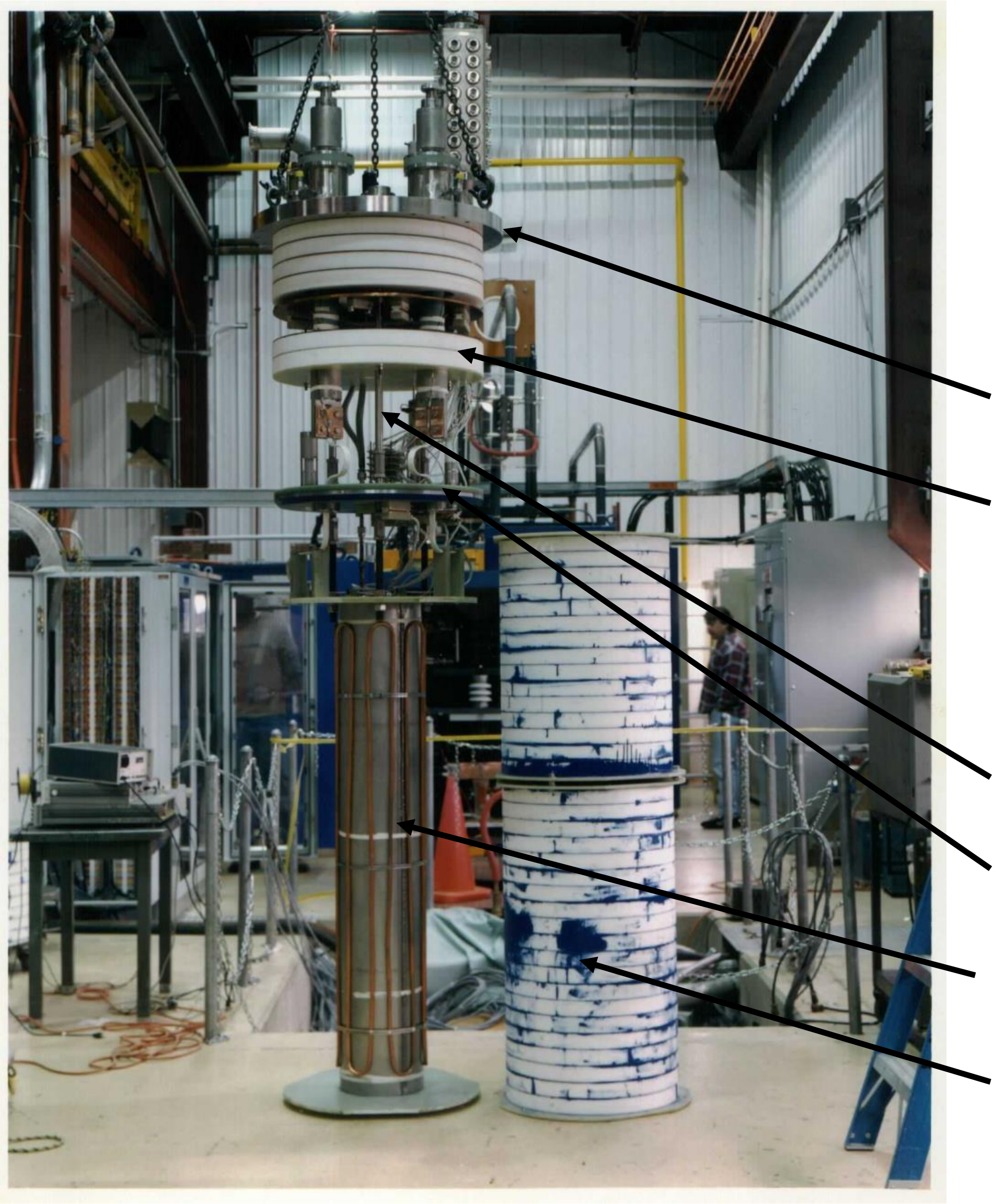
Double-bath control screen


2/24/98
16:01:39
VMTF
HGQ-S01

Alarms 0.0
Quench 0.0
Current 10301.1

TeCgDeAlM_1 2.299
PrWtDeAlM_1 17.228
PoVaDeTopM_1 57.225
PrWtPiPuM_1 19.385
PrWtPiDsrM_1 14.811
PoVaHxLlM_1 30.275
L1ScDeAlM_1 19.735
TeCgMaTopM_1 1.903
TeCgMaBotM_1 1.903
L1ScDiBotC_1 365.995
PoVaDeBotM_1 0.177
PrWtHxMidM_1 15.852
TeCgDeB1M_1 1.903
L1ScHxTopM_1 68.447
L1ScHxBotM_1 203.15
TeCgDiBotM_1 1.903

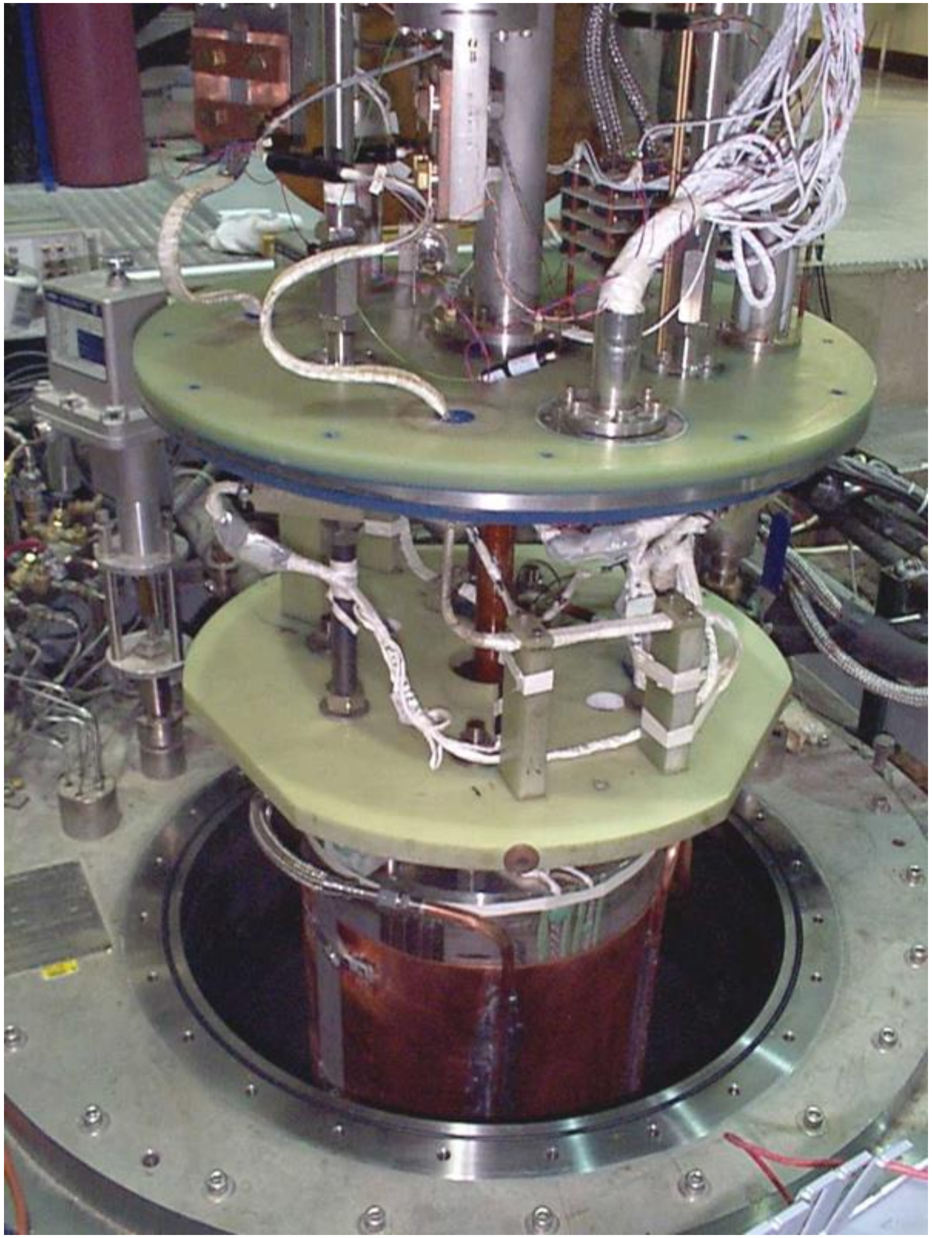
Double-bath insert assembly



- Top plate
- Closed-foam (Rohacel) insulation
- 4.4 K vapor space
- Lambda plate
- Magnet
- Displacer

Lambda plate assembly

- Lambda plate and seal (blue)
- Intermediate support plate
- Copper clad magnet (for cooldown)

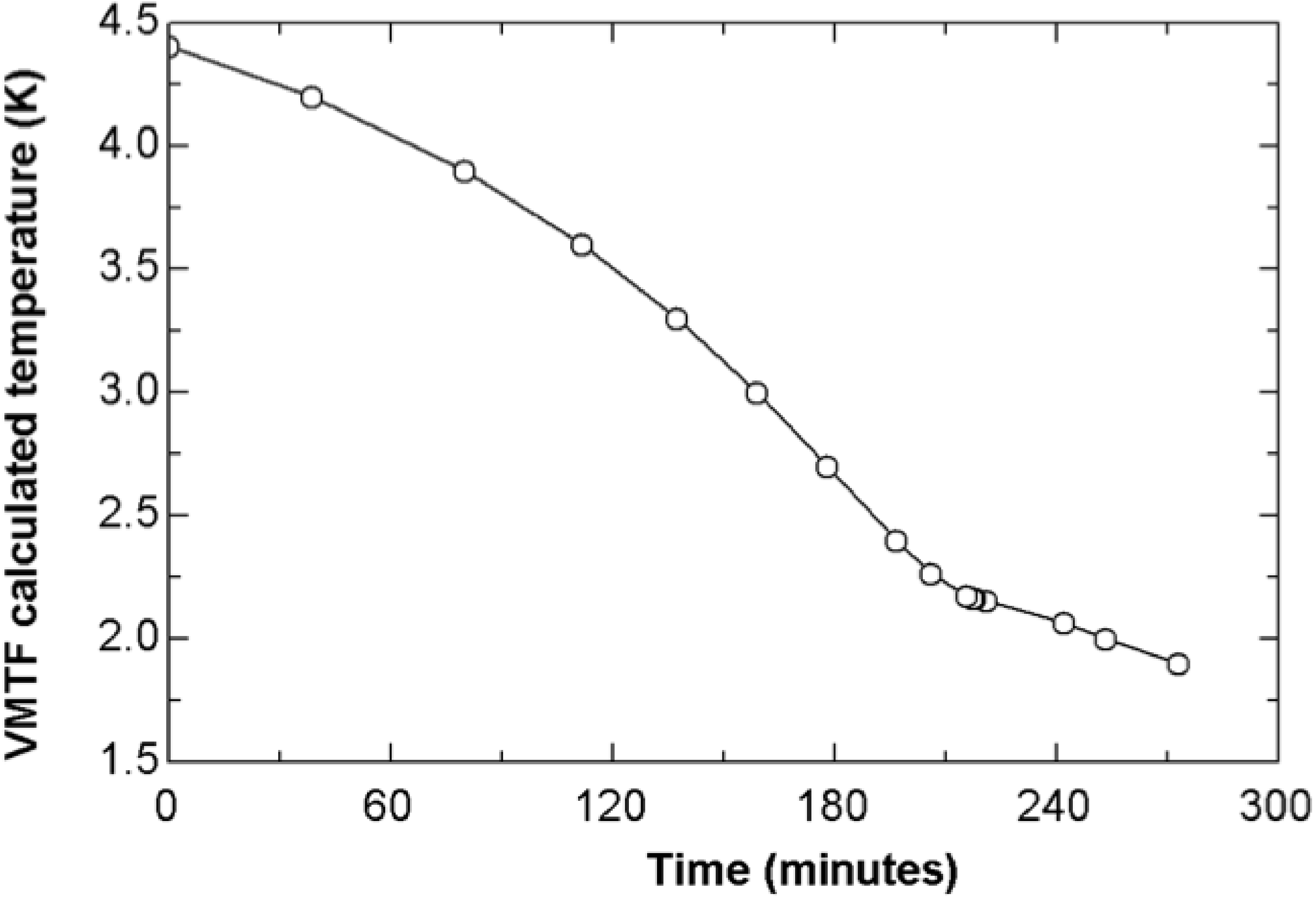


Lambda plate assembly

another view

- Lambda plate and seal (blue)
- Intermediate support plate
- Copper clad magnet (for cooldown)

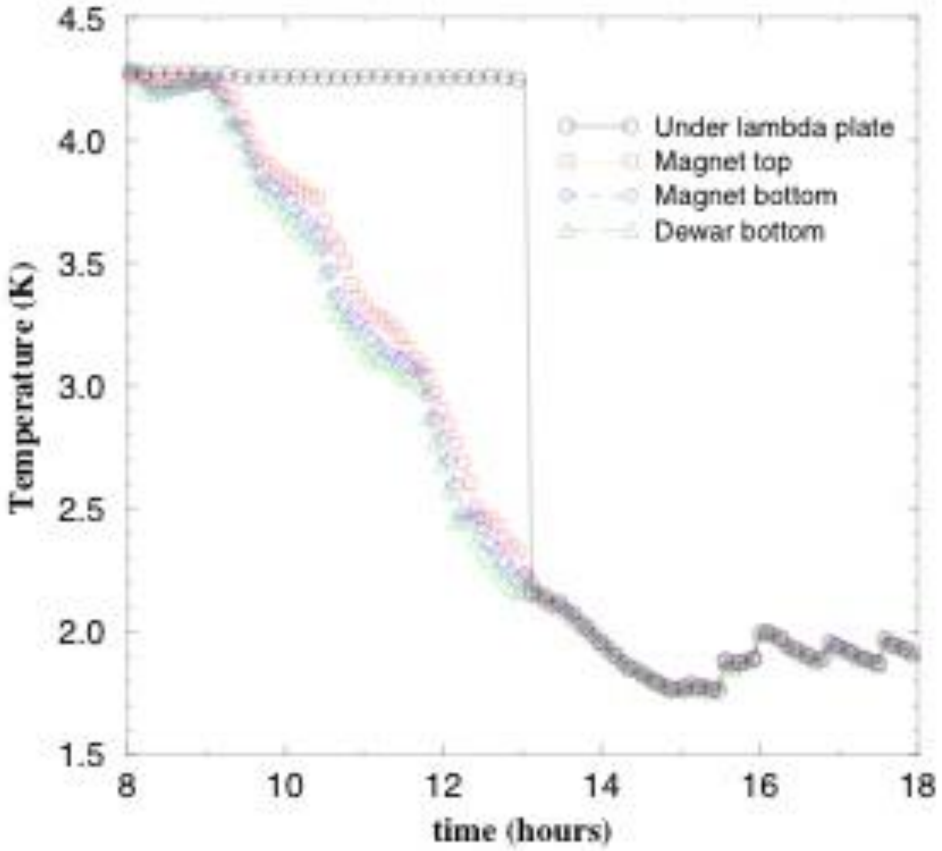
Double-bath cool-down



Predicted double-bath cool-down based on pumping rate and helium properties

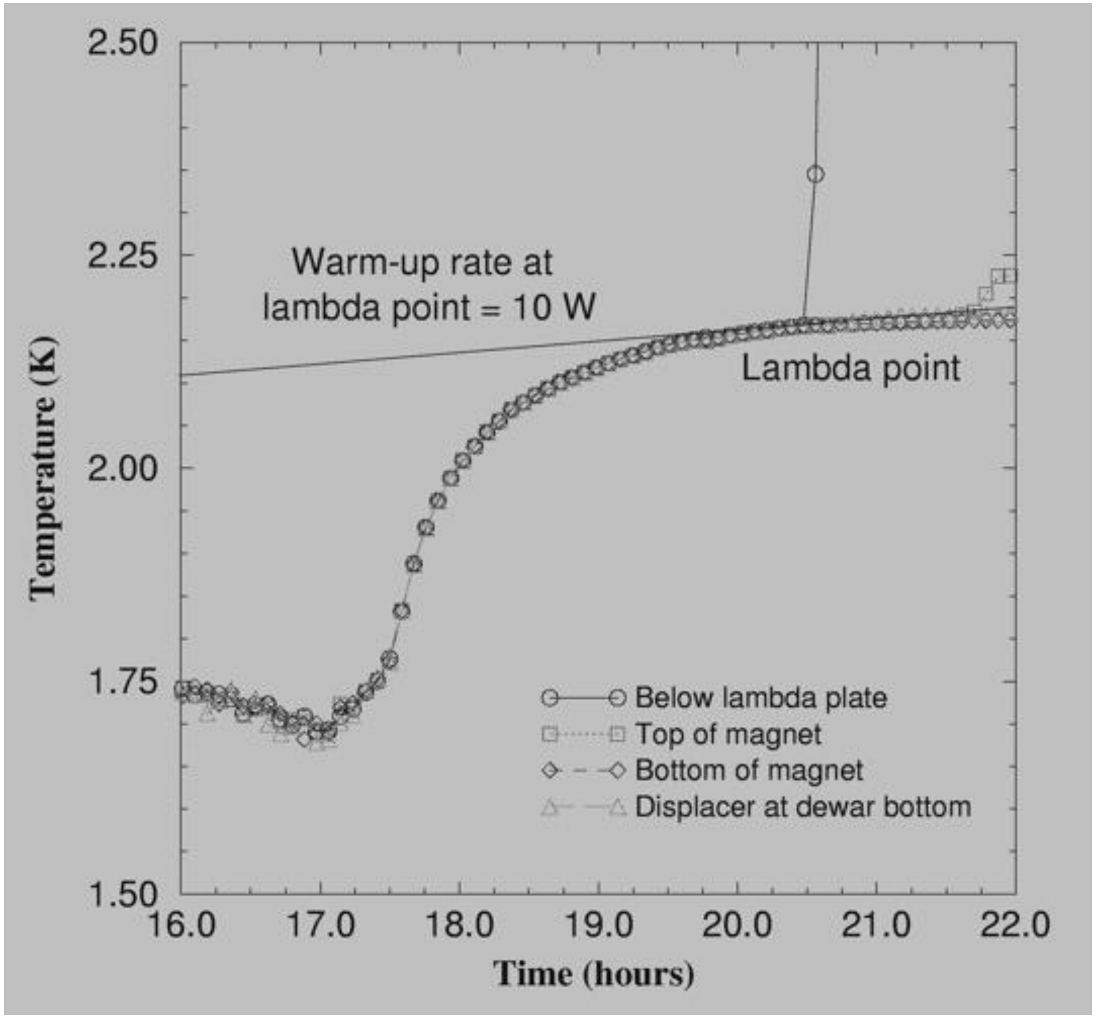
Pressurized SF cooldown

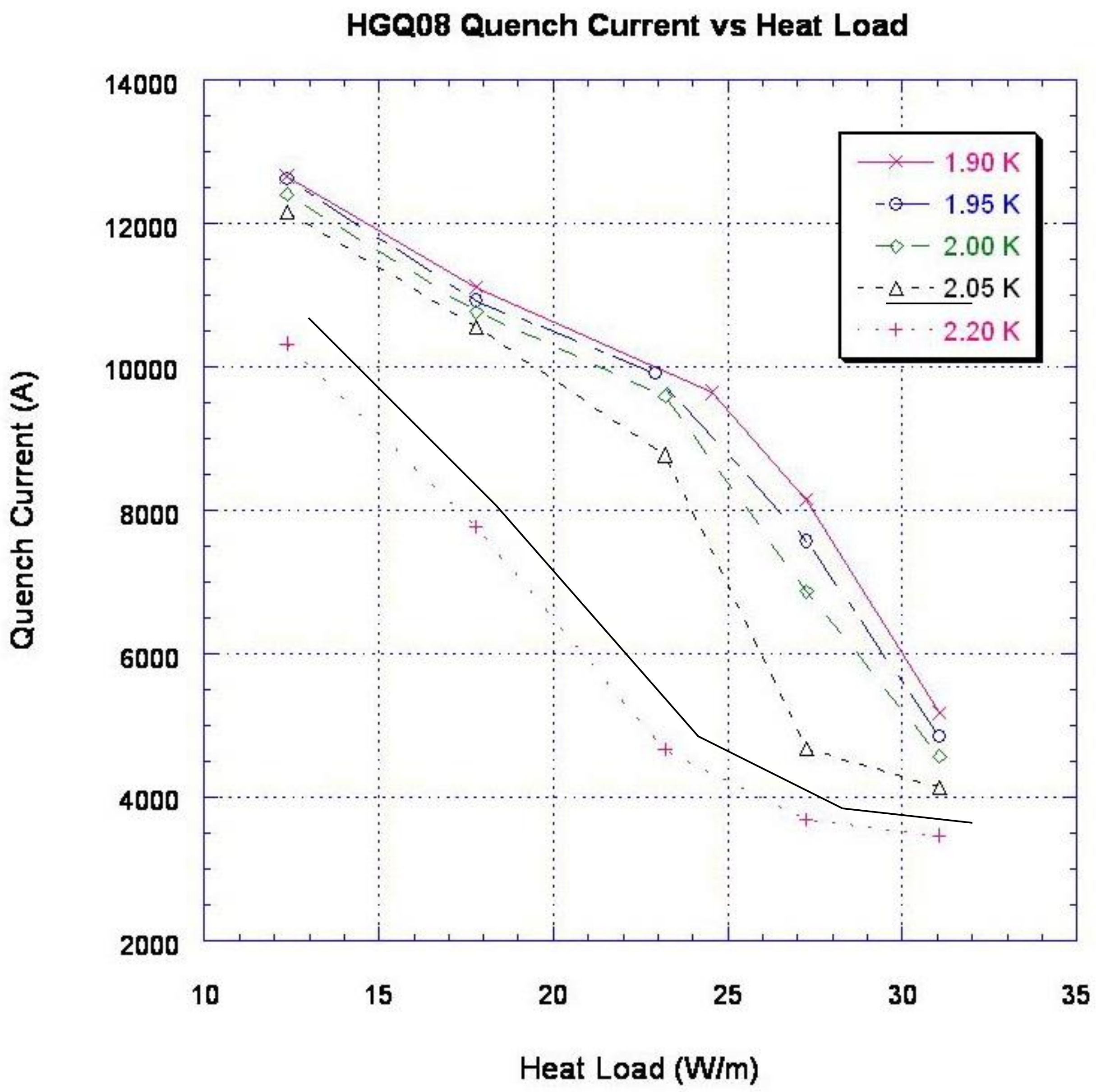
- Single phase, 1.2 bar liquid
- Temperatures equilibrate below lambda point



Pressurized SF warm-up

- Sub-lambda point warm-up shows non-linear effects
  - SF heat transport
  - Heat capacity
  - Pressurization of associated saturated bath
- But essentially isothermal SF bath is excellent calorimeter





Impact of SF heat transport on magnet quench current, measured in a double-bath dewar

Double-bath dewar issues

- Subatmospheric portion of dewar is more limited than in the completely saturated bath dewar, so less extensive but still important to be leak tight
- Heat transport via a "lambda" seal between normal and SF is a problem
  - Seal must be tight with long leak paths
  - Heat loads come from various sources, so difficult to distinguish lambda seal leak from others

Barriers between superfluid and normal fluid

- Lambda plate, lambda plug (detailed example in part 3), check valve (later in this talk)
- If the barrier plane is oriented horizontally and the 4.5 K bath above is quiescent, the bath above slowly stratifies to 2.17 K just above the barrier
- In fact one can operate a "double bath" without a lambda plate down to 2.2 K
  - A 2 K heat exchanger below the surface will subcool the liquid
  - There will still be a 4.4 K layer and positive vapor pressure on top -- vapor and liquid surface equilibrium
- Fermilab routinely tests magnets in subcooled liquid in the positive pressure vertical dewar

Some Common Thermal Prediction Errors

Thermal intercept temperature assumption, overestimating conduction, free convection thermal "short", incidental contact

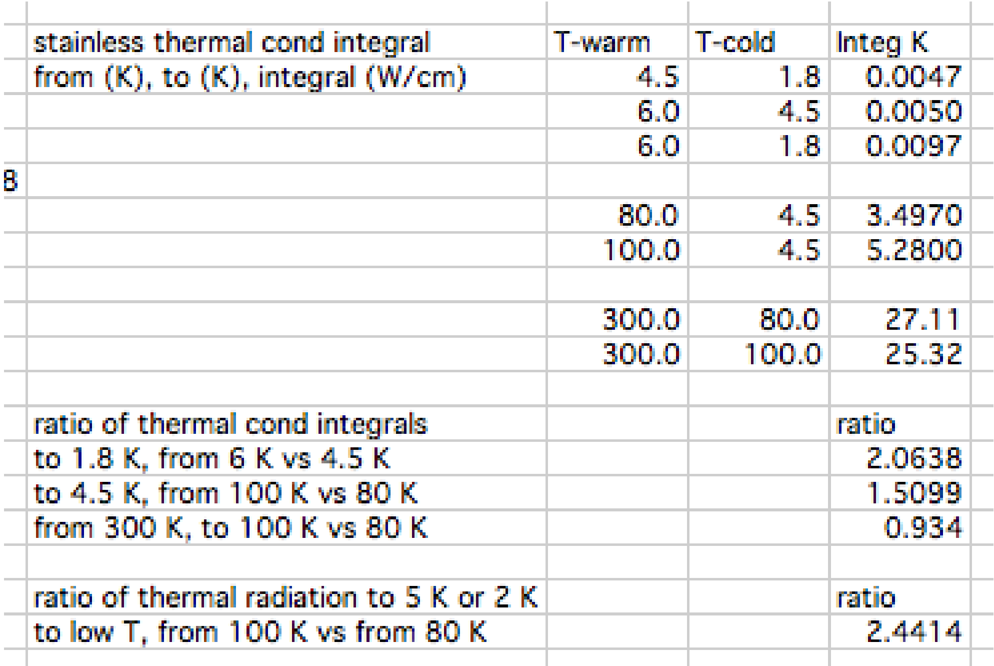
Thermal intercept temperatures

- A common source of underestimated heat loads is analysis which assumes ideal thermal intercept temperatures, for example 77 K or even 80 K for an LN2 thermal intercept, when in fact due to thermal resistance of long thermal strap connections, nitrogen or helium pressure, or other factors, the thermal intercept temperature is higher than assumed.
- The following example for the vertical test cryostat which I just described illustrates the issue.

Analysis for two sets of assumptions

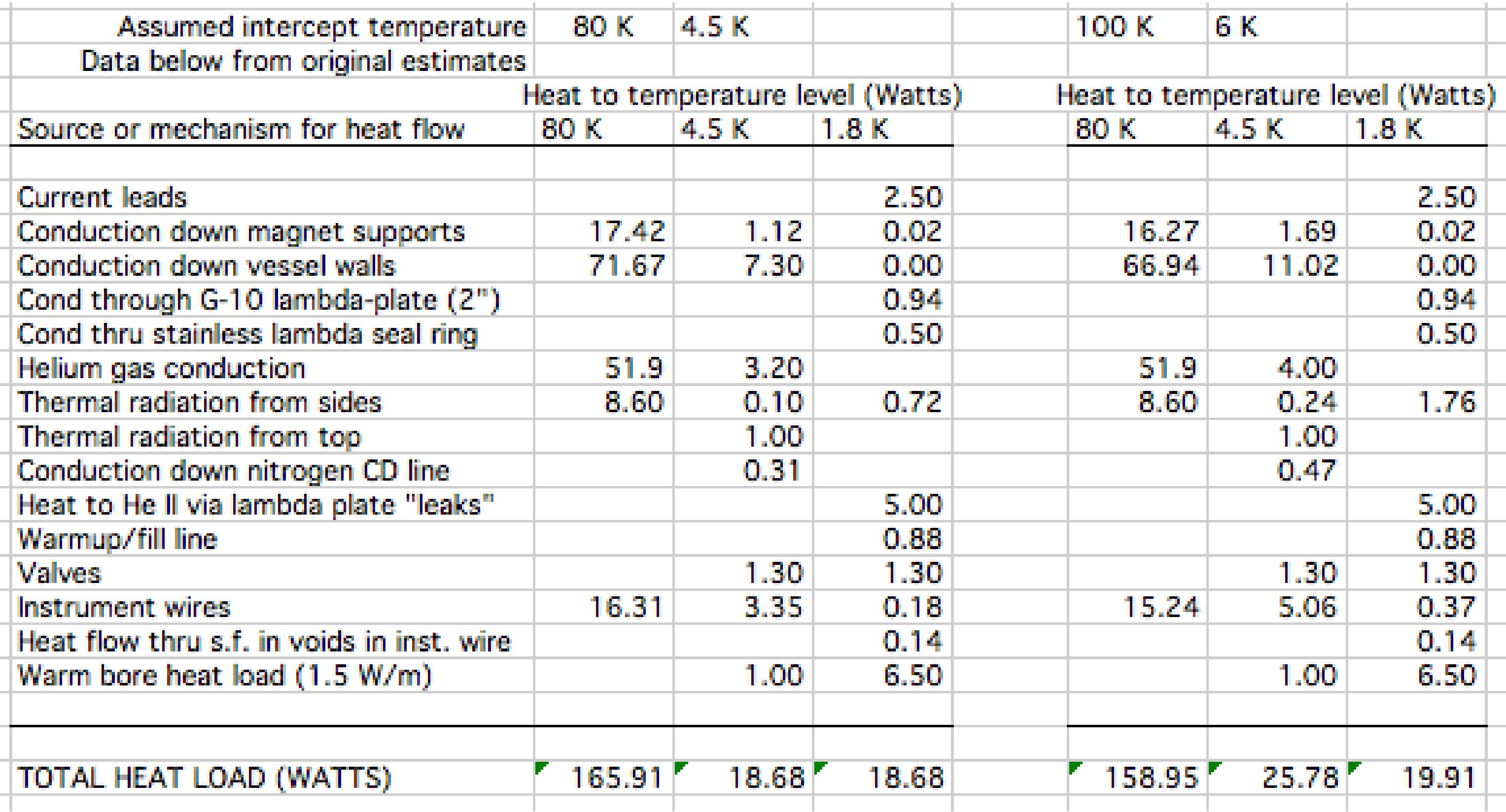
Compare calculated heat loads with thermal intercepts at 100 K vs 80 K and at 6 K vs 4.5 K.

Not a huge difference, quite realistic.



	T-warm	T-cold	Integ K
stainless thermal cond integral	T-warm	T-cold	Integ K
from (K), to (K), integral (W/cm)	4.5	1.8	0.0047
	6.0	4.5	0.0050
	6.0	1.8	0.0097
	80.0	4.5	3.4970
	100.0	4.5	5.2800
	300.0	80.0	27.11
	300.0	100.0	25.32
ratio of thermal cond integrals			ratio
to 1.8 K, from 6 K vs 4.5 K			2.0638
to 4.5 K, from 100 K vs 80 K			1.5099
from 300 K, to 100 K vs 80 K			0.934
ratio of thermal radiation to 5 K or 2 K			ratio
to low T, from 100 K vs from 80 K			2.4414

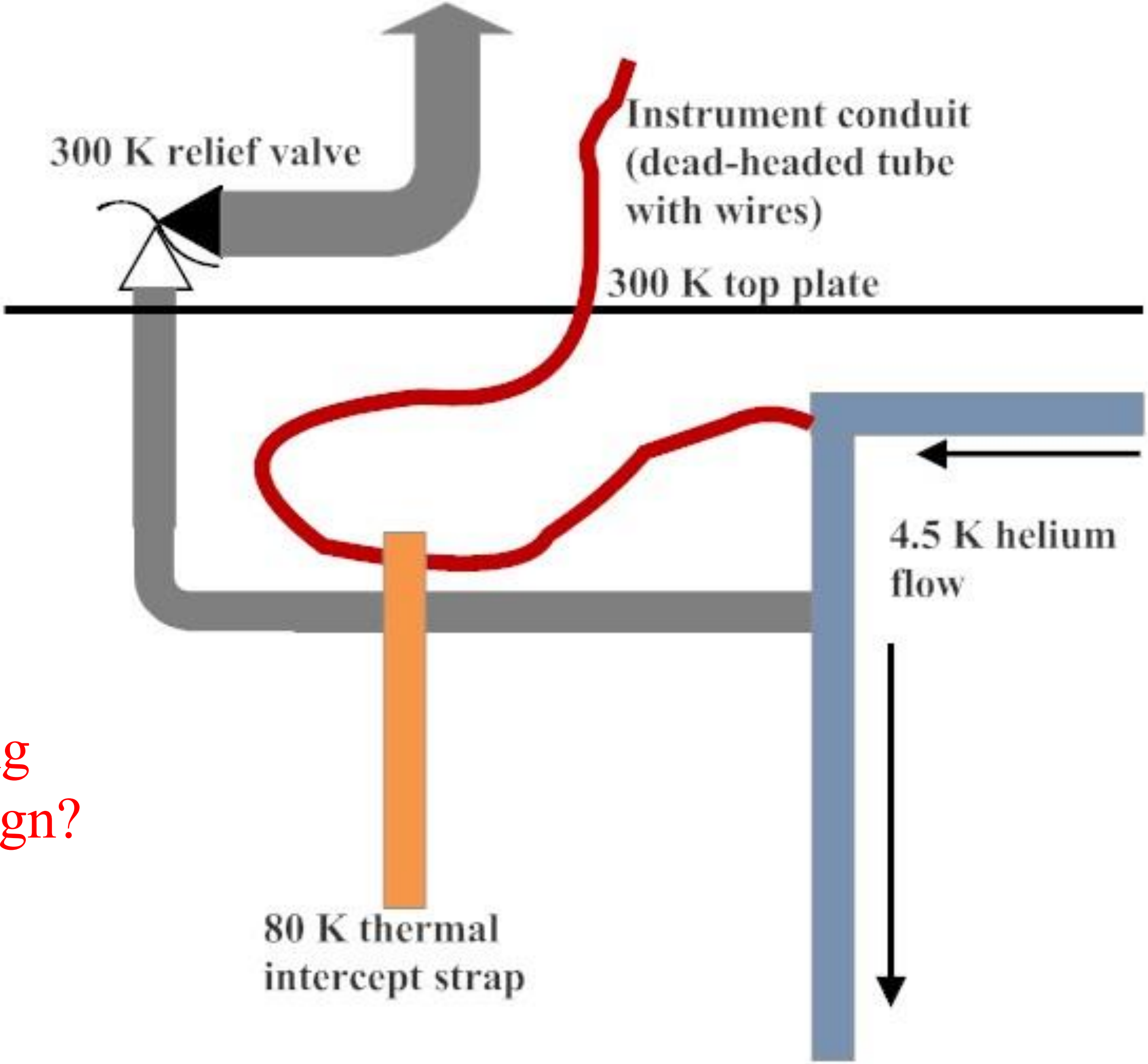
Estimated heat for test dewar



Assumed intercept temperature	80 K	4.5 K			100 K	6 K	
Data below from original estimates							
	Heat to temperature level (Watts)				Heat to temperature level (Watts)		
Source or mechanism for heat flow	80 K	4.5 K	1.8 K		80 K	4.5 K	1.8 K
Current leads			2.50				2.50
Conduction down magnet supports	17.42	1.12	0.02		16.27	1.69	0.02
Conduction down vessel walls	71.67	7.30	0.00		66.94	11.02	0.00
Cond through G-10 lambda-plate (2")			0.94				0.94
Cond thru stainless lambda seal ring			0.50				0.50
Helium gas conduction	51.9	3.20			51.9	4.00	
Thermal radiation from sides	8.60	0.10	0.72		8.60	0.24	1.76
Thermal radiation from top		1.00				1.00	
Conduction down nitrogen CD line		0.31				0.47	
Heat to He II via lambda plate "leaks"			5.00				5.00
Warmup/fill line			0.88				0.88
Valves		1.30	1.30			1.30	1.30
Instrument wires	16.31	3.35	0.18		15.24	5.06	0.37
Heat flow thru s.f. in voids in inst. wire			0.14				0.14
Warm bore heat load (1.5 W/m)		1.00	6.50			1.00	6.50
TOTAL HEAT LOAD (WATTS)	165.91	18.68	18.68		158.95	25.78	19.91

Intercept discussion

- Other factors dominate 1.8 K heat load here, so focus on 4.5 K
- Effect on the estimate is 18.7 W → 25.8 W
- This is a 38% increase
- The higher one is a realistic estimate
  - LN2 system actually operates at the dewar pressure, with flow control downstream of the dewar, so about 50 psig, 4.5 atm absolute, 93 K
  - Thermal straps are often undersized for 4.5 K intercepts
  - Contact resistances for intercepts are underestimated



What is wrong with this design?

Another common problem

- Free convection
  - Within relief valve lines
  - In dead-headed cool-down lines
  - In instrumentation lines
- May even generate thermo-acoustic oscillations
  - Larger heat load to 4.5 K
  - Vibrations

Lesson

- Critically examine assumptions in thermal analyses
- Specify thermal intercepts in detail
- Include thermal intercept links, straps, contact resistances, and real fluid temperatures in the analysis
- Look at temperature gradients in the fluid in dead-headed lines and possible free convection drivers

Back to Test Stands

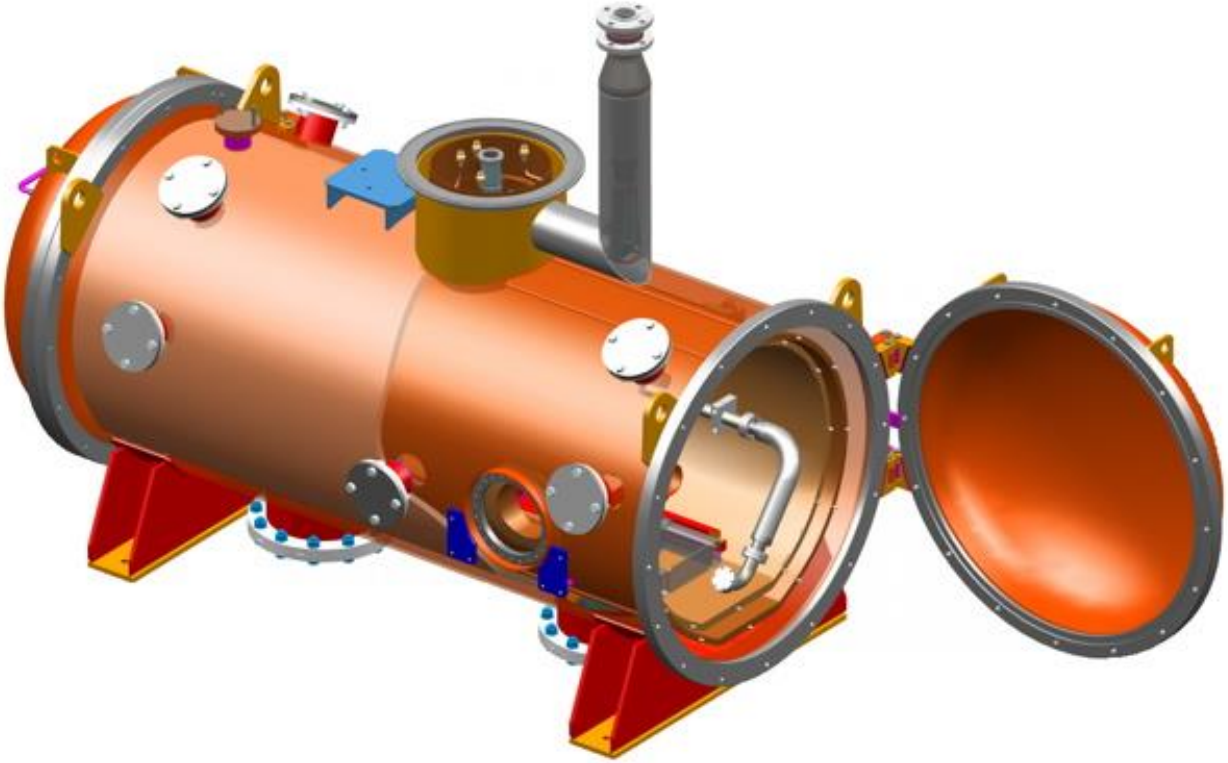
Horizontal test stands

- Horizontal -- simply as opposed to vertical orientation of a long magnet or SRF cavity in a typically vertically oriented dewar
- May consist of just end boxes
  - A supply box for power and cryogens
  - A turnaround box
  - Test object in its own cryostat
  - Interconnects to the end boxes
- Or may be more like a horizontal vacuum chamber or horizontally oriented dewar
- Like vertical test dewars, may provide saturated bath or subcooled liquid

Features due to horizontal configuration

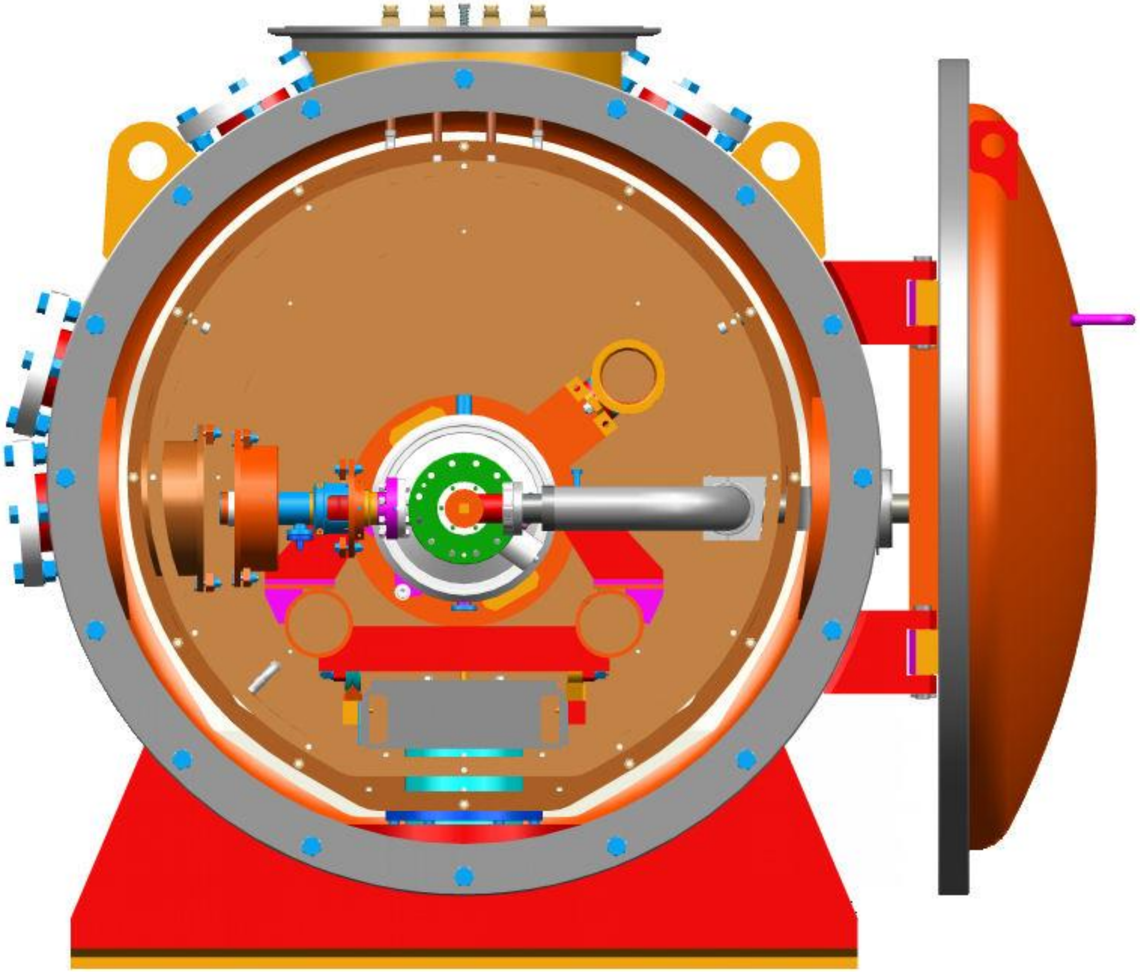
- Not such a simple support structure
- Helium container typically needs separate enclosure within vacuum container
  - Test device typically not hanging but supported with low thermal conductivity structure within the vacuum space
  - Installation of test device more complicated

SRF cavity test cryostat

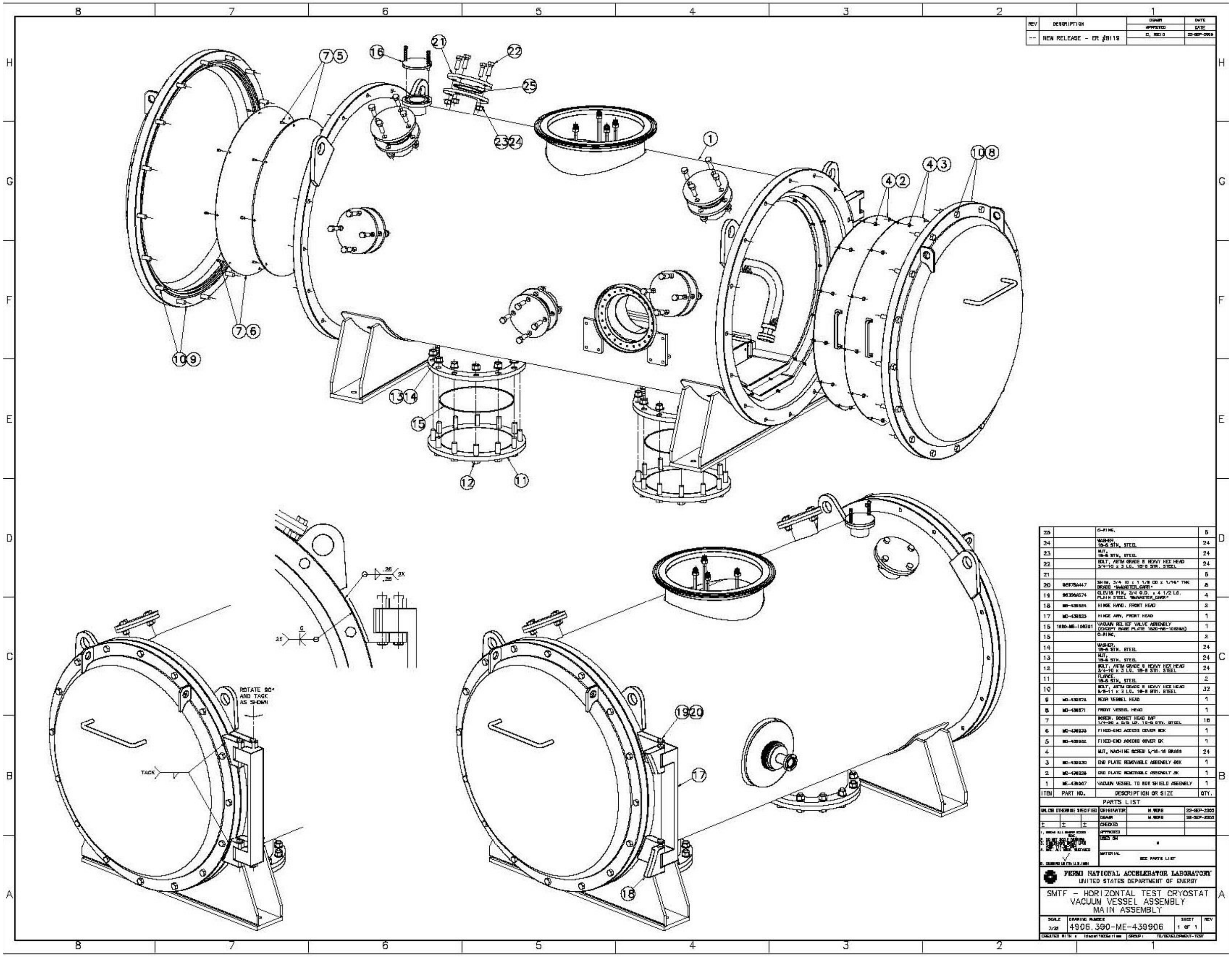


- CAD model of vacuum chamber for SRF cavity tests
- Designed for tests of RF cavities which are pre-installed into helium vessels

SRF cavity test cryostat



- Helium vessel with RF cavity slides in, then cryo pipes and RF coupler connected



REV	DESCRIPTION	DRAWN / APPROVED	DATE
--	NEW RELEASE - ER #8119	C, REID	22-SEP-2008

ITEM	PART NO.	DESCRIPTION OR SIZE	QTY.
25		O-RING,	8
24		WASHER, 18-8 STN. STEEL	24
23		NUT, 18-8 STN. STEEL	24
22		BOLT, ASTM GRADE 8 HEAVY HEX HEAD 3/4-10 x 3 LG. 18-8 STN. STEEL	24
21			8
20	96578A447	SHIM, 3/4 ID x 1 1/8 OD x 1/16" THK BRASS "McMASTER_CARR"	8
19	98306A574	CLEVIS PIN, 3/4 O.D. x 4 1/2 LG. PLAIN STEEL "McMASTER_CARR"	4
18	MD-439824	HINGE HAND, FRONT HEAD	2
17	MD-439823	HINGE ARM, FRONT HEAD	1
16	1620-MB-108301	VACUUM RELIEF VALVE ASSEMBLY (EXCEPT BASE PLATE 1620-MB-108385)	1
15		O-RING,	2
14		WASHER, 18-8 STN. STEEL	24
13		NUT, 18-8 STN. STEEL	24
12		BOLT, ASTM GRADE 8 HEAVY HEX HEAD 3/4-10 x 3 LG. 18-8 STN. STEEL	24
11		FLANGE, 18-8 STN. STEEL	2
10		BOLT, ASTM GRADE 8 HEAVY HEX HEAD 5/8-11 x 3 LG. 18-8 STN. STEEL	32
9	MD-439872	REAR VESSEL HEAD	1
8	MD-439871	FRONT VESSEL HEAD	1
7		SCREW, SOCKET HEAD CAP 1/4-20 x 3/8 LG. 18-8 STN. STEEL	16
6	MC-439833	FIXED-END ACCESS COVER 80K	1
5	MD-439832	FIXED-END ACCESS COVER 5K	1
4		NUT, MACHINE SCREW 5/16-18 BRASS	24
3	MC-439830	END PLATE REMOVABLE ASSEMBLY 80K	1
2	MC-439826	END PLATE REMOVABLE ASSEMBLY 5K	1
1	ME-439907	VACUUM VESSEL TO 80K SHIELD ASSEMBLY	1

PARTS LIST

ORIGINATOR	M.WONG	22-SEP-2008
DRAWN	M.WONG	26-SEP-2008
CHECKED		
APPROVED		

UNLESS OTHERWISE SPECIFIED
± ± ±
1. BREAK ALL SHARP EDGES .XX MAX.
2. DO NOT SCALE DRAWING.
3. DIMENSIONS BASED UPON ASME Y14.5M-1994
4. MAX. ALL MACH. SURFACES √
5. DRAWING UNITS: U.S.INCH

USED ON
MATERIAL SEE PARTS LIST

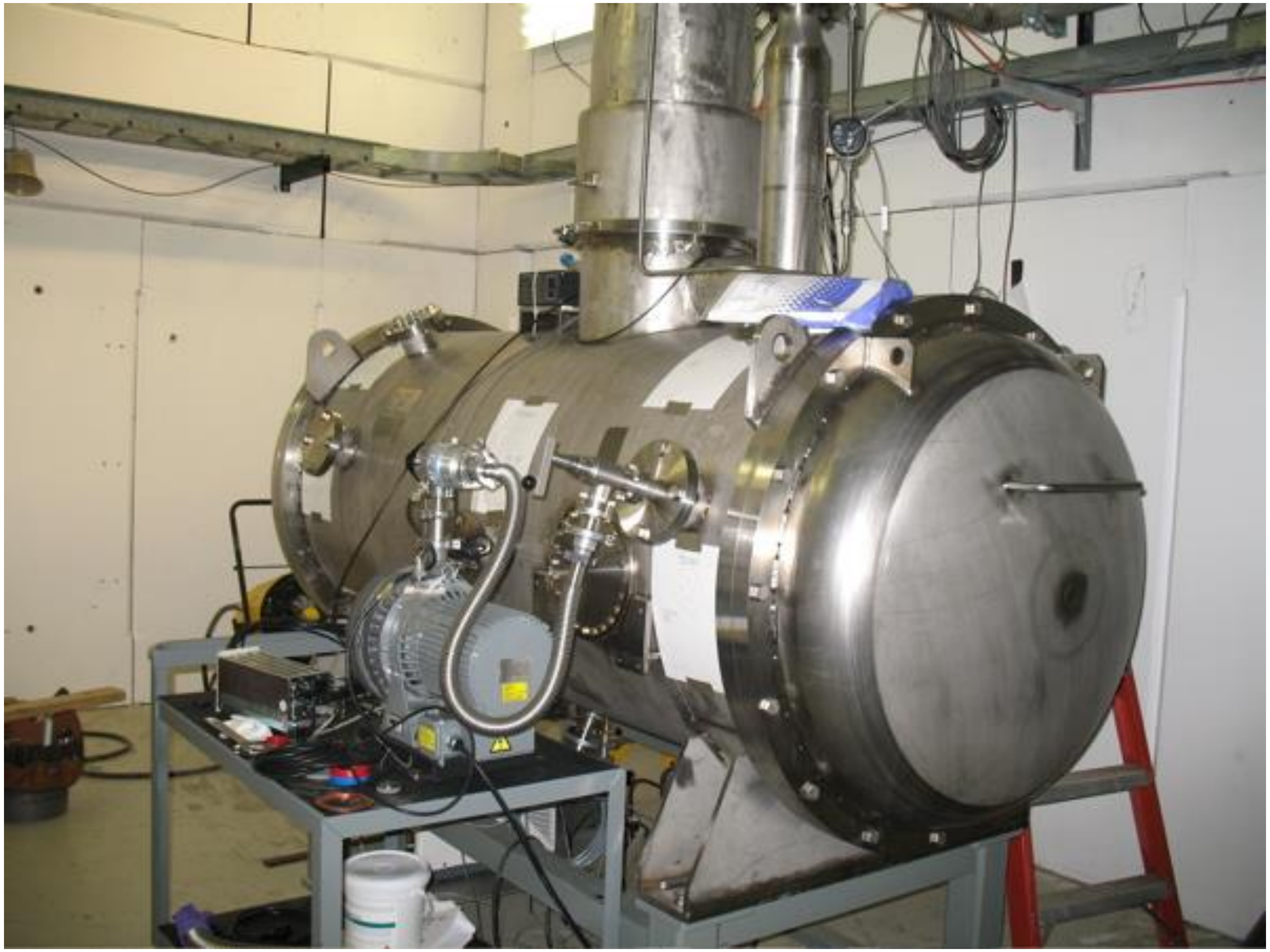
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

SMTF - HORIZONTAL TEST CRYOSTAT
VACUUM VESSEL ASSEMBLY
MAIN ASSEMBLY

SCALE 1/32
DRAWING NUMBER 4906.390-ME-439906
SHEET 1 OF 1
REV
CREATED WITH : Ideas10NXSeries
GROUP : TD/DEVELOPMENT-TEST

SRF horizontal test stand

Fermilab SRF cavity test cryostat



- Stainless vacuum shell
- Rubber O-ring seals vacuum door
- Copper thermal shields
- Cryogenic piping in top
- Indium metal seals connect cryogenic piping

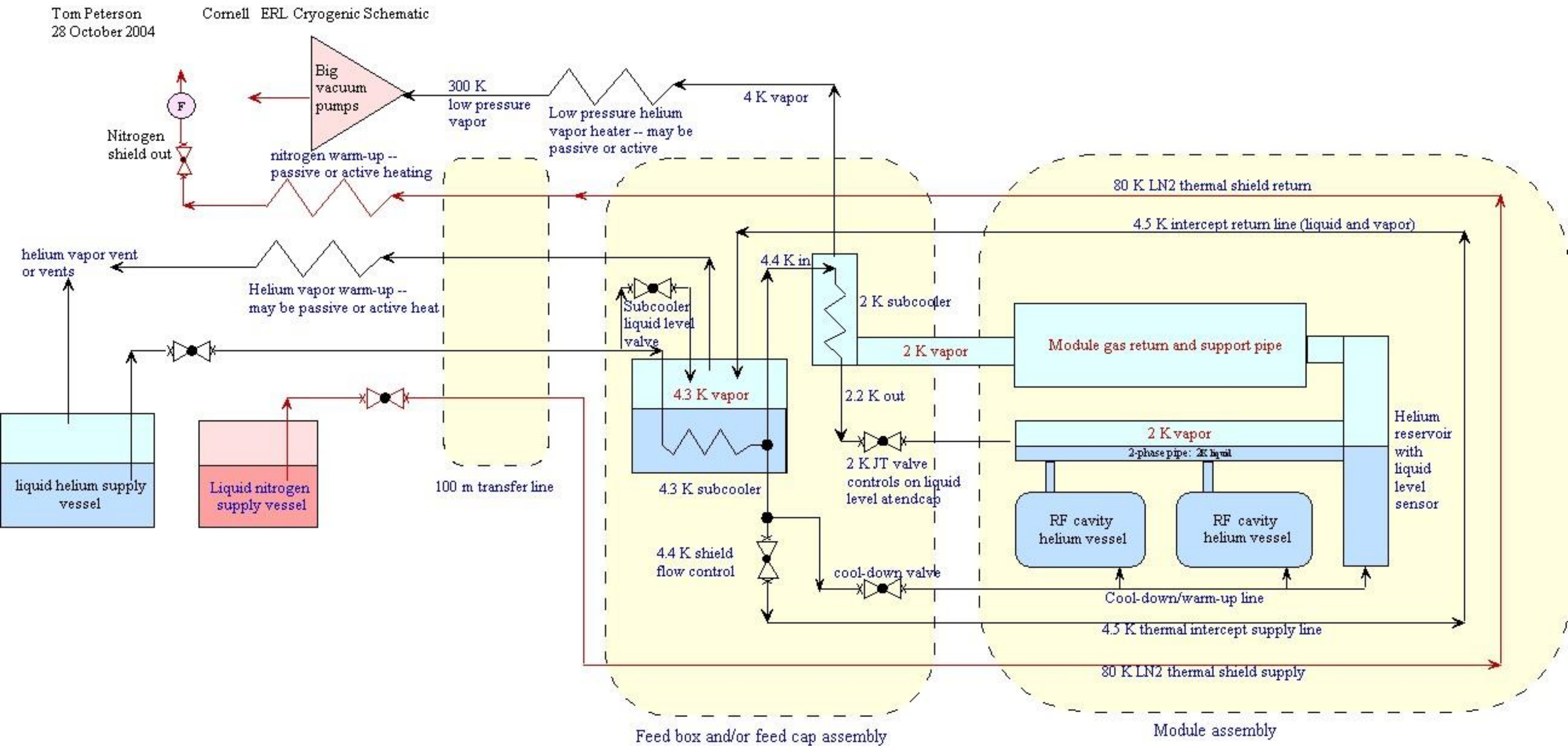
RF power input coupler

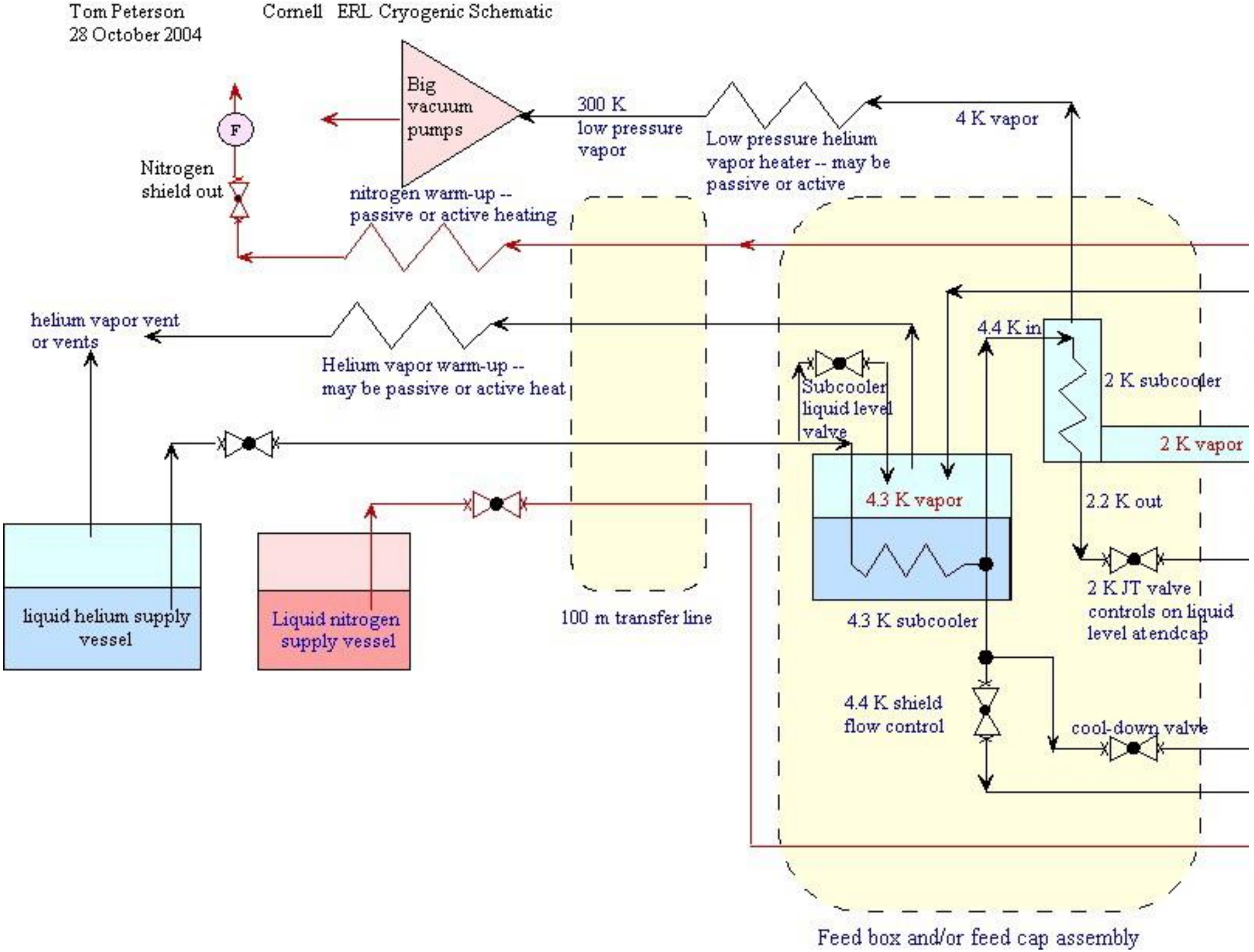
- Carries RF from 300 K to 2 K in horizontal test stand
- Thin sections and thermal intercepts
- Conductor is copper plating on stainless

Providing 2 K on a test stand

- Test stand refrigeration requirements are typically small
  - A large, 2 K cryoplant will not be available
  - 4.5 K helium from either a small liquefier or storage dewars will provide refrigeration
  - Room-temperature vacuum pumps provide the low pressure for the low temperature helium
  - Small heat exchangers may be incorporated for continuous fill duty

Horizontal SRF test stand




Tom Peterson
28 October 2004
Cornell ERL Cryogenic Schematic
Big vacuum pumps
F
Nitrogen shield out
nitrogen warm-up -- passive or active heating
300 K low pressure vapor
Low pressure helium vapor heater -- may be passive or active
4 K vapor
helium vapor vent or vents
Helium vapor warm-up -- may be passive or active heat
4.4 K in
2 K subcooler
Subcooler liquid level valve
2 K vapor
4.3 K vapor
2.2 K out
2 K JT valve controls on liquid level at endcap
liquid helium supply vessel
Liquid nitrogen supply vessel
100 m transfer line
4.3 K subcooler
4.4 K shield flow control
cool-down valve
Feed box and/or feed cap assembly

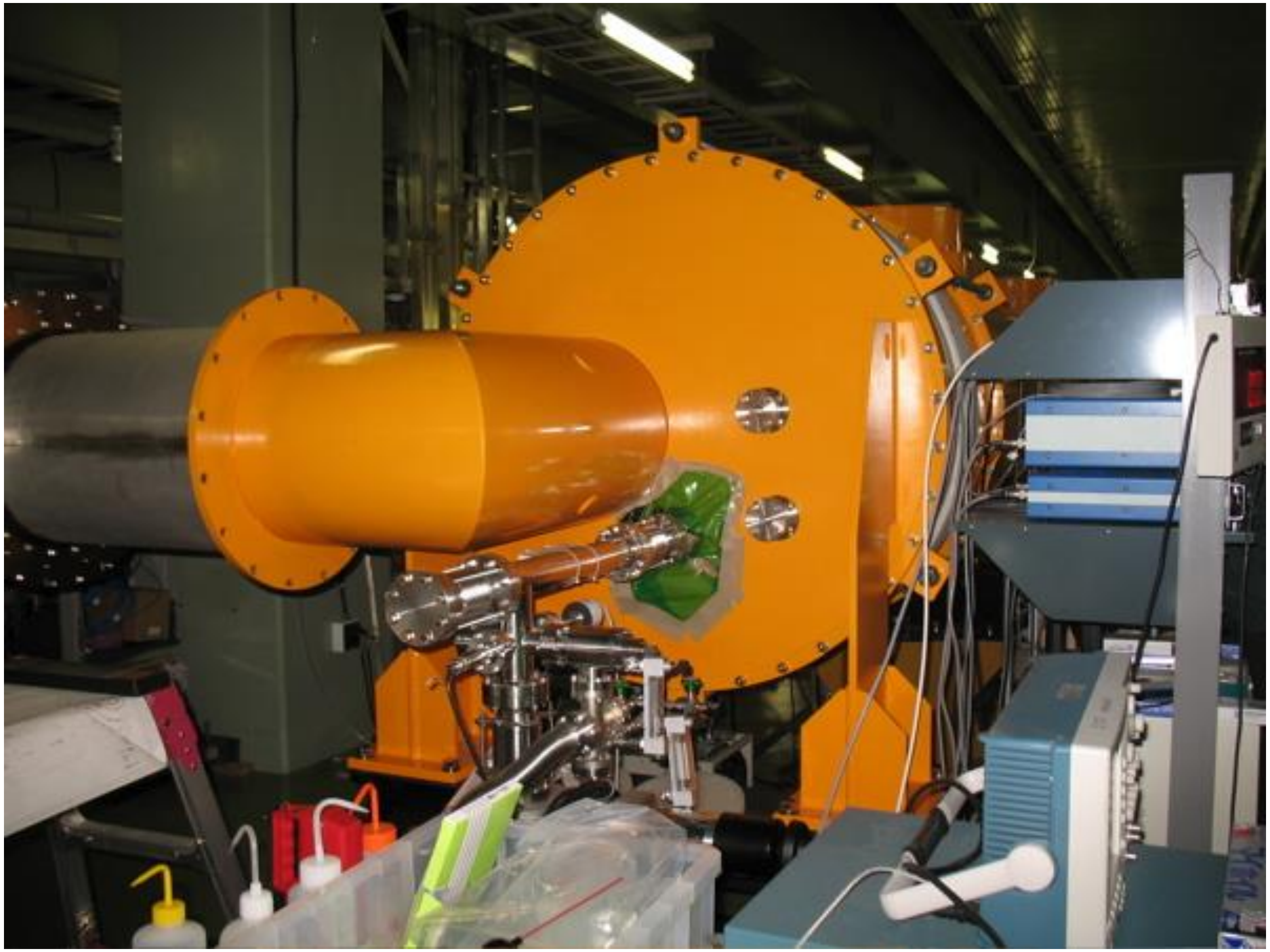
SRF horizontal test stand

Cornell SRF cavity test cryostat

- Helium supply from left into end of cryostat

SRF cryomodule test stand

KEK STF feed box



SRF Cryomodule Test Stand -- DESY - 1

- Feed box
- Cryogenic connections to cryoplant out through top

Cryomodule Test Stand -- DESY - 2

- Feed box and connection to feed interconnect
- Note similar configuration to Cornell and KEK

Cryomodule Test Stand -- DESY - 3

- Feed-end interconnect
- 1 m dia
- Bellows slide back for access

Cryomodule Test Stand -- DESY - 4

- Cryomodule on test stand
- RF distribution under platform

Cryomodule Test Stand -- DESY - 5

- Test stand with cryomodule removed
- View from turnaround end

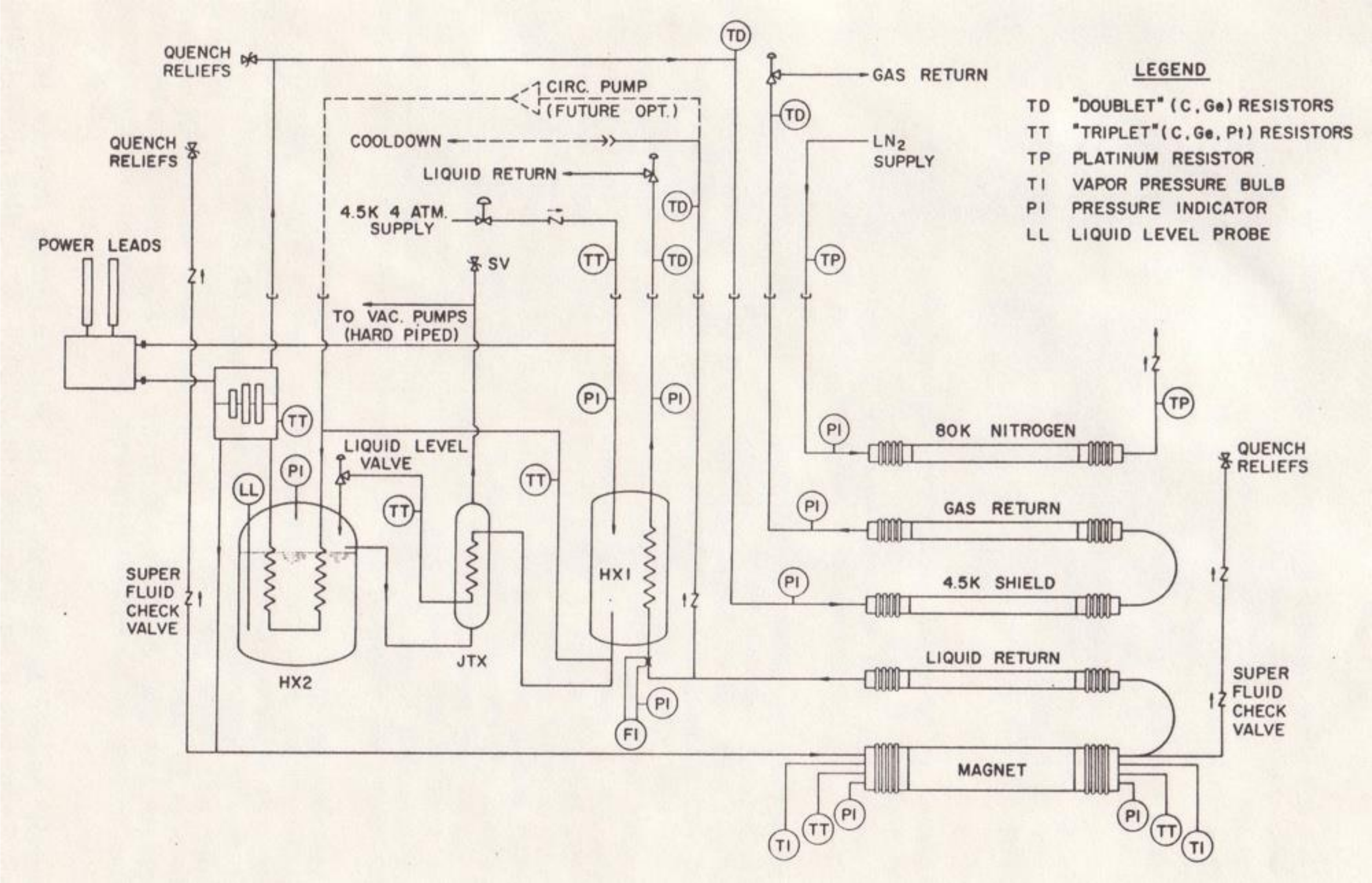
Horizontal magnet test stand

Magnet test stands at Fermilab

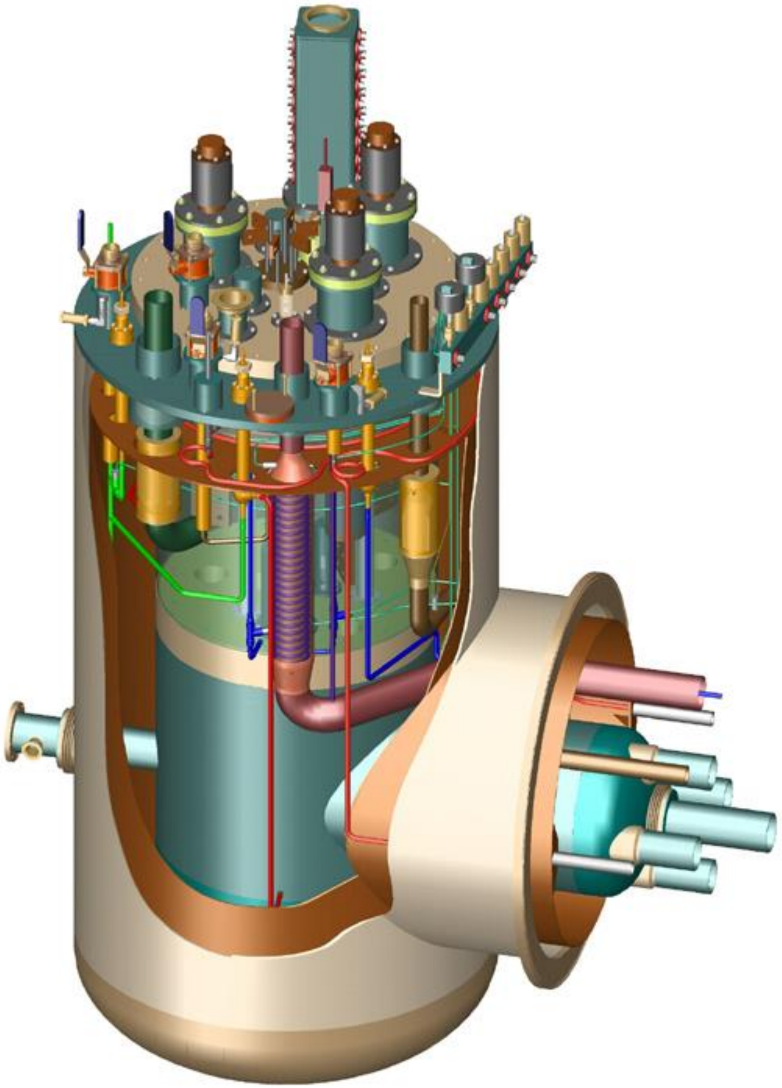
Magnet "test stand 5"

- Our first superfluid magnet test stand at Fermilab, in the 1980's
- Provided stagnant or forced flow operation
- 4.5 K to 1.8 K
- Illustrates use of local test stand heat exchangers in combination with large warm vacuum pumps to provide sub-lambda helium

Superfluid magnet test stand 5



Feed box for LHC magnet test

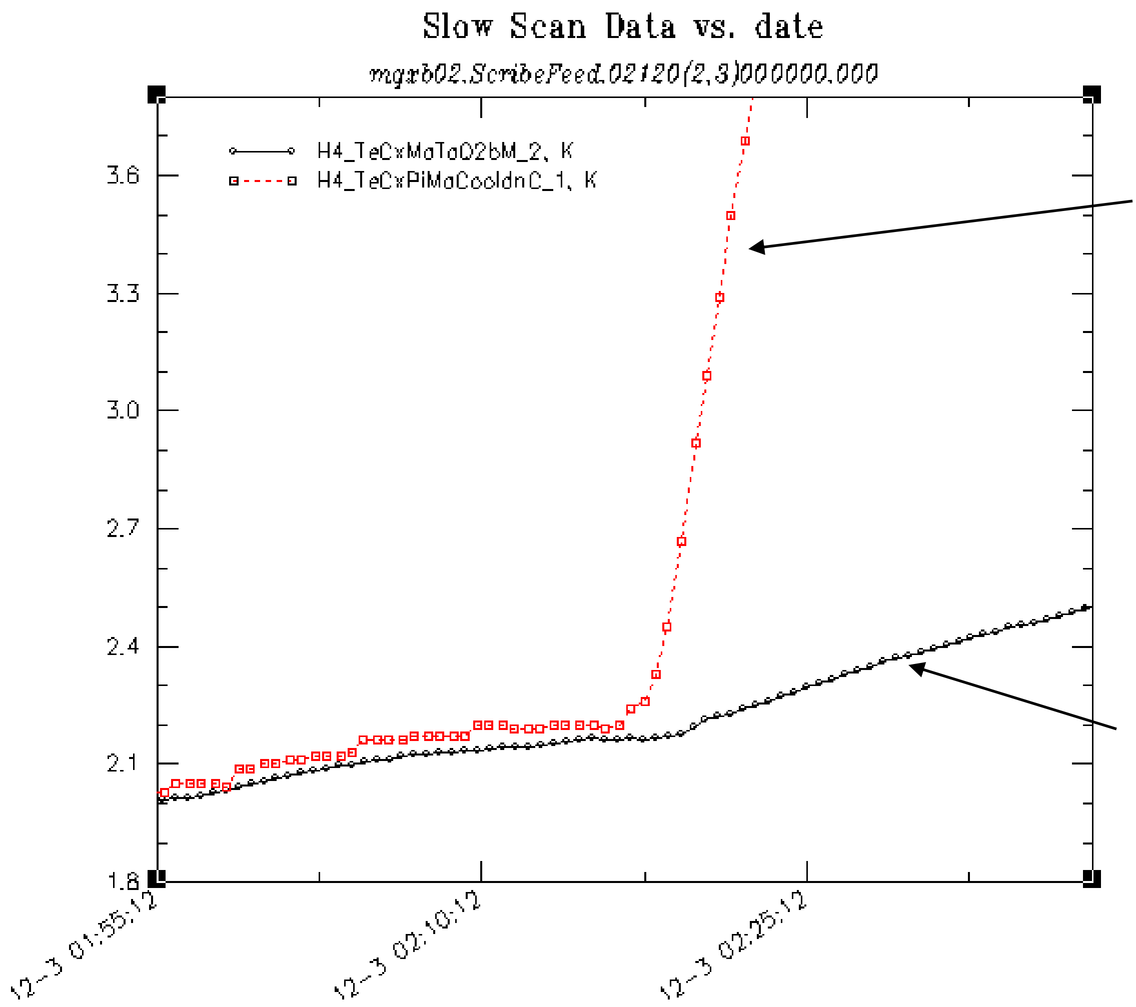


- Essentially a double-bath with a horizontal extension
- Current leads and instrumentation in on the top

Horizontal magnet test stand

LHC magnet test stand at Fermilab

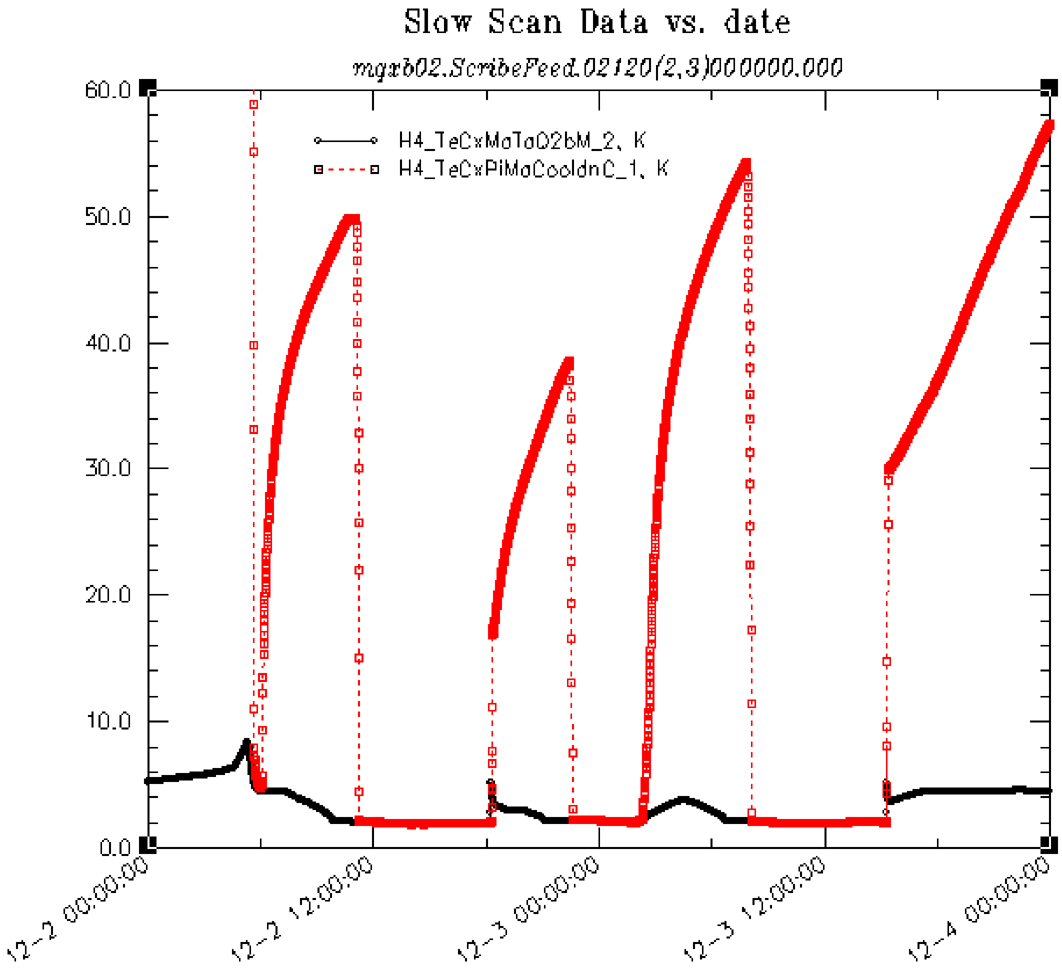
Long pipe cool-down with SF



Temperature at the far end of a 15 m long, 42 mm inner diameter, Cool-down line, with a small heat input at the far end

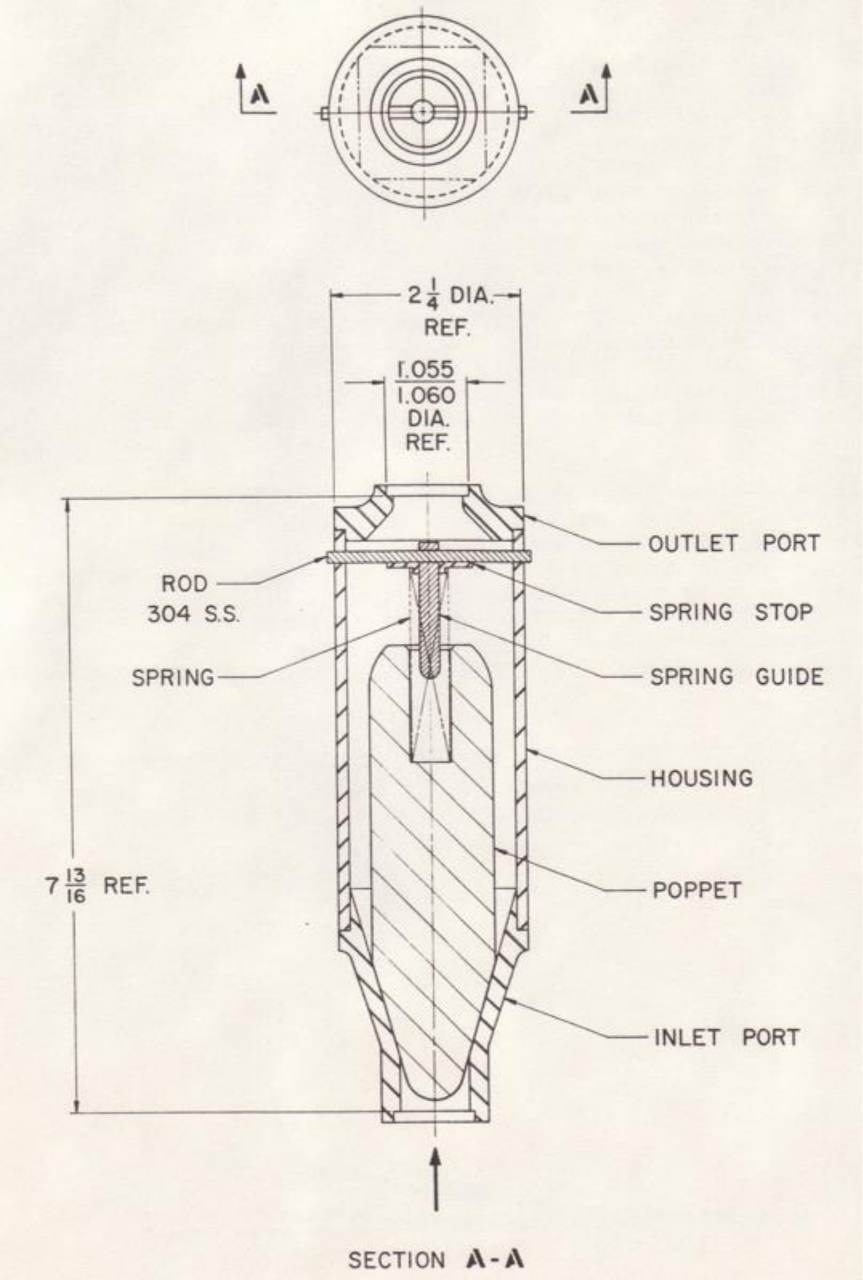
Temperature in a large volume of subcooled liquid helium, slowly warming up

More long-pipe temperatures during cool-down and warm-up



Plot shows temperature history over two days, consisting of a forced-flow filling at 4.5 K early December 2, cool-down from 4.5 K to 1.9 K in stagnant helium, a quench and recovery the evening of the 2nd, an overnight warm-up, cool-down the morning of the 3rd, and finishing with a quench the afternoon of the 3rd.

Superflluid check valve



- Long, conical seal for long heat flow path
- Tiny, axial through-hole for pressure equalization

Procurement strategies

- Design and build in-house
- Design and procure “to print”
- Detail interfaces and critical areas but not entire object -- procure to spec’s and drawings
- Performance specification with only a few key interfaces detailed

Procurement experience

- Test vessels and stands with end boxes are typically unique -- one or a few-of-a-kind
- Industry is small and specialized
- Designs often contain new, risky, or erroneous features
- Close collaboration with a vendor is critical
  - Frequent (once per week or more) inspections and meetings at the vendor

Design, procurement, installation time scale

- Design of a new cryogenic box
  - 0.5 or more man-years engineering
  - 1.0 or more man-years drafting
  - Typically 6 - 9 months calendar time
- Procurement -- another 6 - 12 months
- Installation
  - Complexity of instrumentation, controls, interfaces are often underestimated
  - Several months
- Result -- two years or more

Operations

- Common problems encountered
  - Warm gas in adds large amount of heat
    - A very small leak via a valve isolating warmer helium from the lower temperature system may be a hidden source of heat
    - 1 mg/sec at 300 K ==> 1.5 Watts to 4.5 K!
  - Air leak in (contamination)
    - Subatmospheric operation for sub-4.2 K provides risk of air inleaks, especially through instrumentation and other seals

More about operations

- Instrumentation
  - – Often in doubt
  - – *In situ* checks like at a phase change can provide verification of temperatures and pressures
  - – We generally allow a period of "thermal studies" upon startup of a new test system
    - Check instrumention
    - Review operating procedures
    - Verify thermal performance

References

- More information about Fermilab's and other test stands may be found in Cryogenic Engineering Conference (CEC) and International Cryogenic Engineering Conference (ICEC) proceedings.
- Here is a sample for Fermilab:
  - P.O. Mazur and T.J. Peterson, "A Cryogenic Test Stand for Full Length SSC Magnets with Superfluid Capability," Advances in Cryogenic Engineering, Volume 35A, pg. 785.
  - T. J. Peterson, et al, "A 1400 Liter 1.8 K Test Facility," Advances in Cryogenic Engineering, Volume 43A, pg. 541.
  - R.H. Carcagno, et al, "A Cryogenic Test Stand for LHC Quadrupole Magnets," Advances in Cryogenic Engineering, Volume 49A, pg. 225.