Magnet and RF Cavity Test Stand Design

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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, 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
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.
Estimated heat for test dewar

<table>
<thead>
<tr>
<th>Source or mechanism for heat flow</th>
<th>Assumed intercept temperature</th>
<th>80 K</th>
<th>4.5 K</th>
<th>1.8 K</th>
<th>100 K</th>
<th>6 K</th>
<th>80 K</th>
<th>4.5 K</th>
<th>1.8 K</th>
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<tr>
<td>Current leads</td>
<td>80 K</td>
<td>0.02</td>
<td>0.00</td>
<td>0.02</td>
<td>16.27</td>
<td>1.69</td>
<td>0.02</td>
<td>16.27</td>
<td>1.69</td>
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<td>Conduction down magnet supports</td>
<td>4.5 K</td>
<td>17.42</td>
<td>1.12</td>
<td>1.12</td>
<td>16.27</td>
<td>1.69</td>
<td>1.69</td>
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<td>1.69</td>
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<tr>
<td>Conduction down vessel walls</td>
<td>1.8 K</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
<td>2.50</td>
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<tr>
<td>Cond through G-10 lambda-plate (2&quot;)</td>
<td>100 K</td>
<td>71.67</td>
<td>7.30</td>
<td>7.30</td>
<td>66.94</td>
<td>11.02</td>
<td>11.02</td>
<td>66.94</td>
<td>11.02</td>
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<tr>
<td>Cond thru stainless lambda seal ring</td>
<td>6 K</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
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<tr>
<td>Helium gas conduction</td>
<td>80 K</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>51.9</td>
<td>4.00</td>
<td>4.00</td>
<td>51.9</td>
<td>4.00</td>
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<tr>
<td>Thermal radiation from sides</td>
<td>4.5 K</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>51.9</td>
<td>4.00</td>
<td>4.00</td>
<td>51.9</td>
<td>4.00</td>
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<tr>
<td>Thermal radiation from top</td>
<td>1.8 K</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>51.9</td>
<td>4.00</td>
<td>4.00</td>
<td>51.9</td>
<td>4.00</td>
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<td>Conduction down nitrogen CD line</td>
<td>100 K</td>
<td>0.31</td>
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<tr>
<td>Heat to He II via lambda plate &quot;leaks&quot;</td>
<td>6 K</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
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<td>Warmup/fill line</td>
<td>100 K</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
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<td>Valves</td>
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<td>Instrument wires</td>
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<tr>
<td>Heat flow thru s.f. in voids in Inst. wire</td>
<td>1.8 K</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Warm bore heat load (1.5 W/m)</td>
<td>1.8 K</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>TOTAL HEAT LOAD (WATTS)</td>
<td>165.91</td>
<td>18.68</td>
<td>18.68</td>
<td>18.68</td>
<td>158.95</td>
<td>25.78</td>
<td>25.78</td>
<td>158.95</td>
<td>25.78</td>
</tr>
</tbody>
</table>
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 $\rightarrow$ 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
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
Cornell ERL Cryogenic Schematic

- Nitrogen shield out
- Nitrogen warm-up -- passive or active heating
- Helium vapor warm-up -- may be passive or active heat
- Liquid helium supply vessel
- Liquid nitrogen supply vessel
- 100 m transfer line
- 4.3 K vapor
- 4.3 K subcooler
- 4.4 K shield flow control
- Cool-down valve
- 2 K JT valve I controls on liquid level at endcap
- 2.2 K out
- 2 K vapor
- 4.4 K in
- 2 K subcooler

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
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

SLAC
Fermilab
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.
Superfluid 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 instrumentation
    • 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: