Cryogenics for Superconducting Magnets

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USPAS
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Outline

- Introduction – magnet thermal design issues
- An example of thermal considerations for forced-flow, normal helium I cooling – Tevatron magnet cooling
- An example of thermal considerations for stagnant, pressurized, helium II cooling – LHC final focus quadrupole
- Thermal siphon cooling
Cooling modes in large-scale cryogenic systems recently in operation

- Pool boiling helium I (SRF for HERA, LEP, KEKB, CESR)
- Forced flow of subcooled or supercritical helium I (Tevatron, HERA, SSC)
- Stagnant, pressurized helium II (the Tore Supra tokamak in France demonstrated the technology, LHC)
- Saturated helium II (CEBAF, TTF at DESY, SNS at Oak Ridge, and EuXFEL at DESY, LCLS-II at SLAC)
- This list also illustrates the extent to which superconductivity and cryogenics have become standard technology for accelerators
Helium phase diagram
(S. W. VanSciver, Helium Cryogenics, p. 54)

- Critical point
  - 5.2 K, 2.245 atm
- Lambda transition at 1 atm
  - 2.172 K

- SRF -- HERA, LEP, KEKB, CESR
- Magnets -- HERA, Tevatron
- Magnets -- SSC
- Magnets -- Tore Supra, LHC
- SRF -- CEBAF, TTF, SNS, XFEL, LCLS-II

Fig. 3.1. $^4$He phase diagram.
Cooling modes -- magnets vs RF

- 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 of pressure variation on cavity tune
Pressurized versus pool boiling

• Pressurized helium (normal or superfluid) gives maximum penetration of helium mass in magnet coils, which may be a factor in stability if not also heat transfer. But heat flow results in a temperature rise.

• Pool boiling gives pressure stability (important for superconducting RF), provides maximum local heat transfer, and provides nearly isothermal cooling.
Tevatron
Fermilab’s magnet cooling scheme

• Rapid cycling machine originally designed for fixed target physics implied warm iron magnets
• Warm iron constrained cryostat and helium channels to small diameter
  – Which resulted in somewhat larger static heat
  – plus high pressure drop
• Two phase helium flow to remove static heat
  – Coil bathed in pressurized liquid which is cooled by 2-phase
• Keeping pressure (hence temperature) low required short string lengths
Tevatron dipole cross-section
Fermilab magnet cooling scheme

Q visible, measured heat input to the magnet, is based on single phase flow, T, P out and T, P in.
X = SINGLE-PHASE TEMPERATURE SENSOR LOCATION

TEVATRON CROSS-SECTION at SUSPENSION
Tevatron dipole cooling issue

• We knew that Tevatron dipole magnet helium was probably temperature-stratified
• This could be a limitation for quench current
  – We wanted 1 TeV, had to run at lower energies, finally 980 GeV as limited by the magnets
• In TeV dipole TC0603 at the magnet test facility, we did some rather extensive thermal studies
• Published results – “The Nature of the Helium Flow in Fermilab’s Tevatron Dipole Magnets”, by Thomas J. Peterson, Cryogenics, July 1997
• Here are the highlights
Measured temperatures

Temperatures at the return end of TC0603, with 20 g/s.
(Temperature difference above two-phase in parentheses.)

4.661 (0.377)
4.665 (0.381)
4.618 (0.334)
4.604 (0.320)
4.533 (0.249)
4.475 (0.191)
4.328 (0.044)
4.284 two-phase
Measured temperatures plotted

Two-phase in, out, and single-phase out temperatures (K)

- All 2-phase
- Single-phase at 2.2 bar

Temperature (K)

- 5.00
- 4.80
- 4.60
- 4.40
- 4.20
- 4.00

Elapsed time (seconds)

- 0
- 7200
- 14400
- 21600
- 28800
- 36000

- 26 g/s
- 20 g/s
- 13 g/s

- 2-ph 7.5 cm out
- Collar 12 out
- 2-ph 4.4 cm out
- Collar 6 out
- 2-ph 4.4 cm in
- 2-ph 7.5 cm in
Conclusion – dramatic stratification

• Tevatron dipole cooling flow was indeed quite stratified
• The low liquid level on the 2-phase side contributed to this stratification
• Not much could be done about it – we ran successfully at 980 GeV
Recooler flow scheme

Thermal shield return

String of magnets or other cooled devices

Recooler Assembly

4.4 K return vapor

Subcooler liquid level control valve

4.4 K vapor

4.4 K liquid

Devices cooled with forced flow 4.5 K subcooled liquid helium

Helium return to refrigerator (1.2 bar, 4.4 K)

Liquid helium supply from refrigerator (3 bar, 4.5 K)

Thermal shield supply (80 K nitrogen or helium thermal shield)

String of magnets or other cooled devices
Heat transport through channels--pressurized normal helium

- This plot of helium enthalpy versus T illustrates the large amount of heat absorbed (20+ J/g) if one can tolerate 6.5 K or even more
- Nominally “5 K” thermal intercept flow may take advantage of this heat capacity
### Isobaric Data for P = 3.0000 bar

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Pressure (bar)</th>
<th>Density (g/ml)</th>
<th>Volume (ml/g)</th>
<th>Internal Energy (kJ/kg)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (J/g*K)</th>
<th>Cv (J/g*K)</th>
<th>Cp (J/g*K)</th>
<th>Sound Spd. (m/s)</th>
<th>Joule-Thomson (K/bar)</th>
<th>Viscosity (uPa*s)</th>
<th>Therm. Cond. (W/m*K)</th>
<th>Phase</th>
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### Isobaric Data for P = 4.0000 bar

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<th>Temperature (K)</th>
<th>Pressure (bar)</th>
<th>Density (g/ml)</th>
<th>Volume (ml/g)</th>
<th>Internal Energy (kJ/kg)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (J/g*K)</th>
<th>Cv (J/g*K)</th>
<th>Cp (J/g*K)</th>
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From http://webbook.nist.gov/chemistry/fluid/
LHC magnet cooling scheme
similar to Tevatron in also being indirect cooling, i.e., helium-to-helium heat transfer in the magnets
LHC magnet in tunnel
Heat transport through channels—pressurized superfluid

Conduction through ordinary materials is written as \( q = k \frac{dT}{dx} \), where \( q \) is heat flux, \( T \) is temperature, and \( k \) is thermal conductivity. Heat transport through the pressurized superfluid with constant cross-section and constant heat flux obeys

\[
q^m = \frac{1}{f(T)} \frac{dT}{dx}
\]

where \( m \approx 3 \) and \( q \) is the heat flux in W/cm\(^2\).
Superfluid Heat Transport Function
(Steven W. VanSciver, Helium Cryogenics, p. 144)

From 1.85 K to 1.95 K assume \( f(T) \) is constant, and \( \frac{1}{f(T)} = 1200 \). Then the temperature difference through the conduit is \( \Delta T = \frac{q^3 L}{1200} \) where \( L \) is distance in cm, and \( q \) is the heat flux in W/cm\(^2\).

\[ \frac{1}{f(T)} \]

1.6 T(K)  2.0
Helium II heat transport reference

• “Practical data on steady state heat transport in superfluid helium at atmospheric pressure”
  – By G. Bon Mardion, G. Claudet, and P. Seyfert, in Cryogenics, January 1979

• Solve the last equation on slide 22 for $q$, with a constant diameter channel and length $L$, and integrate over the temperature range from $T_c$ to $T-\lambda$

• One then has $q \cdot L^{1/m} = W(T_c, T_w)$, where the function $W = (\int (dT/F(T)))^{1/m}$
  – Bon Mardion, et. al., use $m = 3.4$
FLUX DE CHALEUR DANS UN CANAL D'HE II SOUS 1 BAR POUR UNE TEMPERATURE T_c A L'EXTREMITé FROIDE DU CANAL SUIVANT LA TEMPERATURE T_W A L'EXTREMITé CHAUE DU CANAL.

Les courbes $W(T_c,T_W)$ données ici pour 6 temperatures de bain, permettent de determiner les valeurs des flux de chaleur et des temperatures $T_W$ a l'extremite chaude, d'un canal de longueur L quelconque :

* On connait la longueur L, cm, et les temperatures $T_c$ et $T_W$, Kelvin ; on determine le flux :

\[ W \text{ cm}^{-2} \times q = \frac{W(T_c,T_W)}{L} \times 0,294 \text{ en cm} \]

* On connait le flux $q$ et les temperatures $T_c$ et $T_W$ ; on determine la longueur du canal :

\[ L = \left( \frac{W(T_c,T_W)}{q} \right)^{3,4} \text{ cm} \]

* On connait le flux $q$ et la longueur du canal $L$ ; on determine les temperatures $T_c$ et $T_W$ :

\[ W \text{ cm}^{-2} \times q = L \times 0,294 \text{ en cm} \]

On calcule : $W(T_c,T_W) = \frac{q}{L} \times 0,294 \text{ cm}$

Sur ce diagramme, pour des fluides de longueur L, on peut rapporter le flux $q$ en W cm$^{-2}$, dans le cas d'un canal de longueur L cm.

---

**Experimental points**

- $L = 98.5 \text{ cm}$
- $T_c = 143 \text{ K}$
- $T_c = 160 \text{ K}$
- $T_c = 180 \text{ K}$
- $T = 1.34 \text{ K}$
- $T = 1.5 \text{ K}$
- $T = 1.95 \text{ K}$
- $T = 2.05 \text{ K}$
- $T = 2.10 \text{ K}$
- $P = 1 \text{ bar}$
LHC final focus quad sketch
A superconducting magnet built by Fermilab for LHC at CERN in Geneva, Switzerland

Consists of layers from cold inside to warm outside -- magnet, inner pipes, thermal insulation, steel vacuum container
LHC IR quadrupole cold mass

- Cross section of “cold mass” of an LHC IR quadrupole SC magnet

- Liquid helium cooling channels

- Helium also in annular space between coil and beam pipe

- Particle beam

- Iron

- Superconducting Cable
LHC IR quad cooling scheme
LHC IR quad heat flow path

- Analyses of two heat load levels on next two slides
DT1: from the Q2b magnet thermal center
to the magnet end within the pressurized helium II, length = 2.8 m

DT2: within the connecting pipe, three segments
L=15.1, D=8.57; L=12.5, D=10.16; L=70.0, D=9.84 cm

DT3: between connecting pipe and
He II heat exchanger, L=9.8 cm and D=9.84 cm.

DT4: within the pressurized He II side of He II heat exchanger, L=450 cm, D_in=9.6 cm, D_out=16 cm.

DT5: across the He II heat exchanger wall.
assuming 22% wetted

DT6: due to the vapor pressure drop.
Vapor V= 336 cm/sec

Tsat (K) = 1.864
Q (W) = 205.5
7.02 W/m

External HX 1X8.5/9.6 cm

| DT1 (mK) | 2.4 |
| DT2 (mK) | 4.5 |
| DT3 (mK) | 1.8 |
| DT4 (mK) | 0.5 |
| DT5 (mK) | 29.5 |
| DT6 (mK) | 7.7 |
| Total DT (mK) | 46.4 |
DT1: from the Q2b magnet thermal center
to the magnet end within the pressurized helium II, length = 2.8 m

DT2: within the connecting pipe, three segments
L=15.1, D=8.57; L=12.5, D=10.16; L=70.0, D=9.84 cm

DT3: between connecting pipe and
He II heat exchanger, L=9.8 cm and D=9.84 cm.

DT4: within the pressurized He II side of He II heat exchanger, L=450 cm, D_in=9.6 cm, D_out=16 cm.

DT5: across the He II heat exchanger wall.
assuming 22% wetted

DT6: due to the vapor pressure drop.
Vapor V= 611 cm/sec

Tsat(K) = 1.900
Q (W) = 414.2
14.14 W/m

<table>
<thead>
<tr>
<th>External HX 1X8.5/9.6 cm</th>
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<tbody>
<tr>
<td>DT1 (mK)</td>
</tr>
<tr>
<td>DT2 (mK)</td>
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<td>DT3 (mK)</td>
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<td>DT4 (mK)</td>
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<td>DT5 (mK)</td>
</tr>
<tr>
<td>DT6 (mK)</td>
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<td>Total DT (mK)</td>
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</table>
Dependence of temperature rise to the coil on yoke hole diameter for heat transport
Trade-off of annular gap height between beam tube and coil, and frequency of radial channels for heat transport out to the yoke holes.
Predicted beam tube helium temperature versus total heat load
Quench current study in our vertical test cryostat – heat generated from current ramp rate to simulate beam heating. Note decline of quench current in normal helium.
Conclusion

• Analyses helped to define channel parameters for cooling the LHC final focus quadrupoles
• The thermal design was also checked with various tests including operation of a dedicated heat transfer model (heaters and pipes) cooled with helium II in a configuration similar to the magnets
• It all works. These magnets focus the LHC beam into the detectors in LHC, meet specifications, and were a critical part of the accelerator in finding the Higgs
Detector magnets

• Different size, shape, and conductor requirements result in different cooling schemes for detector magnets
  – Different from accelerator beamline magnets
  – Various options and design examples for various detectors

• Here I describe a mu2e large magnet cooling concept as an example of thermal siphon cooling
  – Thanks Nandhini Dhanaraj for the slides!
• The Transport Solenoid transport the muons produced in the production solenoid to the detector solenoid whilst filtering unwanted particles along its path.

• The Transport Solenoid has an upstream section and a down stream section which house the magnetic coils within aluminum housings.

• The heat load generated by these coils during operation and the heat loads on the supports will have to be cooled to maintain superconductivity of the solenoid.
Cryogenic Specifications

• The Transport Solenoid will be indirectly/conductively cooled by running 4.5 K helium along the cooling circuit.

• The magnet heat load at 4.5 K is estimated to be around 40 W each for the upstream and downstream sections and about 80% of this is expected at the supports via conduction.

• A conservative estimate of 15 W has been considered for the heat load generated by the coils.

• This is a low enough heat load to incorporate a Thermosiphon cooling scheme for the solenoid.
Thermosiphon Cooling Scheme

- Thermosiphon is a cooling scheme which utilizes the density difference between the liquid and the vapor/warm liquid phase of a coolant as the driving force.
- Thermosiphon is very efficient for low load systems as it eliminates the need for a circulating pump.
- Provides nearly isothermal cooling with no added load from pump work.
- Designing a thermosiphon cooling system involves characterizing the pipe geometry, verification of heat flux and flow regimes and required liquid head.
## Thermosiphon Cooling Tube Selection

### Design Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<td>Estimated Heat Load for TSu</td>
<td>15 Watts</td>
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<tr>
<td>Siphon pipe ID</td>
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<tr>
<td>Siphon pipe length</td>
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<td>Siphon pipe surface</td>
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<td>Fraction of surface heat transfer</td>
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<tr>
<td>Surface heat flux</td>
<td>0.0021 W/cm²²</td>
</tr>
</tbody>
</table>

1/2" diameter bolts -> 4.18 W/K conductance
Spacing of bolts 7.6 cm

**Diagram Notes:**
- He Al saddle
- Conductance per unit length of tube of 49 W/m-K.
- Al thermal bridge (40 cm long azimuthally)
- Al strips: 2 mm x 50 mm, 2 strips/coil
- Contact simulation
- G10 insulation: 4 mm @OD, 2 mm @ID and sides
- Al sheet 2 mm all along IR
Flow Regimes

- Natural Convection
- Nucleate Boiling
- Film Boiling

Graph showing $q$ vs $\Delta T_b$ (K) with curves for nucleate boiling, film boiling, and convection cooling.
TSu Cooling Layout

- HGR Pipe
- Siphon Tubes
- Helium fill pipe
- Helium Supply

Solid Model of TSu - D. Evbota
## Design Comparison

<table>
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<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
<th>MICE</th>
<th>T5u-FNAL</th>
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<td><strong>Cooling Scheme</strong></td>
<td>Forced, Thermosiphon (backup)</td>
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<tr>
<td><strong>Tube ID (cm)</strong></td>
<td>1.8</td>
<td>1.4</td>
<td>2.2</td>
<td>2.54</td>
</tr>
<tr>
<td><strong>Number of tubes</strong></td>
<td>2</td>
<td>96</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td><strong>Length (cm)</strong></td>
<td>3600</td>
<td>?</td>
<td>?</td>
<td>373.6</td>
</tr>
<tr>
<td><strong>Heat Transfer Fraction (assumed)</strong></td>
<td>0.3</td>
<td>?</td>
<td>?</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Heat Flux (W/cm^2)</strong></td>
<td>0.008</td>
<td>0.0012</td>
<td>0.00025</td>
<td>0.002</td>
</tr>
</tbody>
</table>
Thermal siphon comments

• Low heat flux and low vapor fraction required
  – Correlations for avoiding plug flow which would lift liquid out of the tubes
  – Parallel flow paths with no independent control of flow

• Cool-down and warm-up provisions may require some special valve arrangements to permit forced flow

• See the paper by B. Baudouy (references) for a nice report on some thermal siphon test data.
References-1

References-2