Cryogenics for Superconducting Magnets

Tom Peterson, SLAC

USPAS

June, 2019

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

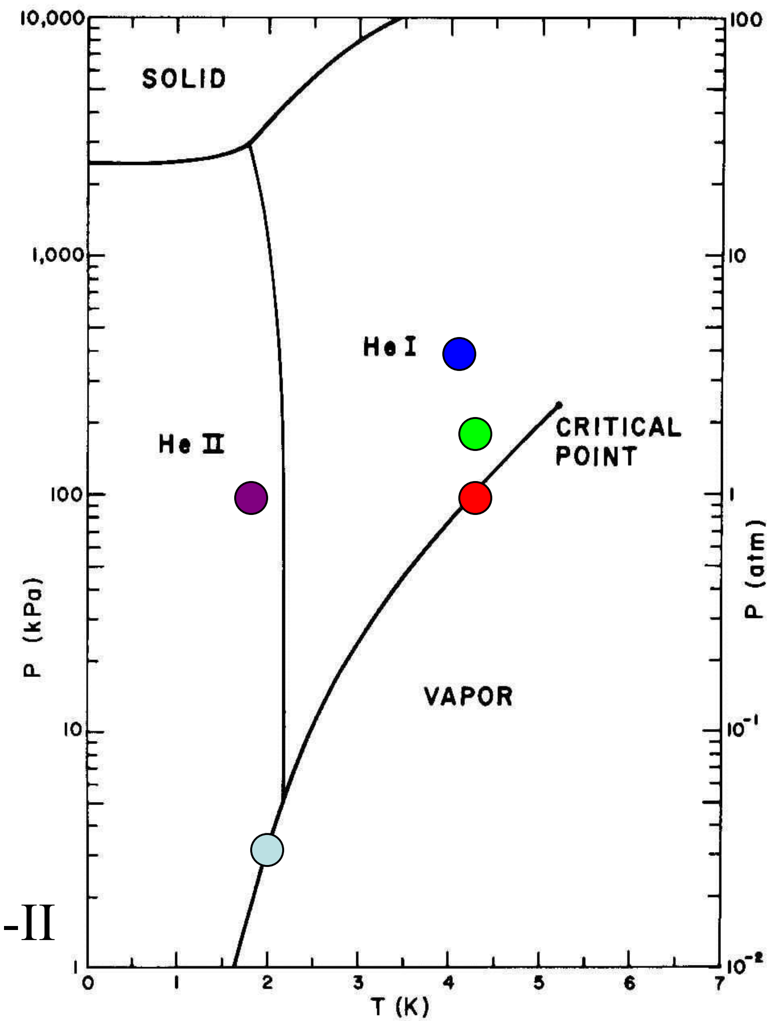


Fig. 3.1. ^{4}He phase diagram.

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

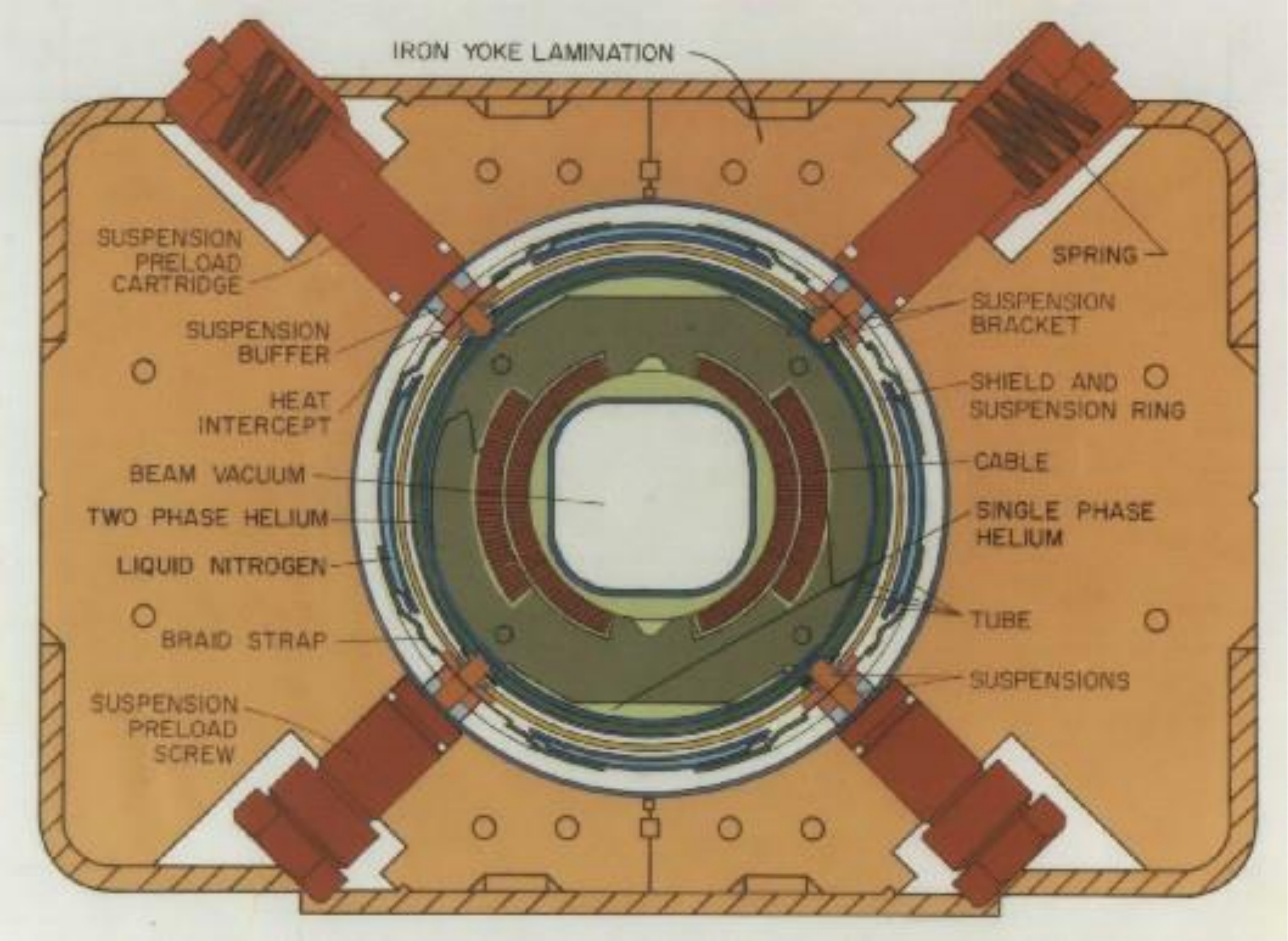
- Pressurized helium (normal or superfluid) gives maximum penetration of helium mass in magnet coils, which may be a factor in stability if not also heat transfer. But heat flow results in a temperature rise.
- Pool boiling gives pressure stability (important for superconducting RF), provides maximum local heat transfer, and provides nearly isothermal cooling.

Tevatron

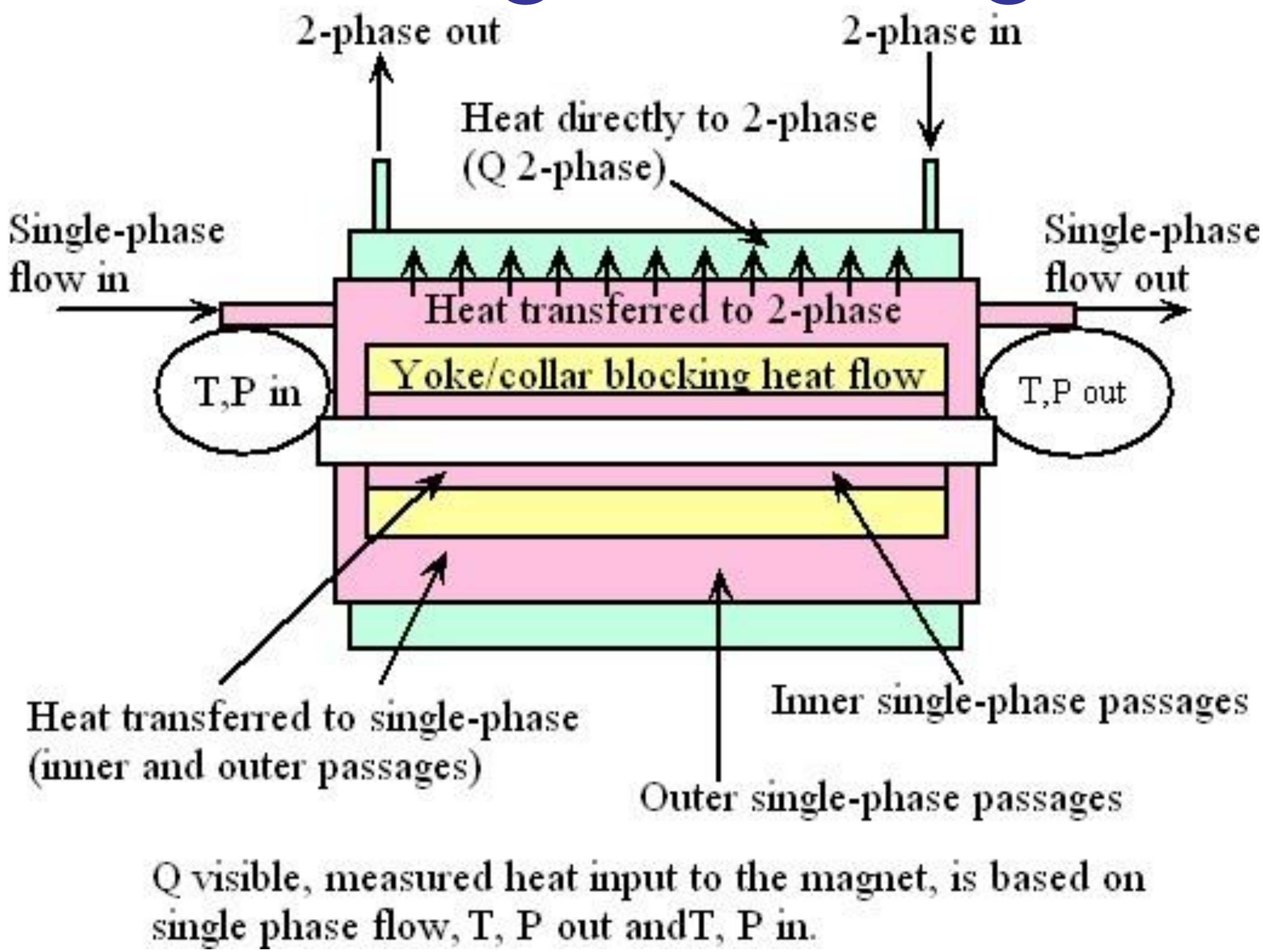
Fermilab's magnet cooling scheme

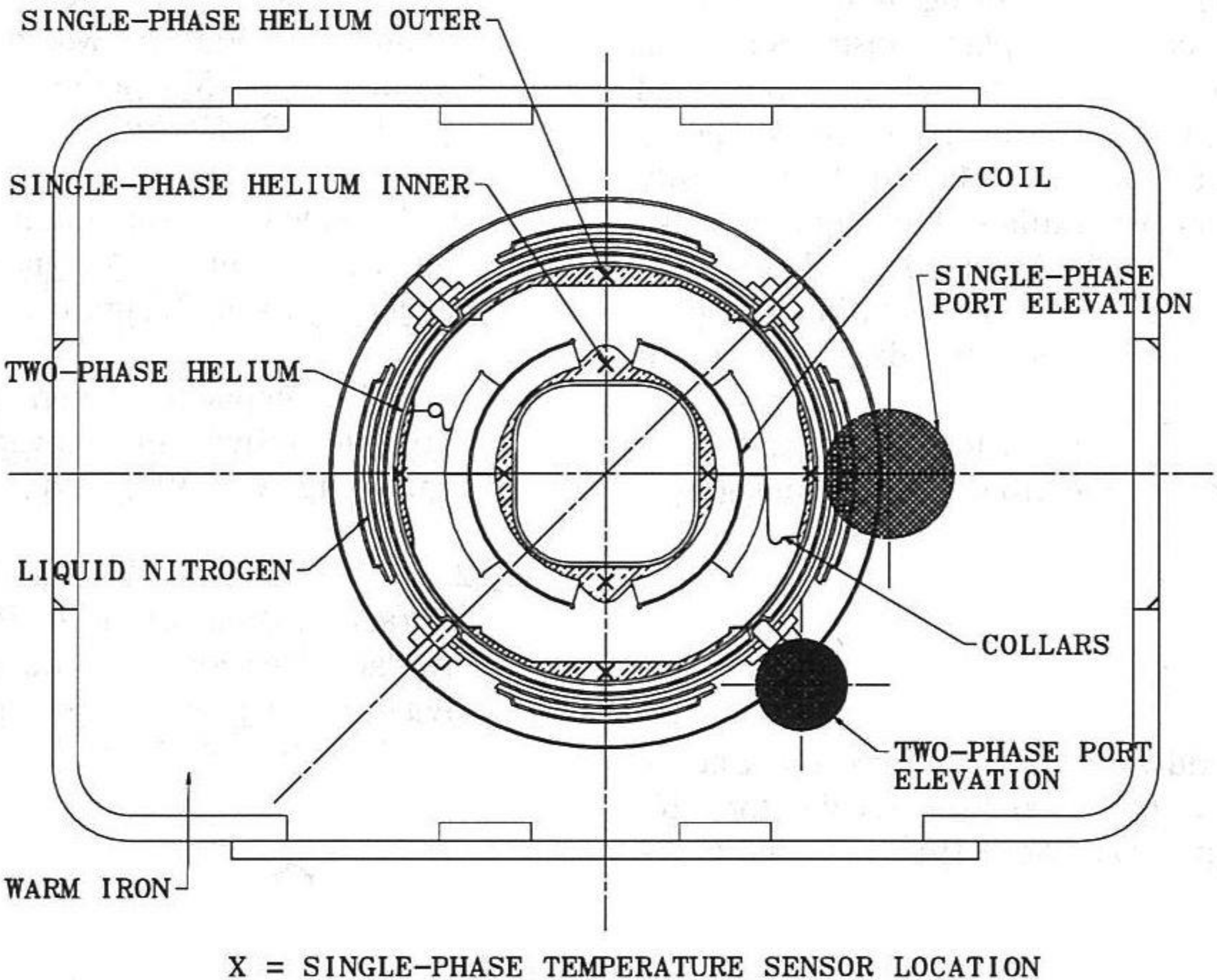
- Rapid cycling machine originally designed for fixed target physics implied warm iron magnets
- Warm iron constrained cryostat and helium channels to small diameter
  - Which resulted in somewhat larger static heat
  - plus high pressure drop
- Two phase helium flow to remove static heat
  - Coil bathed 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



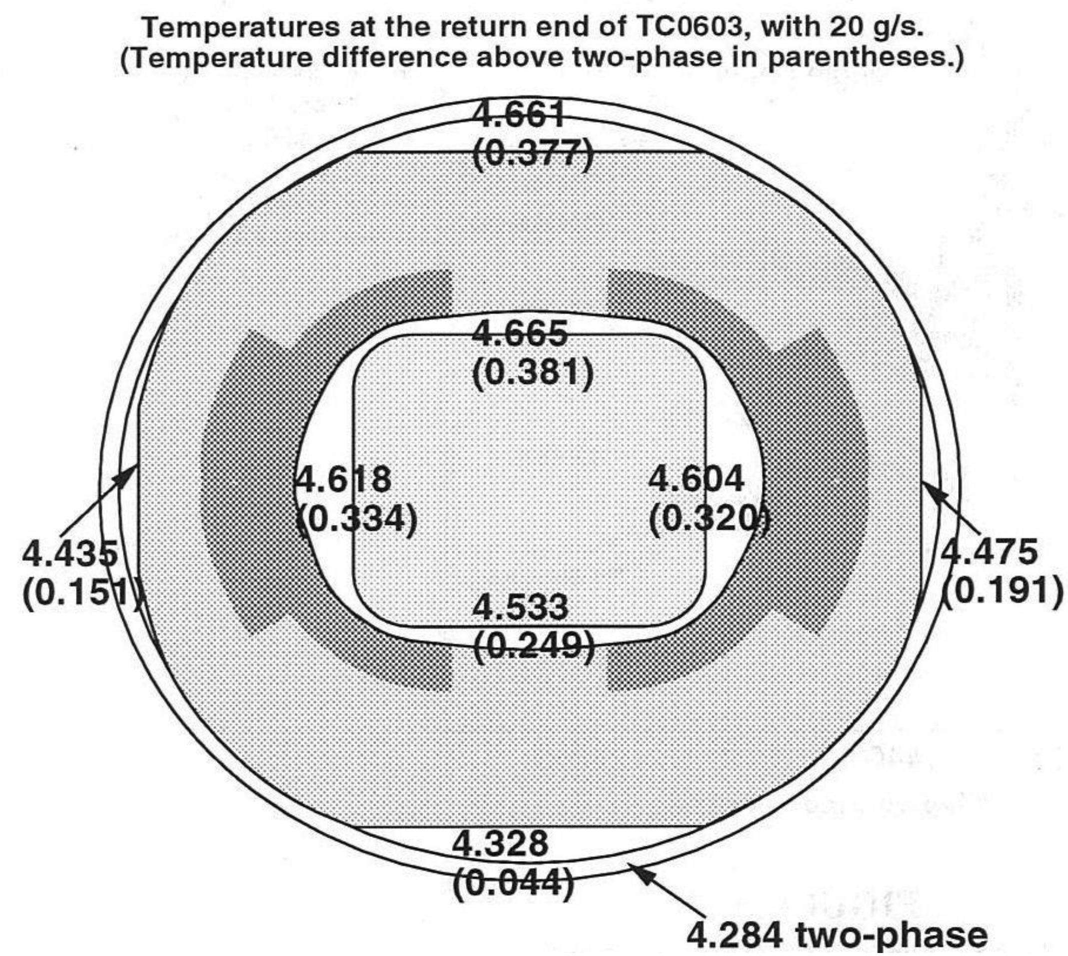


TEVATRON CROSS-SECTION at SUSPENSION

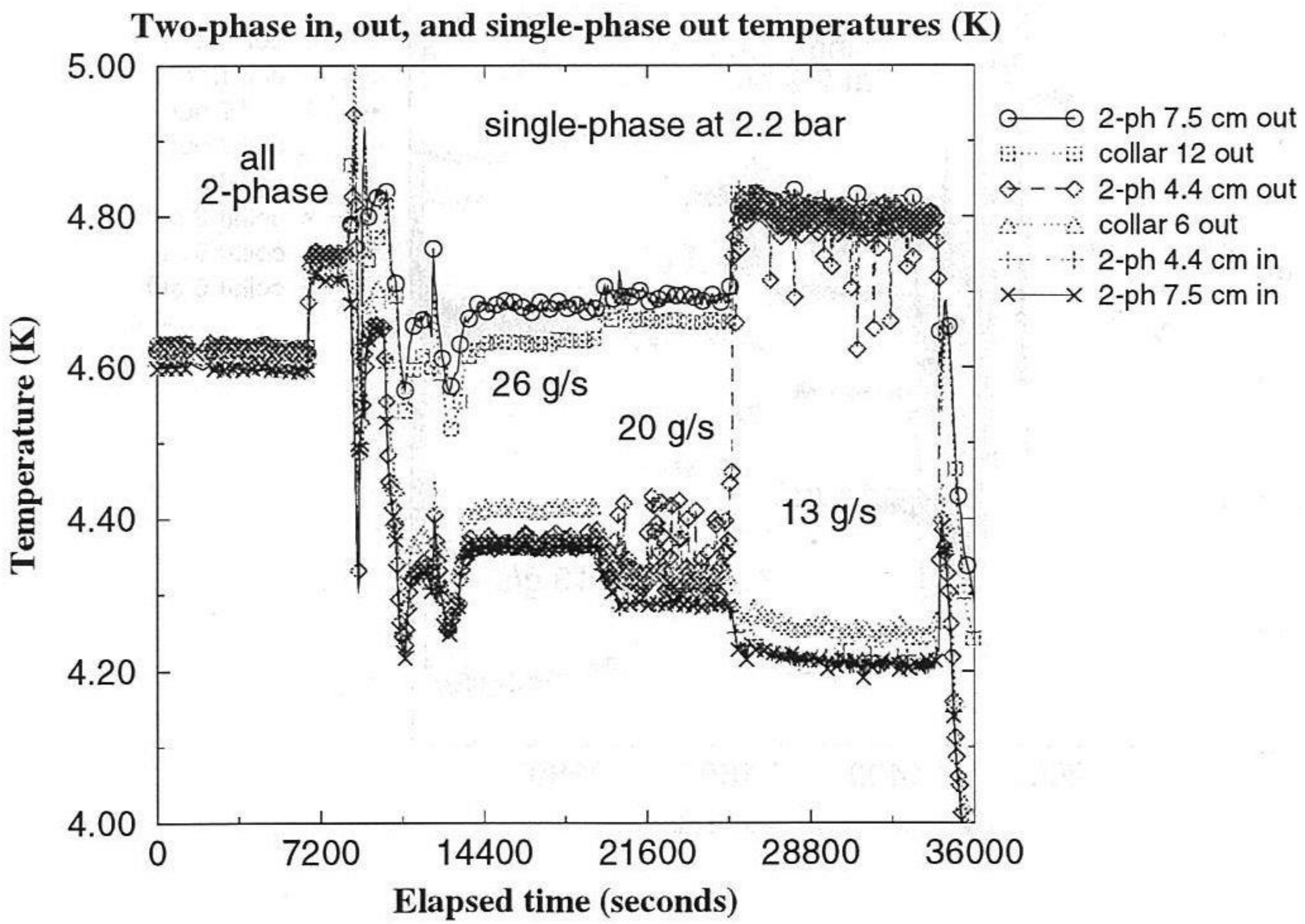
Tevatron dipole cooling issue

- 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



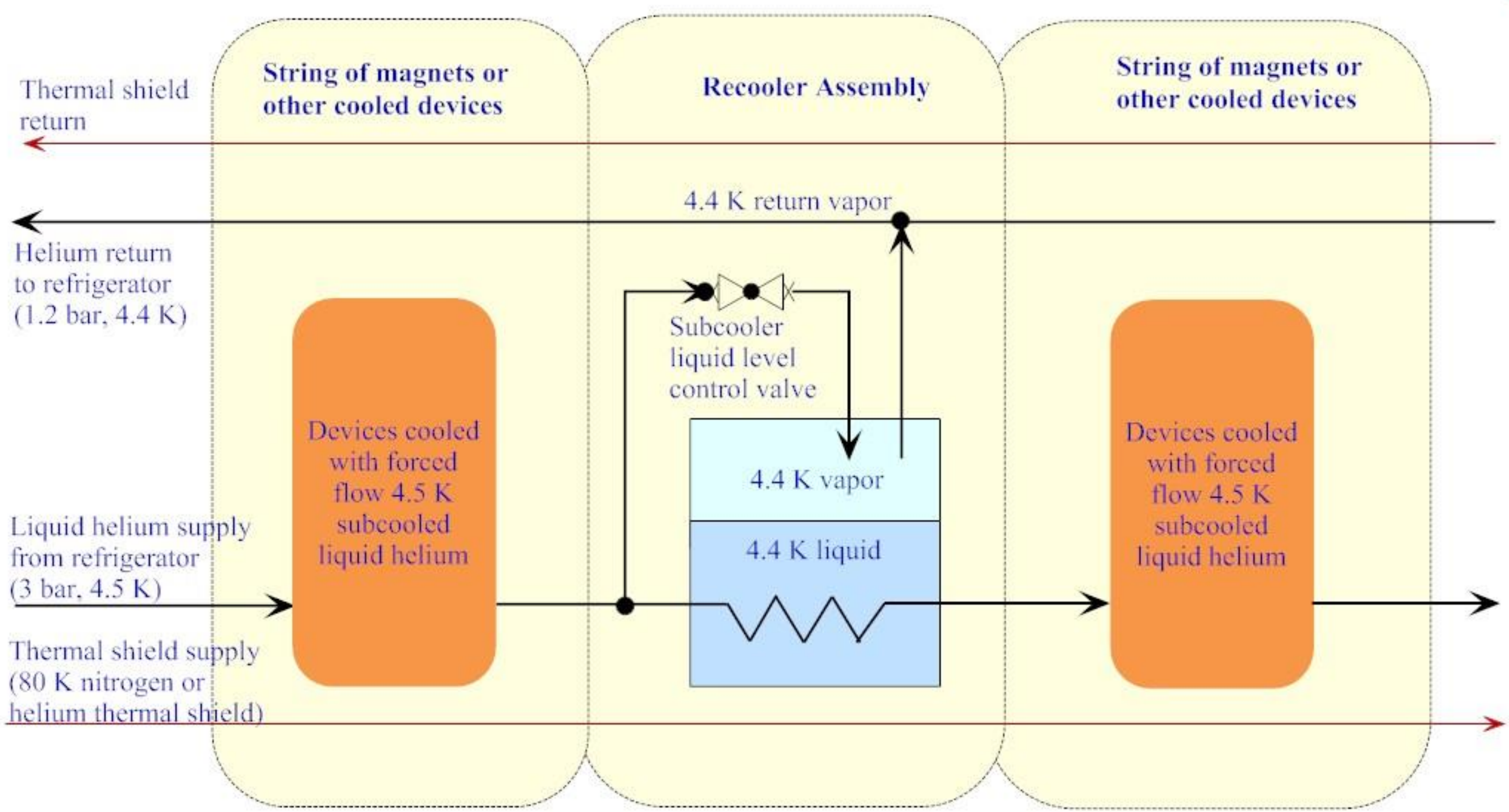
Measured temperatures plotted



Conclusion – dramatic stratification

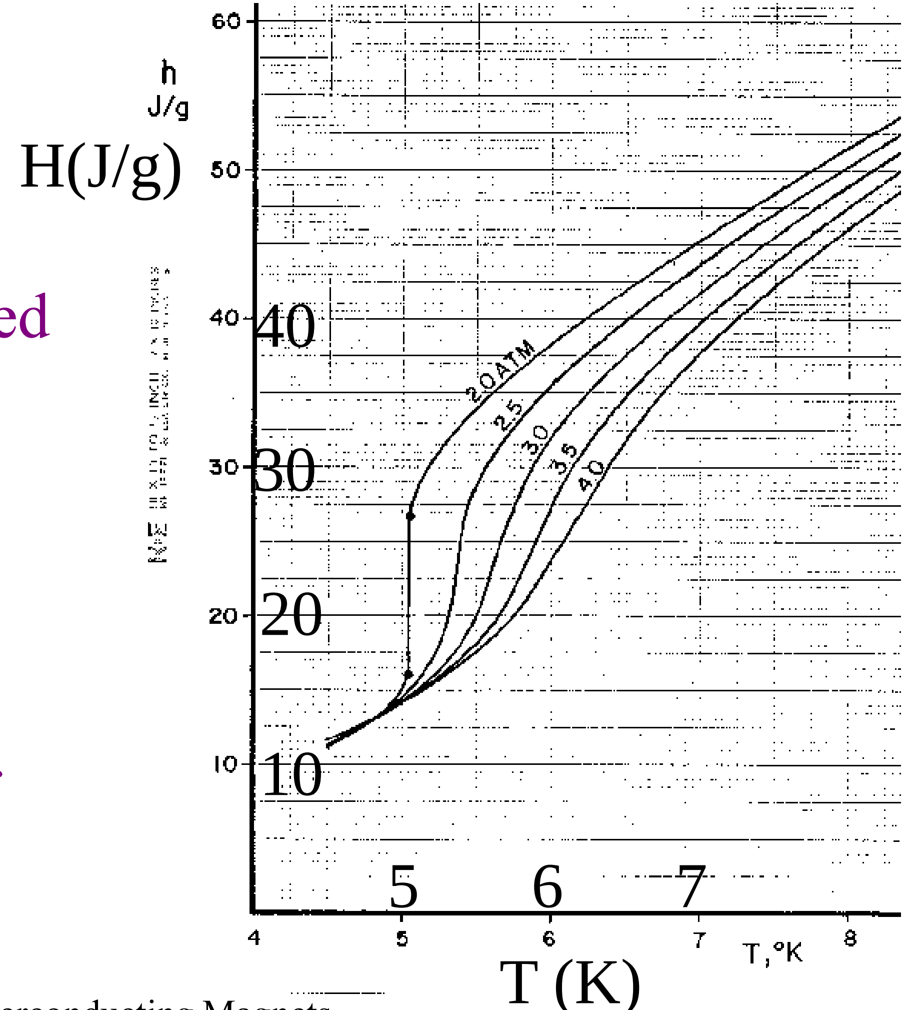
- Tevatron dipole cooling flow was indeed quite stratified
- The low liquid level on the 2-phase side contributed to this stratification
- Not much could be done about it – we ran successfully at 980 GeV

Recooler flow scheme



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

Temperature (K)	Pressure (bar)	Density (g/ml)	Volume (ml/g)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar)	Viscosity (uPa*s)	Therm. Cond. (W/m*K)	Phase
4.3000	3.0000	0.13306	7.5155	-1.4177	0.83691	-0.16434	2.4818	4.1903	211.04	-0.084703	3.5863	0.020198	liquid
4.4000	3.0000	0.13137	7.6122	-1.0173	1.2664	-0.065607	2.5000	4.4039	207.13	-0.071477	3.5256	0.020263	liquid
4.5000	3.0000	0.12955	7.7190	-0.59704	1.7187	0.036015	2.5170	4.6465	202.94	-0.057246	3.4634	0.020306	liquid
4.6000	3.0000	0.12759	7.8378	-0.15435	2.1970	0.14114	2.5332	4.9277	198.43	-0.041725	3.3995	0.020330	liquid
4.7000	3.0000	0.12545	7.9714	0.31450	2.7059	0.25058	2.5491	5.2611	193.55	-0.024548	3.3334	0.020335	liquid
4.8000	3.0000	0.12310	8.1236	0.81457	3.2516	0.36545	2.5652	5.6674	188.25	-0.0052266	3.2644	0.020325	liquid
4.9000	3.0000	0.12048	8.2998	1.3530	3.8429	0.48735	2.5820	6.1797	182.43	0.016921	3.1917	0.020301	liquid
5.0000	3.0000	0.11753	8.5085	1.9404	4.4930	0.61865	2.6002	6.8544	175.99	0.042887	3.1139	0.020266	liquid

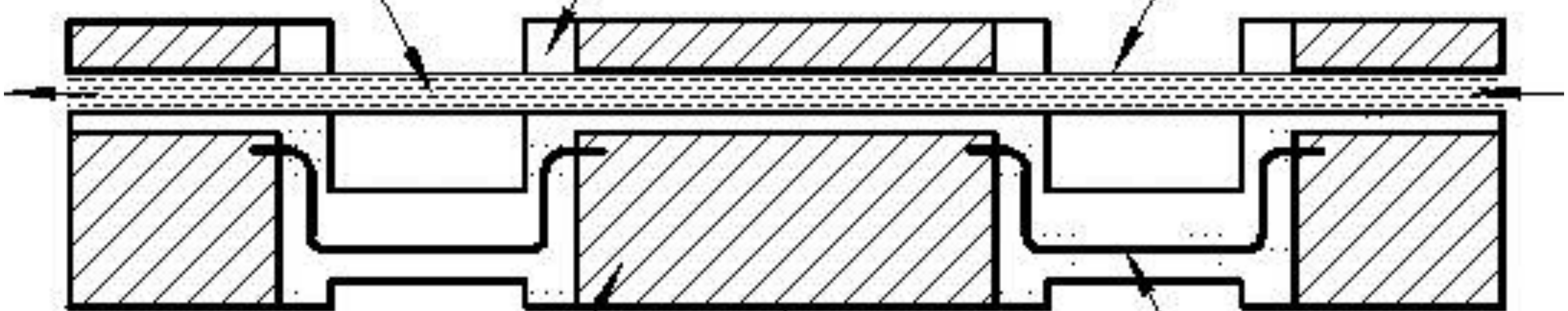
Isobaric Data for P = 4.0000 bar

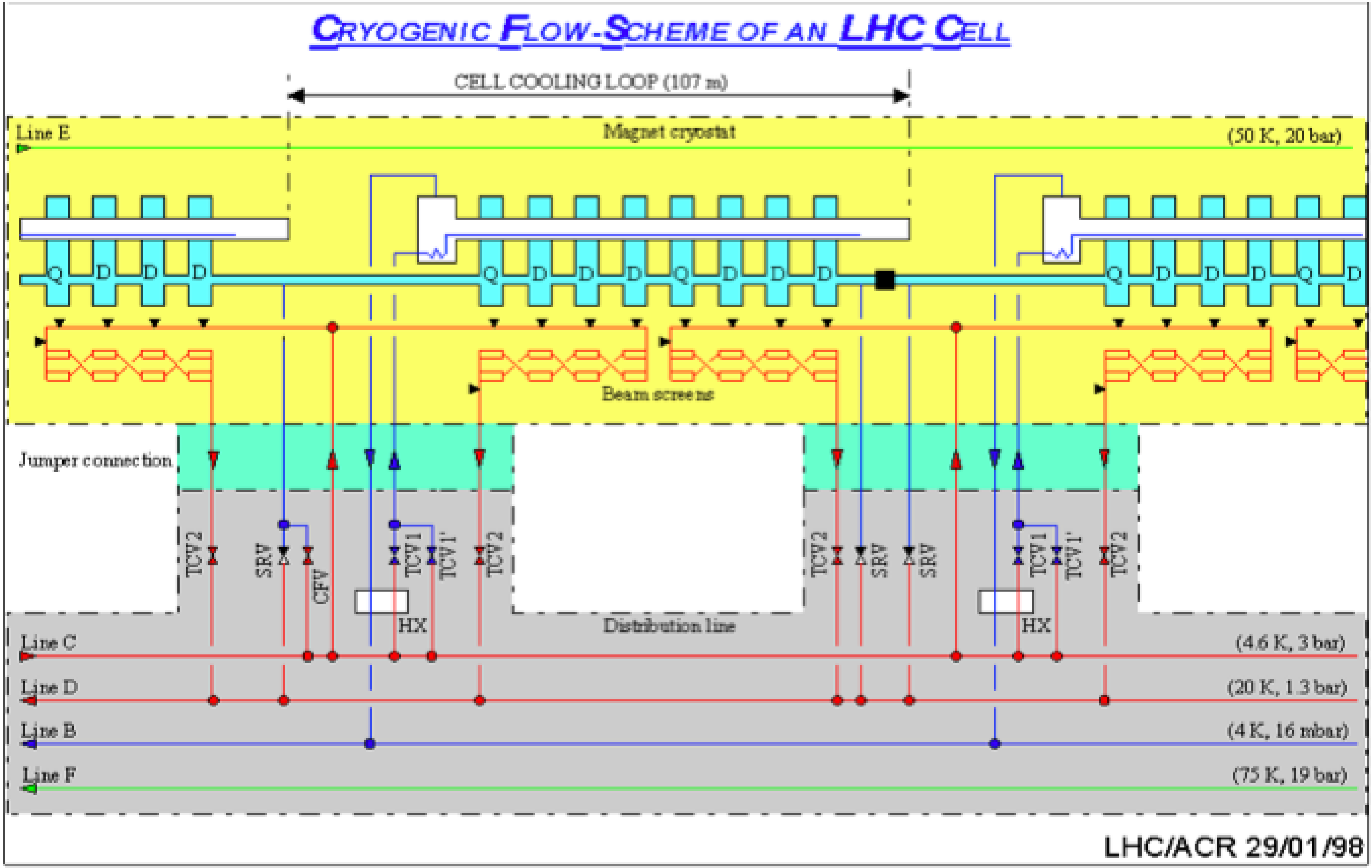
Temperature (K)	Pressure (bar)	Density (g/ml)	Volume (ml/g)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/bar)	Viscosity (uPa*s)	Therm. Cond. (W/m*K)	Phase
4.3000	4.0000	0.13650	7.3261	-1.7089	1.2215	-0.24739	2.4498	3.8925	224.96	-0.10514	3.7825	0.020796	liquid
4.4000	4.0000	0.13506	7.4042	-1.3430	1.6187	-0.15609	2.4675	4.0530	221.78	-0.094509	3.7252	0.020896	liquid
4.5000	4.0000	0.13353	7.4888	-0.96295	2.0326	-0.063079	2.4837	4.2276	218.43	-0.083414	3.6675	0.020976	liquid
4.6000	4.0000	0.13191	7.5807	-0.56750	2.4648	0.031906	2.4988	4.4197	214.87	-0.071729	3.6092	0.021039	liquid
4.7000	4.0000	0.13019	7.6810	-0.15514	2.9172	0.12921	2.5132	4.6339	211.10	-0.059310	3.5502	0.021083	liquid
4.8000	4.0000	0.12835	7.7911	0.27604	3.3925	0.22925	2.5271	4.8759	207.09	-0.045986	3.4903	0.021111	liquid
4.9000	4.0000	0.12638	7.9129	0.72847	3.8936	0.33257	2.5410	5.1535	202.80	-0.031553	3.4293	0.021124	liquid
5.0000	4.0000	0.12425	8.0486	1.2053	4.4247	0.43986	2.5551	5.4770	198.22	-0.015756	3.3667	0.021124	liquid

From http://webbook.nist.gov/chemistry/fluid/

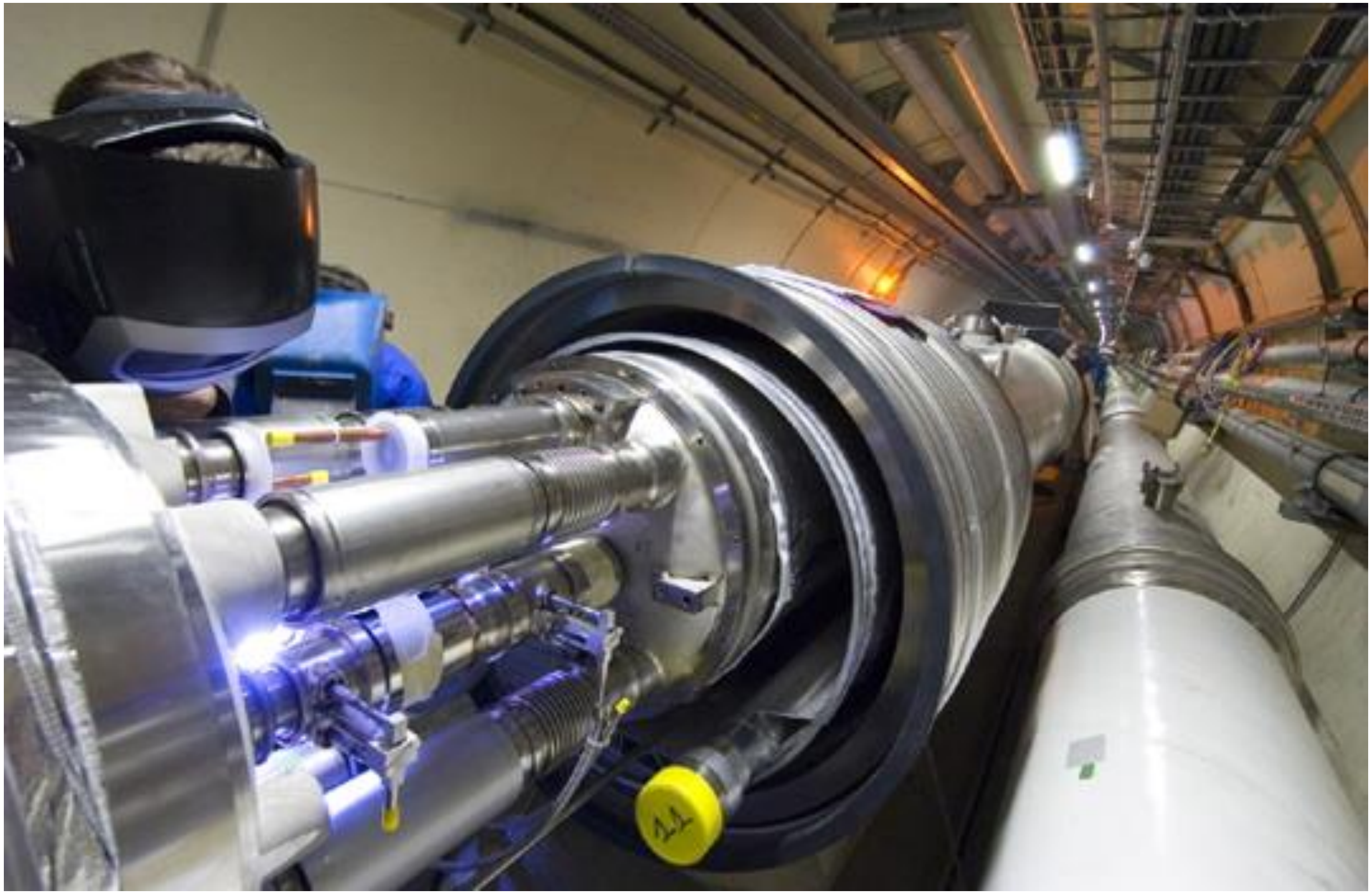
LHC magnet cooling scheme

similar to Tevatron in also being indirect cooling, i.e., helium-to-helium heat transfer in the magnets




CRYOGENIC FLOW-SCHEME OF AN LHC CELL
CELL COOLING LOOP (107 m)
Line E
Magnet cryostat
(50 K, 20 bar)
Q
D
Beam screens
Jumper connection
TCV 2
SRV
CFV
TCV 1
TCV 1'
HX
Distribution line
Line C
(4.6 K, 3 bar)
Line D
(20 K, 1.3 bar)
Line B
(4 K, 16 mbar)
Line F
(75 K, 19 bar)
LHC/ACR 29/01/98

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 ≅ 3 and q is the heat flux in W/cm^2.

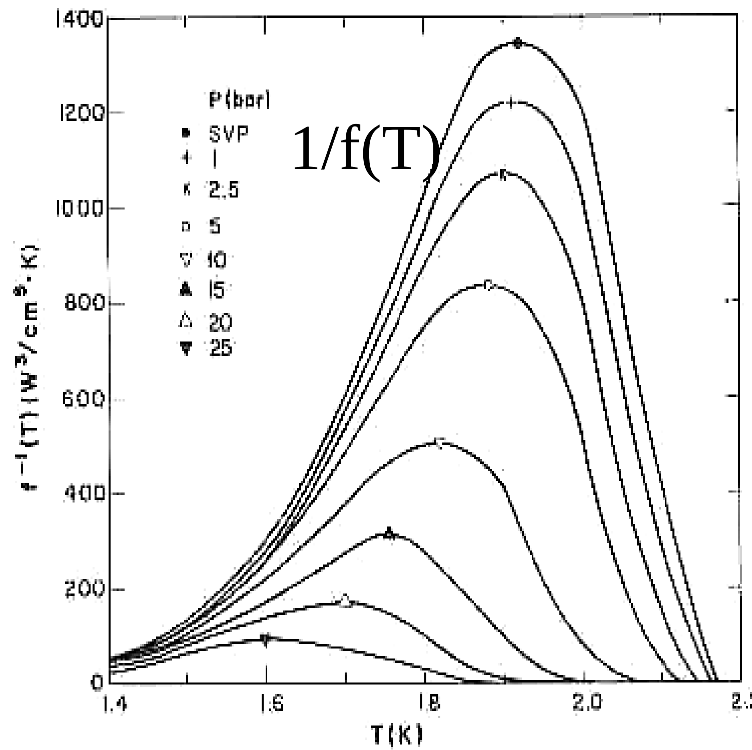
Superfluid Heat Transport Function

(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

$$\Delta T = \frac{q^3 L}{1200}$$

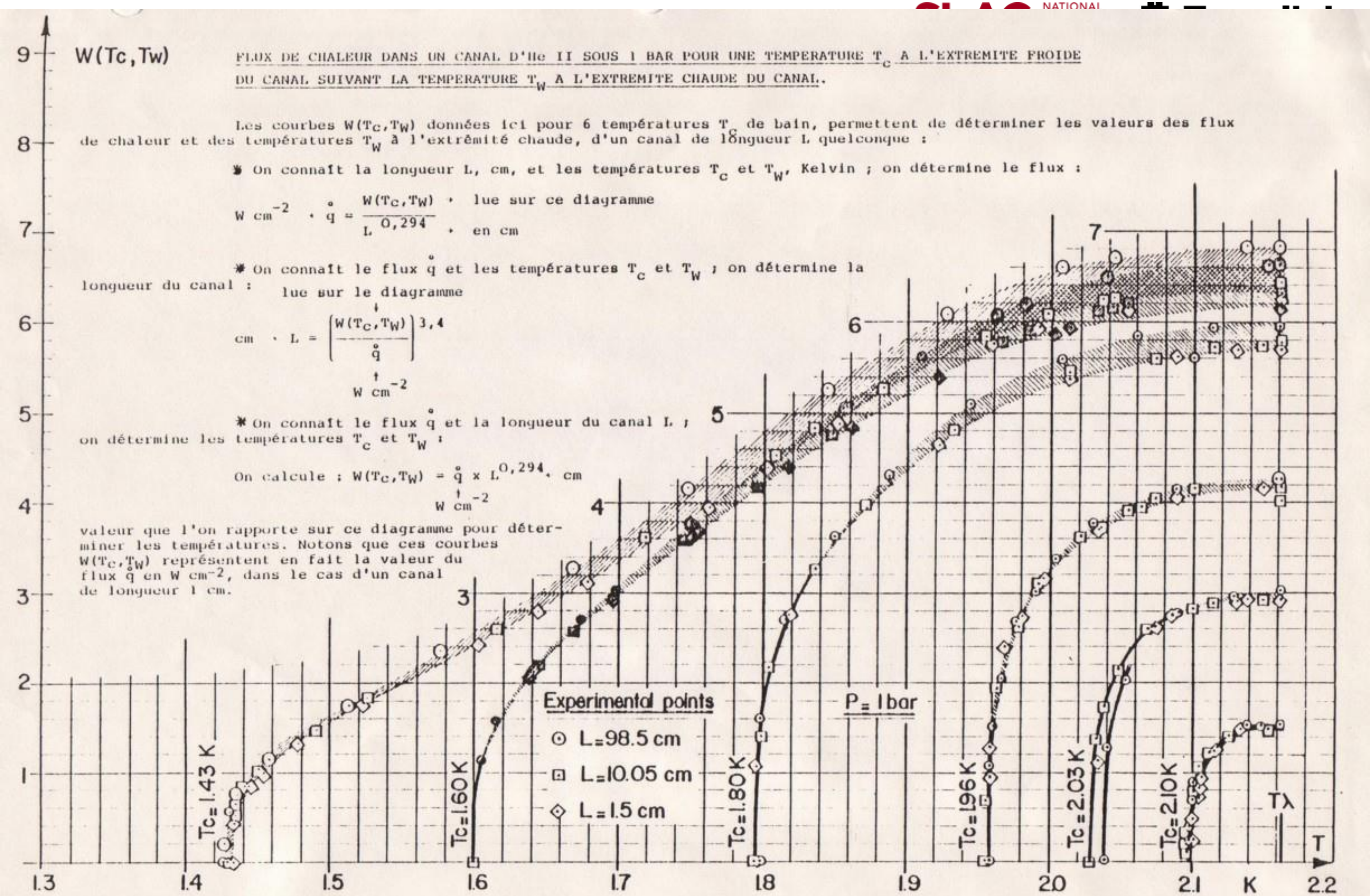
where L is distance in cm, and q is the heat flux in W/cm^2.



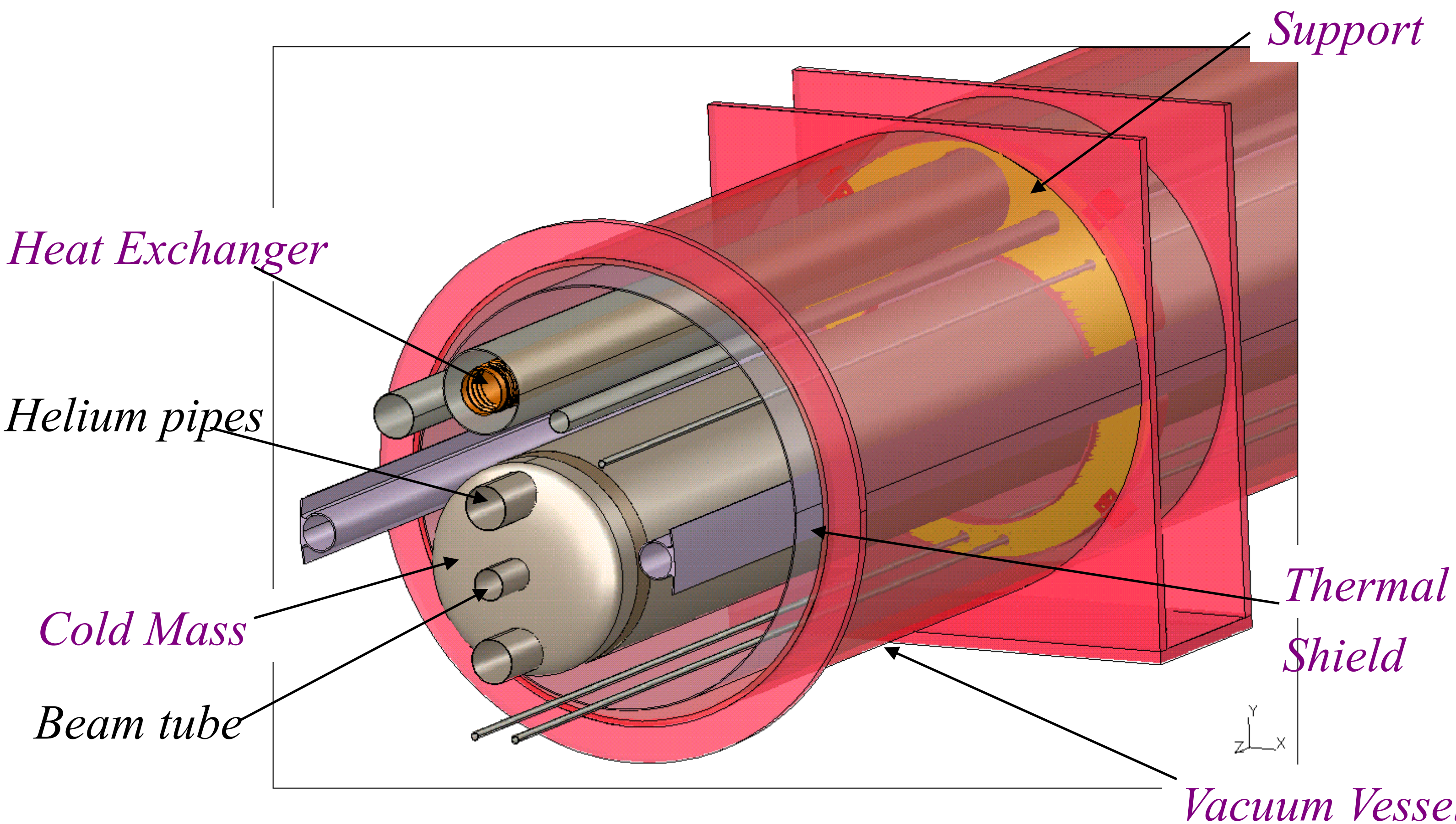
1.6 T(K) 2.0

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 Tc to T-lambda
- One then has $q \bullet L^{1/m} = W(Tc, Tw)$, where the function $W = (\int (dT/F(T)))^{1/m}$
  - Bon Mardion, et. al., use m = 3.4


W(Tc,Tw)
FLUX DE CHALEUR DANS UN CANAL D'He II SOUS 1 BAR POUR UNE TEMPERATURE T_c A L'EXTREMITE FROIDE DU CANAL SUIVANT LA TEMPERATURE T_W A L'EXTREMITE CHAUDE DU CANAL.
Les courbes $W(T_c,T_W)$ données ici pour 6 températures T_c de bain, permettent de déterminer les valeurs des flux de chaleur et des températures T_W à l'extrêmité chaude, d'un canal de longueur L quelconque :
* On connaît la longueur L, cm, et les températures T_c et T_W, Kelvin ; on détermine le flux :
$W\,cm^{-2} \cdot \dot{q} = \frac{W(T_c,T_W)}{L^{0,294}}$ · lue sur ce diagramme · en cm
* On connaît le flux $\dot{q}$ et les températures T_c et T_W ; on détermine la longueur du canal :
lue sur le diagramme
$cm \cdot L = \left[\frac{W(T_c,T_W)}{\dot{q}}\right]^{3,4}$
$W\,cm^{-2}$
* On connaît le flux $\dot{q}$ et la longueur du canal L ; on détermine les températures T_c et T_W :
On calcule : $W(T_c,T_W) = \dot{q} \times L^{0,294}$, cm
$W\,cm^{-2}$
valeur que l'on rapporte sur ce diagramme pour déterminer les températures. Notons que ces courbes $W(T_c,T_W)$ représentent en fait la valeur du flux $\dot{q}$ en $W\,cm^{-2}$, dans le cas d'un canal de longueur 1 cm.
Experimental points
L=98.5 cm
L=10.05 cm
L=1.5 cm
P=1bar
Tc=1.43 K
Tc=1.60 K
Tc=1.80 K
Tc=1.96 K
Tc=2.03 K
Tc=2.10 K
Tλ
T
K
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
1
2
3
4
5
6
7
8
9

LHC final focus quad sketch

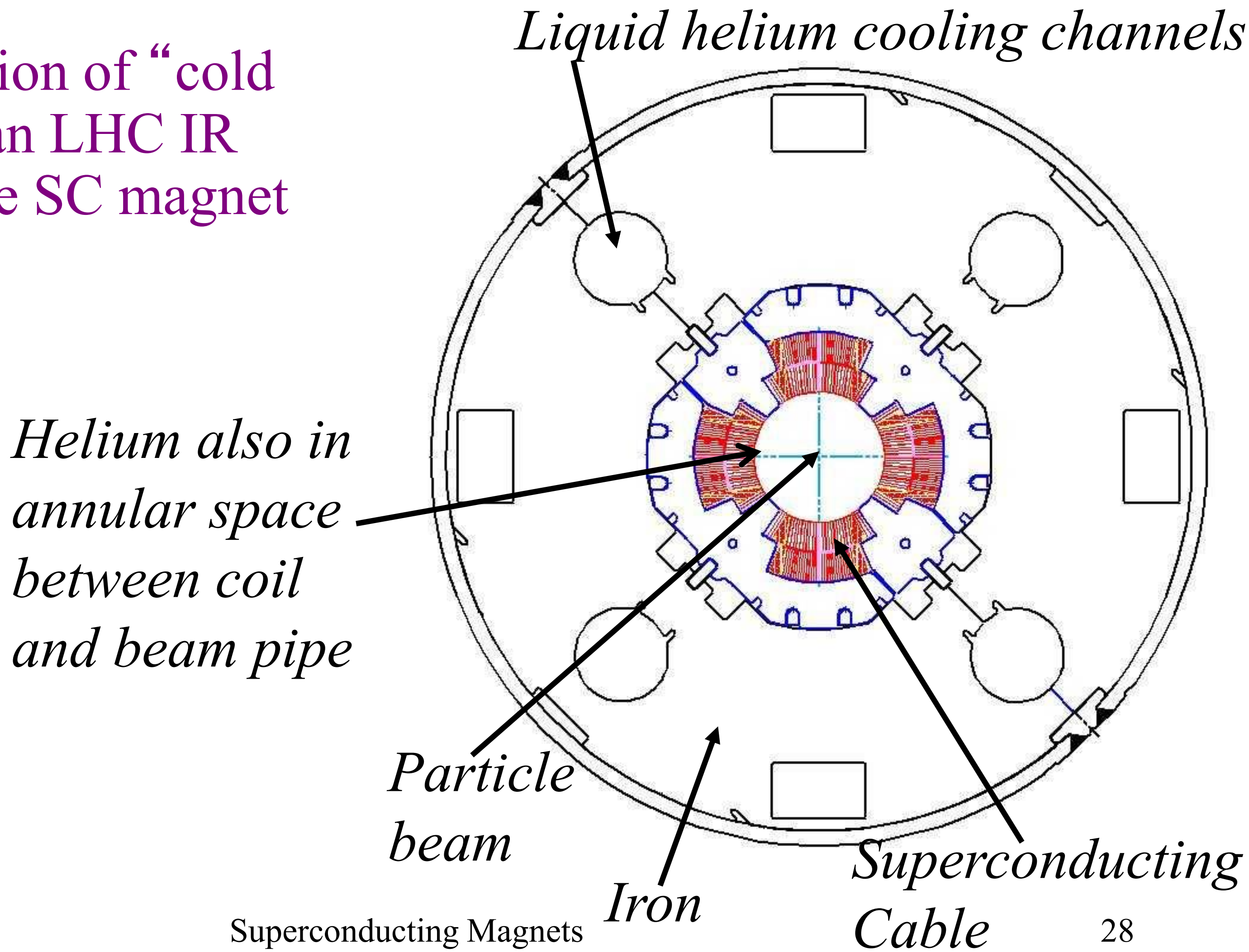


A superconducting magnet built by Fermilab for LHC at CERN in Geneva, Switzerland

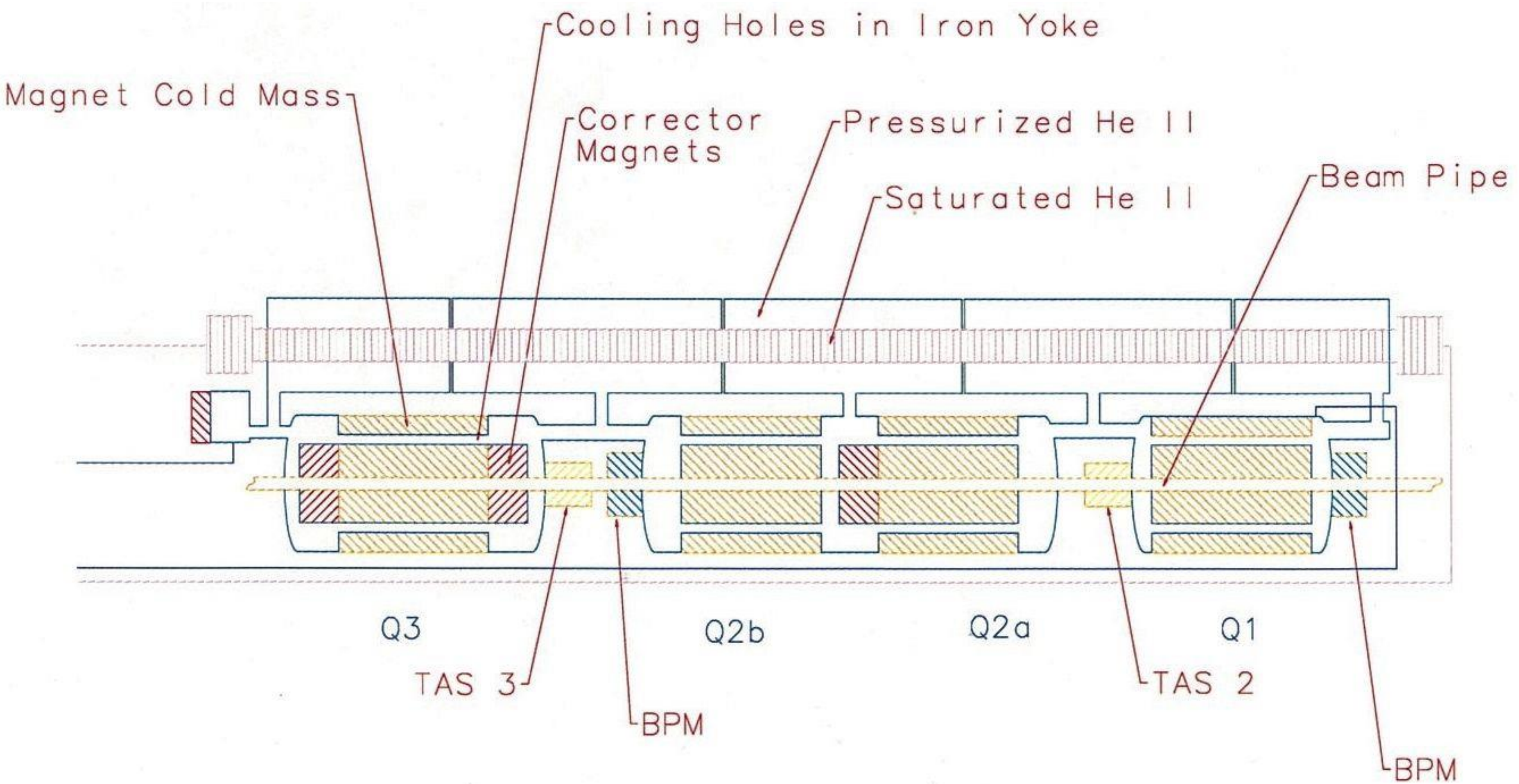
Consists of layers from cold inside to warm outside -- magnet, inner pipes, thermal insulation, steel vacuum container

LHC IR quadrupole cold mass

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

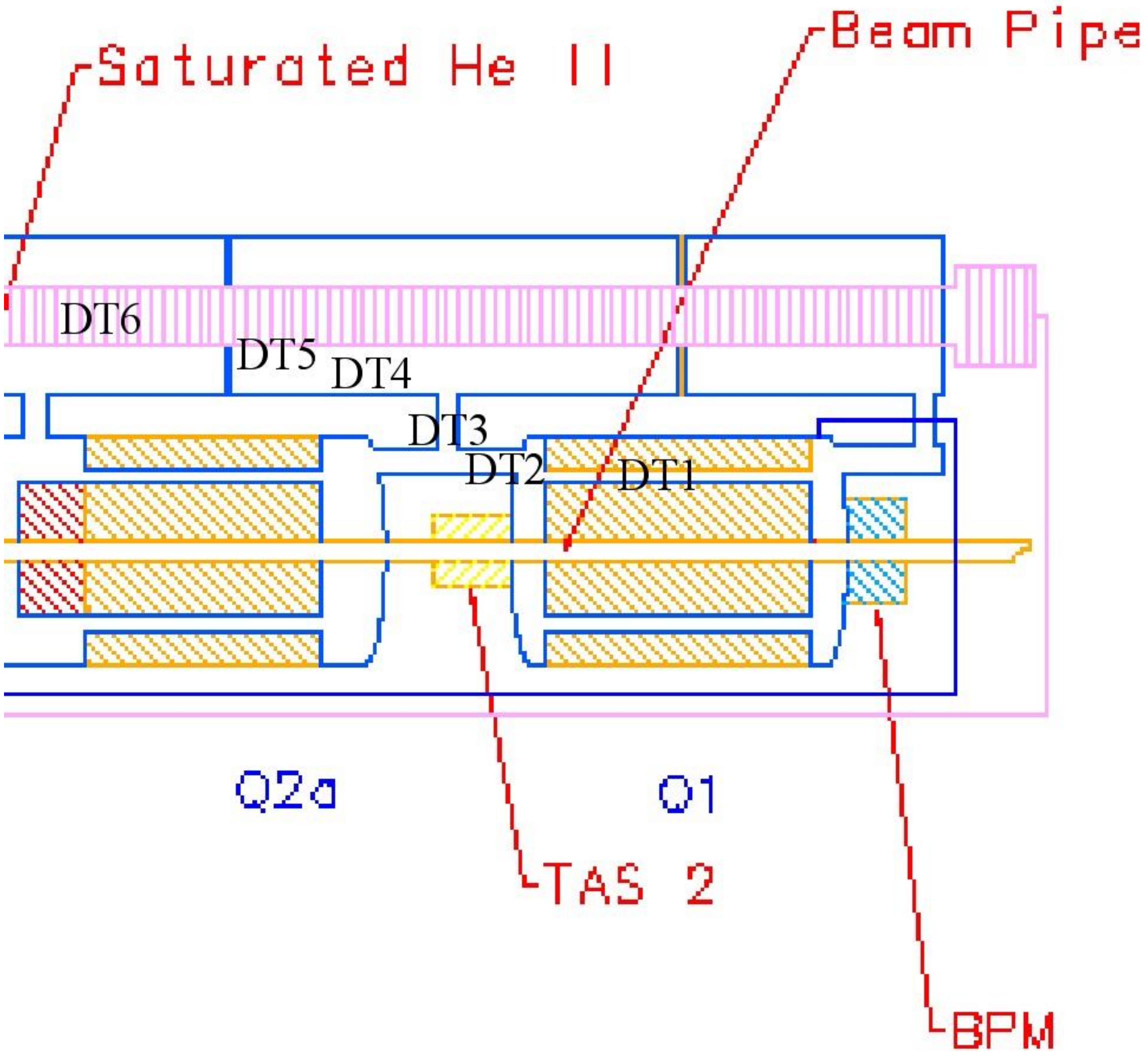


LHC IR quad cooling scheme



SLAC NATIONAL ACCELERATOR LABORATORY Fermilab

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.

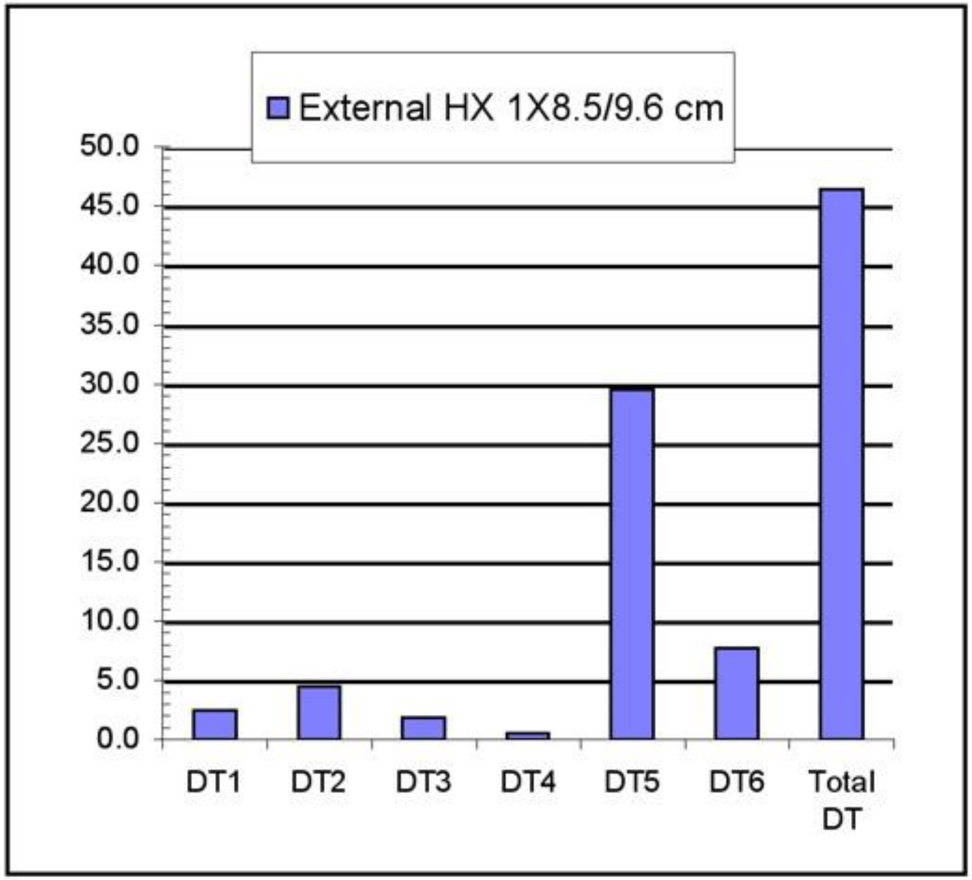
DT4: within the pressurized He II side of He II heat exchanger, L=450 cm, D_in=9.6 cm, D_out=16 cm.

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

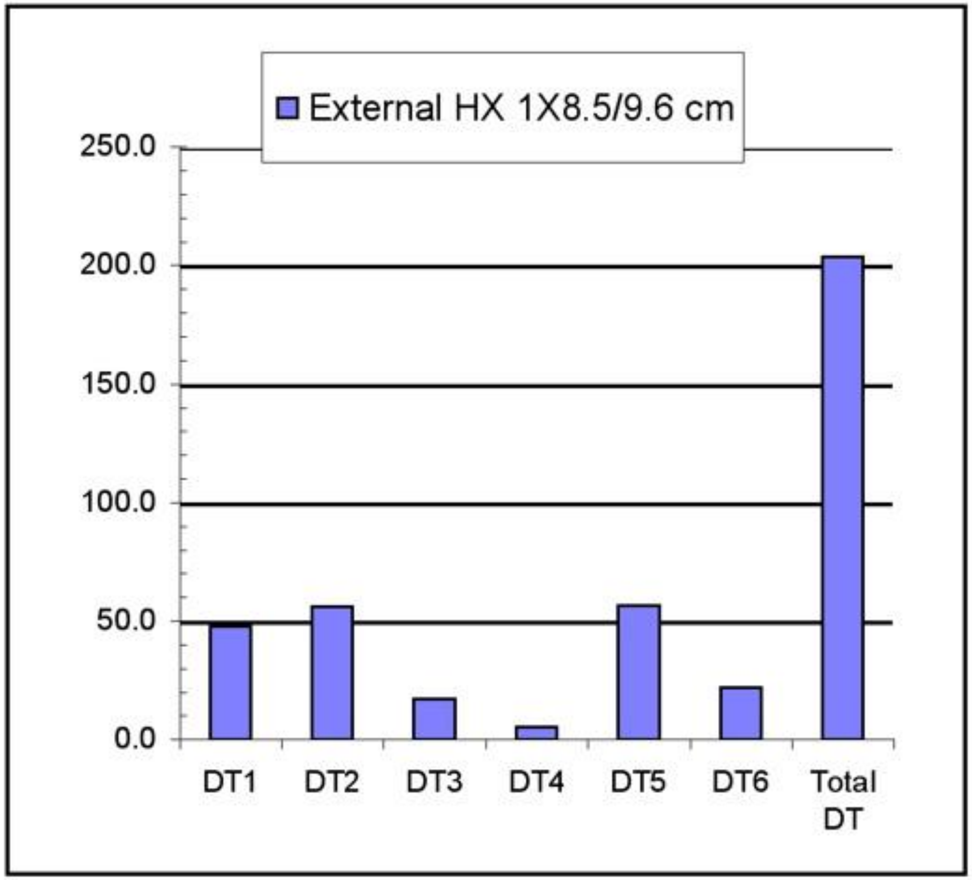
DT6: due to the vapor pressure drop.

Vapor V= 611 cm/sec

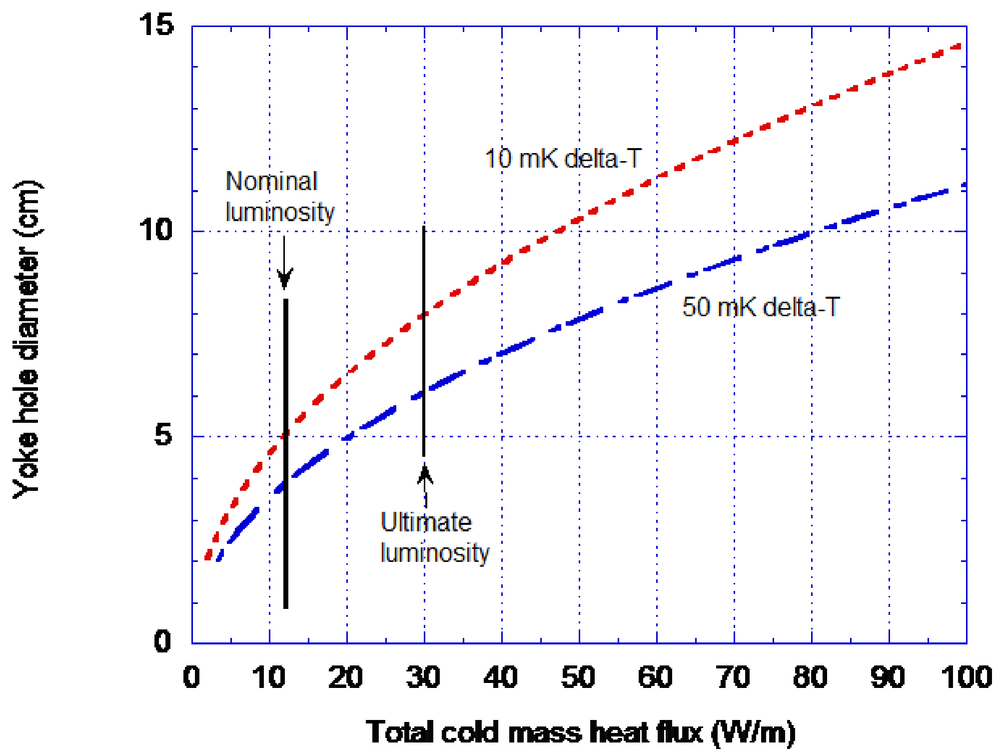
Tsat (K) = 1.900

Q (W) = 414.2 | 14.14 W/m

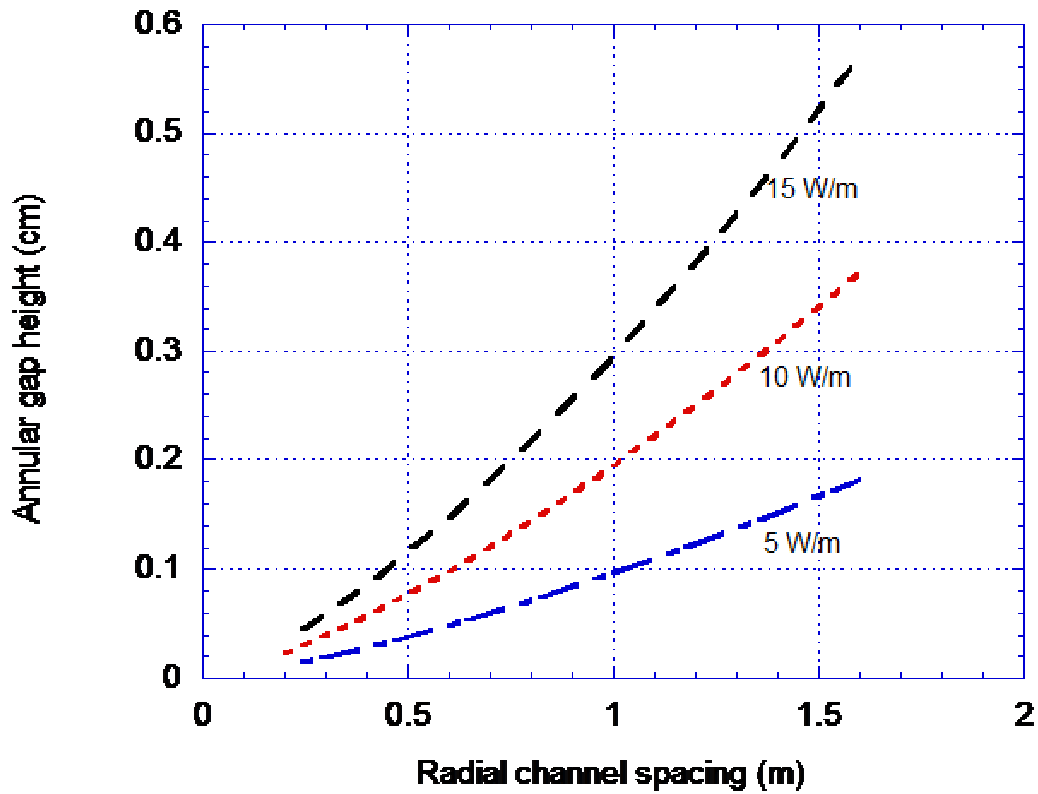
	External HX 1X8.5/9.6 cm
DT1 (mK)	47.6
DT2 (mK)	55.8
DT3 (mK)	17.0
DT4 (mK)	4.9
DT5 (mK)	56.6
DT6 (mK)	21.8
Total DT (mK)	203.7



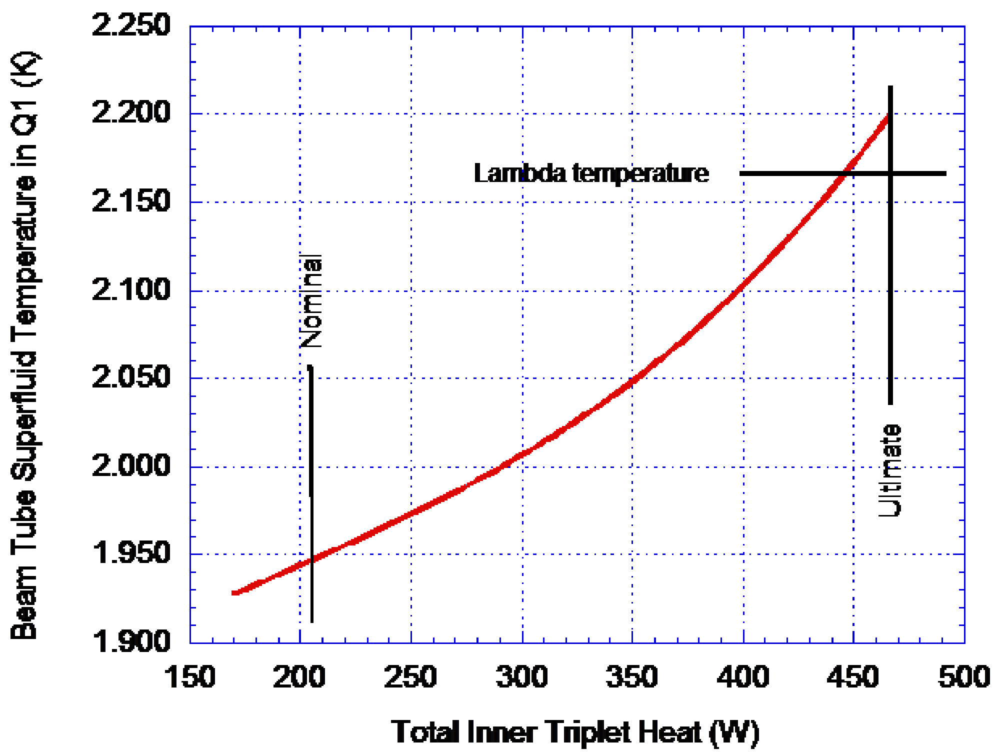
Dependence of temperature rise to the coil on yoke hole diameter for heat transport

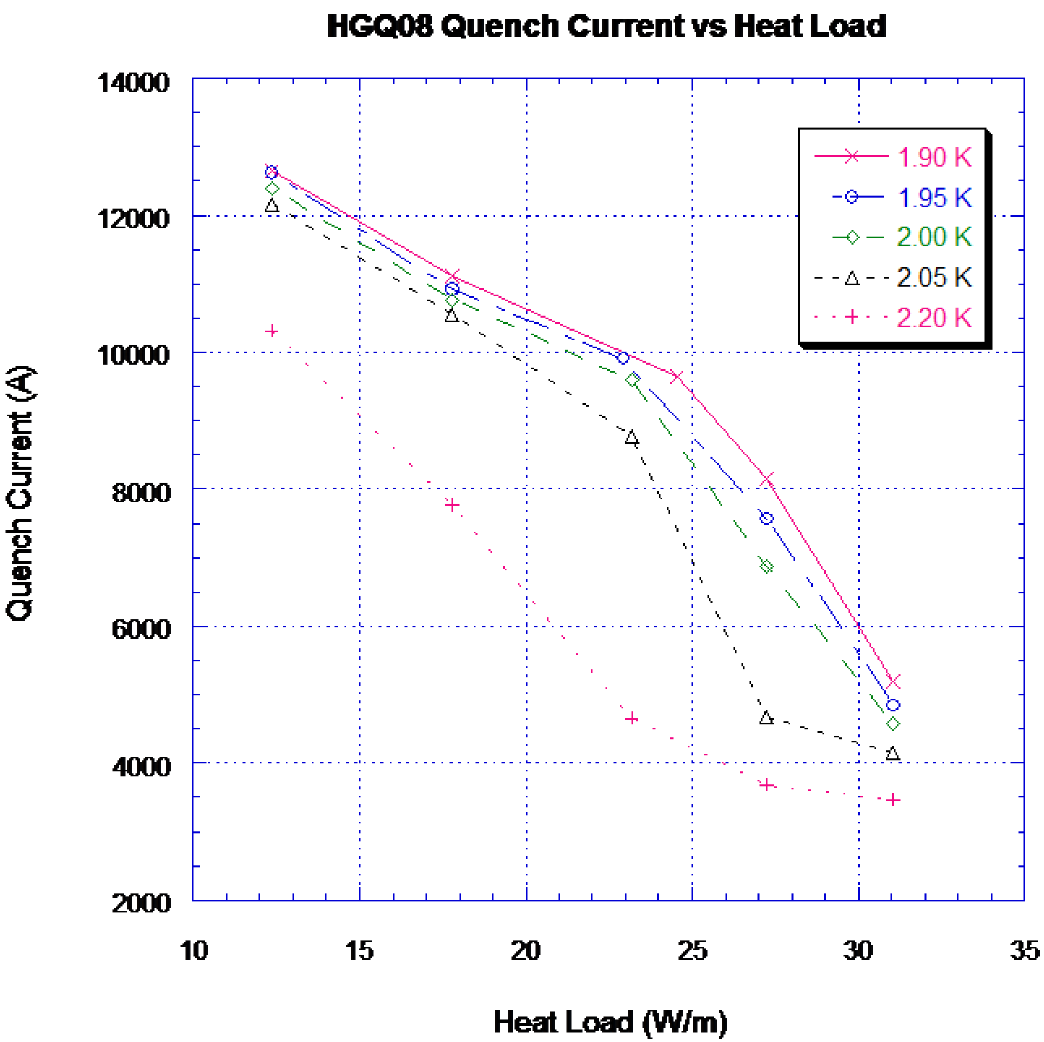


Trade-off of annular gap height between beam tube and coil, and frequency of radial channels for heat transport out to the yoke holes



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!

Background

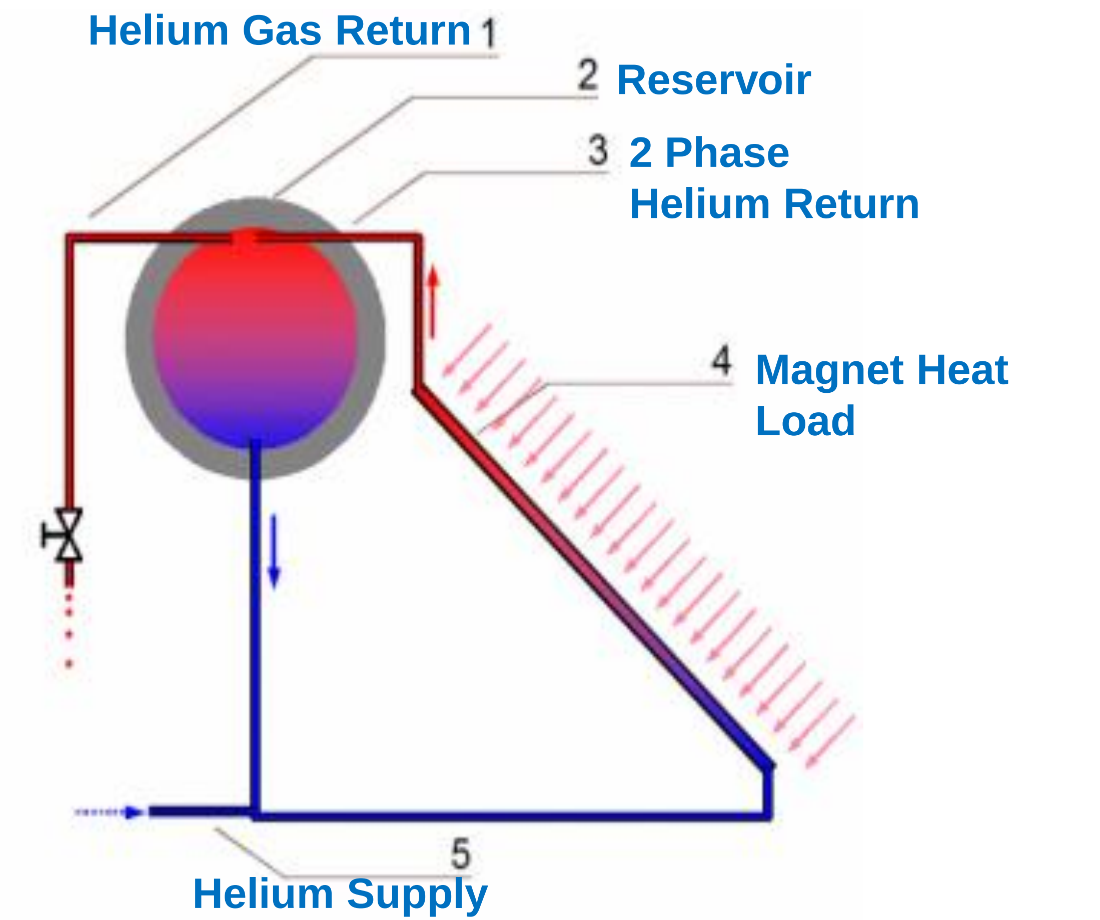
- The Transport Solenoid transport the muons produced in the production solenoid to the detector solenoid whilst filtering unwanted particles along its path.
- The Transport Solenoid has an upstream section and a down stream section which house the magnetic coils within aluminum housings.
- The heat 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.

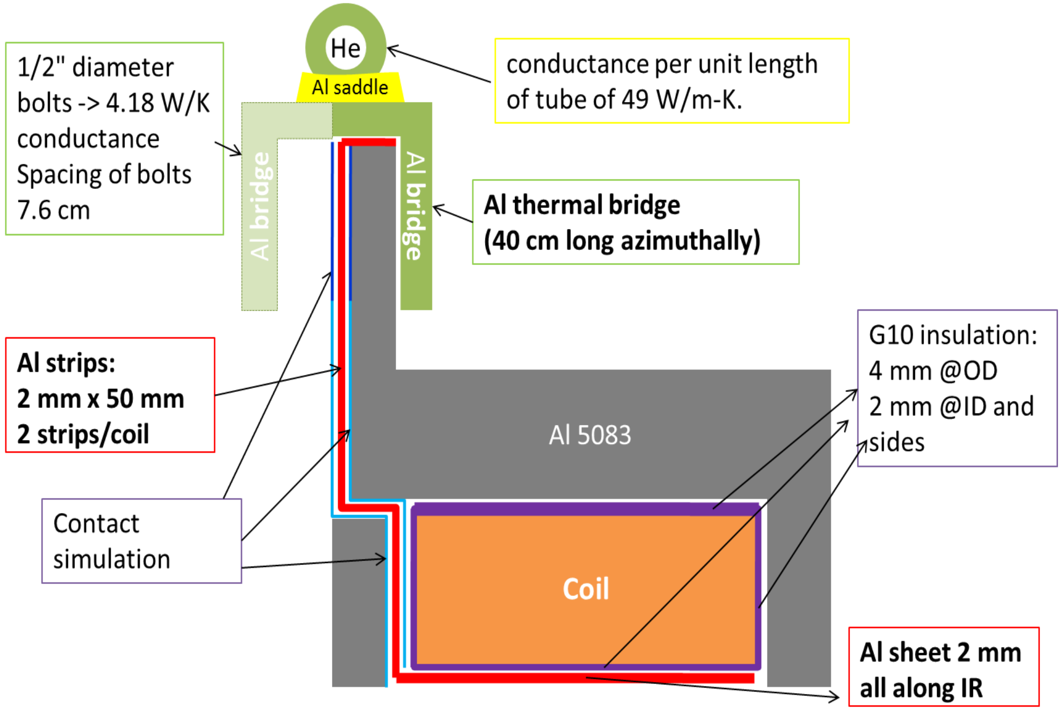
Thermosiphon Cooling Scheme

- 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.

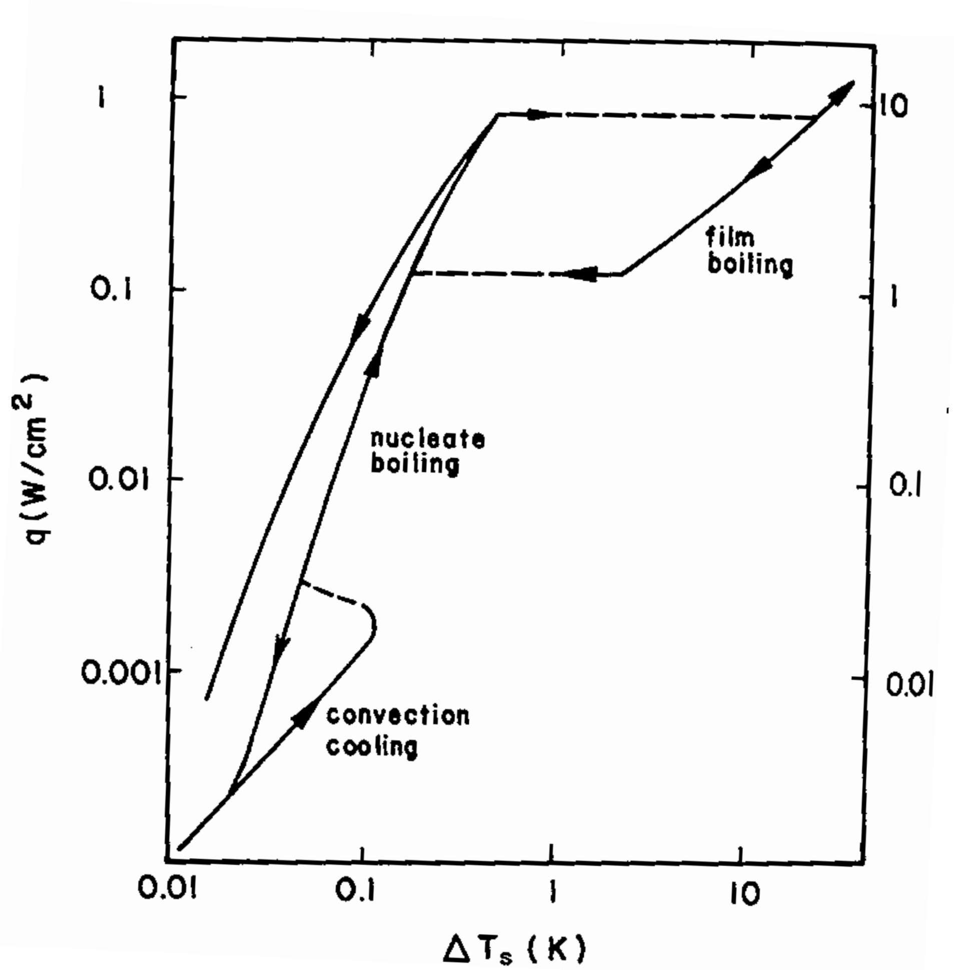


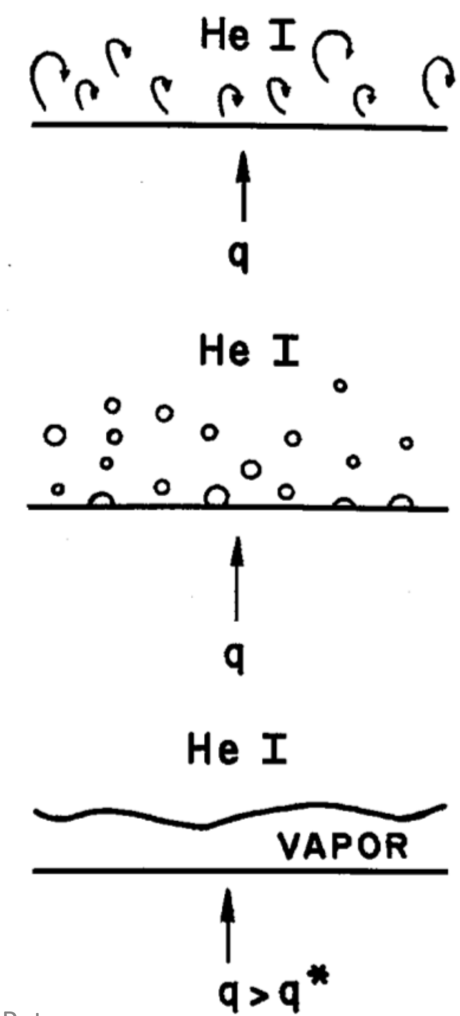
Thermosiphon Cooling Tube Selection

Design Parameters		
Estimated Heat Load for TSu	15	Watts
Siphon pipe ID	2.54	cm
Siphon pipe length	373.6	cm
Siphon pipe surface	2979.7	cm^2
Number of siphon pipes	8	
Fraction of surface heat transfer	0.3	
Surface heat flux	0.0021	W/cm^2



Flow Regimes



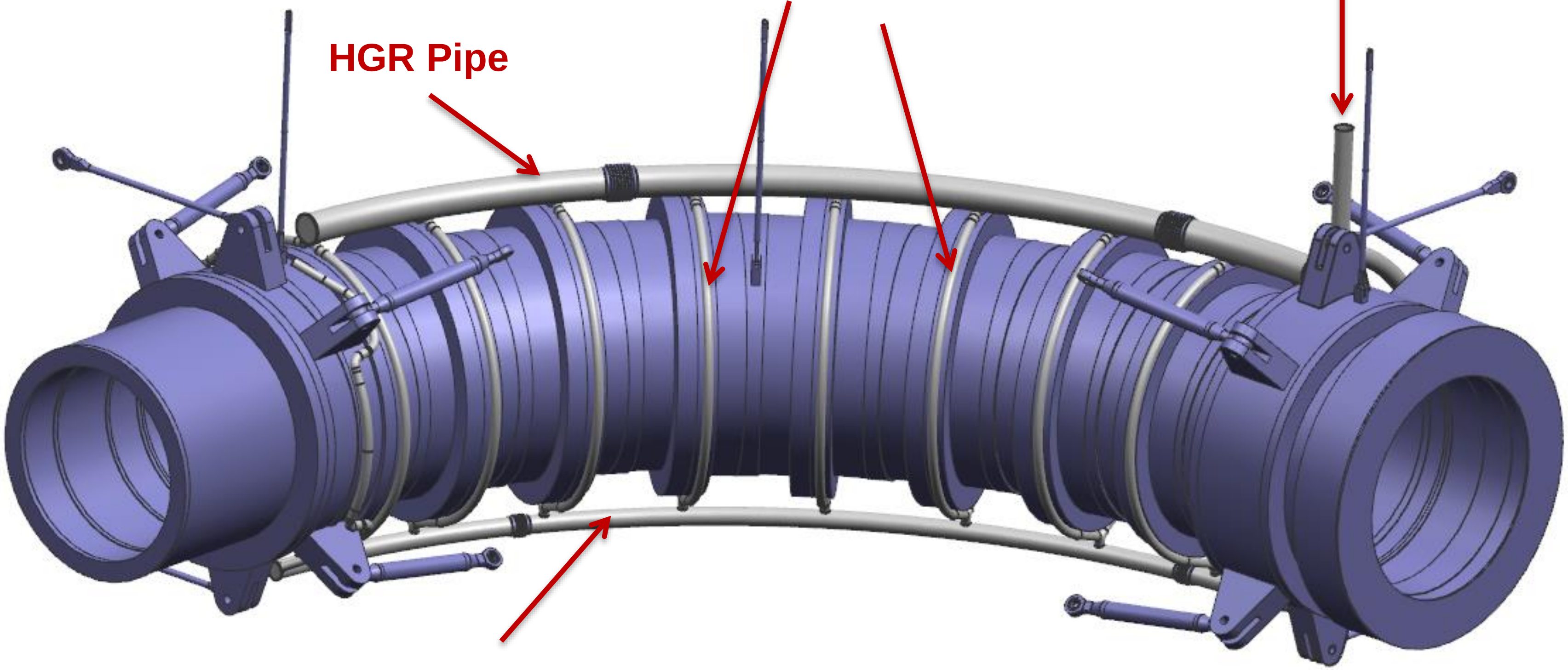


Natural Convection

Nucleate Boiling

Film Boiling

TSu Cooling Layout



Solid Model of TSu- D. Evbota

Design Comparison

	ATLAS	CMS	MICE	TSu-FNAL
Cooling Scheme	Forced, Thermosiphon (backup)	Thermosiphon	Thermosiphon	Thermosiphon
Heat Load (W)	50	400	4.5	15
Tube ID (cm)	1.8	1.4	2.2	2.54
Number of tubes	2	96	8	8
Length (cm)	3600	?	?	373.6
Heat Transfer Fraction (assumed)	0.3	?	?	0.3
Heat Flux (W/cm^2)	**0.008**	**0.0012**	**0.00025**	**0.002**

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

- Thomas J. Peterson, “The Nature of the Helium Flow in Fermilab’s Tevatron Dipole Magnets,” *Cryogenics*, Vol. 37, No. 11, 1997.
- S.W. Van Sciver, *Helium Cryogenics*, Plenum Press, New York, 1986.
- G. Bon Mardion, et al, “Practical Data on Steady State Heat Transport in Superfluid Helium at Atmospheric Pressure,” *Cryogenics*, January, 1979.
- L. Chiesa, et al, “Thermal Studies of a High Gradient Quadrupole Magnet Cooled with Pressurized, Stagnant Superfluid,” IEEE Transactions on Applied Superconductivity, March, 2001.

References-2

- Ch. Darve, et al, "He II Heat Exchanger Test Unit for the LHC Inner Triplet," Advances in Cryogenic Engineering, Vol 47A, 2002, Pg. 147.
- R. Byrns, et al, "The Cryogenics of the LHC Interaction Region Final Focus Superconducting Magnets," 17th International Cryogenic Engineering Conference, Bournemouth, UK, 14 - 17 Jul 1998, pp.743-746.
- B. Baudouy, "Heat and Mass Transfer in Two-Phase He I Thermosiphon Flow," Advances in Cryogenic Engineering, Vol 47B, 2002, Pg. 1514.