Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Engineering for Particle Accelerators –

Mechanical Engineering in Superconducting Magnet and RF Cryomodule Design

Tom Nicol

Fermilab

U.S. Particle Accelerator School - June 19-23, 2017

Presentation materials

This presentation can be downloaded through the end of the week at this link:

https://www.dropbox.com/sh/78ui6pmjcuuevs6/AAAtzZiuSs4vaa1xOUXDOE4wa?dl=0

Tom Nicol – Fermilab

- BSGE – University of Illinois, Urbana, IL
- MSME – University of Oklahoma, Norman, OK
- Mechanical engineer at Chemetron Corp., Chicago – 1974-1977
- Mechanical engineer at Fermilab – 1977-present – Design engineer on Tevatron quadrupole and spool designs, LBQ cryostat design, SSC dipole cryostat design, BTeV cryostat design, LHC high gradient quad cryostat design, SRF cryomodule design, Mu2e transport solenoid design, and many others.
- Adjunct computer programming instructor at Waubonsee Community College and Aurora University.
- Teaching assistant in the Mechanical Engineering Department at the University of Oklahoma.

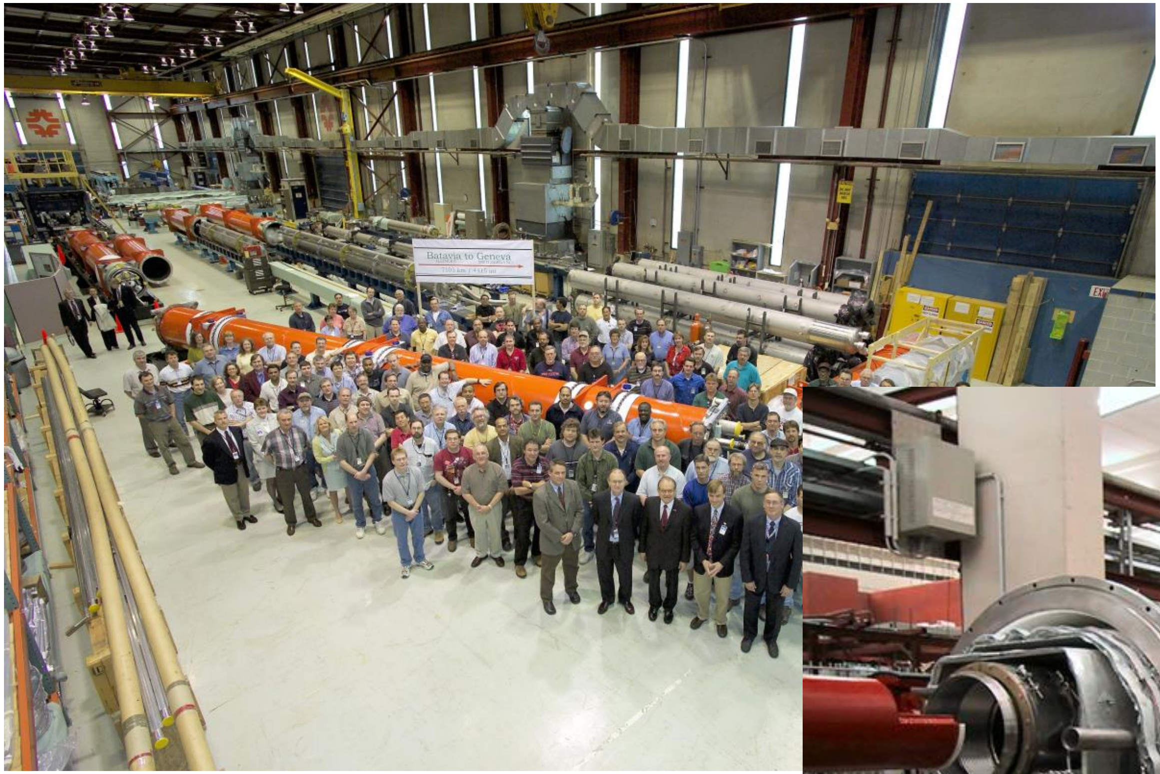
Chapter 1 – Introduction and Scope

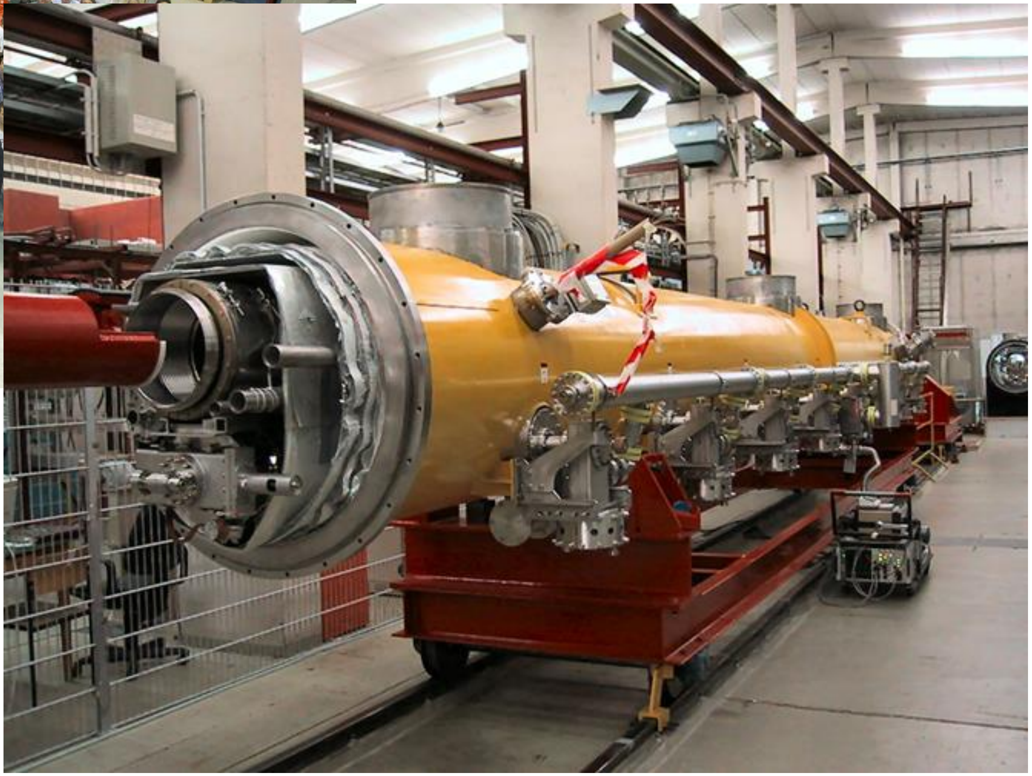
- Overview of the design of cryostats and cryomodules housing superconducting accelerator magnets and superconducting RF cavities.
- We'll cover:
  - Vacuum vessels (Chapter 2)
  - Thermal shields (Chapter 3)
  - Insulation (Chapter 4)
  - Piping (Chapter 5)
  - Support structures (Chapter 6)
  - Heat loads (Chapter 7)
  - Bellows and Interconnects (Chapter 8)
  - Miscellaneous topics (assembly techniques, alignment, loss of vacuum, magnetic shielding, etc.) (Chapter 9)
- This is not meant to be comprehensive, but an introduction so when you look at superconducting magnet or superconducting RF cryomodule on the production floor where you work or visit, you'll have a new understanding of what you're looking at.

Chapter 1 – Introduction and Scope

- The thermal and structural considerations in the design, analysis, and fabrication of cryostats for superconducting magnets and superconducting RF cavity (SRF) cryomodules used in high-energy physics applications will be described in detail with emphasis on material selection, heat load analysis, structural support, multi-layer insulation and internal piping systems.

Chapter 1 – Introduction and Scope





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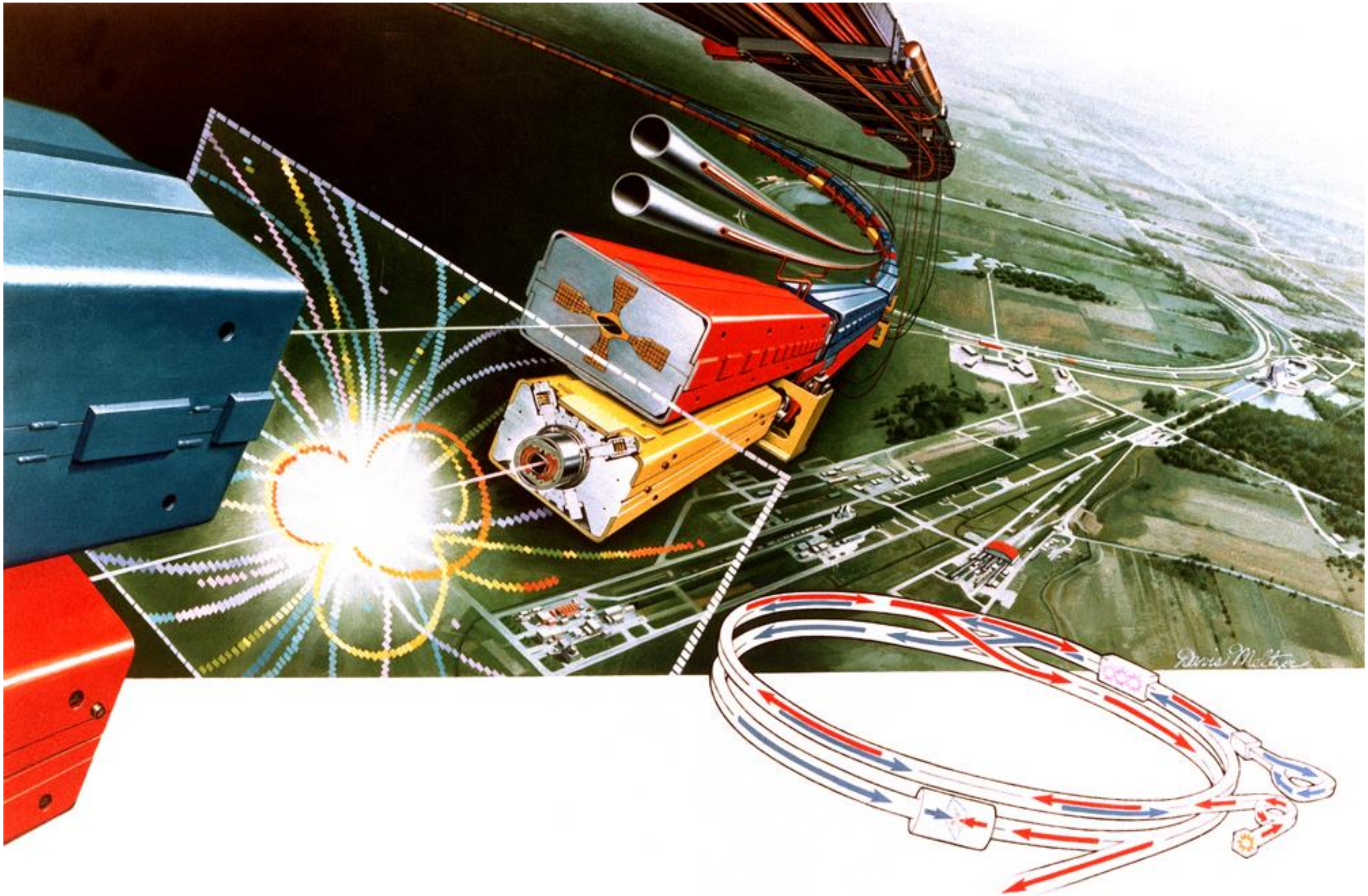

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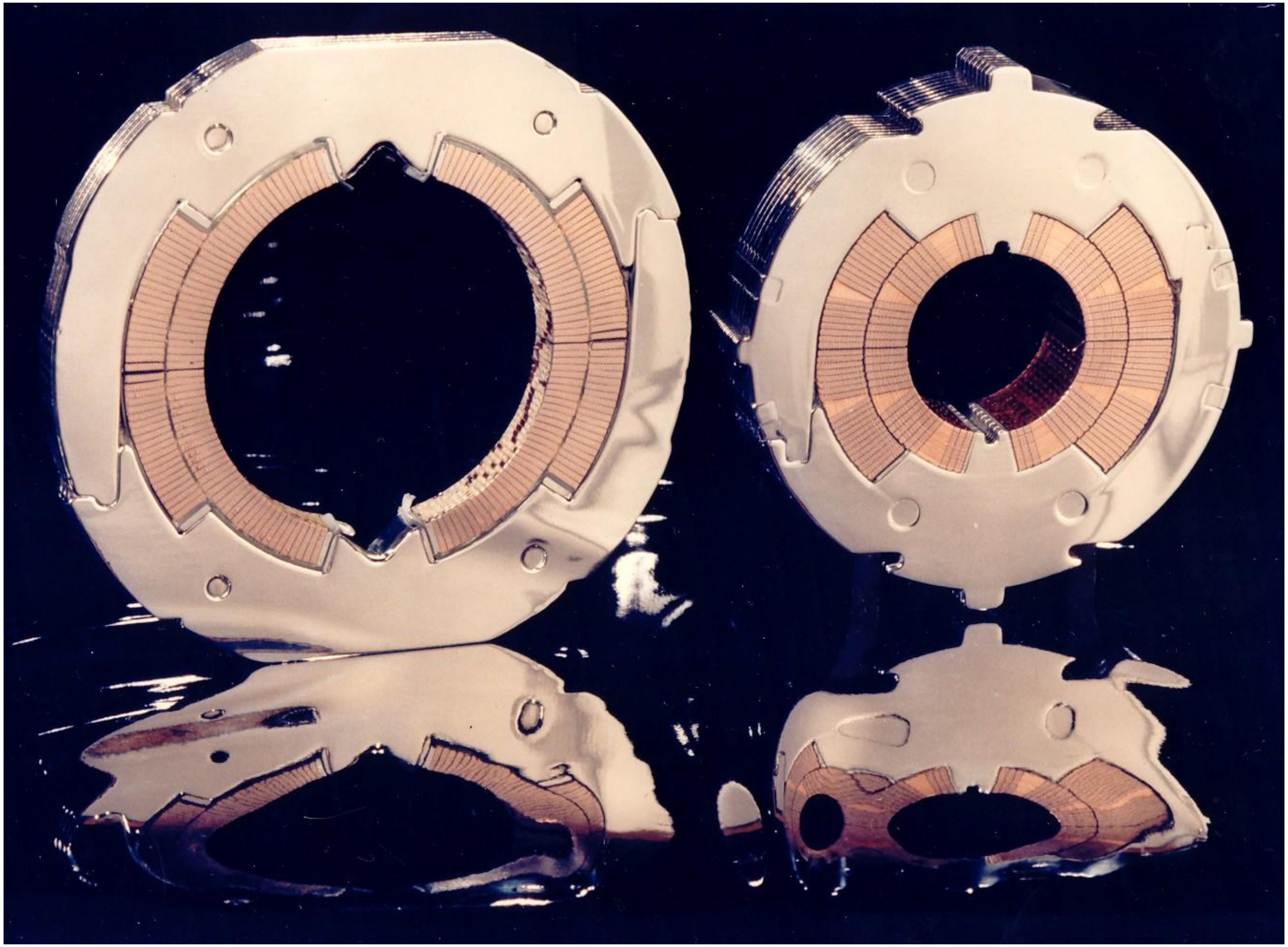

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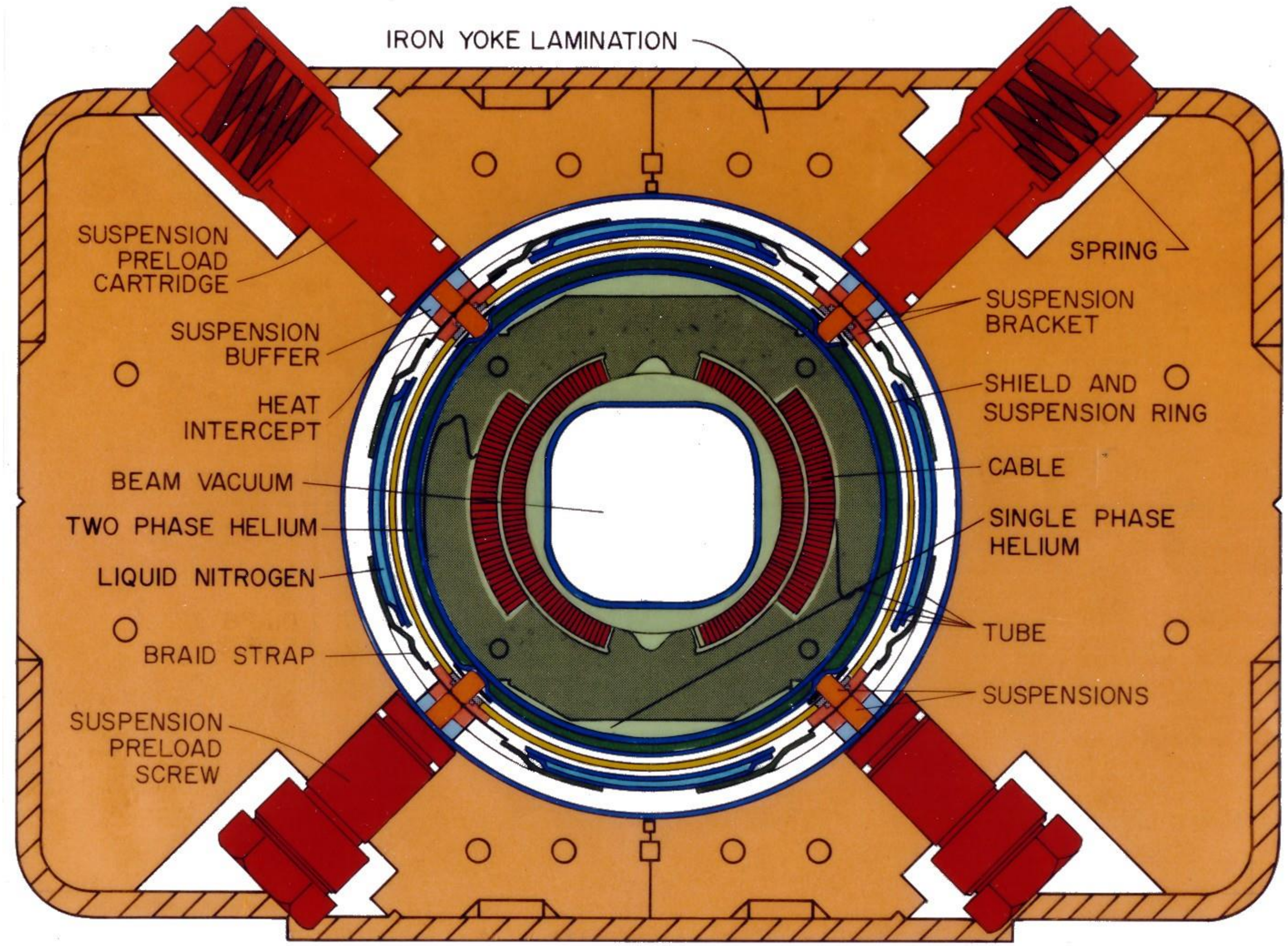

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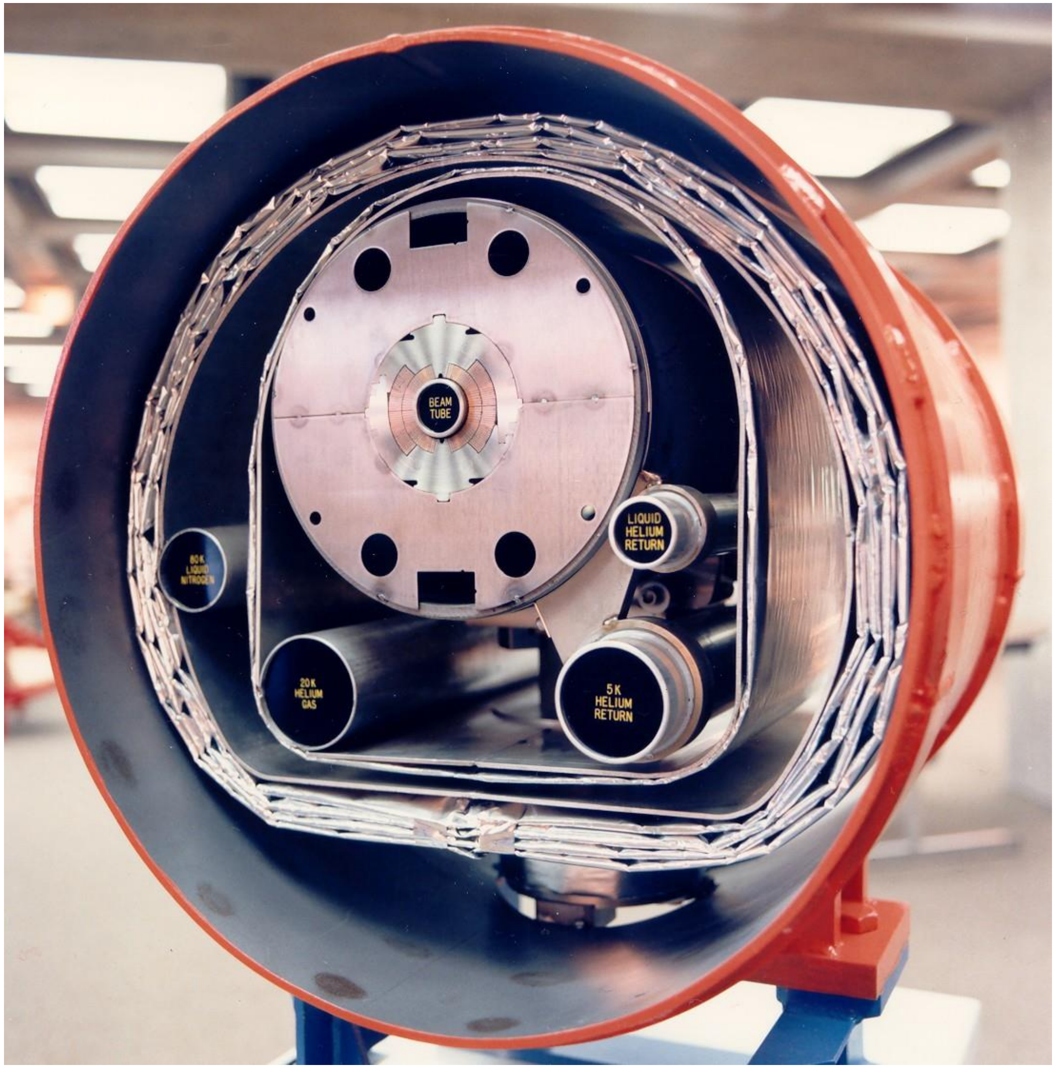

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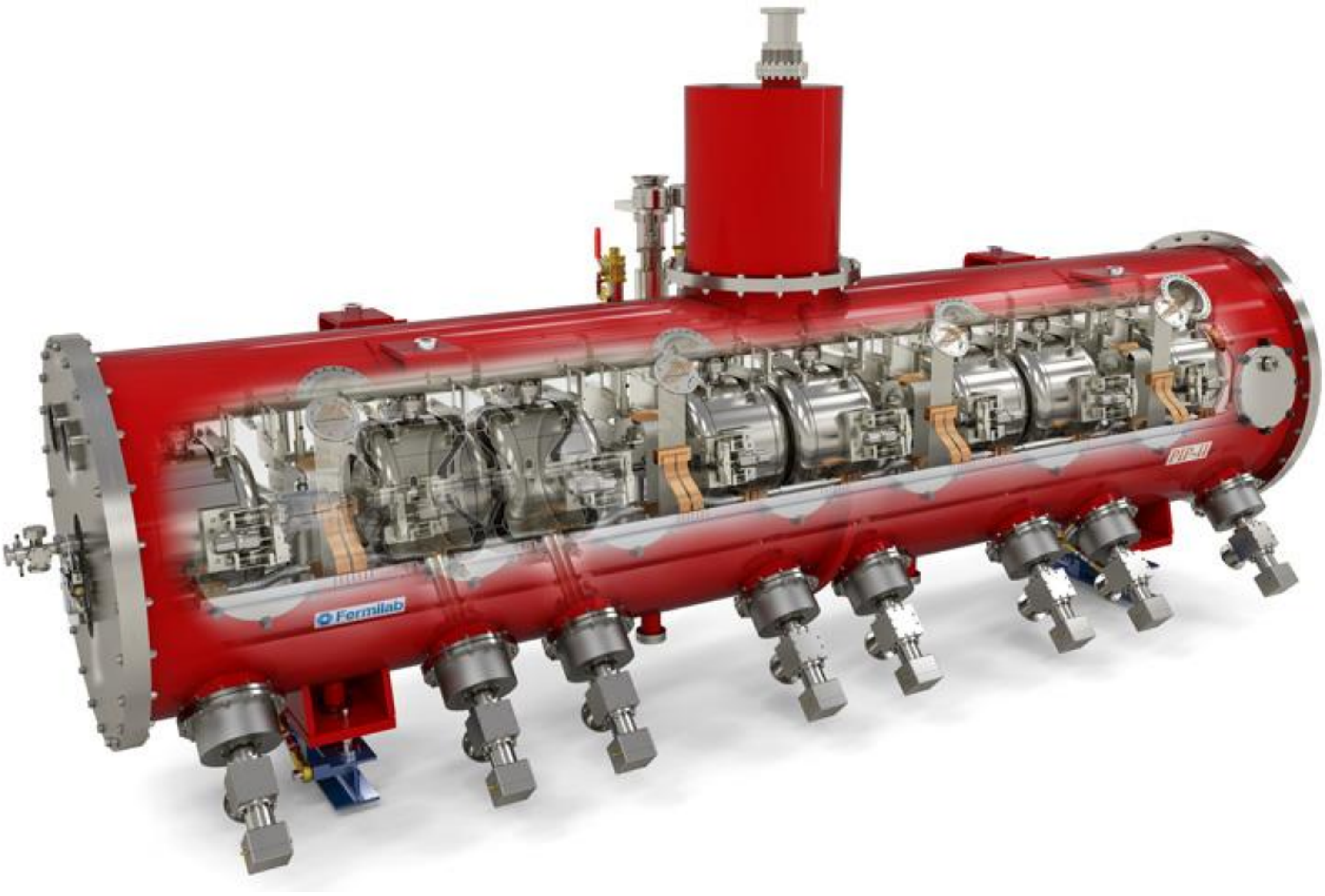
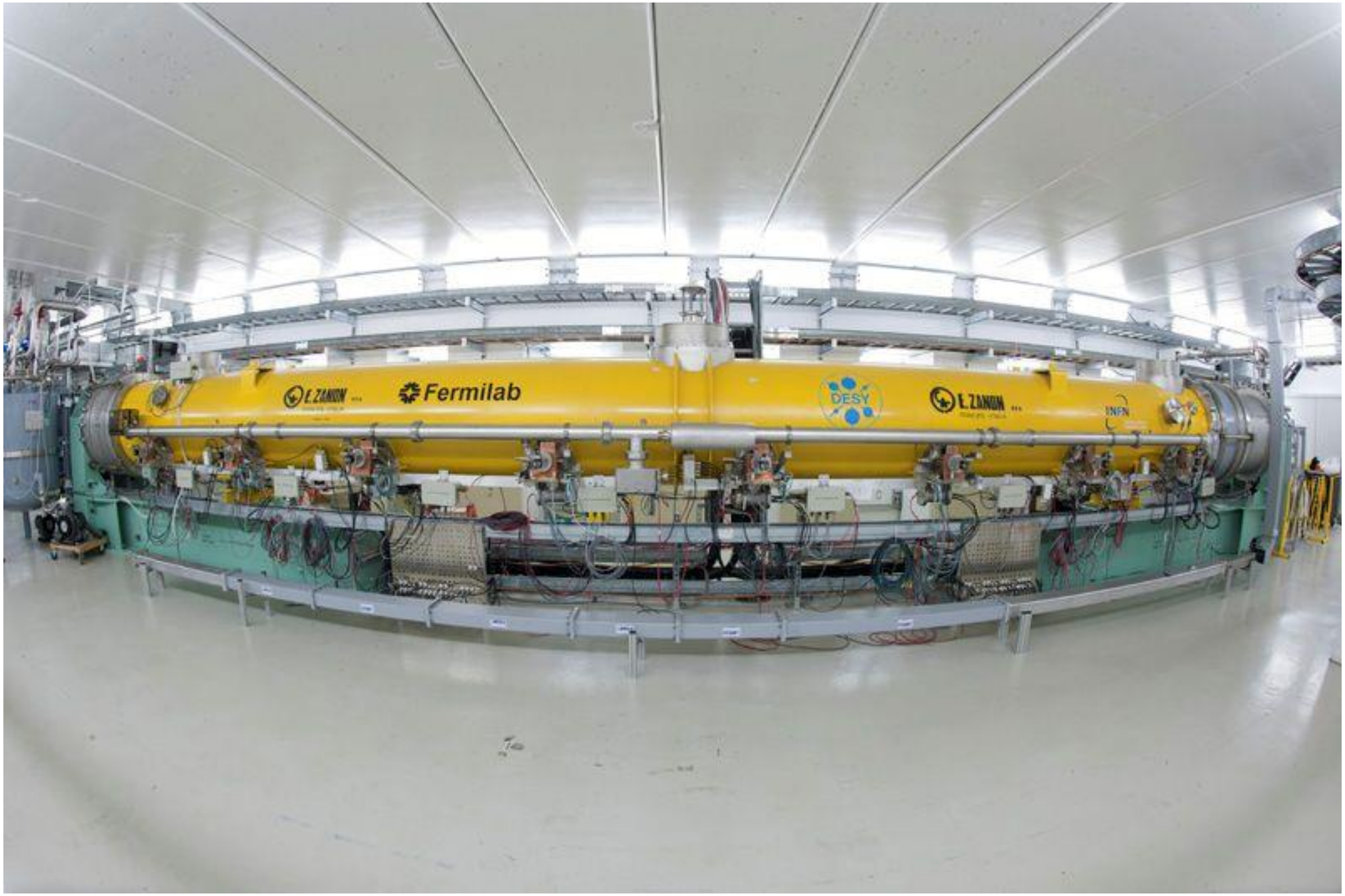
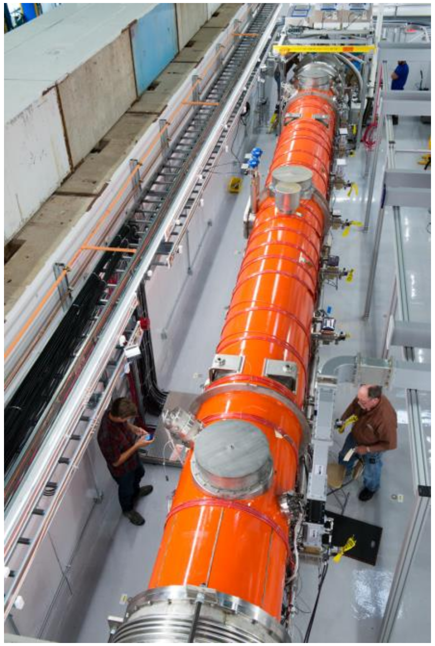
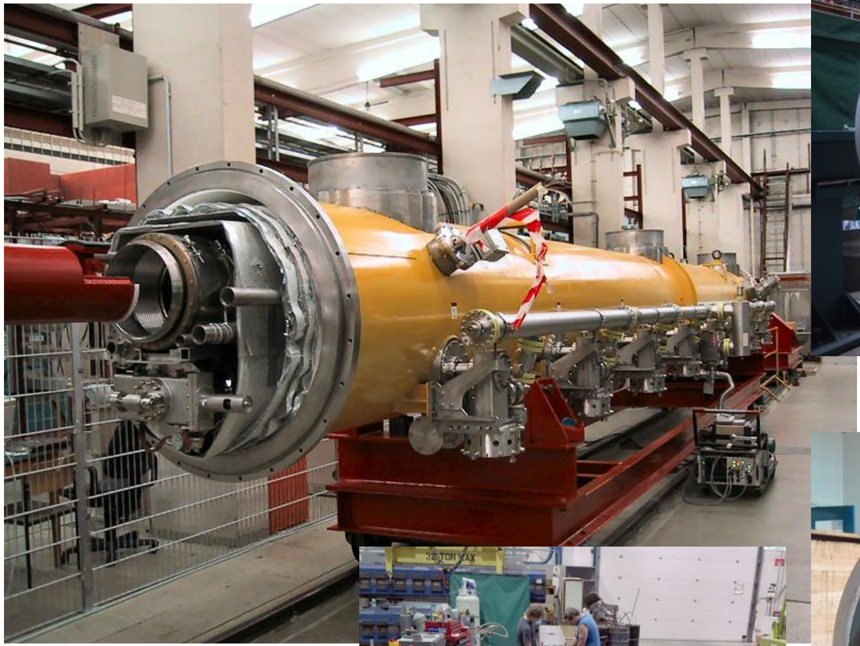


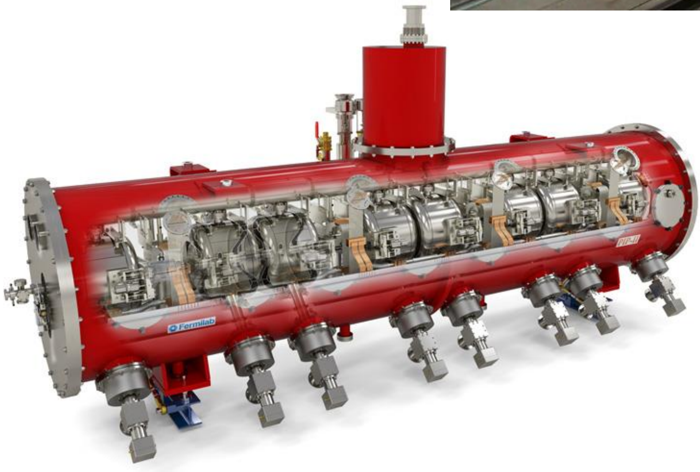
Chapter 2 – Vacuum vessels



Chapter 2 – Vacuum vessels







Chapter 2 – Vacuum vessels

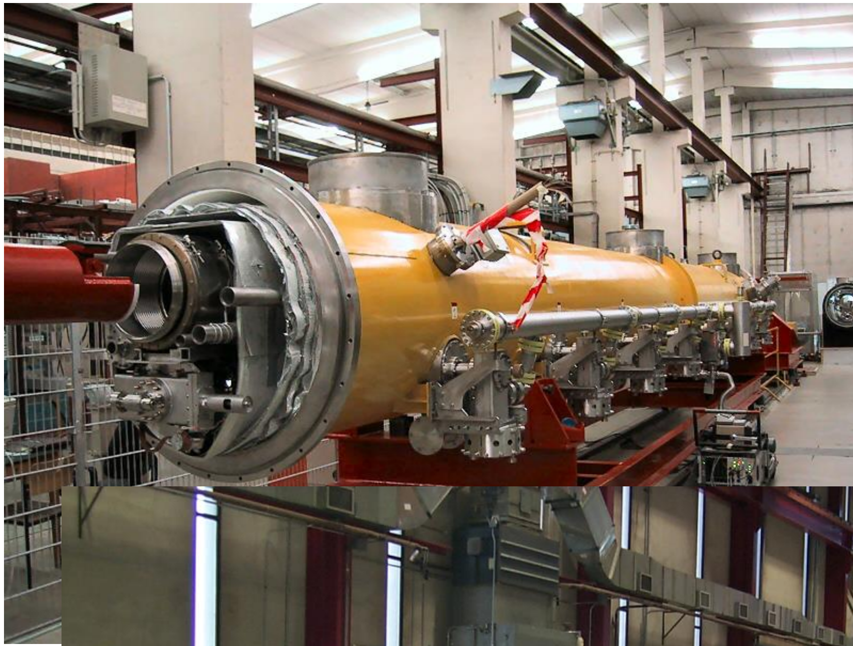
- The outermost cryostat component that:
  - Contains the insulating vacuum.
  - Serves as the major structural element to which all other systems are attached to the accelerator tunnel floor.
  - Serves as a pressure containment vessel in the event of a failure in an internal cryogen line.
- The design for internal and external pressure are addressed by the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2 and specific workplace codes.
- Insulating vacuum is generally in the $1e10^{-6}$ torr range, but can be as high as $1e10^{-4}$. The lower the better.

Chapter 2 – Vacuum vessels

- Materials are nearly always:

	Carbon steel	Stainless steel	Aluminum
Pros	Inexpensive Readily available Weldable	Mostly non-magnetic Weldable Good fracture toughness	Inexpensive Readily available Non-magnetic Weldable Good fracture toughness Light weight
Cons	Magnetic Low fracture toughness Rust preventative required	Expensive	Difficult to implement metal seals Difficult to use threated holes
Alloys	SA 516	304, 304L	6061, 5083

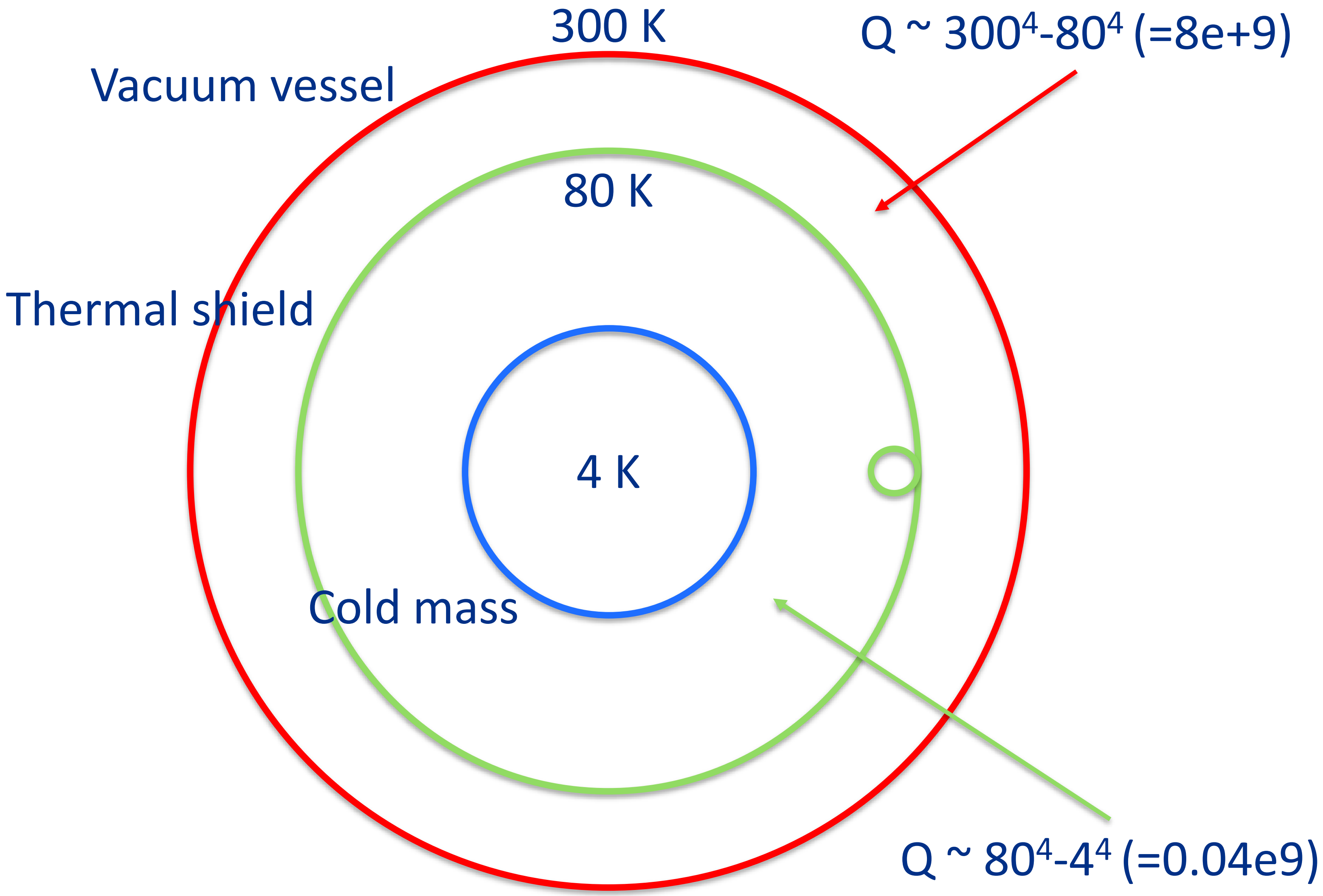
Chapter 3 – Thermal shields



Chapter 3 – Thermal shields

- Intercept radiation heat transfer between the room temperature vacuum vessel and a lower temperature surface, usually nominally 80 K, but can be anywhere from 50 K to 90 K. Some devices use lower temperature shields, e.g. 20 K or 5 K.
- Normally cooled by LN_2 or GHe.
- Serve as the heat sink for structural supports, current leads, power couplers, warm-to-cold transitions, etc.
- Occasionally there are multiple thermal shields – rarely more than two.
- Material is almost always copper or aluminum.
- Surface is usually covered with multi-layer insulation (MLI) (more on this later) or aluminum foil.

Chapter 3 – Thermal shields – radiation heat transfer



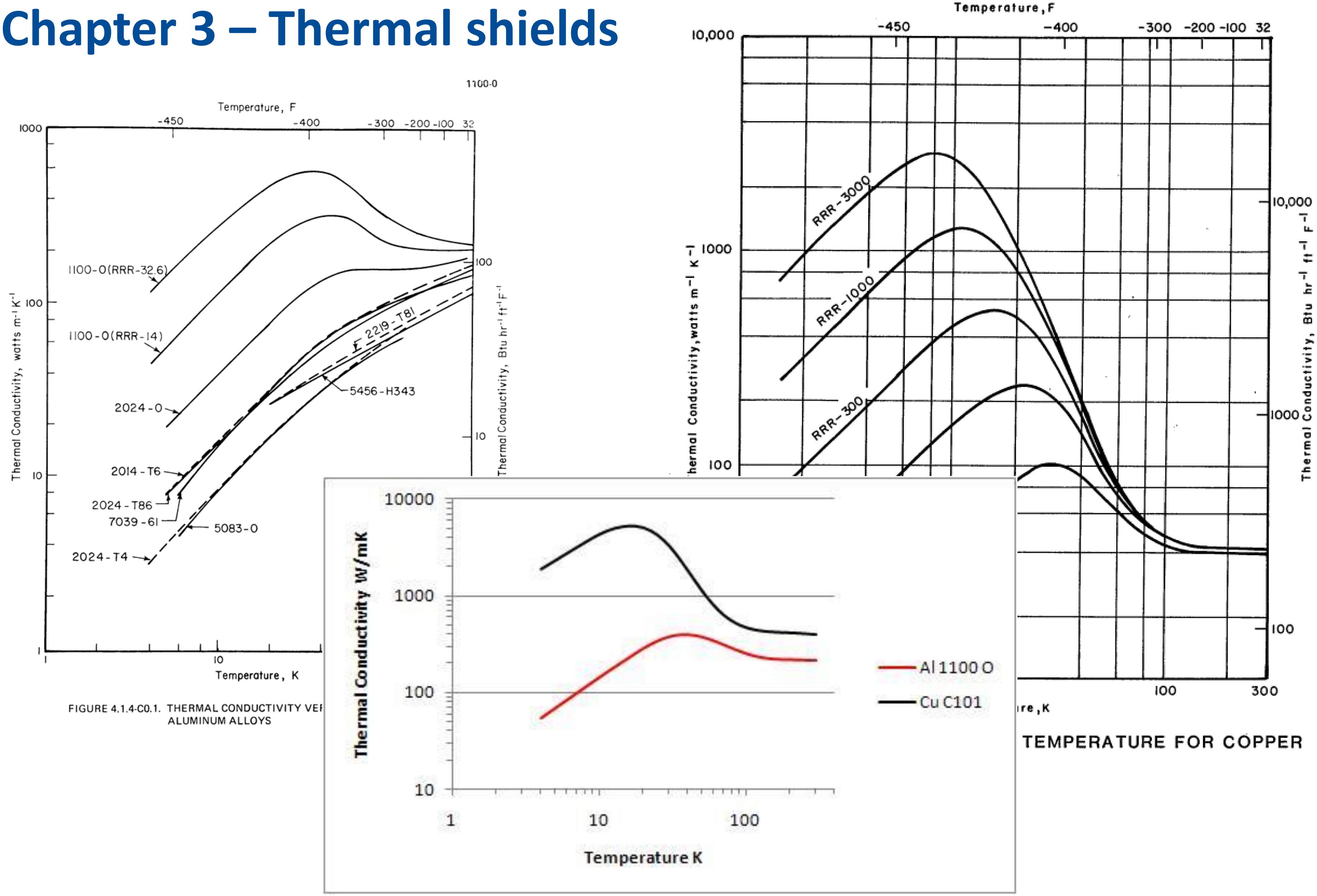
Chapter 3 – Thermal shields

- Materials are nearly always:

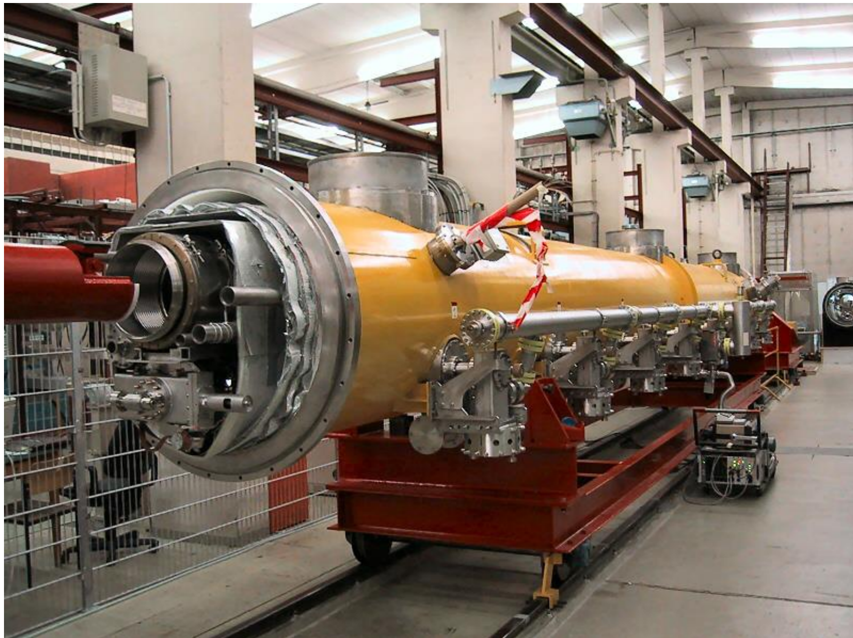
	Copper	Aluminum
Pros	Readily available Good thermal conductivity Readily soldered or brazed	Inexpensive Readily available Good thermal conductivity(*) Weldable Light weight
Cons	Expensive Heavy	(*)Thermal conductivity good, but not as good as copper Difficult to join to stainless steel
Alloys	OFHC, ETP, C101	1100, 6061

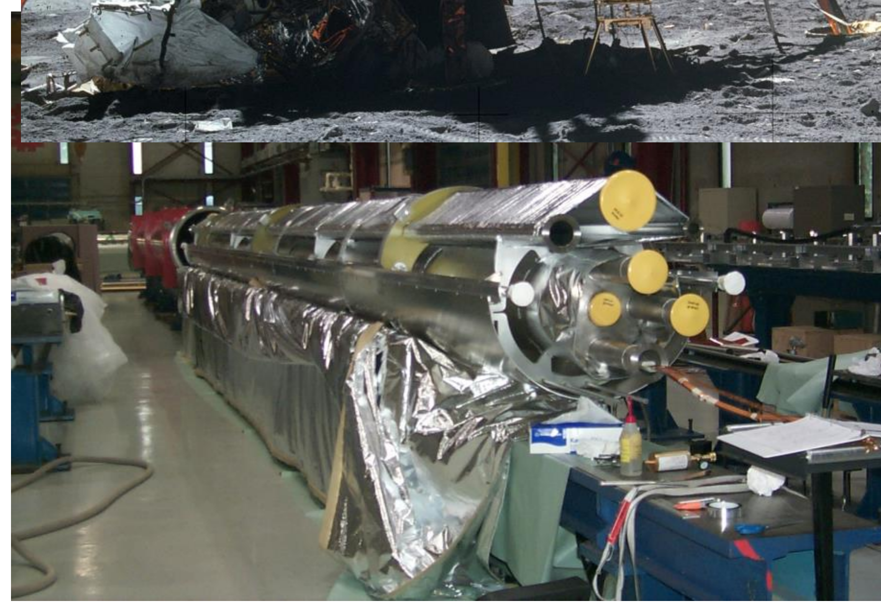
http://www.mtm-inc.com/ac-20100720-trends-in-thermal-shields-copper-or-aluminum.html

Chapter 3 – Thermal shields



Chapter 4 – Insulation

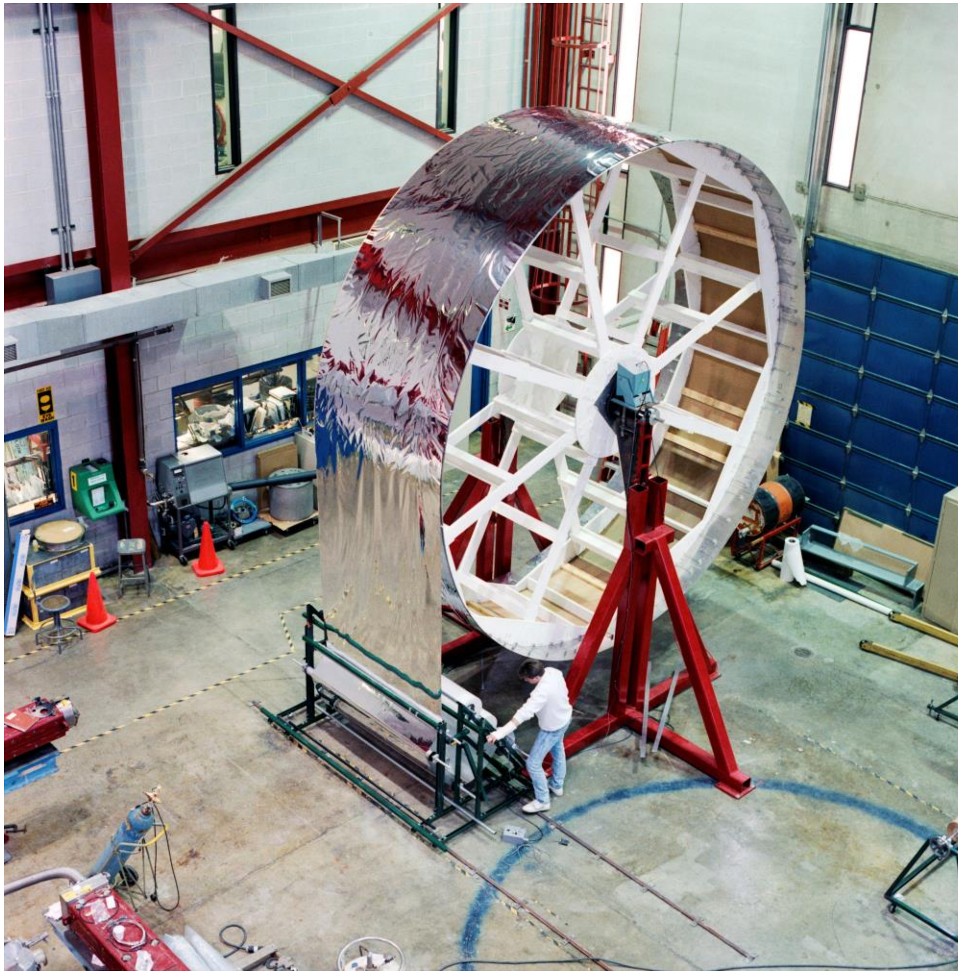




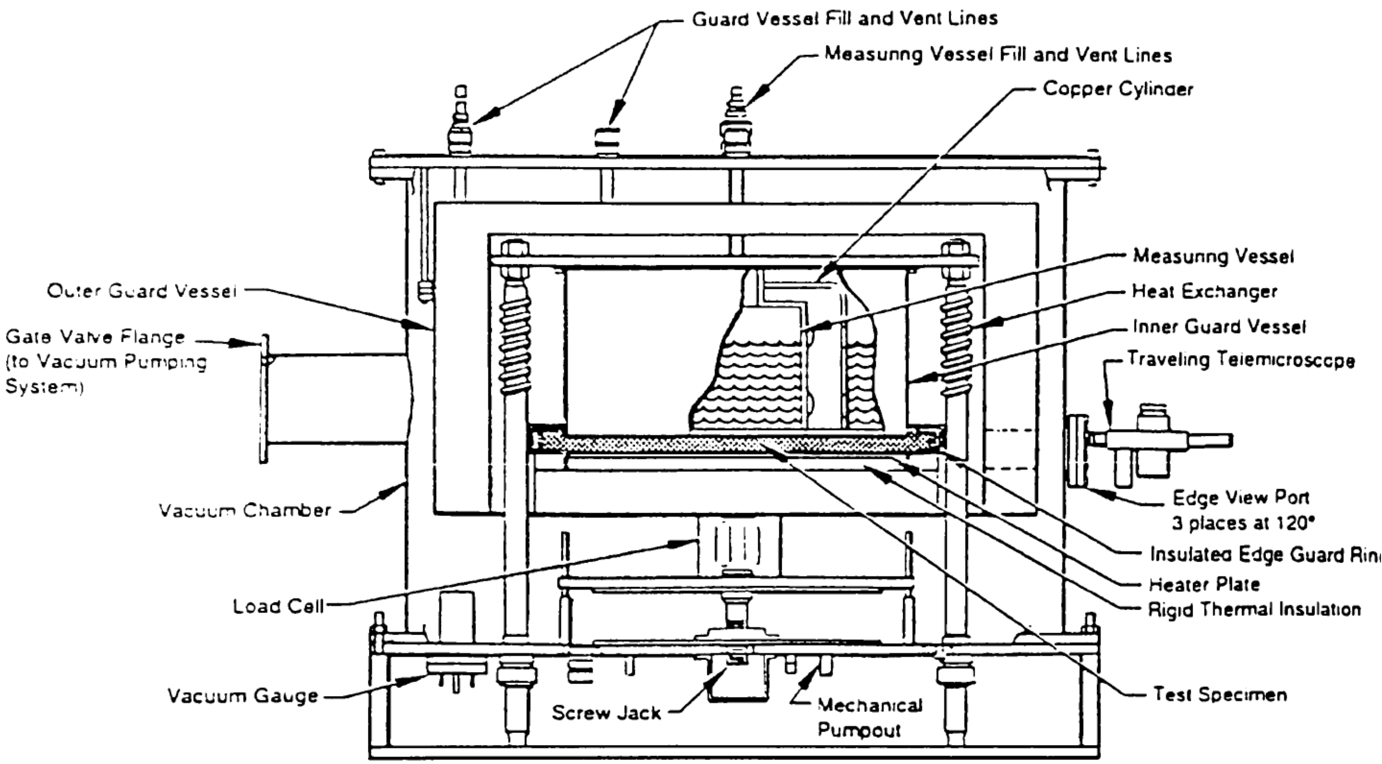
Chapter 4 – Insulation

- Multi-layer insulation (MLI) reflects radiation heat transfer back toward its source.
- Usually mounted on the outside of the colder surface, e.g. the thermal shield or cold mass.
- Consists of alternating layers of reflector and spacer material:
  - Reflector is usually double-aluminized mylar sheets 6-12 μm thick aluminum-coated on both sides with a minimum of 300 Å.
  - Spacer is usually a polyester net, fiberglass net or other similar material compatible with the environment.
  - The reflector can be perforated to facilitate pumpout.
- The number of layers varies, but is usually from 30-60 layers on a thermal shield nominally at 80 K and 10-15 layers on a lower temperature shield or cold mass.
- It must be in vacuum – $1e10^{-4}$ torr or lower.
- To estimate the total heat load due to radiation and residual gas conduction, realistic values are ~1.5 W/m^2 at 80 K and ~0.15 W/m^2 at 4.5 K.

Chapter 4 – Insulation



Chapter 4 – Insulation

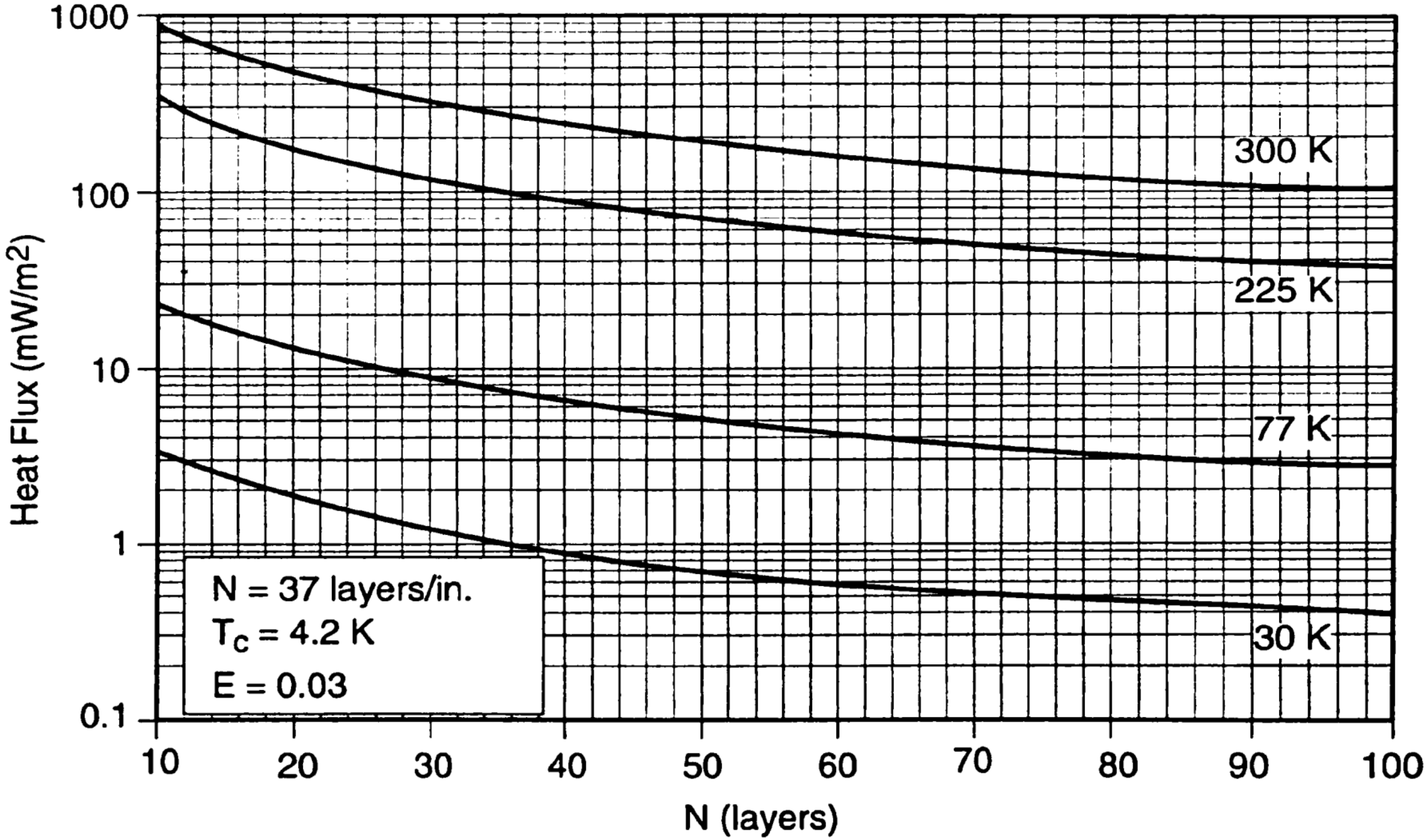


n=no. of layers

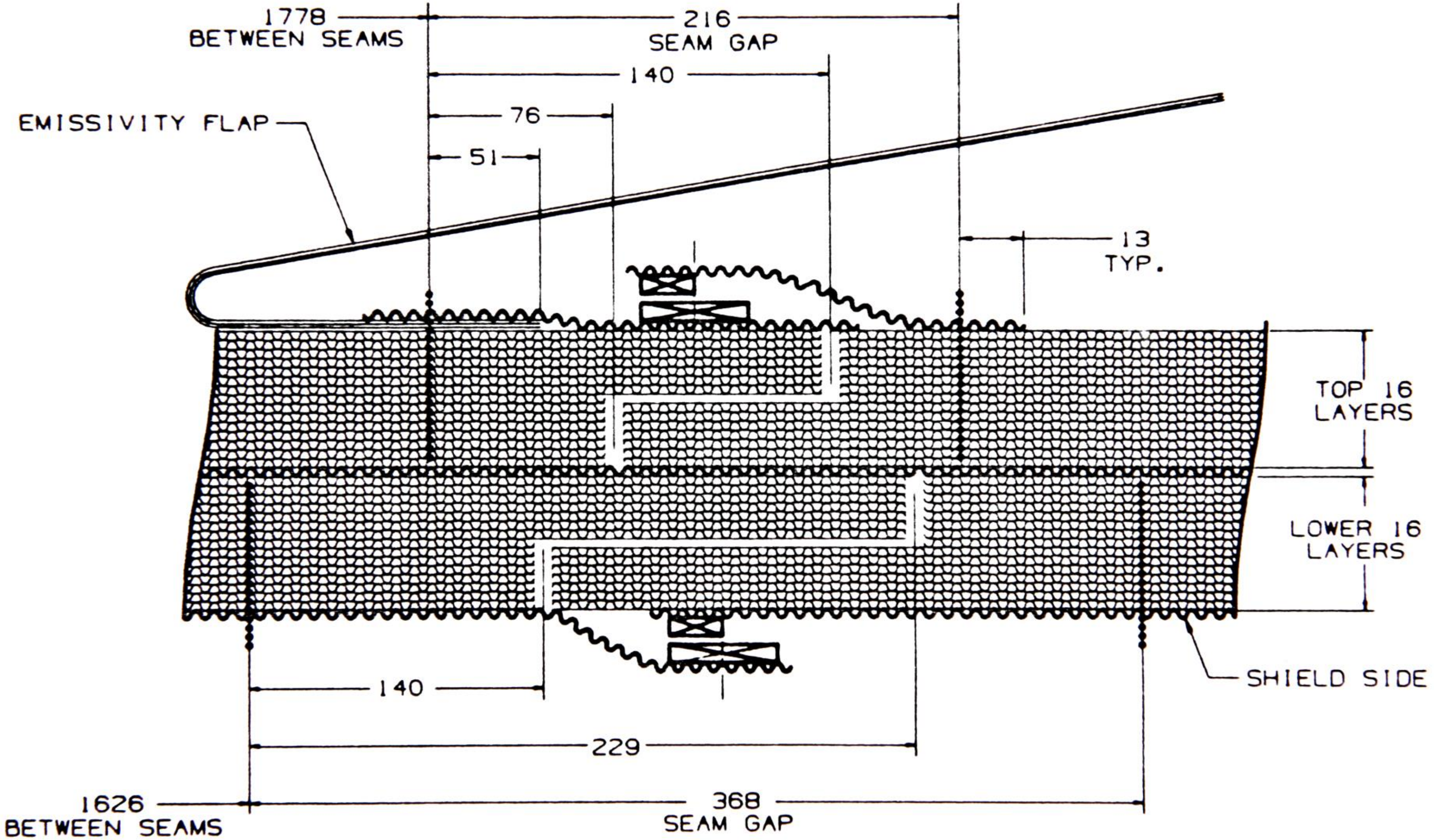
Equation governing multiple freely floating radiation shields:

$$Q = \frac{\sigma A_1 (T_2^4 - T_1^4)}{(n + 1)\left[\left(\frac{2}{\epsilon}\right) - 1\right]}$$

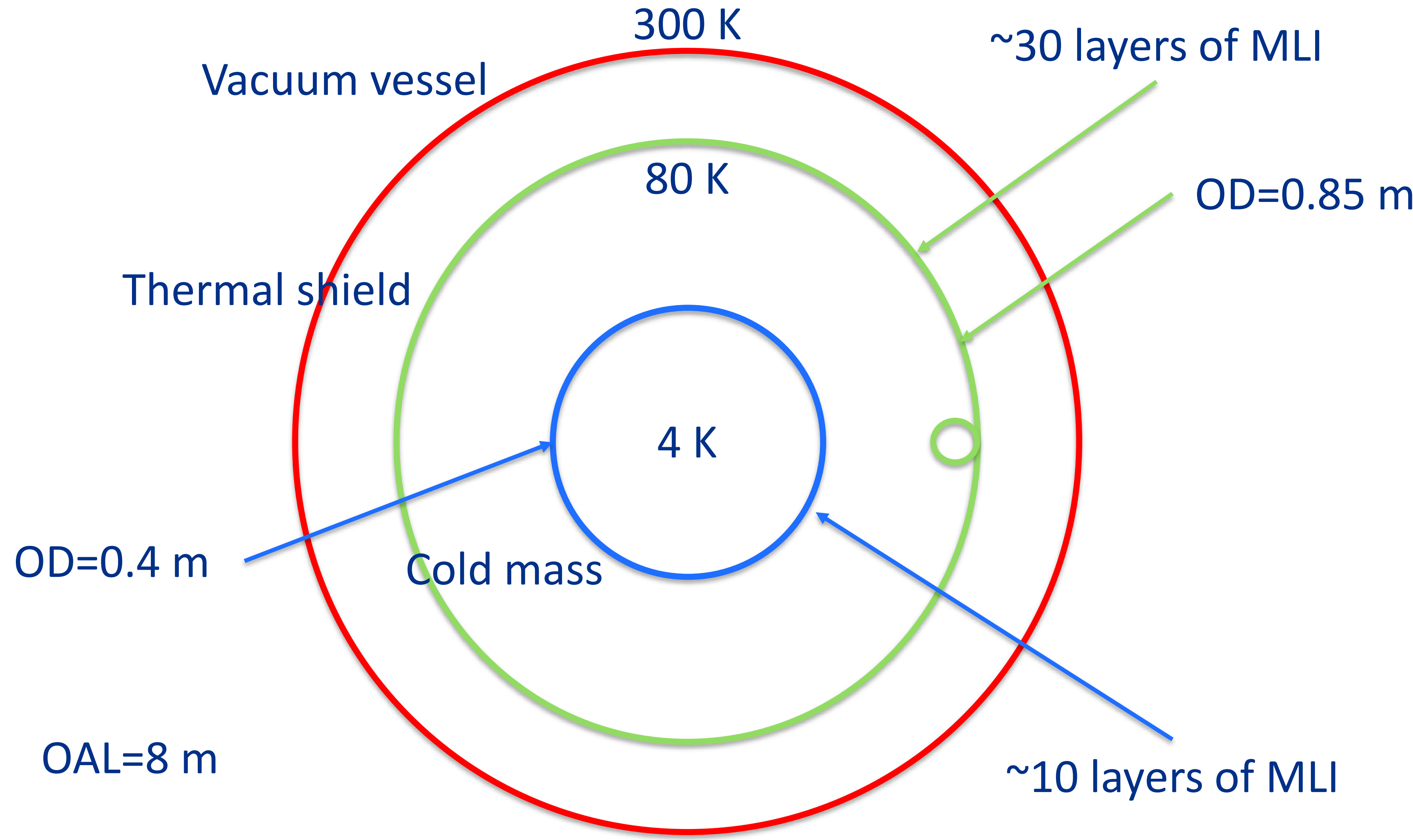
Chapter 4 – Insulation



Chapter 4 – Insulation



Chapter 4 – Sample heat load estimate



Chapter 4 – Sample heat load estimate*

80 K

$A = (0.85\pi)(8)+2(\pi(0.85)^2/4) = 22.5\ m^2$

$Q = (22.5\ m^2)(1.5\ W/m^2) = 33.7\ W$

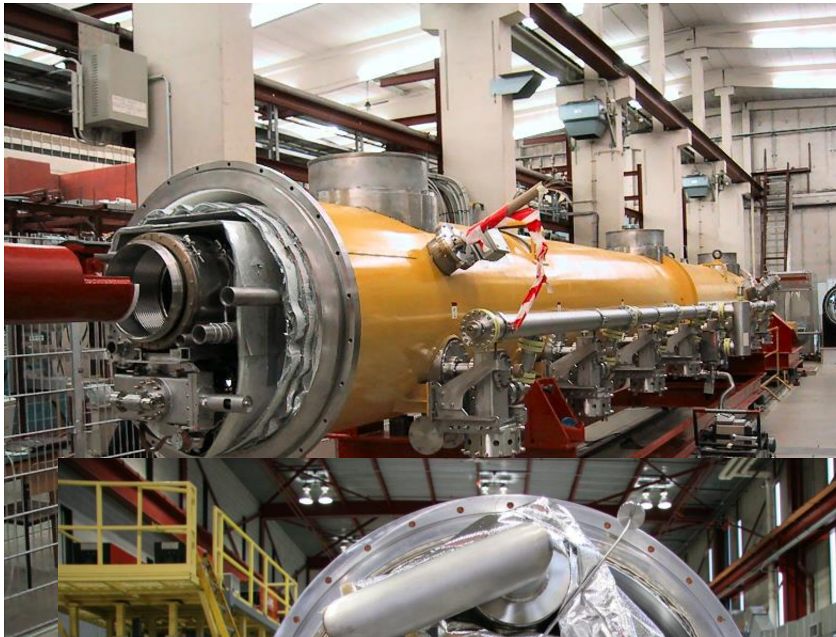
4.5 K

$A = (0.4\pi)(8)+2(\pi(0.4)^2/4) = 10.3\ m^2$

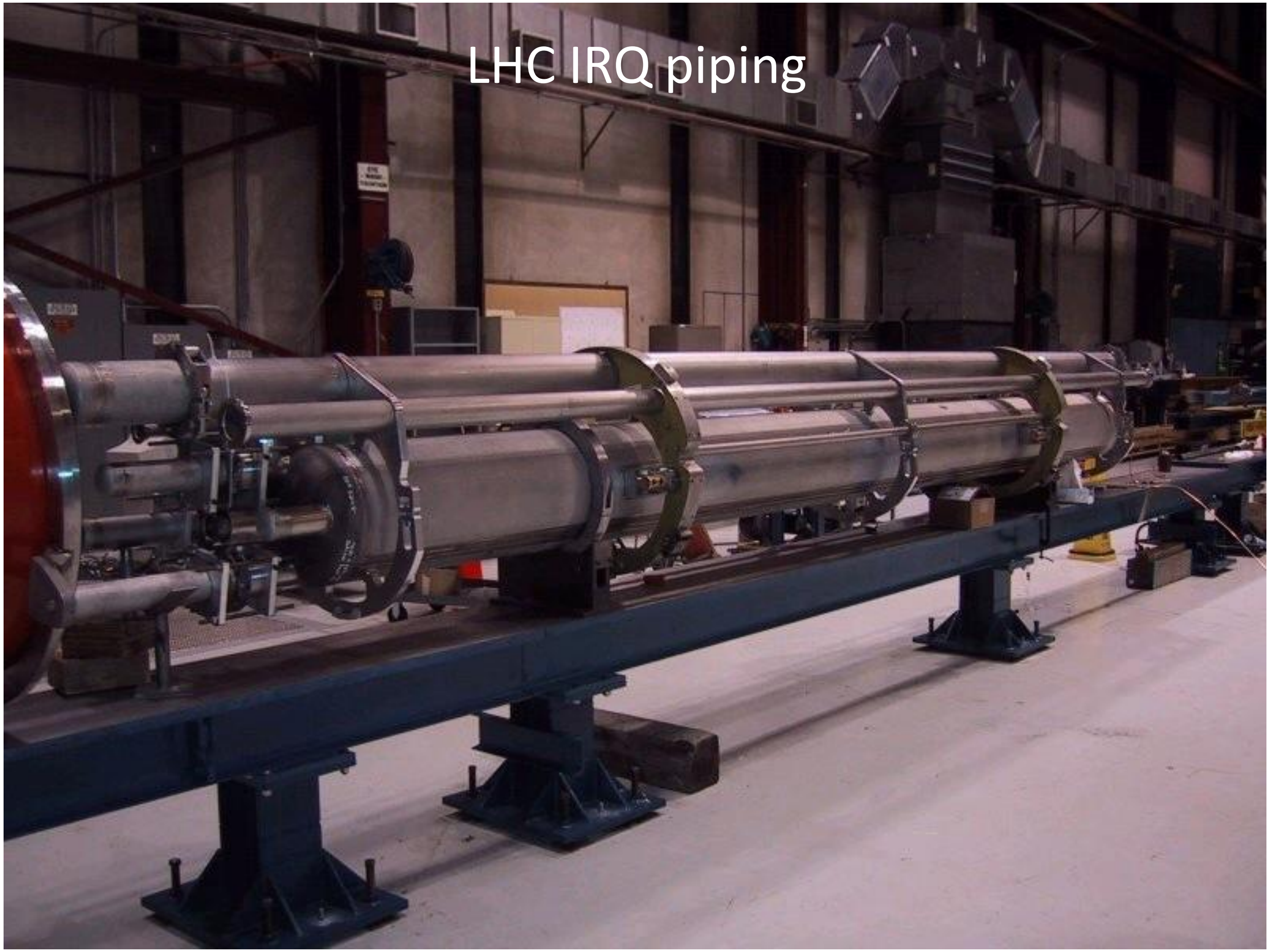
$Q = (10.3\ m^2)(0.15\ W/m^2) = 1.5\ W$

*: Residual gas conduction and radiation only. Assumes ends are also covered.

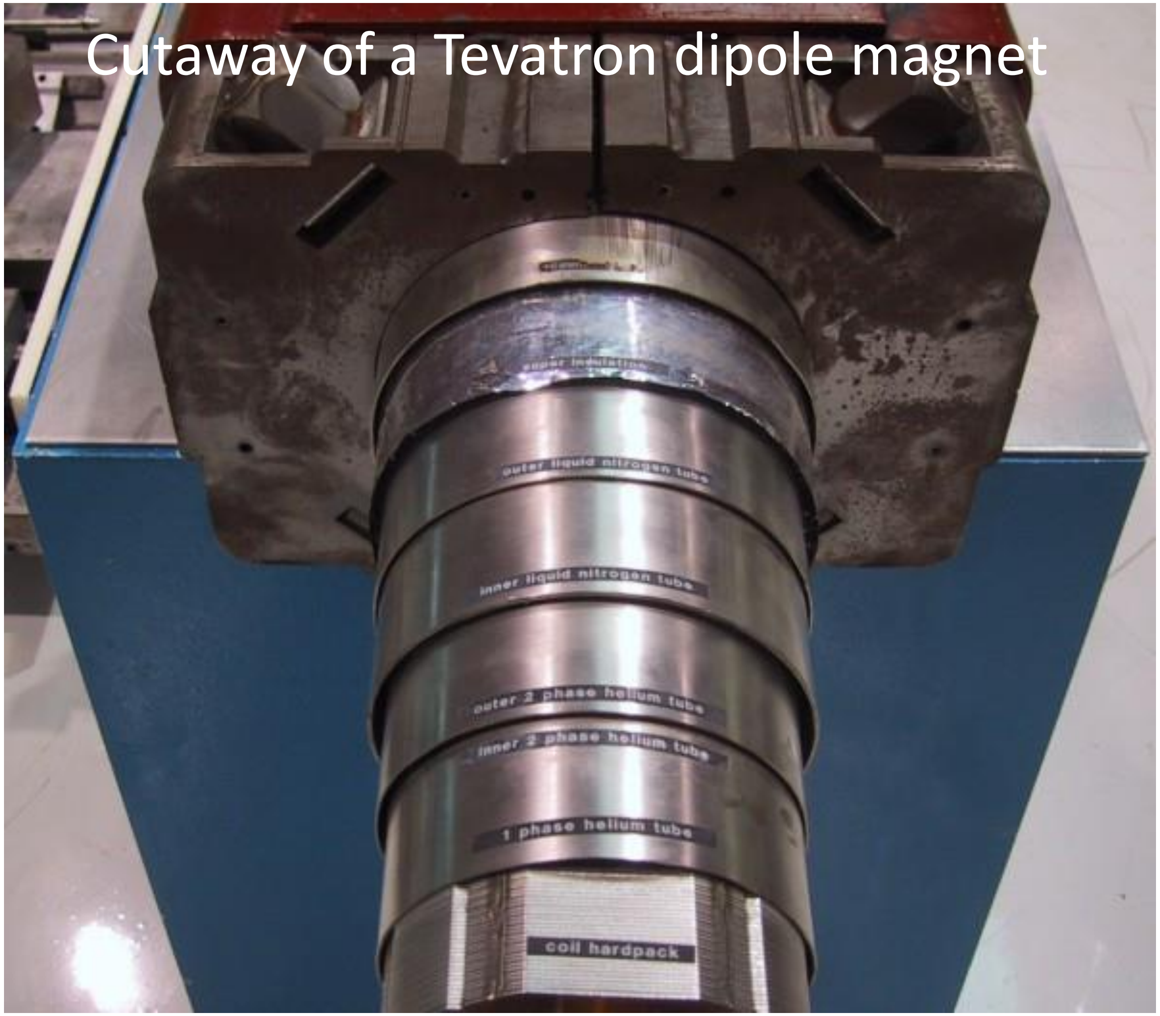
Chapter 5 – Piping



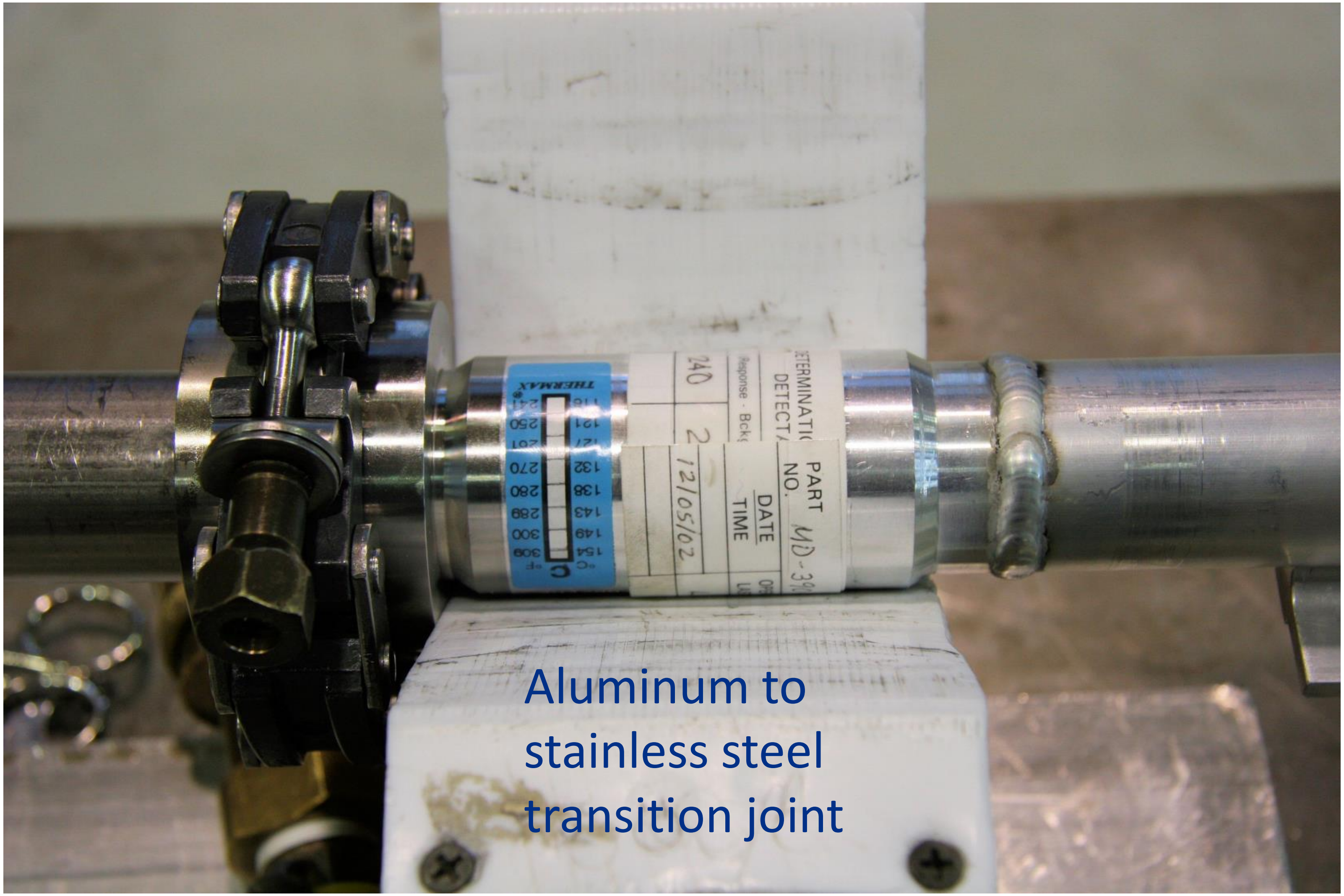
Chapter 5 – Piping



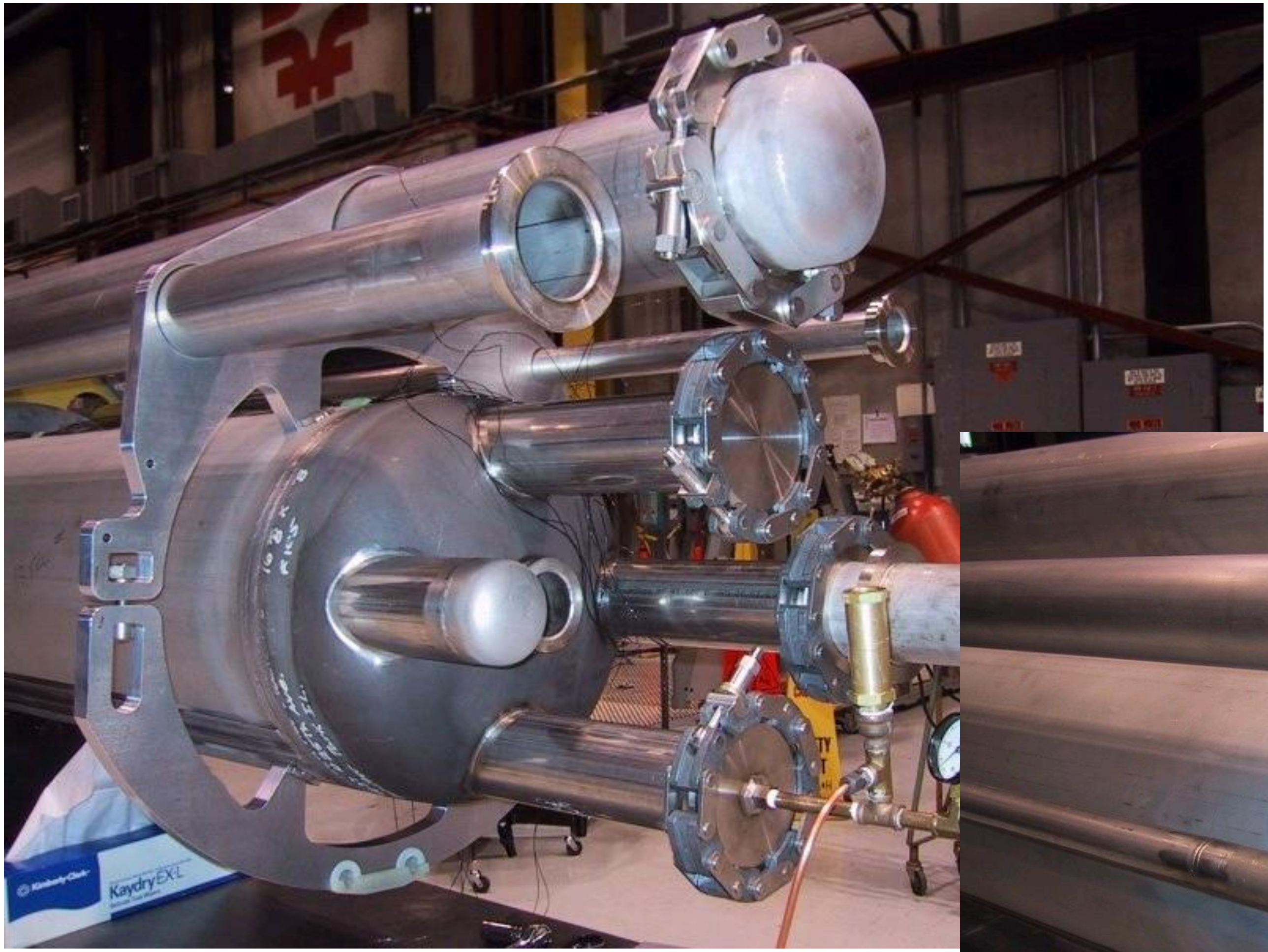
Chapter 5 – Piping



Chapter 5 – Piping



Chapter 5 – Piping



Pipe supports

Chapter 5 – Piping

- Materials are compatible with other parts of the cryostat or cryomodule.
  - Thermal shield piping is usually the same as the shield, i.e. aluminum piping with aluminum shields, copper piping with copper shields.
  - Stainless steel piping can be used with thermal shields, but requires careful consideration of thermal contact.
- Piping materials and dimensions must be compatible with fluids and pressure requirements.
- Piping system designs must be compatible with piping codes, e.g. ASME B31.3, specific workplace codes, etc.
- Typical piping inside the cryostat or cryomodule are helium supply and return, cooldown lines, and thermal shield supply and return. Depending on the cryogenic distribution system, there could be others.
- Pipe support designs need to locate and secure pipes in the cryostat or cryomodule, not impose additional heat loads if possible, and resist bellows forces at the interconnect.

Chapter 5 – Piping

Table 6. Cryostat piping flow parameters					
Description	**Fluid**	**P oper (atm)**	**P max (atm)**	**T (approx)**	**Flow (g/s)**
Pumping line	Ghe	0.016	4.0	1.8 K	8.6
External heat exchanger outer shell	Lhe	3.6	20.0	1.9 K	0.0
External heat exchanger inner tube	Lhe	0.016	4.0	1.8 K	8.6
Cooldown line	Lhe	3.6	20.0	1.9 K	30.0
LHe supply	Lhe	0.016	4.0	1.8 K	8.6
4.5K supply	Lhe	1.3	20.0	4.5 K	1.1
4.5K return	Lhe	1.3	20.0	4.5 K	1.1
50-70K shield supply	Ghe	19.5	22.0	60 K	5.0
50-70K shield return	GHe	19.0	22.0	65 K	5.0

Piping requirements for LHC interaction region quadrupoles

Chapter 5 – Piping

Table 5. Cryostat pipe sizes							
Description	**OD (mm)**	**ID (mm)**	**Tkns (mm)**	**OD (in)**	**ID (in)**	**Tkns (in)**	**Notes**
Vacuum vessel	914.0	890.0	12.0	35.984	35.039	0.472	Carbon steel
Pumping line	88.900	85.598	1.651	3.500	3.370	0.065	
External heat exchanger outer shell	168.275	162.738	2.769	6.625	6.407	0.109	
External heat exchanger inner tube	97.536	96.012	0.762	3.840	3.780	0.030	Copper corrugation (approximate dimensions)
Cooldown line	44.450	41.961	1.245	1.750	1.652	0.049	
LHe supply	15.875	13.386	1.245	0.625	0.527	0.049	
4.5K supply	15.875	13.386	1.245	0.625	0.527	0.049	
4.5K return	15.875	13.386	1.245	0.625	0.527	0.049	
50-70K shield shell	830.0	823.650	3.175	32.677	32.427	0.125	Aluminum shell
50-70K shield supply	76.200	69.850	3.175	3.0	2.750	0.125	Aluminum extrusion
50-70K shield return	76.200	69.850	3.175	3.0	2.750	0.125	Aluminum extrusion
KEK cold mass	500.0	470.0	15.0	19.685	18.504	0.591	ID is estimated
Fermilab cold mass	416.0	400.0	8.0	16.378	15.748	0.315	ID is estimated
Stiffener	950.0	1025.0	na	37.402	40.354	na	OD is width, ID is height

Piping parameters for LHC interaction region quadrupoles

Chapter 6 – Support structures

- Structural supports hold the internal assembly in position with respect to the vacuum vessel – ensuring long term alignment in the tunnel.
- They resist mechanical loads introduced by shipping, handling, and operation.
- They insulate the cold assembly from heat conducted from room temperature.
- Cold masses are generally several thousand pounds – especially in cold iron magnets, e.g. SSC dipole cold masses weighed 25,000 lb, LHC dipole cold masses weigh more than 60,000 lb.
- Heat loads can be as low as 30 to 40 mW per support to 4.5 K.
- Support requirements are generally at odds with one another, i.e. good structural strength and low thermal conductivity.

Chapter 6 – Support structures

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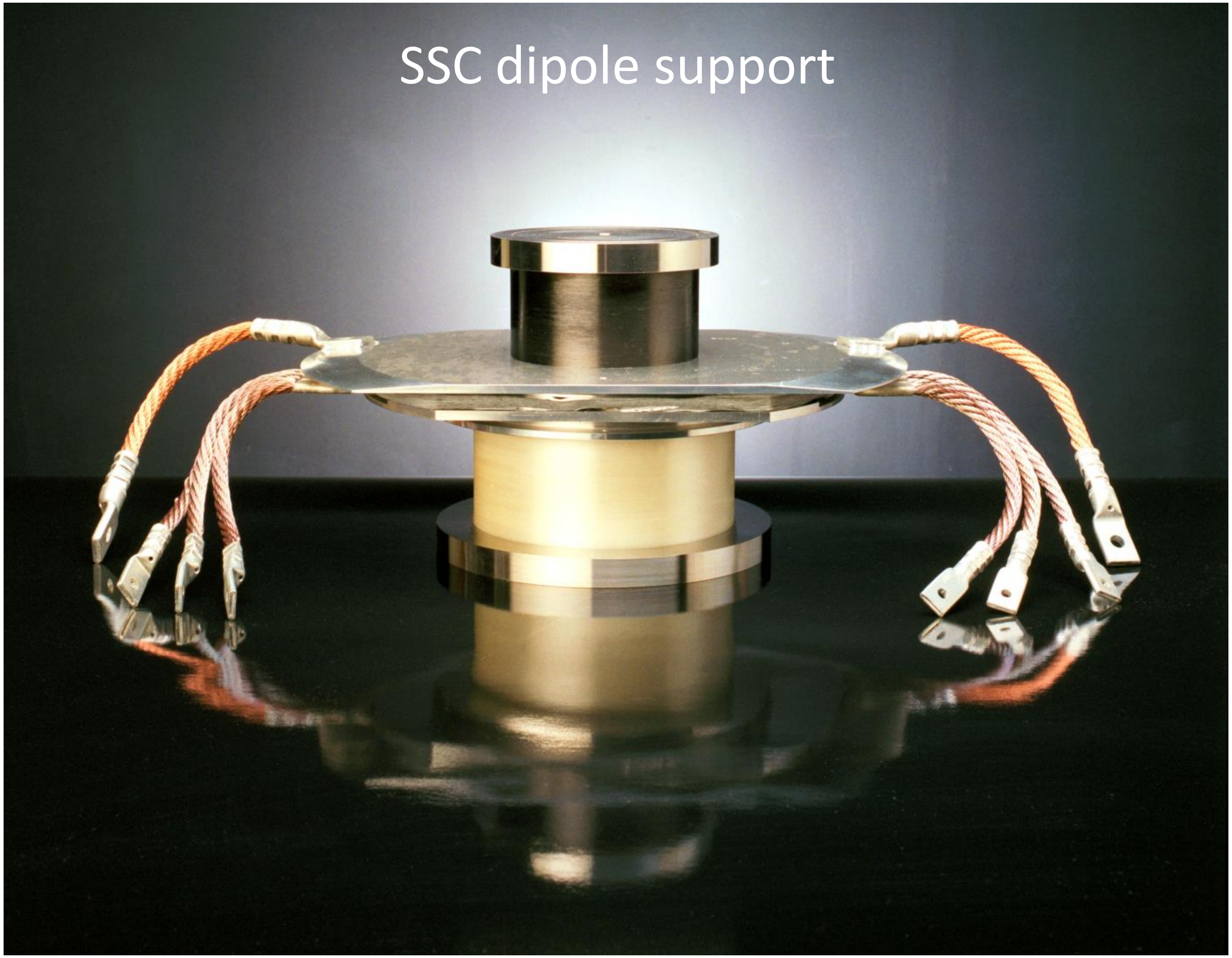

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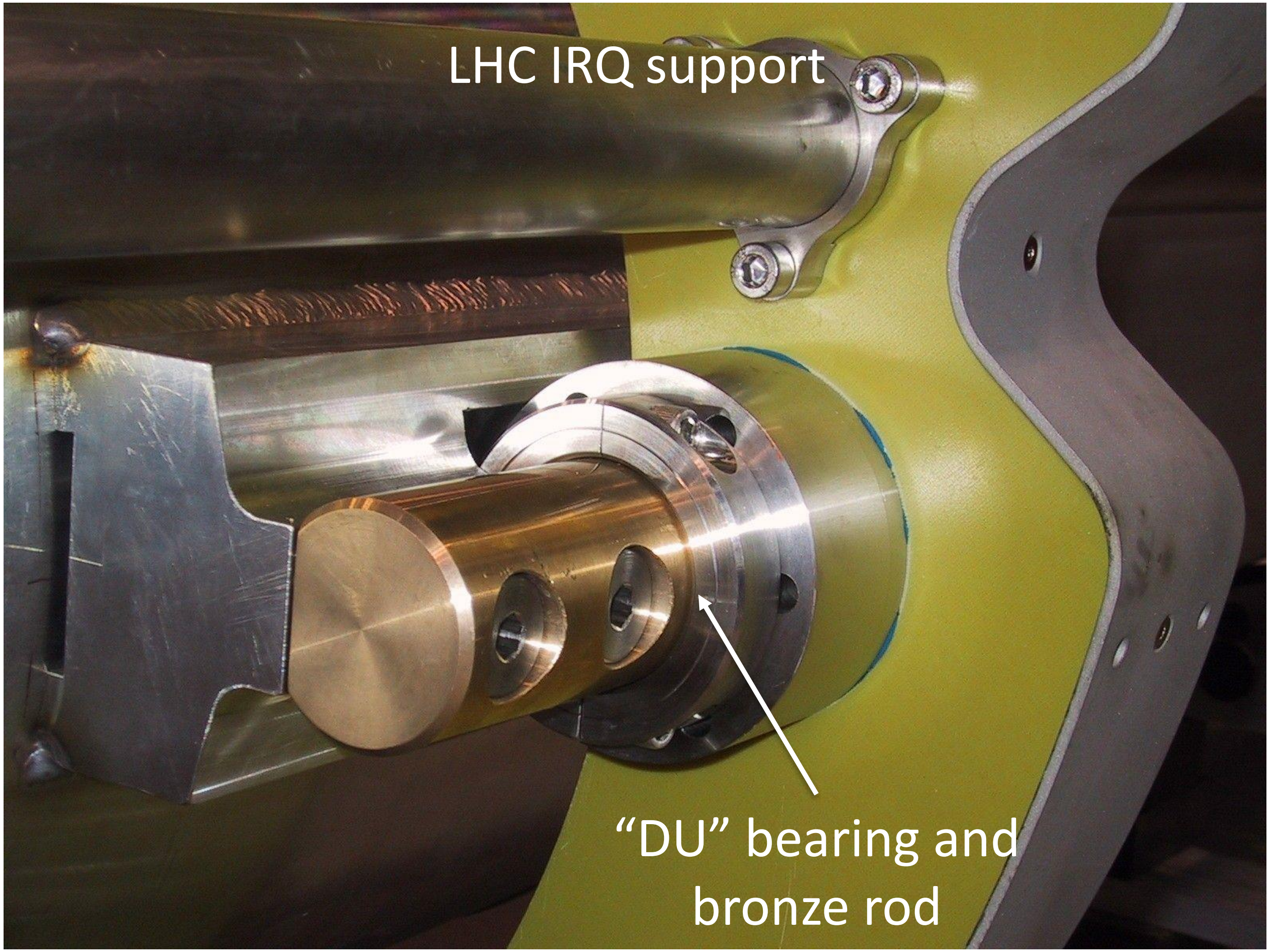
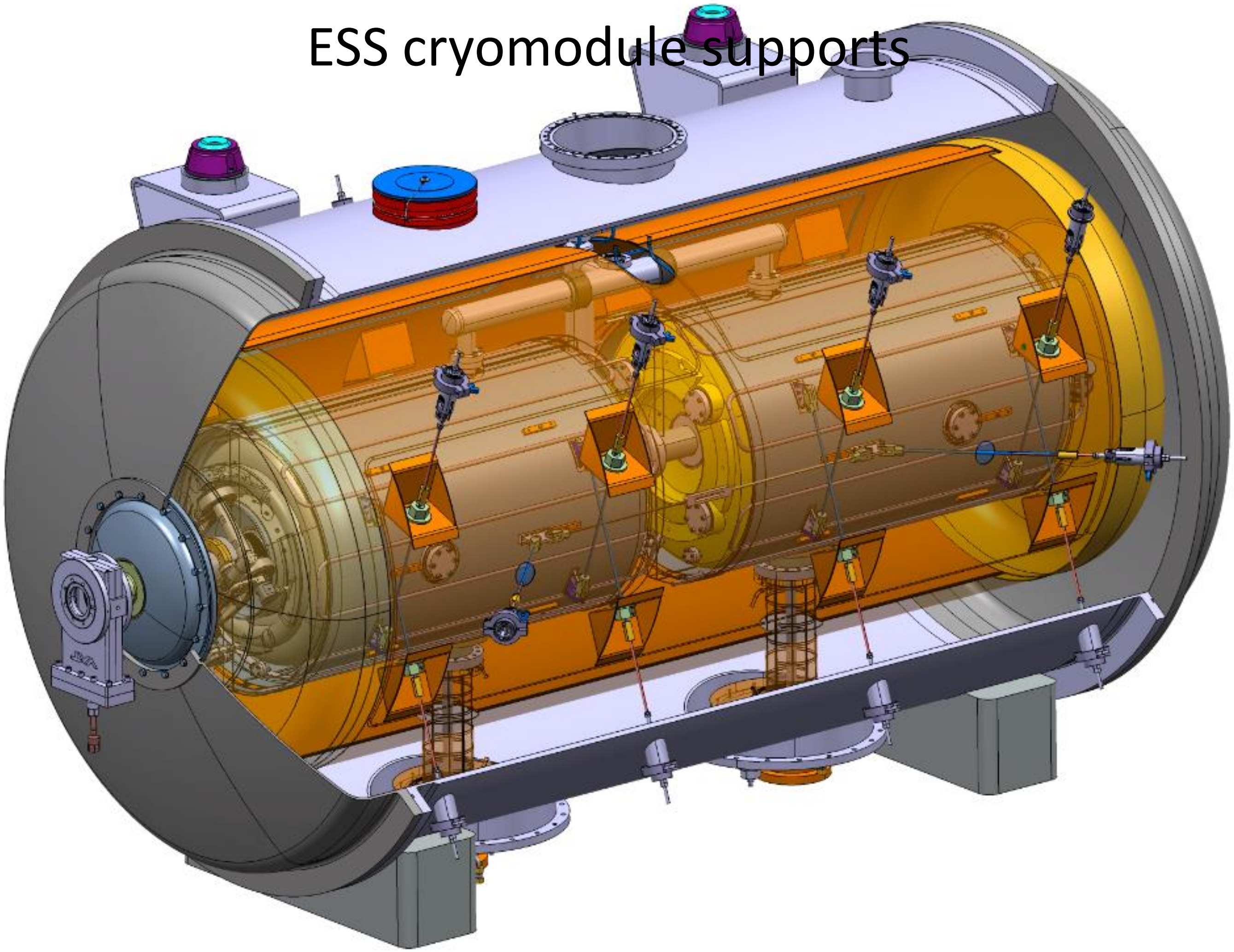


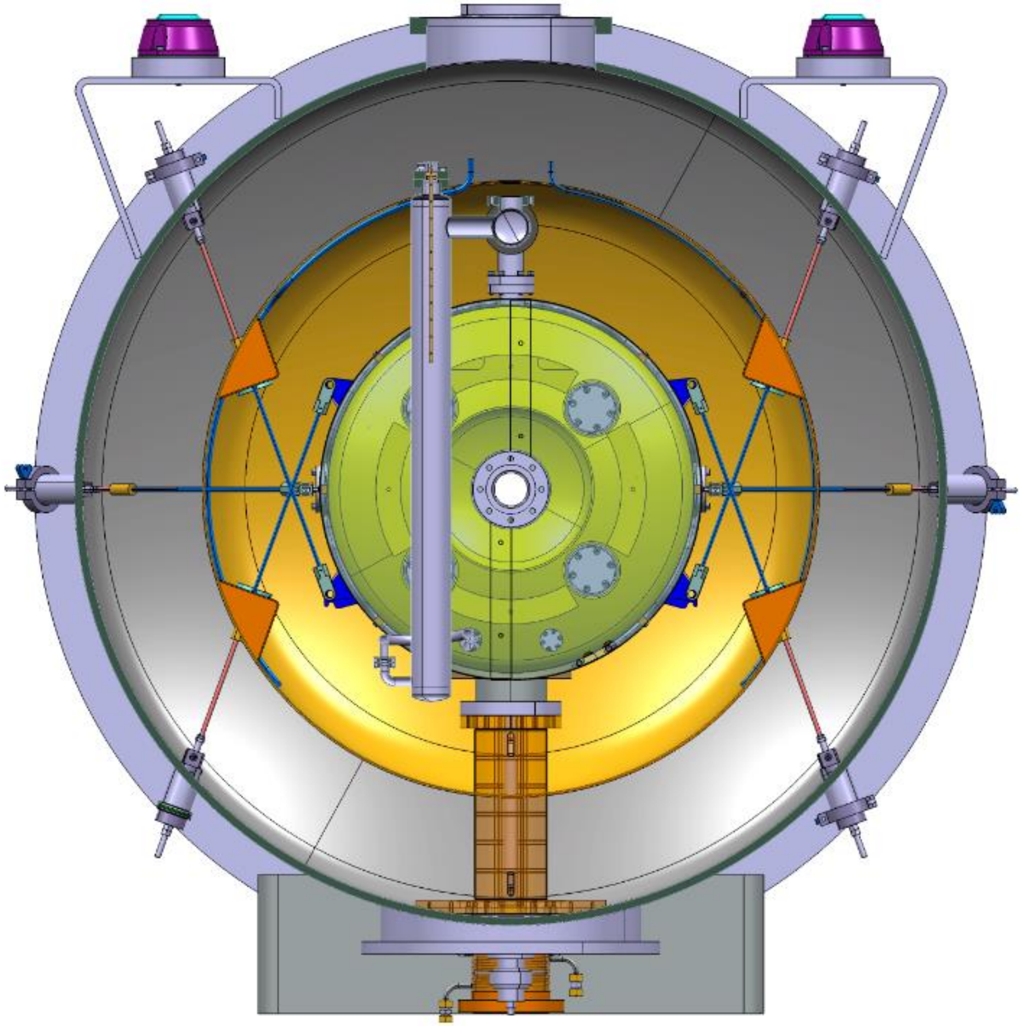
Chapter 6 – Support structures

Chapter 6 – Support structures

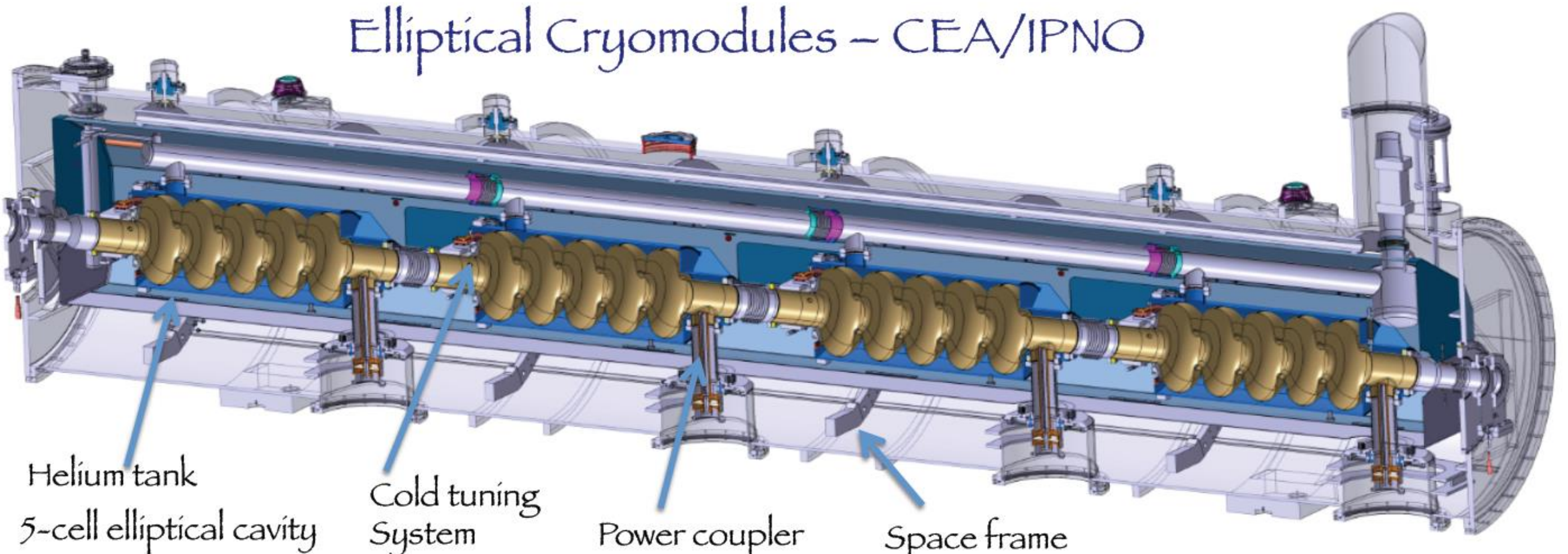
ESS cryomodule supports



Chapter 6 – Support structures



Chapter 6 – Support structures



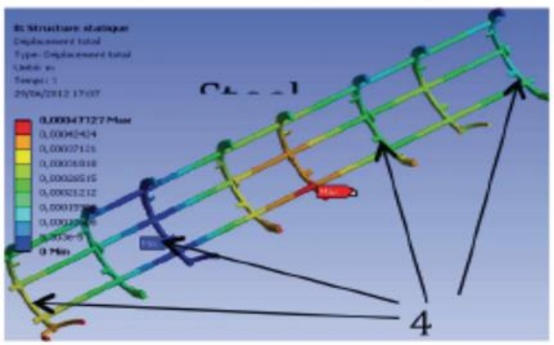
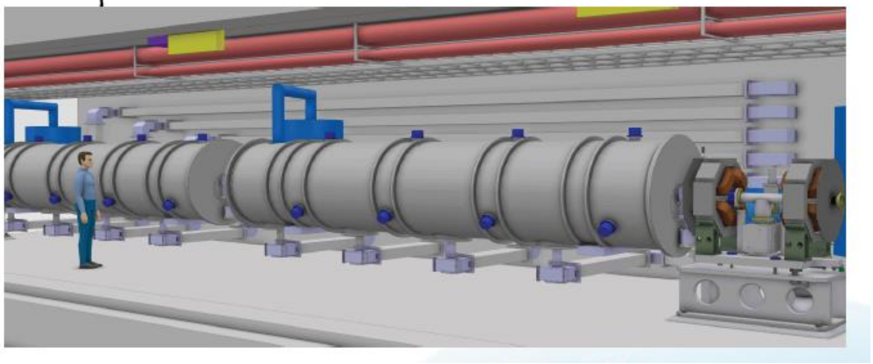


Figure 4.120: Helium vessel with hanging rod



Chapter 6 – Support structures

Table 1. Thermal and Structural Design Criteria			
	4.5 K	20 K	80 K
Static heat loads			
Infrared	0.053 W	2.335 W	19.1 W
Support conduction	0.160 W	2.400 W	15.8 W
Interconnect	0.150 W	0.320 W	2.1 W
Total static	**0.363 W**	**5.055 W**	**37.0 W**
Dynamic heat loads			
Synchrotron radiation	2.169 W		
Splice heating	0.140 W		
Beam microwave	0.195 W		
Beam gas	0.136 W		
Total dynamic	**2.640 W**		
Total dipole	**3.003 W**	**5.055 W**	**37.0 W**
Structural load summary			
Cold mass weight		11,360 kg	
Shipping and handling		2.0 g	vertical
		1.5 g	Axial
		1.0 g	lateral

Heat load budget and structural loads for SSC dipoles

Chapter 6 – Support structures

- Materials are nearly always:

	Composites	Metals
Pros	Readily available Low thermal conductivity Relatively high strength Bonding can be difficult	Readily available High strength Easily joined to adjacent parts
Cons	Not as strong as metals Varying degrees of radiation resistance	Higher thermal conductivity than composities Good radiation resistance
Materials	Glass or graphite reinforced composites, Ultem, Torlon, PEEK	Stainless steel, Inconel, Invar, Titanium, Aluminum

Chapter 6 – Support structures

- Support design needs to consider:
  - Structural loading, both static and dynamic
  - Static heat load budget
  - Material limitations, if any
  - Physical layout of the magnet or cryomodule components
- Design should include an axial anchor somewhere in the cryostat or cryomodule.
- Design must accommodate thermal contraction and expansion during cooldown and warmup.

Chapter 7 – Heat load

Table 1. Thermal and Structural Design Criteria			
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		1.5 g	Axial
		1.0 g	lateral

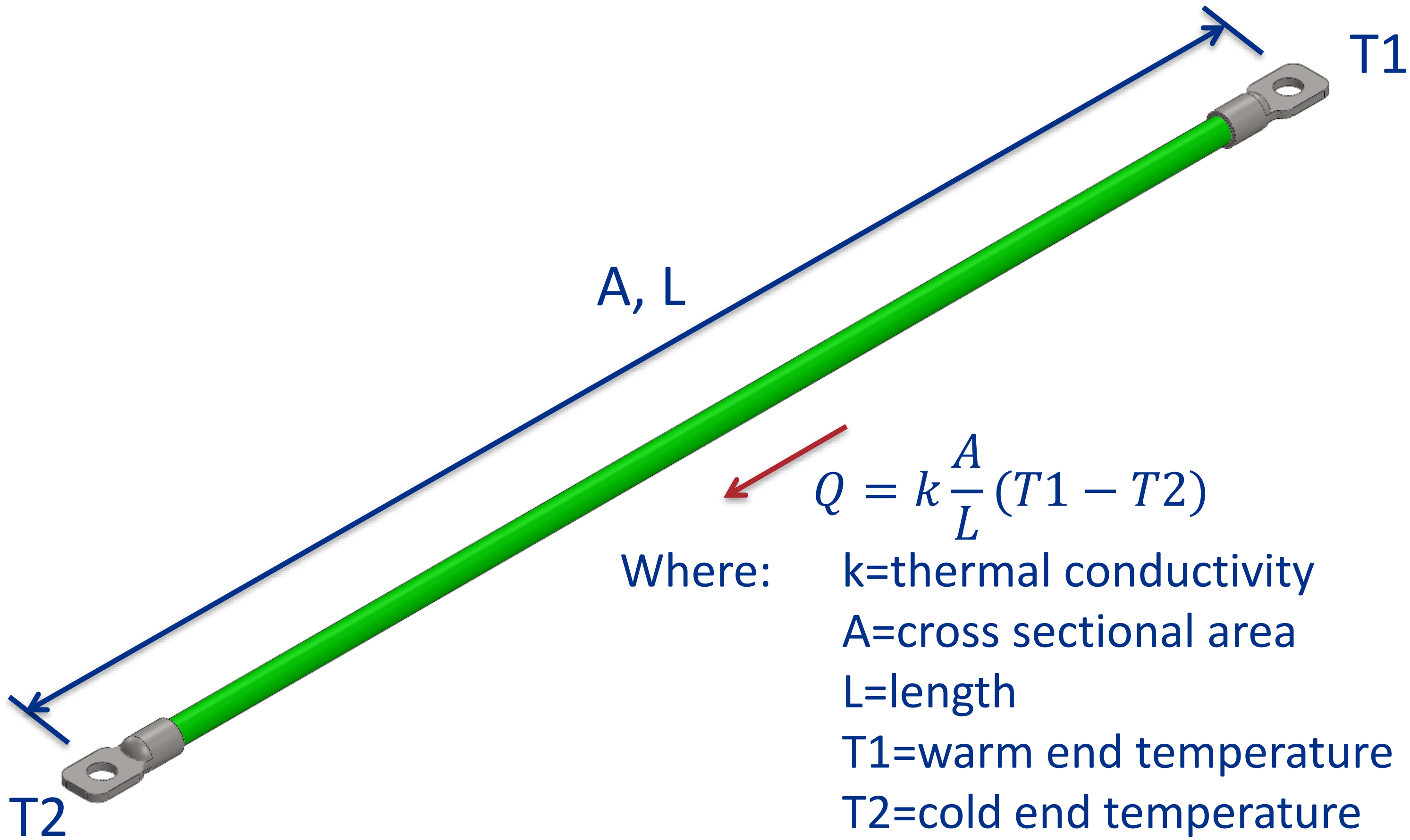
Heat load budget for SSC dipoles

Chapter 7 – Heat load

CM type	Number of CMs	Static loads per CM, (W)			Dynamic loads per CM, (W)	Total load at 2 K per CM, (W)
		70 K *	5 K *	2 K	2 K	2 K
HWR	1	250	60	14	24	38
SSR1	2	166	88	12	16	28
SSR2	7	126	62	9	10	19
LB650	11	48	16	2	73	75
HB650	4	86	32	4	145	149
Total		2336	974	139	1509	1648

Heat load budget for PIP-II cryomodules

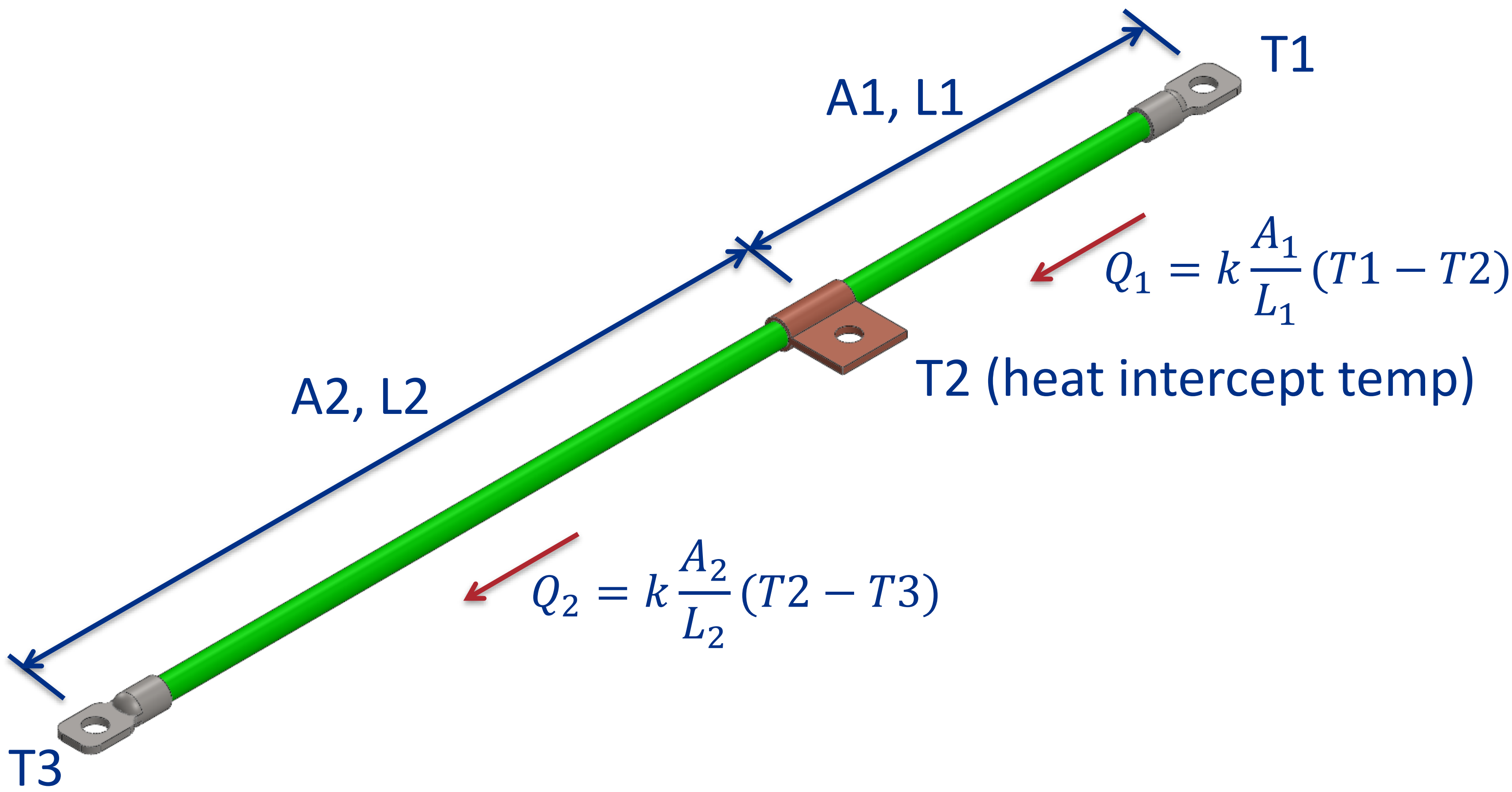
Chapter 7 – Heat load nomenclature



$$Q = k\frac{A}{L}(T1 - T2)$$

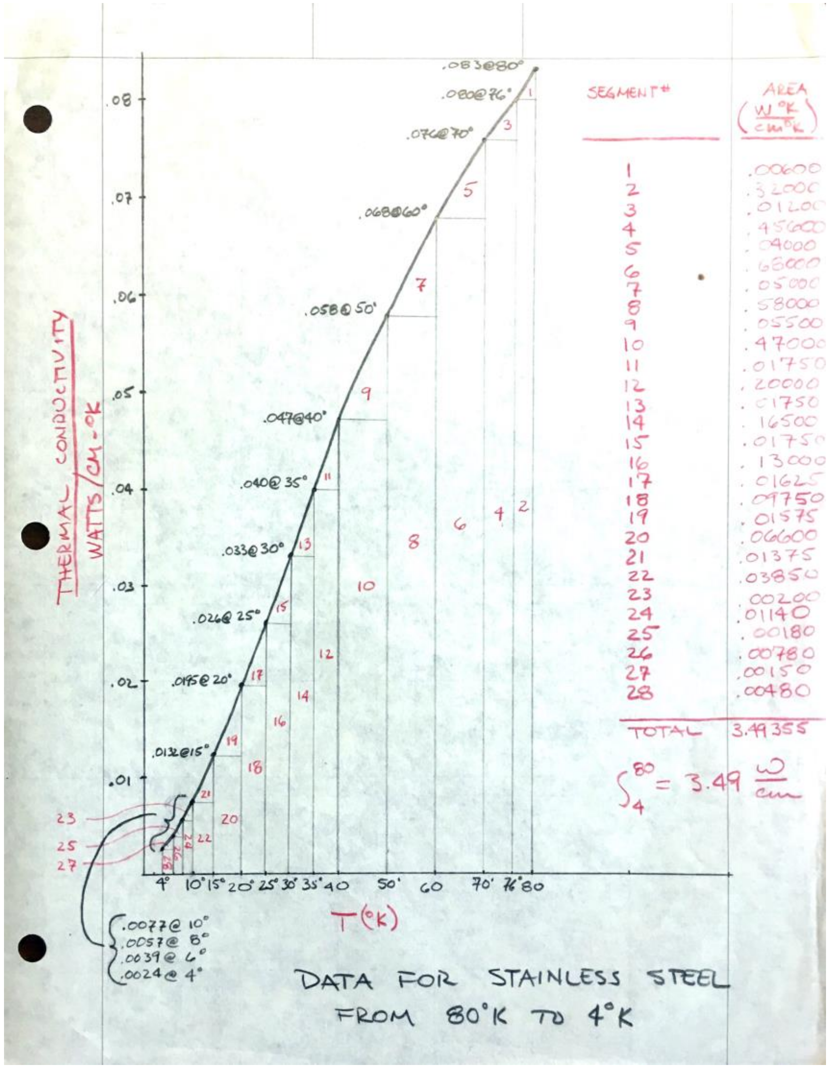
Where: k=thermal conductivity
A=cross sectional area
L=length
T1=warm end temperature
T2=cold end temperature

Chapter 7 – Heat load nomenclature

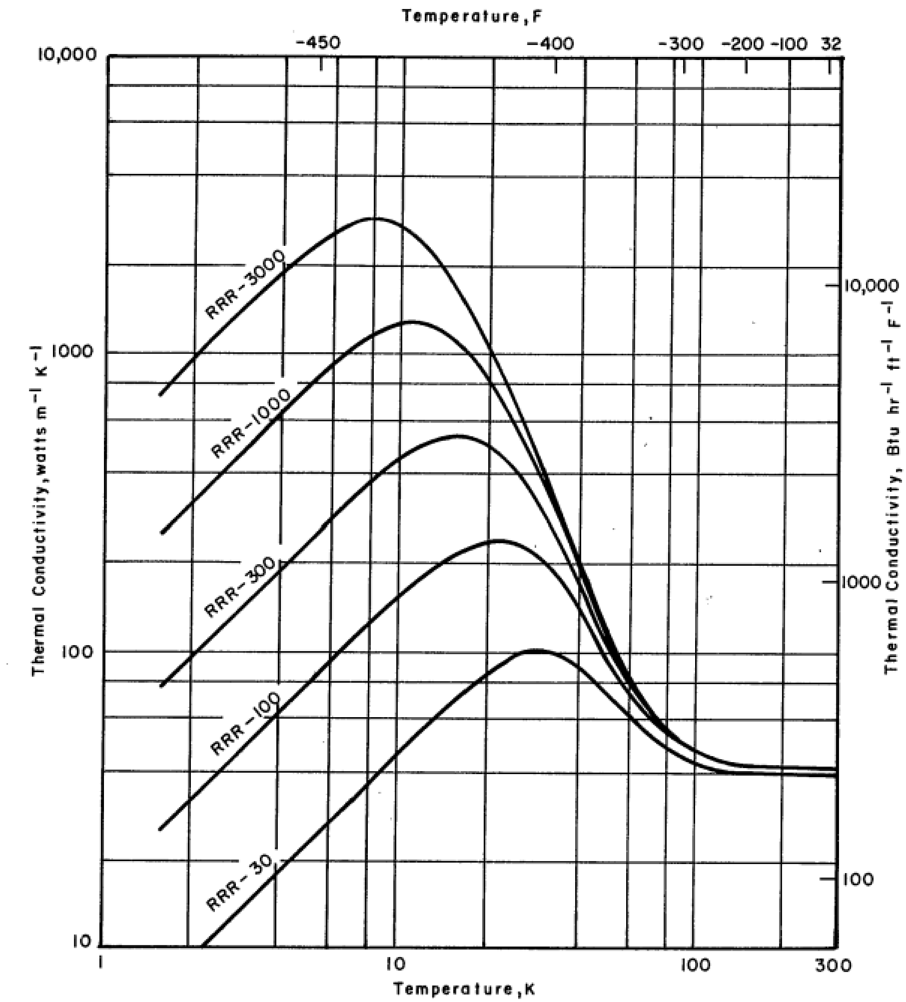


Chapter 7 – Estimating thermal conductivity integrals

For most of the materials we work with, most of their properties vary with temperature, e.g. thermal conductivity, specific heat, thermal expansion, etc. So rather than isotropic values, we need to use integrated values, determined from temperature dependent data.

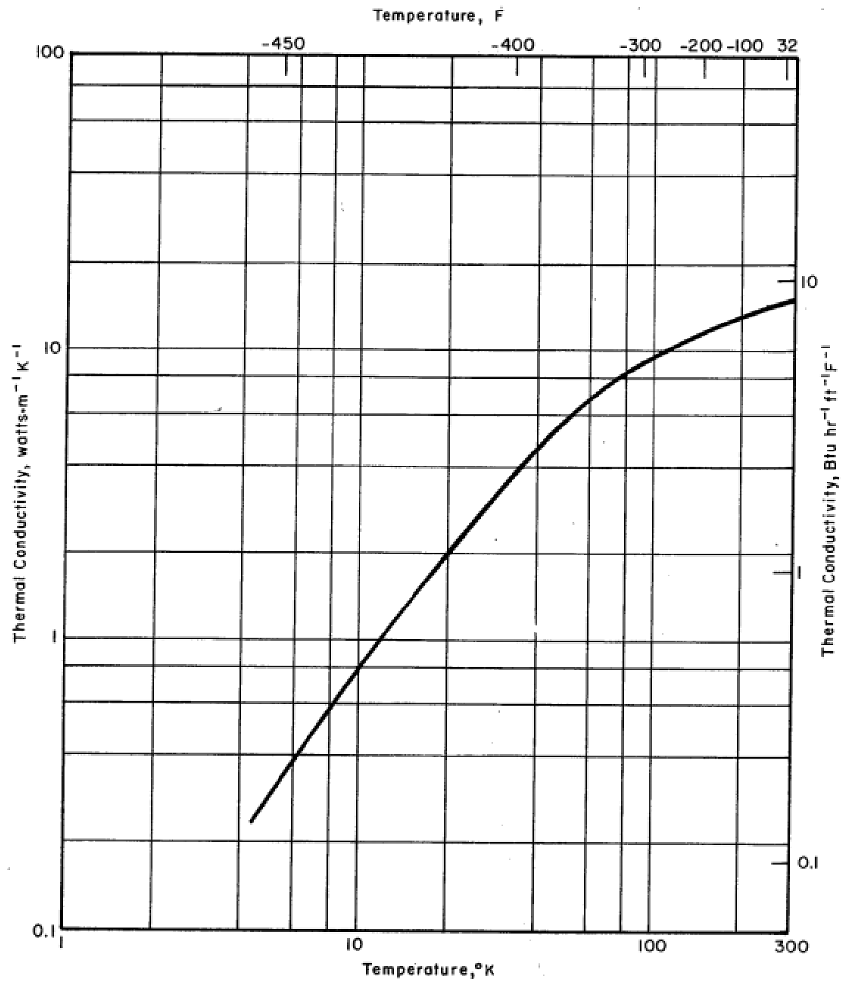


Chapter 7 – Copper thermal conductivity curves



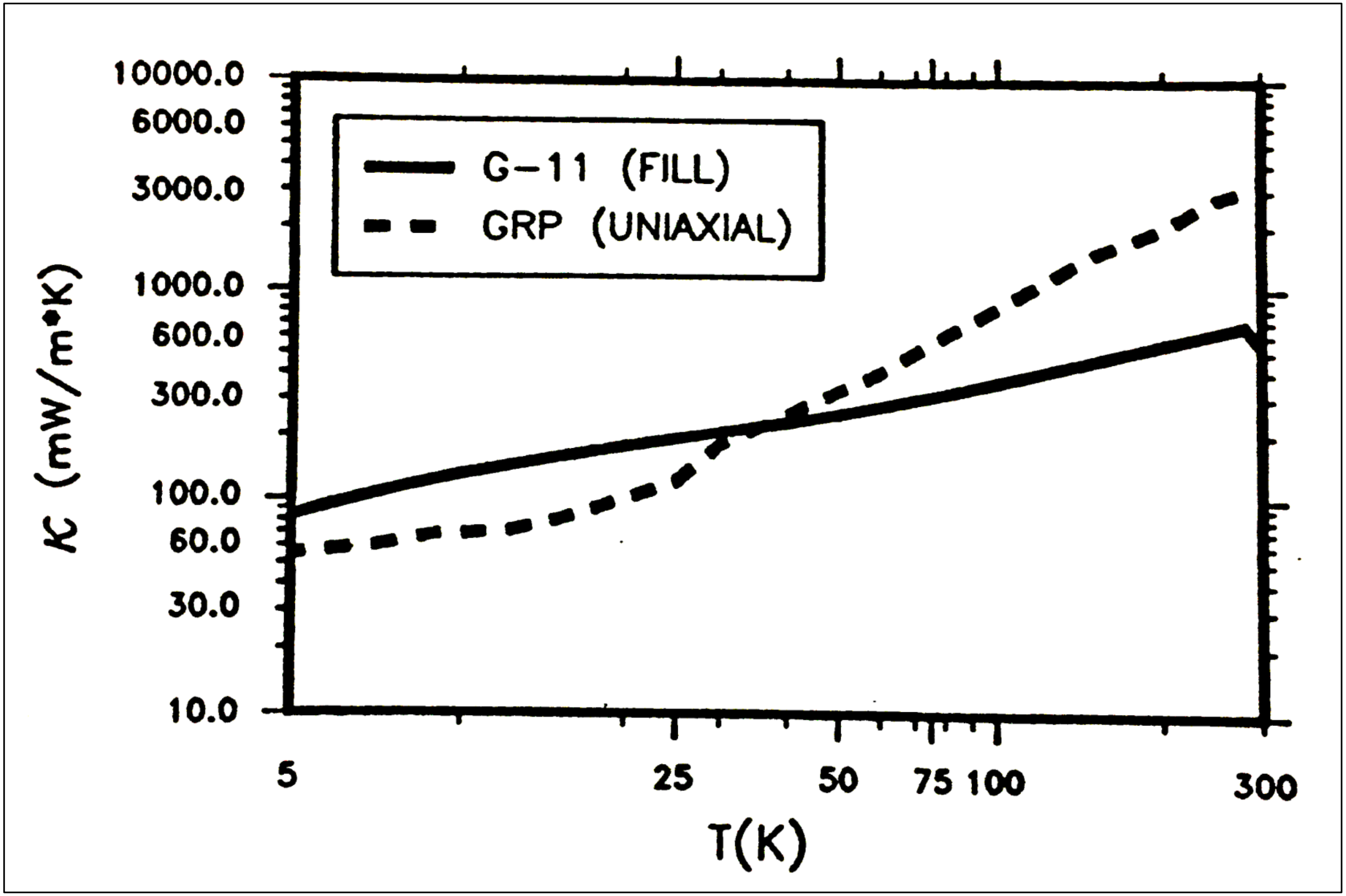
THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR COPPER

Chapter 7 – 304 stainless steel thermal conductivity curve



THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR TYPE 304 STAINLESS STEEL

Chapter 7 – G-11 and GRP thermal conductivity curves



Chapter 7 – NIST cryogenic material database

NIST National Institute of Standards and Technology

Material Measurement Laboratory

Cryogenics Technologies Group

- Staff
- Group Information
- Publications
- Cryocoolers
- Material Properties
- FluidProperties
- About Cryogenics
- Links of Interest
- Software
- Home

CRYOGENIC TECHNOLOGIES GROUP

Thermophysical Properties DIVISION

MML Material Measurement Laboratory

Material Properties

Aluminum 1100 (UNS A91100)

Aluminum 3003-F(UNS A93003)

Aluminum 5083-O (UNS A95083)

Aluminum 6061-T6 (UNS A96061)

Aluminum 6063-T5 (UNS A96063)

Apiezon N

Balsa

Beechwood/phenolic

Beryllium

Beryllium Copper

Brass (UNS C2600)

Copper (OFHC) (UNS C10100/ C10200)
* rev. 02/03/2010

Fiberglass Epoxy G-10

Glass Fabric/polyester

Glass mat/epoxy

Inconel 718 (UNS N107718)

Indium

Invar (Fe-36Ni) (UNS K93600)

Kevlar-49 Fiber

Kevlar-49 composite

Lead

Molybdenum

Nickel Steel Fe 2.25 Ni

Nickel Steel Fe 3.25 Ni (UNS S20103)

Nickel Steel Fe 5.0 Ni (UNS S20153)

Nickel Steel Fe 9.0 Ni (UNS S21800)

Platinum

Polyamide (Nylon)

Polyethylene Terephthalate (Mylar)

Polyimide (Kapton)

Polystyrene

Polyurethane

Polyvinyl Chloride (PVC)

Sapphire

Silicon

Stainless Steel 304 (UNS S30400)

Stainless Steel 304L (UNS S30403)

Stainless Steel 310 (UNS S31000)

Stainless Steel 316 (UNS S31600)

Teflon

Ti-6Al-4V (UNS R56400)

Titanium 15-3-3-3

http://cryogenics.nist.gov/MPropsMAY/material%20properties.htm

Chapter 7 – NIST 304 stainless steel page

NIST National Institute of Standards and Technology

Material Measurement Laboratory

CRYOGENIC TECHNOLOGIES GROUP

Material Properties: 304 Stainless (UNS S30400)

Data Available:
- Thermal Conductivity
- Specific Heat
- Young's Modulus
- Linear Expansion

	Thermal Conductivity	Specific Heat
UNITS	**W/(m-K)**	**J/(kg-K)**
a	-1.4087	22.0061
b	1.3982	-127.5528
c	0.2543	303.647
d	-0.6260	-381.0098
e	0.2334	274.0328
f	0.4256	-112.9212
g	-0.4658	24.7593
h	0.1650	-2.239153
i	-0.0199	0
data range	4-300	4-300
equation range	1-300	4-300
curve fit % error relative to data	2	5

To view a **thermal conductivity** plot Click here

To view a **specific heat** plot Click here

Curve fit equation of the form:

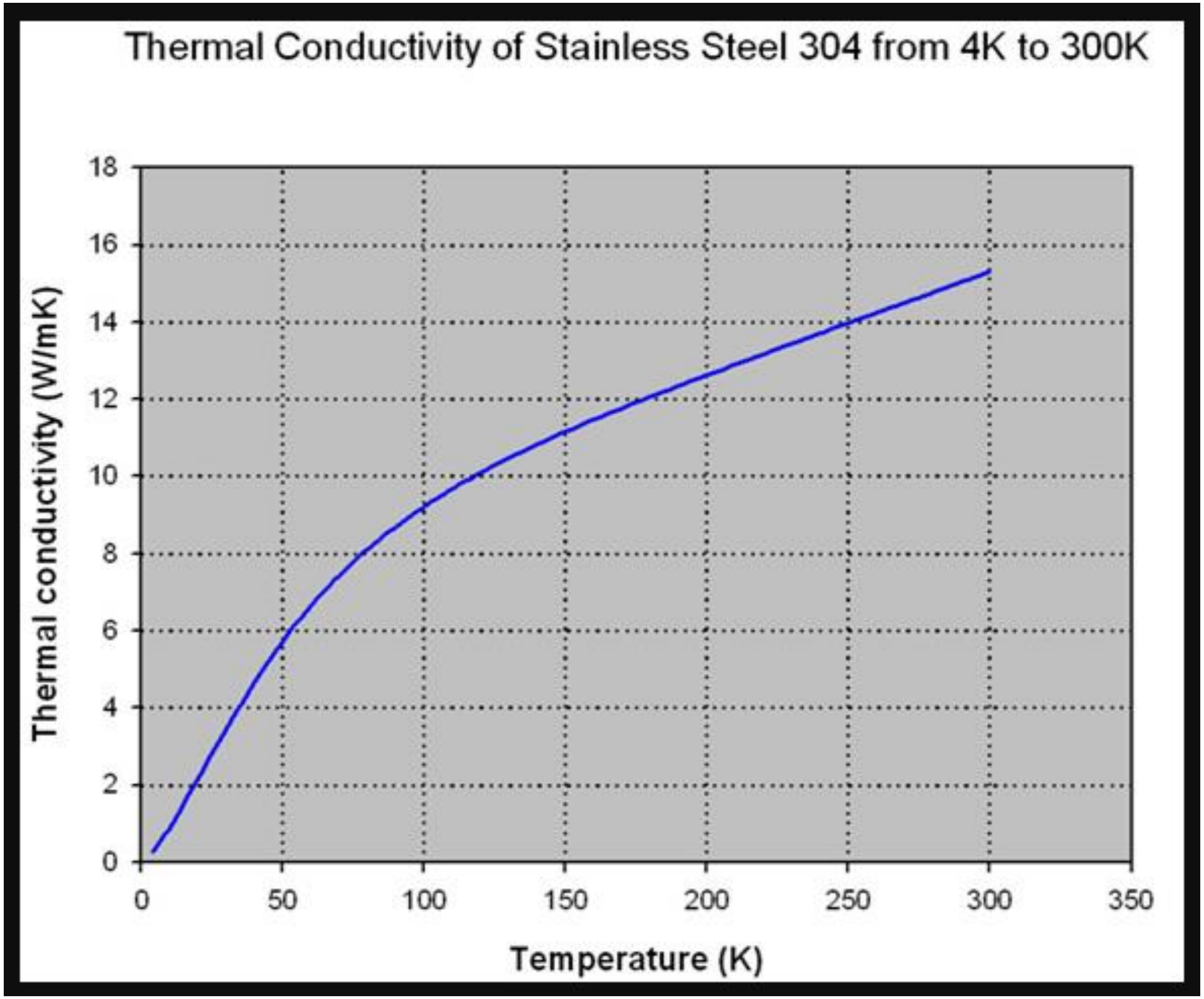
$$\log_{10} y = a + b(\log_{10}T) + c(\log_{10}T)^2 + d(\log_{10}T)^3 + e(\log_{10}T)^4 + f(\log_{10}T)^5 + g(\log_{10}T)^6 + h(\log_{10}T)^7 + i(\log_{10}T)^8$$

Solves as:

$$y = 10^{a + b(\log_{10}T) + c(\log_{10}T)^2 + d(\log_{10}T)^3 + e(\log_{10}T)^4 + f(\log_{10}T)^5 + g(\log_{10}T)^6 + h(\log_{10}T)^7 + i(\log_{10}T)^8}$$

Where: Coefficients a - *i* are summarized in the appropriate table and T is the temperature in K (x-axis), and y is the property to solve for.

Chapter 7 – NIST 304 stainless steel curve



Chapter 7 – Brookhaven Selected Cryogenic Data Notebook

SELECTED CRYOGENIC DATA NOTEBOOK

(DIGITIZED AND PUT ON WEB FROM THE ORIGINAL REPORT : BNL 10200-R, REVISED AUGUST 1980)

Compiled and Edited by J.E. Jensen, W.A. Tuttle, R.B. Stewart, H. Brechna and A.G. Prodell

Brookhaven National Laboratory

NOTE: The indexing is primitive. A useful place to start may be the Subject Index

A PDF viewer is required to see most articles.

- Cover Page
- Introduction
- **Subject Index**
    - **Expanded subject index (under construction)**
- Disclaimer

- **Click here to go to Material Properties Important to the Design of A Large Superconducting Magnet**
- **Click Here to View the Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators**

Go to the Home Page of the Superconducting Magnet Division (SMD) at BNL

- Go to the Workshop Page at SMD
- Go to the Publication Page at SMD

Click Here to Visit Ramesh Gupta's Home Page at BNL

Please e-mail comments, corrections, etc. to Ramesh Gupta at gupta@bnl.gov .

https://www.bnl.gov/magnets/Staff/Gupta/cryogenic-data-handbook/index.htm

Chapter 7 – Copper thermal conductivity

THERMAL CONDUCTIVITY INTEGRALS

for COPPERS

Comments: The six curves were extrapolated to 300°K. The curve for O.F.H.C. was extrapolated to 4°K and the curve for (Pb)Cu was extrapolated to 6°K. It is estimated that the extrapolated values do not deviate more than 10% from the probable values.

$$Q = \frac{A}{L} \int_{T_o}^{T_L} \lambda \, dT; \qquad Q \frac{L}{A} = \int_{T_o}^{T_L} \lambda \, dT$$

Where:

- Q = heat flow in watts
- A = cross sectional area in cm^2
- L = length in cm
- λ = thermal conductivity in watts/cm-°K
- T = temperature in °K
- T_o = initial temperature (6°K for [Pb]Cu and [Te]Cu; 4°K for all other Coppers)

Thermal Conductivity Integrals are on following page.

Temp. °K	Thermal Conductivity watts/cm-°K					
	Hi-Purity Annealed	Coalesced	Elect. T.P.	O.F.H.C.	(Pb) Cu	(Te) Cu
4	70	6.2	3.2	2.4*		
6	96	10.	4.8	3.7*	2.7*	2.2
8	120	14.	6.3	4.7*	3.6*	2.8
10	134	17.5	7.8	6.0*	4.5*	3.4
15	120	23	11	8.5*	6.3*	5.0
20	88	24	13	11 *	8 *	6.5
25	60	23	14	12	9.2	7.3
30	40	22	14	12	9.6	7.8
35	28	18.5	13	11	9.5	7.9
40	20	15	11.5	10	9	7.7
50	12	10	8.8	7.7	6.9	6.8
60	8.0	7.8	7.0	6.2	5.5	5.8
70	6.2	6.5	5.9	5.5	4.7	5.2
76	5.7	6.0	5.5	5.2	4.5	4.9
80	5.2	5.7	5.2	4.9	4.3	4.6
90	4.7	5.1	4.7	4.7	4.0*	4.3
100	4.5	4.8	4.5	4.5	3.8*	4.2
120	4.3	4.5	4.3	4.3	3.7*	4.0
140	4.2	4.3	4.2	4.2	3.6*	3.8
160	4.1	4.2	4.1	4.1	3.6*	3.8
180	4.0	4.2	4.0	4.0	3.6*	3.8
200	4.0	4.2	4.0	4.0	3.6*	3.8
250	4.0	4.2*	4.0	4.0	3.6*	3.8*
300	4.0*	4.2*	4.0*	4.0*	3.6*	3.8*

* Extrapolated Values

Chapter 7 – Copper thermal conductivity integrals

THERMAL CONDUCTIVITY INTEGRALS
for COPPERS (cont.)

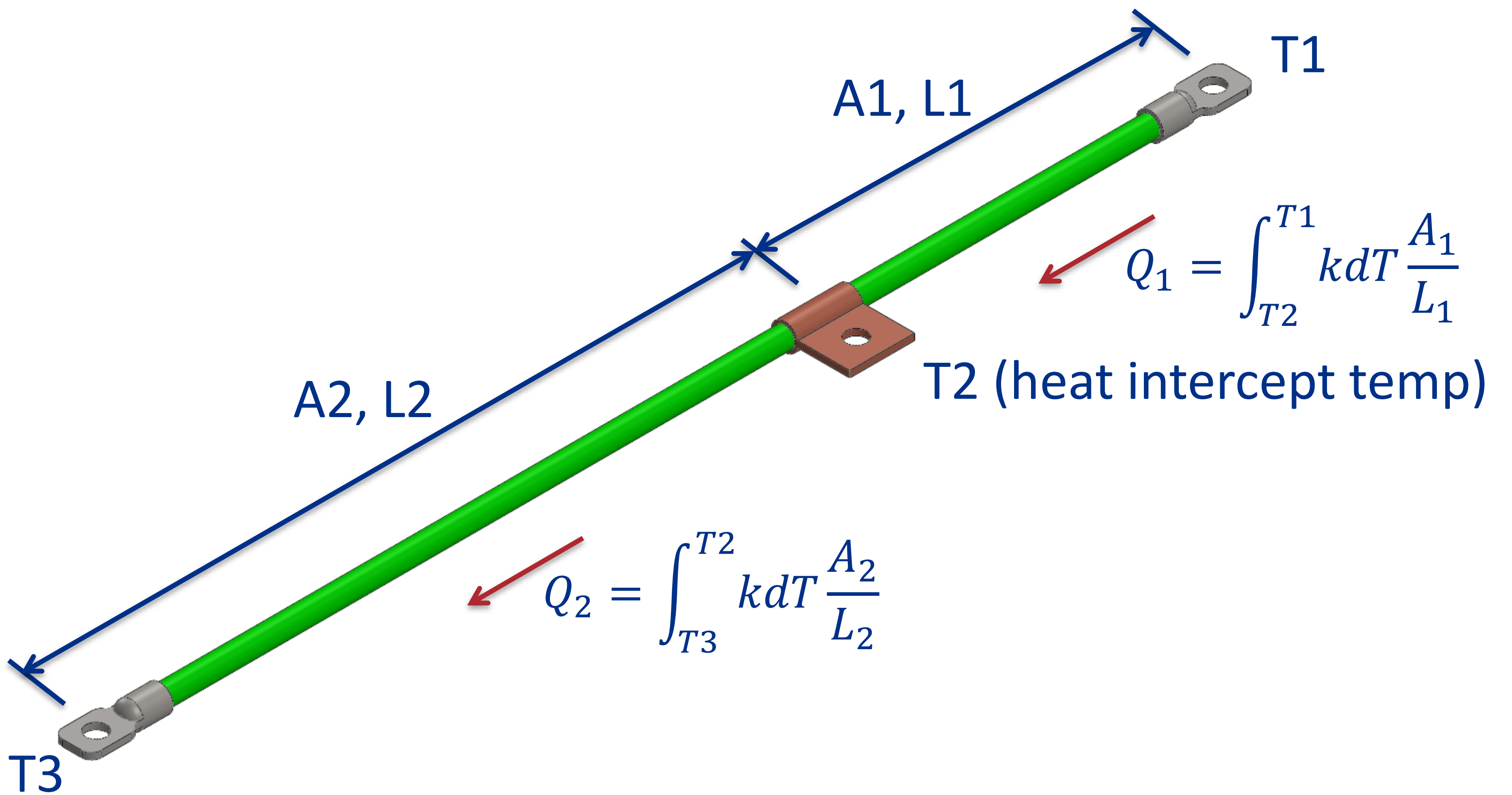
Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm					
	Hi-Purity Annealed	Coalesced	Elect. T.P.	O.F.H.C.	(Pb) Cu	(Te) Cu
6	166	16.2	8.00	6.1		
8	382	40.2	19.1	14.5	6.3	5
10	636	71.7	33.2	25.2	14.4	11.2
15	1270	173	80.2	61.4	41.4	32.2
20	1790	290	140	110	77.2	60.9
25	2160	408	208	168	120	95.4
30	2410	520	278	228	167	133
35	2580	622	345	285	215	172
40	2700	705	406	338	261	211
50	2860	830	508	426	341	284
60	2960	919	587	496	403	347
70	3030	991	651	554	454	402
76	3070	1030	686	586	481	432
80	3090	1050	707	606	499	451
90	3140	1100	756	654	540	496
100	3180	1160	802	700	579	538
120	3270	1250	891	788	654	620
140	3360	1340	976	874	727	698
160	3440	1420	1060	956	799	774
180	3520	1510	1140	1040	871	850
200	3600	1590	1220	1120	943	926
250	3800	1800	1420	1320	1120	1120
300	4000	2000	1620	1520	1300	1310

Reprinted from WADD Tech.Report 60-56

Chapter 7 – Thermal conductivity integrals for common materials

Thermal conductivity integrals (W/cm)			
	300 K - 80 K	**80 K - 4 K**	**300 K - 4 K**
304 SS	27.2	3.5	30.7
OFHC copper	911.0	606.5	1517.5
6063-T5 aluminum	446.0	167.1	613.1
G-11 (warp)	1.2	0.2	1.4

Chapter 7 – Heat load nomenclature (with integrated k)



Chapter 7 – Examples

- Look at two examples with and without thermal intercepts
  - 6.35 mm OD, 305 mm long solid G-11 rod
  - 6.35 mm OD, 0.5 mm wall, 305 mm long stainless steel rod (304)
- Warm end temperature = 300K
- Cold end temperature = 4 K
- Intercept temperature = 80 K
- Intercept at 92.4 mm from warm end

Chapter 7 – Example 1a: Solid G-11 rod, no intercept

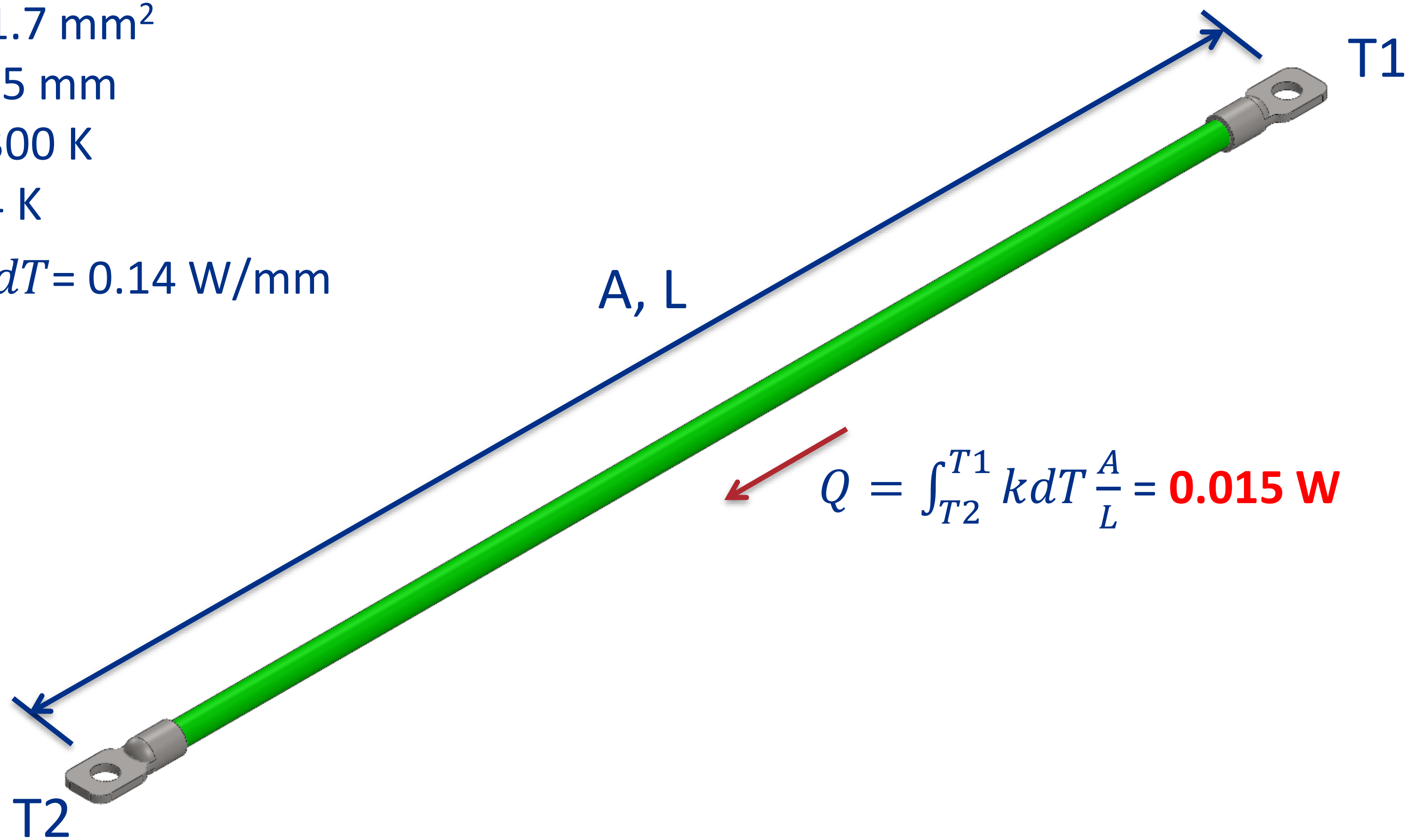
$A = 31.7\ mm^2$

$L = 305\ mm$

$T1 = 300\ K$

$T2 = 4\ K$

$\int_{T2}^{T1} kdT = 0.14\ W/mm$



Chapter 7 – Example 1b: Solid G-11 rod, 80 K intercept

$A1 = A2 = 31.7\ mm^2$

$L1 = 92.4\ mm$

$L2 = 192.4\ mm$

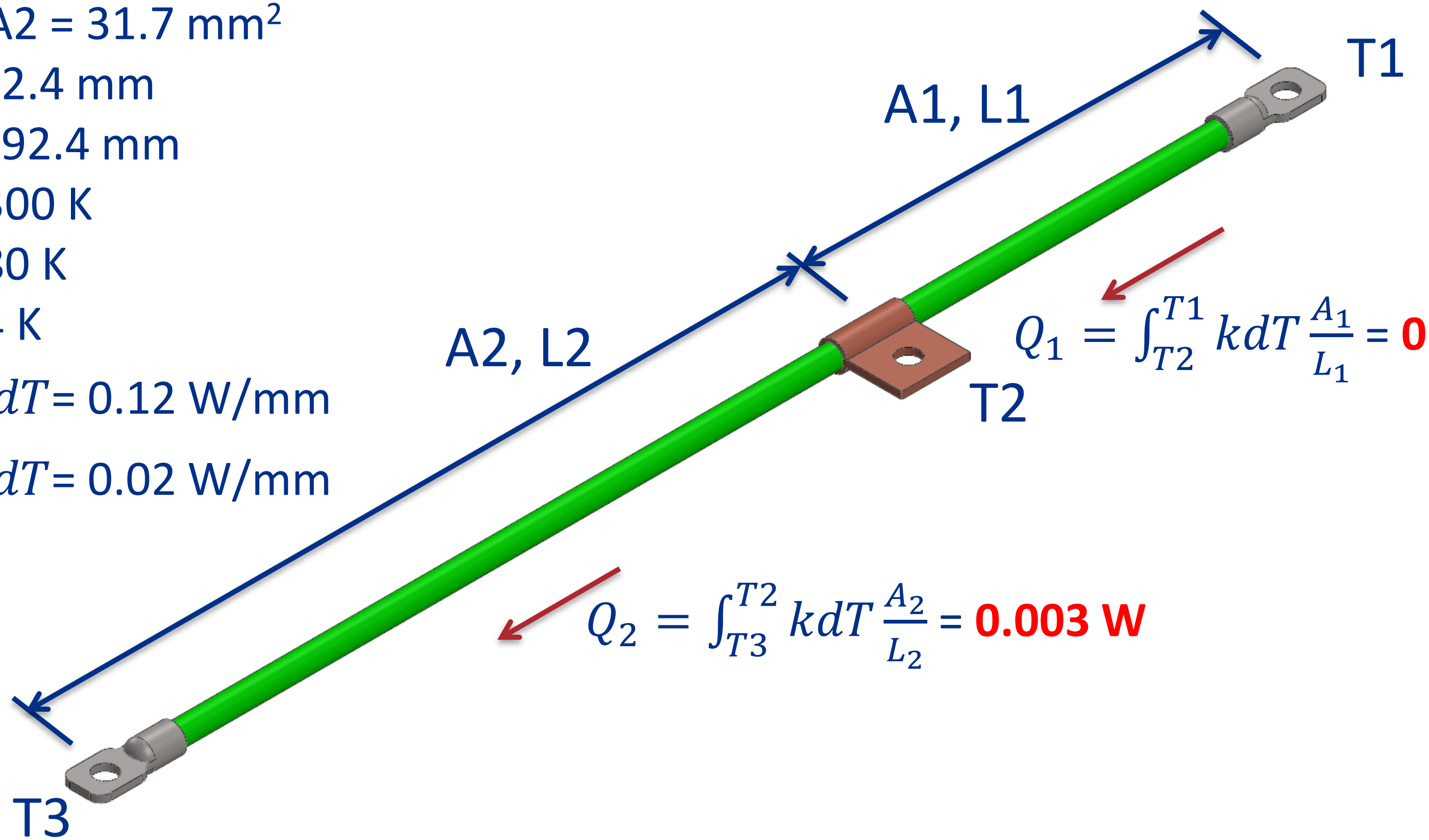
$T1 = 300\ K$

$T2 = 80\ K$

$T3 = 4\ K$

$\int_{T2}^{T1} kdT = 0.12\ W/mm$

$\int_{T3}^{T2} kdT = 0.02\ W/mm$



$$Q_1 = \int_{T2}^{T1} kdT \frac{A_1}{L_1} = \mathbf{0.042\ W}$$

$$Q_2 = \int_{T3}^{T2} kdT \frac{A_2}{L_2} = \mathbf{0.003\ W}$$

Chapter 7 – Example 2a: Hollow stainless rod, no intercept

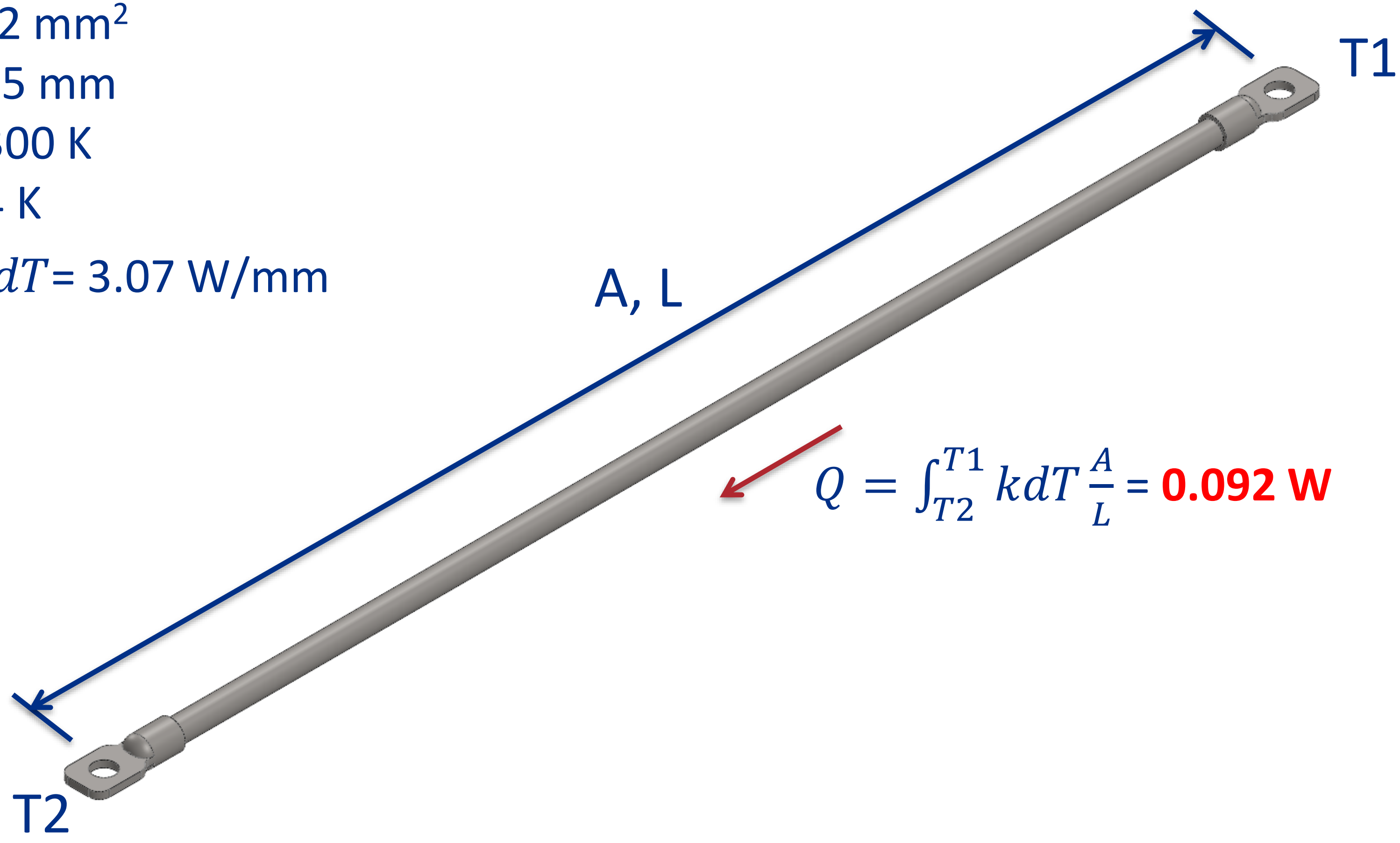
$A = 9.2\ mm^2$

$L = 305\ mm$

$T1 = 300\ K$

$T2 = 4\ K$

$\int_{T2}^{T1} k dT = 3.07\ W/mm$



$$Q = \int_{T2}^{T1} k dT \frac{A}{L} = \mathbf{0.092\ W}$$

Chapter 7 – Example 2b: Hollow stainless rod, 80 K intercept

$A1 = A2 = 9.2\ mm^2$

L1 = 92.4 mm

L2 = 192.4 mm

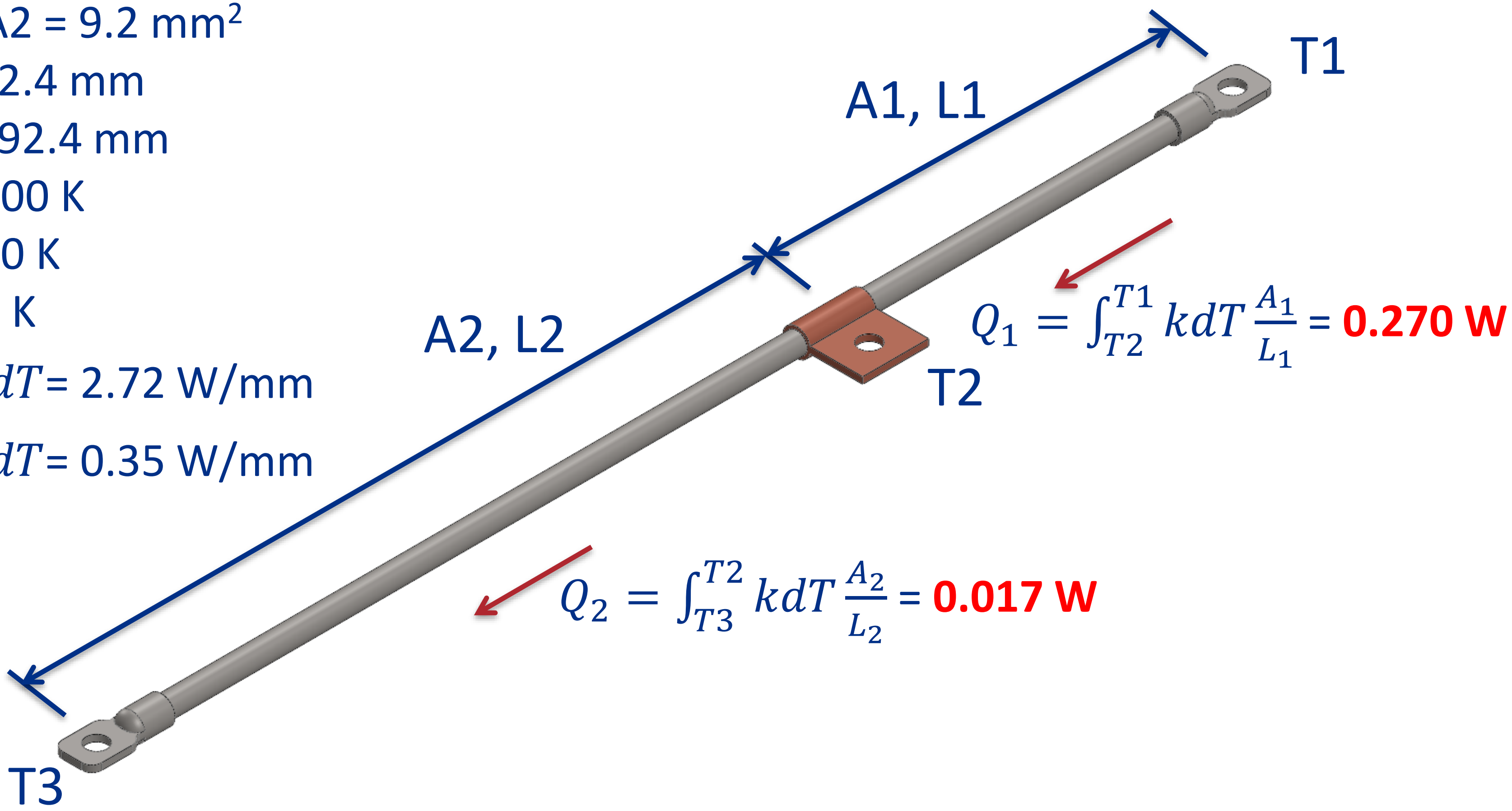
T1 = 300 K

T2 = 80 K

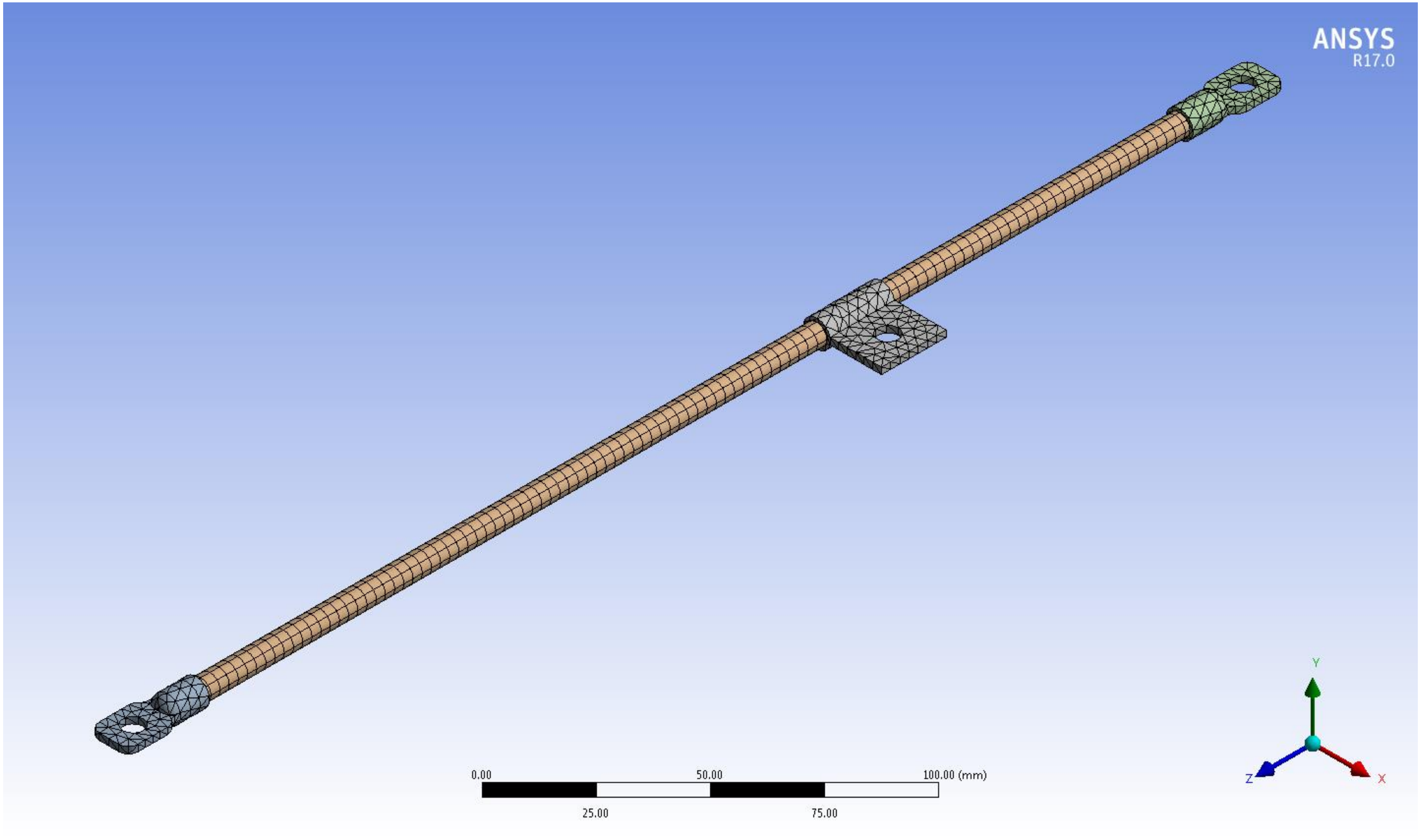
T3 = 4 K

$\int_{T2}^{T1} kdT$ = 2.72 W/mm

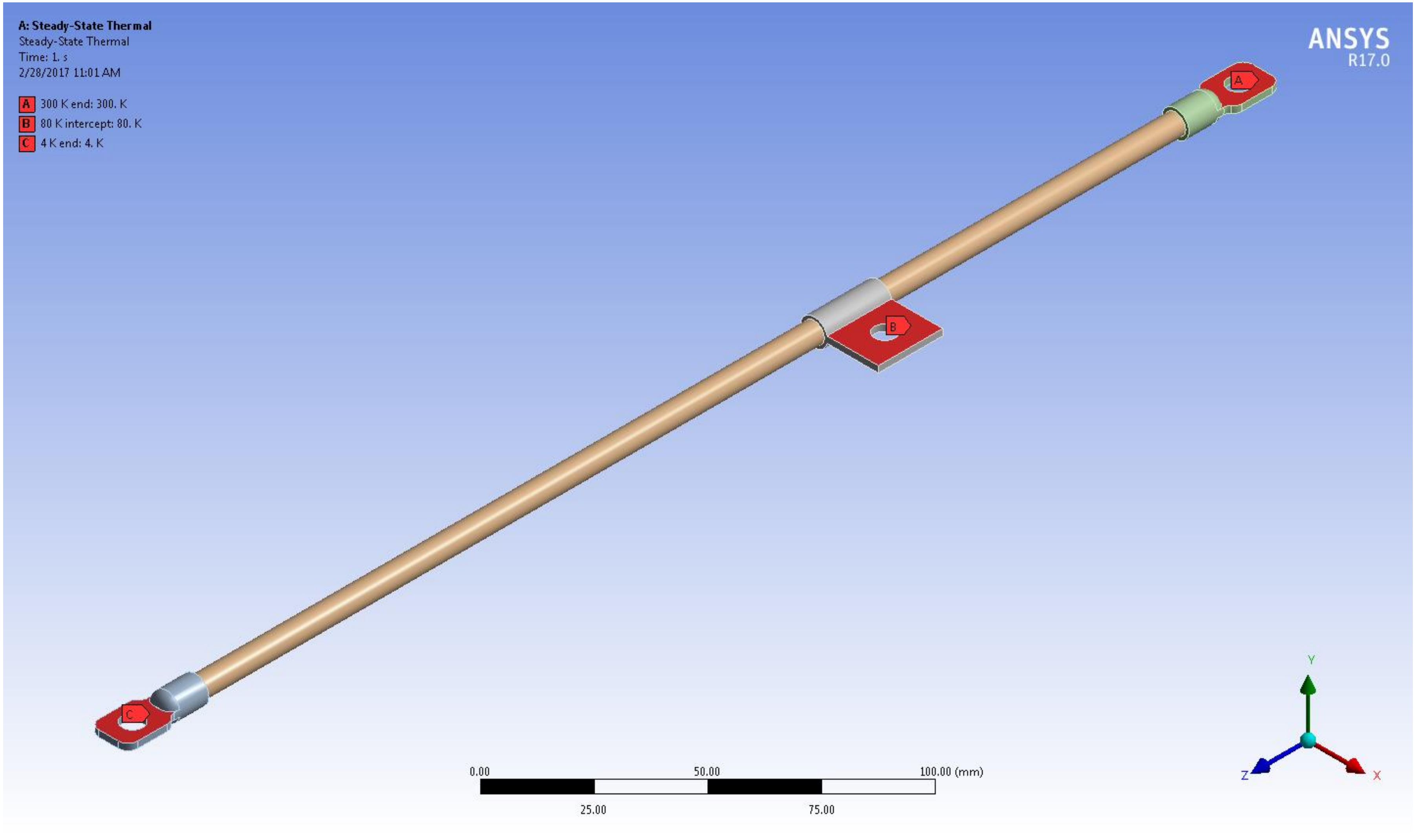
$\int_{T3}^{T2} kdT$ = 0.35 W/mm



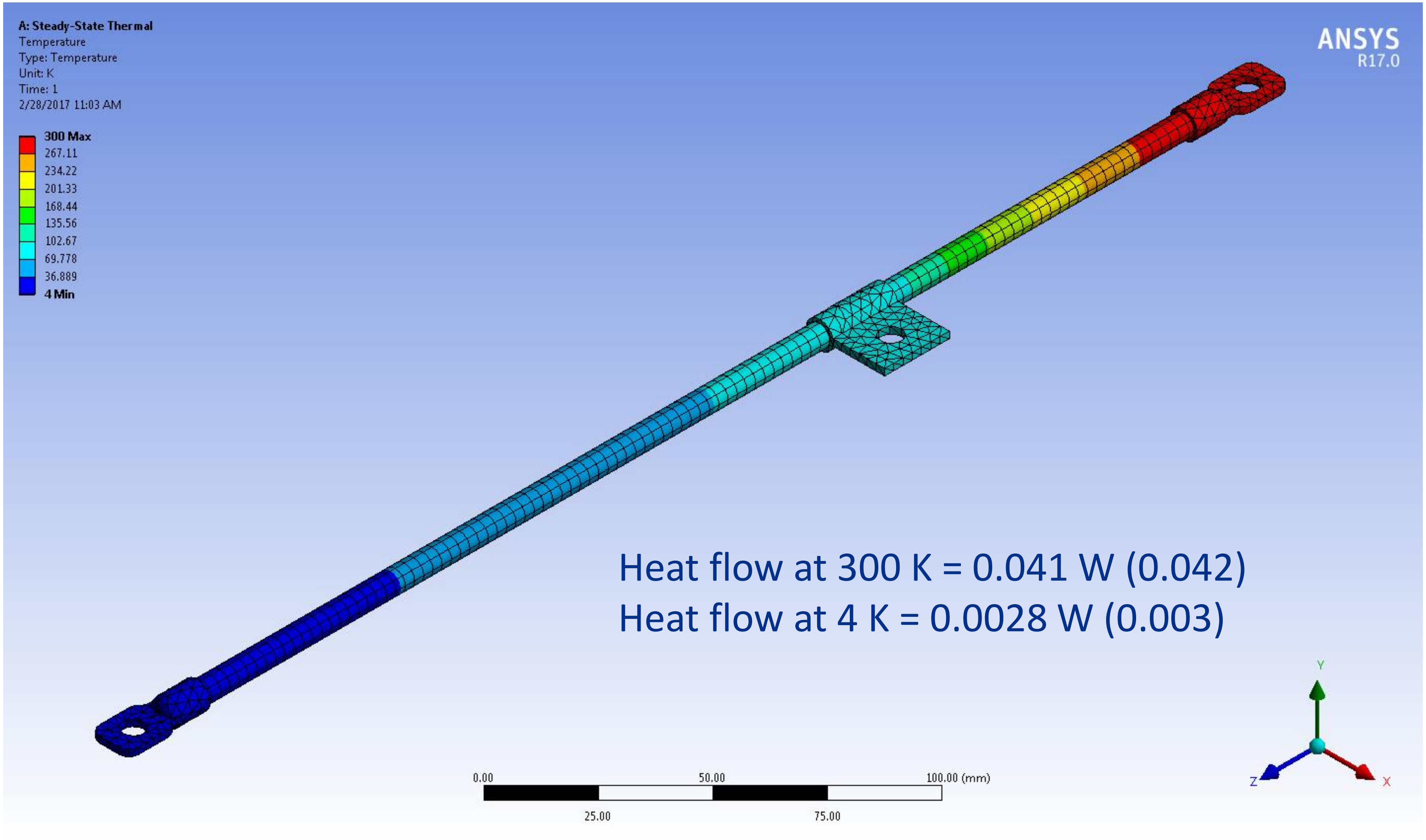
Chapter 7 – Example 1b: Solid G-11 rod, 80 K intercept – FE solution



Chapter 7 – Example 1b: Solid G-11 rod, 80 K intercept – FE solution



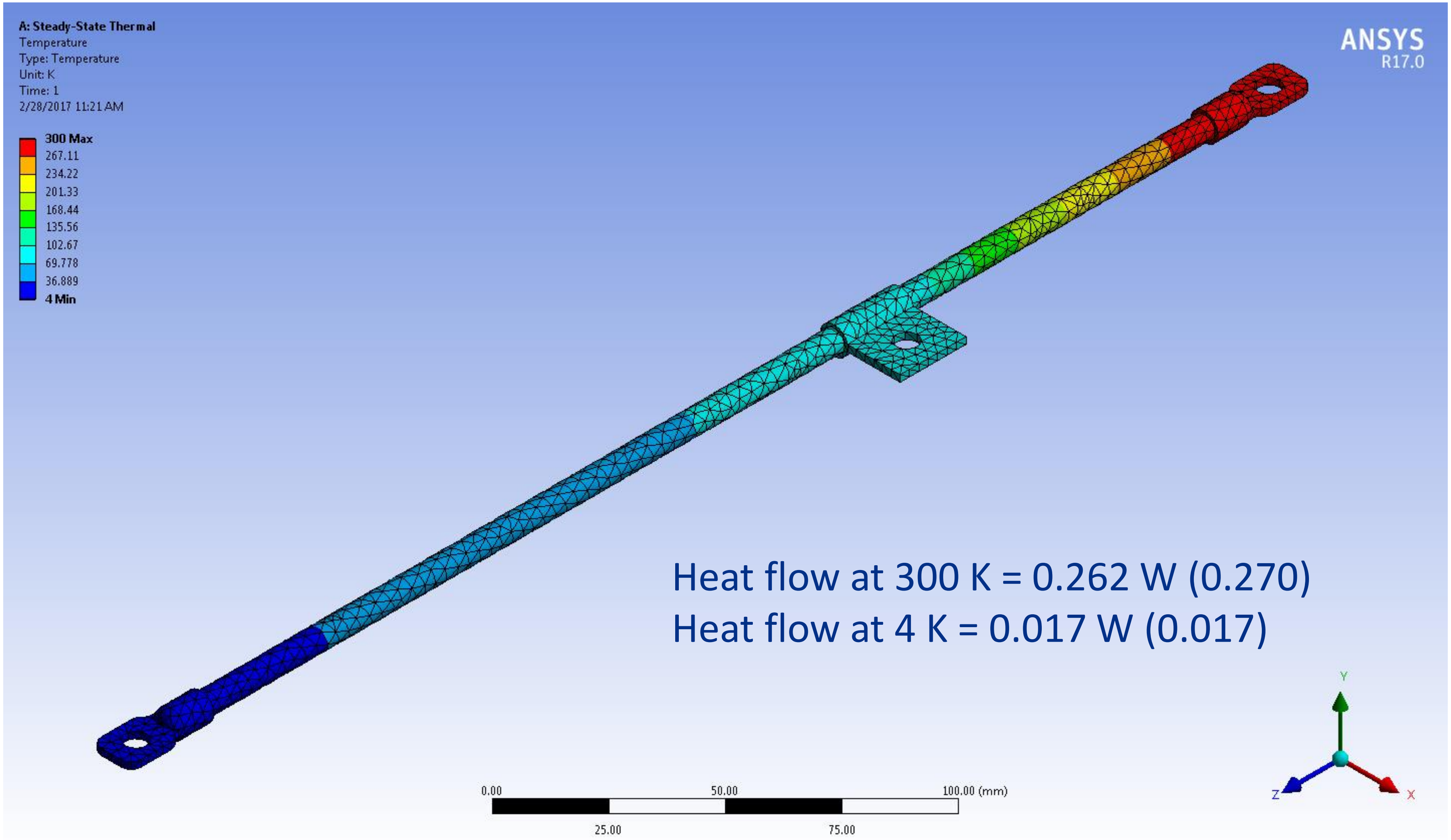
Chapter 7 – Example 1b: Solid G-11 rod, 80 K intercept – FE solution



Heat flow at 300 K = 0.041 W (0.042)

Heat flow at 4 K = 0.0028 W (0.003)

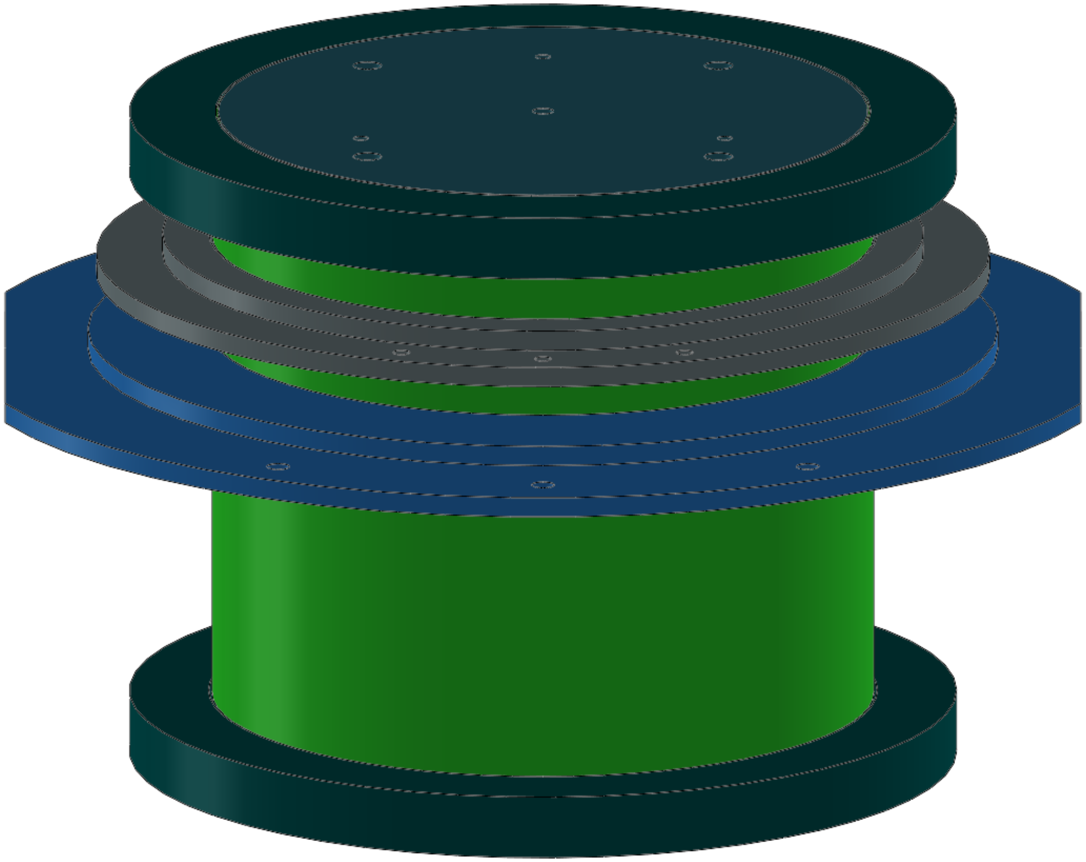
Chapter 7 – Example 2b: Hollow stainless rod, 80 K intercept – FE solution



Heat flow at 300 K = 0.262 W (0.270)

Heat flow at 4 K = 0.017 W (0.017)

Chapter 7 – Support post – a little more practical and thorough example



Chapter 7 – Support post example

$$Q_{4.5} = \frac{A_c}{L_c} \int_{4.5}^{T_t} \kappa_i \, dT$$

$$Q_{20} = \frac{A_i}{L_2} \int_{20}^{80} \kappa_o \, dT - Q_{4.5}$$

$$Q_{80} = \frac{A_o}{L_1} \int_{80}^{300} \kappa_o \, dT - Q_{20} - Q_{4.5}$$

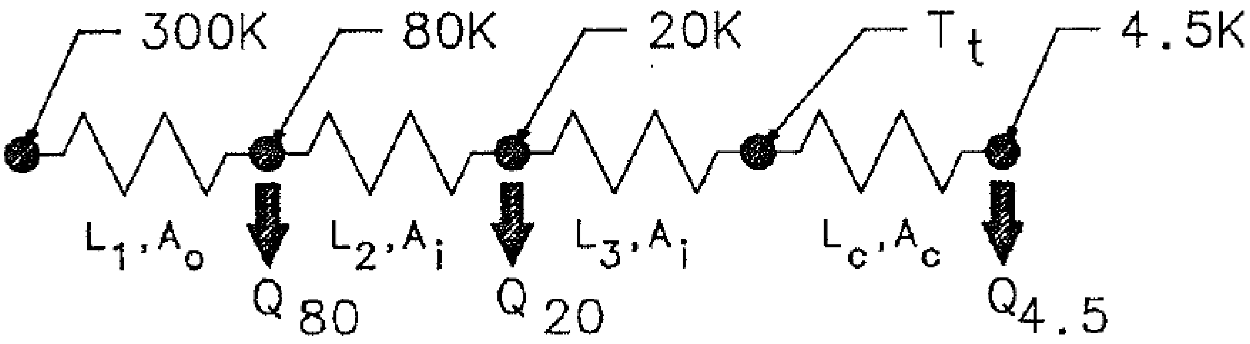
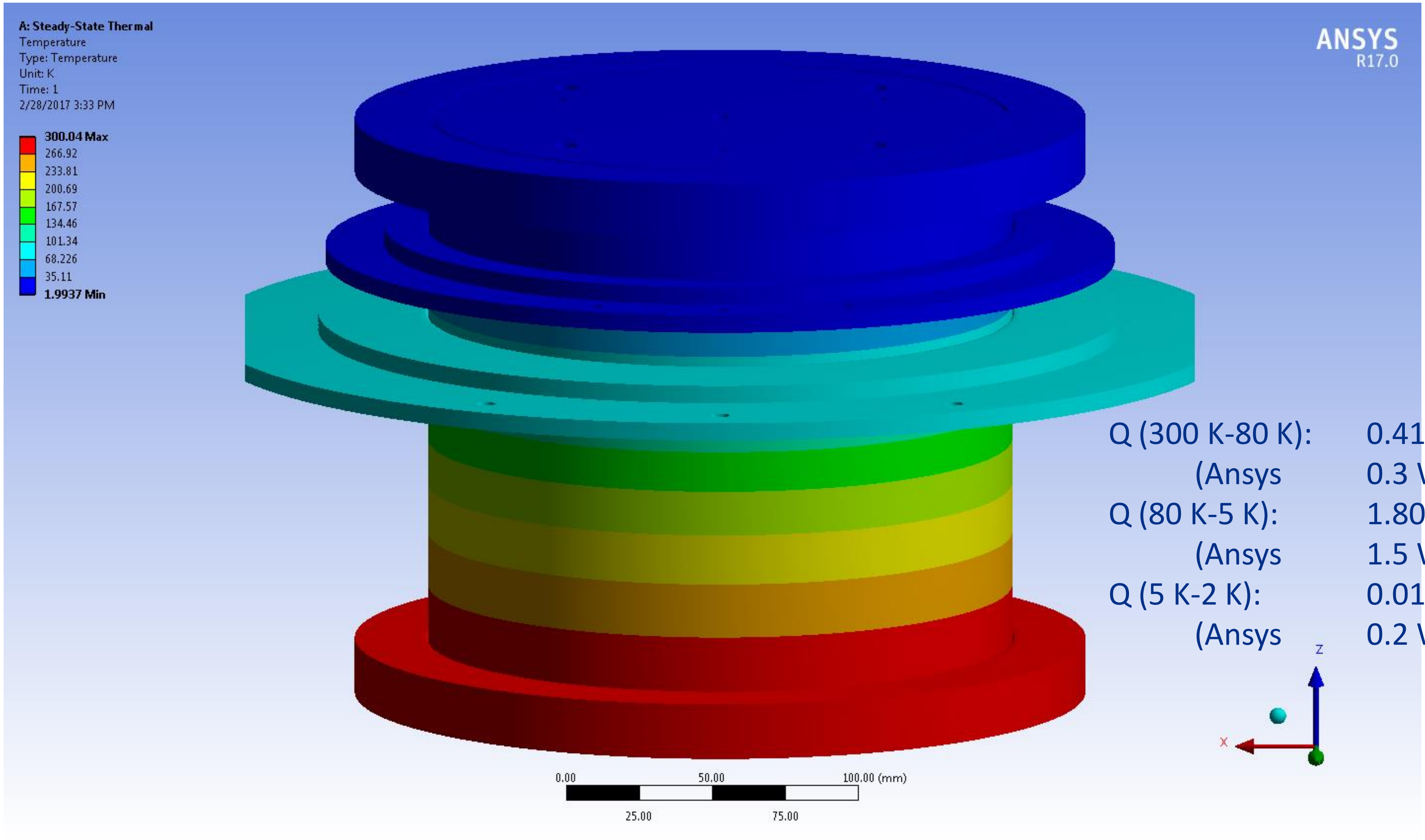


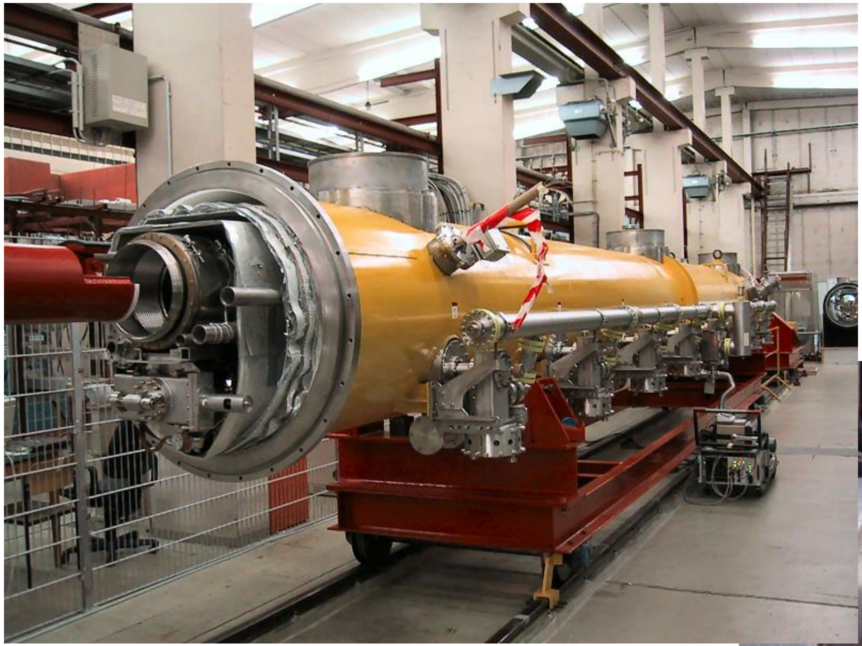
Figure 5. Thermal Analysis Notation

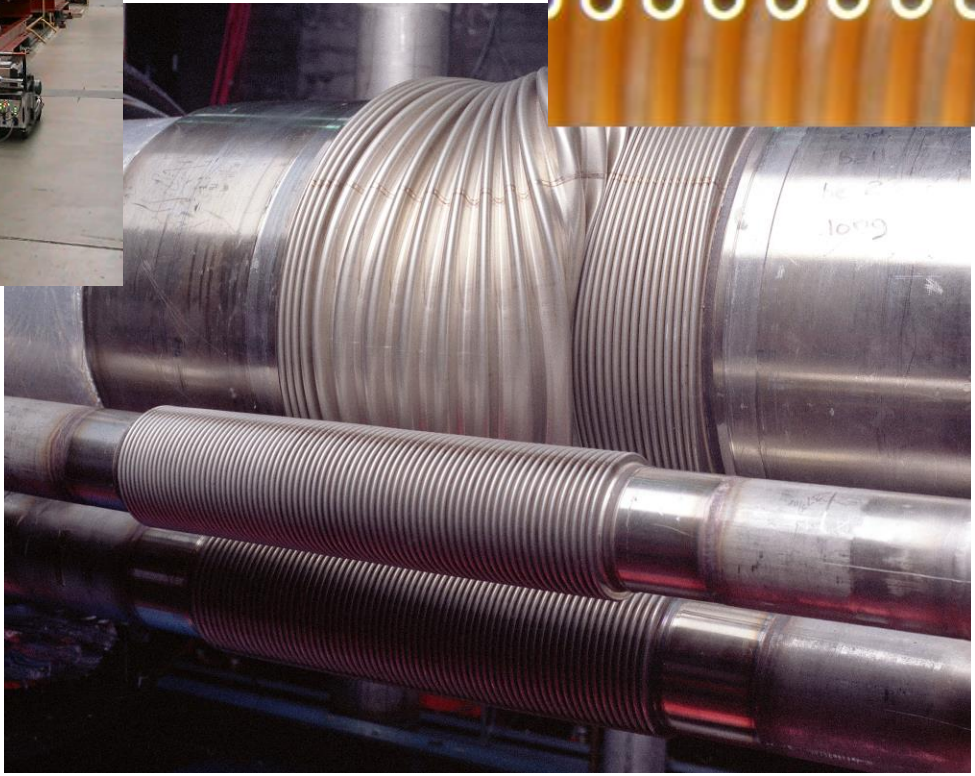
Chapter 7 – Support post example

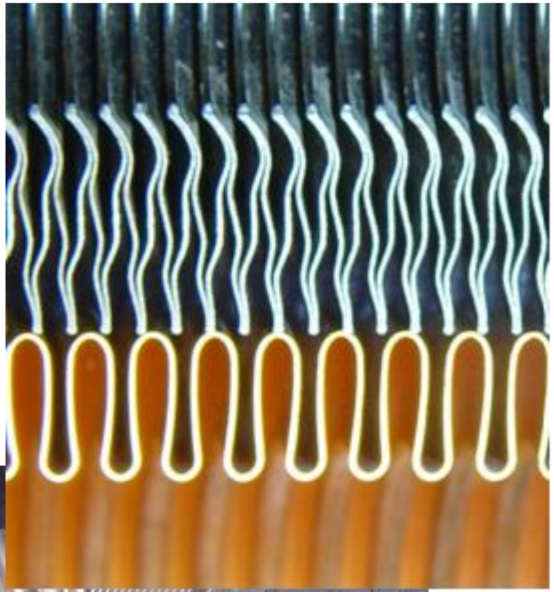


Q (300 K-80 K): 0.412 W
(Ansys 0.3 W)
Q (80 K-5 K): 1.806 W
(Ansys 1.5 W)
Q (5 K-2 K): 0.019 W
(Ansys 0.2 W)

Chapter 8 – Bellows and Interconnects

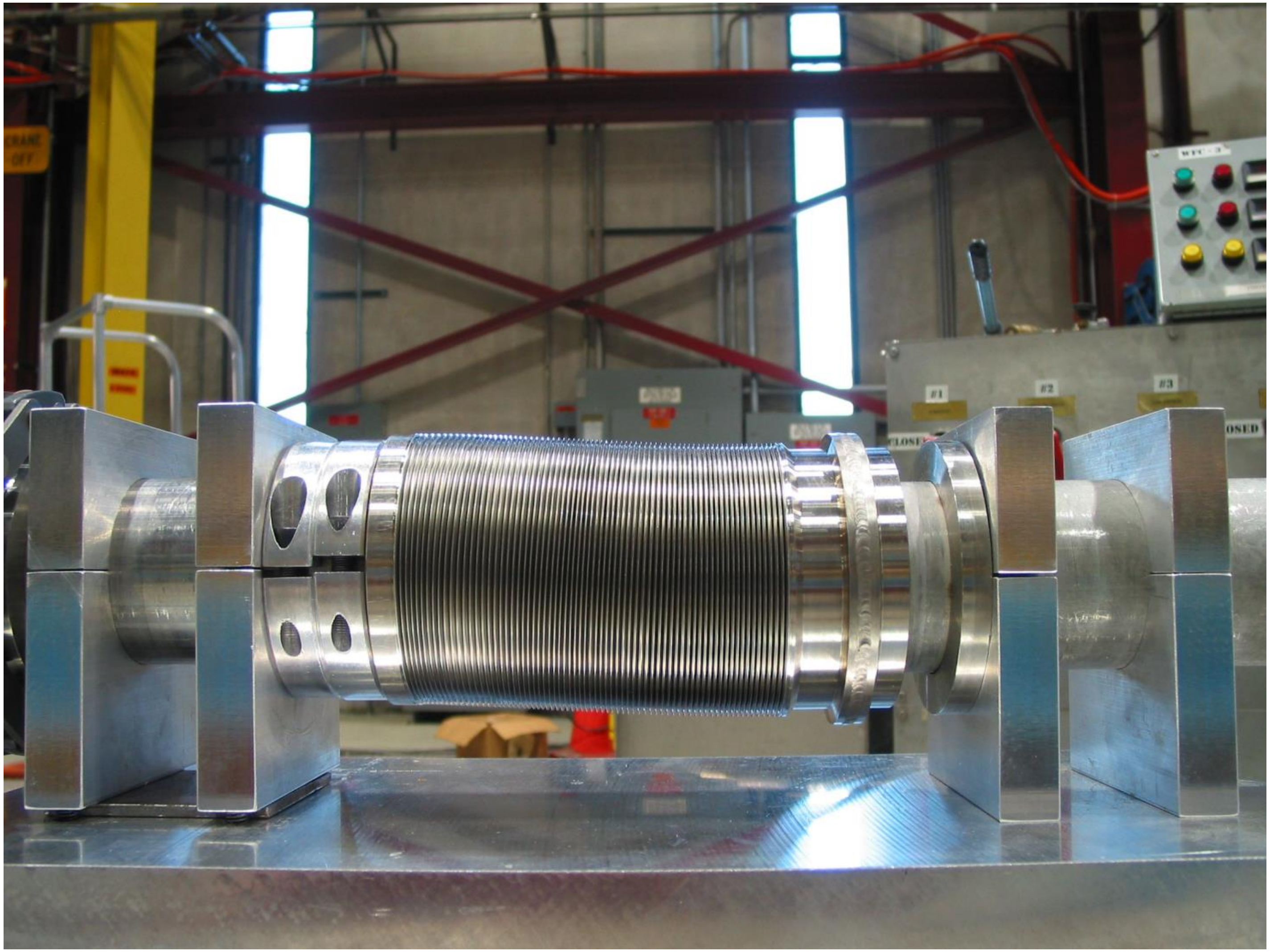






Chapter 8 – Bellows and Interconnects

Chapter 8 – Bellows and Interconnects

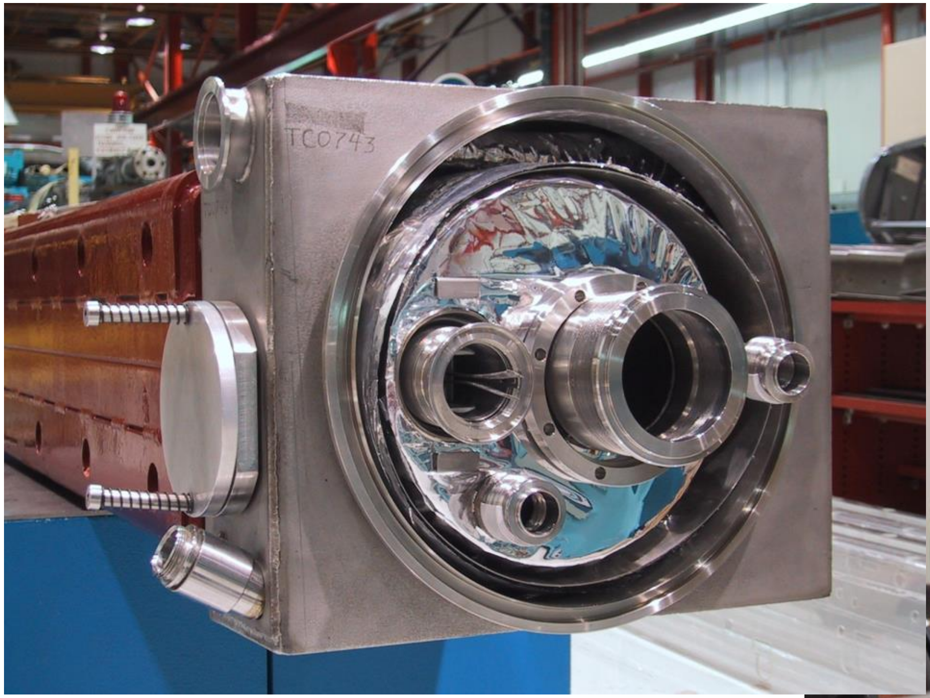


Chapter 8 – Bellows and Interconnects

- Bellows are used in many places and for many reasons in nearly all accelerator devices, but especially in superconducting magnets and RF cryomodules.
  - They accommodate thermal contraction during cooldown and expansion during warm-up.
  - They make up small differences in pipe locations at magnet or cryomodule interconnects.
  - They allow some adjusting capability in the overall cryostat or cryomodule position during alignment.
  - They allow some adjustment in things like RF input couplers and provide tuning capability for SRF cavities.
- There are basically two types of bellows commonly used – hydroformed and edge-welded.
- Design parameters are governed by the ASME Boiler and Pressure Vessel Code and the Expansion Joint Manufacturers Association (EJMA).

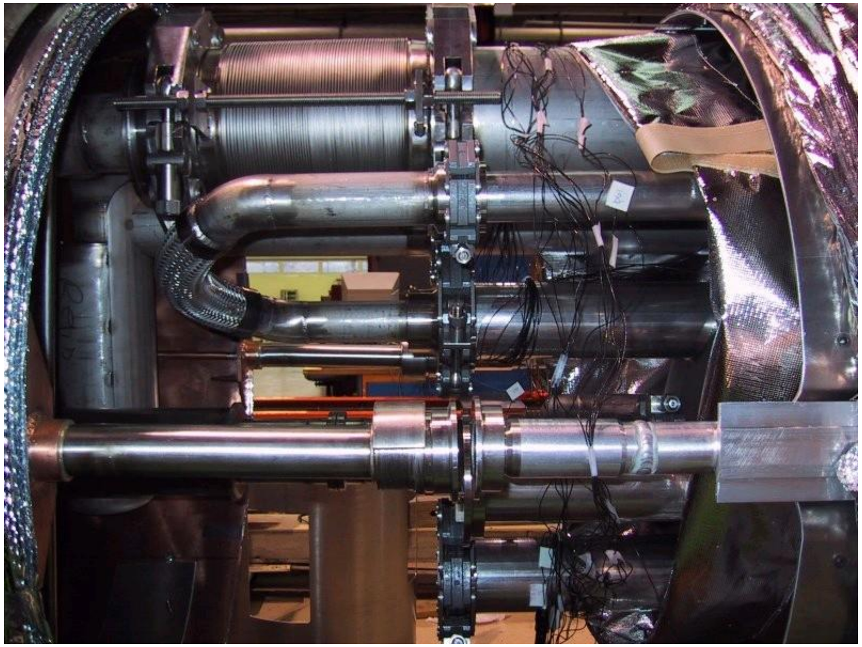
Chapter 8 – Bellows and Interconnects

Tevatron dipole interconnects

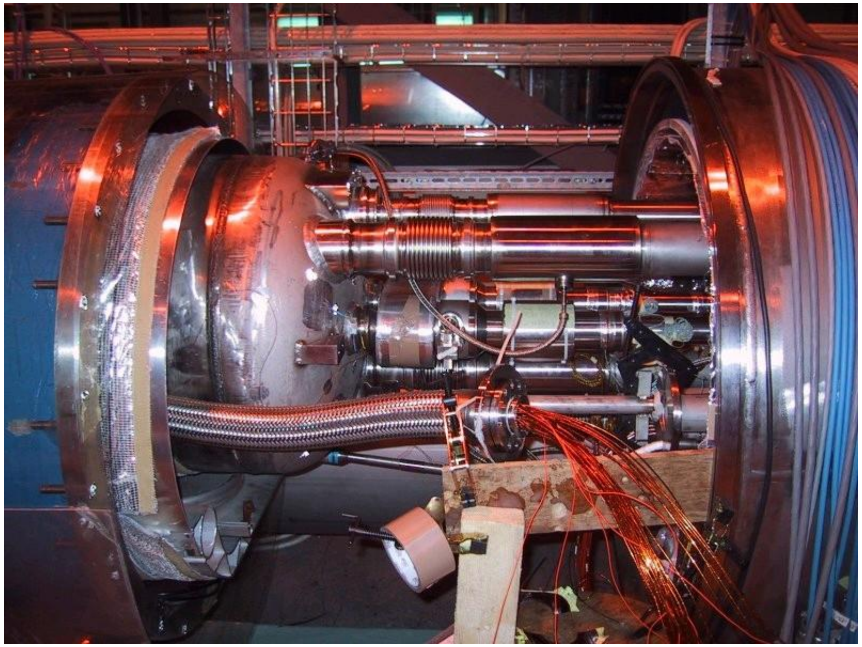


Chapter 8 – Bellows and Interconnects

LHC IRQ to test stand interconnect



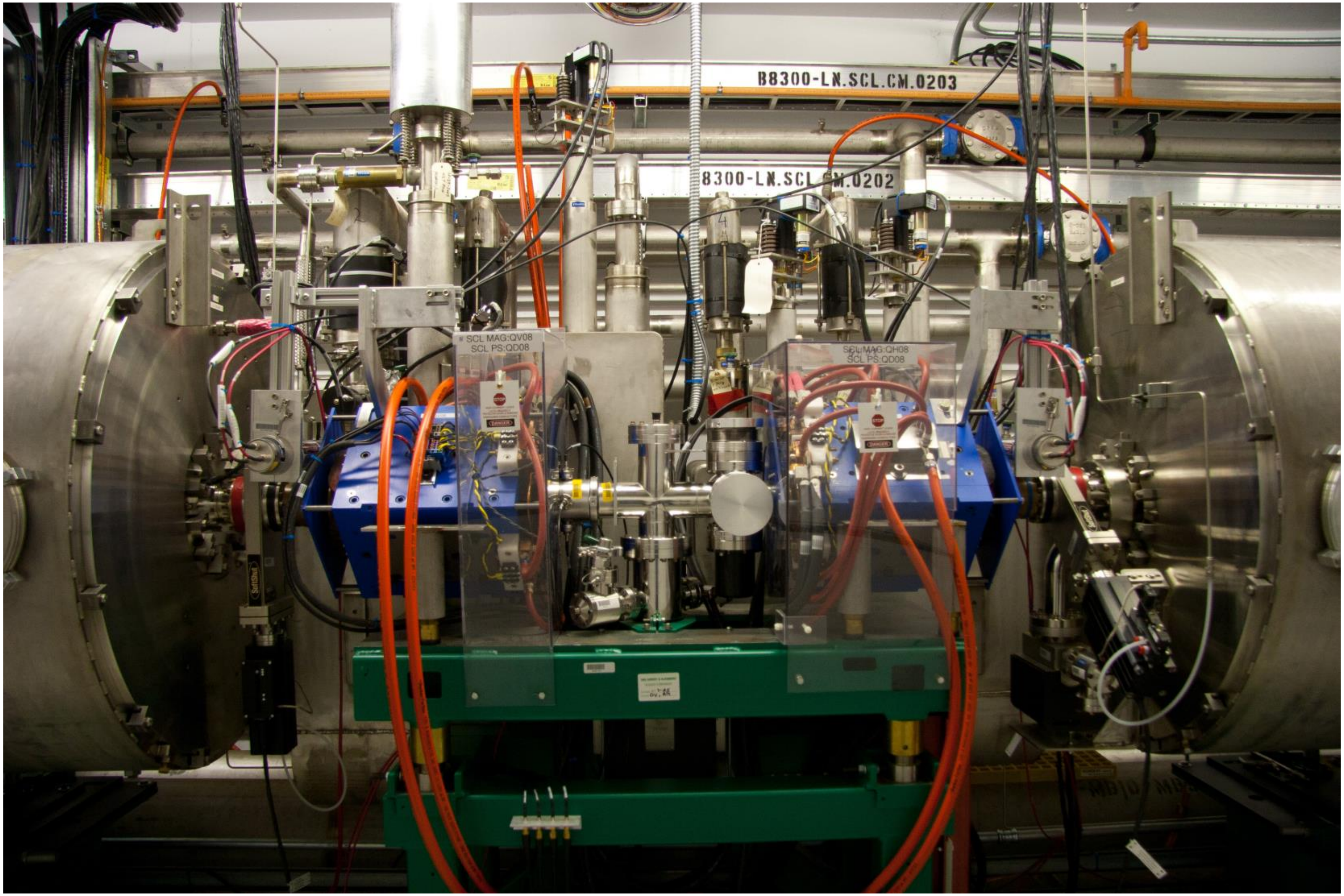
LHC dipole interconnect



Chapter 8 – Bellows and Interconnects

- Magnet cryostat and SRF cryomodule interconnects contain all the electrical and mechanical connections between adjacent devices.
- They accommodate thermal expansion and contraction through the use of bellows for pipes and expansion loops for magnet busses and instrumentation wiring.
- They contain shield bridges to create a continuous thermal shield along the length of the magnet string.
- For "finely segmented" SRF cryomodule strings, the only connection between modules is the beam tube. All other services, cooling lines, etc., enter each individual module.

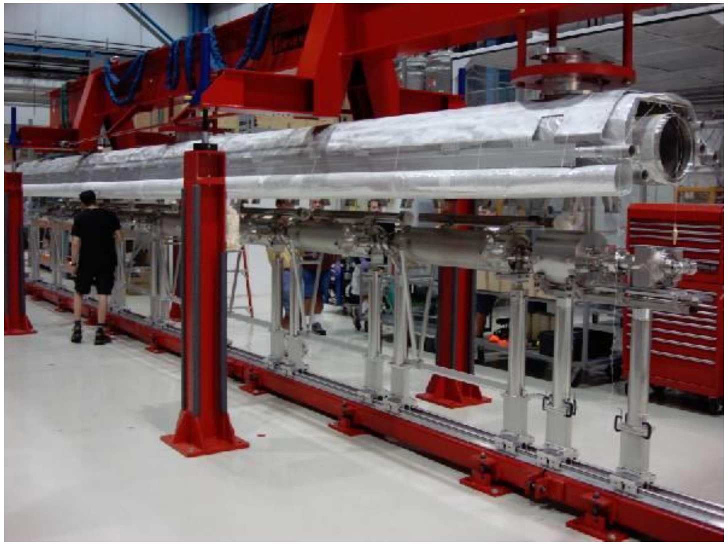
Chapter 8 – Bellows and Interconnects



Chapter 9 - Assembly techniques

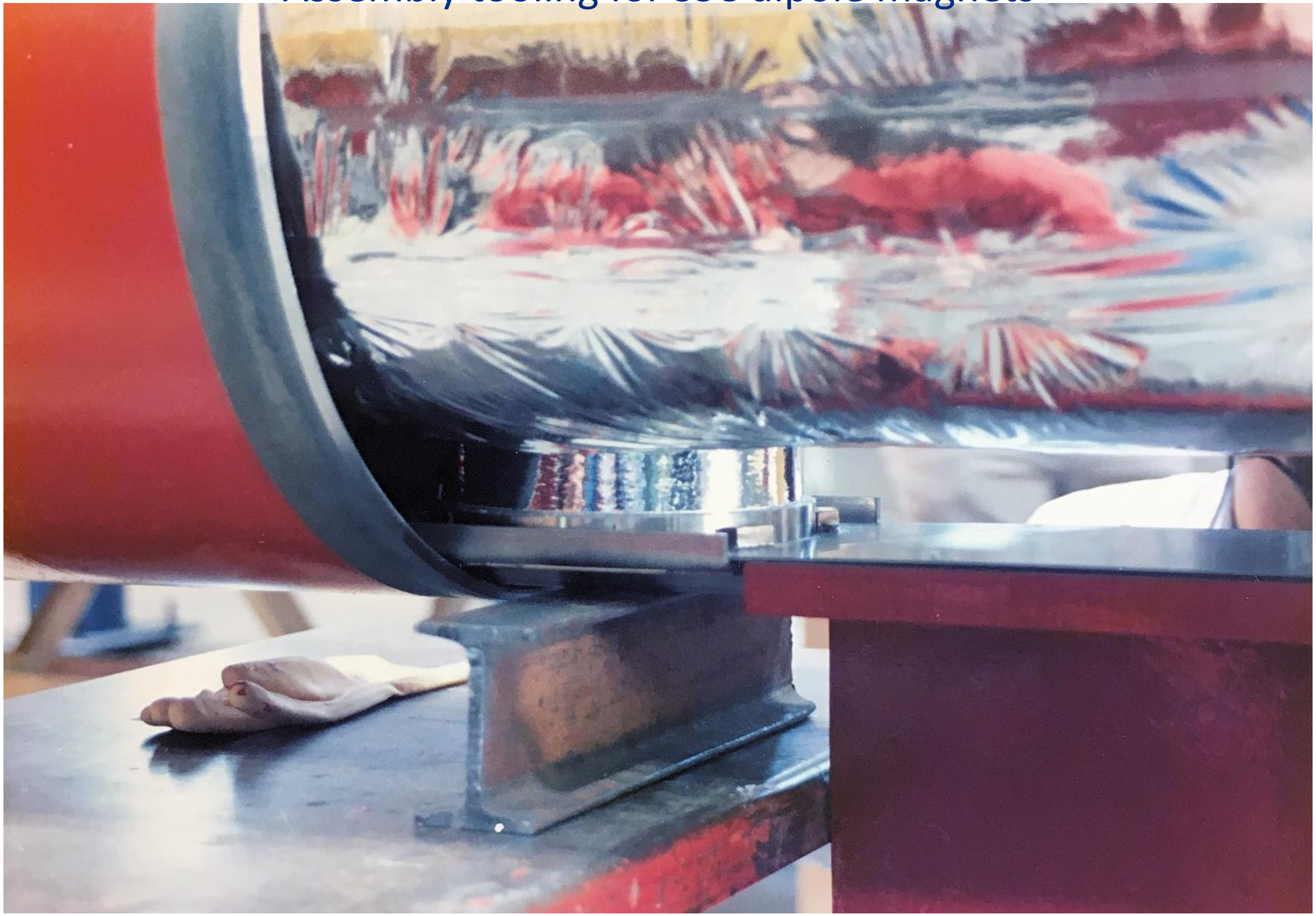
Chapter 9 - Assembly techniques

Assembly tooling for 1.3 GHz cavity cryomodules

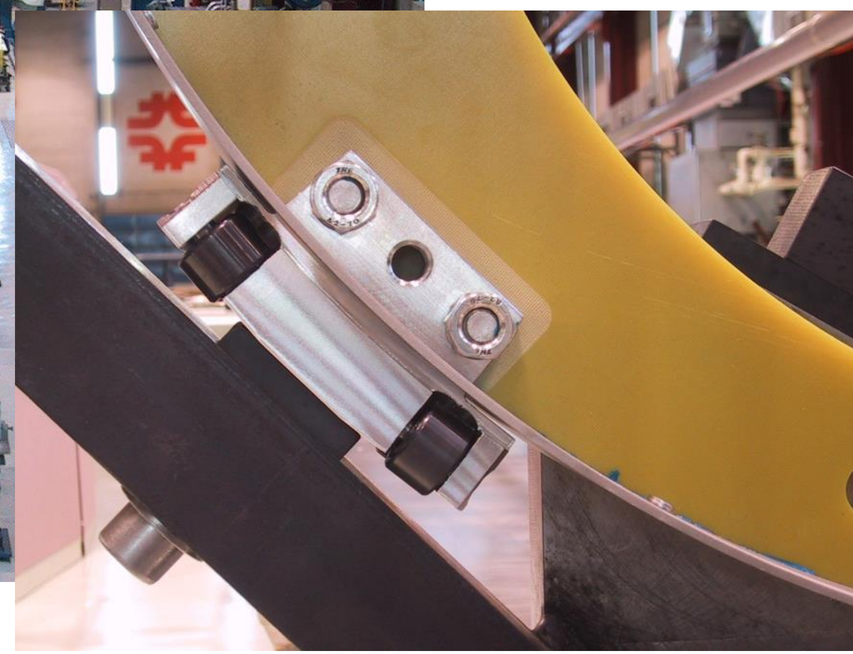


Chapter 9 - Assembly techniques

Assembly tooling for SSC dipole magnets



Chapter 9 - Assembly techniques



Assembly tooling for LHC IRQ magnets

Chapter 9 – Alignment

GENERAL REQUIREMENTS

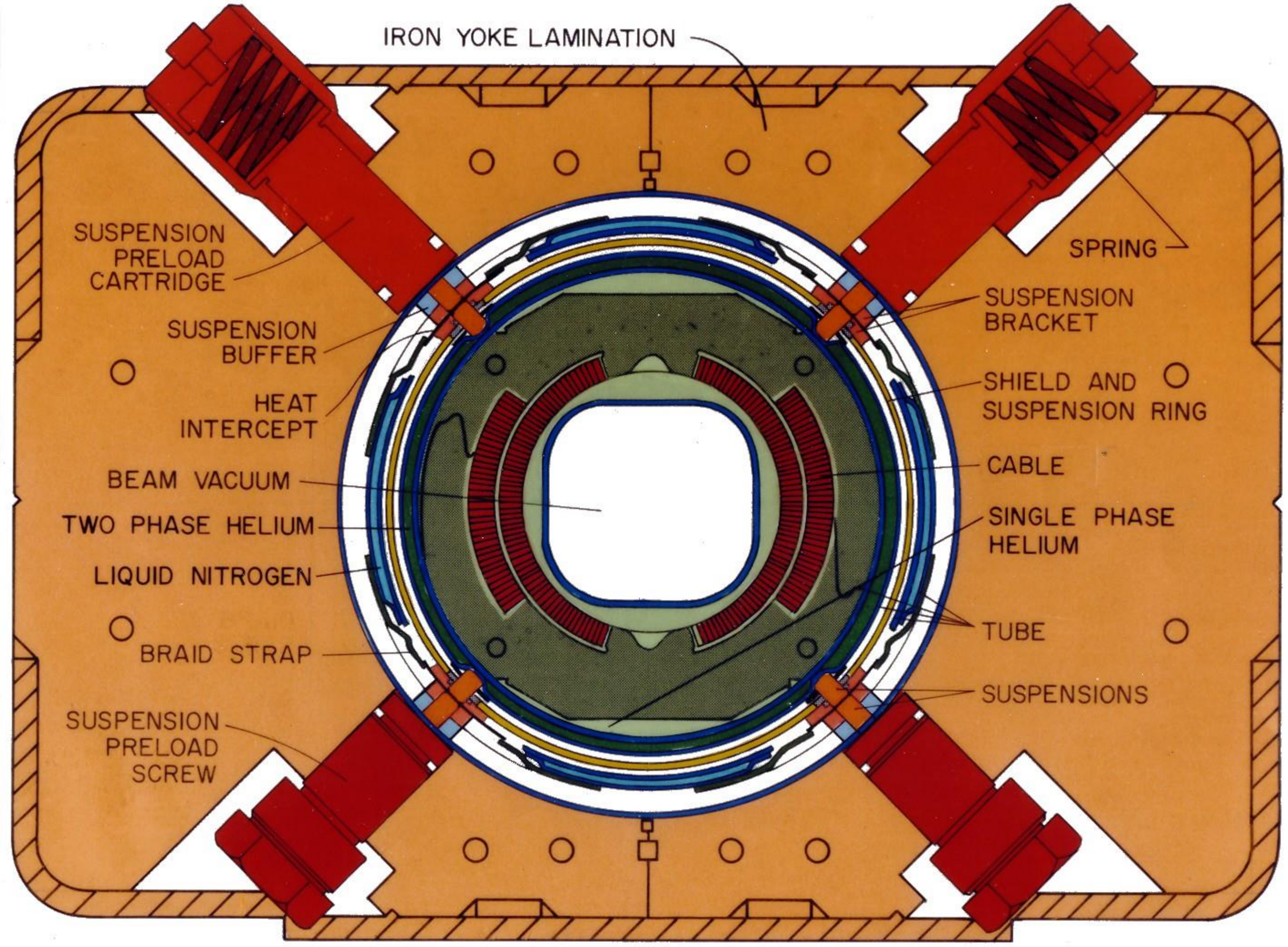
General		
	Physical beam aperture, mm	118
	Overall length (flange-to-flange), m	9.56
	Overall width, m	≤1.6
	Beamline height from the floor, m	1.3
	Cryomodule height (from floor), m	≤2.00
	Ceiling height in the tunnel, m	3.20
	Max allowed heat load to 70 K, W	300
	Max allowed heat load to 5 K, W	25
	Max allowed heat load to 2 K, W	220
	Maximum number of lifetime thermal cycles	50
	Intermediate thermal shield temperature, K	45-80
	Thermal intercept temperatures, K	5 and 45-80
	Cryo system pressure stability at 2 K (RMS), mbar	≤0.1
	Environmental contribution to internal field	10 mG
	Transverse cavity alignment error, mm RMS	<0.5
	Angular cavity alignment error, mrad RMS	≤1
	Beam duration for operation in pulsed regime, ms	≤1
	Repetition rate for operation in pulsed regime, Hz	≤20

Chapter 9 – Alignment

Alignment fiducial

Chapter 9 – Alignment

Tevatron magnet alignment mechanism

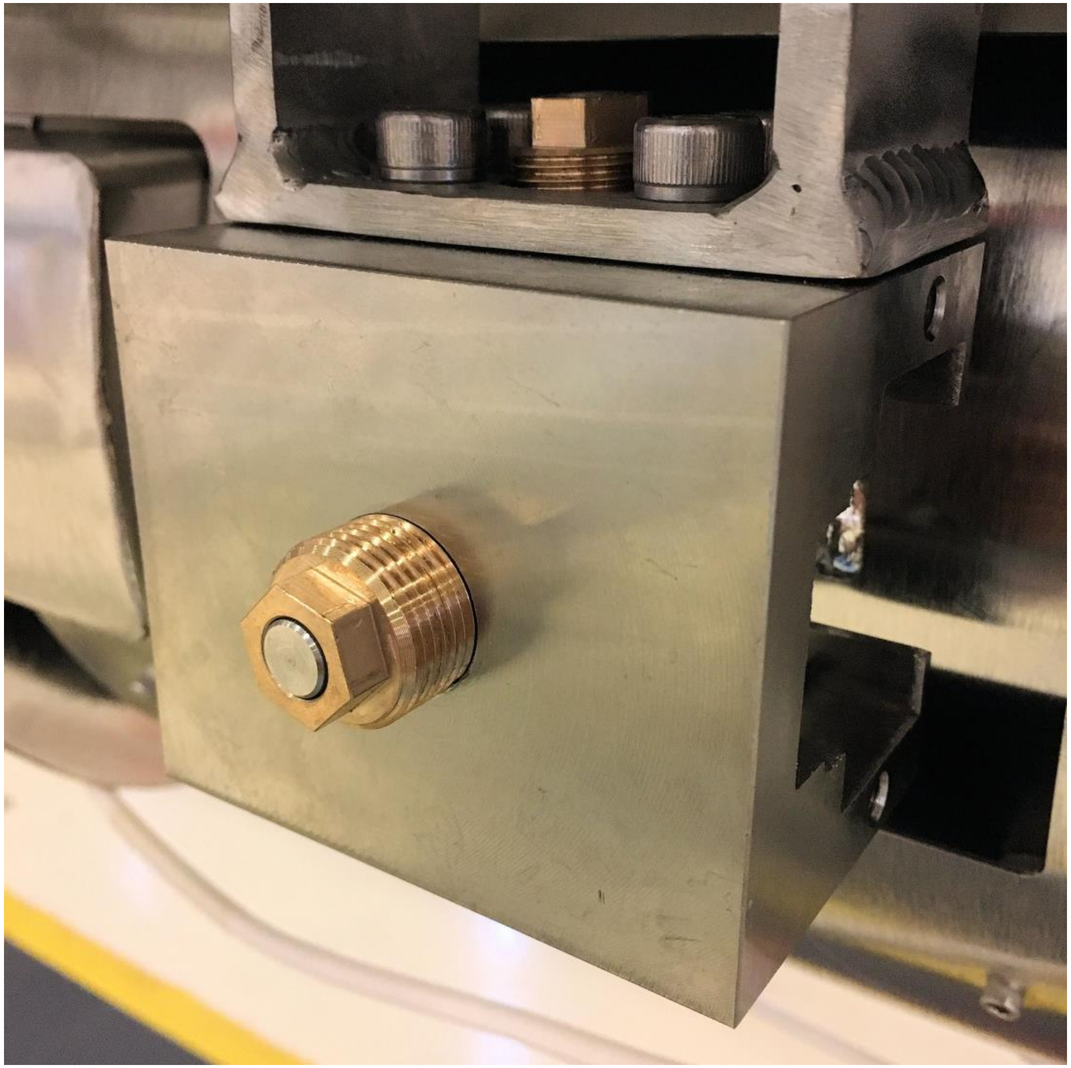


Chapter 9 – Alignment

LHC IRQ magnet alignment adjustment tooling

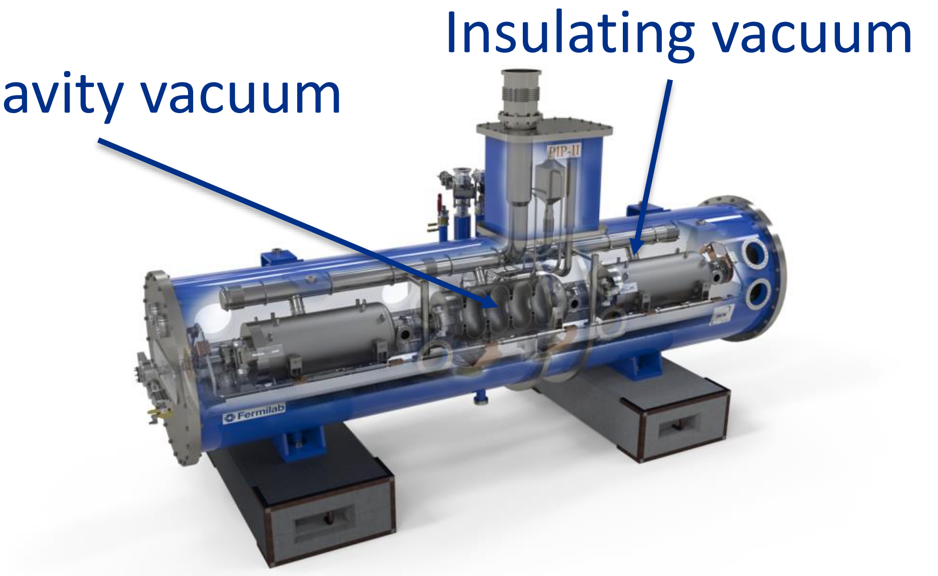
Chapter 9 – Alignment

LCLS-II cavity string alignment adjustment block



Chapter 9 – Miscellaneous topics

- Loss of vacuum due to some failure mechanism – broken connection, broken pumpout, etc.
  - In a magnet is most likely loss of insulating vacuum
  - In an SRF cryomodule is either loss of insulating vacuum or cavity vacuum or both
  - http://newsline.linearcollider.org/readmore_20080612_atw.html



On an uninsulated surface: Q ~4 W/cm^2
On an insulated surface Q: ~0.6 W/cm^2

Chapter 9 – Magnetic shielding

Spoke cavity test cryostat magnetic shield

Chapter 9 – Magnetic shielding

Spoke cavity test cryostat magnetic shield

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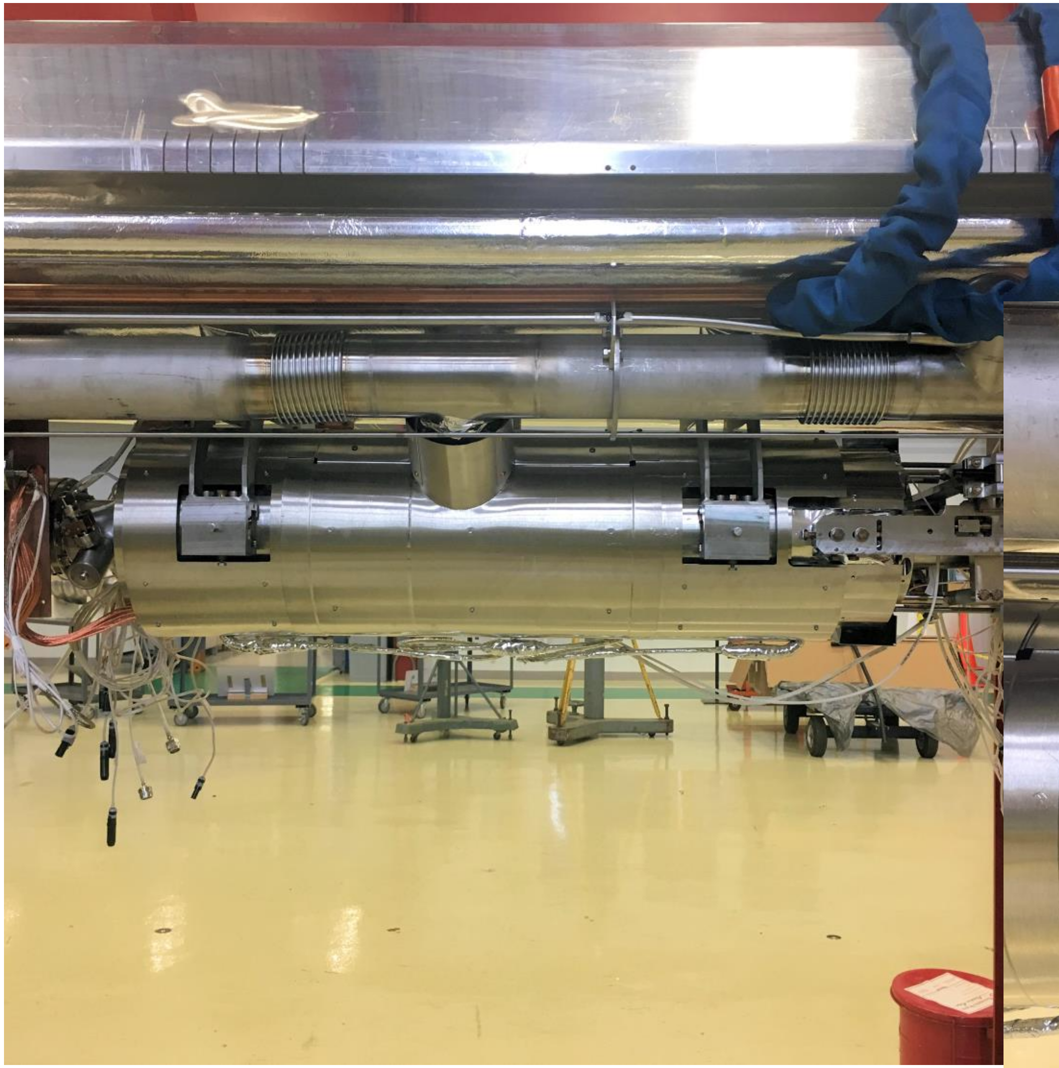
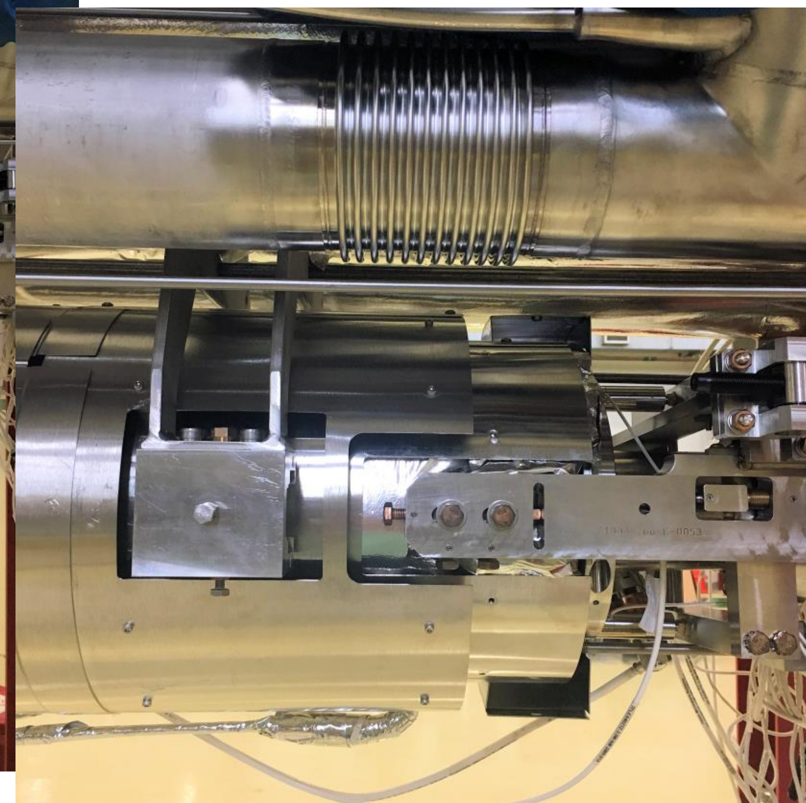


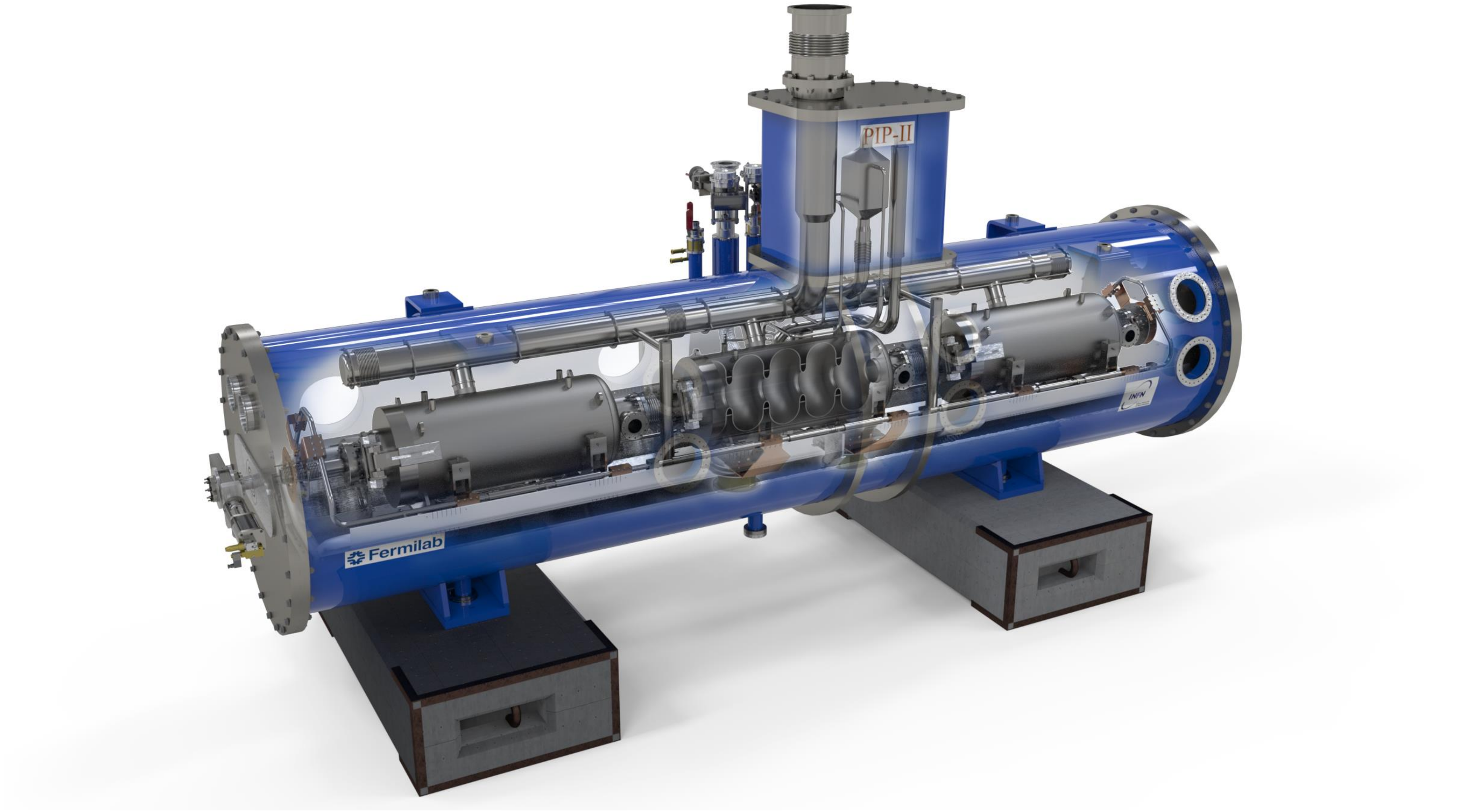
LCLS-II cavity magnetic shield



Suggested references

- Handbook of Cryogenic Engineering, J.G. Weisend II, Taylor & Francis, 1998.
- Cryostat Design, J.G. Weisend II, Springer Publishing, 2016.
- Selected Cryogenic Data Notebook, Bubble Chamber Group, Brookhaven National Laboratory, Upton, NY.
- Materials at Low Temperature, Richard P. Reed and Alan F. Clark, American Society for Metals, Metals Park, OH, 1983.
- Cryogenic Fundamentals, G.G. Haselden, Academic Press, London and New York, 1971.
- Cryogenic Systems, Randall F. Barron, Oxford University Press, New York, 1985.

Thank you for your attention…



Homework

- **Problem 1** – Estimate the radiation heat load per unit length on uninsulated and concentric 80 K, 20 K, and 4.5 K cylindrical surfaces inside a 300 K cylindrical vessel.
  - Assume: Diameters of 1000 mm, 800 mm, 600 mm, and 400 mm for the 300 K, 80 K, 20 K, and 4.5 K surfaces respectively
  - Assume: σ=5.67e-8 W/m^2-K^4
  - Assume: ε=0.3
  - Assume the geometric factor is 1.
  - For each temperature, assume "A" is the area of the warmer surface
- **Problem 2** – Using the information on the next page from the ASME piping code, calculate the required thickness of a stainless steel tube, 6 inches in diameter, 0.083" wall thickness, rated for 20 bar internal pressure.
  - Assume: S=16,700 psi
  - Assume: E=1
  - Assume: W=0.8
  - Assume: Y=1

Homework

304 PRESSURE DESIGN OF COMPONENTS

304.1 Straight Pipe

304.1.1 General

(a) The required thickness of straight sections of pipe shall be determined in accordance with eq. (2):

$$t_m = t + c \quad (2)$$

The minimum thickness, T, for the pipe selected, considering manufacturer's minus tolerance, shall be not less than t_m.

(b) The following nomenclature is used in the equations for pressure design of straight pipe:

- c = sum of the mechanical allowances (thread or groove depth) plus corrosion and erosion allowances. For threaded components, the nominal thread depth (dimension h of ASME B1.20.1, or equivalent) shall apply. For machined surfaces or grooves where the tolerance is not specified, the tolerance shall be assumed to be 0.5 mm (0.02 in.) in addition to the specified depth of the cut.
- D = outside diameter of pipe as listed in tables of standards or specifications or as measured
- d = inside diameter of pipe. For pressure design calculation, the inside diameter of the pipe is the maximum value allowable under the purchase specification.
- E = quality factor from Table A-1A or A-1B
- P = internal design gage pressure
- S = stress value for material from Table A-1
- T = pipe wall thickness (measured or minimum per purchase specification)
- t = pressure design thickness, as calculated in accordance with para. 304.1.2 for internal pressure or as determined in accordance with para. 304.1.3 for external pressure
- t_m = minimum required thickness, including mechanical, corrosion, and erosion allowances
- W = weld joint strength reduction factor per para. 302.3.5(e)
- Y = coefficient from Table 304.1.1, valid for $t < D/6$ and for materials shown. The value of Y may be interpolated for intermediate temperatures. For $t \geq D/6$,

$$Y = \frac{d + 2c}{D + d + 2c}$$

304.1.2 Straight Pipe Under Internal Pressure

(06) *(a)* For $t < D/6$, the internal pressure design thickness for straight pipe shall be not less than that calculated in accordance with either eq. (3a) or eq. (3b):

$$t = \frac{PD}{2(SEW + PY)} \quad (3a)$$

$$t = \frac{P(d + 2c)}{2[SEW - P(1 - Y)]} \quad (3b)$$

Table 304.1.1 Values of Coefficient Y for $t < D/6$

	Temperature, °C (°F)					
Materials	≤ 482 (900 & Lower)	510 (950)	538 (1000)	566 (1050)	593 (1100)	≥ 621 (1150 & Up)
Ferritic steels	0.4	0.5	0.7	0.7	0.7	0.7
Austenitic steels	0.4	0.4	0.4	0.4	0.5	0.7
Other ductile metals	0.4	0.4	0.4	0.4	0.4	0.4
Cast iron	0.0	. . .	. . .	. . .	. . .	. . .

(b) For $t \geq D/6$ or for $P/SE > 0.385$, calculation of pressure design thickness for straight pipe requires special consideration of factors such as theory of failure, effects of fatigue, and thermal stress.

304.1.3 Straight Pipe Under External Pressure. To determine wall thickness and stiffening requirements for straight pipe under external pressure, the procedure outlined in the BPV Code, Section VIII, Division 1, UG-28 through UG-30 shall be followed, using as the design length, L, the running centerline length between any two sections stiffened in accordance with UG-29. As an exception, for pipe with $D_o/t < 10$, the value of S to be used in determining P_{a2} shall be the lesser of the following values for pipe material at design temperature:

(a) 1.5 times the stress value from Table A-1 of this Code, or

(b) 0.9 times the yield strength tabulated in Section II, Part D, Table Y-1 for materials listed therein

(The symbol D_o in Section VIII is equivalent to D in this Code.)

304.2 Curved and Mitered Segments of Pipe

304.2.1 Pipe Bends. The minimum required thickness, t_m, of a bend, after bending, in its finished form, shall be determined in accordance with eqs. (2) and (3c)

$$t = \frac{PD}{2[(SEW/I) + PY]} \quad (3c)$$

where at the intrados (inside bend radius)

$$I = \frac{4(R_1/D) - 1}{4(R_1/D) - 2} \quad (3d)$$

and at the extrados (outside bend radius)

$$I = \frac{4(R_1/D) + 1}{4(R_1/D) + 2} \quad (3e)$$

and at the sidewall on the bend centerline radius, $I = 1.0$, and where

R_1 = bend radius of welding elbow or pipe bend

Homework

- **Problem 3** – Using the following table, estimate the thermal conductivity integrals for the material from 300 K to 80 K, 80 K to 4 K, and 300 K to 4 K.

Temperature	Thermal conductivity (W/cm-K)
4 K	0.0024
80 K	0.083
200 K	0.13
300 K	0.15

Homework

- **Problem 4** – Estimate the total radiation and residual gas conduction heat 80 K and 4.5 K cylindrical surfaces inside a 300 K cylindrical vessel, 12 m long.
  - Assume: Diameters of 0.9 m, 0.75 m, and 0.3 m for the 300 K, 80 K, and 4.5 K surfaces respectively
  - Assume: Effective heat transfer to 80 K of 1.5 W/m^2
  - Assume: Effective heat transfer to 4.5 K of 0.15 W/m^2
  - Assume the ends are closed and covered
  - For each temperature, assume "A" is the area of the cold surface

Homework

- **Problem 5** – Using the hollow G-11 rod below, estimate the heat flows through the rod sections, Q_1 through Q_3 and the heat loads to the two shields, $Q_{shield\ 1}$ and $Q_{shield\ 2}$.

OD = 8 mm
ID = 6 mm
L1 = 100 mm
L2 = 125 mm
L3 = 50 mm
T1 = 300 K
T2 = 80 K
T3 = 20 K
T4 = 4 K

$$\int_{T2}^{T1} k dT = 0.12\ \text{W/mm}$$
$$\int_{T3}^{T2} k dT = 0.016\ \text{W/mm}$$
$$\int_{T4}^{T3} k dT = 0.002\ \text{W/mm}$$