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 – July 15-19, 2024

Presentation materials

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

https://www.dropbox.com/scl/fi/gsjlvv9s2opwtxbzy4wz5/Engineering-for-particle-accelerators-USPAS-July-2024-TNicol.pptx?rlkey=hazkr6khth90ce7h2usftyek3&dl=0

and also at:

https://uspas.fnal.gov

Tom Nicol – Fermilab (Retired)

- BSGE – University of Illinois, Urbana, IL
- MSME – University of Oklahoma, Norman, OK
- Mechanical engineer at Chemetron Corp., Chicago – 1974-1977
- Mechanical engineer at Fermilab – 1977-2024 – 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 (Illinois).
- 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:

Session 1
  - Vacuum vessels (Chapter 2)
  - Thermal shields (Chapter 3)
  - Insulation (Chapter 4)
  - Piping (Chapter 5)
  - Support structures (Chapter 6)

Session 2
  - Heat loads (Chapter 7)
  - Bellows and Interconnects (Chapter 8)
  - Miscellaneous topics (assembly techniques, alignment, loss of vacuum, magnetic shielding, etc.) (Chapter 9)
  - Transportation (Chapter 10)

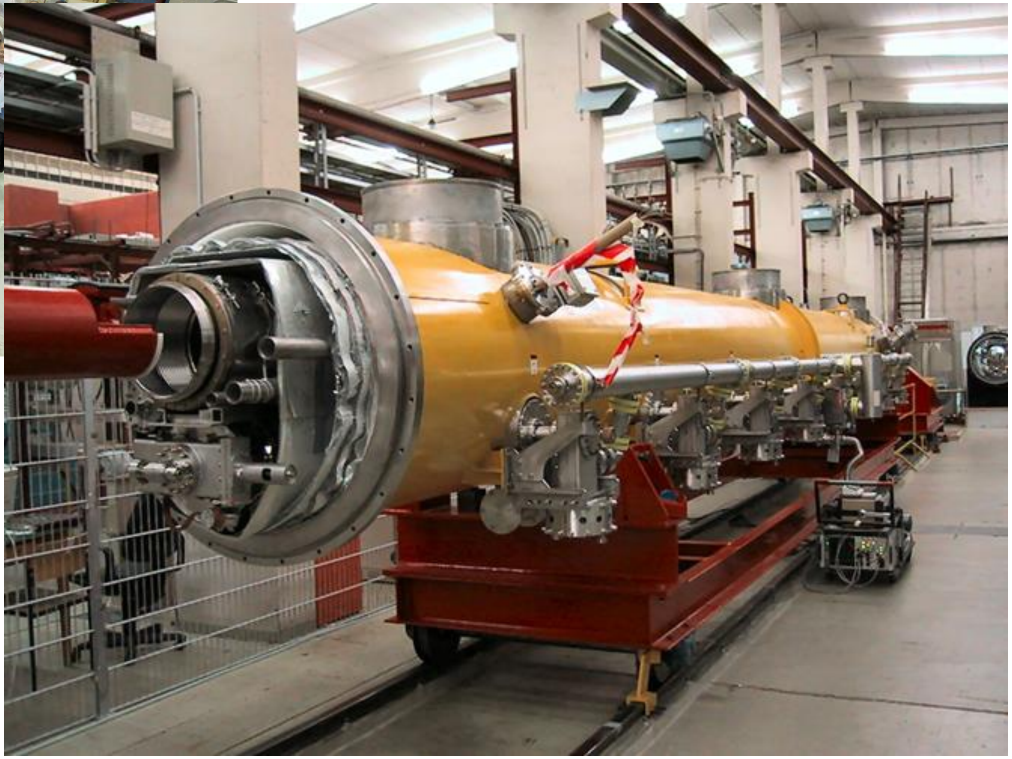
Chapter 1 – Introduction and Scope

- This is not meant to be comprehensive, but rather 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 better understanding of what you're looking at.
- 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, insulation, and internal piping systems.

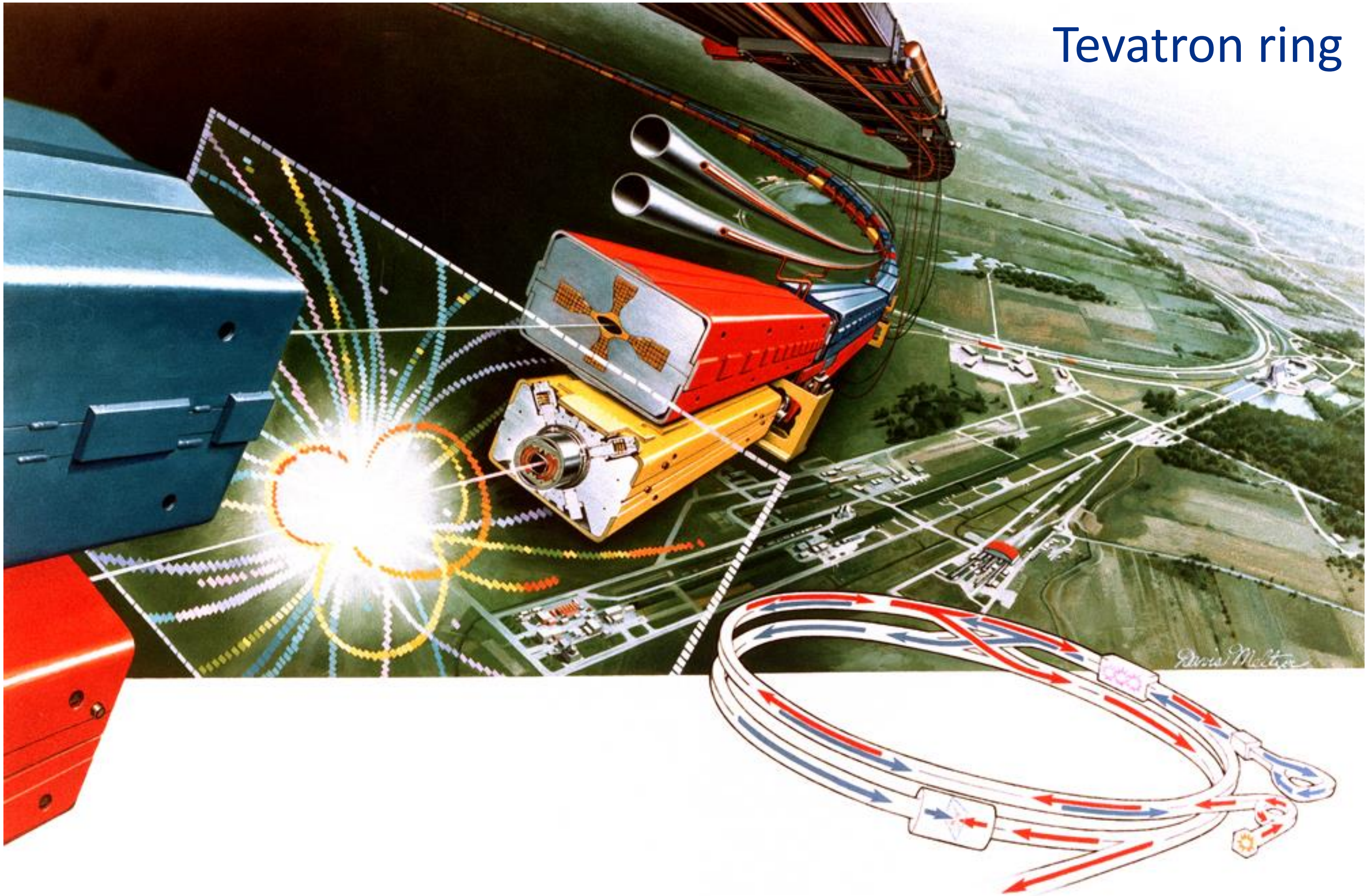
Chapter 1 – Introduction and Scope

First LHC magnet to CERN

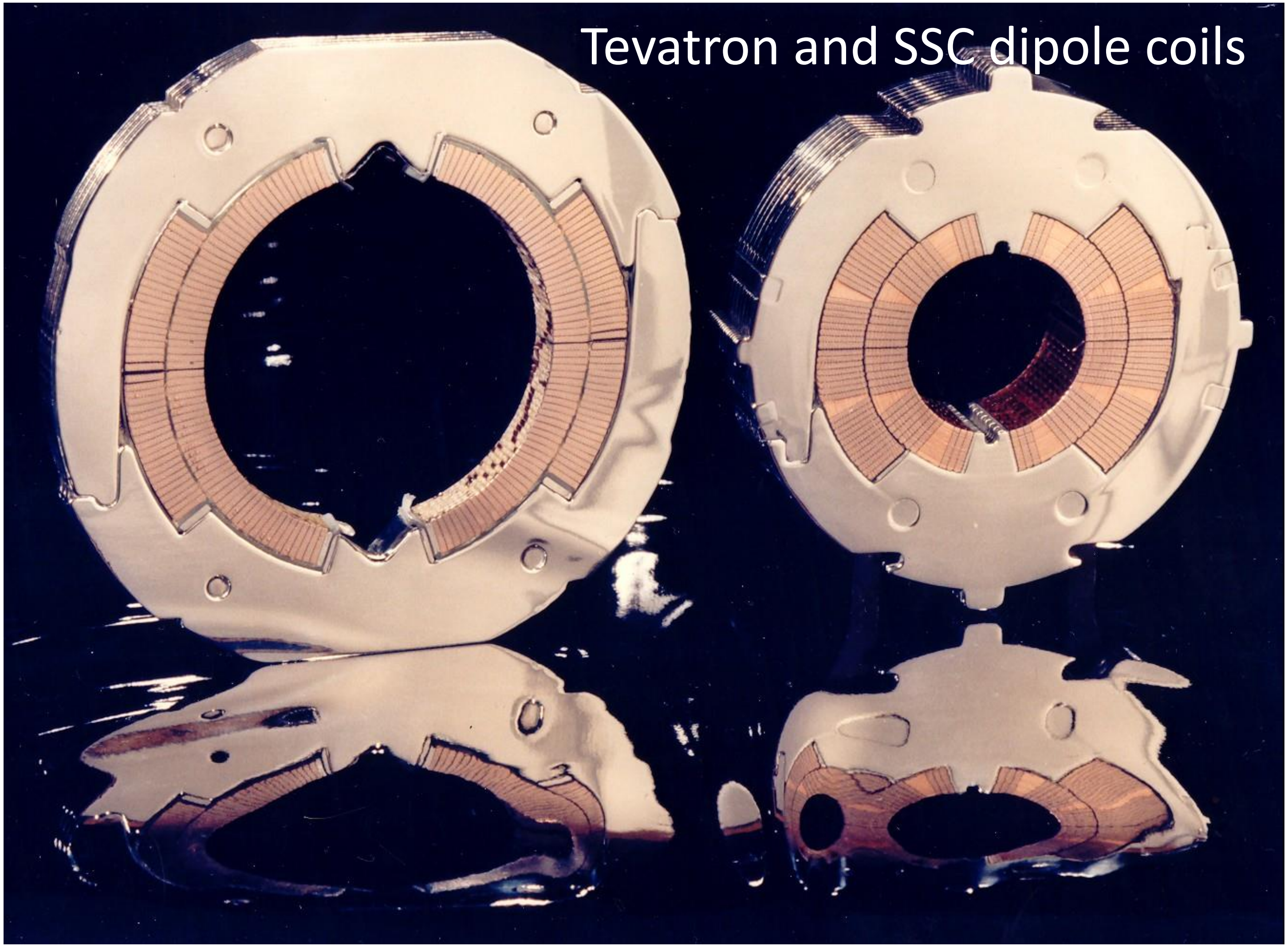
XFEL cryomodule at DESY



Chapter 1 – Introduction and Scope

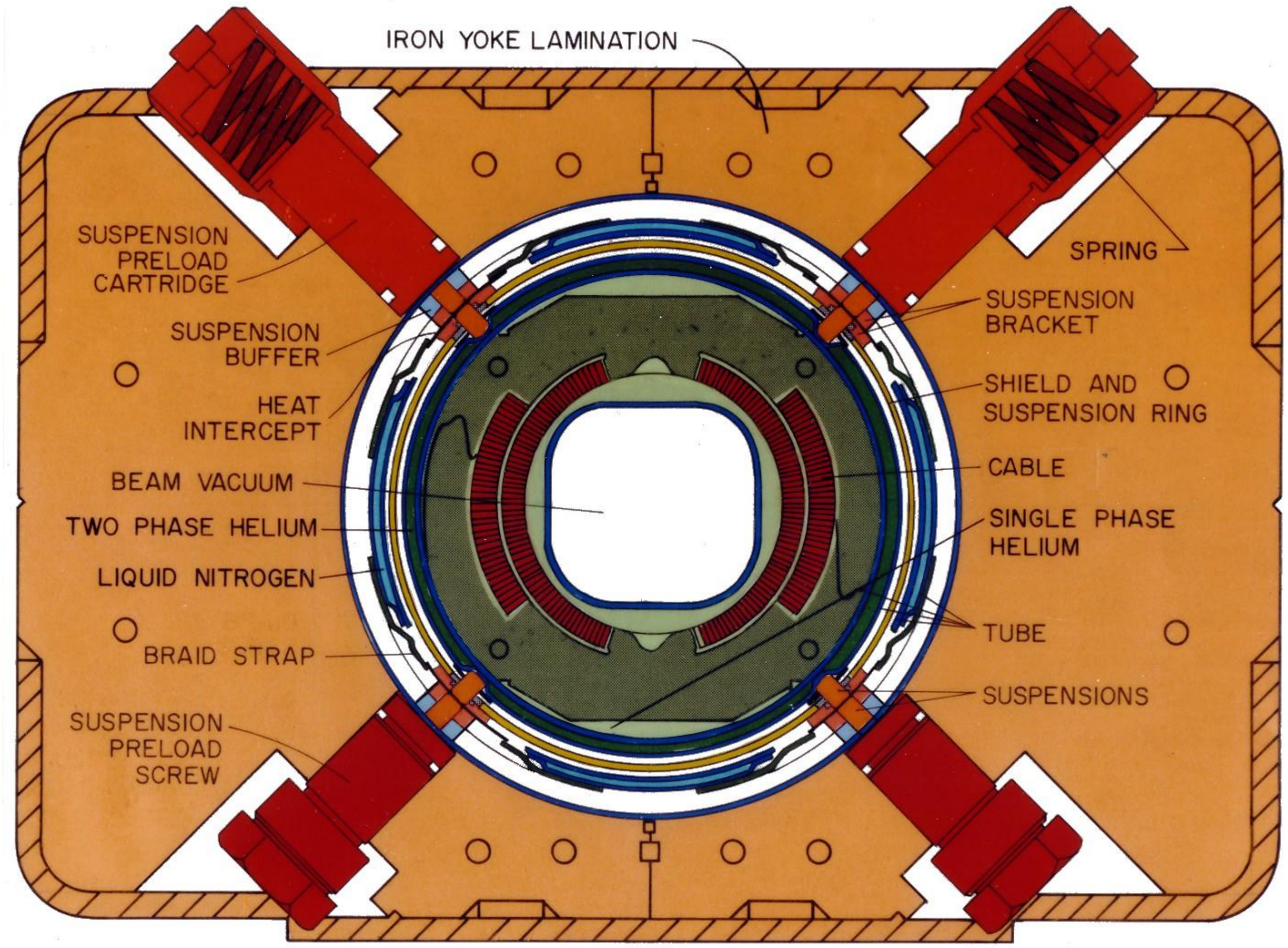


Chapter 1 – Introduction and Scope



Chapter 1 – Introduction and Scope

Tevatron dipole



Chapter 1 – Introduction and Scope

1.3 GHz 9-cell SRF cavity

Chapter 1 – Introduction and Scope

Dressed cavity

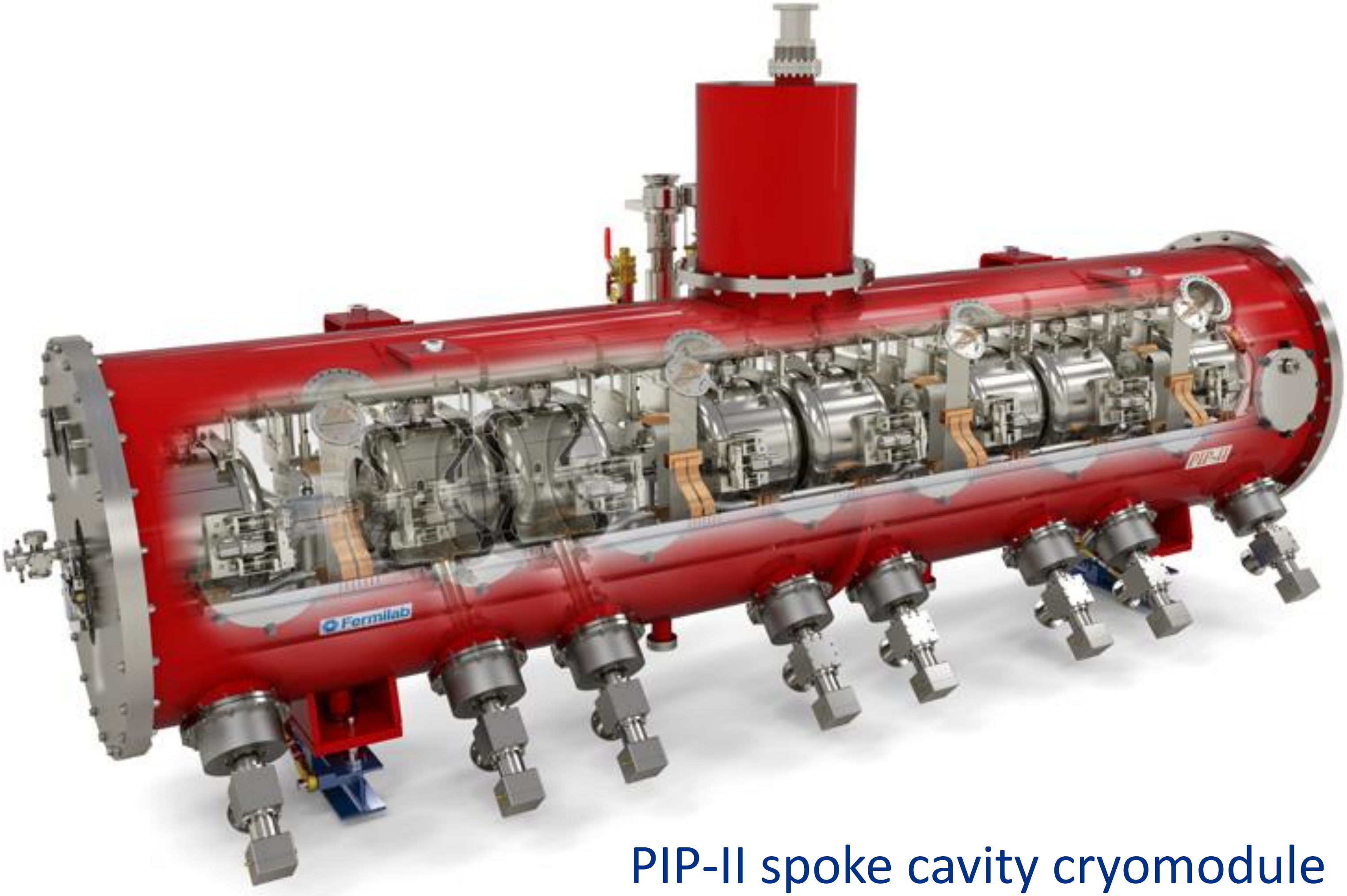
Chapter 1 – Introduction and Scope

LCLS-II 1.3 GHz cold mass

Chapter 1 – Introduction and Scope

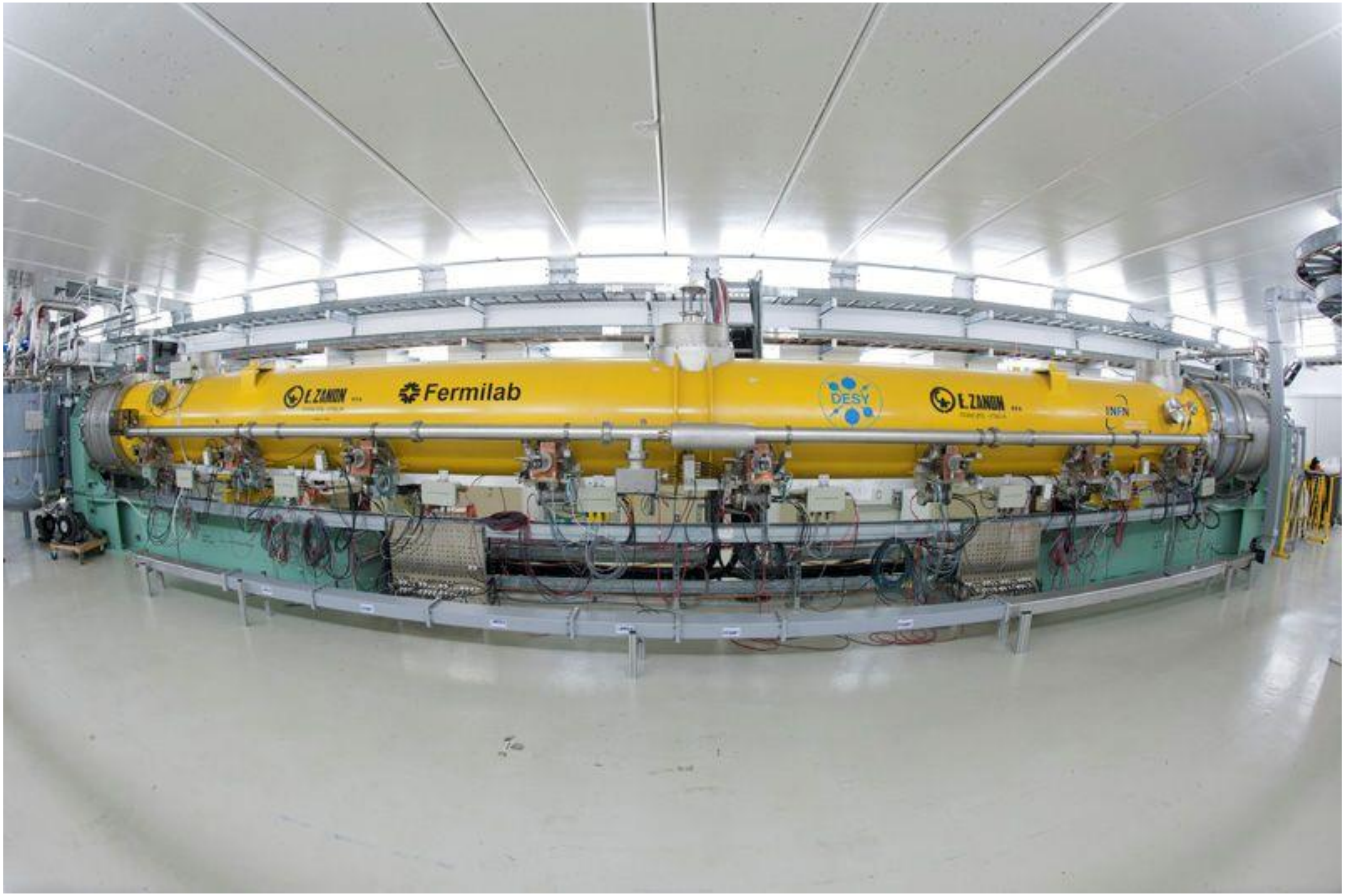
PIP-II spoke cavity

Chapter 1 – Introduction and Scope

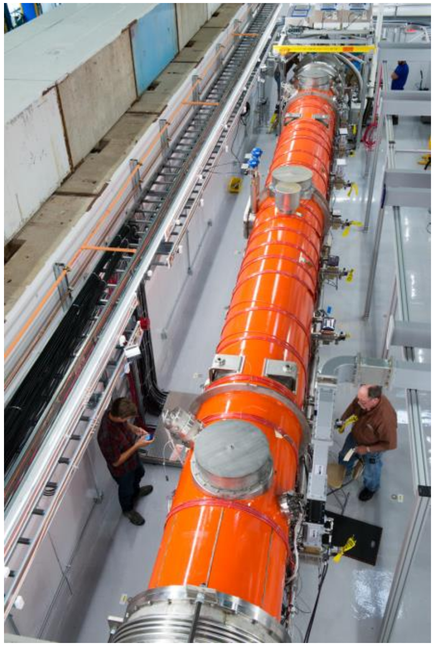


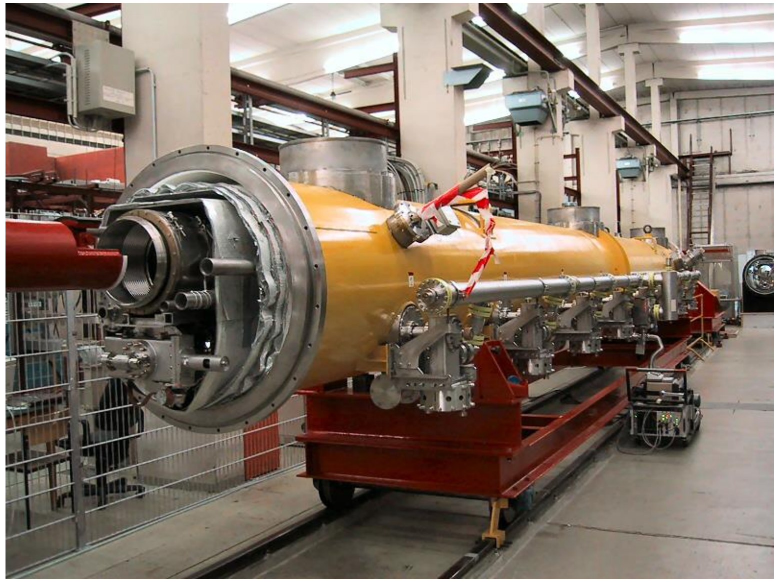
PIP-II spoke cavity cryomodule

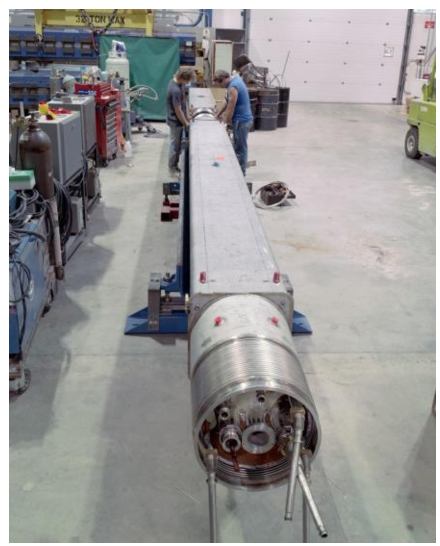
Chapter 2 – Vacuum vessels

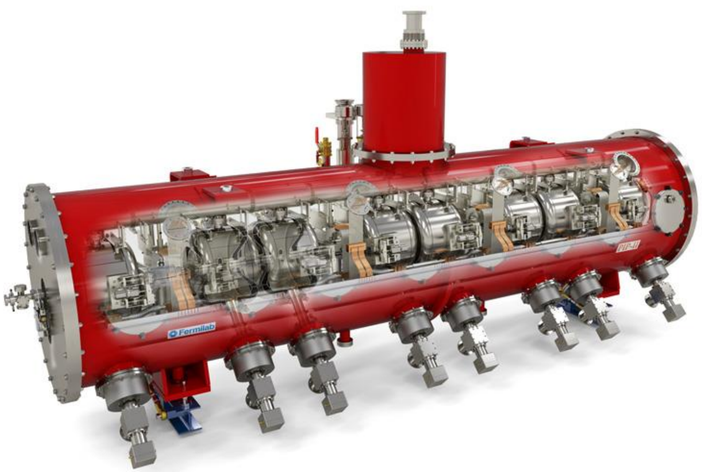


Chapter 2 – Vacuum vessels









Chapter 2 – Vacuum vessels

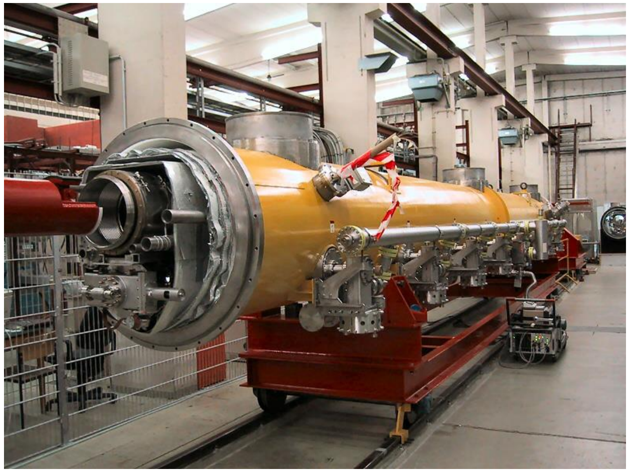
- The outermost cryostat or cryomodule component that:
  - Contains the insulating vacuum.
  - Serves as the major structural element to which all other systems are attached to the accelerator tunnel floor.
  - Serves as a pressure containment vessel in the event of a failure in an internal cryogen line.
- 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
Common alloys	SA 516	304, 304L, 316, 316L	5083, 6061

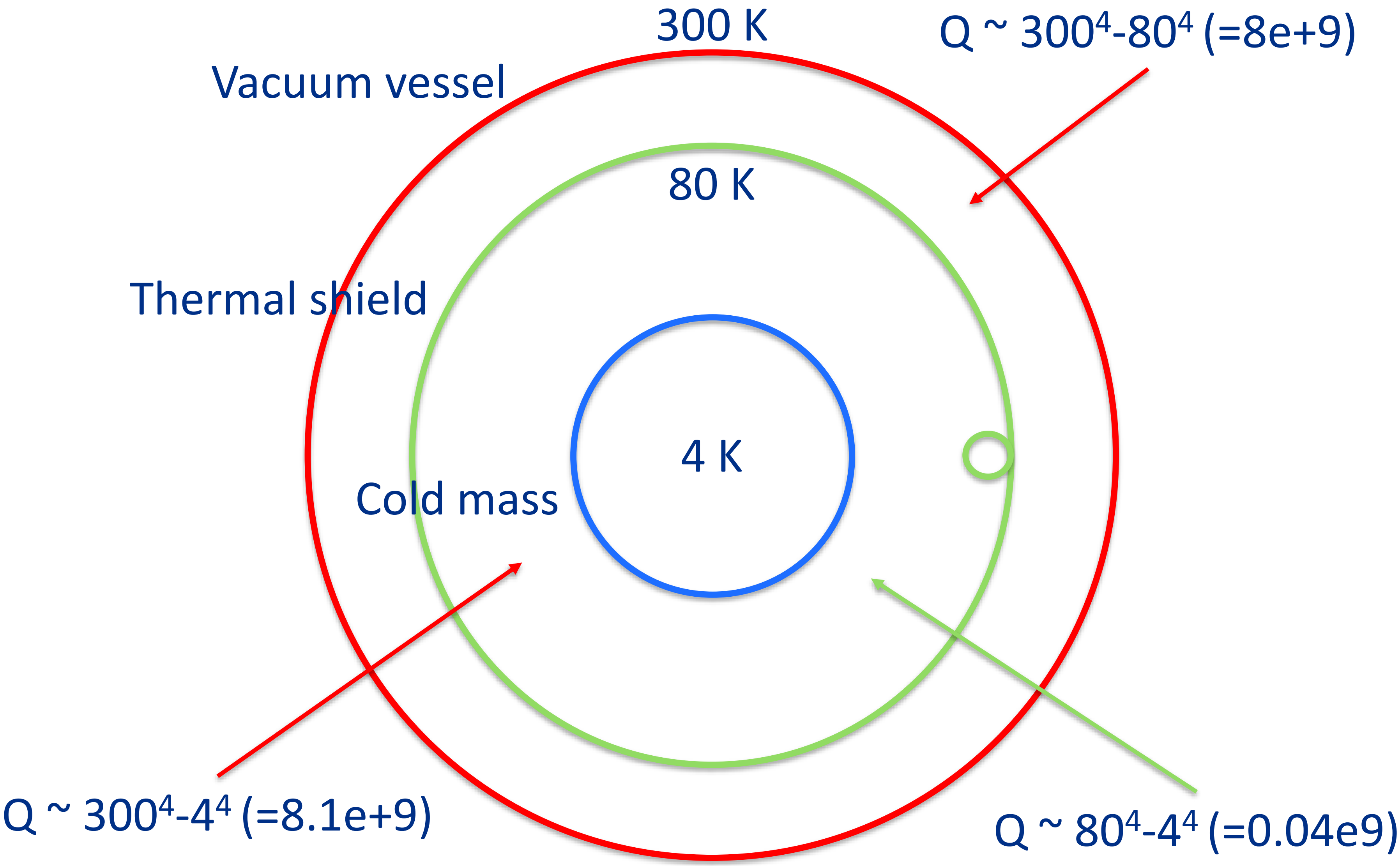
Chapter 3 – Thermal shields



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



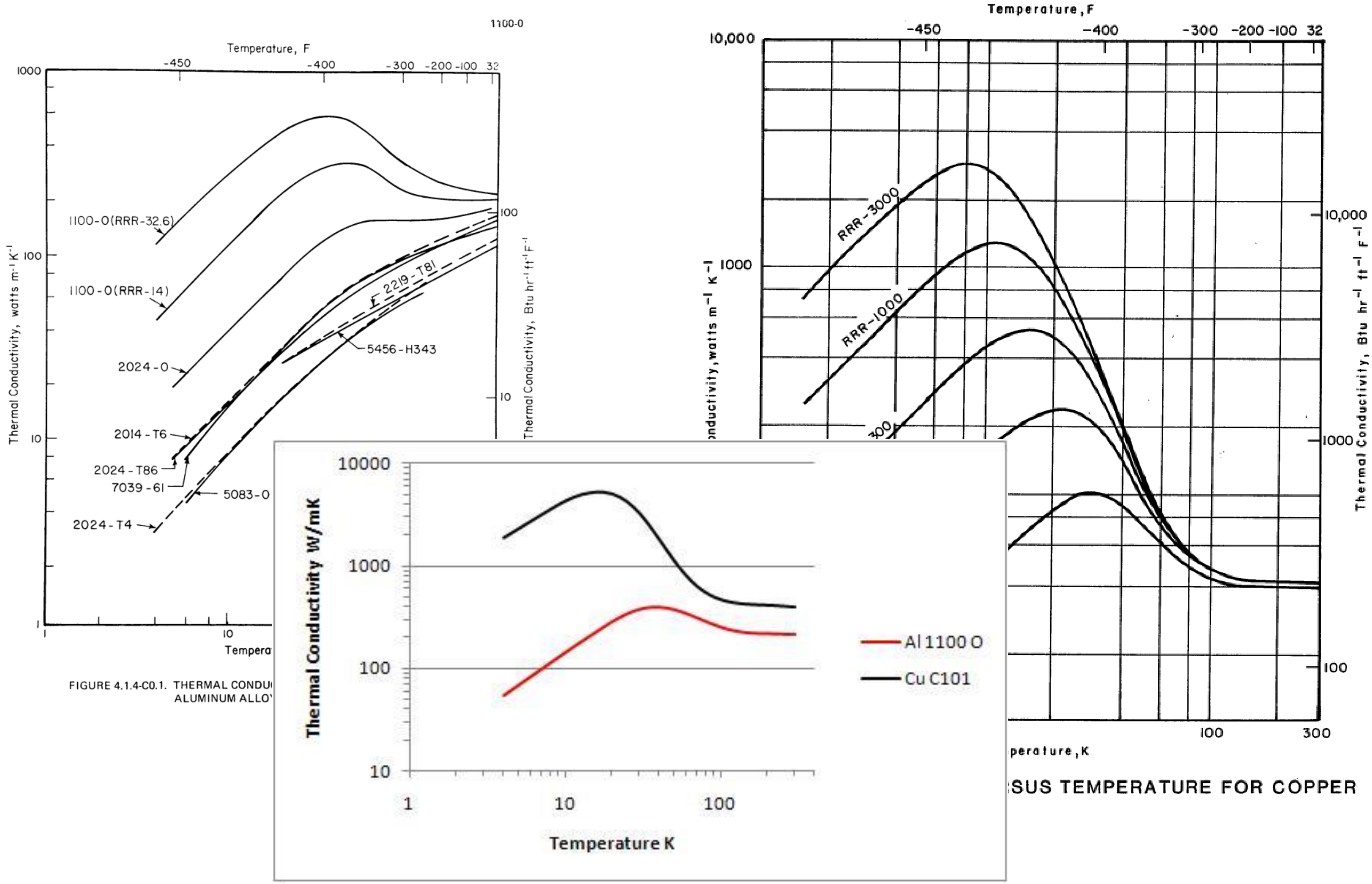
Chapter 3 – Thermal shields

- Materials are nearly always:

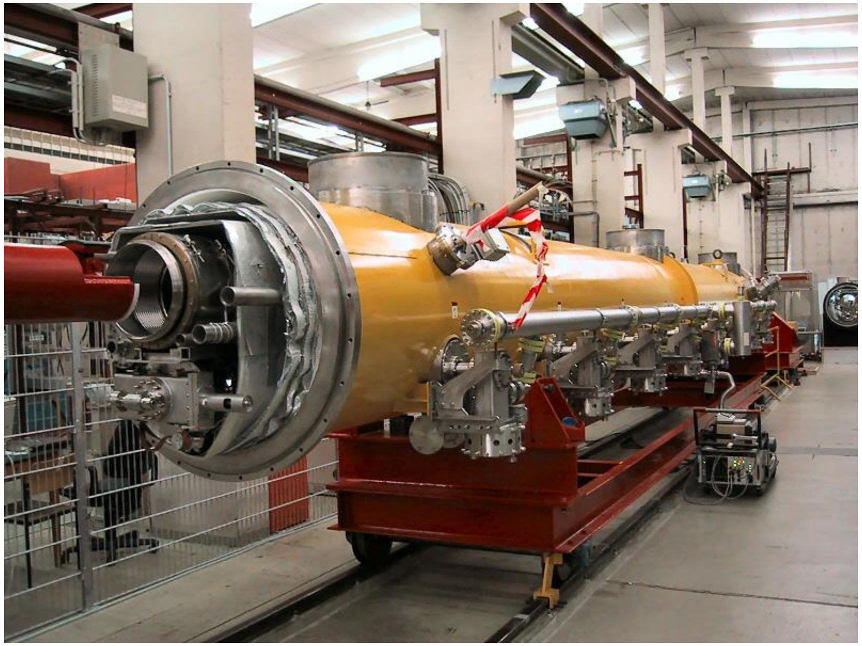
	Copper	Aluminum
Pros	• Readily available • Good thermal conductivity • Readily soldered or brazed	• Inexpensive • Readily available • Good thermal conductivity(*) • Weldable • Light weight
Cons	• Expensive • Heavy	• (*)Thermal conductivity good, but not as good as copper • Difficult to join to stainless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



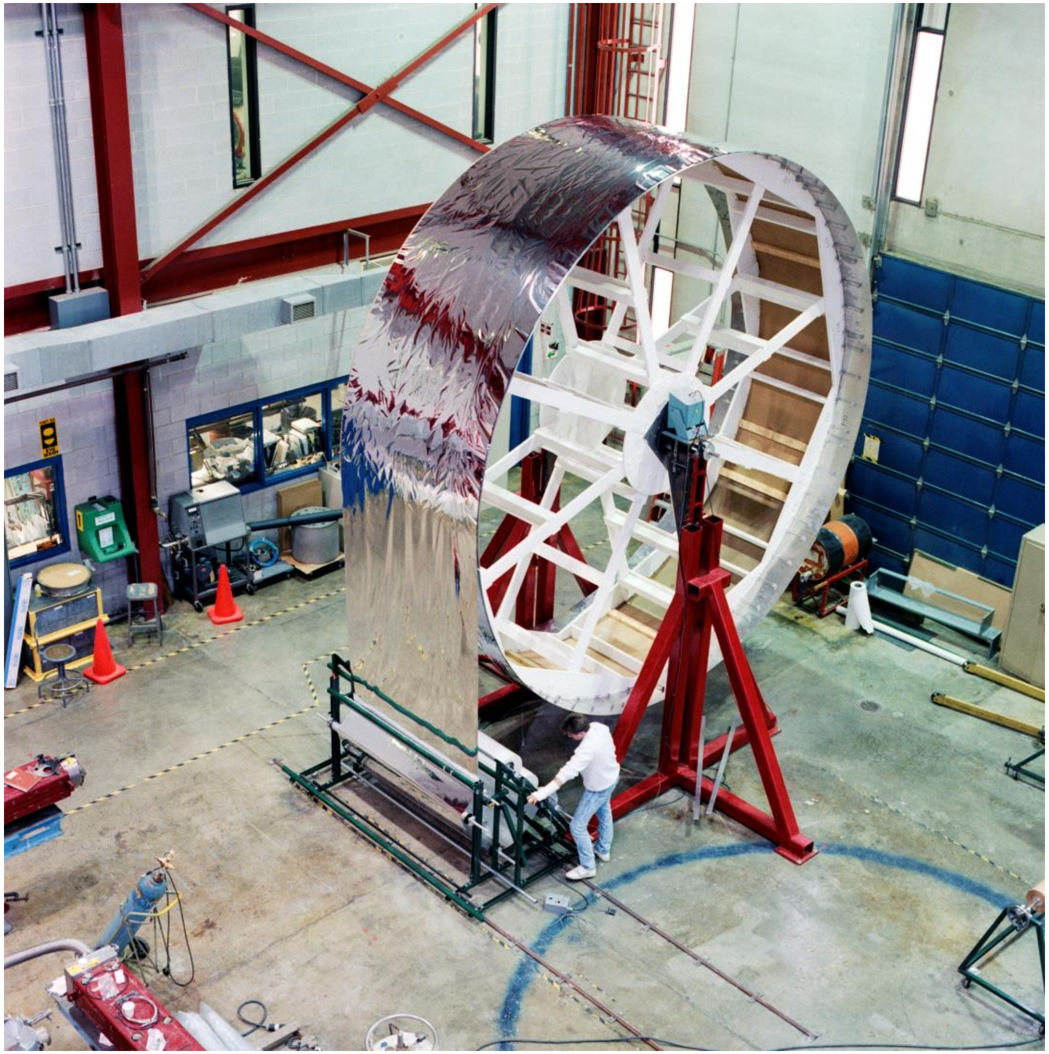
Chapter 4 – Insulation



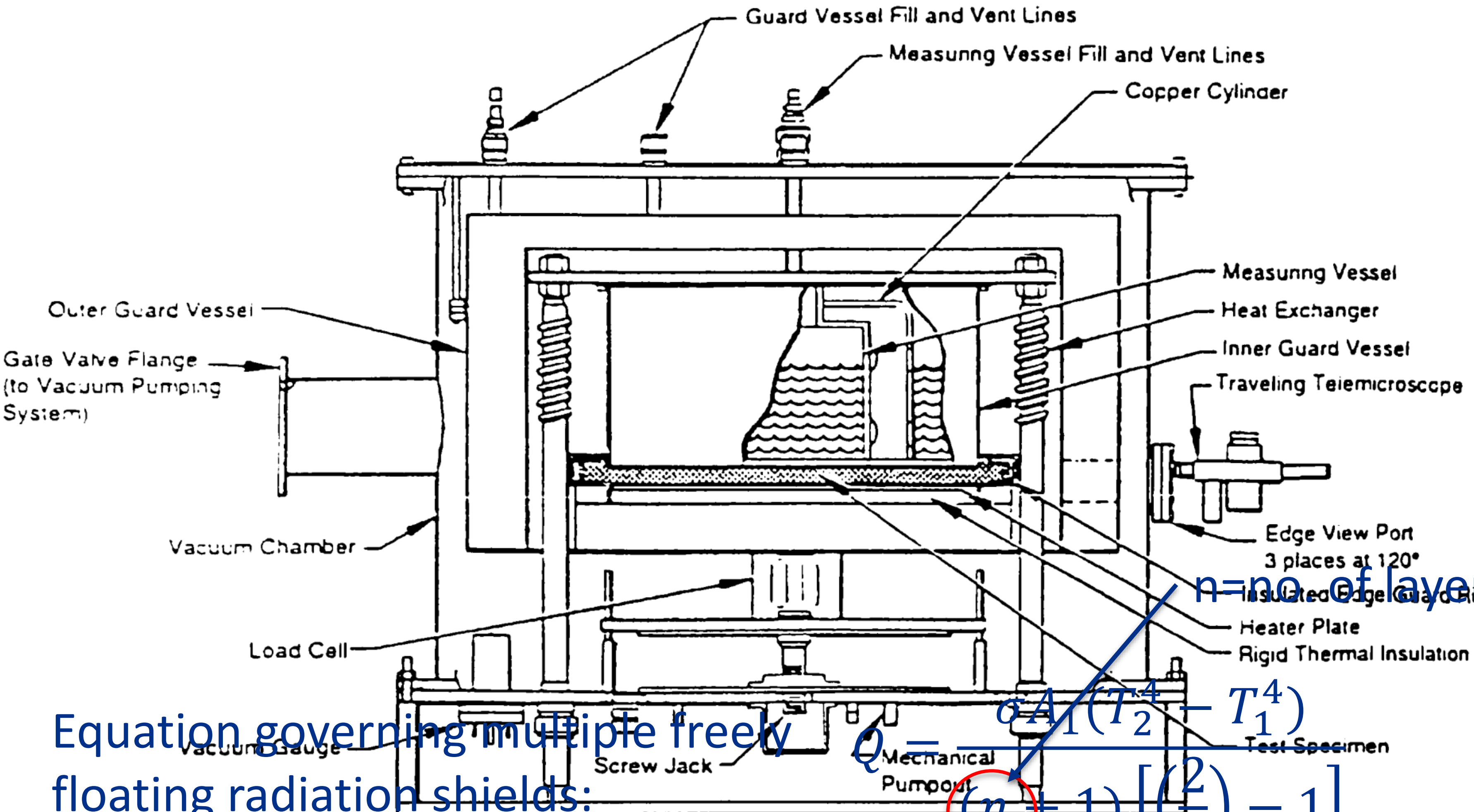
Chapter 4 – Insulation

- Multi-layer insulation (MLI) reflects radiative heat 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.
- MLI is ineffective on surfaces less than ~20 K but is sometimes used to slow pressure increases during loss-of-vacuum situations.

Chapter 4 – Insulation



Chapter 4 – Insulation

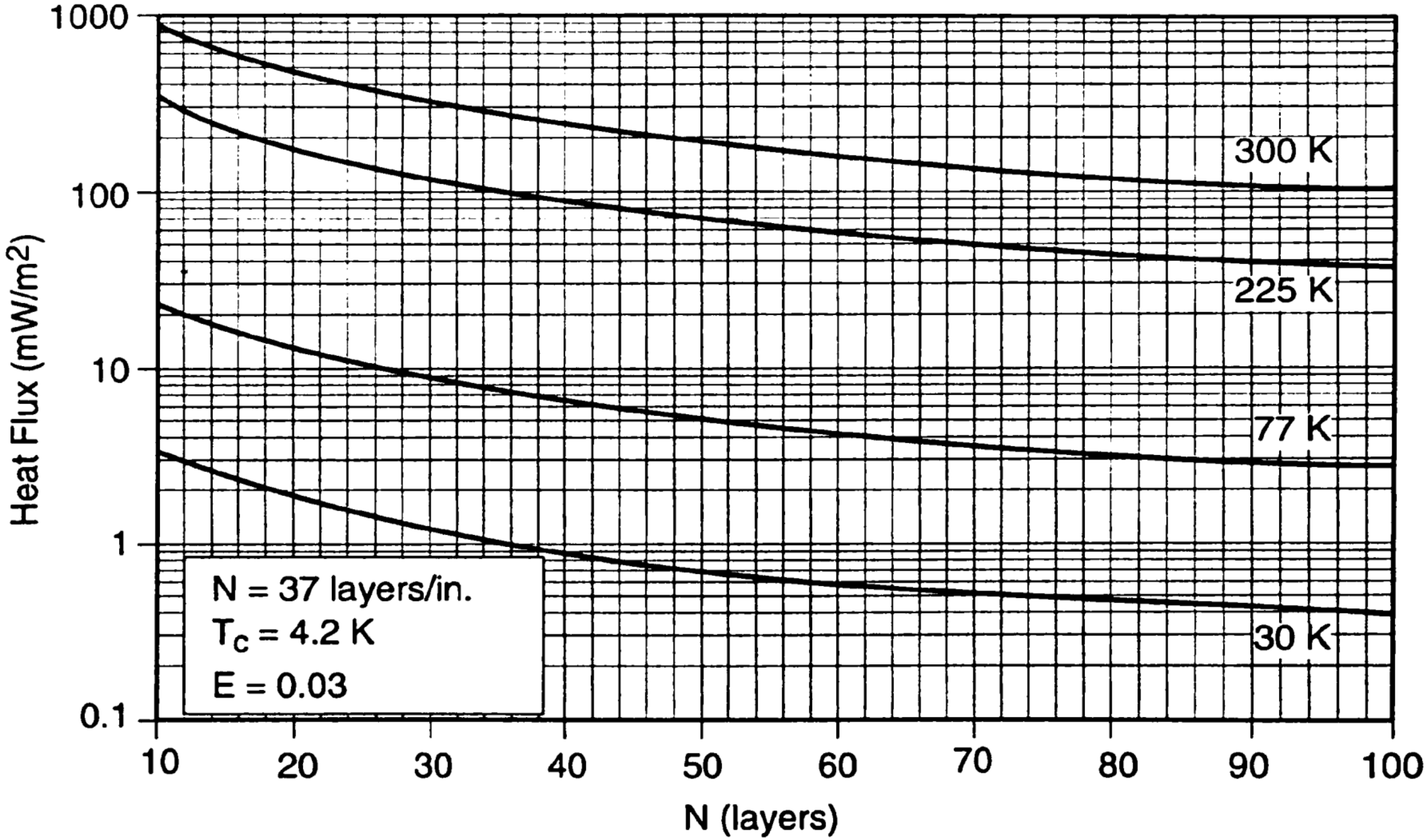


n=no. of layers

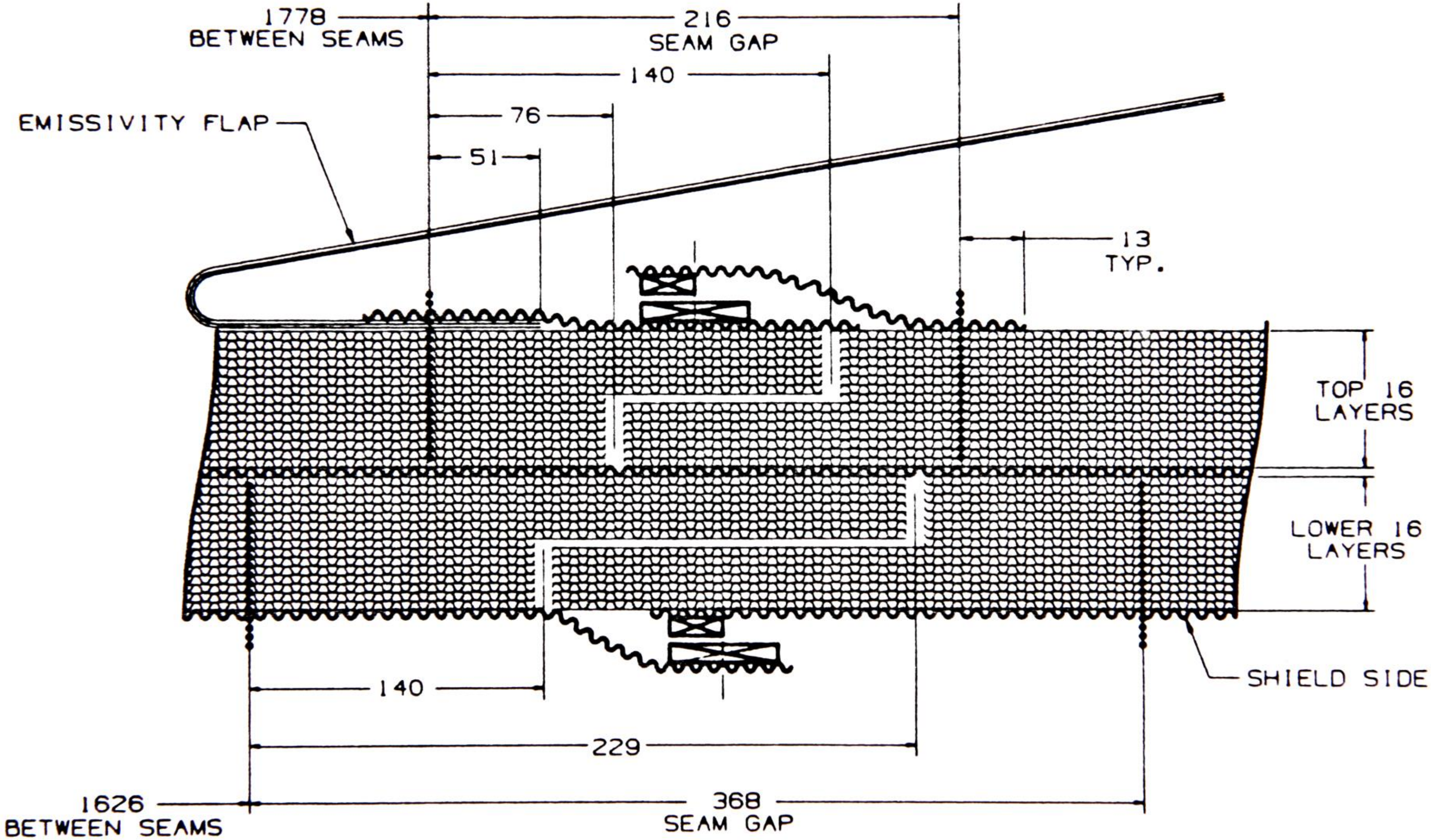
Equation governing multiple freely floating radiation shields:

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

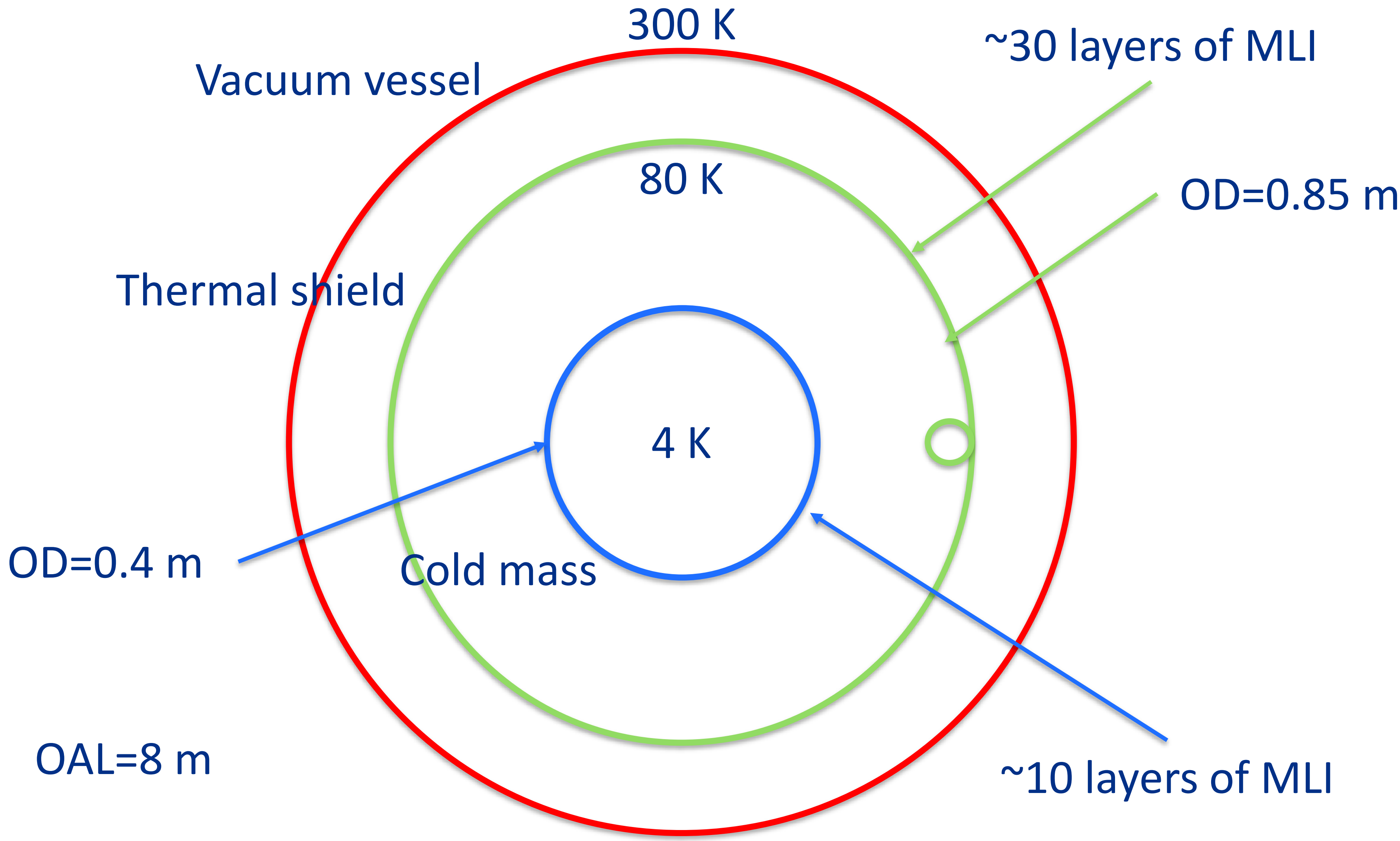
Chapter 4 – Insulation



Chapter 4 – Insulation



Chapter 4 – Sample heat load estimate



Chapter 4 – Sample heat load estimate*

<u>80 K</u> (Body; Ends)

$A = \underbrace{(0.85\pi)(8)}_{\text{Body}}+\underbrace{2(\pi(0.85)^2/4)}_{\text{Ends}} = 22.5\ m^2$

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

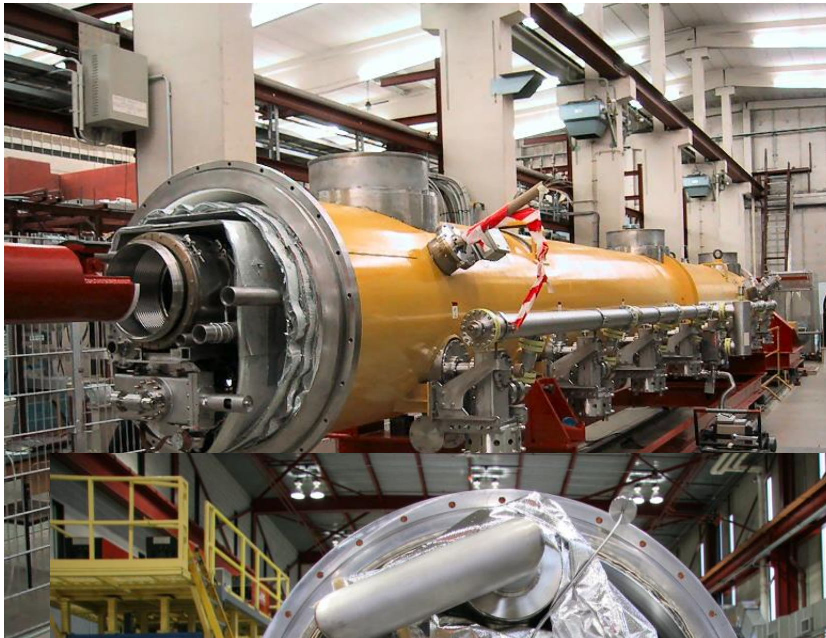
<u>4.5 K</u>

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

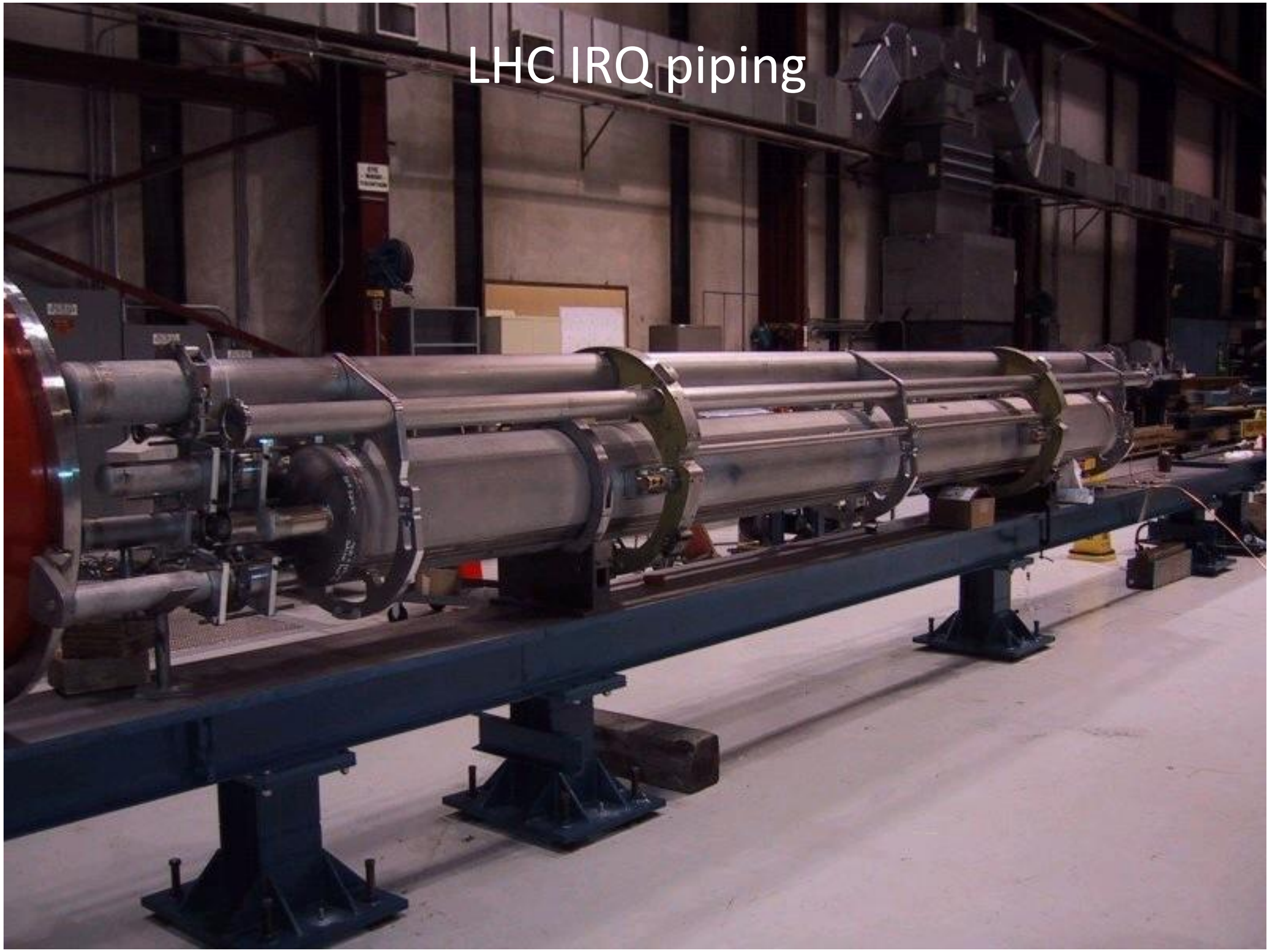
$Q = (10.3\ m^2)(0.15\ W/m^2) = 1.5\ W$

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

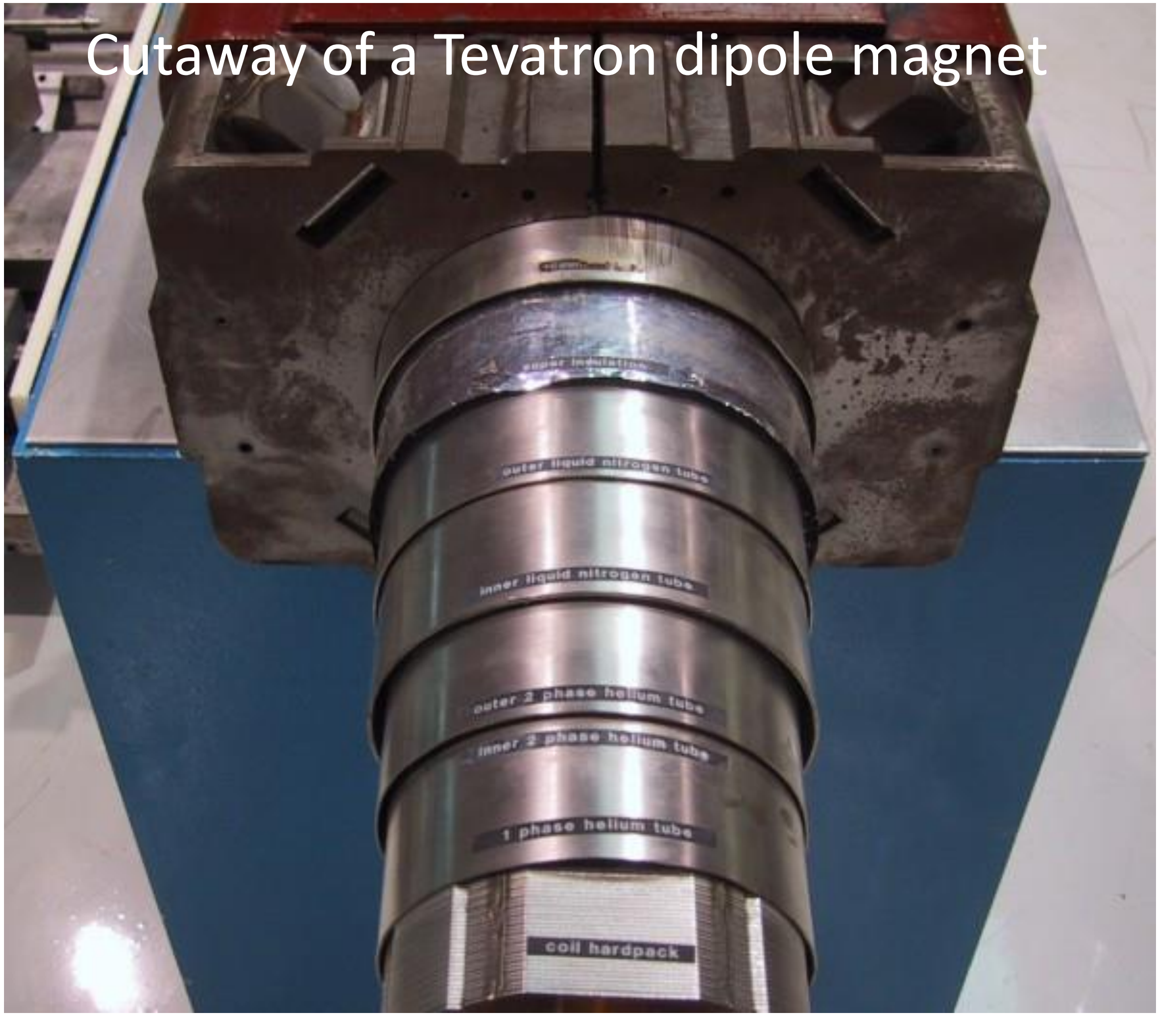
Chapter 5 – Piping



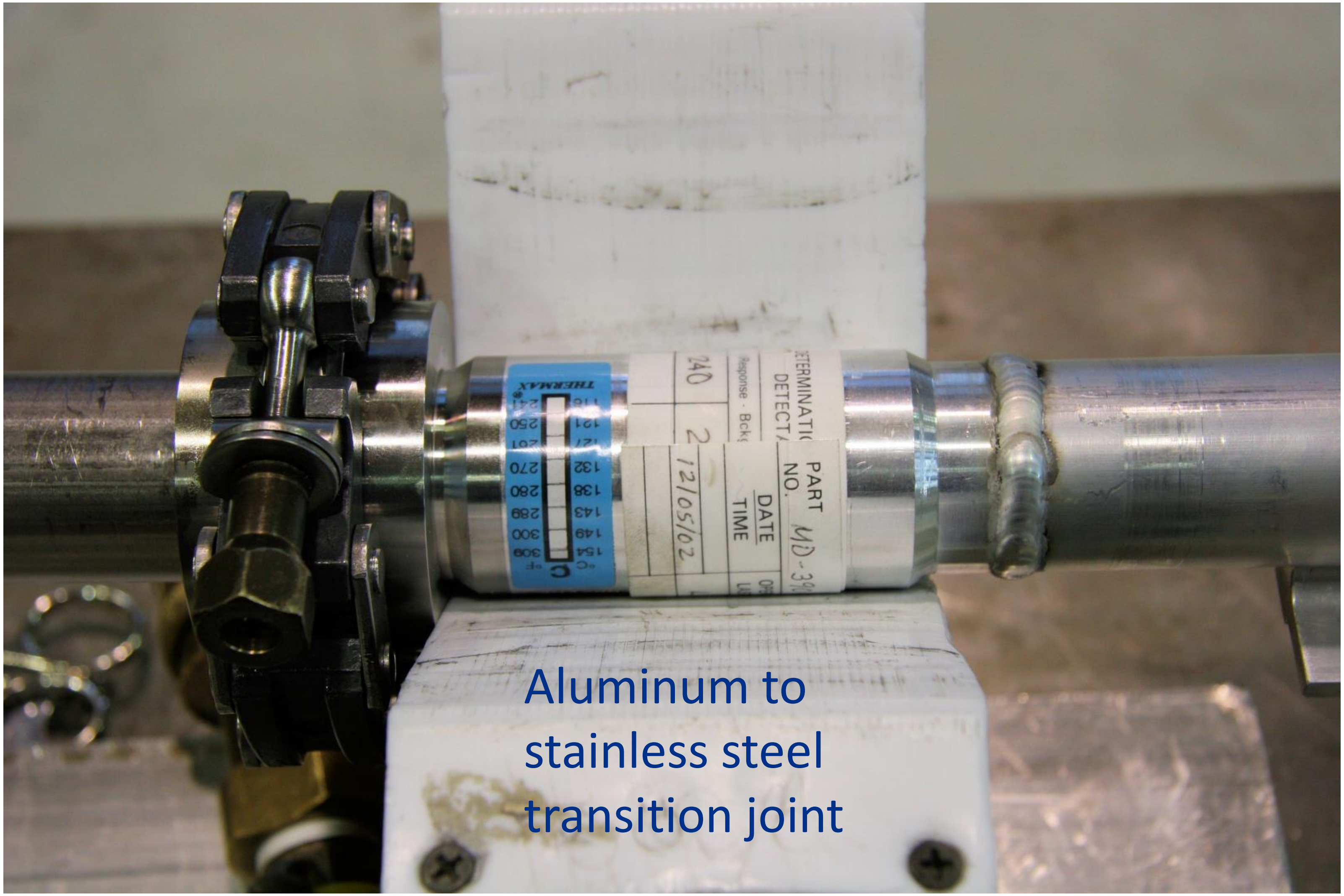
Chapter 5 – Piping



Chapter 5 – Piping



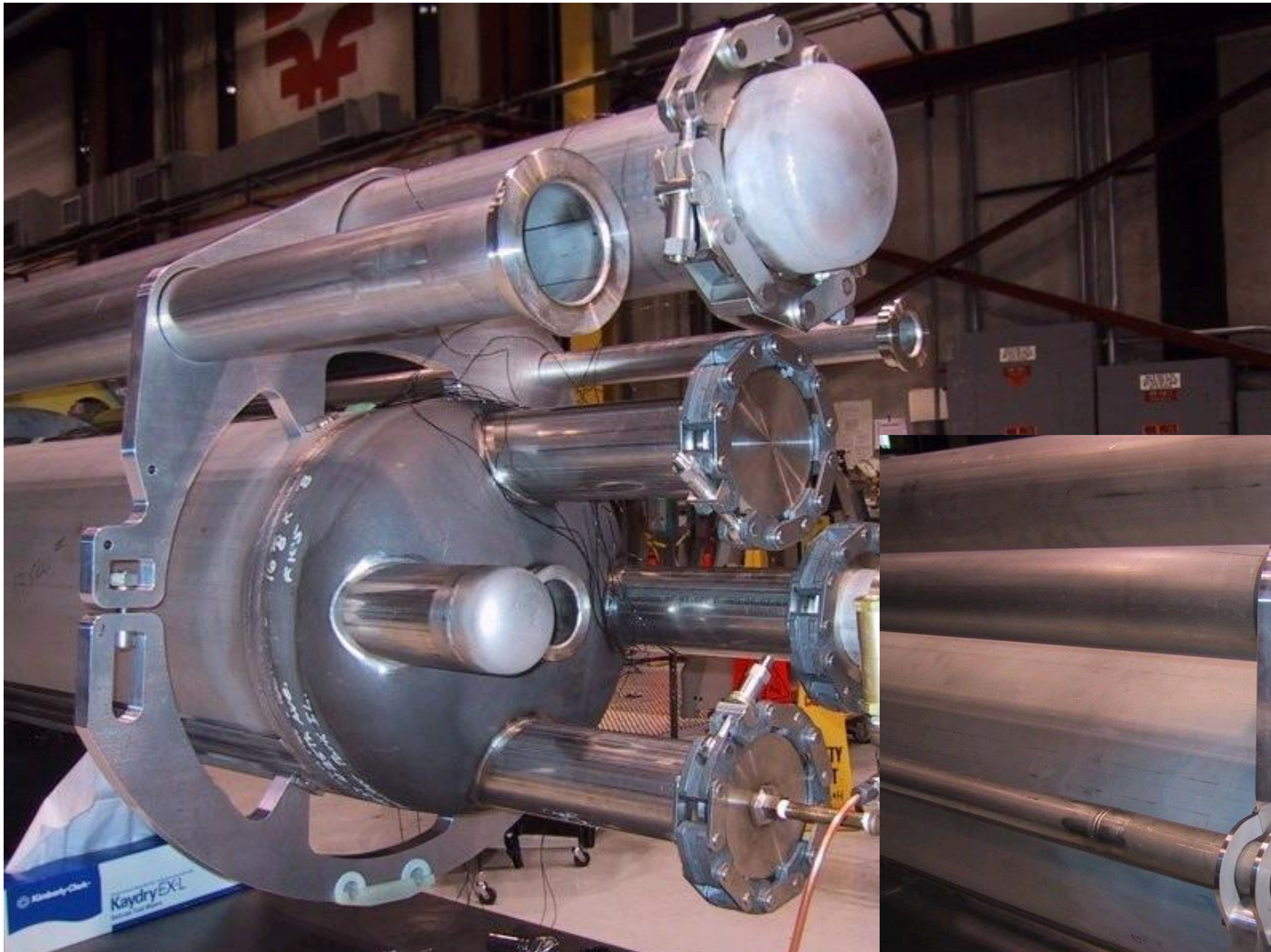
Chapter 5 – Piping



Aluminum to stainless steel transition joint

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.
- Care must be taken to avoid thermo-acoustic oscillations (TAO) that can occur in long gas-filled tubes with a large longitudinal temperature gradient. These oscillations often lead to large heat loads and occasionally to mechanical vibration.

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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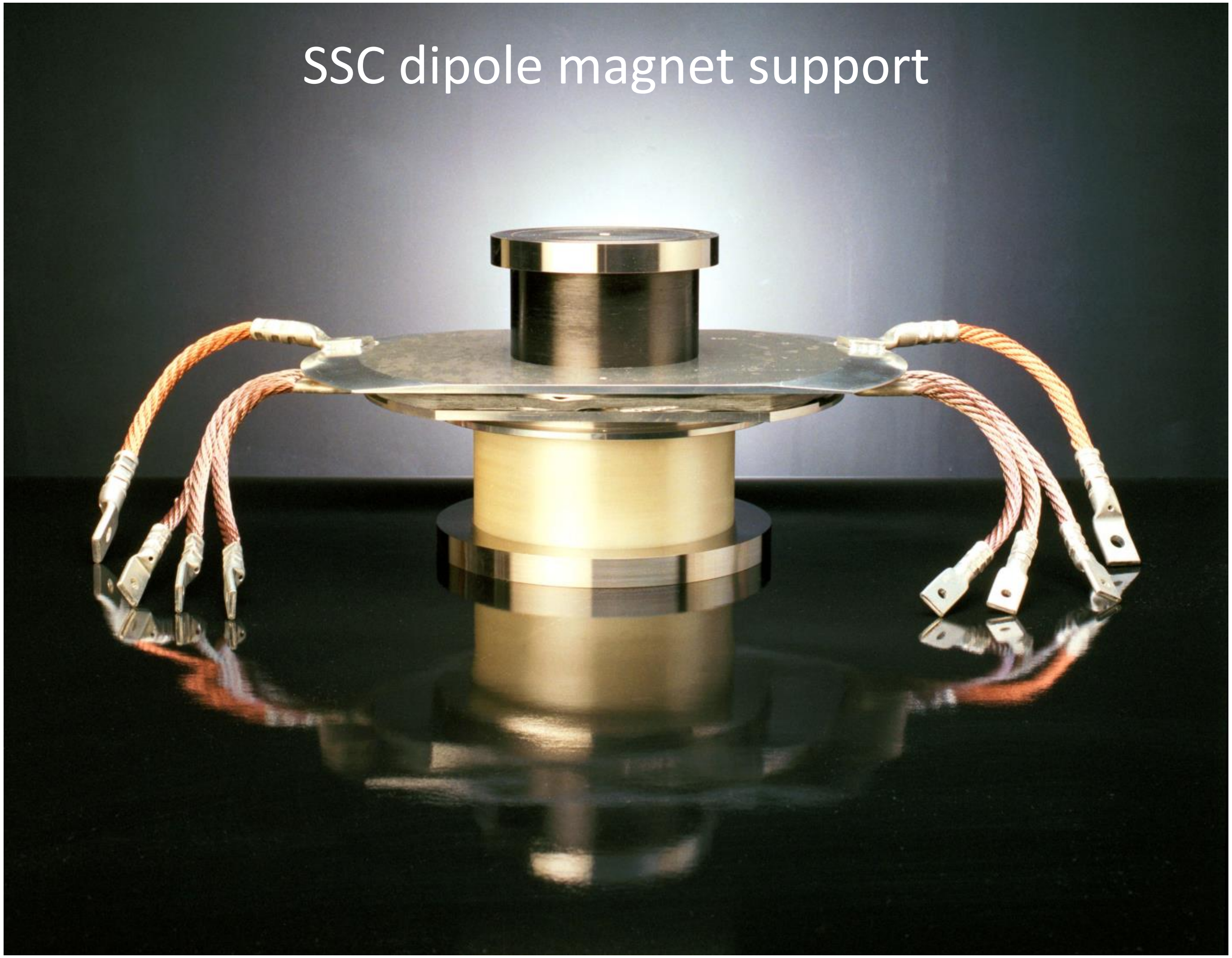
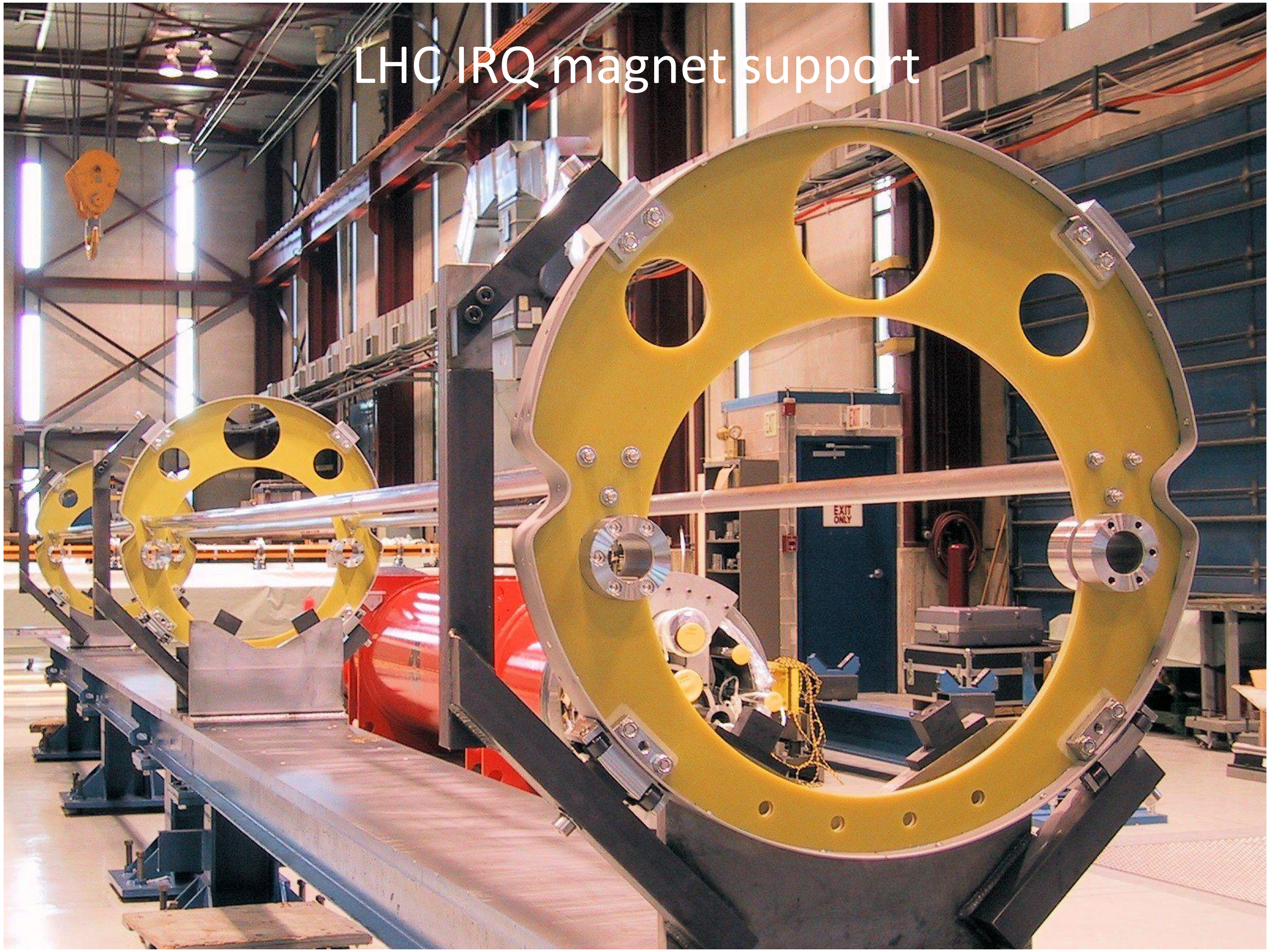
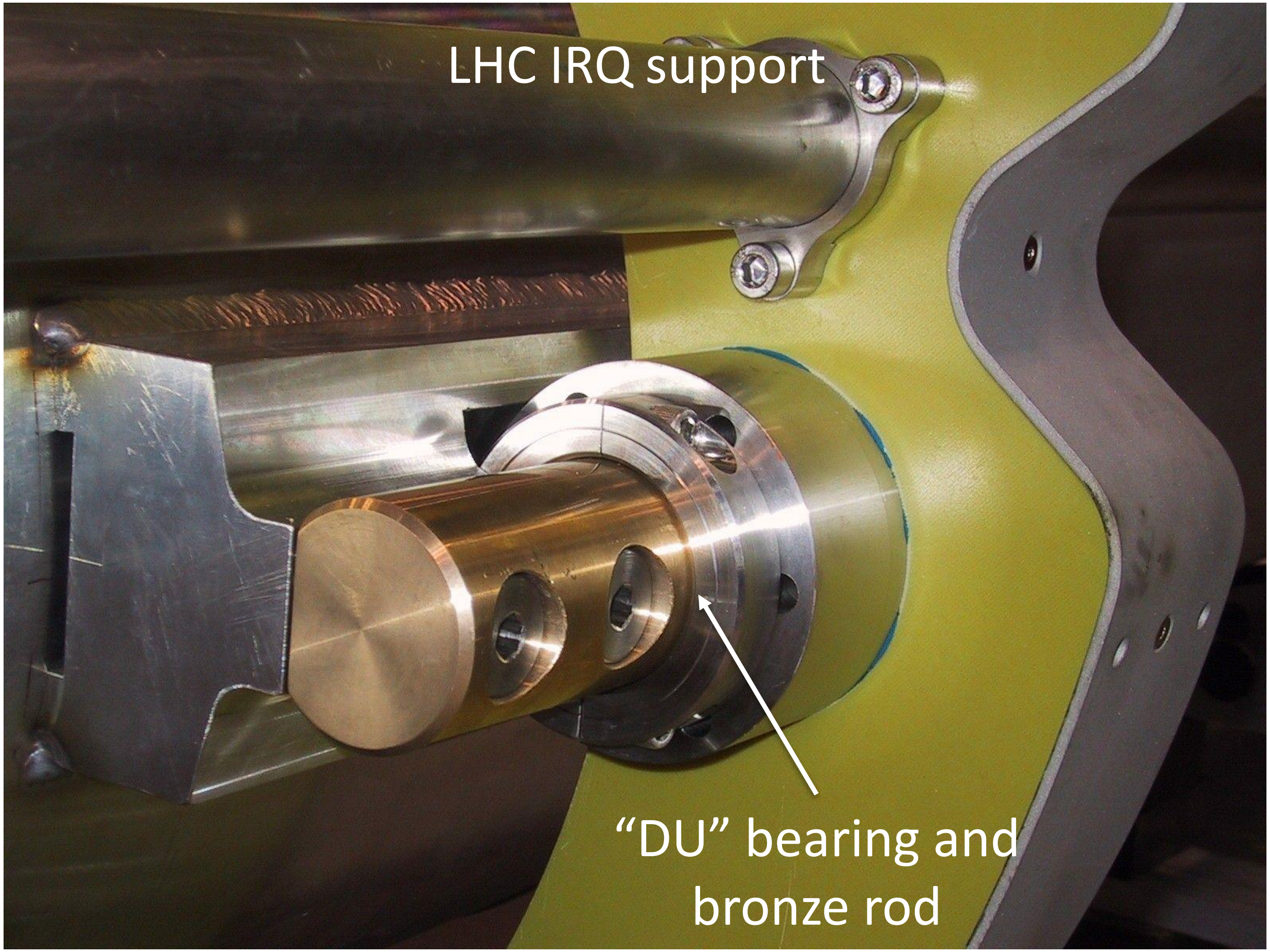


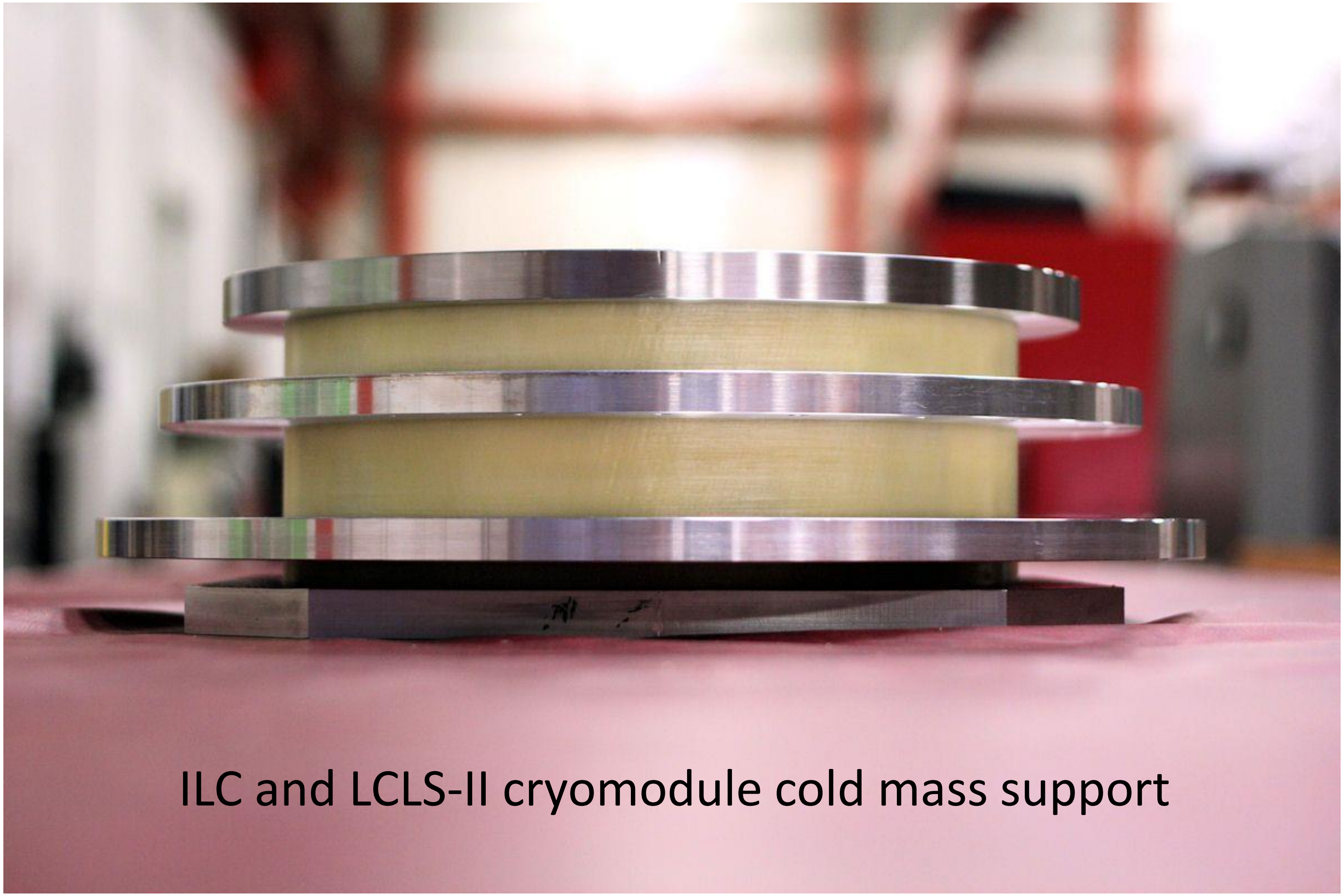
Chapter 6 – Support structures



Chapter 6 – Support structures



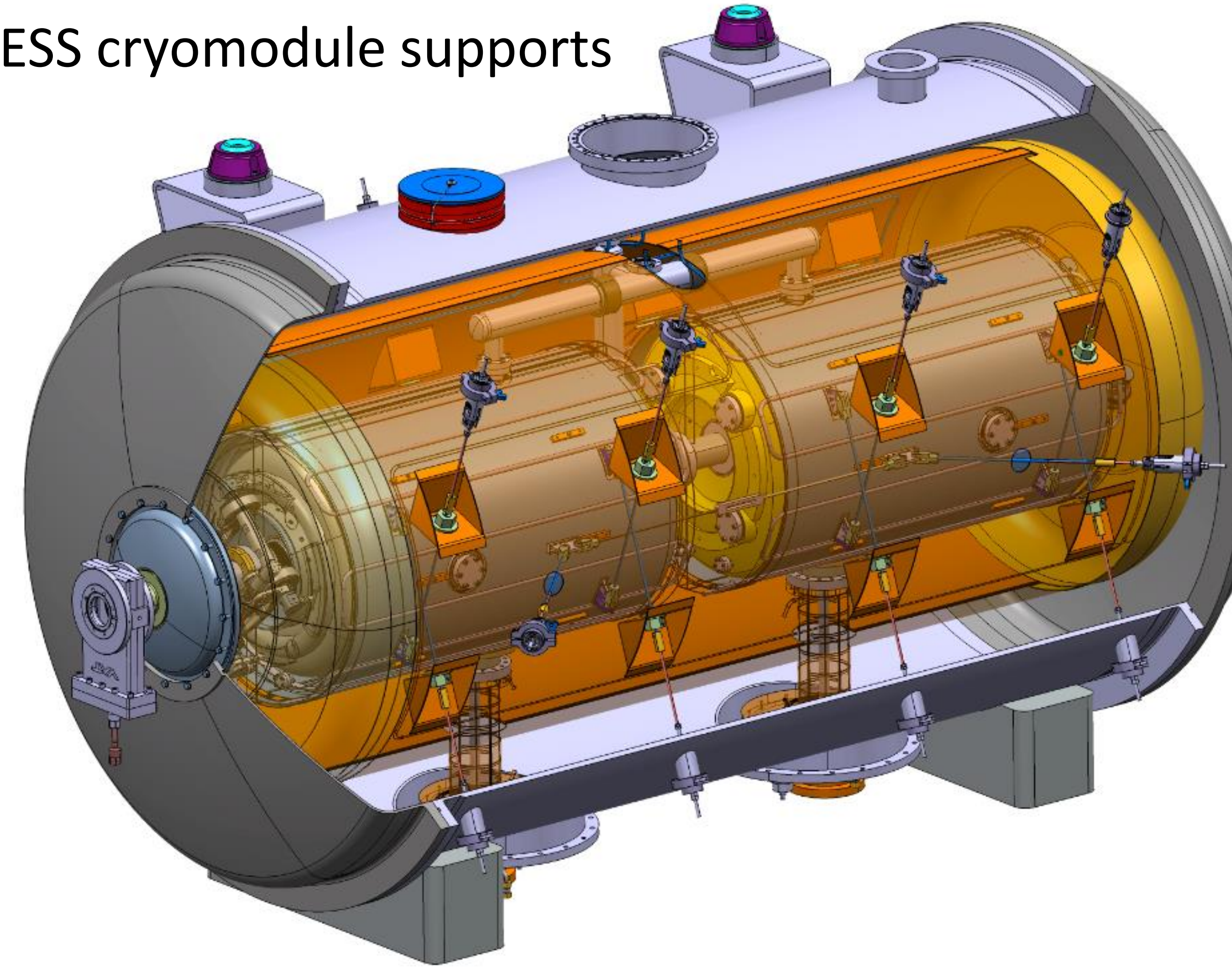
Chapter 6 – Support structures



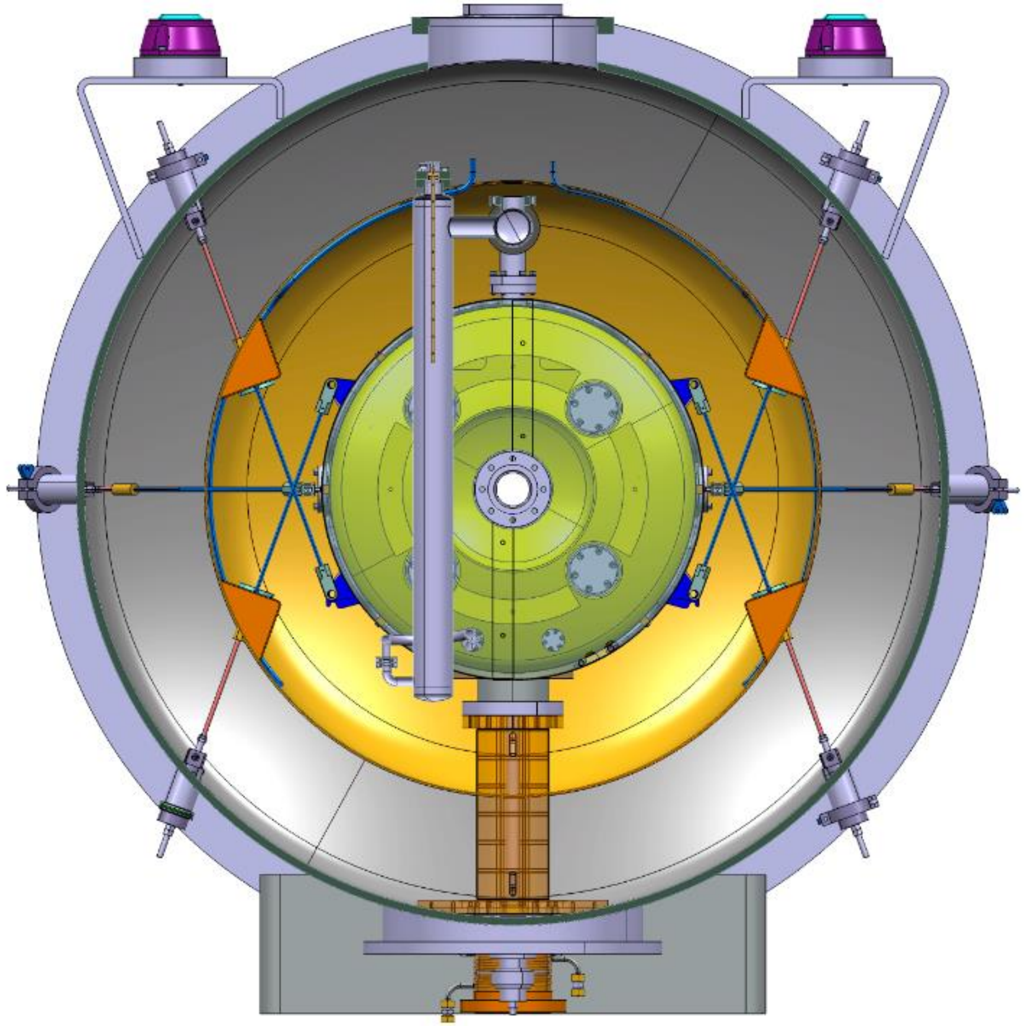
ILC and LCLS-II cryomodule cold mass support

Chapter 6 – Support structures

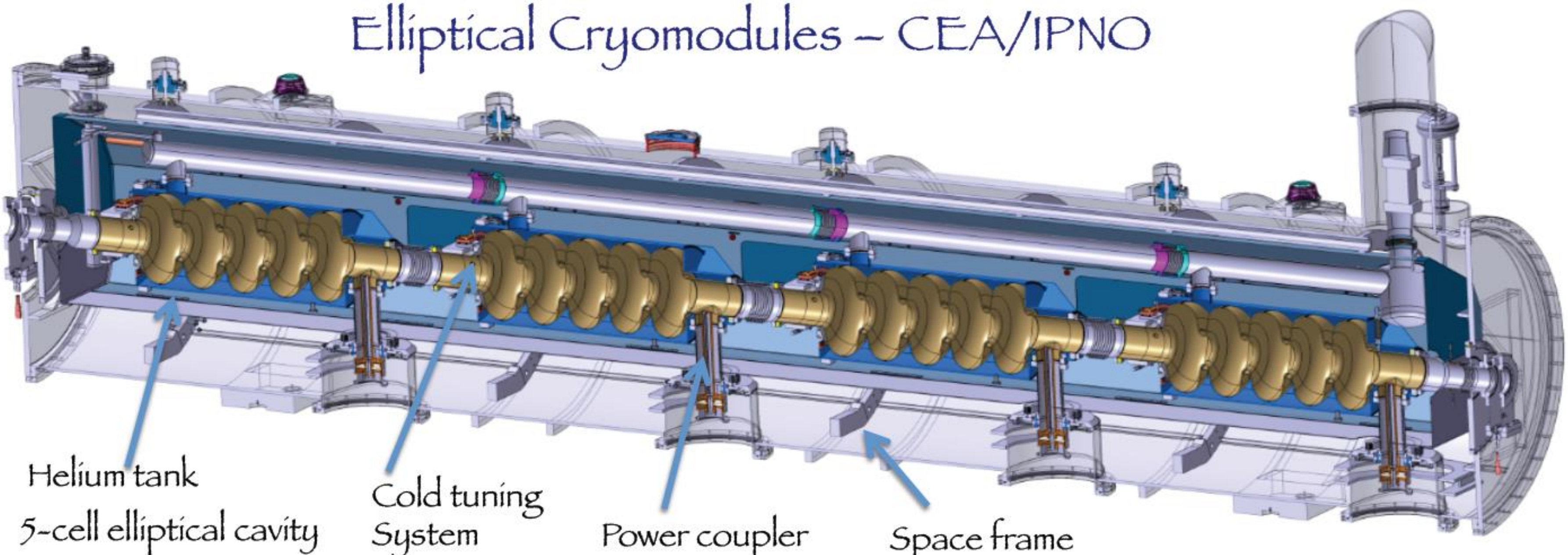
ESS cryomodule supports



Chapter 6 – Support structures



Chapter 6 – Support structures



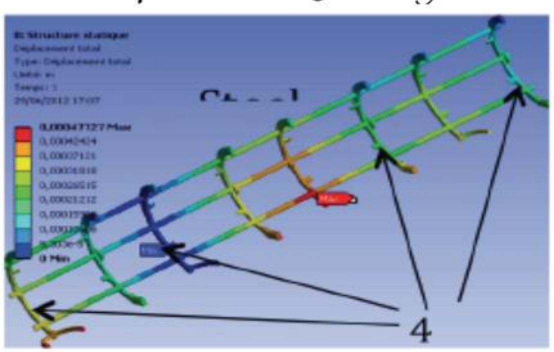
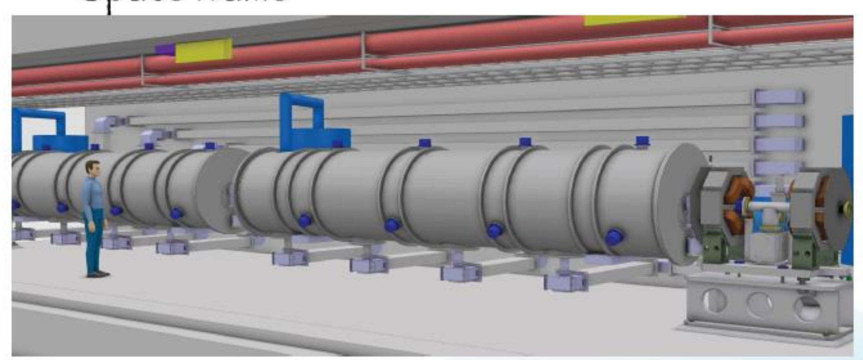


Figure 4.120: Helium vessel with hanging rod



Chapter 6 – Support structures

Always at odds with each other

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 composites • Good radiation resistance
Materials	Glass or graphite reinforced composites, Ultem, Torlon, PEEK	Stainless steel, Inconel, Invar, Titanium

Chapter 6 – Support structures

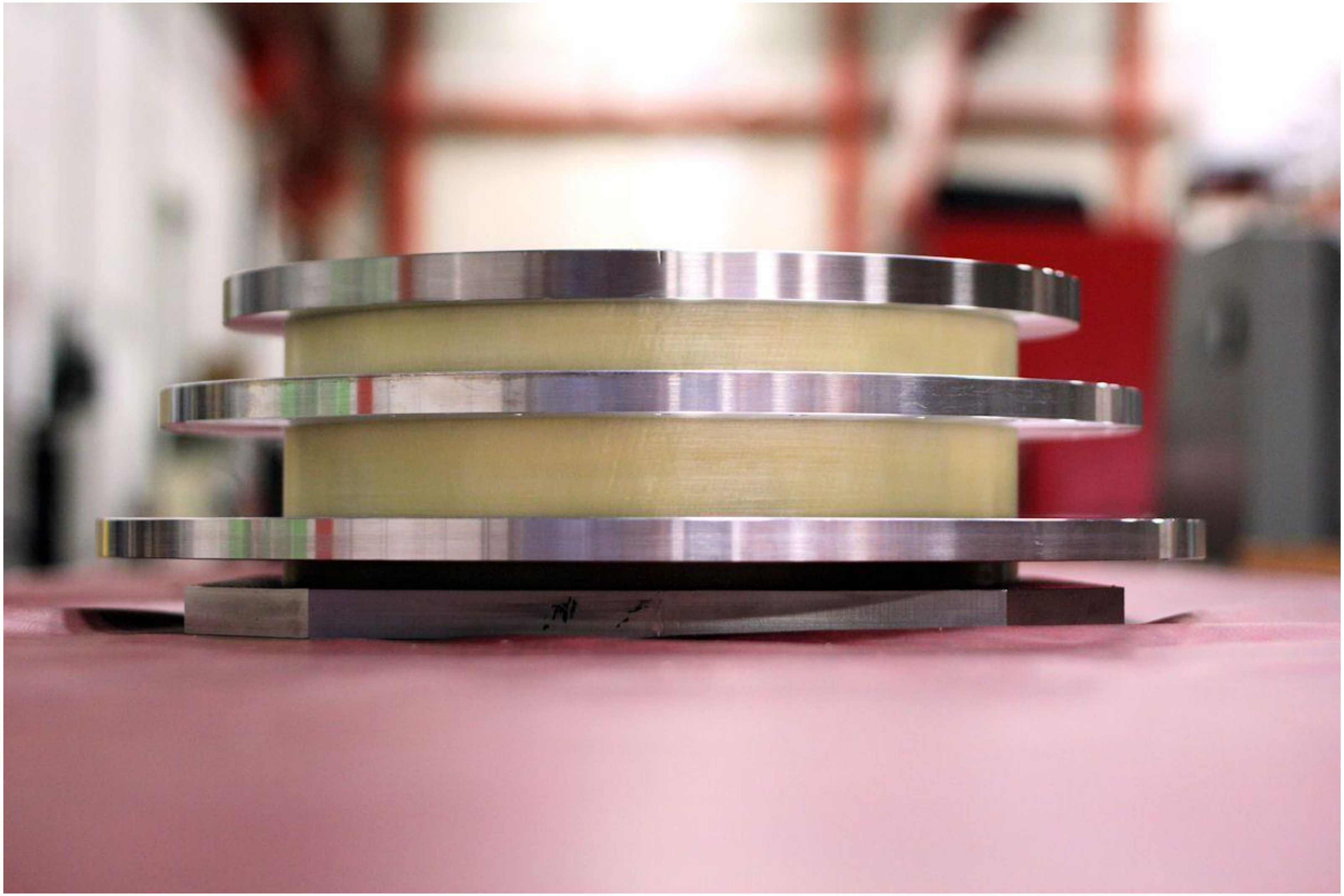
- Support design needs to consider:
  - Structural loading, both static and dynamic
  - Static heat load budget
  - Material limitations, if any, e.g. radiation resistance
  - Physical layout of the magnet or cryomodule components
- Design should include an axial anchor somewhere in the cryostat or cryomodule.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

Chapter 6 – Support structures – Lessons learned

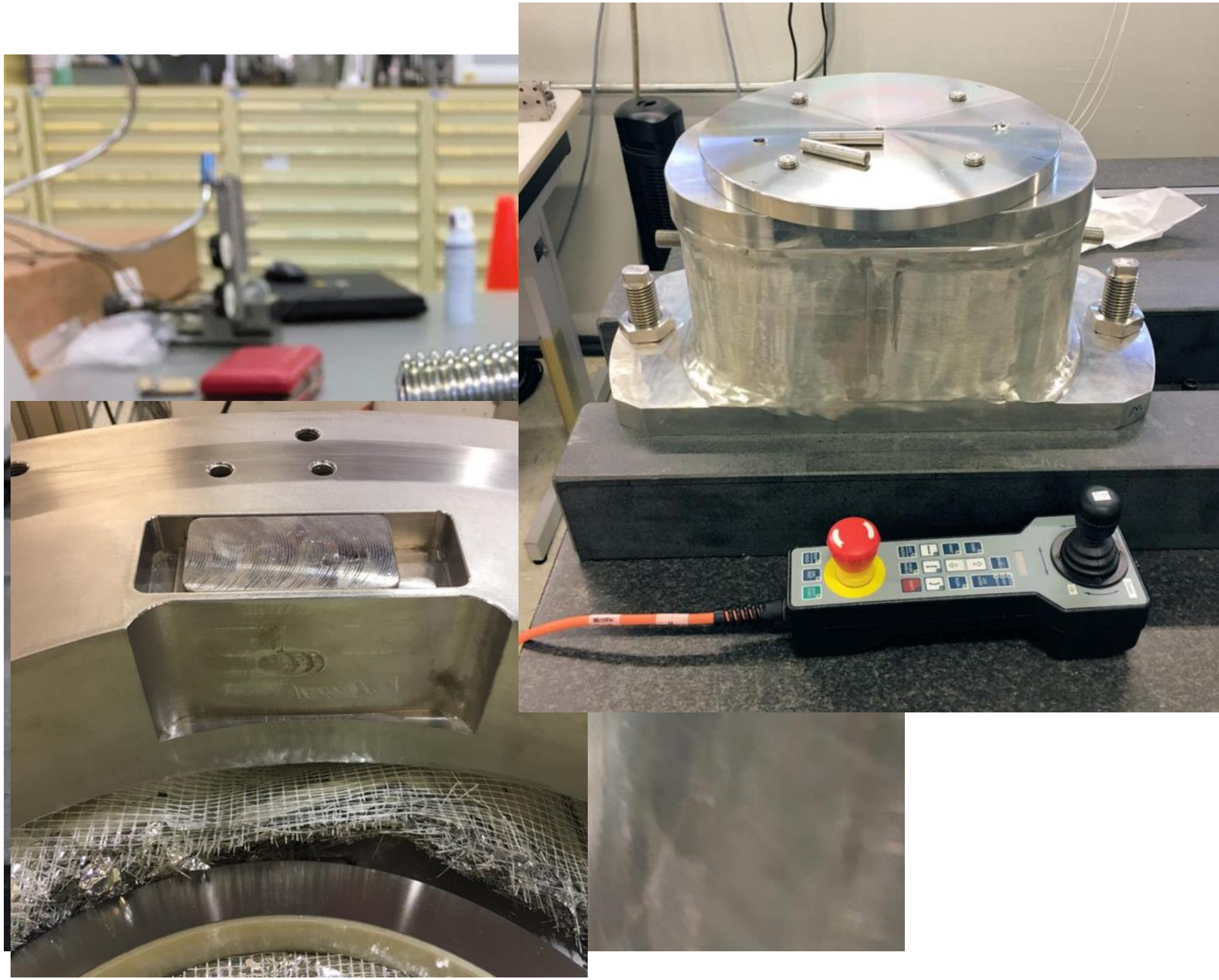
- In July 2018 a failure occurred in CM2 – an XFEL-design cryomodule built by Fermilab with parts supplied by DESY.
- The beam tube had dropped about 25 mm on one end of the cryomodule as the result of the entire cold mass dropping that same amount.
- We found one of the shrink-fit joints in the endmost support post had failed so the end of the cold mass was no longer connected to the vacuum vessel.
- The real problem was not the support, but that the horizontal guides that allow sliding during cooldown had stuck at one end, preventing axial cooldown motion.
- Inspection of the individual parts revealed all were in tolerance, but the shrink-fit was at the low end of the tolerance range. Also, the outer surface of the inner disk was not shot-blasted as specified on the drawing.
- We decided to fabricate a new center disk to give us a little more interference and were able shrink-fit the assembly in place.

Chapter 6 – Support structures – Lessons learned

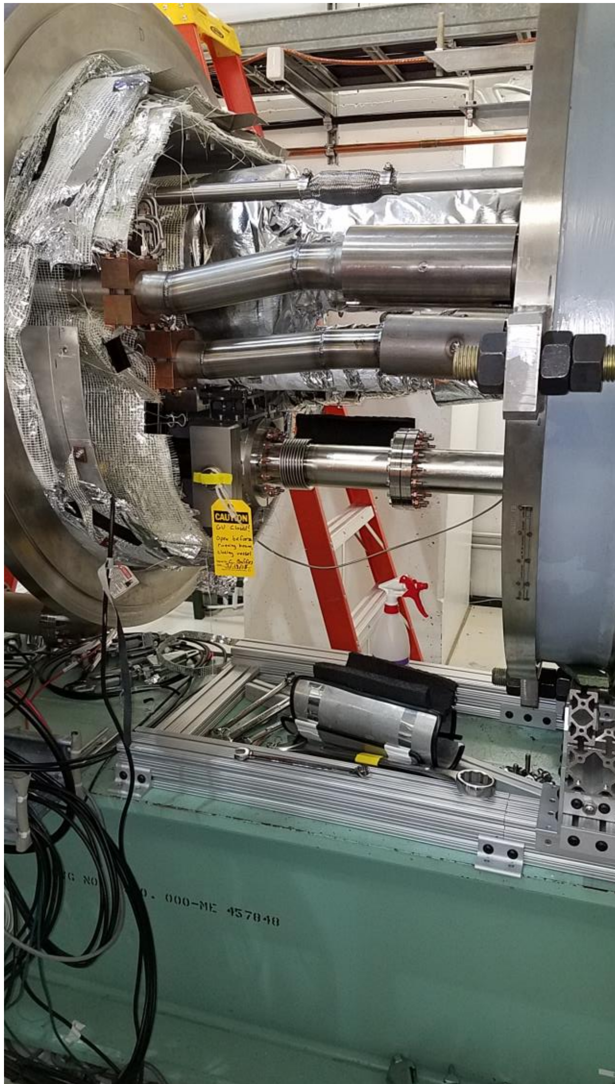
Chapter 6 – Support structures – Lessons learned

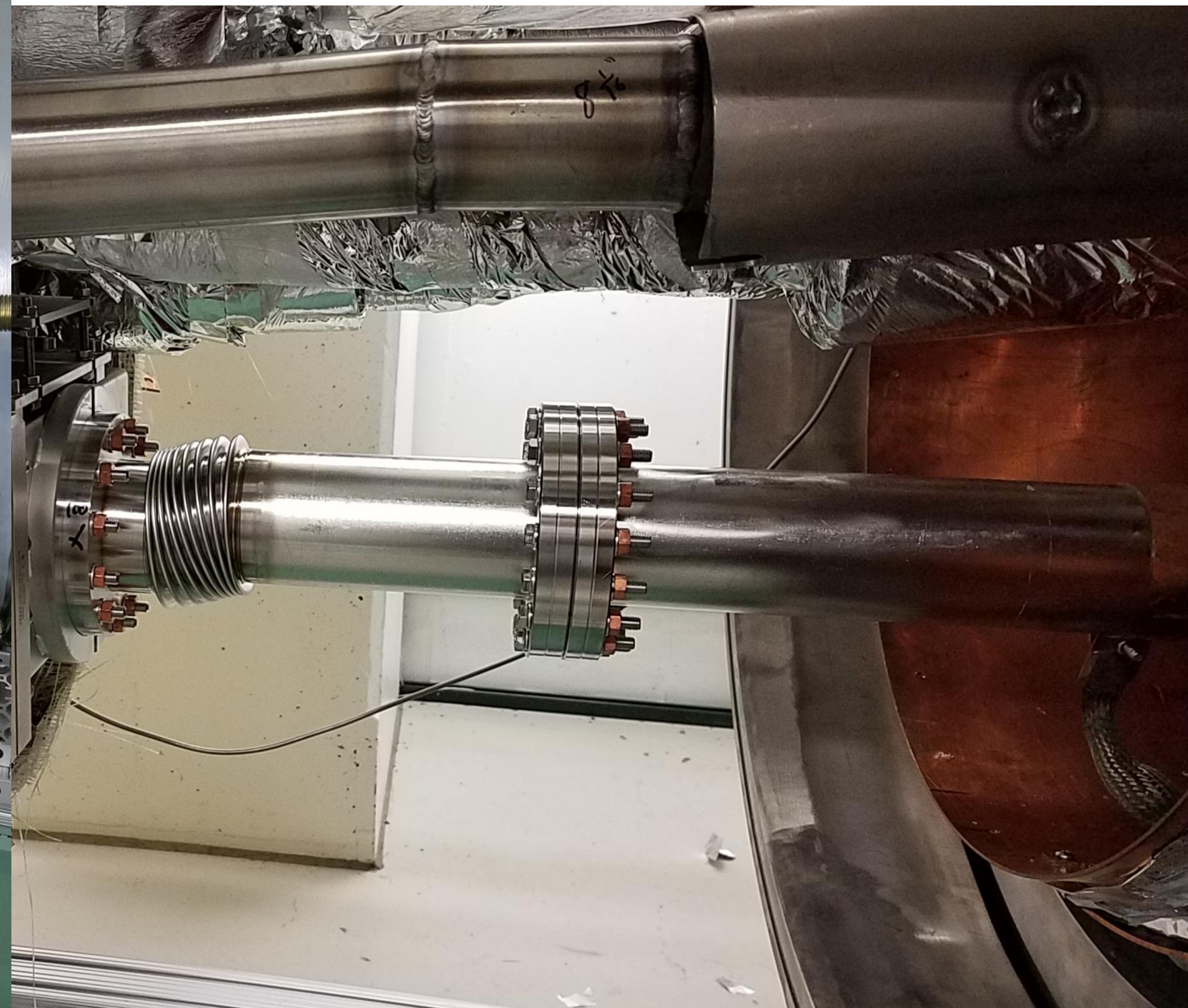


Chapter 6 – Support structures – Lessons learned



Chapter 6 – Support structures – Lessons learned





Chapter 7 – Heat load

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

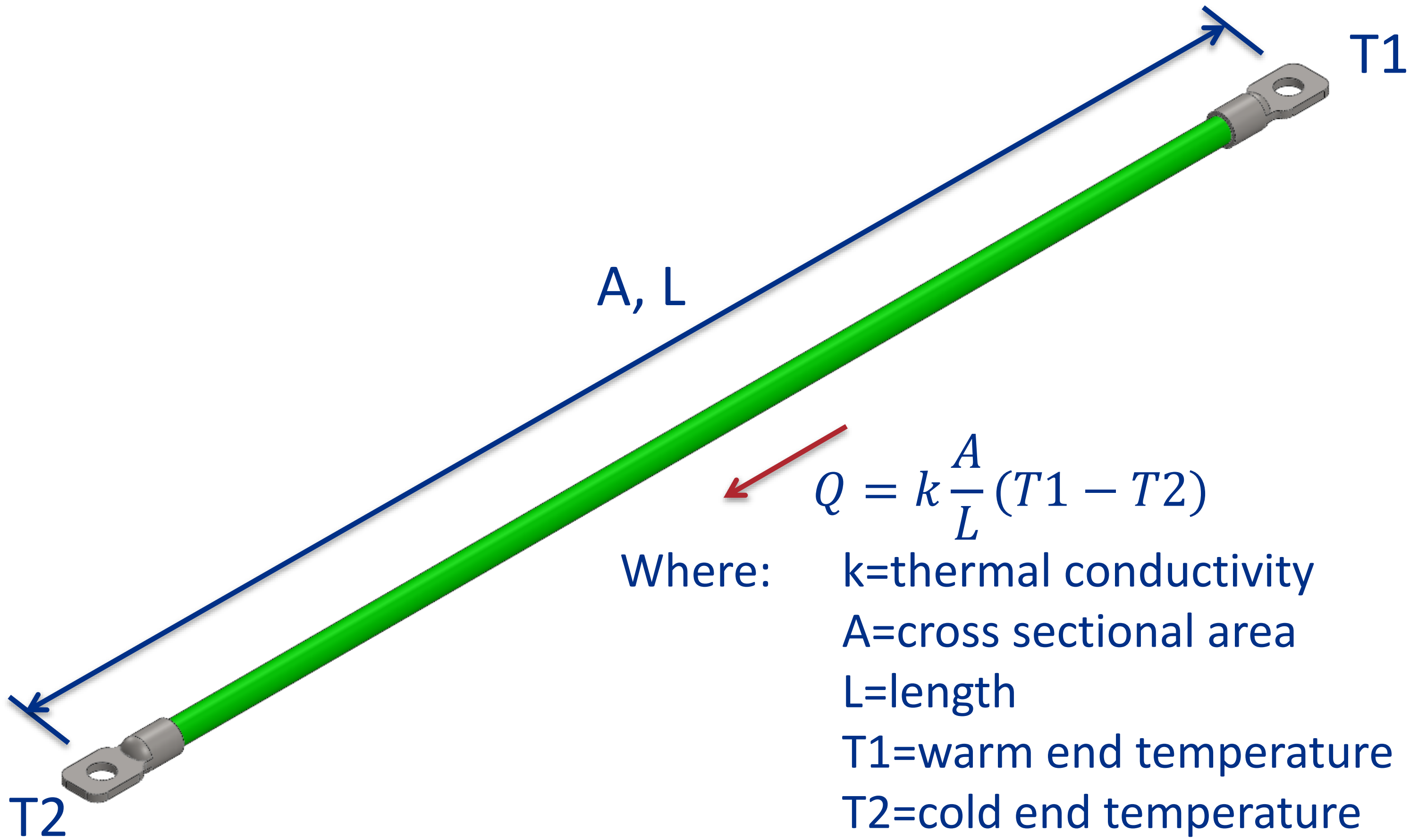
Heat load budget for SSC dipoles

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

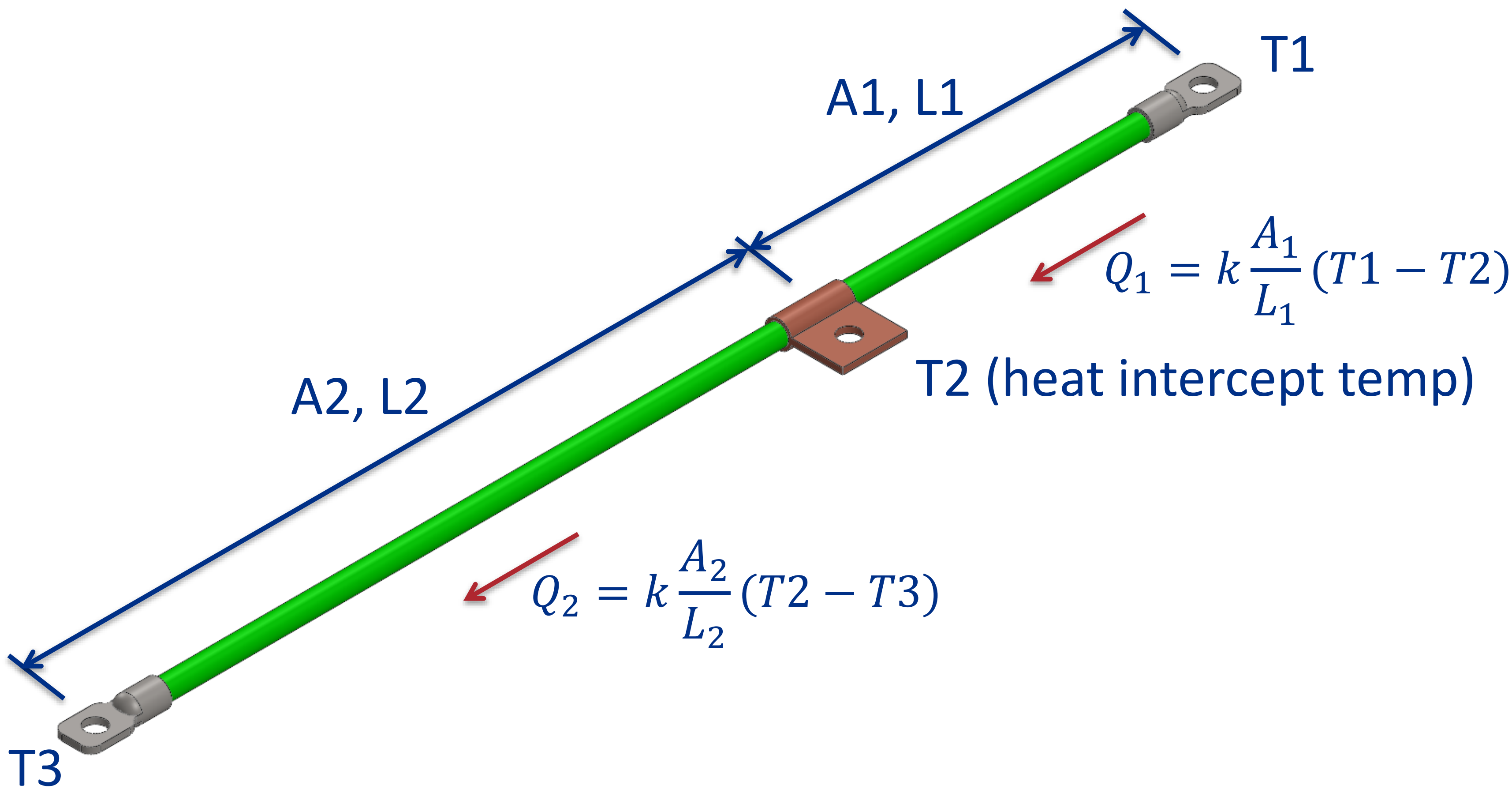
Chapter 7 – Heat load nomenclature



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

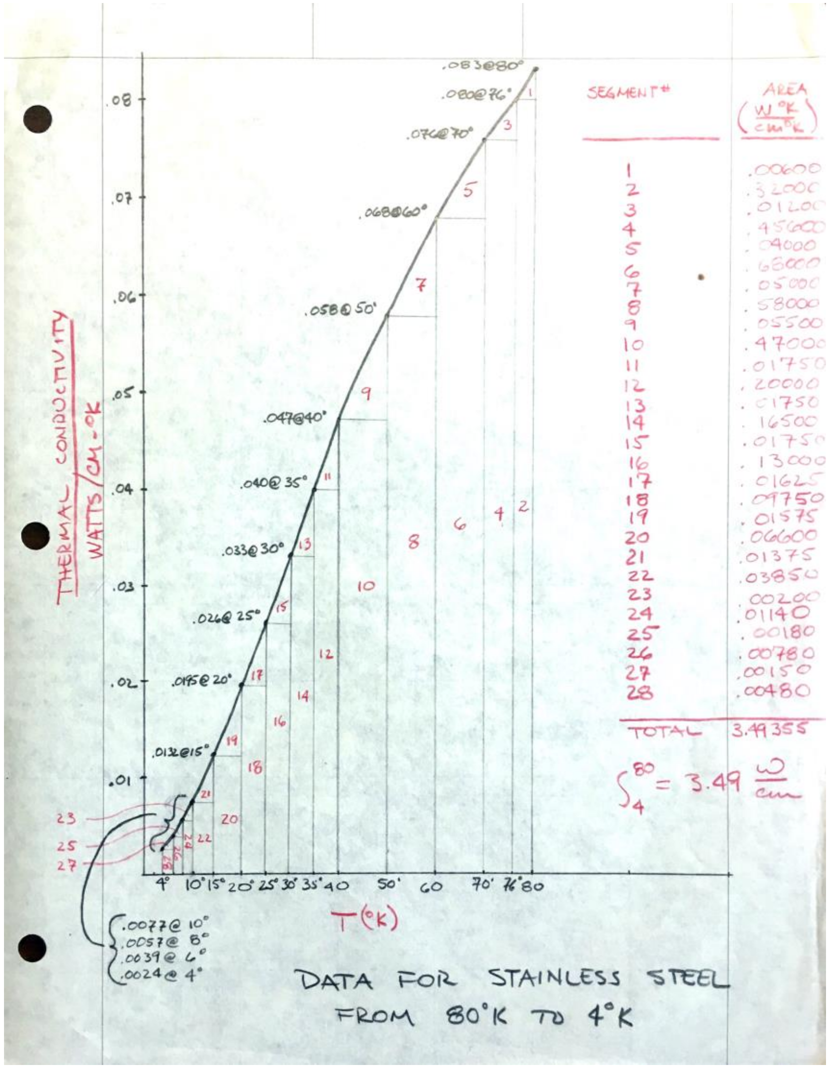
Where:
k=thermal conductivity
A=cross sectional area
L=length
T1=warm end temperature
T2=cold end temperature

Chapter 7 – Heat load nomenclature

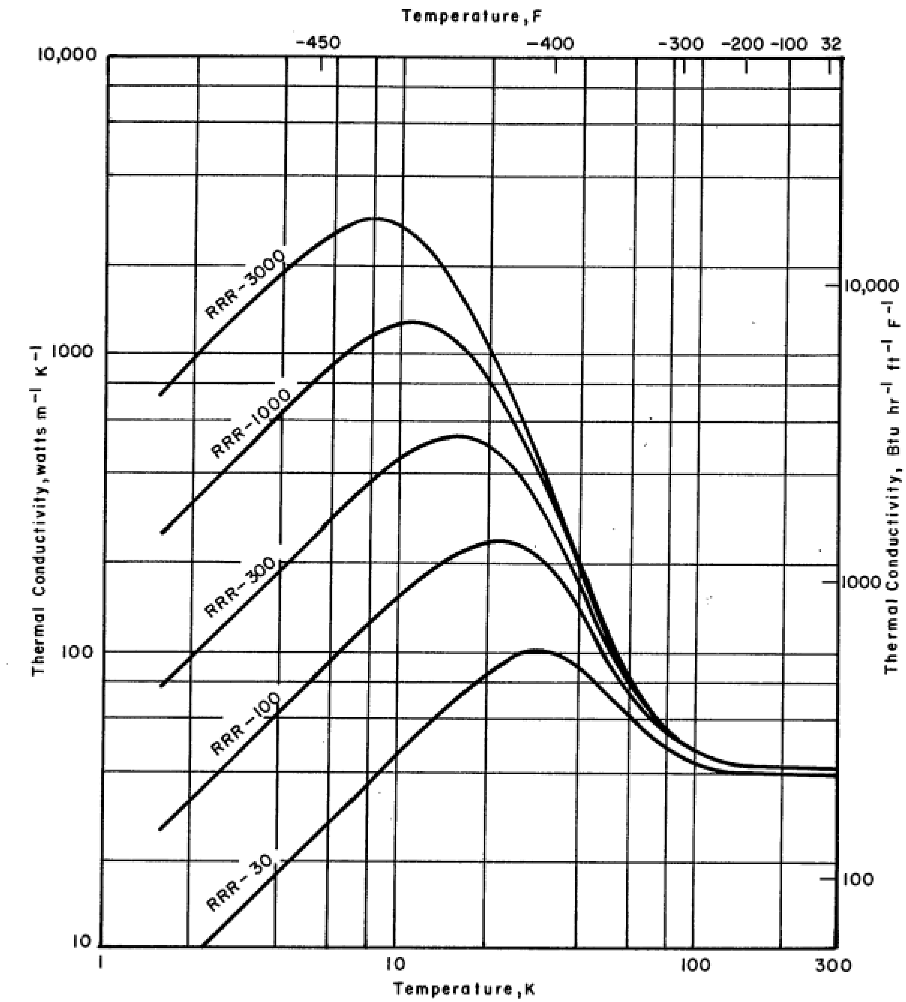


Chapter 7 – Estimating thermal conductivity integrals

For 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.

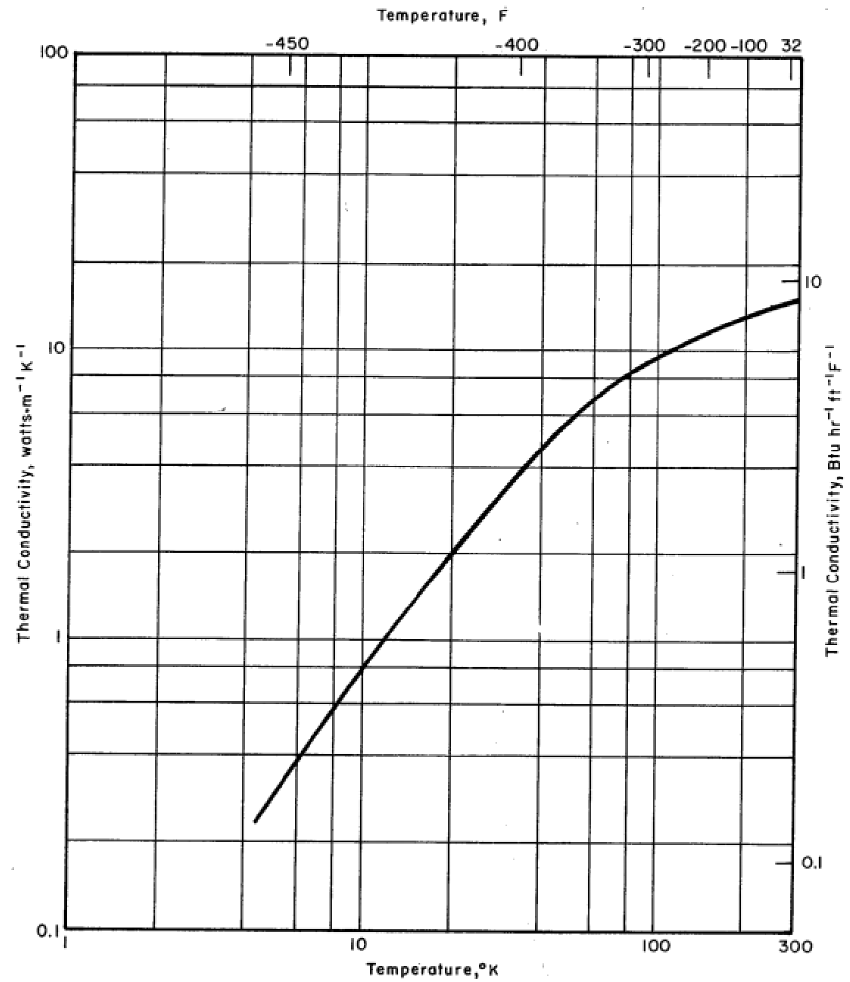


Chapter 7 – Copper thermal conductivity curves



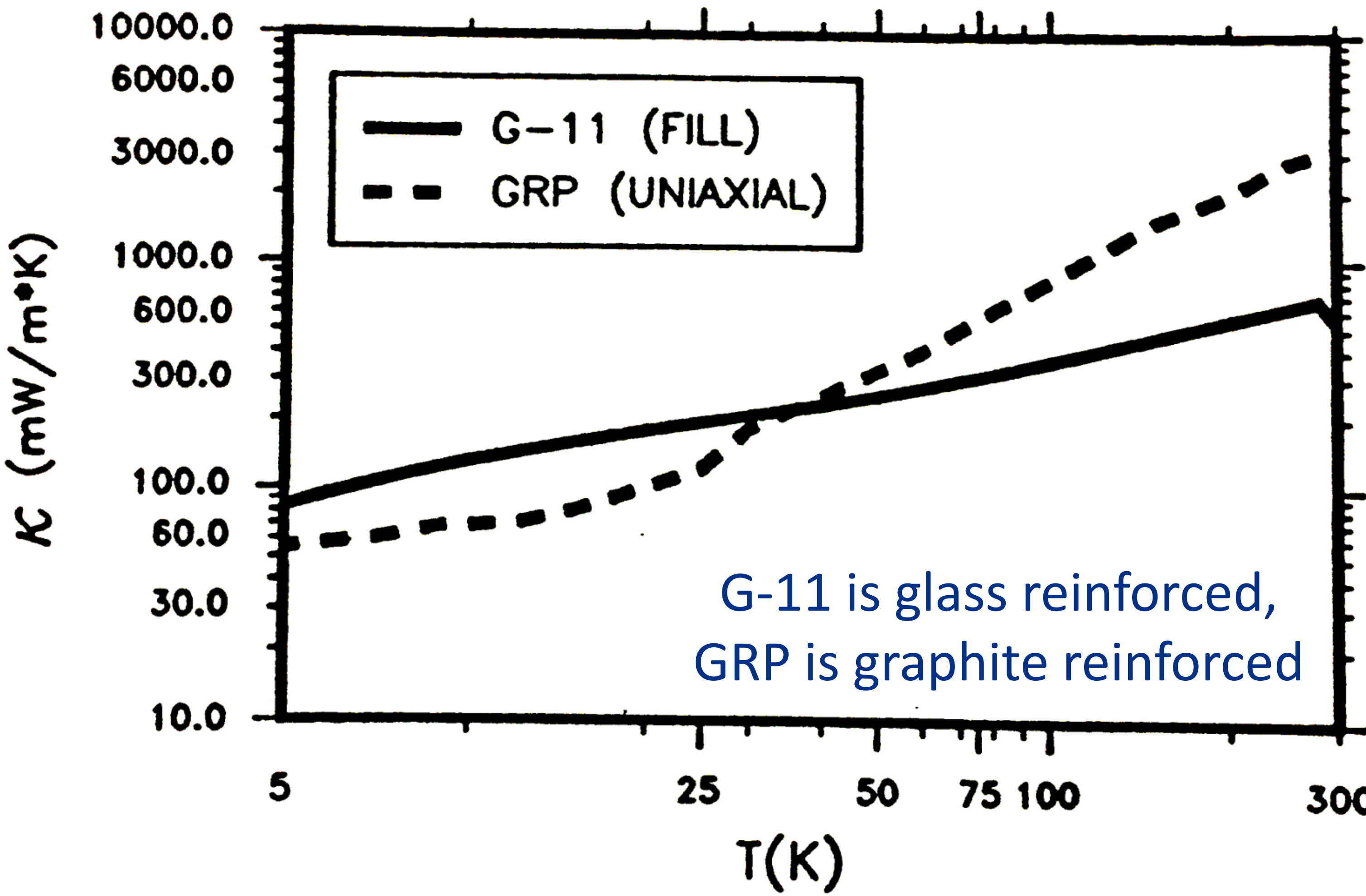
THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR COPPER

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



G-11 is glass reinforced,
GRP is graphite reinforced

Chapter 7 – NIST cryogenic material database

NIST

Material Measurement Laboratory / Applied Chemicals and Materials Division

- ABOUT CRYOGENICS
- MATERIAL PROPERTIES
- FLUID PROPERTIES
- FLOW CALIBRATIONS
- CRYOCOOLERS
- PUBLICATIONS
- SOFTWARE
- LINKS OF INTEREST
- HOME

Index of Material Properties

Properties of solid materials from cryogenic- to room-temperatures

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 (Aramid)
** rev. 10/2012*
Kevlar-49 Composite (Aramid)
**rev 10/2012*
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

Regenerator Materials
These data are presented as a spreadsheet.

https://trc.nist.gov/cryogenics/materials/materialproperties.htm

Chapter 7 – NIST 304 stainless steel page

NIST

Material Measurement Laboratory / Applied Chemicals and Materials Division

ABOUT CRYOGENICS
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Material Properties: 304 Stainless (UNS S30400)

Data Available:

- Thermal Conductivity View plot
- Specific Heat View plot
- Young's Modulus View plot
- Linear Expansion View plot

	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

Curve fit equation of the form:

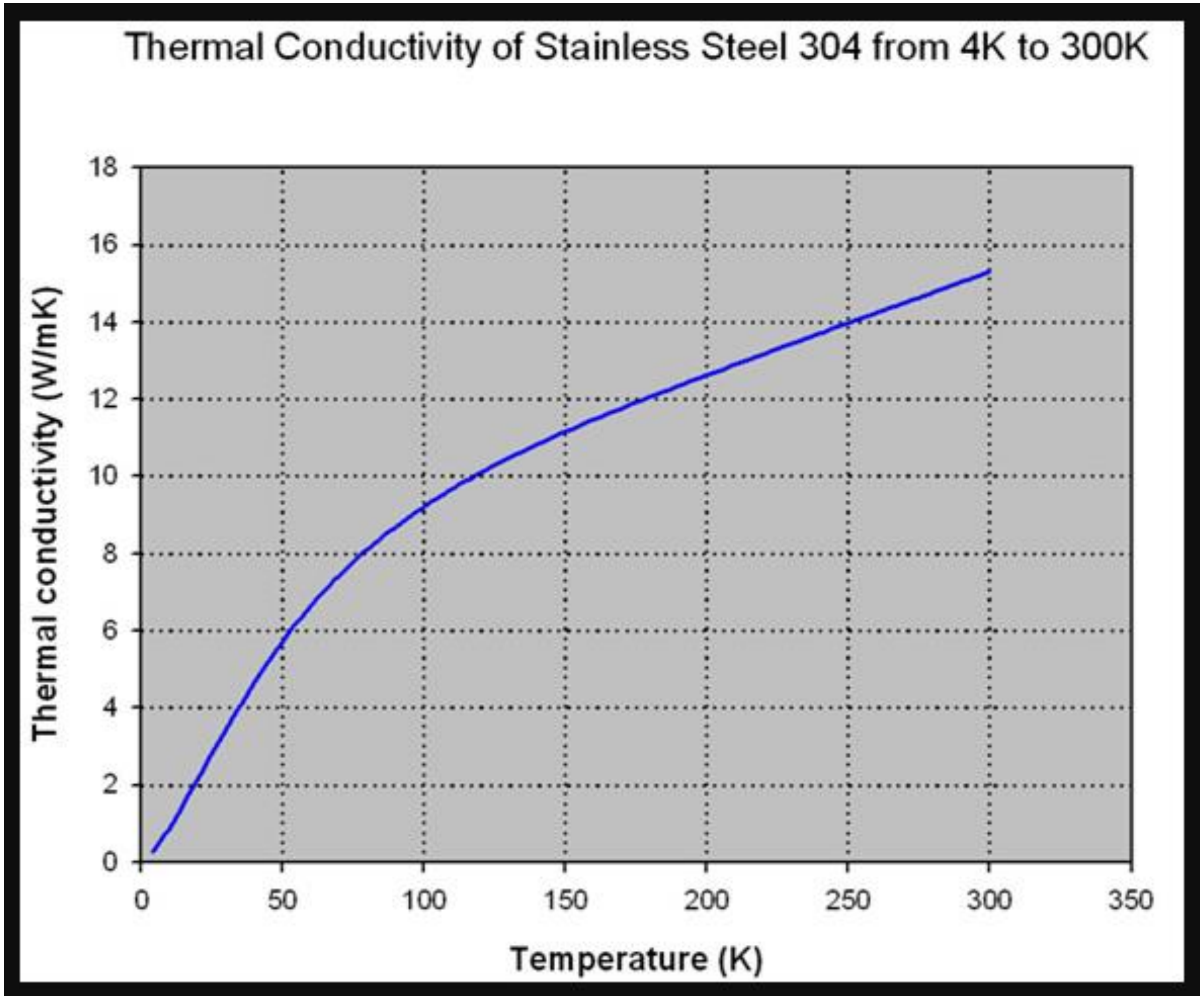
$$\log_{10} y = a+b(\log_{10}T) + c(\log_{10}T)^2 + d(\log_{10}T)^3 + e(\log_{10}T)^4 + f(\log_{10}T)^5 + g(\log_{10}T)^6 + h(\log_{10}T)^7 + i(\log_{10}T)^8$$

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.)

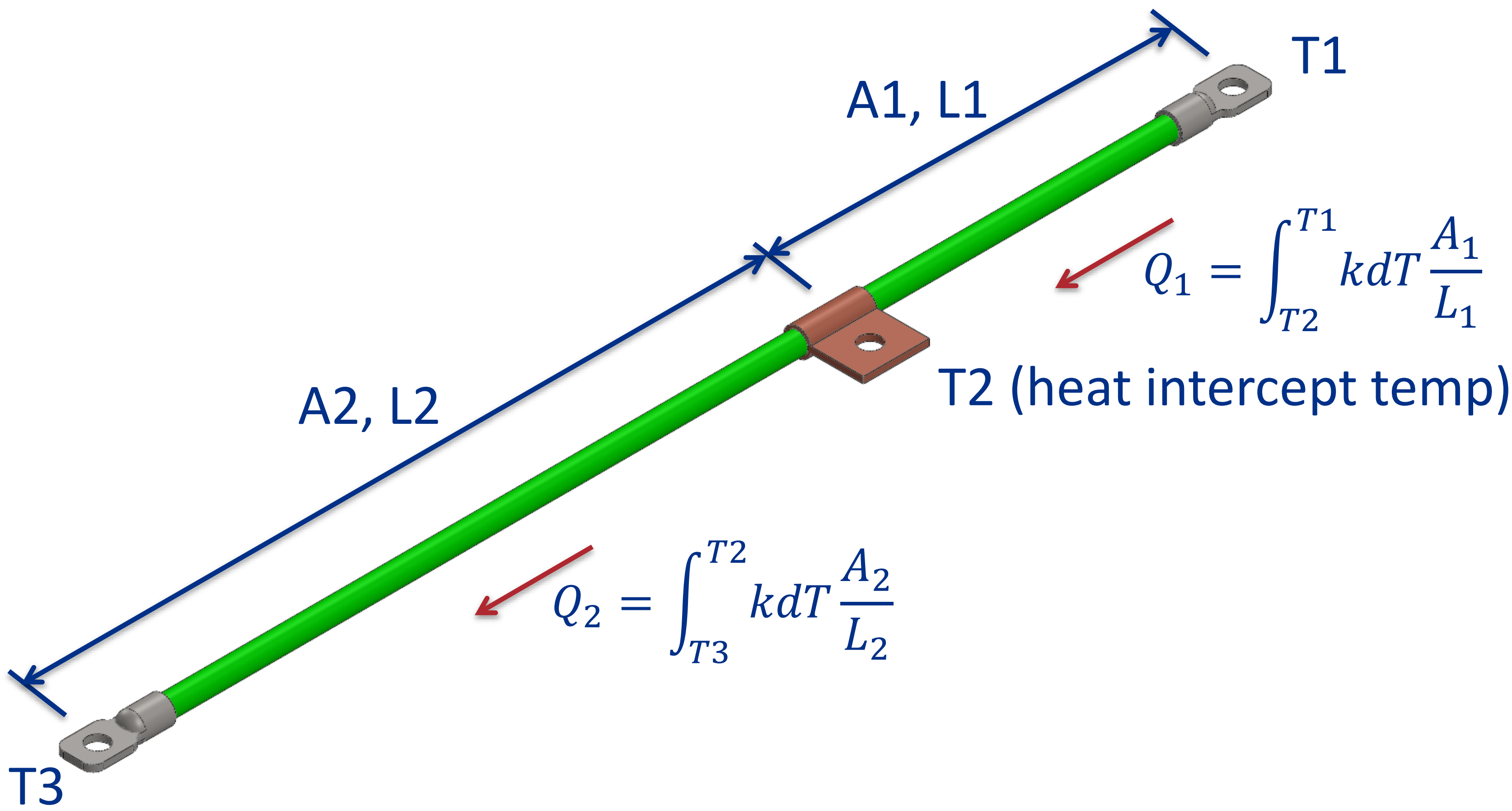
Temp. °K	$\int_{T_o}^{T_L} \lambda \, dT$ watts/cm					
	Hi-Purity Annealed	Coalesced	Elect. T.P.	O.F.H.C.	(Pb) Cu	(Te) Cu
6	166	16.2	8.00	6.1		
8	382	40.2	19.1	14.5	6.3	5
10	636	71.7	33.2	25.2	14.4	11.2
15	1270	173	80.2	61.4	41.4	32.2
20	1790	290	140	110	77.2	60.9
25	2160	408	208	168	120	95.4
30	2410	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)

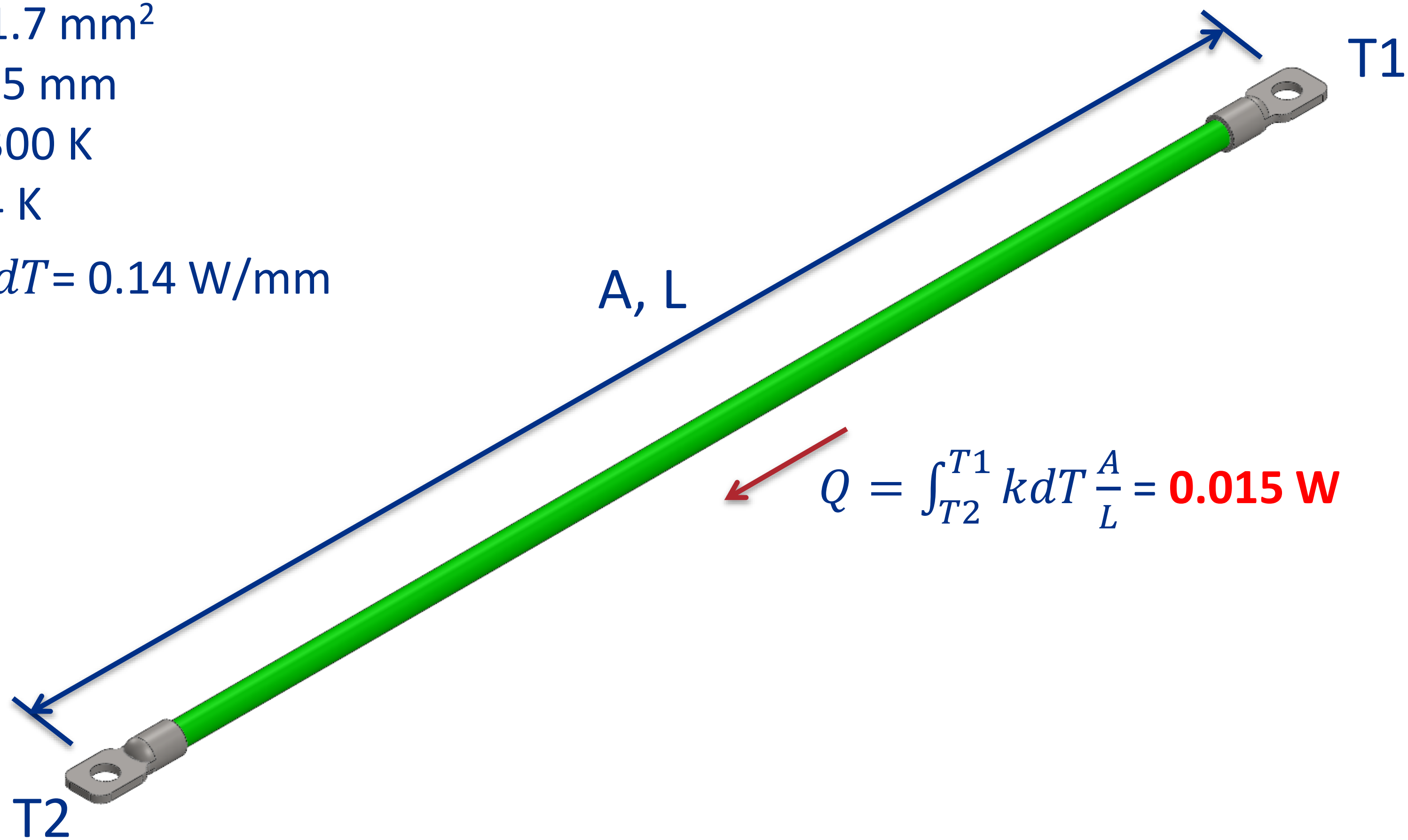


Chapter 7 – Examples

- 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
$\int_{T2}^{T1} k dT$ = 0.14 W/mm



$Q = \int_{T2}^{T1} k dT \frac{A}{L}$ = **0.015 W**

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

$A1 = A2 = 31.7\ mm^2$

$L1 = 92.4\ mm$

$L2 = 192.4\ mm$

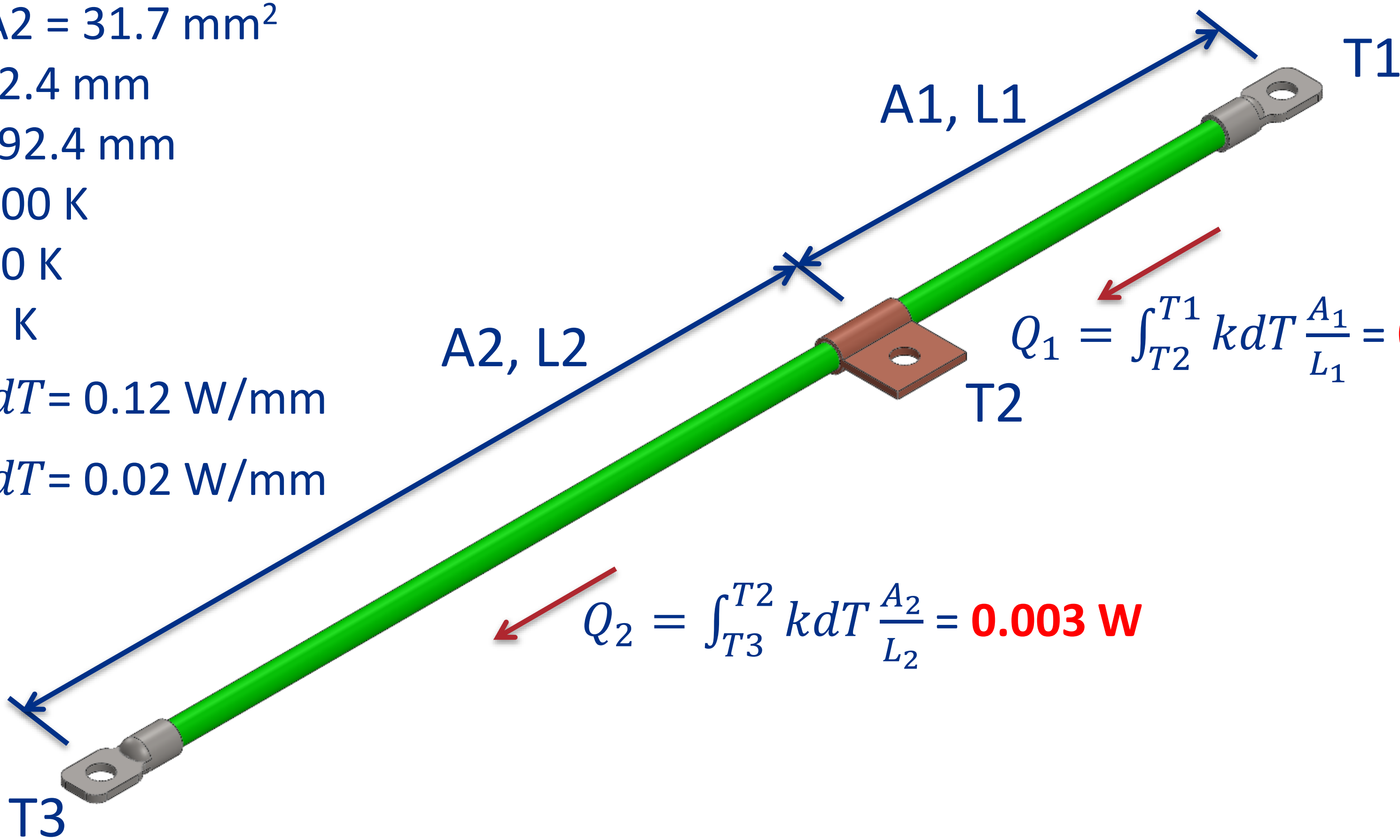
$T1 = 300\ K$

$T2 = 80\ K$

$T3 = 4\ K$

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

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

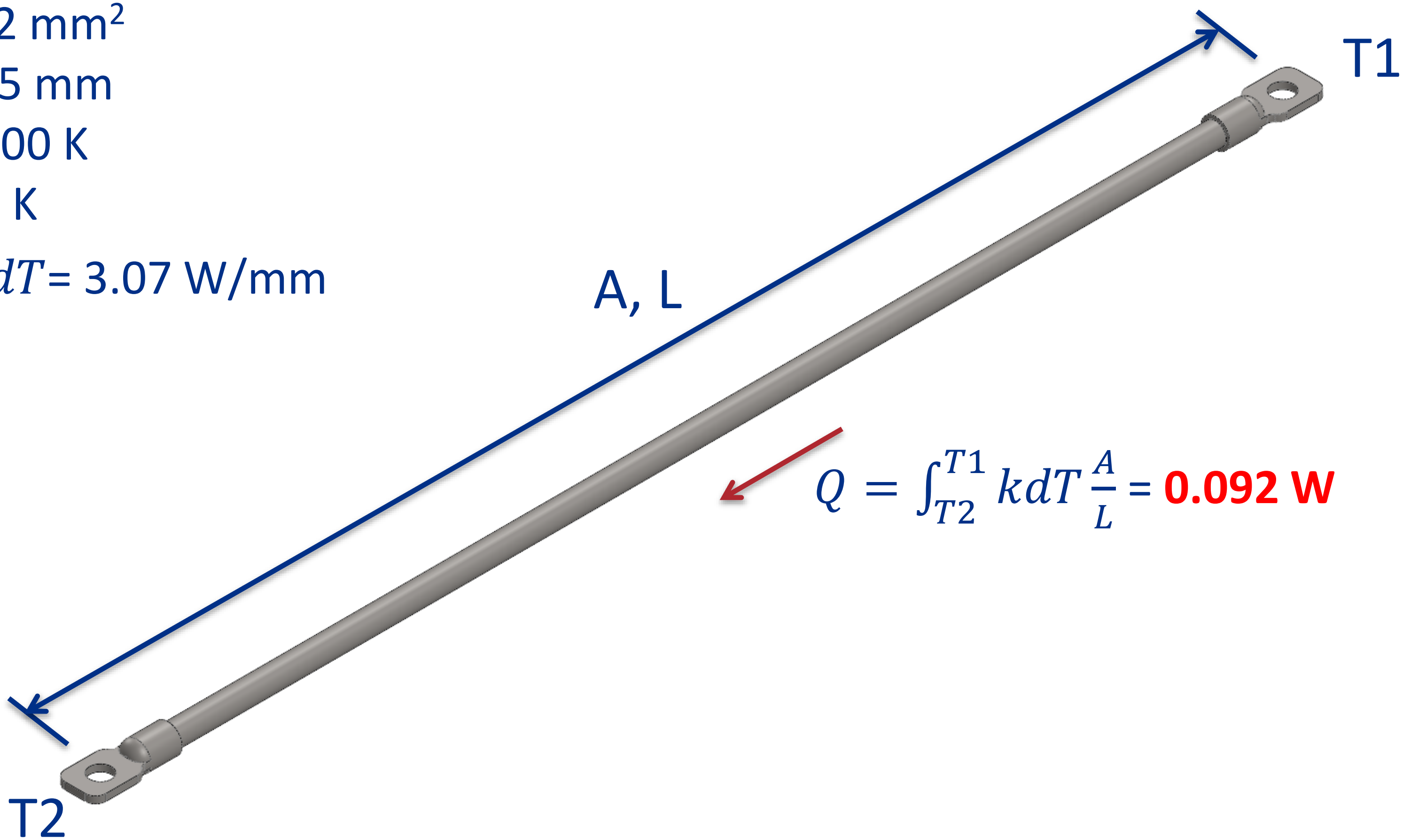


$$Q_1 = \int_{T2}^{T1} k dT \frac{A_1}{L_1} = \mathbf{0.042\ W}$$

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

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

A = 9.2 mm^2
L = 305 mm
T1 = 300 K
T2 = 4 K
$\int_{T2}^{T1} kdT$= 3.07 W/mm



$Q = \int_{T2}^{T1} kdT \frac{A}{L}$ = **0.092 W**

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

$A1 = A2 = 9.2\ mm^2$

$L1 = 92.4\ mm$

$L2 = 192.4\ mm$

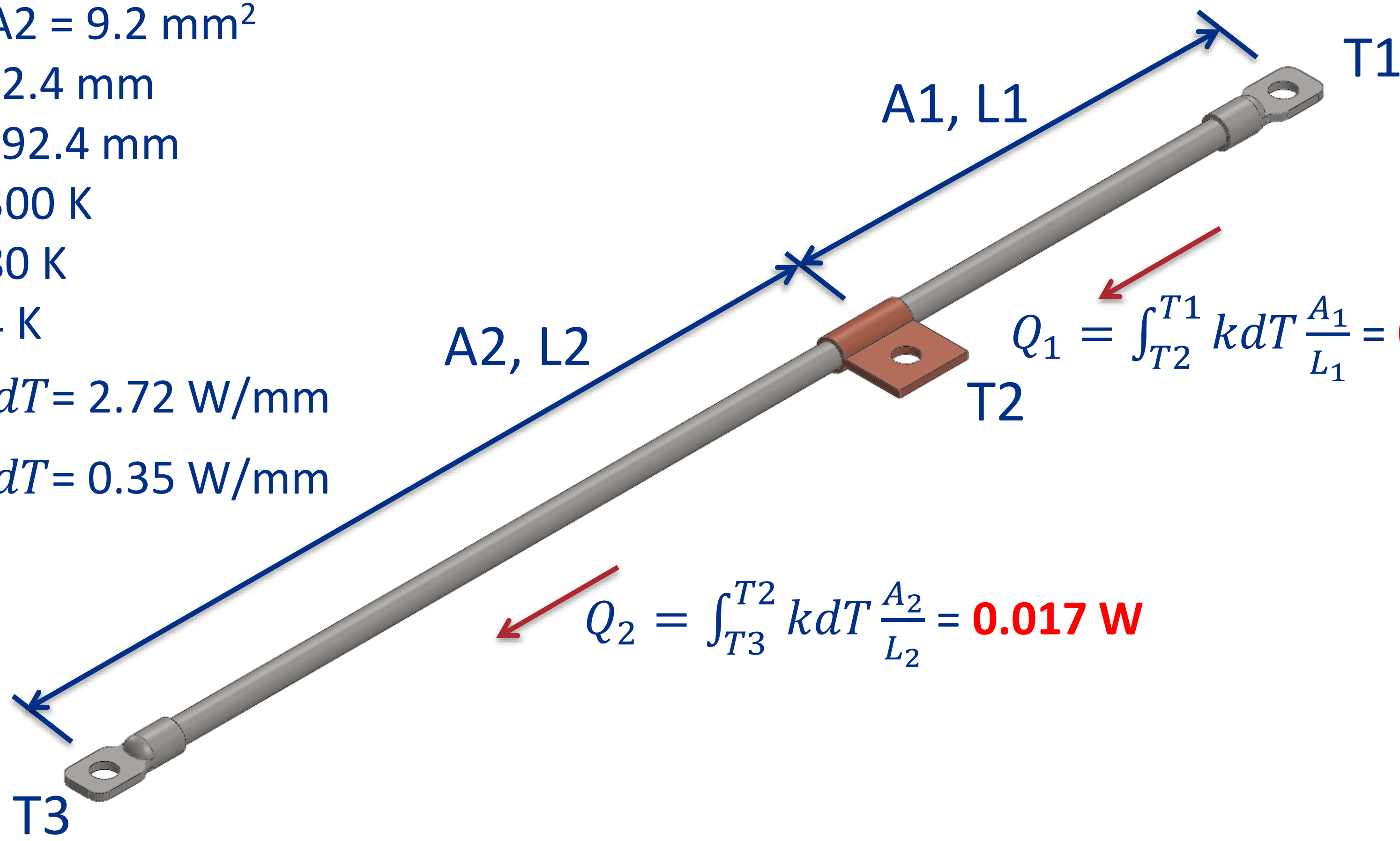
$T1 = 300\ K$

$T2 = 80\ K$

$T3 = 4\ K$

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

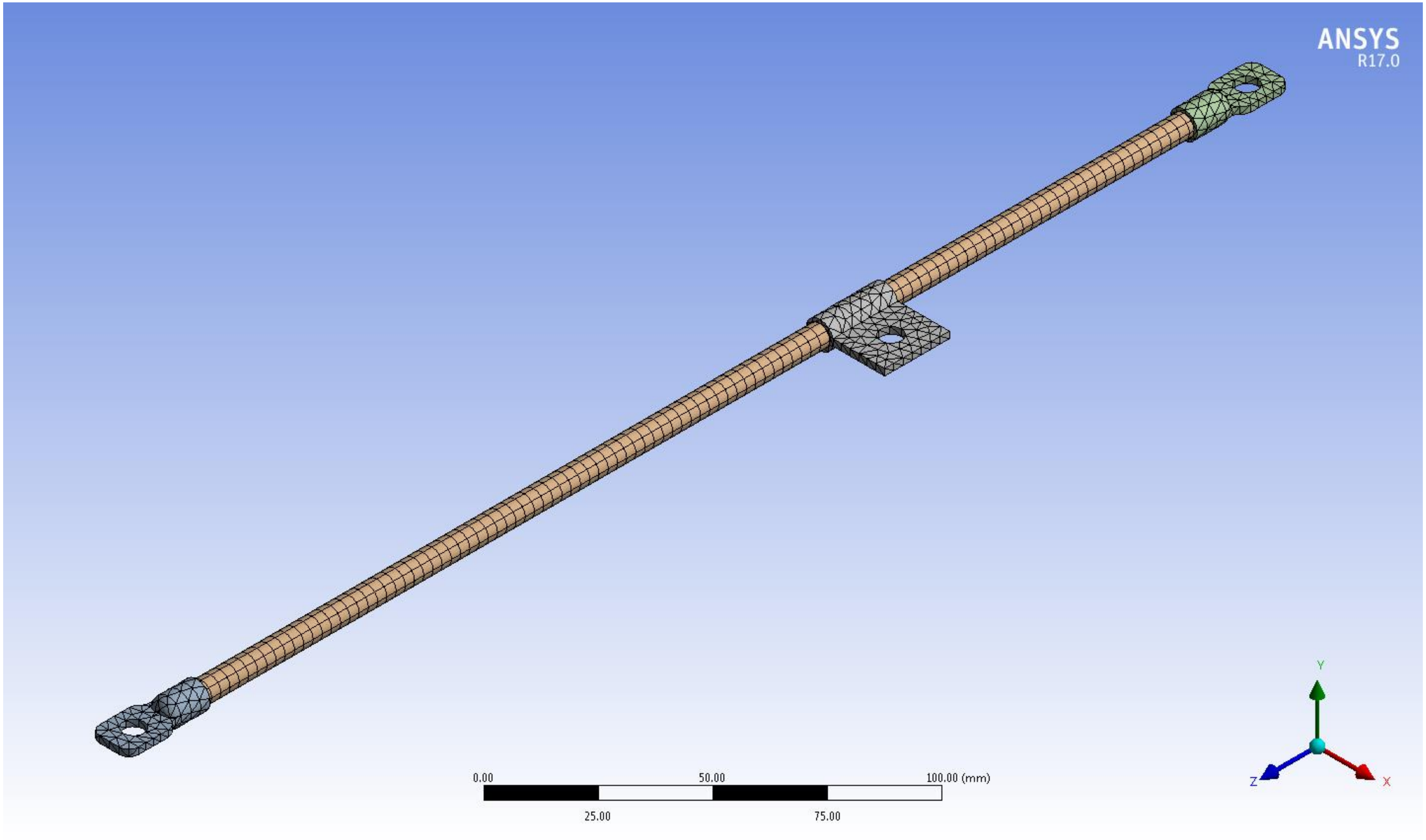
$\int_{T3}^{T2} kdT = 0.35\ W/mm$



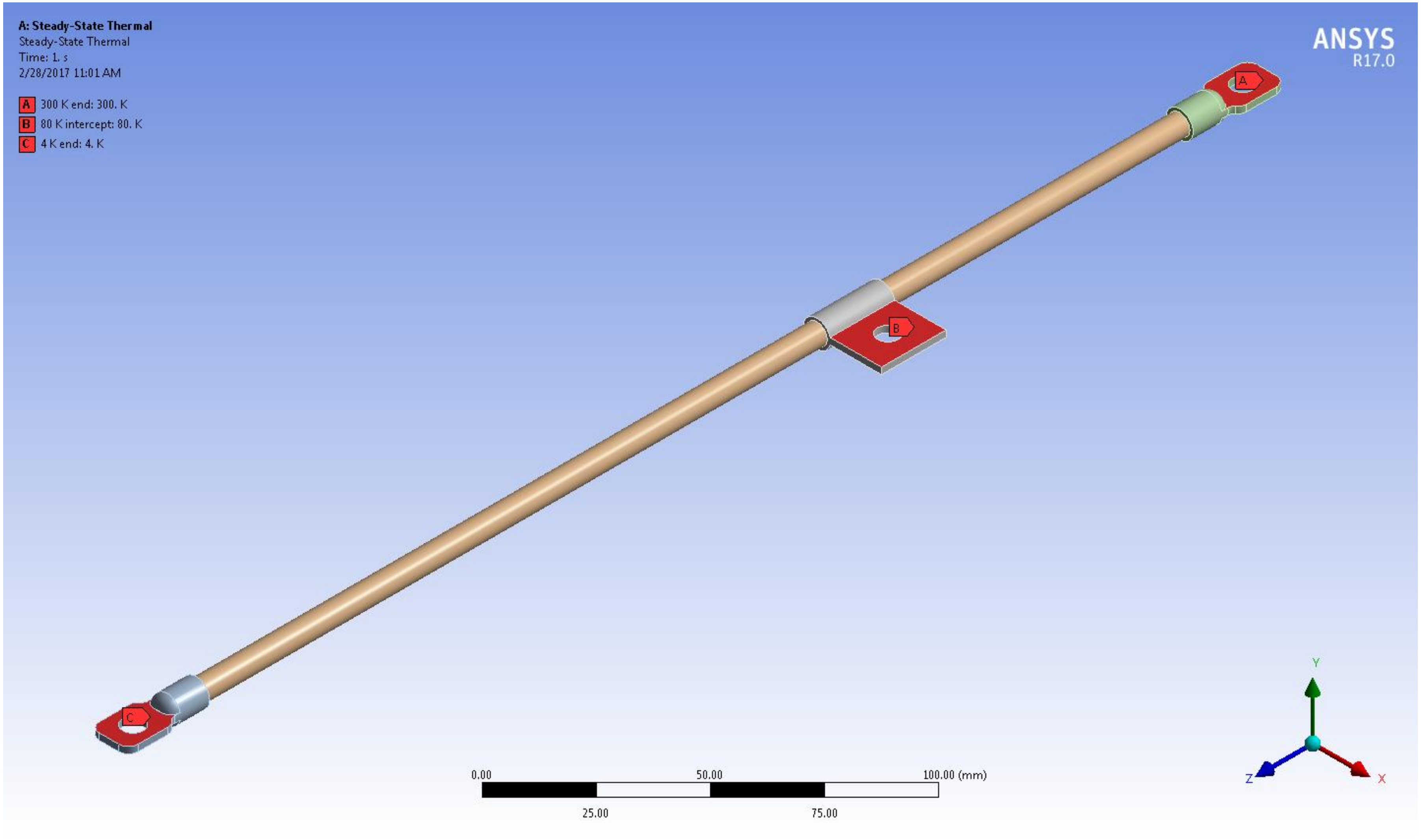
$Q_1 = \int_{T2}^{T1} kdT \frac{A_1}{L_1}$ = **0.270 W**

$Q_2 = \int_{T3}^{T2} kdT \frac{A_2}{L_2}$ = **0.017 W**

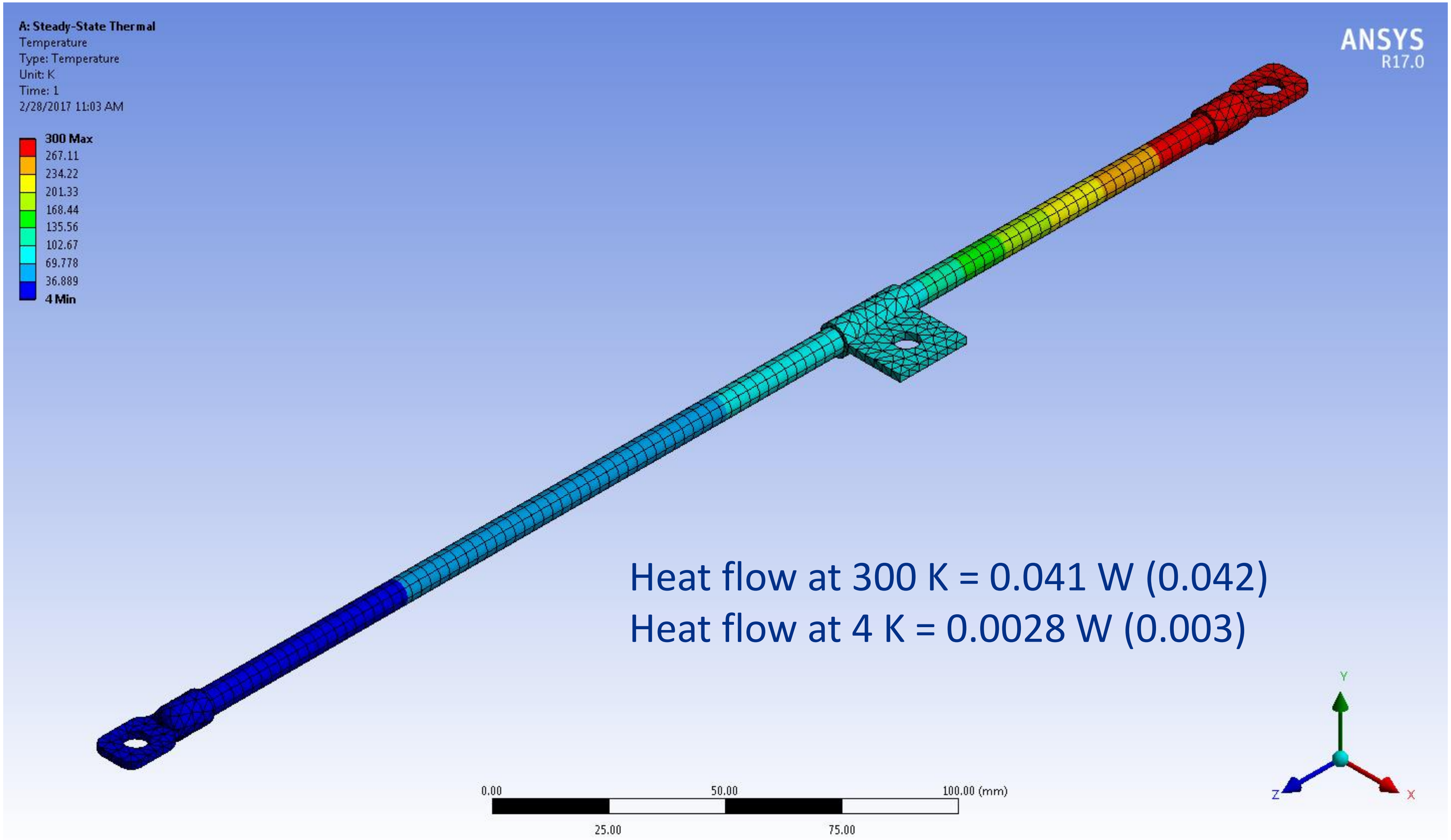
Chapter 7 – Example 1b: Solid G-11 rod, 80 K intercept – FE solution



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



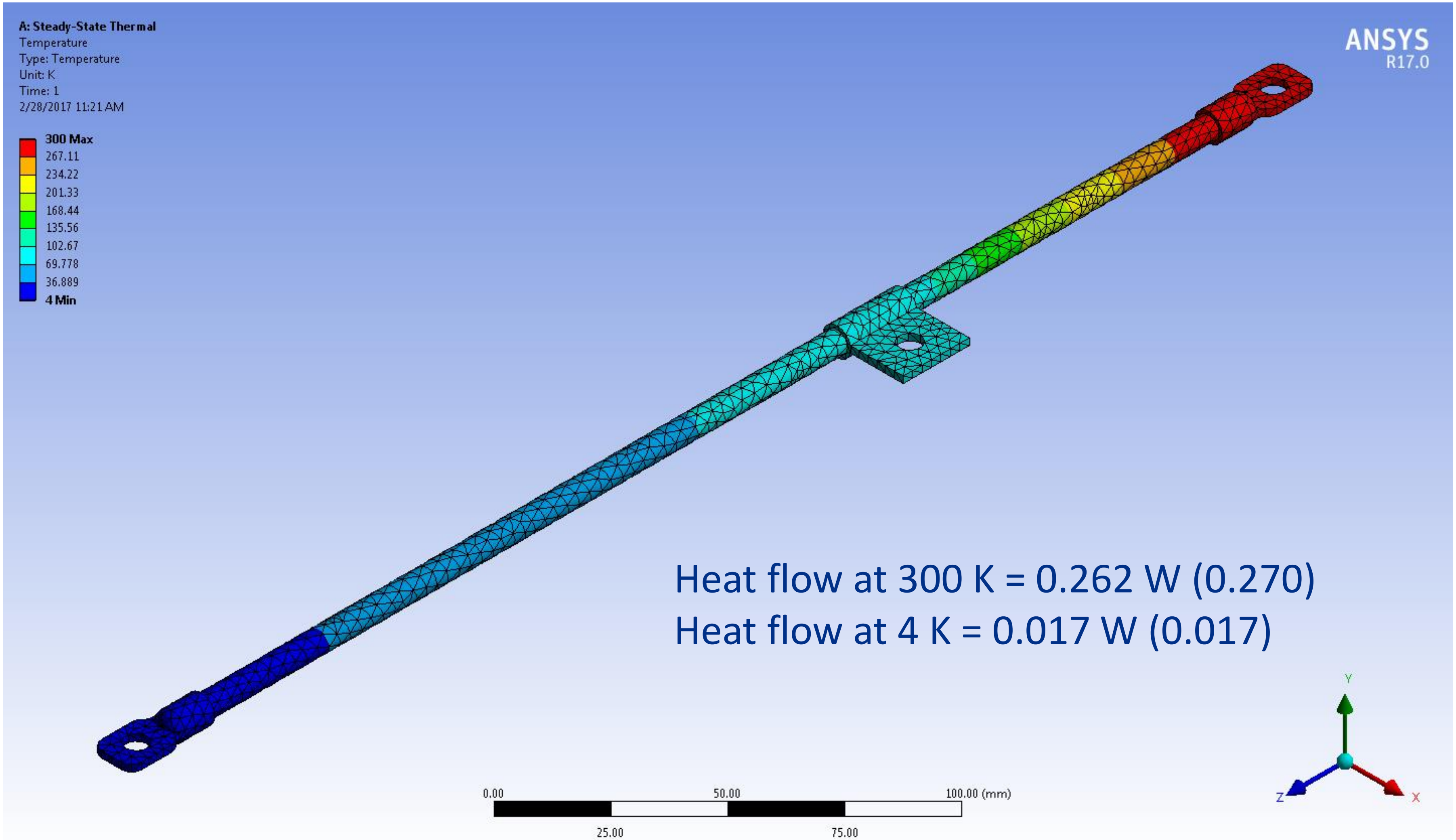
Chapter 7 – Example 1b: Solid G-11 rod, 80 K intercept – FE solution



Heat flow at 300 K = 0.041 W (0.042)

Heat flow at 4 K = 0.0028 W (0.003)

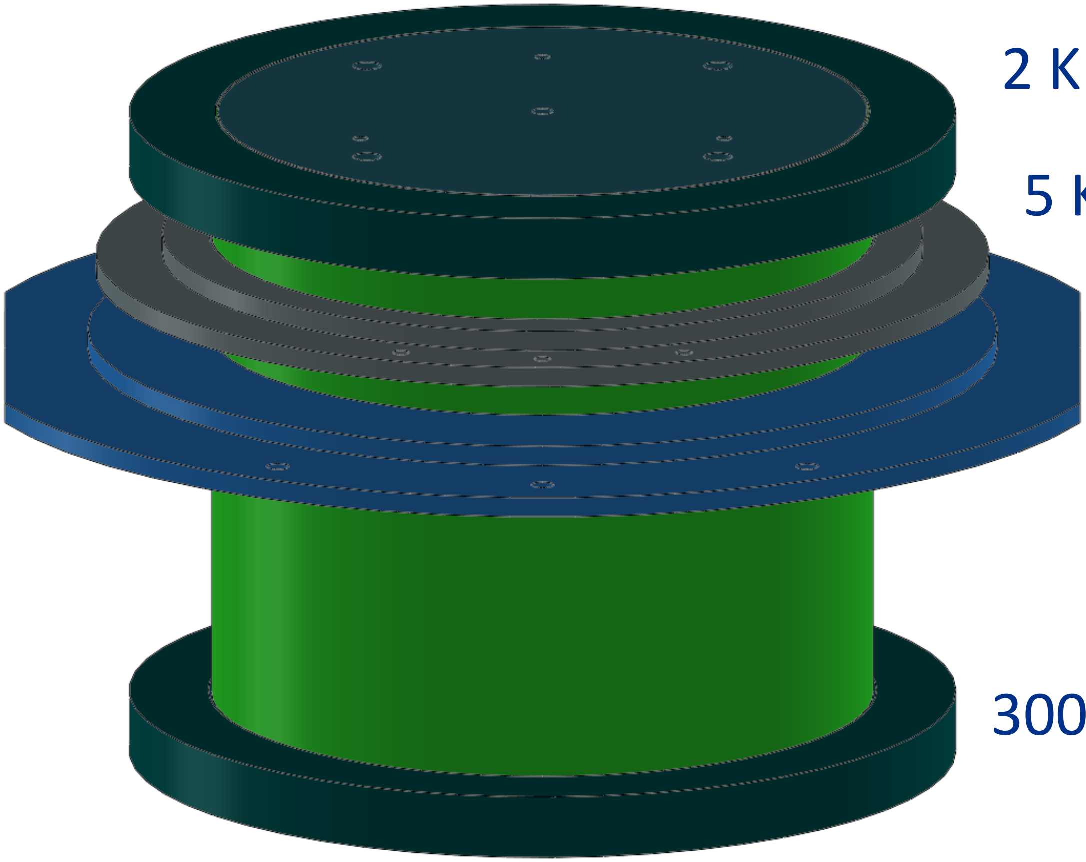
Chapter 7 – Example 2b: Hollow stainless rod, 80 K intercept – FE solution



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

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

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

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

T_t is at the top of the support where it connects to the cold mass

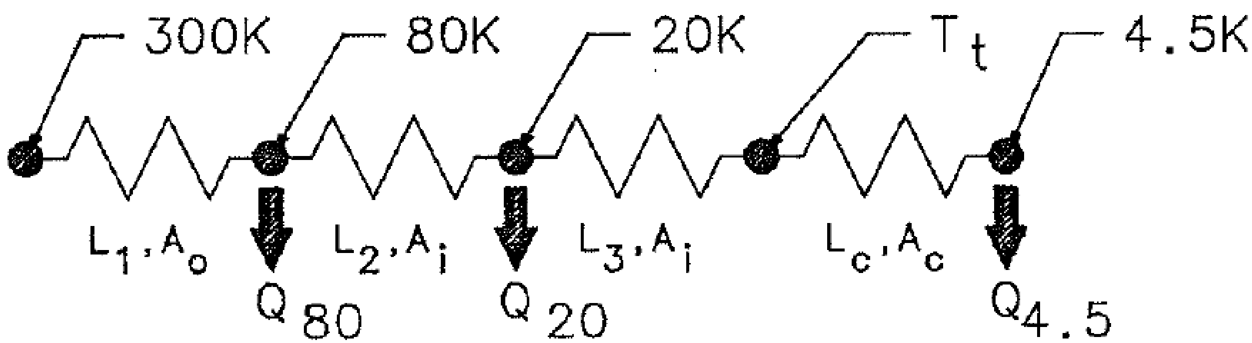
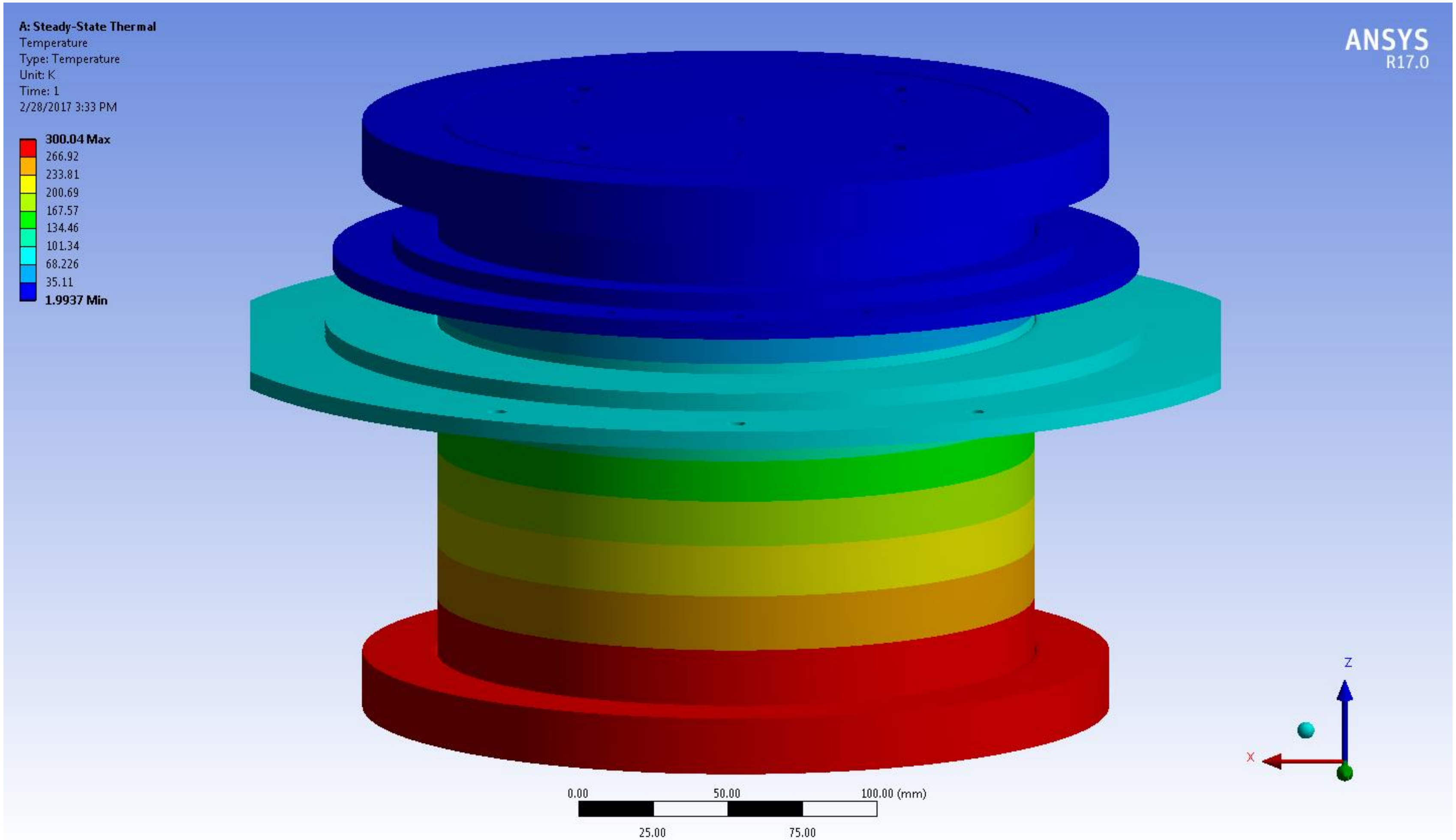


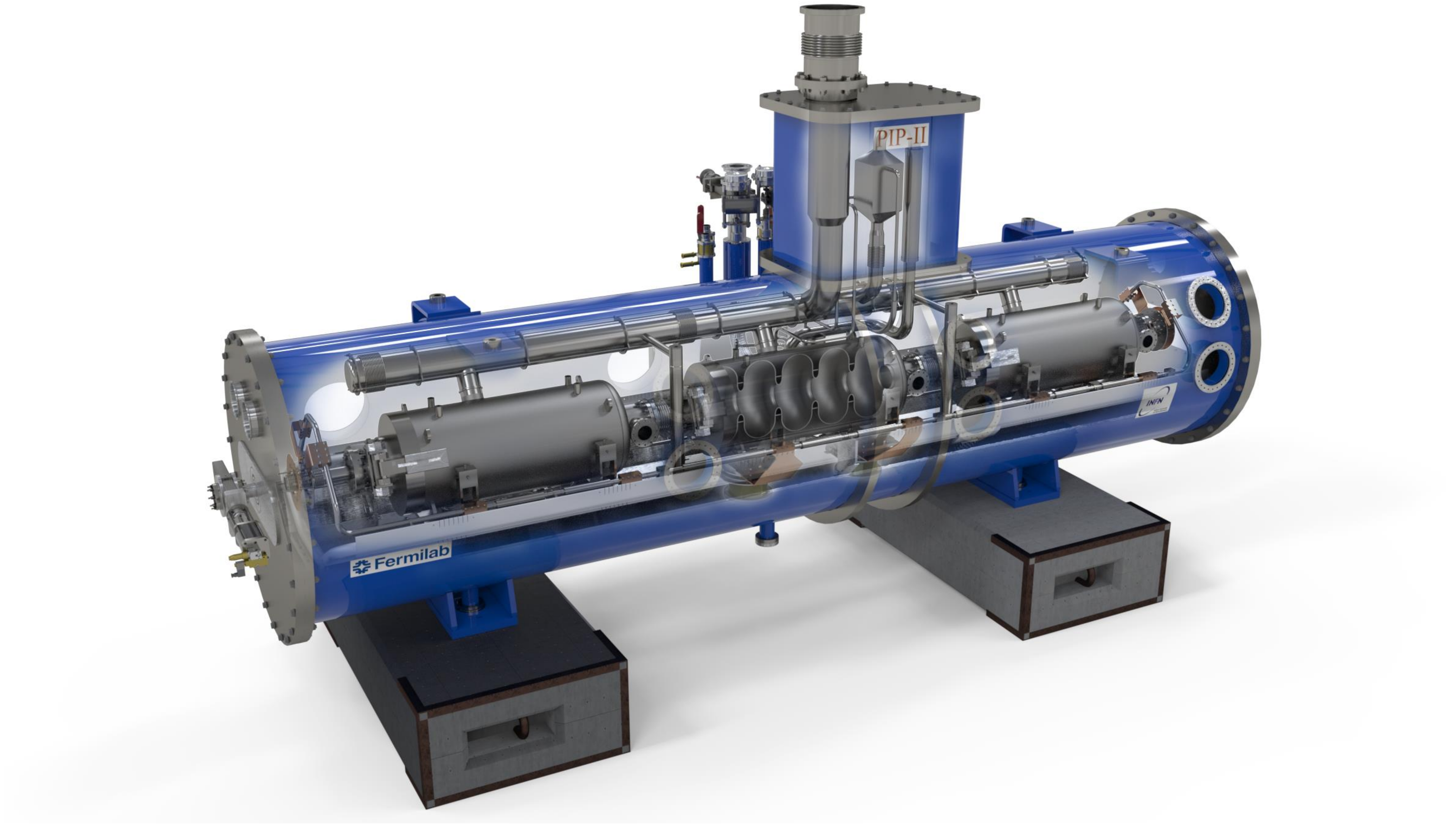
Figure 5. Thermal Analysis Notation

Chapter 7 – Support post example

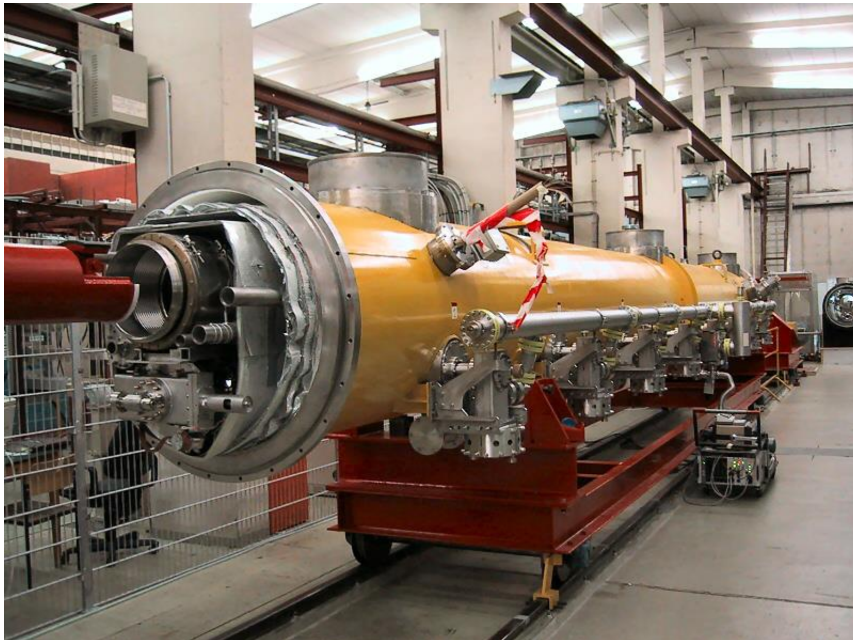


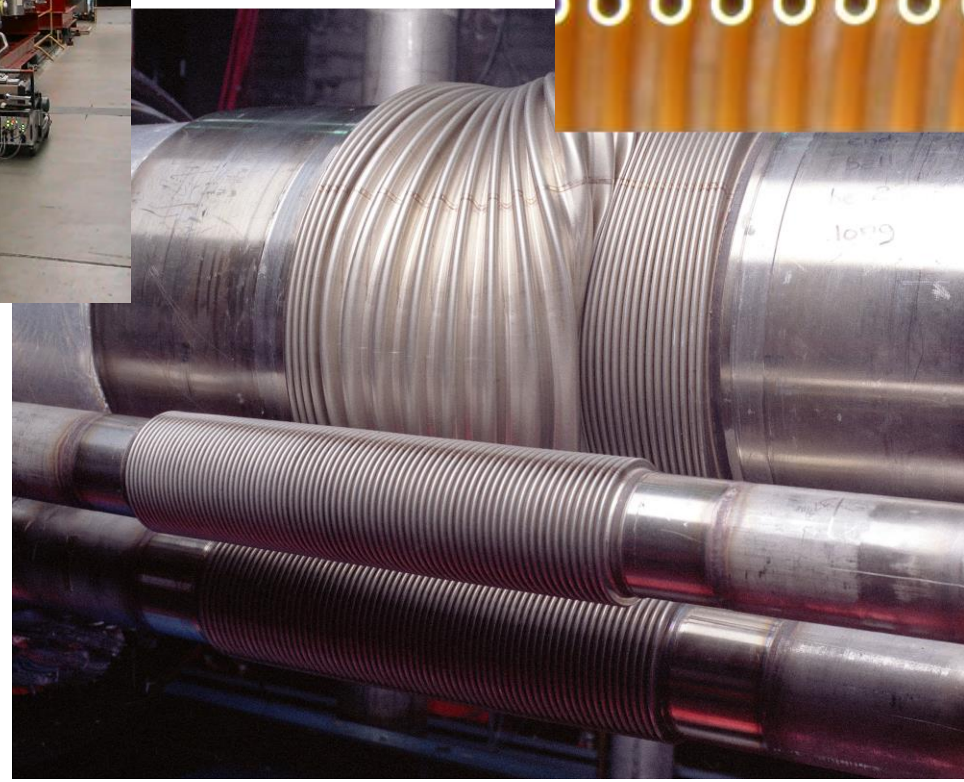
Q (300 K-80 K): 0.412 W (Ansys 0.3 W)
Q (80 K-5 K): 1.806 W (Ansys 1.5 W)
Q (5 K-2 K): 0.019 W (Ansys 0.2 W)

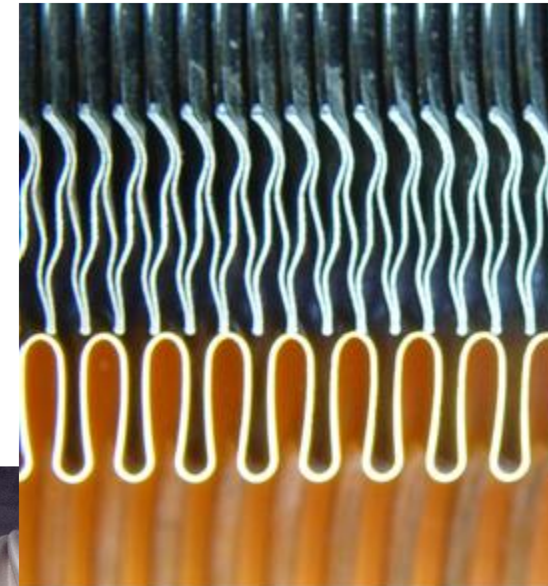
End of session 1…Homework slides at the end…



Chapter 8 – Bellows and Interconnects

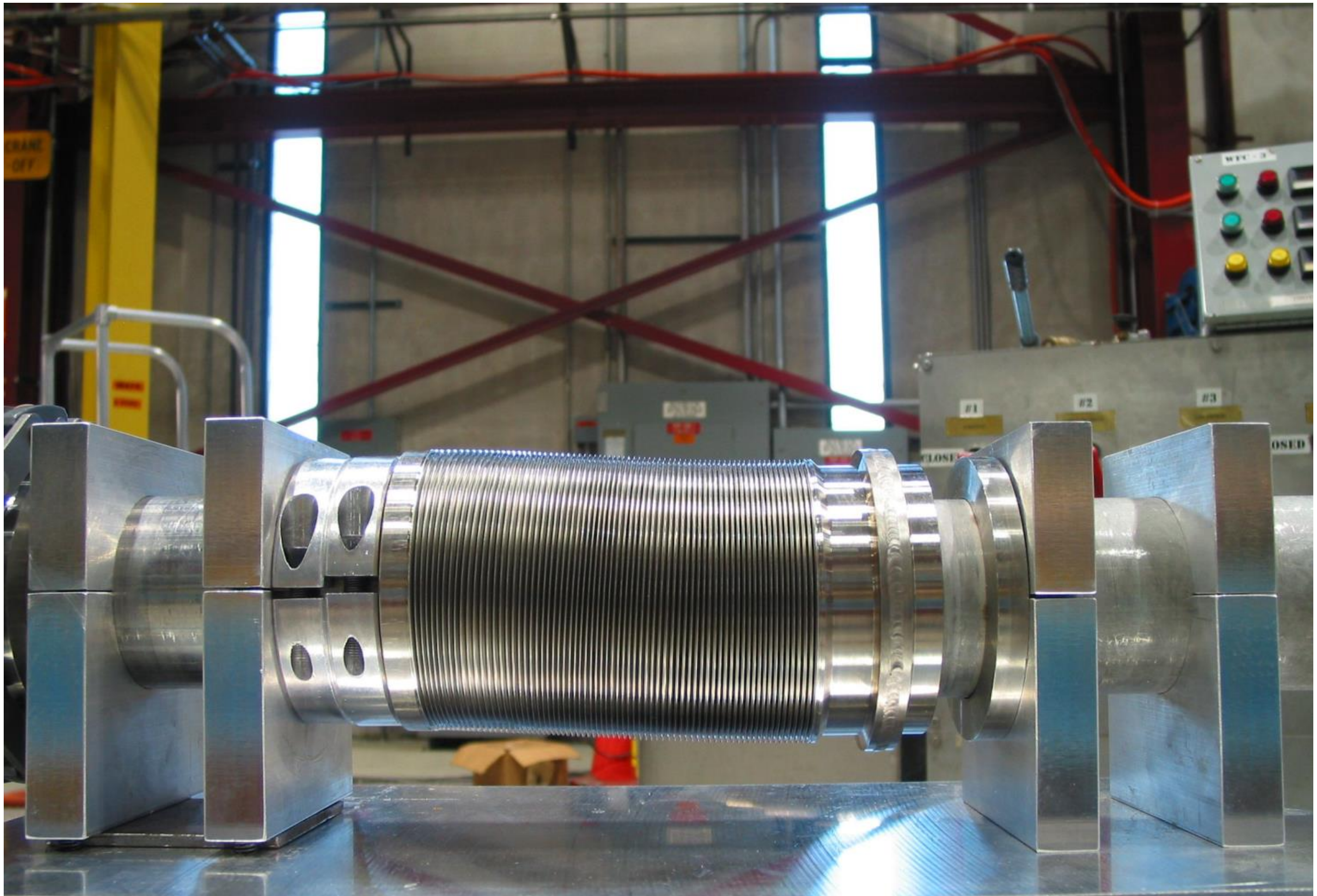






Chapter 8 – Bellows and Interconnects

Chapter 8 – Bellows and Interconnects



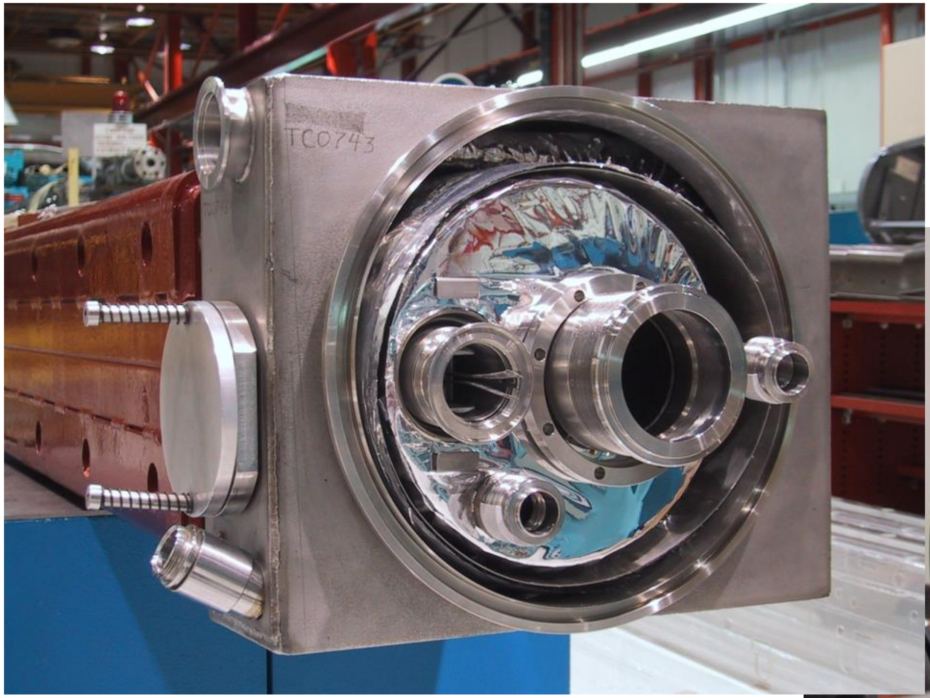
LHC edge-welded bellows being tested

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).

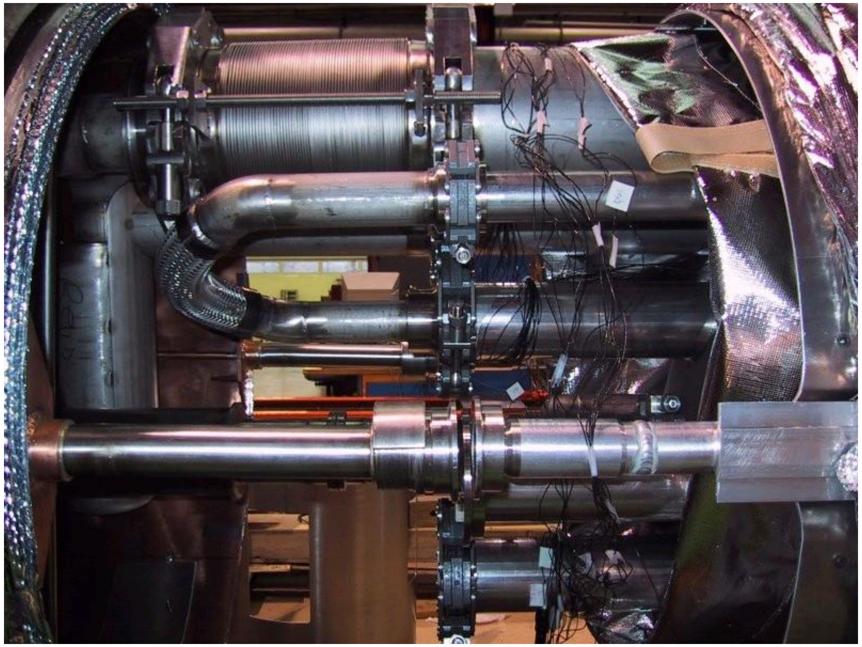
Chapter 8 – Bellows and Interconnects

Tevatron dipole interconnects

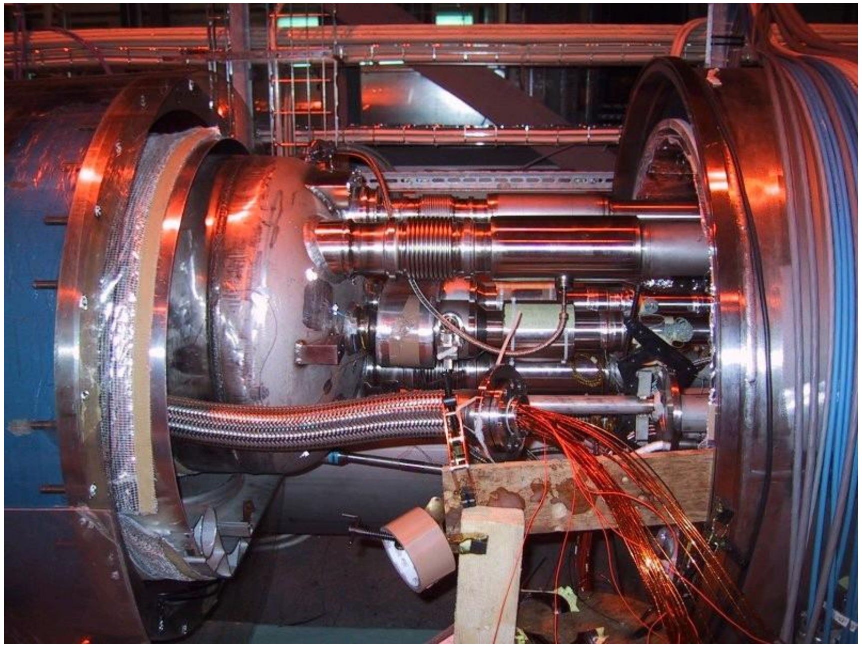


Chapter 8 – Bellows and Interconnects

LHC IRQ to test stand interconnect



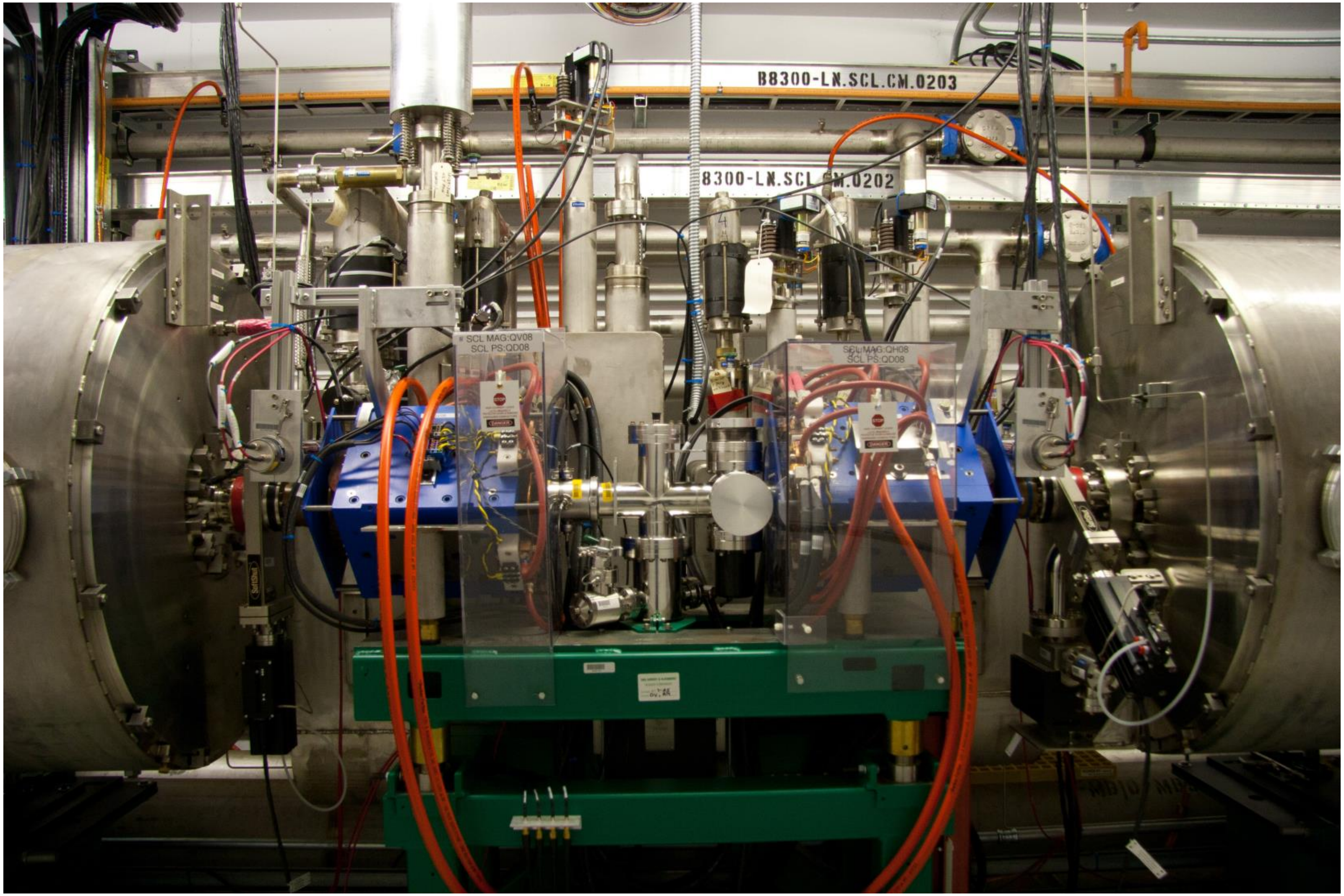
LHC dipole interconnect



Chapter 8 – Bellows and Interconnects

- Magnet cryostat and SRF cryomodule interconnects contain 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 through transfer lines, bayonet connections, etc.

Chapter 8 – Bellows and Interconnects



Chapter 8 – Bellows instability

Chapter 8 – Bellows instability

Chapter 8 – Bellows instability

Bellows Instability Analysis
T. Nicol - Fermilab - November 2018

Run analysis

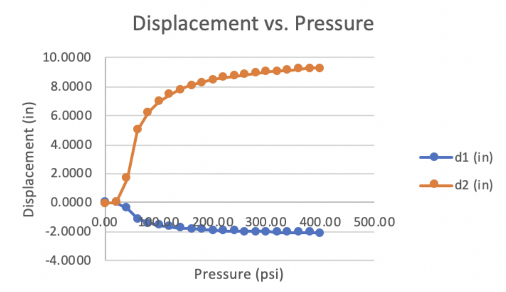
This sheet performs an instability analysis on an interconnect piping system with an initial lateral offset. It is based on a write-up in Fermilab TM-1597 (lateral offset case only). It is based on Basic and Fortran programs that did the same thing developed in 1992.

Bellows and piping parameters - Line A*

Parameter	Value	Units	
K1b	635	(lb/in)	
K2b	141	(lb/in)	
Kbl	100	(lb/in)	
r	2.65	(in)	
l	6	(in)	
di	0.1	(in)	(Must be >=0)
Pfinal	400	(psi)	
Pincr	20.00	(psi)	

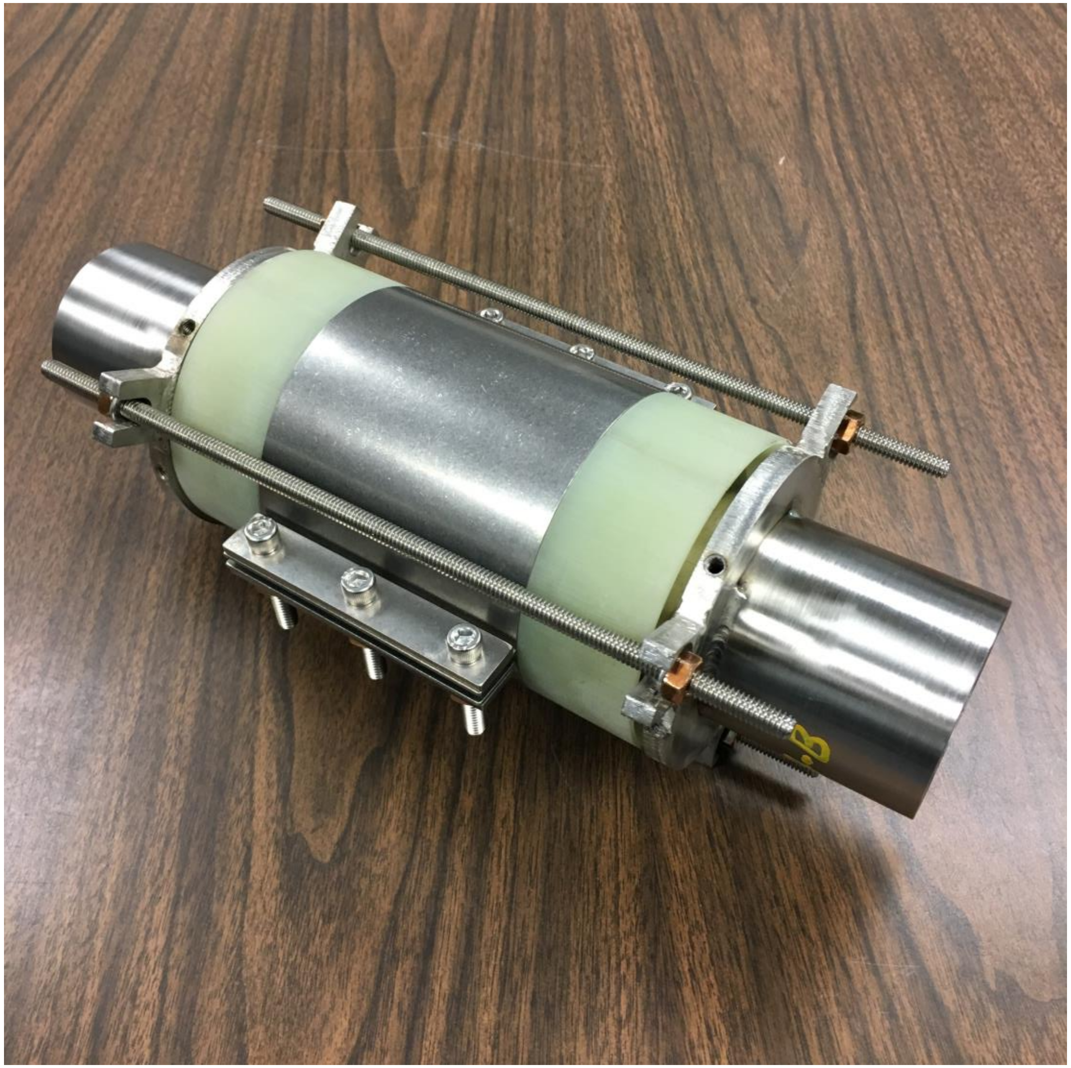
*: Pipe stiffnesses estimated February 2019. Bellows stiffness estimate.

Estimated instability pressure 39.05 (psi)



P (psi)	Fp (lb)	d1 (in)	d2 (in)	alpha (rad)	alpha (deg)	Fp/disl (lb/in)
0.00	0.00	0.0084	-0.0380	0.0134	0.7673	100.00
20.00	12.11	-0.0018	0.0080	0.0274	1.5727	-1136.09
40.00	453.92	-0.3745	1.6866	0.5403	30.9552	-120.23
60.00	1323.41	-1.1080	4.9901	1.5495	88.7813	-117.02
80.00	1651.84	-1.3851	6.2379	1.9307	110.6236	-116.69
100.00	1843.07	-1.5464	6.9644	2.1527	123.3414	-116.56
120.00	1971.35	-1.6547	7.4518	2.3016	131.8727	-116.48
140.00	2064.36	-1.7331	7.8052	2.4096	138.0587	-116.43
160.00	2135.31	-1.7930	8.0747	2.4919	142.7768	-116.39
180.00	2191.40	-1.8403	8.2878	2.5570	146.5072	-116.37
200.00	2236.96	-1.8787	8.4610	2.6099	149.5374	-116.35
220.00	2274.77	-1.9106	8.6046	2.6538	152.0516	-116.33
240.00	2306.67	-1.9375	8.7258	2.6908	154.1736	-116.32
260.00	2333.99	-1.9606	8.8296	2.7225	155.9900	-116.31
280.00	2357.64	-1.9805	8.9195	2.7500	157.5634	-116.30
300.00	2378.34	-1.9980	8.9981	2.7740	158.9400	-116.29
320.00	2396.61	-2.0134	9.0675	2.7952	160.1552	-116.28
340.00	2412.87	-2.0271	9.1293	2.8141	161.2360	-116.28
360.00	2427.42	-2.0394	9.1846	2.8310	162.2037	-116.27
380.00	2440.53	-2.0505	9.2344	2.8462	163.0755	-116.27
400.00	2452.40	-2.0605	9.2795	2.8600	163.8651	-116.26

Chapter 8 – Bellows instability



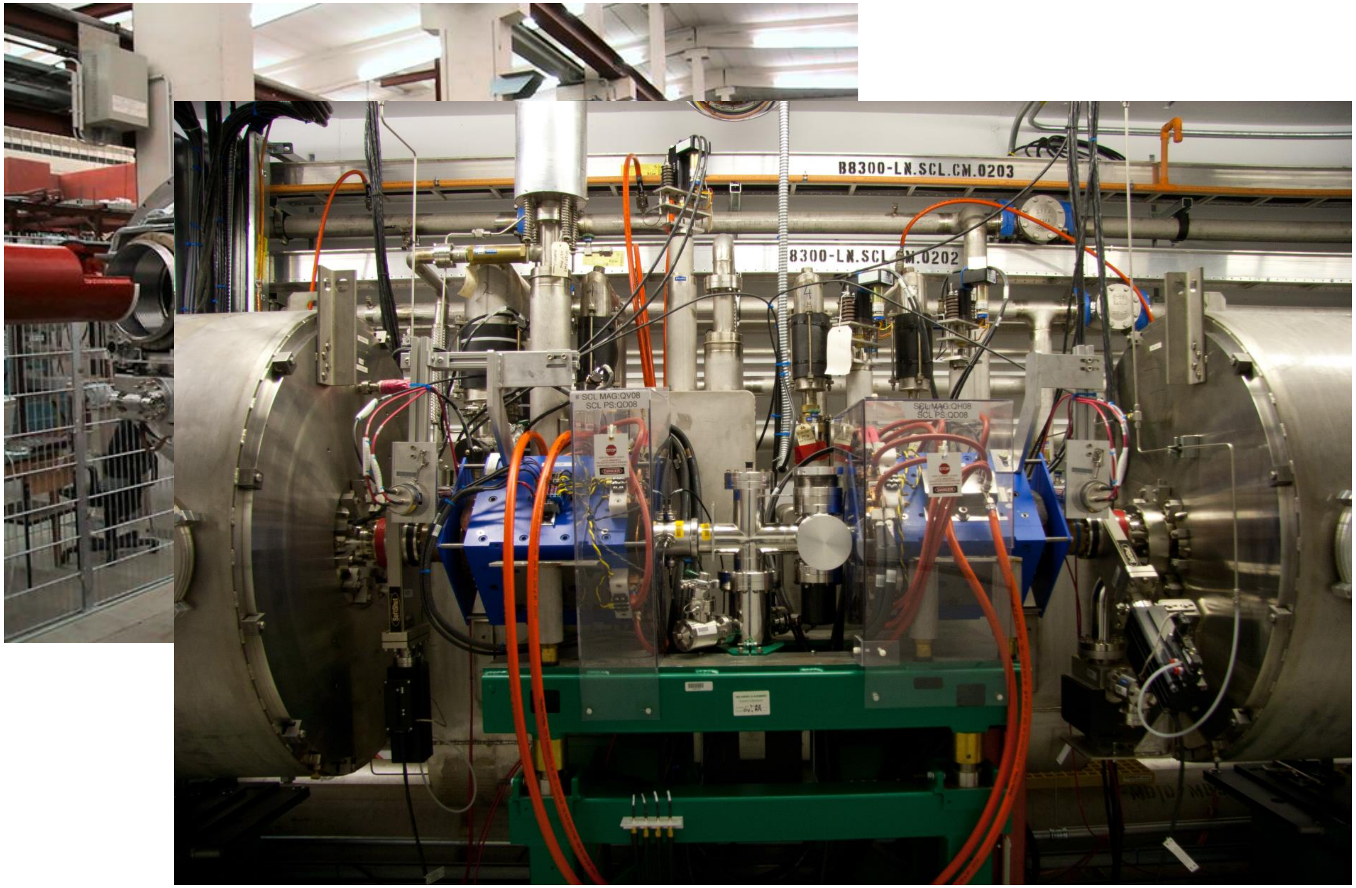
Chapter 8 – Bellows instability

Bellows Description:	LCLS-II bellows - F10061938
Prepared By:	T. Nicol
Date:	3/1/19
Design Basis:	Expansion Joint Manufacturers Association Standard, 7th Edition, ERRATA 2002
Allowable Stress Basis:	ASME Section II, Part D, 1998 Edition, 2000 Addenda

Bellows Geometry		***Design Parameters***	
Bellows Inside Diameter, Db, (in.)	2.29	Design Pressure, P, (psi)	290
Number of Plies, n	2	Axial Extension, +x (in.)	1.181
Ply Thickness, t, (in.)	0.011811024	Axial Precompression, -x (in.)	-1.181
Free length, Lb, (in.)	6.4	Lateral Deflection, +y, (in.)	›
Number of Convolutions, N	26	Lateral Deflection, -y, (in.)	0.000
Depth of Convolution, w, (in.)	0.335	Angular rotation, +Θ, (rad)	0
Bellows Tangent Length, Lt, (in.)	0.394	Angular rotation, -Θ, (rad)	0
Bellows Material	316L SS	Minimum Fatigue Cycles	100
Allowable Stress, Sab, (psi)	16,700	***Collar Geometry***	
Modulus of Elasticity, Eb, (psi)	2.83E+07	Collar Thickness, tc, (in.)	0.433
		Collar Length, Lc, (in.)	0.250
		Collar Modulus of Elasticity, Ec, (psi)	2.83E+07
		Allowable Stress (304 SS), Sac, (psi)	20,000
Intermediate Calculations			
Convolution Pitch, q, (in.)	0.248	Stiffening Factor, k	1.0
Bellows Mean Diameter, Dm, (in.)	2.650	Material Constant, c	1.86E+06
Bellows Outside Diameter, (in.)	3.008	Material Constant, b	54,000
Collar Mean Diameter, Dc, (in.)	2.772	Manufacturing Constant, a	3.4
Axial extension per convolution due to x (in)	0.0454	Factor from Figure C24, Cp	0.6880
Axial extension per convolution due to y (in)	0.0000		
Axial extension per convolution due to Θ (rad)	0.0000		
Axial extension per convolution due to -x (in)	-0.0454		
Axial extension per convolution due to -y (in)	0.0000		
Axial extension per convolution due to -Θ (rad)	0.0000		
Total axial extension per convolution due to x, y, Θ (in)	0.0454		
Total axial extension per convolution due to -x, -y, -Θ (in)	-0.0454	Factor from Figure C25, Cf	1.4377
Total axial extension per convolution (in)	0.0909	Factor from Figure C26, Cd	1.6218
Bellows Mat. Thickness Factor, tp	0.0110	Material Strength Factor, Cm	3.0
Circumferential Stress Factor, Kr	0.817	Transition Point Factor, Cz	1.0533
X-Sect. Area for 1 Conv., Ac, (in.^2)	0.0178	Inplane Instability Stress Ratio, delta	2.8851
Yield Strength at Design Temp., Sy	40,200	Inplane Interaction Factor, alpha	33.8184

Bellows Stress Analysis	*Actual Stress*	*Allowable Stress*	
Tangent Circumferential Membrane Stress Due to Pressure, S1, (psi)	951	16,700	Pass
Collar Circumferential Membrane Stress Due to Pressure, S1', (psi)	1,364	20,000	Pass
Circumferential Membrane Stress Due to Internal Pressure, S2, (psi)	4,370	16,700	Pass
Meridional Membrane Stress Due to Internal Pressure, S3, (psi)	2,209	*N/A*	
Meridional Bending Stress Due to Internal Pressure, S4, (psi)	46,301	*N/A*	
Meridional Membrane + Bending Stress Due to Pressure, S3+S4, (psi)	48,510	50,100	Pass
Meridional Membrane Stress Due to Deflection, S5, (psi)	2,878	*N/A*	
Meridional Bending Stress Due to Deflection, S6, (psi)	259,144	*N/A*	
Maximum Design Pressure Based on Squirm, Psc, (psi)	2		
Maximum Design Pressure Based on Inplane Instability, Psi, (psi)	214		
Fatigue Characteristics		*Minimum*	
Total Stress Range for All Movements, St, (psi)	295,979	*N/A*	
Fatigue Life (cycles to failure), Nc	1,027	100	Pass
Spring Rates			
Theoretical Axial Elastic Spring Rate, (lbs./in.)	241.1		

Machine protection…



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

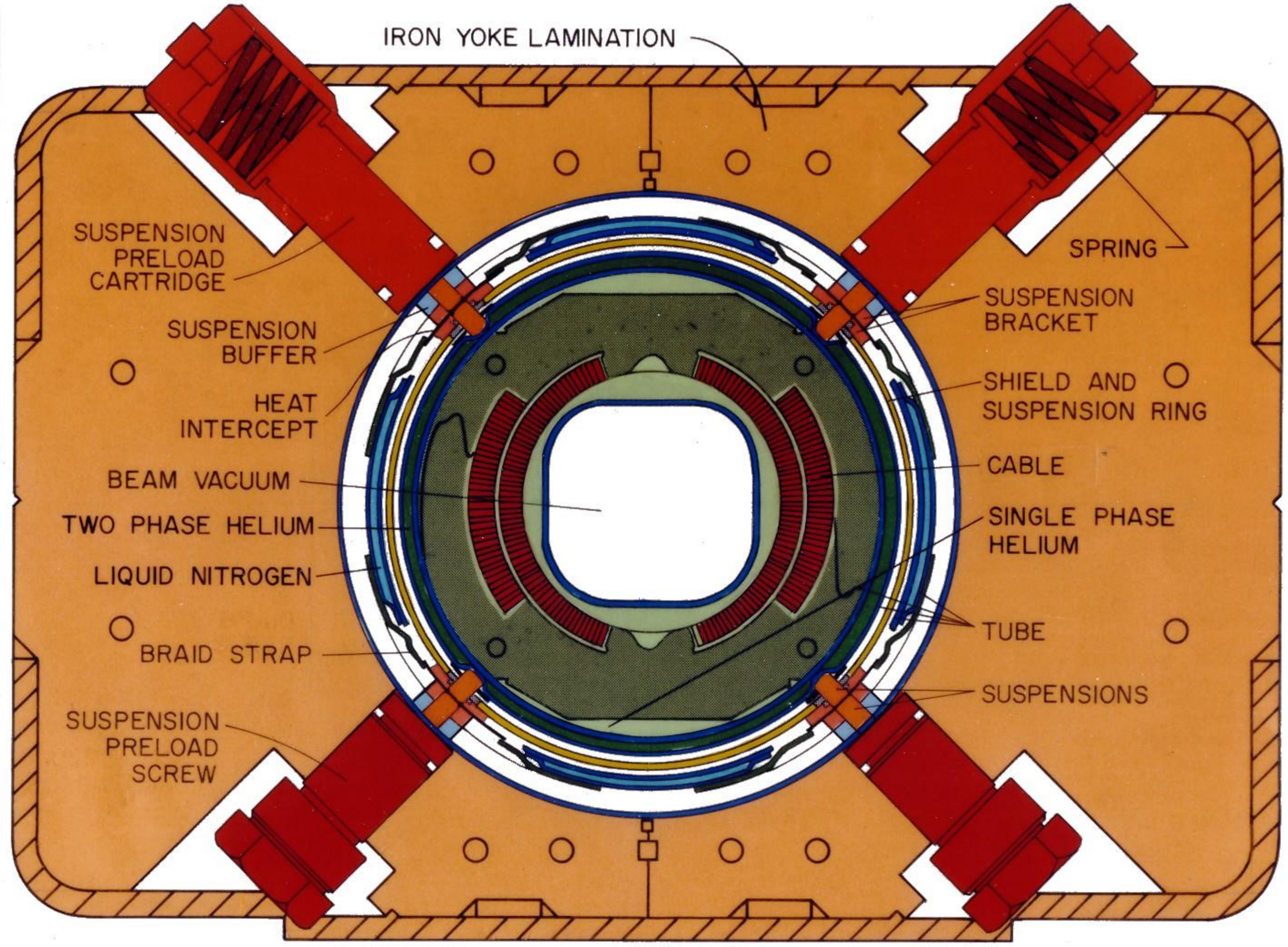
General		
	Physical beam aperture, mm	118
	Overall length (flange-to-flange), m	9.56
	Overall width, m	≤1.6
	Beamline height from the floor, m	1.3
	Cryomodule height (from floor), m	≤2.00
	Ceiling height in the tunnel, m	3.20
	Max allowed heat load to 70 K, W	300
	Max allowed heat load to 5 K, W	25
	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

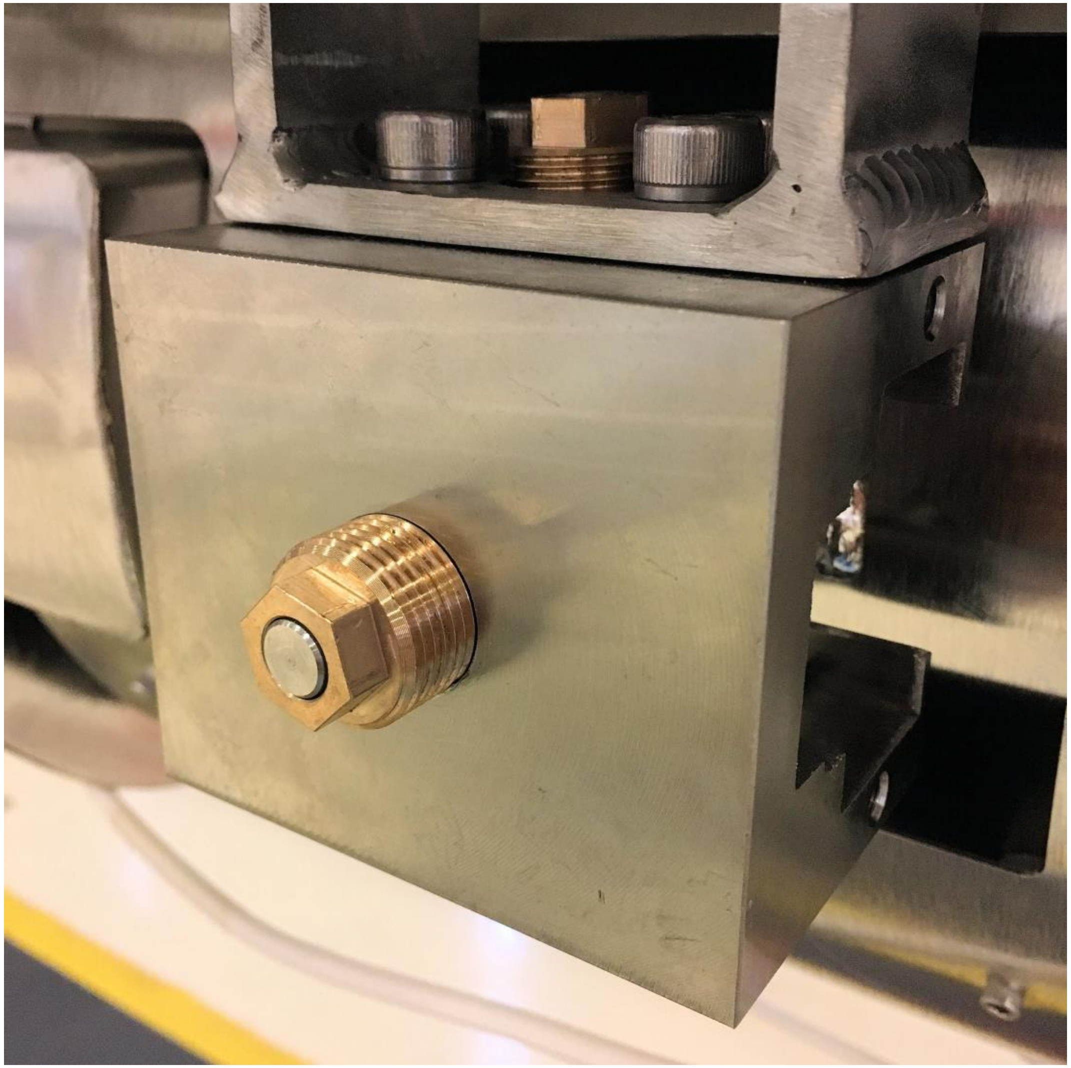


Chapter 9 – Alignment

LHC IRQ magnet alignment adjustment tooling

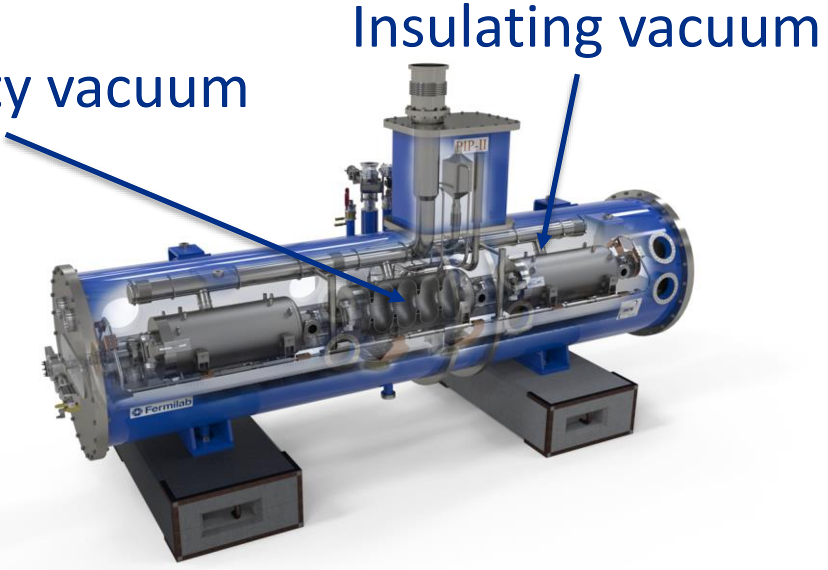
Chapter 9 – Alignment

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 it is most likely loss of insulating vacuum
  - In an SRF cryomodule it is either loss of insulating vacuum or cavity vacuum or both
  - http://newsline.linearcollider.org/readmore_20080612_atw.html



On an uninsulated surface: $Q \sim 4\ W/cm^2$
On an insulated surface Q: $\sim 0.6\ W/cm^2$

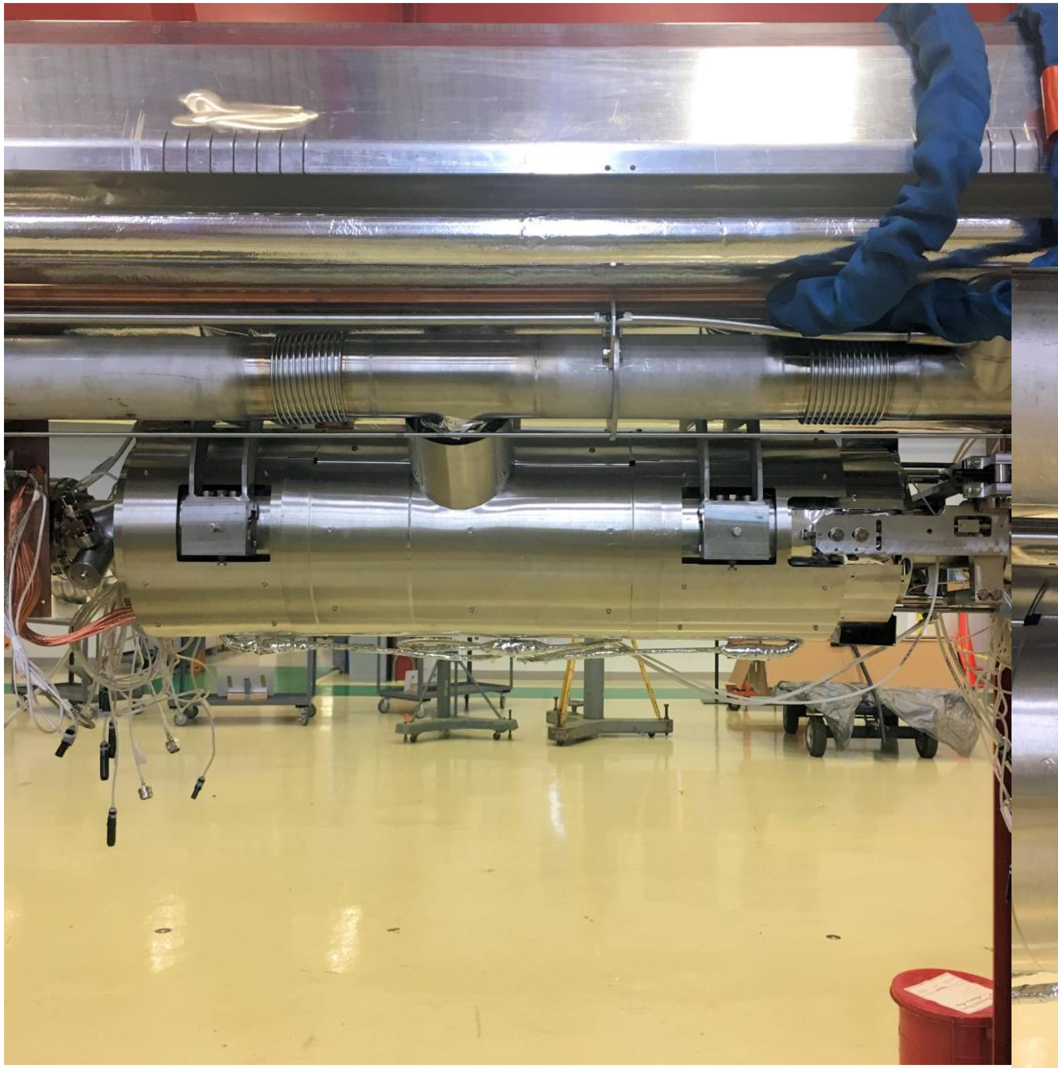
Chapter 9 – Magnetic shielding

Spoke cavity test cryostat magnetic shield

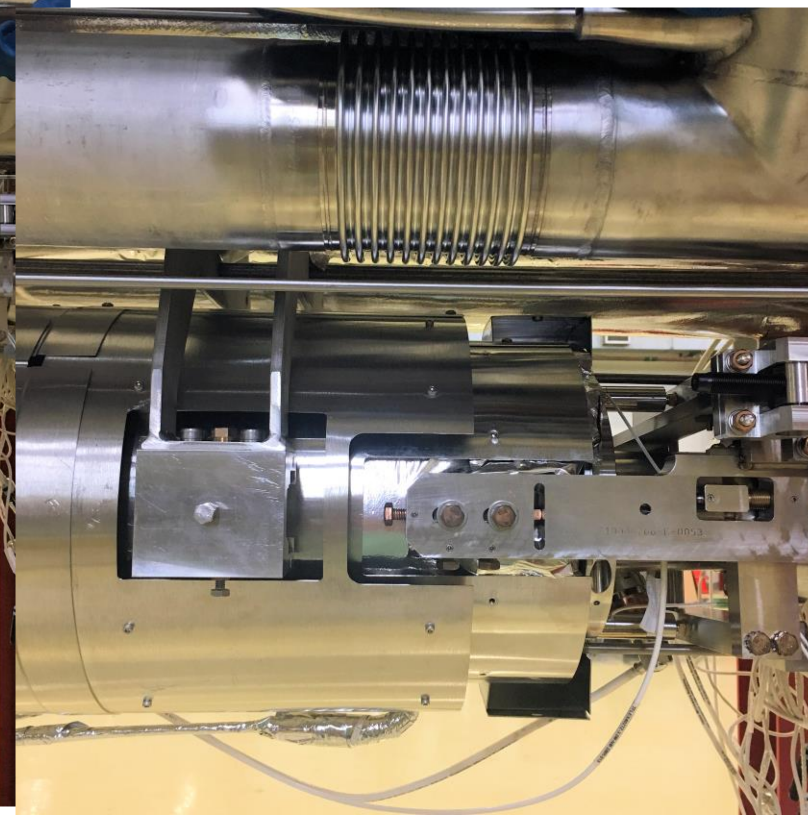
Chapter 9 – Magnetic shielding

Spoke cavity test cryostat magnetic shield

Chapter 9 – Magnetic shielding



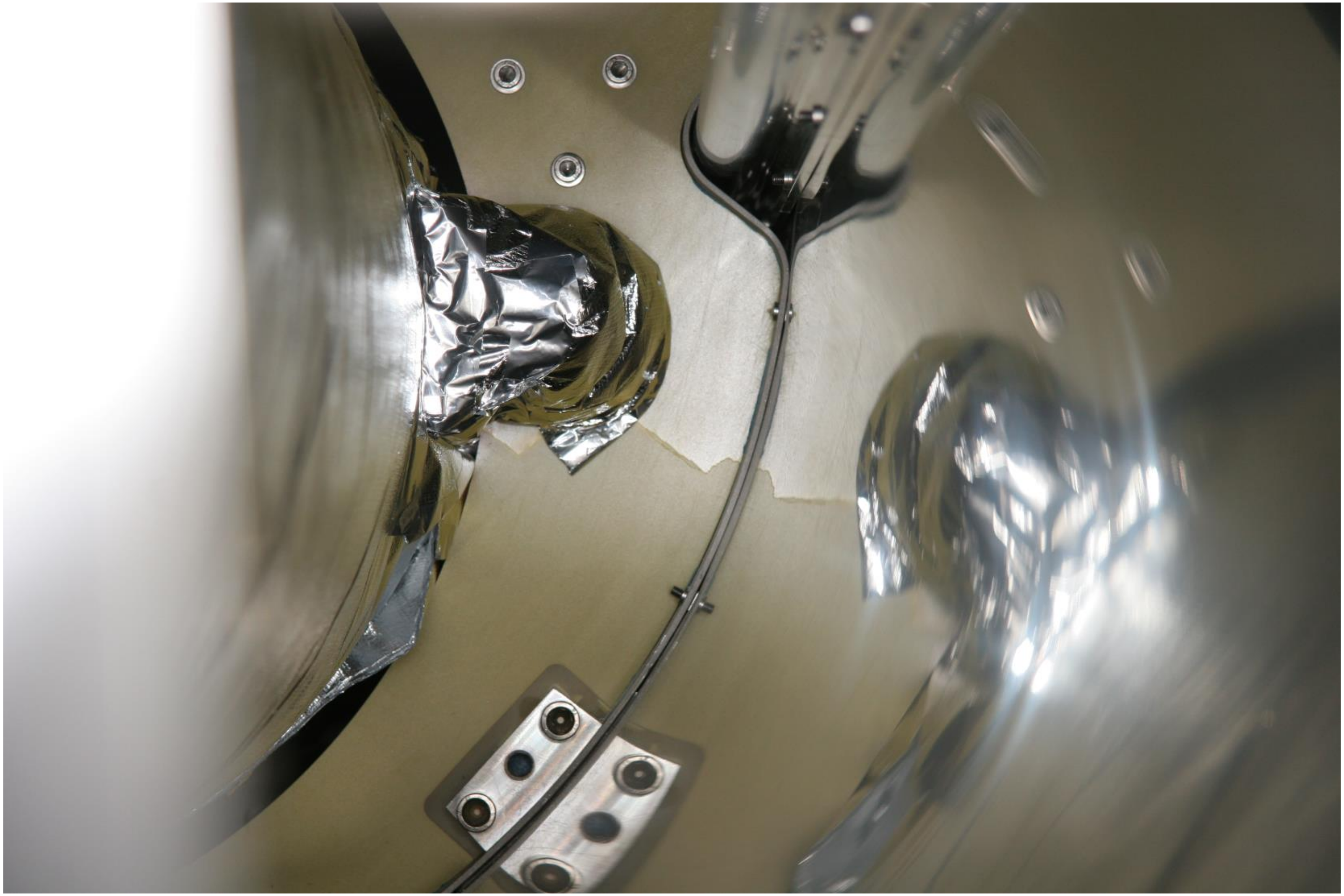
LCLS-II cavity magnetic shield



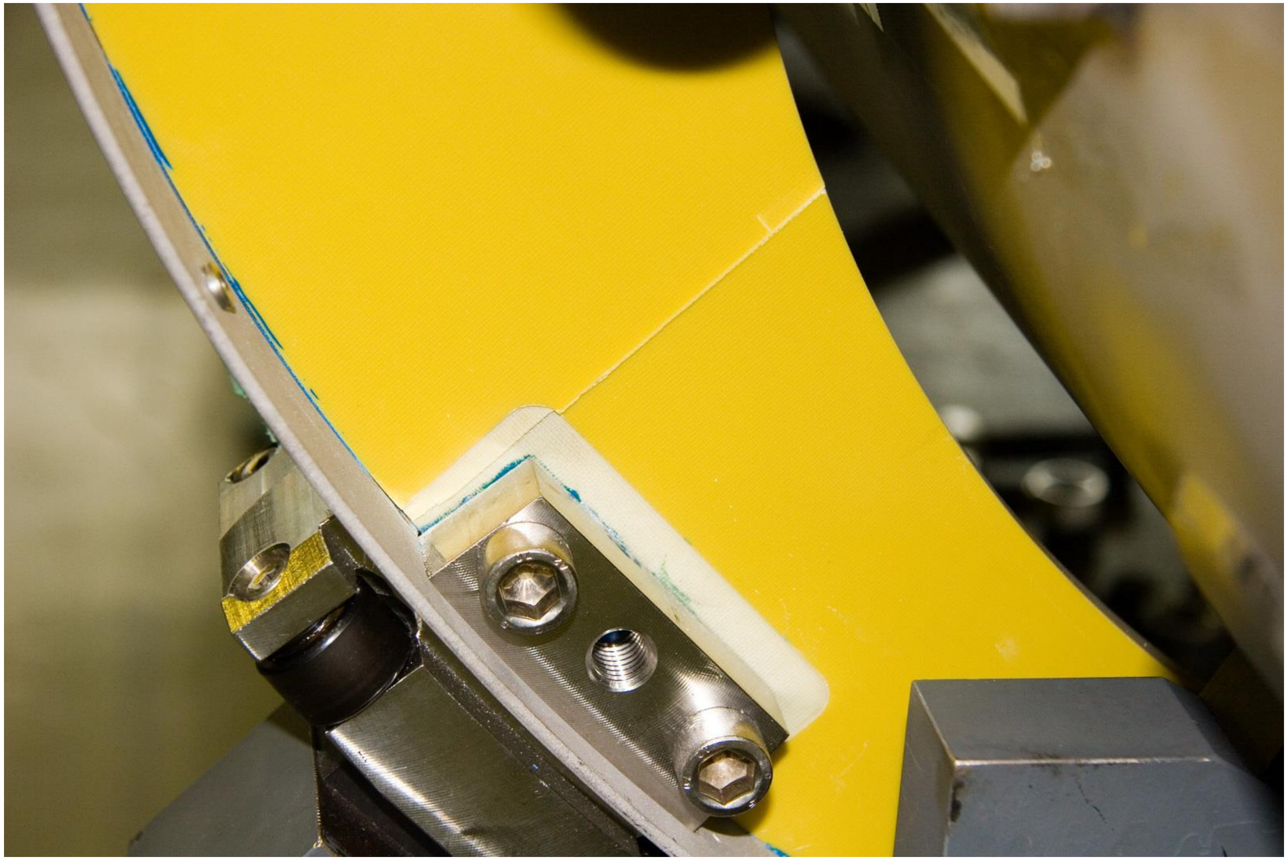
Chapter 10 – Transportation

Chapter 10 – Transportation

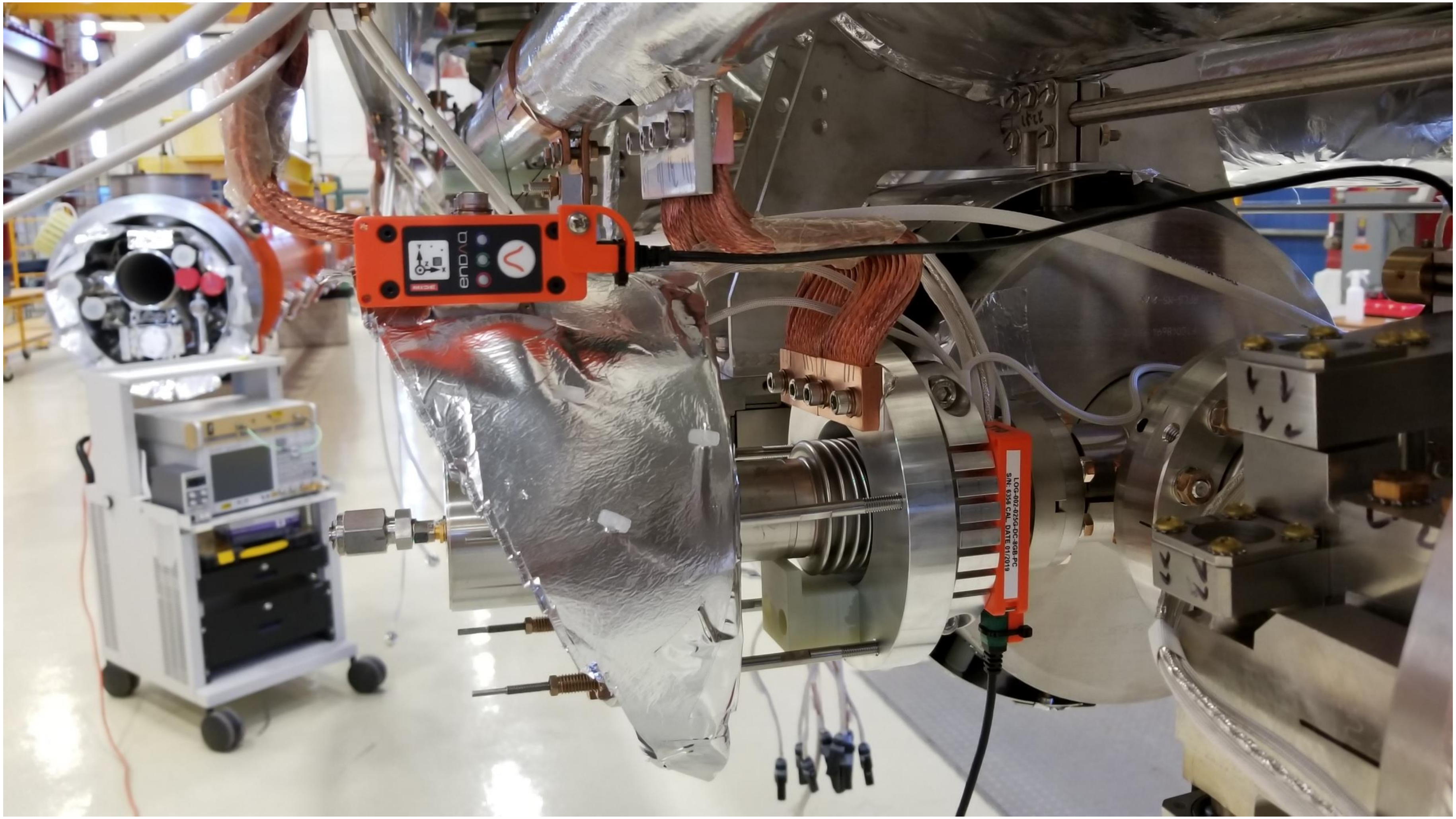
Chapter 10 – Transportation – LHC failed support



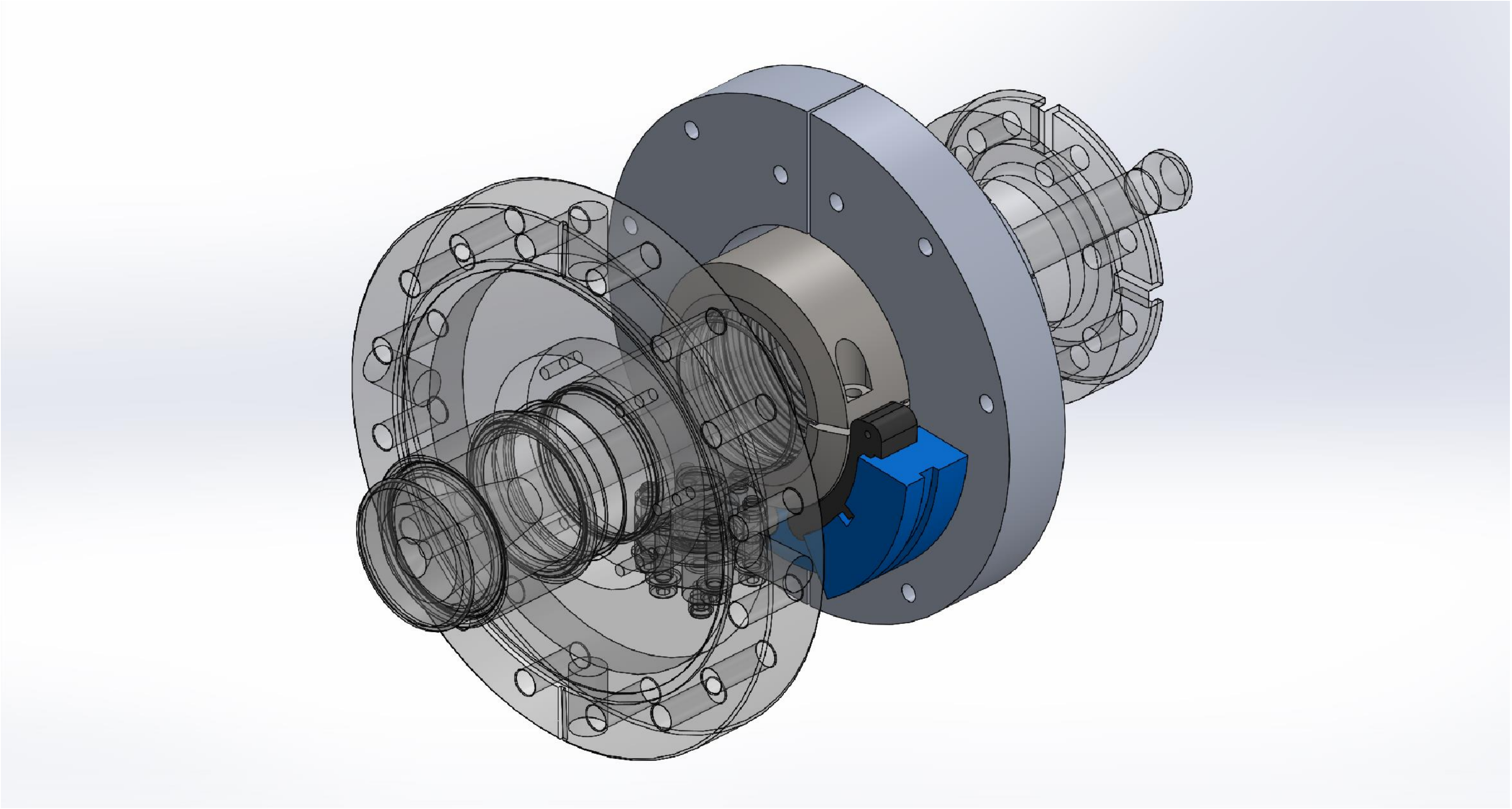
Chapter 10 – Transportation – LHC failed support



Chapter 10 – Transportation – LCLS-II bellows



Chapter 10 – Transportation – LCLS-II bellows



Chapter 10 – Transportation

- Lessons learned from the LHC, LCLS-II, and others.
  - Do all the analysis possible ahead of time, including modal analysis.
  - Spend time ahead of shipping on the design of shipping restraints, frames, etc.
  - Incorporate shipping restraint schemes into the original design.
  - Be sure to include the shipping frame, tractor and trailer, suspension, etc. in final design reviews.
  - Shipping after cold test may be different from shipping before cold test.
    - Thermal cycling can loosen fasteners in ways room-temperature vibration doesn’t.
  - Incorporate shipping restraints into the original design such that they can be removed easily.
  - Don’t assume shippers, either the company or the drivers, can translate load requirements to shipping procedures.
  - Account for potential ambient temperature excursions in the design of shipping restraints.
  - Incorporate sensor selection and placement into the design.
  - Incorporate shipping with dummy loads as much as possible. When a real device is not needed, do not use it.

Chapter 10 – Transportation

- Incorporate the use of components test devices, fixtures, etc., e.g. shaker tables, bellows testing, etc.
- Investigate the use of transport trailer "shaker" systems.
- Cross-disciplinary groups working collaboratively may be critical.
- Provide your own shock, vibration, and load limiting support system.
- Utilize instrumentation on both the shipping frame and the device.
- Road test the actual configuration ahead of actual shipments.
- Control the shipping environment as much as possible with packaging, crating, etc.
- Don't rely on the shipper to limit loads. There's likely no way for them to know how.
- Look at the data from each shipment. Provide feedback to the shipper.
- To the extent possible, be involved in the shipping process. Don't assume that shortcuts won't be taken.
- Install maintenance ports on vacuum vessels when possible.
- Variables such as route, speed, road conditions and weather cannot be controlled; a shipping system should be able to handle deviations.
- Install support structures for heavy external equipment such as ion pumps, etc. If support is not possible, remove external equipment for transportation.

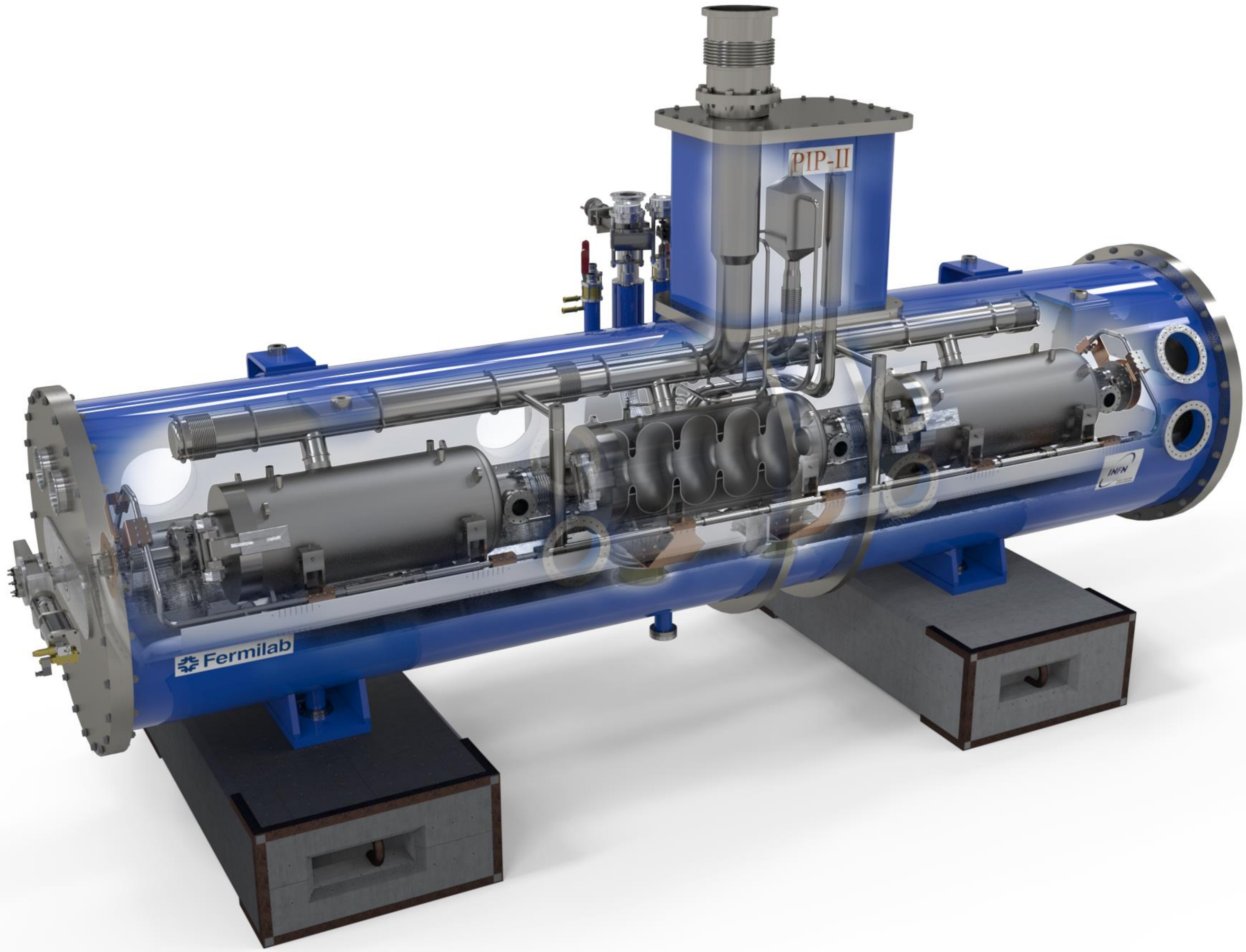
Chapter 10 – Transportation

- Maybe add some material from the TS transport or HL-LHC transport
- Add a slide with the DOT (?) shock load data envelope

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 and participation…



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, rated for 20 bar internal pressure.
  - Assume: S=16,700 psi
  - Assume: E=1
  - Assume: W=0.8
  - Assume: Y=1

(There will be two results for this, both very similar.)

Homework – Handout 1

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):

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

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):

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

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

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)

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

where at the intrados (inside bend radius)

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

and at the extrados (outside bend radius)

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

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 information on handouts 2 and 3***, calculate the minimum thickness of a 36 inch OD, 15 foot long, cylindrical carbon steel vessel subject to an external pressure of 14.7 psi, to the nearest 1/16”. (Hint: Start with t=1/2 inch.)
  - Assume: No additional stiffeners
  - Assume: Minimum yield strength between 24,000 psi to 30,000 psi
  - Assume: E=29e6 psi

(The handout contains section UG-28 from the ASME Code and figures G and CS-1 from Subpart 3.)

Homework – Handout 2

UW-2(a)], except as permitted by ULW-76 for vent holes in layered construction. When telltale holes are provided, they shall have a diameter of $^1/_{16}$ in. to $^3/_{16}$ in. (1.5 mm to 5 mm) and have a depth not less than 80% of the thickness required for a seamless shell of like dimensions. These holes shall be provided in the opposite surface to that where deterioration is expected. [For telltale holes in clad or lined vessels, see UCL-25(b).]

(f) Openings for Drain. Vessels subject to corrosion shall be supplied with a suitable drain opening at the lowest point practicable in the vessel; or a pipe may be used extending inward from any other location to within $\frac{1}{4}$ in. (6 mm) of the lowest point.

UG-26 LININGS

Corrosion resistant or abrasion resistant linings, whether or not attached to the wall of a vessel, shall not be considered as contributing to the strength of the wall except as permitted in Part UCL (see Appendix F).

UG-27 THICKNESS OF SHELLS UNDER INTERNAL PRESSURE

(a) The minimum required thickness of shells under internal pressure shall not be less than that computed by the following formulas,[14] except as permitted by Appendix 32. In addition, provision shall be made for any of the loadings listed in UG-22, when such loadings are expected. The provided thickness of the shells shall also meet the requirements of UG-16, except as permitted in Appendix 32.

(b) The symbols defined below are used in the formulas of this paragraph.

E = joint efficiency for, or the efficiency of, appropriate joint in cylindrical or spherical shells, or the efficiency of ligaments between openings, whichever is less.

For welded vessels, use the efficiency specified in UW-12.

For ligaments between openings, use the efficiency calculated by the rules given in UG-53.

P = internal design pressure (see UG-21)

R = inside radius of the shell course under consideration,[15]

S = maximum allowable stress value (see UG-23 and the stress limitations specified in UG-24)

t = minimum required thickness of shell

(c) Cylindrical Shells. The minimum thickness or maximum allowable working pressure of cylindrical shells shall be the greater thickness or lesser pressure as given by (1) or (2) below.

(1) Circumferential Stress (Longitudinal Joints). When the thickness does not exceed one-half of the inside radius, or P does not exceed $0.385SE$, the following formulas shall apply:

$$t = \frac{PR}{SE - 0.6P} \quad \text{or} \quad P = \frac{SEt}{R + 0.6t} \qquad (1)$$

(2) Longitudinal Stress (Circumferential Joints).[16] When the thickness does not exceed one-half of the inside radius, or P does not exceed $1.25SE$, the following formulas shall apply:

$$t = \frac{PR}{2SE + 0.4P} \quad \text{or} \quad P = \frac{2SEt}{R - 0.4t} \qquad (2)$$

(d) Spherical Shells. When the thickness of the shell of a wholly spherical vessel does not exceed $0.356R$, or P does not exceed $0.665SE$, the following formulas shall apply:

$$t = \frac{PR}{2SE - 0.2P} \quad \text{or} \quad P = \frac{2SEt}{R + 0.2t} \qquad (3)$$

(e) When necessary, vessels shall be provided with stiffeners or other additional means of support to prevent overstress or large distortions under the external loadings listed in UG-22 other than pressure and temperature.

(f) A stayed jacket shell that extends completely around a cylindrical or spherical vessel shall also meet the requirements of UG-47(c).

(g) Any reduction in thickness within a shell course or spherical shell shall be in accordance with UW-9.

UG-28 THICKNESS OF SHELLS AND TUBES UNDER EXTERNAL PRESSURE

(a) Rules for the design of shells and tubes under external pressure given in this Division are limited to cylindrical shells, with or without stiffening rings, tubes, and spherical shells. Three typical forms of cylindrical shells are shown in Fig. UG-28. Charts used in determining minimum required thicknesses of these components are given in Subpart 3 of Section II, Part D.

(b) The symbols defined below are used in the procedures of this paragraph:

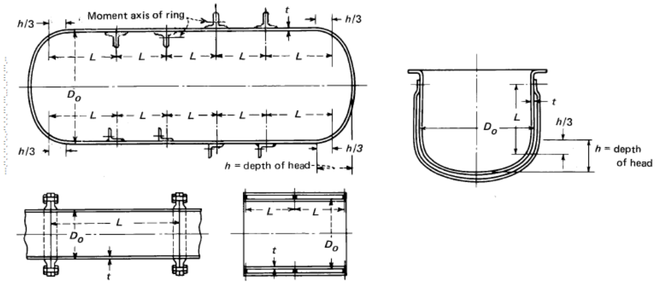
A = factor determined from Fig. G in Subpart 3 of Section II, Part D and used to enter the applicable

[14] Formulas in terms of the outside radius and for thicknesses and pressures beyond the limits fixed in this paragraph are given in 1-1 to 1-3.

[15] For pipe, the inside radius R is determined by the nominal outside radius minus the nominal wall thickness.

[16] These formulas will govern only when the circumferential joint efficiency is less than one-half the longitudinal joint efficiency, or when the effect of supplementary loadings (UG-22) causing longitudinal bending or tension in conjunction with internal pressure is being investigated. An example illustrating this investigation is given in L-2.1 and L-2.2.

FIG. UG-28 DIAGRAMMATIC REPRESENTATION OF VARIABLES FOR DESIGN OF CYLINDRICAL VESSELS SUBJECTED TO EXTERNAL PRESSURE



material chart in Subpart 3 of Section II, Part D. For the case of cylinders having D_o/t values less than 10, see UG-28(c)(2).

B = factor determined from the applicable material chart or table in Subpart 3 of Section II, Part D for maximum design metal temperature [see UG-20(c)]

D_o = outside diameter of cylindrical shell course or tube

E = modulus of elasticity of material at design temperature. For external pressure design in accordance with this Section, the modulus of elasticity to be used shall be taken from the applicable materials chart in Subpart 3 of Section II, Part D. (Interpolation may be made between lines for intermediate temperatures.)

L = total length, in. (mm), of a tube between tubesheets, or design length of a vessel section between lines of support (see Fig. UG-28.1). A line of support is:

(1) a circumferential line on a head (excluding conical heads) at one-third the depth of the head from the head tangent line as shown on Fig. UG-28;

(2) a stiffening ring that meets the requirements of UG-29;

(3) a jacket closure of a jacketed vessel that meets the requirements of 9-5;

(4) a cone-to-cylinder junction or a knuckle-to-cylinder junction of a toriconical head or section that satisfies the moment of inertia requirement of 1-8.

P = external design pressure [see Note in UG-28(f)]

P_a = calculated value of maximum allowable external working pressure for the assumed value of t, [see Note in (f) below]

R_o = outside radius of spherical shell

t = minimum required thickness of cylindrical shell or tube, or spherical shell, in. (mm)

t_s = nominal thickness of cylindrical shell or tube, in. (mm)

(c) Cylindrical Shells and Tubes. The required minimum thickness of a cylindrical shell or tube under external pressure, either seamless or with longitudinal butt joints, shall be determined by the following procedure:

(1) Cylinders having D_o/t values ≥ 10:

Step 1. Assume a value for t and determine the ratios L/D_o and D_o/t.

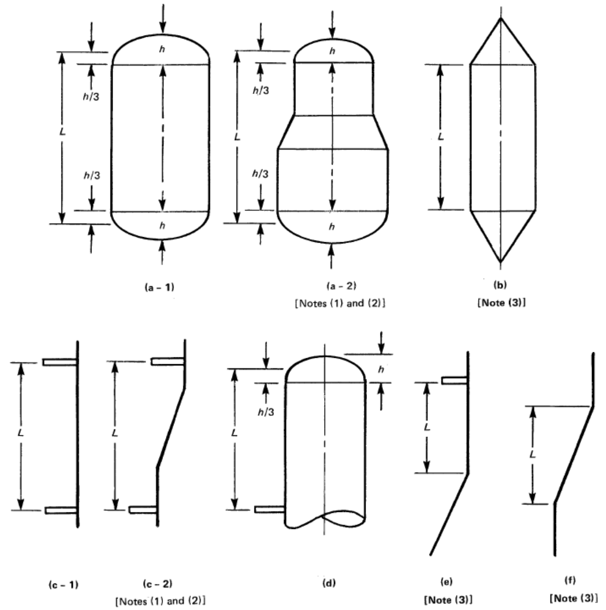
Step 2. Enter Fig. G in Subpart 3 of Section II, Part D at the value of L/D_o determined in Step 1. For values of L/D_o greater than 50, enter the chart at a value of L/D_o = 50. For values of L/D_o less than 0.05, enter the chart at a value of L/D_o = 0.05.

Step 3. Move horizontally to the line for the value of D_o/t determined in Step 1. Interpolation may be made for intermediate values of D_o/t. From this point of intersection move vertically downward to determine the value of factor A.

Step 4. Using the value of A calculated in Step 3, enter the applicable material chart in Subpart 3 of Section II, Part D for the material under consideration. Move vertically to an intersection with the material/temperature line for the design temperature (see UG-20). Interpolation may be made between lines for intermediate temperatures. If tabular values in Subpart 3 of Section II, Part D are used, linear

Homework – Handout 2

FIG. UG-28.1 DIAGRAMMATIC REPRESENTATION OF LINES OF SUPPORT FOR DESIGN OF CYLINDRICAL VESSELS SUBJECTED TO EXTERNAL PRESSURE



NOTES:
(1) When the cone-to-cylinder or the knuckle-to-cylinder junction is not a line of support, the nominal thickness of the cone, knuckle, or toriconical section shall not be less than the minimum required thickness of the adjacent cylindrical shell.
(2) Calculations shall be made using the diameter and corresponding thickness of each cylindrical section with dimension L as shown. Thicknesses of the transition sections are based on Note (1).
(3) When the cone-to-cylinder or the knuckle-to-cylinder junction is a line of support, the moment of inertia shall be provided in accordance with 1-8.

interpolation or any other rational interpolation method may be used to determine a B value that lies between two adjacent tabular values for a specific temperature. Such interpolation may also be used to detemine a B value at an intermediate temperature that lies between two sets of tabular values, after first determining B values for each set of tabular values.

In cases where the value of A falls to the right of the end of the material/temperature line, assume an intersection with the horizontal projection of the upper end of the material/temperature line. If tabular values are used, the last (maximum) tabulated value shall be used. For values of A falling to the left of the material/temperature line, see Step 7.

Step 5. From the intersection obtained in Step 4, move horizontally to the right and read the value of factor B.

Step 6. Using this value of B, calculate the value of the maximum allowable external working pressure P_a using the following formula:

$$P_a = \frac{4B}{3(D_o/t)}$$

Step 7. For values of A falling to the left of the applicable material/temperature line, the value of P_a can be calculated using the following formula:

$$P_a = \frac{2AE}{3(D_o/t)}$$

If tabular values are used, determine B as in Step 4 and apply it to the equation in Step 6.

Step 8. Compare the calculated value of P_a obtained in Steps 6 or 7 with P. If P_a is smaller than P, select a larger value for t and repeat the design procedure until a value of P_a is obtained that is equal to or greater than P. An example illustrating the use of this procedure is given in L-3(a).

(2) Cylinders having D_o/t values <10:

Step 1. Using the same procedure as given in UG-28(c)(1), obtain the value of B. For values of D_o/t less than 4, the value of factor A can be calculated using the following formula:

$$A = \frac{1.1}{(D_o/t)^2}$$

For values of A greater than 0.10, use a value of 0.10.

Step 2. Using the value of B obtained in Step 1, calculate a value P_{a1} using the following formula:

$$P_{a1} = \left[\frac{2.167}{(D_o/t)} - 0.0833\right] B$$

Step 3. Calculate a value P_{a2} using the following formula:

$$P_{a2} = \frac{2S}{D_o/t}\left[1 - \frac{1}{D_o/t}\right]$$

where S is the lesser of two times the maximum allowable stress value in tension at design metal temperature, from the applicable table referenced in UG-23, or 0.9 times the yield strength of the material at design temperature. Values of yield strength are obtained from the applicable external pressure chart as follows:

(a) For a given temperature curve, determine the B value that corresponds to the right hand side termination point of the curve.

(b) The yield strength is twice the B value obtained in (a) above.

Step 4. The smaller of the values of P_{a1} calculated in Step 2, or P_{a2} calculated in Step 3 shall be used for the maximum allowable external working pressure P_a. Compare P_a with P. If P_a is smaller than P, select a larger value for t and repeat the design procedure until a value for P_a is obtained that is equal to or greater than P.

(d) Spherical Shells. The minimum required thickness of a spherical shell under external pressure, either seamless or of built-up construction with butt joints, shall be determined by the following procedure:

Step 1. Assume a value for t and calculate the value of factor A using the following formula:

$$A = \frac{0.125}{(R_o/t)}$$

Step 2. Using the value of A calculated in Step 1, enter the applicable material chart in Subpart 3 of Section II, Part D for the material under consideration. Move vertically to an intersection with the material/temperature line for the design temperature (see UG-20). Interpolation may be made between lines for intermediate temperatures. If tabular values in Subpart 3 of Section II, Part D are used, linear interpolation or any other rational interpolation method may be used to detemine a B value that lies between two adjacent tabular values for a specific temperature. Such interpolation may also be used to determine a B value at an intermediate temperature that lies between two sets of tabular values, after first detemining B values for each set of tabular values.

In cases where the value at A falls to the right of the end of the material/temperature line, assume an intersection with the horizontal projection of the upper end of the material/temperature line. If tabular values are used, the last (maximum) tabulated value shall be used. For values at A falling to the left of the material/temperature line, see Step 5.

Step 3. From the intersection obtained in Step 2, move horizontally to the right and read the value of factor B.

Step 4. Using the value of B obtained in Step 3, calculate the value of the maximum allowable external working pressure P_a using the following formula:

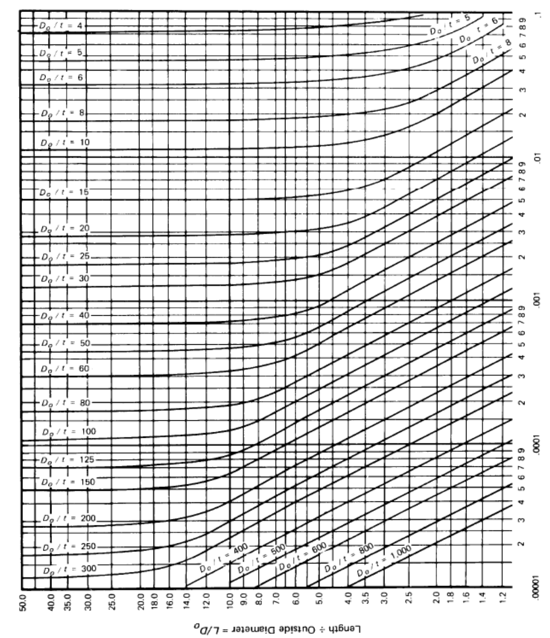
$$P_a = \frac{B}{(R_o/t)}$$

Homework – Handout 3

SUBPART 3
CHARTS AND TABLES FOR DETERMINING SHELL THICKNESS OF COMPONENTS UNDER EXTERNAL PRESSURE

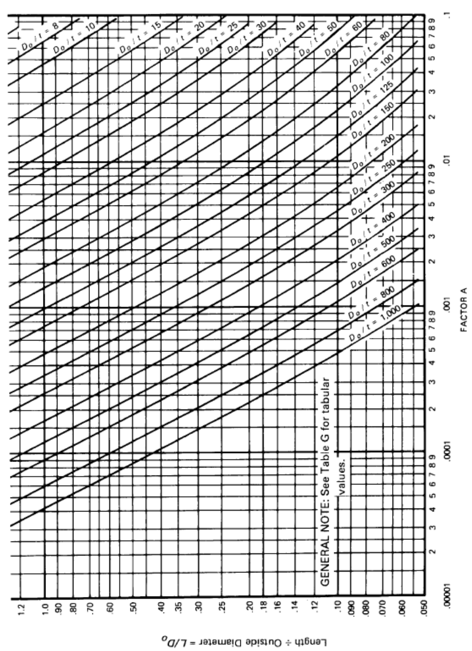
2007 SECTION II, PART D (CUSTOMARY)

FIG. G GEOMETRIC CHART FOR COMPONENTS UNDER EXTERNAL OR COMPRESSIVE LOADINGS (for All Materials)



Homework – Handout 3

2007 SECTION II, PART D (CUSTOMARY)



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2007 SECTION II, PART D (CUSTOMARY)

FIG. CS-1 CHART FOR DETERMINING SHELL THICKNESS OF COMPONENTS UNDER EXTERNAL PRESSURE WHEN CONSTRUCTED OF CARBON OR LOW ALLOY STEELS (Specified Minimum Yield Strength 24,000 psi to, but Not Including, 30,000 psi) [Note (1)]

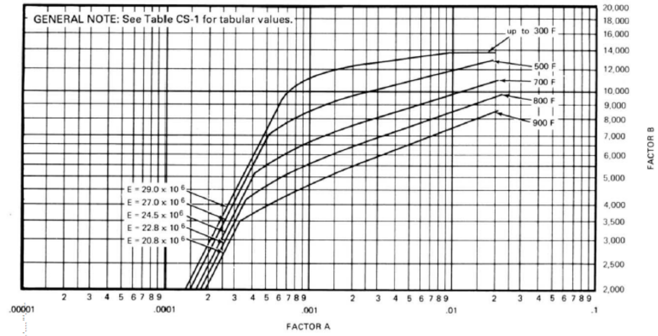
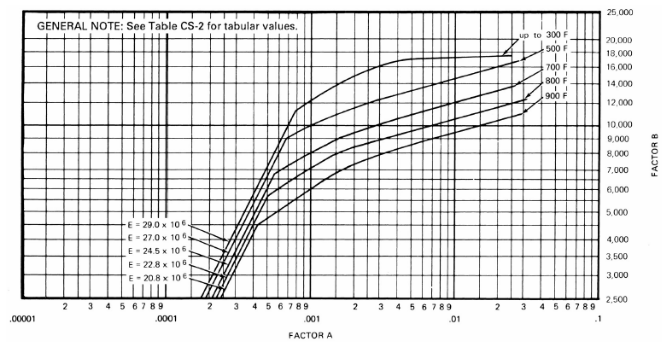


FIG. CS-2 CHART FOR DETERMINING SHELL THICKNESS OF COMPONENTS UNDER EXTERNAL PRESSURE WHEN CONSTRUCTED OF CARBON OR LOW ALLOY STEELS (Specified Minimum Yield Strength 30,000 psi and Over Except for Materials Within This Range Where Other Specific Charts Are Referenced) AND TYPE 405 AND TYPE 410 STAINLESS STEELS [Note (1)]



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Homework

- **Problem 4** – 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 5** – 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 6** – 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

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