CAS School on High Power Hadron Machines

Fundamentals of cryogenics (for Superconducting RF)

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Cryogenics and CAS

- **Two CAS courses**
  - Hamburg 1995, 1996-03 (392 pp.), Ed. S. Turner
    - Superconductivity in Particle Accelerators
  - Erice 2002, 2004-08 (430 pp.), Eds. R. Russenchuck, G. Vandoni
    - Superconductivity and Cryogenics for Accelerators and Detectors
- Many topics involved:
  - Theory side
    - Thermodynamics
    - Superconductivity (& Superfluidity)
  - Technology side (non-exaustive list)
    - Materials issues
      - Be it for magnets, for cavities… and around them
    - Heat transfer mechanisms (and their handling)
    - Vacuum
    - Producing and using cryogens

Summary

- In the following I will mostly illustrate a few key concepts and provide some some “practical engineering considerations”
  - concentrated on superconducting RF linacs
  - SC in magnets is another broad topic, less relevant to High Power Hadron Machines and covered in previous CAS courses
- Lecture deals with two broad topics
  - Cryogenic concepts in general
  - Cryostats and cryogenics for SRF linacs
- This lecture is obviously incomplete in many areas (e.g. cryogenic instrumentation) and intentionally “light” on topics that could easily require an entire course to deal with the details

Why SCRF? RF losses in a RF resonator

$$P_{diss} = \frac{R_s}{2} \int_S H^2 dS$$

- Power is dissipated on the cavity walls, according to their surface resistance R_s

$$R_s = \sqrt{\frac{\pi f \mu_0}{\sigma}} = \frac{1}{\sigma \delta}$$

- For a normal conductor, where δ is the skin depth (which depends on $f^{-1/2}$)

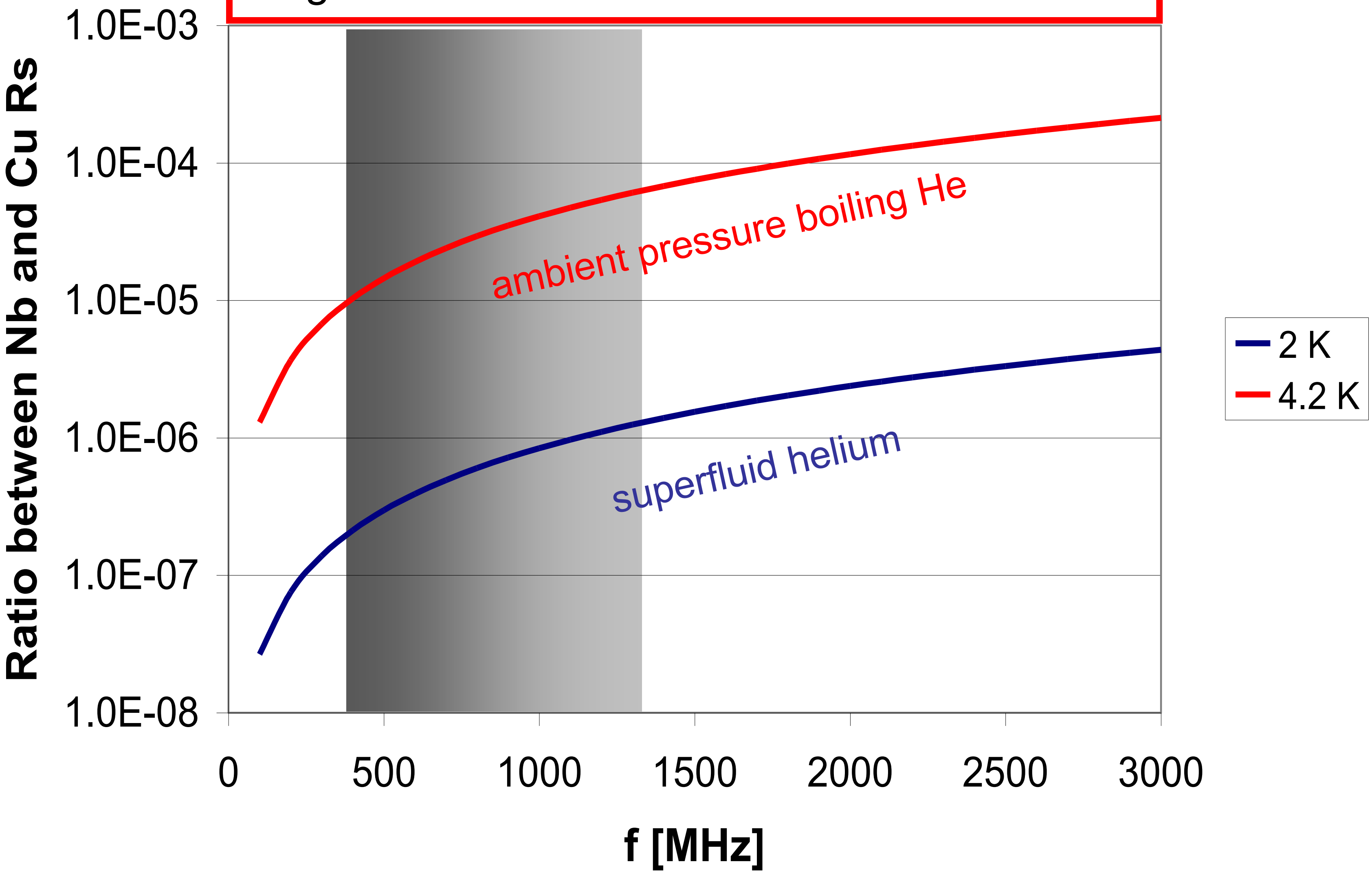
$$R_s[\Omega] = 2 \times 10^{-4} \frac{1}{T} \left(\frac{f[GHz]}{1.5} \right)^2 \exp\left(-\frac{17.67}{T} \right)$$

- For a superconductor, BCS theory
  - Fit for
    - Nb
    - $T < T_c/2$
    - $f \ll 1$ THz

Unlike DC conditions, with RF fields a SC cavity still dissipates power. Not all e- are in Cooper pairs. Surface resistance does not drop to 0!

Superconducting RF “advantage”

Q: Good, are we going to gain 5-6 order of magnitudes for free?



A: No!

- Power is deposited at the (extremely low) operating temperature
- Implications:

$$R_s = R_s^{BCS} + R_s^{mag} + R_s^{residual}$$

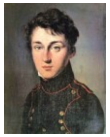
  - Many material & procedure issues to guarantee good R_s
    - Topic: "**SCRF Cavity fabrication technology**"
      - High grade Niobium.
      - Clean joining technology (electron beam welding)
      - Aggressive chemistry (BCP/EP) to remove surface layer damaged by fabrication (rolling, forming, milling, turning, ...)
      - Final treatments in clean room conditions
      - ...
  - We also need to take special measures to guarantee and preserve the low temperature environment
    - i.e. we need a technological complication: a cryogenic infrastructure for the production and handling of the coolant, and for the removal of all heat deposited at low temperatures

We need a Cryoplant

- The cryoplant is a thermal “machine” that performs work at room temperature to extract heat at low temperatures
  - It cools the devices to the nominal temperatures and keep them cold by extracting all heat loads generated at cold
  - Surely we can’t beat thermodynamics and the Carnot cycle!
    - Actually we are lucky if we get to 20-30% of Carnot...
    - Overall, 1 W @ 2 K $\Rightarrow$ 750 W @ 300 K
  - But, even taking into account this factor, there is still a good advantage for superconductivity at moderate frequencies
- Nb critical temperature is 9.2 K, so there is not really a choice for coolants

	$_4$He	H_2	Ne	N_2	Ar	O_2
Normal boiling point	4.22	20.28	27.09	77.36	87.28	90.19

“Réflexions sur la puissance motrice du feu” (1824)
[20 years before 1° law of thermodinamics]



Sadi Carnot (1796-1832)

Work is needed at higher temperatures to remove the heat deposited at lower temperatures

$$W \geq Q_{in} \cdot \frac{T_h - T_c}{T_c}$$

$$Q_{in} = \eta_{tot} W = \eta_{th} \eta_C W$$

$$\eta_C = \frac{T_c}{T_h - T_c} \approx \begin{cases} 1/70 \ \text{ for } \ T_h = 300\,\text{K}, T_c = 4.2\,\text{K} \\ 1/150 \ \text{ for } \ T_h = 300\,\text{K}, T_c = 2\,\text{K} \end{cases}$$

$$\eta_{th} = \begin{cases} 25 - 30\,\% \text{ at } \ T = 4.2\,\text{K} \\ 15 - 20\,\% \text{ at } T = 2\,\text{K} \end{cases}$$

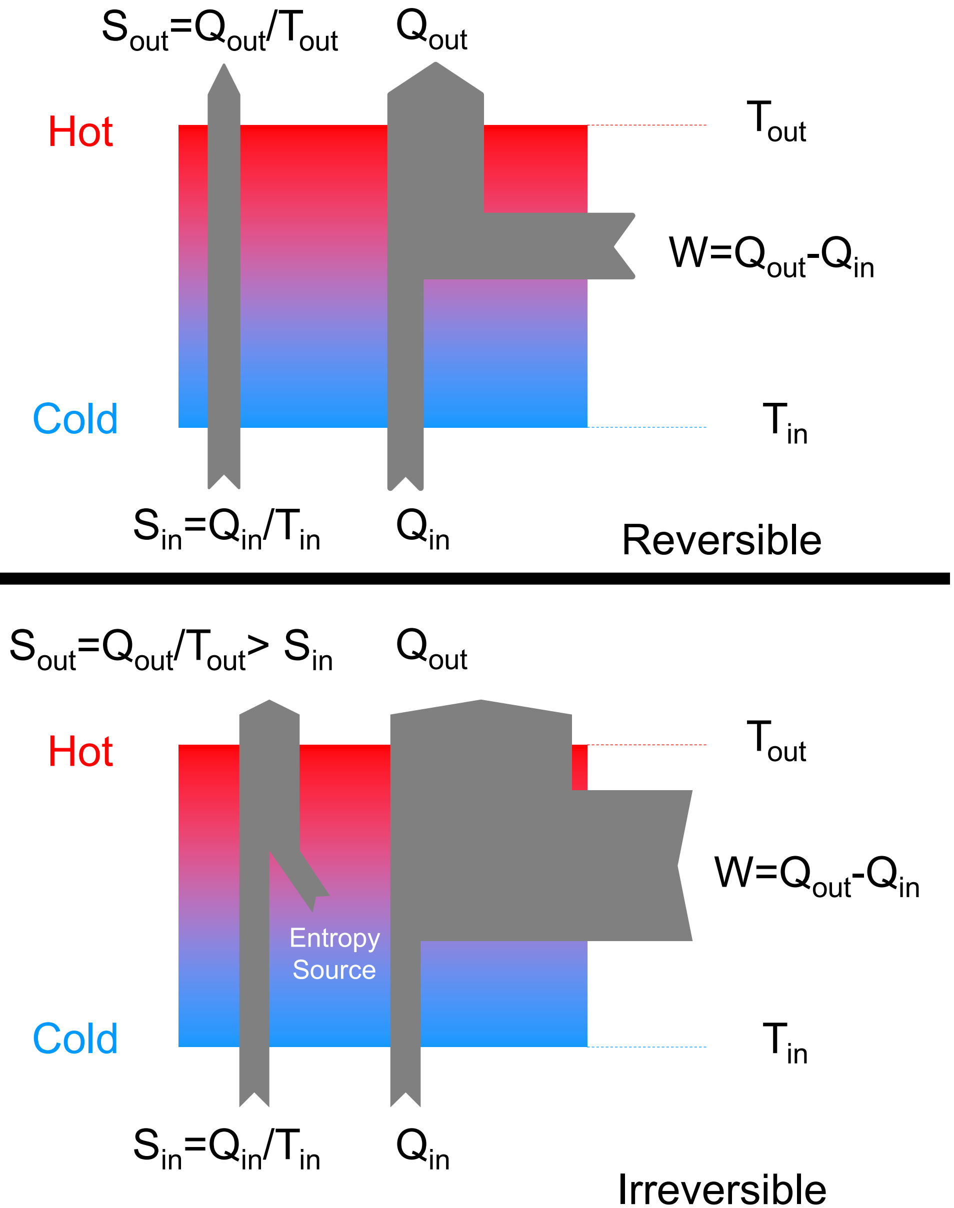
Power to maintain the low temperature environment

- This include ideal Carnot cycle efficiency
- Efficiency of the real thermal machine

Applies to all heat inleaks from the environment to the cold region and cryofluids, not just RF losses

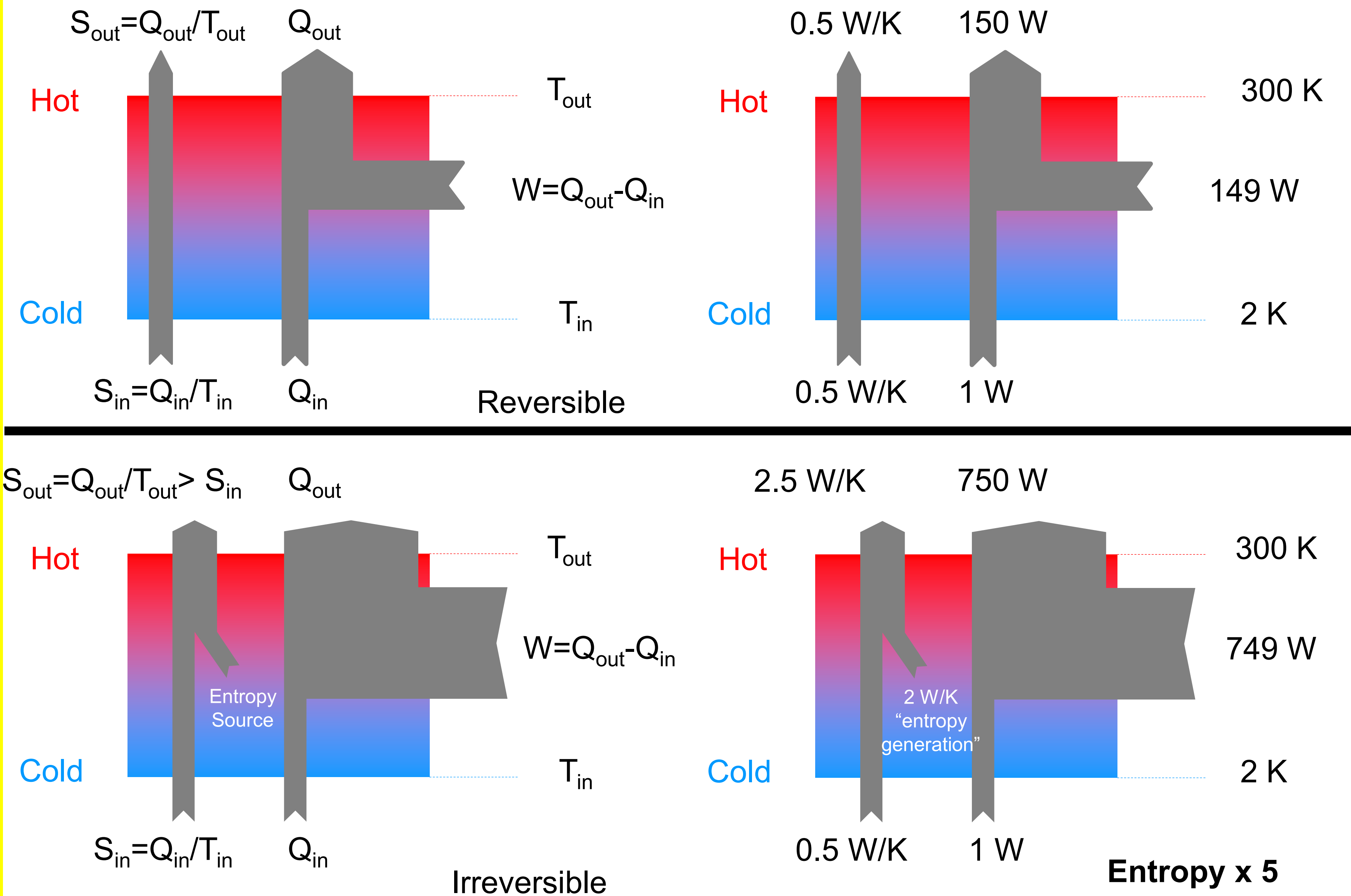
To remove 1 W at 4.2 K we need to use ~ 250 W at 300 K
To remove 1 W at 2 K we need to use ~ 750 W at 300 K

Heat pumps as Entropy pumps



- Entropy is the function of state that allows understanding cryo devices
- Cryogenic systems are entropy pumps, which move entropy from the cold devices into a warmer environment
  - if we provide them energy
- All nonidealities (entropy sources associated to the thermal machine) lead to higher work needed
  - Spurious heat transfers, entropy changes due to compression, expansion, heat exhangers, gas leaks, etc.

What is our non ideality level?



Entropy x 5

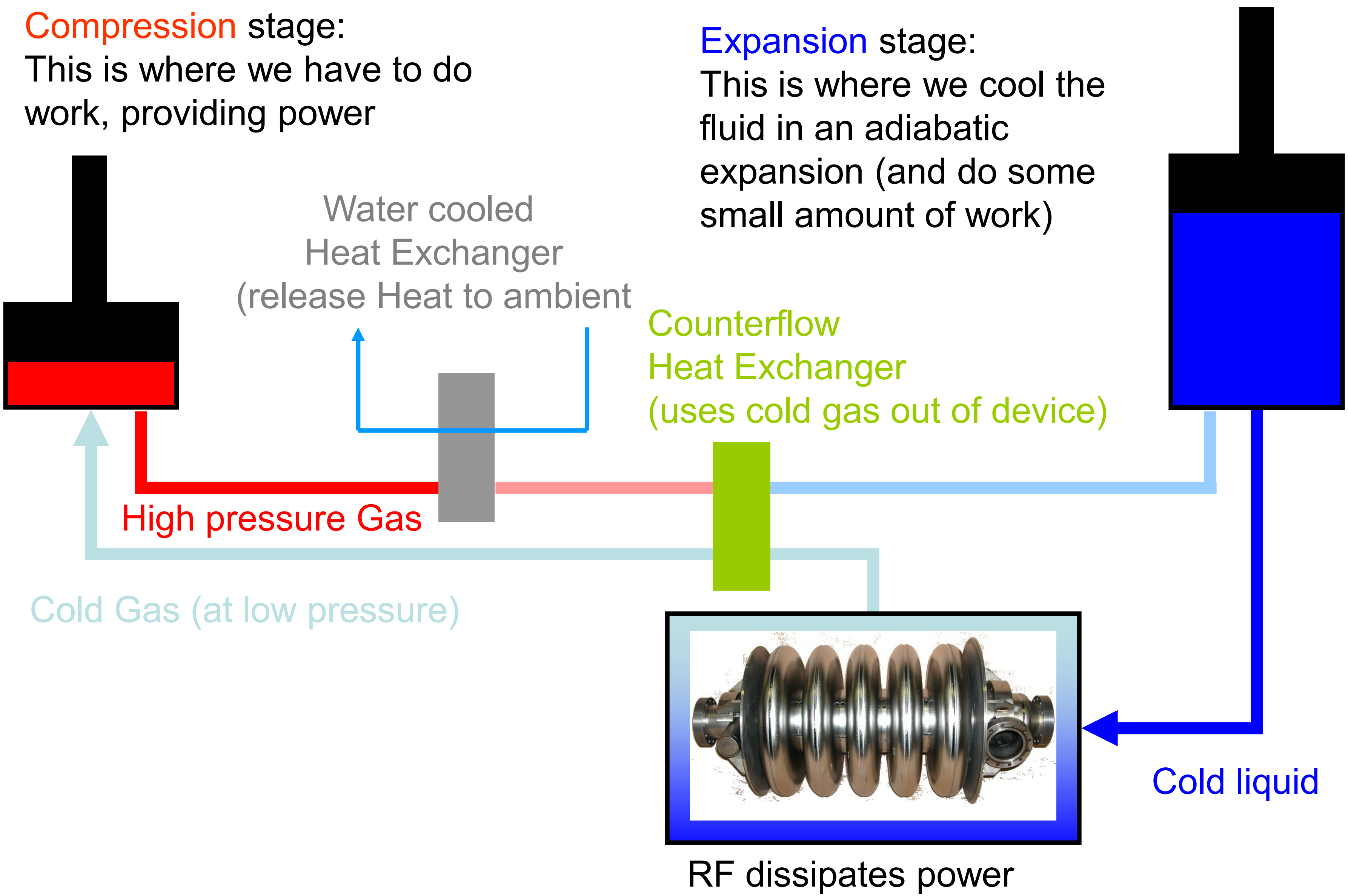
The helium refrigeration process

- A conceptually simple (but impractical) helium liquefier could consist of just two processes or steps
  - **Isothermal compression**
    - Reduce He entropy
  - **Isentropic expansion**
    - Removes energy as work
  - This process illustrates the derivation of the thermodynamic limits for a helium refrigerator
- Real processes just add one more feature -- heat exchangers

The He refrigerator, conceptually

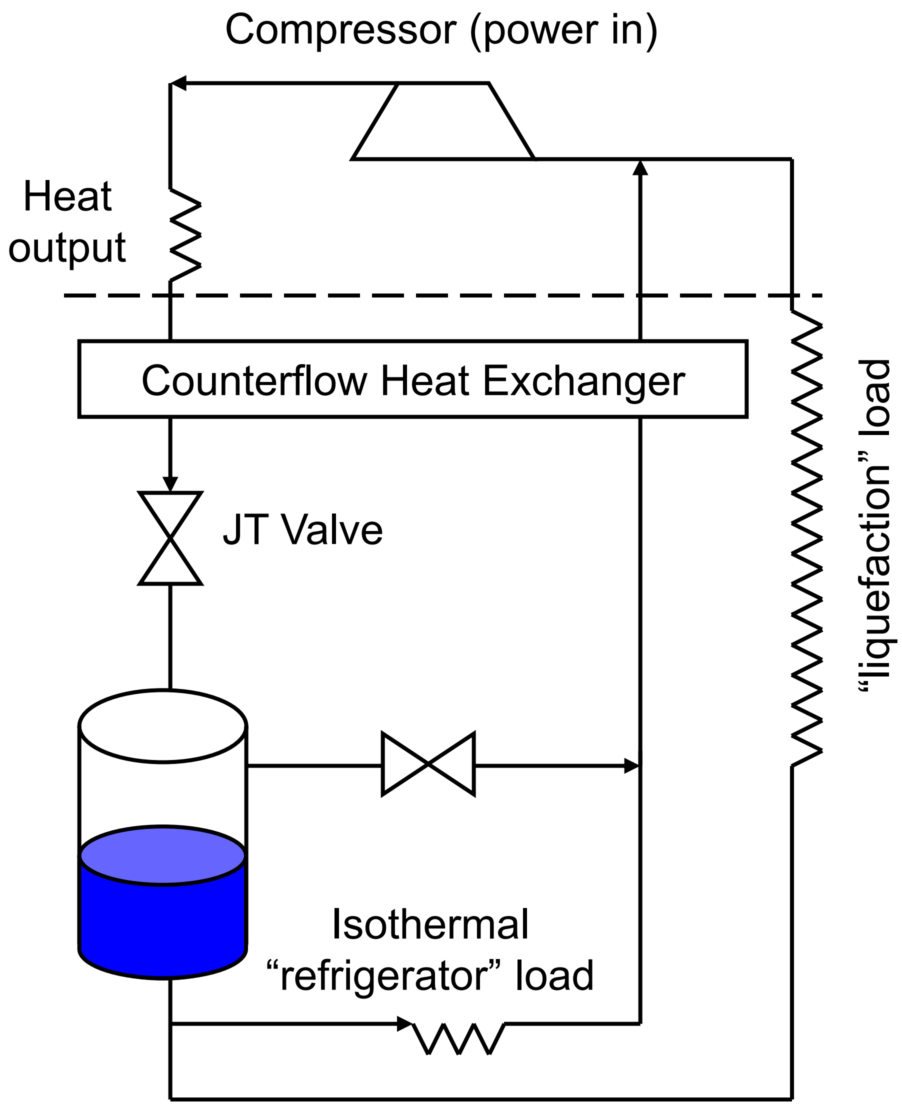
Compression stage:
This is where we have to do work, providing power

Expansion stage:
This is where we cool the fluid in an adiabatic expansion (and do some small amount of work)



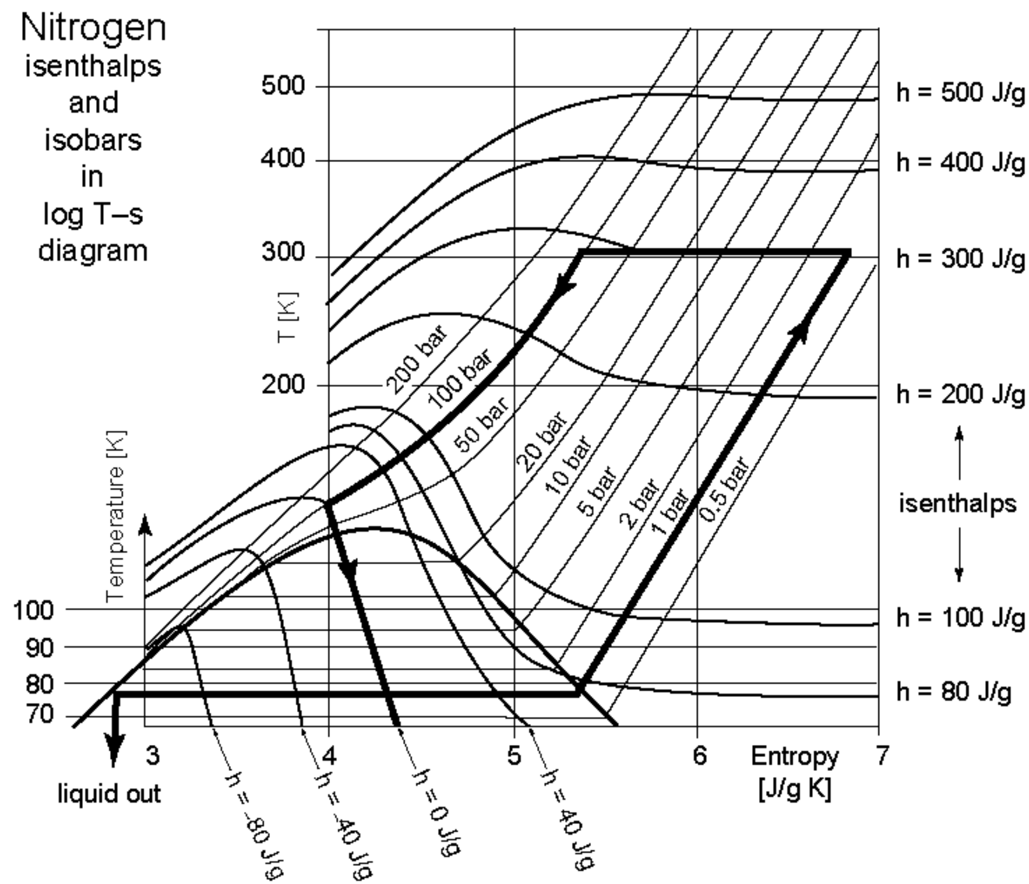
Linde 1895, first industrial liquefaction of air

- Breakthrough with respect to the "cascading" liquefaction experiments
- Use the fact that inversion temperature of air is above ambient temperature, and at sufficiently high pressure an expansion leads to appreciable temperature decreases
  - Joule Thomson effect
- The expansion-cooled gas is then used to pre-cool in counterflow the high pressure gas before the valve
- Gradually decreasing temperature upstream JT, until leading to liquefaction



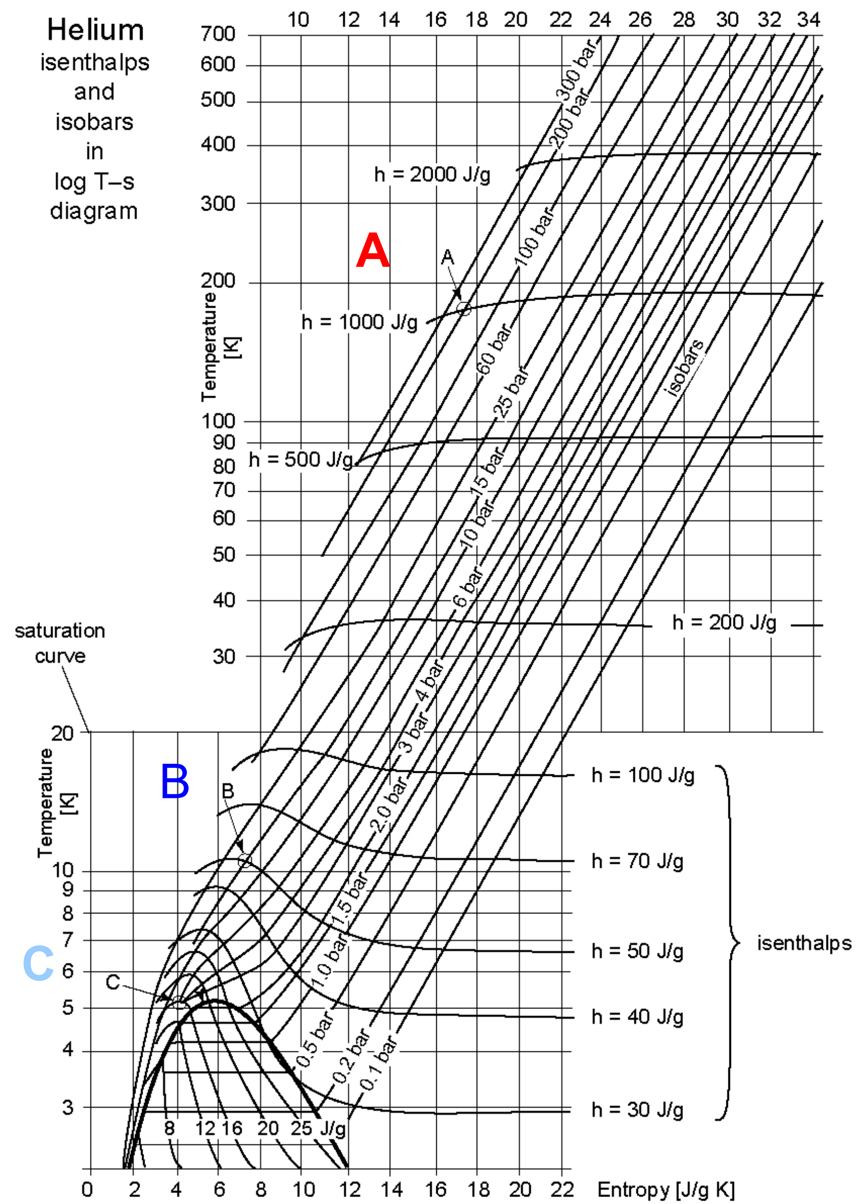
Joule-Thomson Effect

- Understood from T-S diagrams
  - A real gas undergoing an isoenthalp expansion can either cool or warm, depending on the Joule-Thomson effect and the inversion temperature at a given pressure
    - H=U+PV
  - Below inversion temperatu the expansion lead to cooling
  - Above inversion temperatu the expansion lead to warming
  - N_2 T_{inv} = 621 K
  - He T_{inv} = 51 K



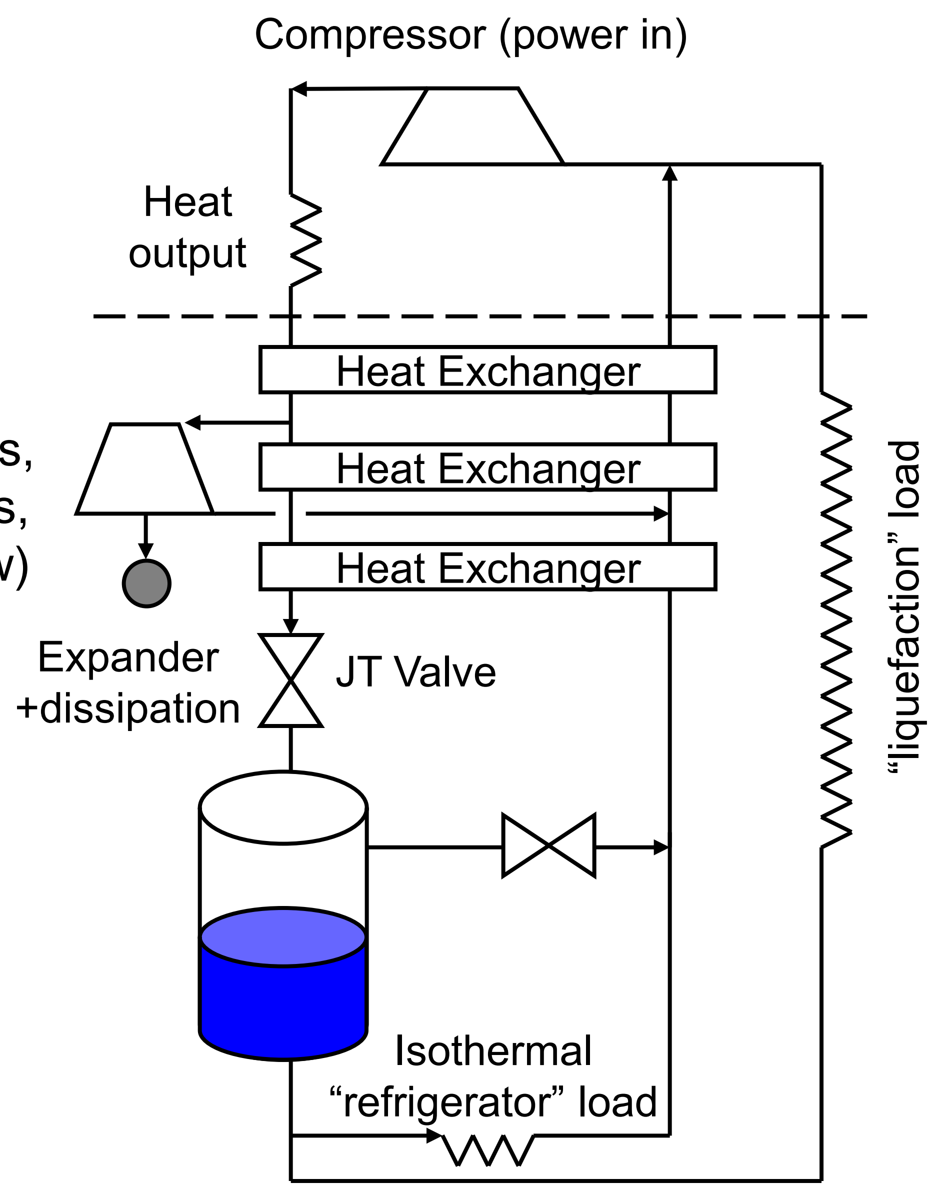
He T-S diagram

- At point A the expansion leads to warming of the gas
- At point B the expansion cools the gas
- At point C it is possible to liquefy the gas to crossing the saturation line (bold) separating one phase domain from the two-phases domain



Real Machines (Claude Cycle, 1902)

- A real cycle adds just more components
  - Several stages of heat exchanges in the flow
  - One or more expansion stages, either using pistons (small systems, versatile) or turbines (bigger plants, efficient at nominal speed and flow)
    - variants with expansion stages in parallel or series
    - not practical to use the work produced by expansion, usually dissipated at ambient temperature
  - The last stage is always the isenthalpic expansion to generate the liquid form (Joule-Thompson valve)



Heat removal by He

- Generally speaking, heat is removed by increasing the energy content of the cooling fluid (liquid or vapor)
  - Heating the vapor
  - Spending the energy into the phase transition from liquid to vapor
    - In the pool boiling mode this is the mechanism, heat is absorbed by evaporation in isothermal conditions
- Cooling capacity is related to the enthalpy difference between the input and output helium (and directly $\propto$ to the mass flow)
- The rest is “piping” (engineering) design to ensure the proper **mass flow, convective exchange coefficient, pressure drop analysis, …**

Heat removal by He

$$P_{removed}\,[\mathrm{W}] = m_{flow}\,[\mathrm{g/s}] \big/ \Delta h [\mathrm{J/g}]$$

		40 K to 80 K	5 K to 8 K	2 K
		Temperature level	Temperature level	Temperature level
		(module)	(module)	(module)
Temp in	(K)	40,00	5,0	2,4
Press in	(bar)	16,0	5,0	1,2
Enthalpy in	(J/g)	223,8	14,7	4,383
Entropy in	(J/gK)	15,3	3,9	1,862
Temp out	(K)	80,00	8,0	2,0
Press out	(bar)	14,0	4,0	saturated vapor
Enthalpy out	(J/g)	432,5	46,7	25,04
Entropy out	(J/gK)	19,2	9,1	12,58

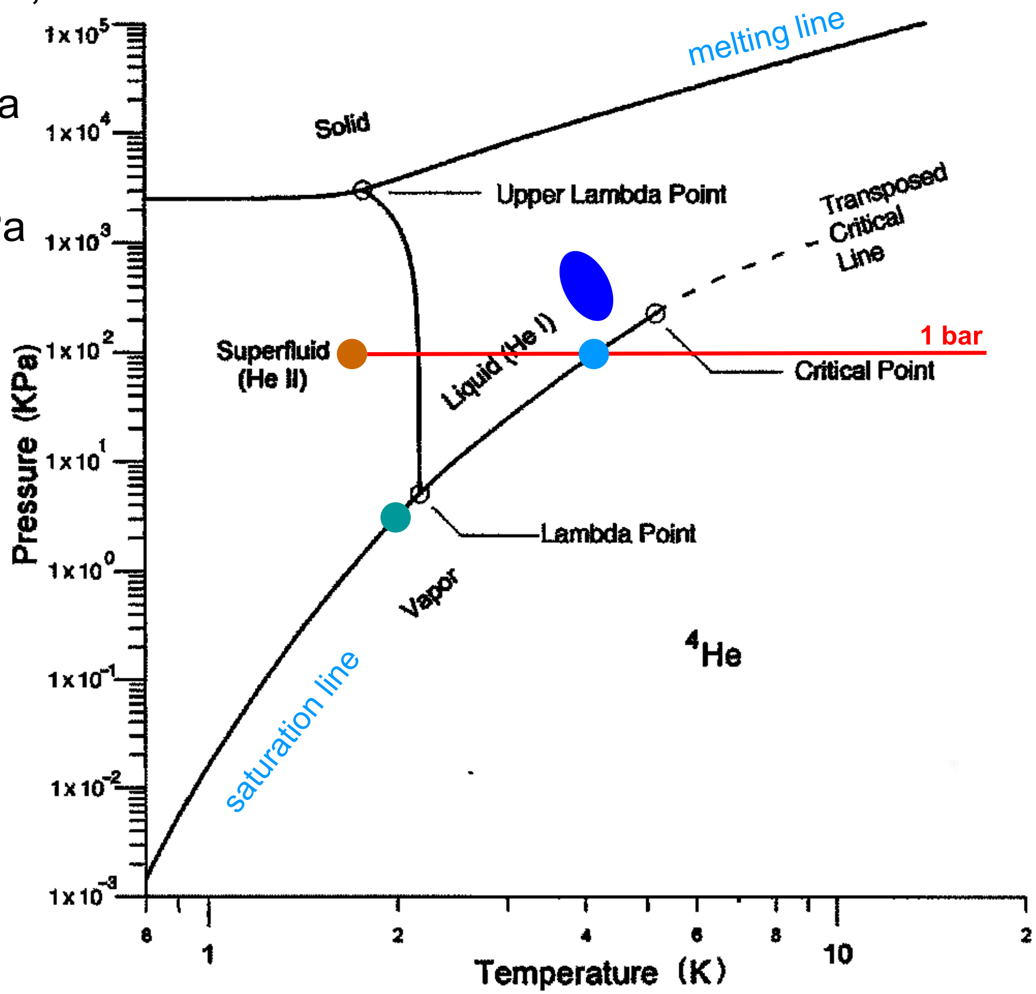
From: T. Peterson, ILC Cryogenic system design spreadsheet, FNAL

- From the assessment of heat loads at the various circuit levels, one can compute the needed mass flows

He: the fluid for SC accelerators

- Unique feature, melting line and saturation line do not intersect, they are separated by the "Lambda" line, separating the superfluid state
  - Critical point: 5.195 K @ 227.5 kPa
  - Normal boiling point: 4.222 K
  - "Lambda" point: 2.177 K @ 5.0 kPa
- Large accelerators use a few "regions", i.e. cooling modes
  - Pool boiling He I
    - LEP, KEKB, HERA SRF
  - Saturated He II
    - CEBAF, FLASH, XFEL, SNS, ILC, ESS, …
  - Force flow supercritical He I
    - Tevatron, HERA, SSC, …
  - Pressurized He II
    - LHC

Helium phase diagram



Operation mode: pool boiling

- SCRF Cavities operate in the **pool boiling mode**, on the saturation curve, either at ambient pressure or below the lambda point
  - Ideally isothermal mode of operation, with good local heat transfer
  - Cavities are thin-walled high-Q resonators, very sensitive to environment pressure, so it is the preferred mode
  - Saturated He II
    - besides a lower temperature, gives the advantage of good heat trasport (vapor coming from the surface in 2 Phase He II flow) and low pressure conditions (30 mbar) lead to quiet environment
    - **but:**
      - requires pumping on the bath,
      - is subject to risks of air inleak
      - the operation close to the minimum of the Paschen curve complicates the operation of electrical and RF feedthroughs (especially true for instrumented vertical test facilities)

Operation modes

- Generally magnets are cooled with a **single phase**, either He I or HeII, for good penetration of He in the coils
  - Pressurized He II
    - has excellent heat conduction capabilities
      - thermal conductivity three orders of magnitude higher than OFHC copper
    - No possibility of air inleaks!
    - Cryogenic stabilization
    - **but**
      - Cooling in non-isothermal conditions, with a temperature gradient
      - Requires an additional pressurized-to-saturated He II heat exchanger, where evaporative cooling carries heat away from the cold mass
      - The pressure conditions discourages to use this cooling method for the high-Q RF resonators

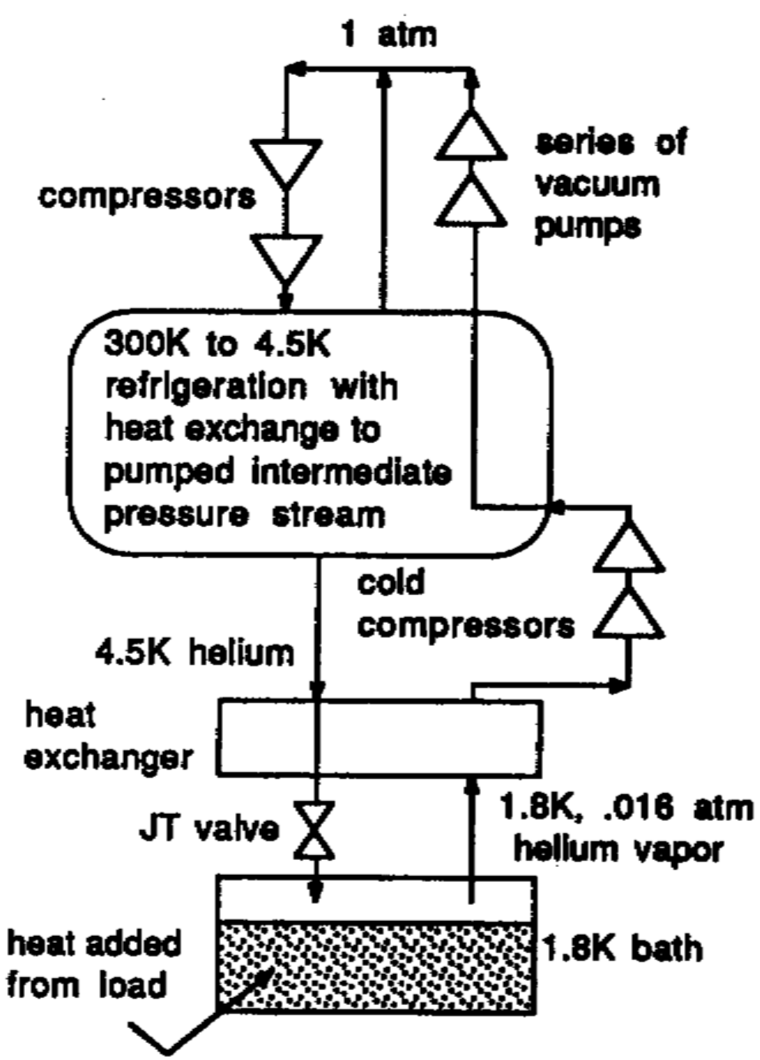
Evaporative cooling

- In any cooling mode ultimately heat is carried away from the cold region by evaporating vapor from a saturated bath and carrying it away
  - LHe (subatmospheric 2 phase 2 K or 1 bar boiling 4.2)
    - ΔH ~ 20 J/g [23.4 J/g - 20.8 J/g]
  - Boiling LN2 at 77 K
    - ΔH = 200 J/g
  - Water... at 100 °C
    - ΔH = 2200 J/g

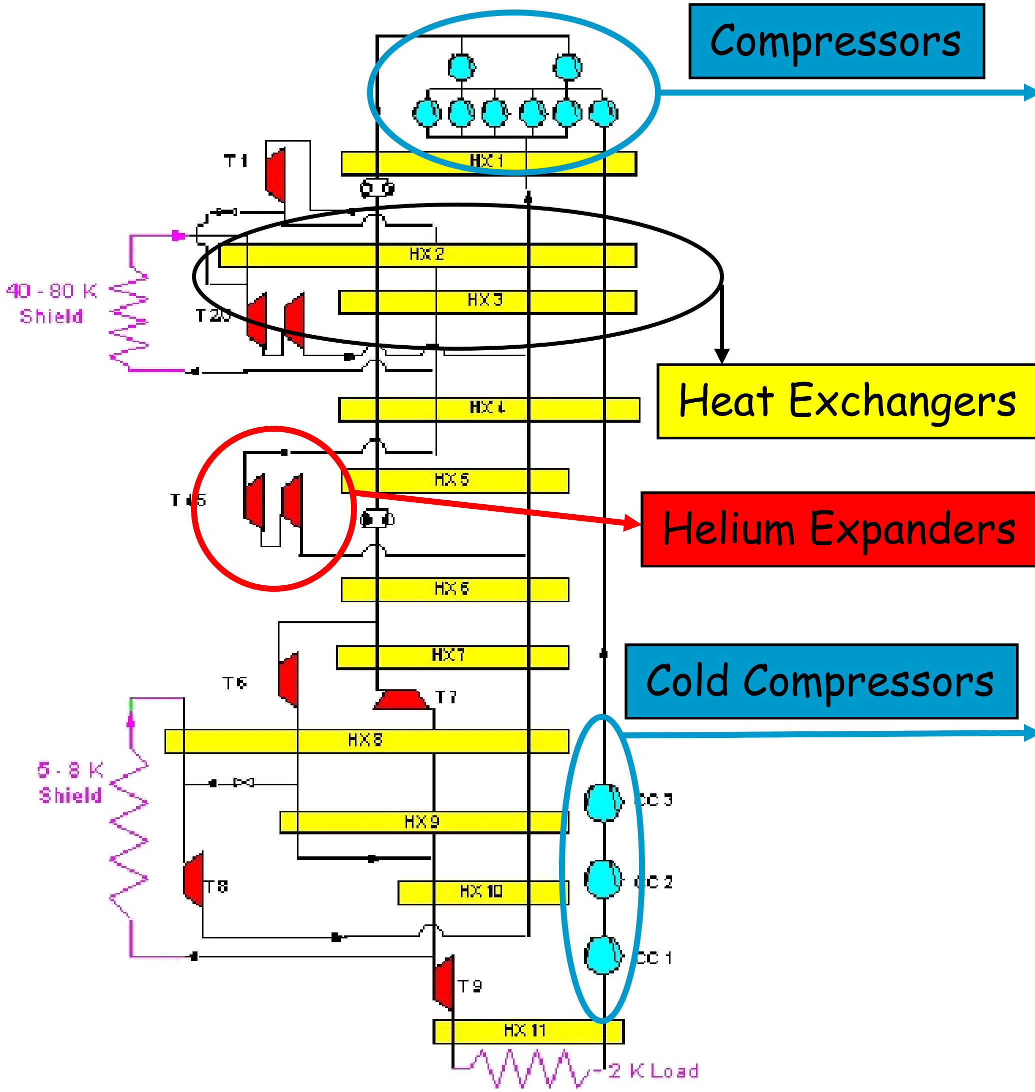
- Therefore, beware, big heat deposition at cold 2 K imply
  - big mass flow of low pressure gas
  - large volume flow

One additional component for Saturated He II

- Temperatures lower than 4.2 K means sub-atmospheric pressure conditions for the He bath where we want to extract the dissipated power
- But with **high heat loads** and lo pressures the gas volume flow from the bath becomes large
  - again, latent heat of evaporation is only approximately 20 J/g
  - cold compressors are needed to increase pressure conditions before the He gas reaches room temperature conditions



ILC Refrigerator Scheme



He cycle efficiency in big plants

	RHIC	CEBAF	HERA	LHC
Equivalent capacity at 4.5 K (kW)	25	13	8.4 /coldbox	18 /coldbox
Power required (W/W)	450	350	285	230
Efficiency	16%	20%	25%	30%

Cooling accelerator components

- Usually physicist and engineers designing an accelerator concentrate on the component design (cavities/magnets)
  - Then “jacket” them into helium tanks and cryostats
  - Finally specify and go out to buy a cryoplant
- The cooling mode, heat transfer mechanisms, fluid pressure drops, cooldown and warmup procedure, transient operation conditions need to be considered early in the component design
  - They can affect the complexity of the cooling system
- The cooled system has to be viewed as part of the overall cryogenic system
  - especially for big machines, where tradoff need to be made between components and support infrastructure

Heat transfer mechanisms

- One important issue in the design of accelerator components operating at cold temperatures is the **understanding and management of heat transfer processes**
- Once again, power deposition at cold temperatures implies the following r.t. power consumptions:
  - ~ 750 W/W at 2 K
  - ~ 250 W/W at 4.5 K
  - ~12 W/W at 70 K
- It is therefore crucial to intercept thermal fluxes from the room temperature environment before they reach the coldest temperatures
  - Deal with all heat transfert modes!

Provide thermal insulation!

- Three mechanisms for transferring heat
  - Conduction
    - Heat is transported inside solid or stagnant fluids, by processes at the atomic scale
  - Convection
    - Macroscopic fluid movement is responsible of heat transfer from the wet surfaces
  - Radiation
    - Heat is trasnported in the form of electromagnetic radiation emitted by surfaces, without requiring any supporting fluid or medium
- Besides loads intrinsically generated at the cold temperature for the device operations (e.g. the dissipated power on the SC RF cavities), we have to deal with heat leaking from the environment due to these three mechanisms

Heat losses issues: Physical mechanisms

- Heat conduction

$$\dot{Q} = \frac{S}{L}\int_{T_c}^{T_h} k_{th}(T)\,dT$$

  - The SRF cold mass has many penetrations from the room temperature environment (RF couplers, cables, …)
    - Proper choice of low thermal conduction, k_{th}, materials whenever possible
    - Minimize thermal paths from r.t. and provide thermalization at intermediate temperatures (small S, big L)
- Convection

$$\dot{Q} = S\,h\,(T_h - T_c)$$

  - Convective exchange from r.t. is managed by providing insulation vacuum between the room temperature vessel and the cold mass
- Thermal radiation

$$\dot{Q} = S\varepsilon\sigma_{SB}\left(T_h^4 - T_c^4\right)$$

  - Radiated power from hot surfaces to vanishingly temperatures is proportional to T^4 (Stephan-Boltzmann). $\sigma_{SB} = 5{,}67\cdot 10^{-8}$ [W m^{-2} K^{-4}]
    - Reduce the surface emissivity, ε (material and geometry issue)
    - Intercept thermal radiation at intermediate temperatures by means of thermal shields

Conduction

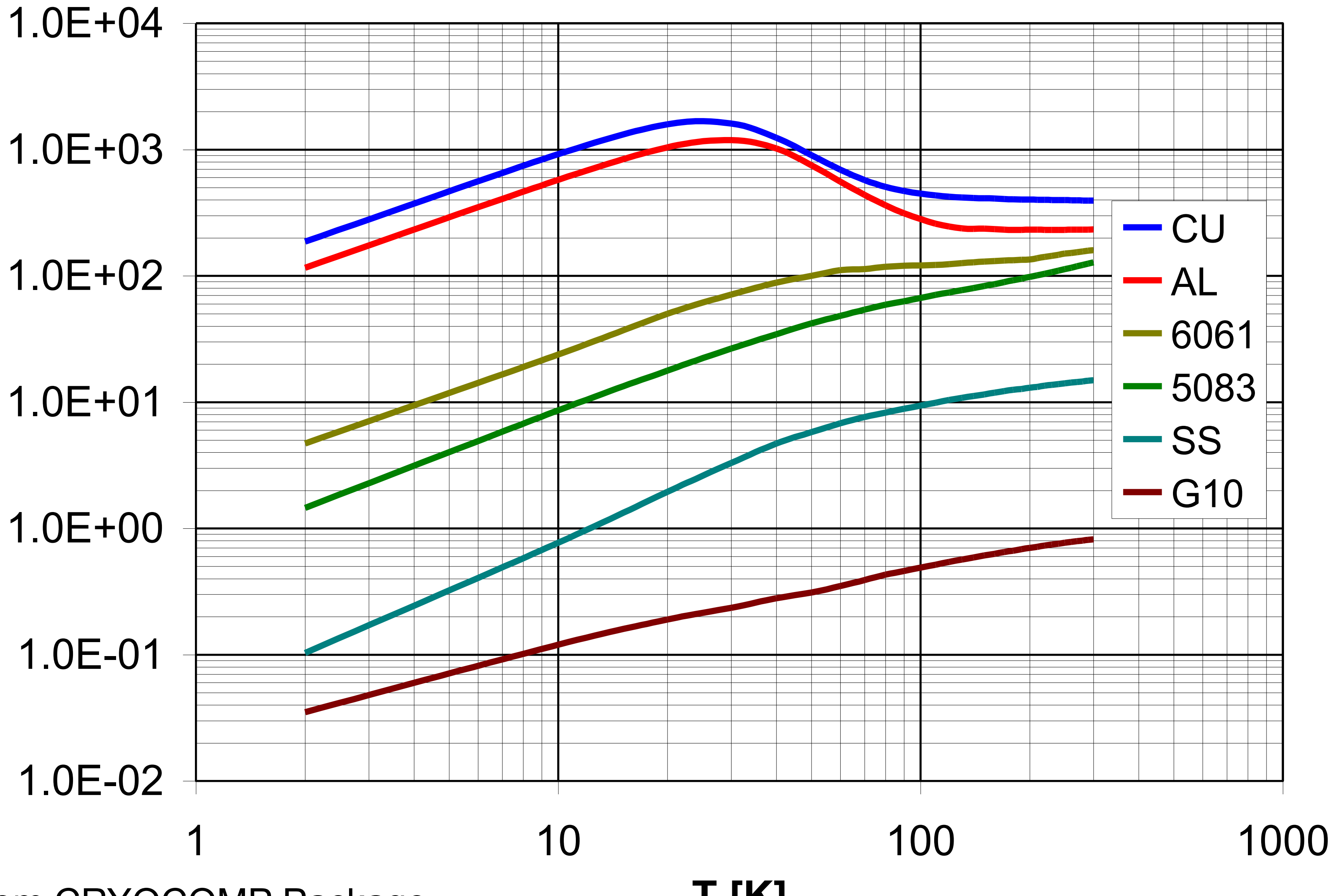
- Obeys Fourier law $\dot{Q} = k(T)\, S\, \nabla T$
- For a 1D steady state conduction problem of flow through an area *S* over a length *L* with fixed temperatures T_{hot} and T_{cold}, we can write it in the form

$$\dot{Q} = \frac{S}{L}\int_{T_{cold}}^{T_{hot}} k(T)\,dT = \frac{S}{L}\left(\int_{T_{reference}}^{T_{hot}} k(T)\,dT - \int_{T_{reference}}^{T_{cold}} k(T)\,dT\right) =$$

$$= \frac{S}{L}\left(K_{\mathrm{int}}(T_{hot}) - K_{\mathrm{int}}(T_{cold})\right)$$

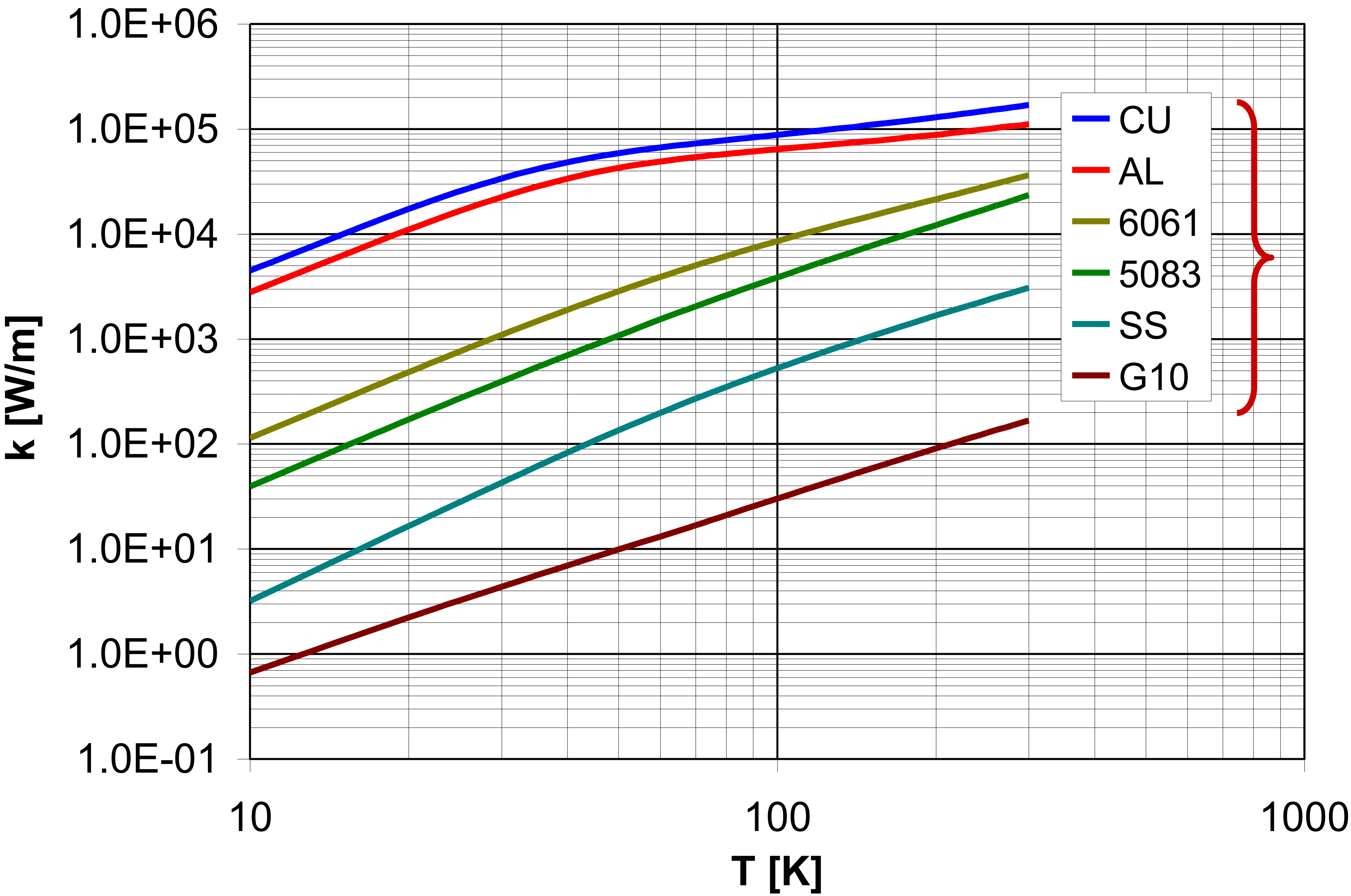
- Thermal conductivity integrals tabulated in literature
- Varies greatly with temperature and with materials, proper choice of material and thermal intercepts for conduction paths to the cold environment is necessary

Temperature dependent thermal conductivity



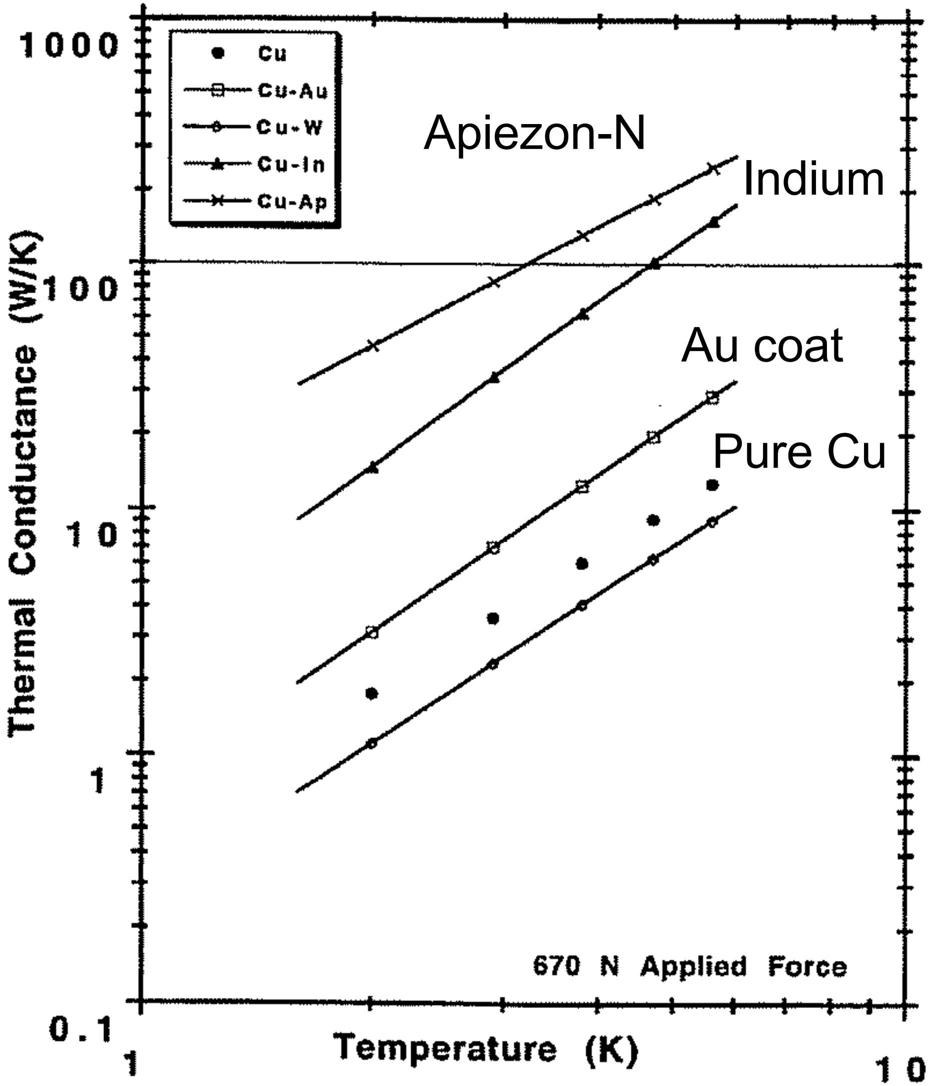
From CRYOCOMP Package

Thermal conduction integral, from 2 K



Thermal contact at interfaces

- Contact between surfaces is made only at discrete locations, not over the full areas
  - Thermal conductance of pressed contacts depend on the applied force (not pressure!) and surface finish
  - Oxyde layers on the surface increase the thermal resistance
  - Indium foils or high thermal conductance grease (Apiezon-N) may be used to enhance the thermal contact
- Important issue when making provision for thermal intercepts to prevent heat leaking into cold environment
  - Indium foils most common



Convection

- Convection is one of the physical mechanism by which we are able to extract heat from our devices and to route it to the cooling fluids flowing in the cryogenic piping
  - Analysis of the convection exchange is necessary to make proper provisions for the cooldown and warmup procedures and for the good work of the thermal intercepts preventing conductive heat leaks
- But also, we need to prevent convective exchanges from the ambient temperature environment to the cold region
  - That's why all the cold devices are ultimately places in a vacuum vessel, where a pressure of 10^{-4}-10^{-3} mbar prevents convective exchange to the low temperature regions
  - i.e. remove the fluid to prevent convective exchanges...

Convection heat transfer

- Heat transfer between a bulk fluid at temperature T_b and a surface of area S at temperature T_w is described by

$$\dot{Q} = S\, h \left(T_w - T_b\right)$$

- Determination of h can be challenging, and is usually done from experimental correlations, via the dimensionless groups

$$Nu = \frac{hD}{k_{th}} \quad \text{(convection/conduction exchanges)}$$

$$Re = \frac{\rho\, v\, D}{\mu} \quad \text{(inertia/viscous forces)}$$

Laminar (<2000) or turbulent (>10^4) flow

$$Pr = \frac{C_p \mu}{k_{th}} \quad \text{(momentum/thermal transport)}$$

Fluid related

Correlations

- Generally $$Nu = f(Re, Pr)$$
- Except for the case of HeII, frequently the same correlations used for non-cryogenic fluids can be used
- But correlations are valid for given flow conditions, and the fluid properties need to be evaluated at the proper temperature and pressure conditions
- Many correlations exist in literature, for various geometrical flow configurations and regimes
  - Natural convection
  - Liquid and Gas monophase flows $Nu = 0.023\, Re^{0.8} Pr^{0.4}$
- **Recipe:** Evaluate regime via *Re*, then *Pr* through fluid properties, and compute *Nu* from correlation
  - Calculate *h* from *Nu*

Radiation heat exchange

- Total radiated flux emitted by a body of emissivity ε at T_h and received at negligible temperatures

$$\dot{q} = \varepsilon \, \sigma_{SB} T_h^4$$

amounts to 500 W/m^2 at 300 K and 2 W/m^2 at 77 K for ε=1

- Flux collected by a surface with emissivity ε and temperature T_c from a black body at T_h is

$$\dot{q} = \varepsilon \, \sigma_{SB} \left(T_h^4 - T_c^4 \right)$$

- Emissivity depends on the temperature and surface finish
  - Examples
    - surface as fabricated
      - from RT to 77 K, SS ε=0.34, Al ε=0.12
      - from 77 k to 4 K, SS ε=0.12, Al ε=0.07
    - polished surfaces
      - from RT to 77 K, SS ε=0.10-0.12, Al ε=0.08-0.10
      - from 77 k to 4 K, SS ε=0.07, Al ε=0.04-0.06

See G. Vandoni in CAS 2004-08 for more data

Mamagement of radiative load

- The first measure is to intercept the thermal flux impinging on the cold surfaces from the room temperature environment with one (or more) thermal screen at actively cooled at higher temperatures
  - E.g. 40 to 80 K Cu or Al shield in all designs for magnets and SRF cavities
- A second effective way to protect the surfaces from radiation load is to wrap them with many “floating” (i.e. radiation cooled) reflective screens
  - Multi Layer Insulation (MLI)
    - Reflective aluminum foils (or aluminized/double aluminized polyester films) separated by an insulating spacer material (a glass-fiber or polyester net or paper foil)
    - Packing density of the layers affects performances, but even more important are the installation procedures
      - don’t leave holes and don’t short circuit layers!

Practical MLI

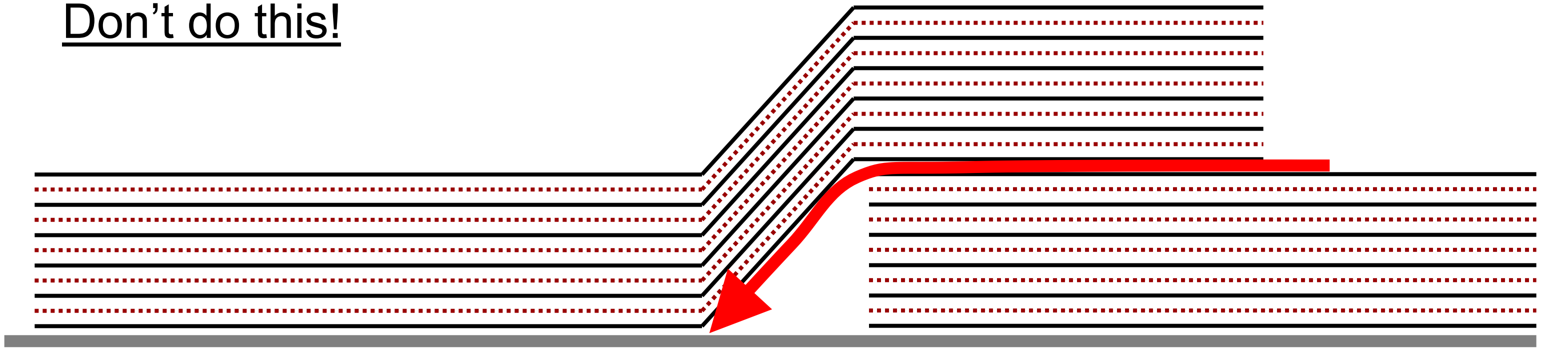
- With proper care MLI can reduce radiative loads to
  - 0.5-1.0 W/m^2 from Room Temperature to 80 K level
  - 0.05-0.1 W/m^2 from 80 K to neglible temperatures

- Any small hole in the shielding that is needed to accomodate for pumping lines, current leads, RF feeds, cabling should be avoided with care in order not to expose a direct line of sight from the room temperature surfaces to the cold region
  - Remember that RT blackbody radiation is as high as 500 W/m^2!

- When joining MLI blankets it is necessary to avoid thermal short circuits, putting in contact inner layers with the outer ones, impairing the “floating” screen concept

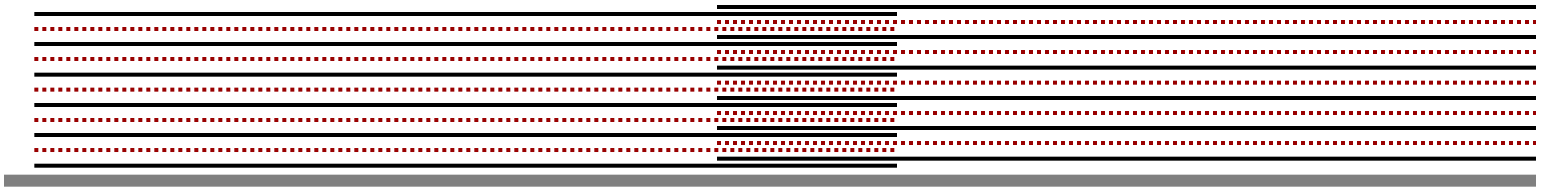
MLI connections

Don't do this!



Cold Surface

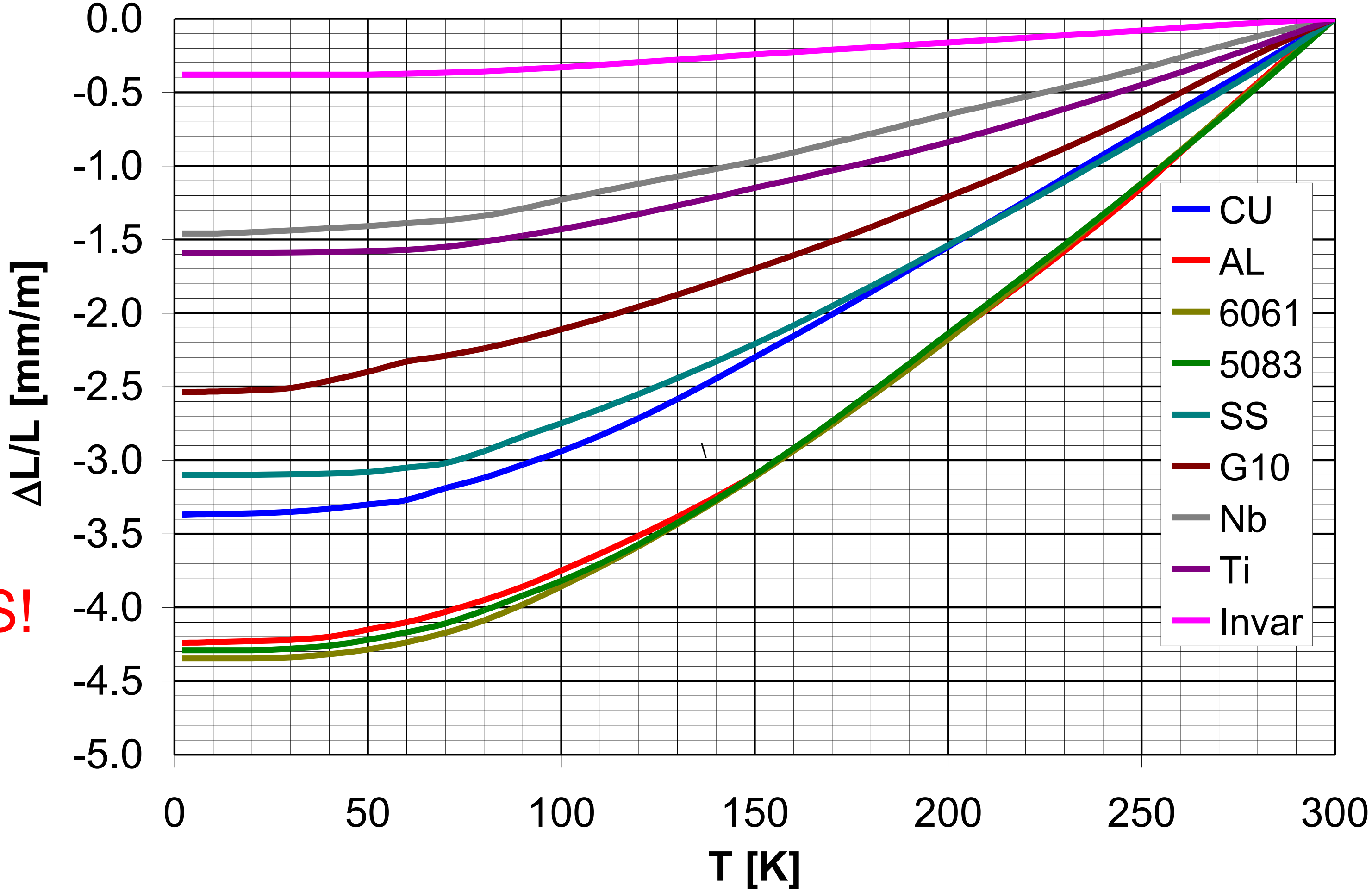
Do this!



Cold Surface

Material contraction at low temperatures

- Materials have huge differences in the thermal contraction coefficients, and high stresses can be induced if relative movements are constrained



- Nb half SS!
- Nb = Ti
- Invar ~ 0
- Al large!

Warmup and Cooldown

- Need to be foreseen in the design

- Cooling down
  - A single fill line from the top of the device (or from one end) will not easily work due to the possibility of interruption of the incoming liquid flow by the generated vapors
    - Either vent the vapor or have separate bottom fill lines

- Warming up
  - Helium flow will stratify with a thermal gradient. Bottom regions will be slow to warm up
    - Provide means of heating lower parts of the cold mass, e.g. electrical heaters or warmup lines bringing warm vapors

Pressure drop

- In a pipe of diameter *D* and length *L* where a fluid with density ρ and velocity *v* flows at a mass flow rate *m'* in the turbolent regime

$$\Delta P = \frac{8}{\pi^2} \frac{m'^2}{\rho D^5} L f$$

no elevation change,
no fluid density variations

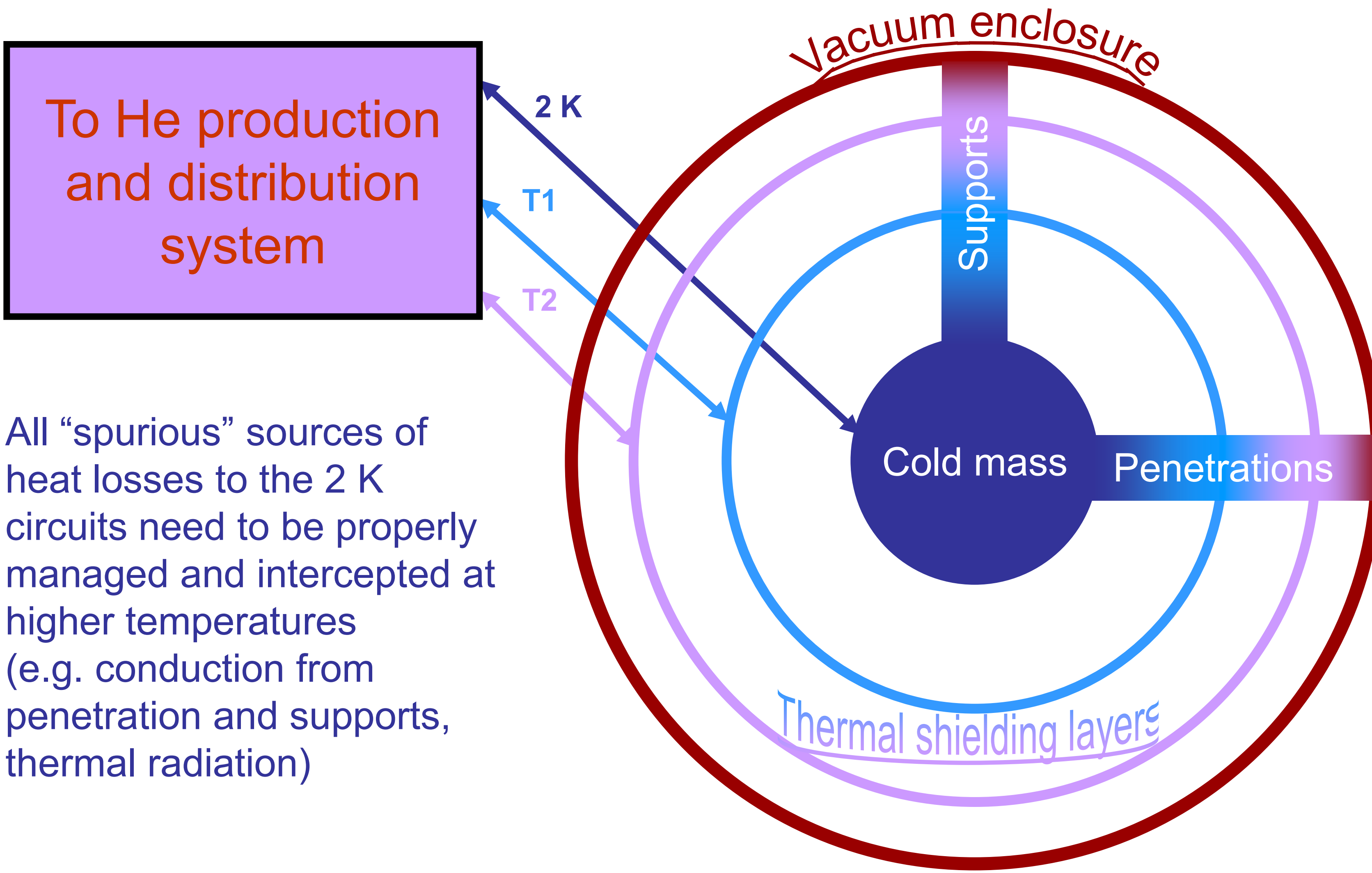
- where *f* is the fluid friction coefficient (depending on geometry, flow and roughness)

- This pressure drop (increase!) is particularly important for the exhaust circuit removing the 2 K vapors from the cavities, since the mass flow can lead to pressure increase at the cavities
  - In a saturated bath T=T(P), therefore an insufficient diameter would lead to inability to maintain operating temperature!

The cavity cryomodules

- All the cryogenic engineering considerations briefly discussed in the previous slides need to be addressed when designing one important item in a Superconducting RF linac: **the cryomodule**
- The cryomodule is the modular building block of the accelerator, it needs to provide
  - the mechanical support of the cavities (and possibly focussing elements)
    - need to address cavity alignment tolerances as well
  - the cold environment needed for operation
    - and adequate protection agains spurious heat leaks to the cold region not to affect efficiency
- The cryomodule is an important part of the cryogenic plant, since it is the region where the important heat loads are located

"Cartoon" view of the system



All "spurious" sources of heat losses to the 2 K circuits need to be properly managed and intercepted at higher temperatures (e.g. conduction from penetration and supports, thermal radiation)

Engineering practices for cryomodule design

- **Thermal design**
  - Minimization of spurious heat loads at the coldest temperatures
  - Heat removal at various temperature levels (for the device operation and for the thermal intercepts)
  - Add provisions for cooldown and warmup, where the large enthalpy content of the cold mass need to be carried away
- **Mechanical design**
  - Support the devices with minimal heat losses
  - Support gravity, vacuum and pressure loads
  - Deal with stresses due to thermal gradients during transient conditions and operation
  - Implement alignment of the sensitive components, and their preservation under differential thermal contractions
- **"Hydraulics" design**
  - Integrate cooling circuits in the cryogenic system

Case Study, TTF (XFEL & variants) modules

- The TTF cryomodules represent the state of the art of low losses cryomodules for 2 K SRF cavities
  - Design conceived for the TESLA linear collider
  - Used for XFEL linac 1.3/3.9 GHz modules, with minimal modifications
  - Baseline for ILC modules
  - Concept followed in other current or proposed projects (e.g. Cornell ERL)

- The module design is illustrated here to "summarize" the interplay of design issues at various system levels for the linac/cryosystem and cryomodule

Initial requirements

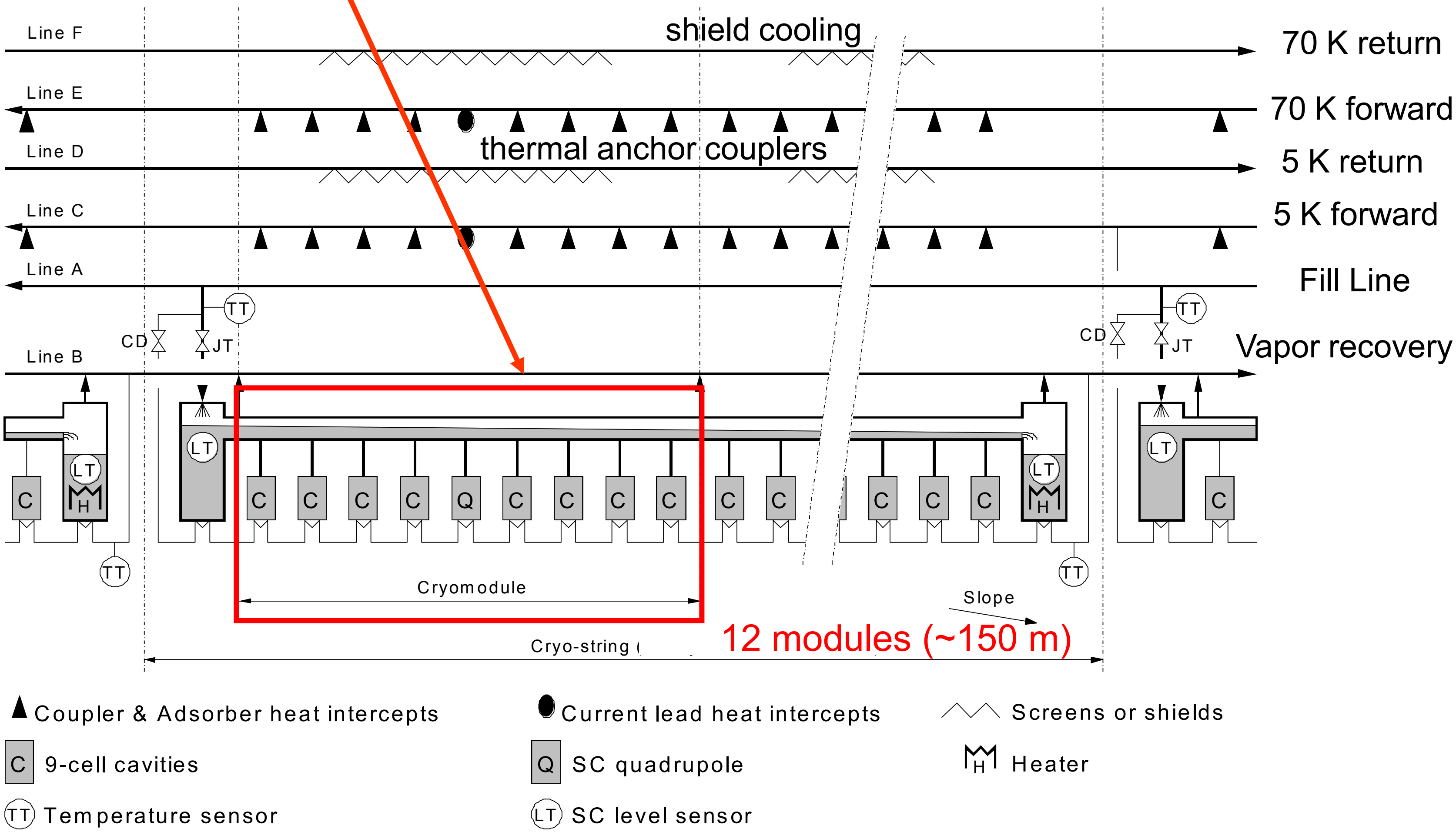
- High filling factor
  - maximize ratio between real estate gradient and cavity perfs
  - long cryomodules/cryo-units and short interconnections
- Moderate cost per unit length
  - simple functional design based on reliable technologies
  - use the cheapest allowable material that respect requirements
  - minimum machining steps per component
  - low static losses, for operation costs (TESLA > 30 km)
- Effective cold mass alignment strategy
  - room temperature alignment preserved at cold
- Effective and reproducible assembling procedure
  - class 100/10 clean room assembly just for the cavity string
  - minimize time consuming operations for cost and reliability

Consequences/II

- The request for a **high filling factor** [machine size] and the necessity to **minimize static heat losses** [operation cost] leads to integrate the cryomodule concept into the design of the whole cryogenic infrastructure
  - Each cold-warm transition along the beamline or cryogenic feed into the module requires space and introduces additional losses
- Thus, long cryomodules, with many cavities (and magnets) are preferred, cryogenically connected, to form cryo-strings, in order to minimize the # of cryogenic feeds
  - Limit to each cryomodule unit is set by fabrication issues, module handling, and capabilities to provide and guarantee alignment
    - practically 10 to 15 meters
  - RF heat loads increase with the number of cavities in the module, and lead to an increase in the sizes of some cryogenic piping

(12) Modules are connected in “Strings”

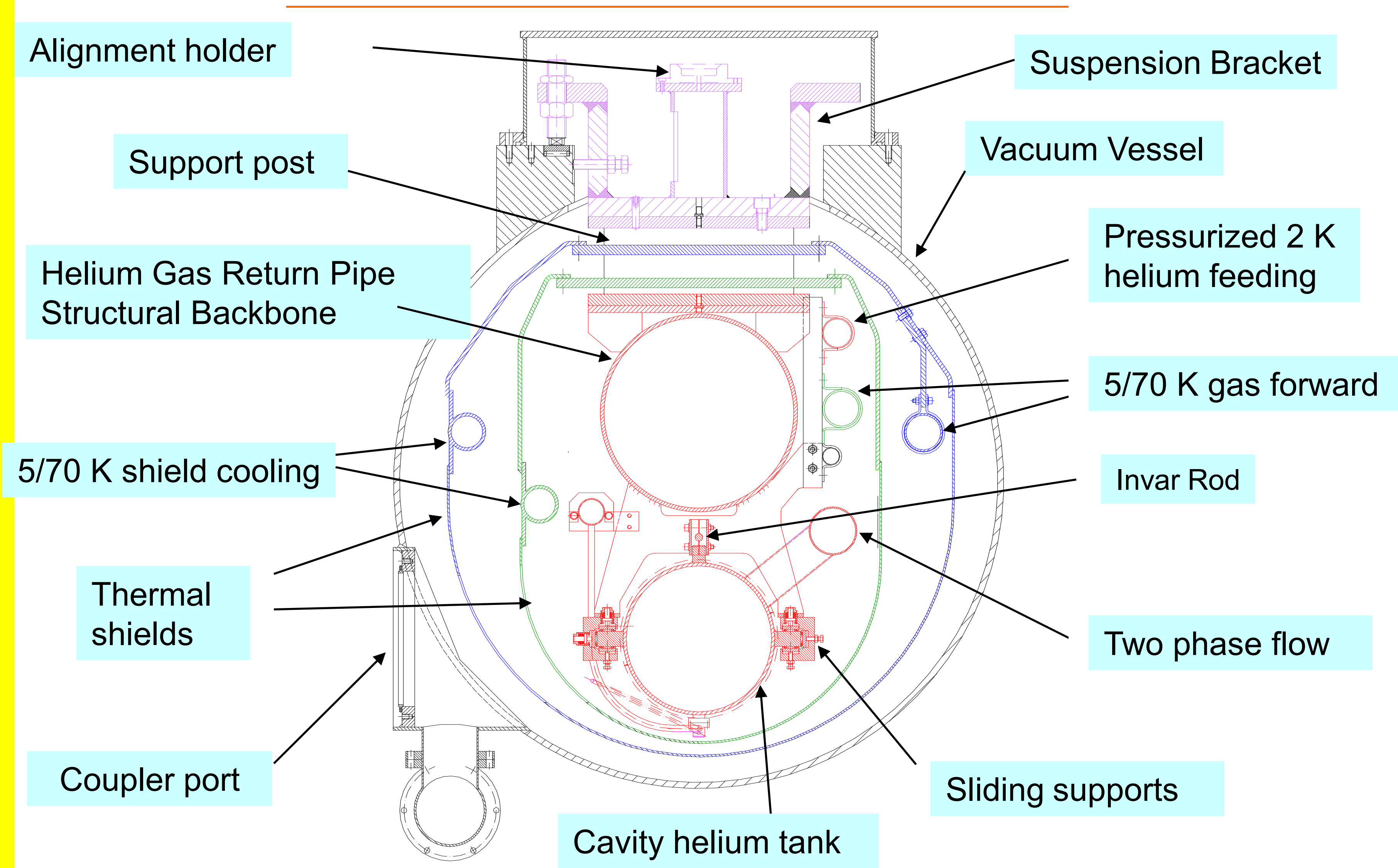
12 m modules / 8 cavities



Consequences/II

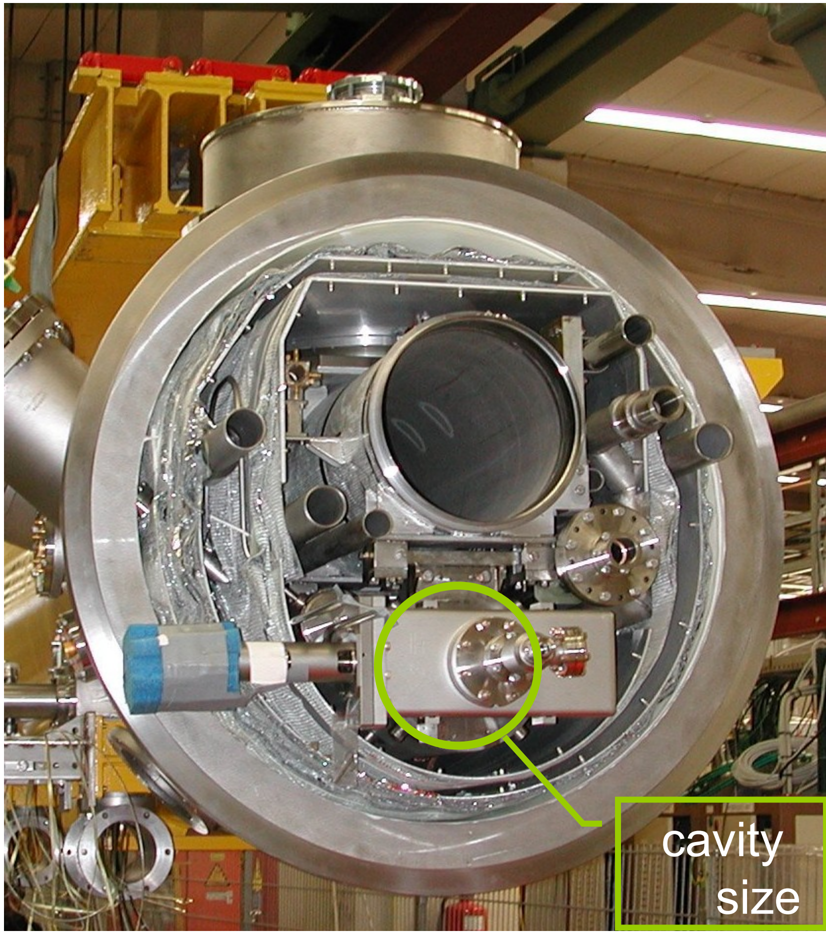
- The cryogenic distribution for the cryo-string is integrated into the cryomodule, again to minimize static losses
  - Several cryogenic circuits along the cold mass to provide the coolant for the cavities and for the heat interception at higher T
- To take out the RF power dissipated along the long cryo-string formed by many cryomodules a large mass flow of 2 K He gas is needed, leading to a big He Gas Return Pipe (HeGRP) to reduce the pressure drop
  - This pipe can be made large and stiff enough so that it can act as the main **structural backbone for the module cold mass**
    - Cavities (and magnet package) are supported by the HeGRP
    - The HeGRP hangs from the vacuum vessel by means of low thermal conduction composite suspension posts

Cross Section: 2 shields at 5 K and 70 K



the TESLA module provides

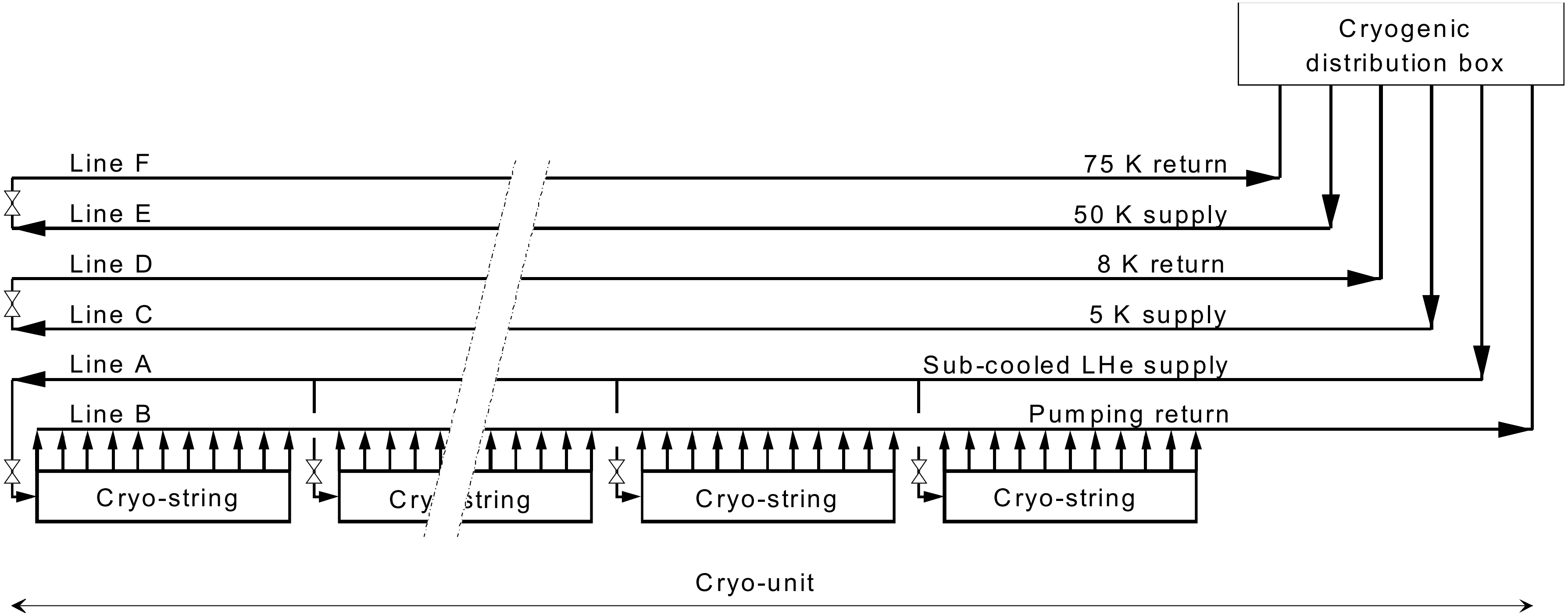
- **cryogenic environment** for the cold mass operation
  - cavities/magnets in their vessels filled with sub atmospheric He at 2 K
  - contains He coolant distribution lines at required temperatures
  - collect large flow of return gas from the module string without pressure increase
  - Low losses penetrations for RF, cryogenics and instrumentation
- **shield "parasitical" heat transfer**
  - **double thermal shield**
- **structural support** of the cold mass
  - different thermal contractions of materials
  - precise alignment capabilities and reproducibility with thermal cycling



12 m, 38" diameter, string of 8 cavities and magnet

Strings are connected in Cryo-units

- At each cryo-string (~ 150 m) there is additional space needed for cryogenic connections (several meters)



ILC: 16 strings per cryogenic unit, so 192 modules per cryo unit (50 GeV)

- All string piping connection are welded (no joints!)

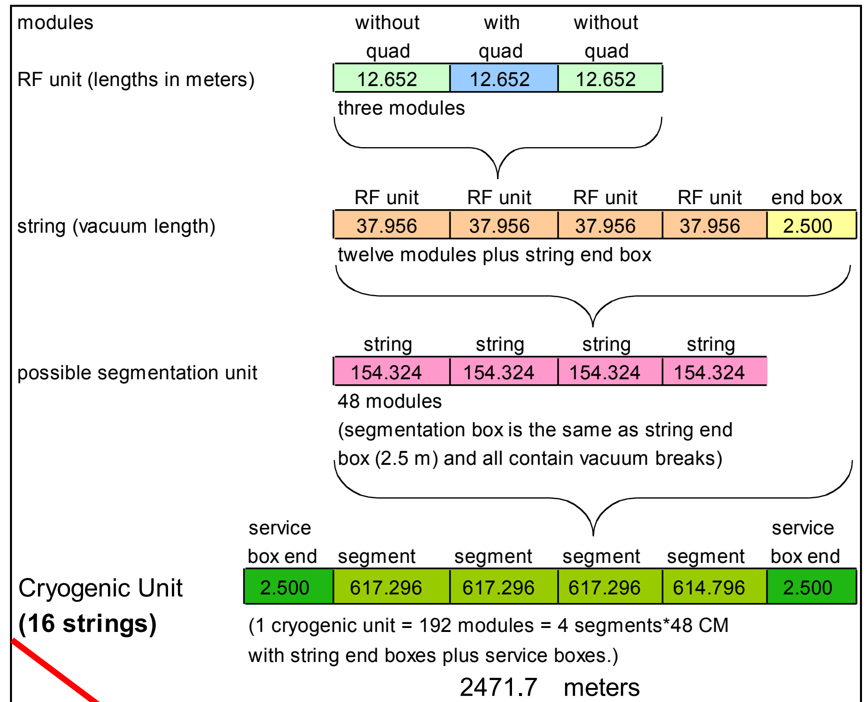
String and Cryogenic unit length limitations

- Strings of 12 modules are also the vacuum segmentations
  - 2 phase line feeding 12*8 cavities runs over the full string
  - String length limit is pressure drop and He level change in the 2 phase line
- Strings are then connected into one cryogenic unit
  - Limit or one cryo-unit is plant size: 25 kW equivalent 4.5 K capacity
    - LHC+20%
    - Heat exchanger sizes
    - Over-the-road sizes
    - Experience
  - Also limited by cold compressors, pressure drops, etc.
- ILC uses 5 units per 250 GeV linac
- XFEL overall is 1 unit of 10 strings (1.7 km)

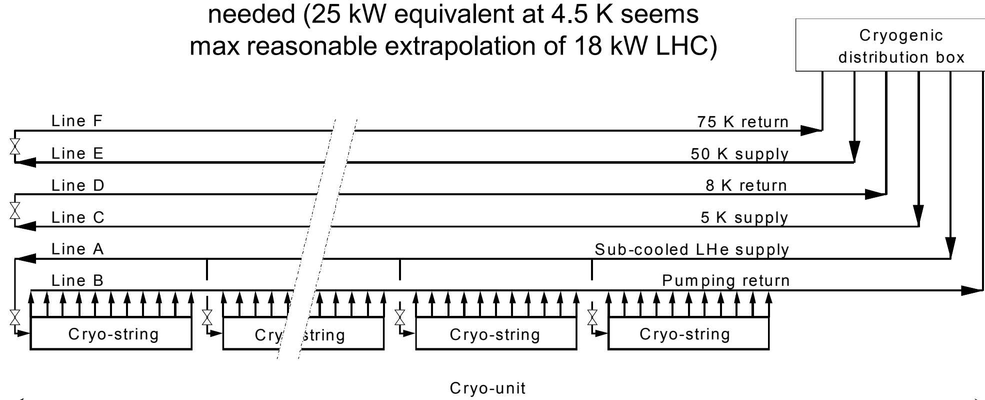
TESLA/ILC/(XFEL) modular cryogenic concept

- each **module** contains all cryo piping
  - each cavity tank in module connected to two phase line
  - vapor is collected from 2 phase line once per module in the GRP
- several modules are connected in **strings**
  - single two phase line along the string
  - a JT valve once per string fills two phase line via subcooled 2.2 K line
- strings are connected into **units**
  - each unit is fed by a single cryogenic plant

ILC scheme for segmentation and distribution



unit length limited by size of cryo plant needed (25 kW equivalent at 4.5 K seems max reasonable extrapolation of 18 kW LHC)



ILC Cryogenic unit spreadsheet

From: T. Peterson, ILC Cryogenic system design spreadsheet, FNAL

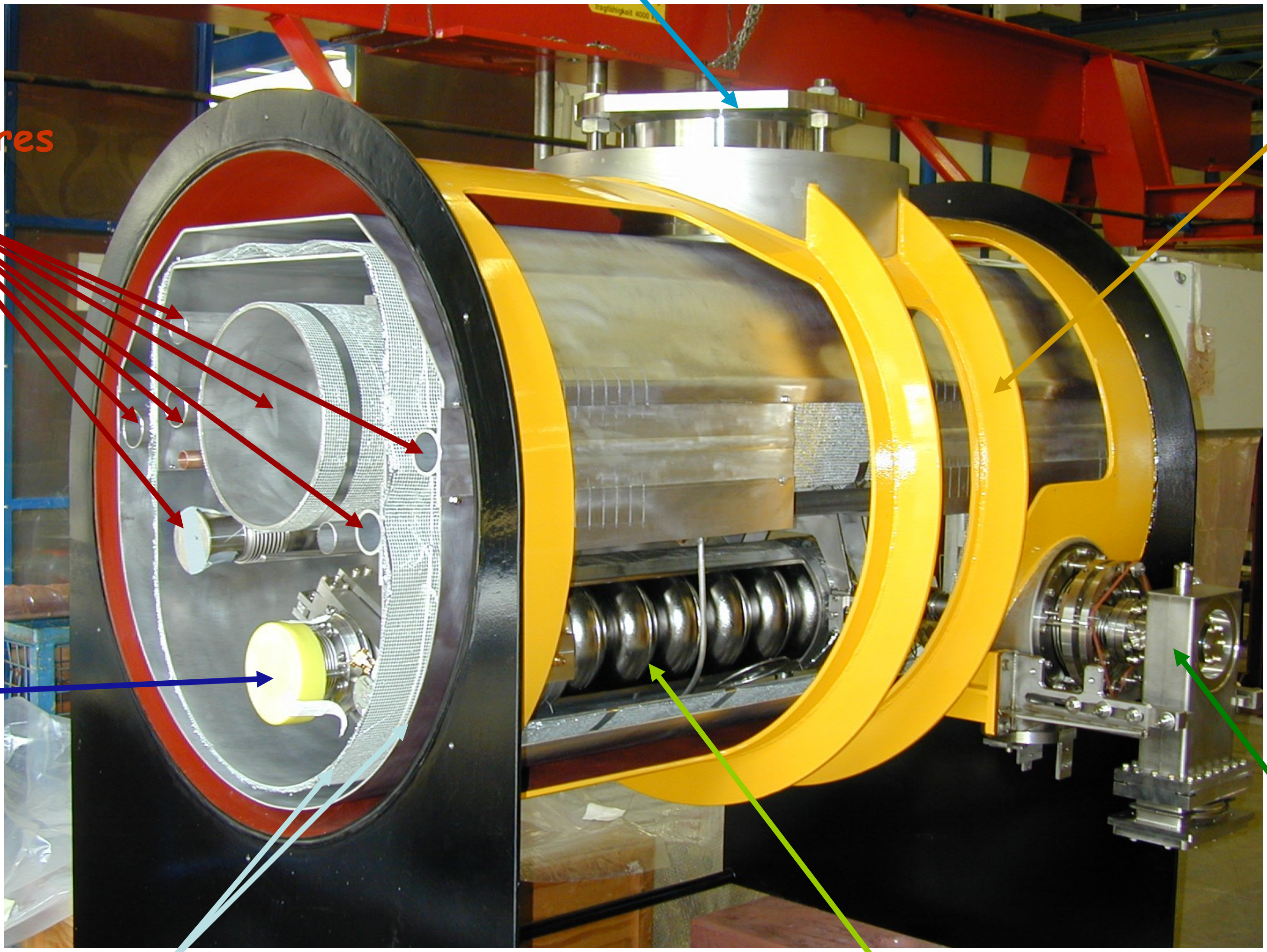
		40 K to 80 K Temperature level (module)	5 K to 8 K Temperature level (module)	2 K Temperature level (module)
Temp in	(K)	40.00	5.0	2.4
Press in	(bar)	16.0	5.0	1.2
Enthalpy in	(J/g)	223.8	14.7	4.383
Entropy in	(J/gK)	15.3	3.9	1.862
Temp out	(K)	80.00	8.0	2.0
Press out	(bar)	14.0	4.0	saturated vapor
Enthalpy out	(J/g)	432.5	46.7	25.04
Entropy out	(J/gK)	19.2	9.1	12.58

		40 K to 80 K	5 K to 8 K	2 K
Predicted module static heat load	(W/module)	59.19	10.56	1.70
Predicted module dynamic heat load	(W/module)	94.30	4.37	9.66
Number of modules per cryo unit (8-cavity modules)		192.00	192.00	192.00
Non-module heat load per cryo unit	(kW)	1.00	0.20	0.20
Total predicted heat per cryogenic unit	(kW)	30.47	3.07	2.38
Heat uncertainty factor on static heat (Fus)		1.10	1.10	1.10
Heat uncertainty factor on dynamic heat (Fud)		1.10	1.10	1.10
Efficiency (fraction Carnot)		0.28	0.24	0.22
Efficiency in Watts/Watt	(W/W)	16.45	197.94	702.98
Overcapacity factor (Fo)		1.40	1.40	1.40
Overall net cryogenic capacity multiplier		1.54	1.54	1.54
Heat load per cryogenic unit including Fus, Fud, and Fo	(kW)	46.92	4.72	3.67
Installed power	(kW)	771.72	934.91	2577.65
Installed 4.5 K equiv	(kW)	3.53	4.27	11.78
Percent of total power at each level		18.0%	21.8%	60.2%
Total operating power for one cryo unit based on predicted heat (MW)			3.34	
Total installed power for one cryo unit (MW)			4.28	
Total installed 4.5 K equivalent power for one cryo unit (kW)			19.57	

TTF module summary

- Cooling of the cold mass by evaporation of HeII
  - cavities and quads immersed in a saturated He II bath @ 2 K
- Static losses minimization (negligible radiation effect reaching 2 K)
  - Thermal shield @5-8 K fed by He gas (no radiation load at 2 K)
  - Thermal shield @40-80 K fed by He gas
- Integration of the distribution lines into cryomodule
  - Two-phase line (liquid helium supply and concurrent vapor return) connects to each helium vessel
  - Two-phase line connects to gas return once per module
  - Sub-cooled helium supply line (for the downstream modules) connects to the big two-phase line via JT valve once per “string”
- Include provisions for warmup/cooldown
  - A small diameter warm-up/cool-down line connects the bottoms of the He vessels (primarily for warm-up)

Cryomodule Mock-up



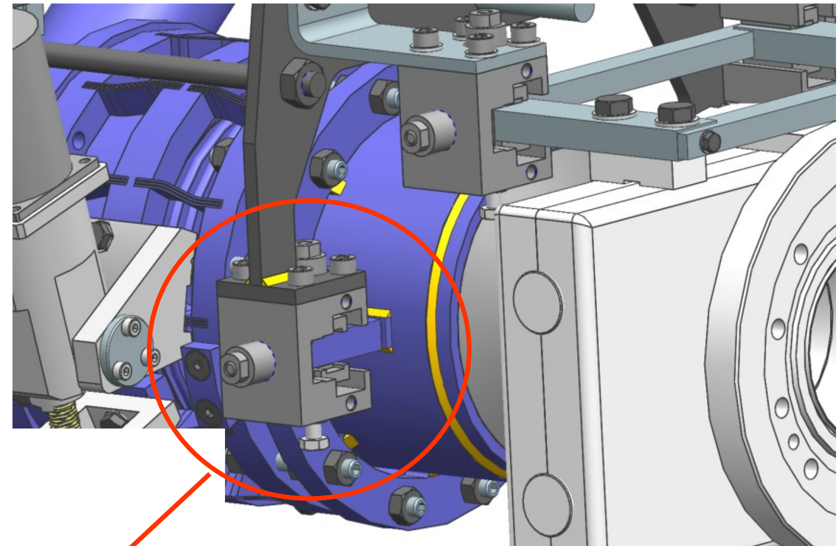
Cold mass alignment strategy

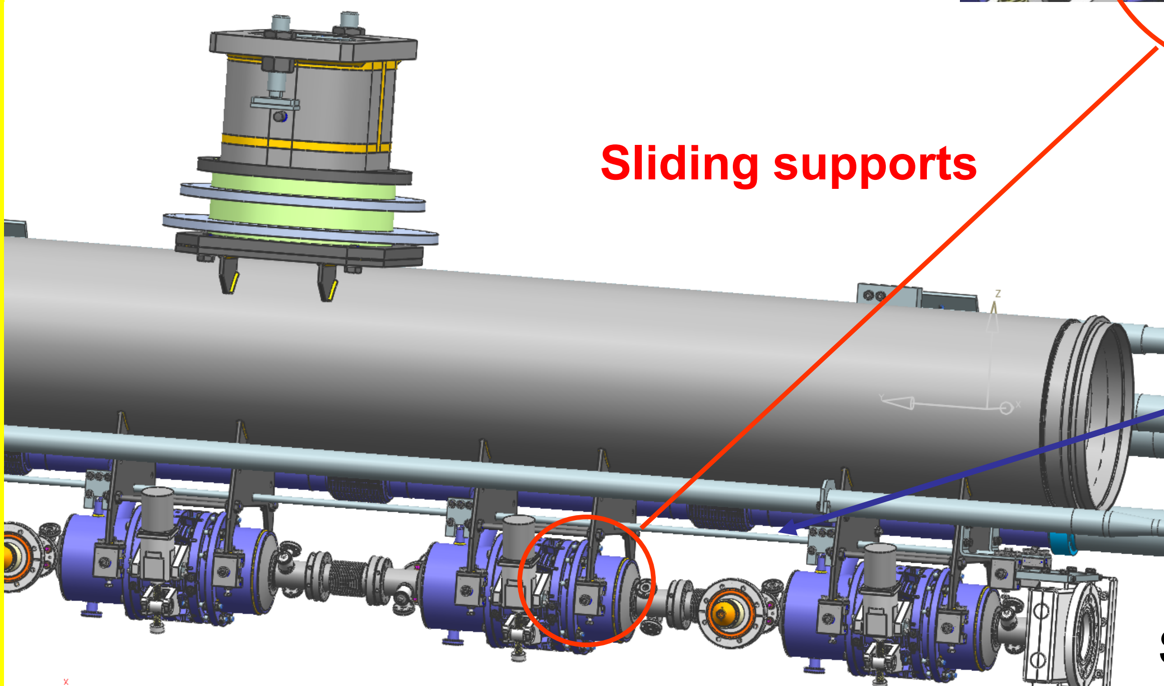
- The Helium Gas Return Pipe (HeGRP) is the system backbone
- The 3 Taylor-Hobson spheres are aligned wrt the HeGRP axis, as defined by the machined interconnecting edge flanges
- Cavities are individually aligned wrt the aligned T-H spheres
- Cavity (and Quad) have a sliding connection with the HeGRP
  - sliding planes are parallel to the HeGRP axis by machining (milling machine)
  - Longitudinal cavity movement is not affecting alignment
  - By design the differential thermal contractions preserve parallelism
  - Variation of axis distances by differential contraction are fully predictable and taken into account
  - Sliding supports and invar rod preserve the alignment while disconnecting the cavities from the huge SS HeGRP contraction
    - 36 mm over the 12 m module length cooling from 300 K to 2 K

Sliding supports and Invar Rod

Thermal contraction depends from the material: SS=0.31% Nb&Ti=0.15%

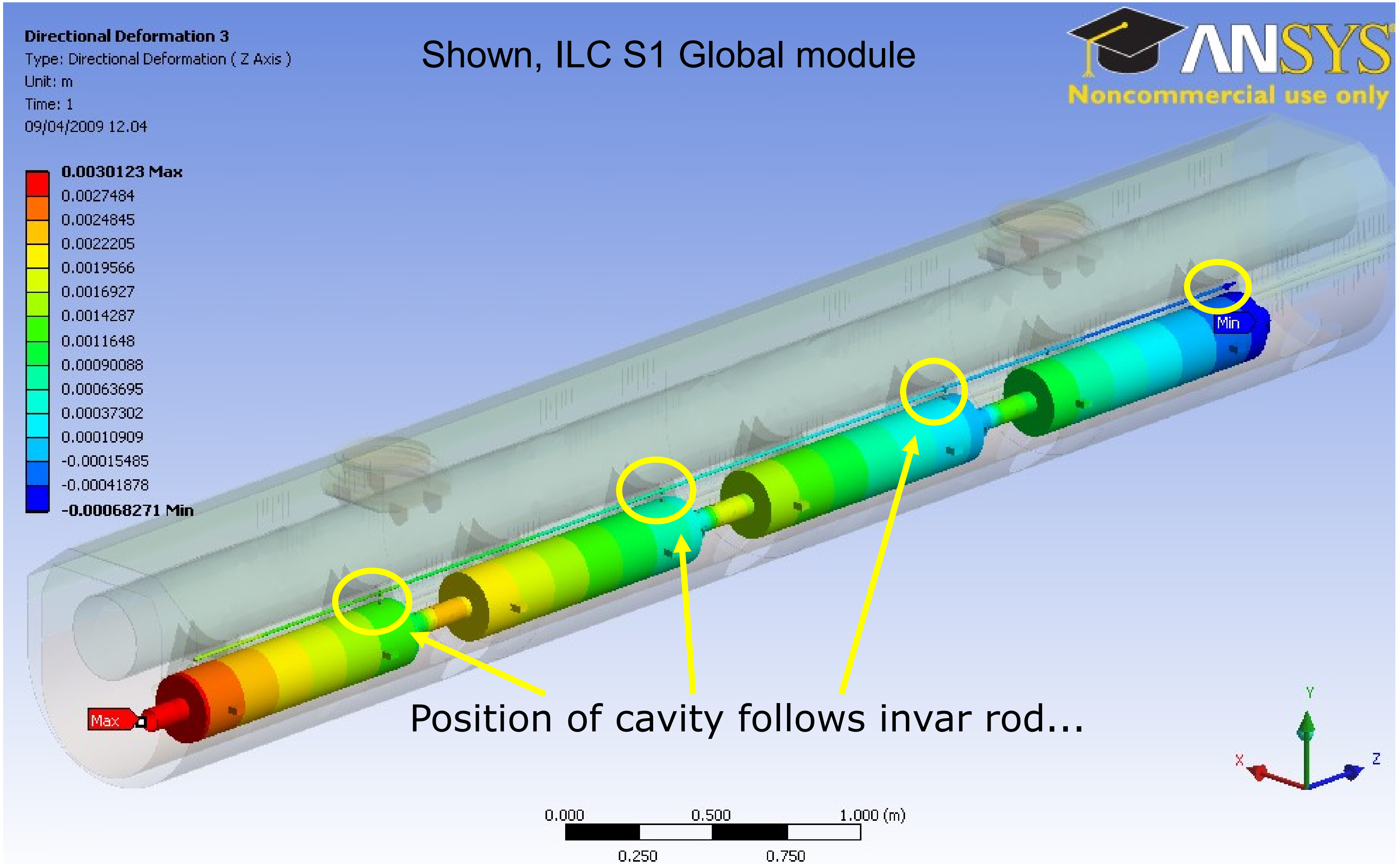
- **The HeGRP is the backbone**
- **HeGRP provides Cavity alignment**
- **Invar Rod for independent z**
  - Independent cavity z position
  - Semi-rigid couplers allowed
  - Less demanding on coupler bellows





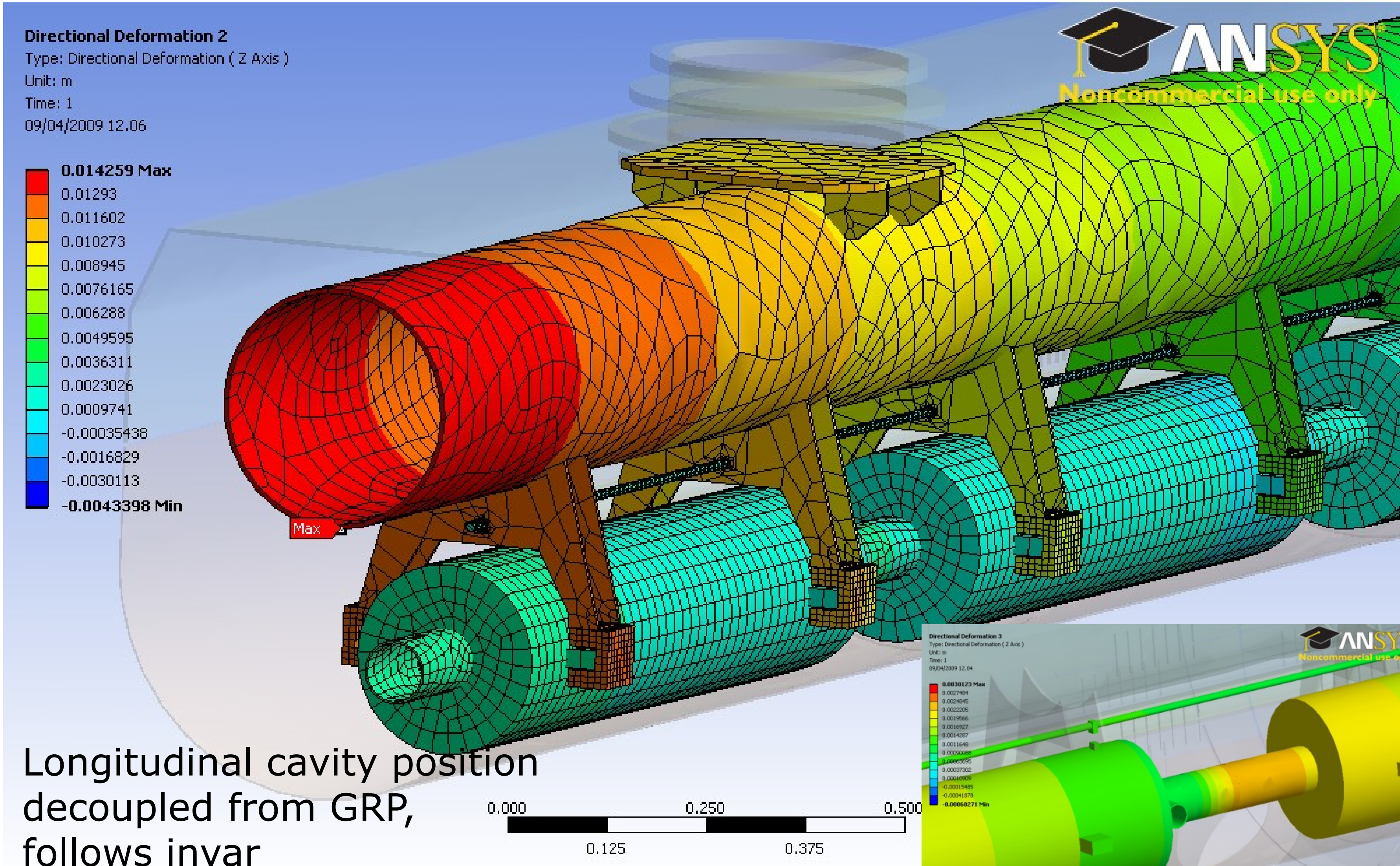
Shown, XFEL 3.9 GHz module

Longitudinal behavior: Decoupling contractions



INFN module for ILC S1 Global @ KEK

Evident comparing with GRP

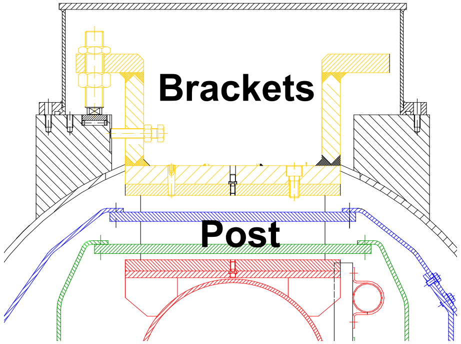


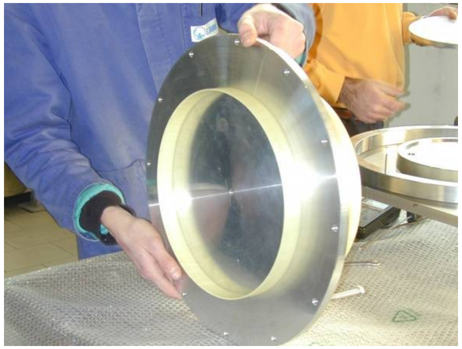
Longitudinal cavity position decoupled from GRP, follows invar

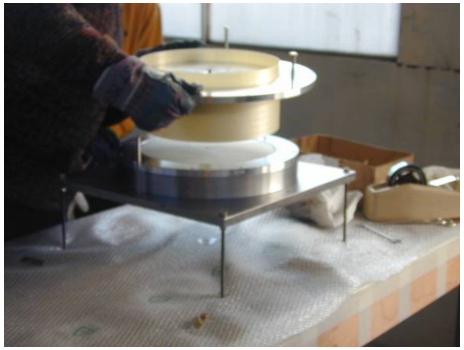
INFN module for ILC S1 Global @ KEK

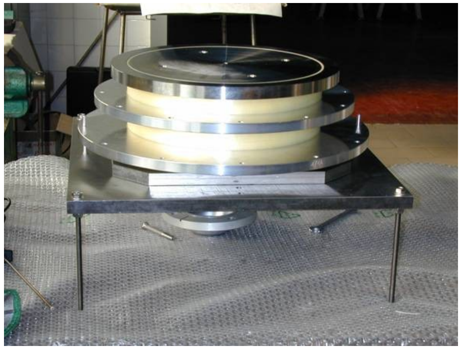
Composite Support Posts

- Designed to sustain the the active items to the HeGRP
- Support posts are qualified for a 5000N tension force on all flanges with a limited thermal conductivity
- SS and Al flanges are connected to the Fiberglass (G10) body by thermal shrink fit







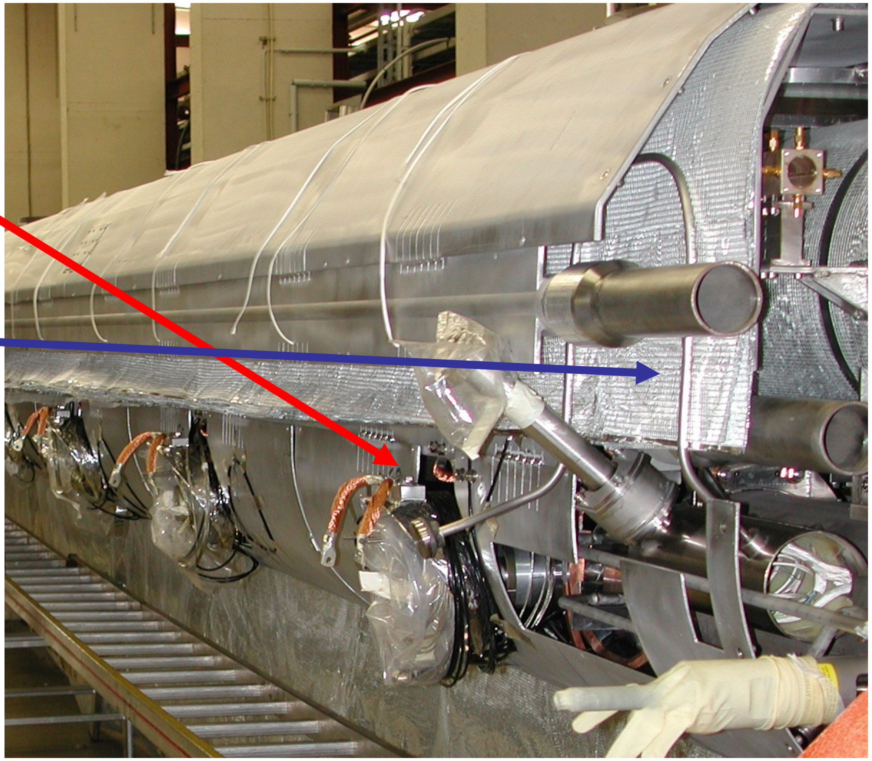


Thermal shields and MLI

- Roles of thermal shield at intermediate temperature:
  - The internal cold mass "sees" a surface at lower temperature than the external (r.t.) chamber, consequently heat load is reduced
  - Provides thermal interception point to all penetration (couplers, etc)
- Role of MLI
  - "floating" radiation shields to reduce flux

$$\dot{Q} = S\varepsilon\sigma_{SB}\left(T_h^4 - T_c^4\right)$$

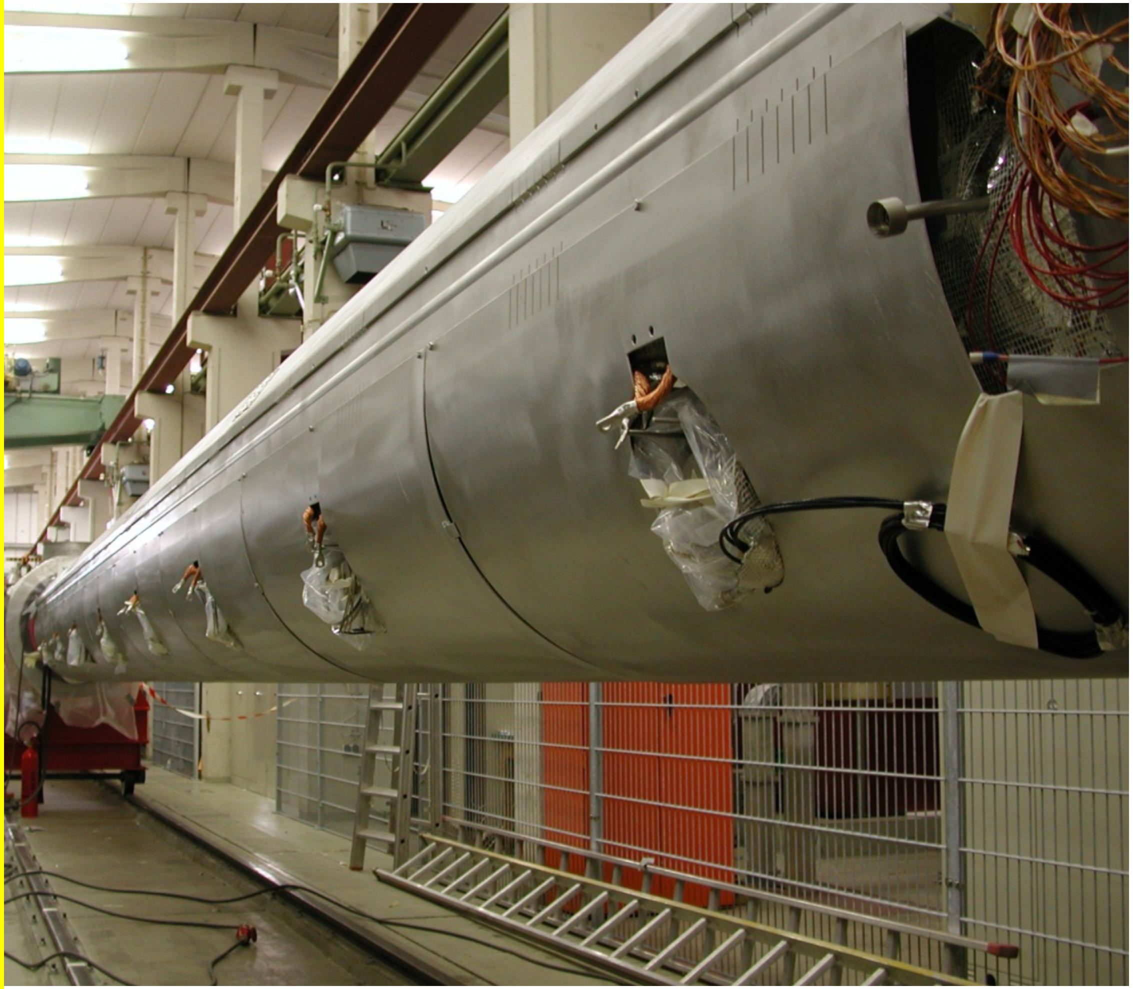
Radiation load from 300 K to low temperatures ~ 500 W/m^2 for e=1 !



Effective Heat Flux (CERN Data)	W/m^2
MLI (30 layers) from 300 K, P< 1 mPa	1-1.5
MLI (10 layers) from 80 K, P< 1 mPa	0.05

The 50-70 K shield

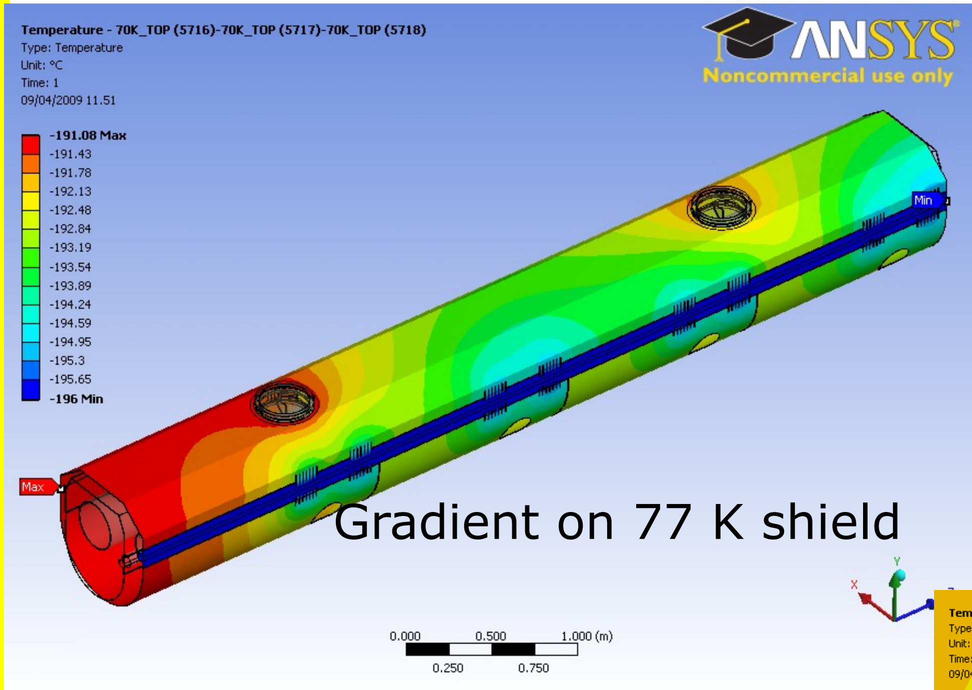
Thermal contact cannot rely on surface contact

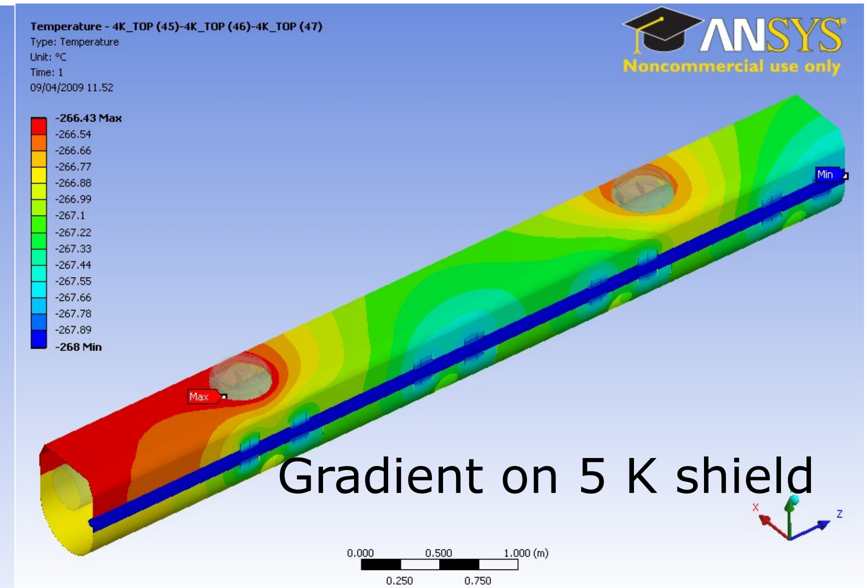


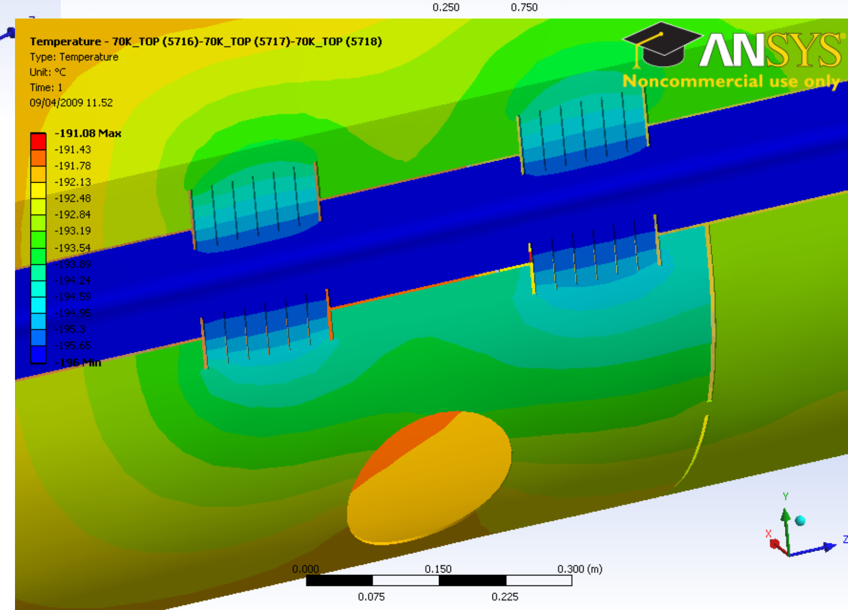
Welding the shield

30 MLI layers on shield

Thermal gradients

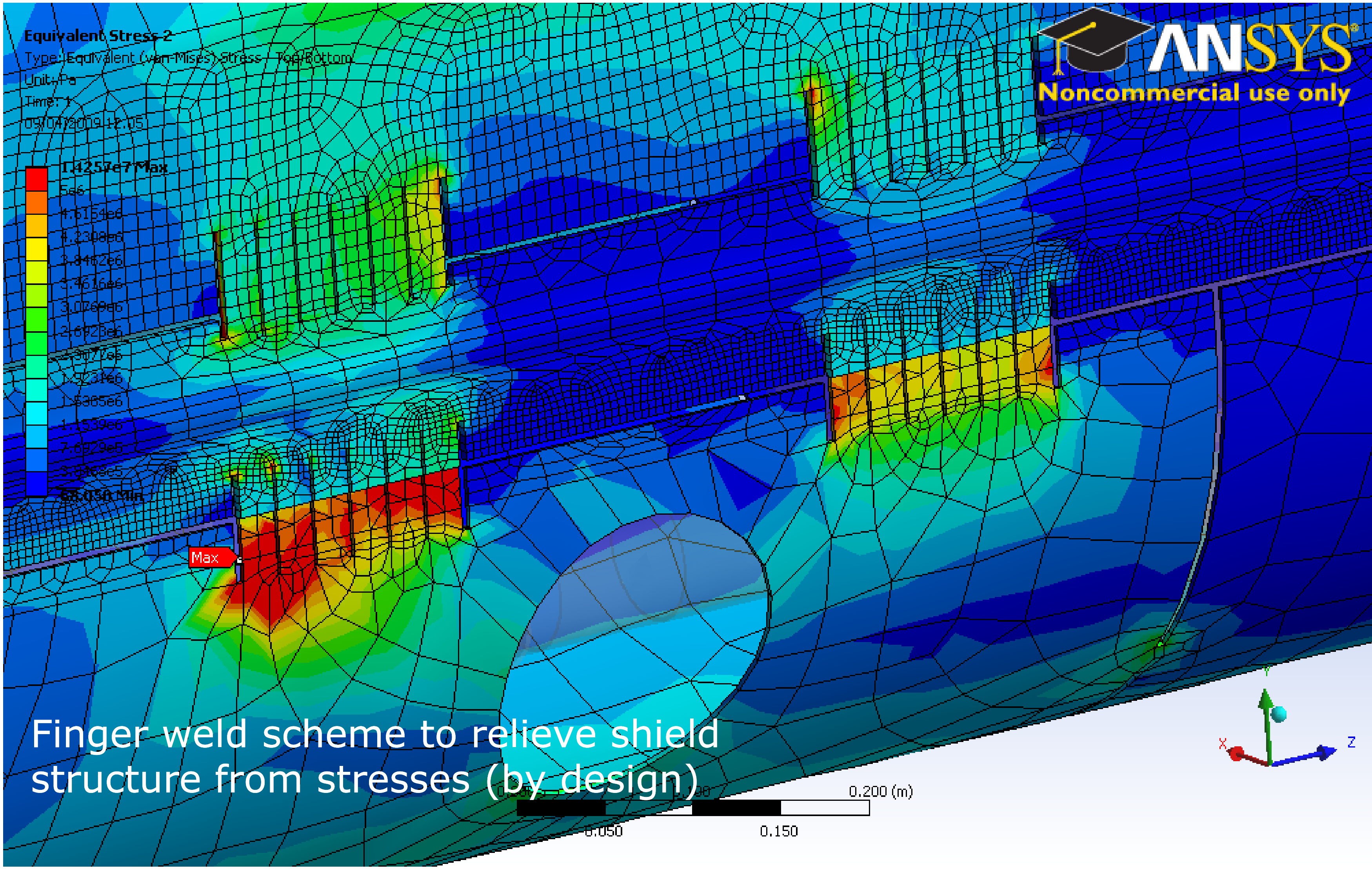






Conduction path only through welded fingers (worst case of no thermal contact between mating surfaces ands strong choking of thermal flux)

Structural analysis, stresses



INFN module for ILC S1 Global @ KEK

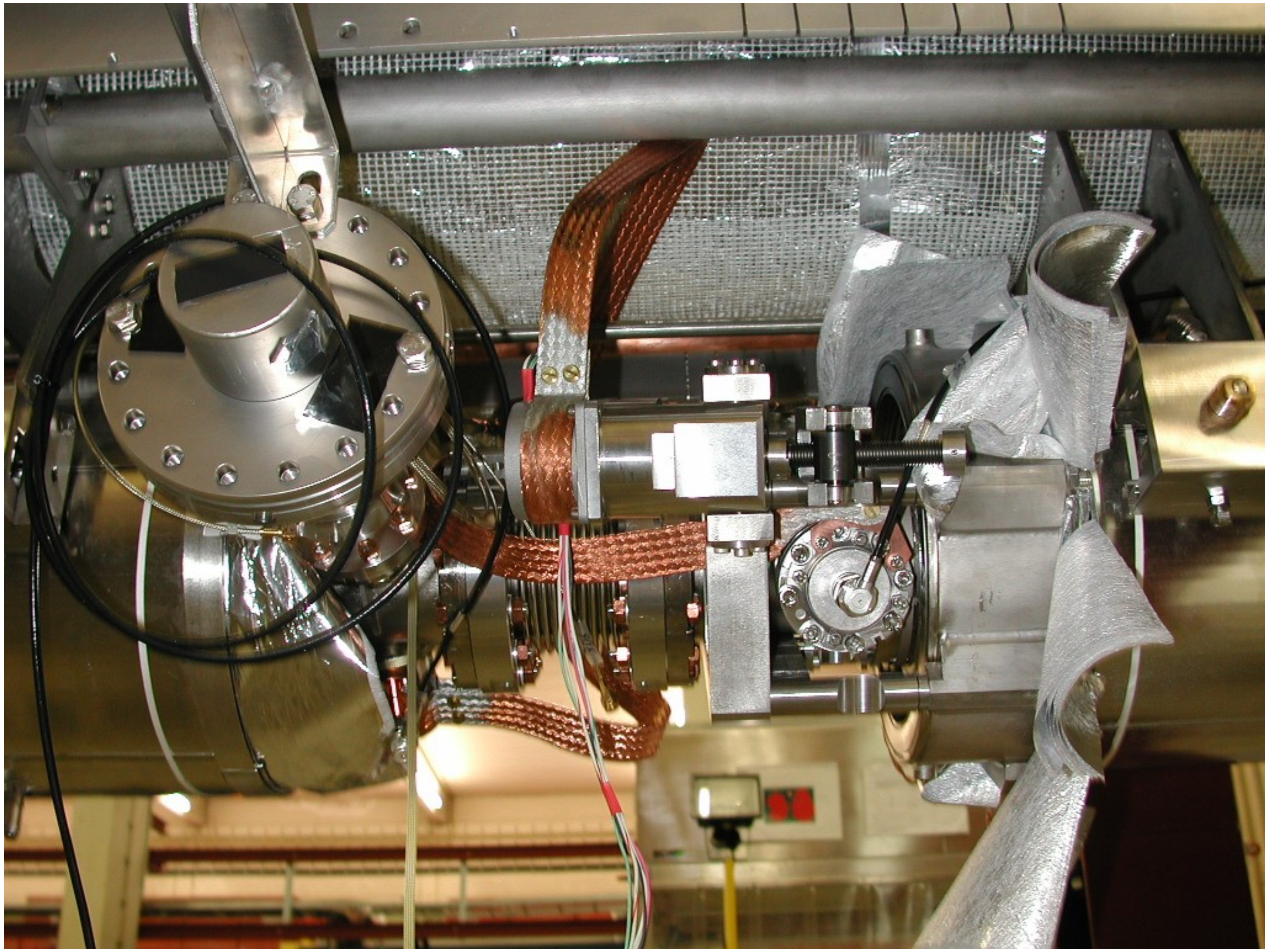
Module assembly picture gallery - 1

String inside the Clean Room

Module assembly picture gallery - 2

String in the assembly area

Module assembly picture gallery - 3



Cavity interconnection detail

Module assembly picture gallery - 4

String hanged to he HeGRP

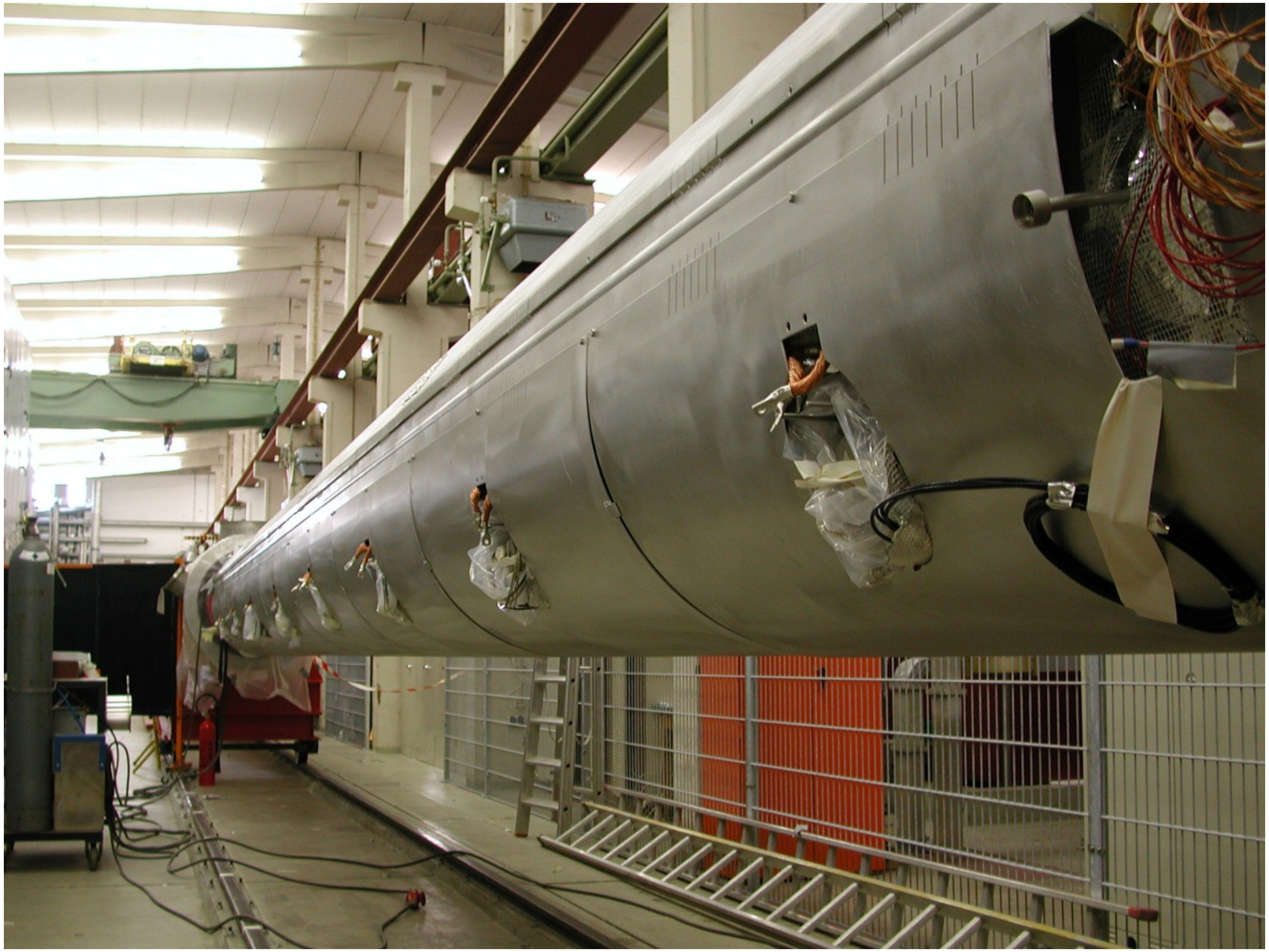
Module assembly picture gallery - 5

String on the cantilevers

Module assembly picture gallery - 6

Close internal shield MLI

Module assembly picture gallery - 7



External shield in place

Module assembly picture gallery - 8

Welding "fingers"

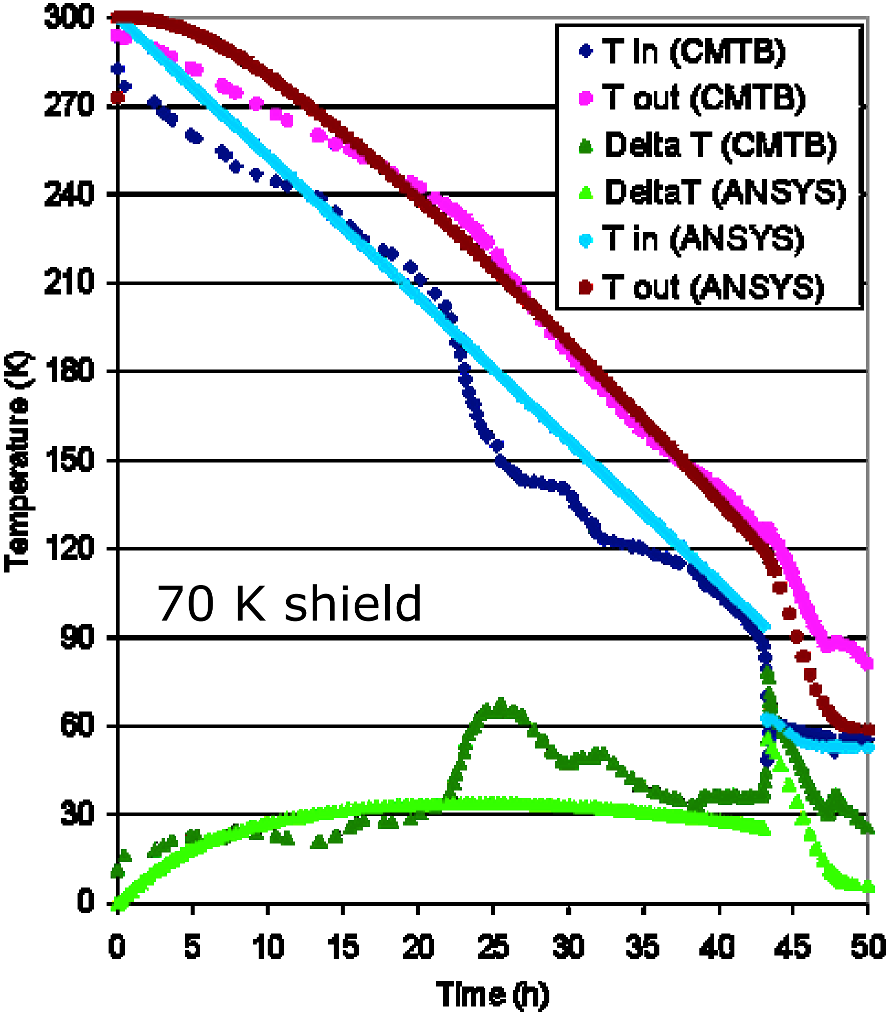
Module assembly picture gallery - 9

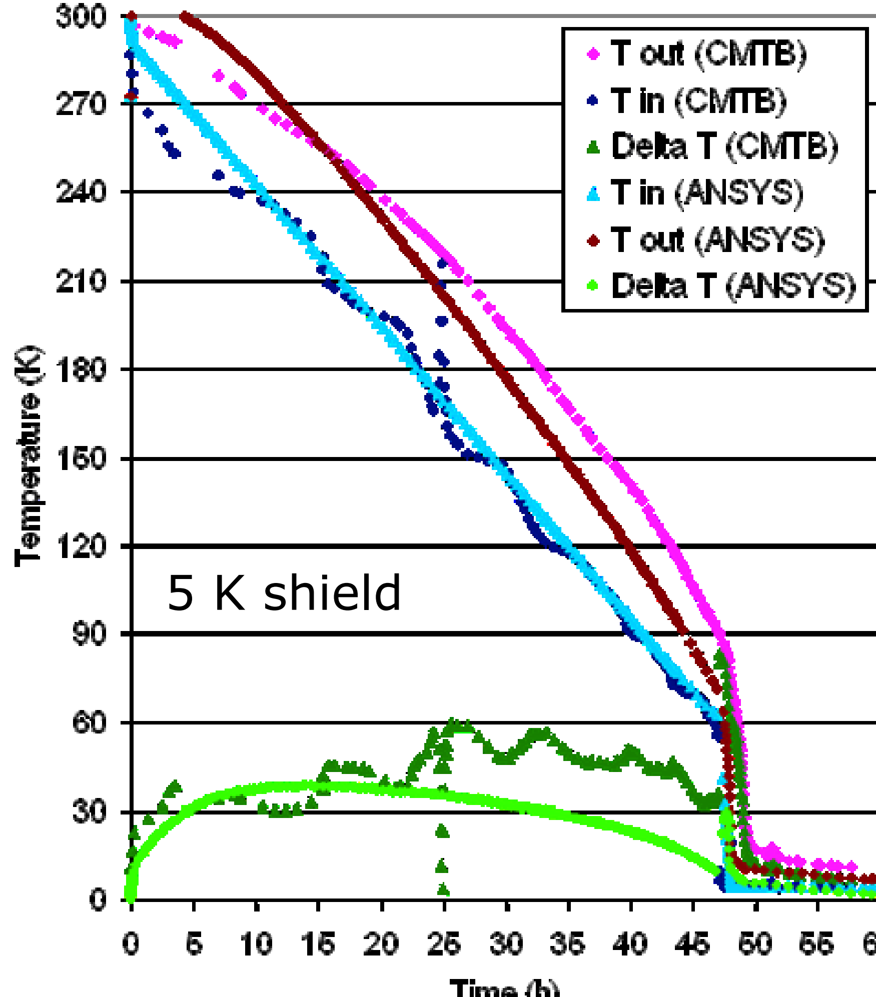
Sliding the Vacuum Vessel

Module assembly picture gallery - 10

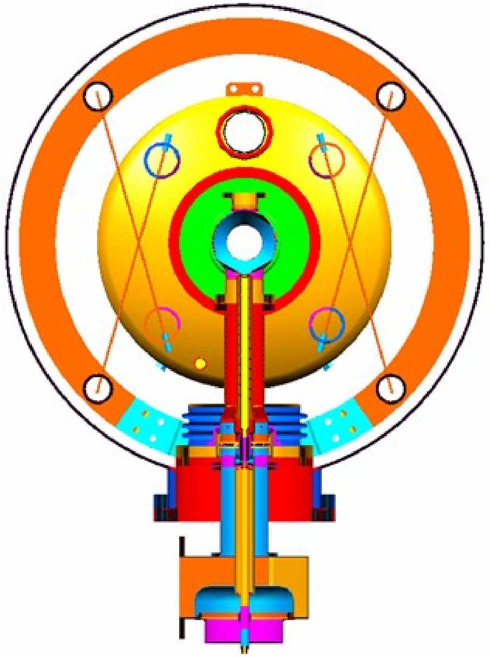
Complete module moved for storage

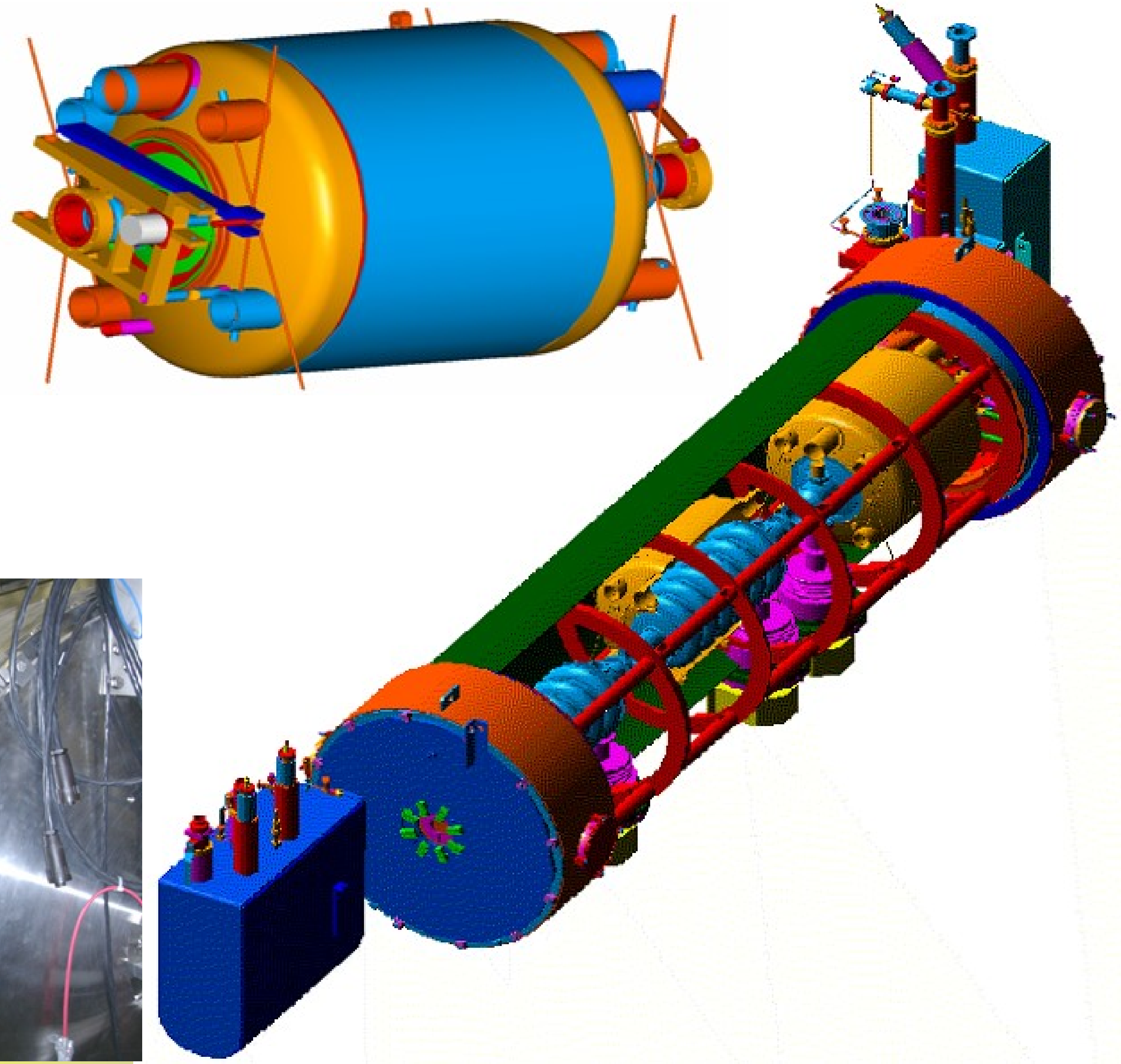
- ANSYS FEA against measured CMTB data a DESY





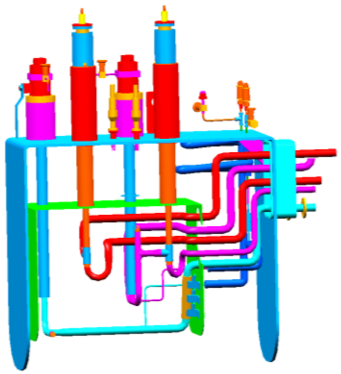
Different design: SNS Cryomodule

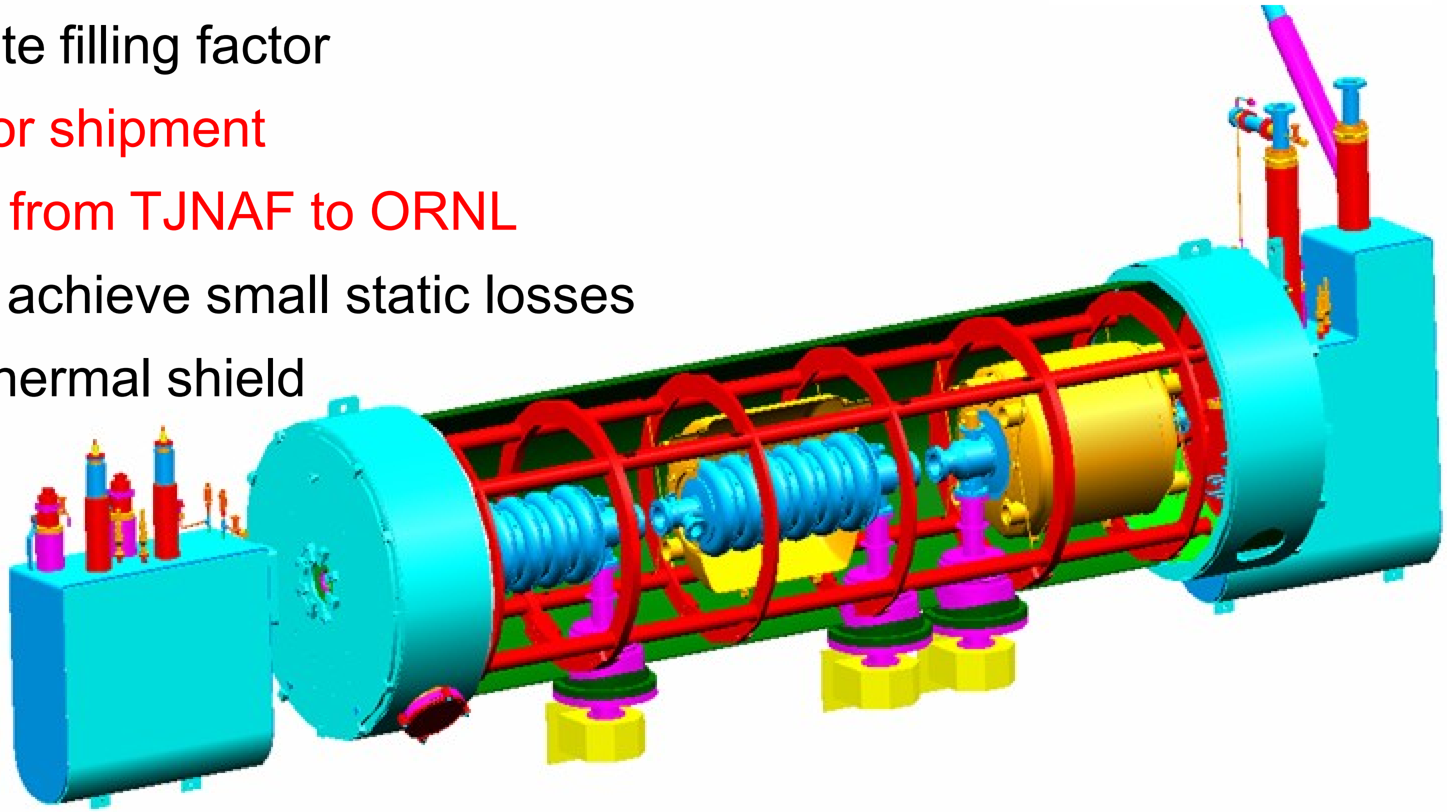




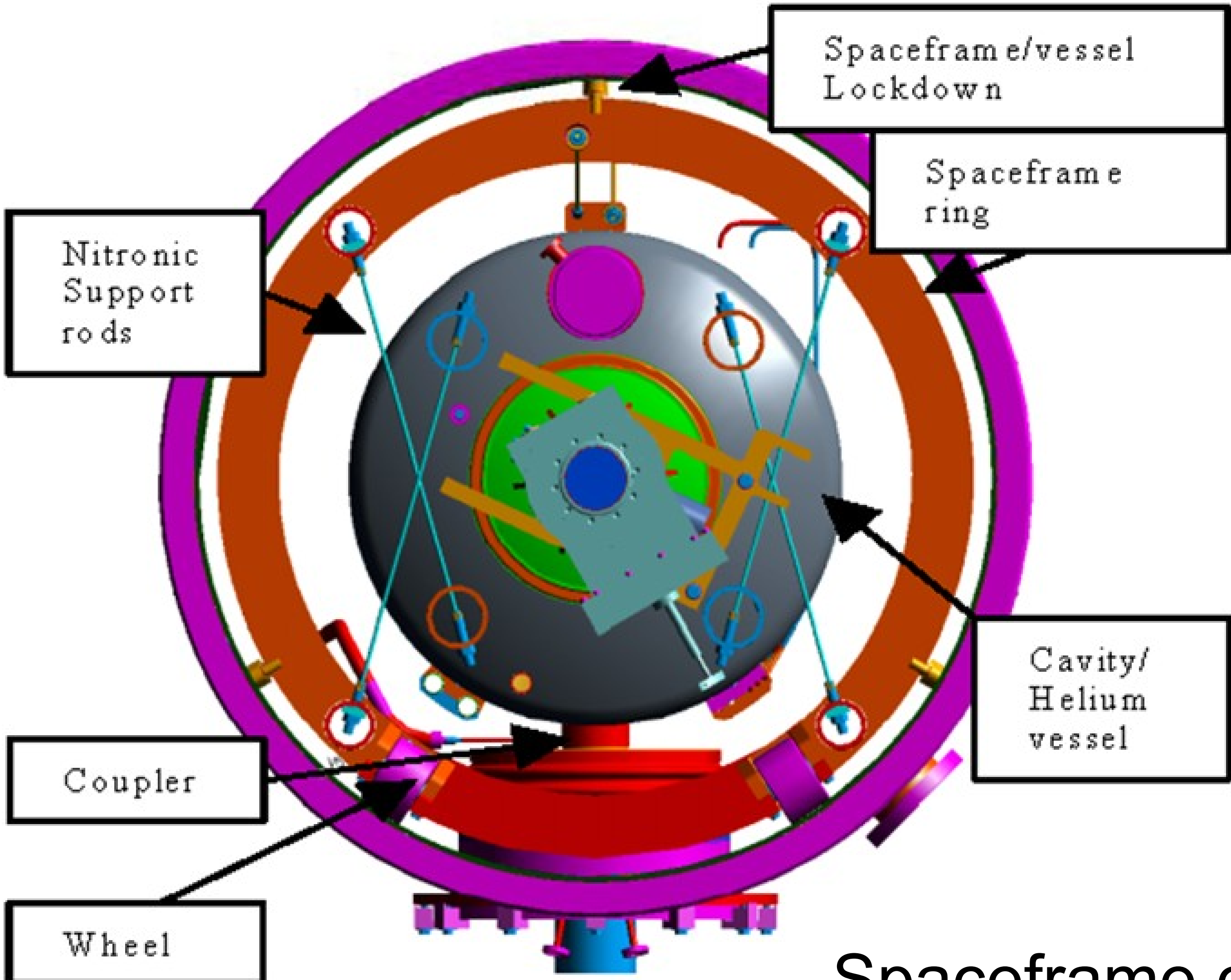
Design Rationales

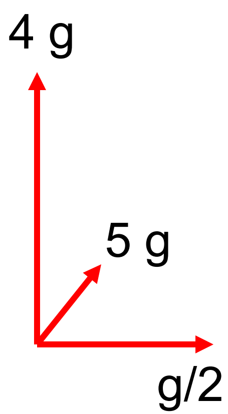
- Fast module exchange and independent cryogenics (bayonet connections)
  - ✓ 1 day
  - ✓ 2K production in CM
- Warm quad doublet
  - ✓ Moderate filling factor
- Designed for shipment
  - ✓ 800 km from TJNAF to ORNL
- No need to achieve small static losses
  - ✓ single thermal shield





Design for shipment (TJNAF to ORNL)

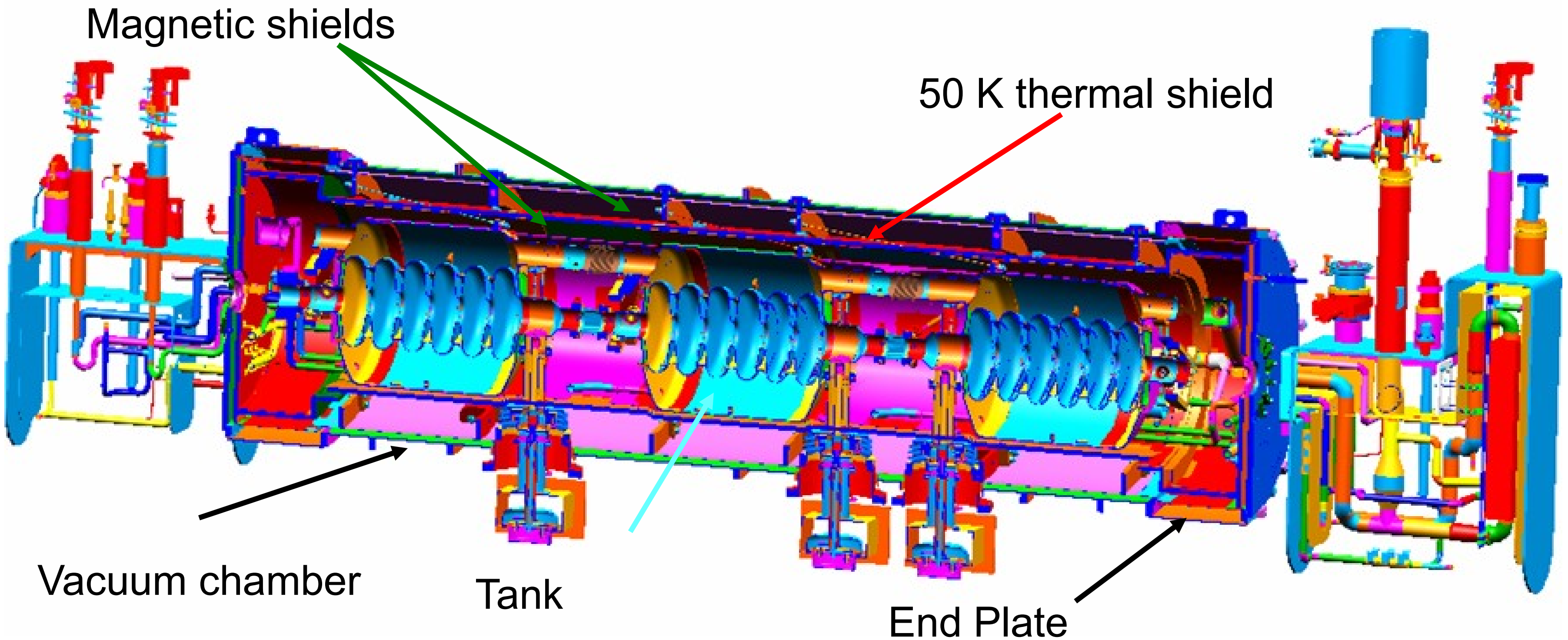




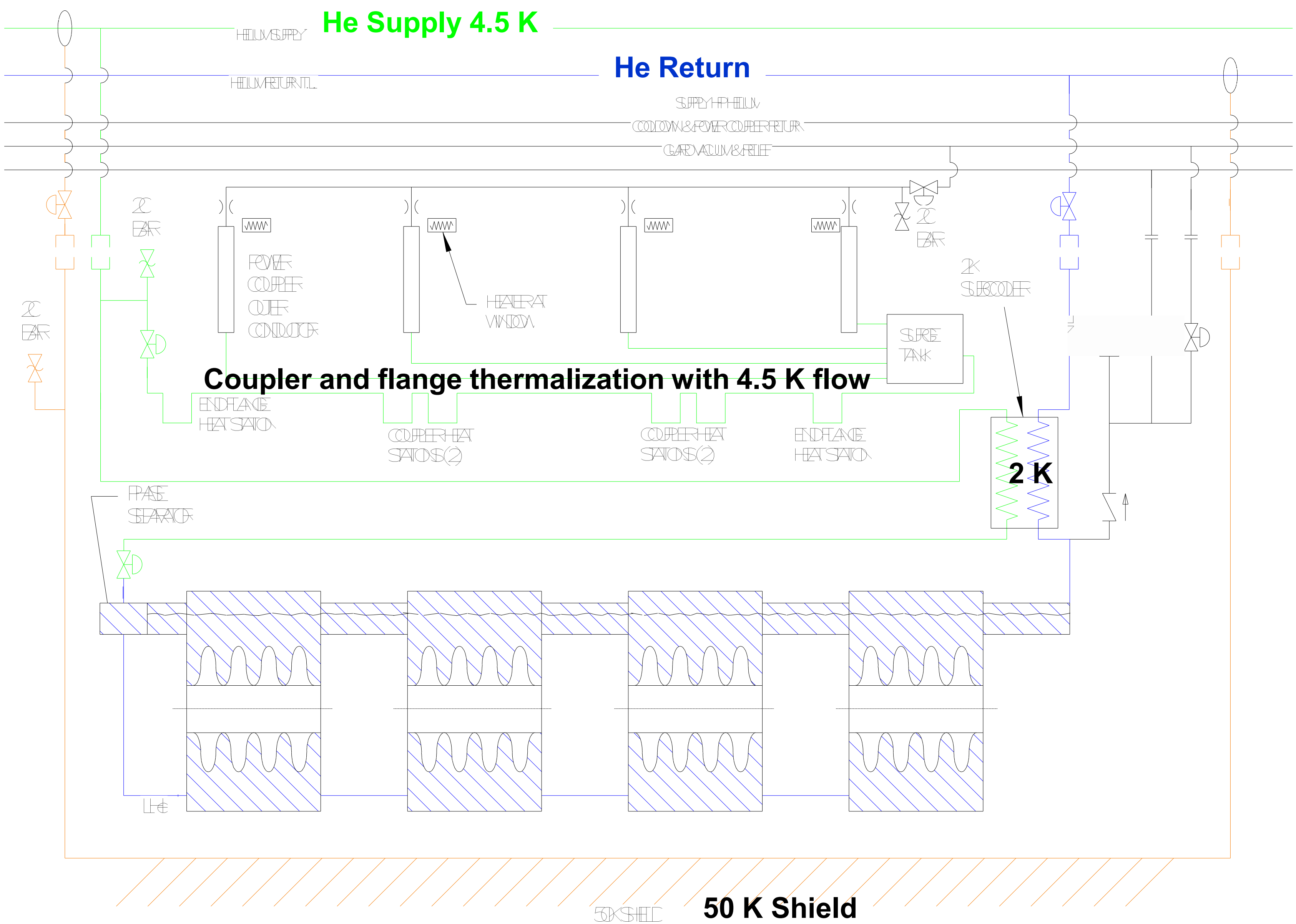
Spaceframe concept

Around the cold mass

- Helium to cool the SRF linac is provided by the central helium liquefier
- He then piped to the 4.5K cold box and sent through cryogenic transfer lines to the cryomodules
- Joule Thomson valves on the cryomodules produce 2.1 K (0.041 bar) LHe for cavity cooling, and 4.5 K He for fundamental power coupler cooling
- Boil-off goes to four cold-compressors recompressing the stream to 1.05 bar and 30 K for counter-flow cooling in the 4.5K cold box



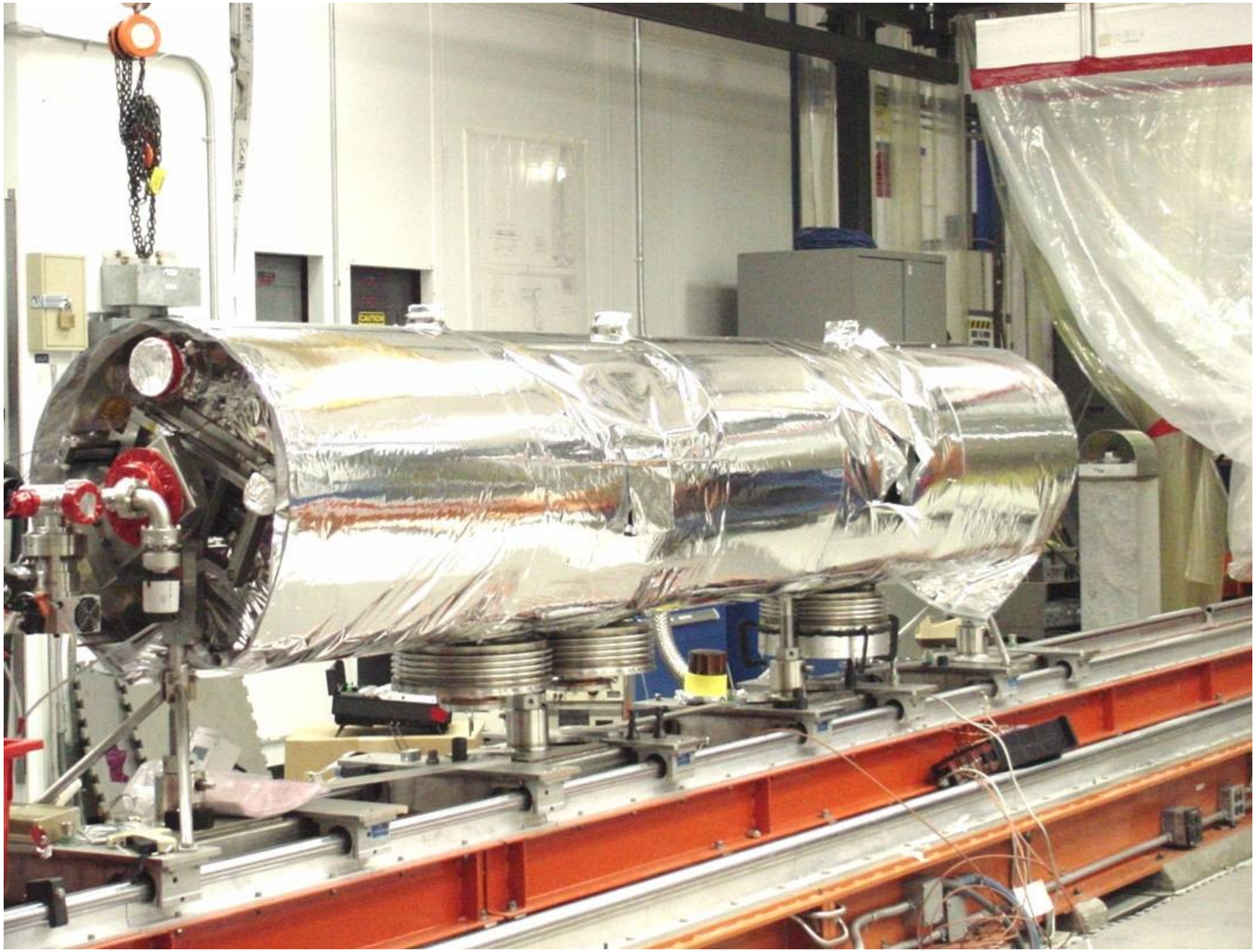
SNS He Flow


He Supply 4.5 K
He Return
Coupler and flange thermalization with 4.5 K flow
2 K
50 K Shield

SNS β=0.61 Cryomodule Assembly -1

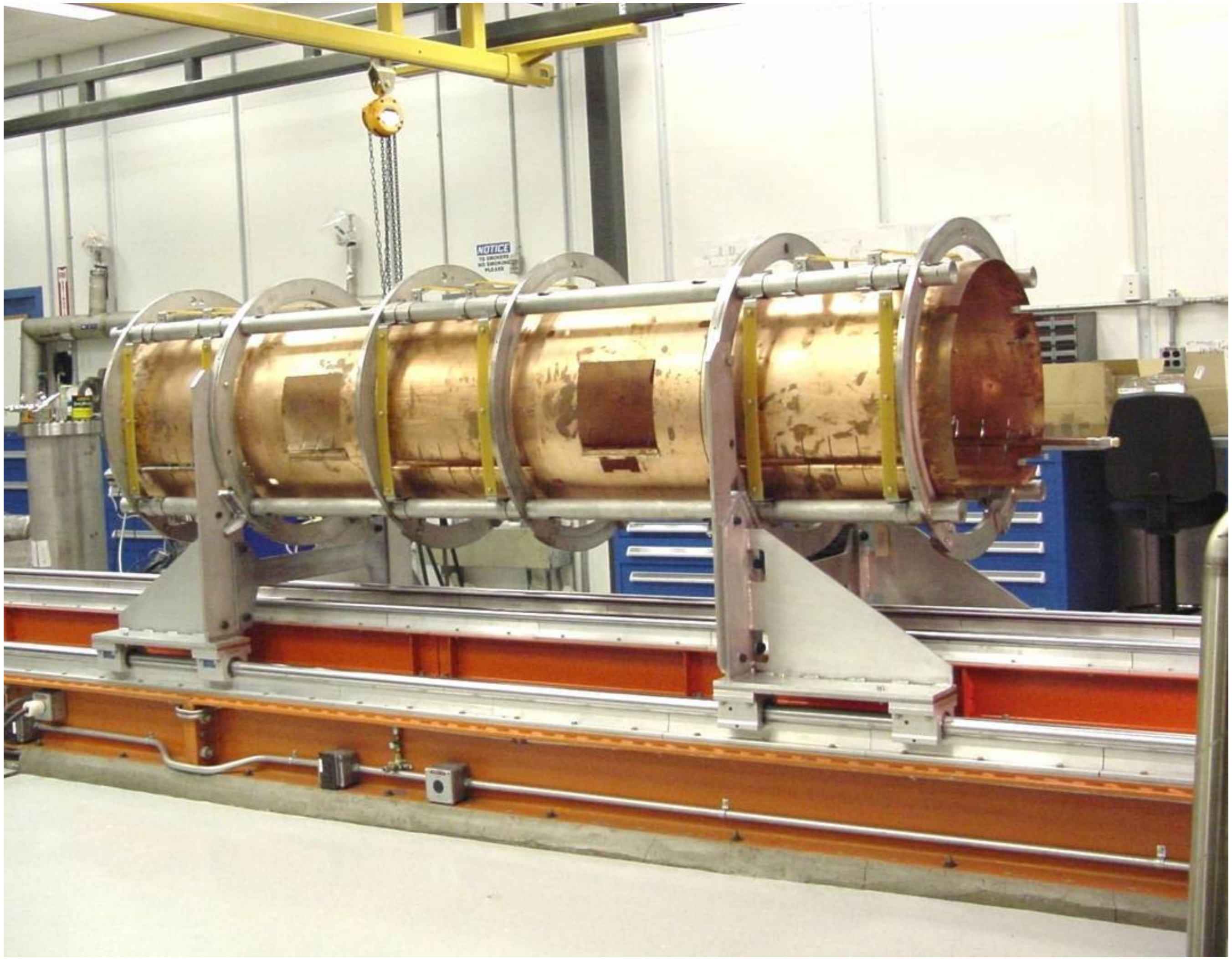
Cavity string in Clean Room

SNS β=0.61 Cryomodule Assembly -2



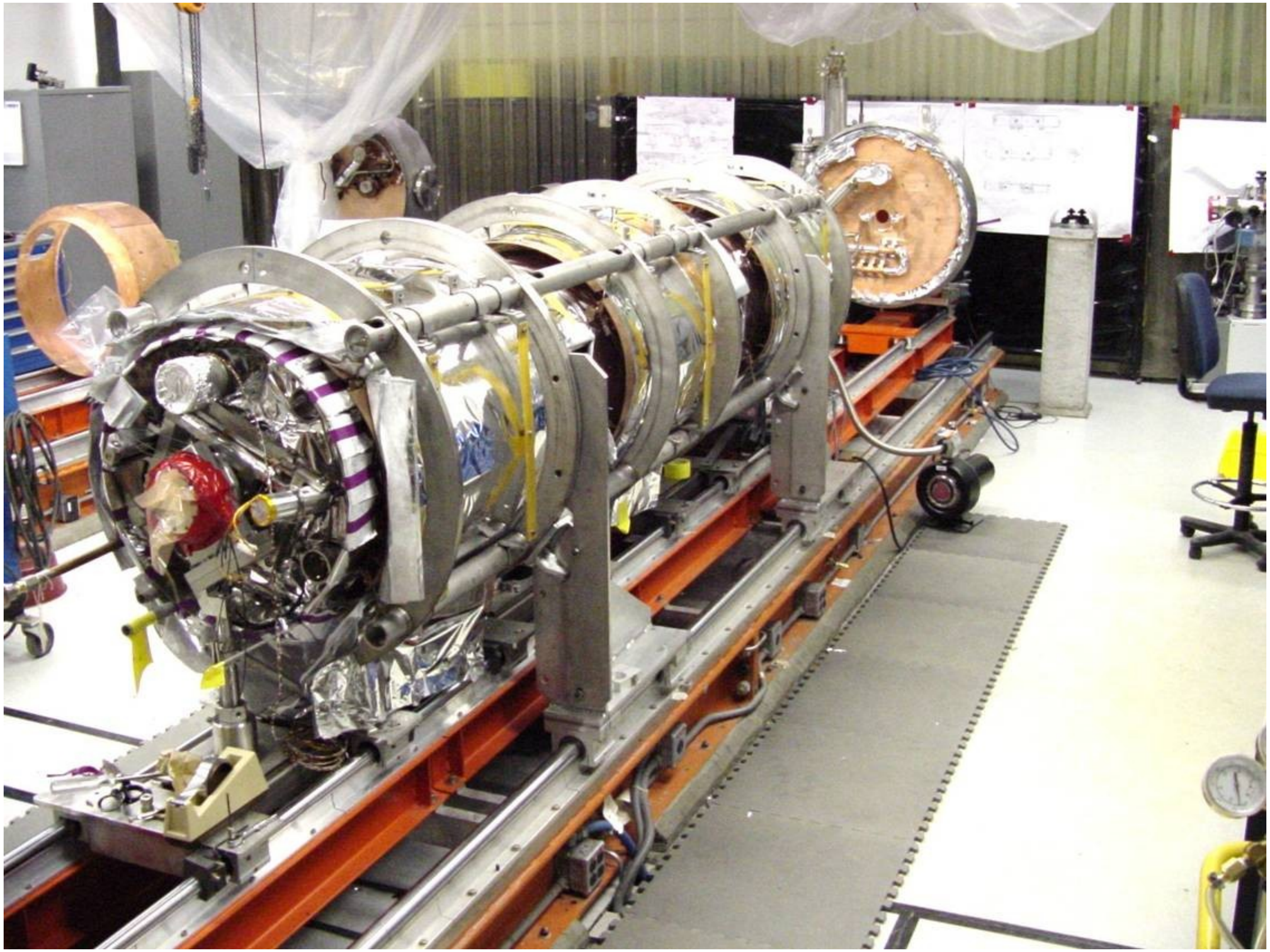
Internal magnetic shield and MLI

SNS β=0.61 Cryomodule Assembly -3



Thermal shield and spaceframe

SNS β=0.61 Cryomodule Assembly -4

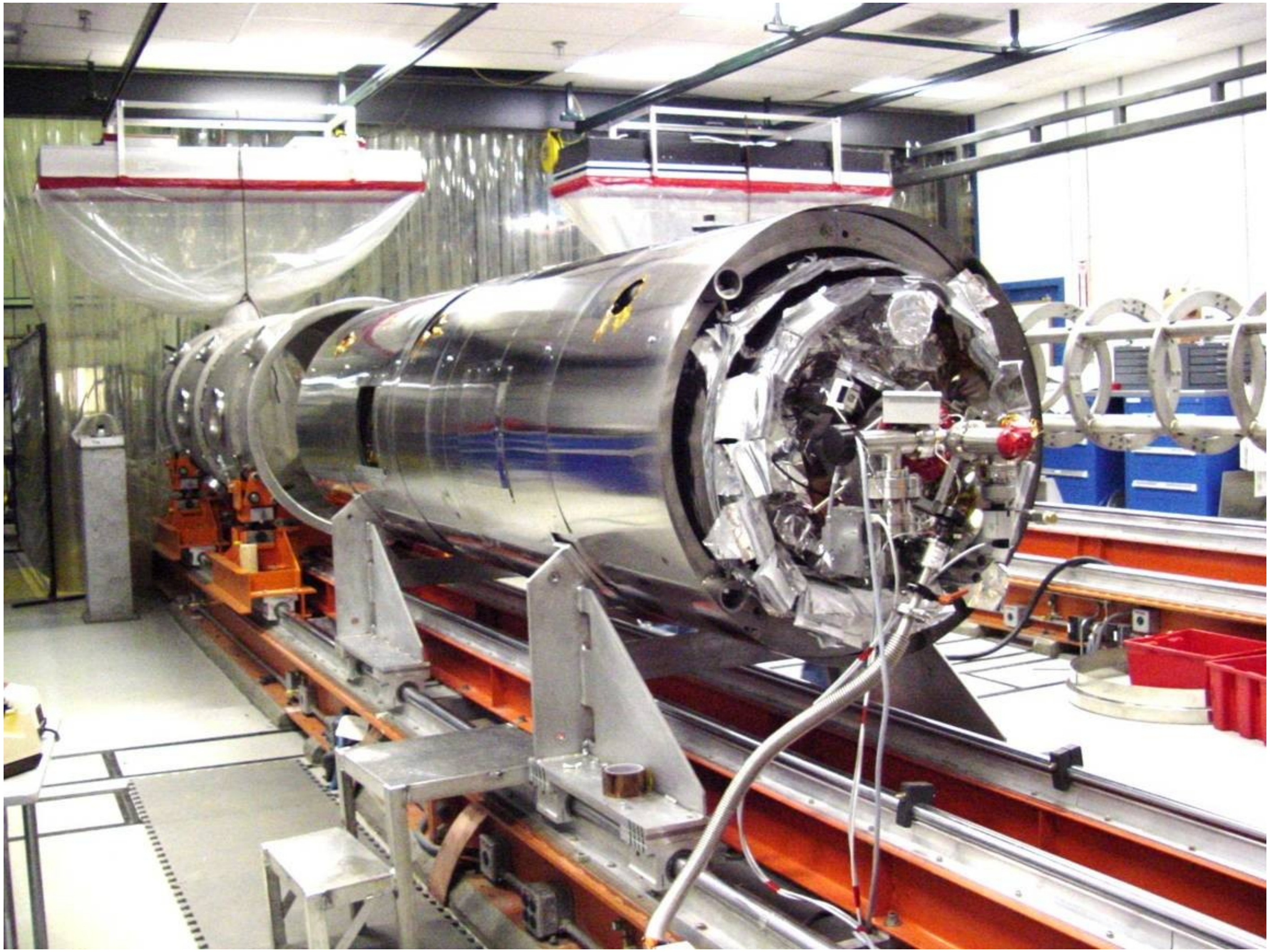


String in spaceframe

SNS β=0.61 Cryomodule Assembly -5

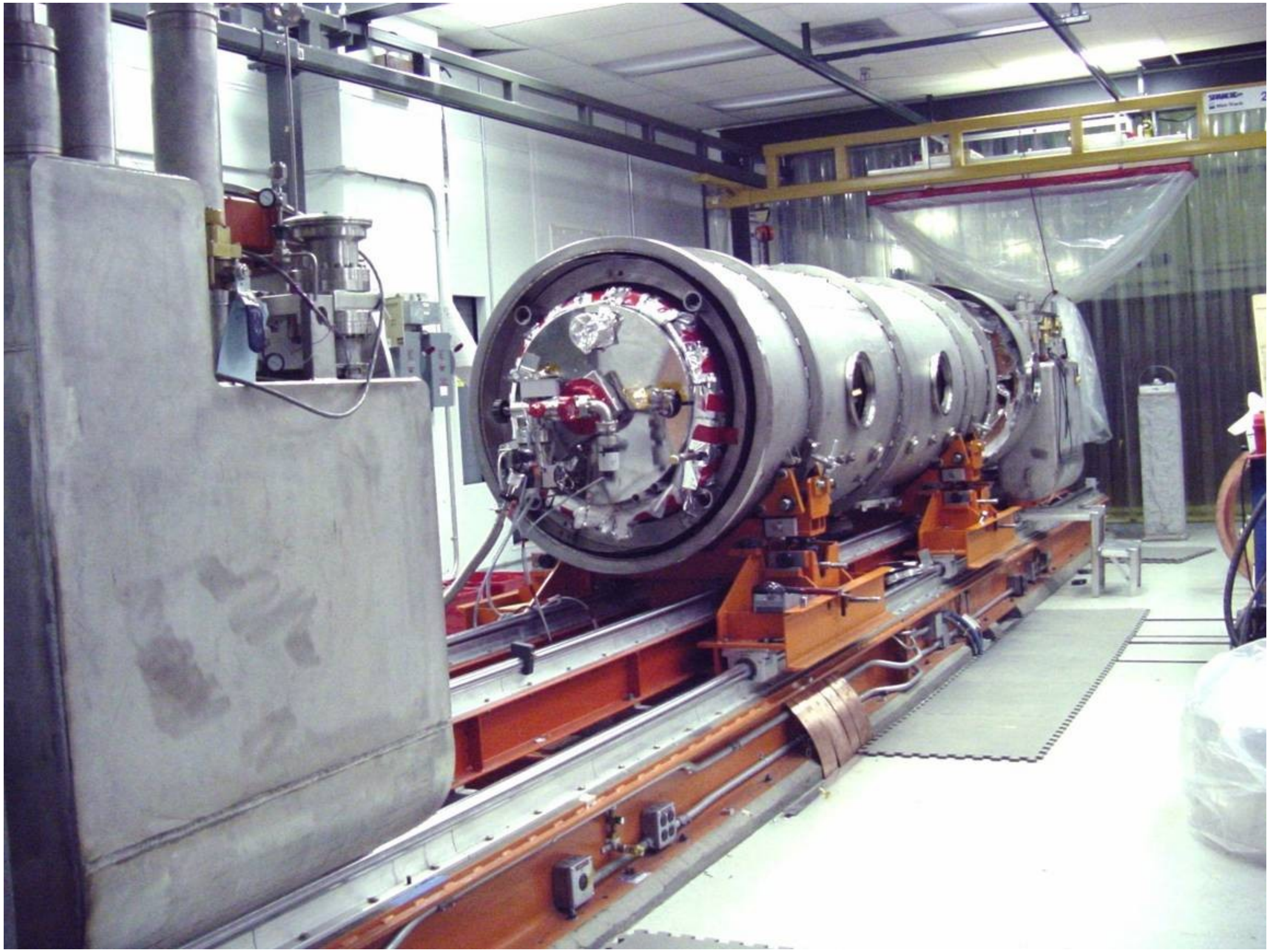
Vacuum vessel

SNS β=0.61 Cryomodule Assembly -6



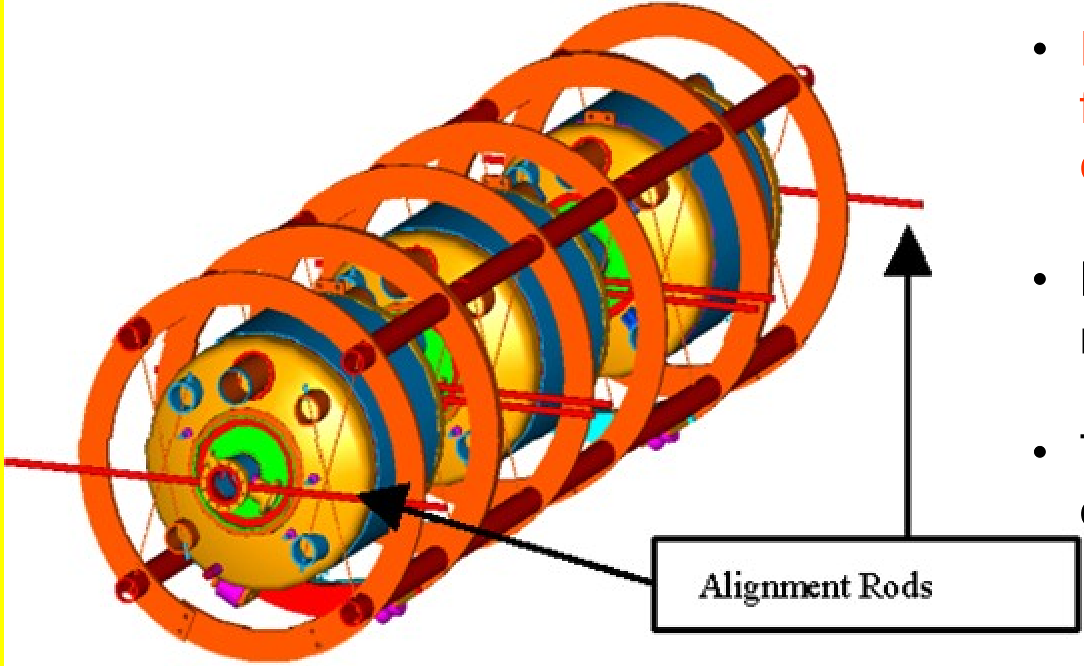
Spaceframe with external magnetic shield

SNS β=0.61 Cryomodule Assembly -7



Sliding the Vacuum Vessel

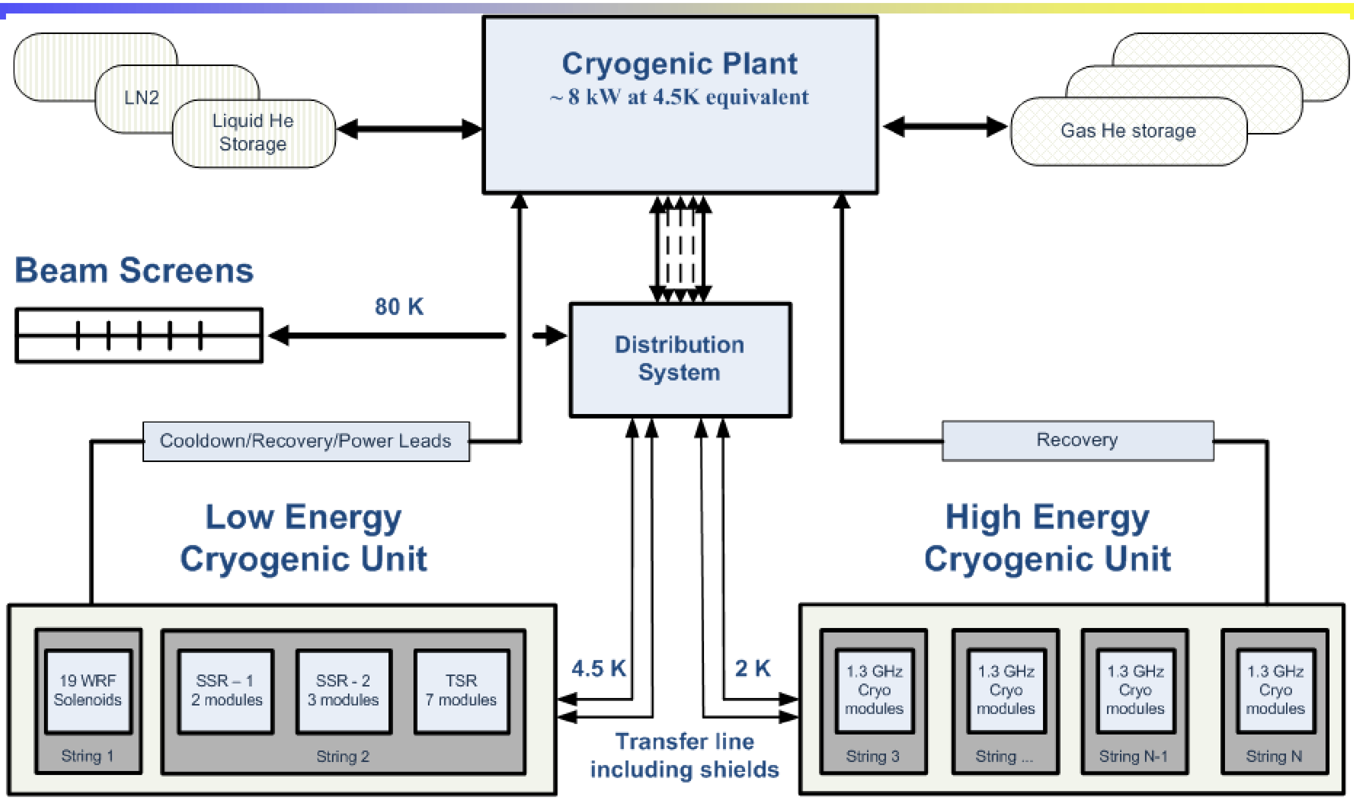
Alignment strategy



- Indexing off of the beamline flanges at either end of each cavity
- Nitronic support rods used to move the cavity into alignment
- Targets on rods on two sides of each flange.

- Cavity string is supported by the spaceframe
- Each target sighted along a line between set monuments (2 ends and sides)
- The nitronic rods are adjusted until all the targets are within 0.5 mm of the line set by the monuments
- Cavity string in the vacuum vessel: the alignment is verified and transferred (fiducialized) to the shell of the vacuum vessel.

Project-X baseline cryogenics



- 2-phase He at 4.5 K
- Strings are fed in parallel
  - first string SC solenoids, warm RF
  - second string SSR/TSR modules
- Cryomodules are fed in series

- Revised TESLA cryo string concept
- 2 phase He line at 2 K
  - concurrent liquid supply and vapor return flow in the string
- Double thermal shielding in strings to limit radiation flow at 2 K

Project-X head load table

Project X ICD									
25 MV/m, 1.5 msec, 5Hz, 20 mA, 1.25 FT	Qty [#]	Heat Load							
		2K		4.5K		5K		40K or 80K	
Item		Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic
WRF Solenoid	19	-	-	42	99	-	-	536	-
SSR1	2	-	-	42	1	-	-	1003	2
SSR2	3	-	-	62	10	-	-	1279	8
TSR	7	-	-	93	50	-	-	1965	40
S-ILC	7	27	17	-	-	69	18	517	477
ILC-1	9	35	43	-	-	105	47	727	1,226
ILC-2	28	110	133	-	-	328	146	2,260	3,813
SCB, End Boxes, etc	1	50	-	100	-	-	-	500	-
Auxiliary Load	1	-	-	-	-	-	-	1000	-
Estimated, [W]		222	193	338	160	502	211	9787	5566
Design Capacity, [kW]		0.8		1.0		1.4		29.9	
4.5K Eqv [kW]		**8.2**							
Plug Power, [MW]		**2.3**							

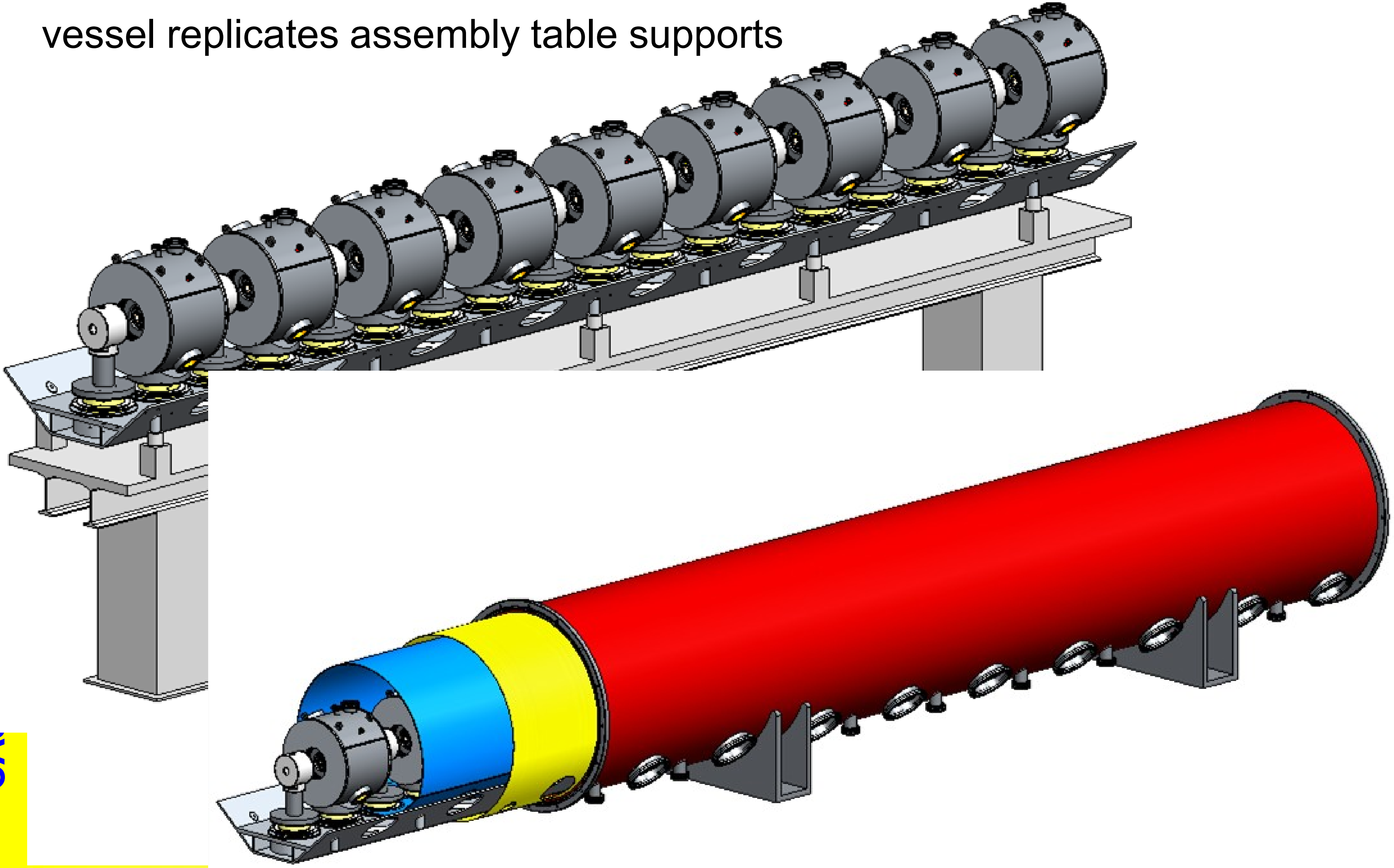
Project-X cryo r&d plan

- cryo distribution and segmentation
  - study existing cryomodules thermal cycling experience
  - stationary, transient, fault, maintenance and commissioning scenarios
  - component over pressure protection study
  - define cryogenic string size limits and segments
  - liquid helium level control strategy development
  - development of tunnel ODH mitigation strategy
- capital and operational cost optimization
  - lifecycle cost optimization & Cryogenic Plant Cycle
  - heat shields operating parameter optimization
- heat load analysis
  - static and dynamic loads analysis for components/sub systems
  - define overcapacity and uncertainty factors
  - fault scenarios heat flux study

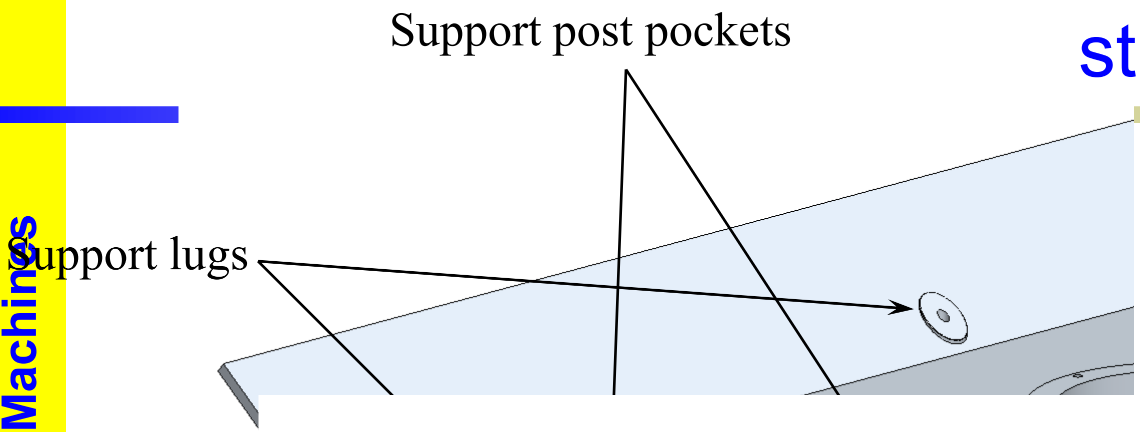
HINS - SSR1 conceptual cryomodule layout

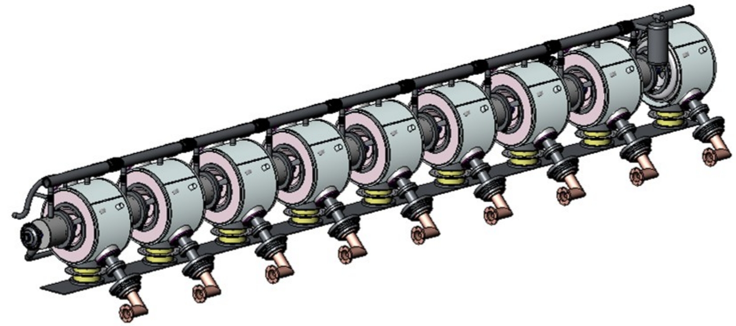
string on strongback, dressed, aligned, shielded

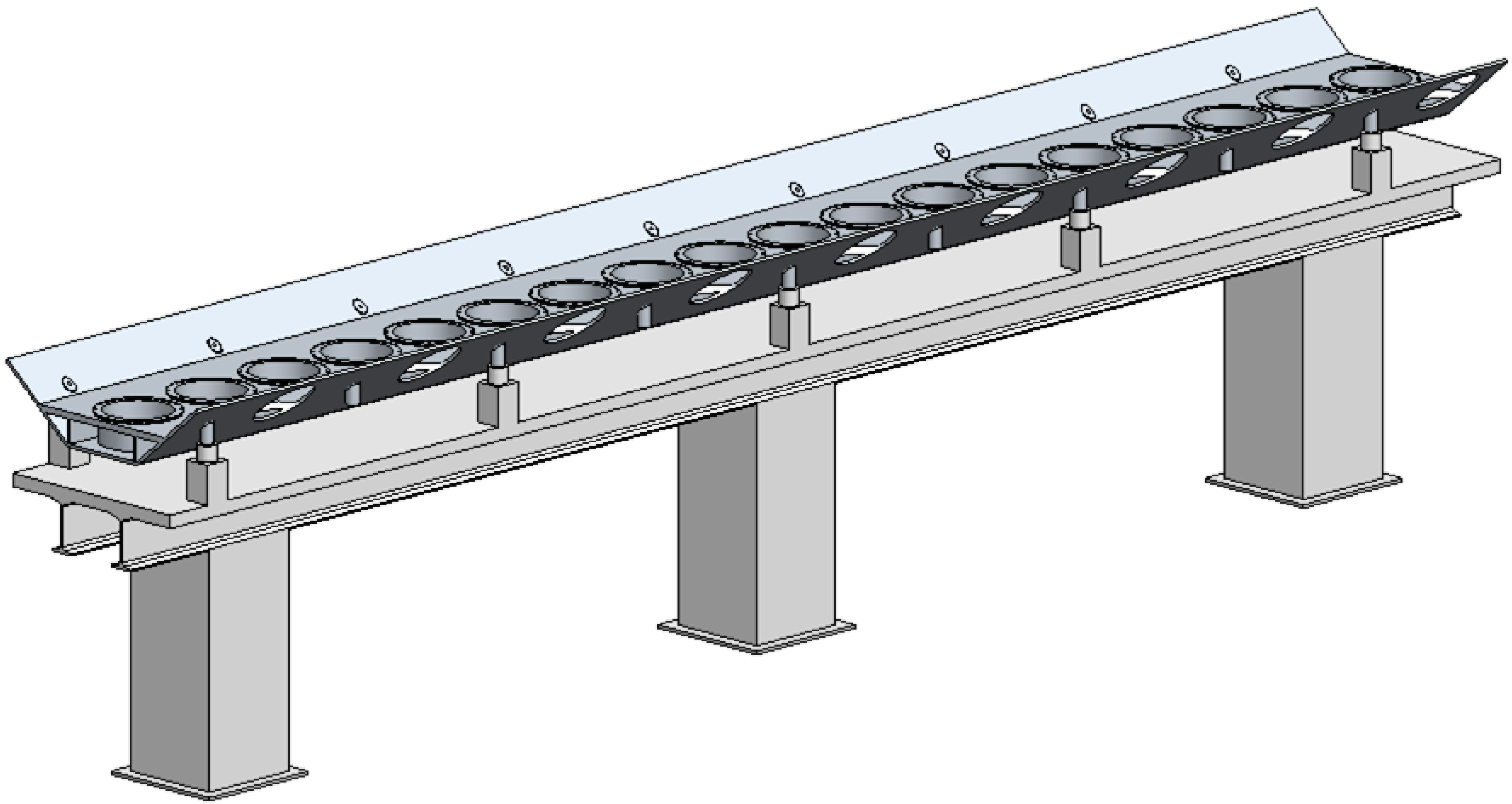
vessel replicates assembly table supports



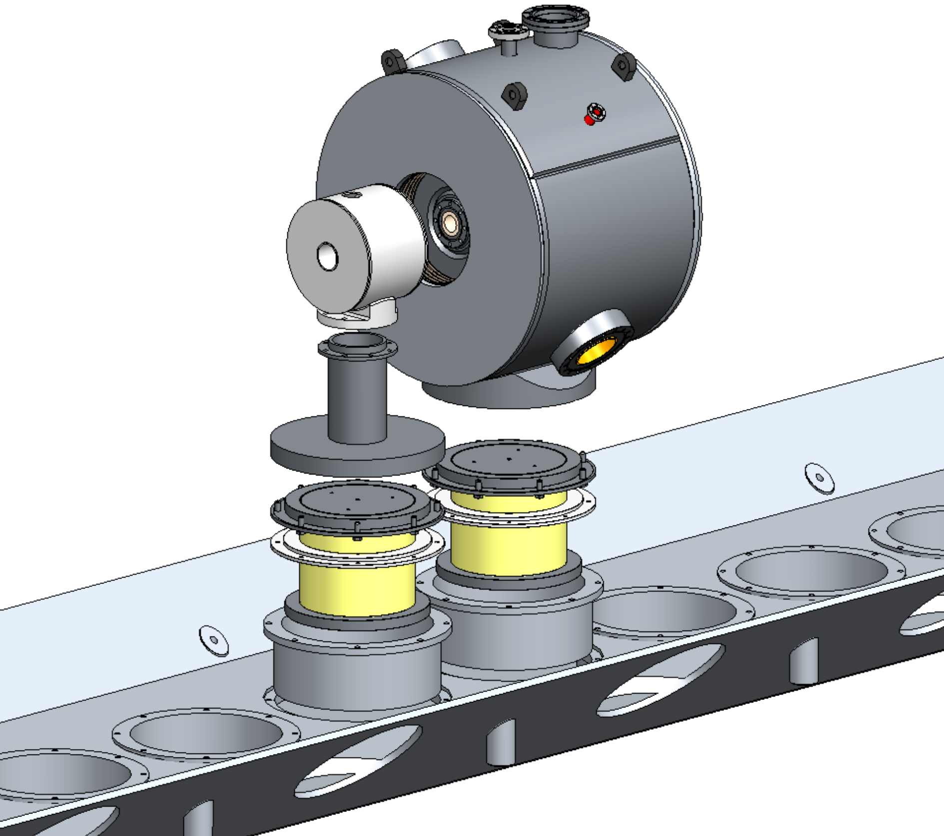
strongback concept

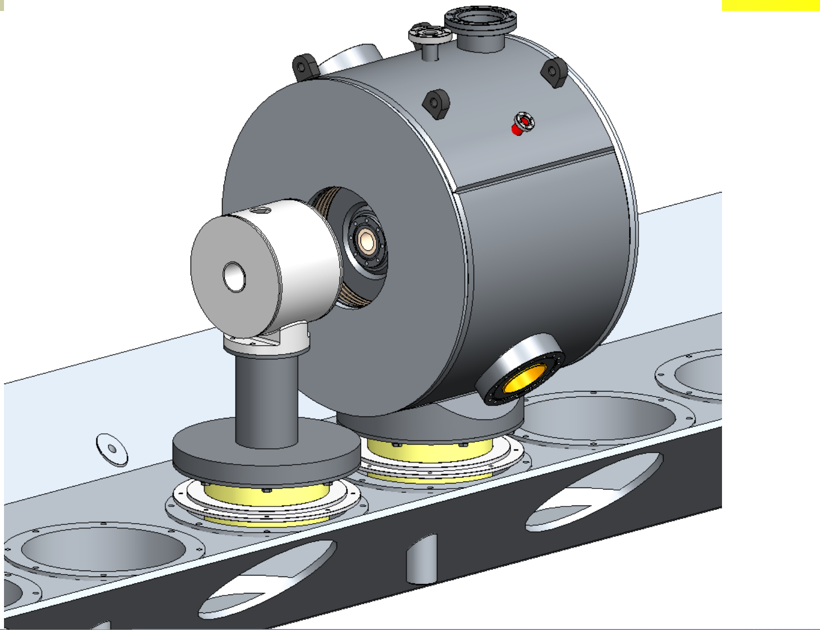


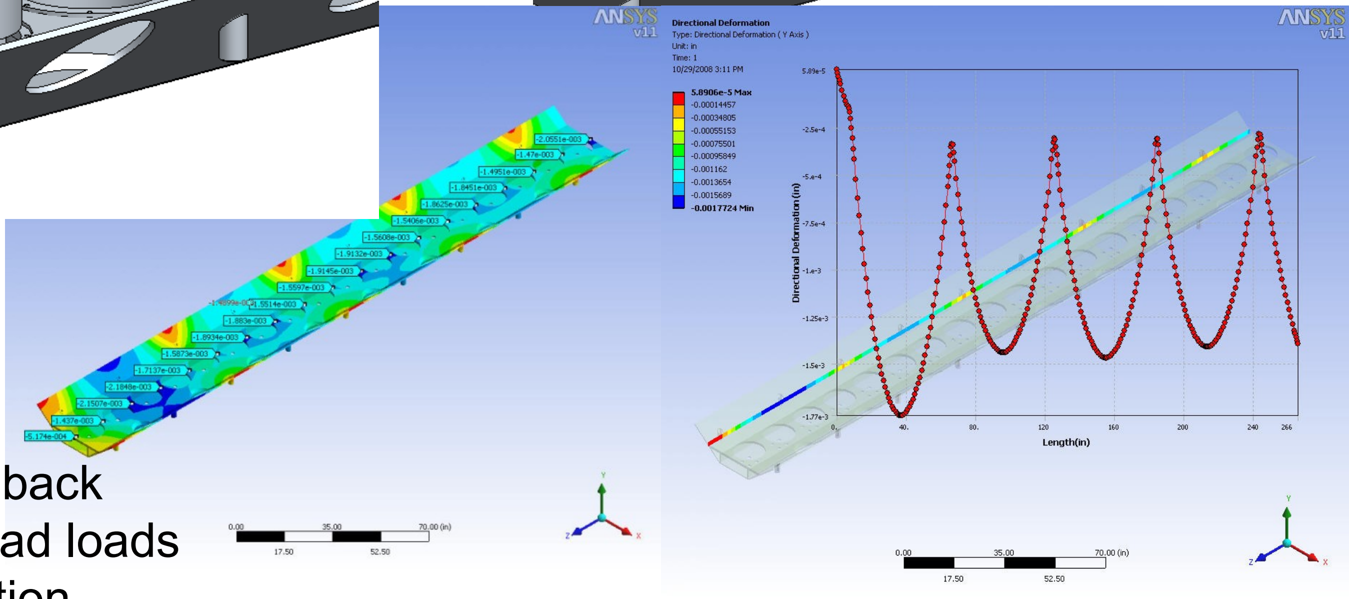




spoke/solenoid mounting scheme

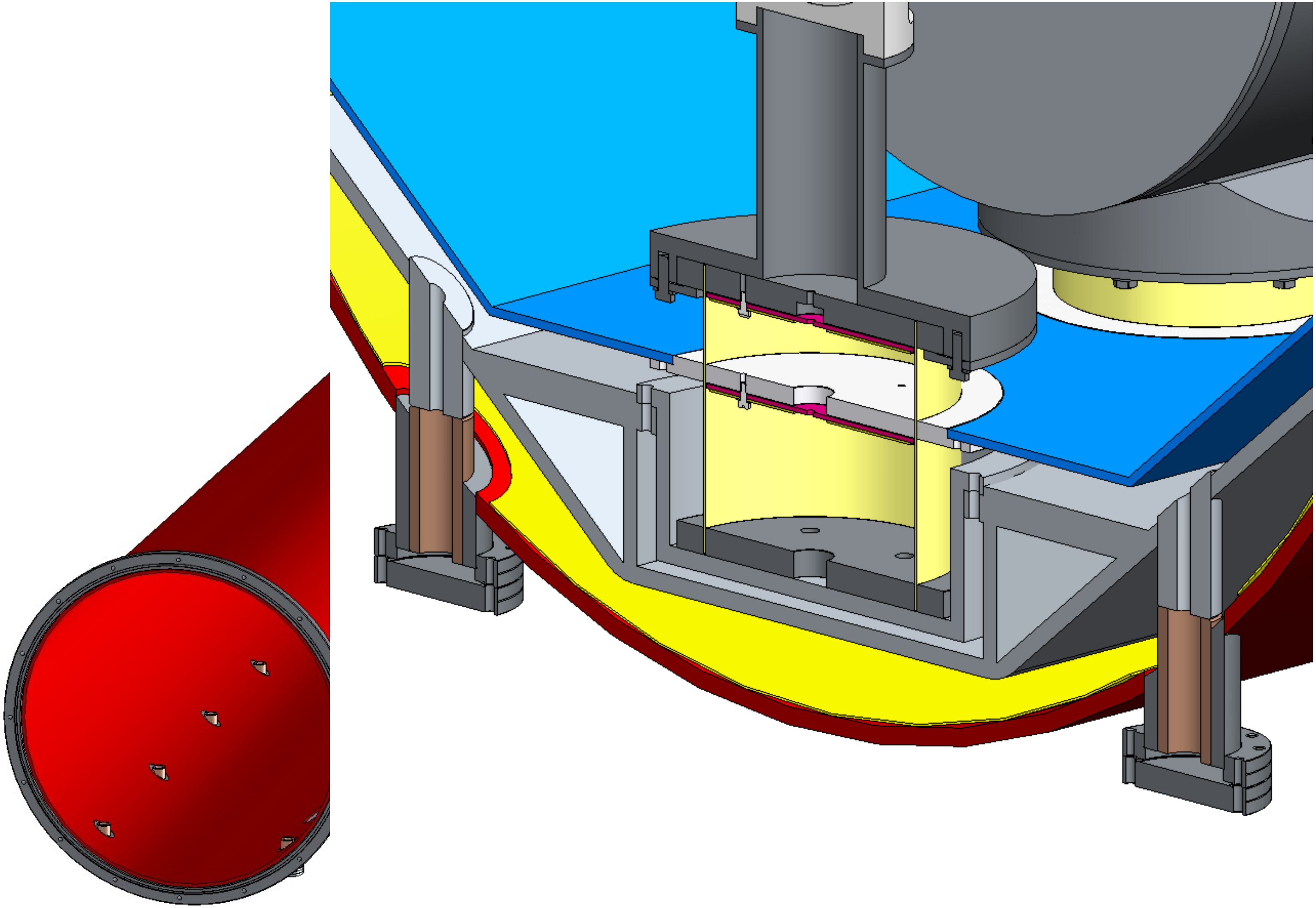






Analysis of the strongback deflections unders dead loads with support optimization

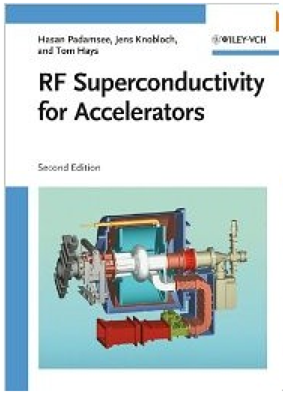
Vacuum vessel with internal strongback supports

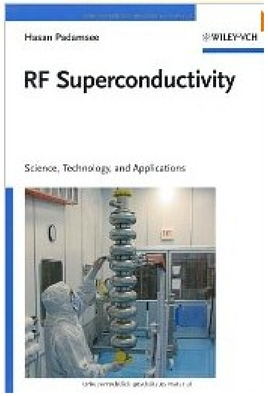


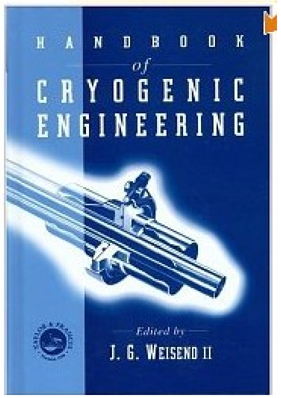
Conclusive remarks

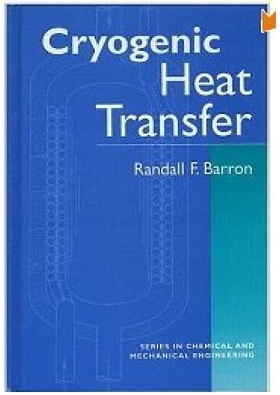
- The design of the “noble” device (the RF cavity) is not the end of the game
  - A lot of physics considerations and detailed engineering goes in its supporting systems that have to provide the operating conditions
- Considerations on the overall linac design choices (especially for large machines) have strong implications on the design on the cryomodule
- Plans for providing adequate mechanism for cooling to nominal levels, heat removal during operation, control of alignment, countermeasures for thermal stresses and spurious heat leaks should be developed early

References & Acknowledgements









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- Tom Peterson, providing an almost endless repository of smart material to feed my curiosity and my slides
  - http://tdserver1.fnal.gov/peterson/tom
- B. Petersen, DESY

- Backup slides with reference data

Role of material properties

- Differential contraction can be big!
  - Can lead to unacceptable stresses if not taken into account
  - Choose proper combination of materials/bellows
    - e.g. Nb/Ti vs Nb/SS

Material	**$(L_{300}-L_2)/L_{300}$**
Nb	0.146%
Ti	0.159%
Stainless Steel (304)	0.310%
Al 6061	0.419%
Invar	0.038%
G10 composite	0.274%

• Thermal radiation from hot surfaces to cold mass

Blackbody radiation to negligible temperatures	
Temperature (radiating surface)	**Specific heat flux [W/m^2]**
300 K	460 W/m^2
70 K	1.4 W/m^2
4.5 K	22 10^{-6} W/m^2

With MLI Insulation	
Temperature (radiating surface)	**Specific heat flux [W/m^2] at low T**
From 300 K, 30 layers	1.2 W/m^2
From 80 K, 10 layers	0.06 W/m^2

Thermal conduction integrals

Thermal conduction integral: 2 to 4.5 K [W/m]	
G10 composite	0.134
Steel	0.453
Aluminum (6061)	19.3
Copper	471
Thermal conduction integral: 4.5 K to 70 K [W/m]	
G10 composite	16.8
Steel	270
Aluminum (6061)	5000
Copper	55000
Thermal conduction integral: 70 K to 300 K [W/m]	
G10 composite	150
Steel	2800
Aluminum (6061)	31300
Copper	93700

$$\dot{Q} = \frac{S}{L}\int_{T_c}^{T_h} k_{th}(T)\,dT$$