Cryogenic Considerations for Cryomodule Design

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Outline

- Introductory comments about considerations for cryomodule design and helium flow
- Practical superfluid heat transport considerations
- Overview of typical cryomodule requirements
- Stand-alone versus long cryogenic string
- Survey of cryomodule configurations

Cryomodule requirements -- major components

- Dressed RF cavities
- RF power input couplers
- Intermediate temperature thermal shield or shields
- Heat exchanger for 4.5 K to 2.2 K precooling of the liquid supply flow if stand-alone style
- Cryogenic valves if stand-alone style
  - 2.0 K liquid level control valve
  - Cool-down/warm-up valve
  - 5 K thermal intercept flow control valve
- Pipe and cavity support structure
- Instrumentation -- RF, pressure, temperature, etc.
- Bayonet connections for helium supply and return

Cryomodule requirements -- major interfaces

- Bayonet connections for helium supply and return
- Vacuum vessel support structure
- Beam tube connections at the cryomodule ends
- RF waveguide to input couplers
- Instrumentation connectors on the vacuum shell
- Alignment fiducials on the vacuum shell with reference to cavity positions.

Design considerations

- Cooling arrangement for integration into cryo system
- Pipe sizes for steady-state and emergency venting
- Pressure stability factors
  - Liquid volume, vapor volume, liquid-vapor surface area as buffers for pressure change
    - Evaporation or condensation rates with pressure change
- Heat load estimates and uncertainty
- Options for handling 4.5 K (or perhaps 5 K - 8 K) thermal intercept flow
- Alignment and support stability
- Thermal contraction and fixed points with closed ends

CW cryomodule requirements

1. A "stand-alone" cryomodule is closed at each end, individual insulating vacuums, with warm beam pipe and magnets in between cryomodules such that individual cryomodules can be warmed up and removed while adjacent cryomodules are cold.
2. Provide the required insulating and beam vacuum reliably
3. Minimize cavity vibration and coupling of external sources to cavities
4. Provide good cavity alignment (typically <0.5 mm)
5. Allow removal of up to 250 W at 2 K per cryomodule if CW
6. Protect the helium and vacuum spaces including the RF cavity from exceeding allowable pressures.
7. Intercept significant heat loads at intermediate temperatures above 2.0 K to the extent possible (cavity internal power generation cannot be intercepted)
8. Provide high reliability in all aspects of the cryomodule (vacuum, alignment stability, mechanics, instrumentation) including after thermal cycles
9. Provide excellent magnetic shielding for high Q0
10. Minimize cost (construction and operational)

Further considerations

- Support structure
  - Stiffness of pipe if used as support backbone
  - Or other support structure options
- Emergency venting scenarios drive pipe sizes and influence segmentation
  - Cold MAWP may be low, driving up pipe sizes and/or reducing spacing between relief vent ports
  - Trade-off of pipe size with vent spacing
  - Thermal shield pipe may also require frequent venting
    - 5 K may have large surface area for large heat flux
    - 70 K helium typically starts at a high pressure
- Liquid management length
  - May want to subdivide strings for liquid management due to large specific liquid flow rate per cavity

Pool boiling and 2-phase flow

- Considerations for pool boiling systems
  - Control of liquid levels, long time constants, inventory management
  - Forced convection for warm-up and cool-down
- Two-phase flow
  - Liquid and vapor phases separate with any acceptably low pressure drop
  - Baker Plot does not apply!

Provisions for cool-down and warm-up

- Cool-down
  - Return vapor may block liquid supply flow in the same channel; a simple fill from the top or one end might not work. A cool-down vent and/or a bottom-fill port may be required.
- Warm-up
  - Flow will stratify. Local electric heat, a bottom vent port, or other feature to force heat down to the lower parts of a cold mass may be required.
    - The small "capillary" tubes connected to a manifold and providing helium to the bottoms of helium vessels in TESLA-style cryomodules were included primarily with warm-up in mind

Helium II heat transport

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

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

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

He II heat function

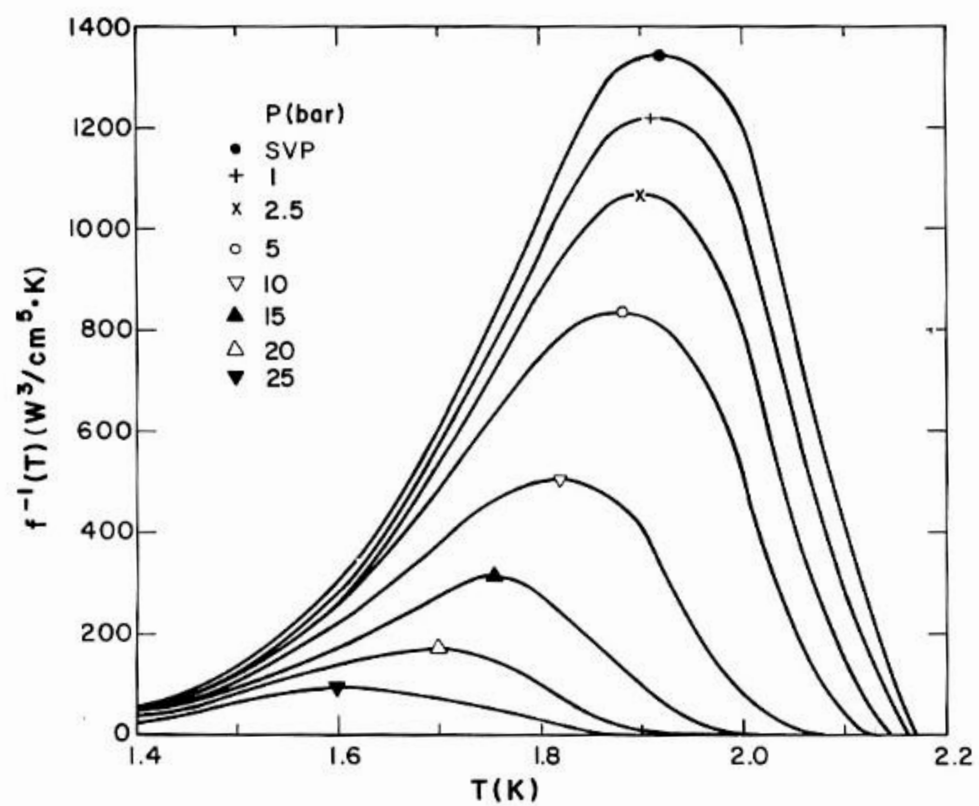


Fig. 5.3. Heat conductivity function for turbulent He II. Symbols indicate the location of the peak value.

Figure from
Steven Van Sciver,
Helium Cryogenics,
Plenum Press,
New York, 1986.

Helium II heat transport -- near saturation pressure

For the small temperature differences which we consider in heat transport from below the surface up to the surface of the saturated helium liquid, differences of at most 10's of mK, nominally all at 2.0 K, we may take constant $\frac{1}{f(T)} = 1200$ (W^3/cm^5-K), with units for q of W/cm^2. With constant heat flux through a channel (heat added at one end of the channel), m = 3, and constant $\frac{1}{f(T)} = 1200$, we have

$$\frac{1200 \Delta T}{L} = q^3 \qquad (2)$$

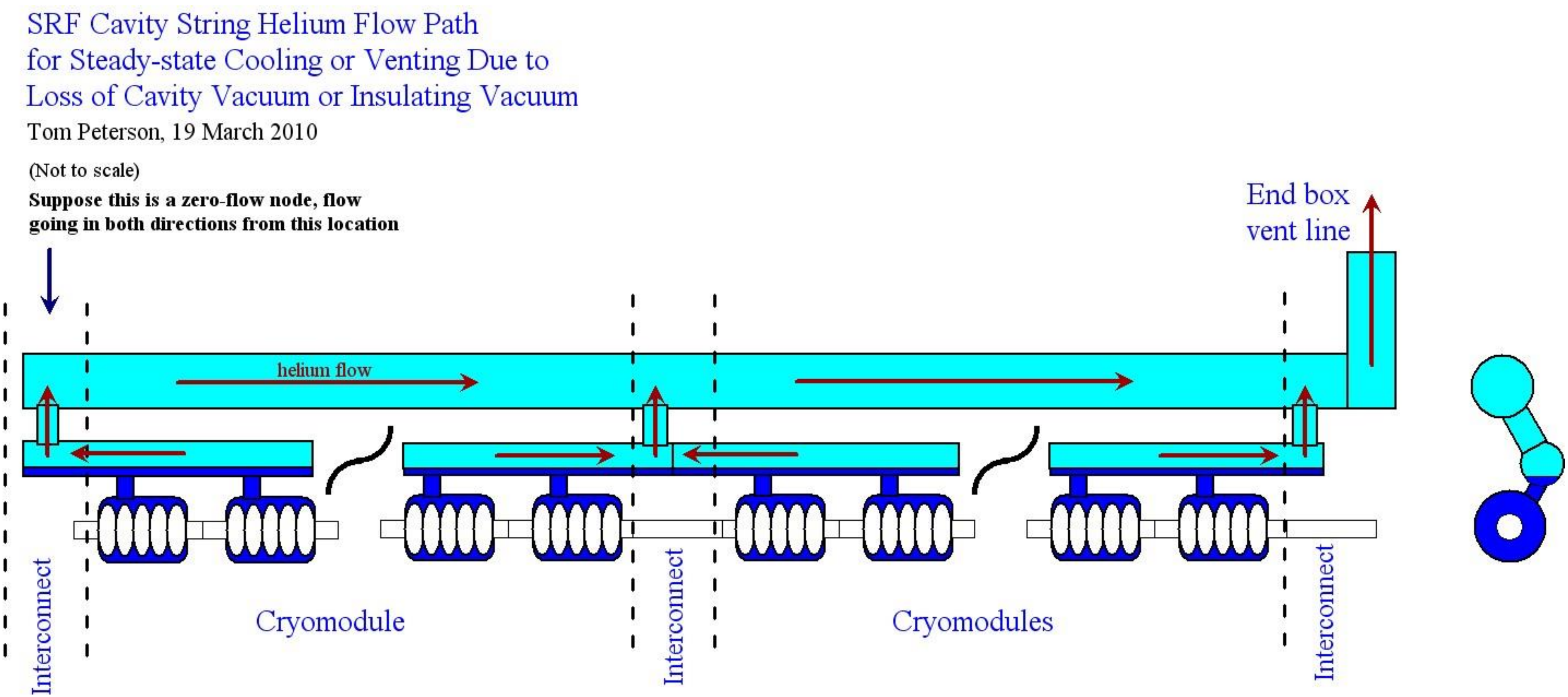
or

$$q = \left(\frac{1200 \Delta T}{L} \right)^{1/3} \qquad (3)$$

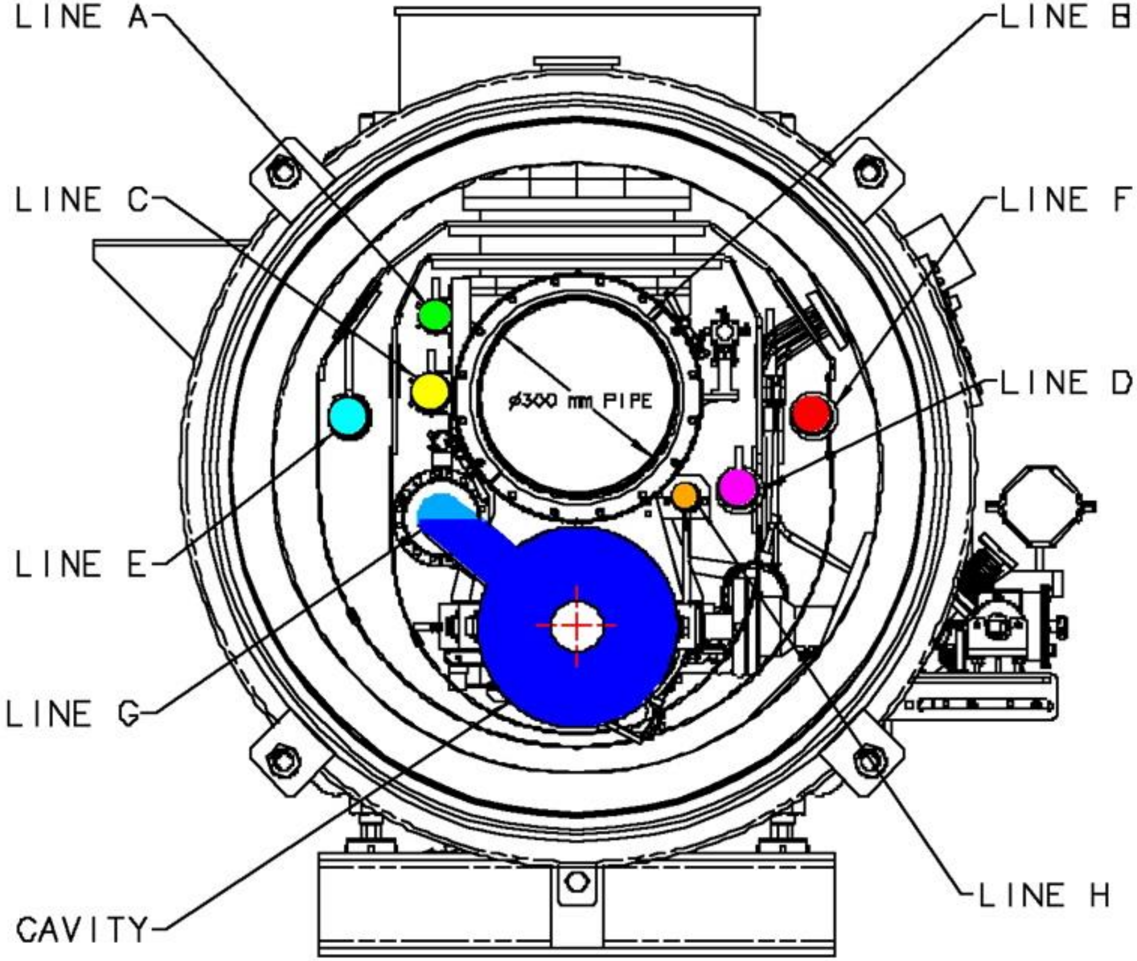
where L is distance in cm, q is the heat flux in W/cm^2, and delta-T is the temperature difference through the conduit in K.

2-pipe 2 Kelvin vapor system

650 MHz cryomodule a modified TESLA-type



TTF cryomodule cross-section



Heat transport vertically to surface

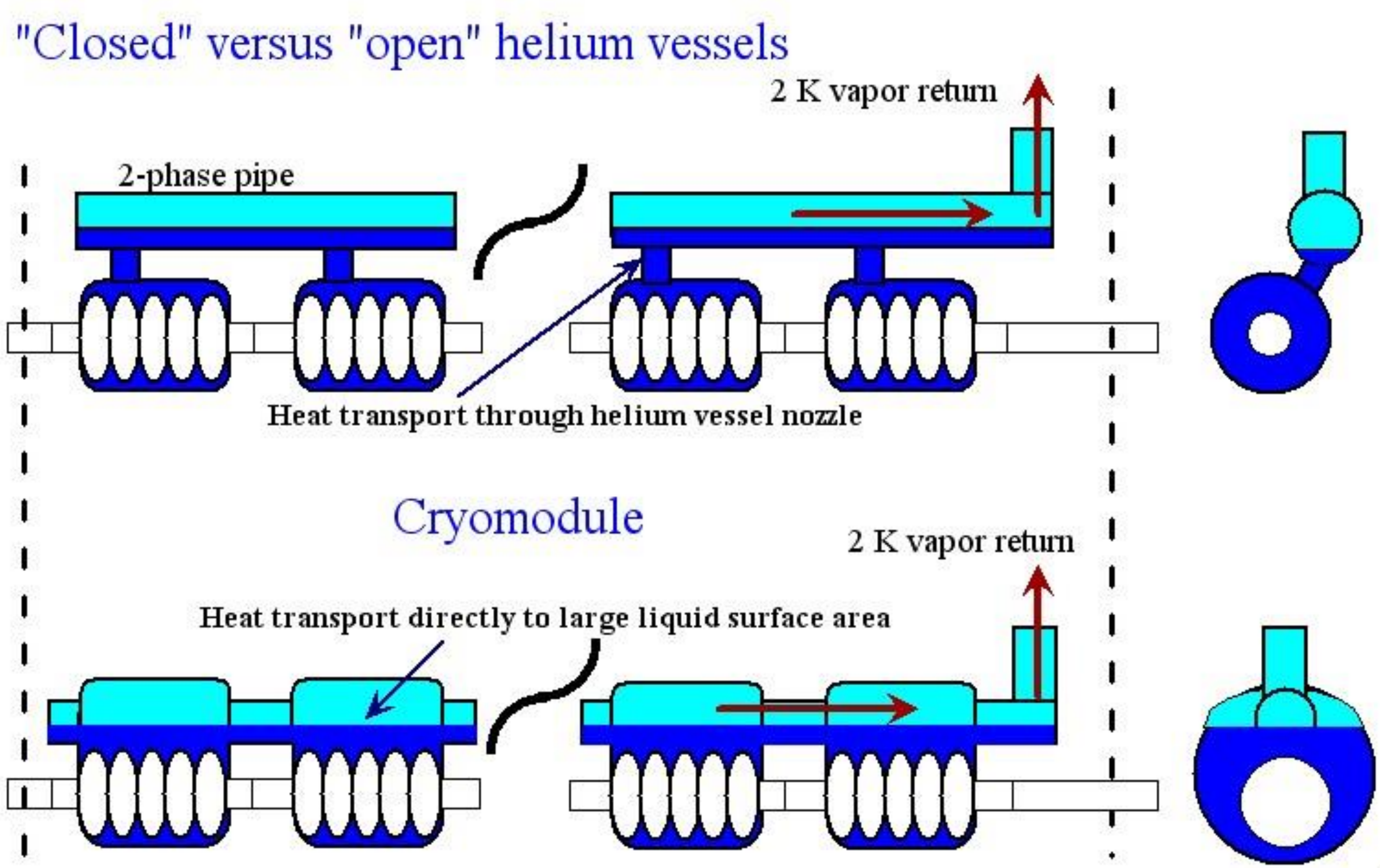
Recall from our normal fluids behavior discussion, the pressure head of liquid helium and Clapeyron Equation tell us that helium saturation temperature increases by about 1.5 mK/cm of depth.

Substituting 0.0015 K/cm into equation (3) on slide 12 results in 1.2 W/cm^2 heat flux vertically to the surface of the helium II. Note that this heat flux is essentially independent of depth for the depths of 10's of cm typical of RF helium vessels. I use 1 W/cm^2 as a limit for sizing a conduit for heat transport to the surface of a saturated helium II bath.

Helium vessel style

- Helium vessel style (open vs. closed) is independent of support style (hung from 300 mm pipe, space frame, rails)
- High heat loads and tight pressure stability ==>
  - Large liquid-vapor surface area for liquid-vapor equilibrium
  - Acts as thermal/pressure buffer with heat and pressure changes
- Linac is short enough that total helium inventory not an issue ==>
  - Open helium vessel is feasible
- For the stand-alone CW cryomodule, a closed TESLA-type helium vessel may be favored by
  - Tuner design
  - Input coupler design
  - And allowed by reduced pressure sensitivity

Helium vessel style and pressure stability



Rate of return to vapor-liquid equilibrium following a pressure change is limited by the rate of heat transport through the "chimney" for the closed helium vessel. Rate based on surface areas is about a factor 60 higher for the "open" vessel.

Cryomodule Pipe Sizing Criteria

- Heat transport from cavity to 2-phase pipe
  - 1 Watt/cm^2 is a conservative rule for a vertical pipe (less heat flux with horizontal lengths)
- Two phase pipe size
  - 5 meters/sec vapor "speed limit" over liquid
  - Not smaller than nozzle from helium vessel
- Gas return pipe (also serves as the support pipe in TESLA-style CM)
  - Pressure drop < 10% of total pressure in normal operation
  - Support structure considerations
- Loss of vacuum venting P < cold MAWP at cavity
  - Path includes nozzle from helium vessel, 2-phase pipe, may include gas return pipe, and any external vent lines

Cryomodule requirements -- typical vessel and piping pressures

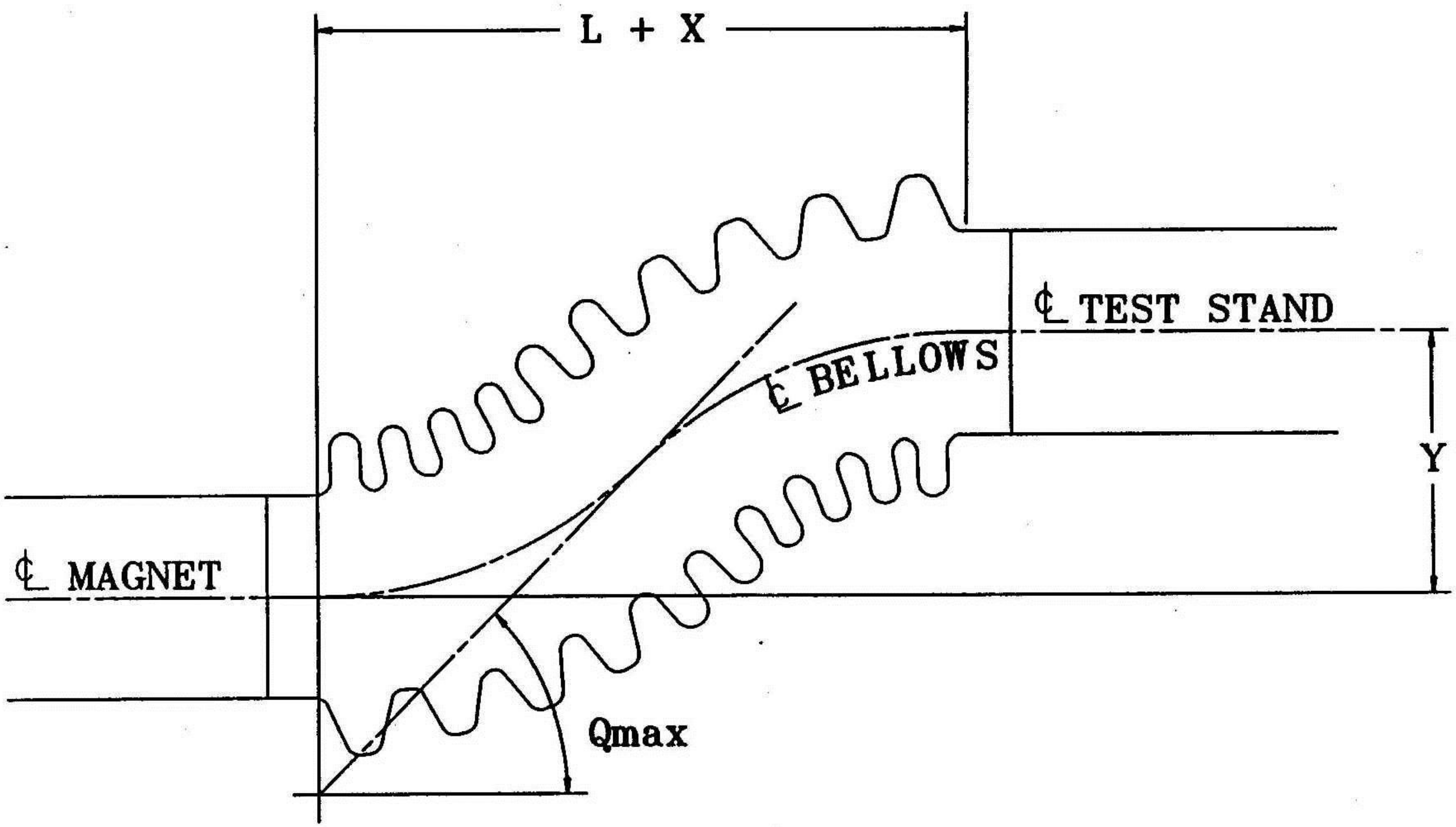
Region	Warm MAWP (bar)	Cold MAWP (bar)
2 K, low pressure space	2.0	4.0
2 K, positive pressure piping (separated by valves from low P space)	20.0	20.0
5 K piping	20.0	20.0
70 K piping	20.0	20.0
Insulating vacuum space	1 atm external with full vacuum inside 0.5 positive differential internal	
Cavity vacuum	2.0 bar external with full vacuum inside 0.5 positive differential internal	4.0 bar external with full vacuum inside 0.5 positive differential internal
Beam pipe vacuum outside of cavities	1 atm external with full vacuum inside 0.5 positive differential internal	1 atm external with full vacuum inside 0.5 positive differential internal

Pressure-induced pipe instability

Lateral elastic pipe instability

- Lateral displacement force is proportional to lateral displacement and to pressure
- If the restoring spring constant of the piping system in which the bellows is installed is less than the constant relating lateral displacement force to lateral displacement (a "negative spring constant") at a given pressure, the system is transversely, elastically unstable at that pressure.
- Relatively light pipe supports near the bellows can prevent this instability by adding stiffness.

Displacement force proportional to displacement

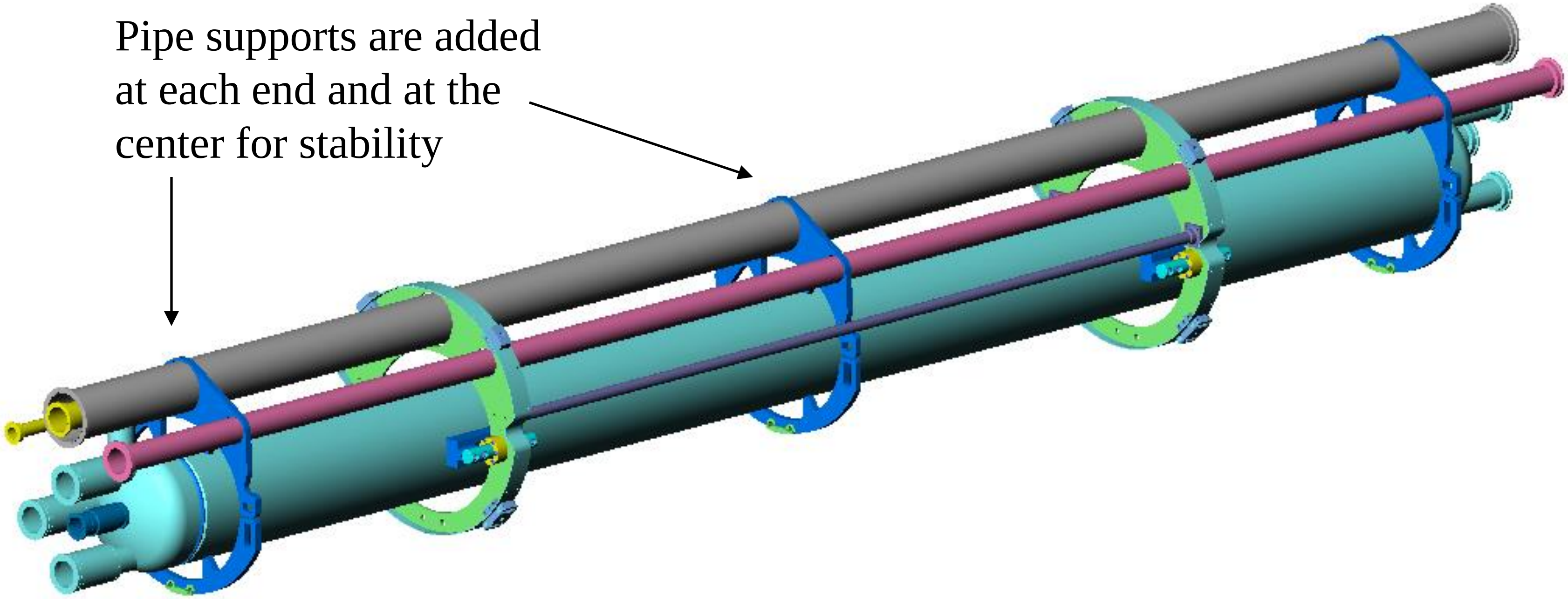


Pipe instability analysis

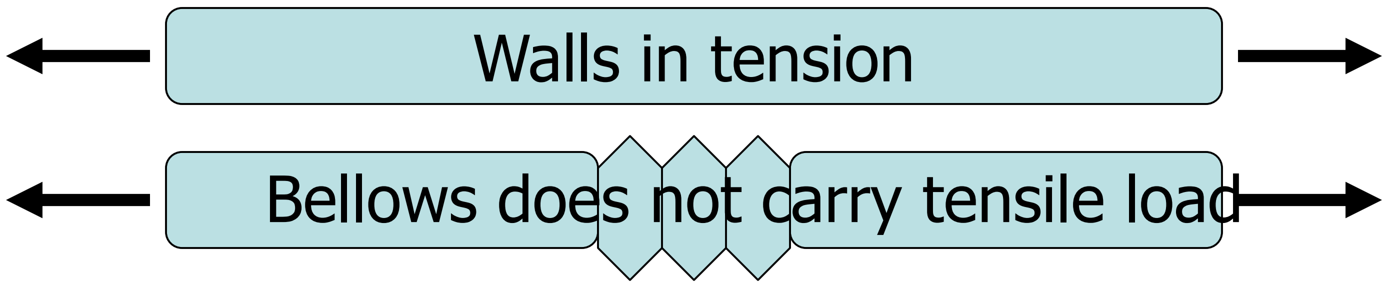
- Lateral pipe instability: displacement force is proportional to displacement (unpublished paper by P.O. Mazur, Fermilab)
- $F(P) = PA\sin(Q_{max})$ where F(P) is the lateral force as a function of pressure, P is pressure in the system (vacuum outside), A is bellows areas, and Q_{max} is the maximum angle of displaced convolutions
- $Q_{max} = 3Y/(2(L+X))$, where X, Y, and L are shown in the previous figure
- For small angles, $F(P)/Y = 3\ PA/(2(L+X))$
- Instability occurs when F(P)/Y exceeds the restoring spring constant, determined by bellows and pipe stiffness

US LHC high gradient quad (Q2P1) cold mass, support rings, and internal piping (from Tom Nicol, Fermilab)

Pipe supports are added at each end and at the center for stability

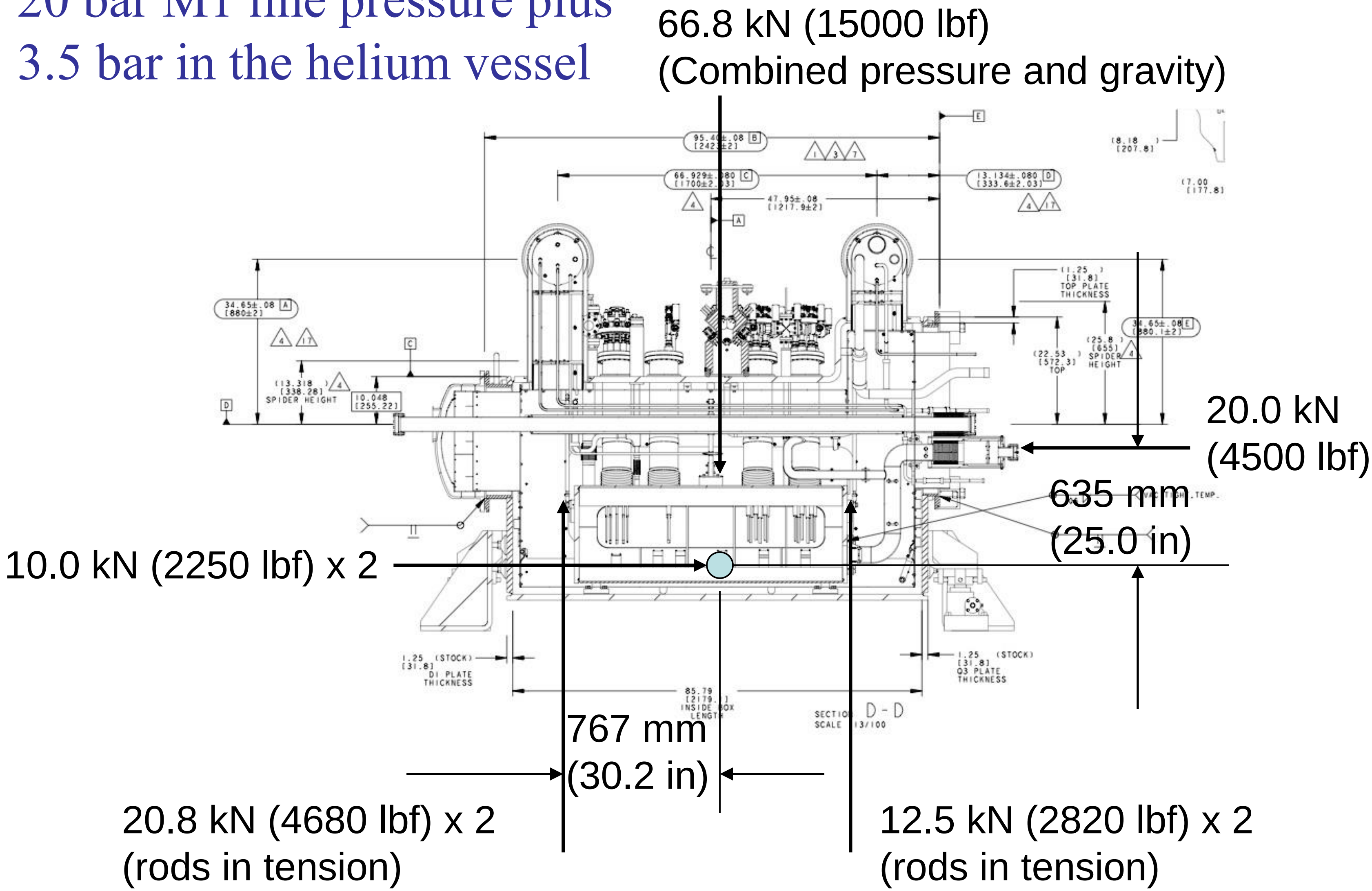


Axial pressure forces

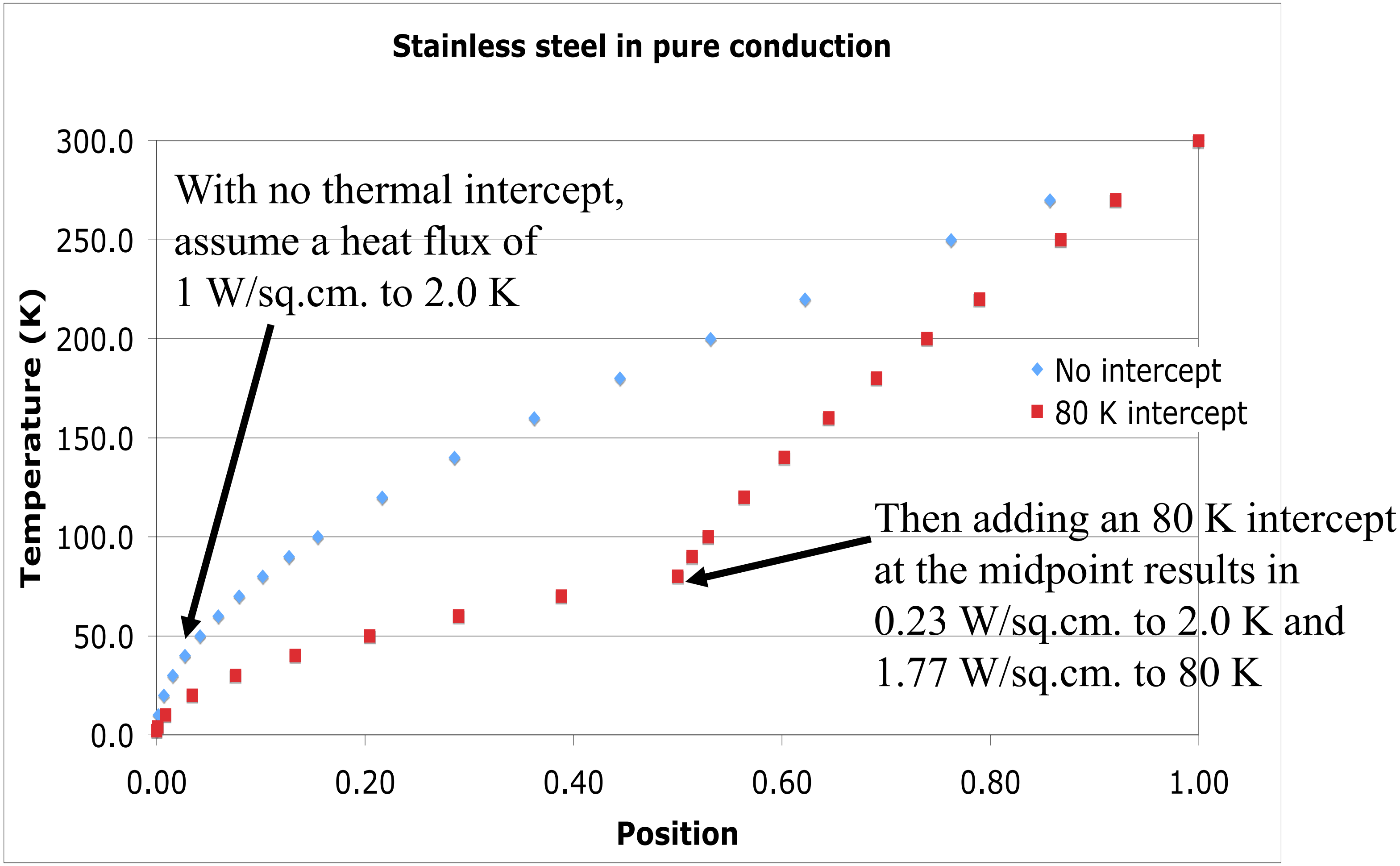


- Pressure-containing pipes and vessels carry tension in their walls due to pressure forces
- Introduction of a bellows or elastic element introduces the possibility of unbalanced forces on the piping
  - Combination of bellows and elbow are often overlooked
- The following slide shows a free body diagram for a helium vessel within a cryogenic supply box for LHC at CERN

Forces on DFBX-E due to 20 bar M1 line pressure plus 3.5 bar in the helium vessel



Thermal intercepts



Thermal intercept benefit

- From previous illustration:
  - No thermal intercept:
    - 1 W/sq.cm. to 2 K x 700 W/W = 700 W of room temperature power per sq.cm. of rod between 2 K and 300 K
  - With thermal intercept:
    - 0.23 W/sq.cm. to 2 K x 700 W/W + 1.77 W/sq.cm. to 80 K x 12 W/W = 161 W + 21 W = 182 W of room temperature power per sq.cm. of rod between 2 K and 300 K

S1-Global cryomodule

- Tested at KEK in 2010 – 2011
- A TESLA-type cryomodule but consisting of two 4-cavity cryomodules joined end-to-end
- Cavities from FNAL, DESY, KEK
- Thoroughly instrumented and careful heat load studies conducted by Norihito Ohuchi (KEK)

From Norihito Ohuchi (KEK)

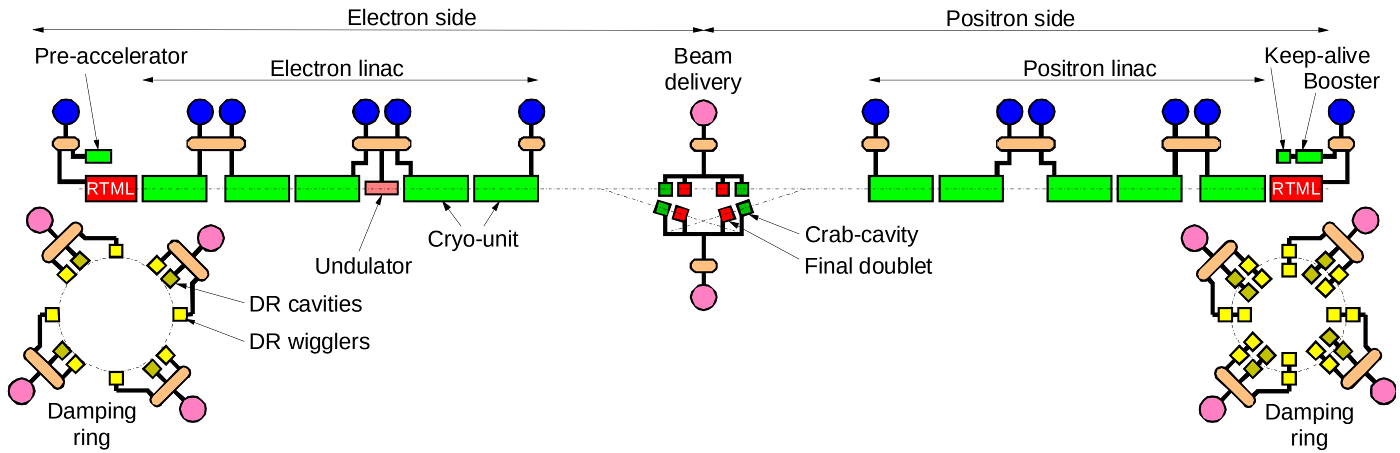
Summary - 1

1. The S1-G cryomodule (Module-C and Module-A) was successfully cooled down to 2K and the thermal performances of different types of components were measured under the same thermal conditions.
2. The static heat loss to the eight cavities at 2 K was measured.
   - Measured static heat loss = 7.2 W, estimated static heat loss = 6.2 W
   - By calculation (excluding heat loss via signal wires), heat loss at four 2 K cavities:
     - Four cavities in Module-A = 2.85 W
     - Four cavities in Module-C = 0.3 W
     - Main source of static heat loss in Module-A was HOM RF cables.
3. The static heat losses at 80 K and 5 K were measured by temperature rise of thermal shields.
   - Heat loss at 80 K:
     - Module-A = 49 W, Module-C = 34 W
   - Heat loss at 5 K:
     - Module-A = 7.3 W, Module-C = 5.3 W
4. Flange temperatures of the movable support post in Module-C was 4 K higher than those of the other posts.
   - Need to strengthen the thermal intercepts for this post.

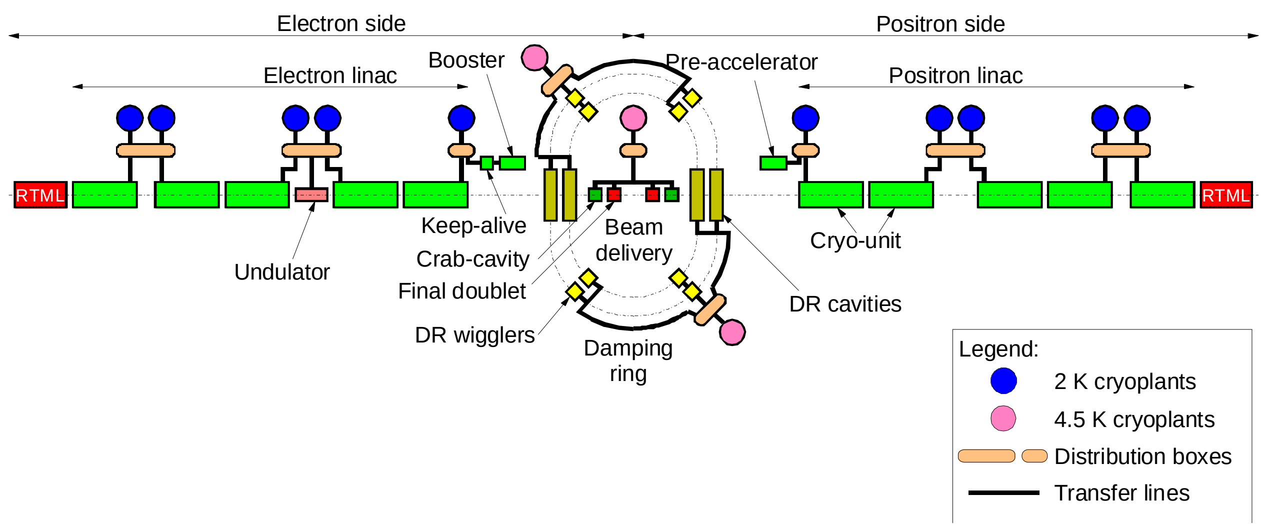
Measured thermal radiation heat

- Measured in above-mentioned S1-Global studies at KEK
  - 1.62 W/m^2 from 300 K to 80 K thermal shield
  - 0.045 W/m^2 from 80 K thermal shield to 5 K thermal shield
- My "rule of thumb" (pre-dates S1-Global)
  - 1.5 W/m^2 from 300 K to 80 K thermal shield
  - 0.05 W/m^2 from 80 K thermal shield to 5 K thermal shield

Baseline Configuration Layout



Reference Design Layout



Cryogenic unit length limitations

- **25 KW total equivalent 4.5 K capacity**
  - **Heat exchanger sizes**
  - **Over-the-road sizes**
  - **Experience**
- **Cryomodule piping pressure drops with 2+ km distances**
- **Cold compressor capacities**
- **With 192 modules, we reach our plant size limits, cold compressor limits, and pressure drop limits**
- **192 modules results in 2.47 km long cryogenic unit**
- **5 units (not all same length) per 250 GeV linac**
  - **Divides linac nicely for undulators at 150 GeV**

Heat loads scaled from TESLA TDR

Cryomodule	TESLA	ILC 9-8-9	
E, [MV/m]	23.4	31.5	G
Q	1.E+10	1.E+10	
Rep rate, [Hz]	5	5	
Number of Cavities	12	8.667	avg number of cavities per module
Fill time [µsec]	420	597	Tf
Beam pulse [µsec]	950	969	Tb
Number of bunches	2820	2670	Nb
Particles per bunch [1e10]	2	2.04	Qb
Gfac		2.09	Stored Energy Factor = G^2*(Tb + 1.1*Tf)
Pfac		1.54	Input Power Factor = G*(Tb + 2*Tf)*Cfac
Bfac		0.99	Bunch Factor = Nb*Qb^2
Cfac		0.95	Beam Current Factor = Qb*Nb/Tb

ILC 8-8-8 and 9-8-9 refers to the number of cavitie

Module predicted heat loads -- 2K

	TESLA		ILC 9-8-9		
	Static	Dynamic	Static	Dynamic	
Temperature Level	**2K**		**2K**		
RF load		4.95		7.46	Dynamic load scaled by the number of cavities and Gfac
Supports	0.60		0.60	-	Assume independent of nuimber of cavities
Input coupler	0.76	0.14	0.55	0.16	Static load scaled by number of cavities, dynamic by Pfac also
HOM coupler (cables)	0.01	0.27	0.01	0.18	Static and dynamic load scaled by number of cavities, dynamic by Cfac a
HOM absorber	0.14	0.02	0.14	0.01	Dynamic load scaled by Bfac
Beam tube bellows		0.24		0.36	Dynamic load scaled by the number of cavities and Gfac
Current leads	0.04		0.28	0.28	Weigh by a factor of 1/3 since only 1 in 3 modules have quads**
HOM to structure		1.68		1.20	Static load scaled by the number of cavities, dynamic by Bfac also
Coax cable (4)	0.05		0.05		Assume indepent of nuimber of cavities
Instrumentation taps	0.07		0.07		Assume indepent of nuimber of cavities
Scales as Gfac		5.19		7.83	
Scales as Pfac		0.14		0.16	
Independent of G,Tf	1.67	1.97	1.70	1.68	
Static, dynamic sum	1.67	7.30	1.70	9.66	Total for 9-8-9 RF unit below
2K Sum [W]	**9.0**		**11.4**		34.08

Module predicted heat loads -- 5K

	TESLA		ILC 9-8-9		
	5K		5K		
Radiation	1.95		1.41		Static load scaled by number of cavities
Supports	2.40		2.40		Assume indepent of nuimber of cavities
Input coupler	2.05	1.19	1.48	1.32	Static load scaled by number of cavities, dynamic by Pfac also
HOM coupler (cables)	0.40	2.66	0.29	1.82	Static and dynamic load scaled by number of cavities, dynamic by Cfac a
HOM absorber	3.13	0.77	3.13	0.76	Dynamic load scaled by Bfac
Current leads			0.47	0.47	Weigh by a factor of 1/3 since only 1 in 3 modules have quads**
Diagnostic cable	1.39	-	1.39	-	Assume independent of nuimber of cavities
Scales as Pfac		1.19		1.32	
Independent of G,Tf	11.32	3.43	10.56	3.04	
Static, dynamic sum	11.32	4.62	10.56	4.37	Total for 9-8-9 RF unit below
5K Sum [W]	**15.9**		**14.9**		44.80

Module predicted heat loads -- 40K

	TESLA		ILC 9-8-9		
	40K		40K		
Radiation	44.99		32.49		Static load scaled by number of cavities
Supports	6.00		6.00		Assume indepent of nuimber of cavities
Input coupler	21.48	59.40	15.51	66.08	Static load scaled by number of cavities, dynamic by Pfac also
HOM coupler (cables)	2.55	13.22	1.84	9.04	Static and dynamic load scaled by number of cavities, dynamic by Cfac a
HOM absorber	(3.27)	15.27	(3.27)	15.04	Dynamic load scaled by Bfac
Current leads			4.13	4.13	Weigh by a factor of 1/3 since only 1 in 3 modules have quads**
Diagnostic cable	2.48		2.48		Assume indepent of nuimber of cavities
Scales as Pfac		59.40		66.08	
Independent of G,Tf	74.23	28.49	59.19	28.22	
Static, dynamic sum	74.23	87.89	59.19	94.30	Total for 9-8-9 RF unit below
40K Sum [W]	**162.1**		**153.5**		460.46

Power required for a non-isothermal load

- Use $P = \dot{m}\left\{T_{amb}\left(s_{out} - s_{in}\right) - \left(h_{out} - h_{in}\right)\right\}$
- Where P is the ideal room-temperature power required to remove a non-isothermal heat load
- I will show the use of this later in calculating the ILC cryogenic system power

Cryogenic unit parameters

		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	

CERN LHC capacity multipliers

- We have adopted a modified version of the LHC cryogenic capacity formulation for ILC
- Cryo capacity = Fo x (Qd x Fud + Qs x Fus)
  - Fo is overcapacity for control and off-design or off-optimum operation
  - Qs is predicted static heat load
  - Fus is uncertainty factor static heat load estimate
  - Fud is uncertainty factor dynamic heat load estimate
  - Qd is predicted dynamic heat load

Heat Load evolution in LHC

Basic Configuration: Pink Book 1996
Design Report: Design Report Document 2004

Temperature level	Heat load increase w/r to Pink Book	Main contribution to the increase
50-75 K	1,3	Separate distribution line
4-20 K	1,3	Electron-cloud deposition
1,9 K	1,5	Beam gas scattering, secondaries, beam losses
Current lead cooling	1,7	Separate electrical feeding of MB, MQF & MQD

At the early design phase of a project, margins are needed to cover unknown data or project configuration change.

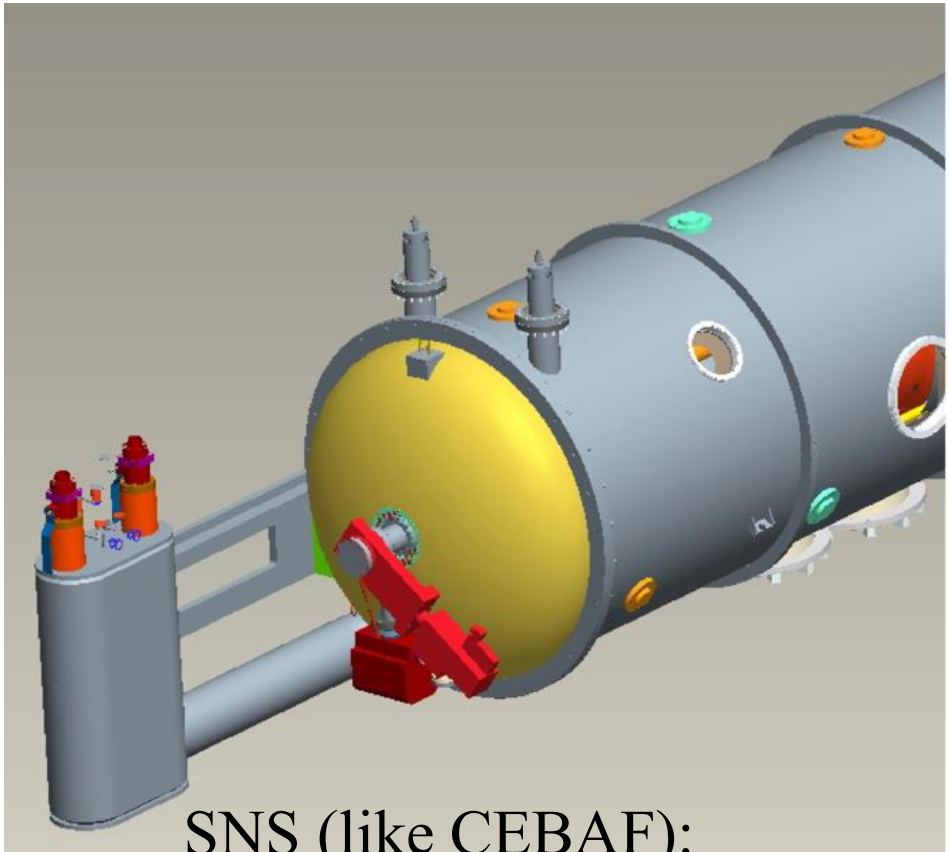
Cryogenic system design

- Fairly complete accounting of cold devices with heat load estimates and locations
  - **Some cold devices still not well defined**
  - **Some heat loads are very rough estimates**
- Cryogenic plant capacities have been estimated
  - **Overall margin about 1.54**
  - **Main linac plants dominate, each at 20 kW @ 4.5 K equiv.**
- Component conceptual designs (distribution boxes, end boxes, transfer lines) remained sketchy
  - **Need these to define space requirements and make cost estimates**
  - **Used area system lattice designs to develop transfer line lengths and conceptual cryosystem layouts**

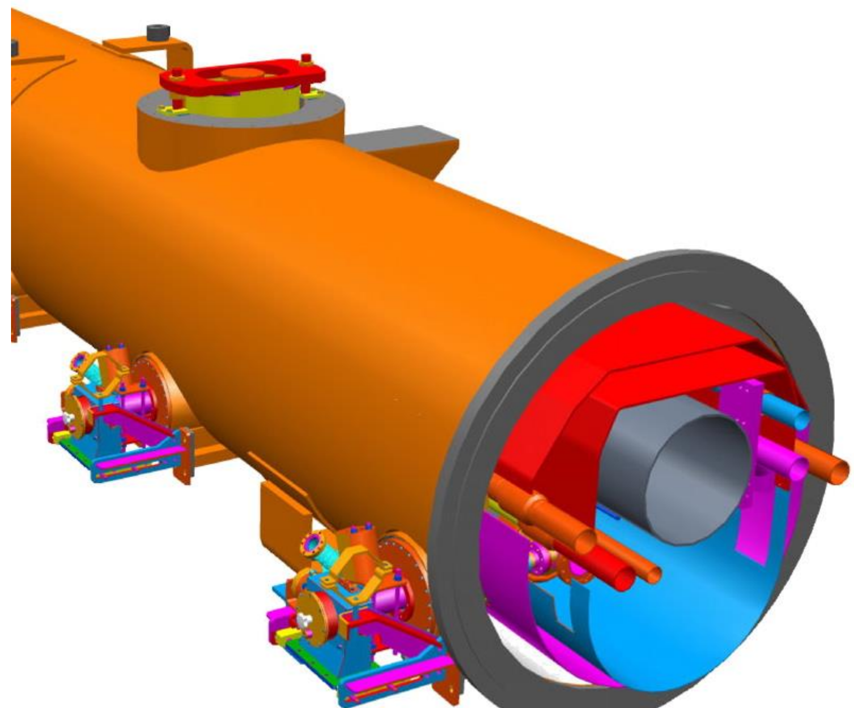
Cryomodule string segmentation

- Various degrees of possible segmentation
  - Total isolation and warm-up with adjacent cryomodule cold
  - Total separation of vacuum and cryogenic circuits but no provisions for maintaining segments cold which are adjacent to warm cryomodules
    - Limits extent of control lengths and vacuum
    - No end buffer from adjacent cold segment for vacuum let-up of warm segment. E.g., one must warm three segments to let up one.
    - Segments downstream of warm one may not be held cold
  - Vacuum isolation and/or cryo circuit extent of various lengths, not all equal
    - For example, liquid flow path shorter than thermal shield circuits
    - Some valves distributed more finely than others. May have small "feed boxes" or valves in cryomodules for 2 K liquid supply.
  - Relief valve frequency -- low MAWP may force frequent vents
- Pipe sizes trade off with segmentation lengths

SNS vs TTF cryomodule



SNS (like CEBAF):
self-contained vacuum vessel
“stand-alone” style



TTF: vacuum vessel string.
End boxes and bellows
would become part of
vacuum/pressure closure

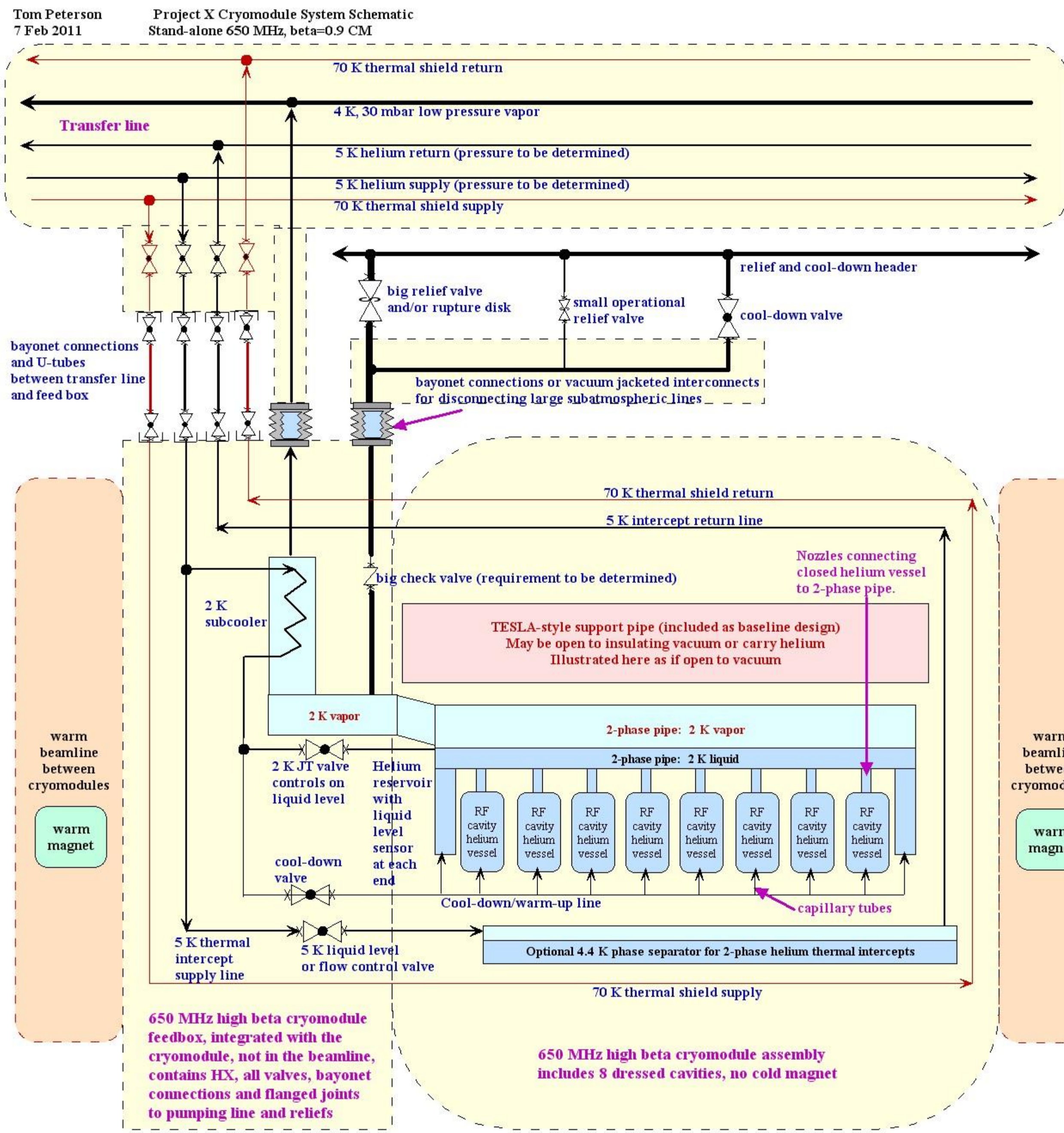
Advantages of separated cryomodules (1)

1. Separated liquid management. High heat loads for high duty factor or CW cryomodules imply high 2 Kelvin boil off rates. Managing the liquid level in the helium vessels and flow through the JT valve and 2-phase pipe or series of helium vessels will be easier with a shorter length of liquid baths.
2. Prefer small heat exchangers, distributed with cryomodules. In general, in my opinion, a JT heat exchanger of a size comparable to those in LHC which place the heat loads in the large transfer line at the 4.5 K level will be preferable.
3. Warm magnets and instrumentation between cryomodules. Separate cryomodules allow warm beam line components between cryomodules, especially useful for easier alignment of magnets and BPM's, other instrumentation, and also for absorbing some HOM power if applicable.
4. Active pumping between cryomodules. If needed, the insulating vacuum of a single cryomodule may be pumped, and the beam vacuum is accessible for pumping.

Advantages of separated cryomodules (2)

5. Loss of insulating vacuum to air is limited to one cryomodule (assuming vacuum isolation from the transfer line). The sudden rush of air into insulating vacuum and resulting heat fluxes with air condensation can deposit up to several Watts per square cm on liquid helium-temperature vessels and piping, depending on insulation. For a string of cryomodules, this can result in huge flow rates with requirements for extremely large vent lines and venting devices. The separate cryomodule vacuums limit this disaster to one cryomodule for the insulating vacuum loss.
6. Replacement for maintenance. Separate cryomodules allow replacement of individual cryomodules without warming the entire string.
7. Testing and commissioning. Separate cryomodules allow installation and cryogenic operation of individual cryomodules or parts of the linac during installation and commissioning.
8. Incorporation and connection of low-beta cryomodules of different types, for example FRIB. Separated cryomodules will reduce constraints imposed by matching cold interconnects and allow easier transitions among different types of cryomodules, also allowing the top-loading configuration.

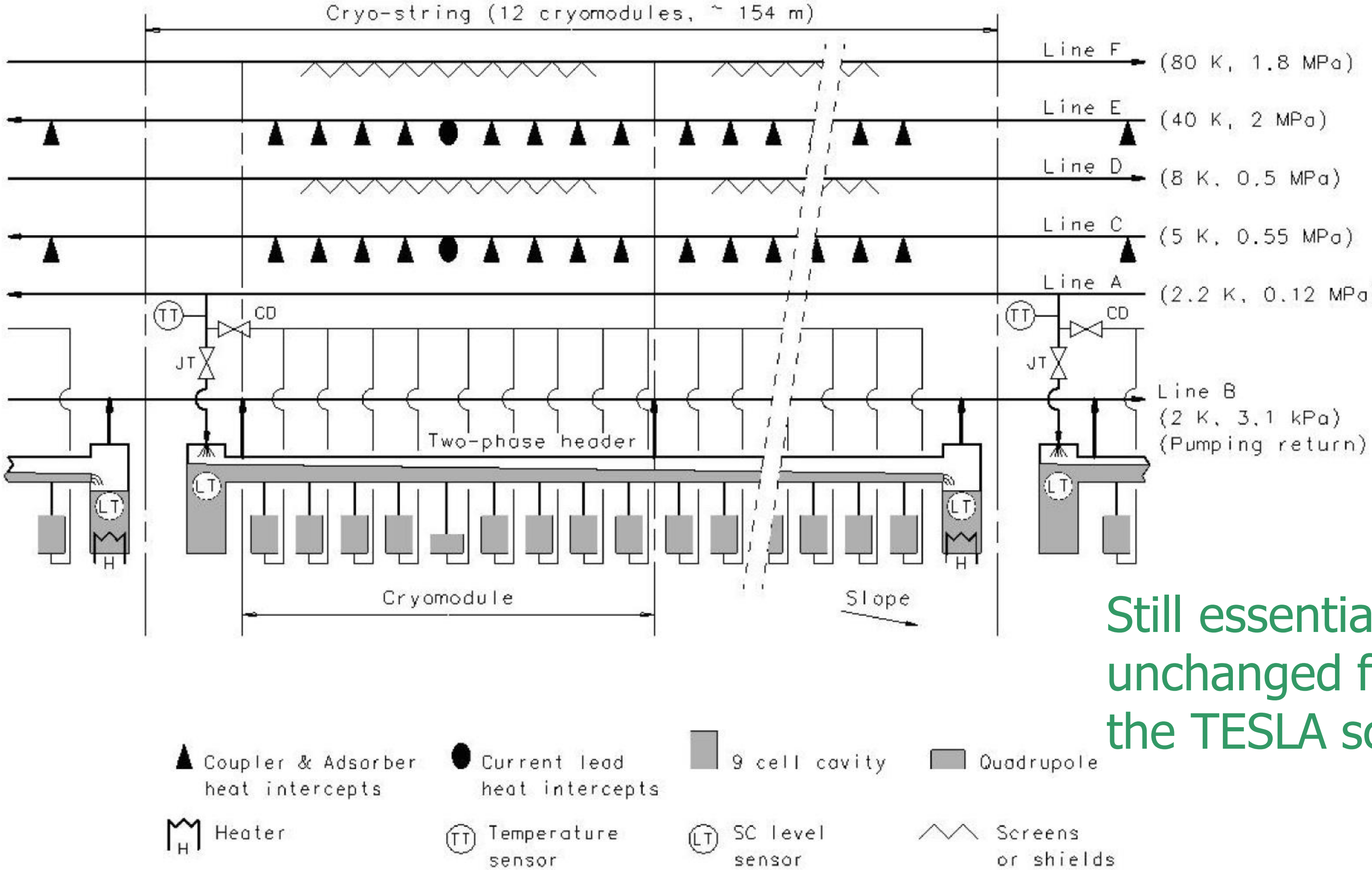
Stand-alone cryomodule schematic



Advantages of string

1. No external transfer line. A large transfer line with vacuum-jacketed 4 K pumping line may be $5000 to $10,000 per meter including all the connections to the cryomodules. So for a 10 meter long cryomodule, it may add the equivalent of another $50K to $100K or so to the CM cost, as well as occupy tunnel space. I think the external transfer line cost is the major cost difference between these two configurations. Incorporation of the transfer line into the cryomodule piping was one of the main motivations for the TESLA design.
2. Fewer cryogenic valves. By placing the helium vessels and other piping of multiple cryomodules in series, one valve at a feed or turnaround box controls the flow through many cryomodules. This may provide significant cost reduction (in addition to the elimination of the external transfer line) and also simplify operations (assuming control of the long volumes is not a problem) by resulting in fewer control valves.
3. No warm-cold transitions at the ends. Especially for systems with relatively low dynamic heat loads where static heat load is more significant, eliminating the warm-cold transitions at each end helps reduce heat load. It may also result in a simpler end since one just has a connection to another pipe, no turn-arounds or pressure-load-bearing ends. However, I do not believe that closing the end is more expensive (as some have claimed) than the huge vacuum bellows and other features of an interconnect.

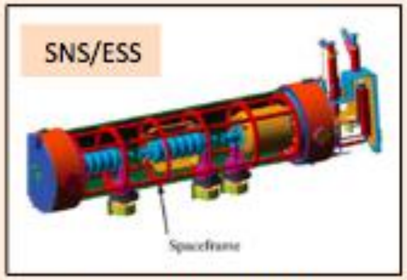
ILC cryomodule cooling scheme



Still essentially unchanged from the TESLA scheme

Design Approach - Survey of existing designs

We Conducted a preliminary survey of existing cryostat designs.
Some of the representative design are shown here …

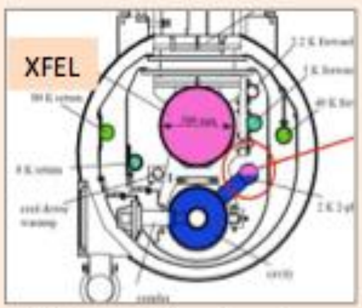


Internal 2K Heat Exchanger
Space Frame

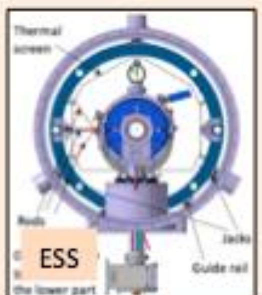
Coupler used as support

Modified XFEL design

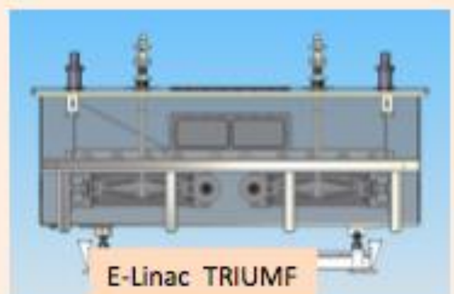
Internal Helium reservoir
Thermal Intercepts , Tuner



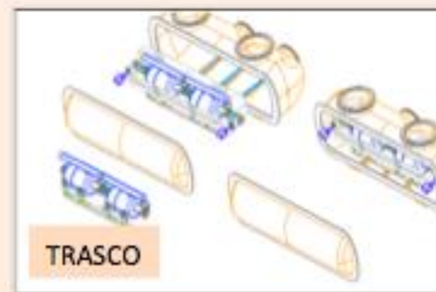
Reference/ benchmark



Same as SNS



Easy assembly
Ease of access to internal parts



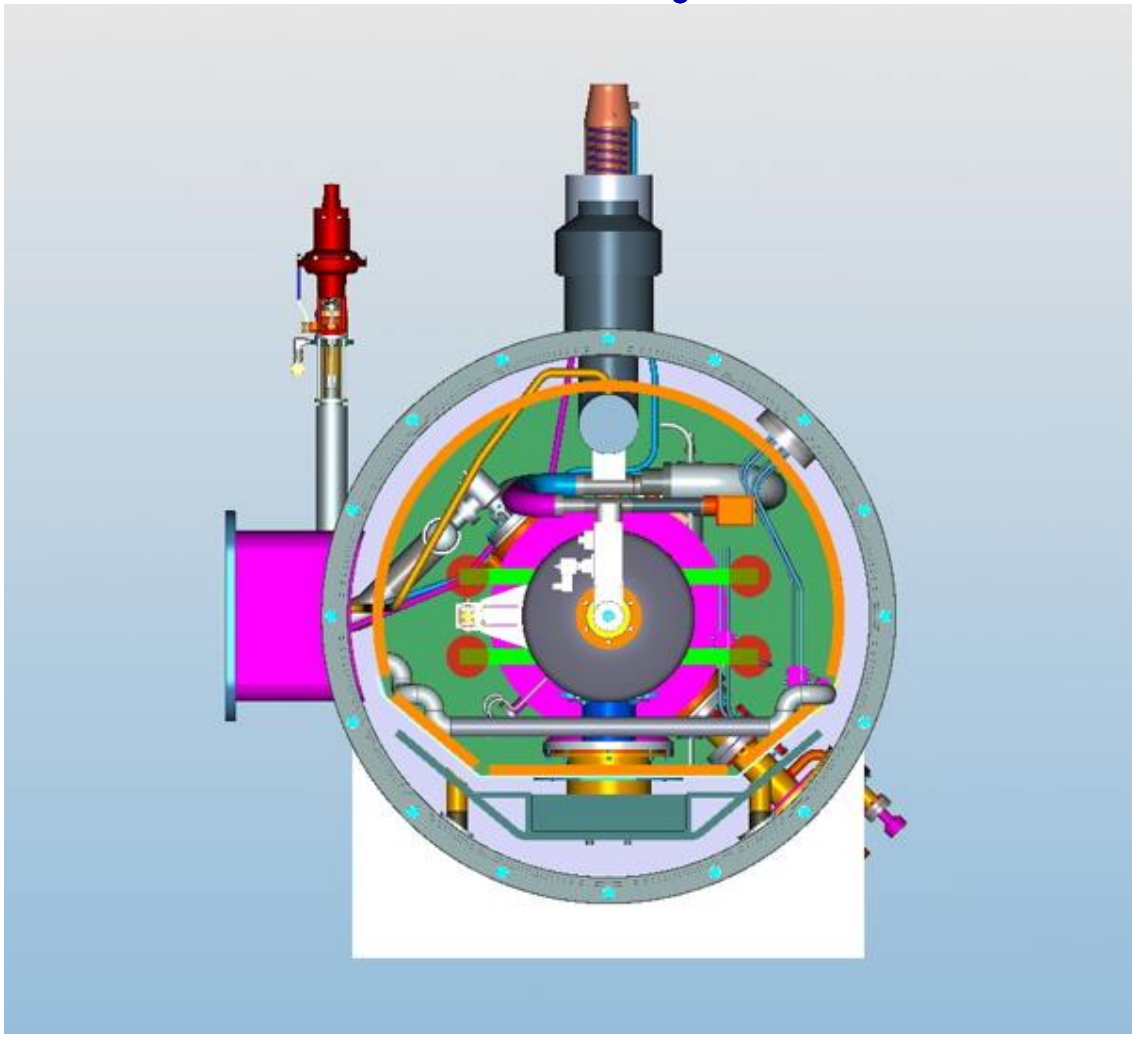
Easy assembly
Ease of access to internal parts
Easy alignment

From Shrikant Pattalwar, STFC Daresbury, UK

Various cryomodule concepts

- Single Spoke Resonator (SSR) cryostat concept using support posts under the cavities and magnets
- TESLA/ILC
- SNS/Jlab 12 GeV upgrade style "space frame" supports
- Closed-ended "TESLA" style
- BESSY/HZB CW cryomodule string rather than stand-alone cryomodules
- Cornell's ERL cryomodule
- ANL/FRIB/TRIUMF-style top-loading rectangular cryostats

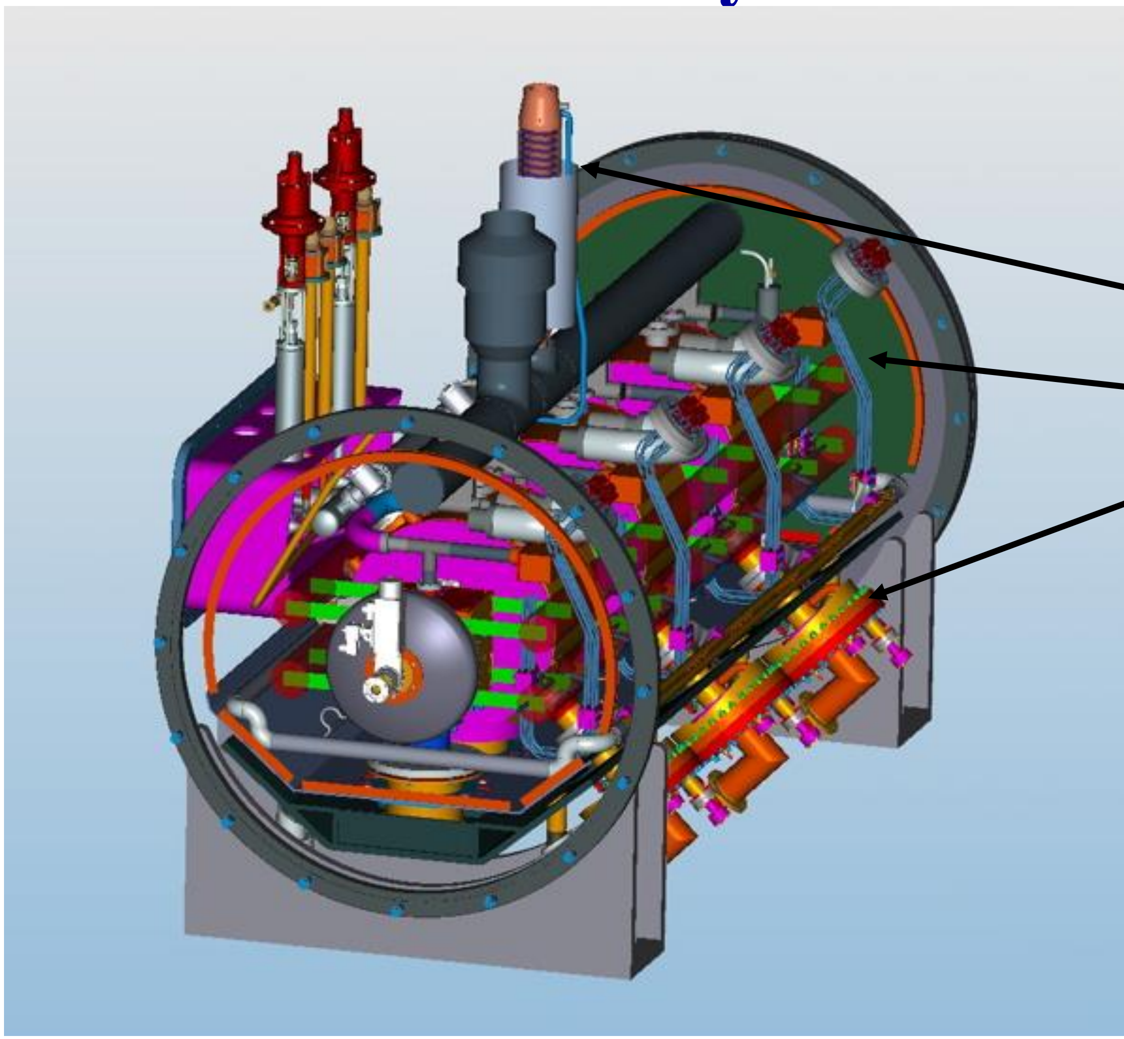
SSR cryomodule concept



Vacuum vessel end removed

Support structure is a cradle on which magnets and cavities are supported

SSR cryomodule concept



Heat exchanger

Current leads

Input couplers

48 inch diameter vacuum vessel

SSR cryomodule concept

Still working on conceptual design as 3-D model, but becoming a complete model

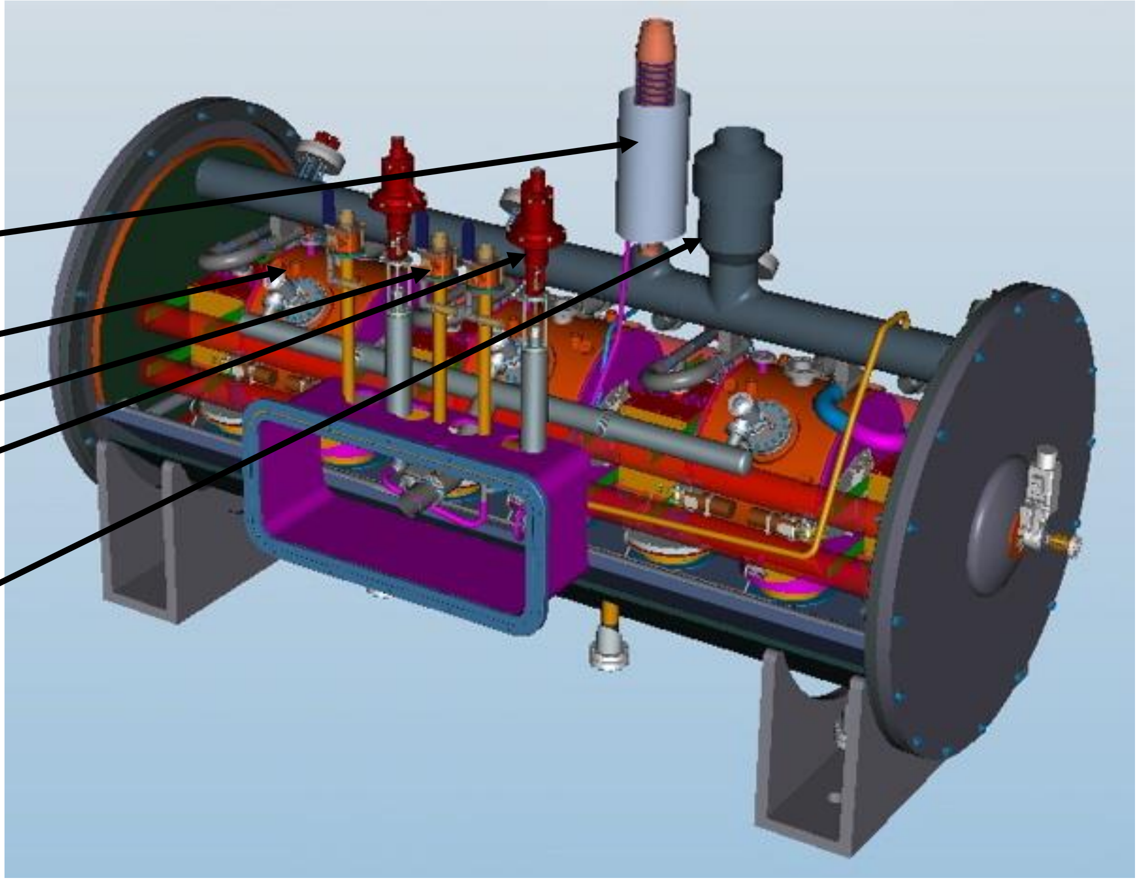
Heat exchanger

Cavity helium vessel

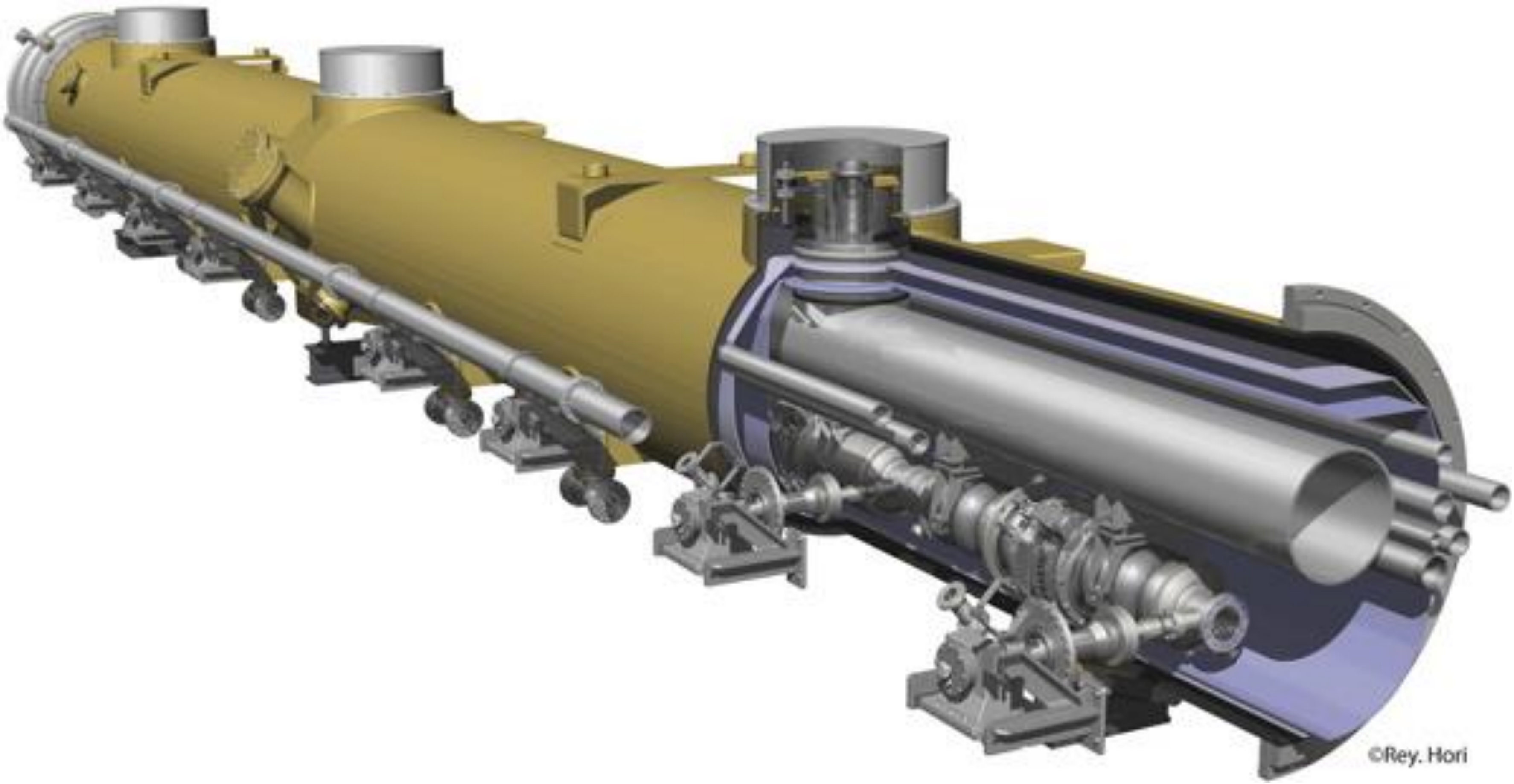
Bayonet connection

Control valve

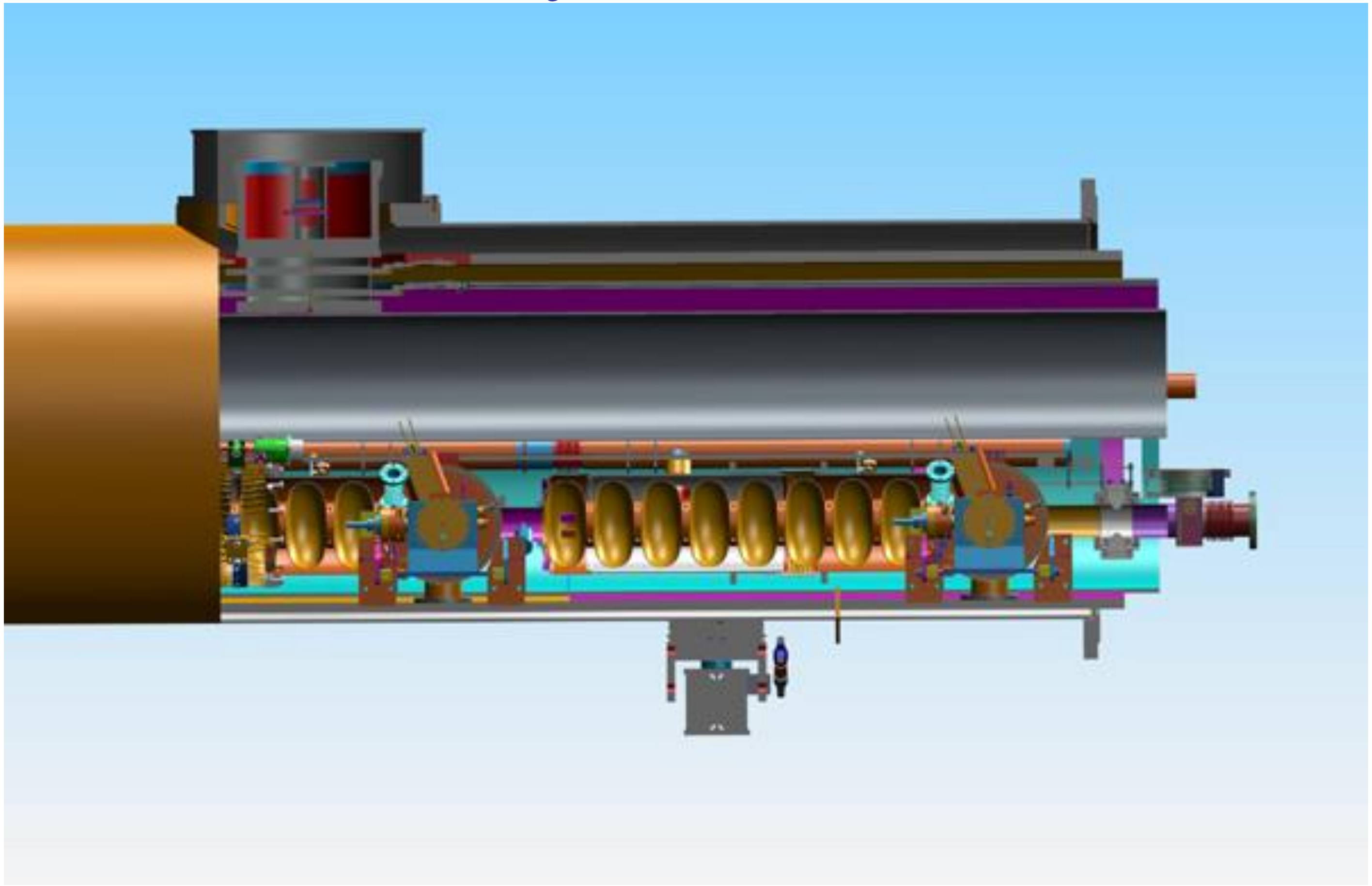
Vent line with check valve



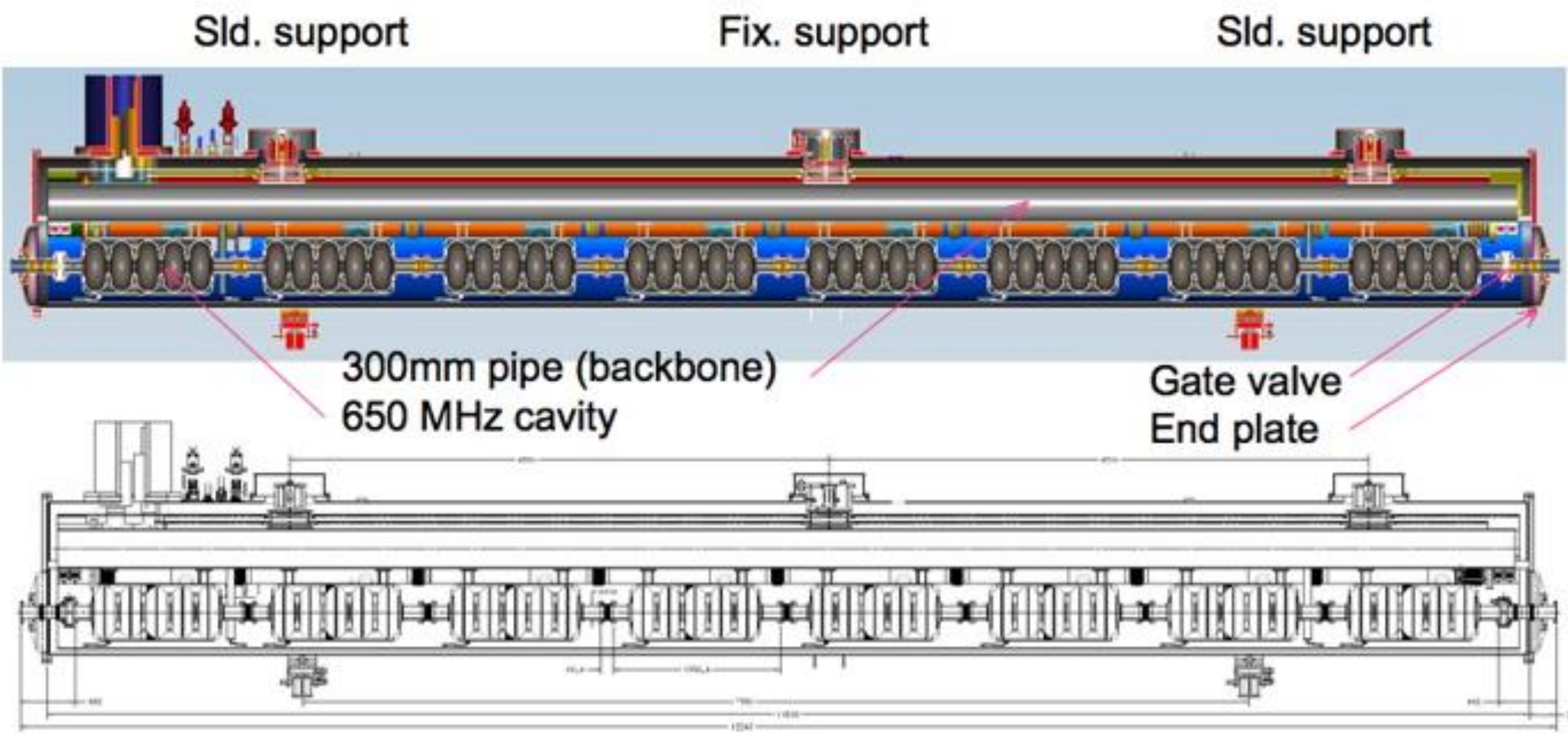
TESLA-style Cryomodule



Cutaway view of cavity within a cryomodule



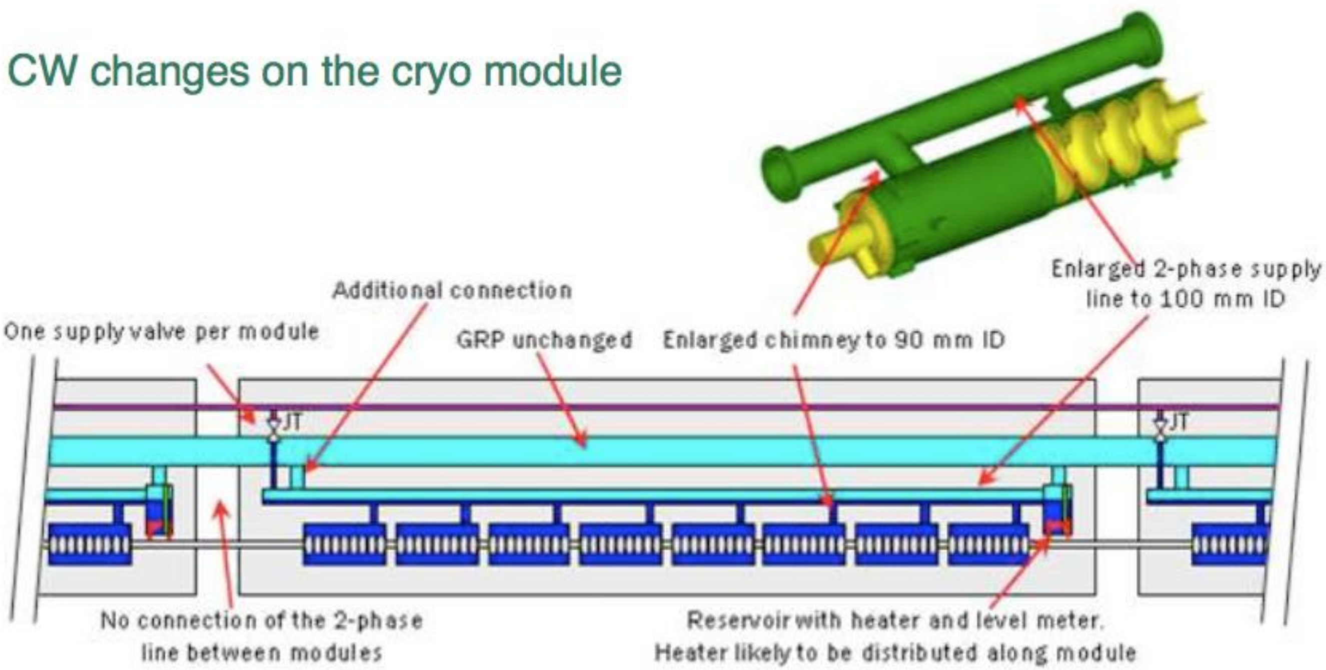
Closed ended "TESLA" style



BESSY

CW Cryo Module

CW changes on the cryo module



W. Anders, BESSY CW Operation of SC TESLA Cavities ESLS RF Meeting 5.10.2007

ERL cryomodule features

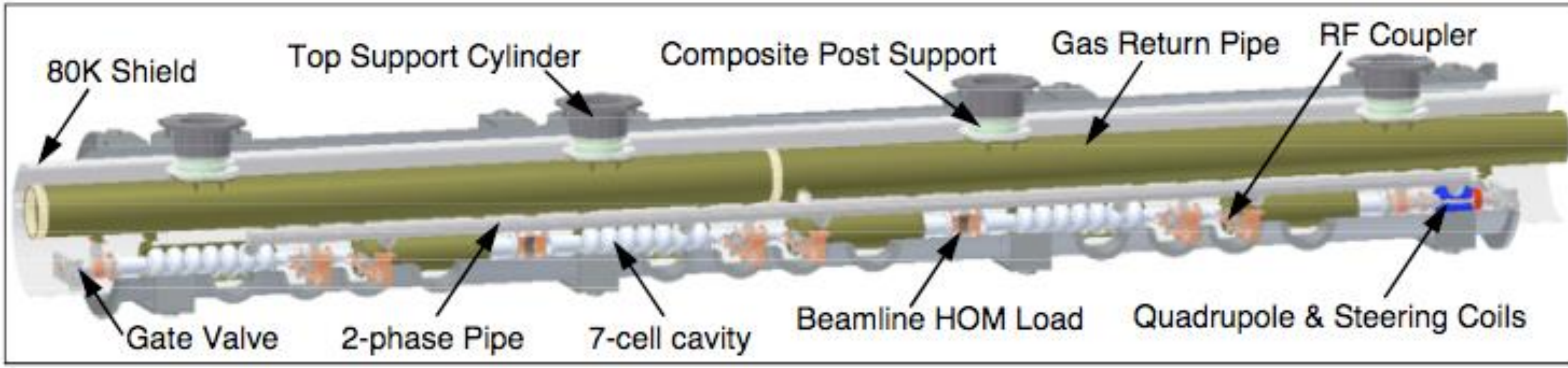


Figure 1: A cut-away CAD model showing the main features of the ERL Linac cryomodule.

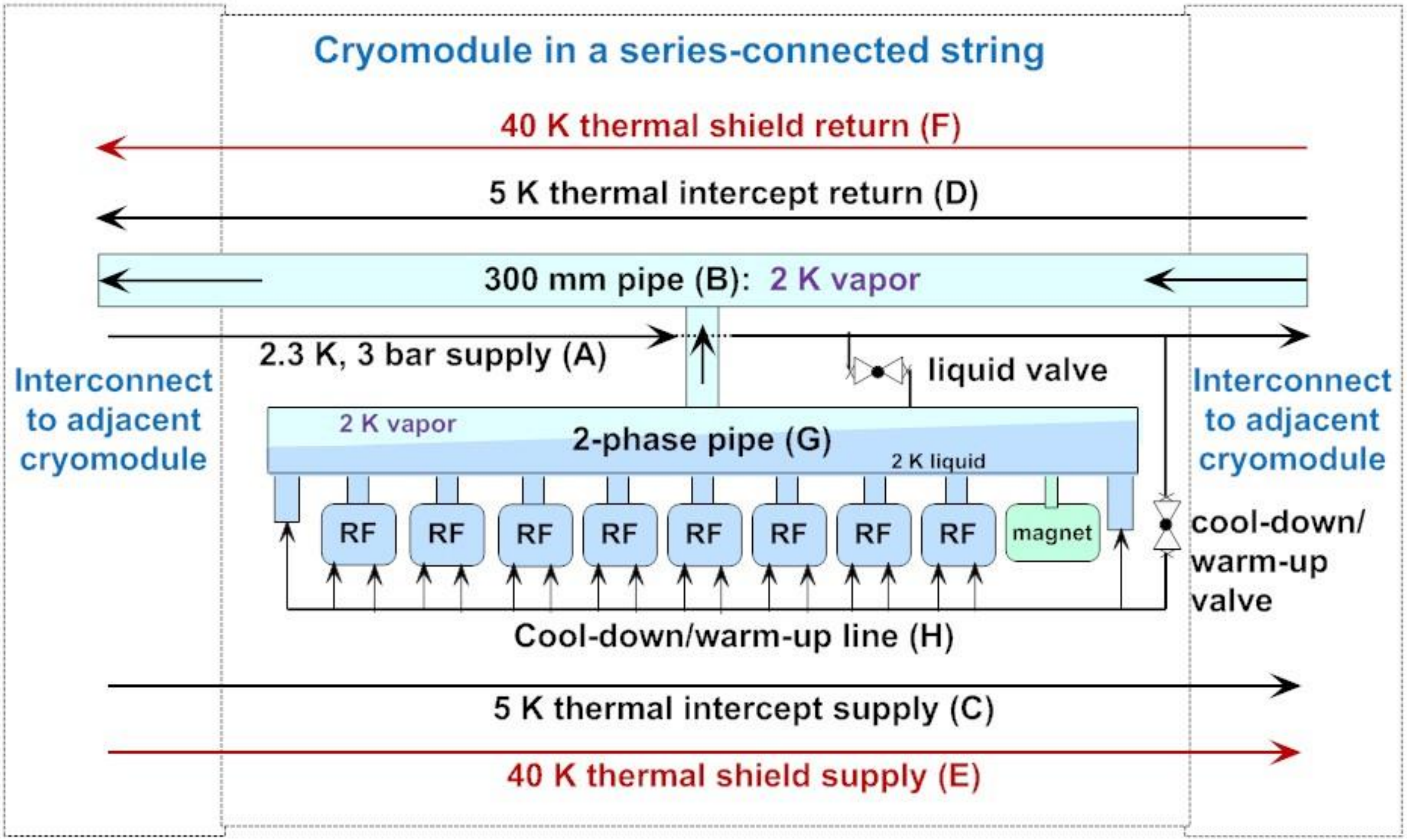
Figure 1 from CRYOGENIC HEAT LOAD OF THE CORNELL ERL MAIN LINAC CRYOMODULE, by E. Chojnacki, E. Smith, R. Ehrlich, V. Veshcherevich and S. Chapman, Cornell University, Ithaca, NY, U.S.A.

Published in Proceedings of SRF2009, Berlin, Germany

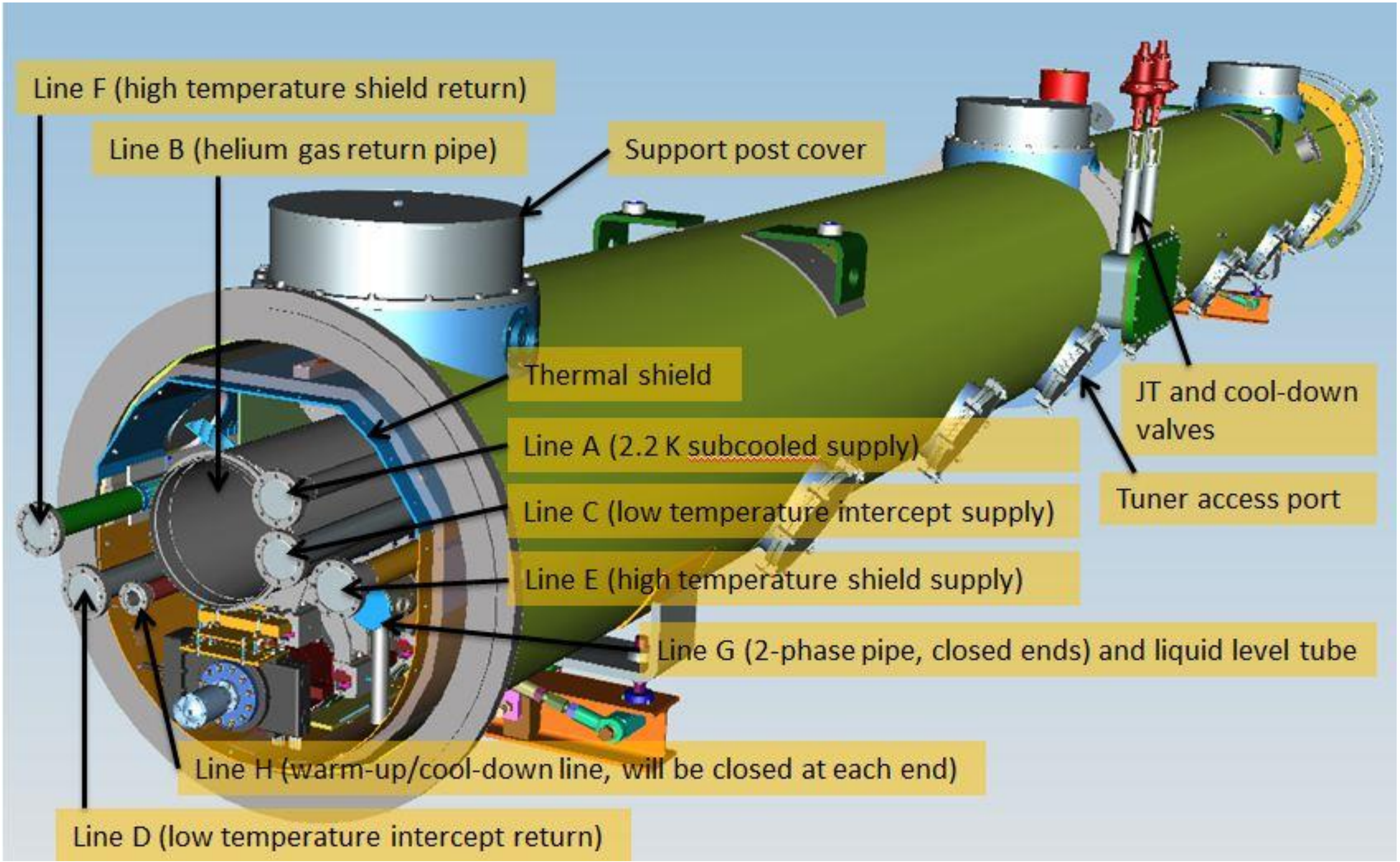
ERL cryomodule features

- TESLA-style support structure -- dressed cavities hang from gas return pipe (GRP), but
  - Titanium GRP
  - No invar rod, no rollers
  - 6 cavities per CM, 9.8 m total CM length
  - HOM absorbers at 40 - 100 K between cavities
  - GRP split with bellows at center, 4 support posts
  - Helium vessels pinned to GRP
  - Some flexibility in the input coupler
  - De-magnetized carbon-steel shell for magnetic shielding (this is like TTF)
  - 2-phase pipe closed at each CM end, JT valve on each CM (like BESSY design)
  - String rolls into vacuum vessel on rails

LCLS-II cryomodule flow scheme

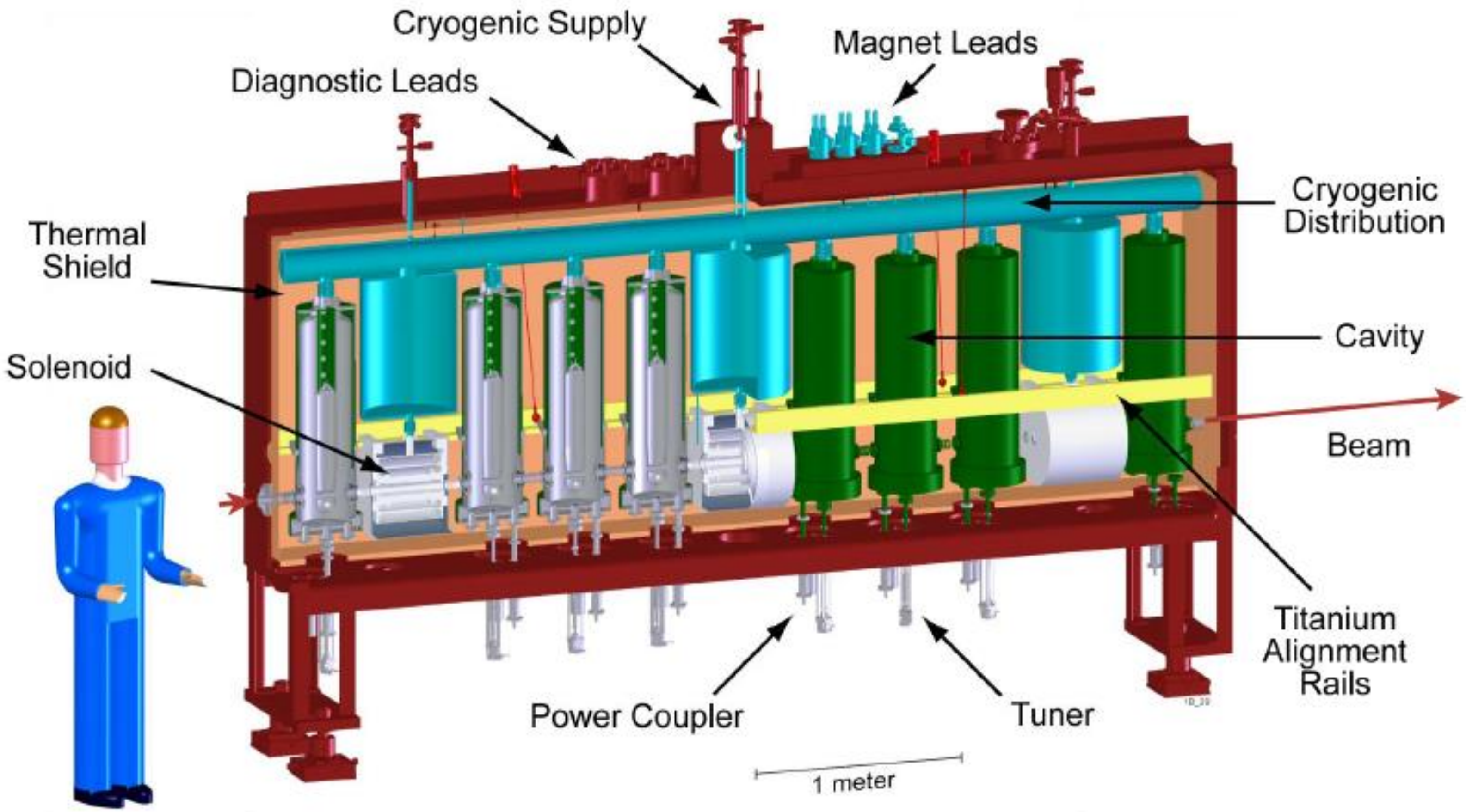


LCLS-II cryomodule model



FRIB cryomodule

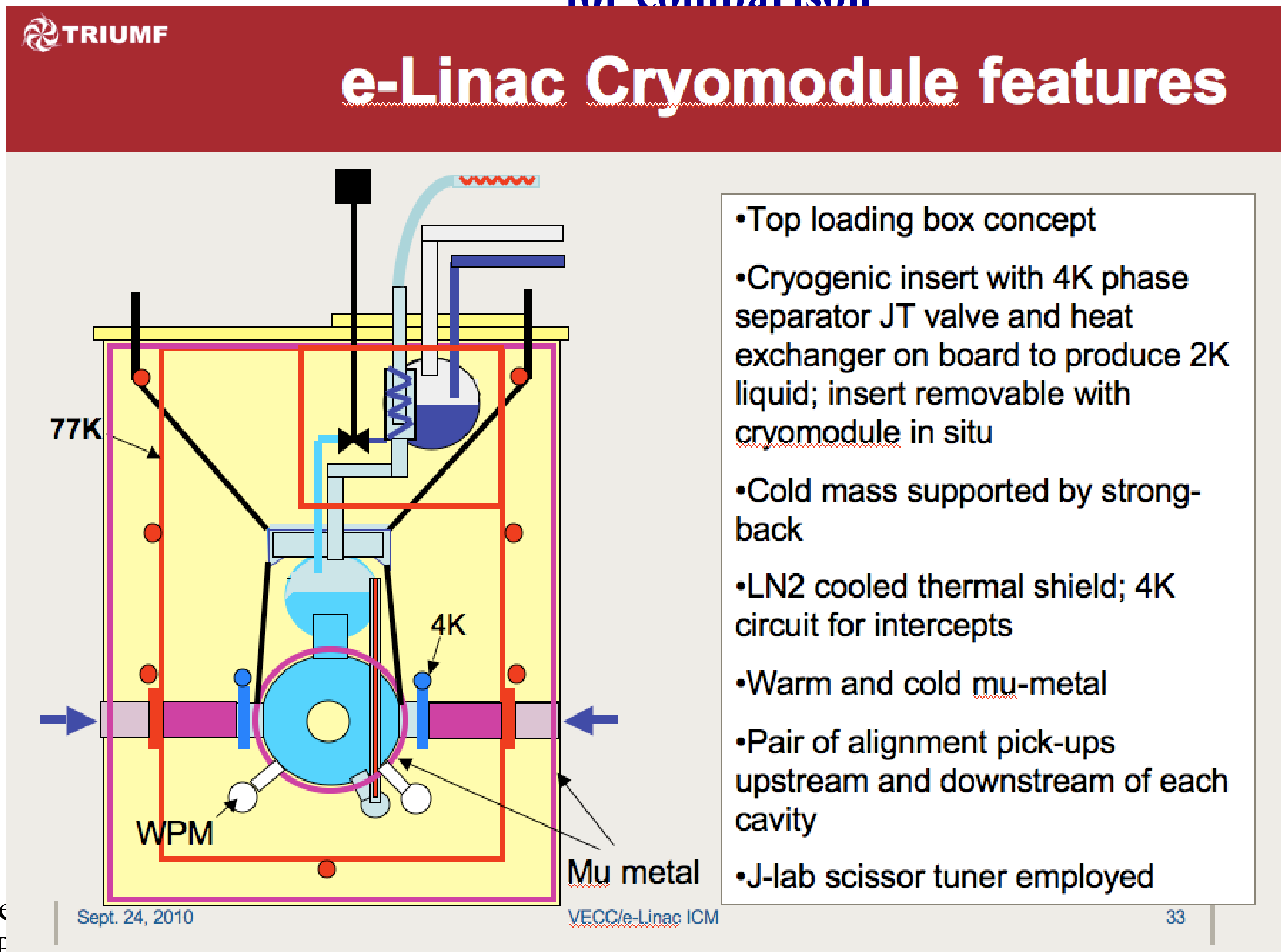
“bathtub” style for comparison



TRIUMF cryomodule concept

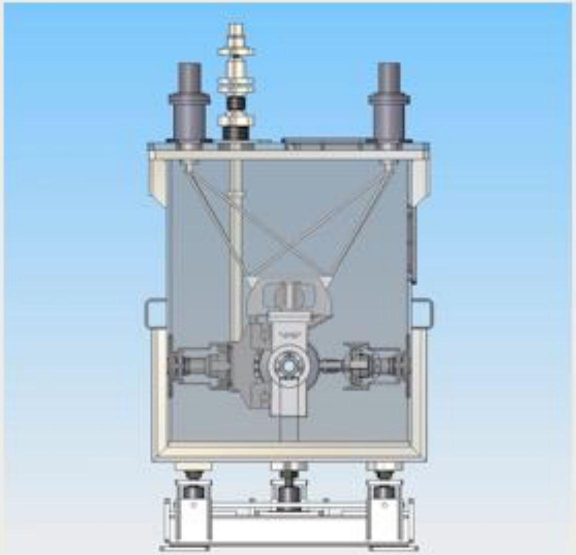
“bathtub” style with 1.3 GHz cavities

for comparison

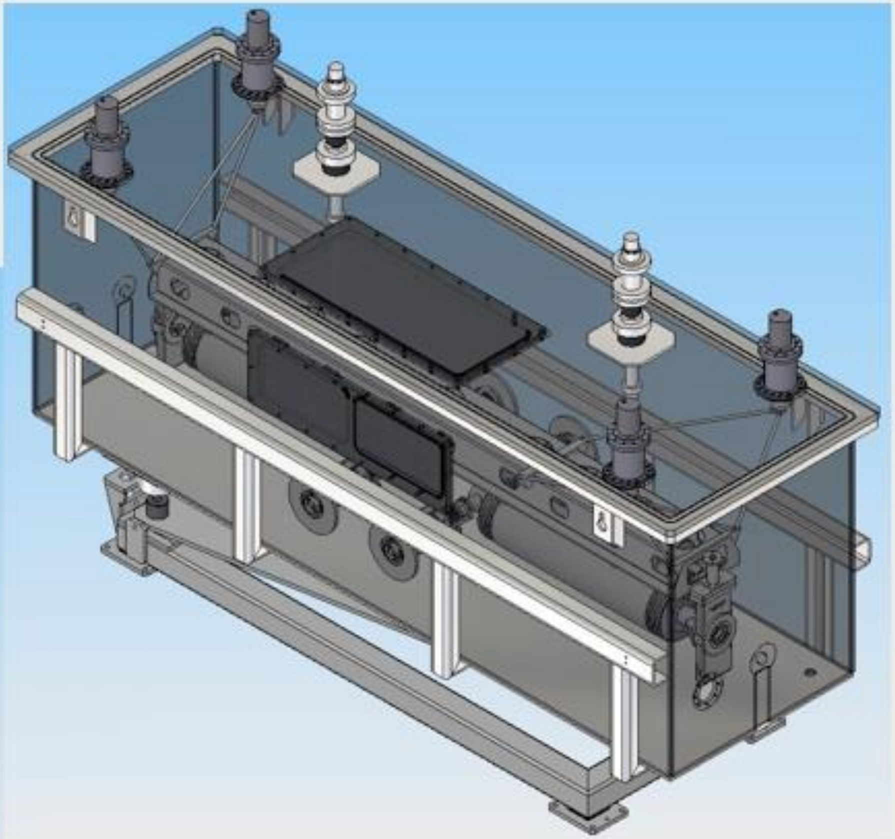


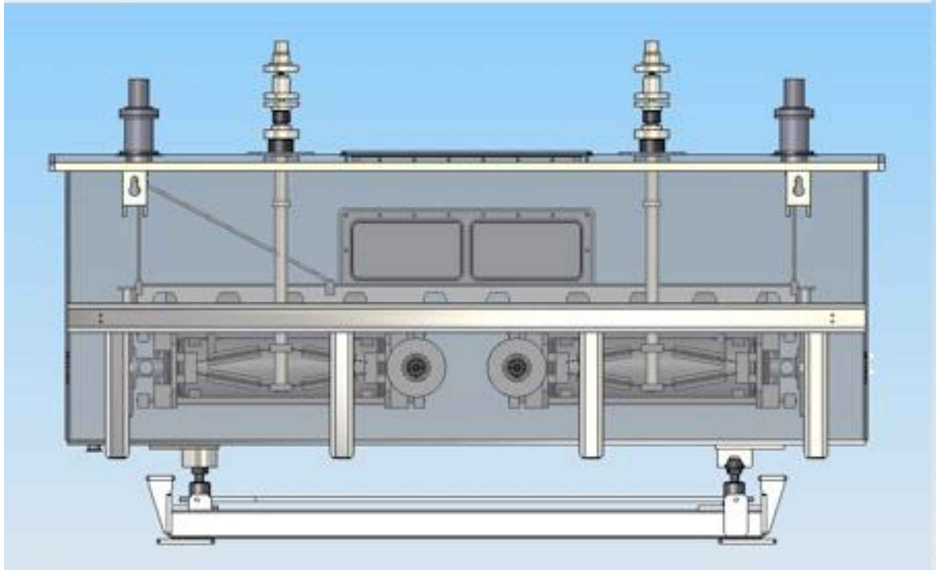
TRIUMF

e-Linac top-load box concept



- Cold mass (cavity string, tuners) supported from strongback
- Strongback held in place by support posts strung from the lid





Conclusions

- Cryomodule must be designed as part of the larger cryogenic system
- Vacuum and cryogenic line segmentation choices depend on heat loads as well as various mechanical, alignment, and reliability considerations
- Off-design requirements such as emergency venting may determine line sizes and design features
- There is no single best design configuration. A variety of quite different designs already exist with features appropriate to the various specific applications

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  - http://esh-docdb.fnal.gov/cgi-bin/ShowDocument?docid=456
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  - And associated document: "Guidelines for the Design, Fabrication, Testing and Installation of SRF Nb Cavities," Fermilab Technical Division Technical Note TD-09-005
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