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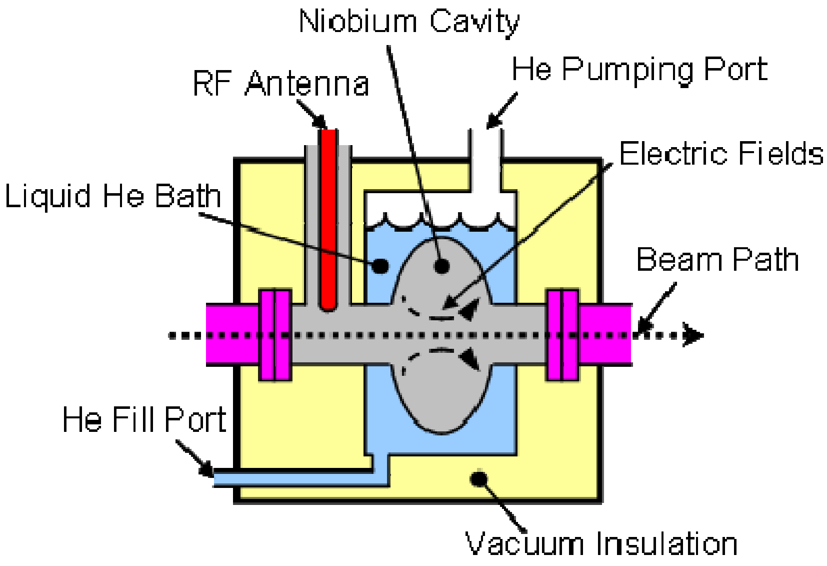
Superconducting RF for storage rings, ERLs, and linac-based FELs:

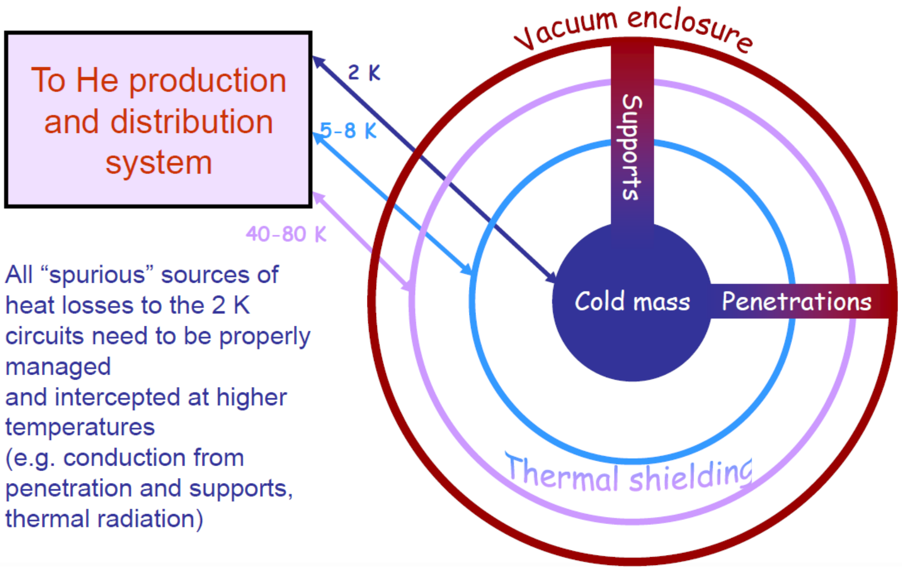
- Lecture 9 ***Cryomodule design***

SRF cryomodule

Basic cryomodule design:

- **The cavity is immersed in a liquid helium bath, which is pumped to remove helium vapor boil-off as well as to reduce the bath temperature.**
- **The helium vessel is often pumped to a pressure below helium's superfluid lambda point (2.172 K, 0.0497 atm) to take advantage of superfluid's unique thermal properties.**
- **An RF input coupler and other penetrations create "spurious" sources of heat losses to LHe. To reduce the heat losses proper design methods must be used (material choice, heat intercepts at intermediate temperatures, etc.)**
- **The cold portions of the cryomodule need to be extremely well insulated, which is best accomplished by a vacuum vessel surrounding the helium vessel and all ancillary cold components.**





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)

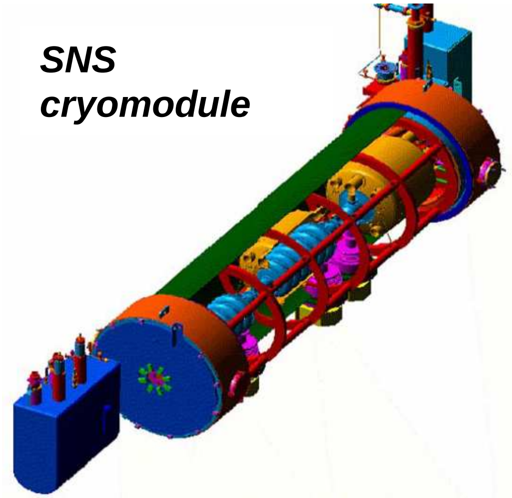
Cryomodule design considerations

Cryomodule functions and design considerations

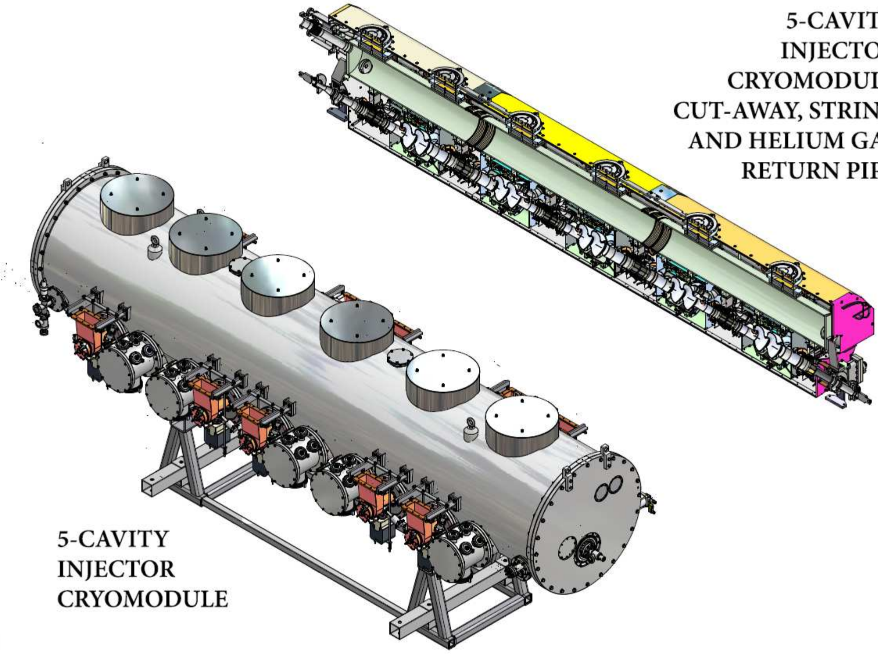
- Cryogenic environment for the cold mass :
    - Cavities/magnets in their vessels filled with liquid He either at atmospheric pressure at ~4.2 K or sub atmospheric He below lambda point;
    - He coolant (liquid and gas) distribution at required temperatures;
    - Low-loss penetrations for RF, cryogenics and instrumentation.
- Shields and insulation (vacuum and superinsulation) for the sources of “parasitic” heat transfer from room to cryogenics temperature produced by three mechanisms:
    - Thermal radiation;
    - Heat conduction;
    - Heat transfer by convection.
- Component integration:
    - Structural support of the cold mass;
    - Issues concerning different thermal contractions of materials;
    - Precise alignment capabilities and reproducibility with thermal cycling.
- Magnetic shielding (< 10 G residual field).
- Pulsed vs CW operation: number of thermal shields, LHe pipe dimensions.
- High vs low RF power: heat handling → more complicated input coupler design.

SRF cryomodules

A cryomodule contains a variety of complex technological objects: cavities and their ancillaries, but also magnets and BPMs.

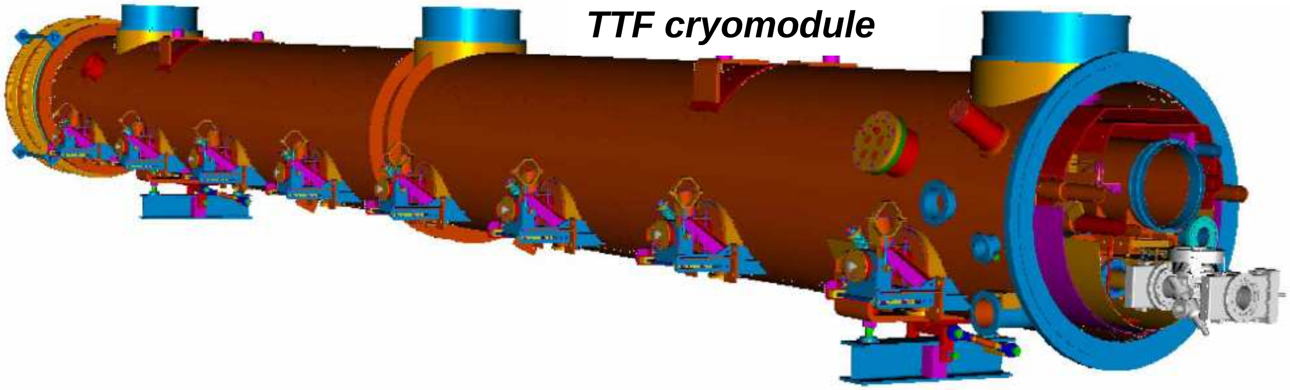


SNS cryomodule



5-CAVITY
INJECTOR
CRYOMODULE
CUT-AWAY, STRING
AND HELIUM GAS
RETURN PIPE

5-CAVITY
INJECTOR
CRYOMODULE



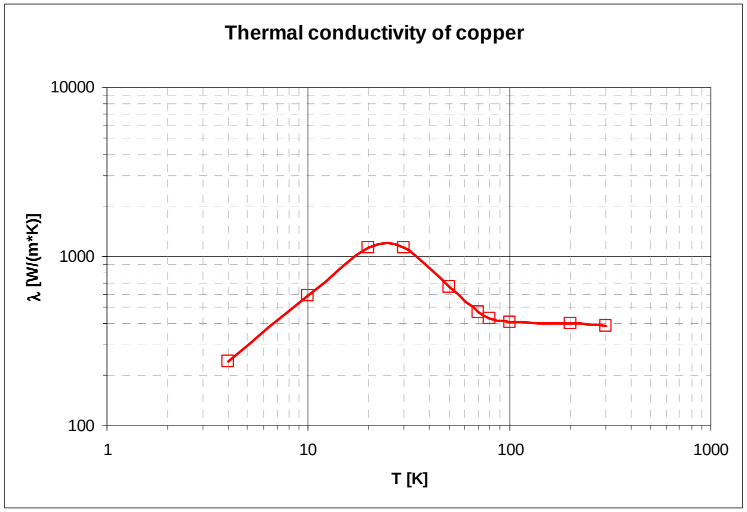
TTF cryomodule

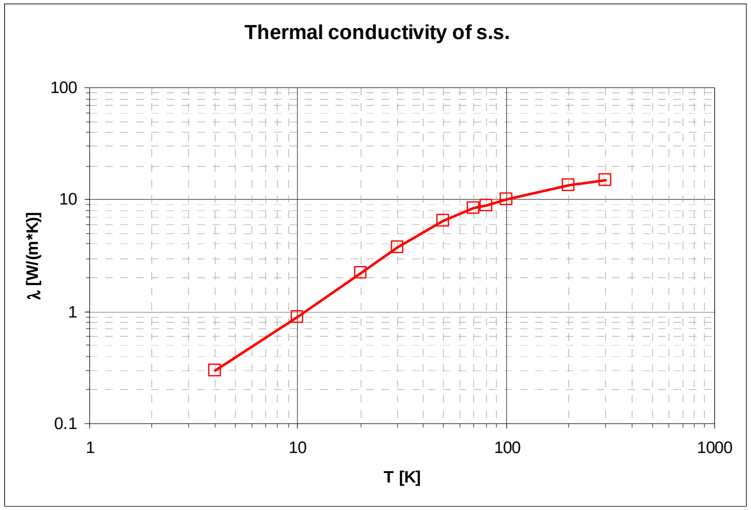
Physical mechanisms of heat losses

Heat conduction

- **There are many penetrations from RT environment: input couplers, Rf cables, instrumentation, …**
- **Proper choice of materials with low thermal conductivity (temperature dependent) and thermal path length is crucial.**
- ***Example*: copper-plate stainless steel instead of pure copper for input couplers.**
- **Thermal intercepts at intermediate temperatures can reduce heat leak to LHe.**

$$P = \frac{A}{L}\int_{T_1}^{T_2} \lambda(T)\,dT$$





Heat transfer by convection

- **Convective exchange from RT is managed by providing insulation vacuum between the room temperature vessel and the cold mass.**

Physical mechanisms of heat losses (2)

Heat radiation

- Even though vacuum is a very good insulator, the radiative power from 300 K to 2 K is significant:

$$P_{12} = A_1 \times \sigma_{SB} \times \frac{\left(T_1^4 - T_2^4\right)}{\left[\frac{1}{\varepsilon_1} + \frac{(1-\varepsilon_2)A_1}{\varepsilon_2 A_2}\right]}$$

  where the Stefan-Boltzman constant $\sigma_{SB} = 5.67\times10^{-8}$ W/m^{2}K, the radiative power is transferred from a surface area A_1 having an emissivity ε_1 at temperature T_1, into a surface area A_2.
- For $A_1 = A_2 = 1$ m^2, $T_1 = 300$ K, $T_2 = 2$ K, $\varepsilon_1 = \varepsilon_2 = 0.1$, we get $P_{12} = 23$ W.
- Materials with low emissivity are utilized when possible.
- *Example*: electropolished copper (shiny surface) has emissivity of ~0.02 as opposed to ~0.1 for a dull surface.
- Thermal shields anchored to ~80 K and/or ~5 K and multilayer superinsulation (MLI) are used to reduce this number.
- For all practical purposes 30 layers of MLI on top of the thermal shields is enough to reduce the radiative load to acceptable level.

Magnetic shielding

- Reduces 1 G background field to < 10 mG → need attenuation factor = 1 / 0.010 = 100. The 1 G background field includes earths field as well as fields from other sources (i.e. rebar and magnet stray fields).
- May need two or three layers of shielding if the vacuum vessel is made of stainless steel.
- If the vacuum vessel is made of soft iron, it has to be de-gaussed, but will effectively shield the magnetic field afterwards. May still need one internal layer of shielding.
- Shield around components of the cryomodule may be hindered by geometric constraints.
- There are two type of materials available from industry: AMUMETAL is effective at RT, but its shielding degrades at lower temperatures; CRYOPERM-10 performs well at very low temperatures.

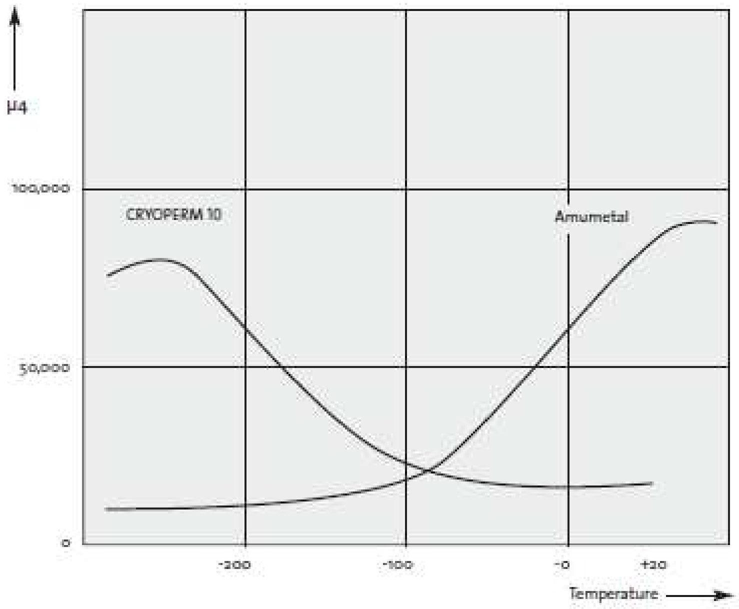
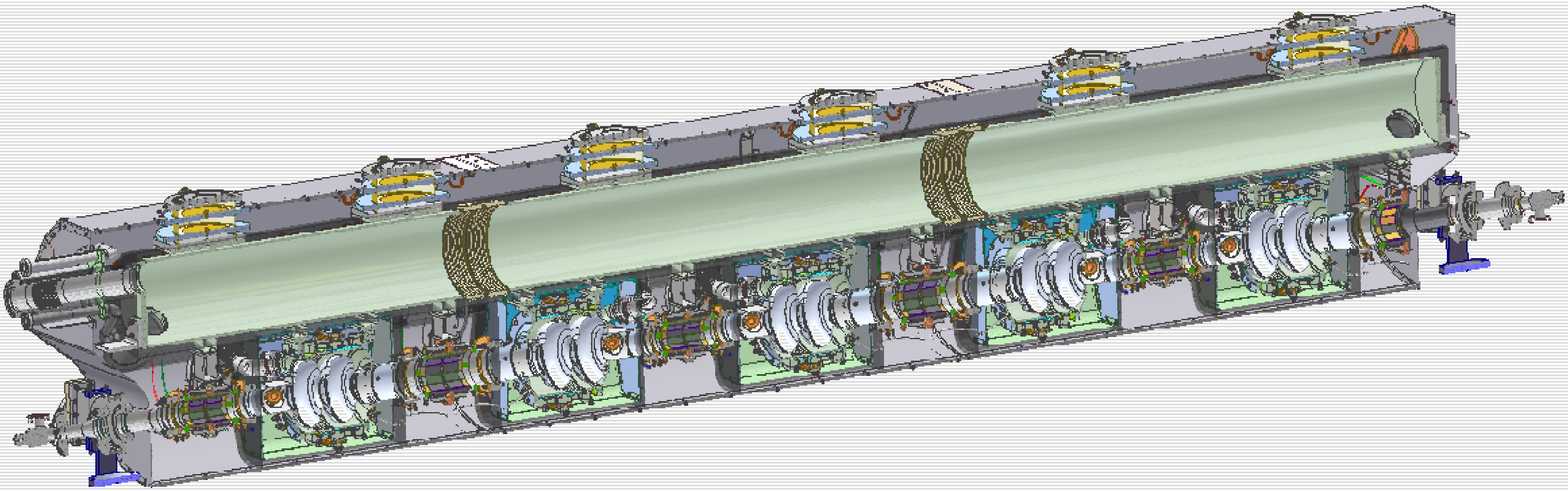


Fig. 1
Permeability of CRYOPERM 10 and Amumetal versus ambient temperature.

CW vs pulsed operation

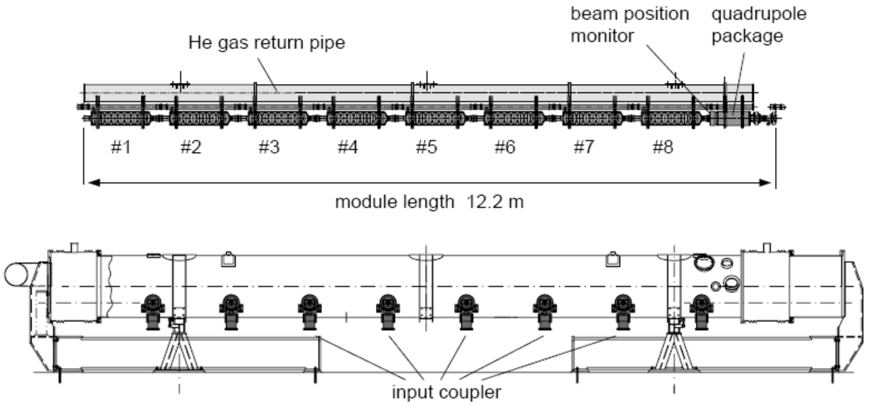
$$P_{AC} = COP \times \left(P_{dynamic} + P_{static} \right)$$

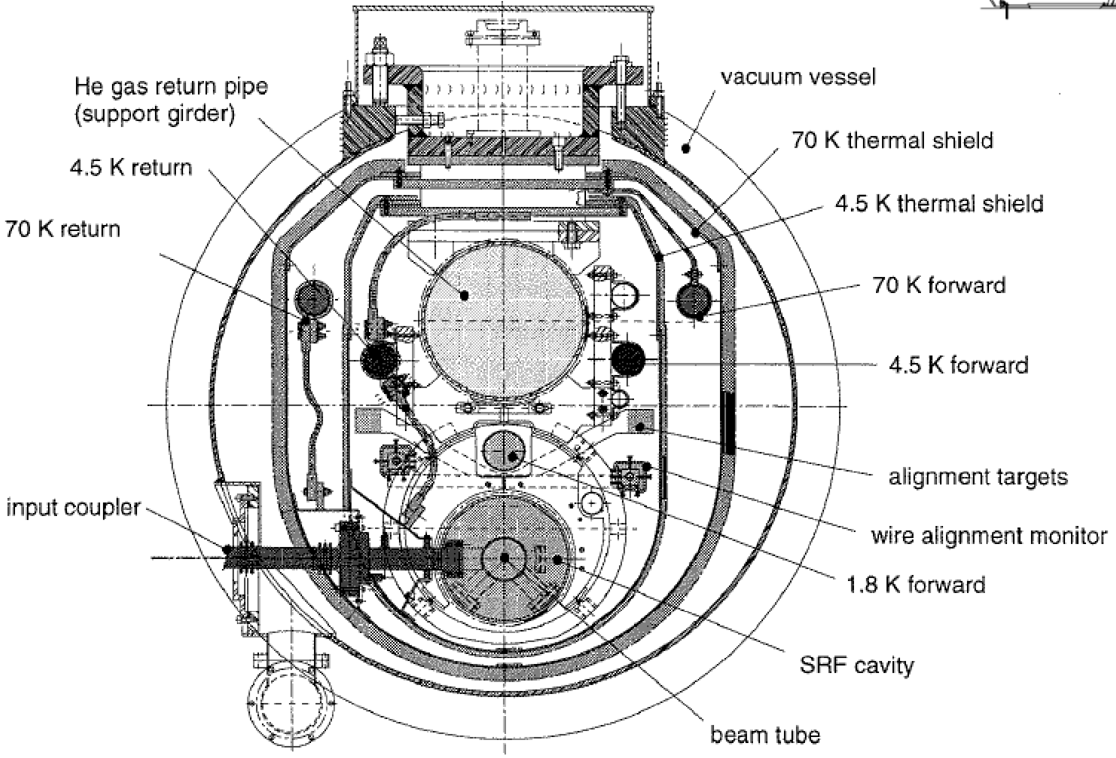
- **Pulsed operation with low duty cycle (XFEL, ILC): $P_{static} >> P_{dynamic} \rightarrow$ very important to thermally insulate the cold mass as good as possible, may require additional thermal shields (5 K) and better superinsulation.**
- **CW operation (CEBAF, Cornell ERL): $P_{dynamic} >> P_{static} \rightarrow$ may not need as good thermal shielding as in the pulsed mode, but may need to increase cryogen piping cross section and address some heating issues with dedicated thermal intercepts.**



Example 1: TTF cryomodule

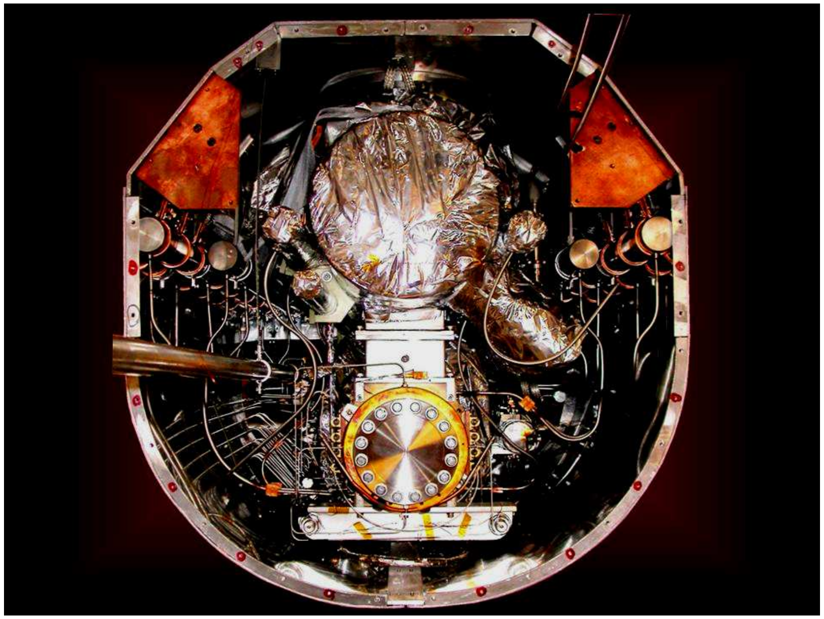
- **Cryomodule for pulsed operation**
- **Static heat load (2 K) < 3 W for a 12 m long cryomodule!**





Major challenge for CW: cryogenics

- High gradient CW operation: dynamic cavity heat load dominates at 2 K
- Module design:
  - Heat transfer through LHe ⇒ need large enough pipes
  - Mass transport of helium gas ⇒ need large enough pump pipes
  - High HOM losses ⇒ need cooling of absorbers
  - High CW RF power ⇒ more cooling for input couplers (dedicated heat intercepts)
- Cavity:
  - Cavity treatment for high Q_0 is desired
  - Optimal bath temperature: 1.8 K vs 2 K



Cryogenic loads in the ERL injector module:

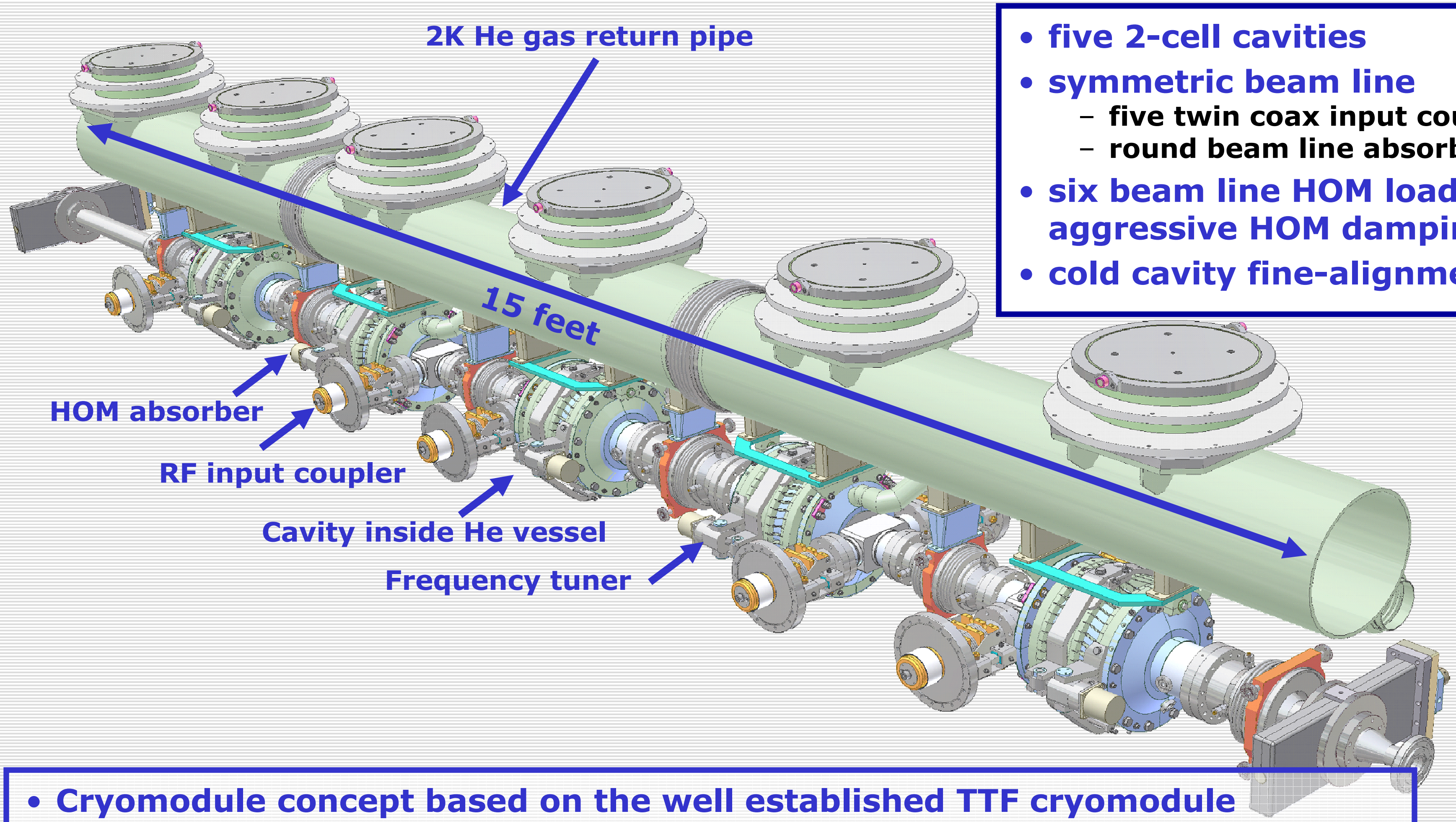
~ 25 W at 2 K (dominated by the dynamic cavity load),

~ 70 W at 5 K (dominated by the input coupler and HOM absorber load),

< 700 W at 80 K (dominated by the input coupler load).

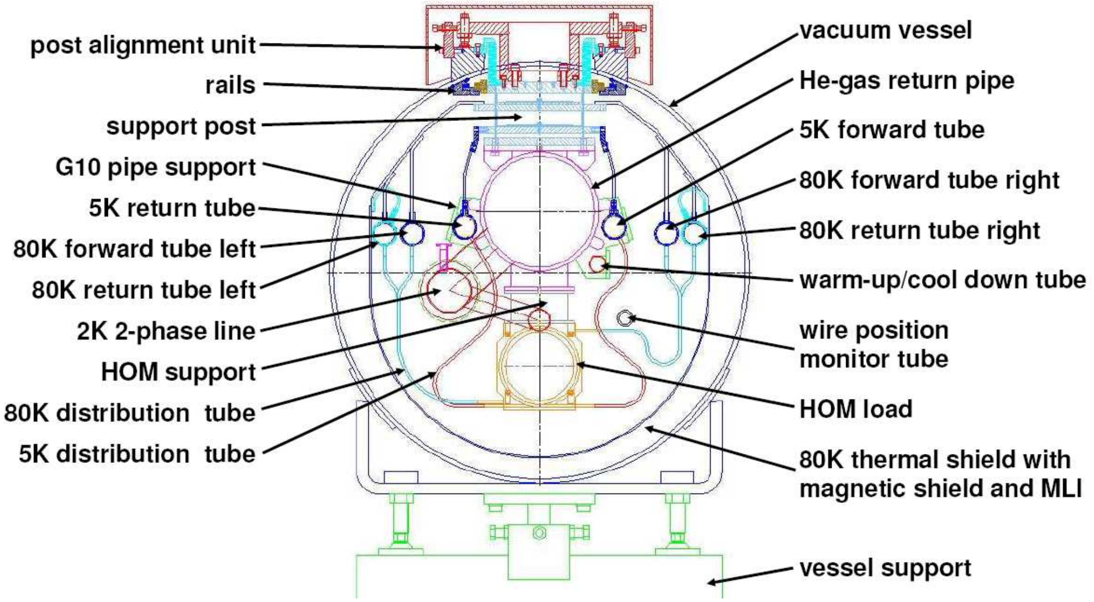
Example 2: ERL injector cryomodule

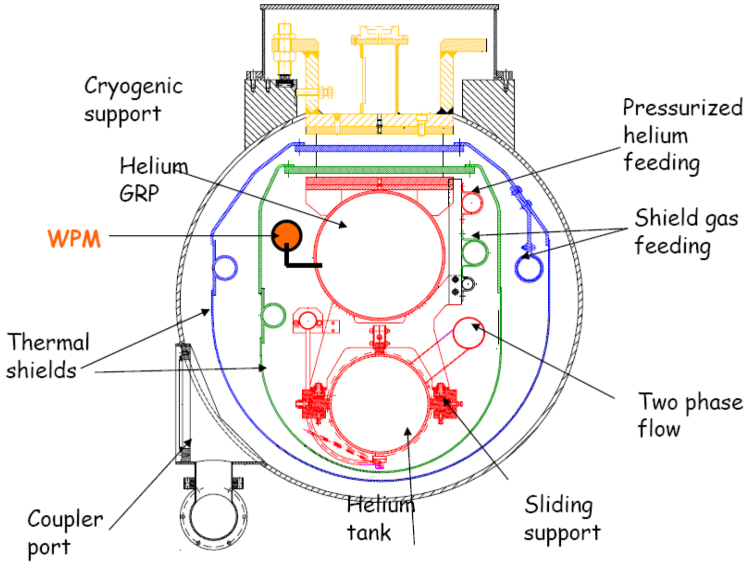
- five 2-cell cavities
- symmetric beam line
  - five twin coax input couplers
  - round beam line absorbers
- six beam line HOM loads for aggressive HOM damping
- cold cavity fine-alignment



- Cryomodule concept based on the well established TTF cryomodule
  - Cavities supported by large diameter Helium-gas return pipe (HGRP)
- Significant modifications for ERL specific needs:
  - high cryogenic loads at 2 K (cavity), 5 K and 80 K (HOM power, input couplers), HOM loads, …

Design modifications



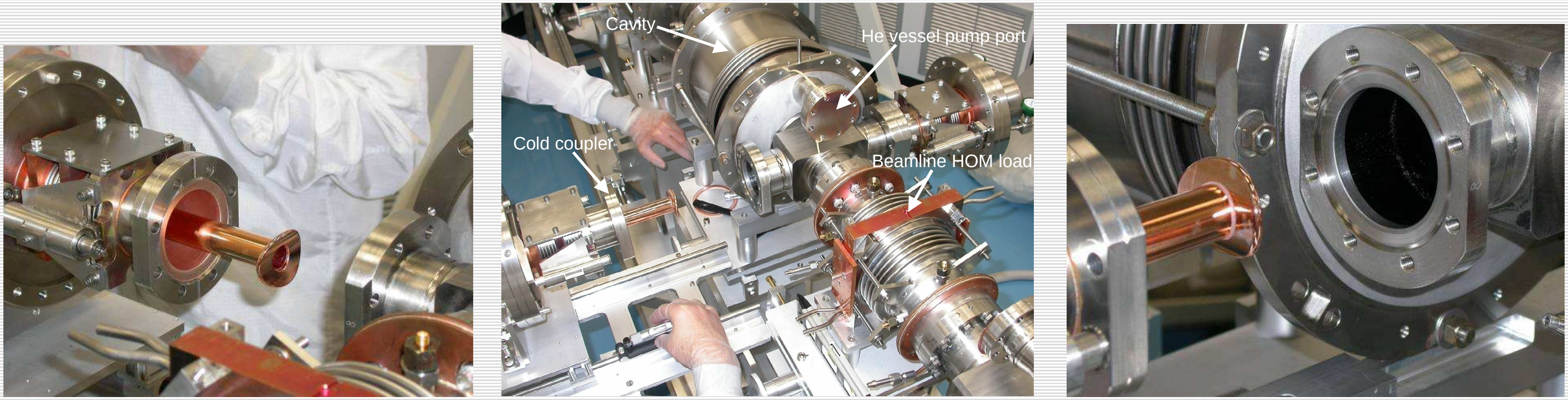


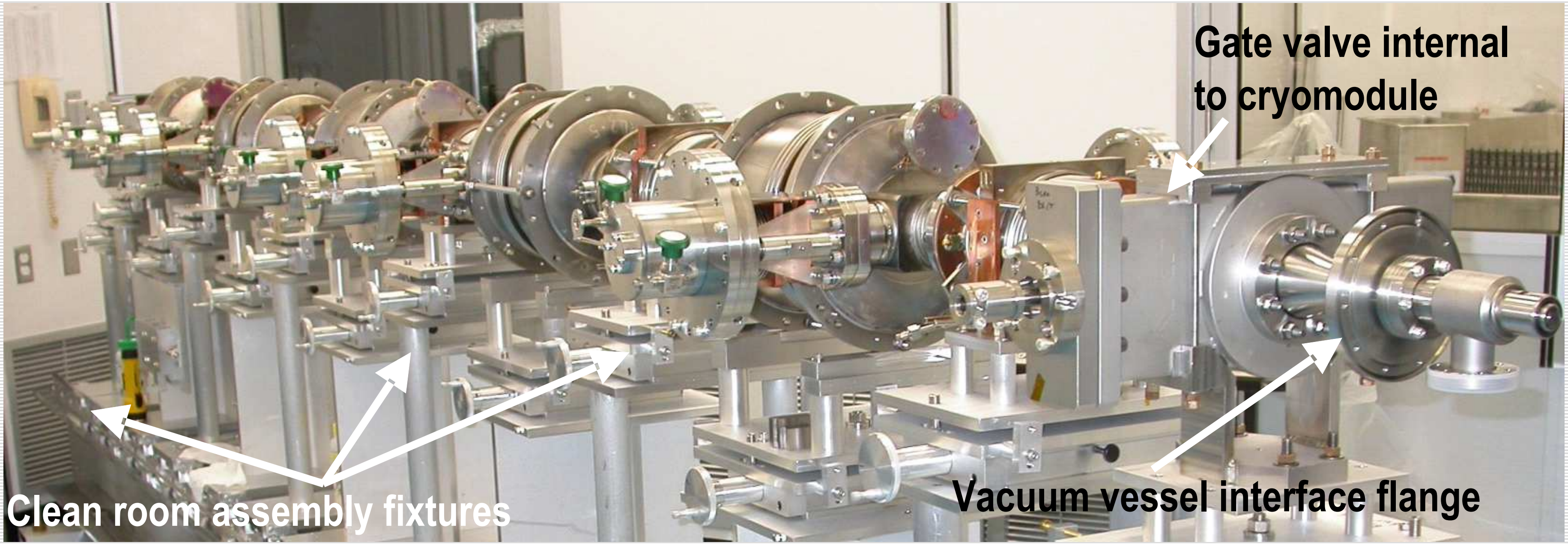
Changes compared to TTF cryomodule:

- Increase diameter of 2-phase 2 K He pipe for CW cavity operation
- Direct gas cooling of chosen 5 K and 80 K intercept points with He gas flow through small heat exchangers
- HOM absorbers between cavities
- 3 layers of magnetic shielding for high Q_o
- No 5 K shield, only a 5 K cooling manifold

Beam line string assembly

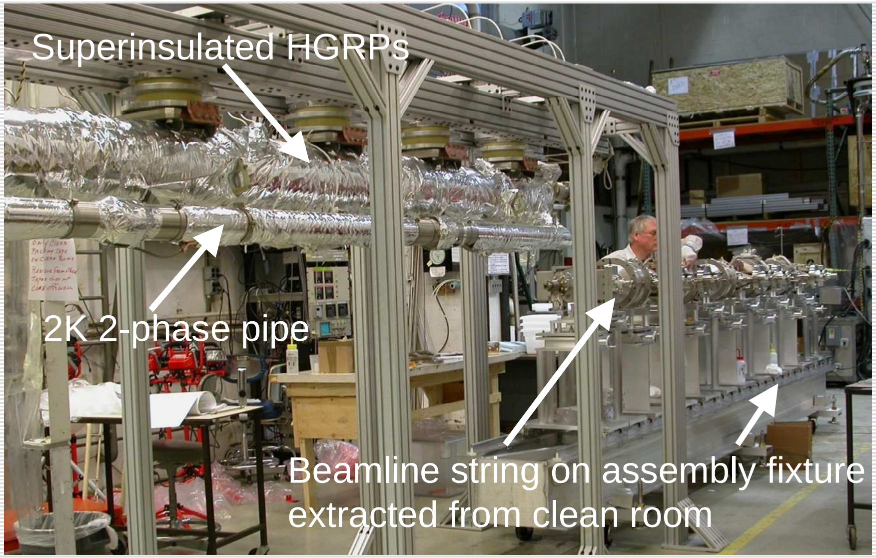
Attach cold couplers to beamline string



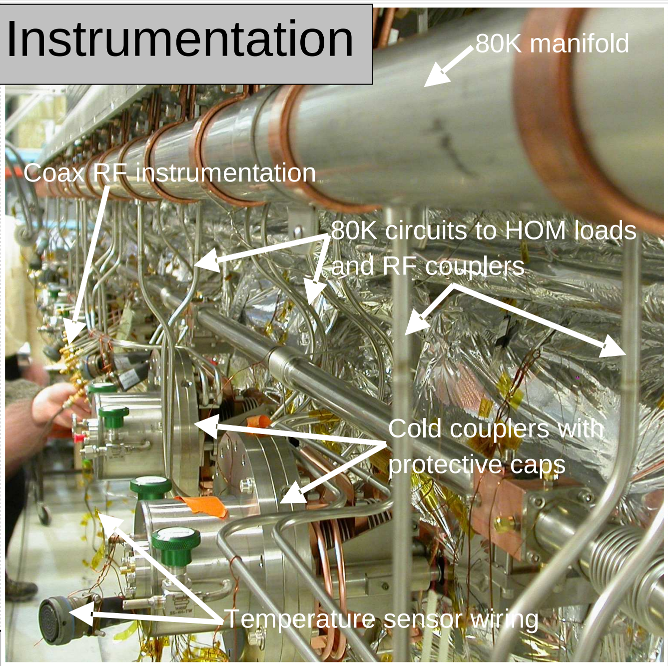


Cold mass assembly

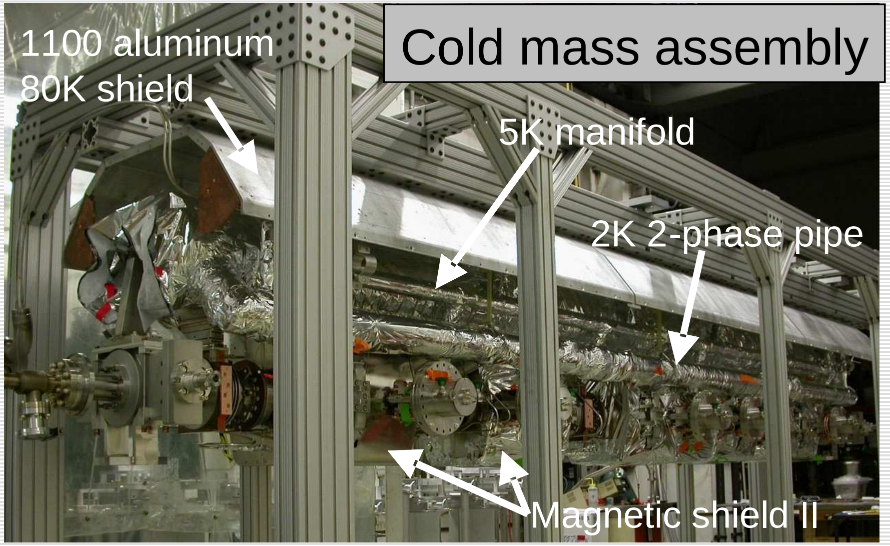
Beamline string rolling under HGRPs



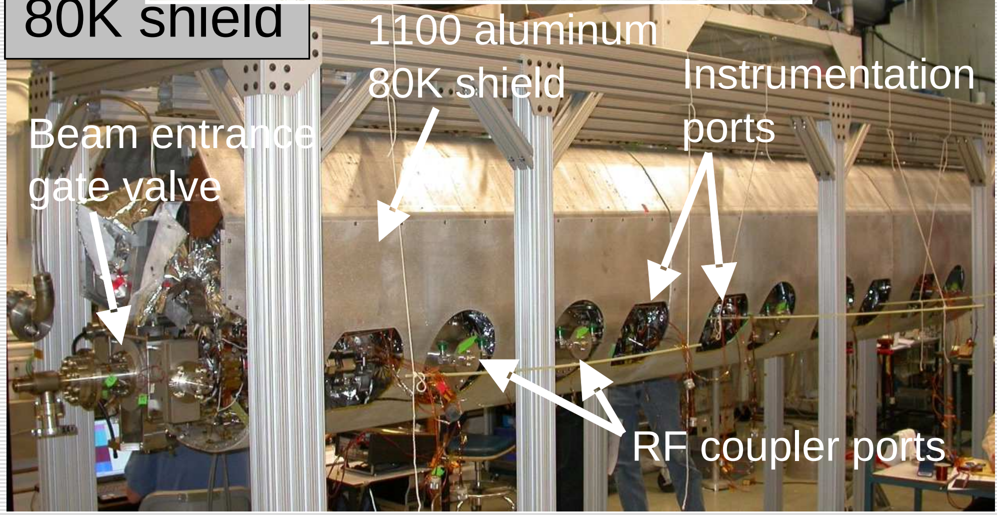
Instrumentation



Cold mass assembly

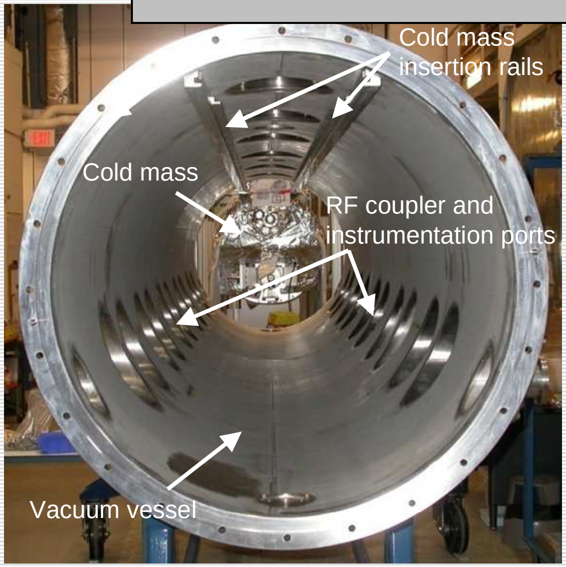


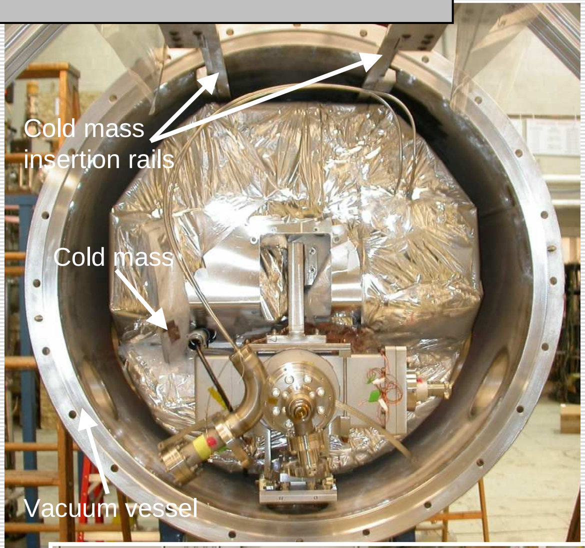
80K shield

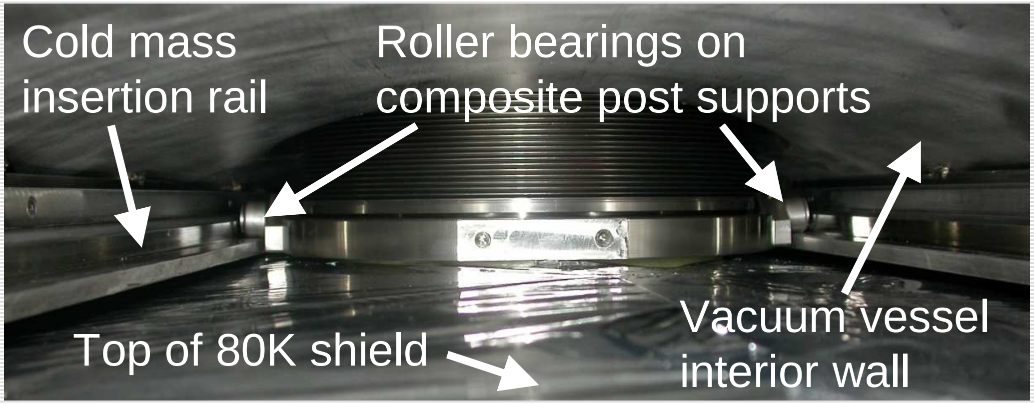


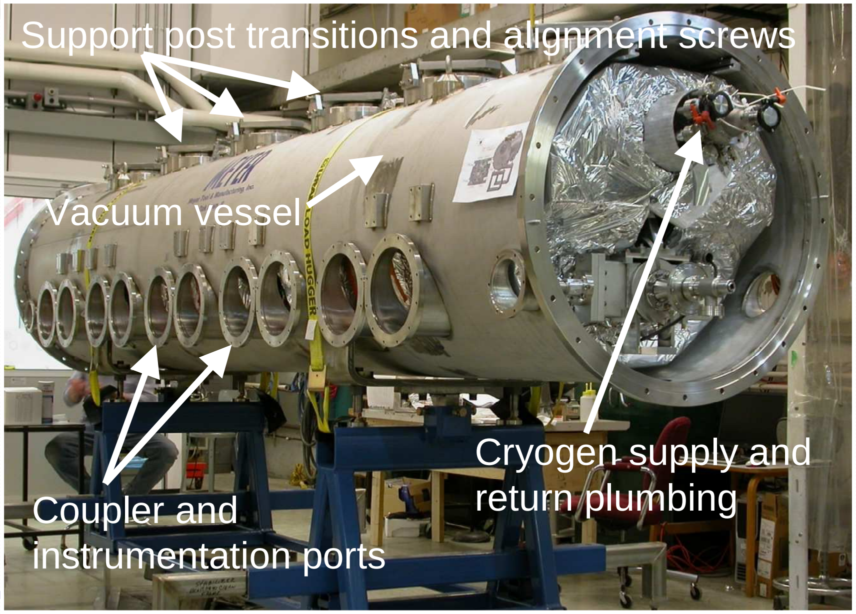
Cold mass & vacuum vessel

Cold mass rolled into vacuum vessel

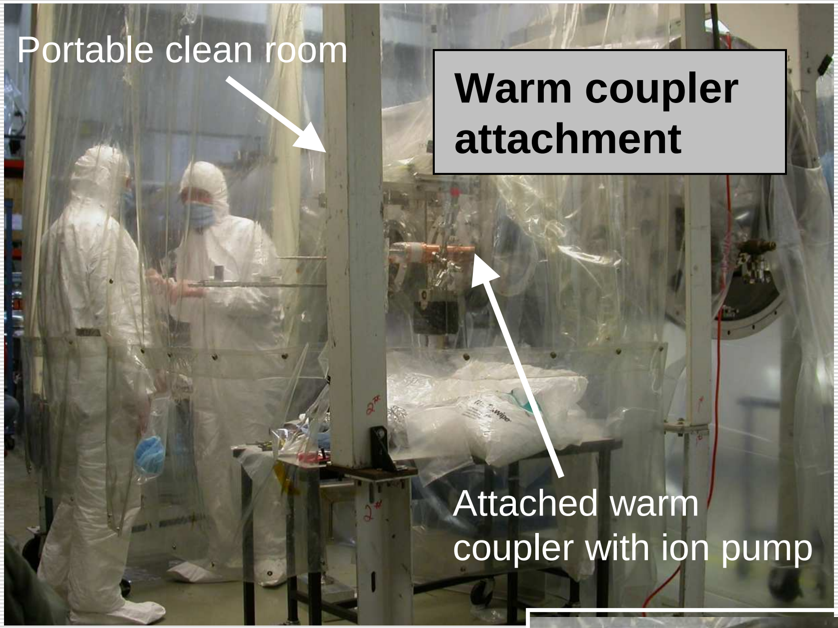




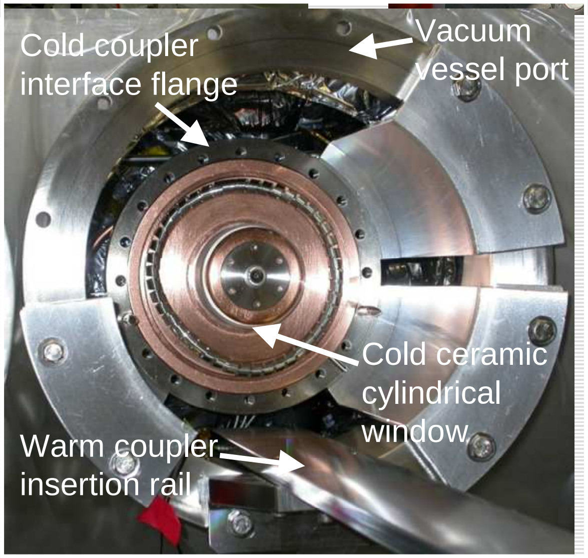




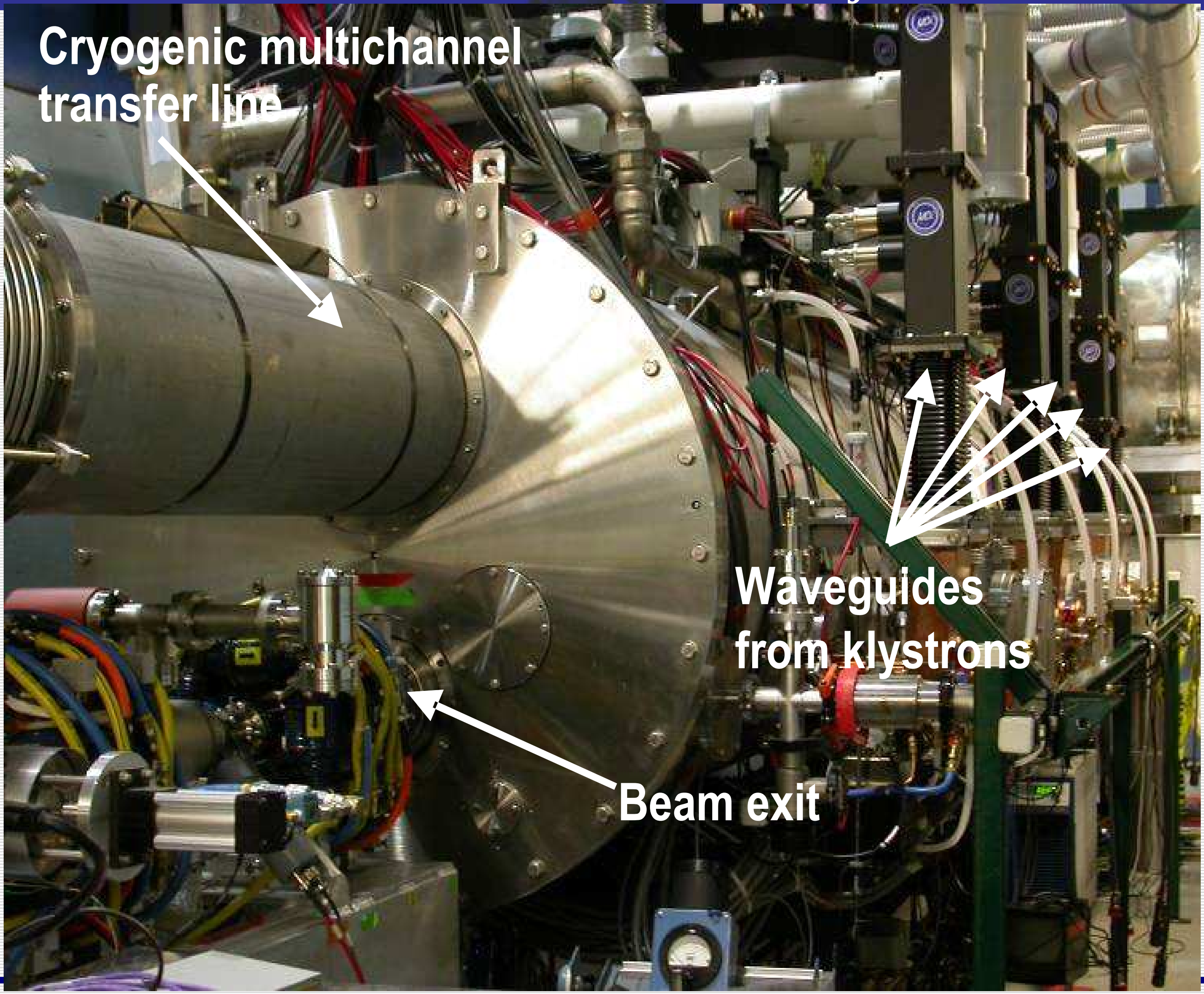
Completion of the assembly



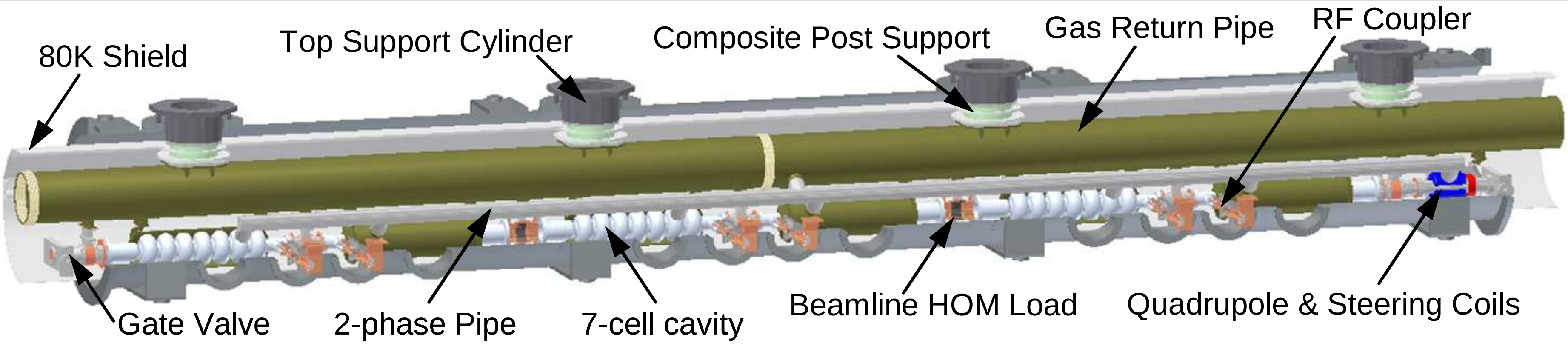
Transport from Newman Lab to Wilson Lab

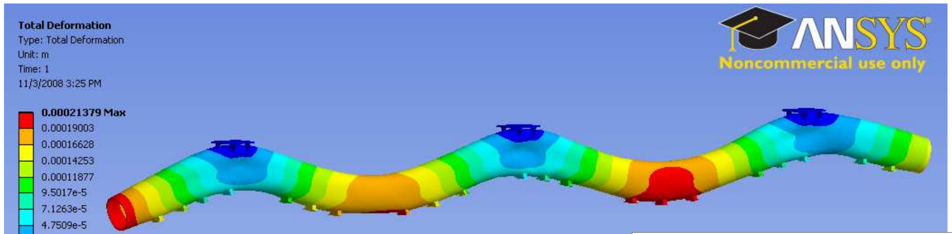


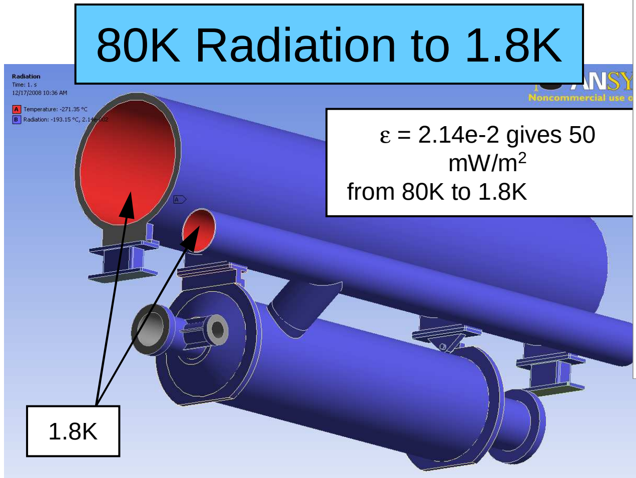
Cryomodule installed in the ERL injector

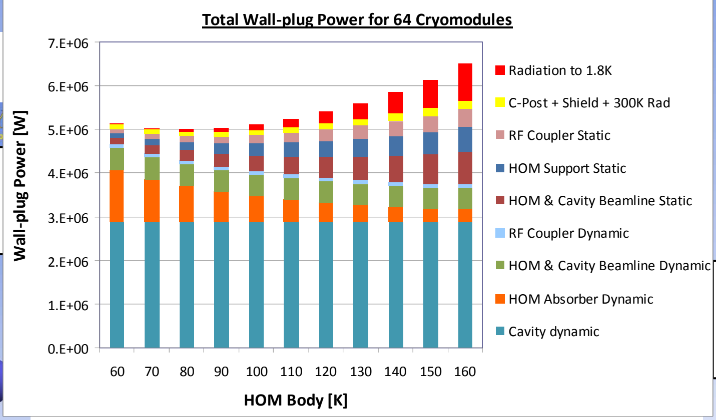


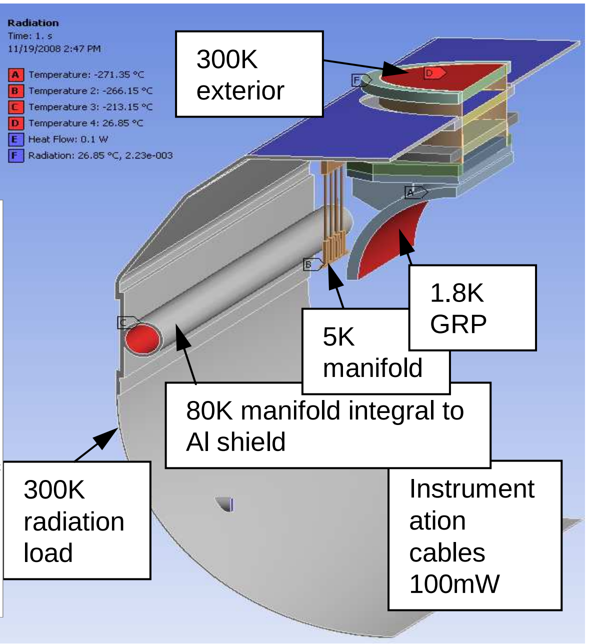
Example 3: ANSYS simulations of the ERL main linac cryomodule



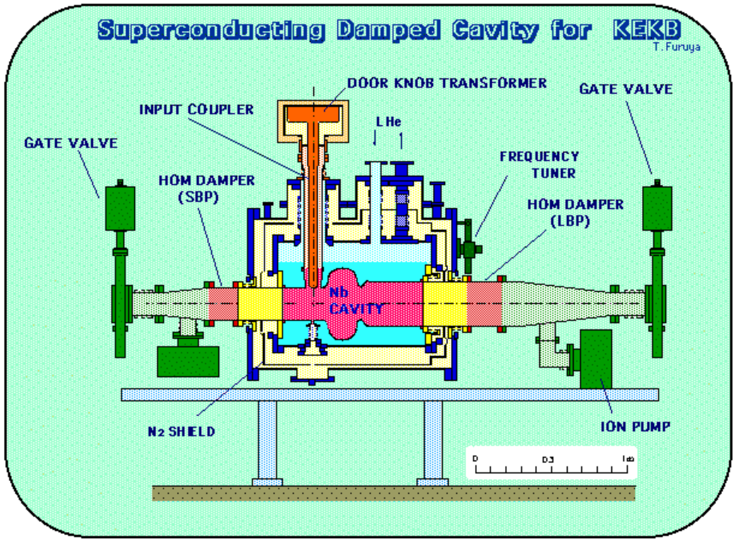




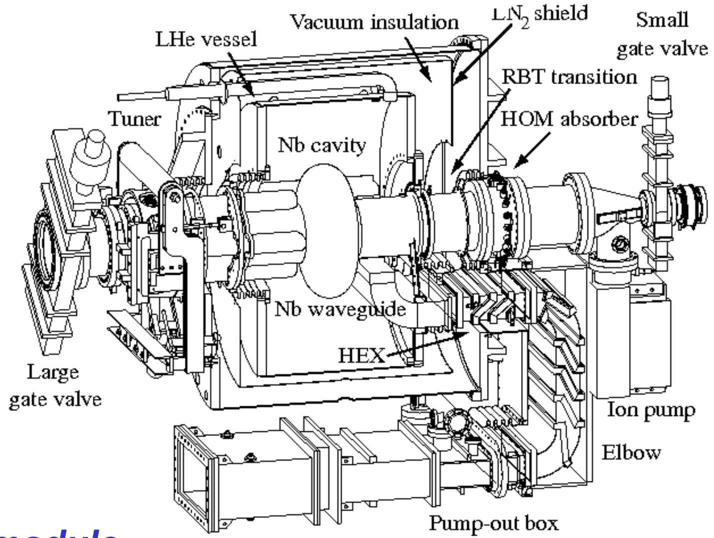




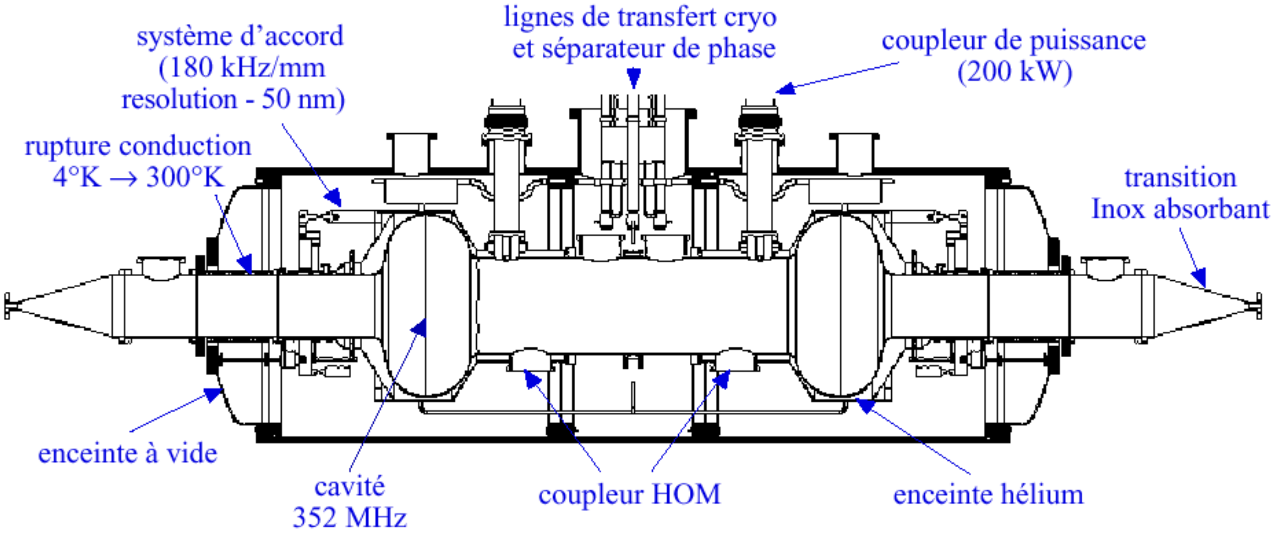
Cryomodules for storage rings



CESR cryomodule



SOLEIL cryomodule



Cryomodule instrumentation and ancillary equipment

RF

- Cavity field probes
- HOM antennae
- Arc detectors for input couplers
- e^- pick-up probes in the input couplers
- High voltage bias for input couplers

Temperature sensors

- Low temperature: carbon resistors, silicon diods, Cernox sensors
- CLTS's for the temperature range from 4 K to 300 K
- Thermocouples and/or Platinum Resistance Thermometers (PT-100, PT-1000) for places that are near/above RT
- IR sensors for input couplers

Cryogenics

- LHe level sticks
- He bath heater
- HOM load heaters
- He gas flow meters
- Pressure transducers

Vacuum

- Ion pumps for cavity and input coupler
- Turbo and roughing pumps for insulation vacuum
- Vacuum gauges (cold cathode and convectron)
- Gate valves

Tuner

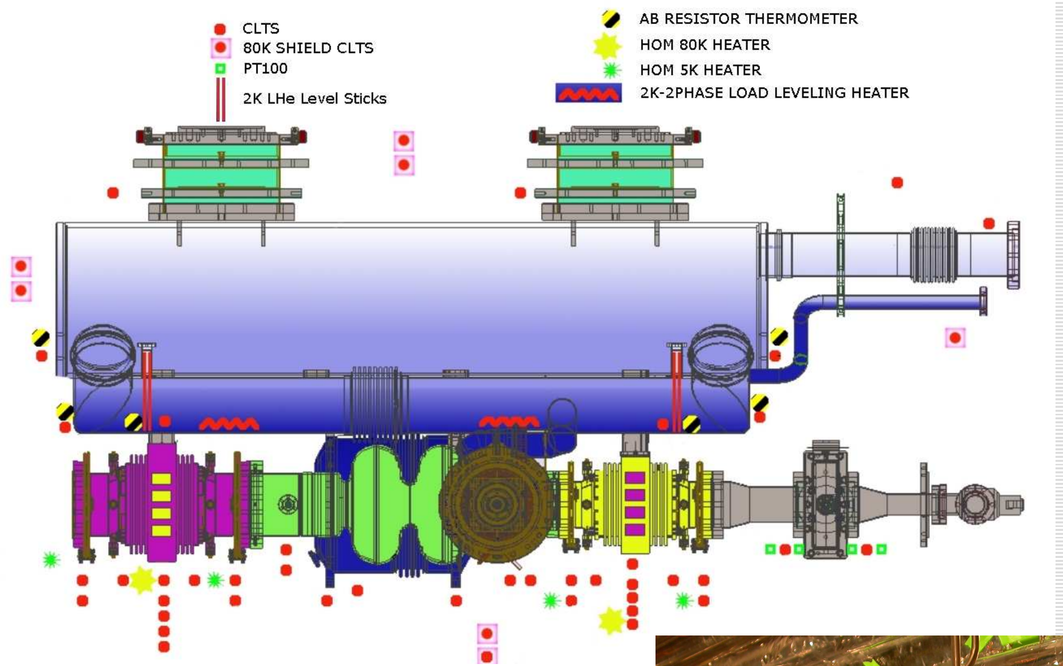
- Stepping motor
- Piezo elements
- Position sensors
- Limit switches and mechanical limits
- Tuner force

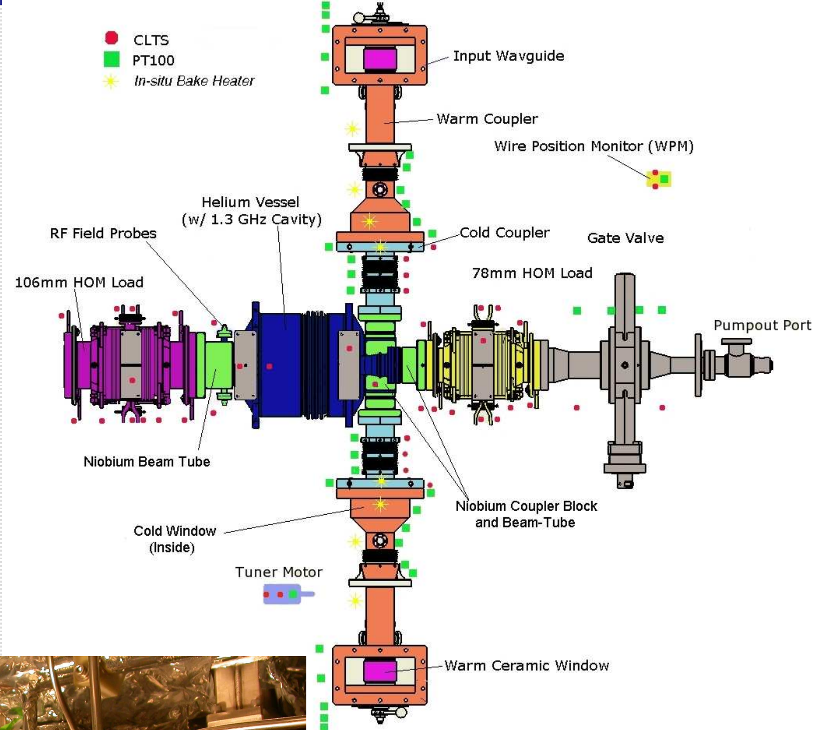
Other

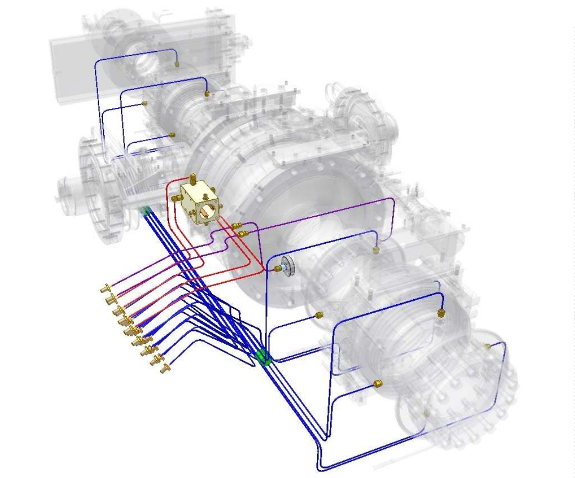
- Wire Position monitors (WPM)
- Cooling air flow and pressure
- Safety hardware: safety valve, burst disk, …

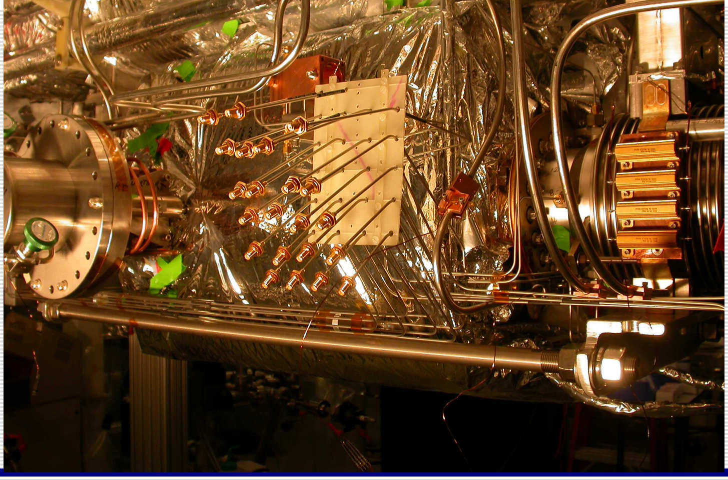
Cornell University
Laboratory for Elementary-Particle Physics

Cryomodule instrumentation maps









Cryomodule assembly movies

- APT cryomodule
- CESR cryomodule
- Cornell ERL HTC cryomodule

What have we learned?

- Cryomodule main functions: provide cryogenic environment for the cold mass; component integration (structural support; heat & thermal stress management; precise alignment.)
- A cryomodule contains a variety of complex technological objects: cavities and their ancillaries, but also magnets and BPMs.

✪ Next lecture: input couplers and HOM dampers.