S. Belomestnykh

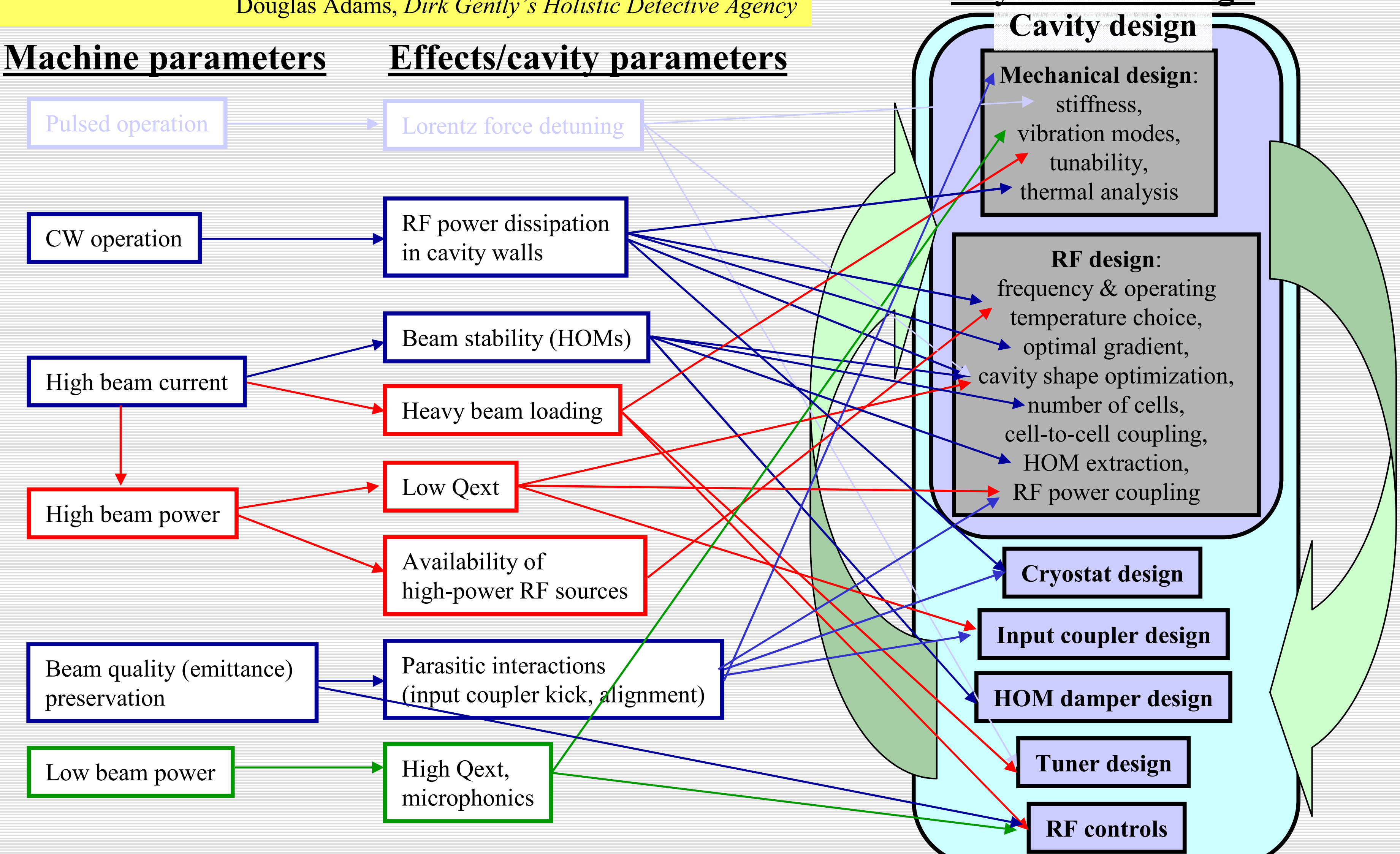
Superconducting RF Technology 2:

- Cavity design, fabrication & preparation
- SRF cryomodules

SC RF system design issues

"I believe,…, Mrs Sauskind, in the fundamental interconnectedness of all things."
Douglas Adams, *Dirk Gently's Holistic Detective Agency*

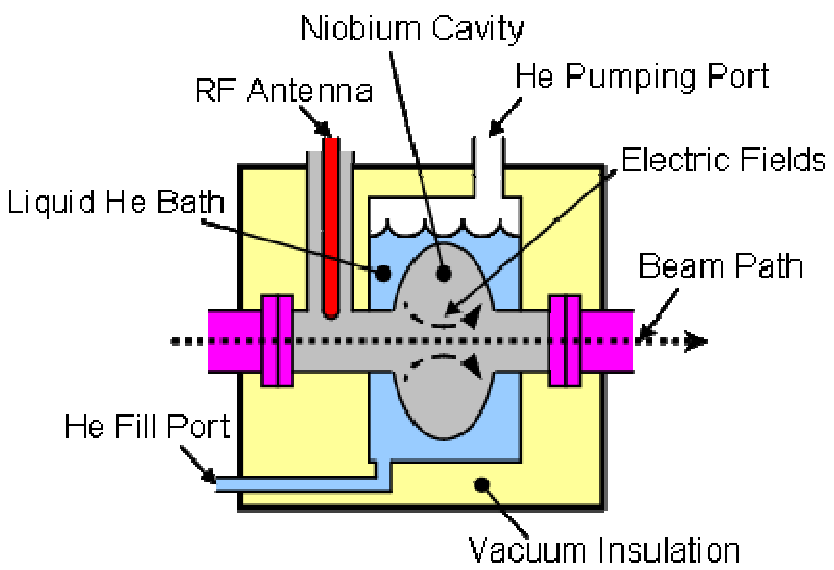
Cryomodule design



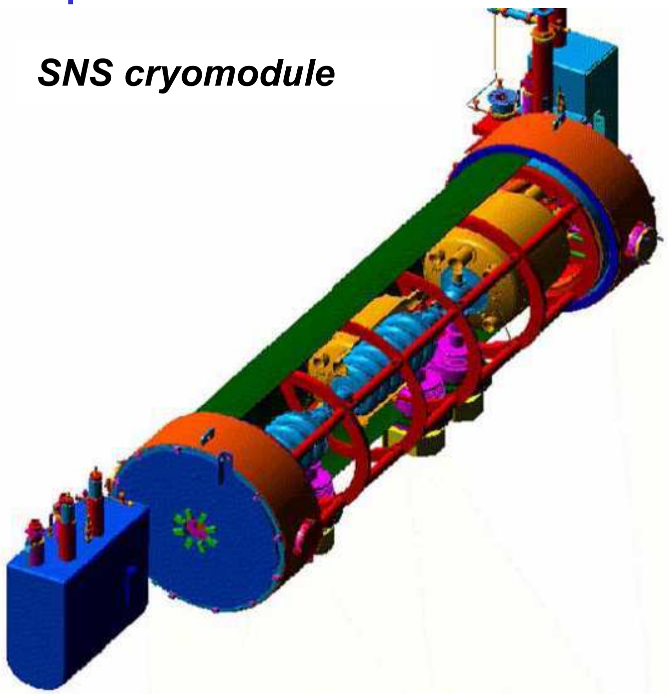
SRF cryomodule

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 antenna is needed to couple RF power to the cavity fields and any passing particle beam.
- 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.

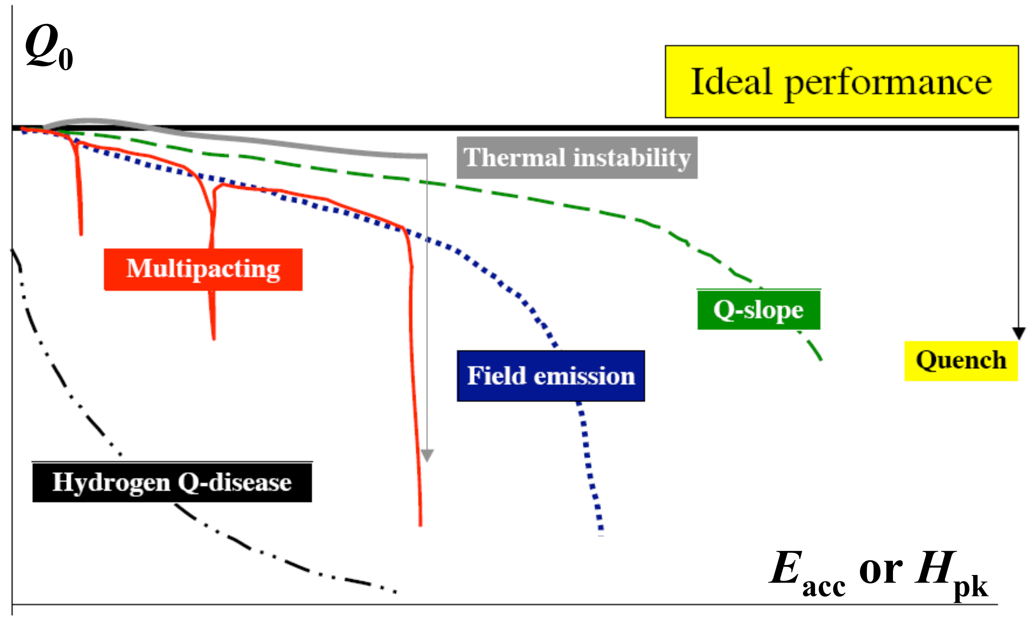


SNS cryomodule



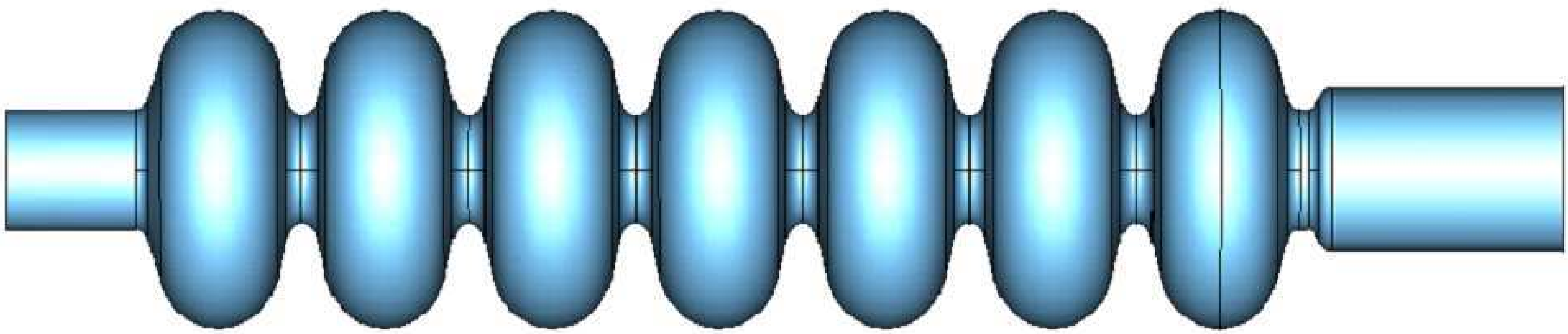
SC cavity performance limitations

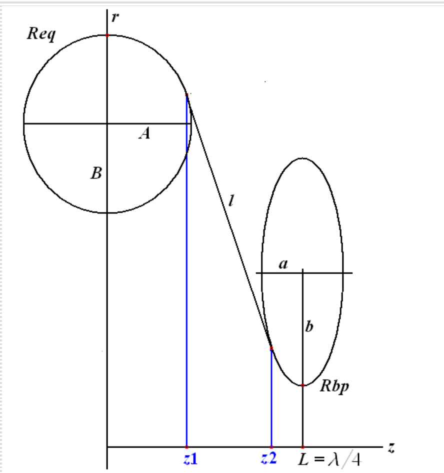
- Maximal surface magnetic field → fundamental limitation.
- Maximal surface electric field → field emission → can be cured by applying proper preparation techniques: clean room (dust-free) assembly, high-pressure DI water rinsing (HPR).
- Thermal quench → use of high-purity material (RRR) to improve thermal conductivity, material quality control to avoid mechanically damaged surfaces, particulate free assembly.
- Multipacting → use of elliptical cell shapes.
- Long-pulse operation tends to favor the highest reliably achievable gradient (23.6 MV/m for XFEL, 31.5 MV/m for ILC).
- CW operation → cryogenics vs linac cost optimization determines operating gradient (15 – 20 MV/m).



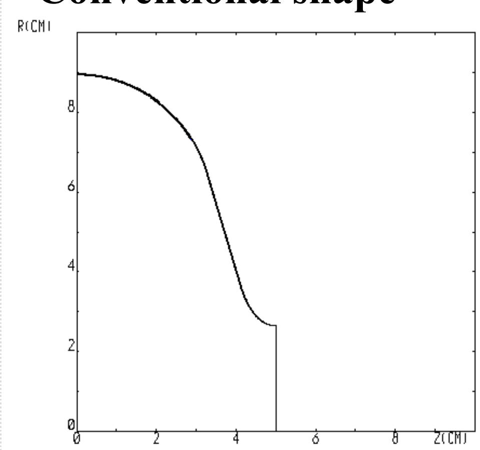
Cavity design (RF)

- Cell shape chosen for optimal performance
- The criteria are: maximal G*R/Q, smooth curved geometry to avoid multipacting and peaks of surface EM field,
- Elliptical shapes (re-entrant and conventional) are used.

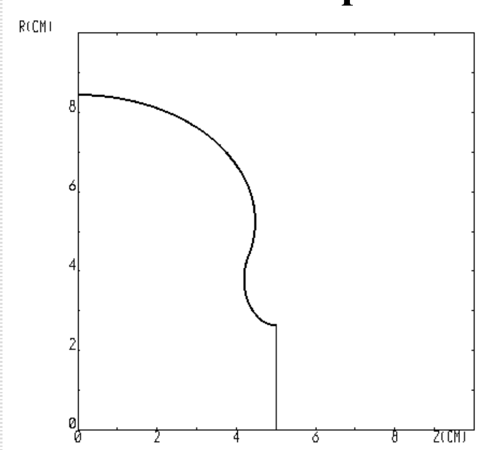




Conventional shape

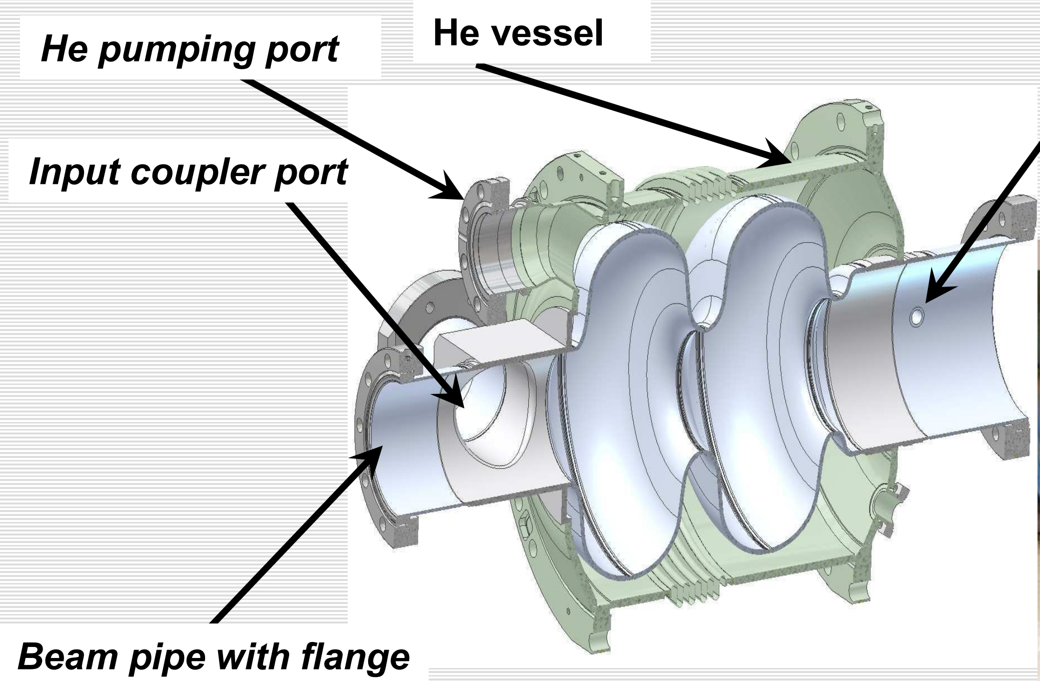


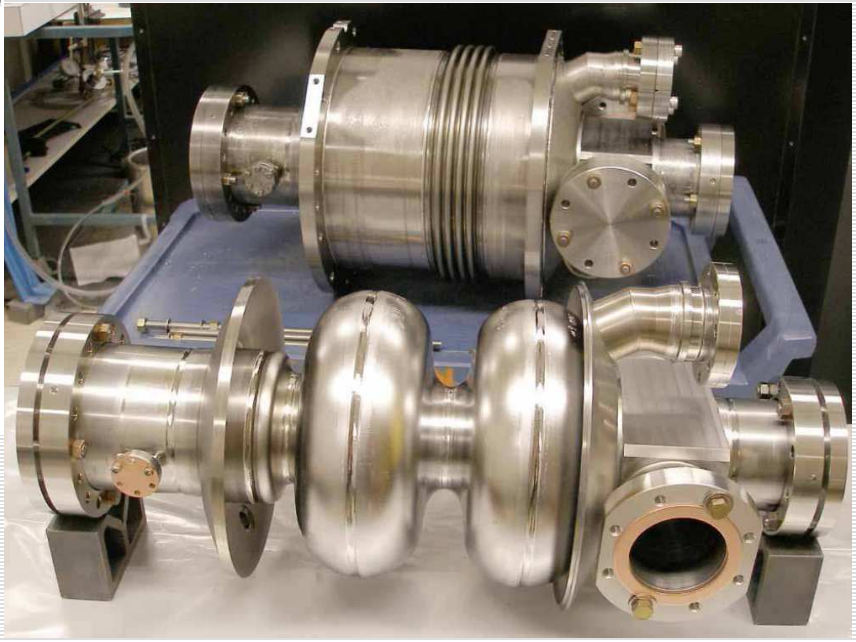
Re-entrant shape



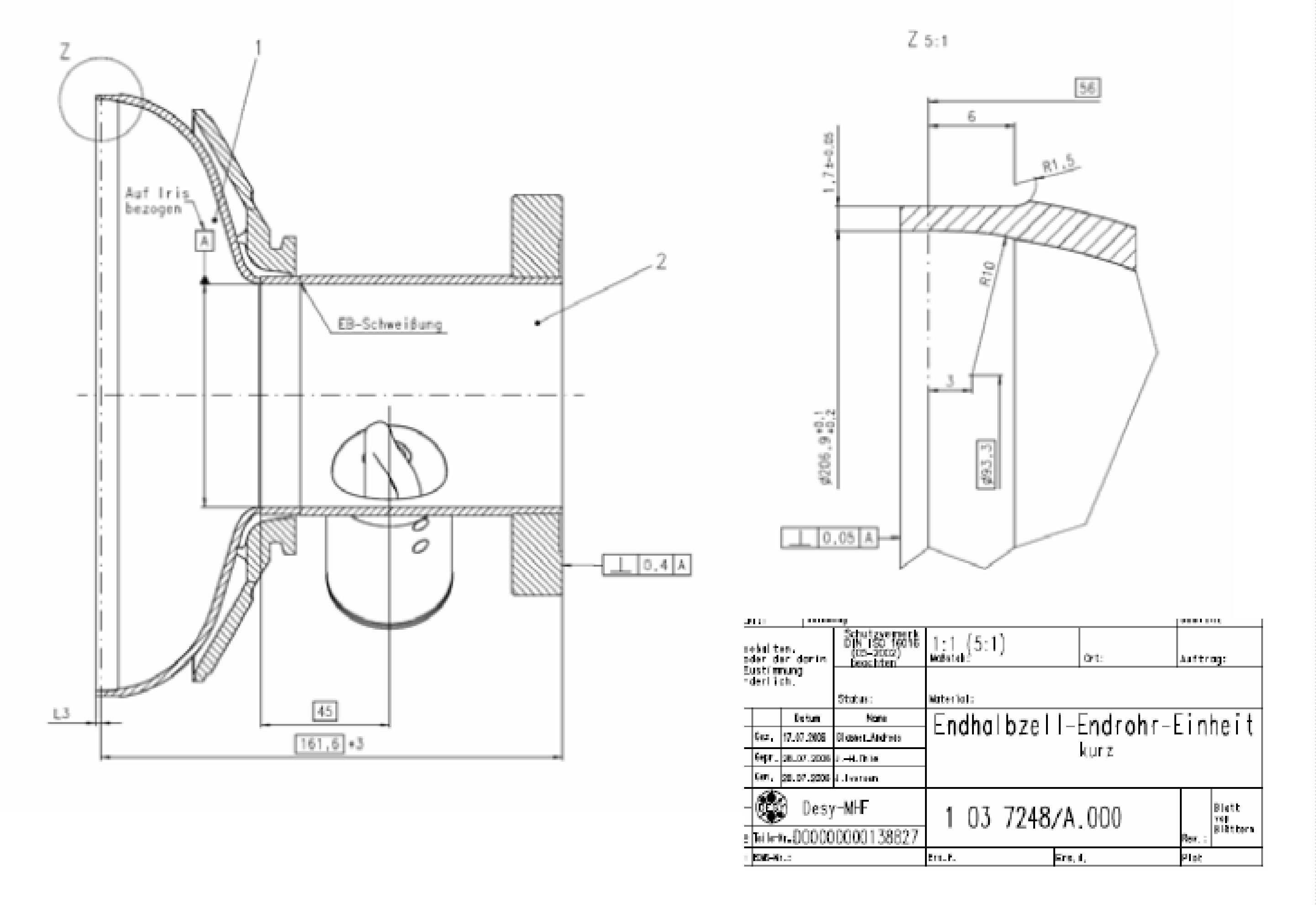
Cavity design (mechanical)

In addition, cavities have to accommodate RF input coupler ports & field probes. All interfaces (to liquid helium vessel, beam pipe flanges,…) should be defined. Mechanical design includes computer simulations of mechanical stresses due to cooldown, pressure differentials, tuning of the cavity frequency, etc., simulations of the heat transfer, and determining most dangerous vibrations modes. At this point all fabrication techniques are specified, and a package of drawings is produced.



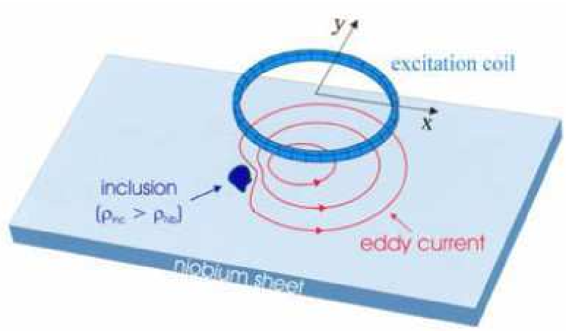


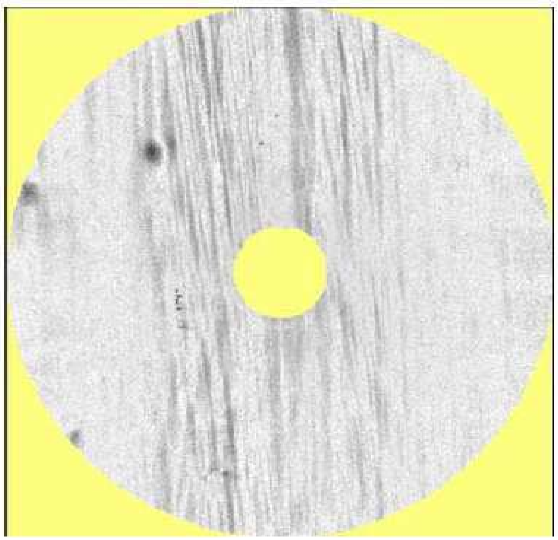
An example of production drawing



Material inspection

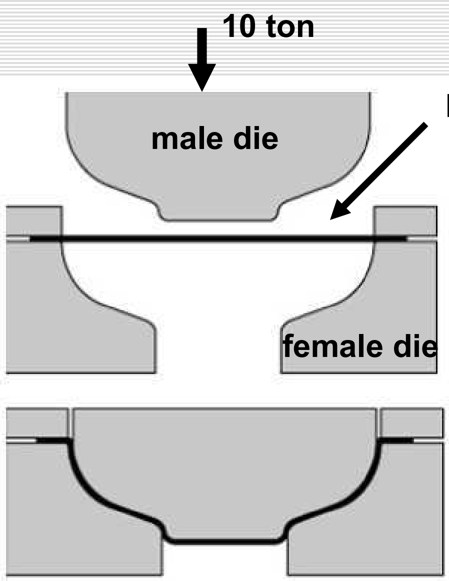
- Cavities are fabricated from sheets of high RRR (~300) niobium, which is readily available from industry. Typical sheet thickness is a few millimeters.
- Nb sheets are inspected upon receiving, visually and using eddy-current or SQUID scanning (more sensitive). The basic principle is to detect the alteration of the eddy currents with a double coil sensing probe to identify inclusions and defects embedded under the surface.
- Usually a very small fraction, <5%, of sheets is rejected at this stage.



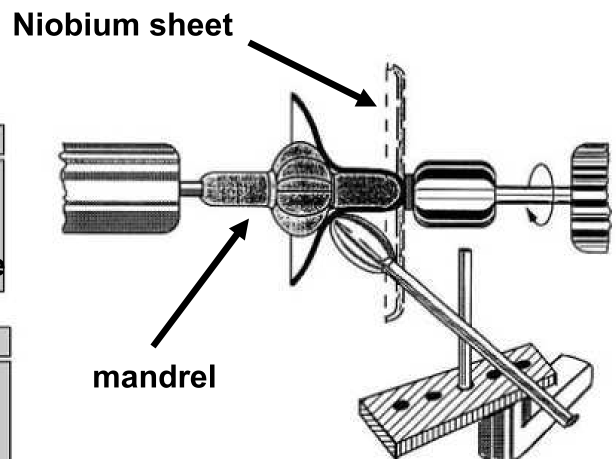


Cavity fabrication techniques

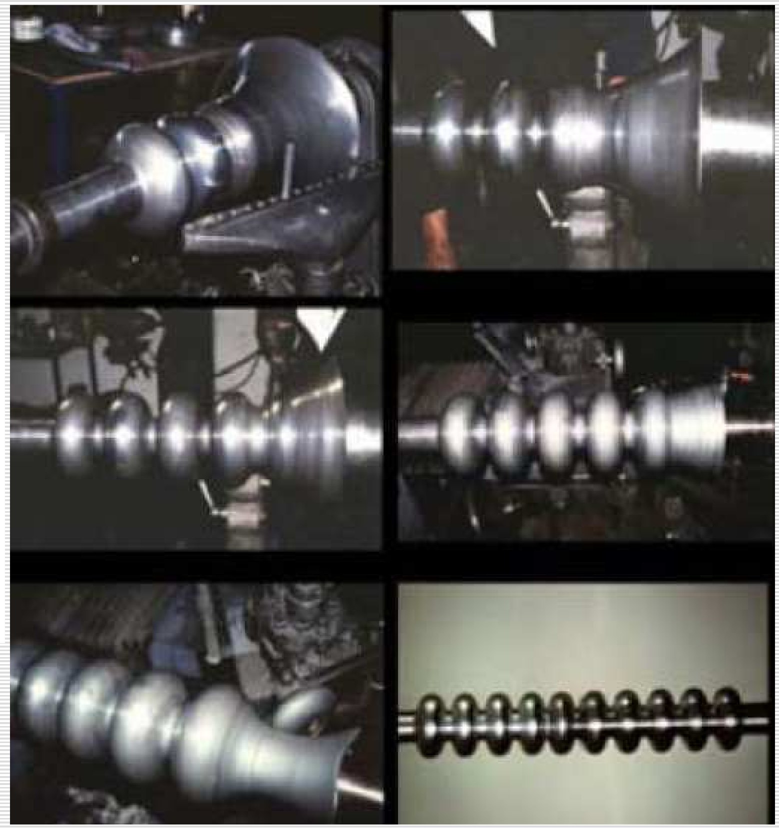
- The most common fabrication techniques are to deep draw or spin half-cells.
- Beam pipes and other ports are then fabricated, some parts can be made of a lower grade Nb.
- Alternative techniques (still in R&D phase): hydroforming and spinning an entire cavity out of single sheet or tube.



Deep drawing



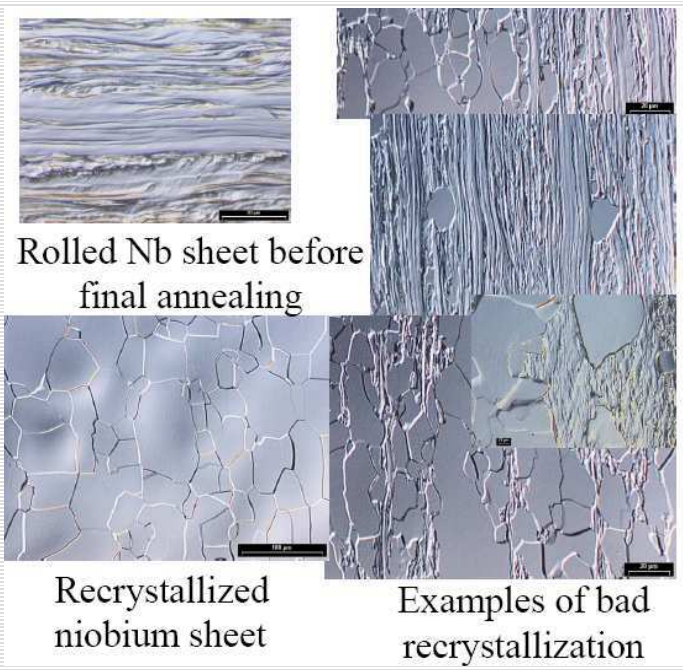
Spinning



Cornell University
Laboratory for Elementary-Particle Physics

Cavity fabrication techniques (2)

- Sheet metal forming is sensitive to mechanical properties. In particular, a uniform grain size is essential. Material must be fully recrystallized.
- After forming and trim machining, the parts are electron beam welded together under vacuum better than 10^{-5} Torr.
- Some parts, e.g. flanges, are brazed to cavity ports.



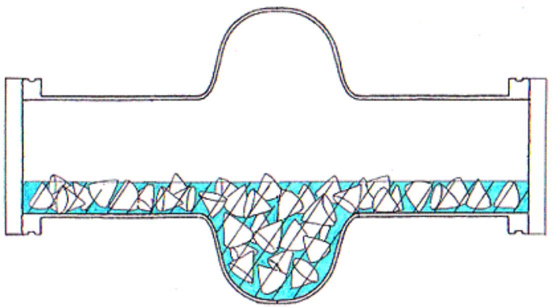
Rolled Nb sheet before final annealing

Recrystallized niobium sheet

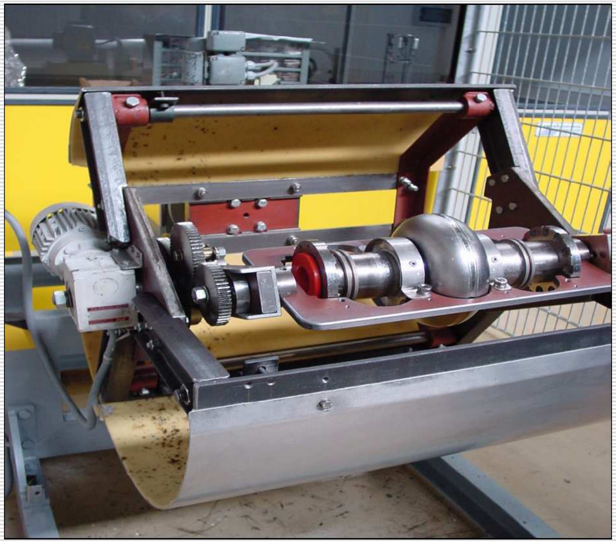
Examples of bad recrystallization

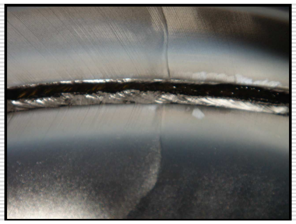
Cavity fabrication techniques (3)

- To achieve the best RF performance, the surface of the cavity must be as close as possible to the ideal. Chemical etching or electropolishing to a depth of 100 – 200 μm removes mechanically damaged layer.
- If the welds have imperfections, tumbling or CBP (Centrifugal Barrel Polishing) can be used for smoothening. Although it is not used widely, this procedure provides a fairly uniform surface, removing imperfections such as roughness at welds, pits, and mild scratches remaining from the starting sheet material. A light etch usually about 50 μm removes the tumbling abrasive embedded in the surface.
- Cavity frequency and field flatness then checked and tuned. Usually the goal is to achieve 98% field flatness.



Cavity filled with liquid soap and plastic chips embedded with abrasive ceramic powder.



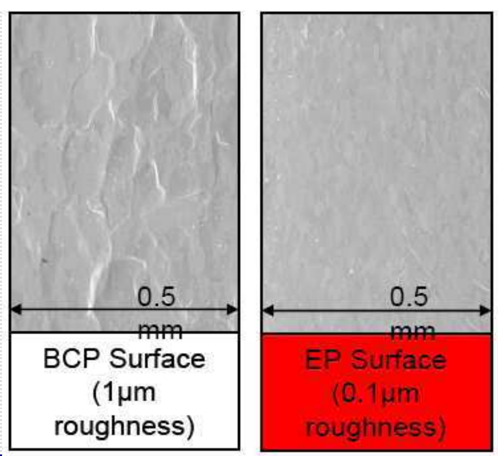


Weld region before CBP

Weld region after CBP

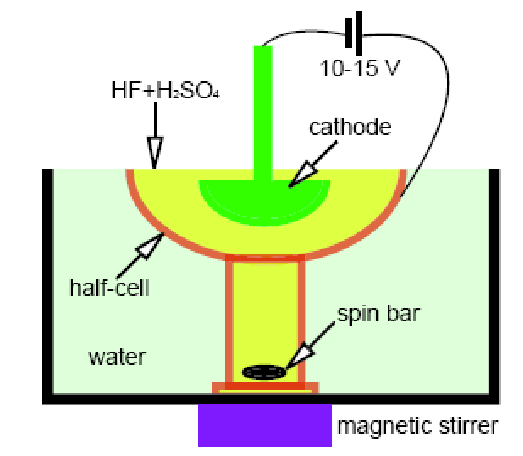
BCP

- Final light etching (~20 μm) is necessary before the cavity is tested.
- 1:1:2 BCP (Buffered Chemical Polish) acid solution is used for chemical etching. BCP consists of two alternating processes: dissolution of the Nb_2O_5 layer by HF and re-oxidation of the niobium by a strongly oxidizing acid such as nitric acid (HNO_3). To reduce the etching speed a buffer substance is added, for example phosphoric acid H_3PO_4 , and the mixture is cooled below 15°C to ensure zero pick up of hydrogen. The standard procedure with a removal rate of about 1 μm per minute is 1:1:2 BCP with an acid mixture containing 1 part HF (40%), 1 part HNO_3 (65%) and 2 parts H_3PO_4 (85%) in volume.
- BCP gives rise to a major problem for gradients higher than 20 MV/m: the development of steps at grain boundaries due to different etch rates of niobium grains with different orientations. Surface roughness (usually the steps are a few μm) is responsible for premature quench and possibly plays a role in aggravating the high-field RF losses.

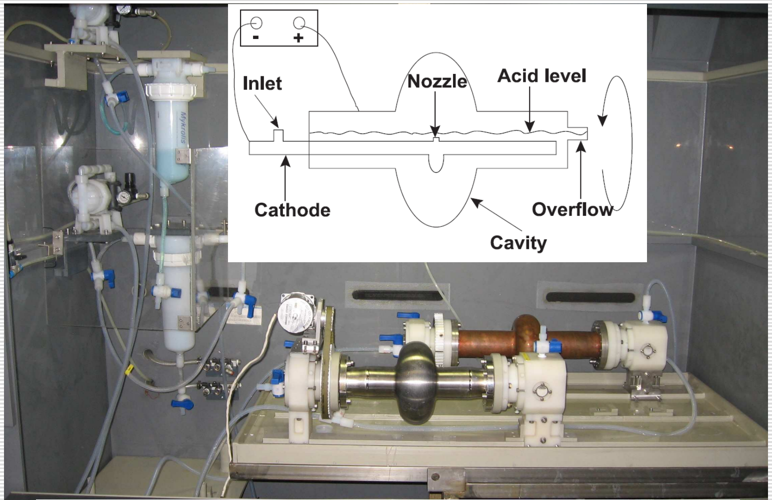


Electropolishing

- **Electropolishing is typically used for cavities that must operate at high gradients, > 20 MV/m.**
- **The niobium cavity is the anode (+) in an electrolytic cell and the cathode (-) is made from pure aluminum (1100 series). The electrolyte is a mixture of hydrofluoric and sulfuric acid in a volume ratio of 1:9, using typical commercial strengths HF (40%) and H2SO4 (98%). As current flows through the electrolytic cell, the niobium surface absorbs electrons and oxygen to convert to niobium pentoxide which subsequently dissolves in the HF present in the electrolyte.**



Set up for vertical EP developed at Cornell



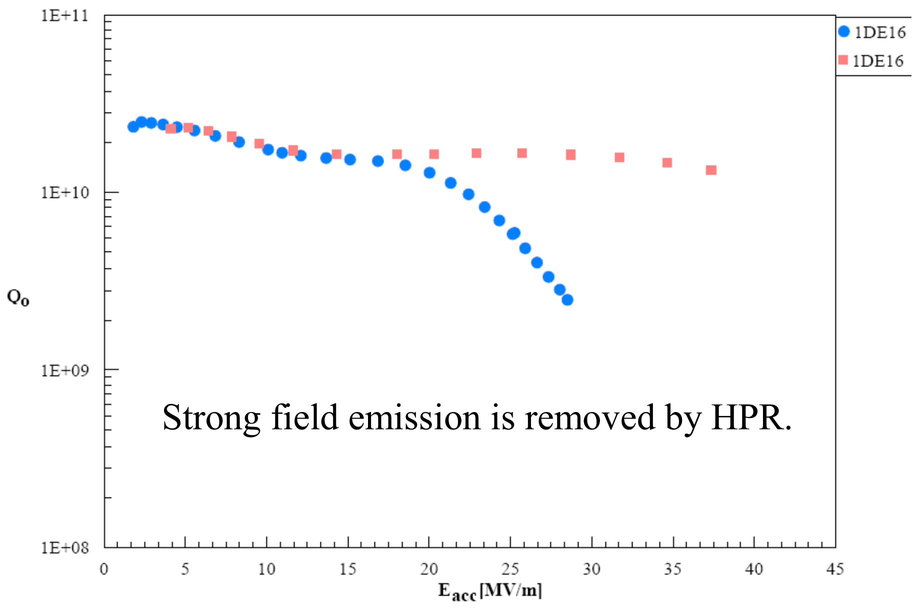
Set up for horizontal EP at KEK

Clean cavity preparation

- Micro-particle contamination is the leading cause of field emission. This stresses the importance of cleanliness in all final treatment and assembly procedures.
- After etching, the cavity is thoroughly rinsed in 18 MOhm·cm purity dust-free water and, while still filled with water, is moved to a clean room..
- From that point the cavity surface must be exposed only to dust-free, clean air in a class 100 (fewer than 100 particles of size larger than 1 µm in a volume of 100 cu. ft.) or better clean room.

HPR

- Upon arrival in the clean room, the cavity is given a High Pressure (100 Bar) Rinsing (HPR) with ultra-pure water as this is proven to be the most effective tool to remove micro-particles and therefore reduces field emission.
- Finally, the cavity is either assembled for a vertical acceptance test or becomes part of a cavity string for horizontal cryomodule.



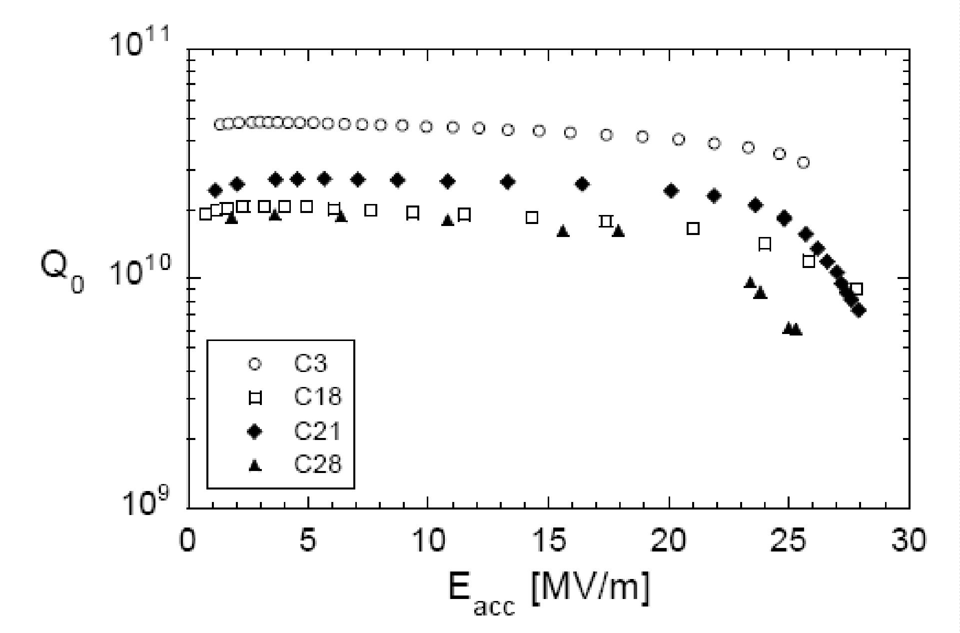
Strong field emission is removed by HPR.

HPR system at Cornell.

High pressure water jet stream.

Cavity performance test

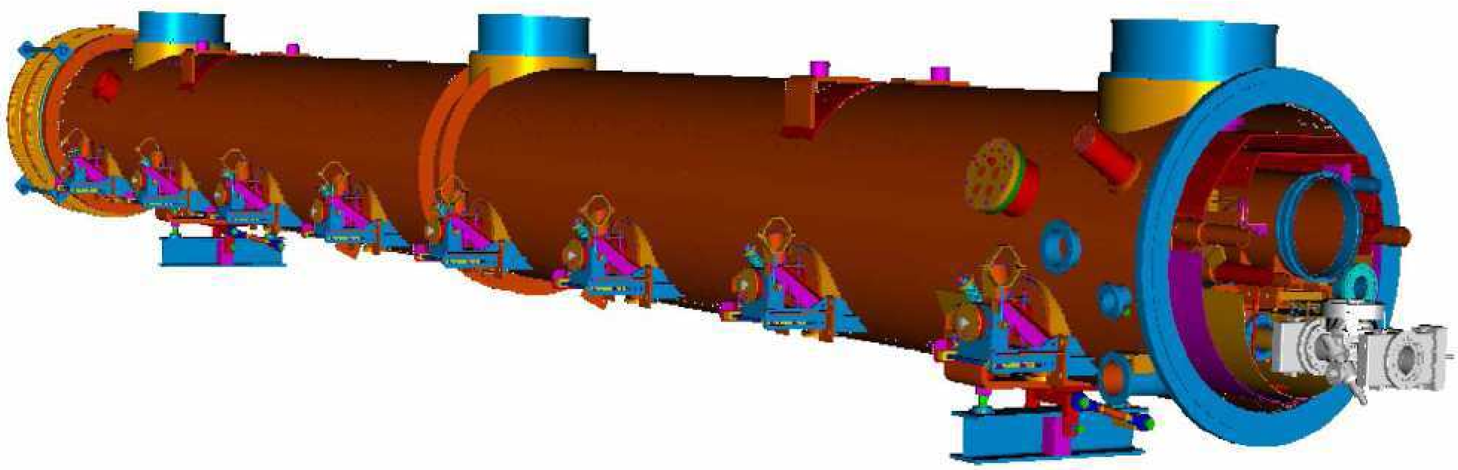
- **Acceptance test in a vertical dewar.**
- **RF losses are measured as a function of the accelerating field.**
- **Results are presented as Q vs E_{acc} plots.**



SRF cryomodules

Basic design considerations:

- **Cryogenics issues: heat removal by LHe, thermal shields, superinsulation.**
- **Pulsed vs CW operation: number of thermal shields, LHe pipe dimensions.**
- **High vs low power: heat handling → more complicated input coupler design.**
- **Magnetic shielding (< 10 G residual field).**
- **Component integration.**



Cryogenics

Refrigerator's Coefficients of Performance (COP) for different temperatures.

$COP_{real} = 1/(K * \eta\ CARNOT)$

$\eta\ CARNOT = T/(300 - T)$

Refrigeration Temperature	Carnot 1/η IDEAL WORLD	XFEL-Spec REAL WORLD	% Carnot
2 K	149	870	17
5 K	79	220	36
40 K	7	20	33

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

Heat transfer by radiation

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

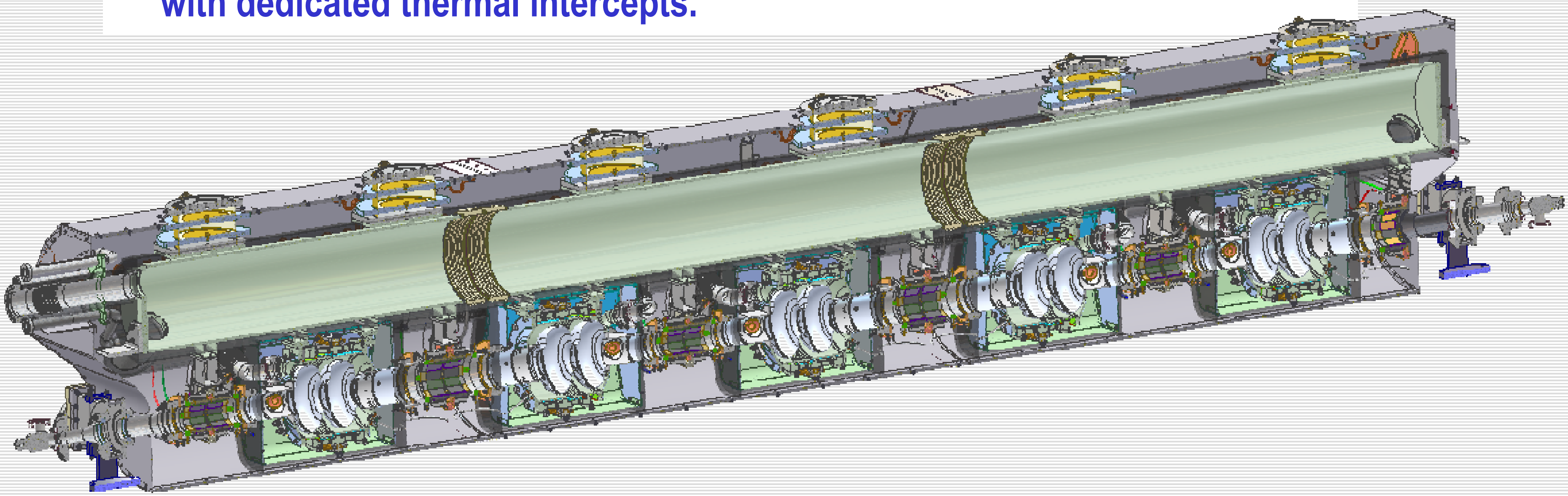
$$P_{12} = A_1 \times \sigma_{SB} \times \frac{\left(T_1^4 - T_2^4\right)}{\left[\frac{1}{\varepsilon_1} + \frac{(1-\varepsilon_2)A_1}{\varepsilon_2 A_2}\right]}$$

- Where the Stefan-Boltzman constant σ_{SB} = 5.67×10^{-8} W/m^{2}K, radiative power is transferred from a surface, area A_1 having an emissivity e1 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.
- 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.

CW vs pulsed operation

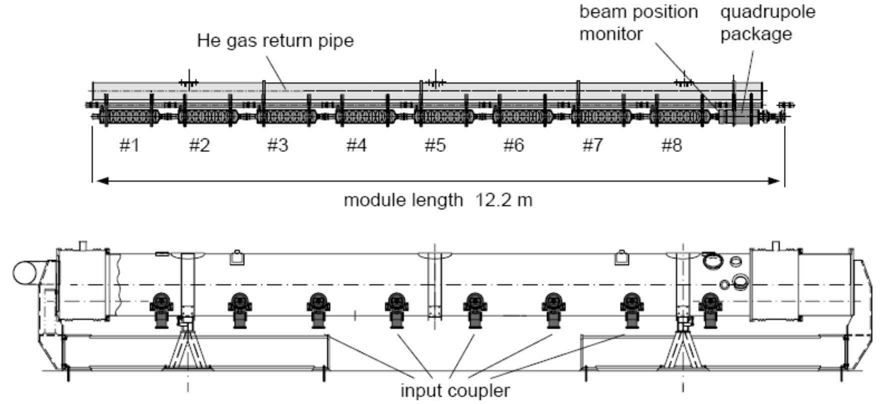
$$P_{AC} = COP \times \left(P_{dynamic} + P_{static}\right)$$

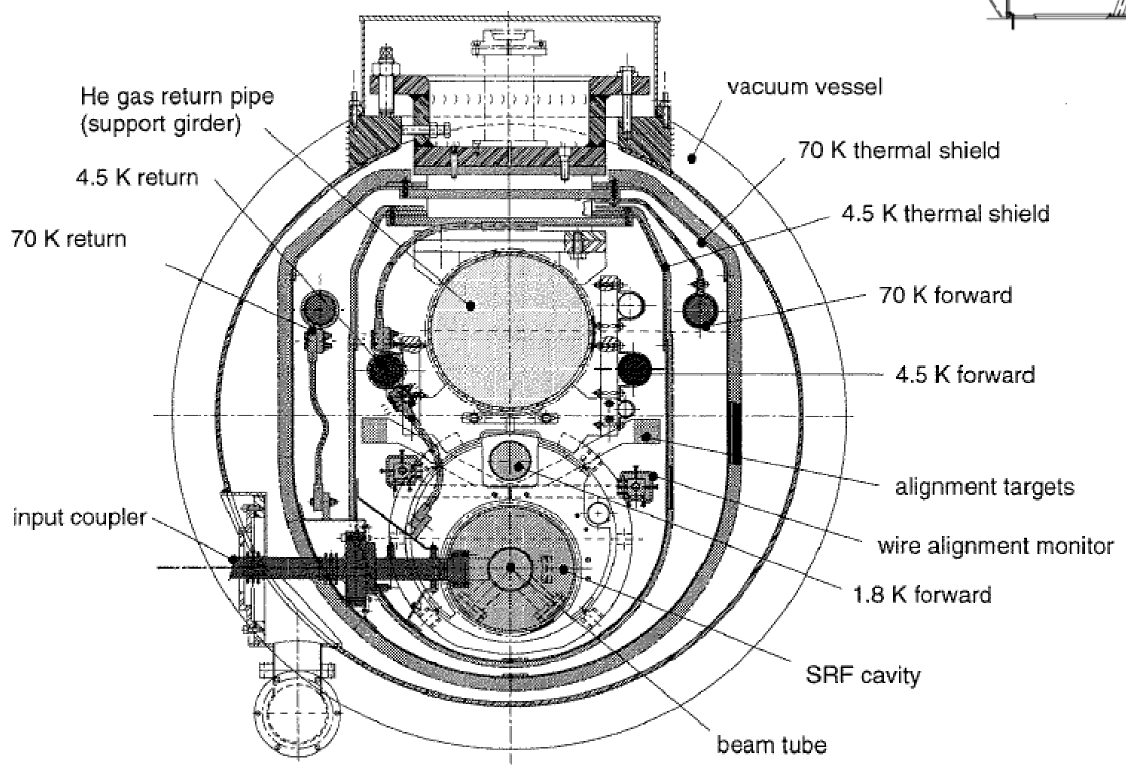
- **Pulsed operation with low duty cycle (XFEL, ILC): $P_{static} >> P_{dynamic} \rightarrow$ very important to thermally insulate the cold mass as good as possible, may require additional thermal shields (5 K) and better superinsulation.**
- **CW operation (CEBAF, Cornell ERL): Pdynamic >> Pstatic $\rightarrow$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



Example 1: TTF cryomodule

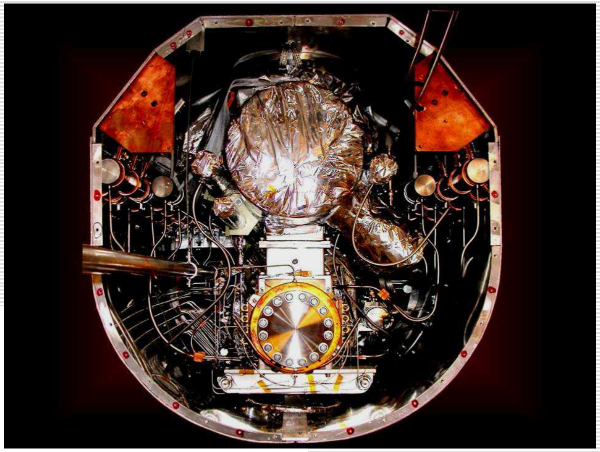
- Cryomodule for pulsed operation
- Static heat load (2 K) < 3 W for a 12 m long cryomodule!





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:

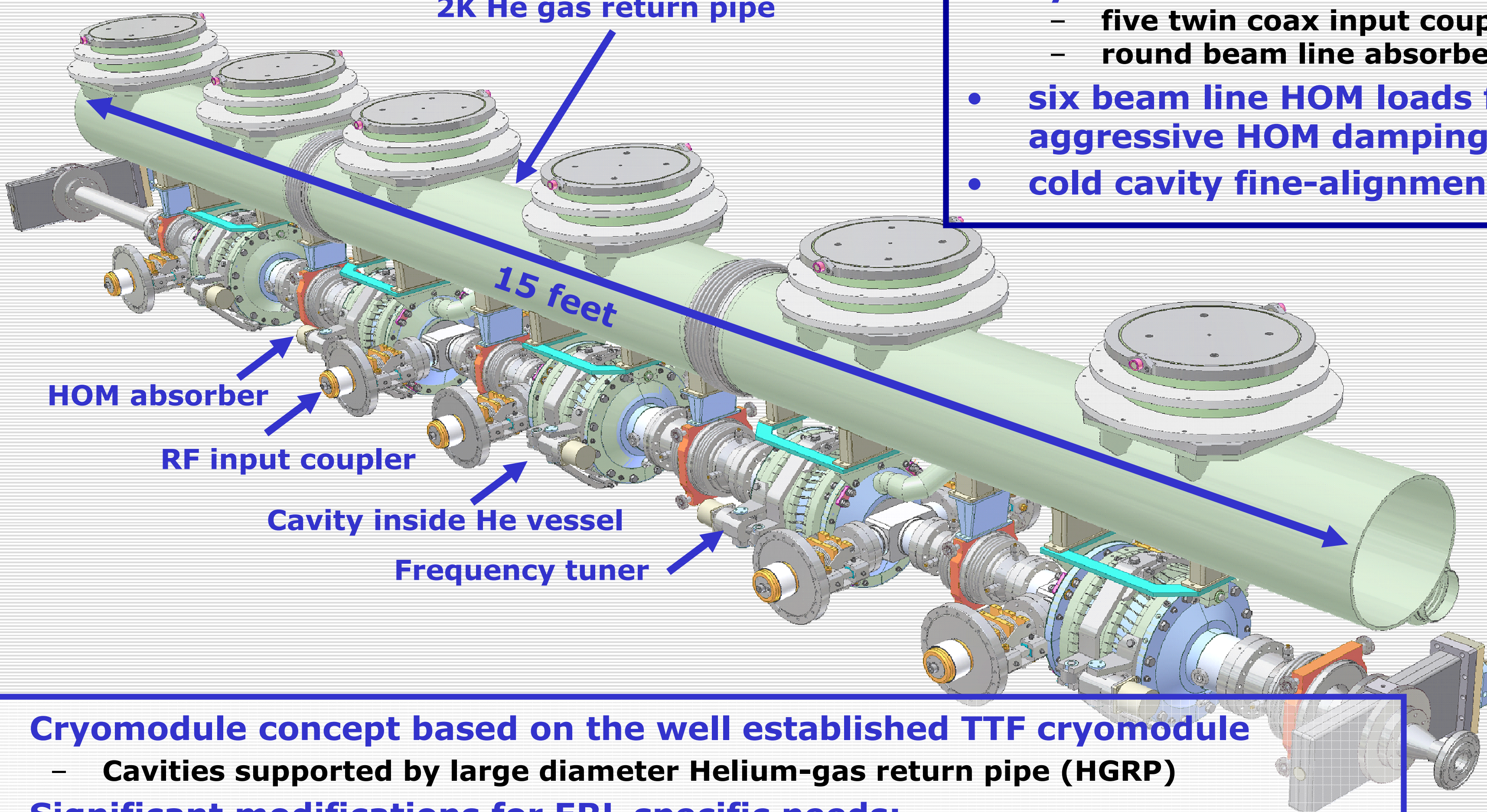
~ 25 W at 2 K (dominated by the dynamic cavity load),

~ 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).

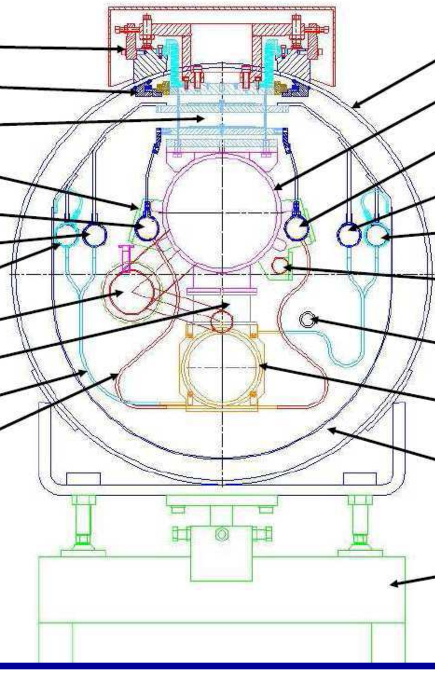
Example 2: ERL injector cryomodule

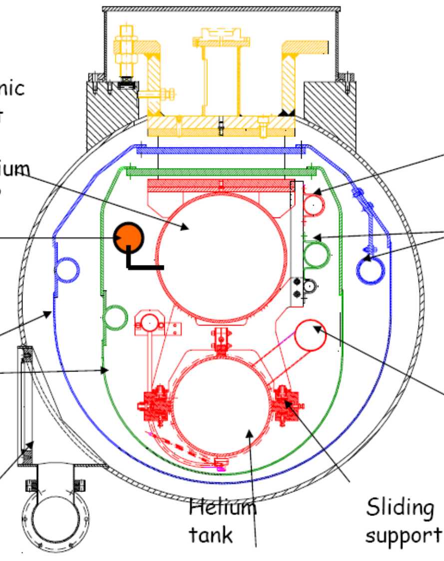
- five 2-cell cavities
- symmetric beam line
  - five twin coax input couplers
  - round beam line absorbers
- six beam line HOM loads for aggressive HOM damping
- cold cavity fine-alignment



- 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

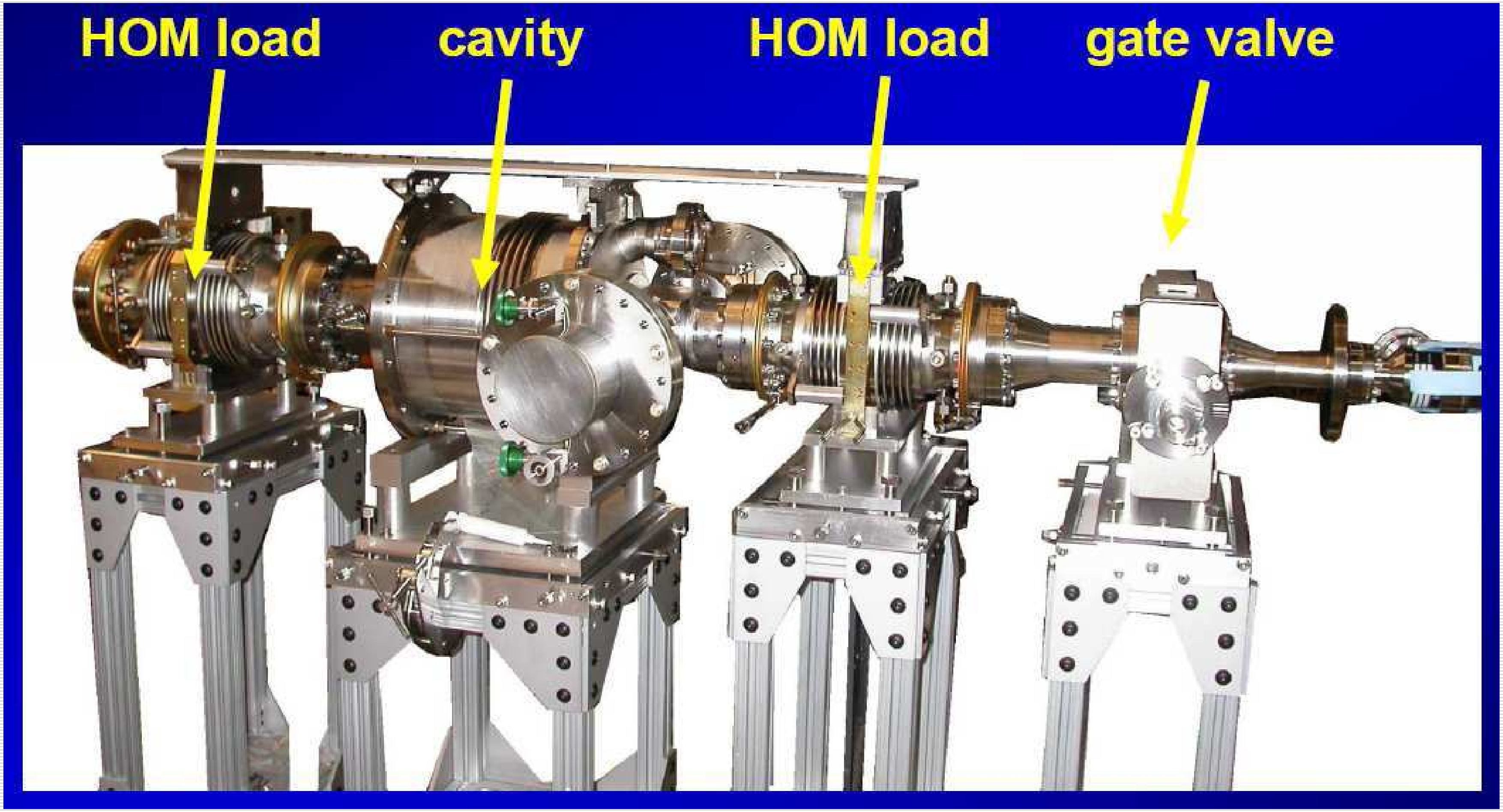




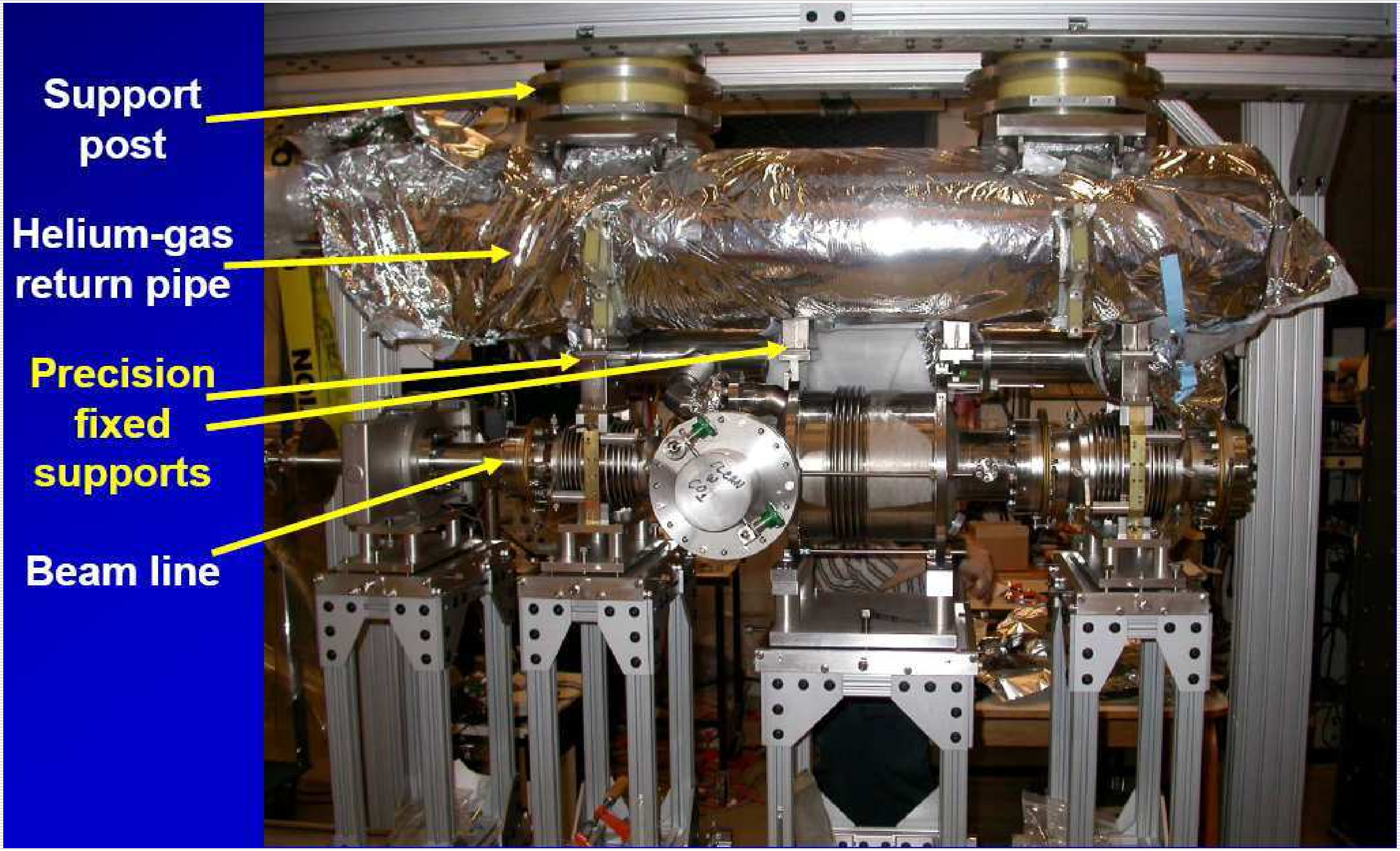
Changes compared to TTF cryomodule:

- **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_0**
- **No 5 K shield, only a 5 K cooling manifold**

Slide show of HTC assembly



HTC assembly (2)



HTC assembly (3)

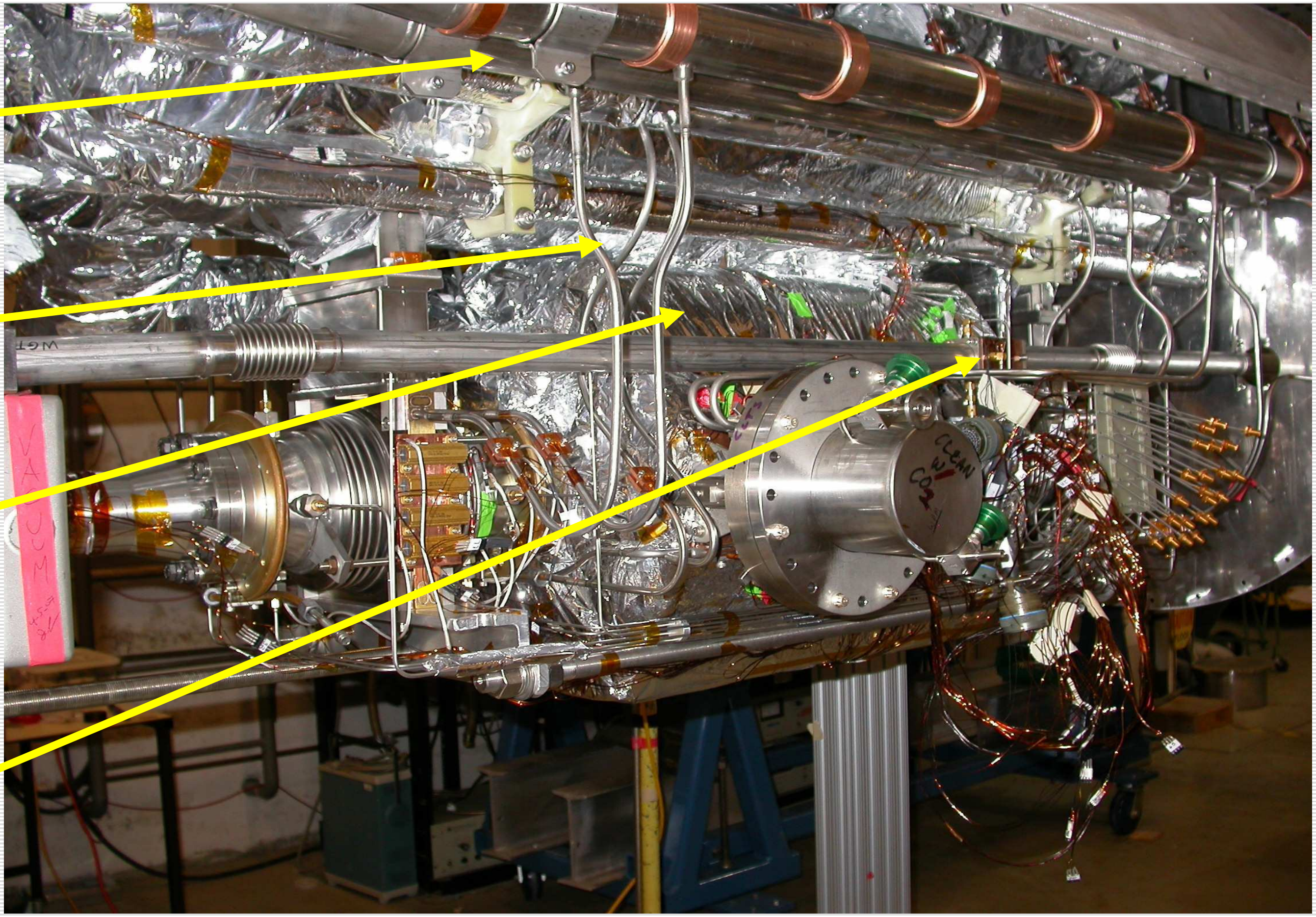
Add 5K and 80K Cryogenic Pipes, Wire Position Monitor, Magnetic Shield II, Cables, …

5K and 80K supply / return pipes

¼" cryogen distribution tubes

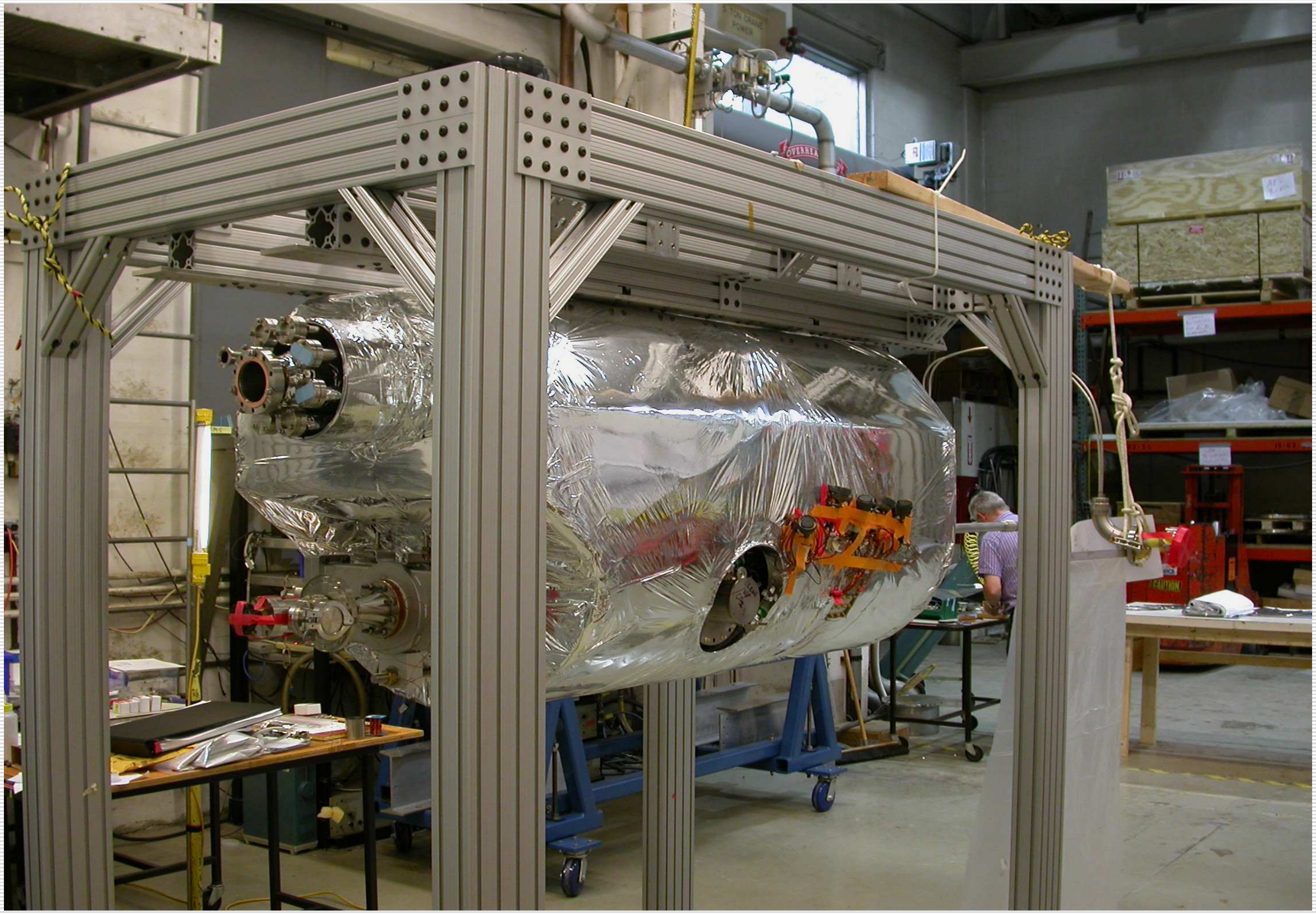
Second magnetic shield around cavity

Wire position monitor block mounted to cavity



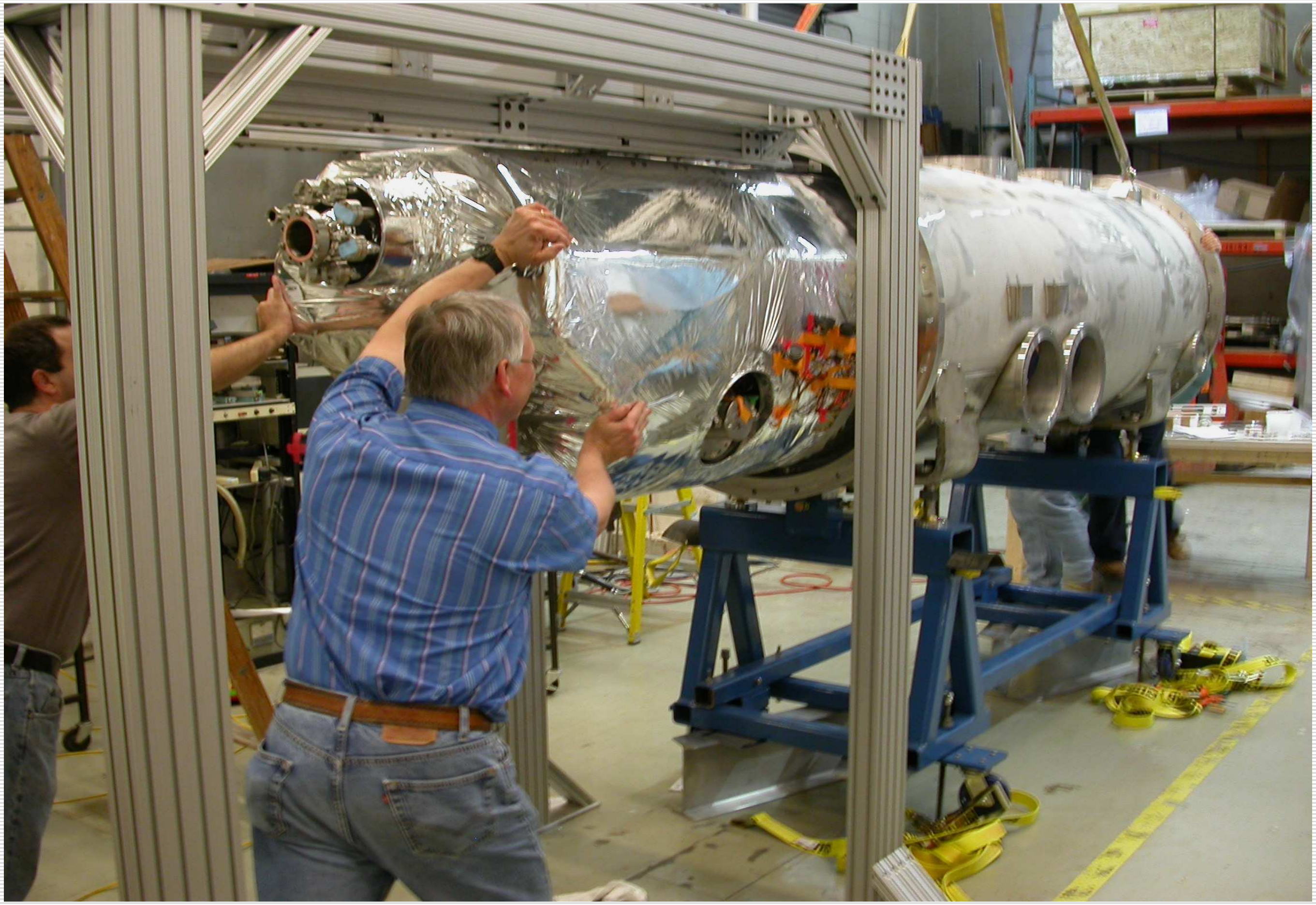
HTC assembly (4)

80 K Shield, magnetic shield, MLI

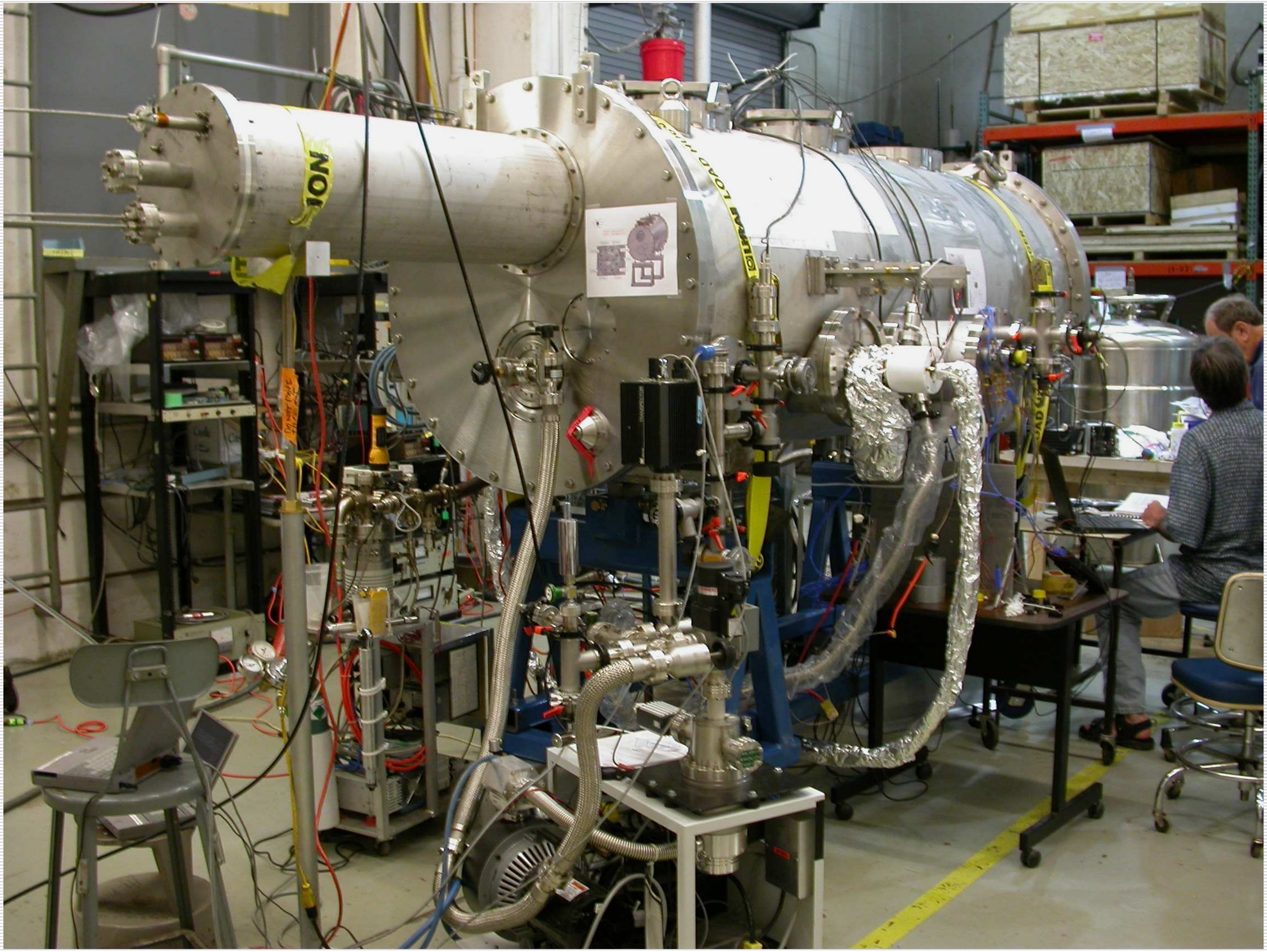


HTC assembly (5)

Slide Cold-Mass into Vacuum Vessel



HTC assembly completed



Recommended reading

- **Introductory textbook on superconductivity**

  W. Buckel and R. Kleiner, *Superconductivity: Fundamentals and Applications*, Wiley-VCH, 2004.

- **Textbooks on RF superconductivity**

  H. Padamsee, J. Knobloch and T. Hays, *RF Superconductivity for Accelerators*, Wiley-VCH, 2008.

  H. Padamsee, *RF Superconductivity: Science, Technology and Applications*, Wiley-VCH, 2008 (in print).

- **Tutorials from *International Workshops on RF Superconductivity*:**

  SRF2003: http://srf2003.desy.de/fap/

  SRF2005: http://www.lns.cornell.edu/public/SRF2005/program.html

  SRF2007: http://www.pku.edu.cn/academic/srf2007/program.html

- **Websites:**

  Superconducting RF Cavities: A Primer by J. Graber from http://w4.lns.cornell.edu/public/CESR/SRF/BasicSRF/SRFBas1.html

  Superconducting Radio Frequency from Wikipedia http://en.wikipedia.org/wiki/Superconducting_RF

- **Various *US Particle Accelerator Schools, CERN Accelerator Schools*, etc.**