S. Belomestnykh

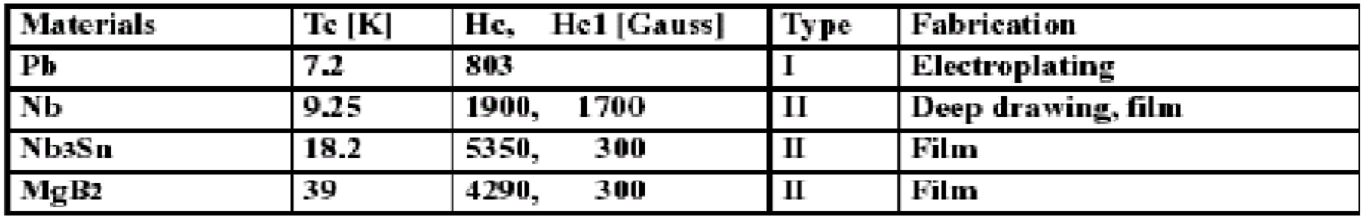
Superconducting RF for storage rings, ERLs, and linac-based FELs:

- **Lecture 13** *Cavity fabrication techniques, preparation & testing*

Niobium

- Niobium is the elemental superconductor with the highest critical temperature and the highest critical field
- Formability like OFHC copper
- Readily available in different grades of purity (RRR > 250)
- Can be further purified by UHV heat treatment or solid state gettering
- High affinity to interstitial impurities like H, C, N,O (in air T < 150 C)
- Joining by electron beam welding
- Metallurgy not so easy
- Hydrogen can readily be absorbed and can lead to Q-degradation in cavities
- High Purity Niobium (RRR>250) is made by multiple electron beam melting steps under good vacuum, resulting in elimination of volatile impurities
- There are several companies, which can produce RRR niobium in larger quantities:

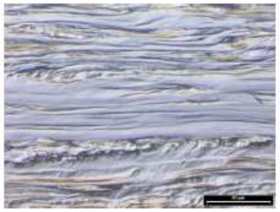
  Wah Chang (USA), Cabot (USA), W.C.Heraeus (Germany), Tokyo Denkai(Japan), Ningxia (China), CBMM (Brasil)

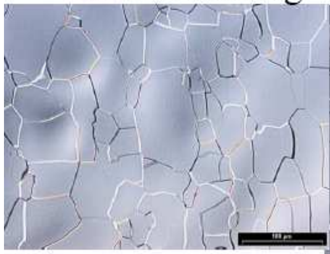


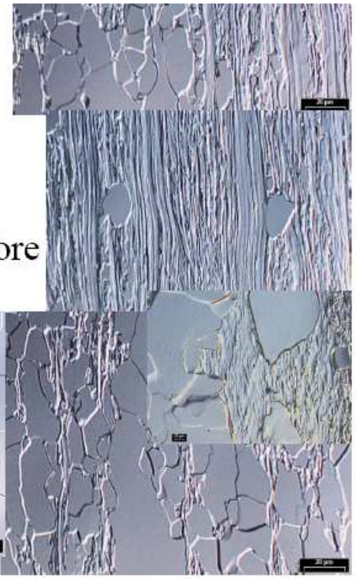
Materials	Tc [K]	Hc, Hc1 [Gauss]	Type	Fabrication
Pb	7.2	803	I	Electroplating
Nb	9.25	1900, 1700	II	Deep drawing, film
Nb_3Sn	18.2	5350, 300	II	Film
MgB_2	39	4290, 300	II	Film

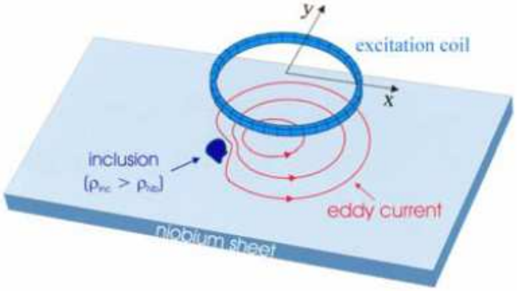
Material inspection

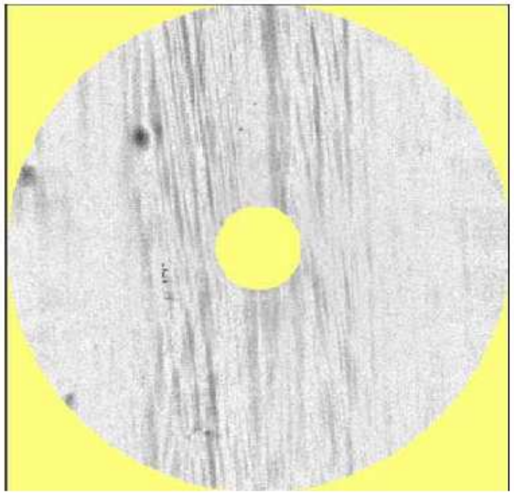
- **The material must be fully recrystallized, other wise mechanical properties are affected. Sheet metal forming is sensitive to mechanical properties. In particular, a uniform grain size is essential**
- **Nb sheets are inspected upon receiving, visually and using eddy-current or SQUID scanning (more 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.**


Rolled Nb sheet before final annealing


Recrystallized niobium sheet

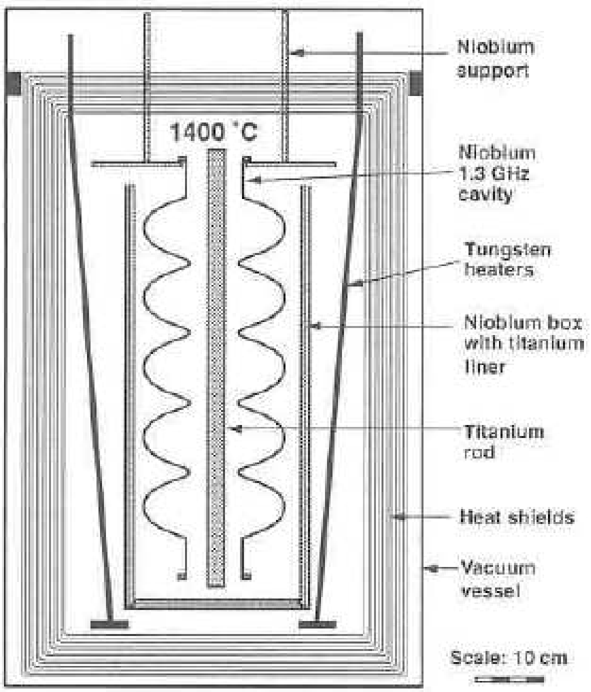

Examples of bad recrystallization

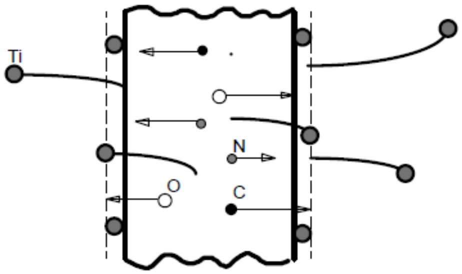


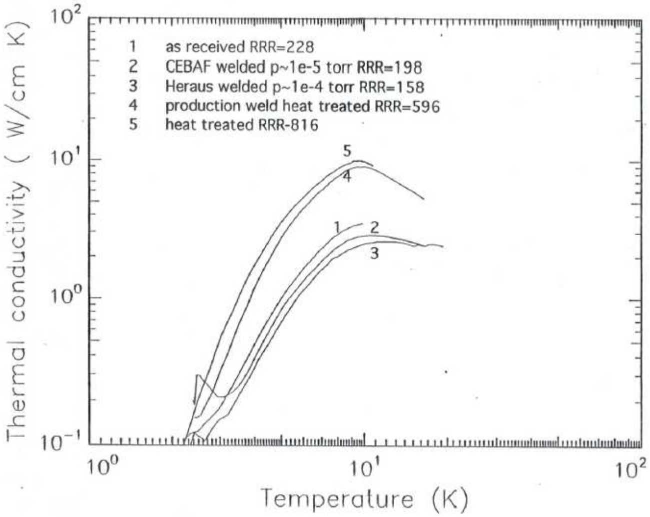


Post-purification

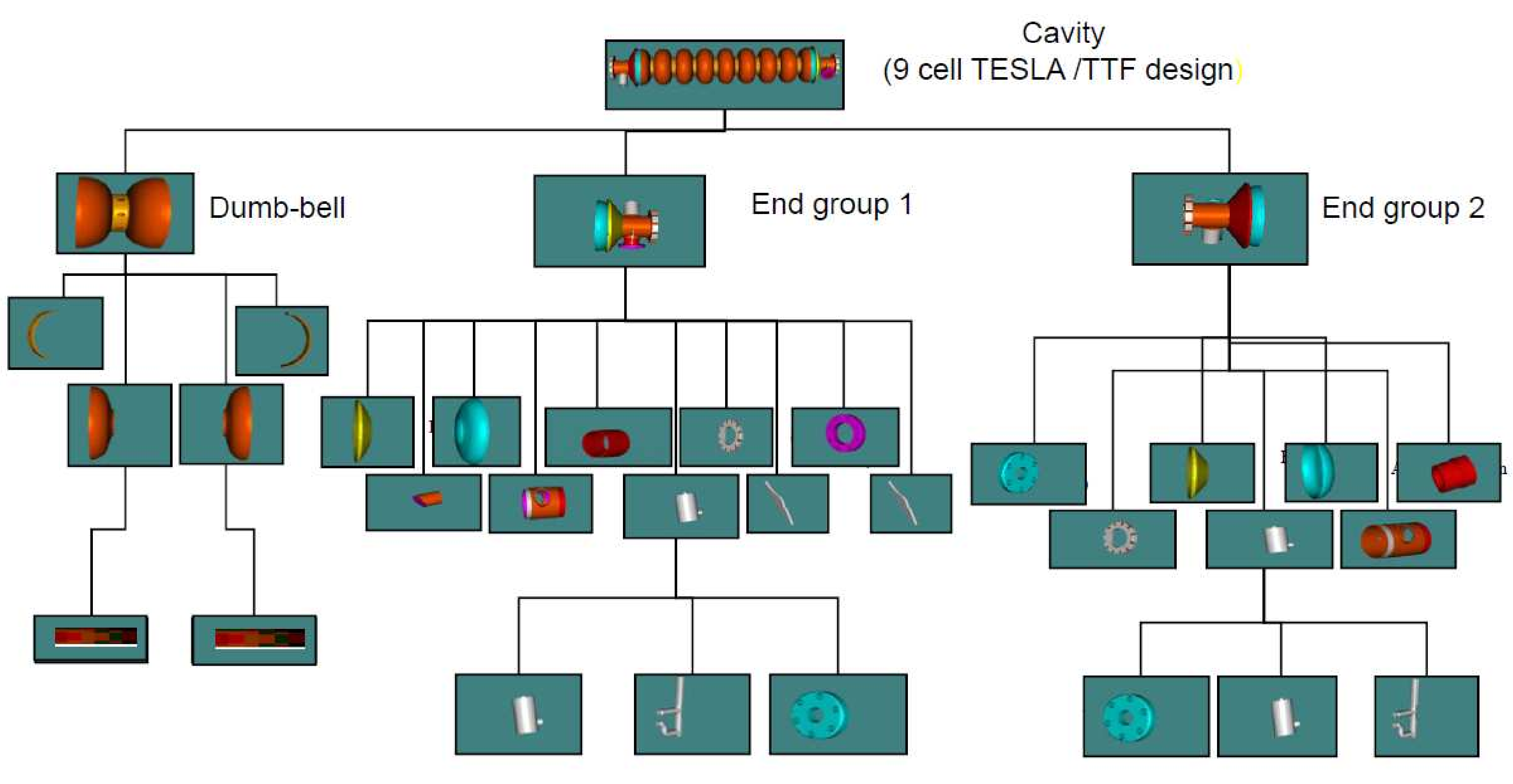
- **It is possible to post-purify niobium cavities in presence of Ti as a solid state getter material in a high temperature furnace.**
- **During the purification process the interstitial impurities (O,N,C) diffuse to the surface and react with the evaporated Ti atoms; Ti has higher affinity to these impurities than Nb.**
- **Ti layer then has to be etched away.**







Overview of cavity fabrication



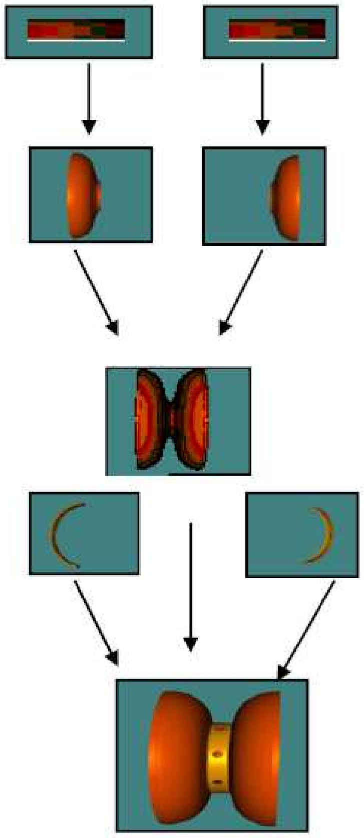
Cavity
(9 cell TESLA /TTF design)

Dumb-bell

End group 1

End group 2

Dumb-bell fabrication steps



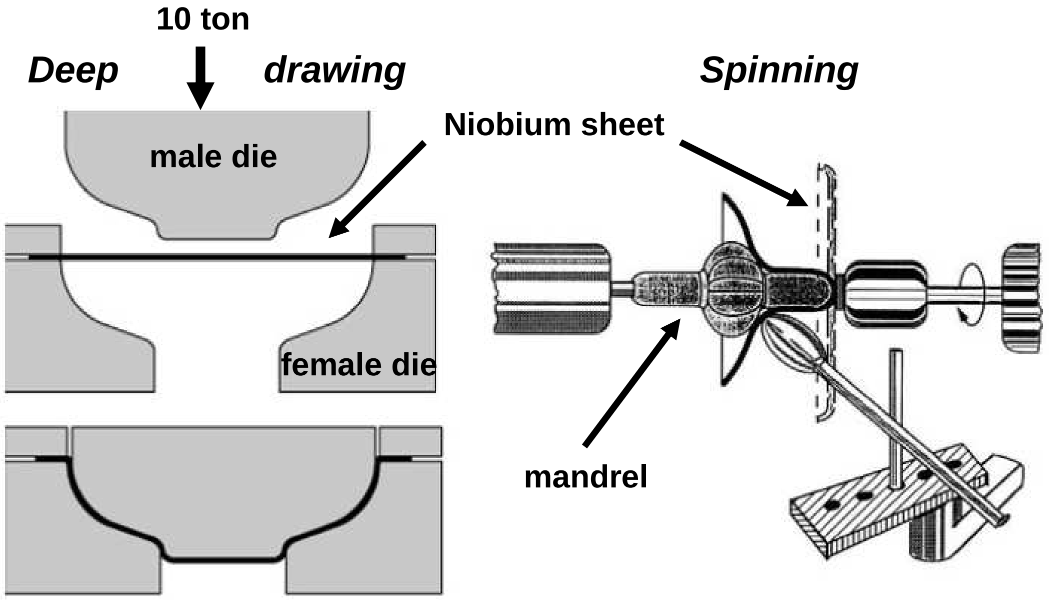
Dumb- bell

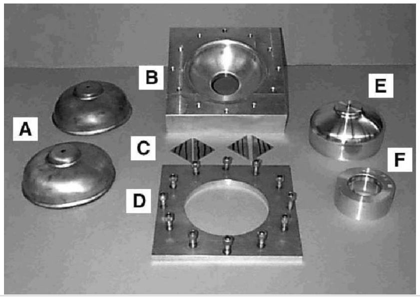
1. Mechanical measurement
2. Cleaning (by ultra sonic [us] cleaning +rinsing)
3. Trimming of iris region and reshaping of cups if needed
4. Cleaning
5. Rf measurement of cups
6. Buffered chemical polishing + Rinsing (for welding of Iris)
7. Welding of Iris
8. Welding of stiffening rings
9. Mechanical measurement of dumb-bells
10. Reshaping of dumb bell if needed
11. Cleaning
12. Rf measurement of dumb-bell
13. Trimming of dumb-bells (Equator regions)
14. Cleaning
15. Intermediate chemical etching (BCP /20- 40 μm)+ Rinsing
16. Visual Inspection of the inner surface of the dumb-bell local grinding if needed + (second chemical treatment + inspection)

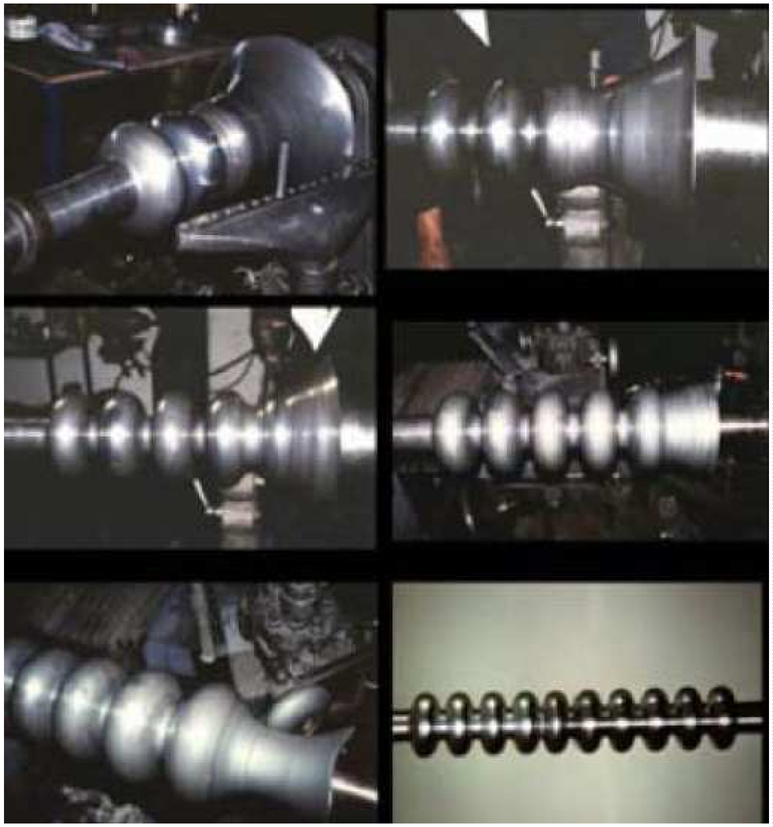
Dumb-bell ready for cavity

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.







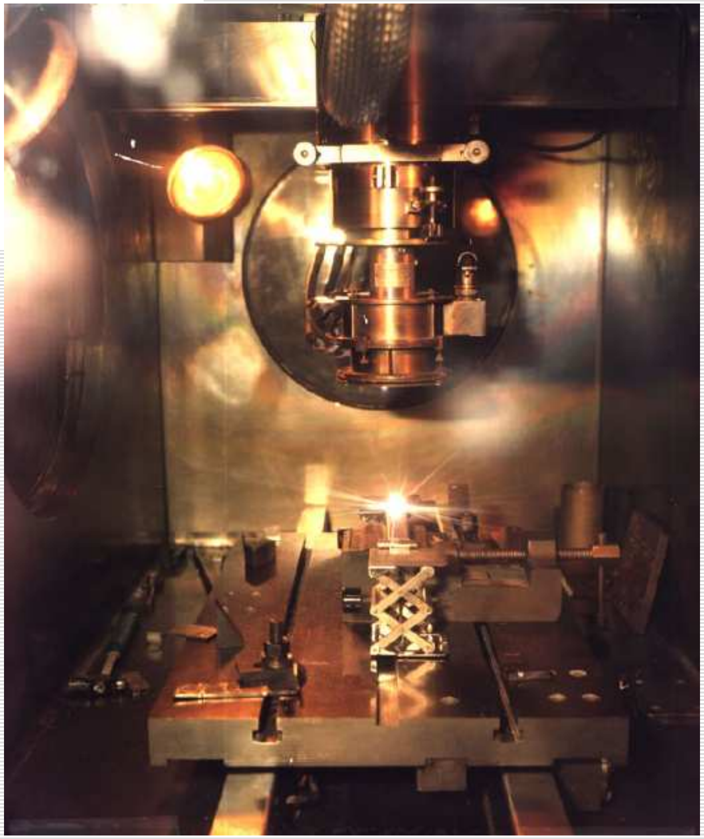
Cavity fabrication techniques (2)

After forming and trim machining, the parts are electron beam welded together.

Welding must be under vacuum, better than 10^{-5} Torr. Things to check:

- **Broad welding seam**
- **Operate with defocused beam**
- **Smooth underbead**
- **Overlap at end of welding to avoid accumulation of impurities**
- **Wait to cool down before opening chamber**

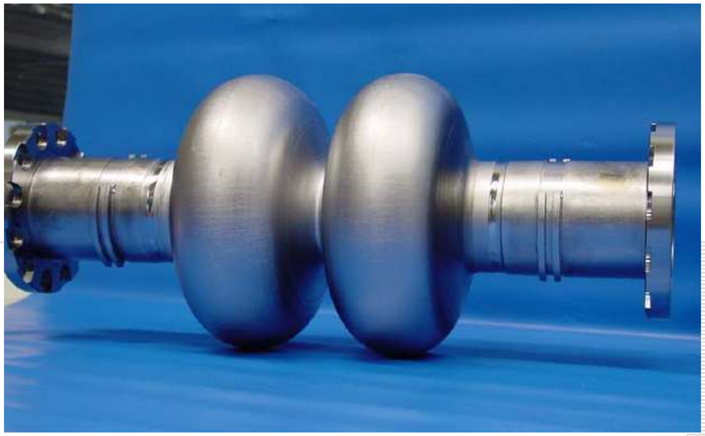
Some parts, e.g. flanges, can be brazed to cavity ports.

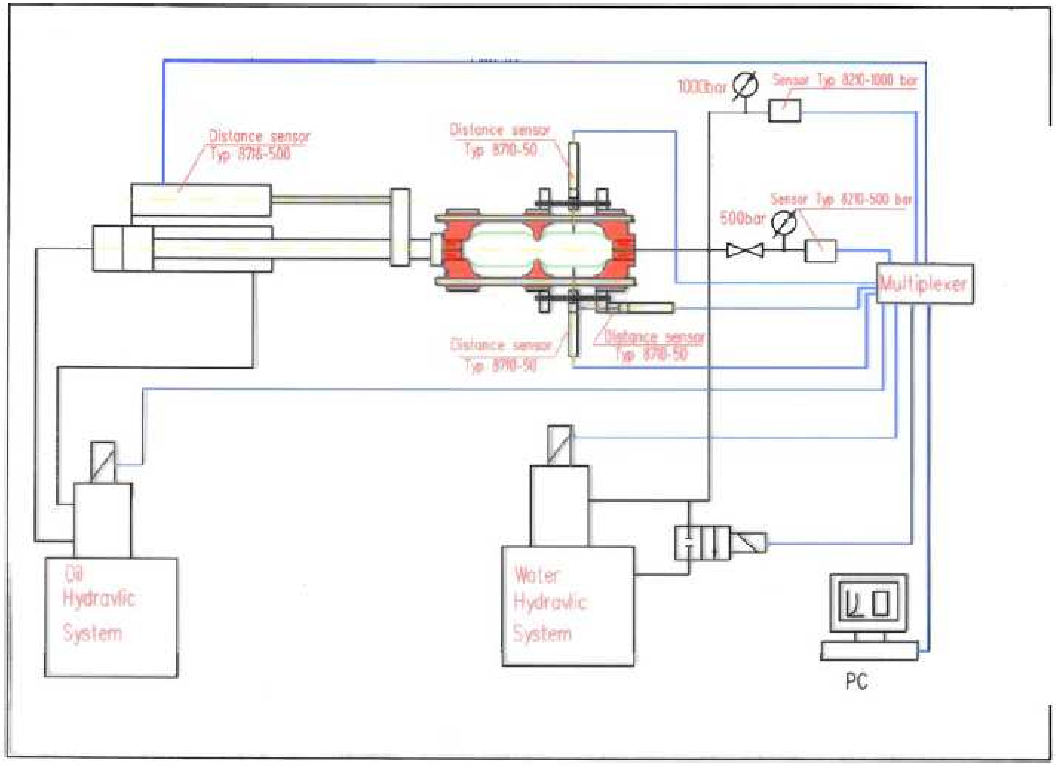


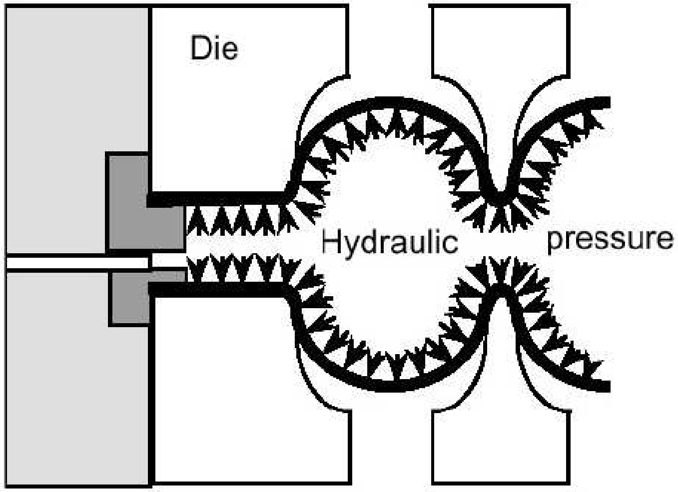
Alternative fabrication techniques

Besides the “standard” cavity fabrication of producing niobium half cells and electron beam weld them into multi-cell cavities there exist alternative methods:

- Spinning of multi-cell cavities
- Hydroforming
- Nb thin film coating of copper cavities







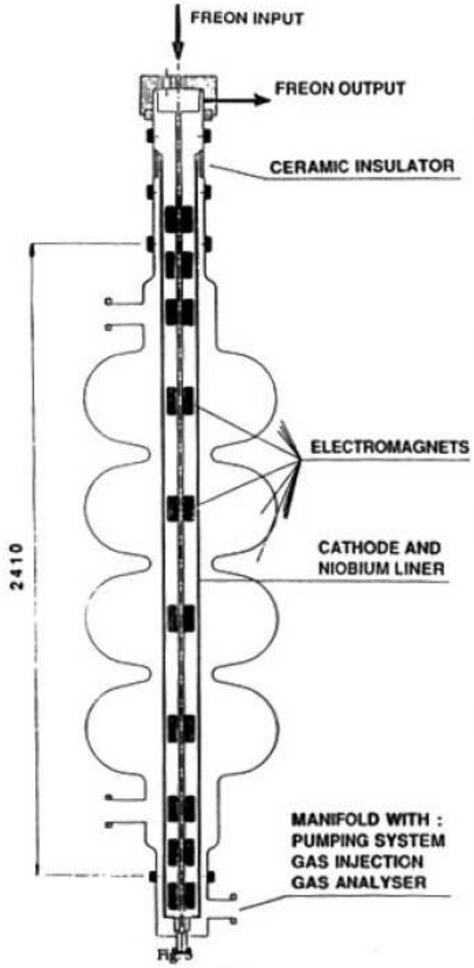
Nb sputtering (2)

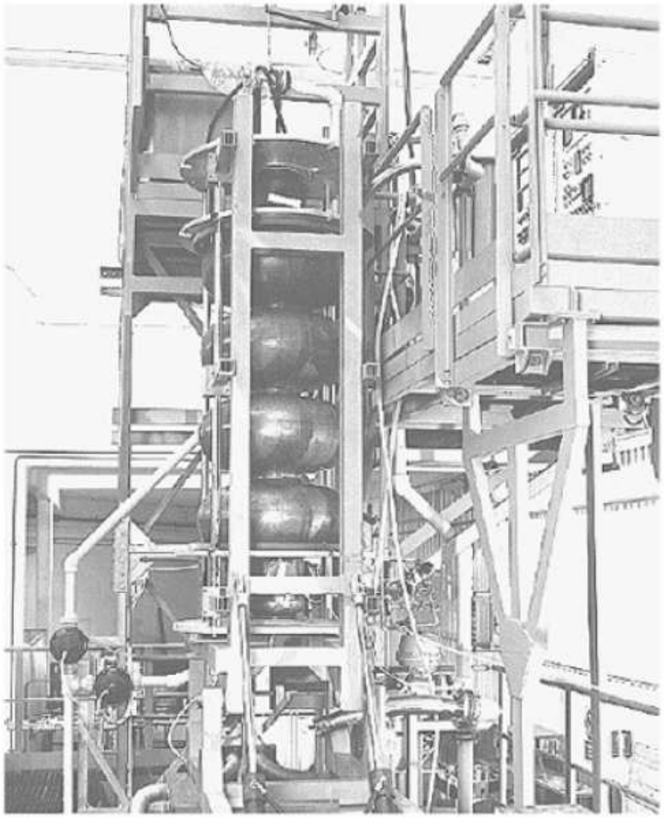
Niobium Film Coated Cavities

Developed in CERN for LEP II Superconducting RF cavities

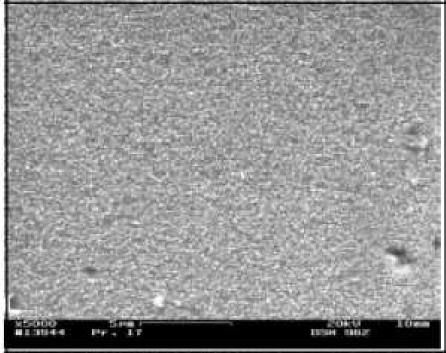
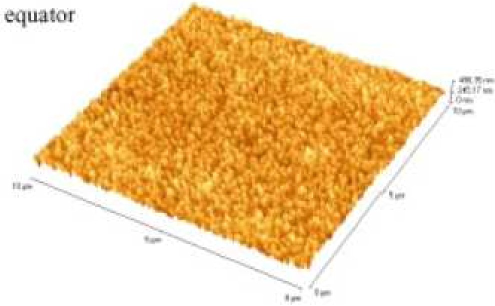
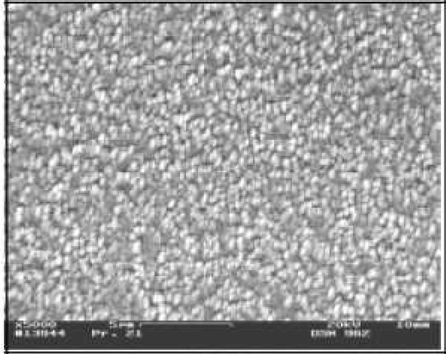
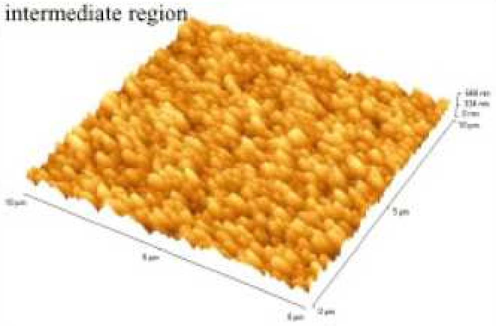
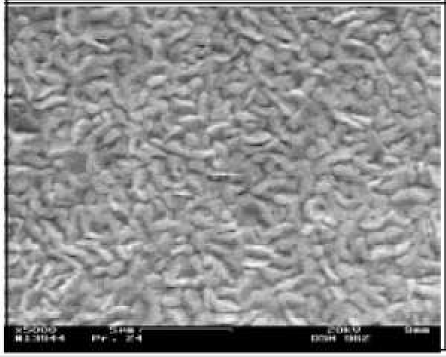
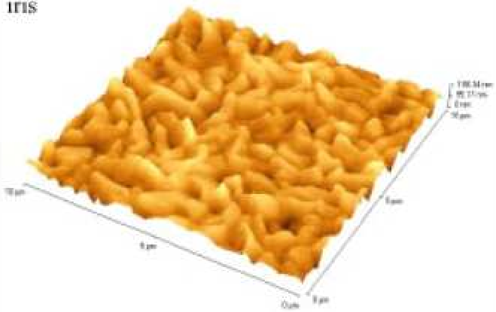
f=350 MHz → big cavity (diameter :780mm) → Reduce Nb material for cost down

Copper half cell for LEP-II SC cavity

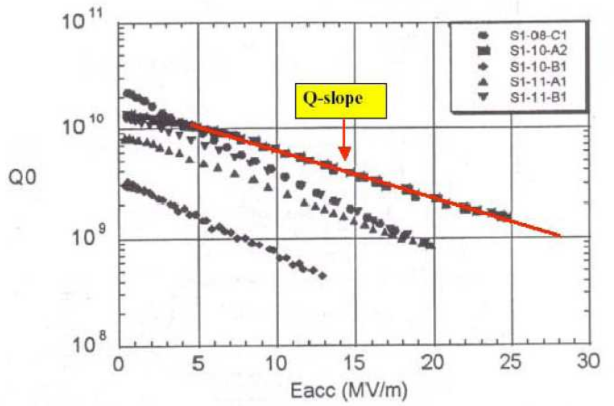




Surface structure of Nb/Cu

SEM images	AFM images
	equator 
	intermediate region 
	iris 

Niobium Film Coated Cavities - Application for 1300 MHz cavities -



Q-slope is a problem for the high gradient application.

Frequency tuning of sub-components

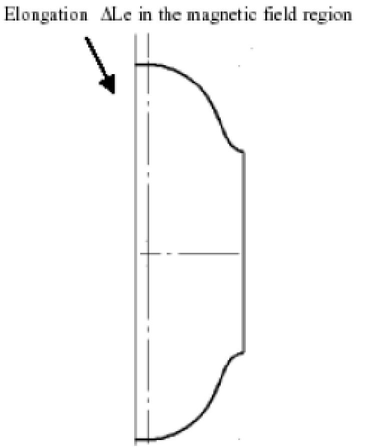
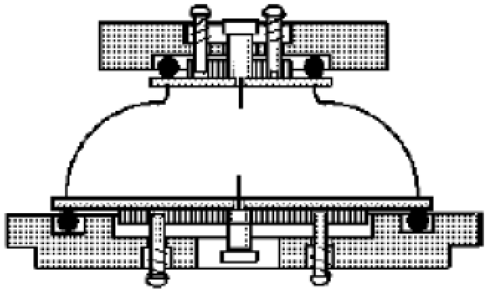


Figure 3: Trimming of the equator to adjust the elongation at the equator

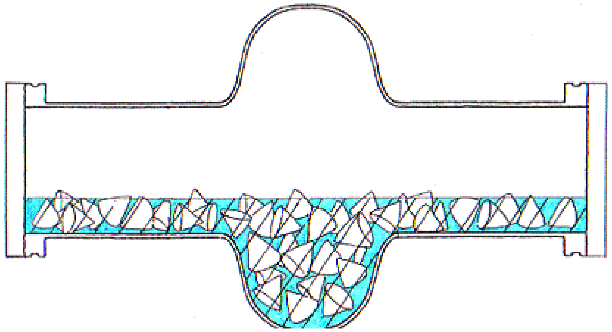


Half-cell

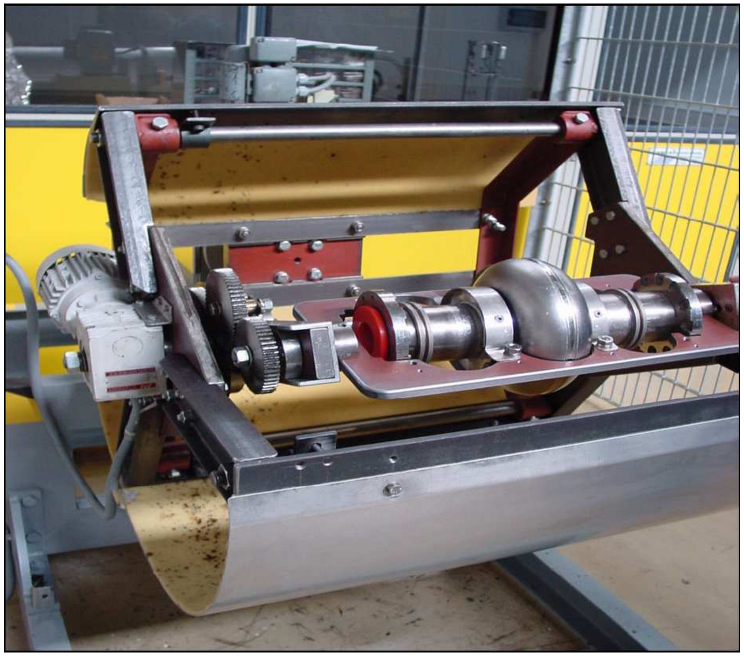
Dumb-bell

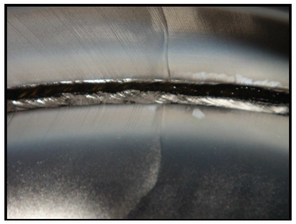
Cavity surface preparation

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





Weld region before CBP

Weld region after CBP

Cavity inspection at DESY

Tuning field flatness & frequency

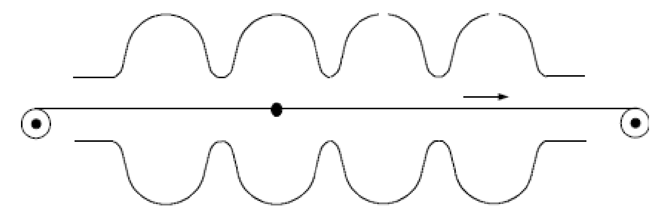
- **Cavity frequency and field flatness then checked and tuned. Usually the goal is to achieve 98% field flatness.**
- **Set-up for field profile measurements: a metallic needle is perturbing the RF fields while it is pulled through the cavity along its axis; the stored energy in each cell is recorded.**

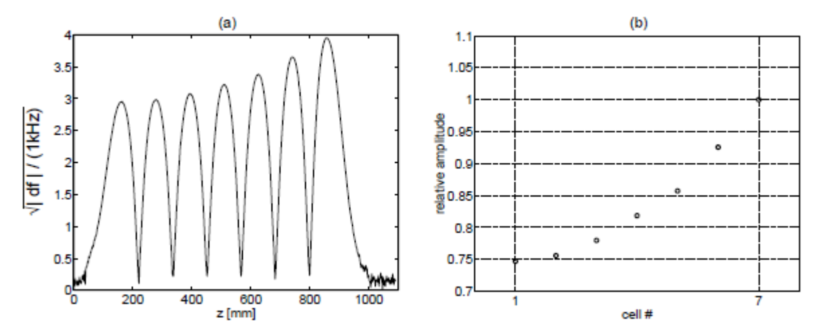
Due to the volume occupied by the metal bead the resonance frequency of a eigenmode j is shifted according to [Sla 50] by

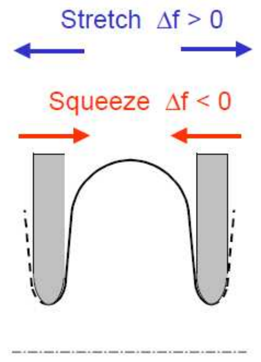
$$\left(\frac{f^{(j)\prime}}{f^{(j)}}\right)^2 \approx 1 + \frac{1}{U^{(j)}}\int_{\Delta V_{bead}}\left(\frac{\mu_0}{2}\left|\vec{H}^{(j)}\right|^2 - \frac{\varepsilon_0}{2}\left|\vec{E}^{(j)}\right|^2\right)dv \quad . \tag{6.2}$$

Here $\vec{E}^{(j)}$ and $\vec{H}^{(j)}$ are the unperturbated fields, $U^{(j)}$ is the stored energy and ΔV_{bead} is the volume occupied by the metal bead. Since the TM_{010} eigenmodes have a vanishing magnetic field on the cavity axis, we can use the following approximation for a small metal bead placed on the cavity axis at $z = z_{bead}$

$$\frac{\delta f^{(j)}_{bead}}{f^{(j)}} \approx -\frac{\varepsilon_0 \Delta V_{bead}}{4}\,\frac{|\vec{E}^{(j)}(z_{bead})|^2}{U^{(j)}} = -\frac{\Delta V_{bead}}{2}|\vec{e}^{(j)}(z_{bead})|^2 \quad . \tag{6.3}$$





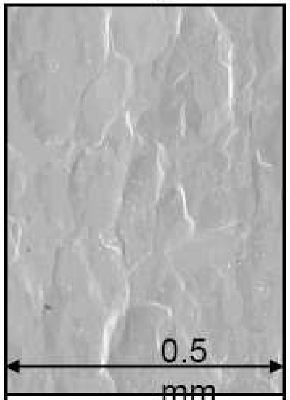


Stretch Δf > 0

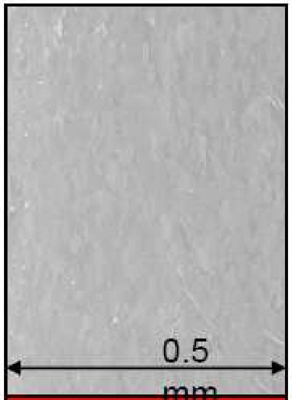
Squeeze Δf < 0

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.**



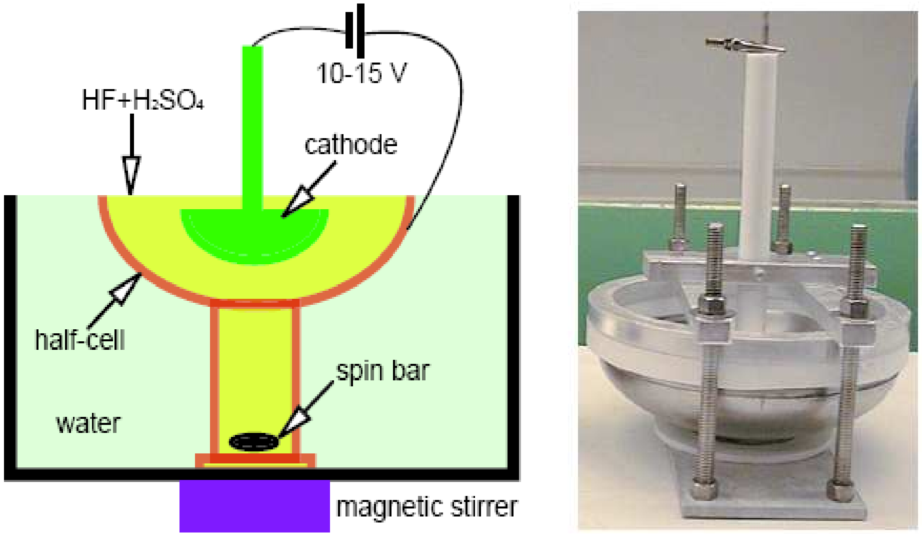
BCP Surface
(1μm
roughness)



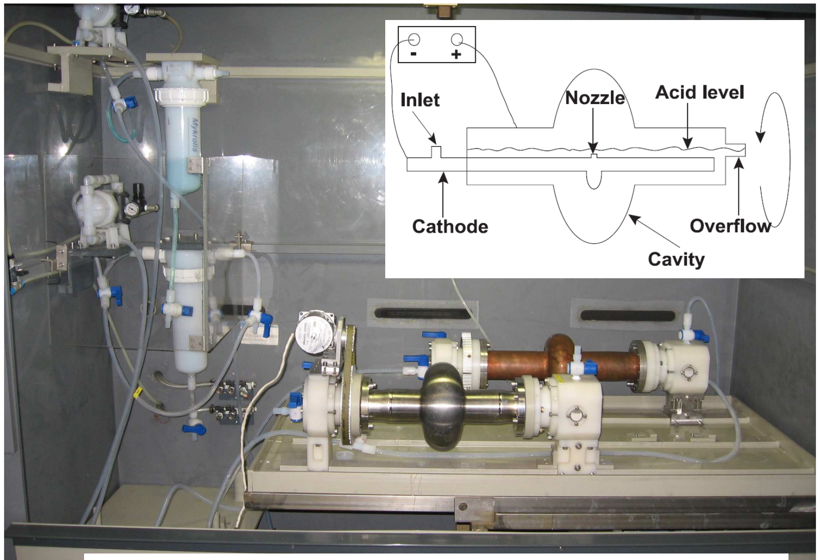
EP Surface
(0.1μm
roughness)

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

Contamination prevention

- Micro-particle contamination is the leading cause of field emission. This stresses the importance of cleanliness in all final treatment and assembly procedures.

Sources of contamination:

- Processing chemicals (filtered!)
- High purity water (>18 MΩcm, <0.02 µm filter)
- Clean room environment (entrance, class 10)
- Particulates on equipment, tooling, hardware, clothing, gloves, …

Contamination control:

- Stringent control of processes and procedures
- In-line monitoring of particulate levels in air and liquids
- Scheduled maintenance
- "Blow-off" with filtered N2 , monitored by particle counter
- Use of appropriate hardware (e.g. bolts..)
- Clever designs (e.g. gaskets, clamp rings, fixtures…)
- Consistent use of "best practices" through whole assembly process

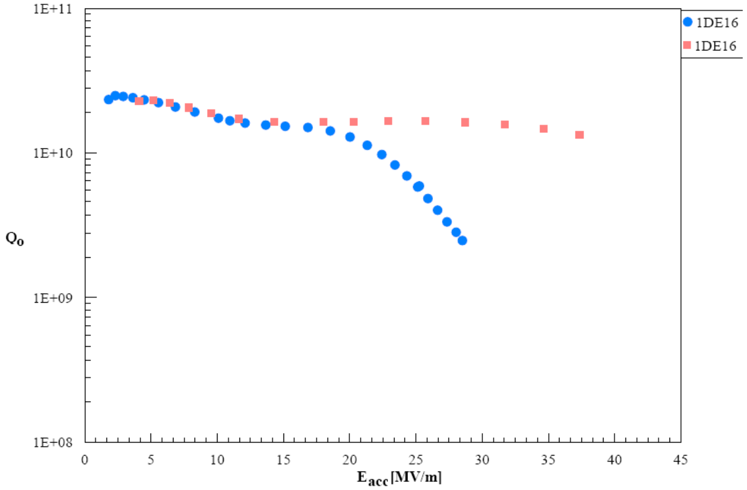
Clean cavity preparation

- 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.

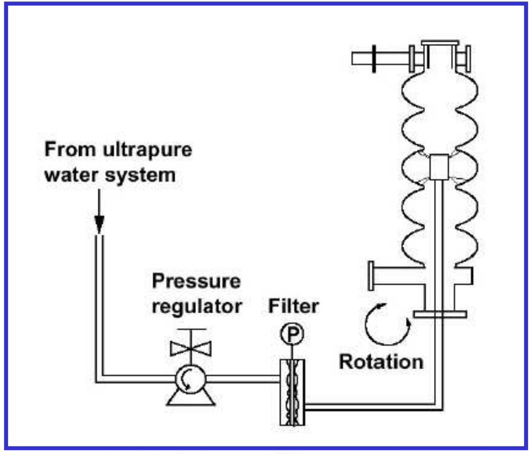
HPR

- 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.



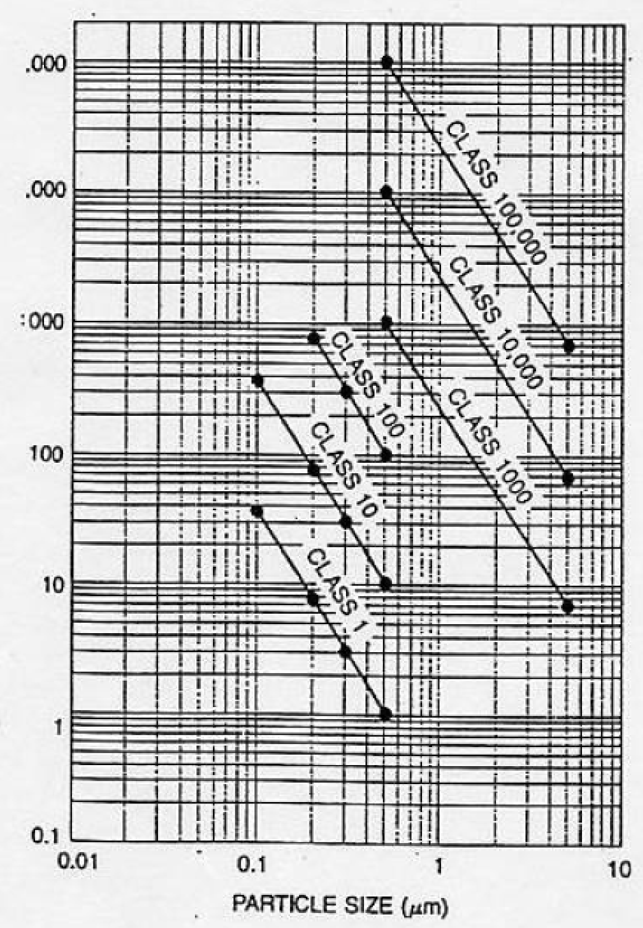
HPR system at Cornell.



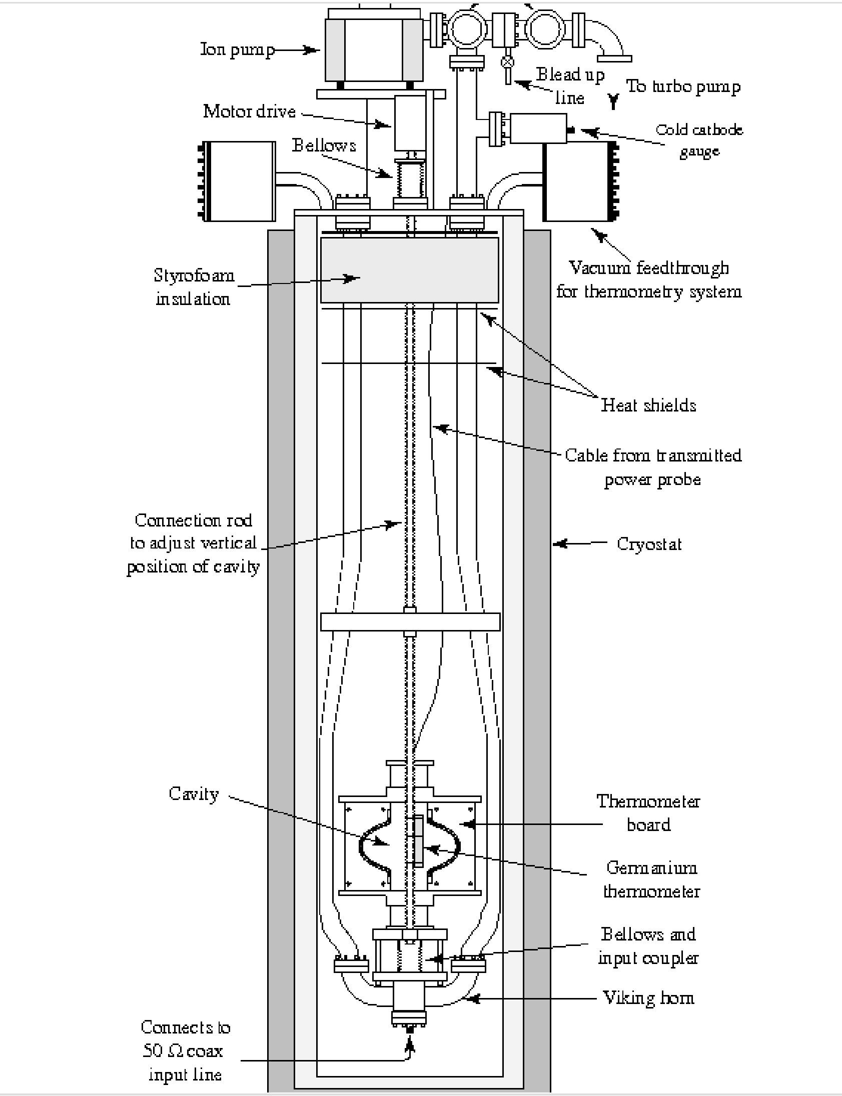
High pressure water jet stream.

Clean room cavity assembly

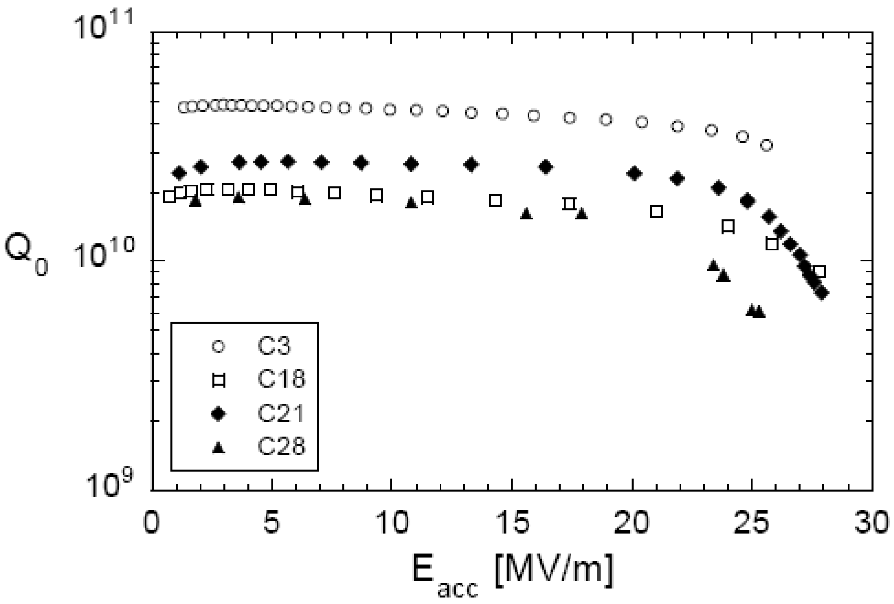
- **From that point the cavity surface must be exposed only to dust-free, clean air in a class 100 (fewer than 100 particles of size larger than 0.5 μm in a volume of 1 cu. ft., equivalent to ISO class 5) or better clean room.**



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.**



What have we learned?

- Nb is the standard material for SRF cavities today.
- Material quality (impurities, mechanical damage) plays important role.
- Nb with RRR > 250 is typically used.
- Fabrication processes are well developed.
- Alternative fabrication techniques and materials are actively pursued.
- Performance of SC cavities depends on the quality of a thin surface layer, hence it is very important to properly process cavities and carefully follow all preparation steps.

✪ We will discuss remaining challenges in our last lecture.