CAVITY FABRICATION

Jean Delayen

Thomas Jefferson National Accelerator Facility
Old Dominion University

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

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

Niobium

Quality/purity of niobium used for accelerator application is specified by the RRR ratio

$$RRR = R(300)/[R(10) + S\ dR_i/dC_i\ ]$$

dR_i/dC_i are the contributions by interstitial impurities such as H,C,N,O and Ta

H:	0.8×10^{-10} Wcm/at ppm
C:	4.3×10^{-10} Wcm/at ppm
N:	5.2×10^{-10}Wcm/at ppm
O:	4.5×10^{-10} Wcm/at ppm
Ta:	0.25×10^{-10} Wcm/at ppm

K.Schulze,Journal of Metals, 33 (1981), p. 33ff

Typical specifications for impurities (wt ppm)

H	< 2
C	< 10
N	< 10
O	< 10
Ta	< 500

RRR	> 250
Grain size	50 mm
Yield strength	> 50 Mpa
Tensile strength	> 100 Mpa
Elongation	> 30 %
VH	< 50

Thermal conductivity at 4.2K

$$\lambda(4.2K) \sim RRR/4$$

Niobium:Electron Beam Melting

- 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:

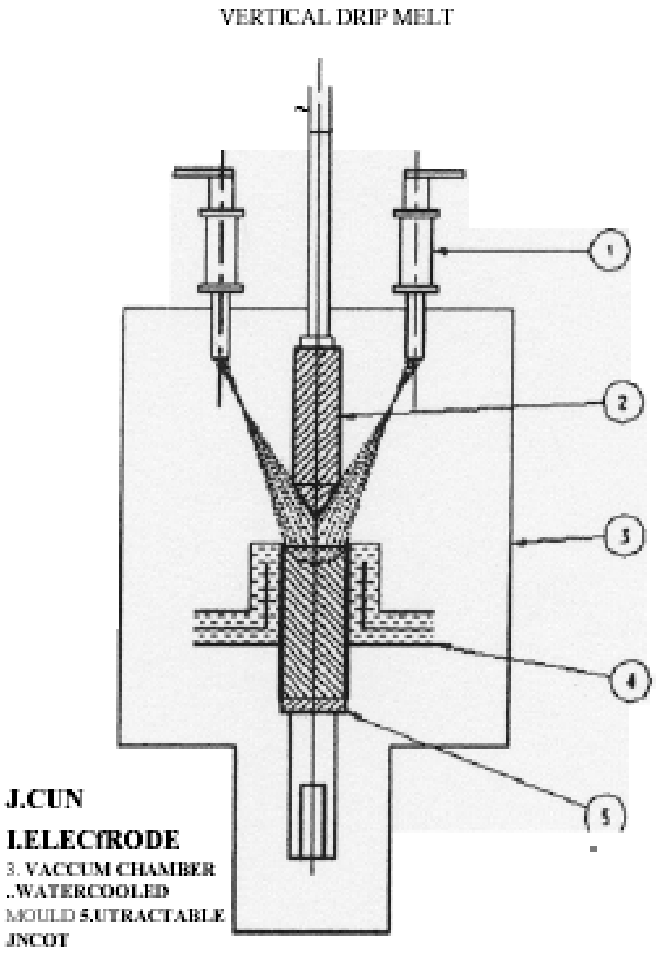
  Wah Chang (USA), Cabot (USA), W.C.Heraeus (Germany), Tokyo Denkai(Japan), Ningxia (China), CBMM (Brasil)

CBMM deposit in Araxa, Brasil

EBM Ingots at CBMM

Electron beam melting furnace in Tokyo Denkai

Electron Beam Melting



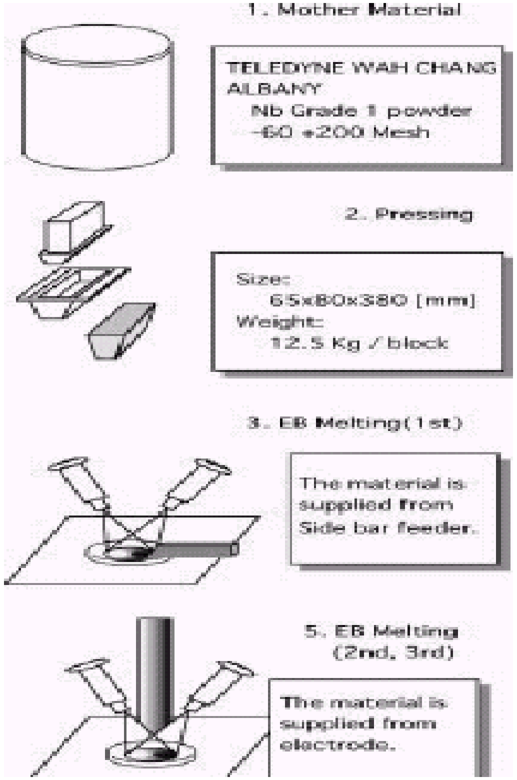
1 Gun
2 Electrode
3 Vacuum Chamber
4 Water Cooled Mold
5 Retractable Ingot

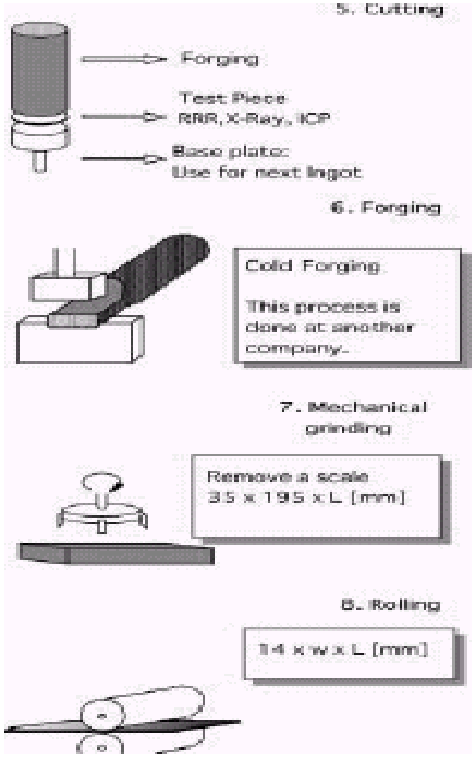
[from H.R.S. Moura, "Melting and Purification of Niobium" ,p. 147 in Proc. of Int. Symposium Niobium 2001]

Niobium

US-CERN-JAPAN-RUSSIA Accelerator School, Nov. 6-14 2002 Long Beach, California, USA

Industrial Niobium Production - Production Process (Tokyo Denkai Co. Ltd.) -





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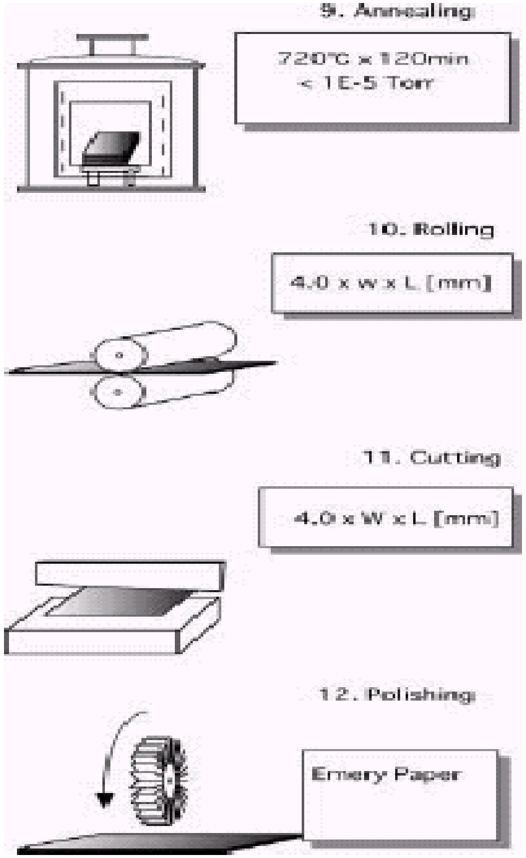
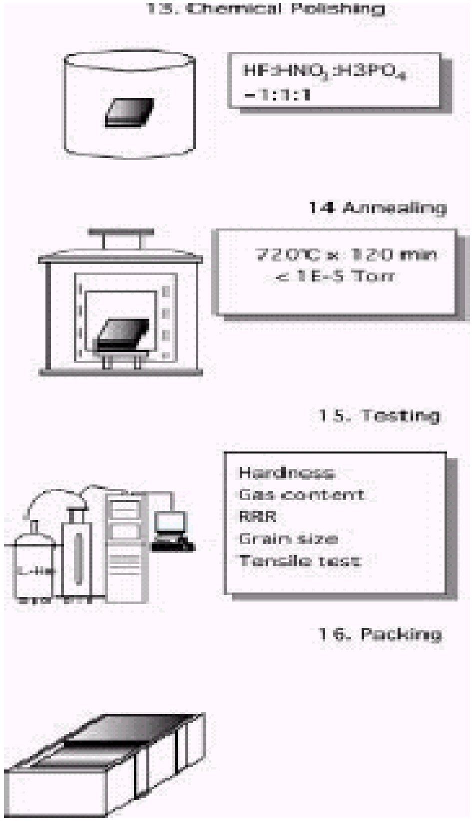
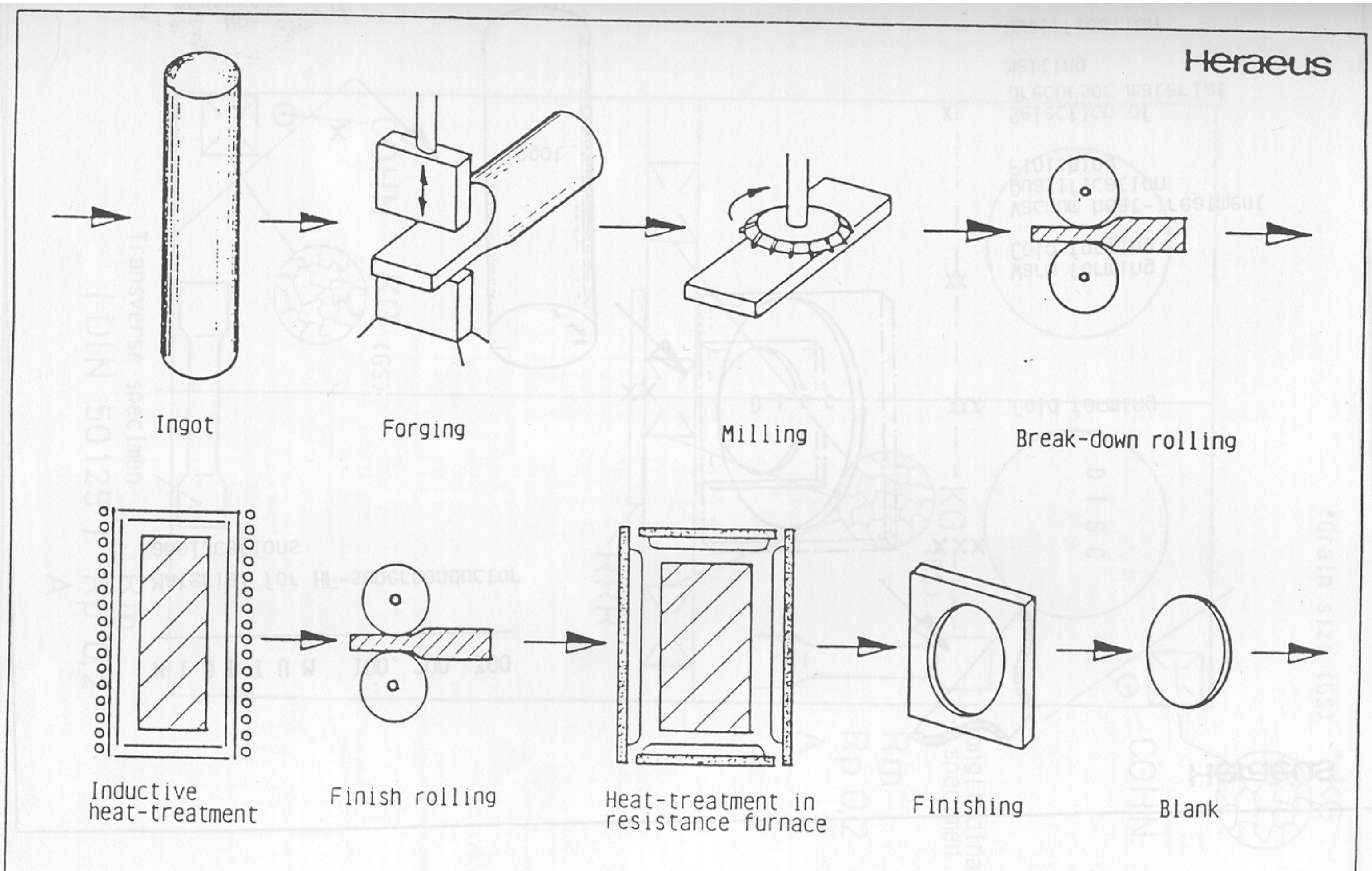




Niobium

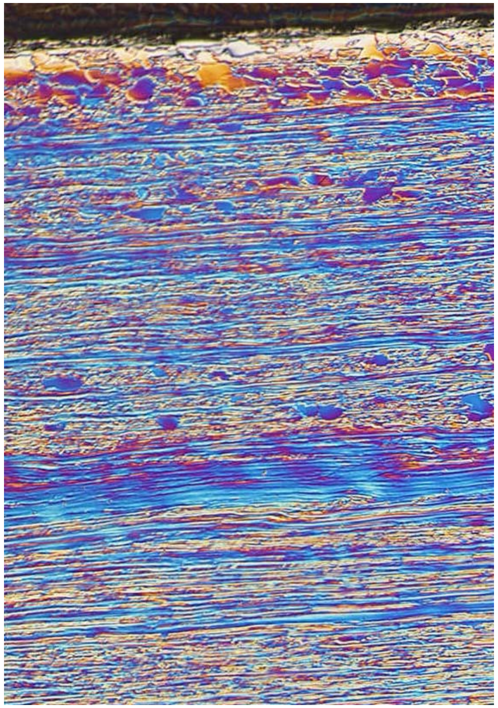


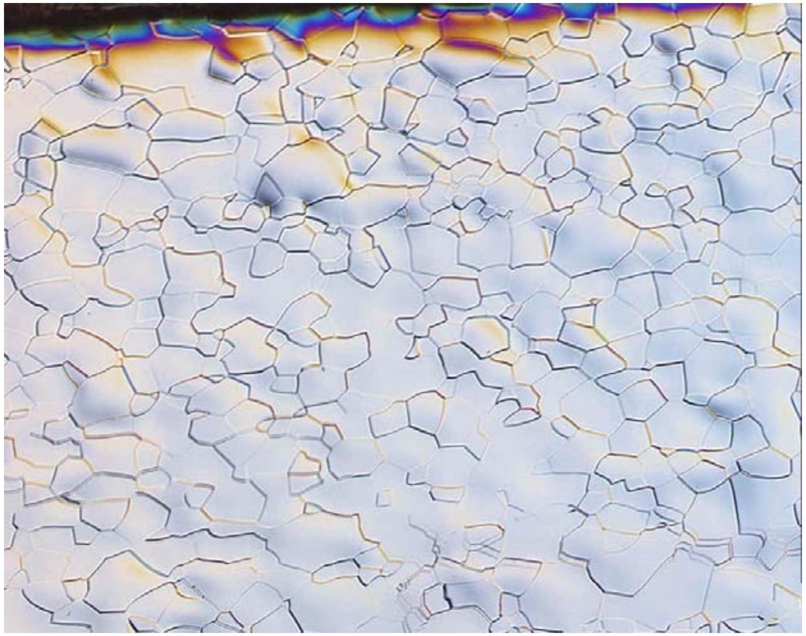
FLOW DIAGRAM SHOWING PROCESSING TO Nb SEMI-PRODUCTS

Niobium

Insufficient recrystallization, formability and mechanical properties are affected

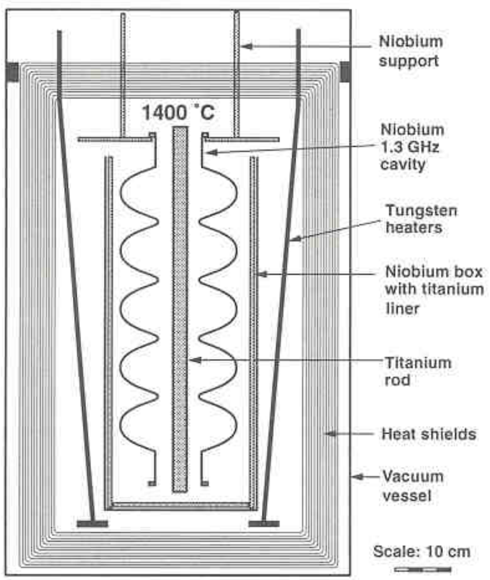
Fully recrystallized material after appropriate heat treatment (after rolling operation)





Niobium

Post –Purification of niobium in presence of Ti as a solid state getter material



•During the purification process the interstitial impurities (O,N,C) diffuse to the surface and react with the evaporated Ti atoms; Ti has a higher affinity to these impurities than Nb

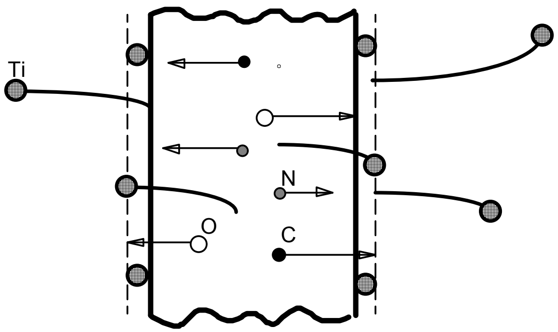
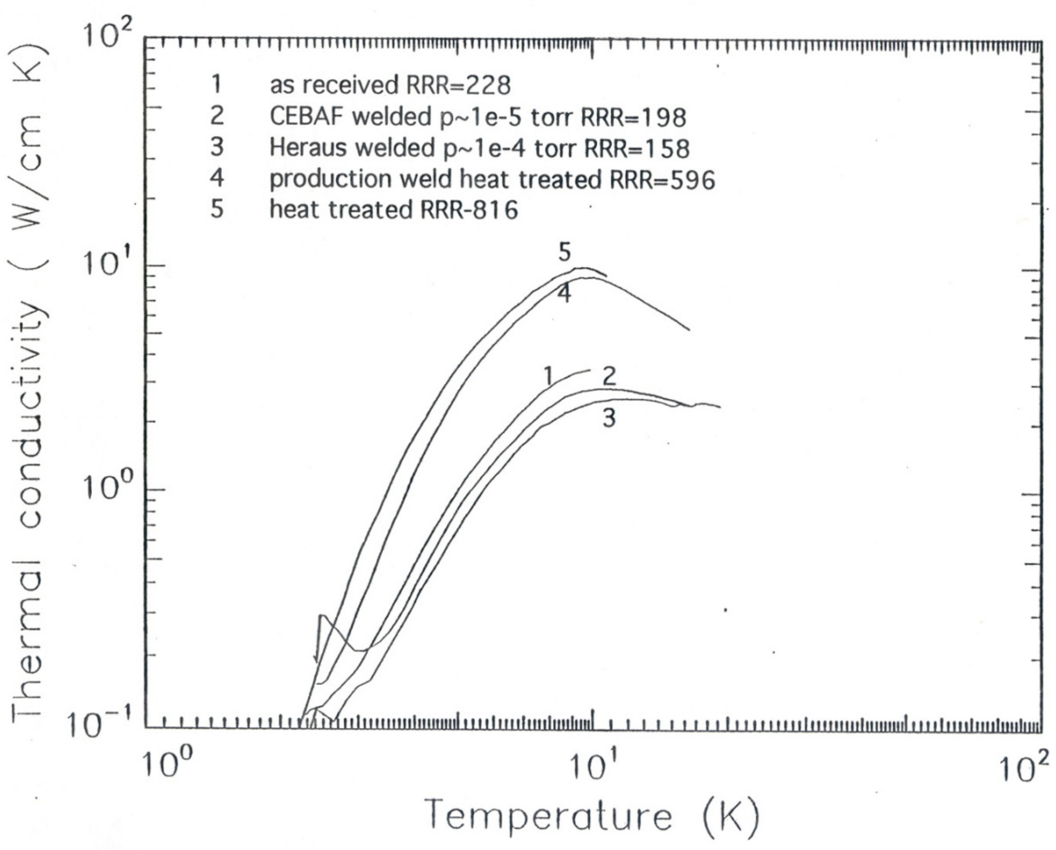


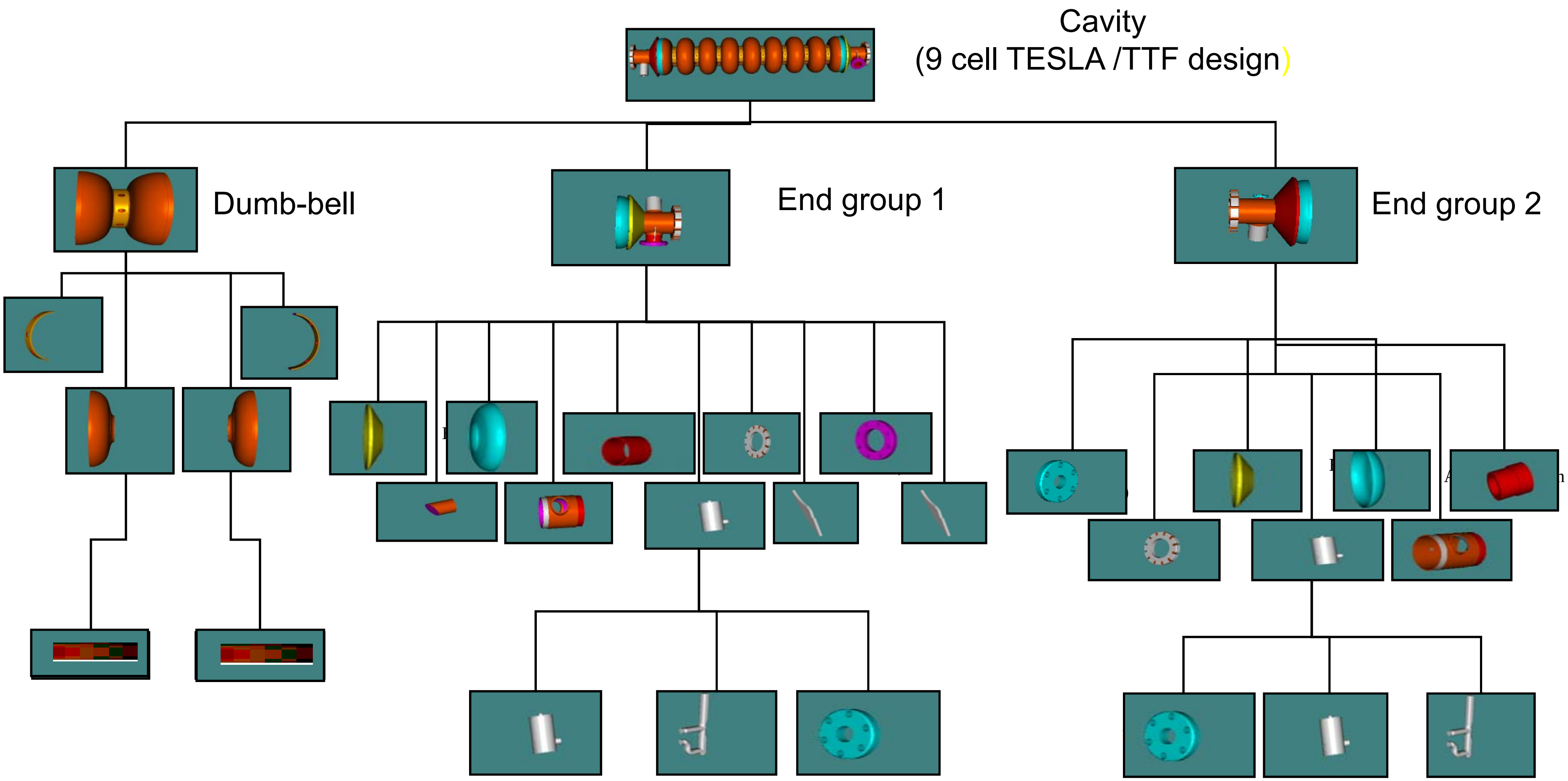
Fig. 1 Scheme of the Nb refining by high temperature gettering

Niobium

- Post-Purification Treatment (G.R.Myneni, Jlab)



Overview of Cavity Fabrication (TESLA)



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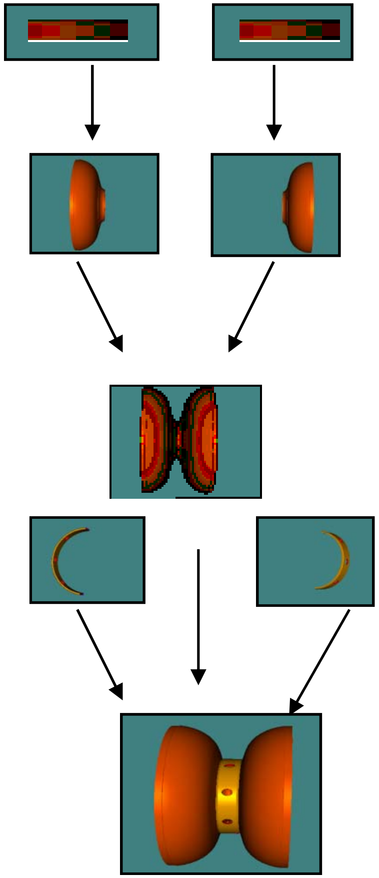
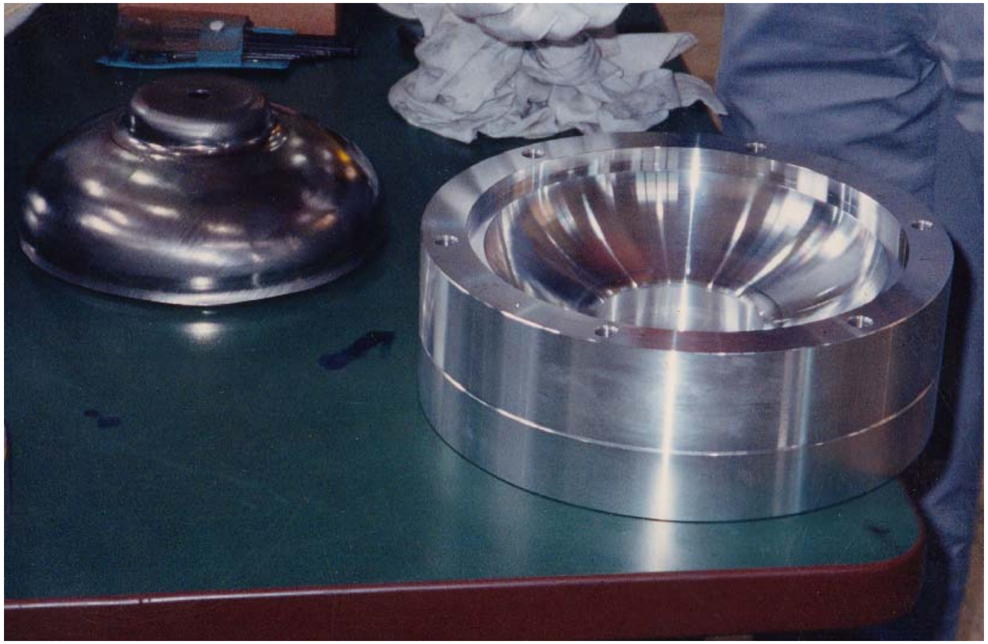


Dumb- bell

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

Overview of Cavity Fabrication (TESLA)



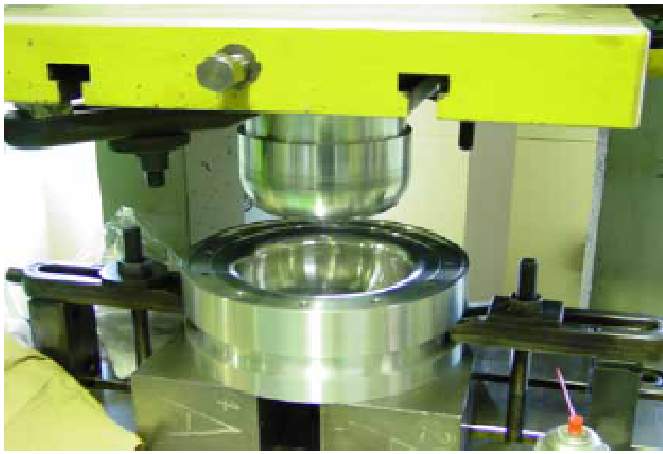
Overview of Cavity Fabrication (TESLA)

Overview of Cavity Fabrication (TESLA)

Overview of Cavity Fabrication (KEK)

Fabrication of ICHIRO Cavity in KEK(1)

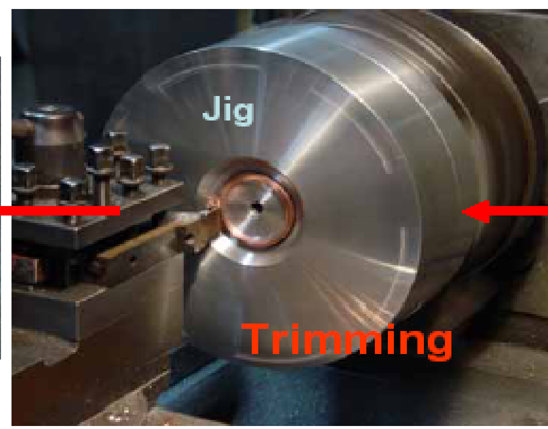
Pressing Nb plate



56 half-cells were pressed in a few hours

21 February 2005

After pressing

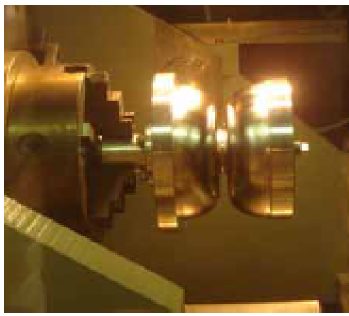


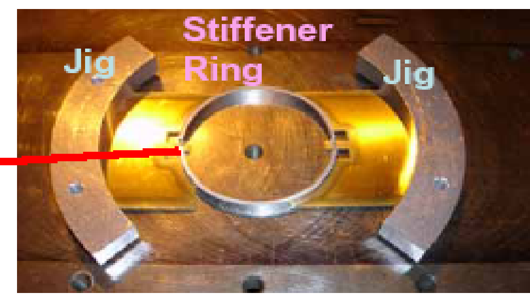
After trimming

Overview of Cavity Fabrication (KEK)

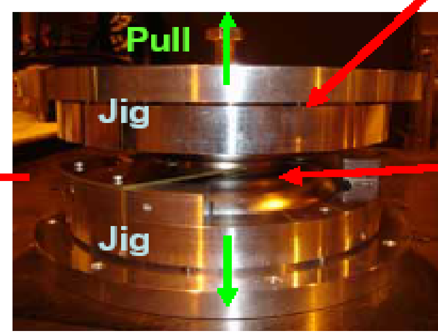
Fabrication of ICHIRO Cavity in KEK(2)

Electron Beam Welding (EBW)
In KUROKI corporation





Insert stiffener-ring into the iris part of dumbbell.



Pull and extend dumbbells to insert stiffener-ring.
=> EBW (dumbbell + ring)

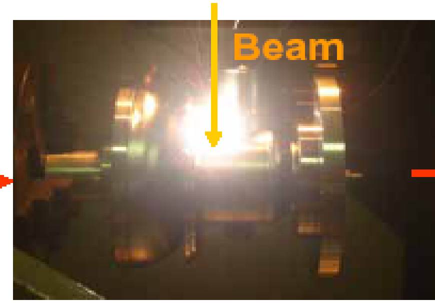
Dumbbell with stiffener-ring after EBW.

Overview of Cavity Fabrication (KEK)

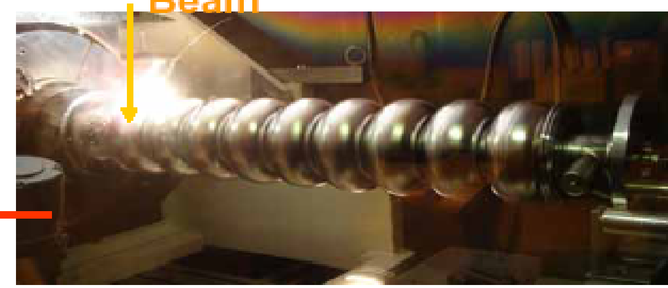
Fabrication of ICHIRO Cavity in KEK(4)

EBW of dumbbells

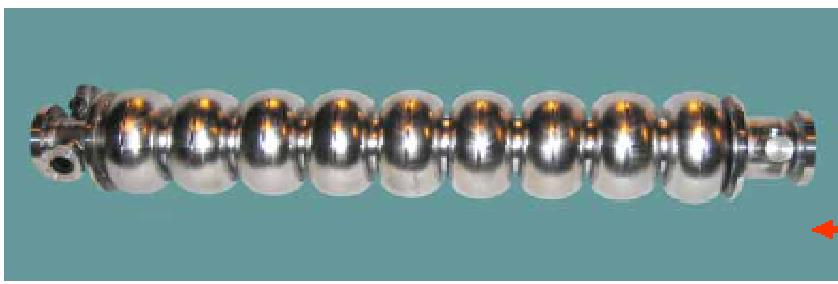
EBW of end-beam-pipe



End-beam-pipes with HOM and flanges



EBW of end-beam-pipes and cell-part



Four 9-cell ICHIRO high-gradient LL Cavities were successfully delivered to KEK ! (4 July 2005)

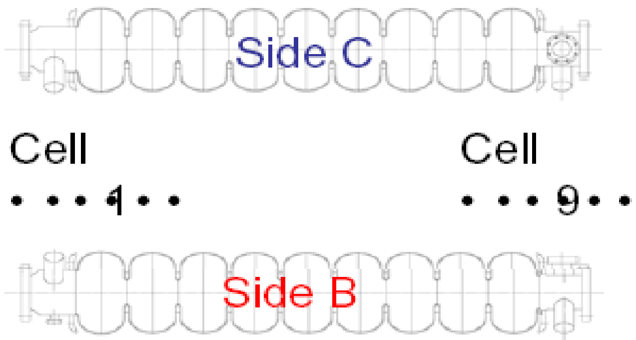
Overview of Cavity Fabrication (KEK)

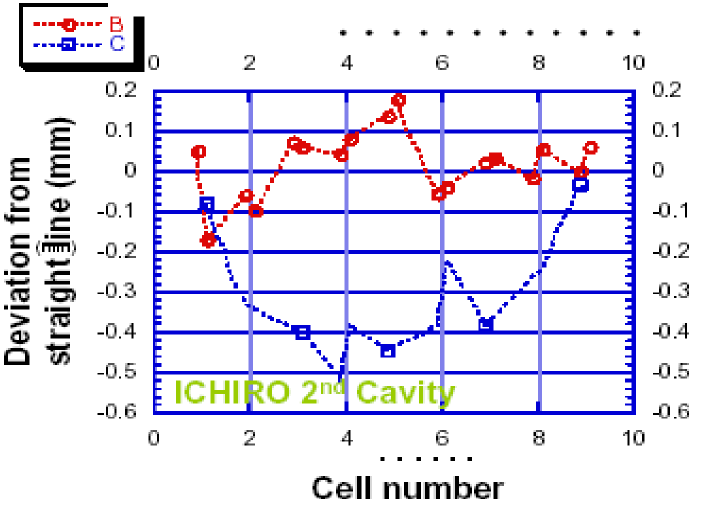
Dimensional measurements

Length and straightness of the cavities were measured by 3D-measurement machine.

	EBW shrinkage
iris	0.148+-0.044 mm
equator	0.424+-0.125 mm

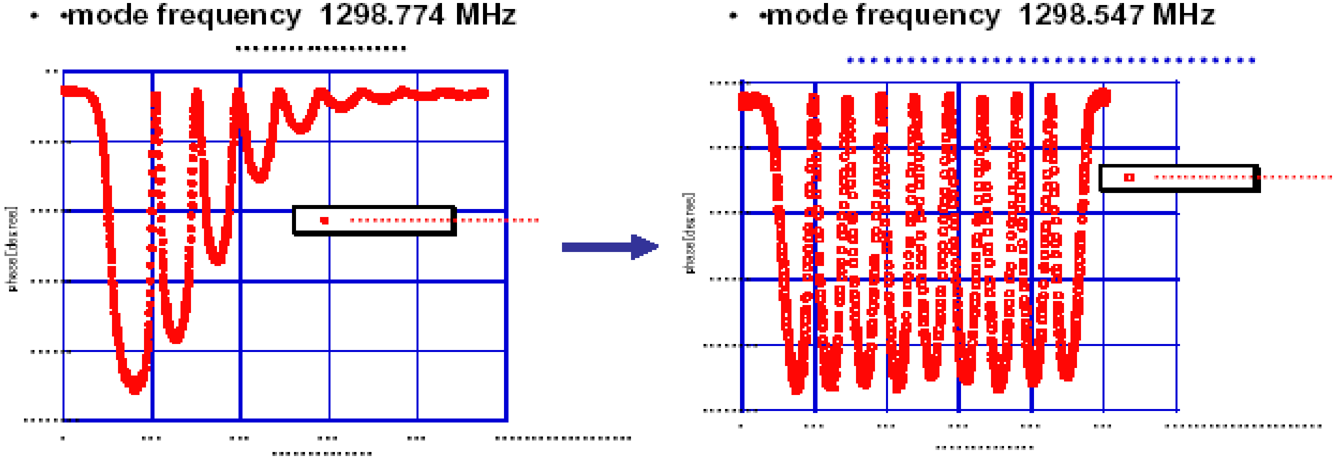
Dimensional deviation of length
(only 9-cell part: 1038.5 mm)
-10 mm (1st 9-cell ICHIRO cavity)
- 0.7 mm (2nd 9-cell ICHIRO cavity)
- 0.1 mm (3rd 9-cell ICHIRO cavity)





Overview of Cavity Fabrication (KEK)

Field flatness after pre-tuning



Field flatness = 0.1 %
(as delivered to KEK)

Field flatness = 98 %
(after pre-tuning)

Cavity	Field flatness (min/max) as delivered / after pre-tuning	Freq. target 1298.141 (MHz) @R.T. as delivered / after pre-tuning
1st	0.1% / 98%	1298.774 / 1298.547
2nd	57.6% / Not yet	1301.447 / Not yet
3rd	31.5% / Not yet	1301.577 / Not yet
4th	51.5% / Not yet	1301.696 / Not yet

Cell-to-cell coupling is as small as 1.6%, but no problem in pre-tuning.

Overview of Cavity Fabrication (JLab)









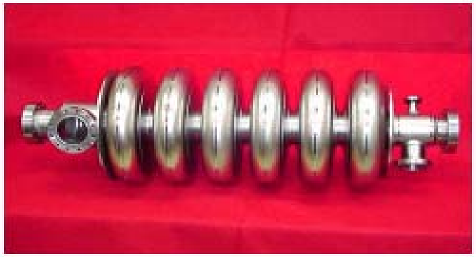
Overview of Cavity Fabrication (JLab)



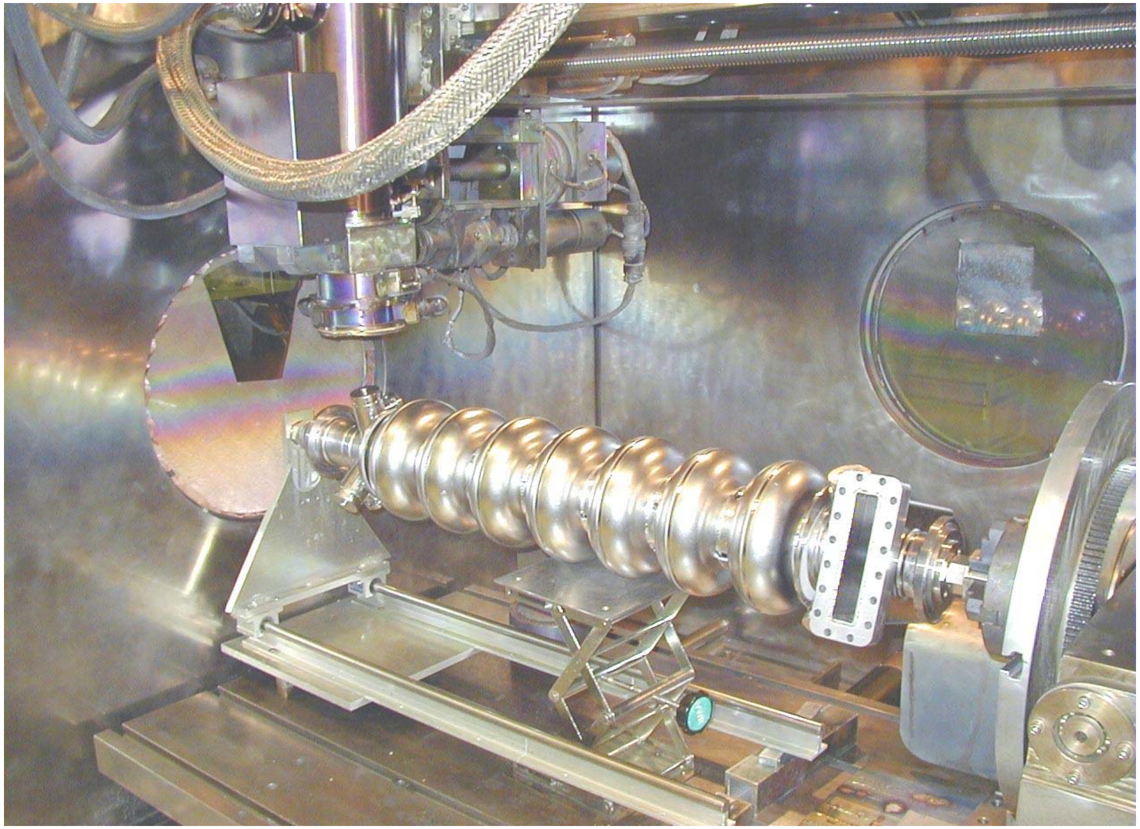








Overview of Cavity Fabrication (JLab)



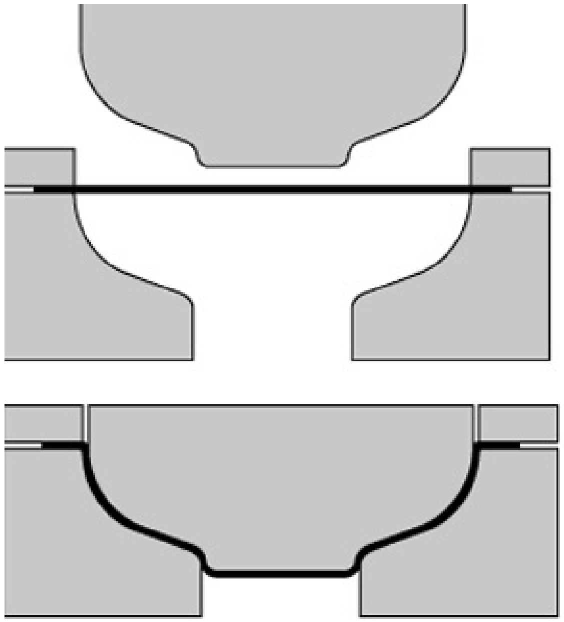
Overview of Cavity Fabrication (JLab)

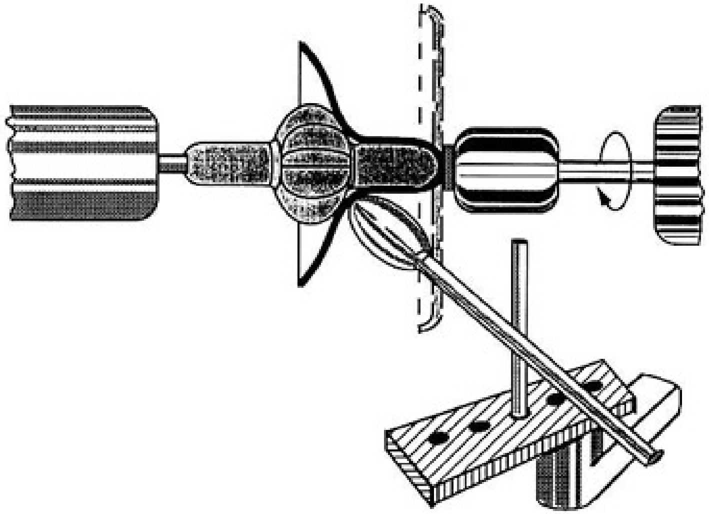
Tack- Welding:	4 tacks, focused beam
Voltage :	50 kV
Current:	15 mA
Rotational Speed :	20 inches/min
Distance of gun to work : 6 "	
Final weld Current:	33 mA
Rotational speed:	18"/min
Focussing:	elliptical pattern

Overview of Cavity Fabrication (JLab)

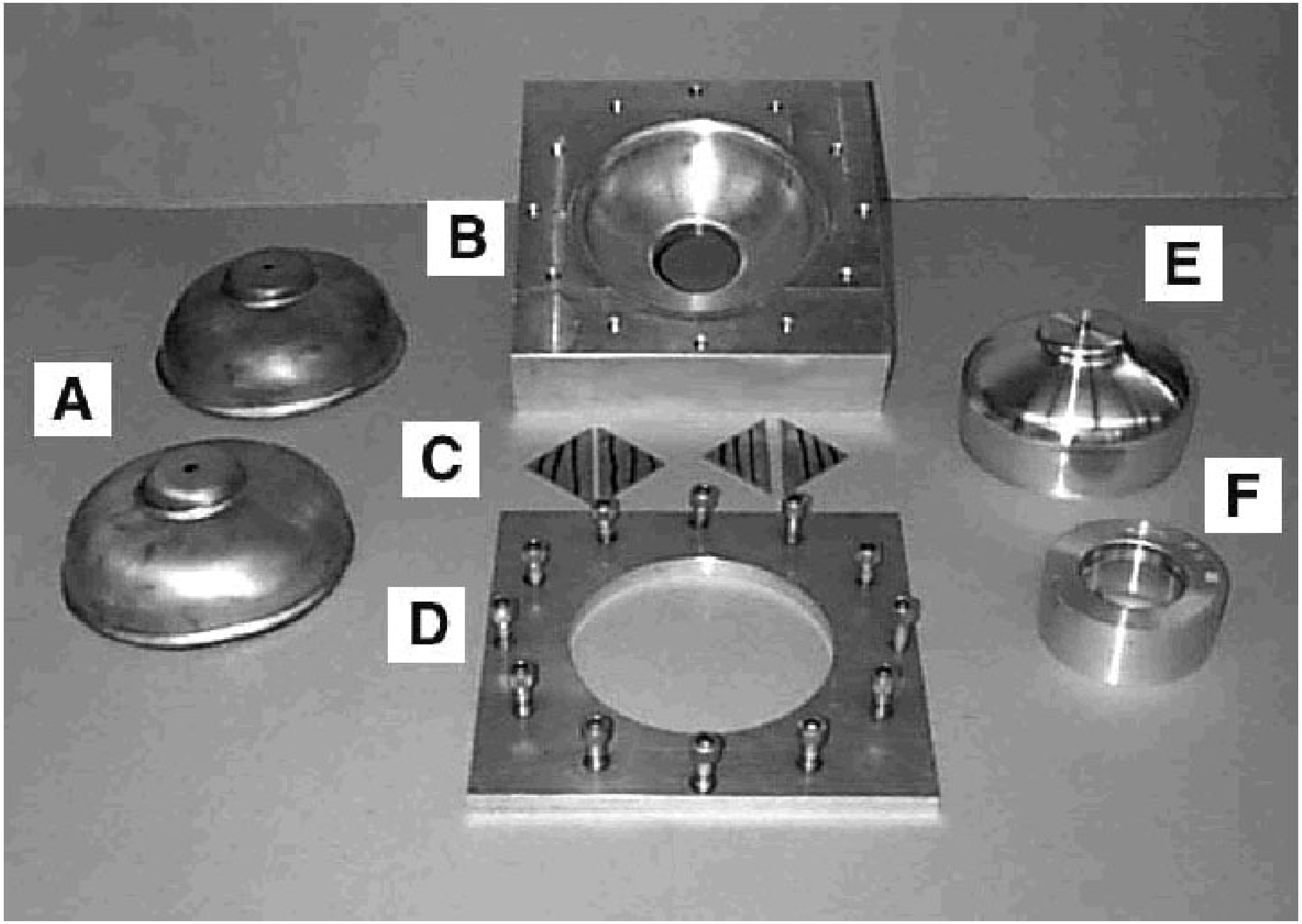
Fabrication of Cups

- Deep drawing or spinning
- Measurement of contour
- Better: measurement of frequency
- Trimming length at iris and equator plane
  - Consider welding shrinkage
- Slight chemical cleaning for welding



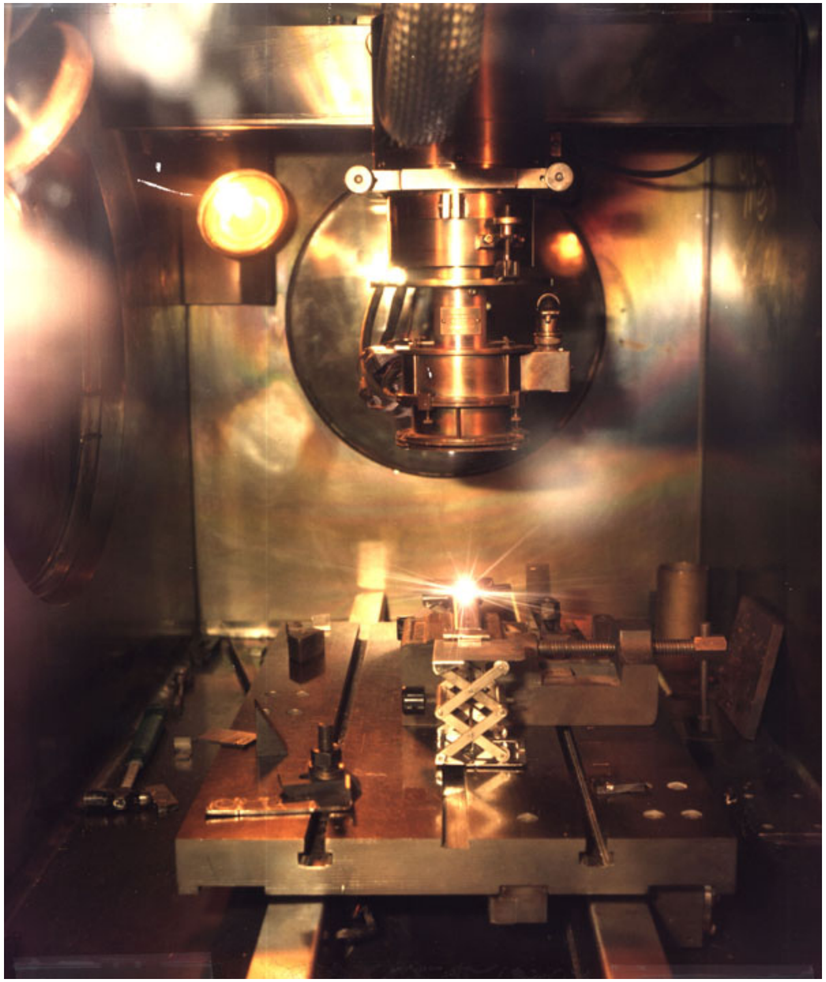


Fabrication of Cups



Electron Beam Welding

- Welding under good vacuum, 10^-5 range
- Broad welding seam
  - Operate with defocussed beam
  - Smooth underbead
- Overlap at end of welding to avoid accumulation of impurities
- Wait to cool down before opening chamber



Tuning (Electrical)

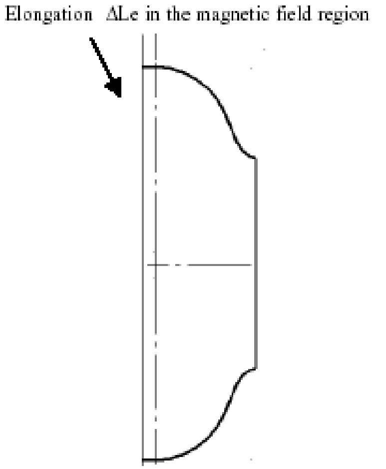
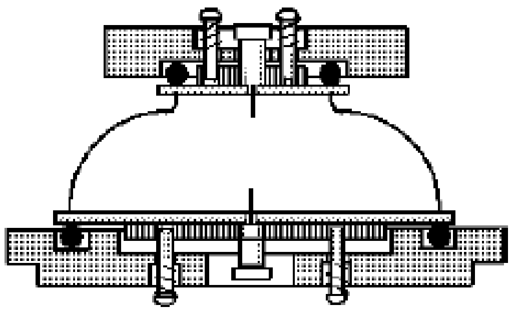


Figure 3: Trimming of the equator to adjust the elongation at the equator



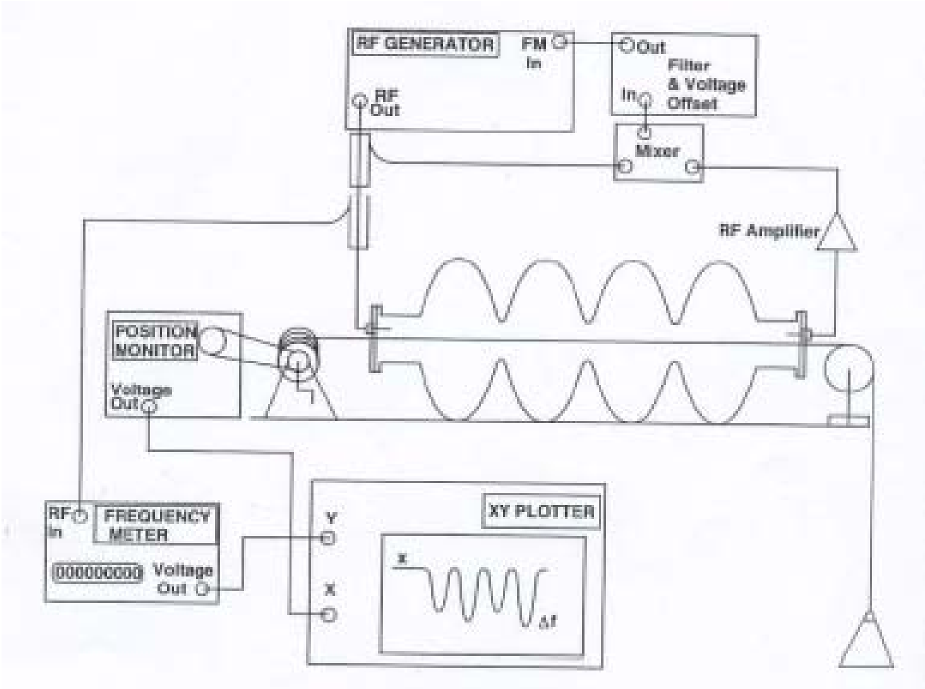
Frequency measurement of half cell

Frequency measurement of dumbbell

Field Flatness Tuning

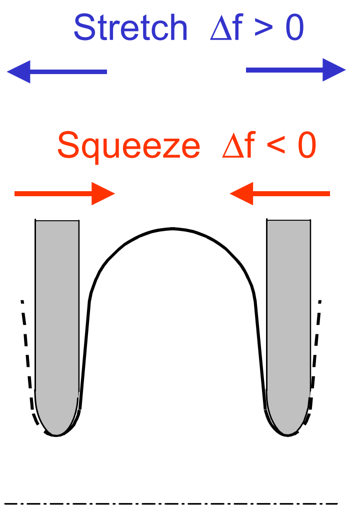
H.Padamsee et al;""RF Superconductivity for Accelerators"

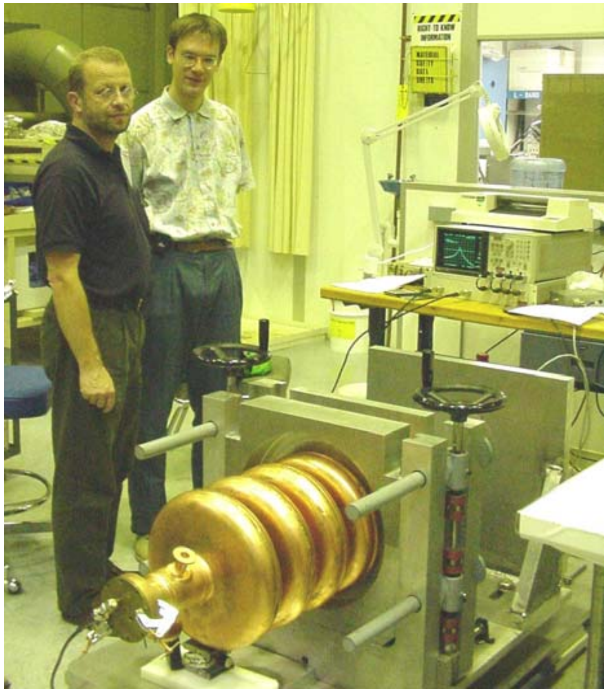
Set-up for field profile measurements: a metallic needle is perturbing the rf fields while it is pulled through the cavity along its axis; the stored energy in each cell is recorded.



Tuning (Mechanical)

Tuning system

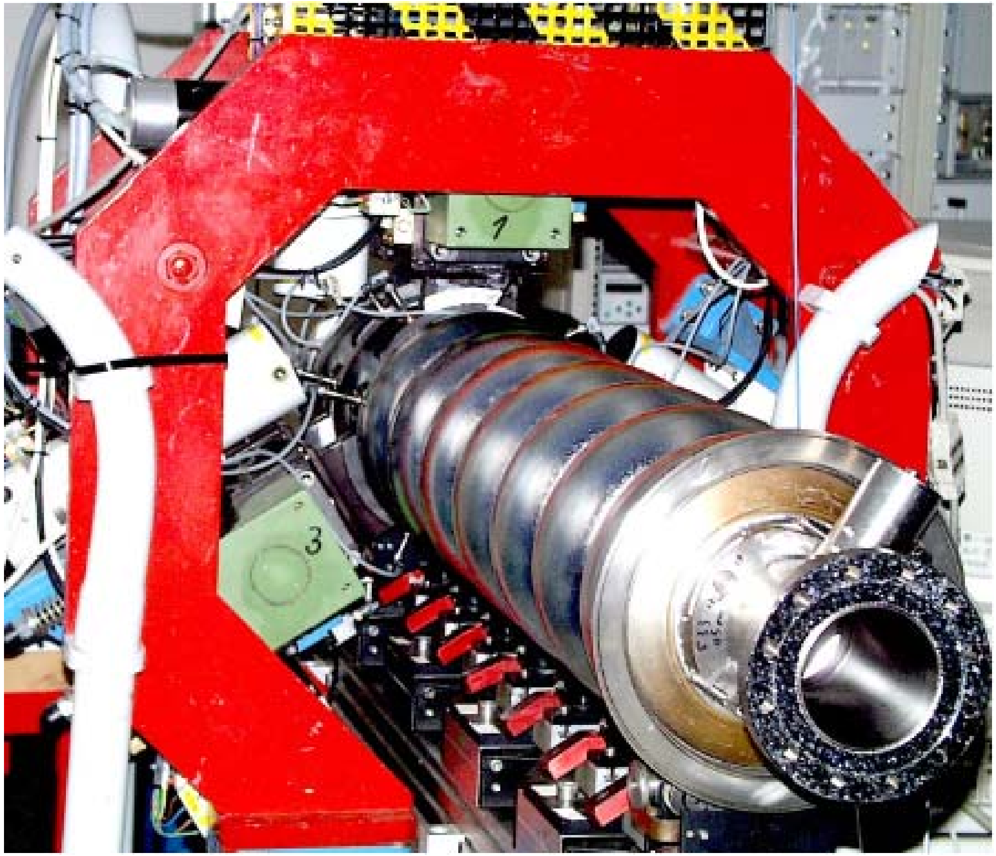




Tuning (Mechanical)

Computerized tuning machine at DESY

- •Equalizing stored energy in each cell by squeezing or pulling
- •Straightening of cavity

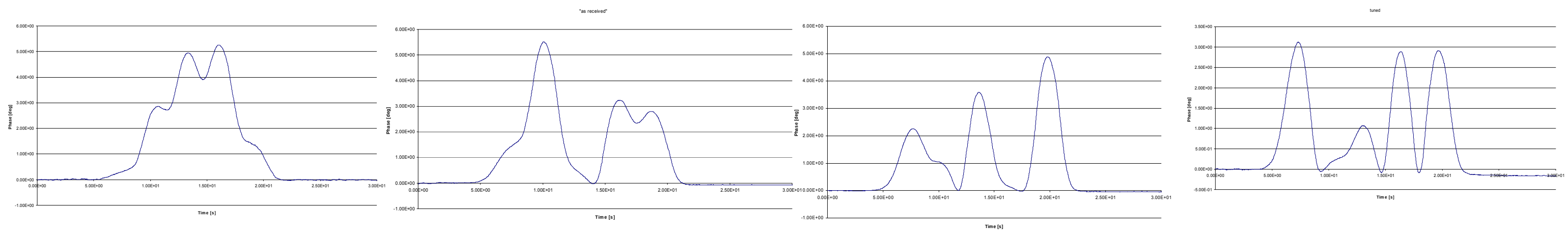


Tuning code (Chen Yinghua, J. Sekutowicz, Wei Yixiang, DESY M-89-11)

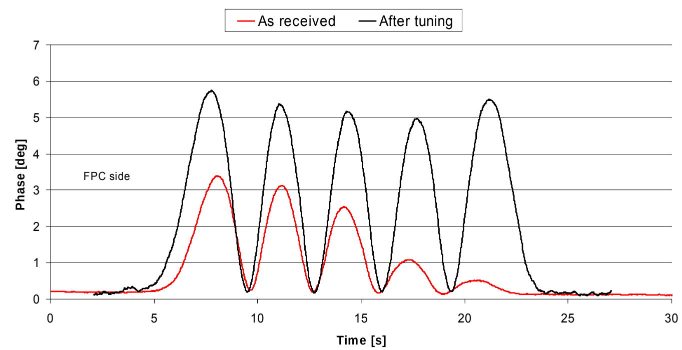
- Frequency and field profile measurement of all the 6 modes of the TM_{010} pass-band
- Preparing an input file with frequency and field amplitudes at the center of the cells for each mode
- Running the tuning code developed by J. Sekutowicz based on a lumped-circuit model where only the coupling between neighboring cells is considered
- Obtaining the Δf to be applied to each cell to tune the cavity at the frequency requested

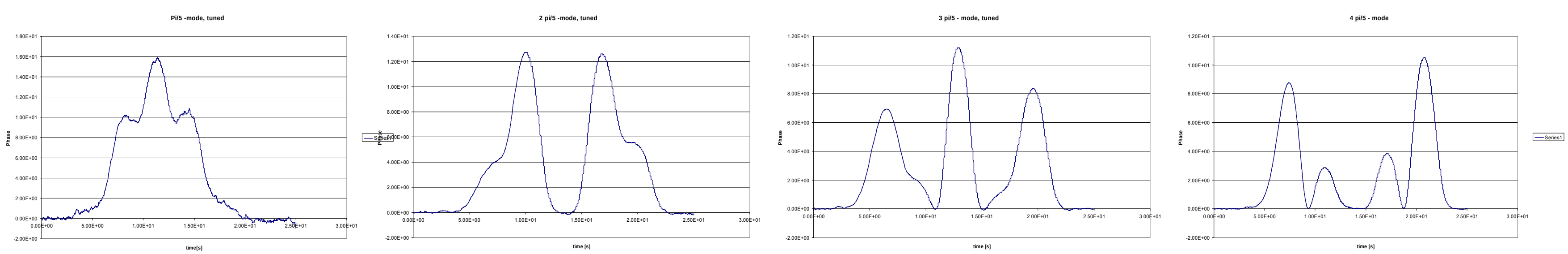
Tuning:Example 5-cell TRASCO Cavity

As manufactured



Tuned

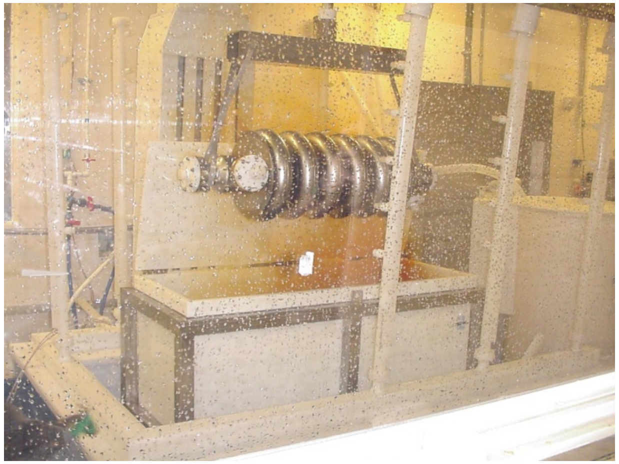




Cavity Inspection

Cavity Inspection

External Chemistry



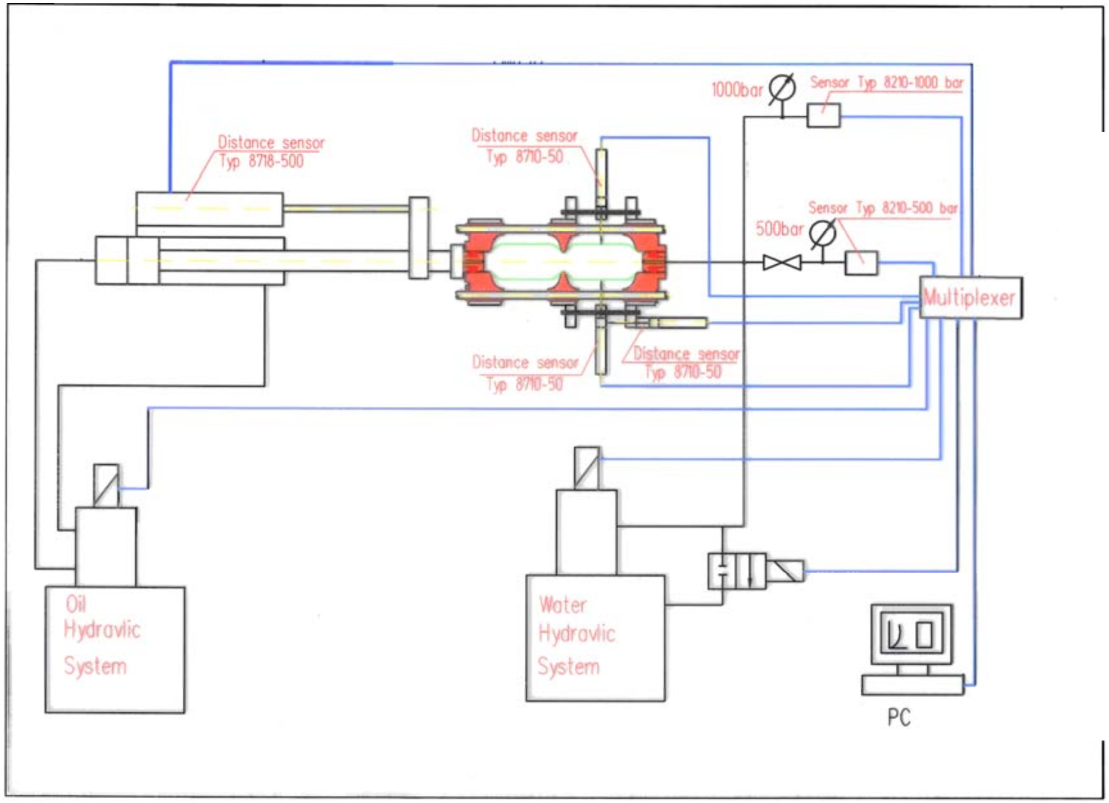
Alternative Fabrication Techniques

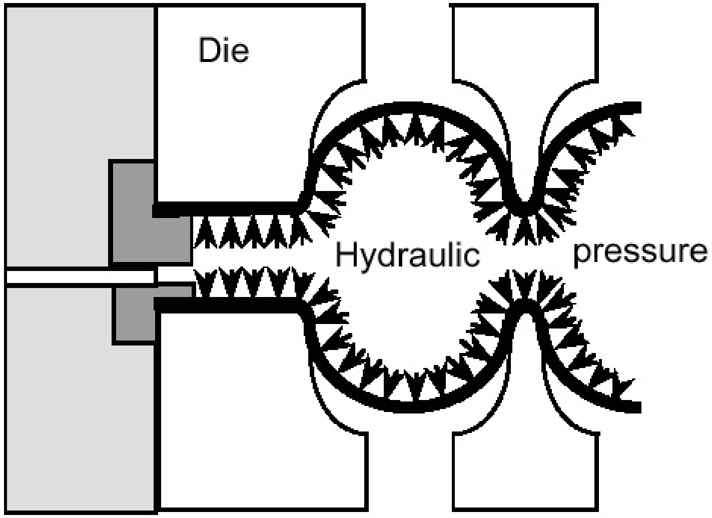
Besides the "standard" cavity fabrication of producing niobium half cells and electron beam weld them into multi-cell cavities there exist alternative method:

- Spinning of multi-cells
- Hydroforming of multi-cells
- Use of composite material NbCu
- Thin film coating of Cu cavities

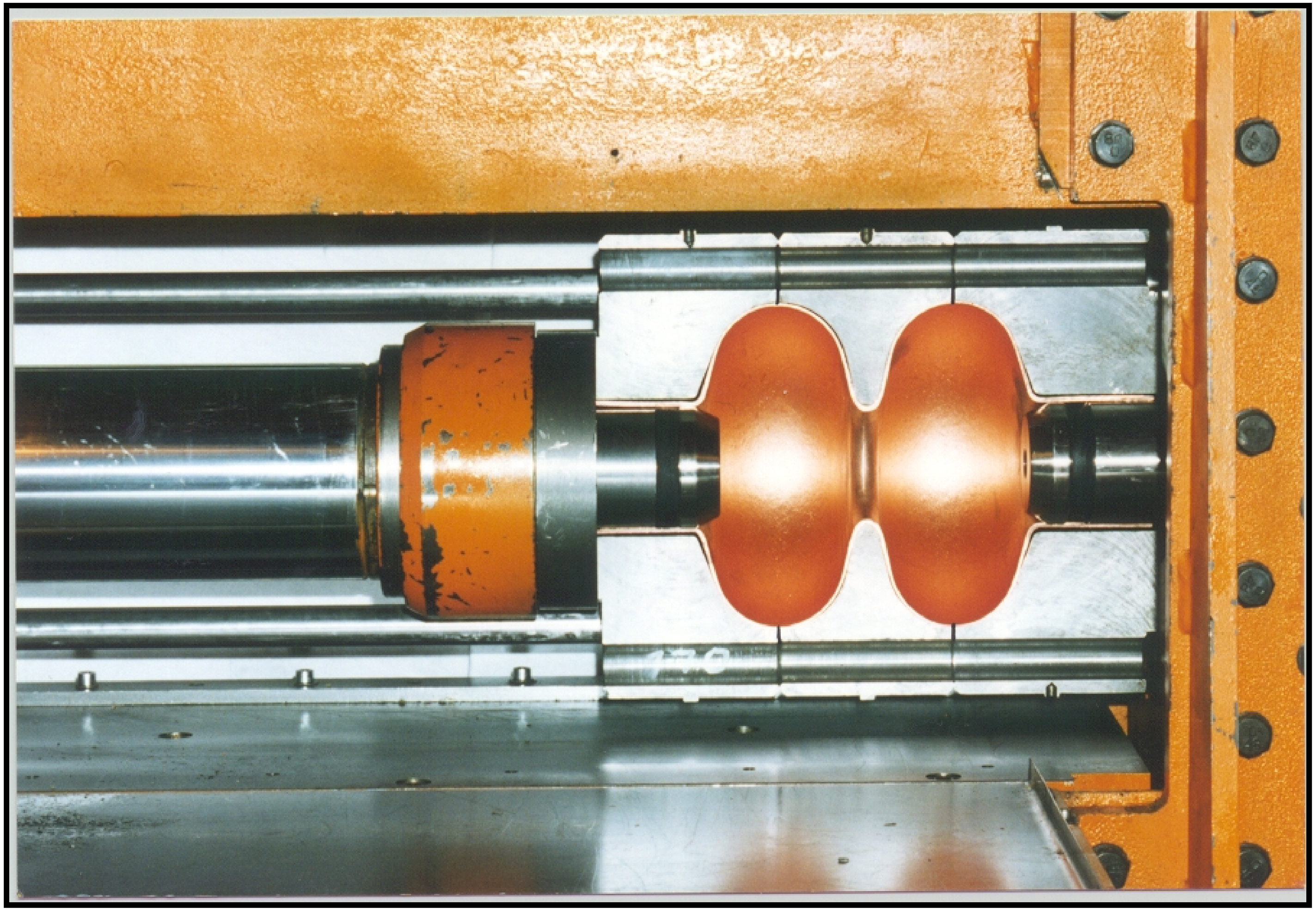
Hydroforming

Hydro forming (W.Singer,DESY)





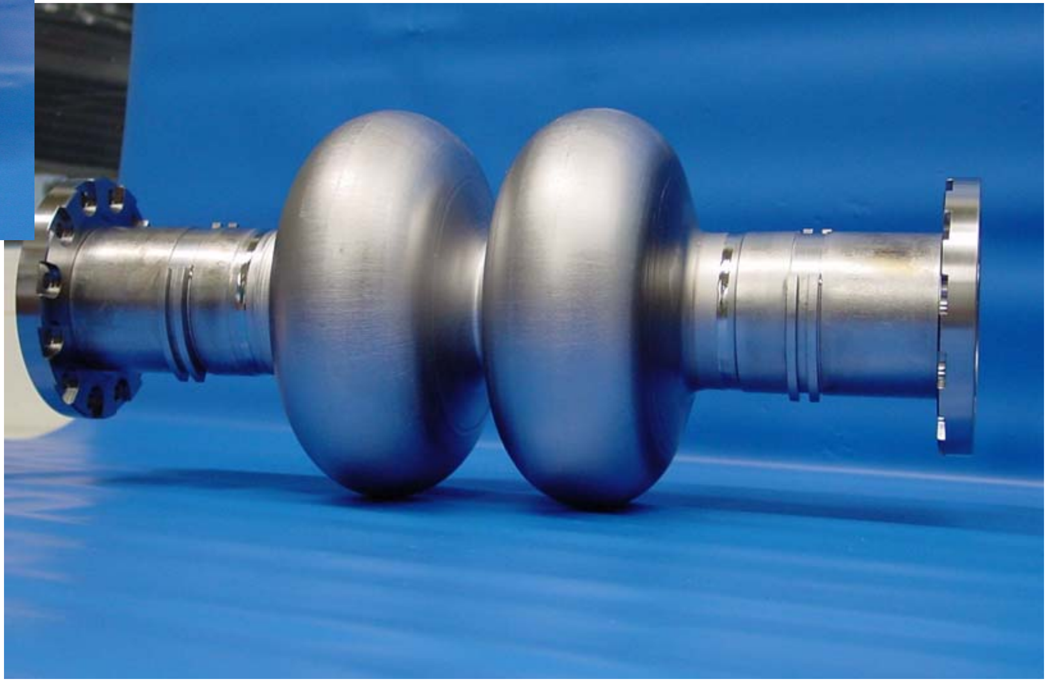
Hydroforming



Hydroforming of a two-cell structure - H. Kaiser, W.Singer et al.

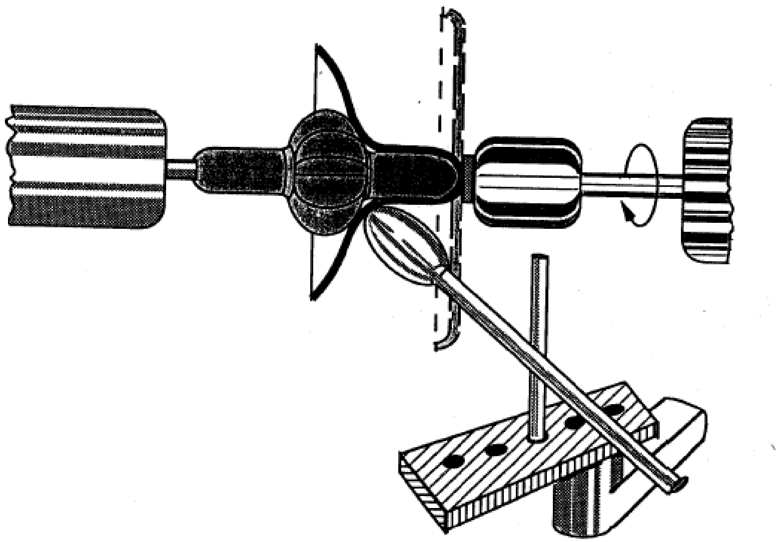
Hydroforming

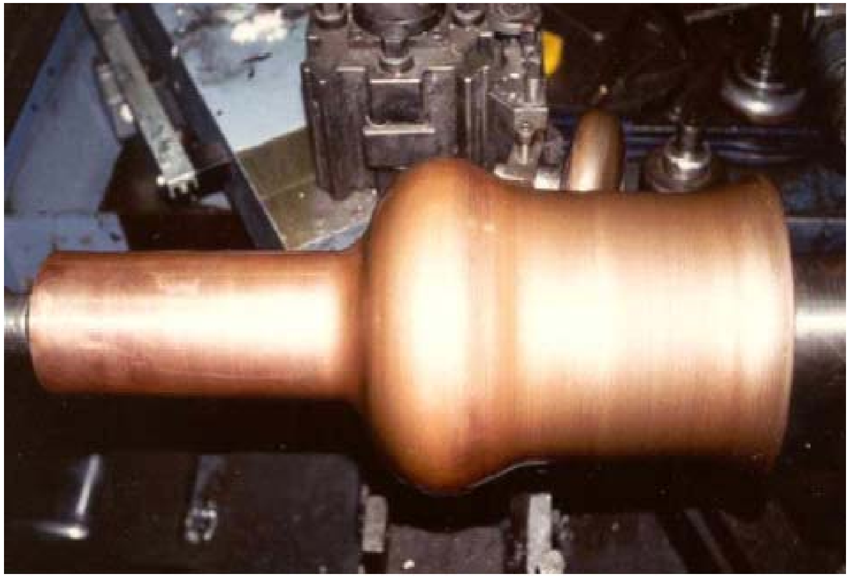
Hydroforming



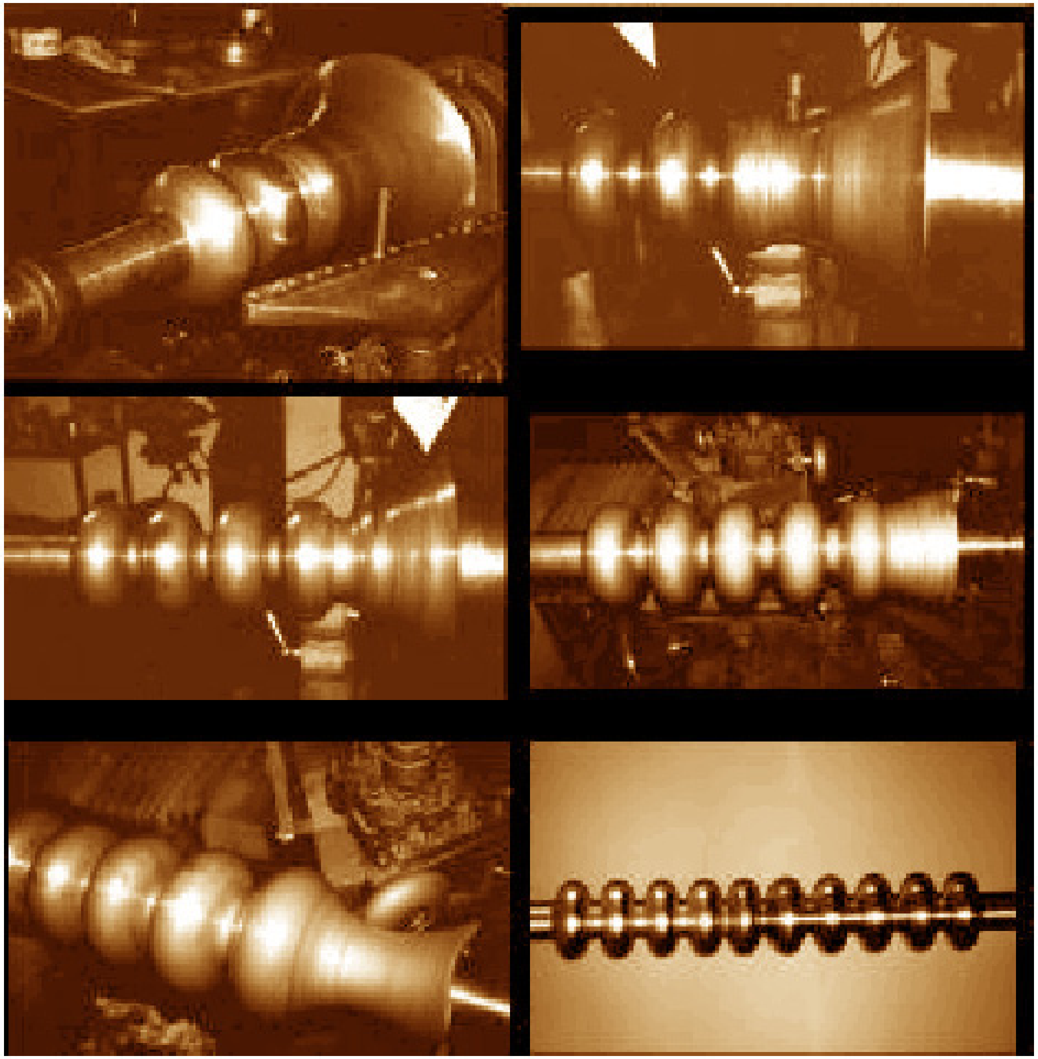
Spinning

Spinning (V.Palmieri,INFN Legnaro)

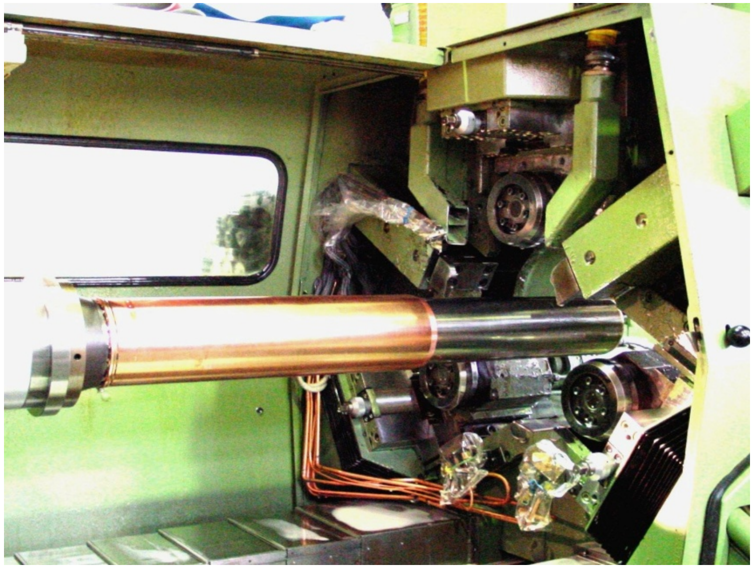


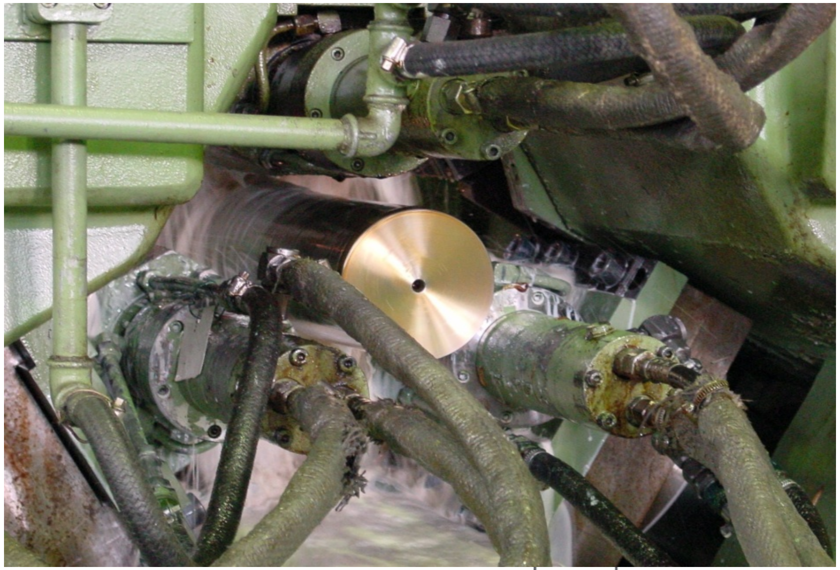


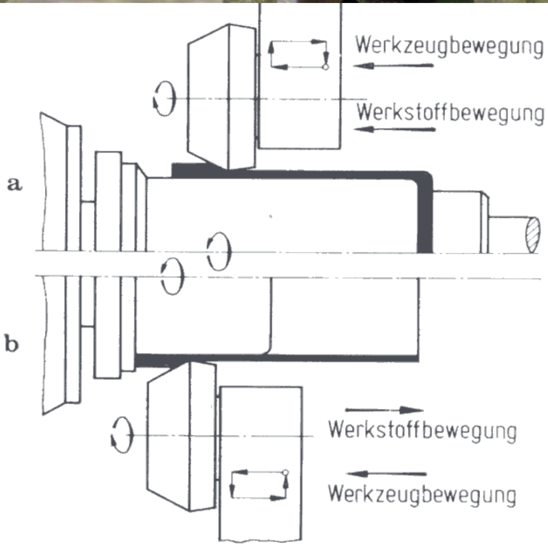
Spinning



Tube Forming



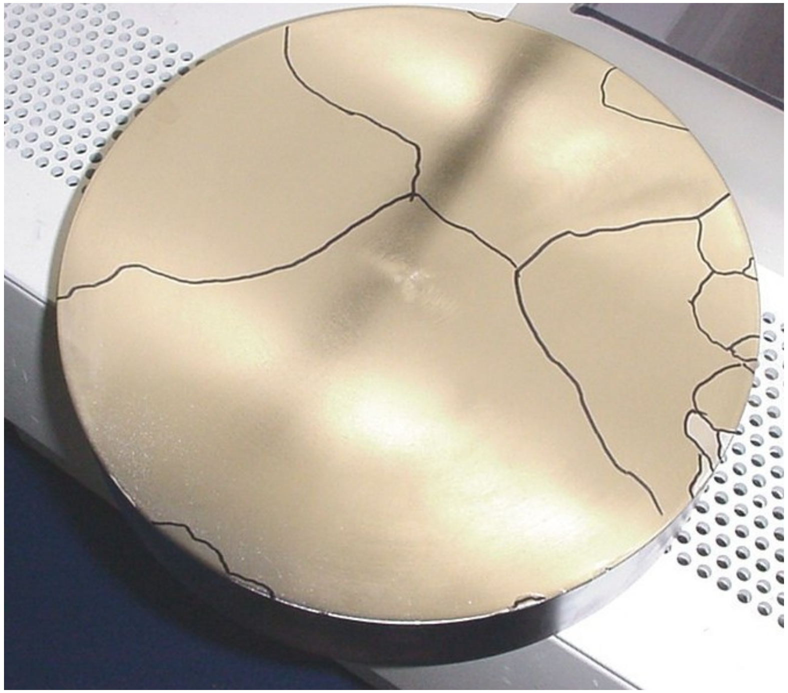


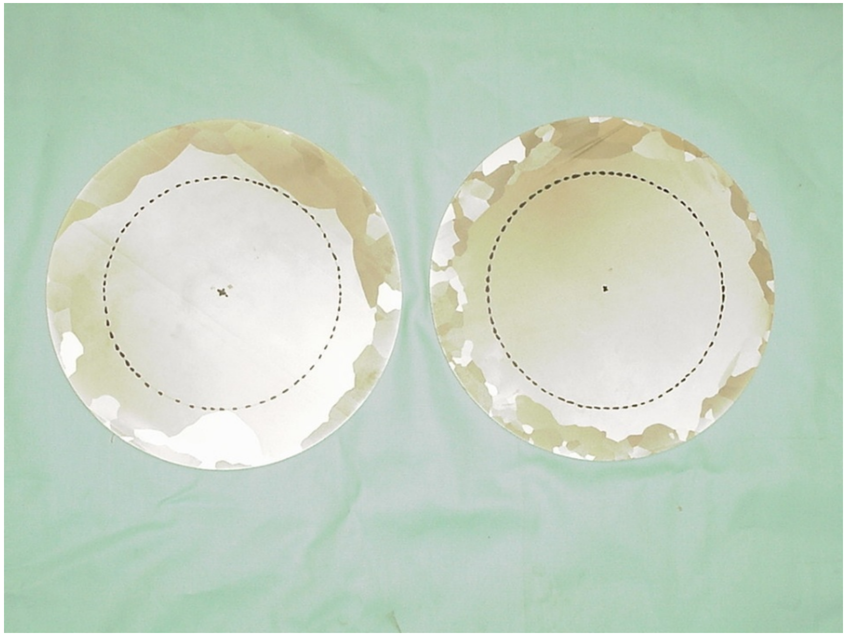


Flow forming over a cylindrical mandrel with three work rollers allows to produce long and very precise tubes from thick walled cylindrical part.
After optimization of several parameters shiny Nb surface and small wall thickness variations (less then +/-0,1 mm) have been achieved.

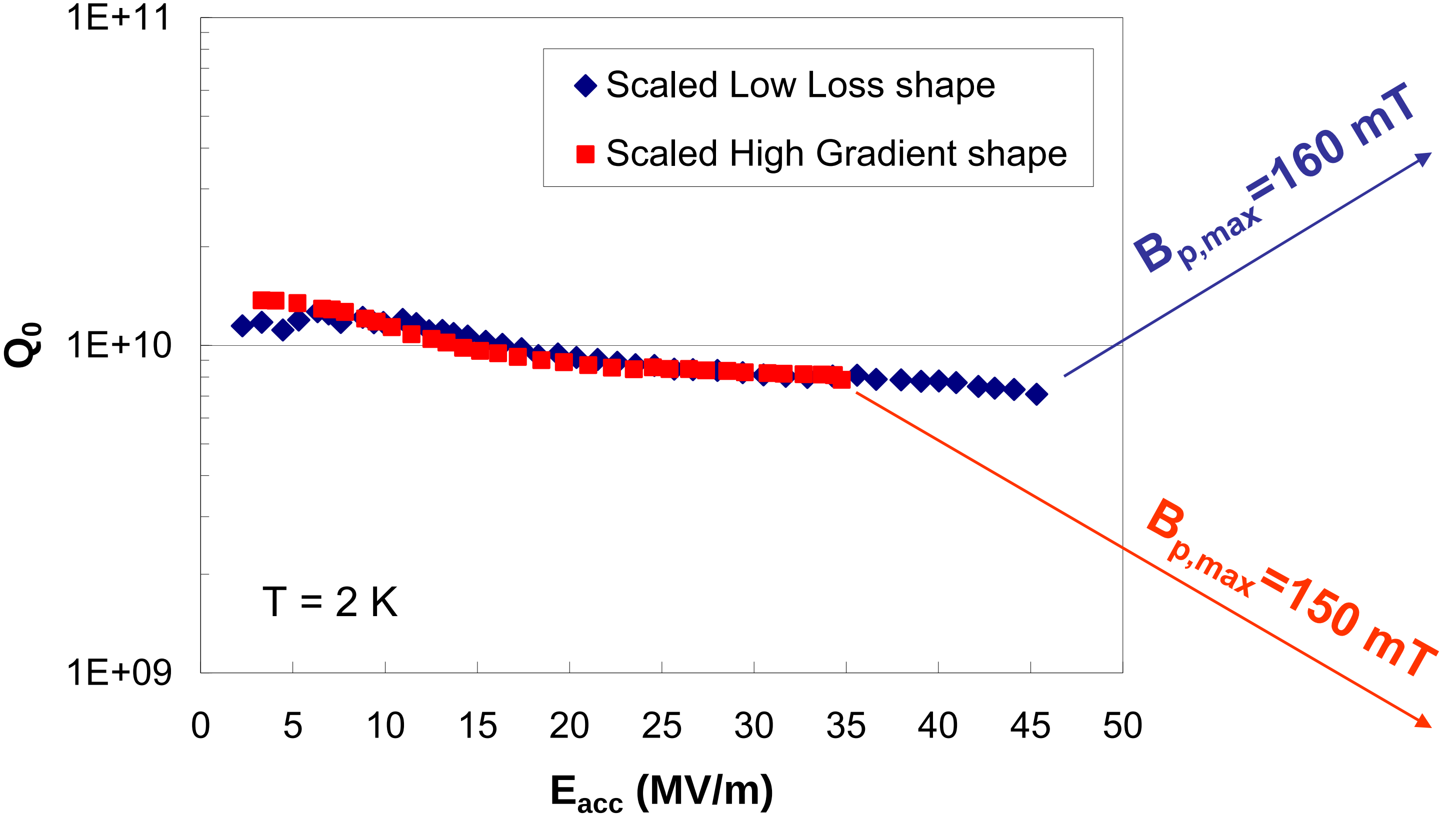
CBMM Niobium: large grain and single crystal

RRR value: ~300   Ta content: ~500 ppm

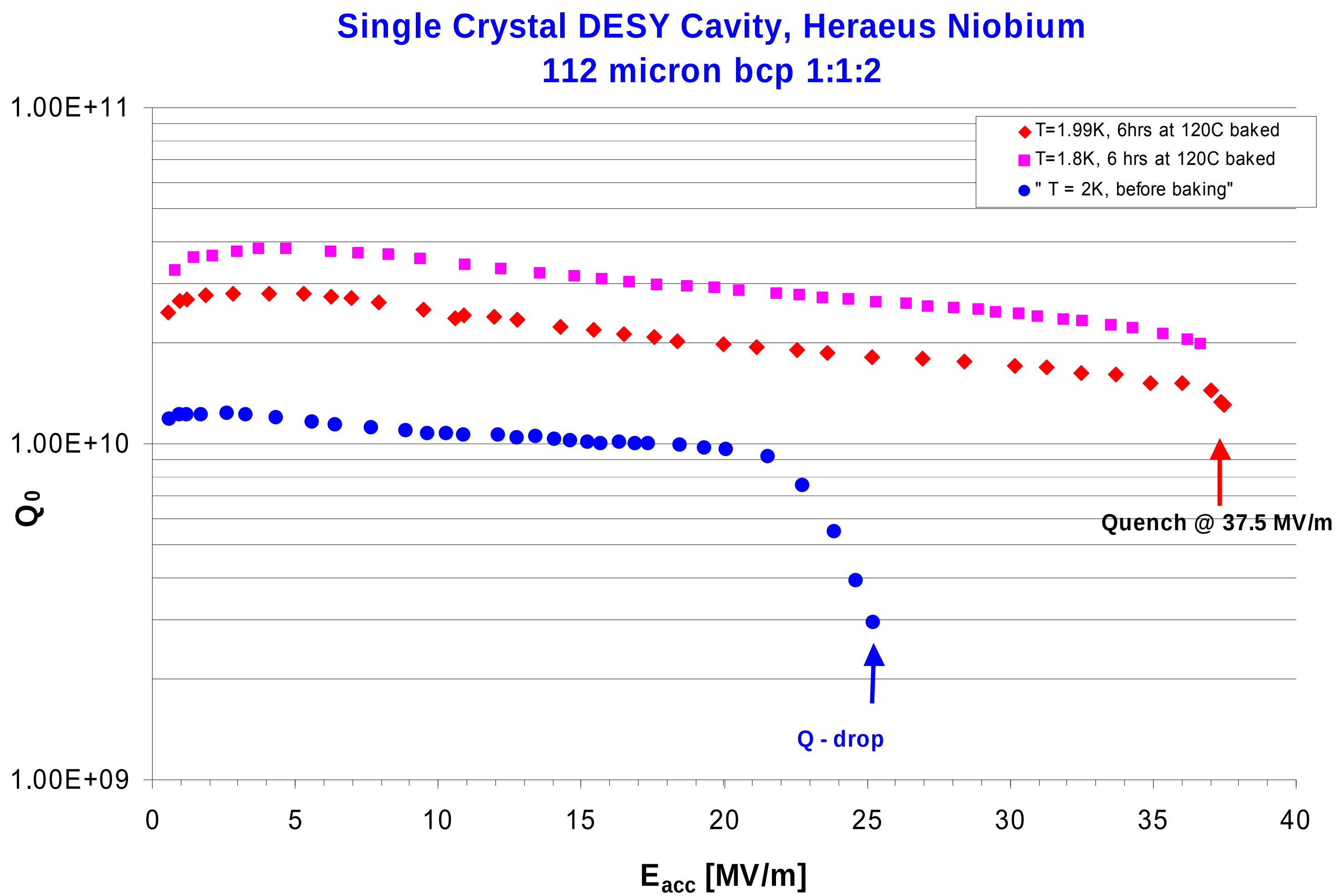




Single crystal cavities



Single crystal cavity



Potential Benefits of Single Crystal Nb

- Reduced cost
- Comparable performance of fine grain niobium
- Very smooth surfaces with BCP, no EP necessary
- Better cleaning (FE reduction?)
- Elimination of Q-drop with short baking times
- Less material QA (eddy current/squid scanning)
- Possibly very low residual resistance
  - Lower losses
  - Lower operating temperature
- Higher thermal stability (phonon peak)
- Good or better mechanical performance

Nb/Cu clad Material

Advantages

- cost effective: allows saving a lot of Nb (ca. 4 mm cavity wall has only ca. 1 mm of Nb and 3 mm Cu). Especially significant for large projects like ILC
- bulk Nb microstructure and properties (the competing sputtering technique does not have such advantages)
- the treatment of the bulk Nb BCP, EP, annealing at 800°C, bake out at 150°C, HPR, HPP can be applied (excluding only post purification at 1400°C).
- high thermal conductivity of Cu helps for thermal stabilization
- stiffening against Lorentz - force detuning and microphonics can be easily done by increasing of the thickness of Cu layer.
- fabrication by seamless technique allows elimination of the critical for the performance welds especially on equator

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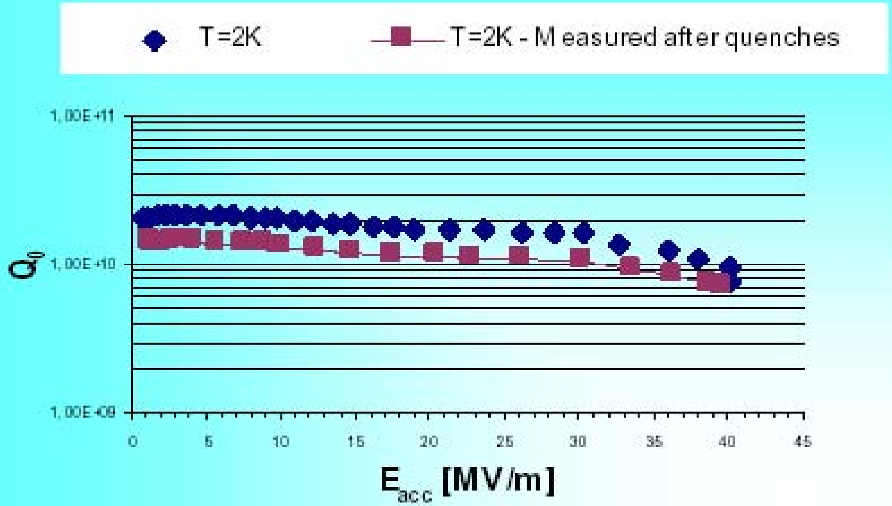
Nb/Cu clad Material



NbCu single cell cavity 1NC2 produced at DESY by hydroforming from explosively bonded tube. Preparation and HF tests at Jeff. Lab: 180 µm BCP, annealing at 800°C, baking at 140°C for 30 hours, HPR (P. Kneisel).

40 MV/m without EP

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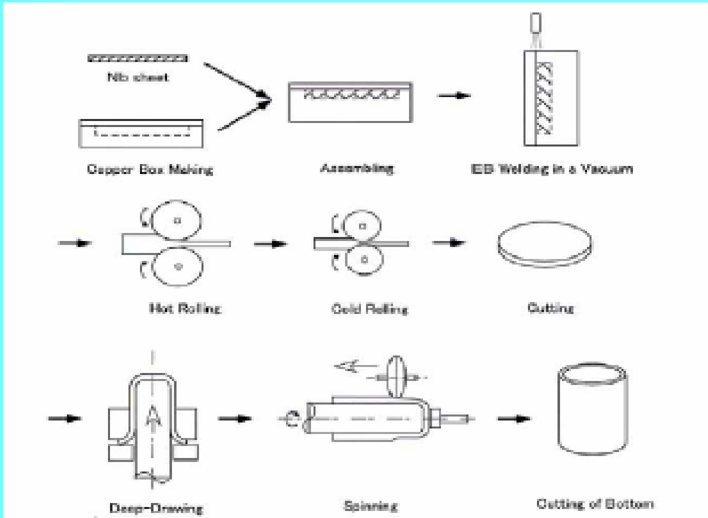
NbCu cavities hydroformed from explosively bonded tubes at DESY.

Difficult to get reproducibly high bonding quality. Hot bonding fabrication procedure of NbCu tubes seems to be more promising

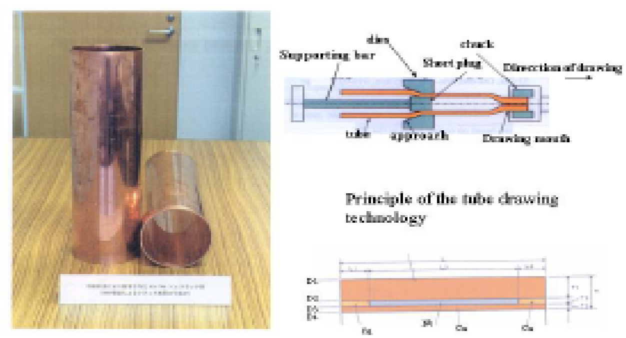
Nb/Cu clad Material

- Hot bonded NbCu tubes



Fabrication principle of sandwiched hot rolled Cu-Nb-Cu tube (KEK and Nippon Steel Co.)

Hot roll bonded Cu-Nb-Cu tube produced at Nippon Steel Co.



Cu-Nb-Cu Sandwiched Tubes (KEK)

Fabrication principle of sandwiched coextruded Cu-Nb-Cu tube (KEK)

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Nb/Cu clad Material

Nb/Cu Clad Seamless Tubes and Cutting

Nb/Cu clad Material

Problems

- Possibility of leaky welds because of Cu contamination
- Nb/Cu cavities still quench,resulting in Q-degradations
- Cooldown needs to be very uniform because of thermo – currents
- Cooldown of cryomodules would need modification
- Cracks sometimes appear in iris region during fabrication
- No industrialization efforts yet

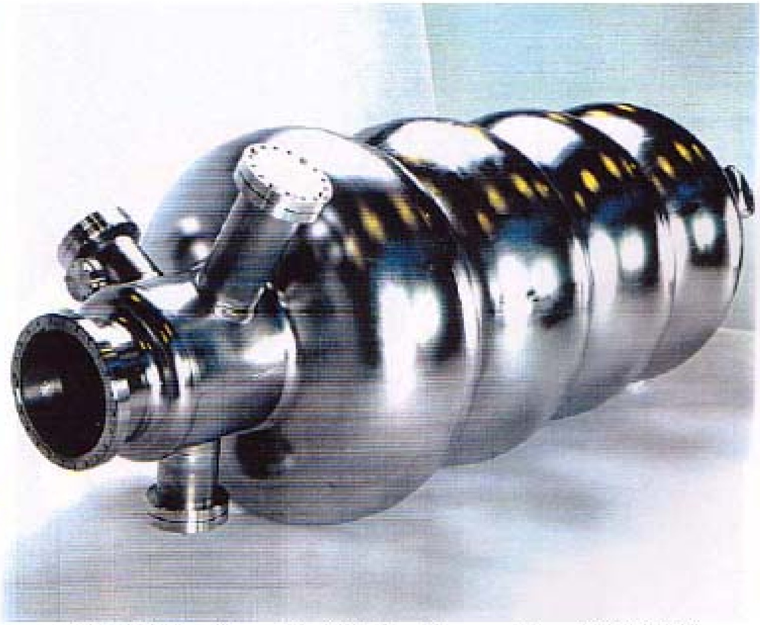
Thin Niobium Films

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

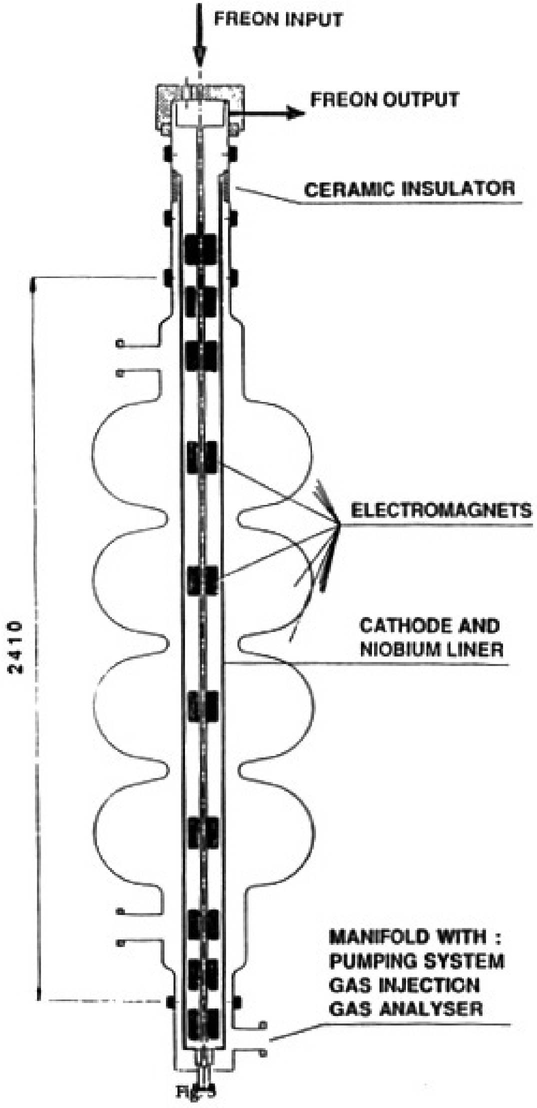
Copper half cell for LEP-II SC cavity

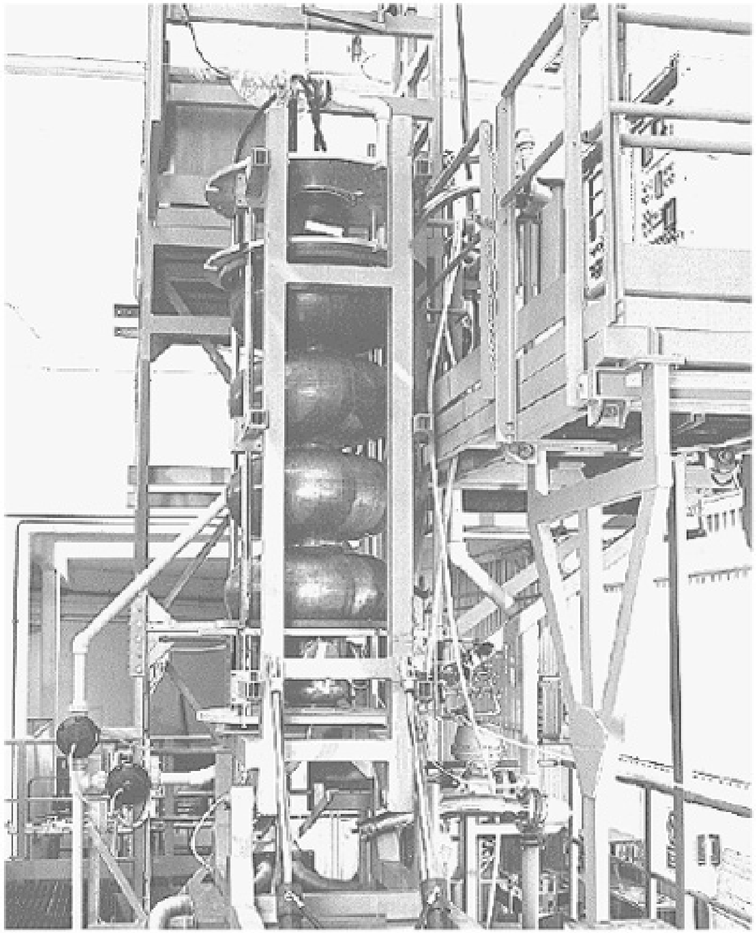


350MHz 4-cell Nb bulk cavity (CERN)

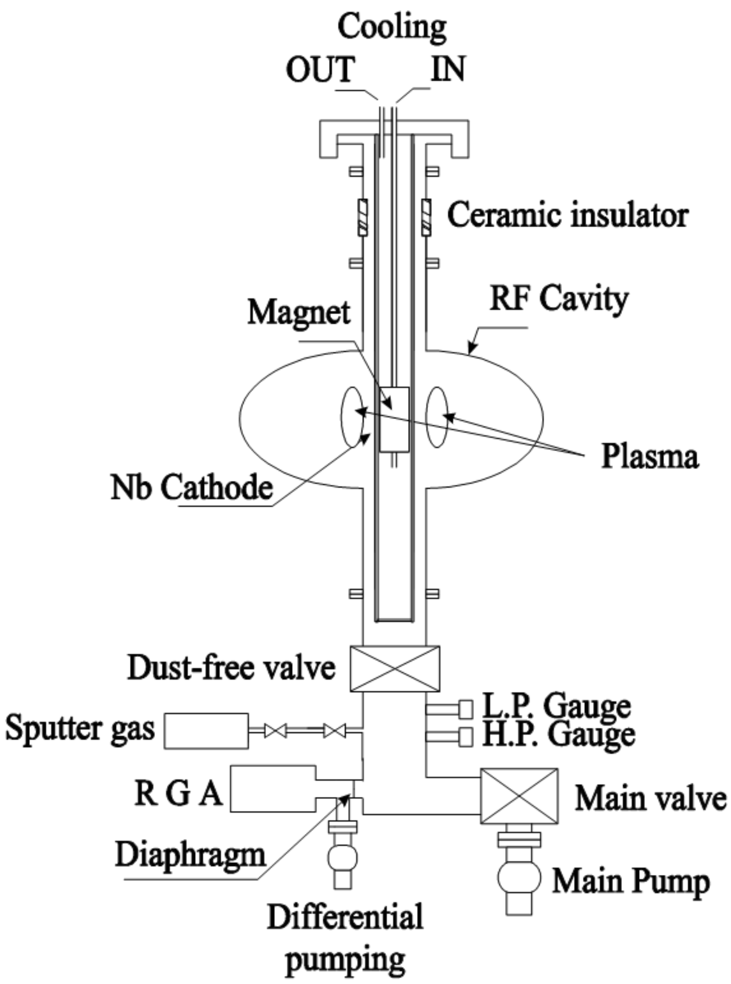
Niobium on Copper Cavities

Fabrication





Nb Sputtering



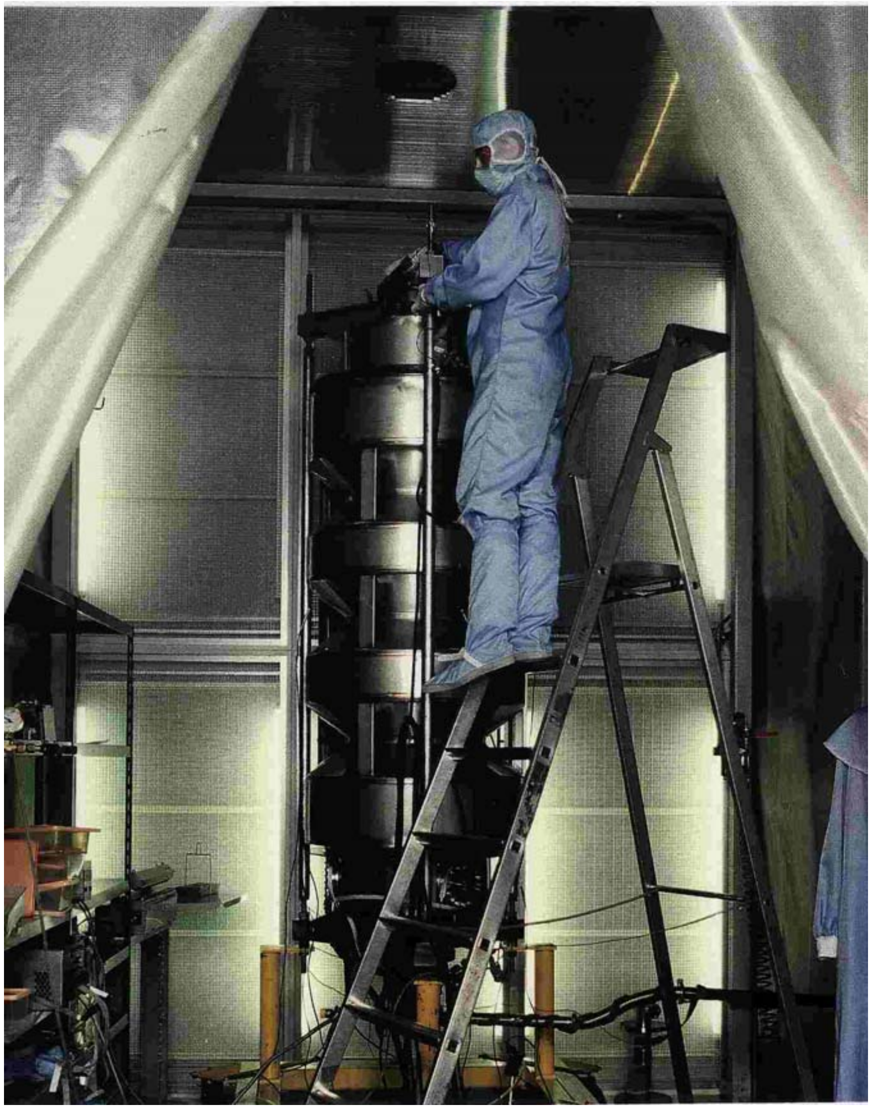
Sputtering parameters for 1.5 GHz cavities

- Discharge current stabilized at 3 A.
- Sputter gas pressure of 1.5×10^{-3} mbar, corresponding to ~ 360 V.
- Coating temperature is 150 °C.
- Thickness: 1.5 µm

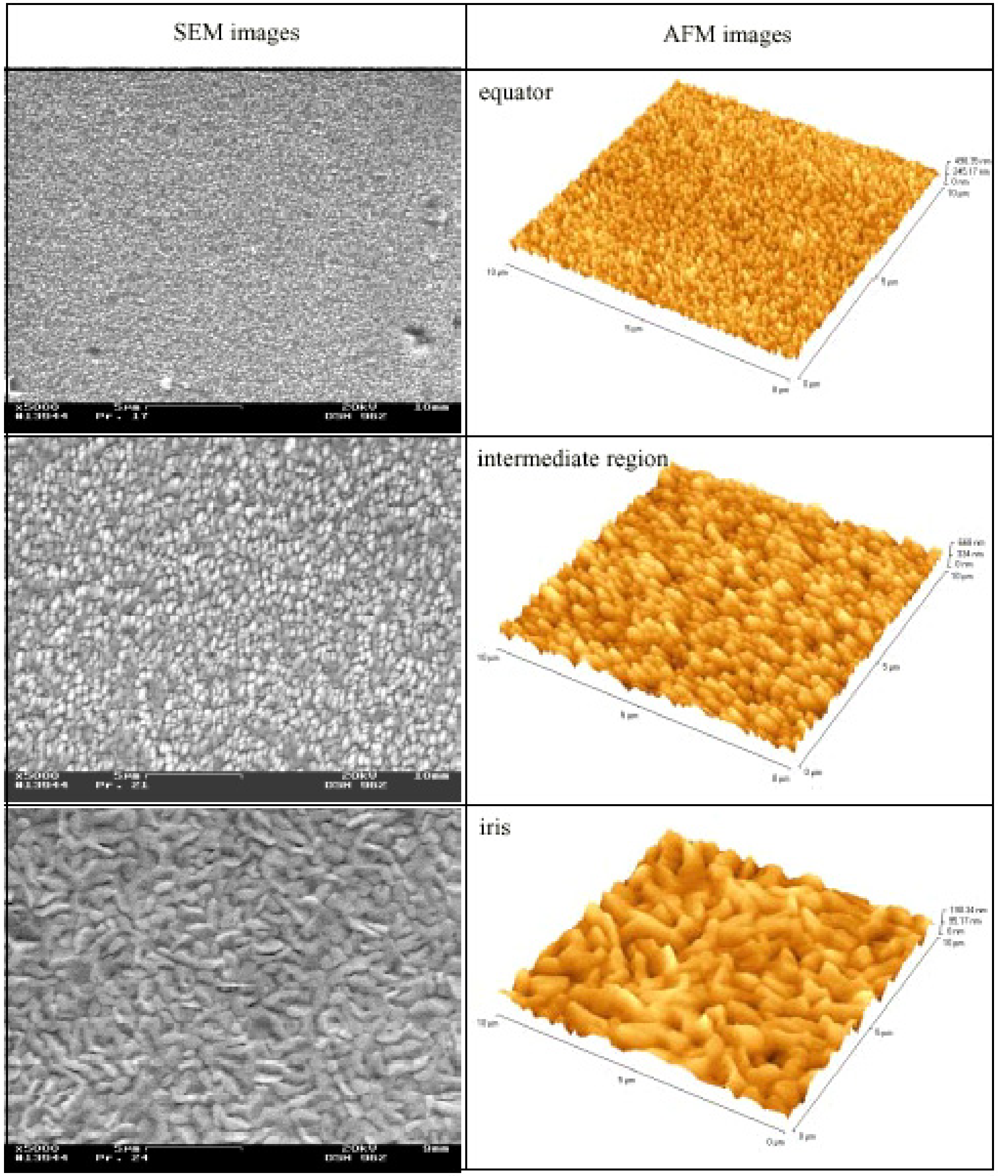
Film characteristics (same as for LEP):

- RRR: 11.5 ± 0.1
- Argon content: 435 ± 70 ppm
- Grain size: 110 ± 20 nm
- Tc: 9.51 ± 0.01 K

Nb Sputtering



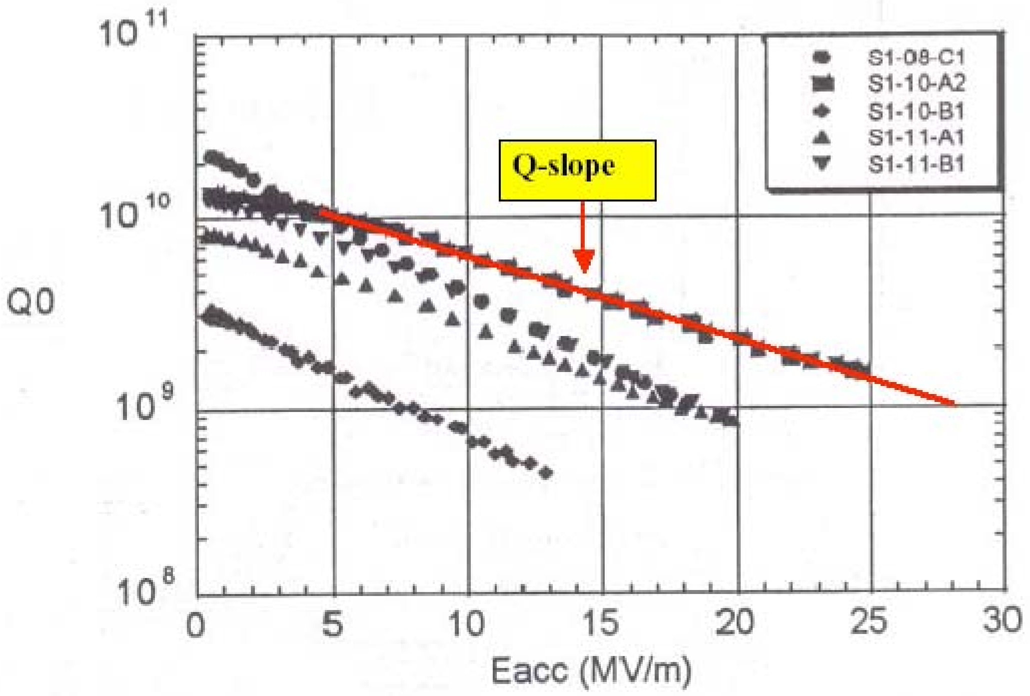
Surface Structure of Nb/Cu



Thin Niobium Films

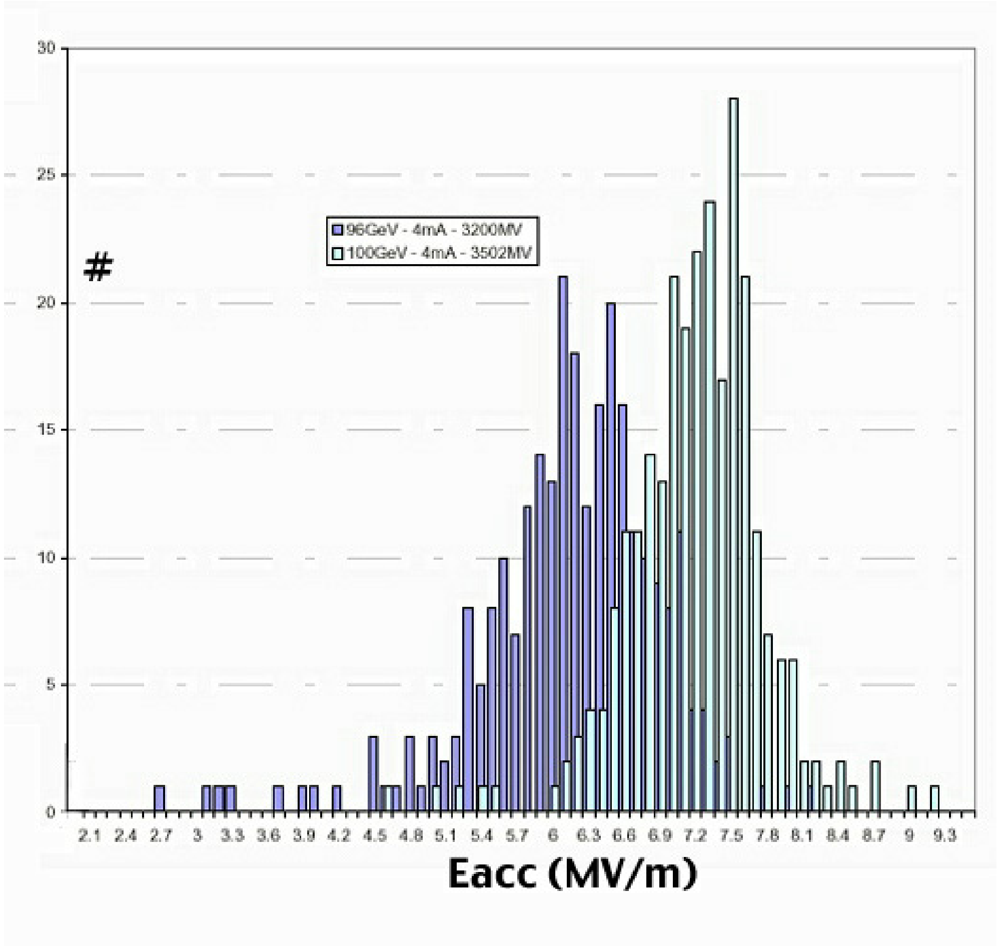
US-CERN-JAPAN-RUSSIA Accelerator School, Nov. 6-14, 2002, Long Beach, California, USA

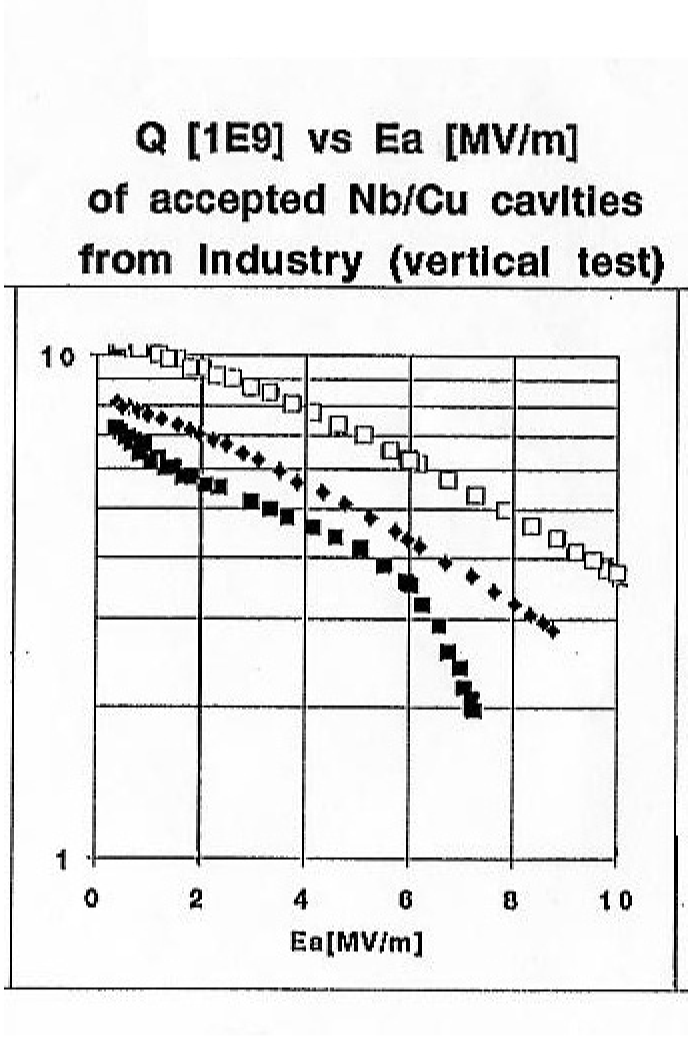
Niobium Film Coated Cavities - Application for 1300 MHz cavities -



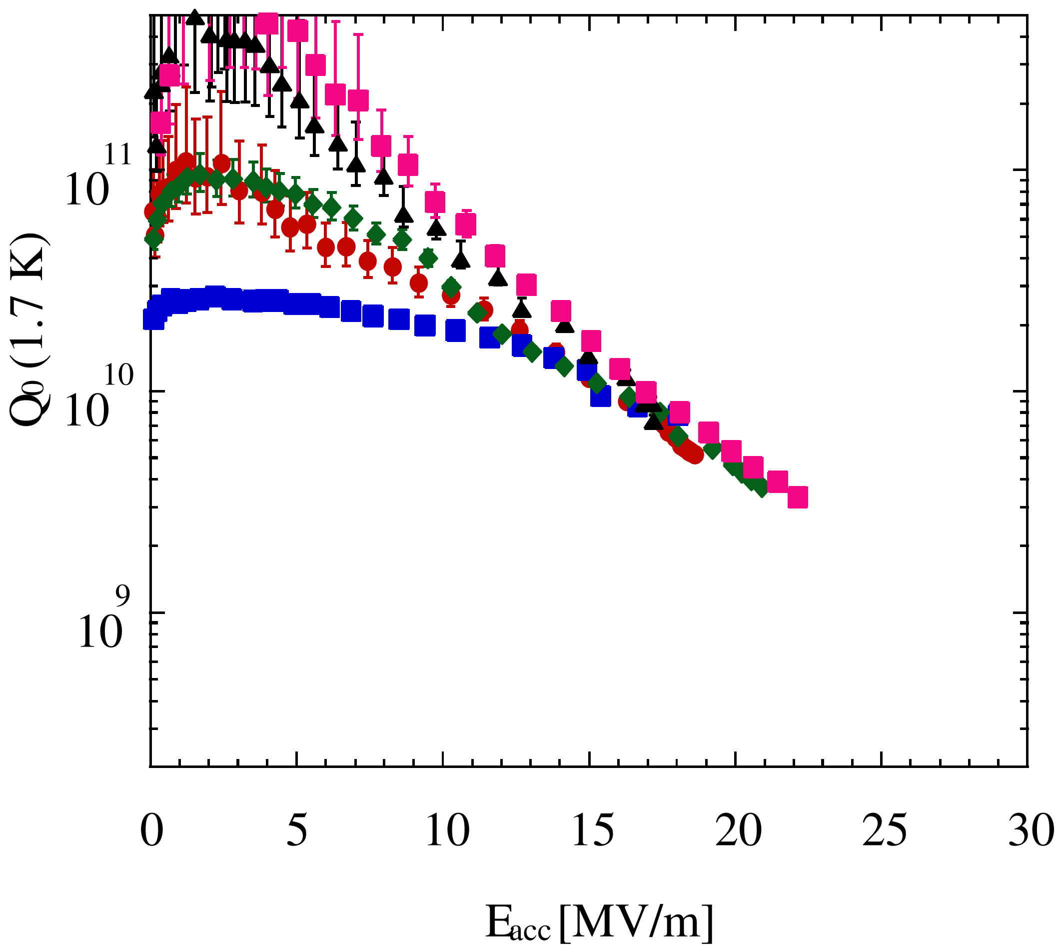
Q-slope is a problem for the high gradient application.

Performance of LEP Cavities





Some results at high field (1.5 GHz cavities)



Electropolished cavities

Coatings performed using krypton

Rinsed with upgraded HPWR installation

Max RF power: 100W

Small cryostat: 60l of liquid He

Cu Plasma-Sprayed on Nb

Experiences on cavity fabrication

Deep drawing:

1. Reproducibility depends on tool design and tool material
   → specification – investigation in tooling
2. Dependency on Nb supplier found
3. Different shape from ingot to ingot found (Hardness / grain size)
   → Better quality control + specification ➔ reproducibility

Measurements:

1. Rf measurement of cups / dumb bells ➔ Time consuming
2. Mechanical measurements of sub units → Time consuming
   (F part HOM tube / flanges /dumb-bell 3 D measurement complex
   → combination of mechanical and rf measurement possible ?
   (3 D imaging of units)

Fabrication:

1. Sequences need to be adopted to the company hardware
2. Companies need to be trained an <u>stay trained</u>
   → learning curve to stable production
3. Control on subcontractors
4. Dependency on major products of company → training of personal