SC Cavities;

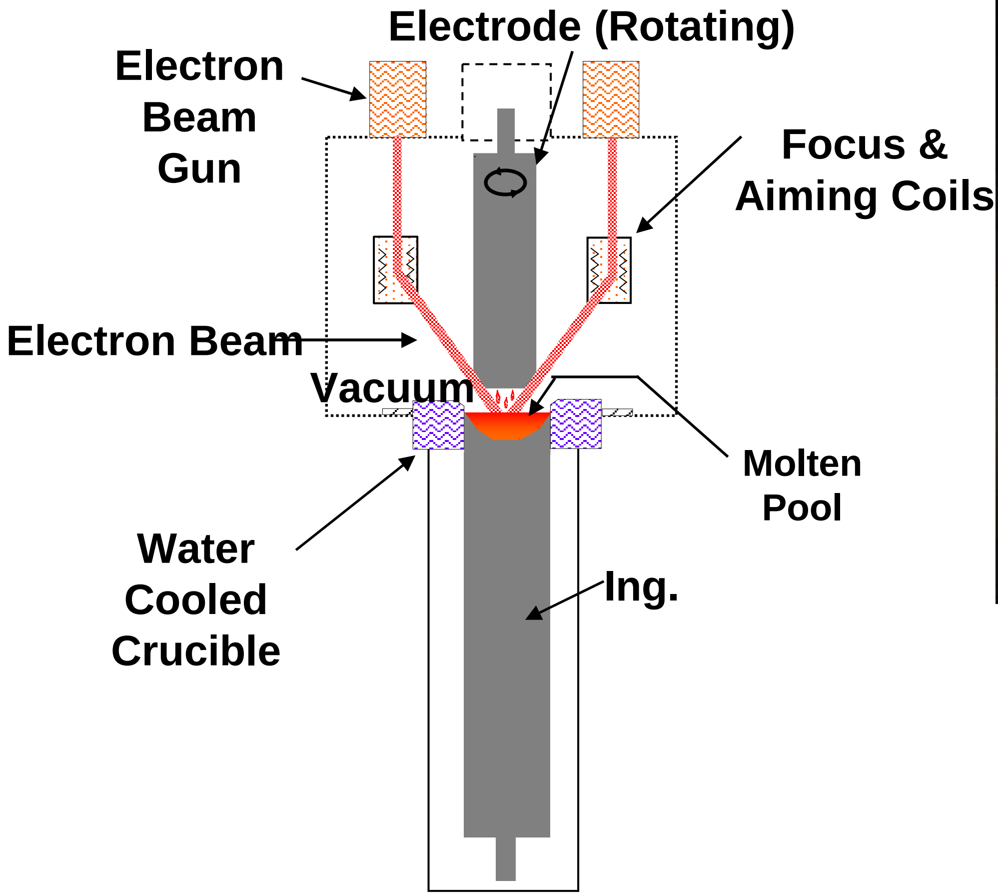
Material, Fabrication and QA

W. Singer
DESY

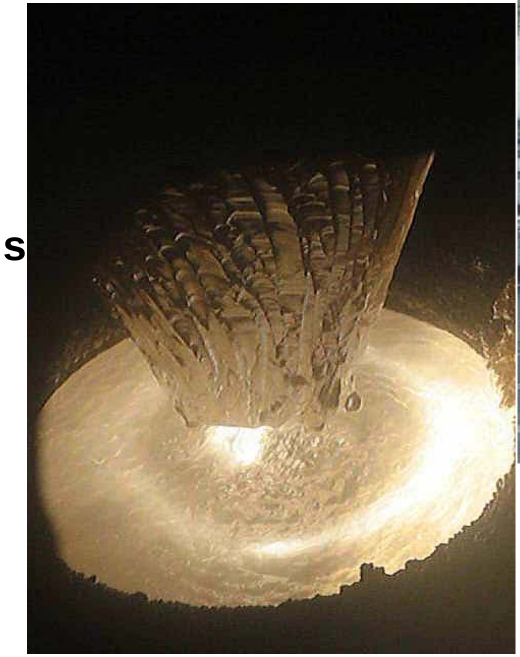
Material

- Niobium (Nb) (Tc=9.2 K; superheating field of approx. 240 mT) is the favorite material for the fabrication of superconducting RF cavities.
- chemically inert (pentoxide layer)
- easily machined and deep drawn
- available as bulk and sheet material
- majority of s.c. RF cavities worldwide are formed from Nb sheet material

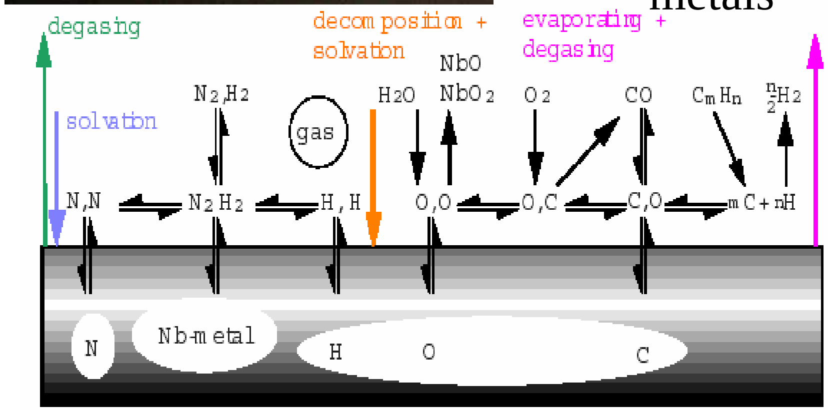
Mass production of high purity Nb for RF cavities



Electron Beam melting of Nb

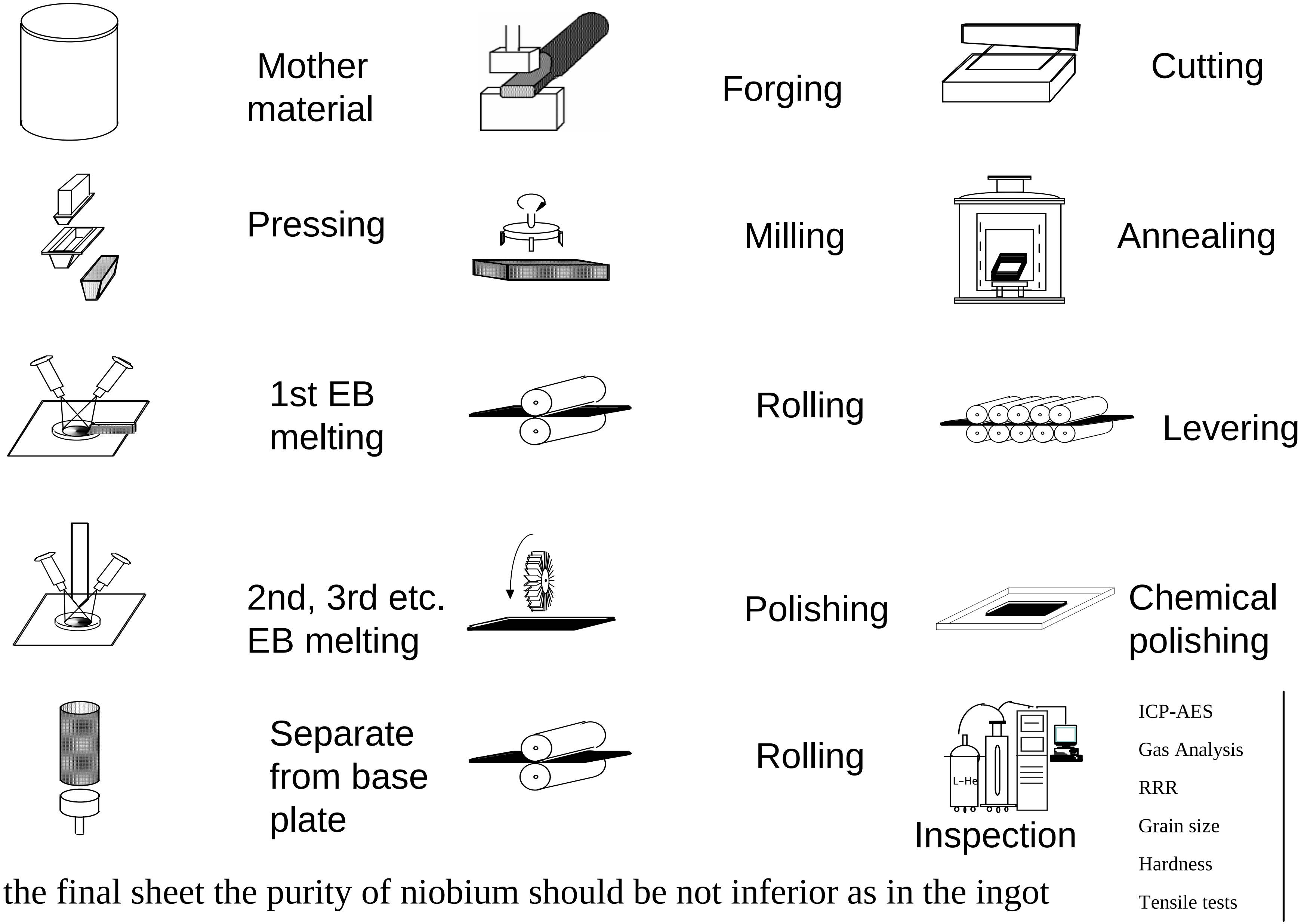


EB furnace for melting of refractory metals



The melting temperature is a compromise between the maximization of purification and minimization of the material losses by evaporation.

Fabrication of Nb sheets at Tokyo Denkai



In the final sheet the purity of niobium should be not inferior as in the ingot

TD equipment for the quality control of high purity niobium

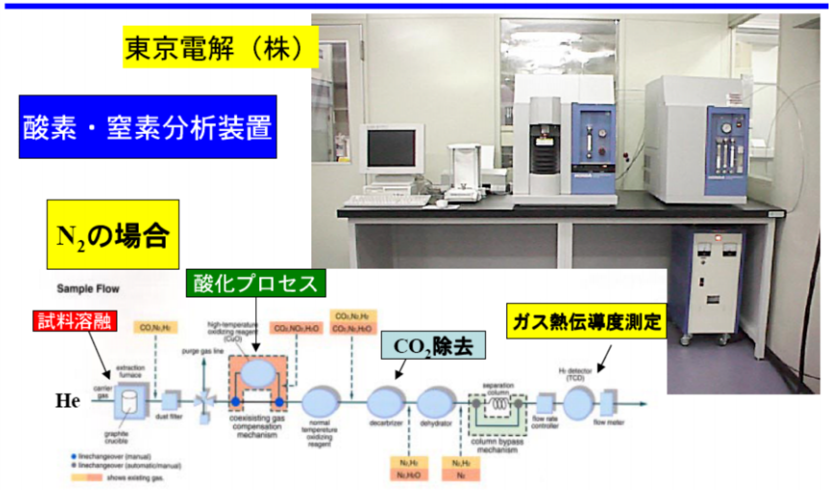
RRR measurement

東京電解（株）

東京電解（株）

Tensile test

Gas analysis



Gas analysis (Hydrogen, Oxygen, Nitrogen) ：HORIBA

Could you please test the sugar content in my coffee

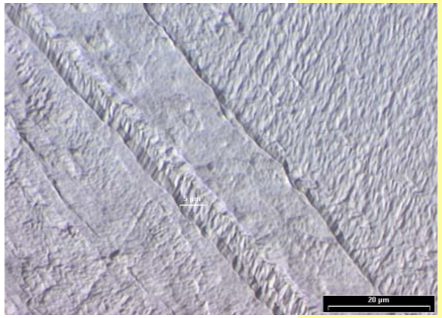
Technical Specification to Niobium Sheets for XFEL Cavities.

Concentration of impurities in ppm (weight)				Mechanical properties	
Ta	≤ 500	H	≤ 2	RRR	≥ 300
W	≤ 70	N	≤ 10	Grain size	≈ 50 μm
Ti	≤ 50	O	≤ 10	Yield strength, $\sigma_{0,2}$	$50<\sigma_{0,2}<100$ N/mm^2 (Mpa)
Fe	≤ 30	C	≤ 10	Tensile strength	> 100 N/mm^2 (Mpa)
Mo	≤ 50			Elongation at break	30 %
Ni	≤ 30			Vickers hardness HV 10	≤ 60

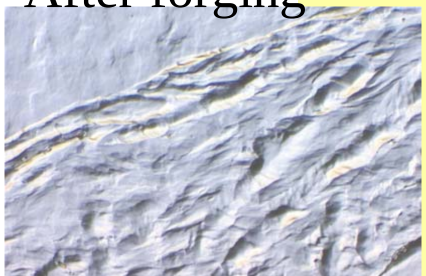
No texture: The difference in mechanical properties (Rm, Rp0,2, AL30) orthogonal and parallel to main rolling direction < 20% (cross rolling).

Structure of Nb on different stages of sheet production

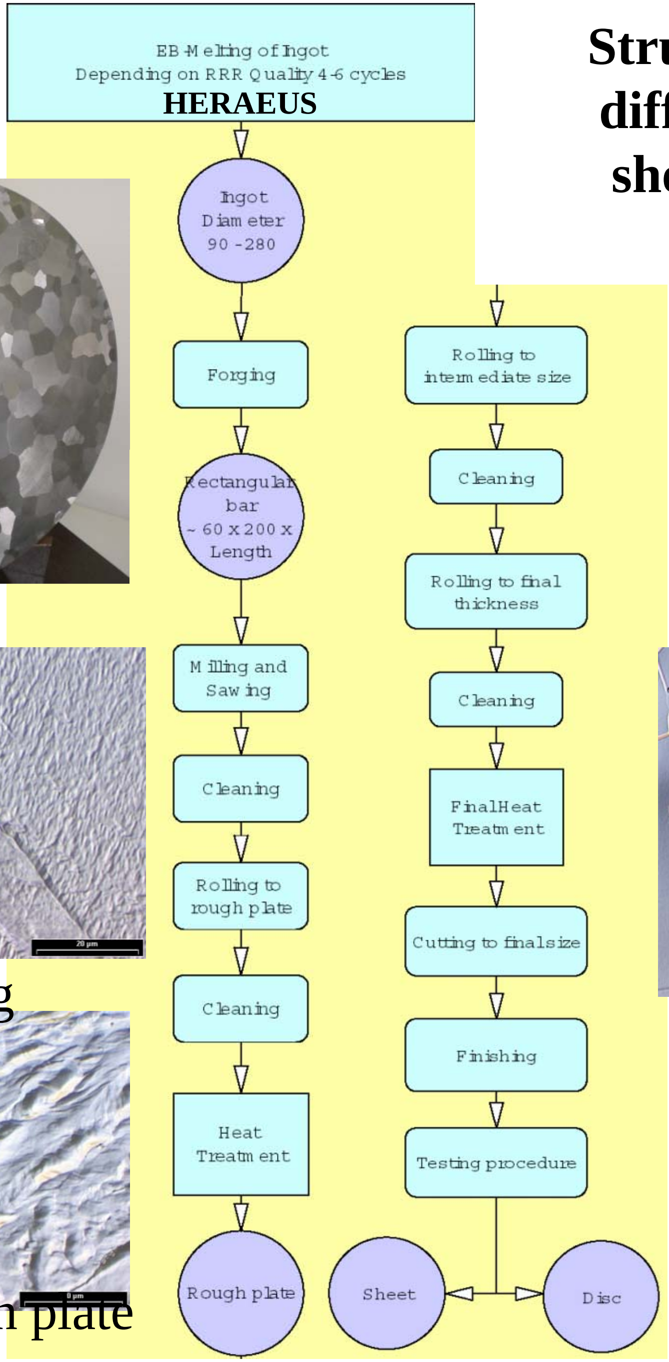
Ingot

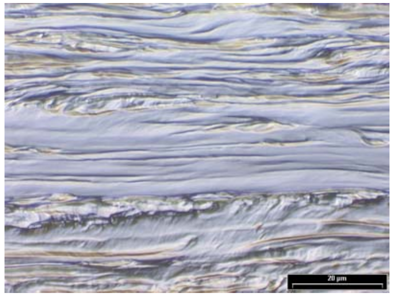


After forging

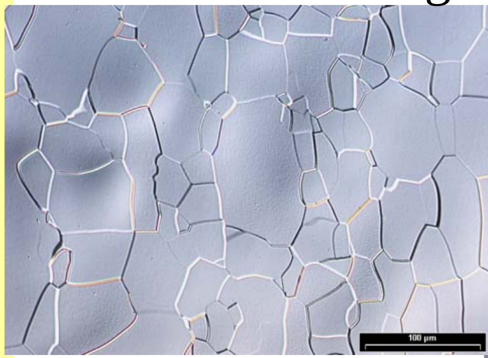


Rolled rough plate

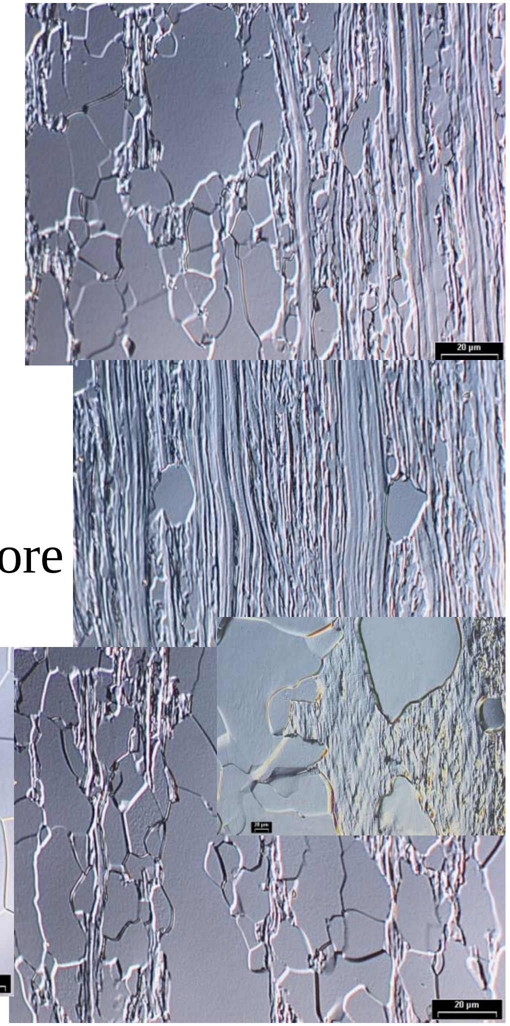




Rolled Nb sheet before final annealing

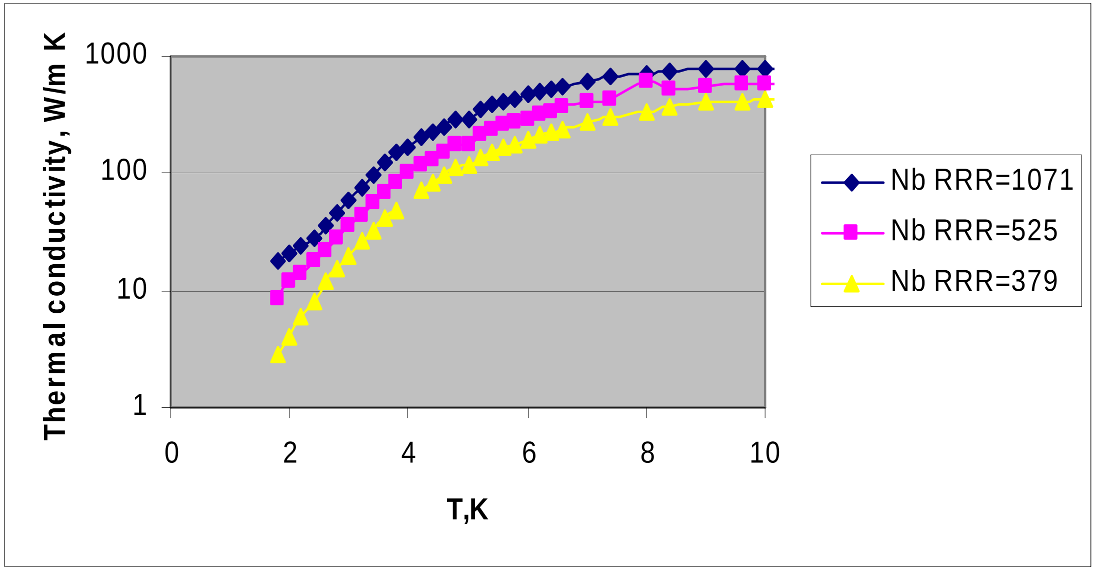


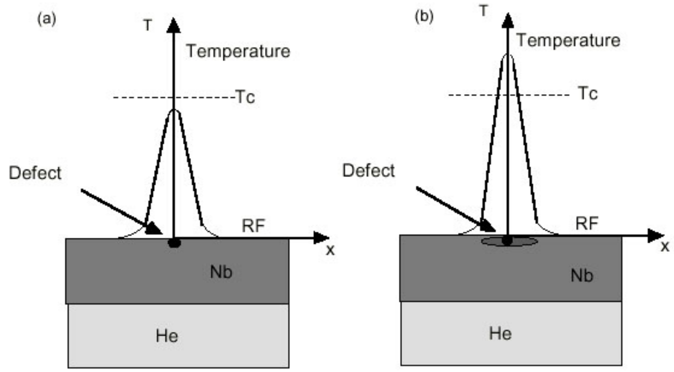
Recrystallized niobium sheet



Examples of bad recrystallization

Task: starting with cm size grain of ingot finish with ca. 50 µm uniform grain without contamination of Nb





Thermal conductivity of high purity Nb at low temperatures

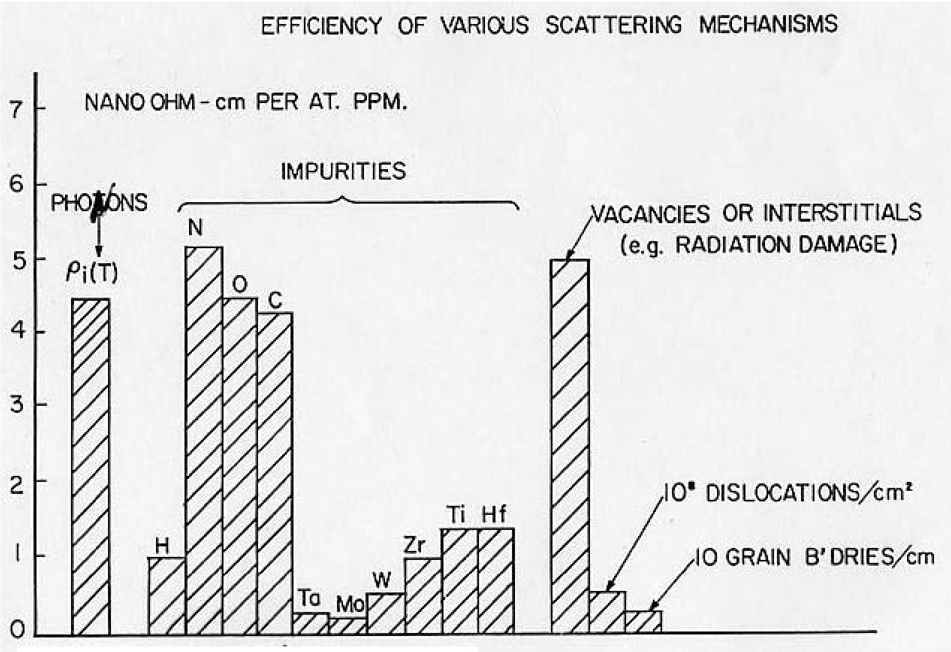
Normal conducting cluster triggers the quench, if the temperature exceeds Tc

Rule of thumb

$$\lambda(4{,}2K) = C \cdot \left(W/_{m \cdot K}\right) \cdot RRR$$

$$C \approx 0{,}25 \div 0{,}14$$

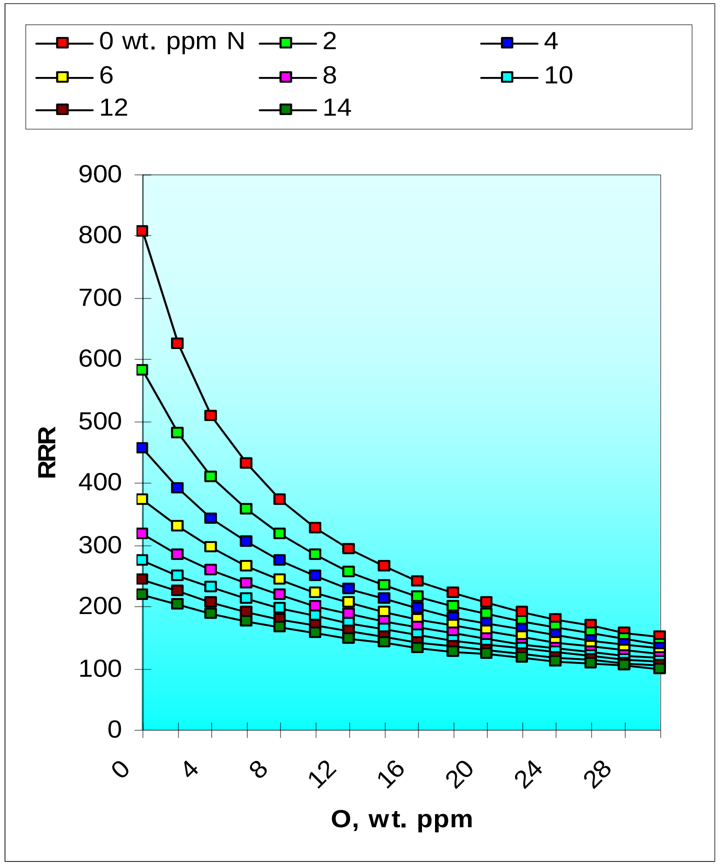
Influence of impurities on RRR



Contribution of different defects in the scattering mechanism (Schulze)

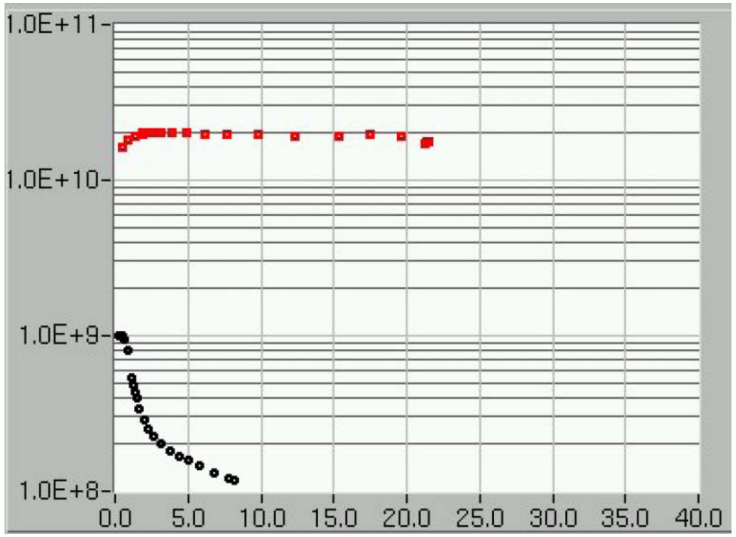
$$RRR = \frac{R(300K)}{R(10K) + \sum_{i=1}^{4} \frac{\partial R_i}{\partial C_i} C_i}$$

R(300K)=1,46.10-5 Ω cm, R(10K)=8,7.10-9 Ω cm, C=1 wt. ppm

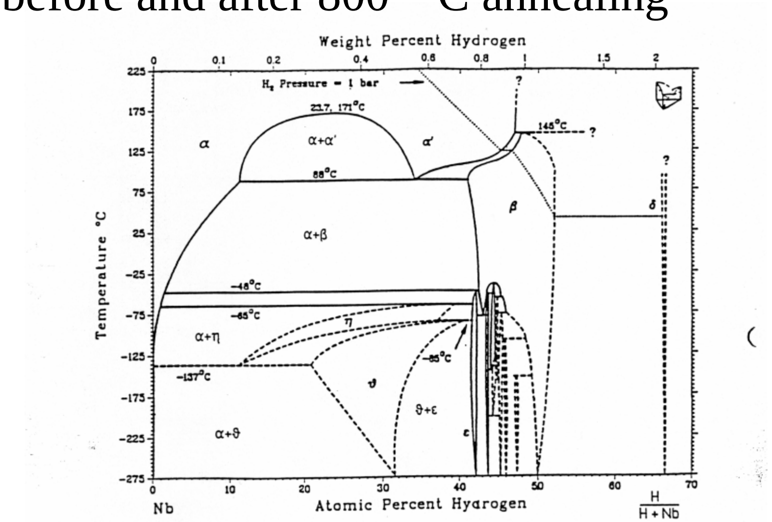


Calculated RRR versus oxygen and nitrogen content.

Hydrogen Q decease



Q(Eacc) of Single crystal cavity1AC6 before and after 800° C annealing



NbH phase diagram

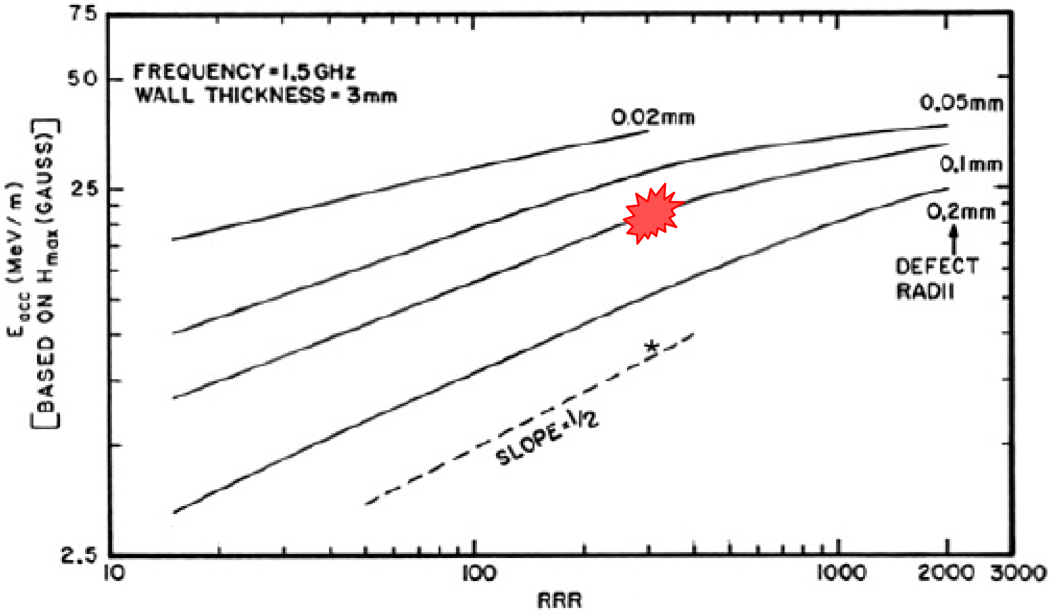
A slow cool down through 75 – 150 K caused the Qo disease. A fast cool down usually prevents the Qo disease

The longer the system is parked in the danger zone the worse the *Q* degradation

Warm up restored each time the maximal quality factor Qo

Reason: Hydrogen is very mobile at room temperature and even at 100K. During cool down the former dissolved hydrogen creates the Nb hydrides at the surface and produces high RF losses. (Nb - hydride has Tc=2,8 K, Hc= 60 Oersted) A fast cool down prevents hydride formation. At low temperature diffusion is slower and phase transition takes time

Quench field caused by local defect



Simulation of the thermal break down (Quench)

$$H_{tb} = \sqrt{\frac{4\kappa_T (T_c - T_b)}{r_d R_d}}$$

Scanning allow to avoid rough errors

κT: Thermal conductivity Nb

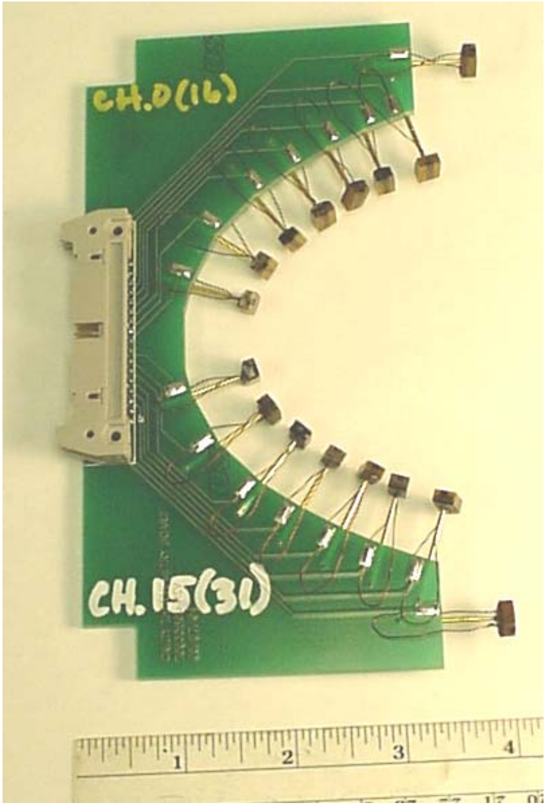
Rd: Surface resistance of the defect

Tc: Critical temperature of Nb

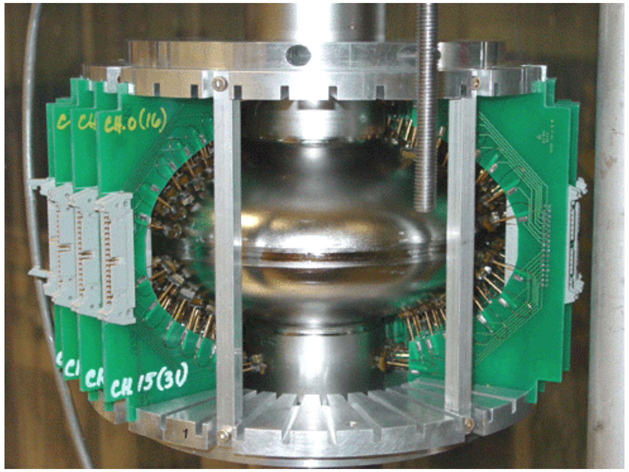
*T*b: Bath temperature

rd: Radius of defects

T-Mapping

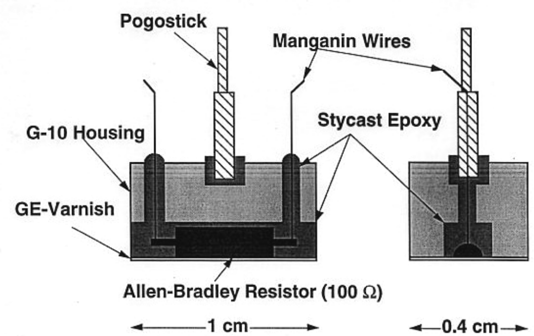


CH.0(16)
CH.15(31)
1
2
3
4



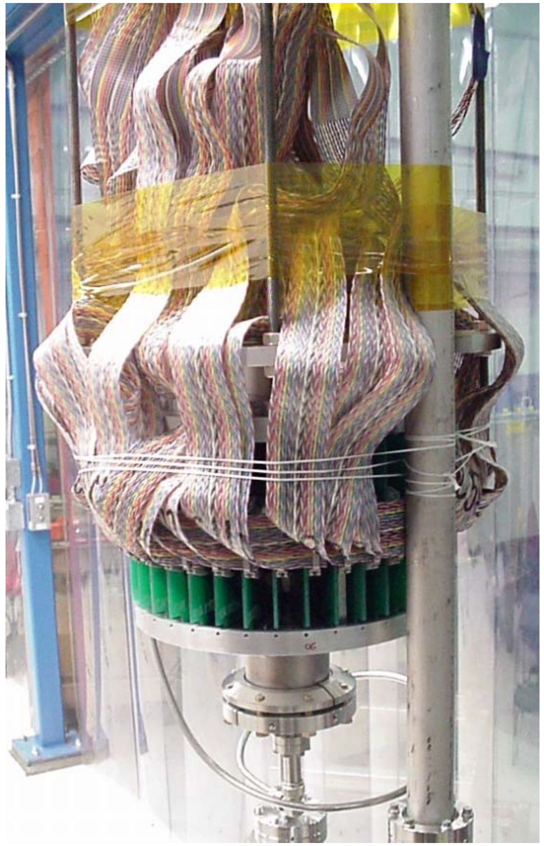
CH.0(16)
CH.15(31)

a)

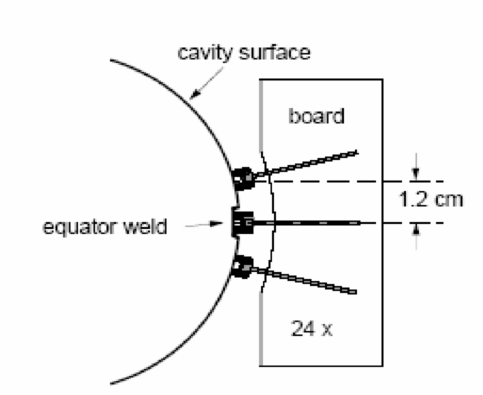


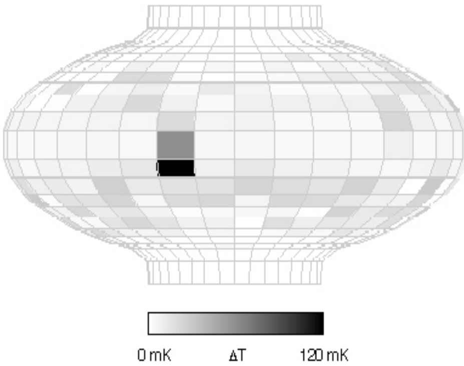
Pogostick
Manganin Wires
G-10 Housing
Stycast Epoxy
GE-Varnish
Allen-Bradley Resistor (100 Ω)
1 cm
0.4 cm

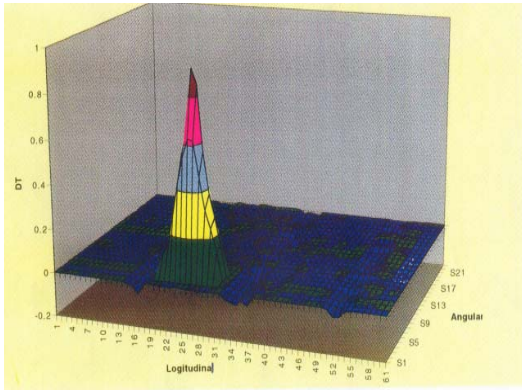
b)



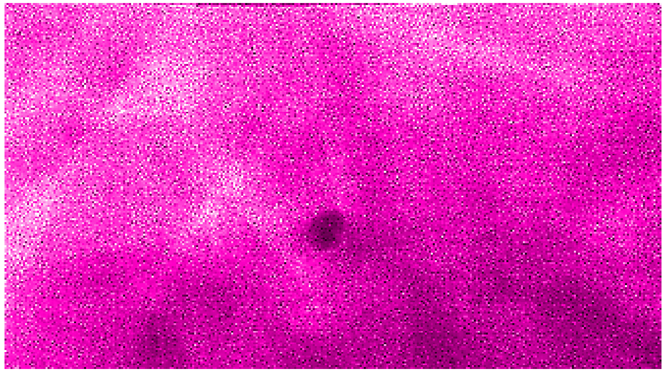
Foreign material inclusions





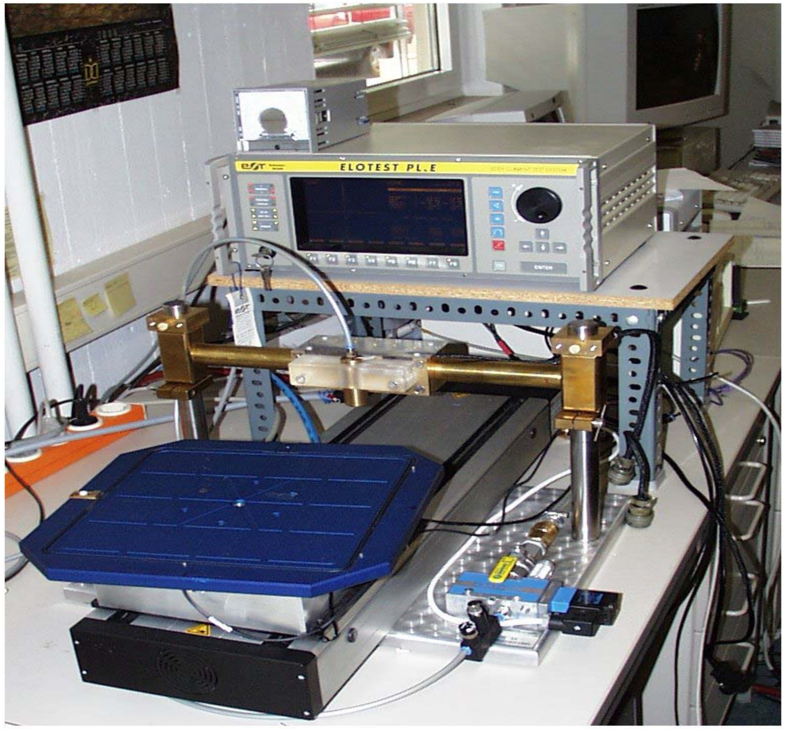


Temperature mapping: Cavity D6 with Eacc=13 MV/m shows excessive heating at a localized spot

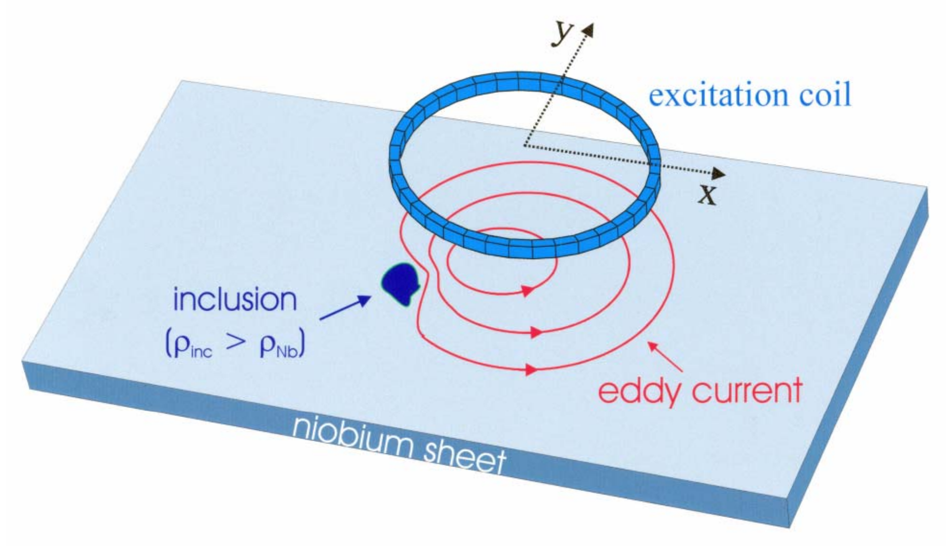


Positive print of a X-ray radiograph showing the "hot spot" as a dark point (0.2 mm large Ta inclusion).

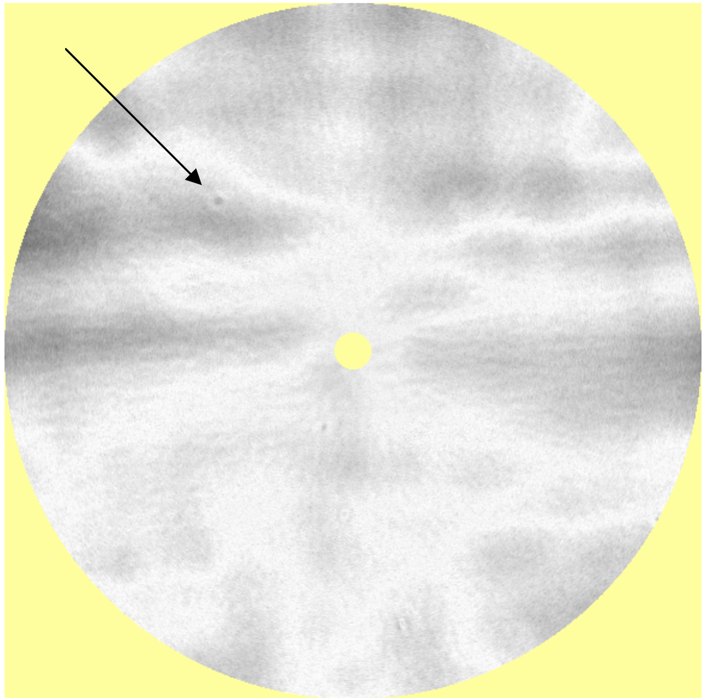
Search for clusters in Nb sheets.
Eddy current system.



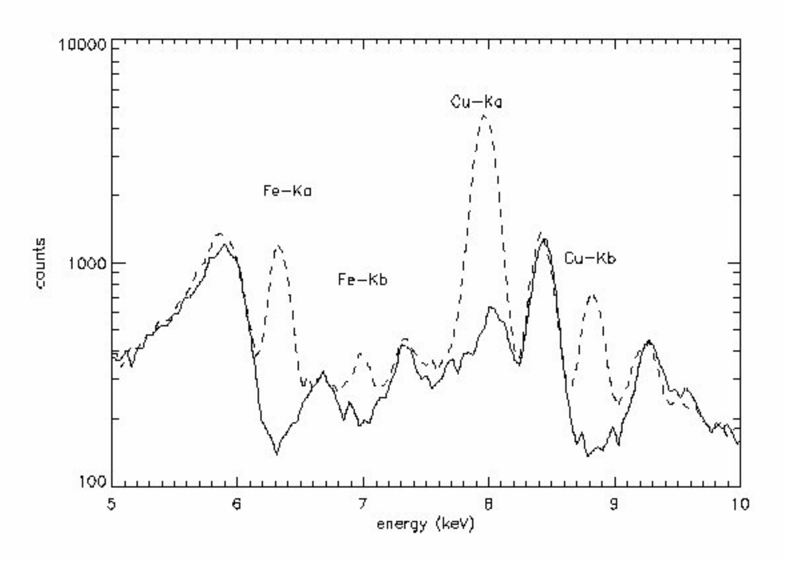
DESY eddy current scanning apparatus for niobium discs. 100% Nb sheets for TTF scanned and sorted out



Principle of eddy current measurement



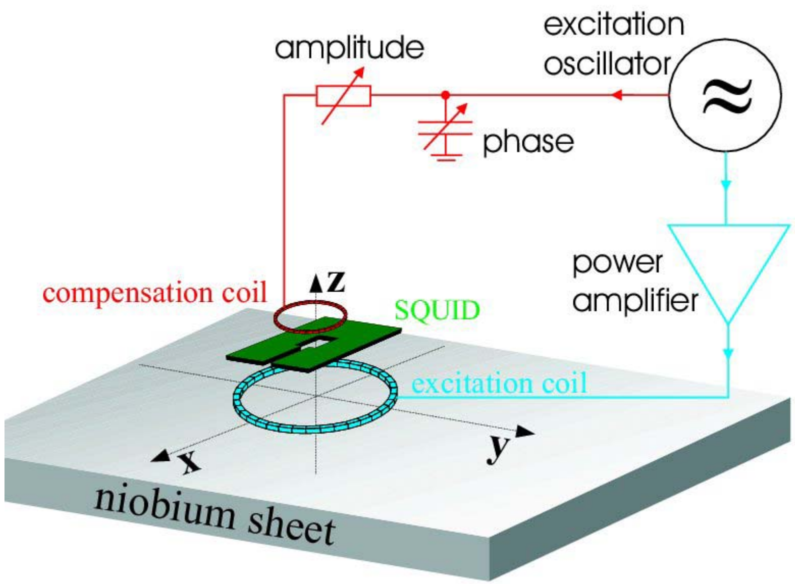
Example of the Nb sheet eddy current scanning test. Arrow indicates the suspicious spot.



SURFA (Synchrotron Radiation Fluorescence Analysis). Spectrum of K-lines at the spot area (dashed line) in comparison with spot free area (full line).

The spot was identified as an inclusion of foreign material. Cu and Fe signal has been observed in the SURFA spectrum in the spot area.

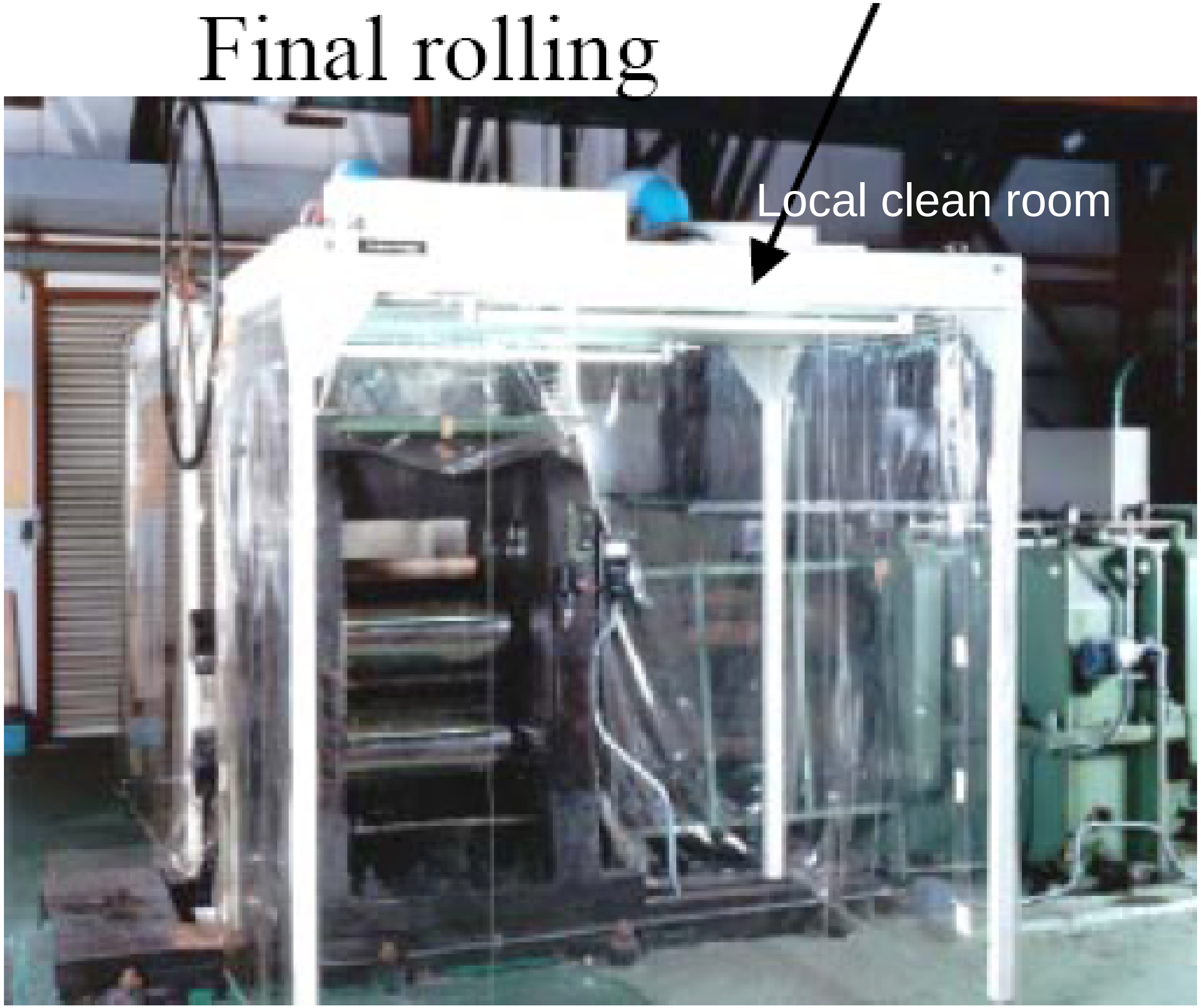
Development of SQUID based scanning system for testing of niobium sheets



An excitation coil produces eddy currents in the sample, whose magnetic field is detected by the SQUID.

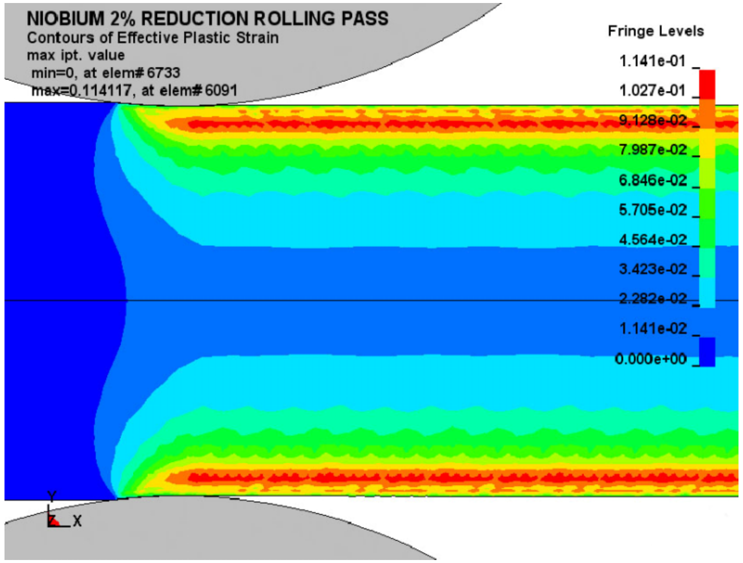
Prototype of SQUID based scanning system for niobium sheets (in work)

Final rolling

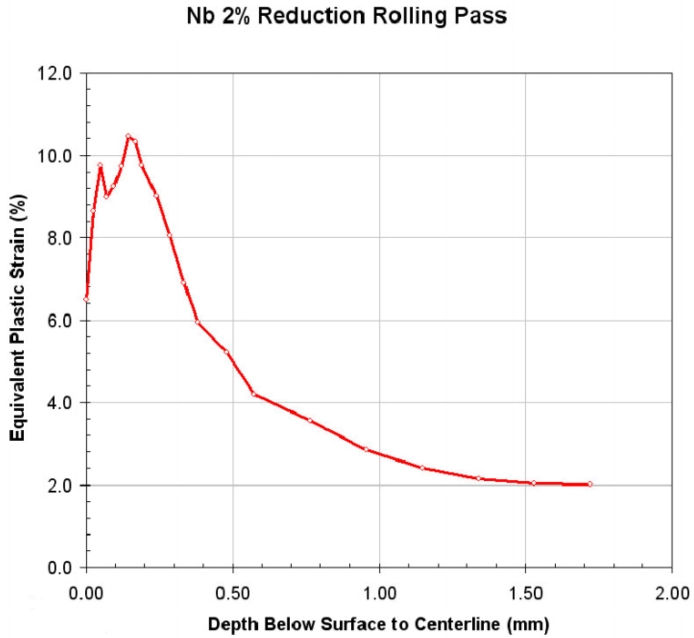


Example of the companies feed back : Tokyo Denkai improved the cleanness around of the rolling equipment

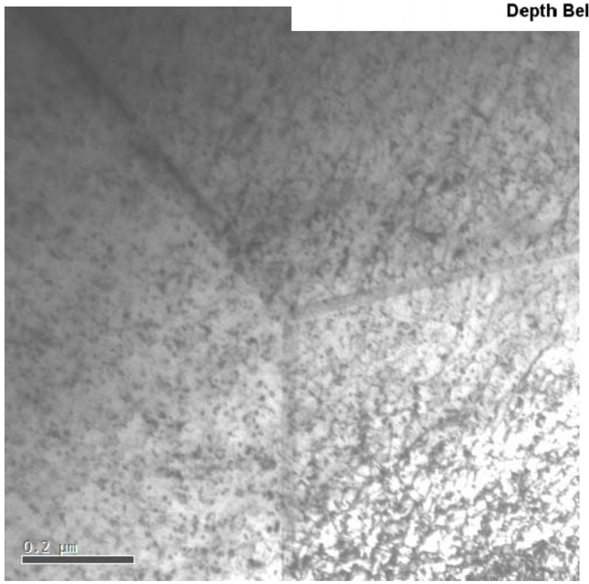
Damage layer by rolling (R. Crooks)



Finite element simulation of 2% reduction of 3.5 mm sheet with 1 cm diameter rolls. Strain is concentrated in the near-surface region



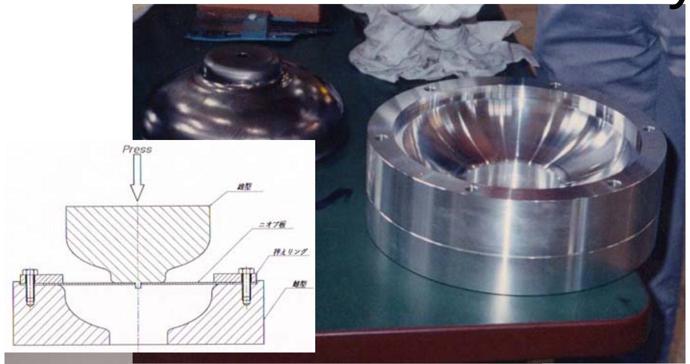
As-received RRR Nb Sheet, 20 µm below surface (ion milled thin foil)



Transmission electron microscopy image (BFTEM)

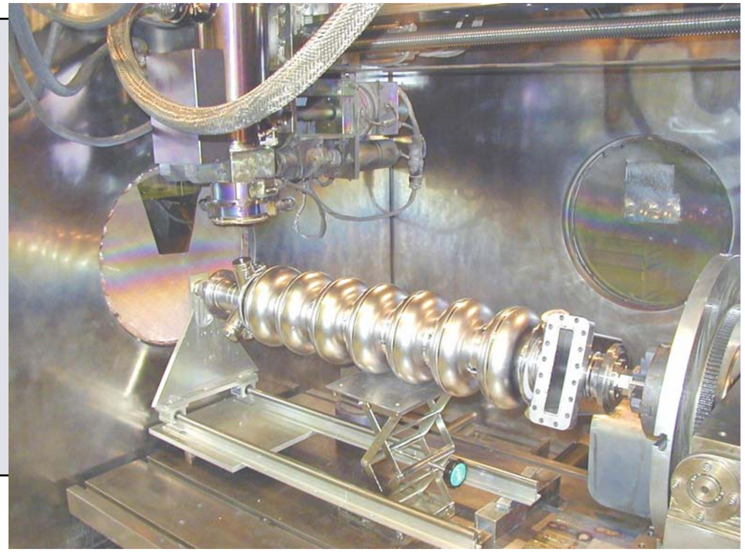
High dislocation density.

Fabrication: Conventional fabrication (deep drawing and EB welding of fine grain Nb). Experiences of ca. 20 years of industrial cavity fabrication are available



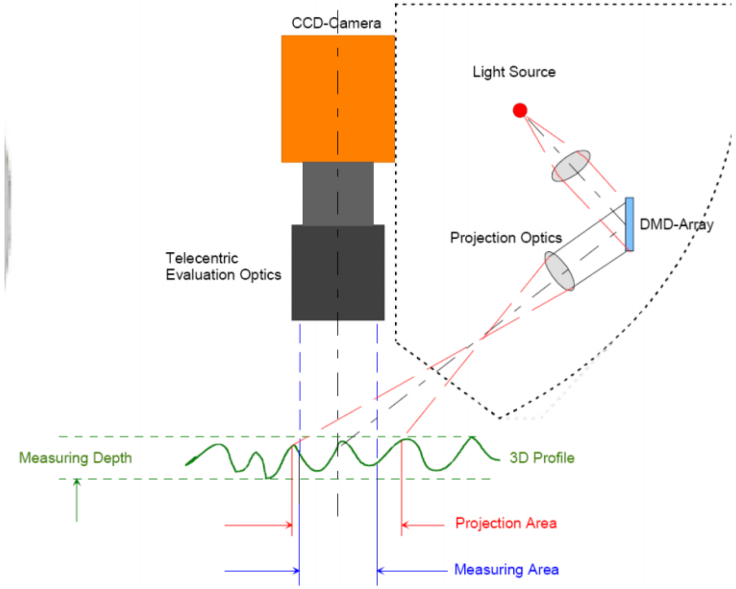
Half cells are produced by deep drawing.

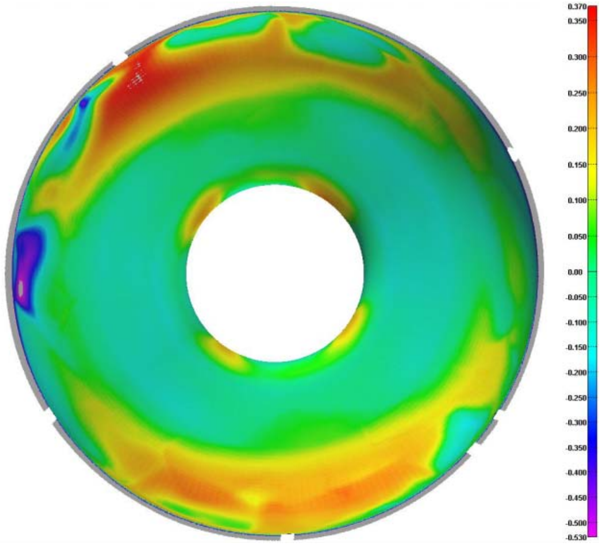
Dumb bells are formed by electron beam welding.

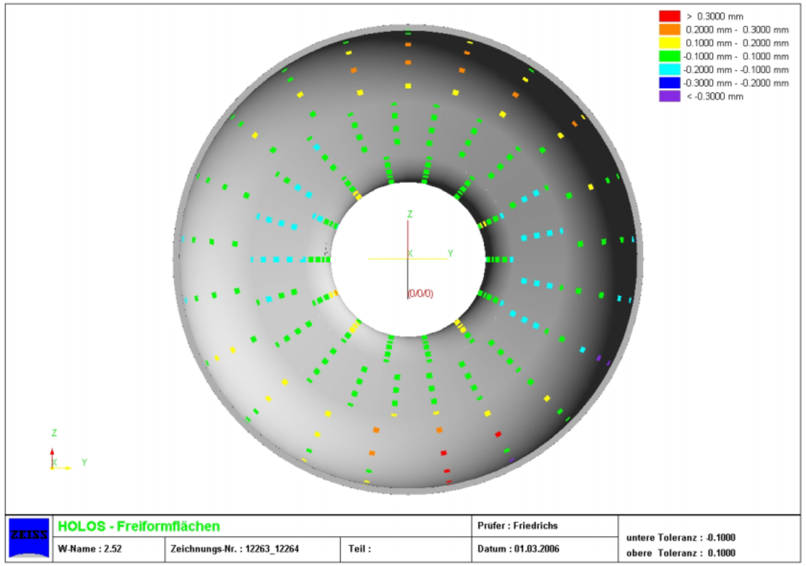


After proper cleaning eight dumb bells and two end group sections welded by electron beam together

Important: clean conditions on all steps
shape accuracy, preparation and EB welding



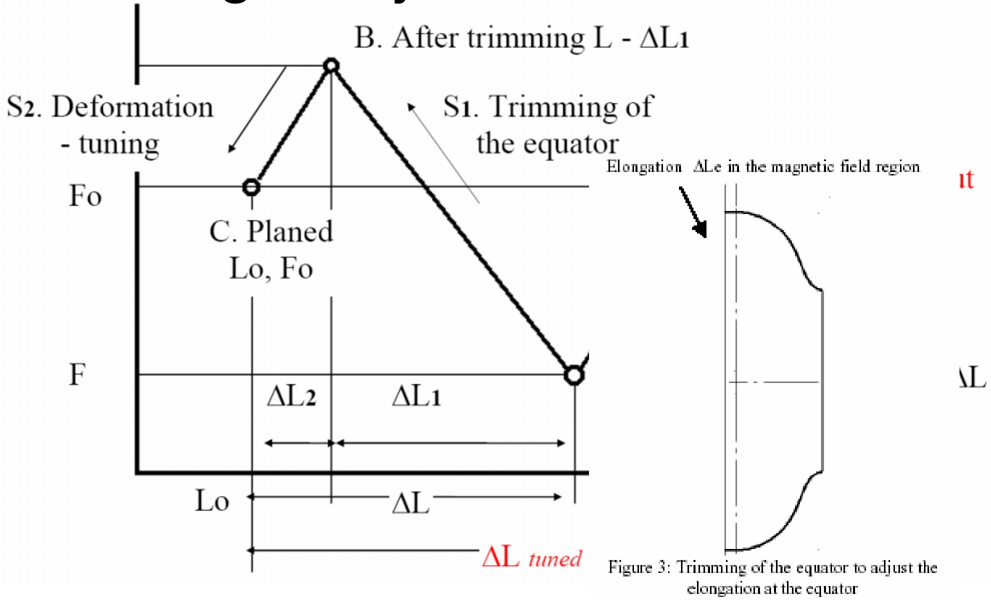




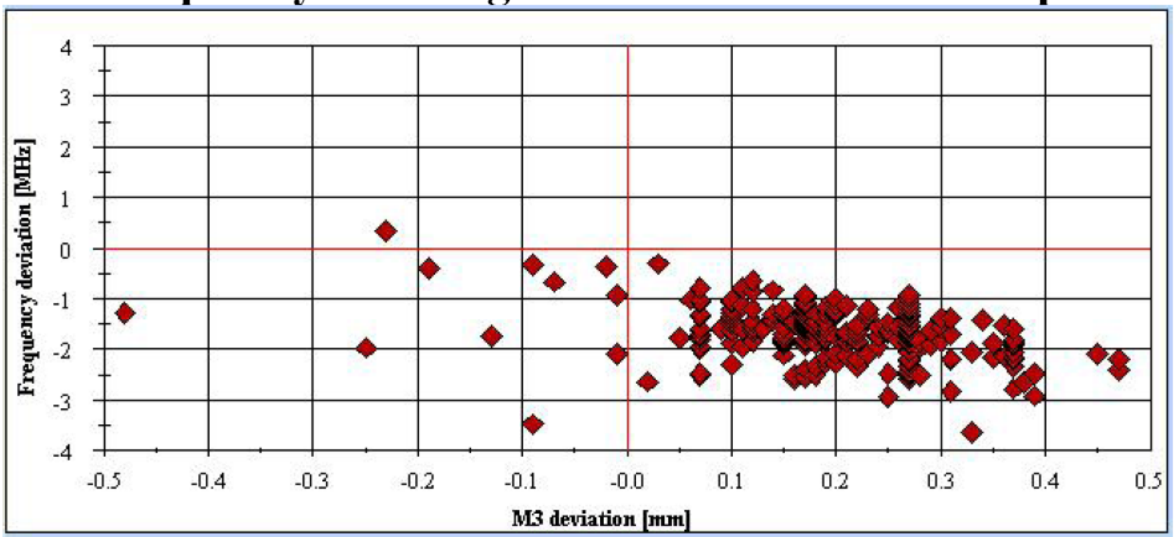
Optical and mechanical 3D measurement measurements of the HO52 half cell shape

W. Singer. Tutorial 4a2. 13th International Workshop on RF Superconductivity, October 15-19, 2007, Beijing, China

Frequency and the length adjustment

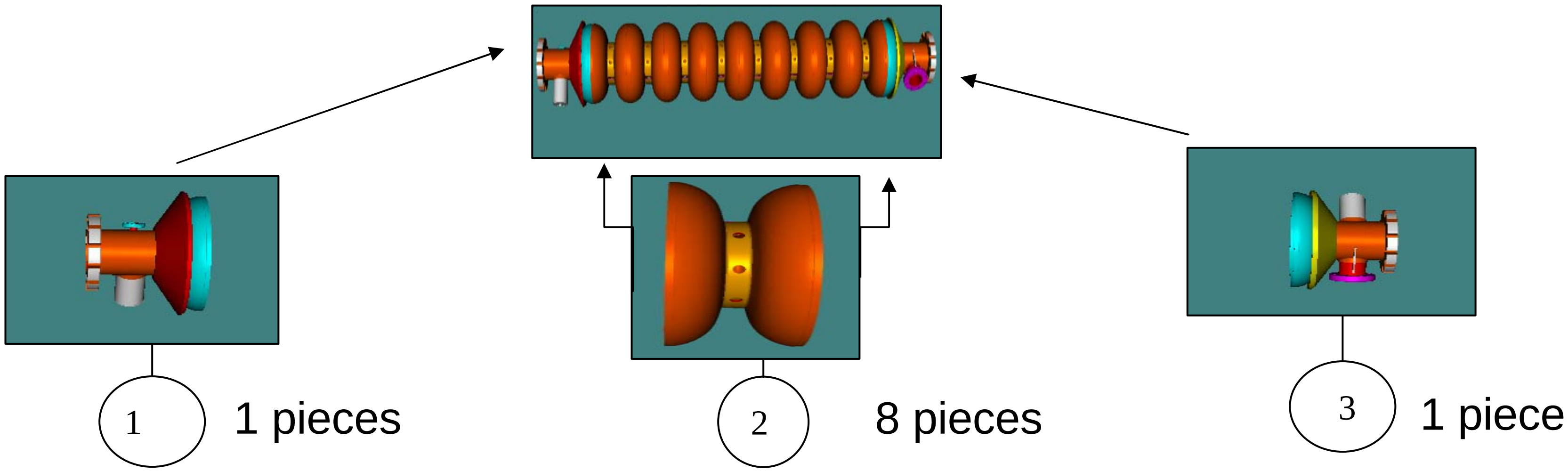


Frequency and length deviation of middle cups



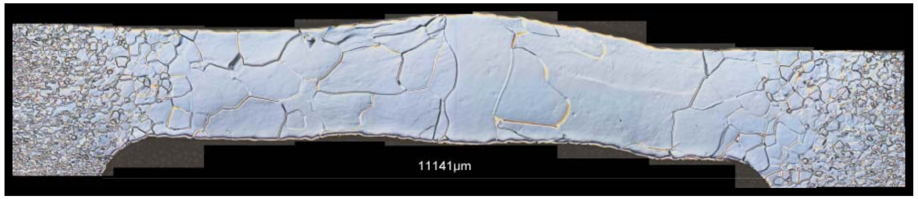
Wah Chang (EDMS-DB)

Cavity welding: the general way
There are differences of welding processes in industry

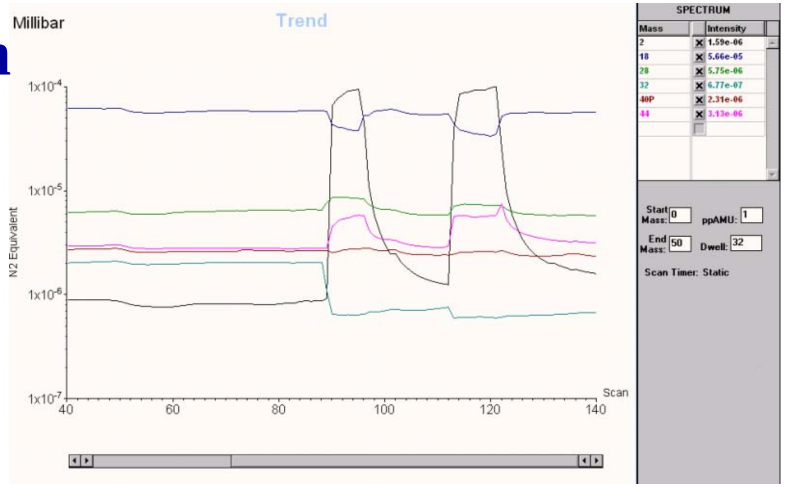


1. Degreasing and rinsing of parts
2. Drying under clean condition
3. Chemical etching at the welding area (Equator)
4. Careful and intensive rinsing with ultra pure water
5. Dry under clean conditions
6. Install parts to fixture under clean conditions
7. Install parts into electron beam (eb) welding chamber
   (no contamination on the weld area allowed)
8. Install vacuum in the eb welding chamber <= 1E-5 mbar
9. Welding and cool down of Nb to T< 60 C before venting
10. Leak check of weld

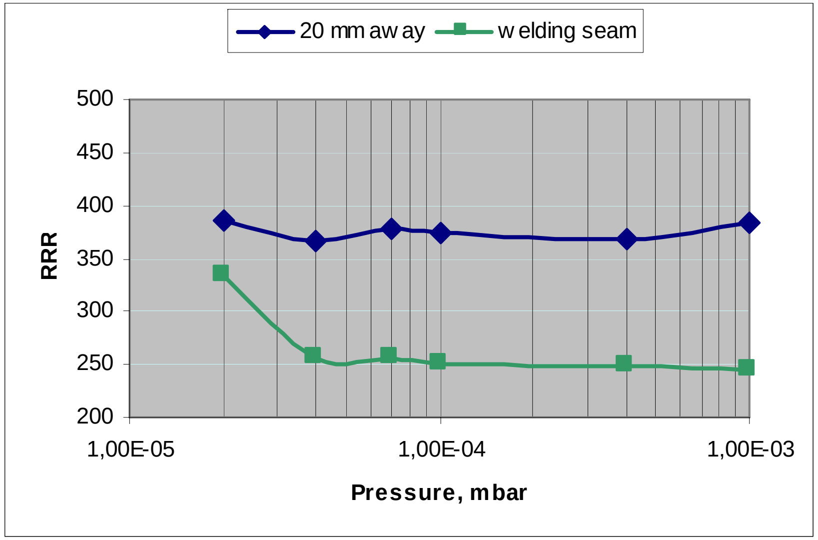
Electron beam welding of niobium



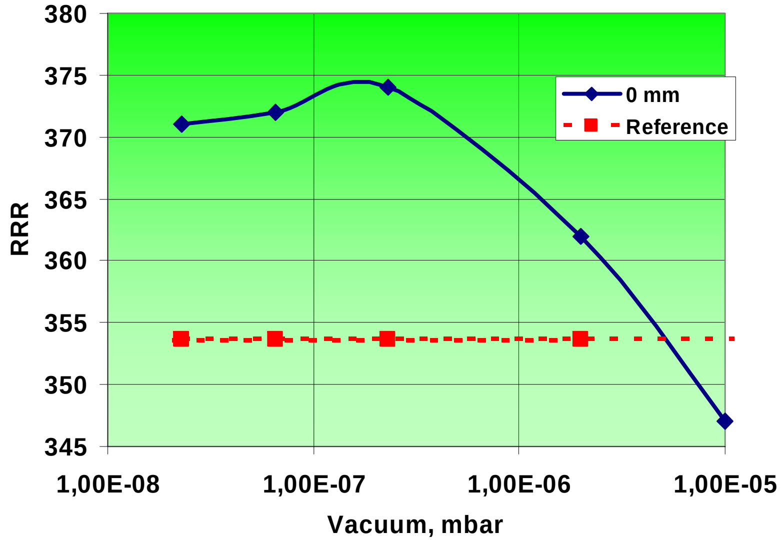
Microstructure of the EB welding area.
The grain size G=50 ÷ 2000 µm



Partial pressure in the EB chamber (CERCA) during welding of Nb300sample



RRR in the welding seam and 20 mm away versus pressure in the chamber during EB welding

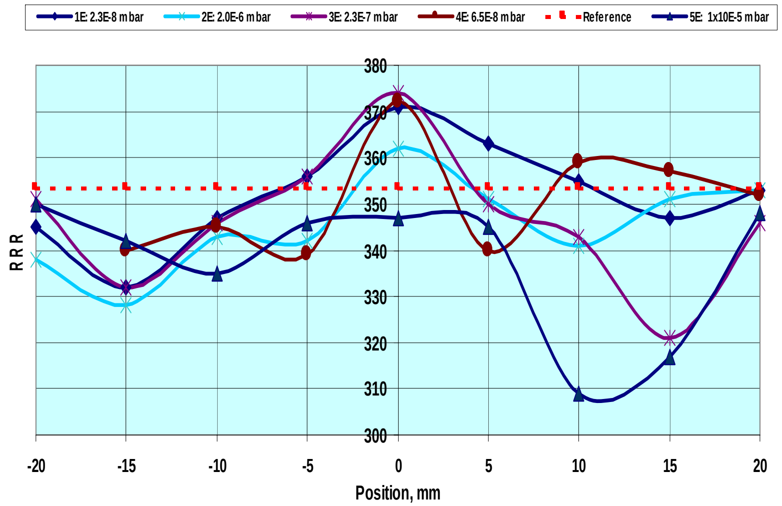


RRR in the welding seam versus pressure in the welding chamber

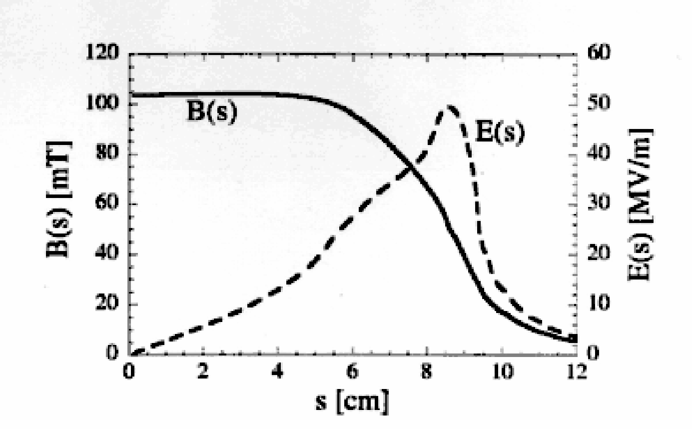
The RRR degradation at welding seam started since pressure of ca. 10-5 mbar.

RRR degradation

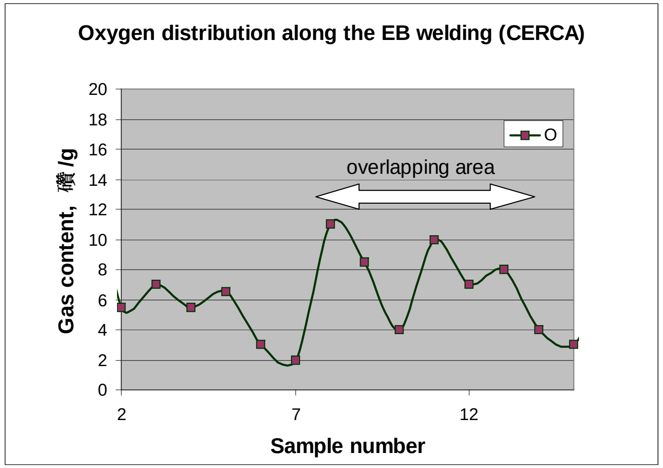
The RRR degradation can take place in the welding seam itself, but also in the thermally affected area and overlapping



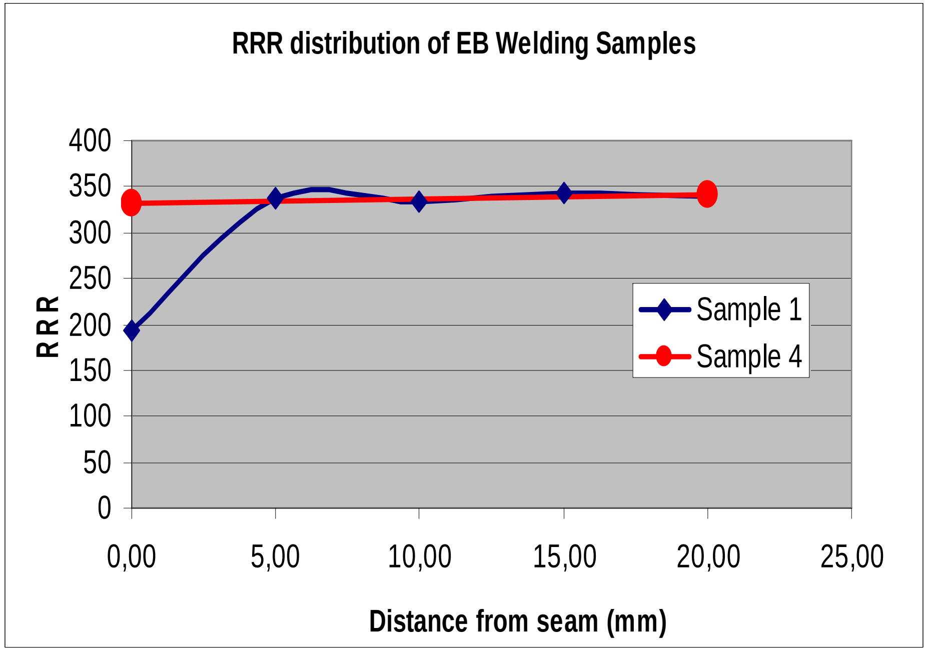
RRR in the EB welding area versus distance from the welding seam at different pressures of DESY EB facility



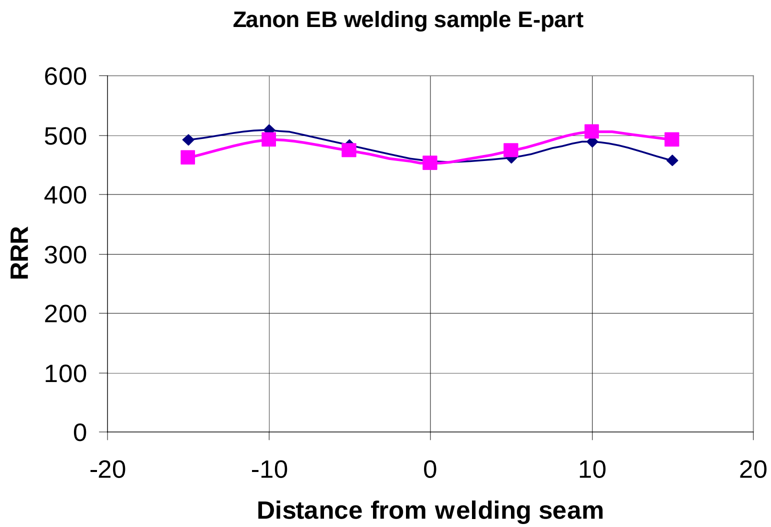
Distribution of the magnetic and electrical field from equator to the iris on the surface of the TESLA cavity Thermally affected area of the welding seam can be critical for break down.



Oxygen distribution along the welding seam. RRR= 280 in the welding seam and RRR= 207 in the overlapping.

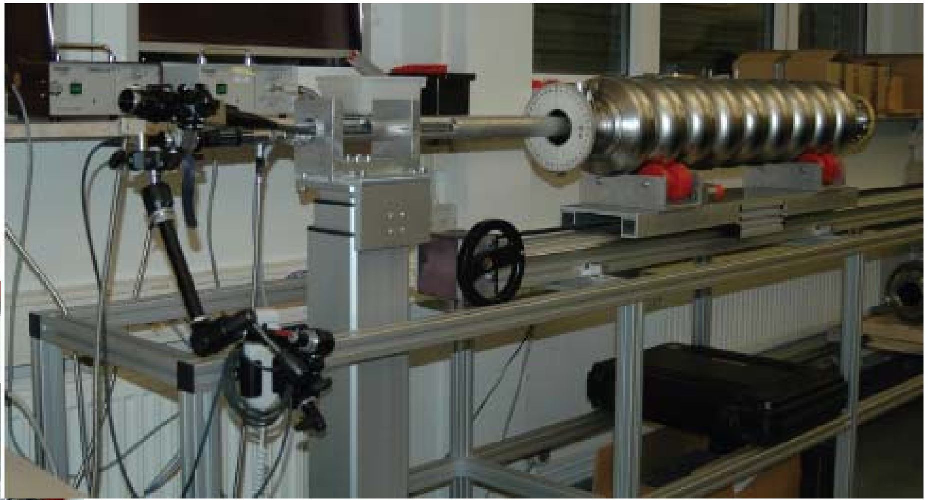


RRR in the welding seam area with (sample 4) and without (sample 1) of Nb evaporation in the EB chamber (Julich)



RRR in the welding seam of the welded sample RRR=485

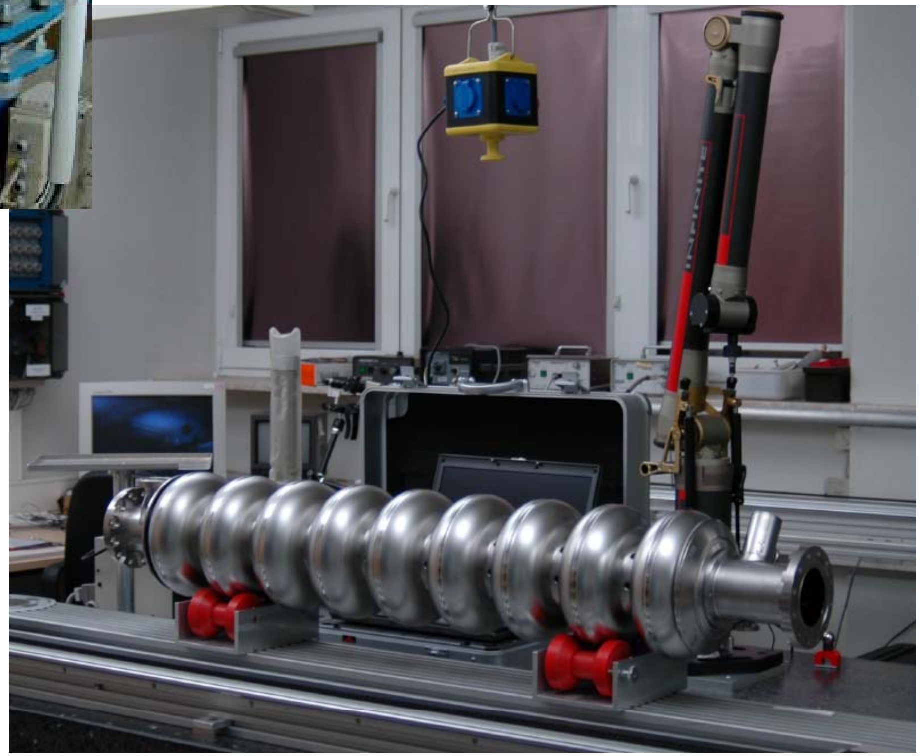
The RRR degradation at welding seam started since pressure of ca. 10-5 mbar. The vacuum conditions for EB welding of cavities are specified.



Optical control of the inside surface

Eccentricity measurement

Dimensions check



Fabrication of large grain LG cavities

Possible advantages (hope):

- Cost effective
- Higher purity. RRR=600 of ingot is achievable
- No danger that during many steps from ingot to sheet the material will be polluted.
- Simplified quality control (reduced number of measurements: grain size, eddy current scanning etc.)
- Higher thermal conductivity at low temperatures (phonon peak)
- Less RF losses on grain boundaries. Fine grain Nb sheet corresponds to length ~ 3000 m, LG Nb disc corresponds to length ~ 3 m (B. Spaniol, Linac2006)
- Seems to be less susceptible to field emission
- Seems that the baking at 120° C works better after BCP (compare to fine grain BCP)

LG DESY: Fabricated several single cell and three LG 9-cell cavities at ACCEL from HERAEUS material (AC112-AC114)

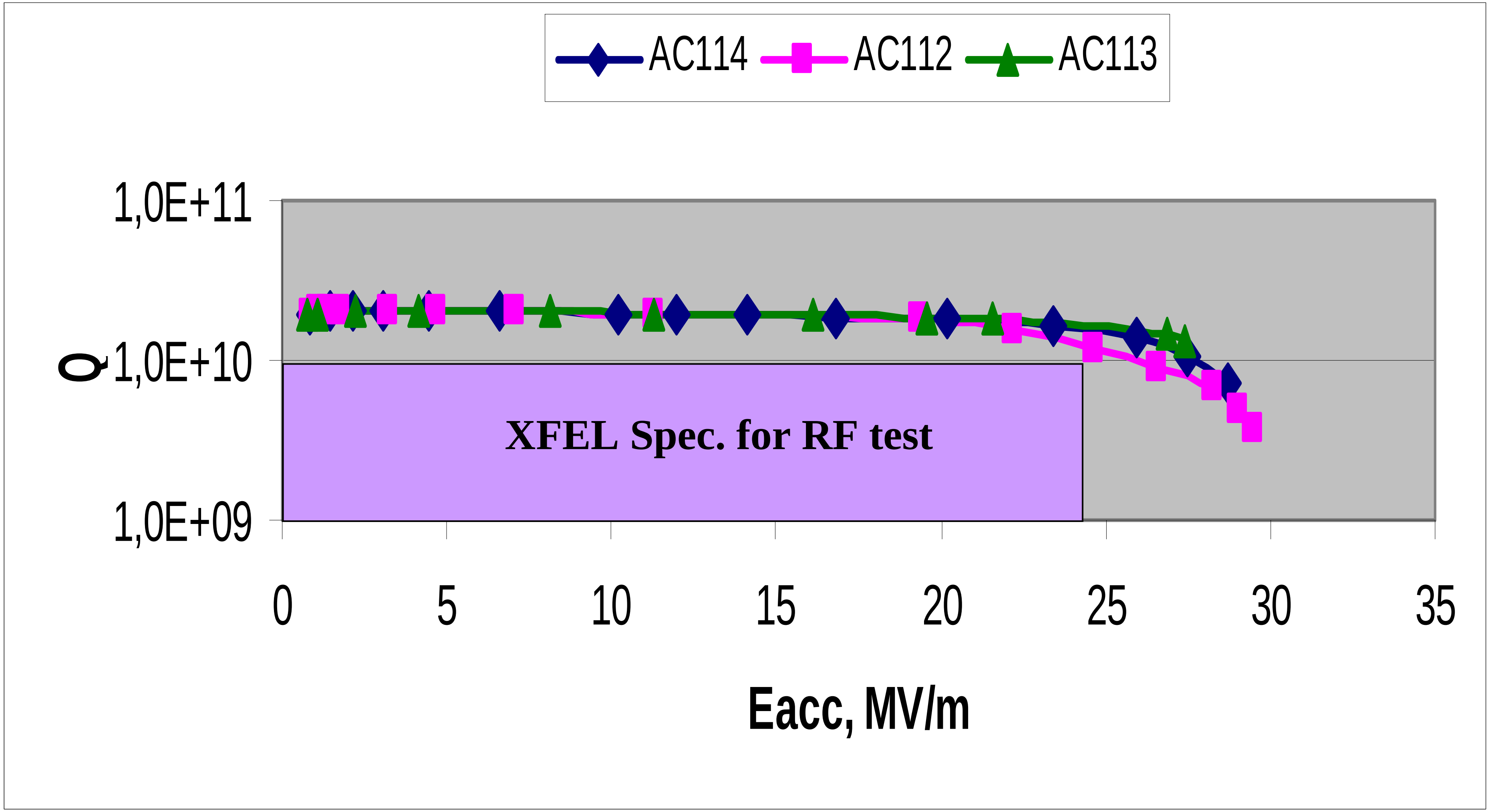
Fabrication:

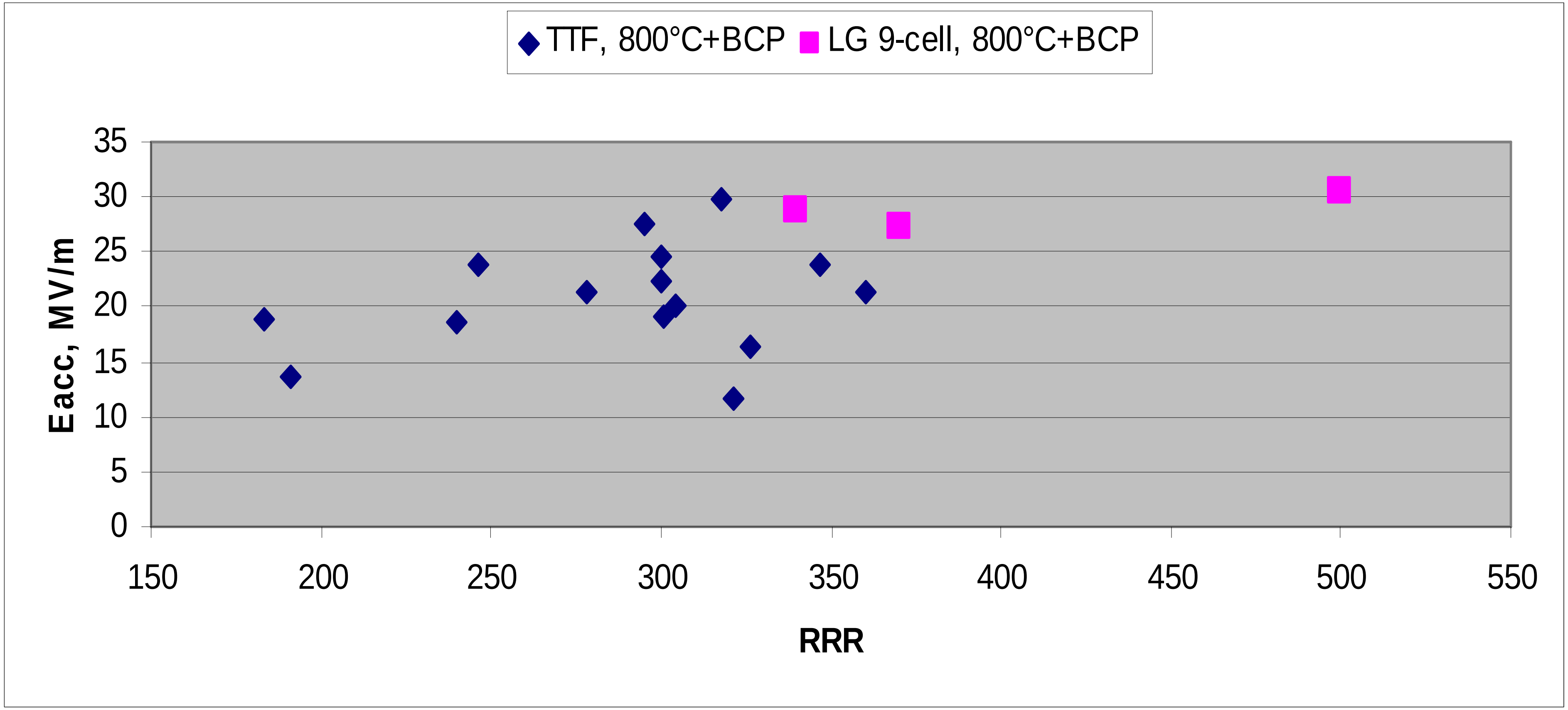
- **disc of HERAEUS cut by diamond saw (B.Spaniol,LINAC 2006, TUP024)**
- **Discs scanned only for two cavities.**
- **Deep drawing**
- **Machining**
- **EB welding**
- **No grinding of grain boundaries**

- No problems at EB welding
- Very smooth (shiny) surface in grain areas after BCP;
- the steps at grain boundaries are more pronounced as in polycrystalline material

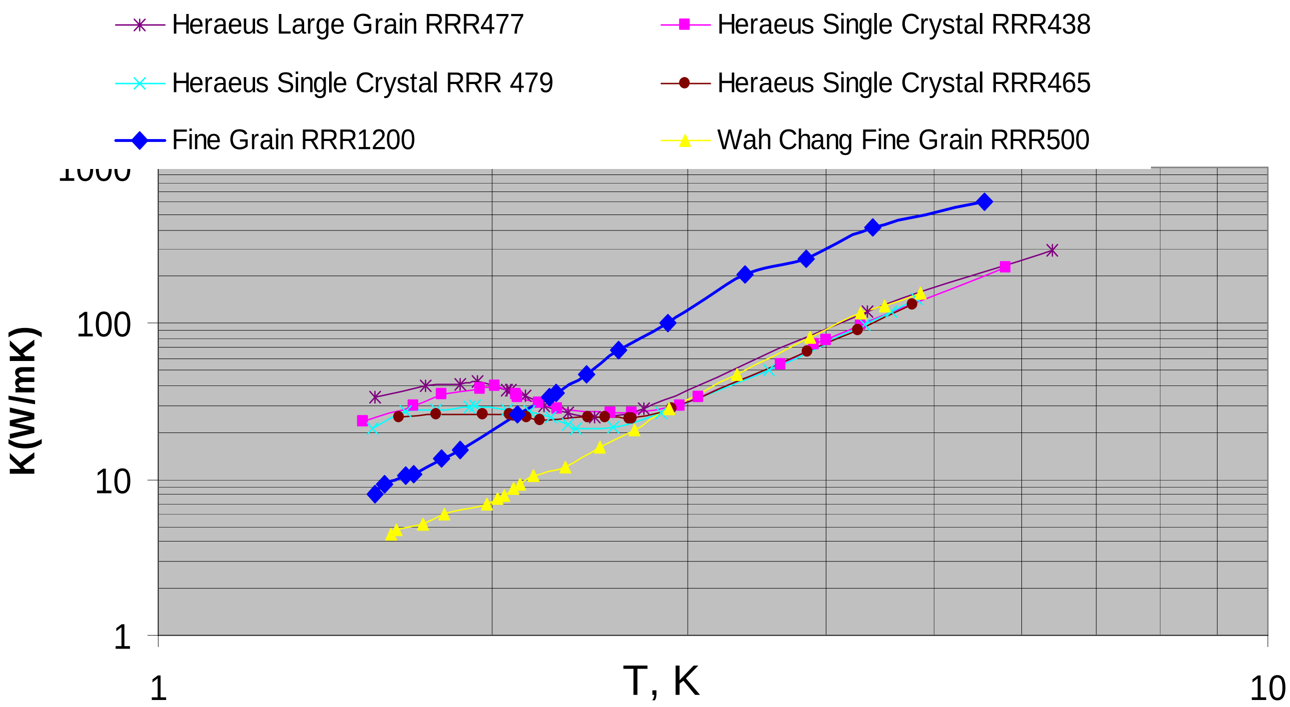
Preparation and RF tests

First test Q(Eacc) curve of the LG nine cell cavities AC112-AC114 at 2K after 100 µm BCP, 800° C, 20 µm BCP, HPR



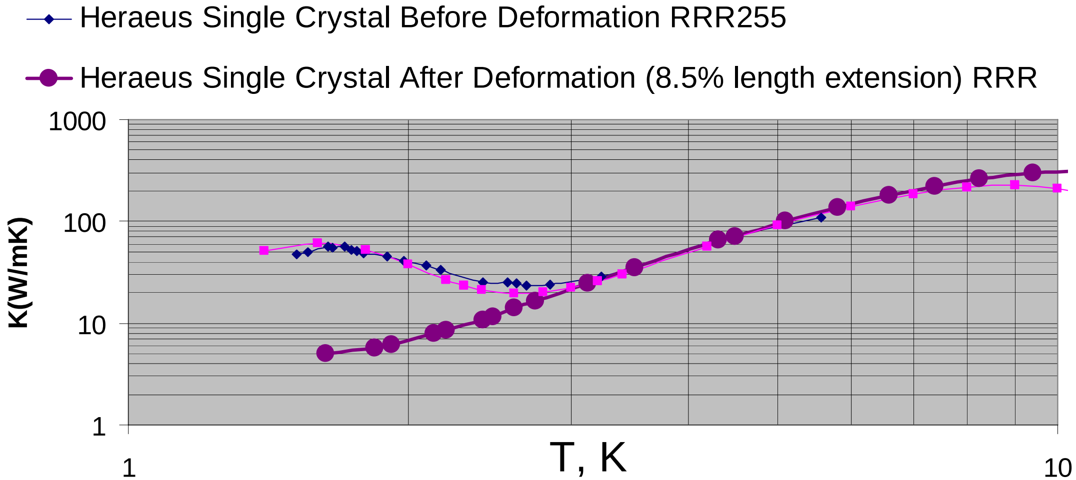


Comparison of the Eacc performance of large grain (LG) 9-cell cavities with similarly treated fine grain TTF cavities



Parameterizations of F. Koechlin and B. Bonin

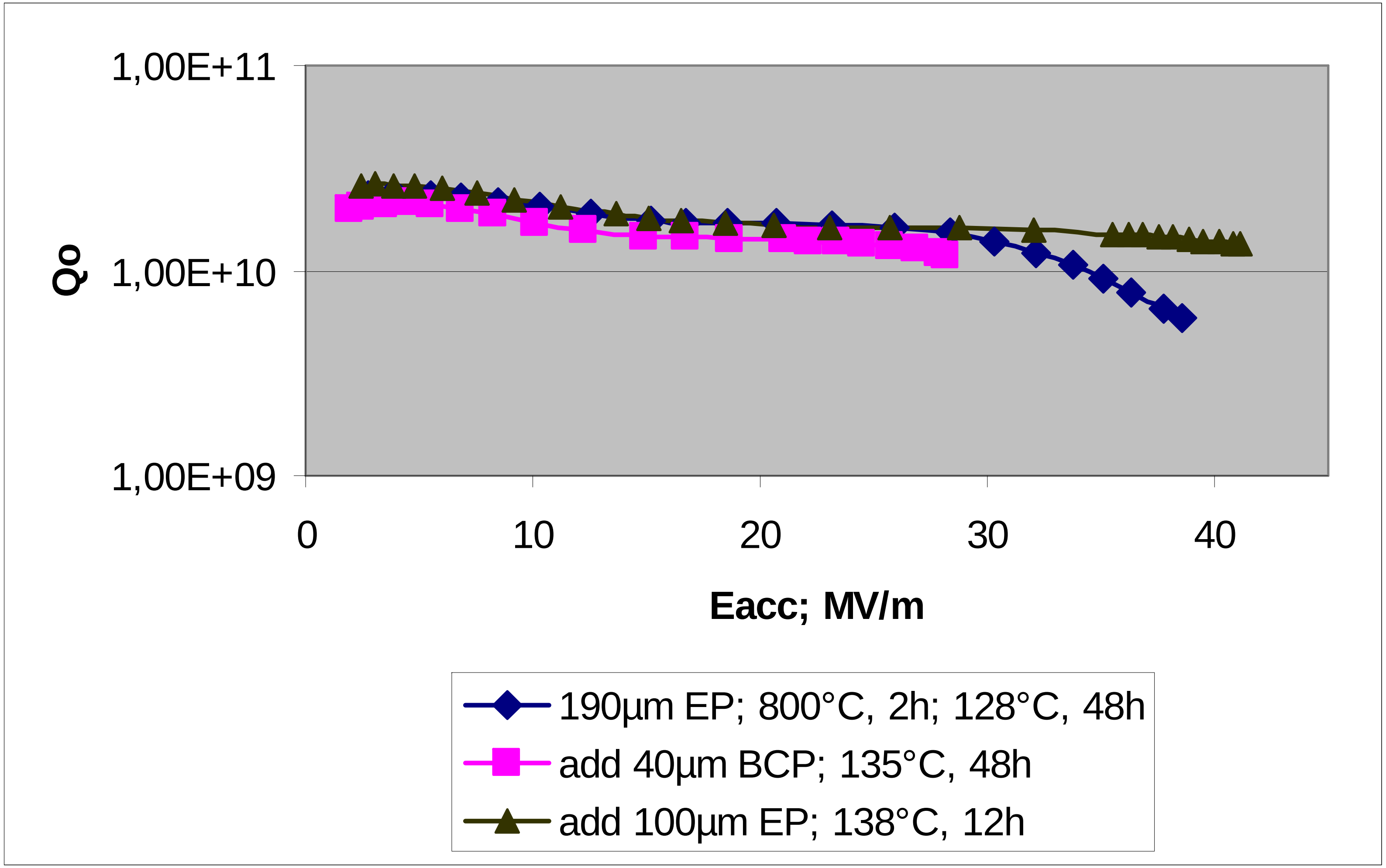
$$\lambda(T,RRR,G)=R(y)\cdot\left[\frac{\rho_{295K}}{L\cdot RRR\cdot T}+a\cdot T^2\right]^{-1}+\left[\frac{1}{D\cdot\exp(y)\cdot T^2}+\frac{1}{B\cdot G\cdot T^3}\right]^{-1}$$



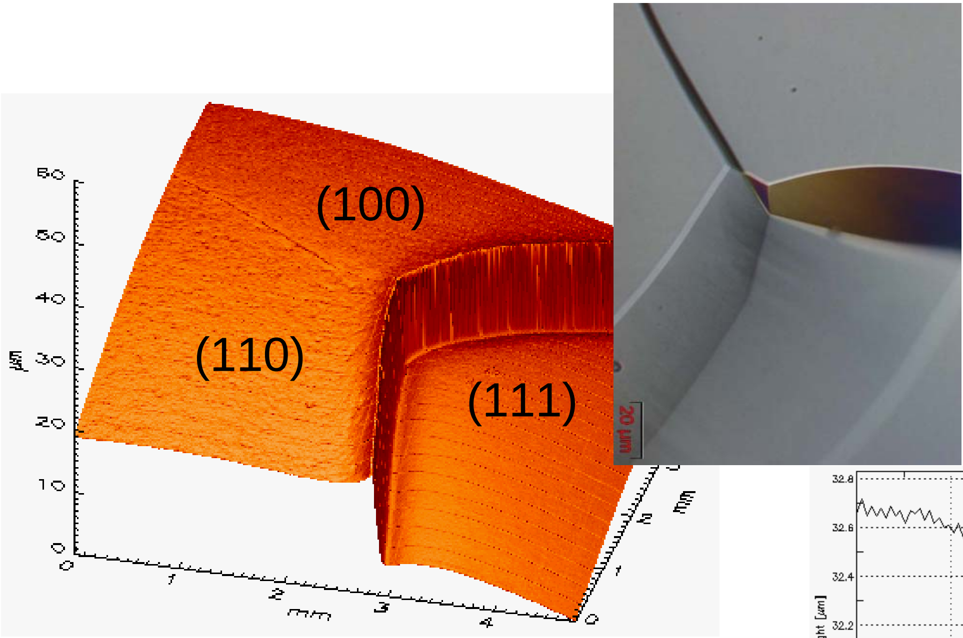
Thermal conductivity

of single crystals in comparison with polycrystalline material. Phonon peak is clearly pronounced for single crystals.

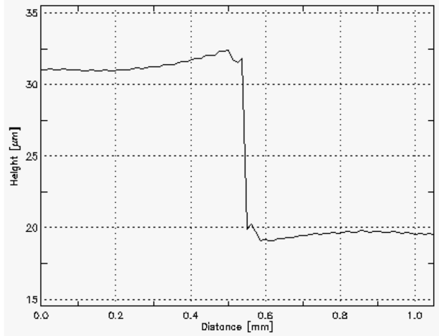
Already small deformation destroy the phonon peak

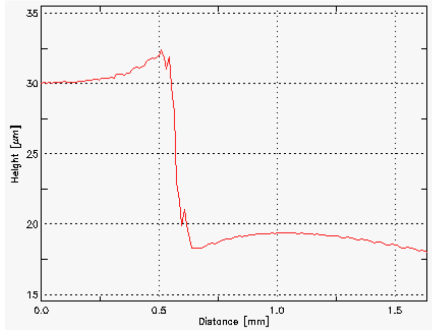


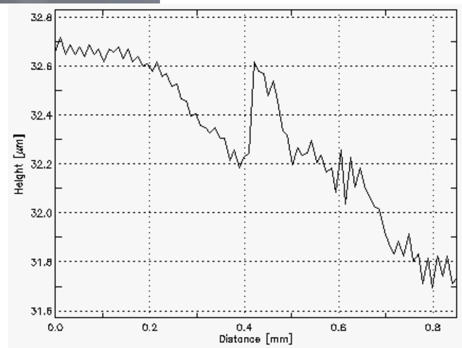
Q(Eacc) curve of the single cell cavity 1AC4
after EP and BCP treatment



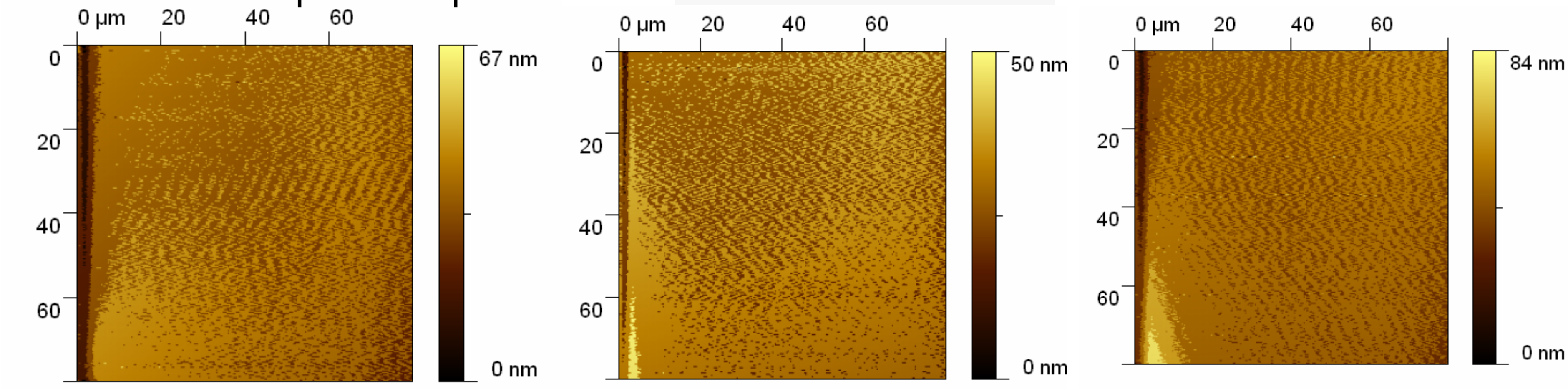
Light microscope and AFM image of LG Nb, BCP etched up to 100 µm





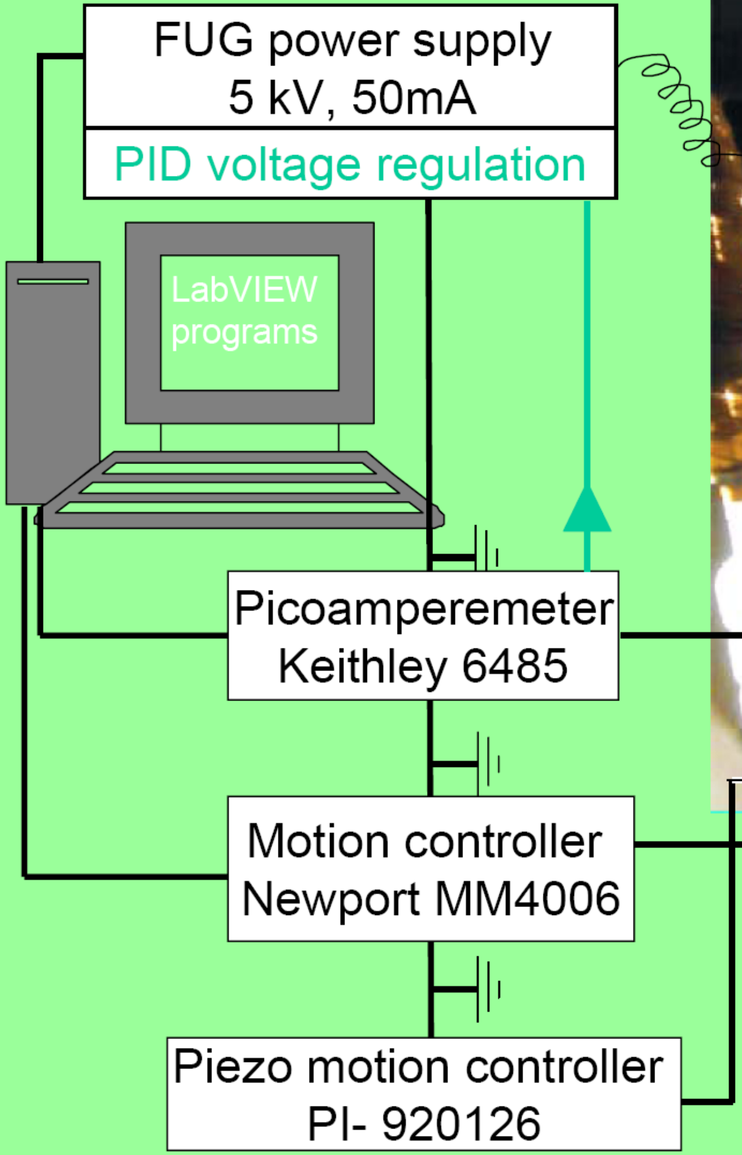


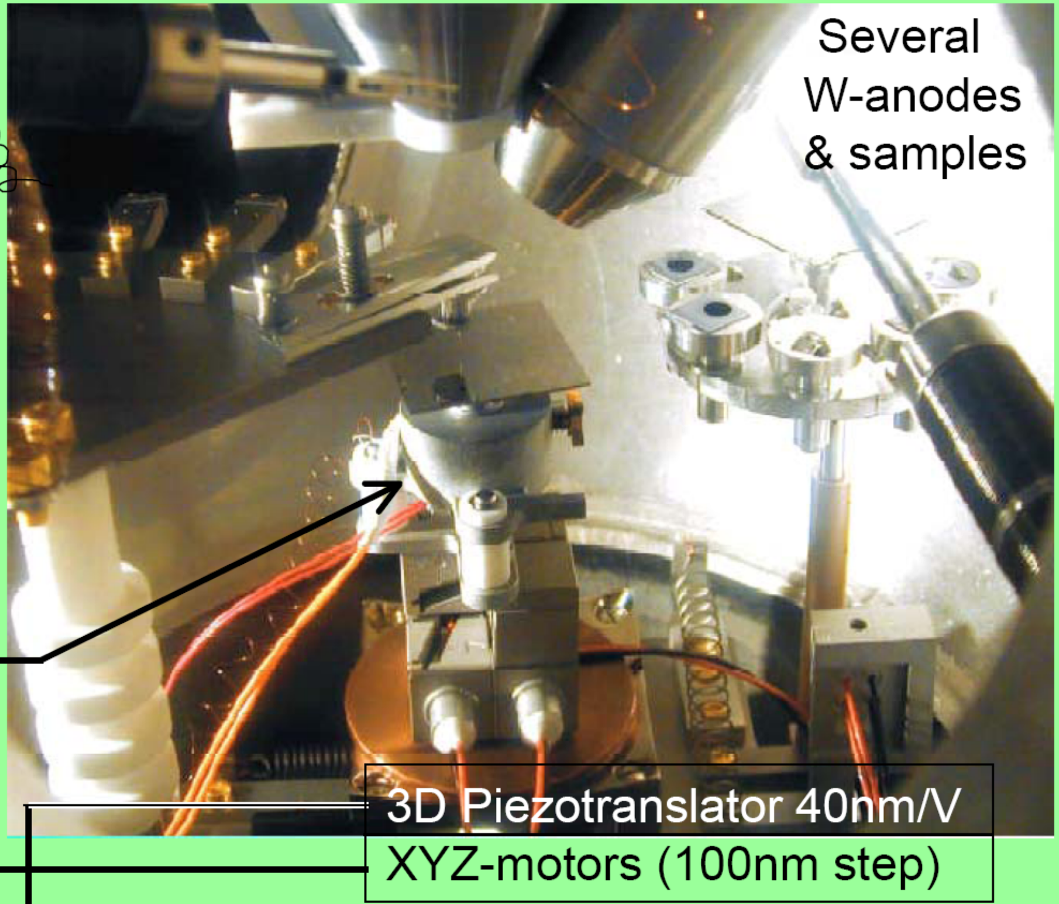
Profile and step heights of the three grain sample at the grain boundary intersection



AFM roughness measurement (X. Singer, A. Dangwal-Pandey). Roughness of fine grain Nb after EP is 251 nm (A. Wu) .

Field emission scanning microscope (FESM)



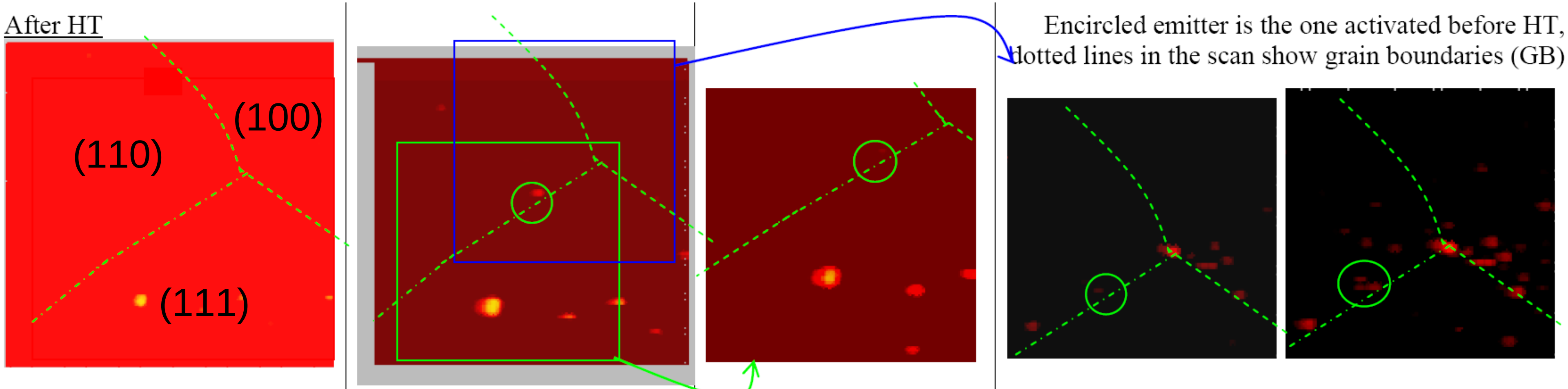


UHV system typically at $2 \cdot 10^{-7}$ Pa

LabVIEW automated scans of U(x,y) for 2 nA

Scanning speed: (100×100) pixels in 1 hr

I/V curves and localization of stable emitters



@ 90MV/m, (10 mm)^2
Emitters activated during V-scans before HT.

@ 150 MV/m, (7.5 mm)^2

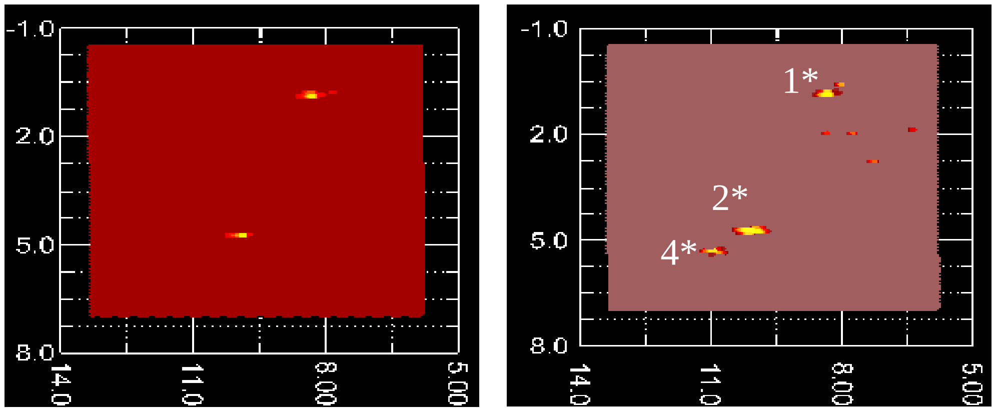
@ 200 MV/m, (5 mm)^2
4 old +1 new emitters observed.

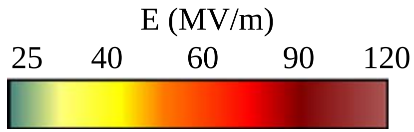
@ 250 MV/m, (5 mm)^2 @ 300 MV/m, (5 mm)^2
Increased number density after HT, all emitting sites appear near GB. Strongest emission observed at the intersection of three grain boundaries.

FE scans on three LG after 100 µm BCP and baking 150° C, 14hs

A. Dangwal, G.Mueller

Wuppertal Univ.





Example of similar FE scans on fine grain EP Nb sample. (left) E = 90 MV/m, 3 emitters (right) E = 120 MV/m, 8 emitters

Orientation (111) is the worst one. Another data indicates that the (100) is the best one. A lot of emitters are close to grain boundaries.

Single Crystal Option

Better not to have the grain boundaries at all

Fabrication of TESLA shape single crystal single cell cavities was proposed at DESY.

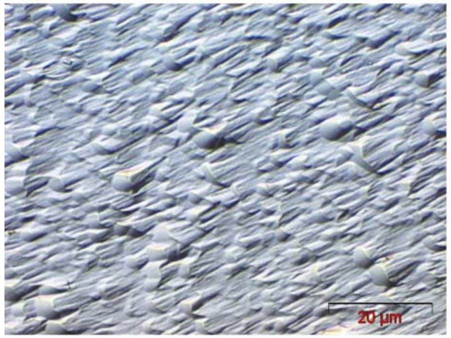
Following aspects have been investigated and taken into consideration during cavity fabrication

• Definite enlargement of the discs diameter is possible without destroying the single crystal structure in an existing state.

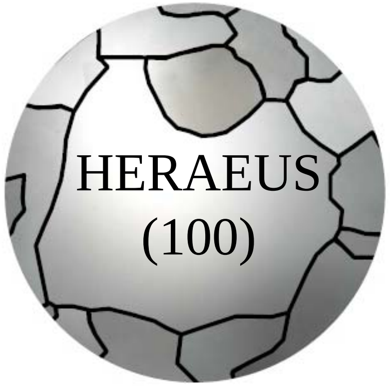
• Appropriate heat treatment will not destroy the deformed single crystal

• The single crystals keep the crystallographic structure and the orientations after deep drawing and annealing at 800° C

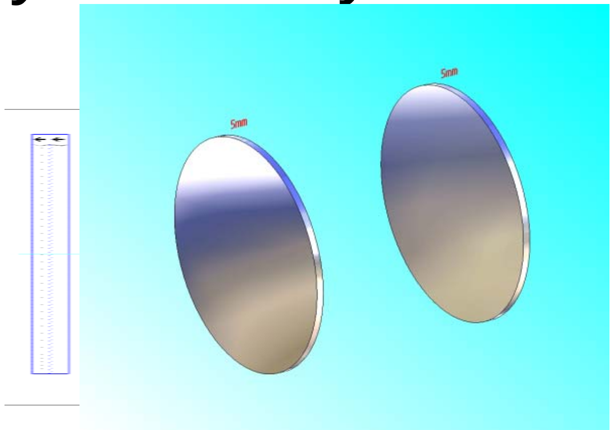
• Two single crystals will grow together by EB welding, if the crystal orientations is taken into account.



DESY Single crystal cavity fabrication

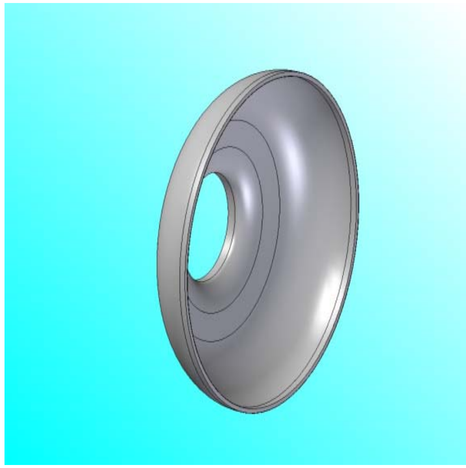


1. Take out central single crystal of definite thickness

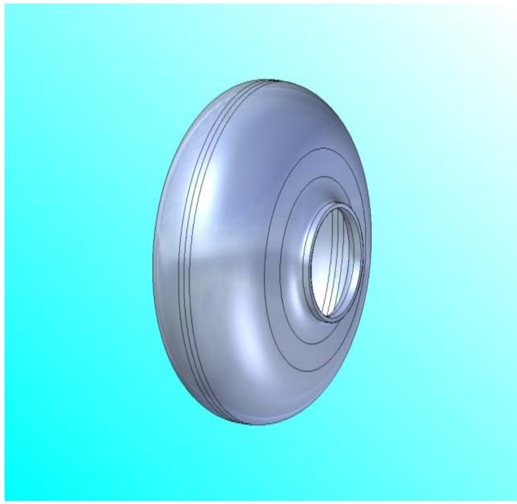


2. Cutting through the disc

3. Increasing of diameter by special rolling with an intermediate annealing

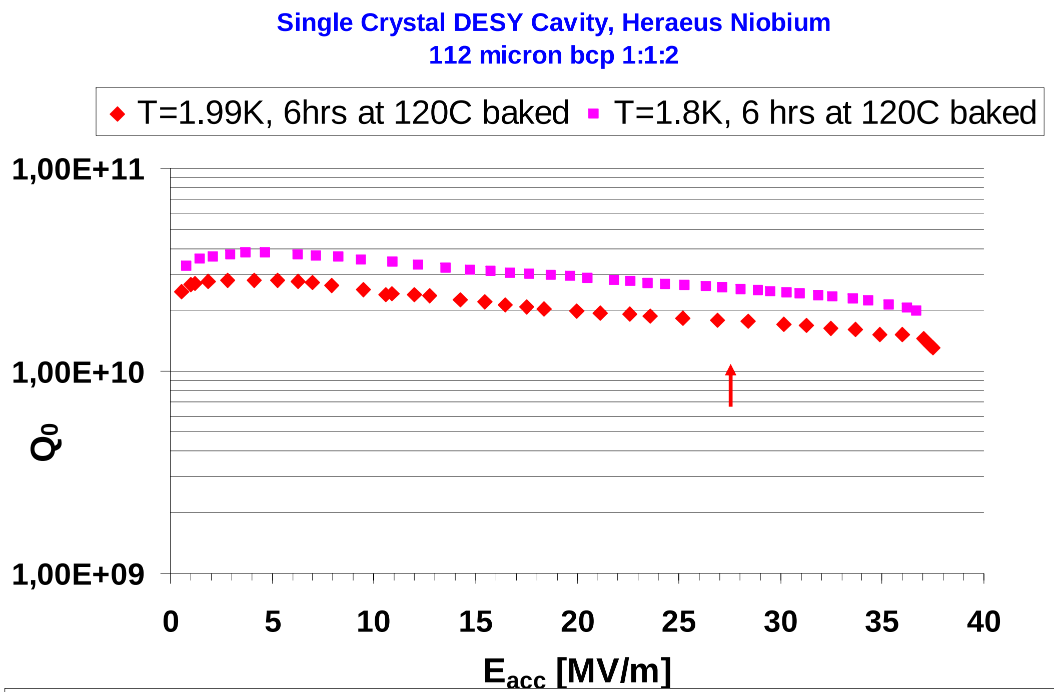


4. Deep drawing



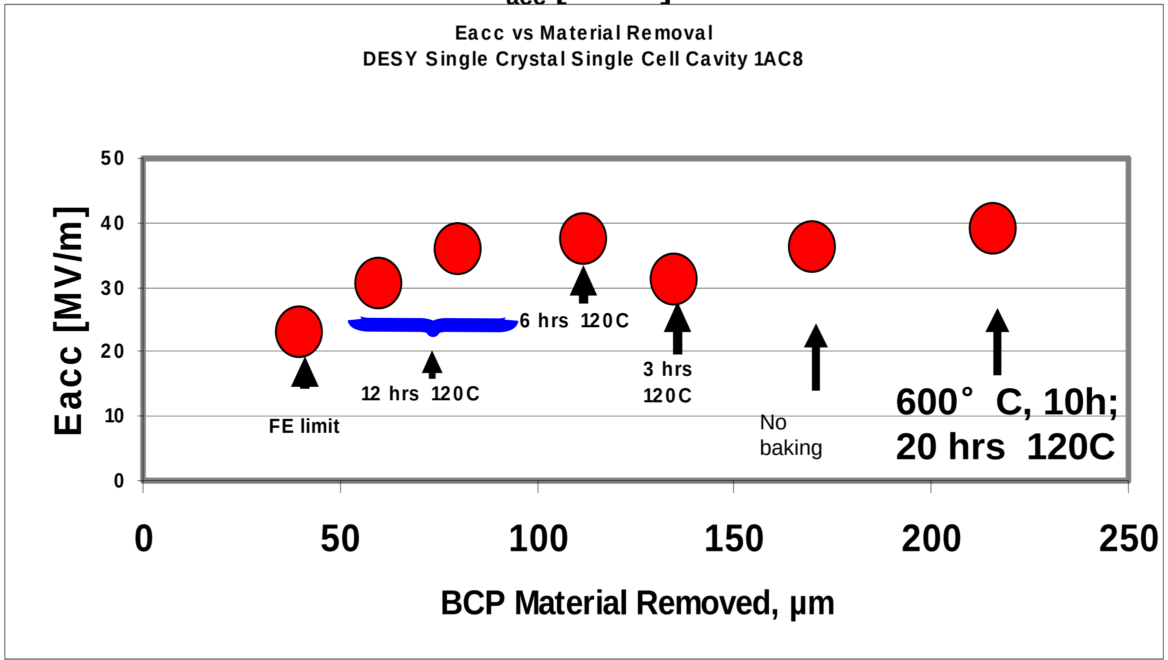
5. EB welding by matching the crystal orientation

DESY SC cavity 1AC8 (TESLA shape) build from Heraeus disc by rolling at RWTH, deep drawing and EB welding at ACCEL



1AC8

Q(Eacc) curve of 1AC8 after only 112 µm BCP and in situ baking 120° C for 6 hrs 37,5 MV/m (equivalent to 160 mT)

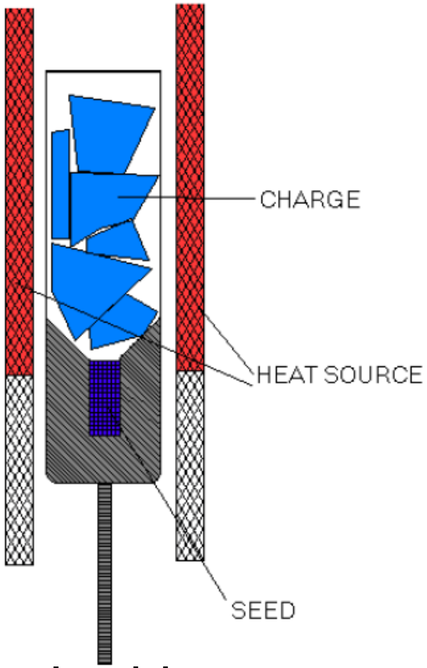


Eacc vs. material removal on single crystal single cell cavity 1AC8. Best Eacc= 38,9 MV/m (equivalent to $B_{p,max}$ =166 mT)

Preparation and RF tests of P.Kneisel, JLab

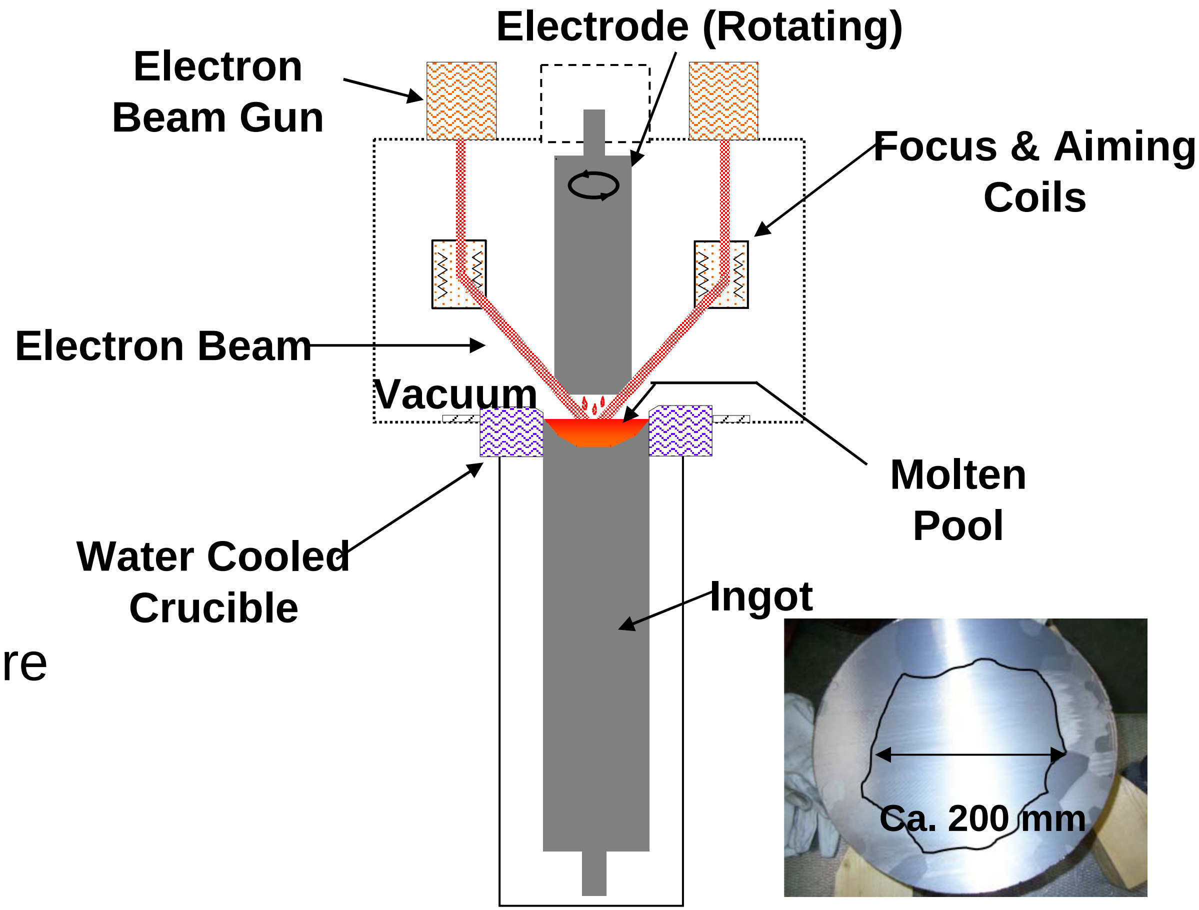
The proposed method can be extended on fabrication of multi cell cavities

Is it realistic produce single crystal cavities of sizes required for ILC?



Vertical Bridgman procedure for single crystal grow

1. Seed, partially melted
2. Axial temperature gradient
3. Interface between solid and liquid phase is shifted by movement of container or temperature gradient

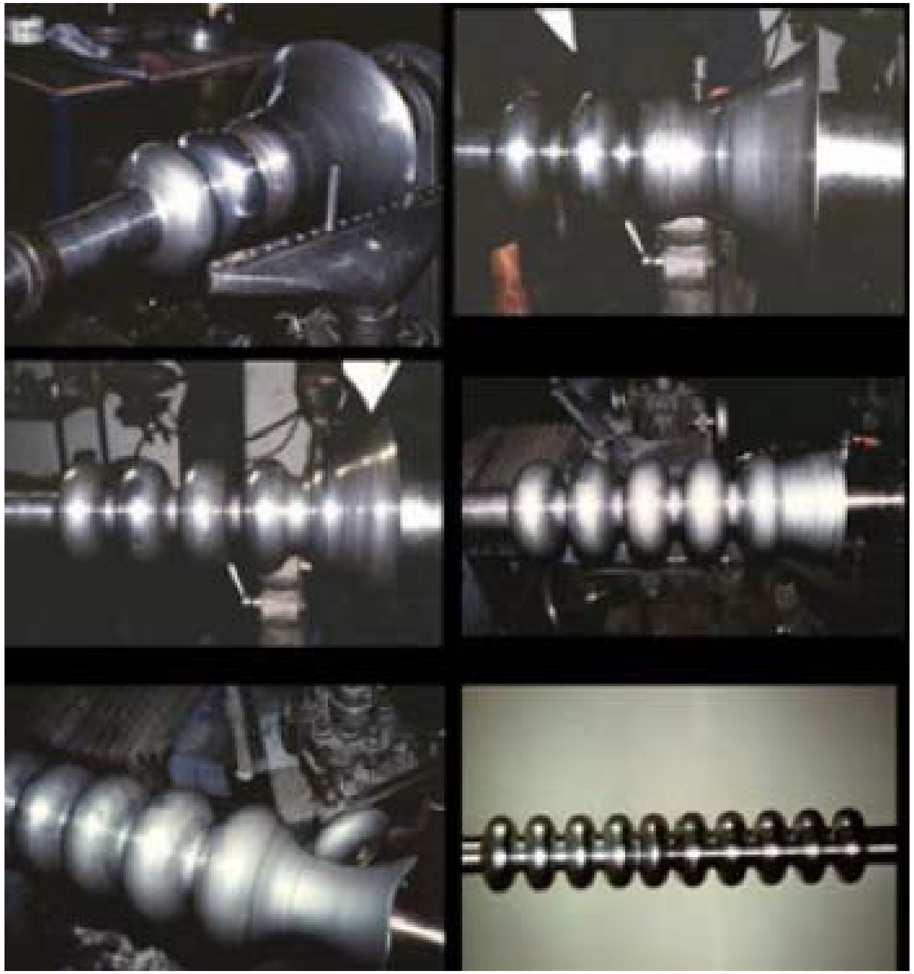


Electron beam melting principle

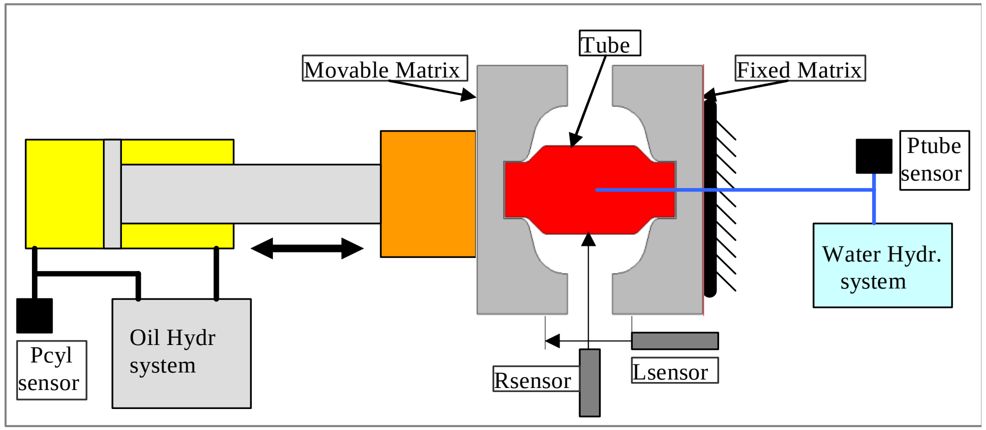
Challenge for the industry

Alternative fabrication methods

Spinning (V.Palmieri,INFN Legnaro)

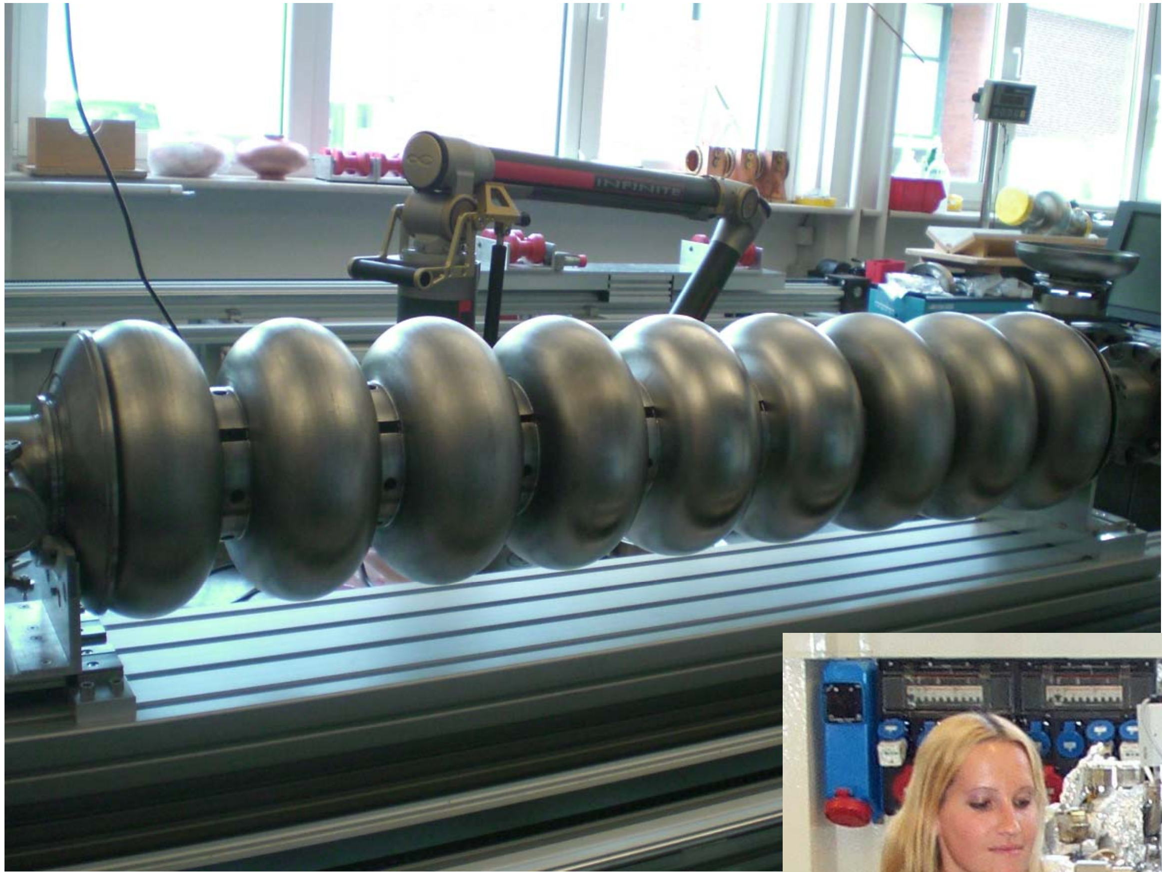


Hydroforming, DESY, KEK



DESY hydroforming machine
HYDROFORMA

Fabrication of 9 cell cavities became a reality

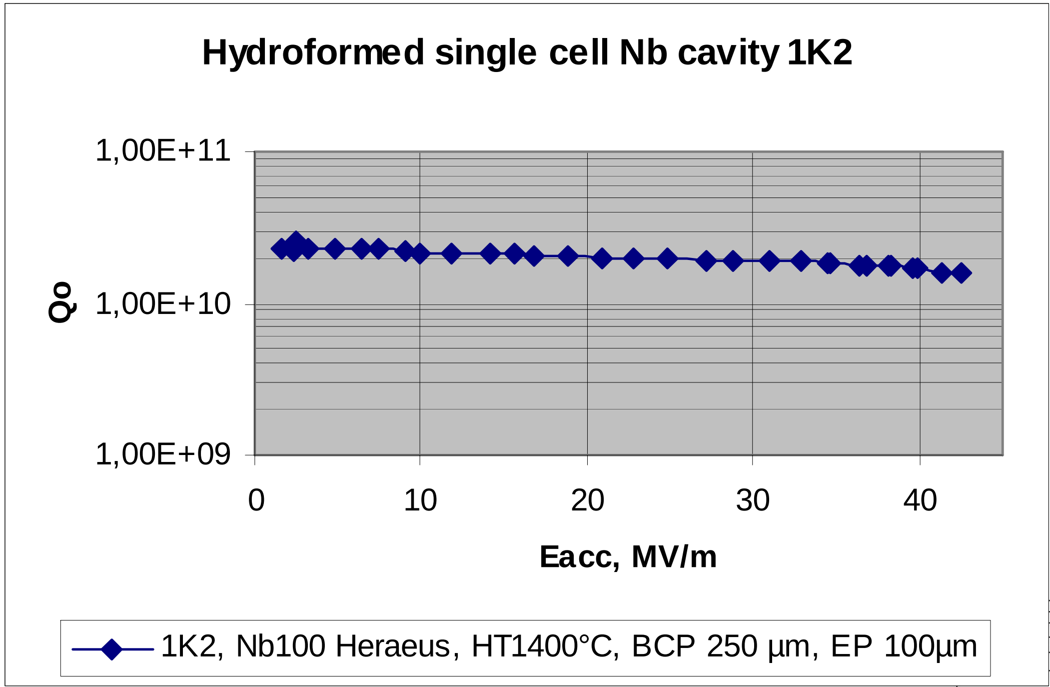


DESY Hydroformed cavity

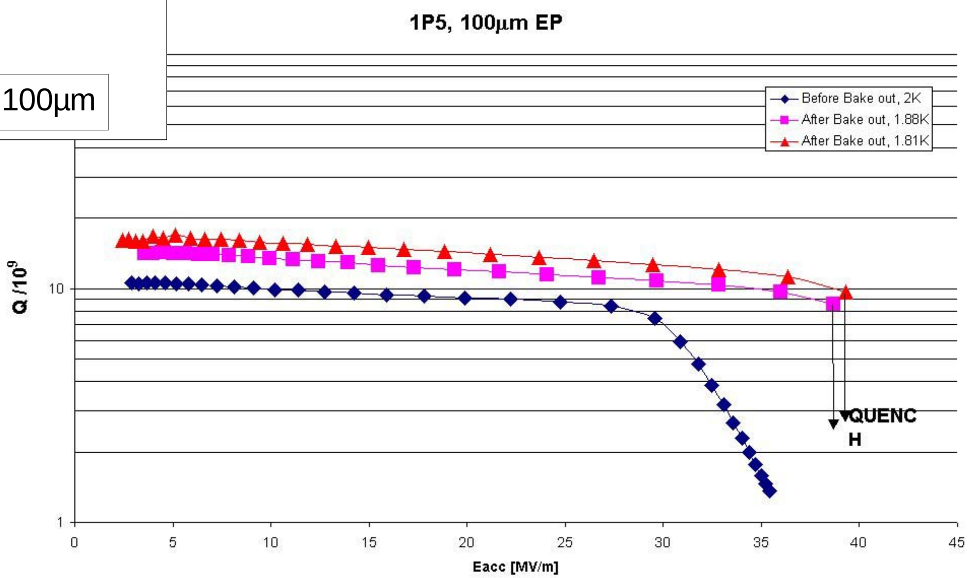
INFN Spun cavity

Hydroforming, Spinning

Proof of principle is done



The best Q(Eacc) result of by hydroforming produced single cell cavity



The best Q(Eacc) result of by spinning produced single cell cavity

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