SC Cavities;
Material, Fabrication and QA

W. Singer, DESY

Outlook

Niobium as main material for SC cavities

- From raw niobium to ingot
- From ingot to semi-finished products (sheet, tube, etc.)
- Purification

Conventional SC cavity fabrication

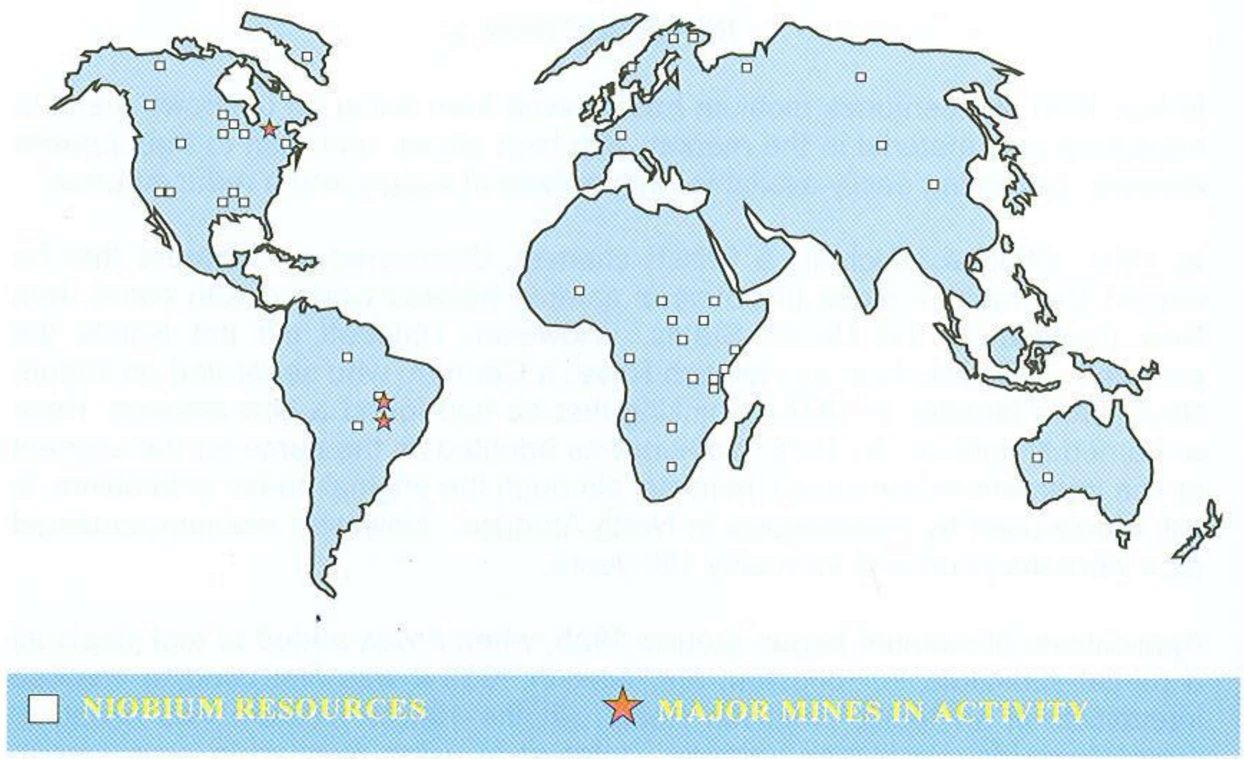
- EB welding peculiarities
- Pressure code (Pressure Equipment Directive PED)
- QA (quality assurance) and documentation

Alternative fabrication R&D

- Large grain LG and single crystal cavities
- Seamless cavities

Nb is mostly used material for SC cavities.

- high critical magnetic field Hc=200 mT
- high transition temperature Tc= 9,3 K
- chemically inert (surface covered by oxide layer)
- can be machined and deep drawn
- is available as bulk and sheet material in any size



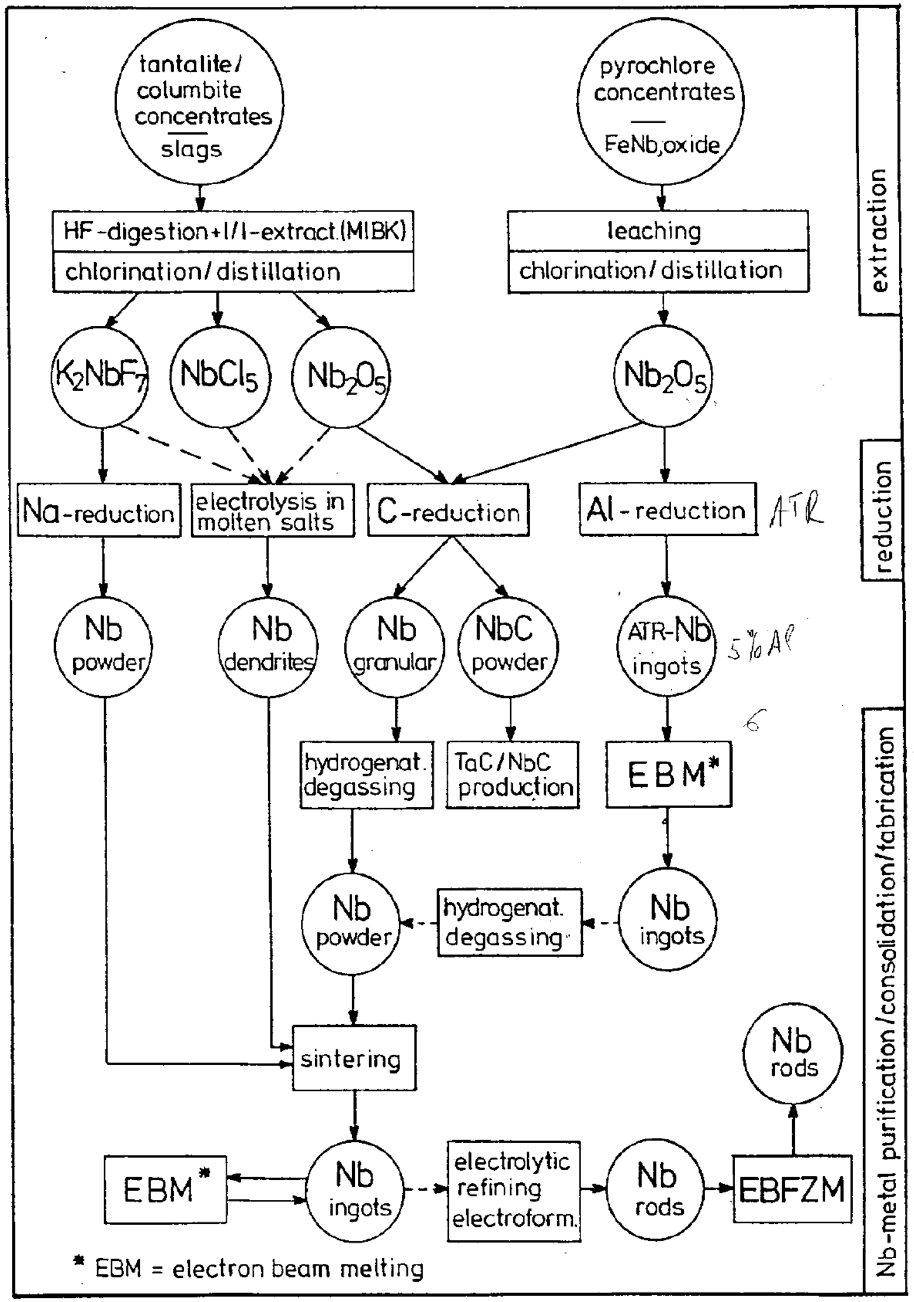
Raw niobium

Niobium is mostly obtained from mineral known as pyrochlore ($NaCaNb_2O_6F$). The pyrochlore mineral is processed by primarily physical processing technology to give a concentrate ranging from 50 to about 60% niobium oxide (Brazil, CBMM).

Columbite ($(Fe, Mn)(Nb,Ta)_2O_6$), a mineral with a ratio of $Nb_2O_5:Ta_2O_5$ ranging from 10:1 to 13:1, occurs in Brazil, Nigeria, and Australia, also other countries in central Africa. Niobium is recovered when the ores are processed for tantalum.

The world's largest niobium deposit is located in Araxá, Brazil owned by Companhia Brasileira de Metalurgia e Mineração (CBMM). The reserves are enough to supply current world demand for about 500 years, about 460 million tons. The mining of weathered ore, running between 2.5 and 3.0% Nb_2O_5, is carried out by open pit mining. By chemical processes the ore is concentrated in Nb contents (50 –60 % of Nb_2O_5)

The way from ore to pure Nb



Main routes of Nb fabrication process

Classical routes for Nb, consist of the carbothermic reduction of Nb_2O_5 and the aluminothermic reduction of Nb_2O_5 followed by EBM.

$$Nb_2O_5 + 7C \rightarrow 2NbC + 5CO$$

$$5NbC + Nb_2O_5 \rightarrow 7Nb + 5CO$$

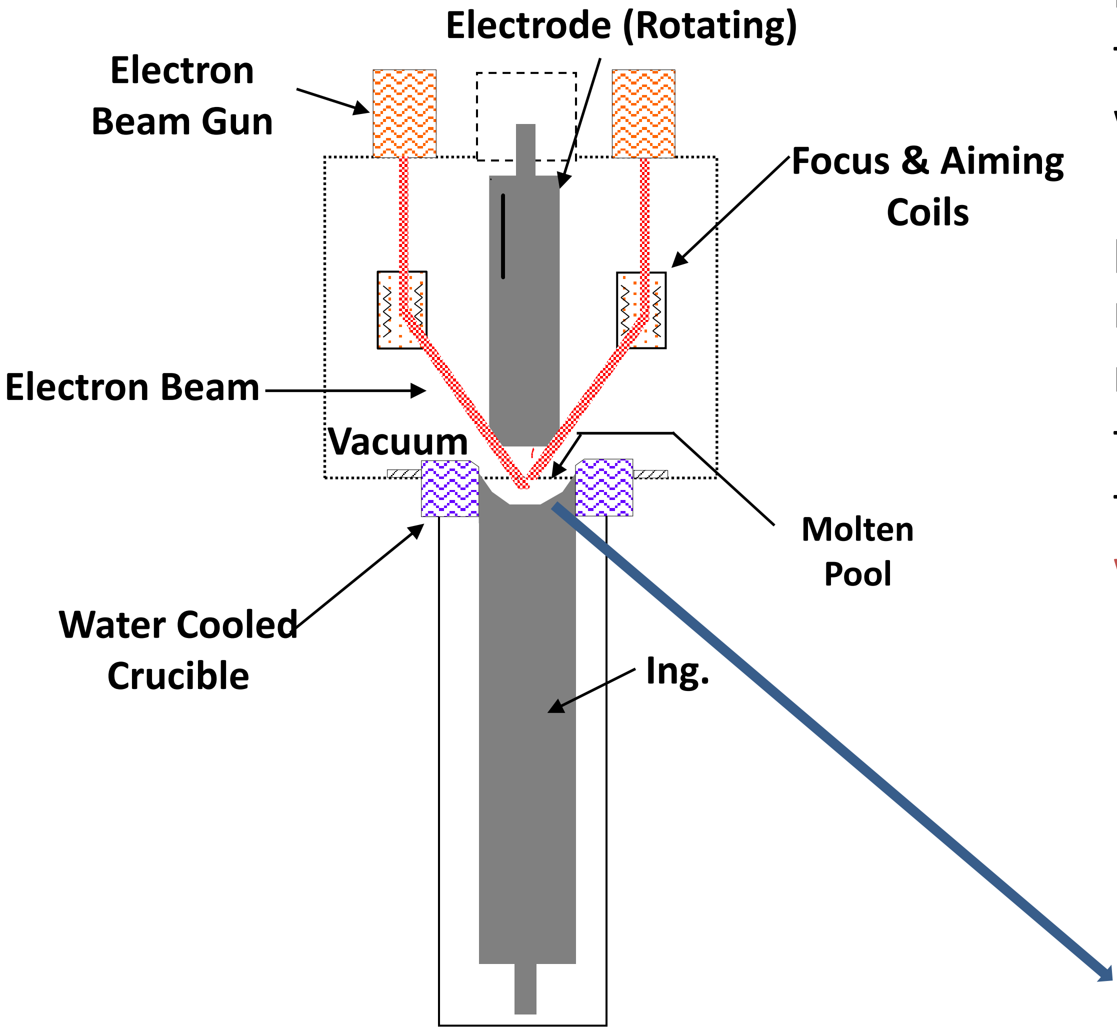
$$3Nb_2O_5 + 10Al \rightarrow 5Al_2O_3 + 6Nb$$

An alternative route of niobium fabrication and alloying is powder metallurgy. For special applications it may be convenient to produce powder with high purity hydriding. The production of high-grade niobium with small Ta-concentration can be performed via the sodium reduction of purified K_2NbF_7.

$$K_2NbF_7 + 5Na \rightarrow Nb + 2KF + 5NaF$$

Electron Beam Melting

During of the ingot melts, molten metal globules fall into a pool on the ingot which is contained in a water cooled copper crucible. Impurities are evaporated and pumped away. Power impact is maintained to keep the pool molten out to within a few mm of the crucible wall. During melting the ingot formed is continuously withdrawn through the crucible.

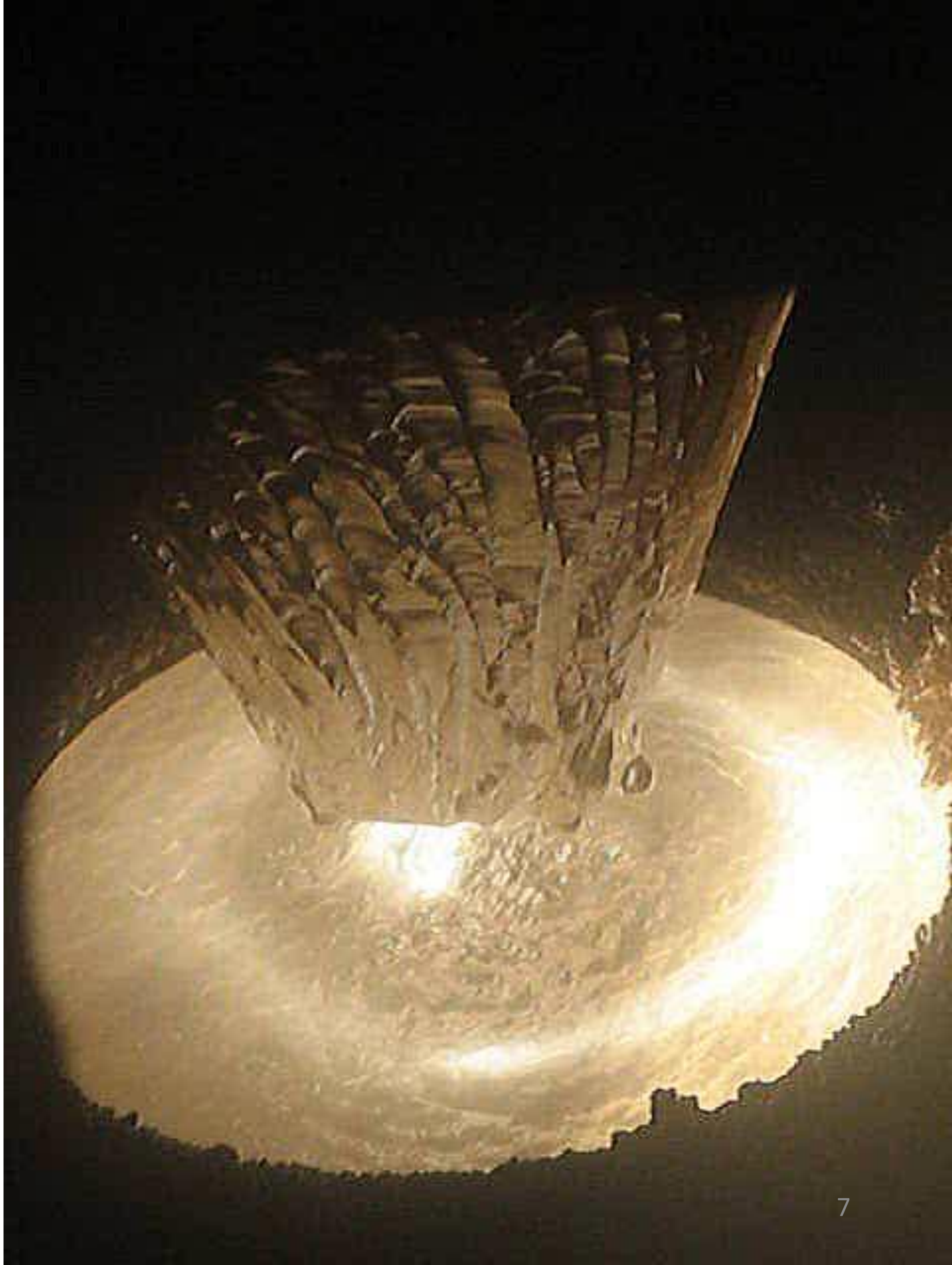


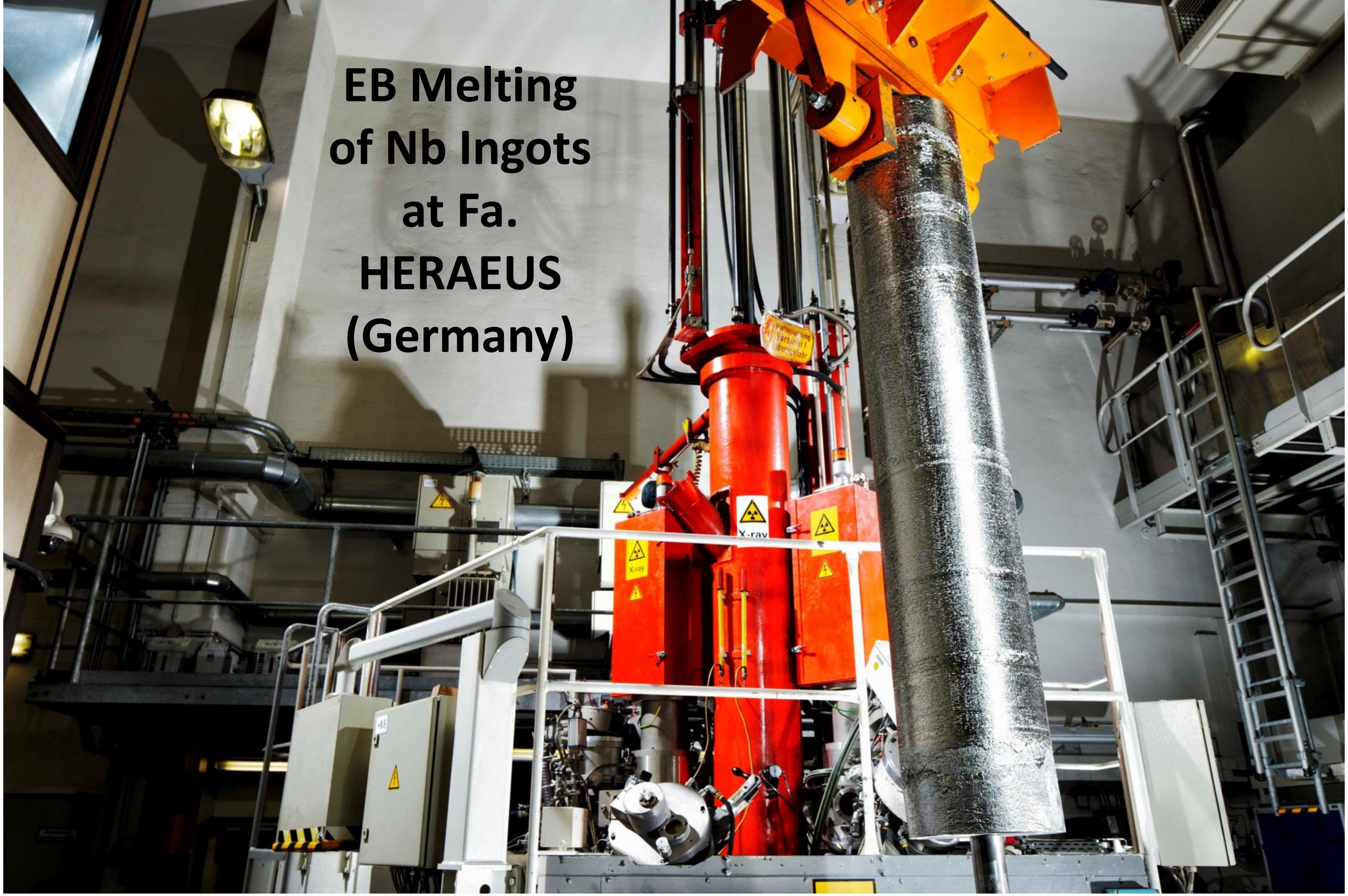
Electron beam melting of Nb

W. Singer. CERN Accelerator School. Erice, Italy, 24 April-4 May, 2013

Electron Beam Melting

As a result of the increasing demand for refractory metals in the last few decades, the electron-beam furnace has been developed to a reliable, efficient apparatus for melting and purification.





One problem sometimes observed with e-beam melted ingots is the nonhomogeneous distribution of impurities. The skin of the ingot contains more impurities than the inside. Top to bottom inhomogeneity.

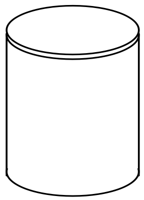
Sheet : Technical Specification for High Purity Niobium

Concentration of impurities in wt.ppm				Mechanical properties	
Ta*	≤ 500	H*	≤ 2	Yield strength**, $\sigma_{0,2}$	$50<\sigma_{0,2}<100$ N/mm^2 (Mpa)
W*	≤ 70	N*	≤ 10	Tensile strength**	> 100 N/mm^2 (Mpa)
Ti*	≤ 50	O*	≤ 10	Elongation at break**	30 %
Fe*	≤ 30	C*	≤ 10	Vickers hardness** HV 10	≤ 60
Mo*	≤ 50	RRR*	≥ 300	Absence of foreign material inclusions*	Proven by scanning
Ni*	≤ 30	Recrystal. degree. Grain size* ,** ?	≈ 50 µm	Texture *, ** ?	

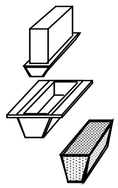
* - relevant for performance

** - relevant for successful fabrication

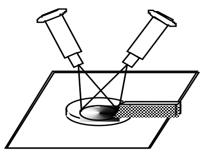
Fabrication of Nb Sheets at Company Tokyo Denkai



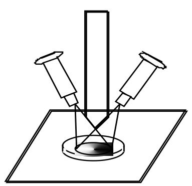
Mother material



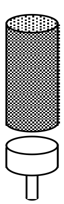
Pressing



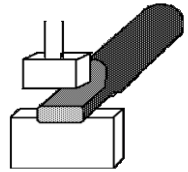
1st EB melting



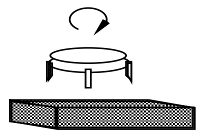
2nd, 3rd etc. EB melting



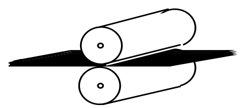
Separate from base plate



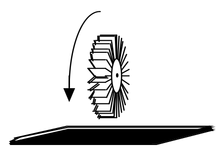
Forging



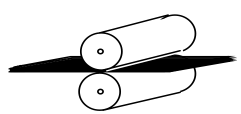
Milling



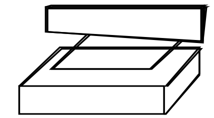
Rolling



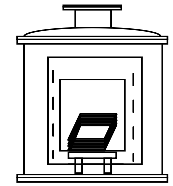
Polishing



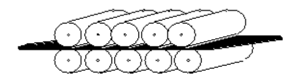
Rolling



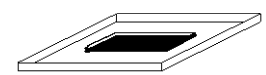
Cutting



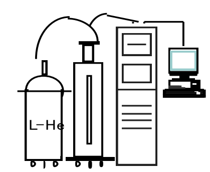
Annealing



Levering



Chemical polishing



Inspection

- ICP-AES
- Gas Analysis
- RRR
- Grain size
- Hardness

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

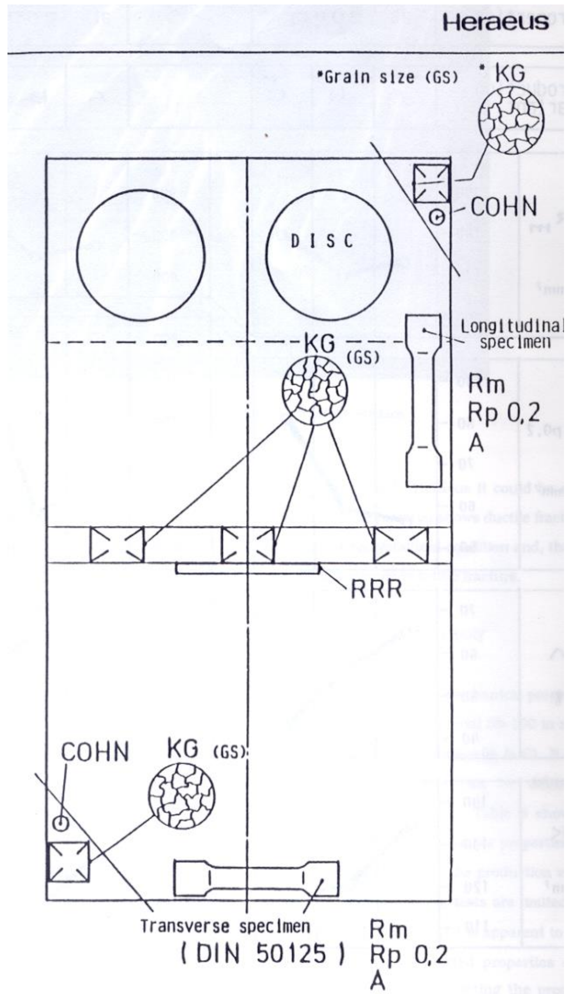
Industrial Analytic Laboratory

For QC of RM production

Could you please test the sugar content in my coffee

In House

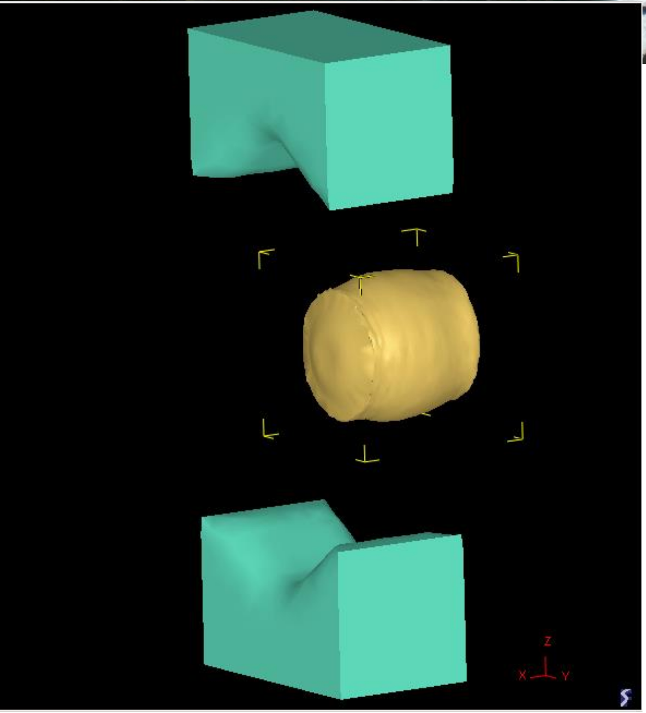
- RRR
- Scanning - Apparatus
- Interstitial impurity analysis (H,N,O, C)
- Metallic impurities analysis (another RM, Fe, Ni etc.)
- Metallographie
- Tensile test
- Hardness, HV
- Surface roughness

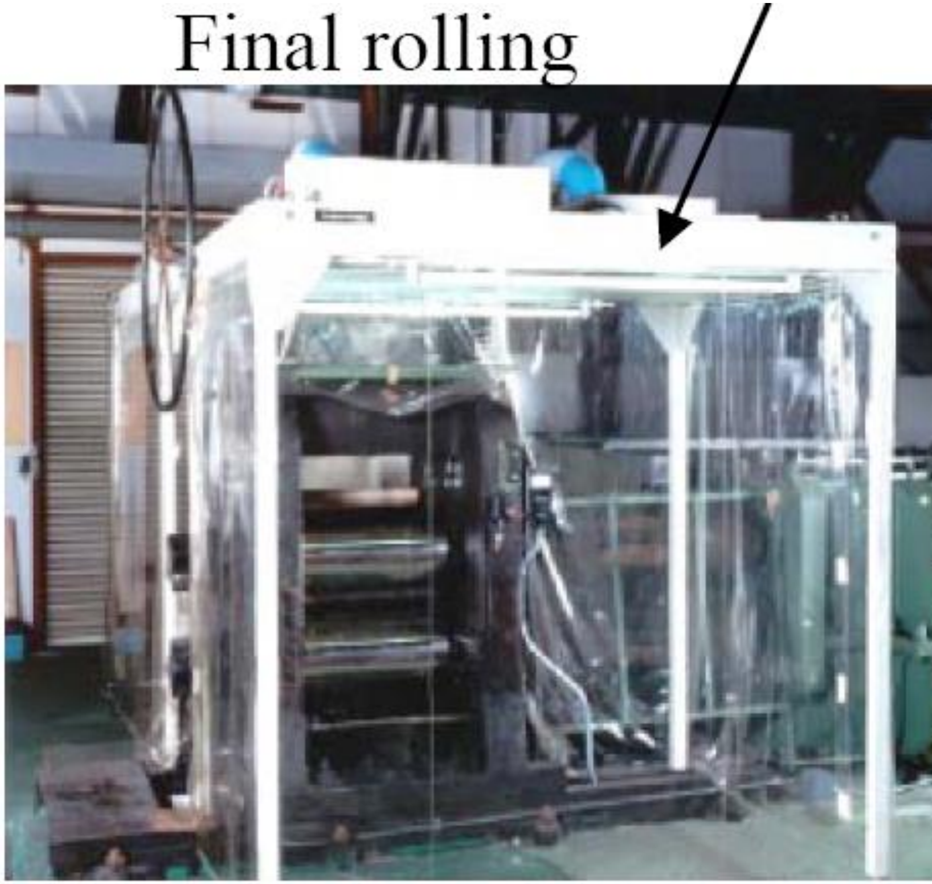


Scheme of QC of Nb sheets at Fa. HERAEUS in Germany

Outsource

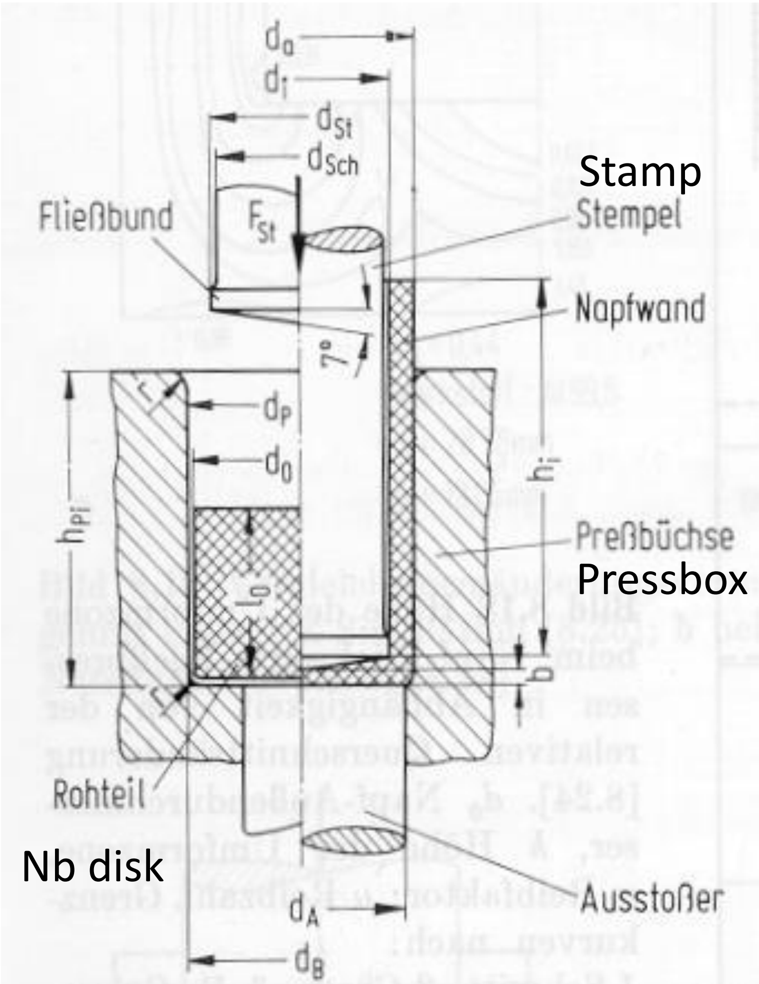
- Thermal conductivity
- NAA Neutron Activation Analysis
- Radiation Fluorescence Analysis
- SEM, EDX
- SIMS, XPS, AUGER
- X-ray radiography
- Neutron radiography
- Texture analysis
- Bulging test





Forging and rolling of niobium (can be done at room temperature). Courtesy of Ningxia OTIC and Tokyo Denkai

Tubes: back extrusion



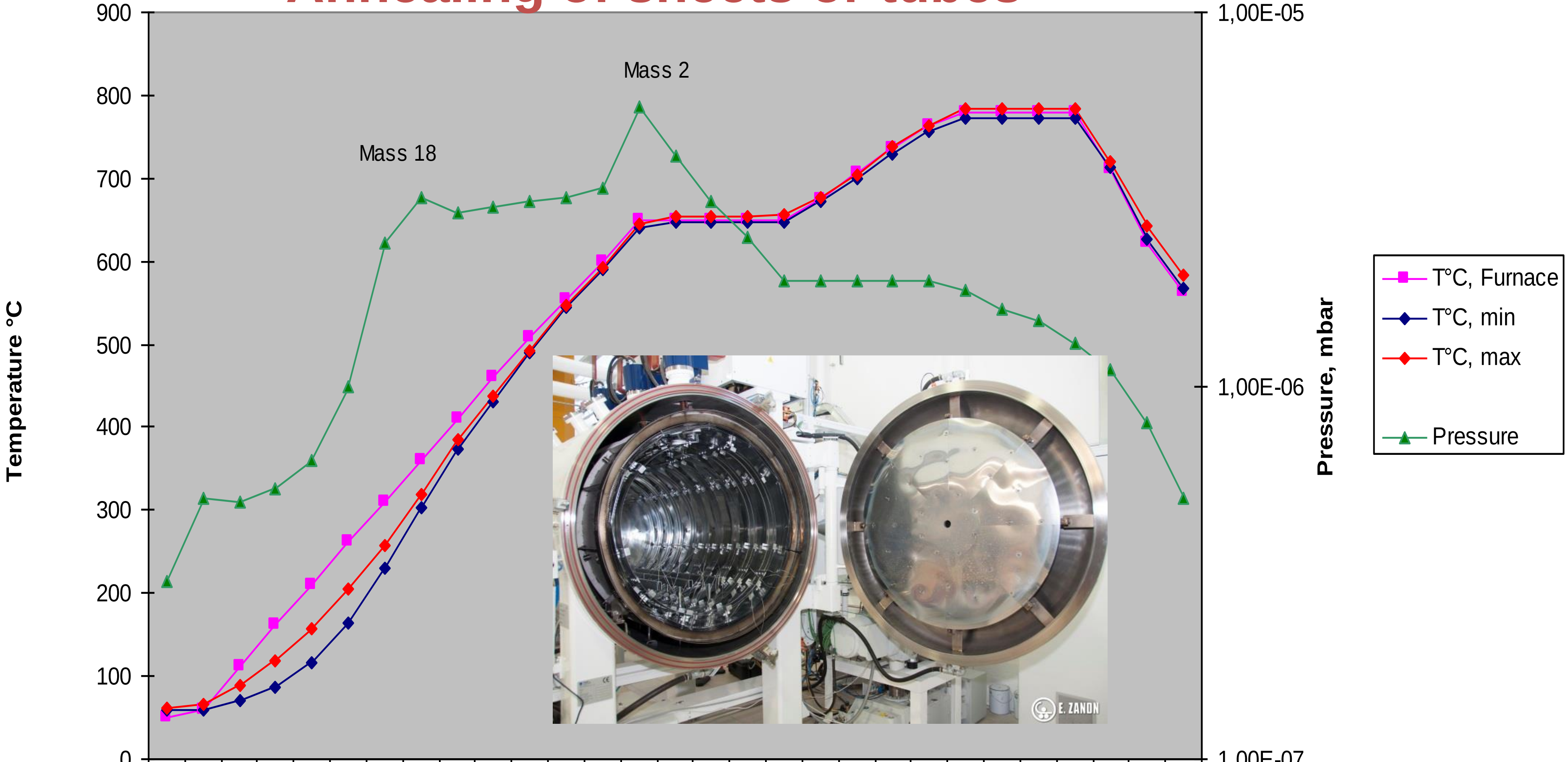
Principle of seamless tube fabrication by back extrusion

Back extruded Nb tubes for EXFEL

Other tube production methods:

- **Production from sheet (welding)**
- **Forward extrusion**
- **Deep drawing**
- **Spinning**

Annealing of sheets or tubes

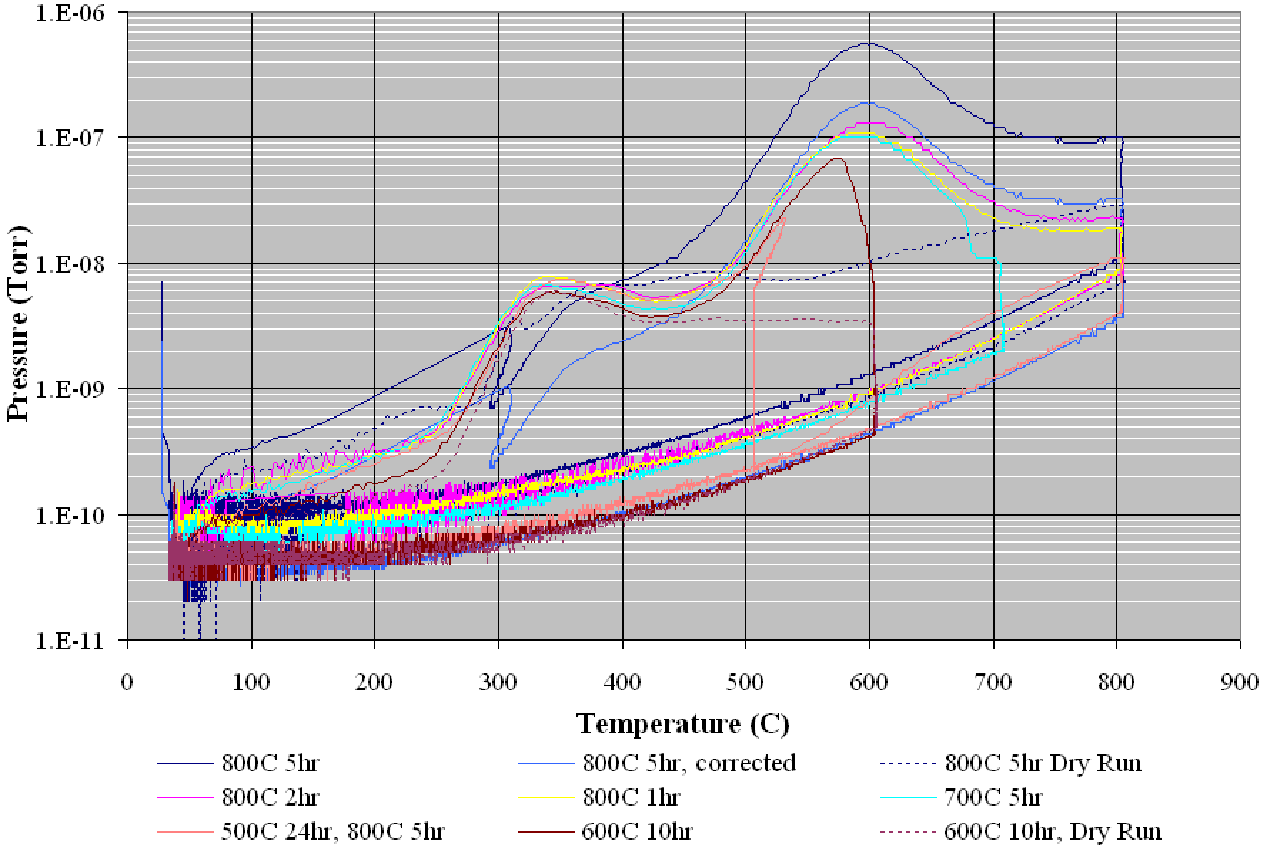


	08:30	08:45	09:00	09:15	09:30	09:45	10:00	10:15	10:30	10:45	11:00	11:15	11:30	11:45
T °C, Furnace	50	59	112	161	210	261	310	361	411	460	507	554	600	650
T °C, min	60	60	70	87	117	165	229	304	374	430	489	544	591	640
T °C, max	61	65	89	119	157	205	257	319	384	438	492	547	593	645
Pressure	3,0E-7	5,0E-7	4,9E-7	5,3E-7	6,3E-7	1,0E-6	2,4E-6	3,2E-6	2,9E-6	3,0E-6	3,1E-6	3,2E-6	3,4E-6	5,6E-6

	12:00	12:15	12:30	12:45	13:00	13:15	13:30	13:45	14:00	14:15	14:30	14:45	15:00	15:15	15:30
T °C, Furnace	650	650	650	650	675	706	736	763	780	780	780	780	710	621	562
T °C, min	646	647	648	647	672	700	730	756	773	773	773	773	713	627	568
T °C, max	655	655	654	656	677	705	738	763	783	783	783	783	721	642	583
Pressure	4,1E-6	3,1E-6	2,5E-6	1,9E-6	1,9E-6	1,9E-6	1,9E-6	1,9E-6	1,8E-6	1,6E-6	1,5E-6	1,3E-6	1,1E-6	8,0E-7	5,0E-7

The temperature and the total pressure in the chamber during annealing of Nb300.

Outgassing of hydrogen



Hydrogen partial pressure versus annealing temperature.

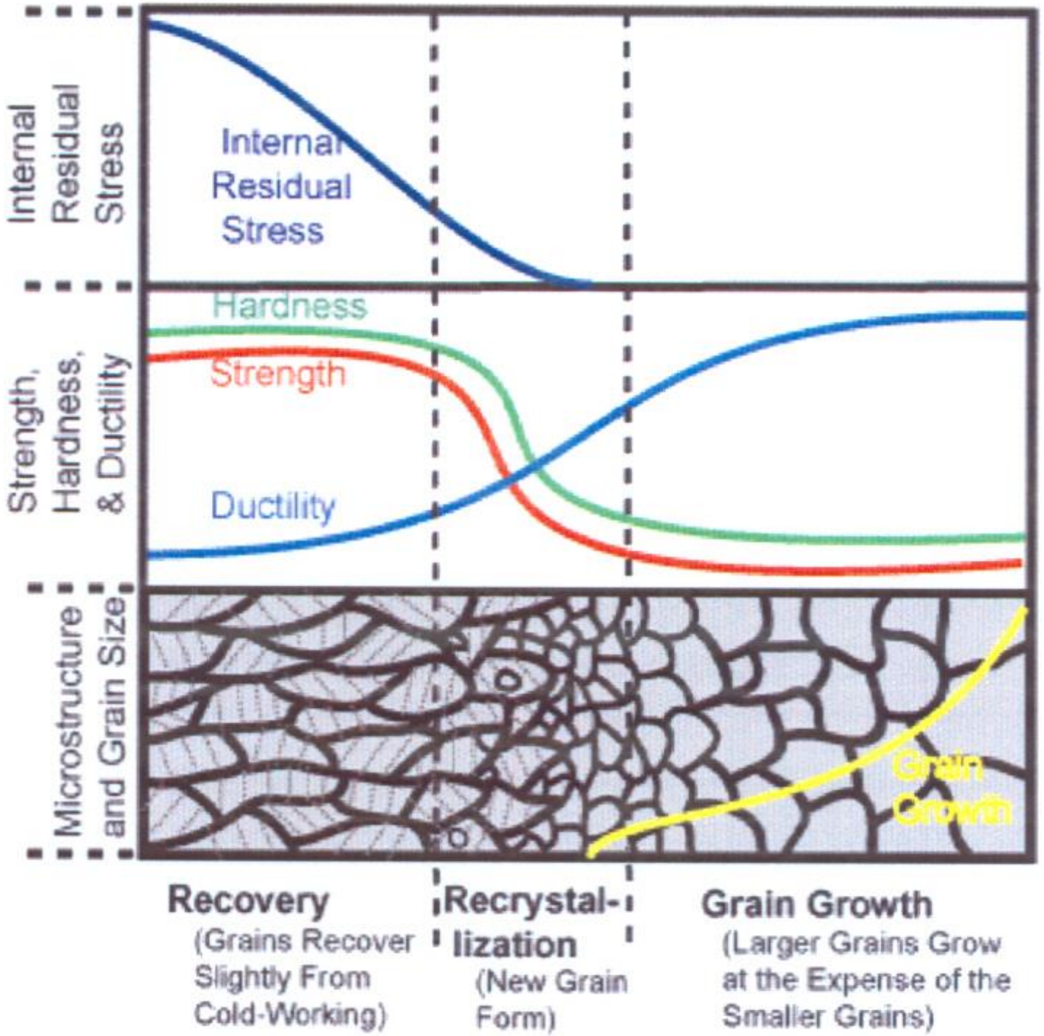
How the outgassing of hydrogen take place?

Nb hydrides decomposes mostly at T> 100-150°C. Outgassing of hydrogen is however not possible at these temperatures because the Nb_2O_5 protecting layer is stable up to 250-300°C.

The most efficient annealing of high purity niobium is 750-800°C, 2 hours.

- Complete outgassing of hydrogen
- Recrystallization of Nb.

Recrystallization



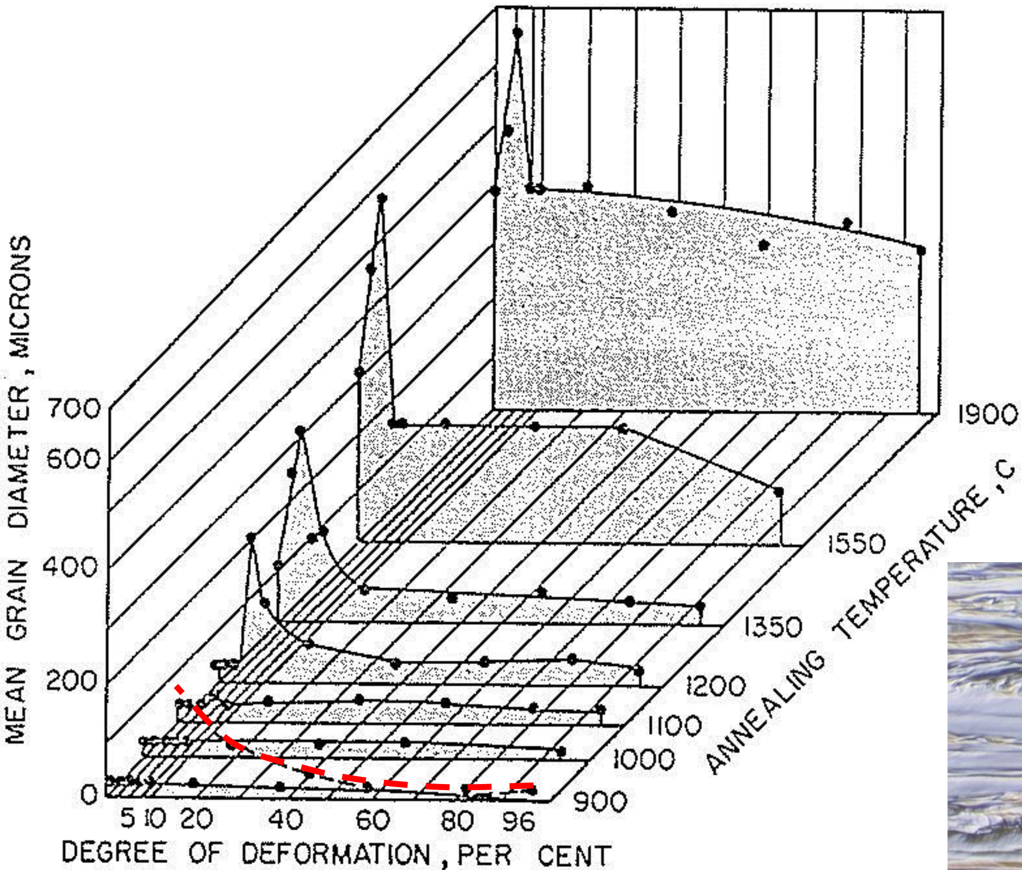
Choosing the proper annealing conditions is important to produce the correct grain size near 100% recrystallization and keep the highest possible purity (RRR).

Recovery: - removing during annealing the point defects, decrease and change of orientation of dislocations

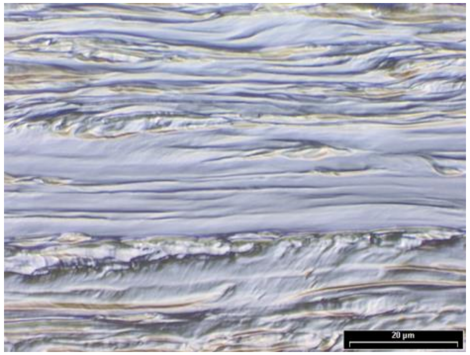
Recrystallization: - nucleation of new grains and growing of new crystals

Grain growth: - grain size increases

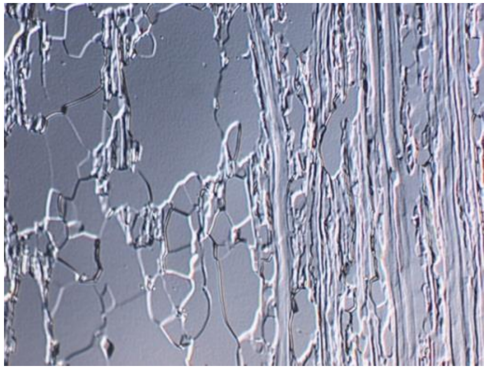
Commercial "Pure Nb". RRR ~ 50-100



- deformation > 65% =>
  - uniform nucleation
  - small grains
- if purity ↑, $T_{recryst}$ ↓
  - RRR ≤ 100 => $T_{recryst}$ ≥ 900 C
  - RRR 300 => $T_{recryst}$ ~ 800 C
  - RRR 400 => $T_{recryst}$ ~ 750 C



Rolled Nb sheet before final annealing



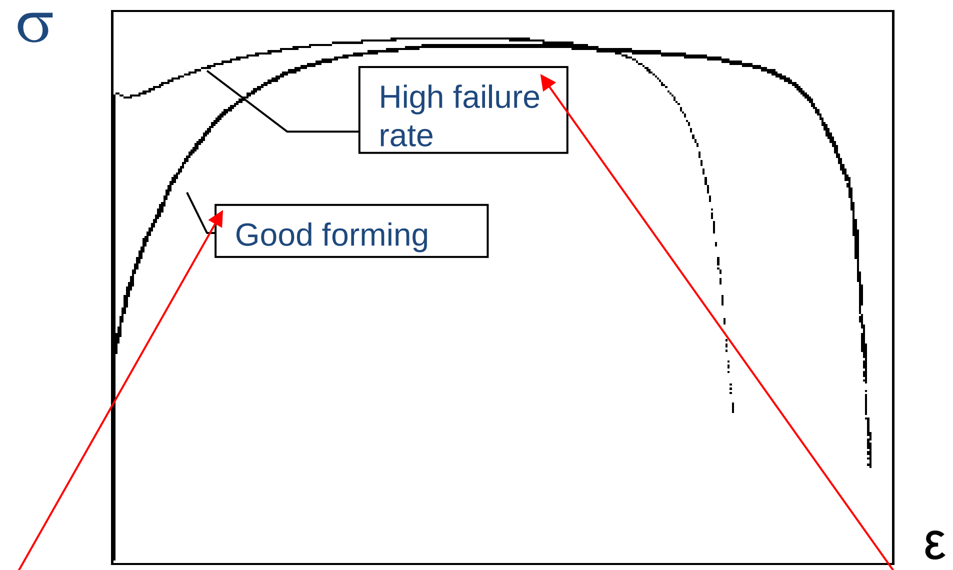
Not completely recrystallized Nb

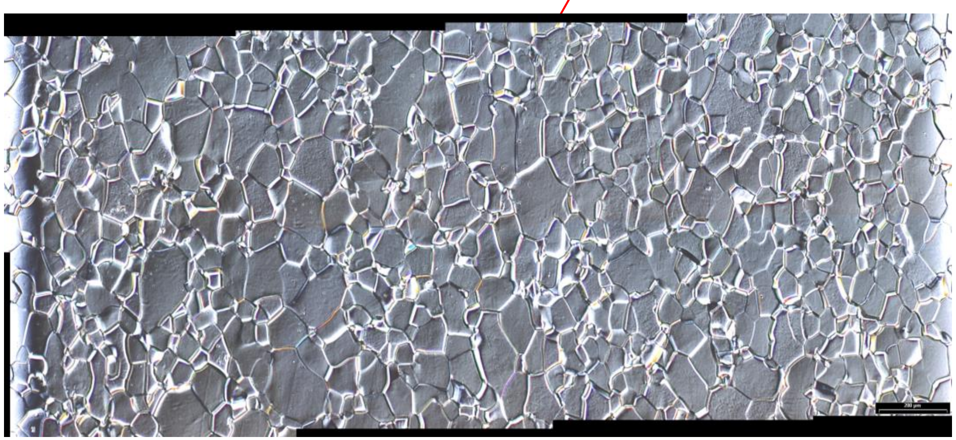
Recrystallization

We need recrystallized material

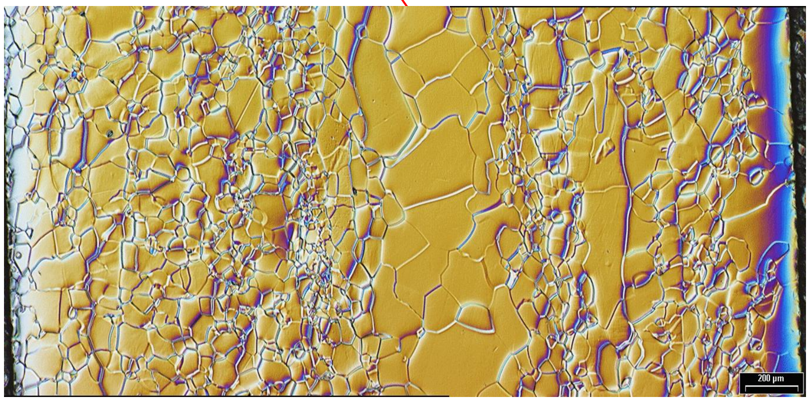
Formability of Nb sheet by deep drawing

High degree of deformation homogeneously distributed in the balk of Nb sheet has to be the aim





Uniform deformation before recrystallization

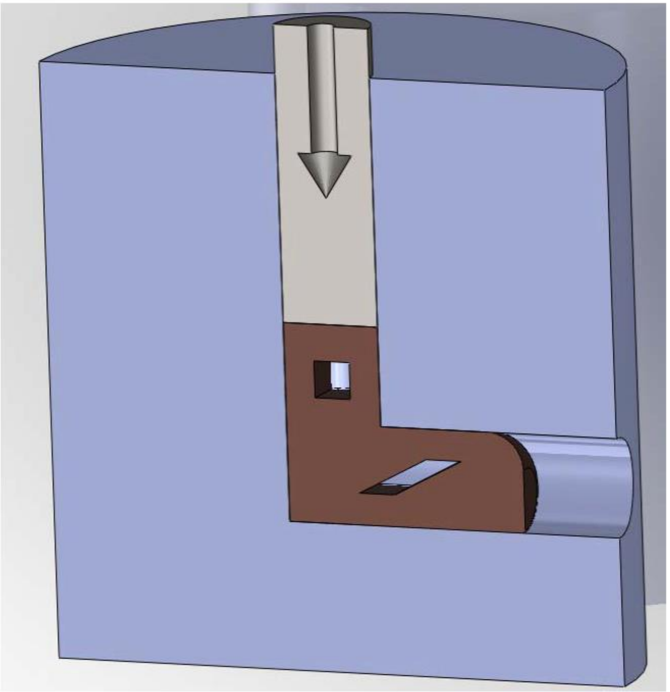


Not uniform deformation before recrystallization

ECAE Description

Equal Channel Angular Extrusion

- Concept
  - Intersecting channels
  - Simple Shear Deformation
- Results
  - Uniform Deformation
  - Grain refinement
- Benefits
  - Fine grains
  - Uniformity
  - Some texture control

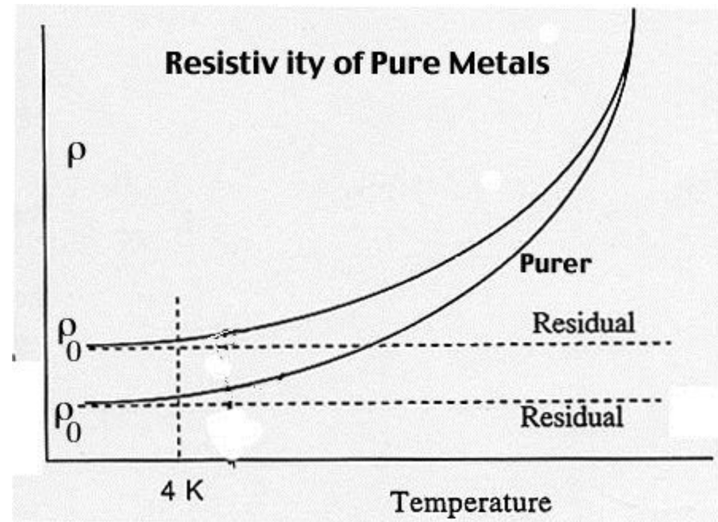


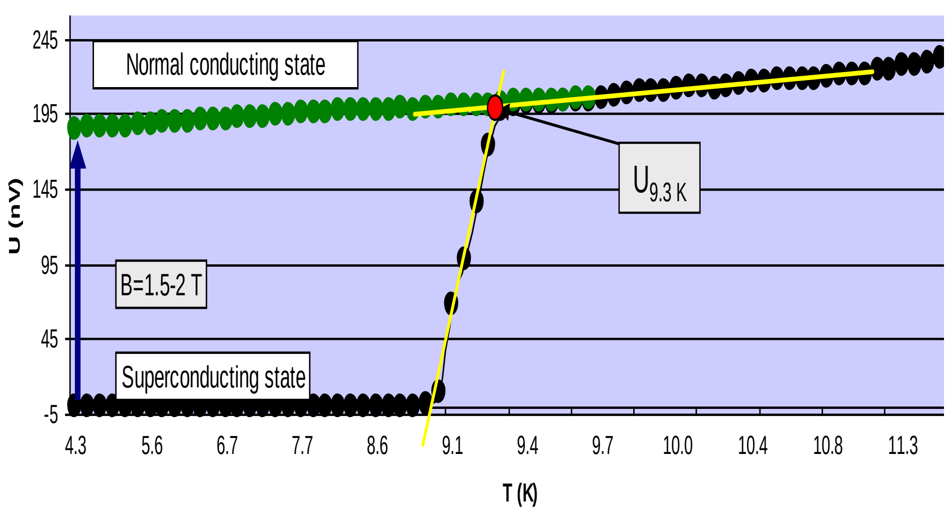
One of interesting method for reaching high and uniform deformation degree

Material Purity: Electrical resistivity of metals at low temperatures is an excellent tool to determine impurity concentrations. The residual resistivity at T =0K is caused mainly by scattering of electrons on impurities.

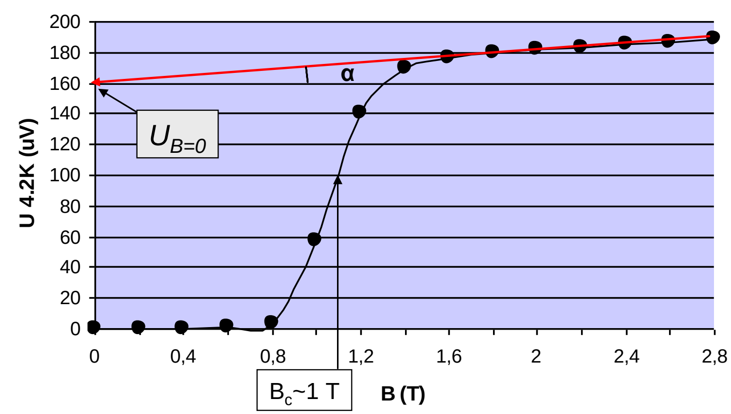
Residual Resistivity Ratio $$RRR = \frac{\rho(295\,K)}{\rho(4.2K)}$$

$$\rho(T) = \rho_{res} + \rho_{ideal}(T)$$



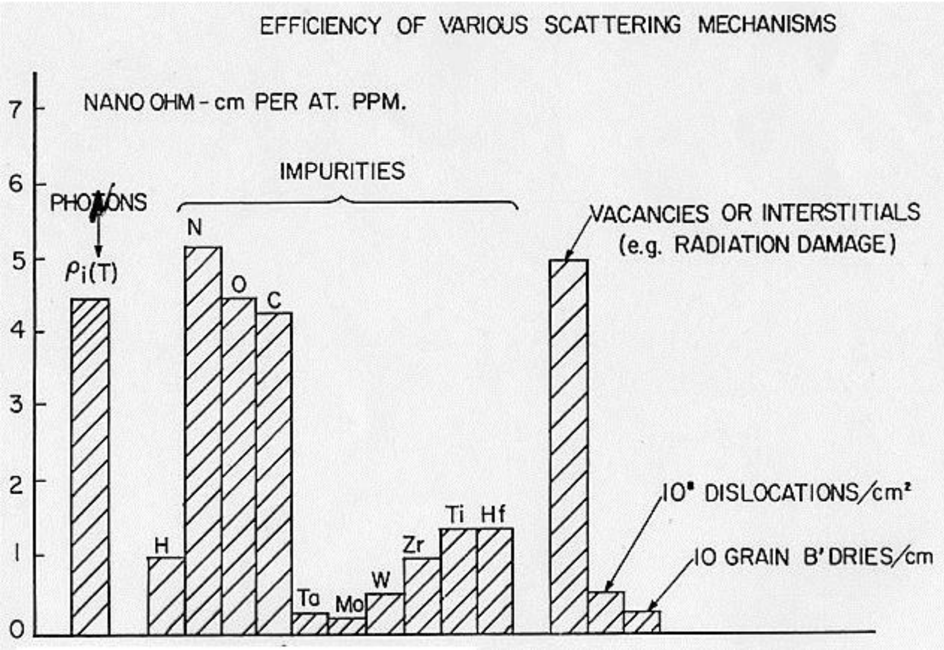


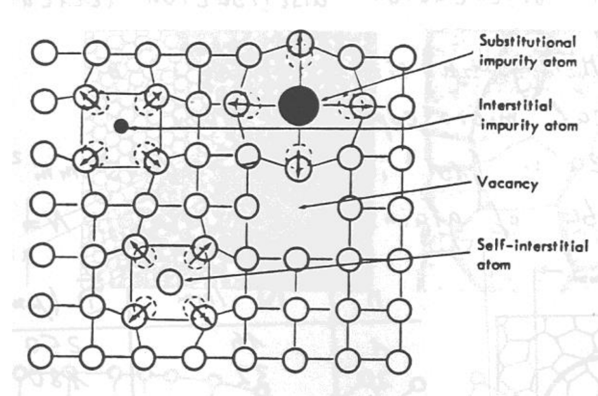
RRR DC determination by extrapolation of U(T) curve



RRR determination by extrapolation of U(B) curve

Influence of impurities on RRR





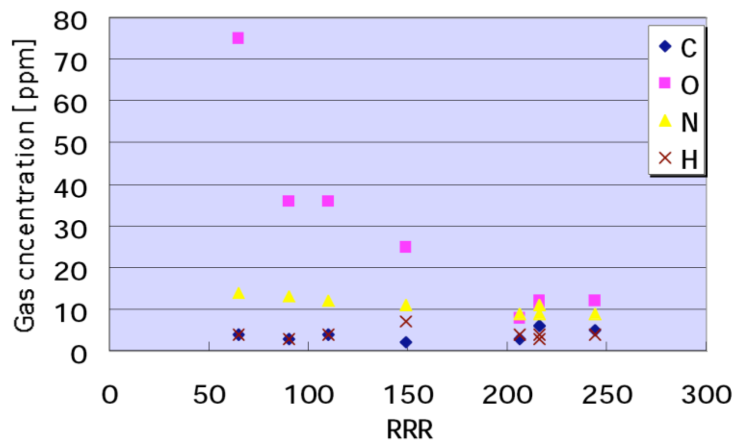
Substitutional and interstitial impurities

Contribution of different defects in the scattering mechanism (Schulze)

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

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

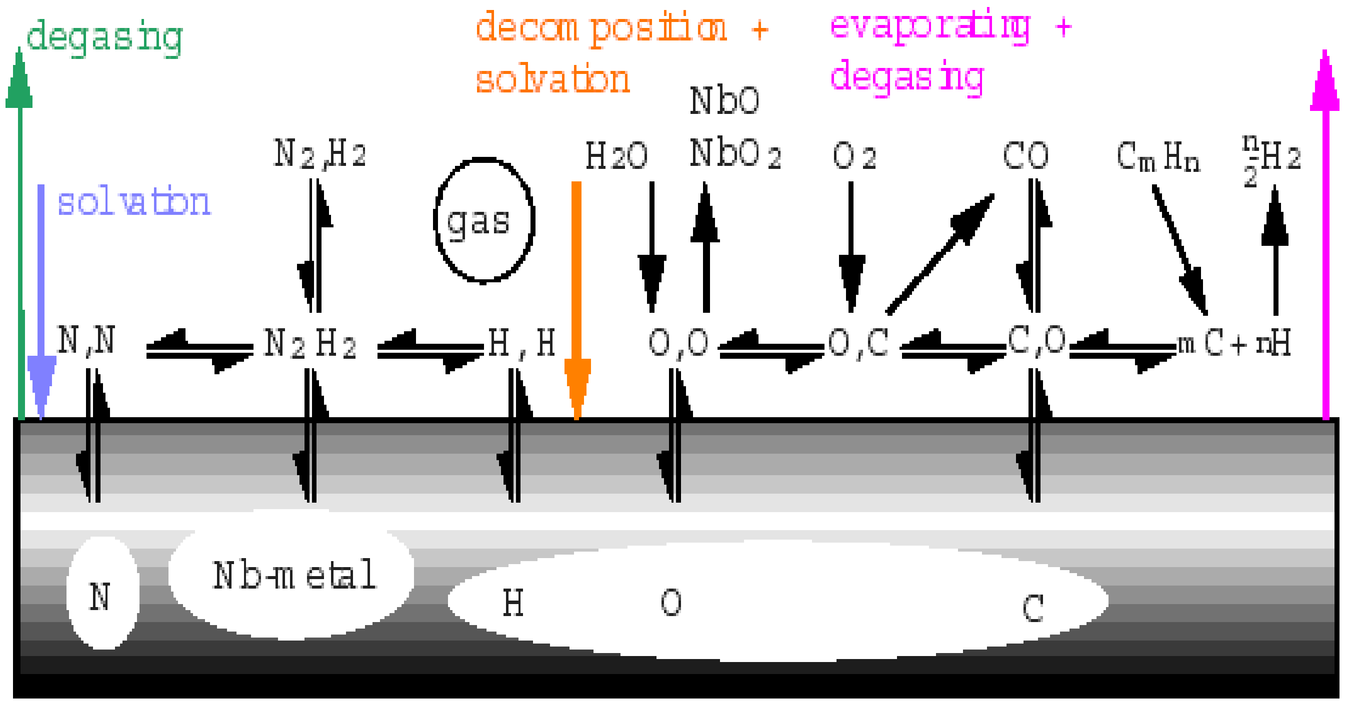
Industrial Niobium Production – Intestinal impurities and RRR(Tokyo Denkai Co. Ltd.)



Relationship between RRR and nonmetallic impurities (Tokyo Denkai)

W. Singer. CERN Accelerator School. Erice, Italy, 24 April-4 May, 2013

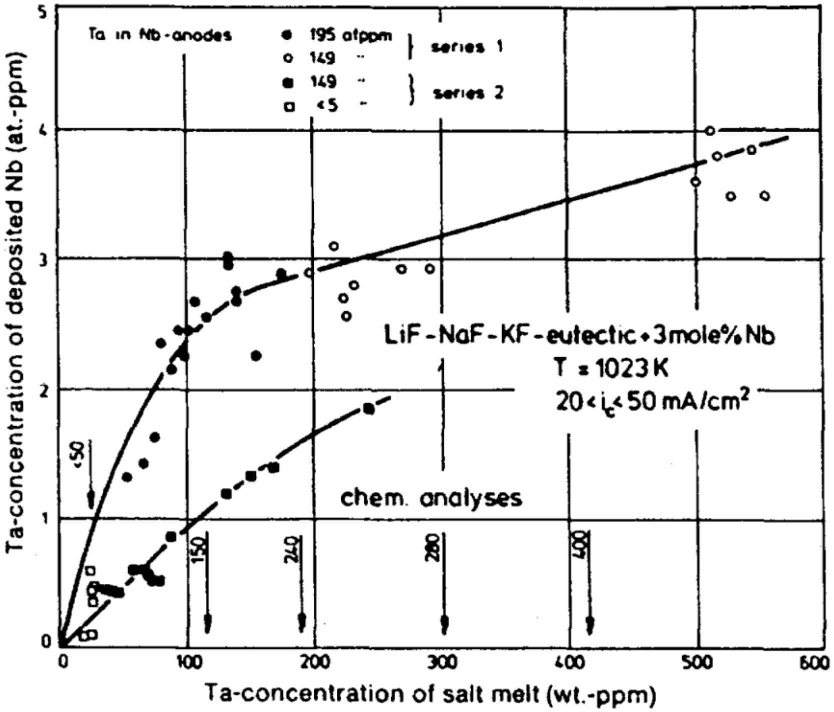
Nb-Purification by Electron Beam Melting



Schema of niobium and residual gases in vacuum at high temperatures

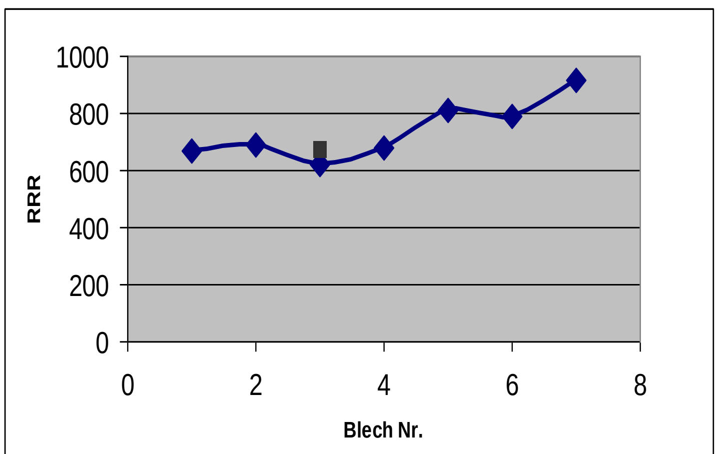
- **H_2 and N_2:** Thermodynamic equilibrium are established between H_2 and N_2 and dissolved H and N atoms.
- For **O_2, and H_2O** steady states at temperatures T > 2000K and partial pressures $p < 10^{-4}$ mbar between oxygen uptake and oxide evaporation of NbO or NbO_2.
- **C:** In opposite to oxygen carbon desorbs only in the form of CO.
- Traces of hydrocarbons which are always present in vacuum lead to a continuous decomposition at the niobium surface with a steady uptake of C and the liberation of H_2.

Nb-Purification by Electrolysis in Molten Salts



Fundamental investigations of the electrodeposition of Nb- from LiF-NaF-KF melts containing K_2NbF_7, at T = 1000 K have shown that this electrolyte was suited for the the material refining;

Nb become extremely pure especially concerning of Ta



RRR up to 1000

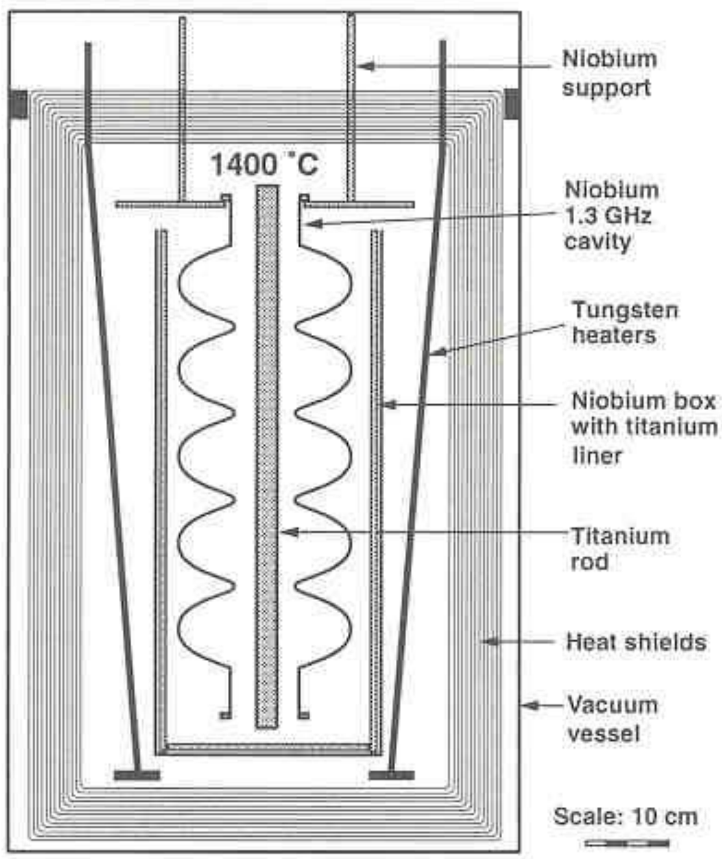
Chemical analysis:

Ta = 6 wt. ppm,

N = 1 wt. ppm, O = 5 wt. ppm,

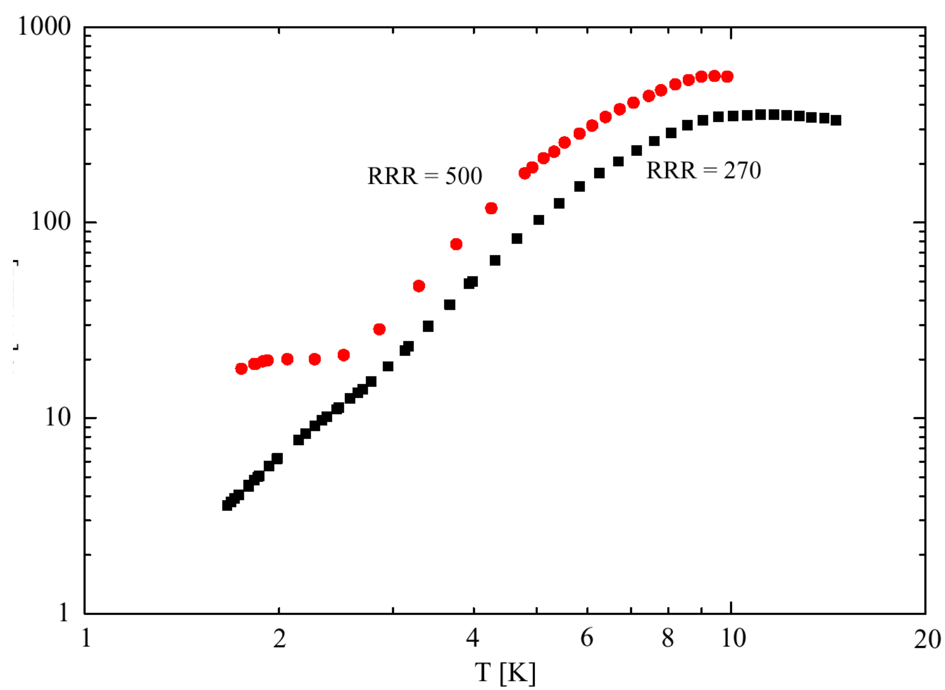
W, Ti, Fe, Si, Mo, Ni < 5 wt. ppm all together

Post purification (solid state gettering)



Schema of cavity post purification applied at DESY for FLASH cavities

Thermal conductivity and RRR of samples from the niobium sheets before (in black) **and after the 1400 ºC heat treatment** (in red)



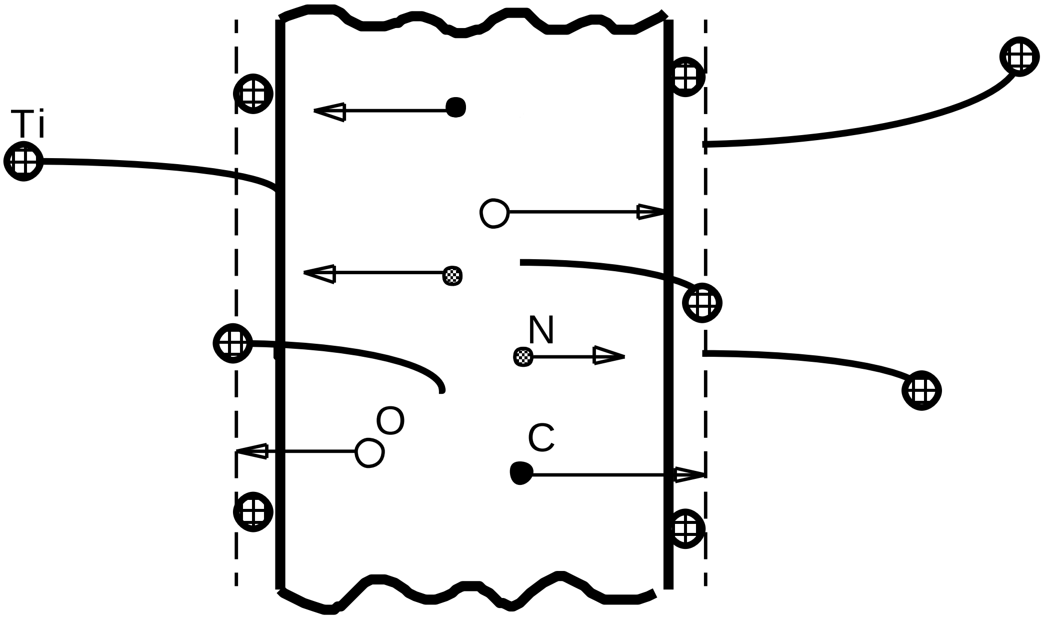
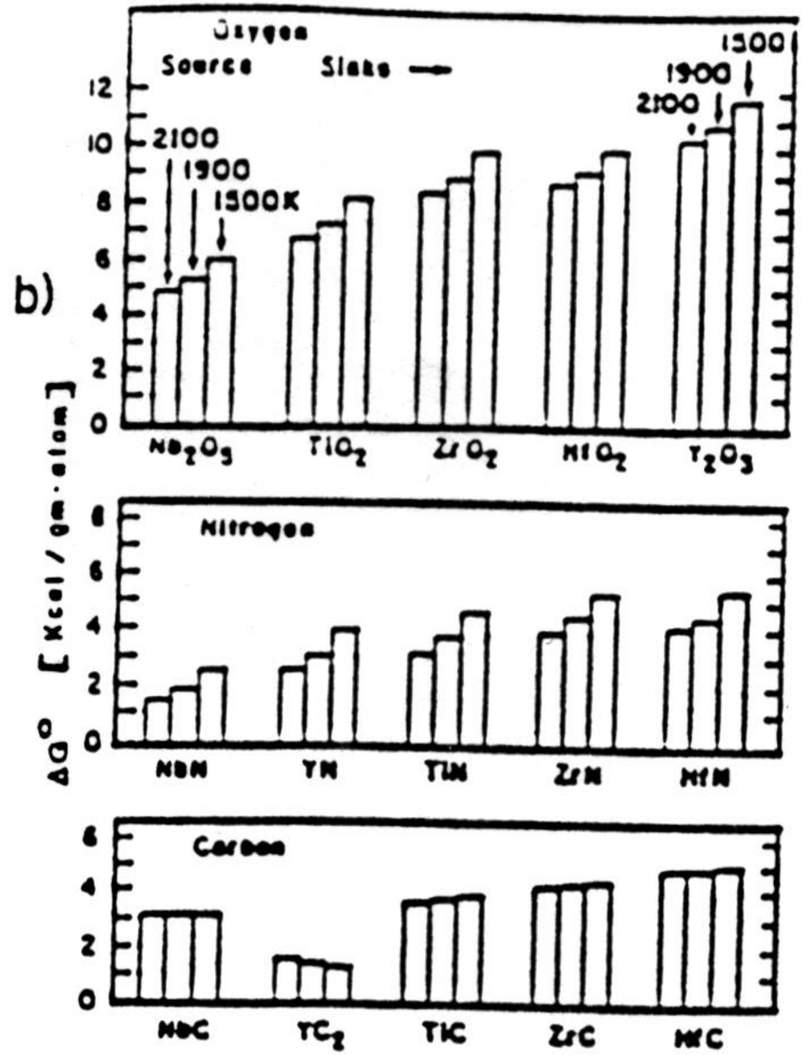
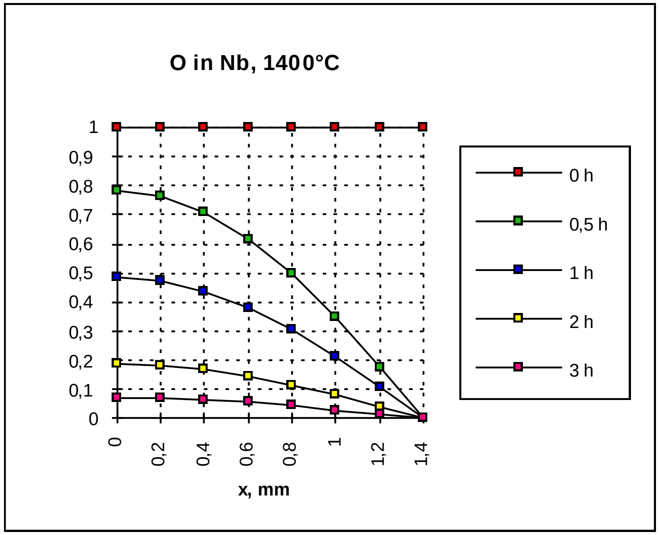


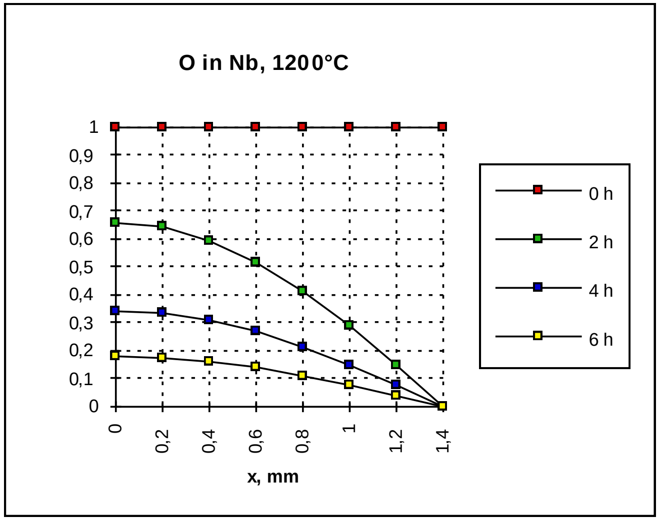
Fig. 1 Scheme of the Nb refining by high temperature gettering

During refining the interstitial impurities O, N, C move to the surface and build compounds with Ti, because the affinity of Ti to O, N and C is higher as of Nb. The concentration gradient of interstitial impurities between surface and inside of Nb keep the refining. On the other hand the Ti diffuse into Nb (drawback).

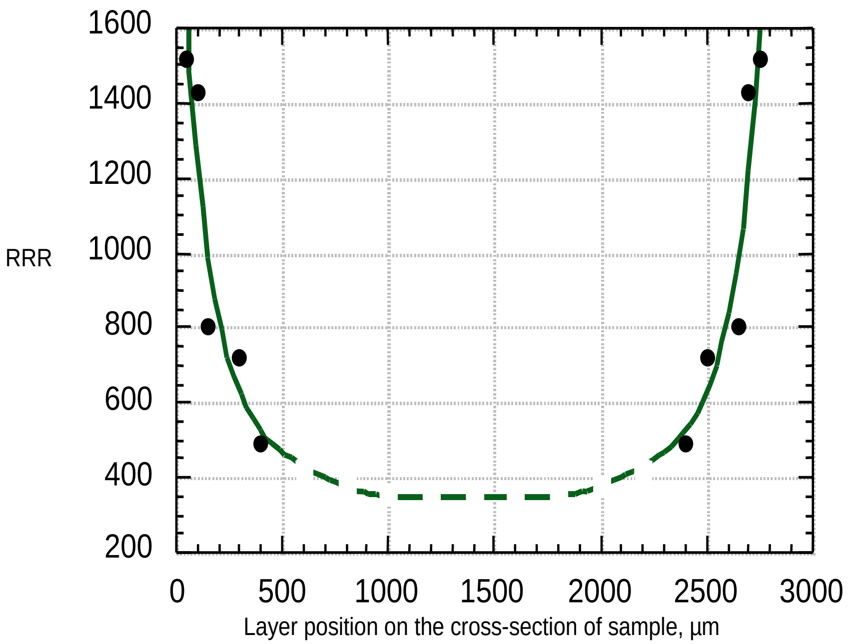


Comparison of Nb, Ti, Y, Zr, Hf bonding enthalpy with oxygen, nitrogen and carbon





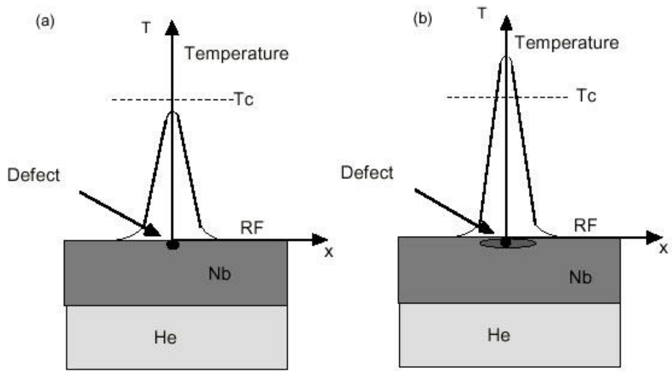
$$\frac{C}{C_0} = \frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}EXP\left(-\frac{D\pi^2 t(2n+1)^2}{4l^2}\right)\cos\frac{(2n+1)\pi x}{2l}$$



Oxygen distribution in cross section from the middle to the surface of Nb sheet after refining

Measured RRR distribution in Nb sample cross section from the middle to the surface of Nb sheet after refining

Local defects and thermal conductivity of Nb at low temperatures



Local defect triggers the quench, if the temperature exceeds Tc (H. Padamsee)

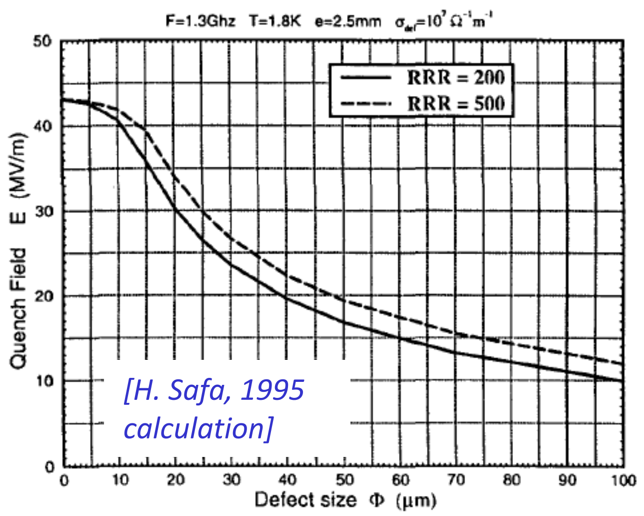
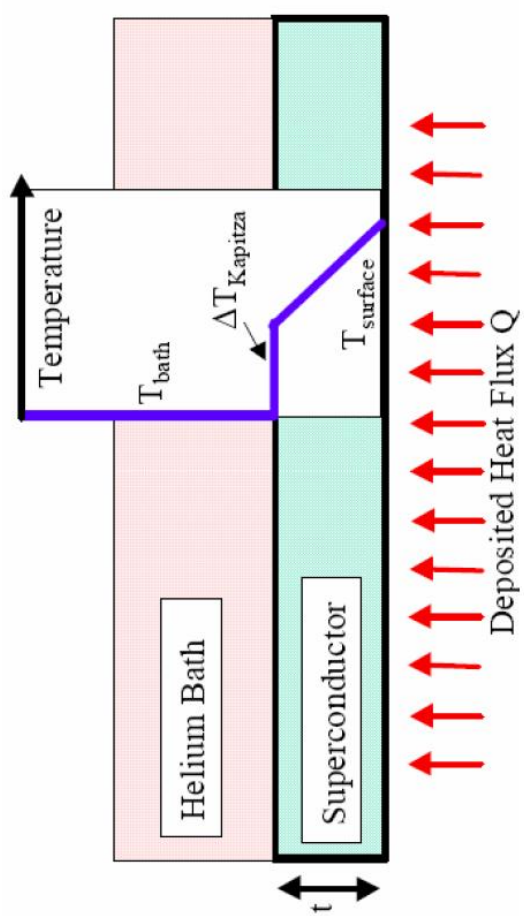


Figure 8– Quench field as a function of defect size.

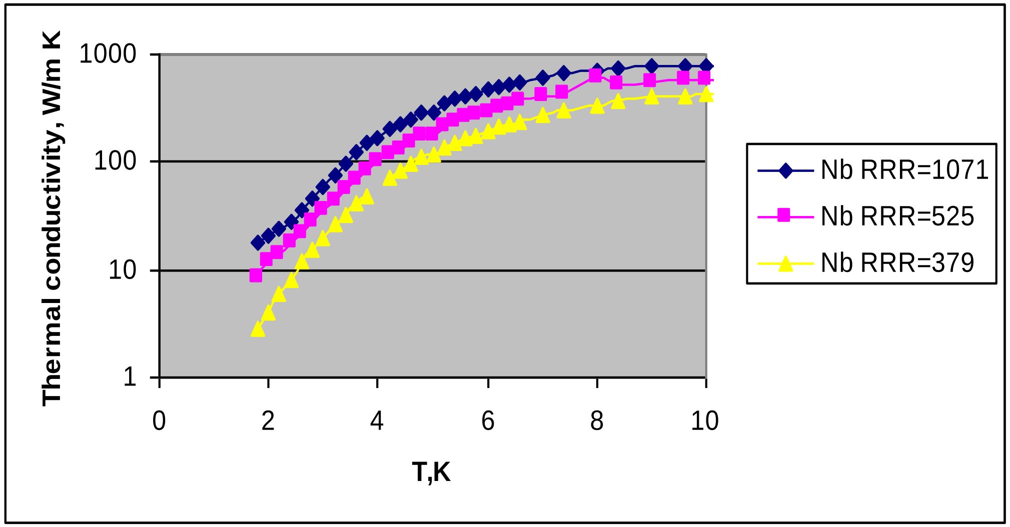
Defect of 50-100 μm caused quench field of < 15-20 MV/m:

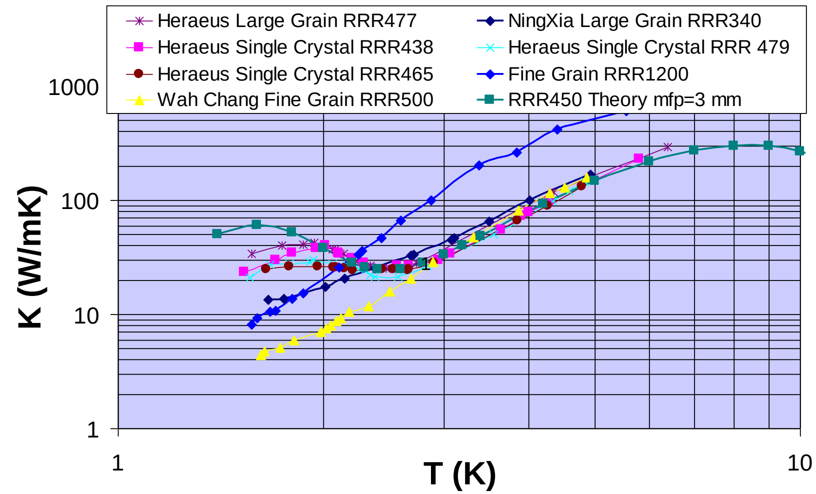


High thermal conductivity is required

We need high purity for thermal stabilization of defects

RRR and thermal conductivity of Nb at low temperatures





Thermal conductivity of polycrystalline (fine grain) and single crystal niobium. Phonon peak is clearly pronounced for single crystals.

Rule of thumb

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

$\lambda_T \approx$ RRR $\approx$ purity (restricted)

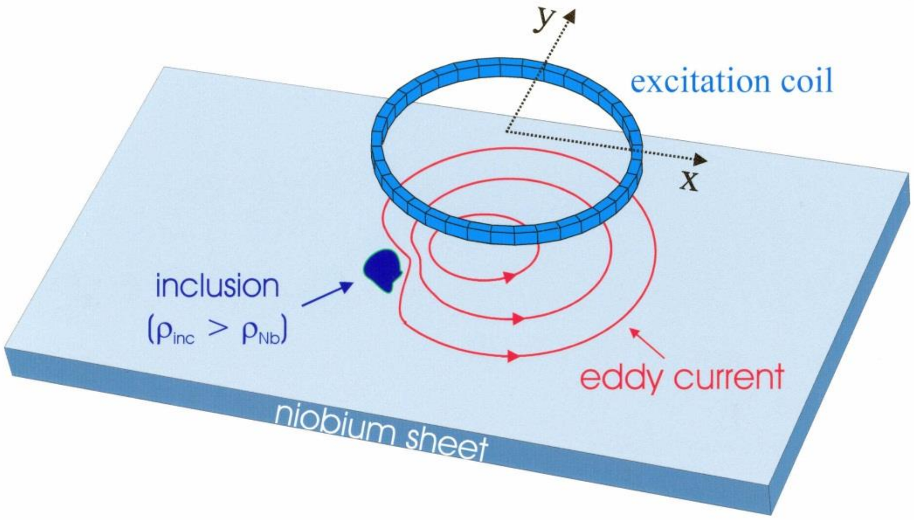
$$C \approx 0{,}25 \div 0{,}14$$

B.Bonin, CEA

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

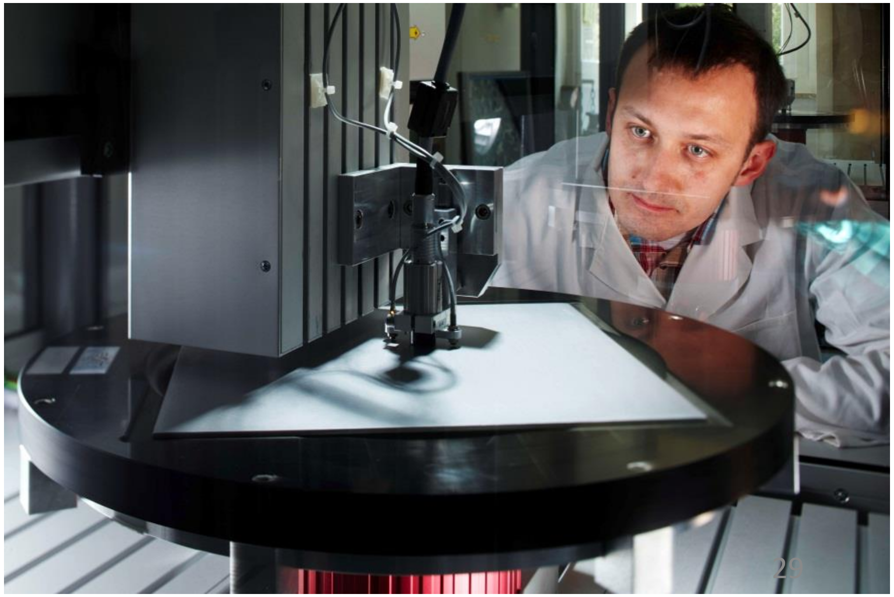
First term: scattering of electrons on impurities, lattice defects and scattering of electrons on phonons. Second term: scattering of phonons on electrons, scattering of phonons on grain boundaries

Search for local defects in Nb sheets. Eddy current system.

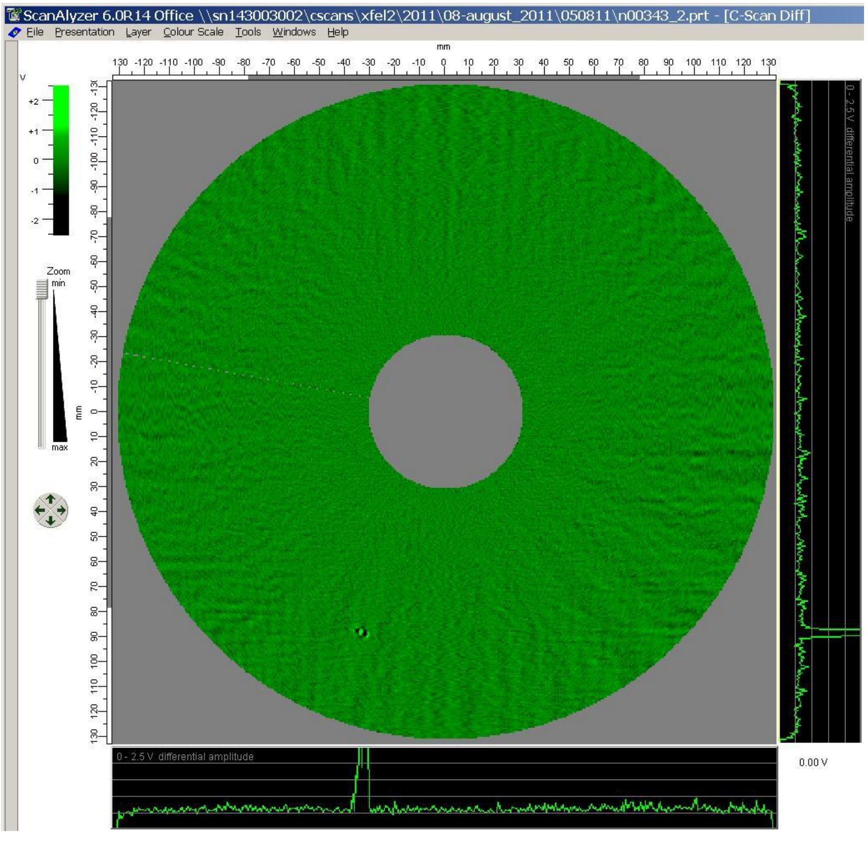


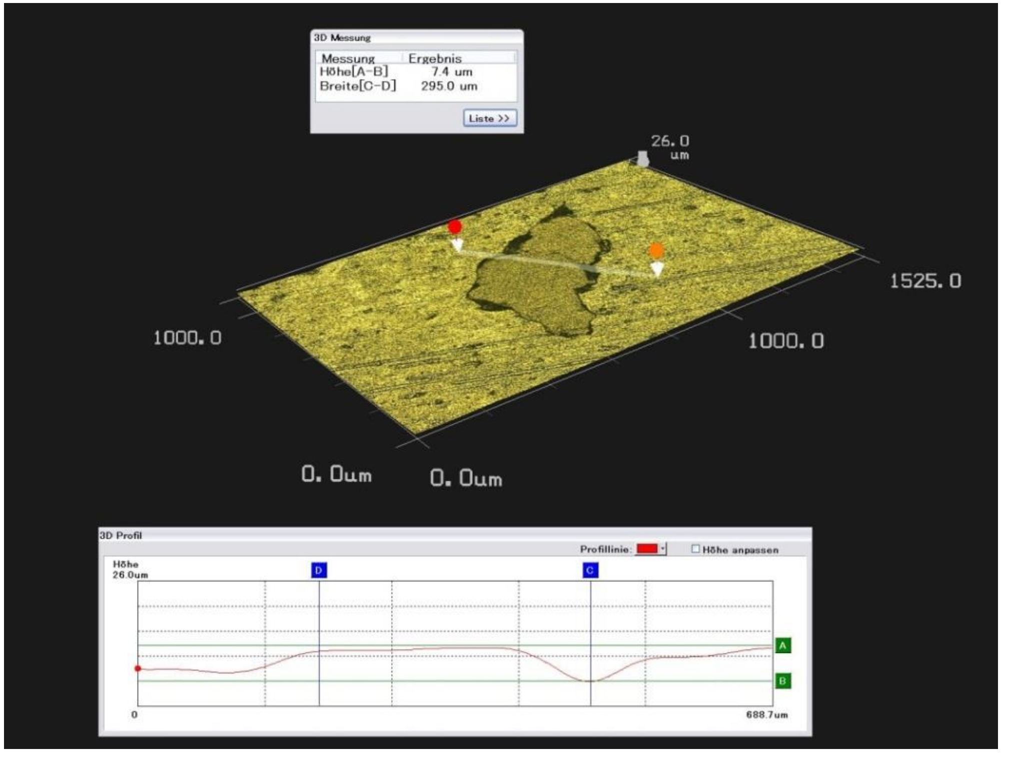
Principle of eddy current measurement

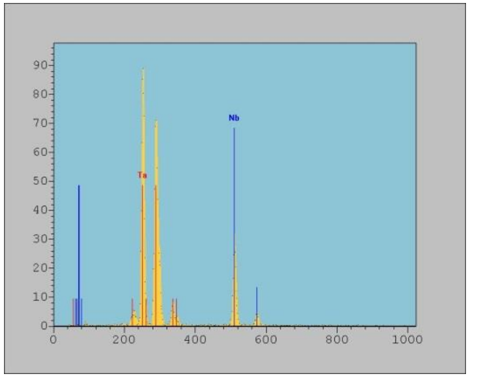
DESY eddy current scanning of niobium sheets. 100% Nb sheets for European XFEL scanned and sorted out. **Feed back to Nb producer was very important**



One example of foreign material inclusion (Ta) detected in the Nb sheets

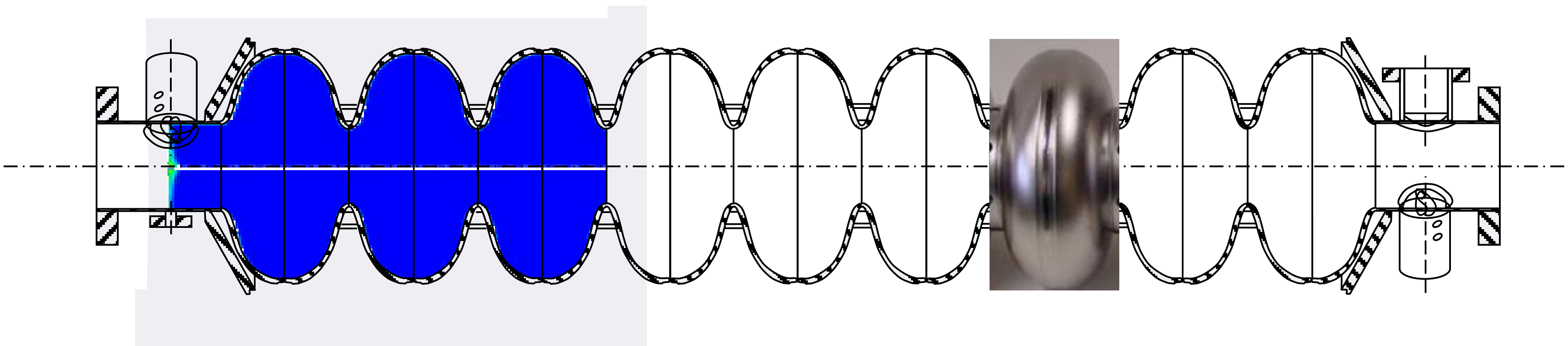






Eddy current scan, 3D-Microscope image and result of the nondestructive element analysis

Conventional SC cavity fabrication



Frequency 1.3 GHz

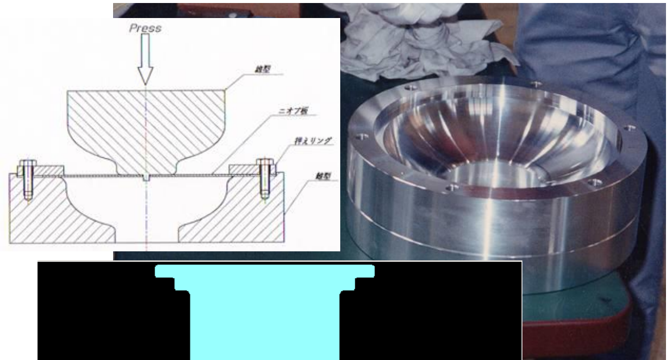
High purity niobium RRR 300

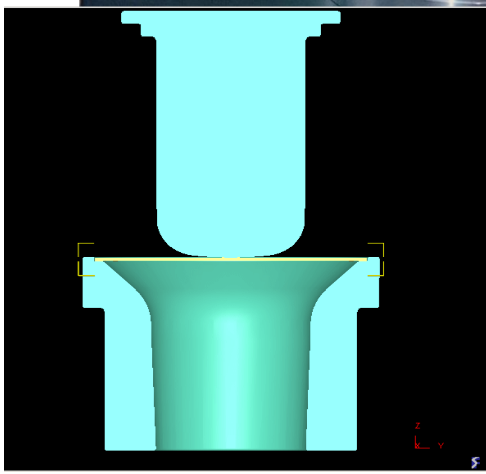
Deep drawn from sheets

Welding with electron beam

Operating temperature 2K

Experiences of ca. 30 years of industrial cavity fabrication by deep drawing and EB welding are available

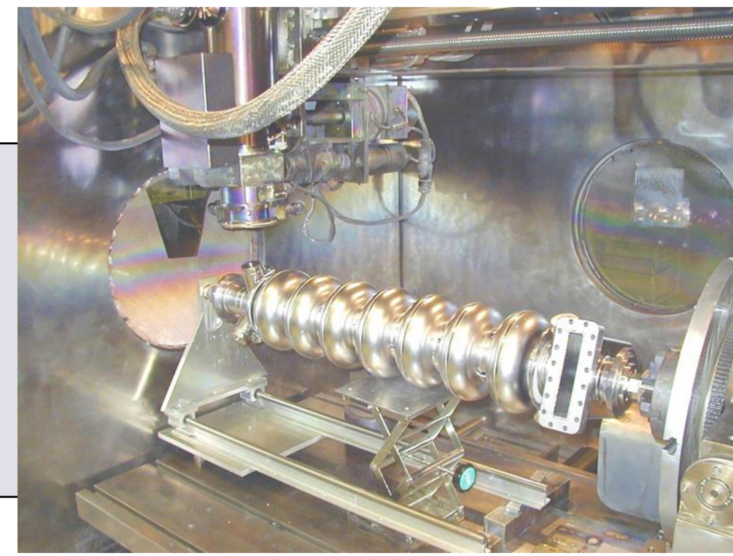





Half cells are shaped by deep drawing.

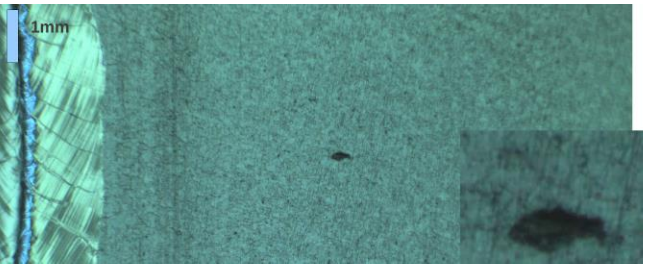
Dumb bells are assemled by electron beam welding.

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

Foreign elements (aluminium particle) close to the welding seam. Quench in π-mode at 13,7 MV/m



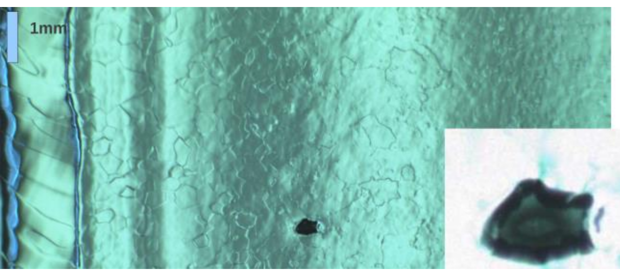
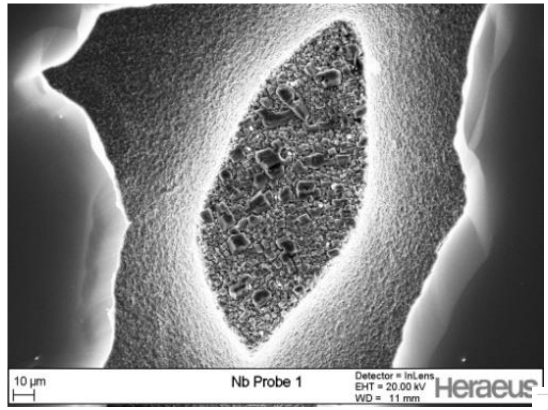
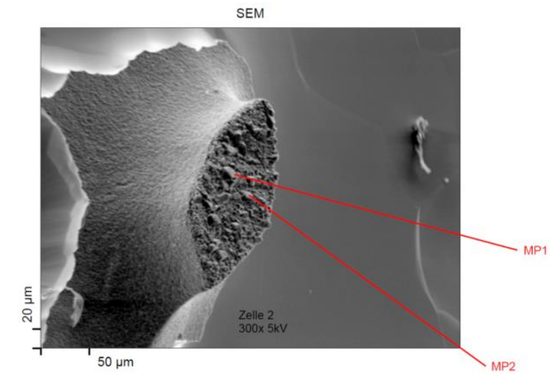
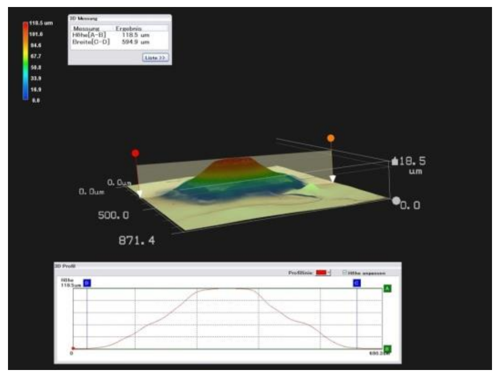
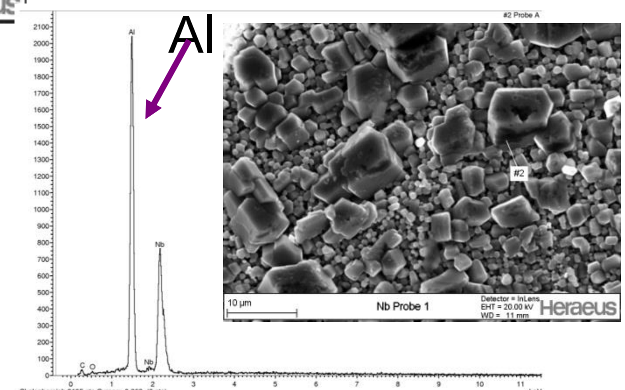


Image of high resolution camera done on the cavity Z161 as delivered (top) and after EP (bottom)





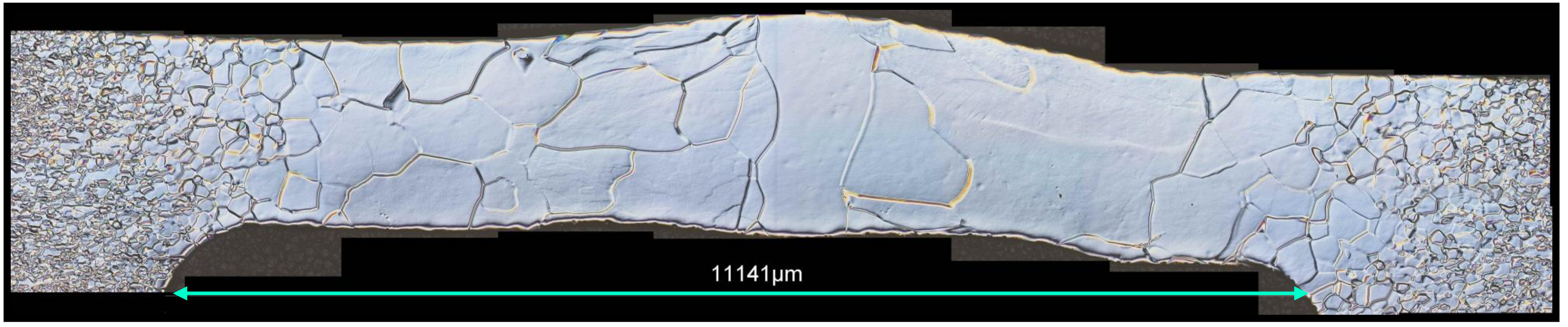




3D microscope, SEM Images and EDX analysis of samples

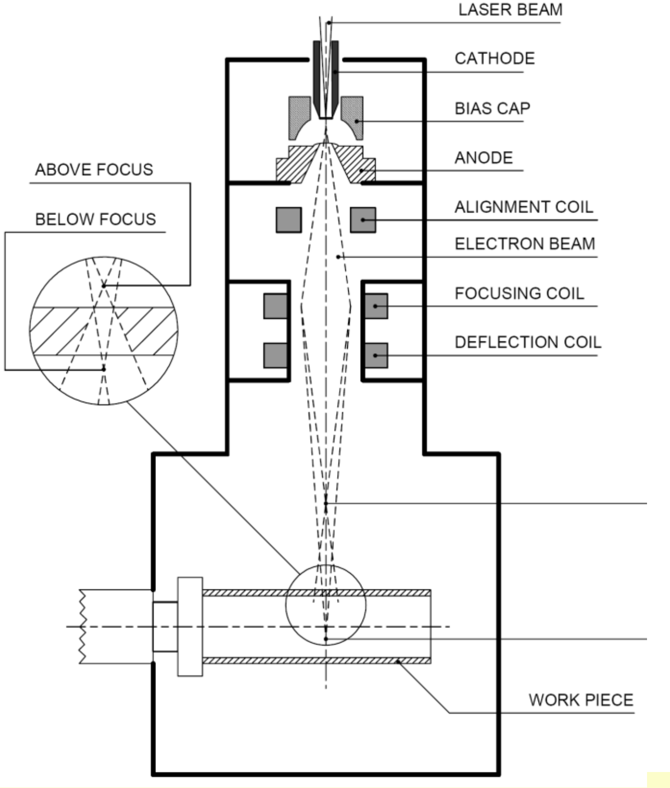
Particle adhered during welding and did not disappear after electropolishing

Electron Beam Welding EBW



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

Electron Beam Welding Machine



Specification of DESY Electron Beam Welding Machine

Voltage: 70 - 150 kV

Beam power: max. 15 kW

Beam current: 0 bis 100 mA

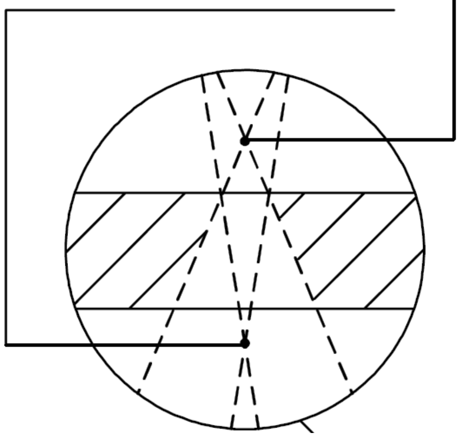
Chamber size: 3300mm x 1400mm x 1600mm (ca. 7,4 m³)

Vacuum: > $5x10^{-6}$ mbar (ca. $2x10^{-8}$ mbar)

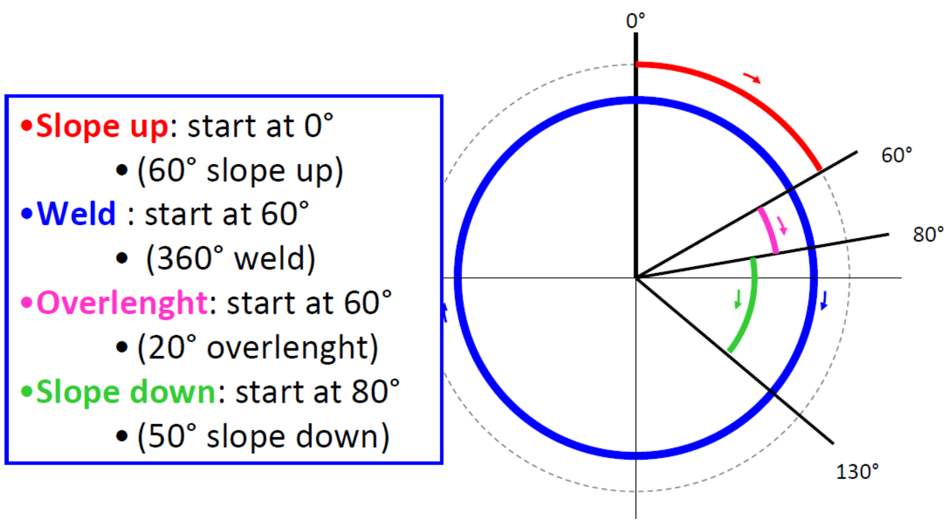
Pumping time: ca. 20 min =$3x10^{-6}$ mbar

2 Cryogenic - Pumps: ca. 2 × 10.000 l/s

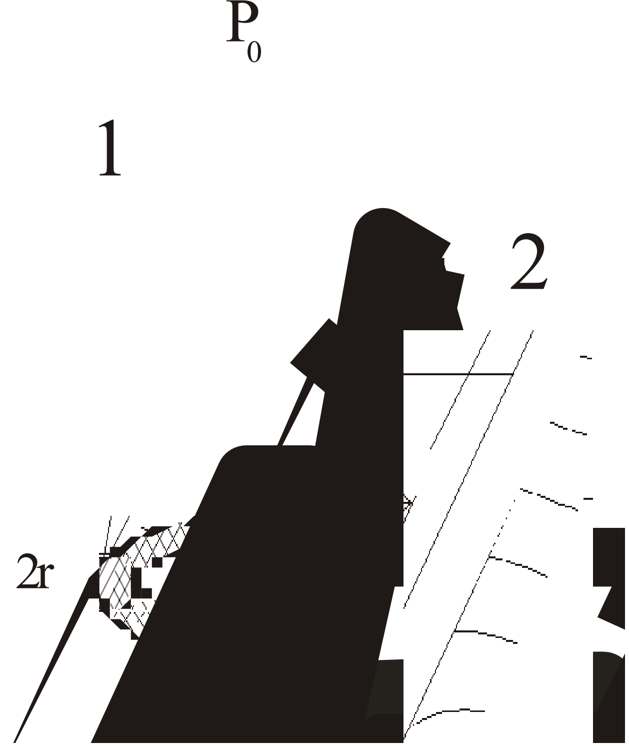
Displacement along the X-Axes ca. 1400 mm



Focusing possibilities (above focus; below focus)



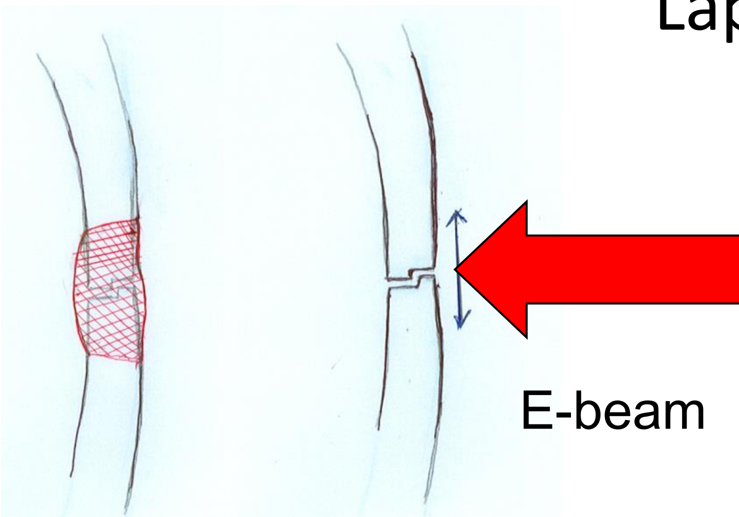
Circular welding. Power slope up/down. Tacking and two passes (70 and 100% penetration)



Welding Scheme (circular raster)
1-Electorn beam (P_0-power of the beam, r- spot radius on the surface, L- scanning amplitude, V- velocity of the beam movement), 2-Nb sheet, 3- melting zone (z-depth of the melting zone).

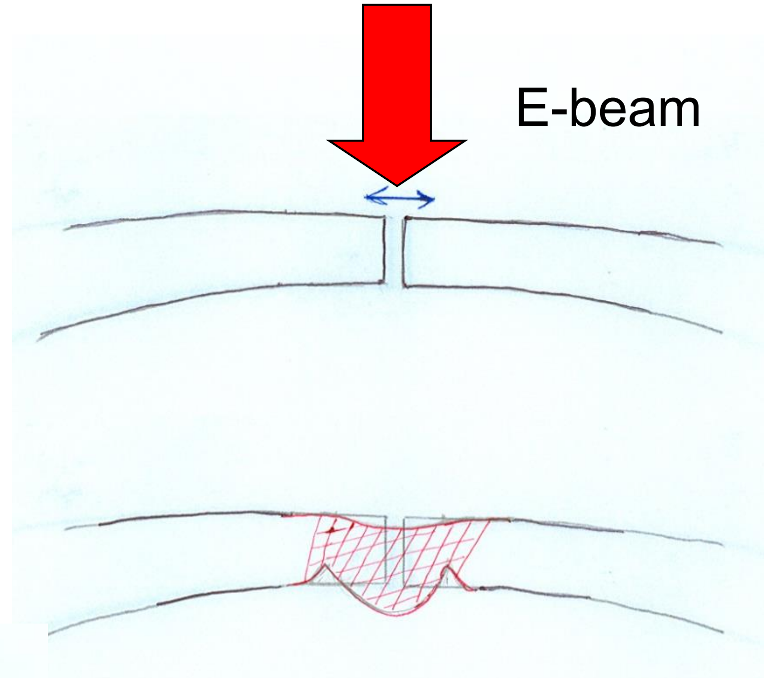
EBW with vertical or horizontal positioning of cavity?

Lap or butt joint?



E-beam

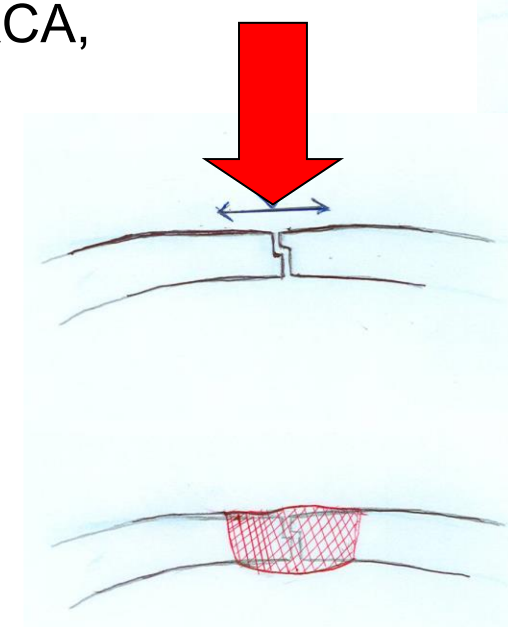
Vert. Pos. EBW: lap joint (recess) e.g. RI, CERCA, Sciaky

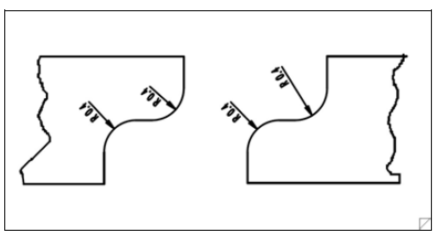


E-beam

EBW: butt joint (e.g. JLab, PAVAC)

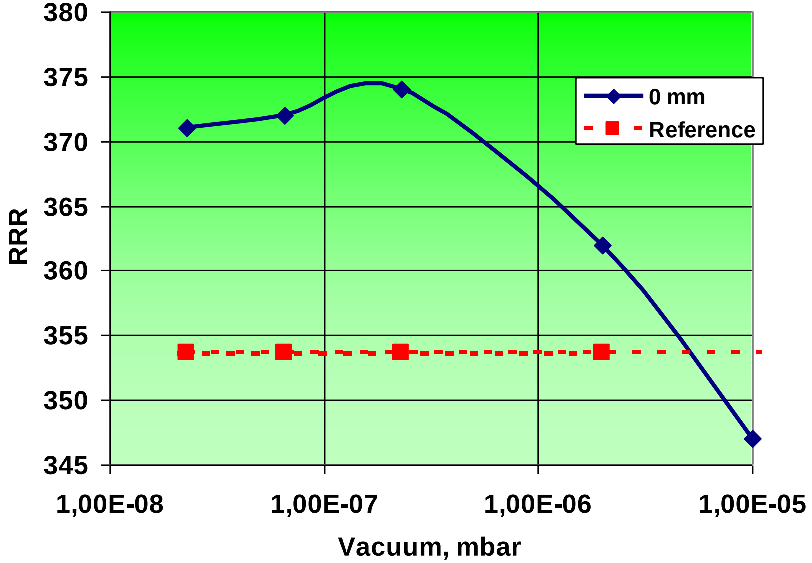
E-beam



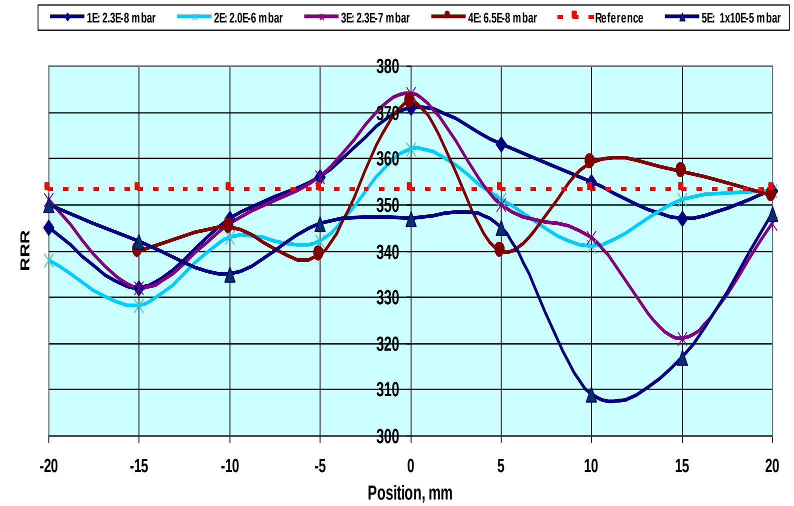


Horiz. Pos. EBW: lap joint (recess) DESY, AES, E.Zanon

RRR degradation during EB welding

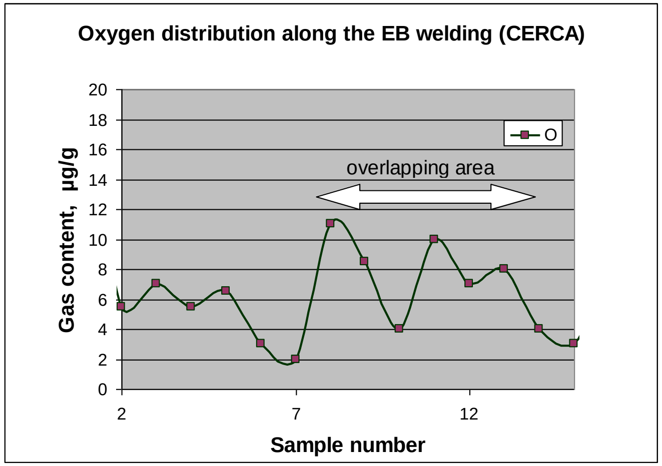


RRR in the welding seam versus pressure in the welding chamber



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

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

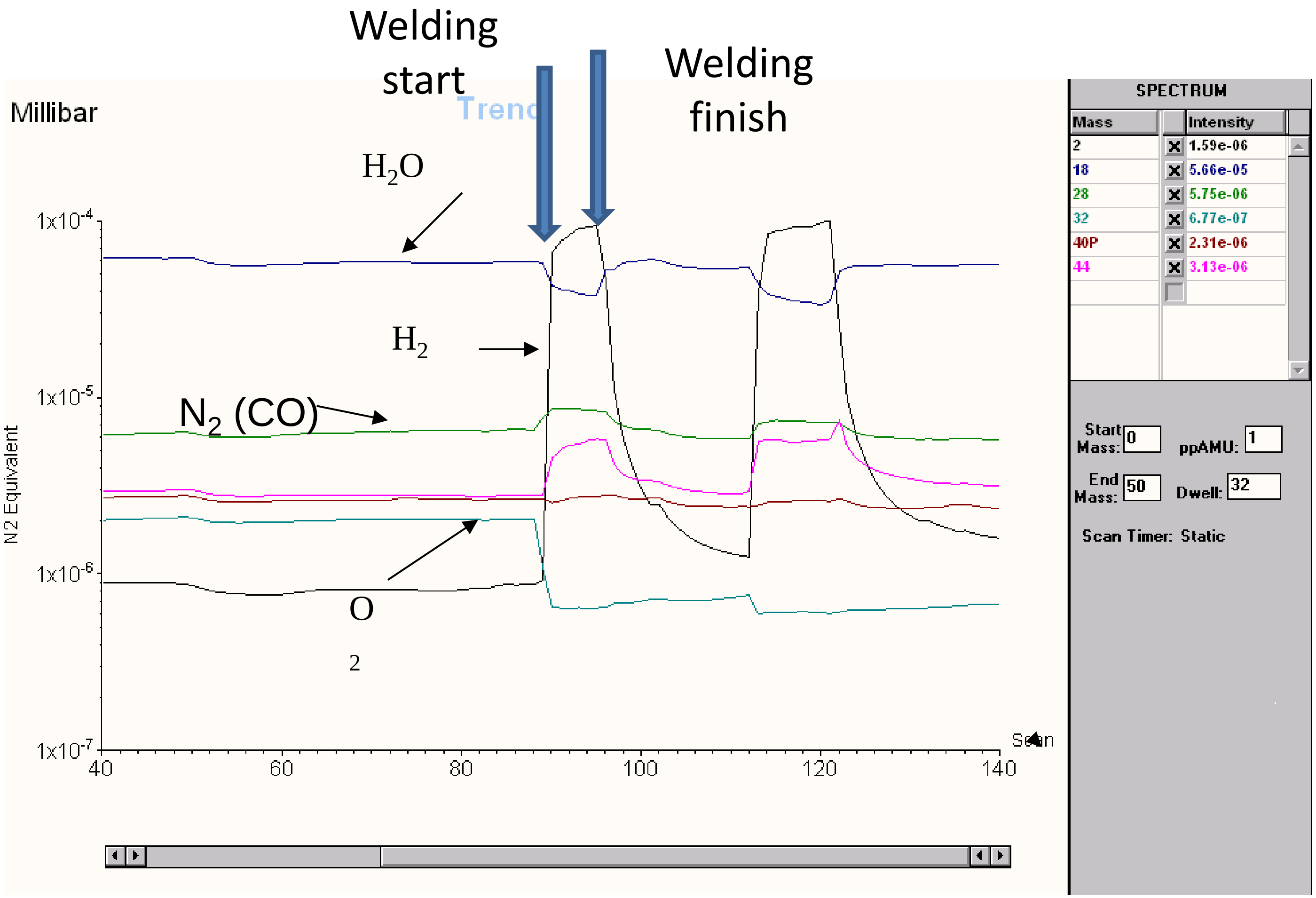


Oxygen distribution along the welding seam. RRR= 280 in the welding seam and RRR= 207 in the overlapping.

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

W. Singer. CERN Accelerator School. Erice, Italy, 24 April-4 May, 2013

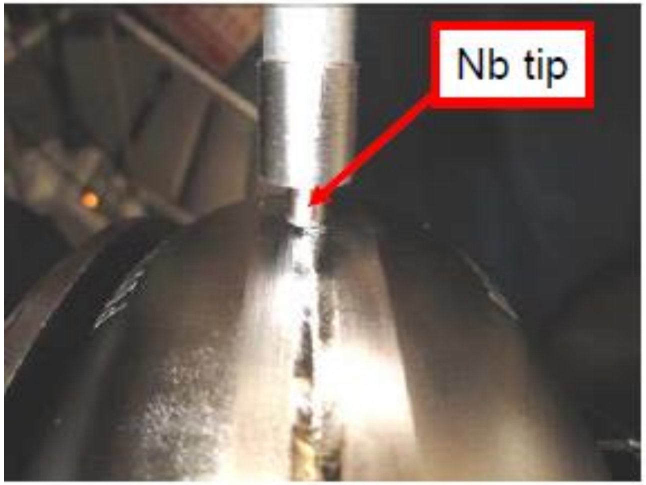
Partial pressure in the EB chamber during tack welding of Nb300

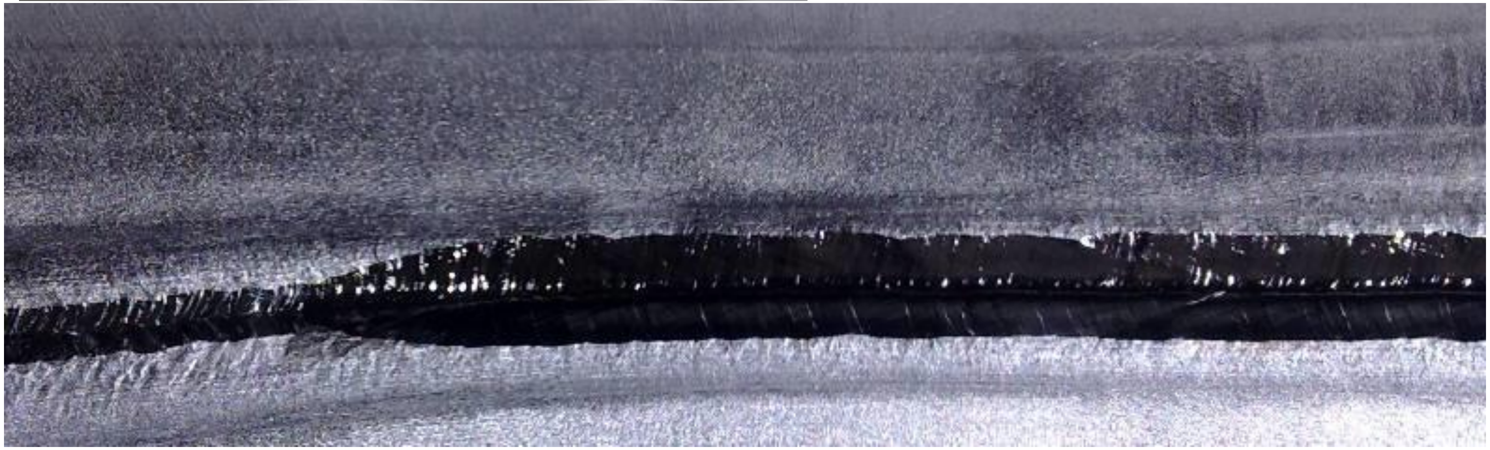


- **Water decomposition during welding**
- **Hydrogen from water and due to degassing**
- **Oxygen uptake**

Temporal changes of gas partial pressure in vacuum chamber during the EB welding process.

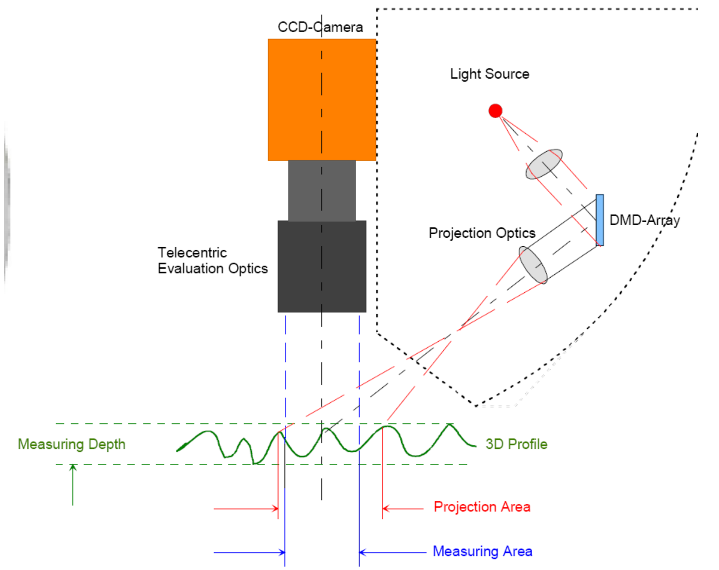
Repair procedure for equatorial EB welds. Up to 30 MV/m reachable

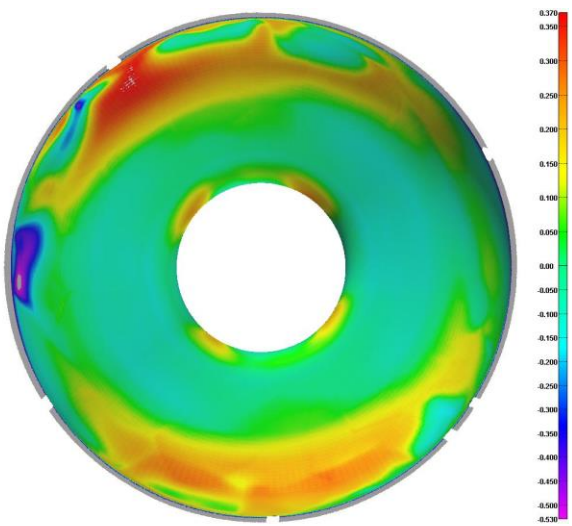


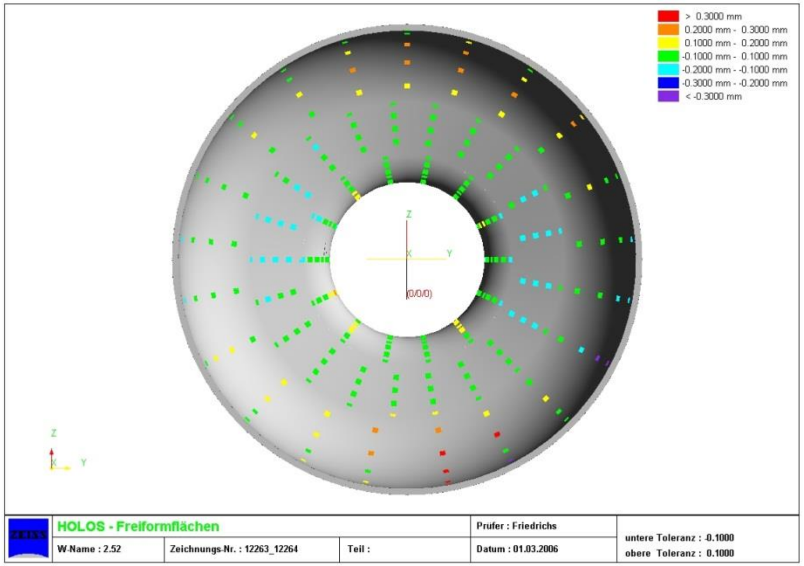


Repaired welding seam

Shape accuracy

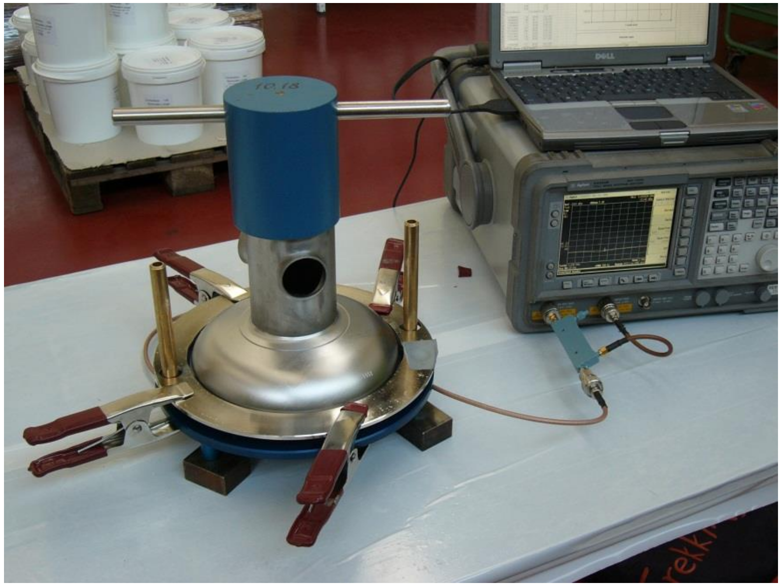


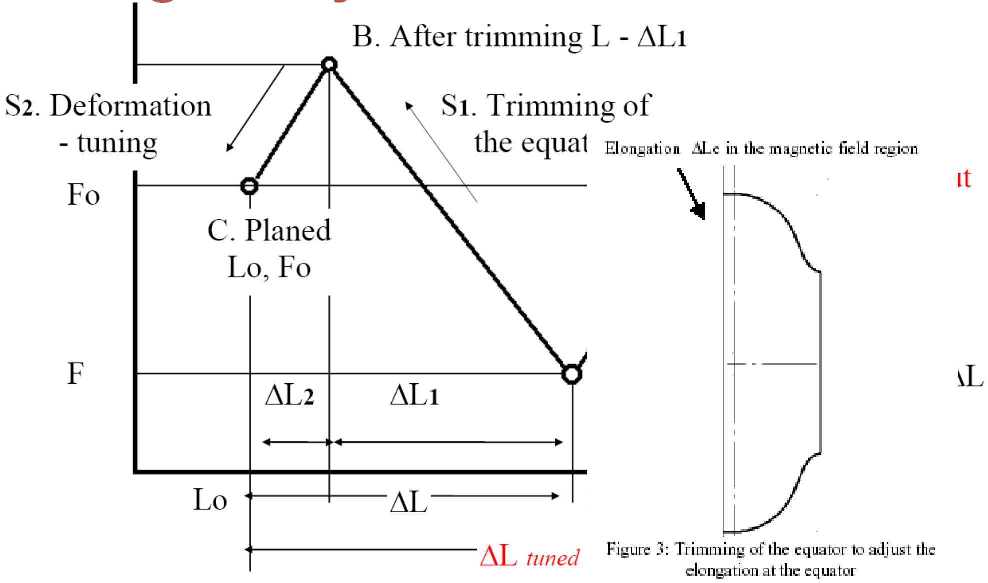


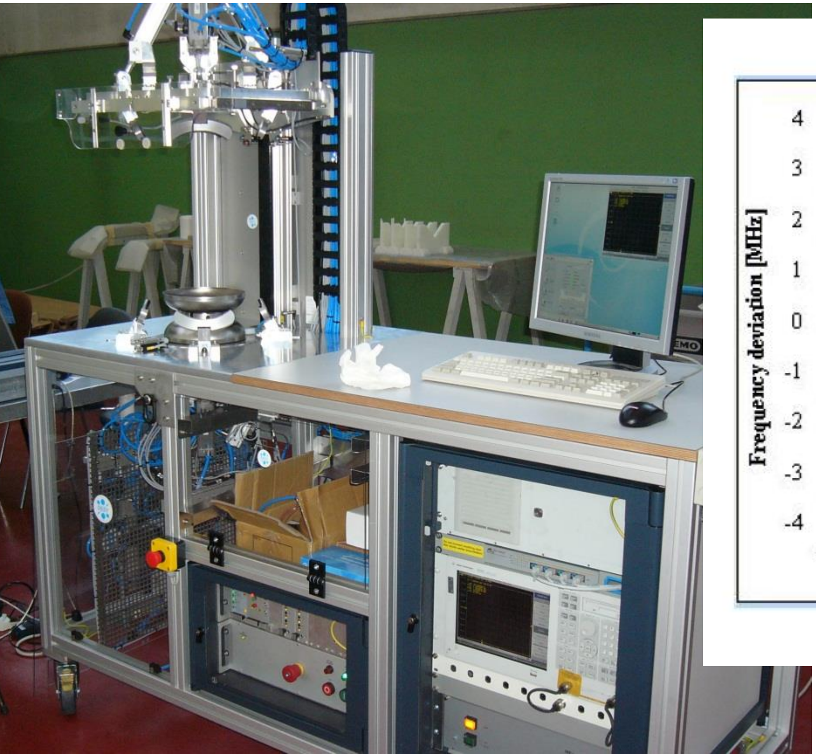


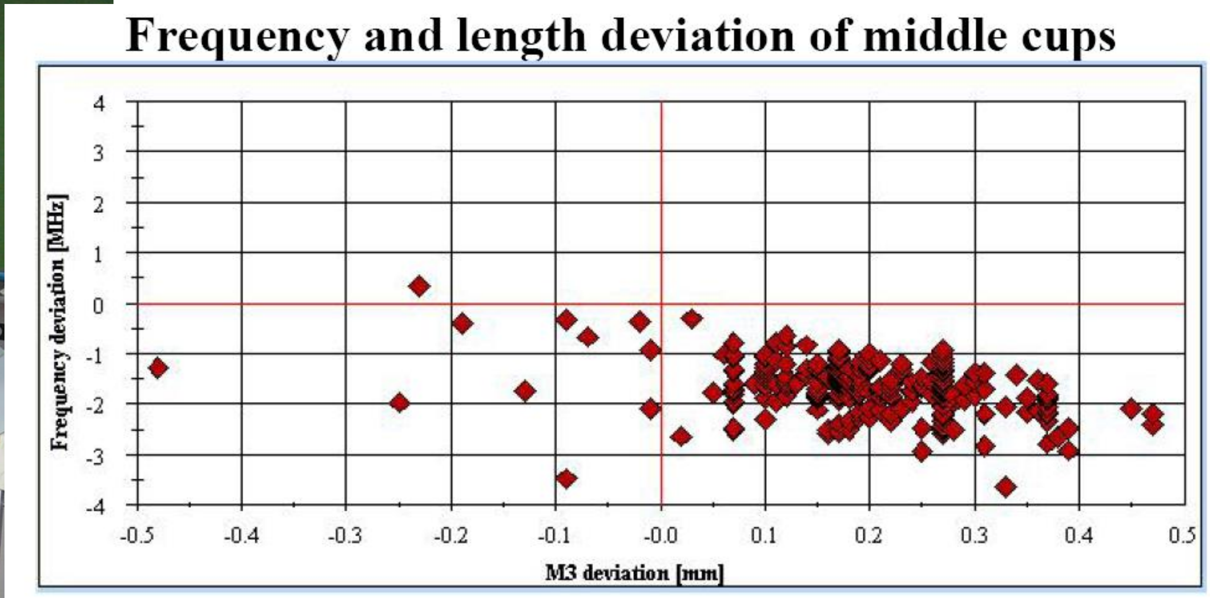
Control of the shape accuracy (critical): Optical and mechanical (tactile) 3D measurement of the half cell shape

Frequency and length adjustment



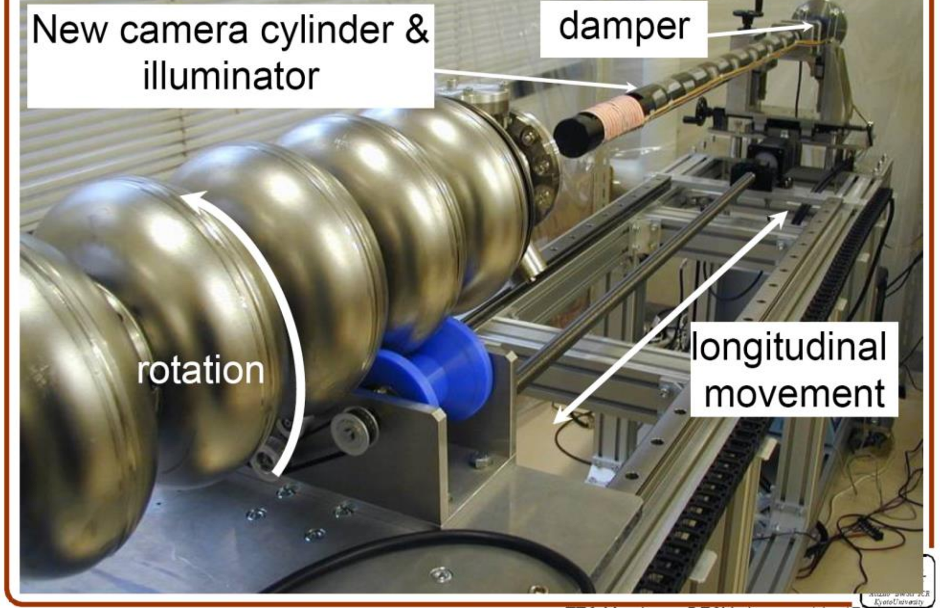






Wah Chang (EDMS-DB)

Cavity inspection

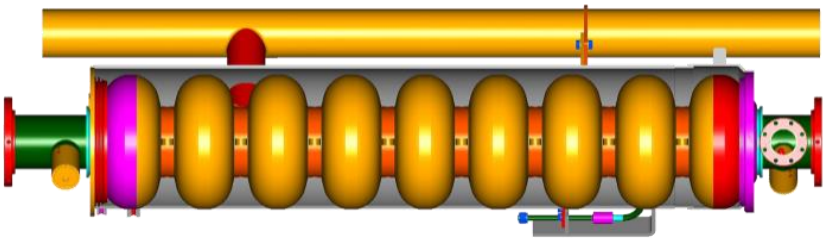


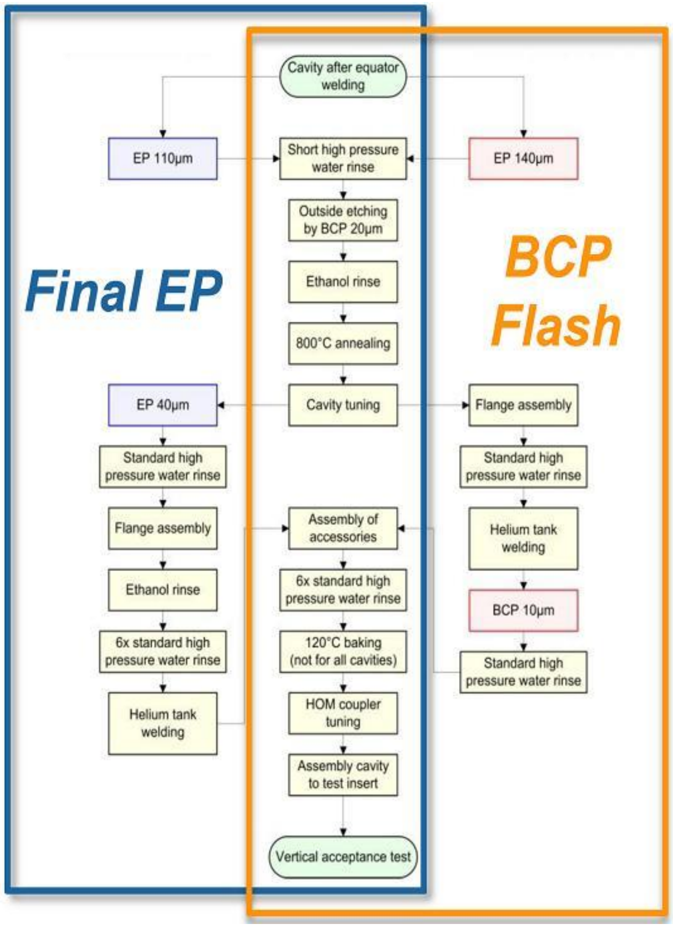
Optical control by high resolution camera

Frequency and
eccentricity measurement

Dimensions check by 3D arm

Trend: Complete Industrialization (not only mech. fabrication)





Example: EXFEL cavity

- Mechanical fabrication
- Prior surface treatment.

EP 110-140 µm (main EP), ethanol rinse, outside BCP, 800°C annealing, tuning

- Final surface treatment - two alternative options

1. Final EP of 40 µm, ethanol rinse, high pressure water rinsing (HPR) and 120°C bake
2. Final BCP of 10 µm (BCP Flash), HPR and 120°C bake.

- Integration of the helium tank, assembly of HOM, pick up and high Q antennas, shipment for RF test

Cavity with helium tank has to be produced according Pressure Equipment Directive PED (Pressure code). Example: EXFEL

PED activities for CAV material production:

company certification, qualification of material (creation the particular material appraisal (PMA)), traceability, Inspection Certificates type 3.1

PED Activities for CAV Production

Module B (EC type-examination)

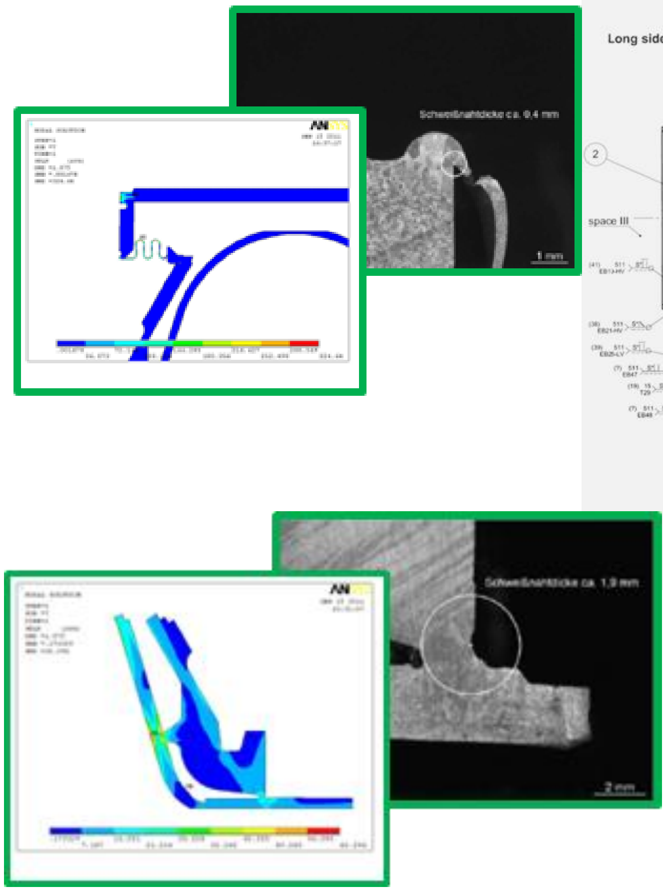
- examination of design, FEM calculation
- qualification of welding processes
- qualification of another PED relevant processes (annealing, deep drawing, forming)
- **production of test pieces 2 pieces/Fa**
- destructive tests on test pieces
- supervising the production qualification on pre-series cavities PCVs
- find PED relevant testing methods for the series production of the cavities

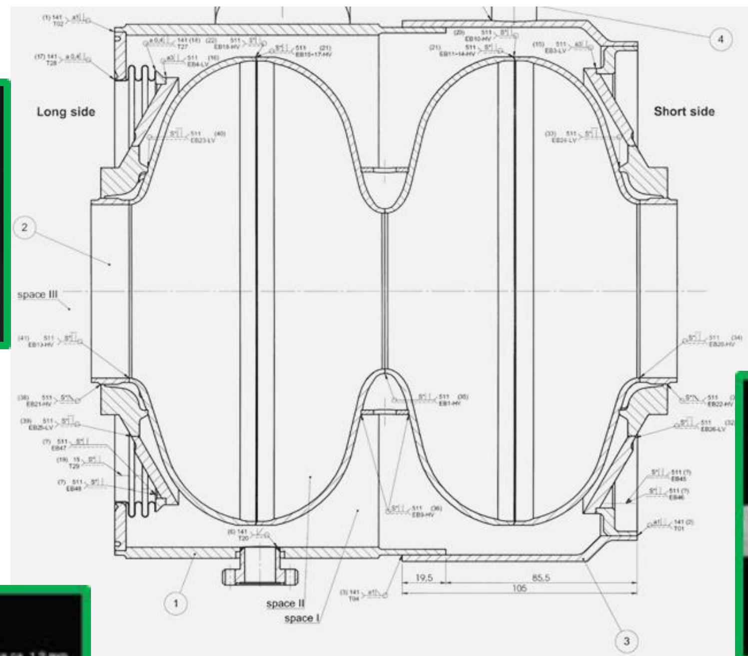
Module F (product verification)

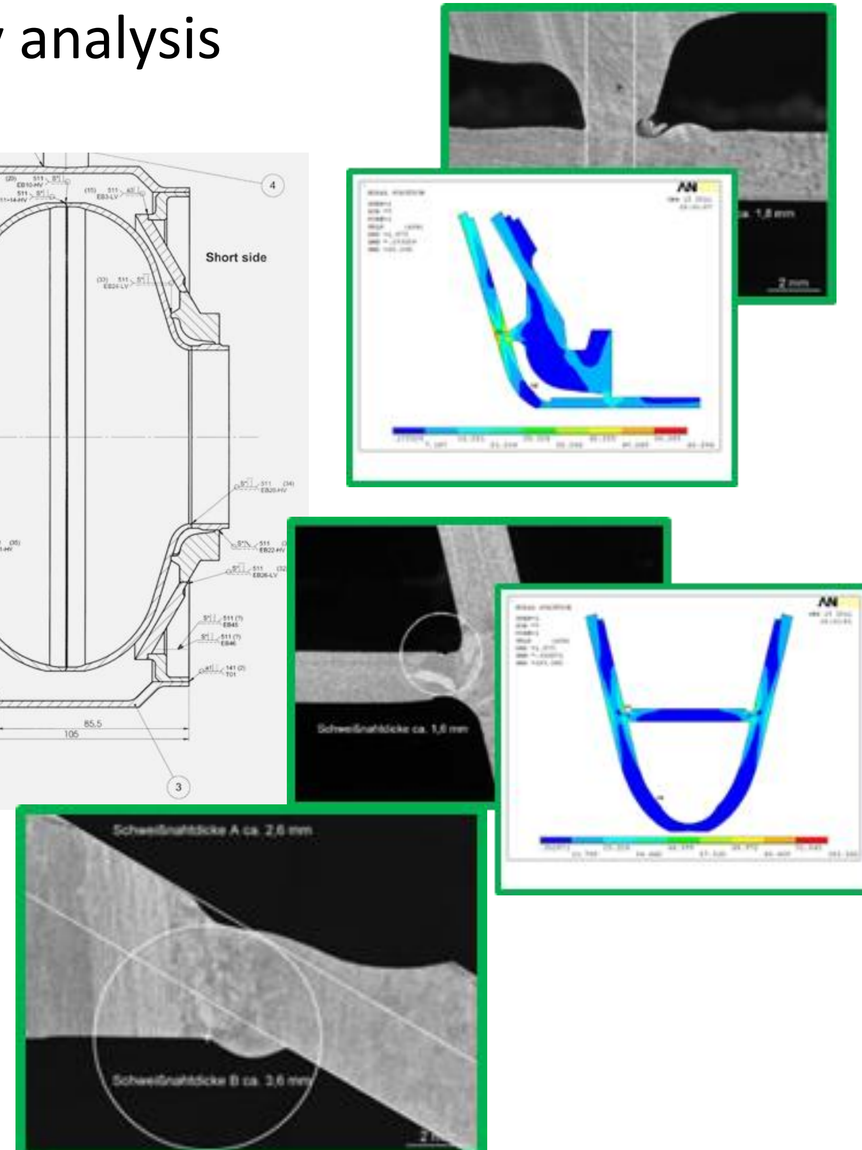
The **notified body** supervises the material and cavity production

Cavities should be produced according pressure equipment directive PED (pressure code).

Test piece representing all pressure bearing parts and welds:
Notified body analysis







Two types of production: performance guarantee; build to print (specs)

Quality Assurance – Main Strategy

- The Manufacturer has to create and maintain a Quality Management System according EN ISO 9000 and
- According to requested by Orderer quality checks incl. documentation

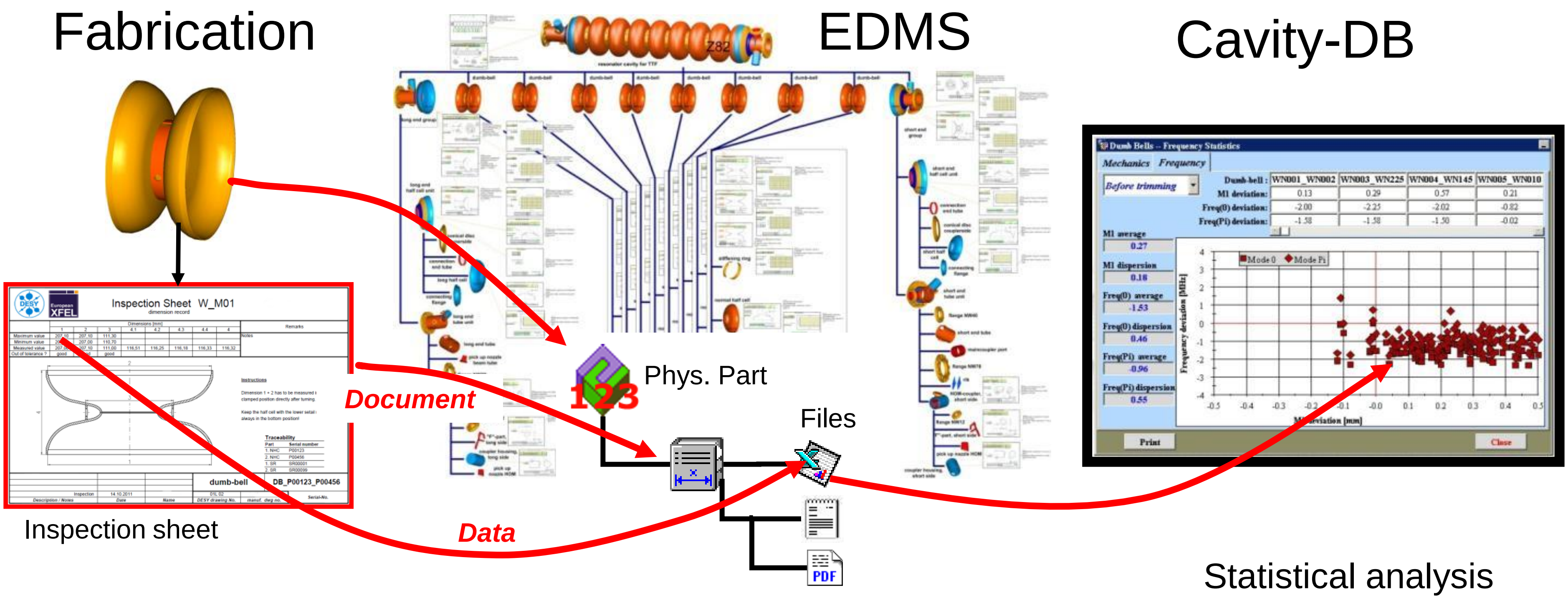
Traceability

- For each completed cavity, a traceability report is to be prepared
- It must be possible to reconstruct the development history of all products
- A conclusion concerning the raw material used should be possible.

Quality Assurance – special documents

- Conformity Report (Confirmation of Conformity)
  - The manufacturer will prepare a conformity certificate for each completed cavity
  - It confirms that the cavity has been produced according to specification, and that all requirements have been checked and complied with the orderer.
  - All deviations from specification to be reported to orderer with proposal to corrections (NCR). Acceptance of orderer required.

EXFEL –Production: EDMS for document management
Database for statistics

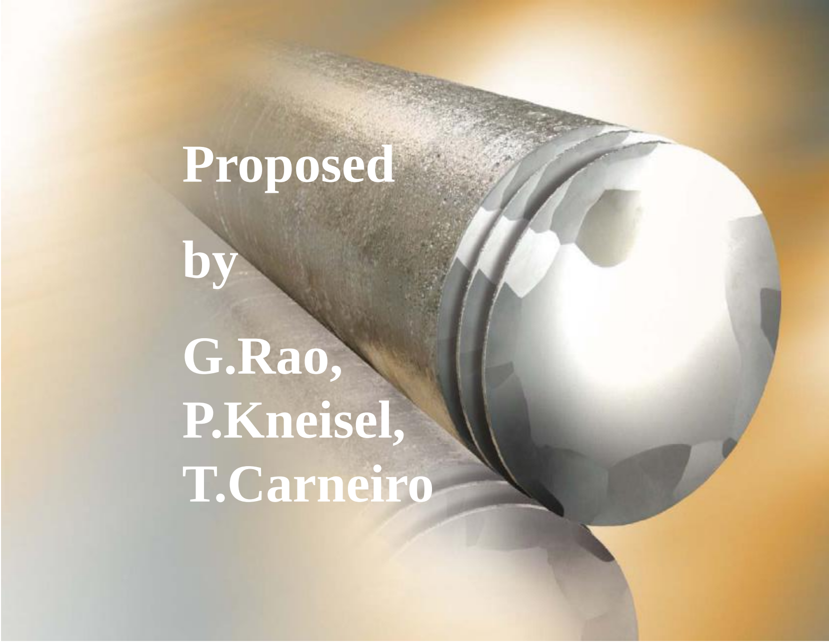


Inspection sheets for QM documentation

Fabrication structure.
Subassembly parts related.
Procedure related

- All XFEL SC cavity documents (specifications, inspection sheets, meeting minutes, PED data etc.) recorded in EDMS.
- Cavity producers have access to documents and data (to relevant only)

Alternative Fabrication R&D: Large grain LG cavity produced from ingot discs

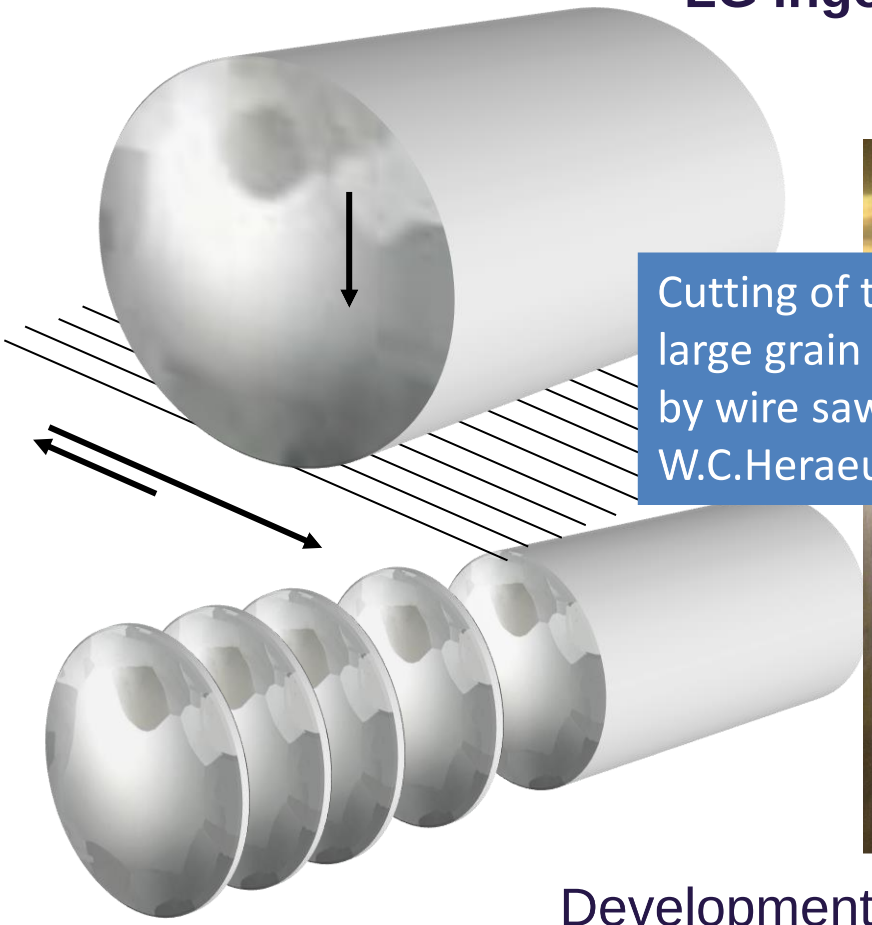


Possible advantages:

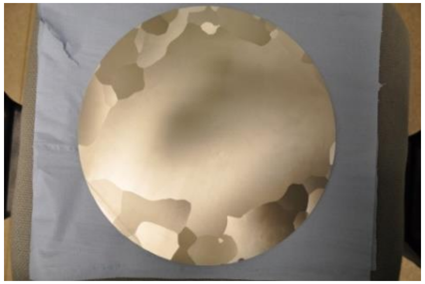
- Cost effective
- Higher purity. RRR=600 of ingot is achievable
- No danger that during many steps from ingot to sheet the material will be polluted.
- Simplified quality control (reduced number of measurements: grain size, eddy current scanning etc.)
- Higher thermal conductivity at low temperatures (phonon peak)
- Seems to be less susceptible to field emission (Univ. Wuppertal)
- Seems that the baking at 120°C works better after BCP (compare to fine grain BCP)

Alternative fabrication: Large Grain LG Cavity

LG ingot and disc fabrication



Cutting of the large grain Ingots by wire sawing at W.C.Heraeus



Development of LG disc production was done within the framework of the XFEL R&D program of DESY and the W. C. HERAEUS.

Similar development done in collaboration of KEK and Tokyo Denkai (Japan)

LG cavity fabrication: For example 11 LG 9-cell cavities at RI from HERAEUS material fabricated DESY (**AC112-AC114, AC151-AC158**)

Fabrication similar to fine grain cavities:

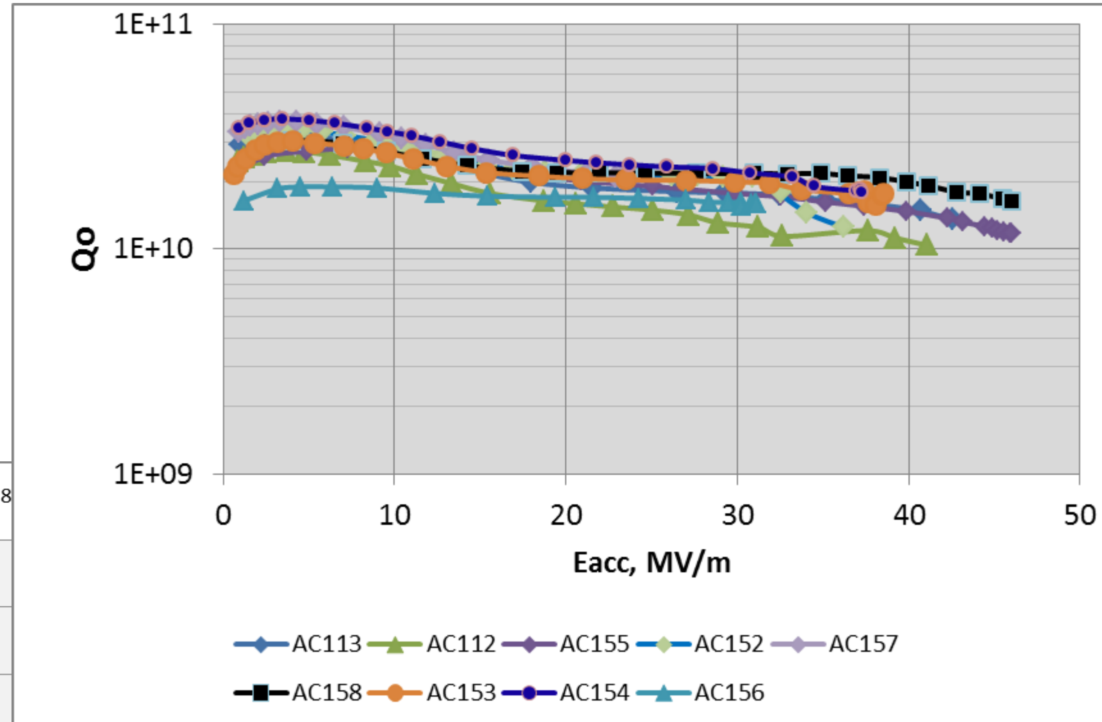
- **Deep drawing**
- **Machining**
- **EB welding**

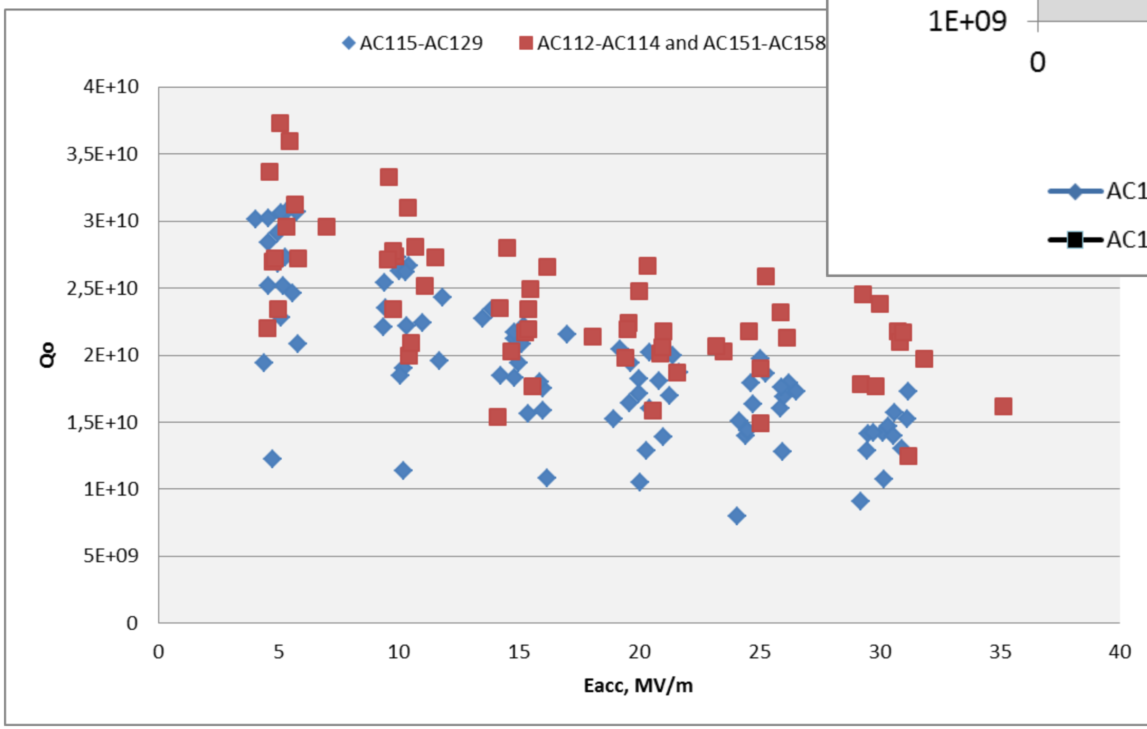
- Very smooth (shiny) surface in grain areas after BCP
- the steps at grain boundaries are more pronounced as in polycrystalline material

Alternative Fabrication R&D: Large grain LG cavity

Best result of 45 MV/m reached after EP is a world record for this cavity type.

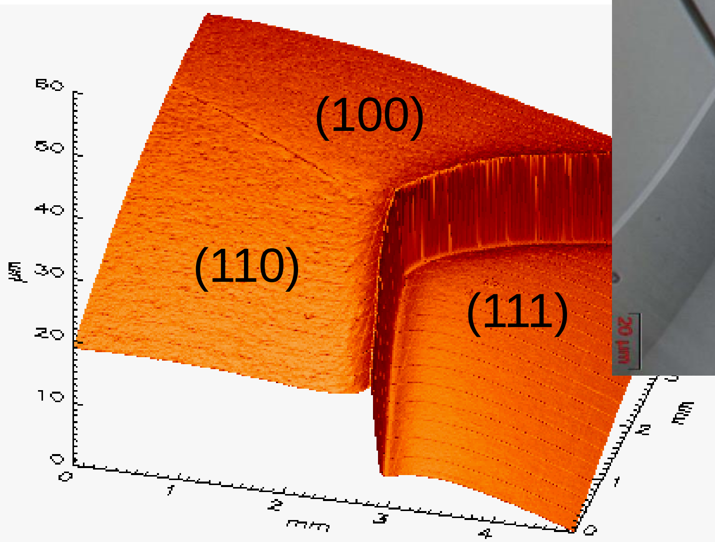
Q_0 is ca. 25-30% higher for EP treated LG- compared to similar fine grain cavities

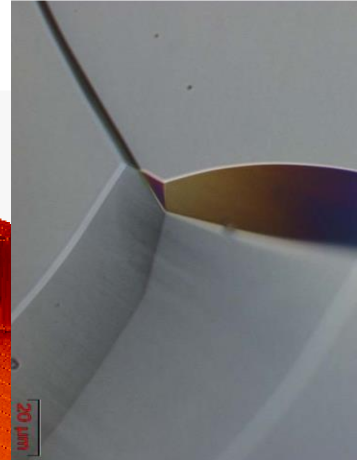


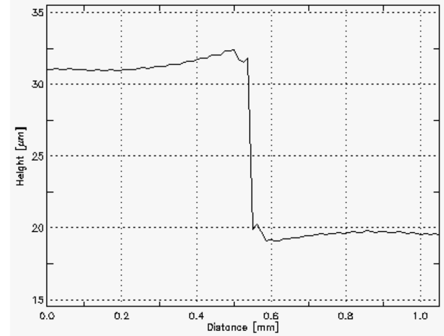


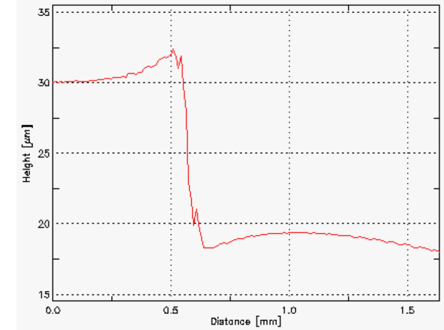
Comparison of unloaded quality factor Q_0 at 2K for 11 EP treated LG cavities with Qo at 2K of XFEL prototype cavities

LG cryo-module for EXFEL in production

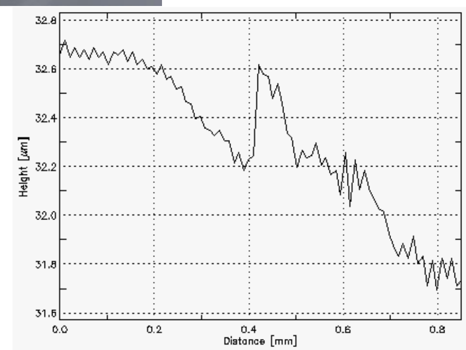




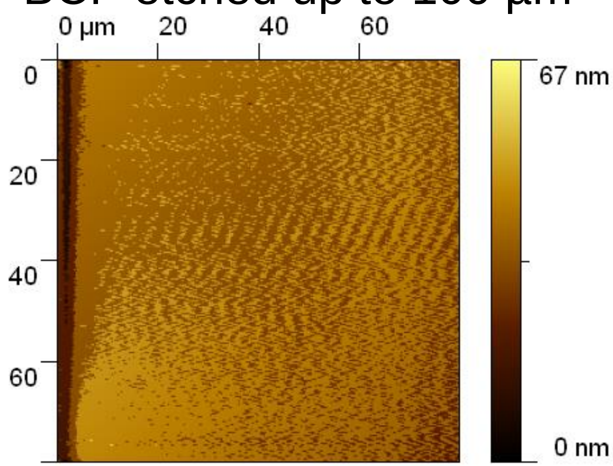


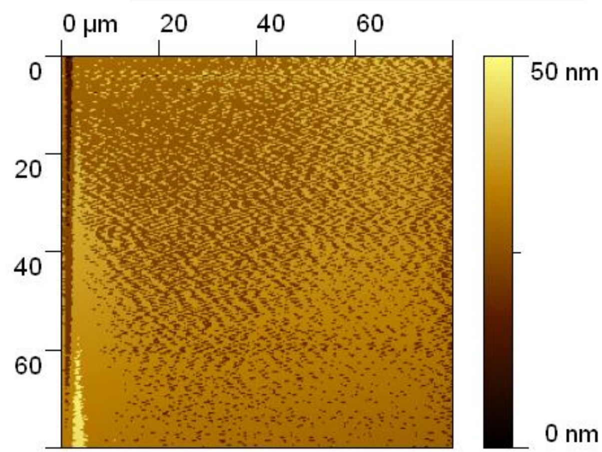


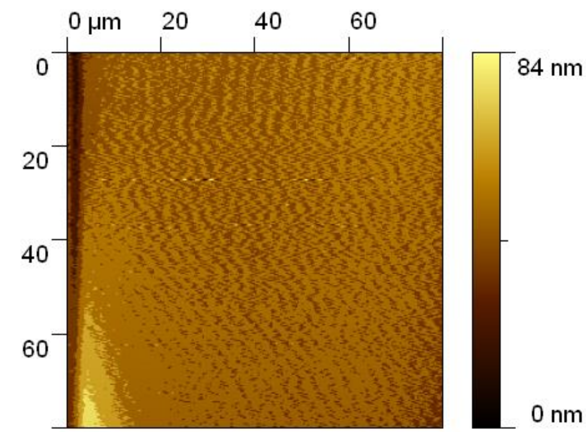
Light microscope and AFM image of LG Nb, BCP etched up to 100 µm



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







AFM roughness measurement Ra (below 100 nm). Roughness of fine grain Nb after EP is 251 nm (for example in work of A. Wu) .

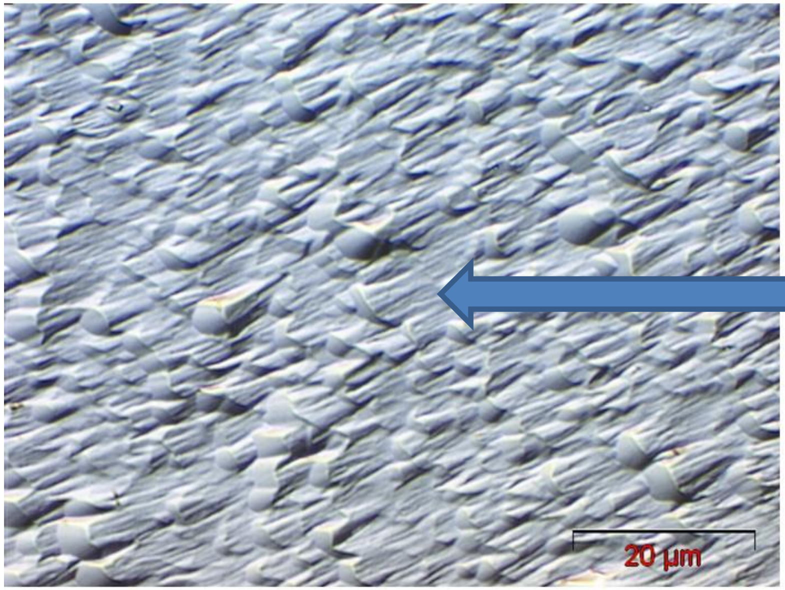
Single Crystal Option

Better not to have the grain boundaries at all

Fabrication of TESLA shape single crystal cavities at DESY.

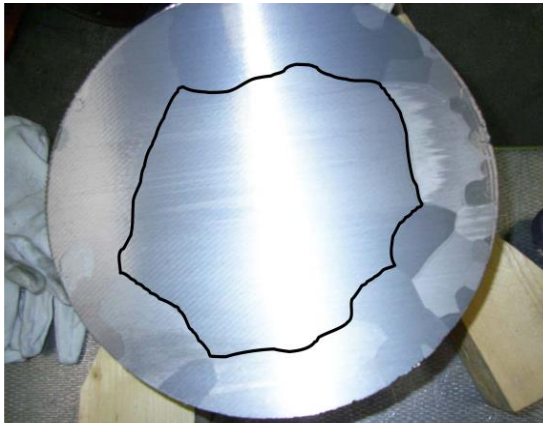
- Definite enlargement of the discs diameter is possible without destroying the single crystal structure in an existing state.
- Appropriate heat treatment will not destroy the deformed single crystal
- The single crystals keep the crystallographic structure and the orientations after deep drawing and annealing at 800°C

- Two single crystals grows together by EB welding, if the crystal orientations is taken into account.

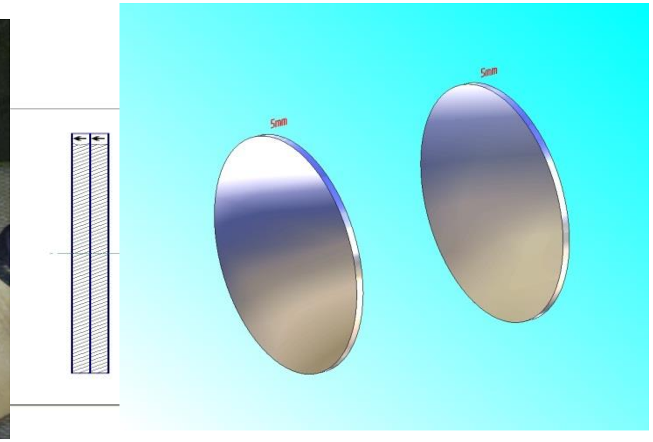


EB welding area

Single crystal cavity fabrication (DESY- JLab)

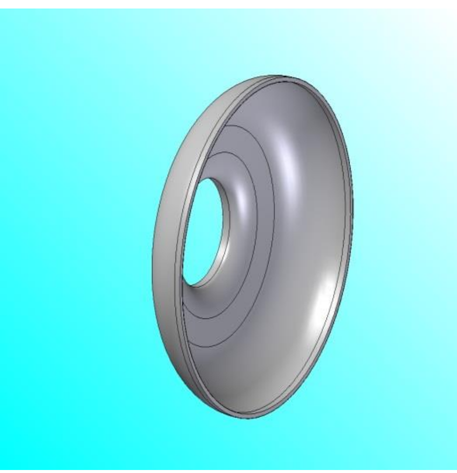


1. Take out central single crystal of definite thickness

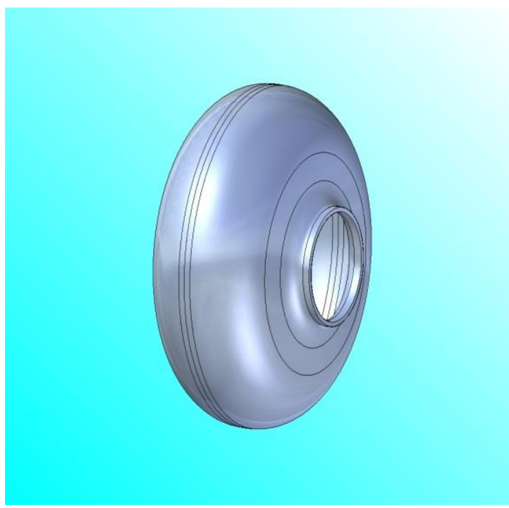


2. Cutting through the disc

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



4. Deep drawing

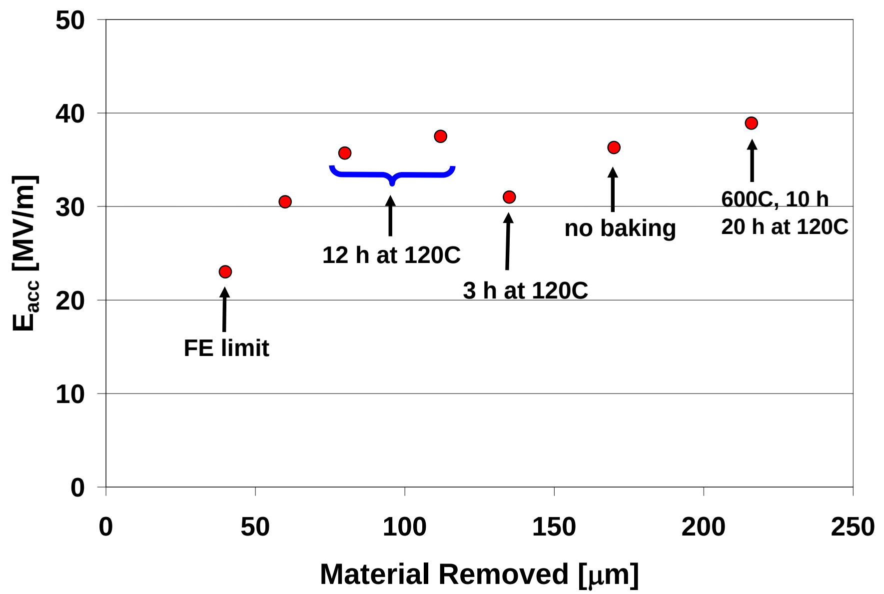


5. EB welding by matching the crystal orientation

Single Crystal Cavities with three different crystal orientation

One large grain (single crystal) is a promising option that allows stably reach very high gradient by simple BCP treatment

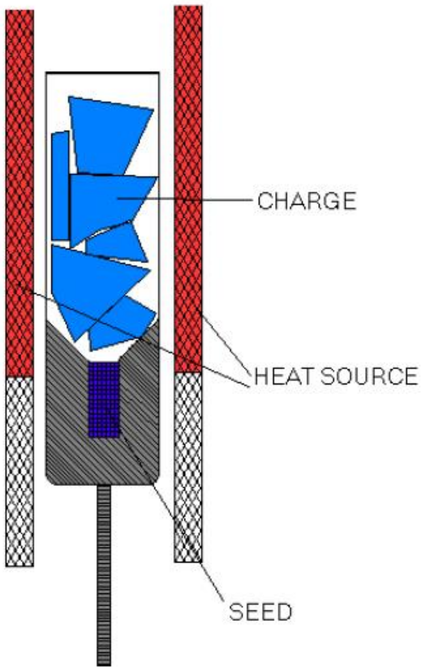
Cavity #	$E_{acc,max}$ (MV/m)	Treatment
1	38	200µm BCP, 800°C 3h, HPR, 120°C 48h
2	45	200µm BCP, 800°C 3h, HPR, 120°C 24h
3 (1AC6)	41	250µm BCP, 750°C 2h, 120µm EP, HPR, 135°C 12h
4 (1AC8)	38.9	216µm BCP, 600°C 10h, HPR, 120°C 12h
5	38.5	170µm BCP, HPR, 120°C 12h



Evaluation of maximum E_{acc} with material removal: best performance after ~ 216 µm removal by BCP

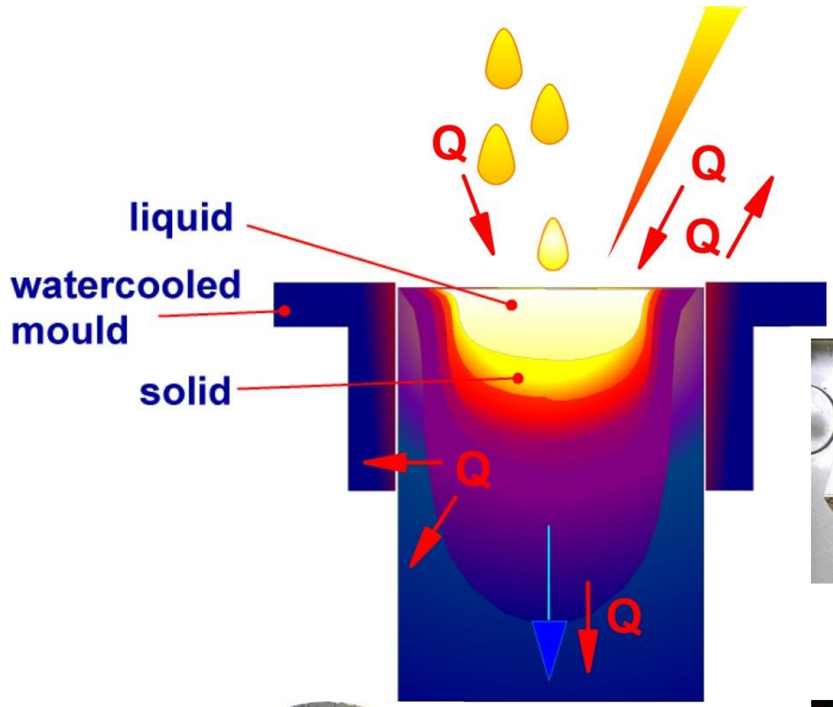
W. Singer. CERN Accelerator School. Erice, Italy, 24 April-4 May, 2013

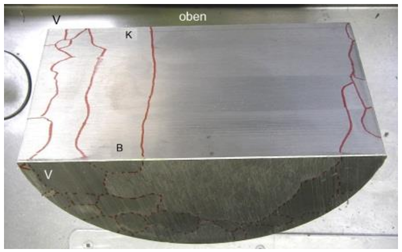
Is it realistic produce single crystal cavities of sizes required for ILC cavities?



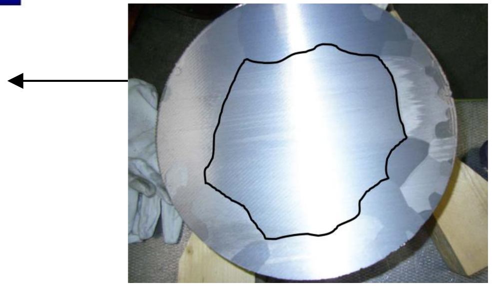
Vertical Bridgman procedure for single crystal grow

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





SC Ca. 200 mm



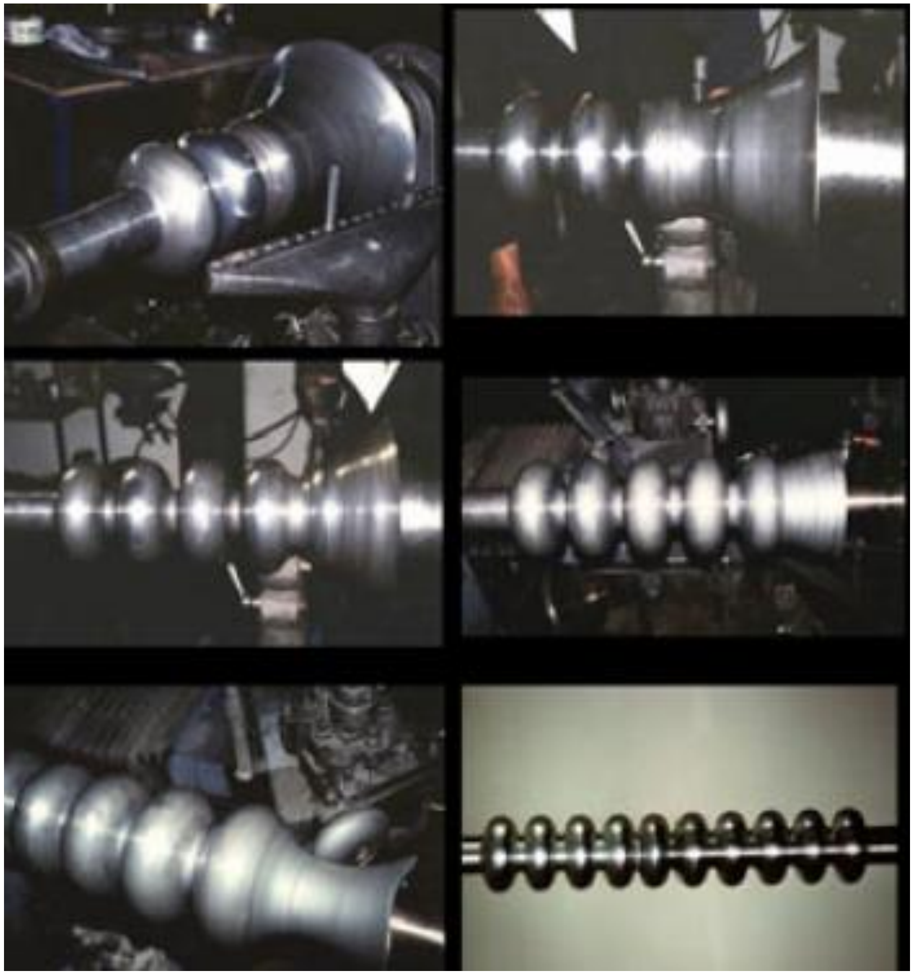
Electron beam melting principle

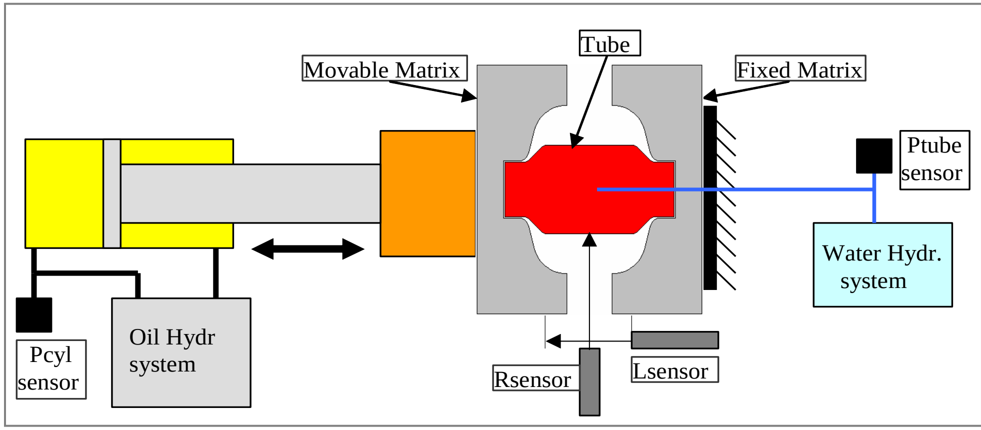
Challenge for the industry

Fabrication R&D: Seamless fabrication

Hydroforming, DESY, KEK, MSU

Spinning (V.Palmieri,INFN Legnaro)

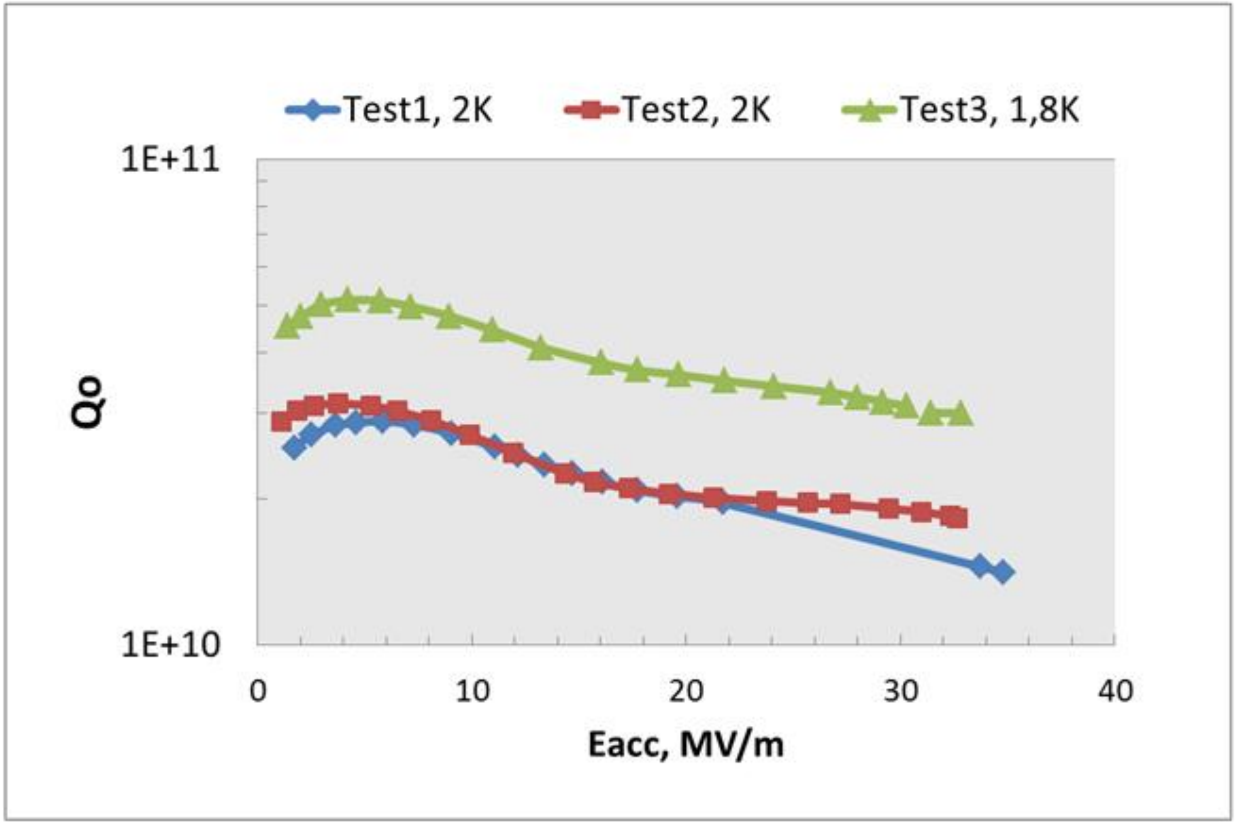




DESY hydroforming machine HYDROFORMA

Proof of principle is done on single cell cavities, Eacc > 40MV/m achieved

Several 9-cell cavities produced by hydroforming



Hydroformed at DESY 9-cell cavity of TESLA shape fulfilled the ILC requirement

After 50 µm BCP, HT 800 C, 144 µm EP, 800 °C; 48 µm EP, baking at 130°C for 48 h (vacuum leak during test). Test2: Limited by quench, no FE. Quench at cell 8 above equator area. Another cells shows Eacc>40 MV/m

Thank you
Molte Grazie

Acknowledgement

For this presentation I used freely material from presentations of colleagues, whom I want to thank:

C. Antoine, SACLAY
R. Edinger, PAVAC
R.Graham, Wah Chang
P. Kneisel, Jlab
M. Liepe, Cornell University
J. Iversen, DESY
H. Padamsee, Cornell University
V. Palmieri, INFN
M. Pekeler, RI
D. Reschke, DESY
X. Singer, DESY
B. Spaniol, W.C. HERAEUS
F. Schölz, W.C. HERAEUS
H. Umezawa, Tokyo Denkai

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