



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

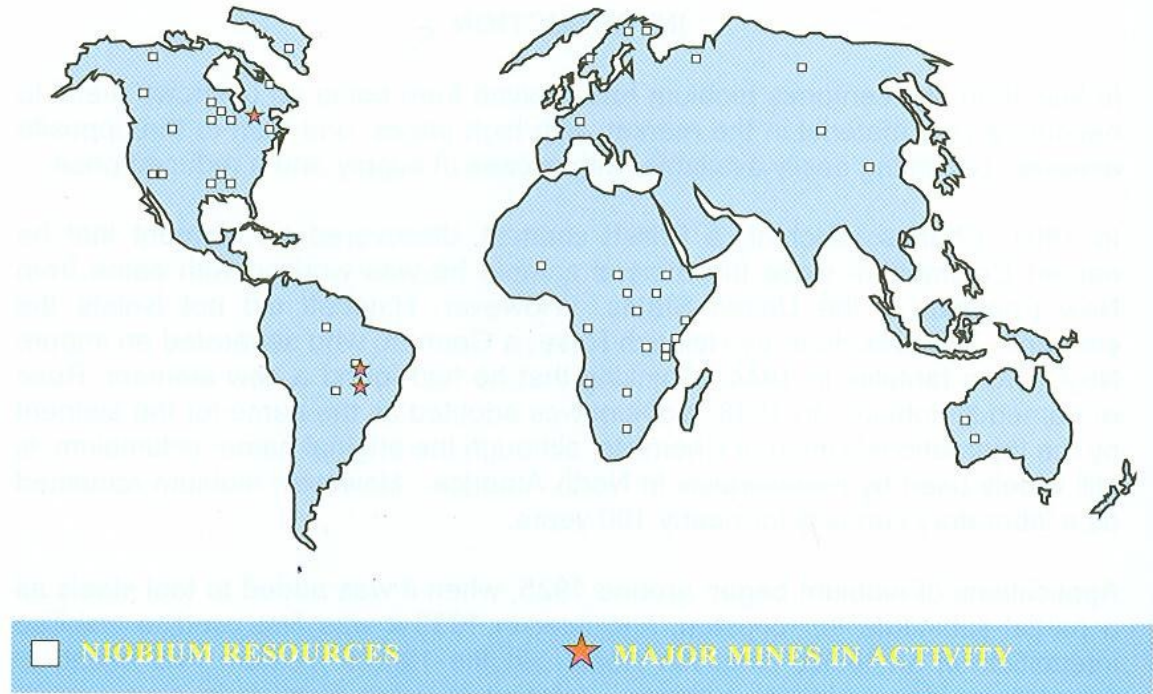
- EB welding peculiarities
- Pressure code (Pressure Equipment directive)
- QA (quality assurance) and documentation

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 $H_c=200$ mT
- high transition temperature $T_c= 9,3$ 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 ($\text{NaCaNb}_2\text{O}_6\text{F}$). The **pyrochlore** mineral is processed by primarily physical processing technology to give a **concentrate ranging from 55 to about 60% niobium oxide** (Brazil, CBMM).

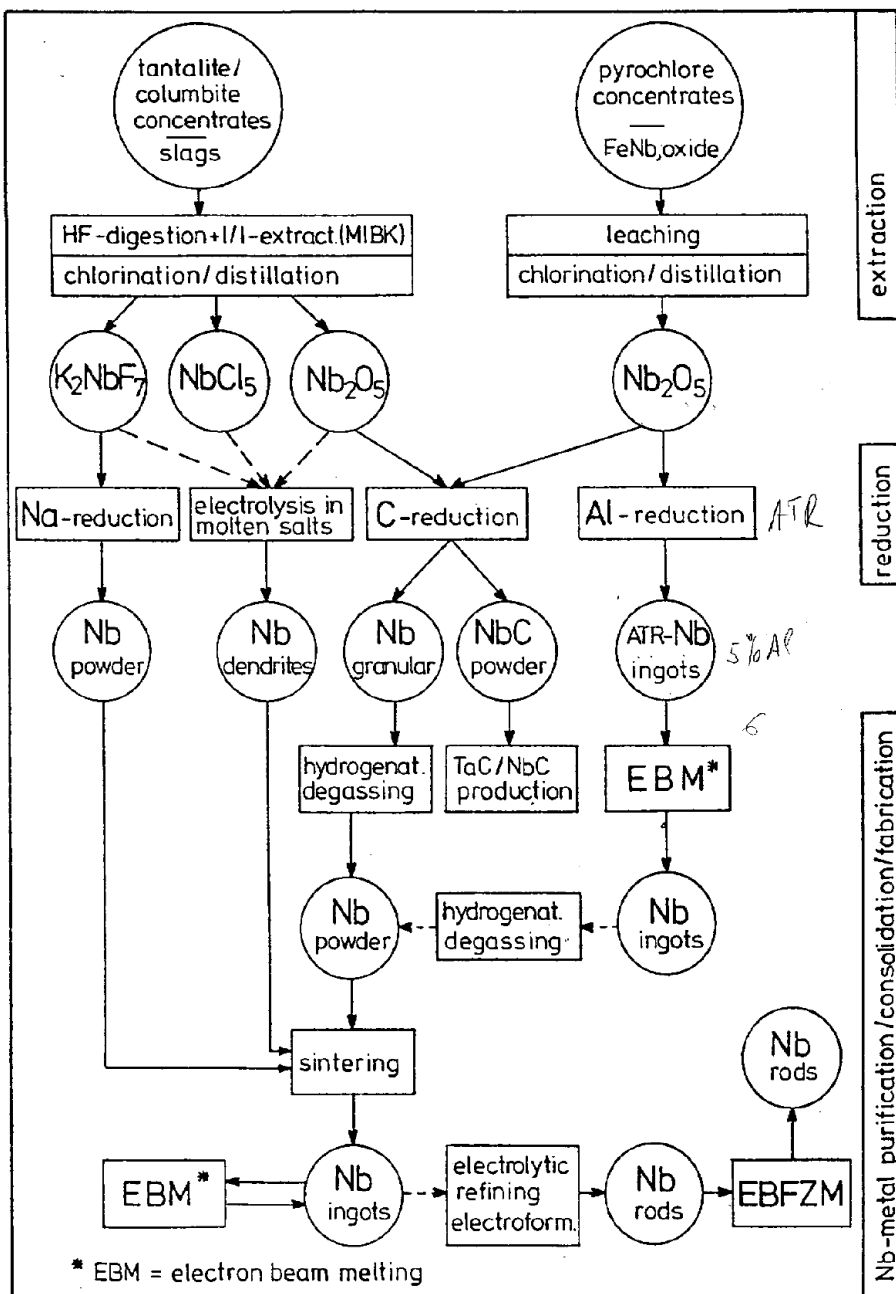
Columbite ($(\text{Fe}, \text{Mn})(\text{Nb}, \text{Ta})_2\text{O}_6$), a mineral with a ratio of $\text{Nb}_2\text{O}_5:\text{Ta}_2\text{O}_5$ ranging from 10:1 to 13:1, occurs in Brazil, Nigeria, and Australia, also other countries in central Africa. Niobium is recovered when the ores are processed 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)

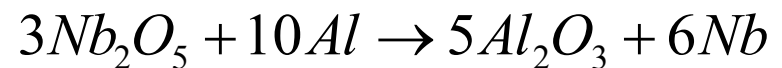
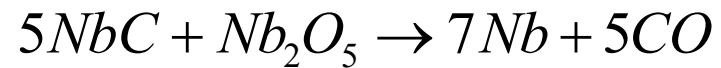
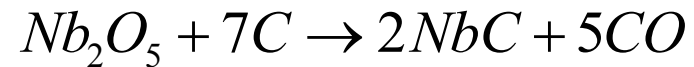


The way from ore to pure Nb



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.

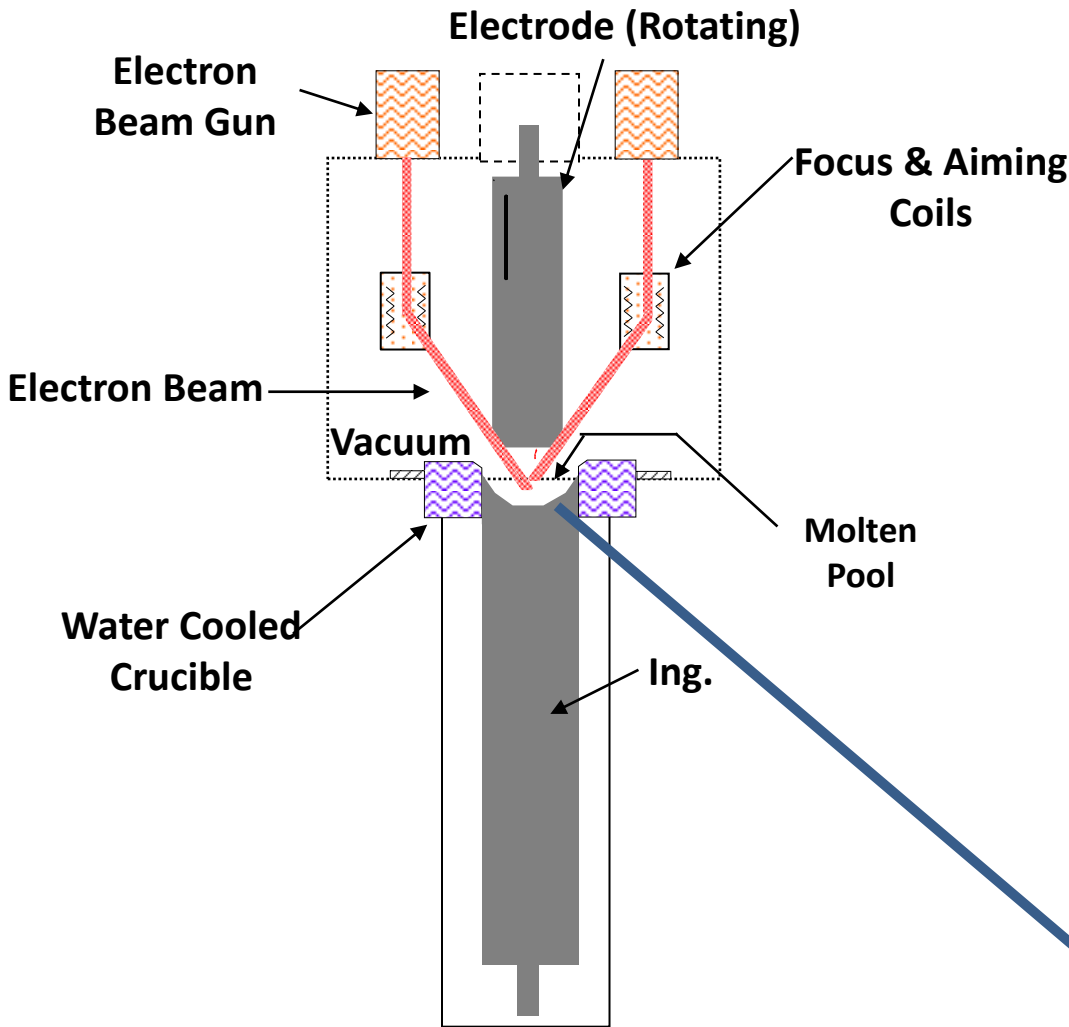


An alternative route of niobium fabrication and alloying is **powder metallurgy**. For special applications it may be convenient to produce powder with high purity **hydrating**. The production of high-grade niobium with small Ta-concentration can be performed via the **sodium reduction** of purified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



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. The rate of withdrawal has to be carefully coordinated with the rate of the material to insure complete melting and proper outgassing.

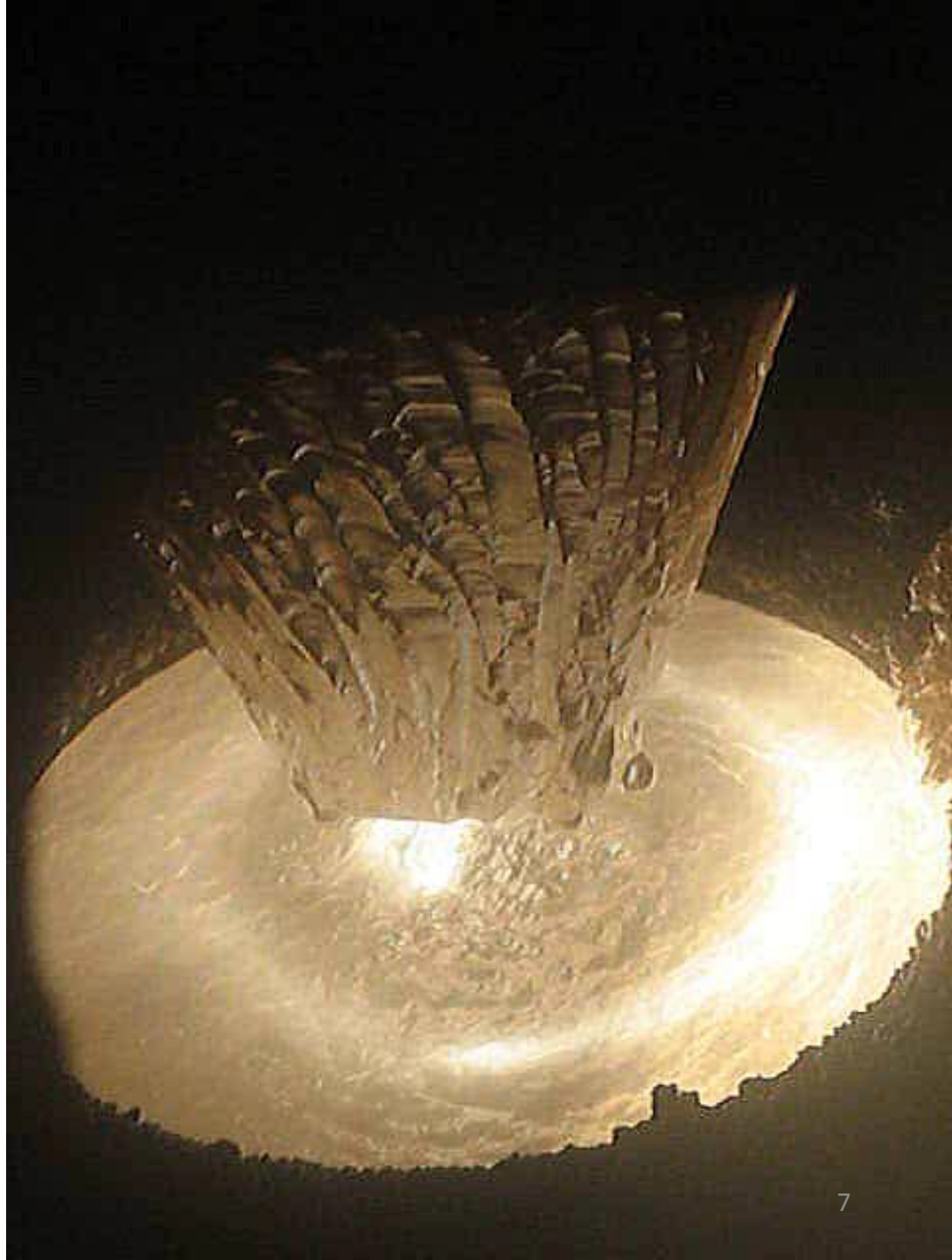


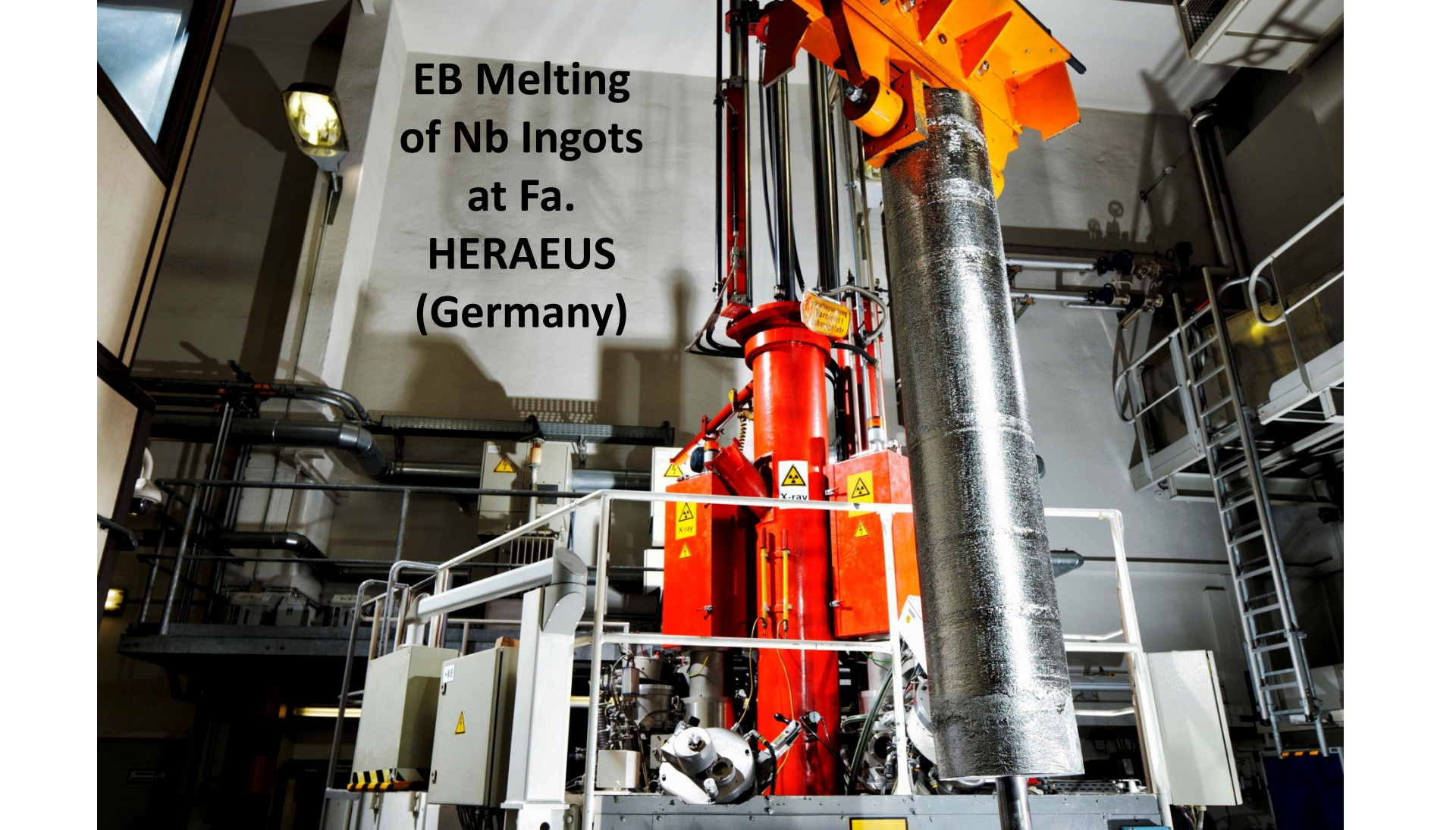
Electron beam melting of Nb



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.





EB Melting
of Nb Ingots
at Fa.
HERAEUS
(Germany)

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**. The first part of the melt which usually ends up at the **bottom getters impurities in the early stages of the melt**.

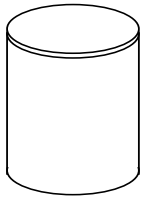
Sheet : Technical Specification for High Purity Niobium

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 *, ** ?	

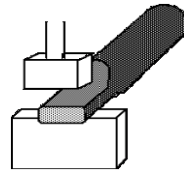
* - relevant for performance

** - relevant for successful fabrication

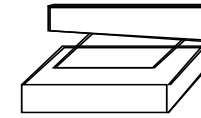
Fabrication of Nb sheets at Company Tokyo Denkai



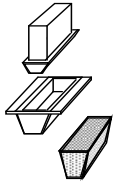
Mother material



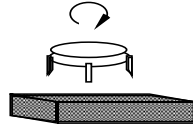
Forging



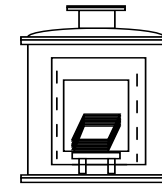
Cutting



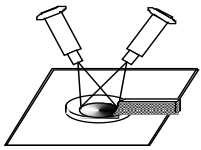
Pressing



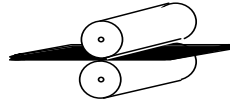
Milling



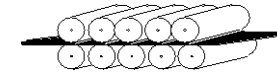
Annealing



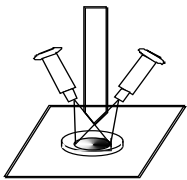
1st EB melting



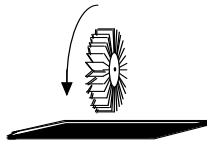
Rolling



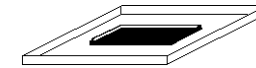
Levering



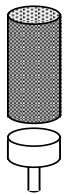
2nd, 3rd etc. EB melting



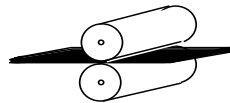
Polishing



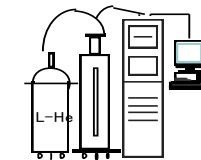
Chemical polishing



Separate from base plate



Rolling



Inspection

ICP-AES

Gas Analysis

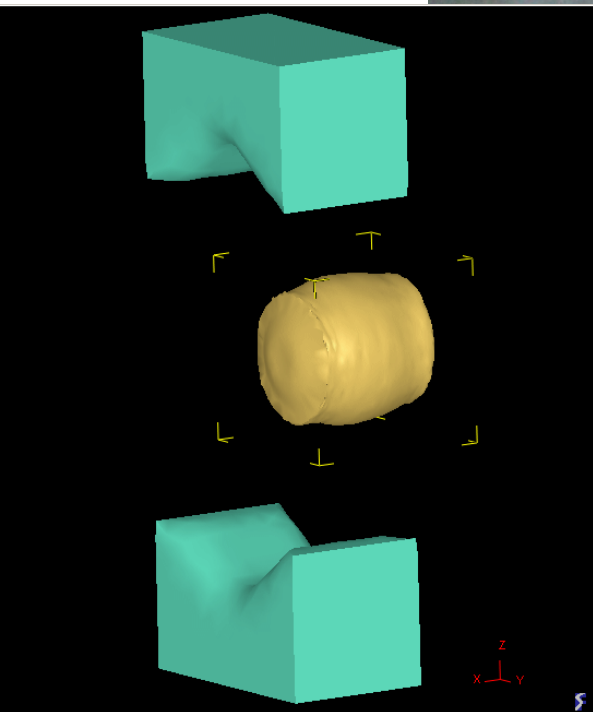
RRR

Grain size

Hardness

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

Forging



Forging of niobium (possible at room temperature). Courtesy of Ningxia OTIC

Rolling



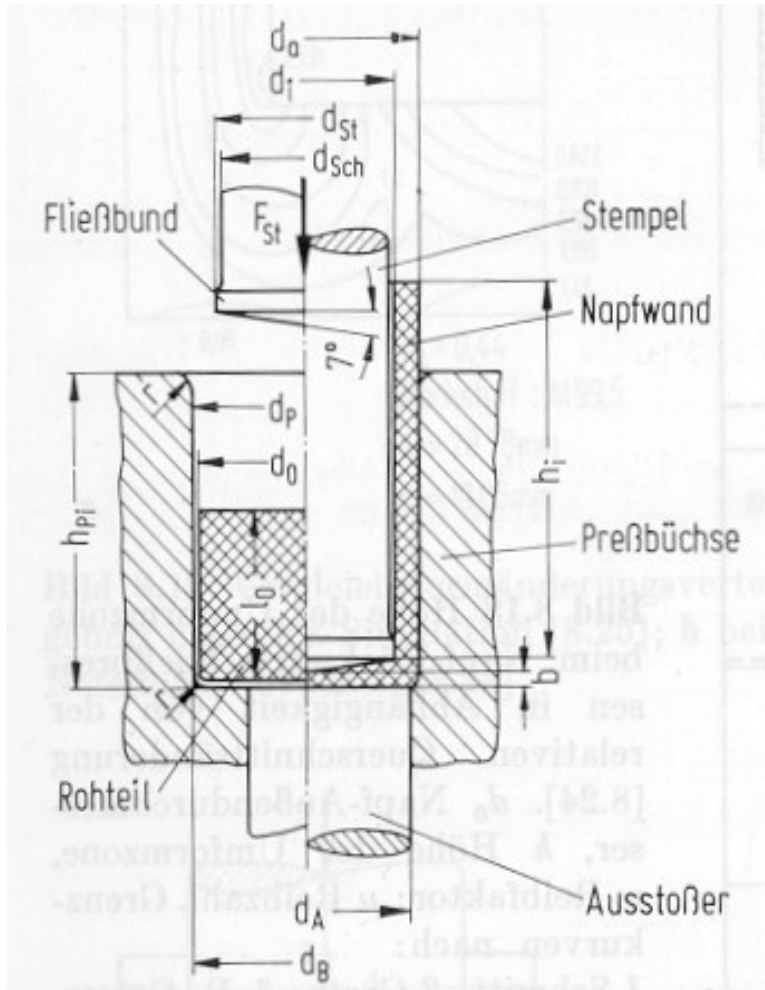
Cold rolling mill
(Courtesy of NOTIC)



800 mm wide
hot rolling mill
(Wah Chang)

Hot rolling, used mainly to produce sheet metal is when industrial metal is passed or deformed between a set of work rolls and the temperature of the metal is generally above its recrystallization temperature. Cold rolling takes place below recrystallization temperature. Nb can be cold rolled

Tubes: back extrusion



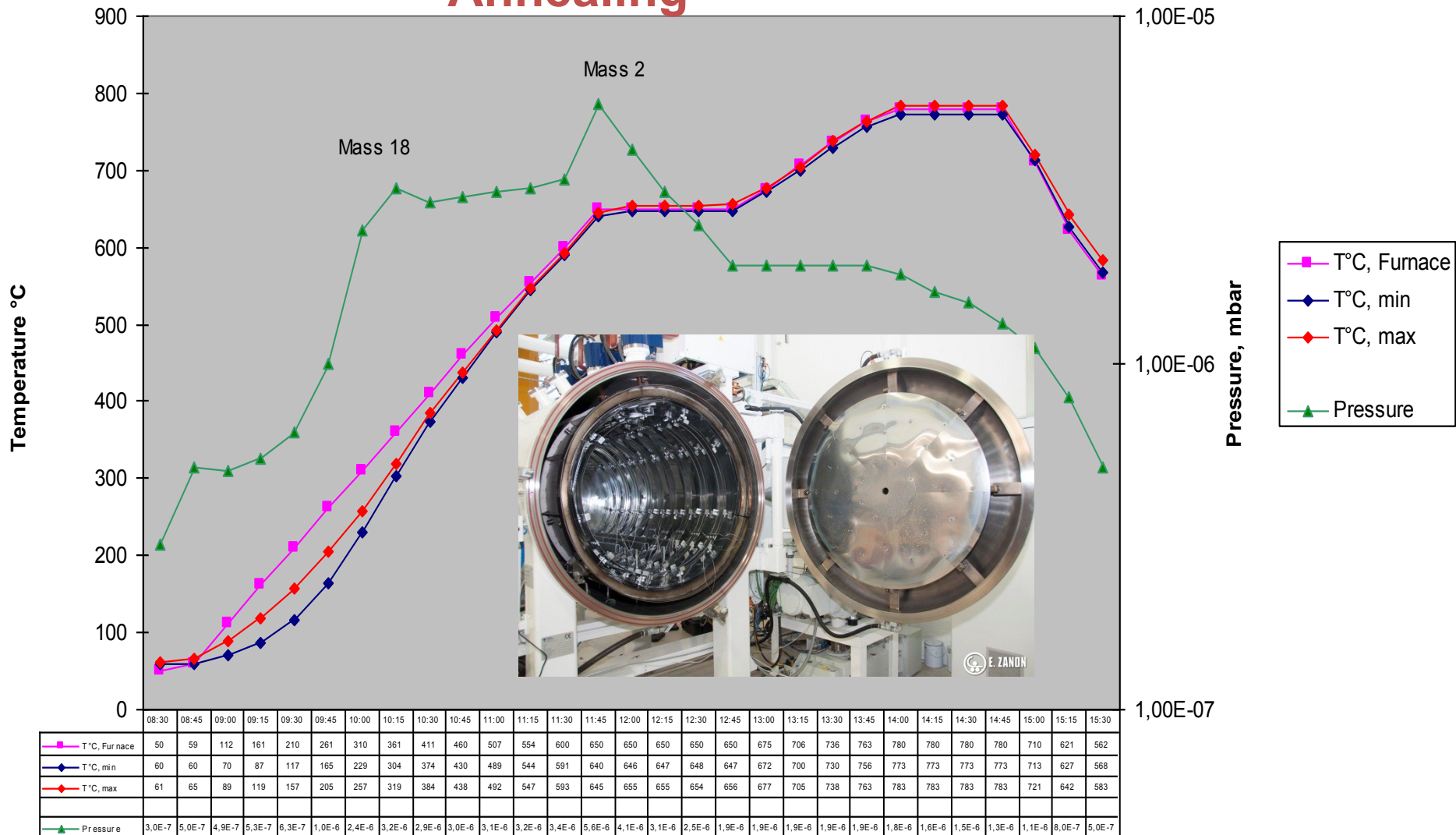
Back extruded Nb tubes for EXFEL

Other tube production methods:

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

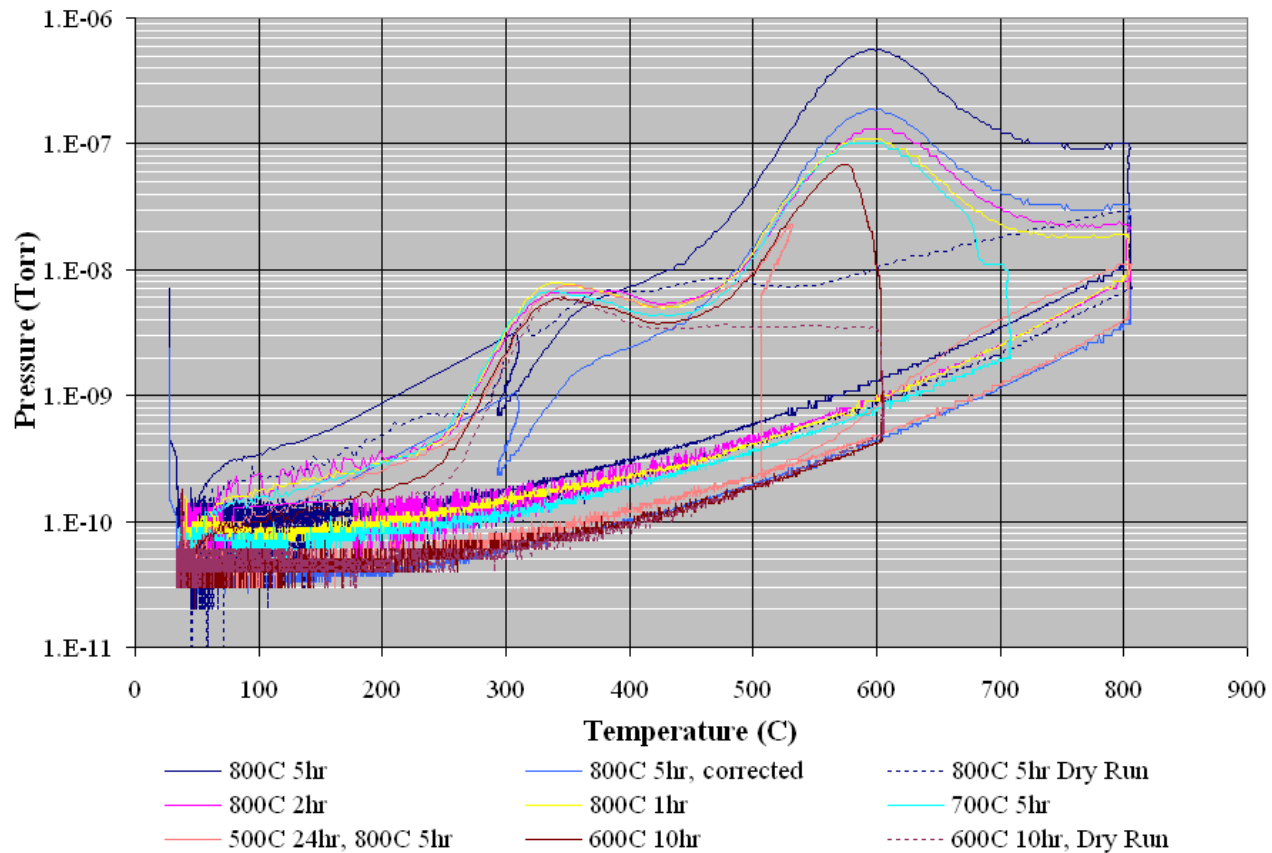
Principle of seamless tube fabrication by back extrusion

Annealing



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

Outgassing of hydrogen



Hydrogen partial pressure versus annealing temperature.

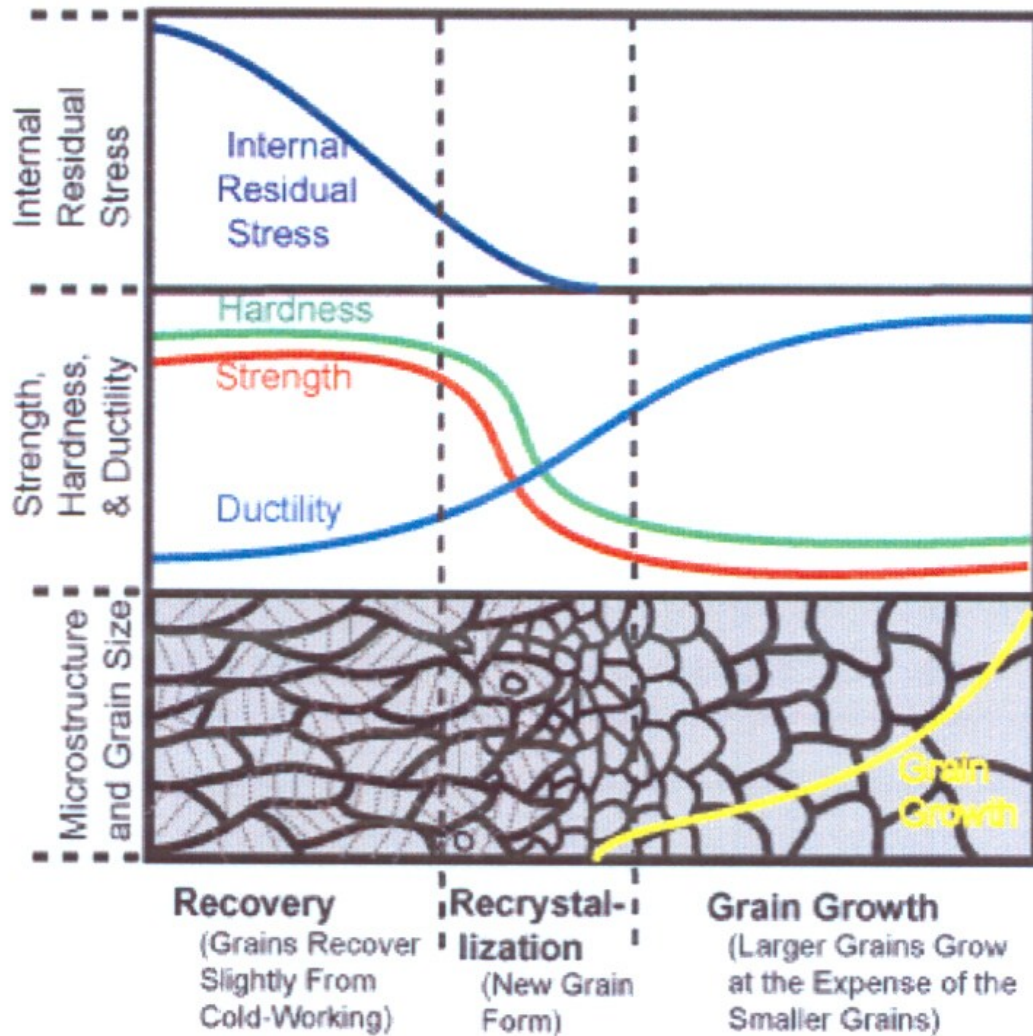
How the outgassing of hydrogen take place?

Nb hydrides decomposes mostly at $T > 100-150^{\circ}\text{C}$. Outgassing of hydrogen is however not possible at these temperatures because the Nb_2O_5 protecting layer is stable up to $250-300^{\circ}\text{C}$.

The most efficient annealing of high purity niobium is $750-800^{\circ}\text{C}$, 2 hours.

- Complete outgassing of hydrogen
- Recrystallization of Nb.

Recrystallization



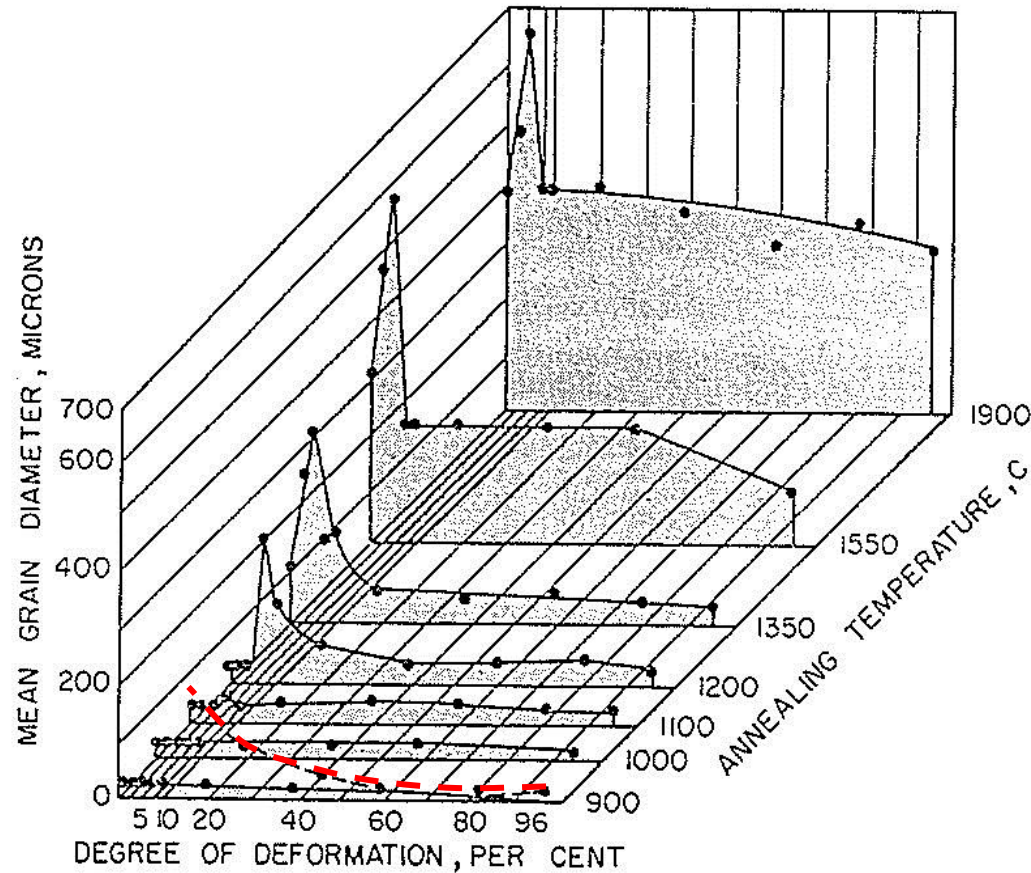
Choosing the proper annealing conditions is important to produce the correct grain size near 100% recrystallization and keep the highest possible purity (RRR).

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



Recrystallization

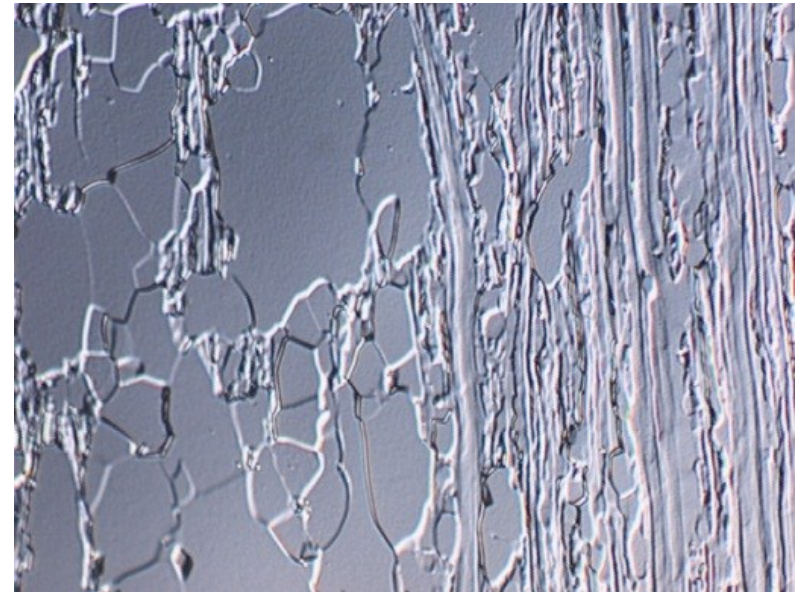
We need recrystallized material

— deformation > 65% =>

- uniform nucleation
- small grains

— if purity \uparrow , $T_{\text{recryst}} \downarrow$

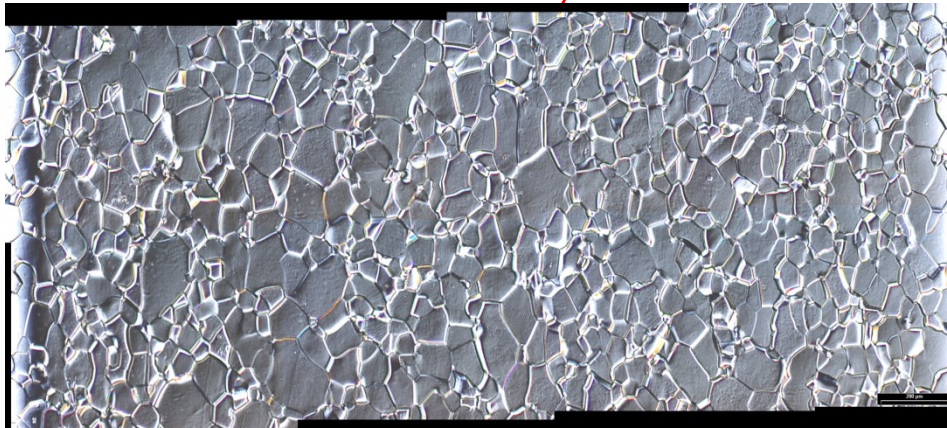
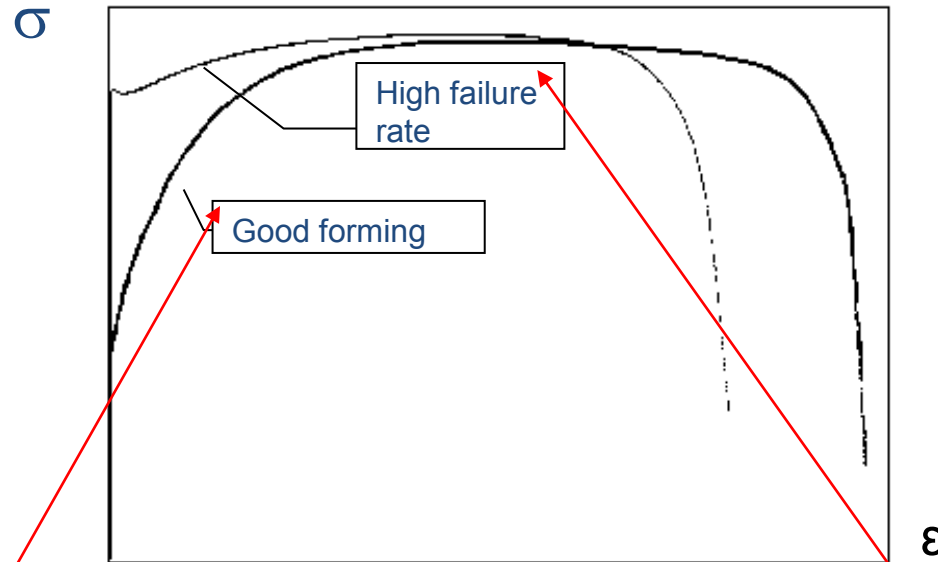
- RRR $\leq 100 \Rightarrow T_{\text{recryst}} \geq 900 \text{ C}$
- RRR 300 $\Rightarrow T_{\text{recryst}} \sim 800 \text{ C}$
- RRR 400 $\Rightarrow T_{\text{recryst}} \sim 750 \text{ C}$



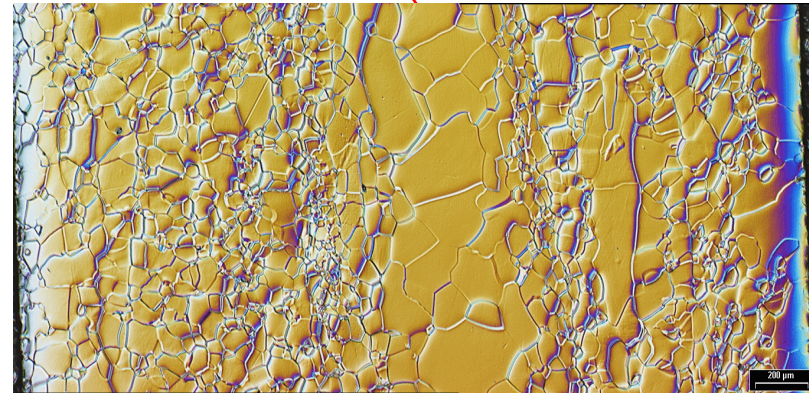
Not completely recrystallized Nb

Formability of Nb sheet by deep drawing

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



Uniform deformation before recrystallization

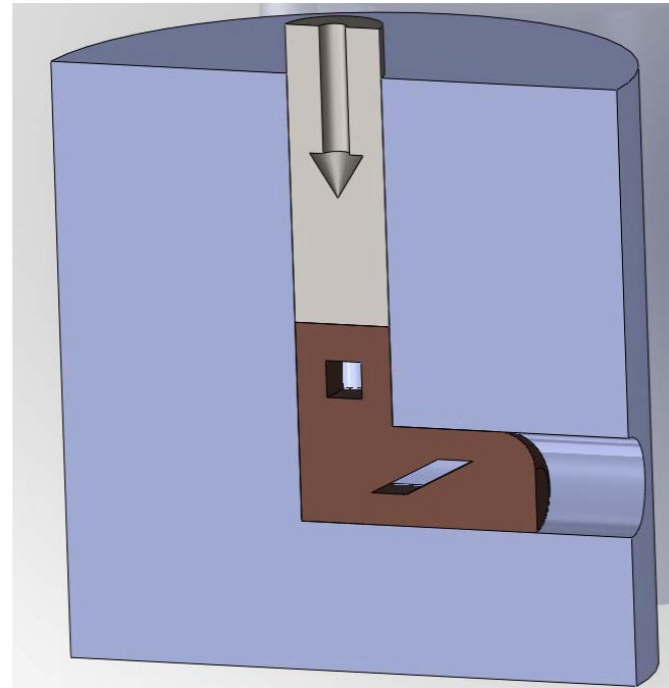


Not uniform deformation before recrystallization

ECAE Description

Equal Channel Angular Extrusion

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

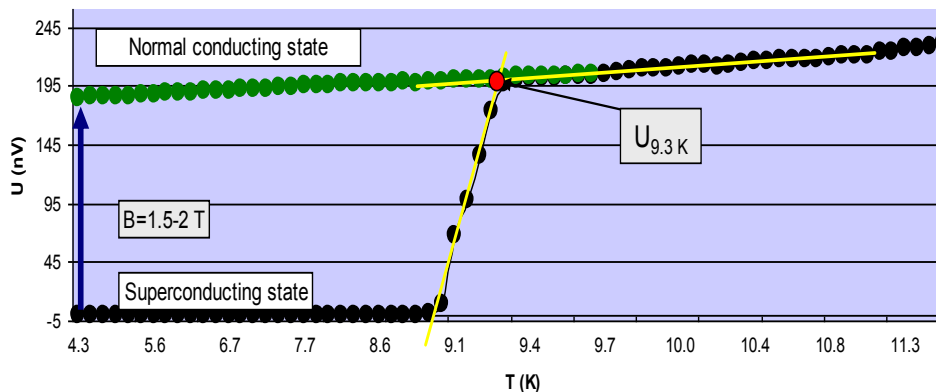
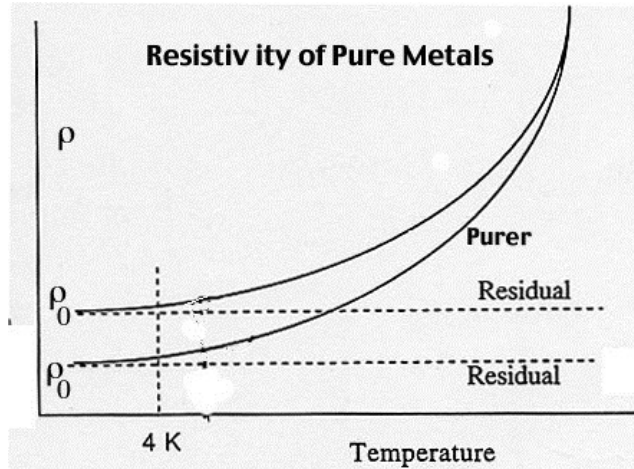


One of interesting method for reaching high and uniform deformation degree

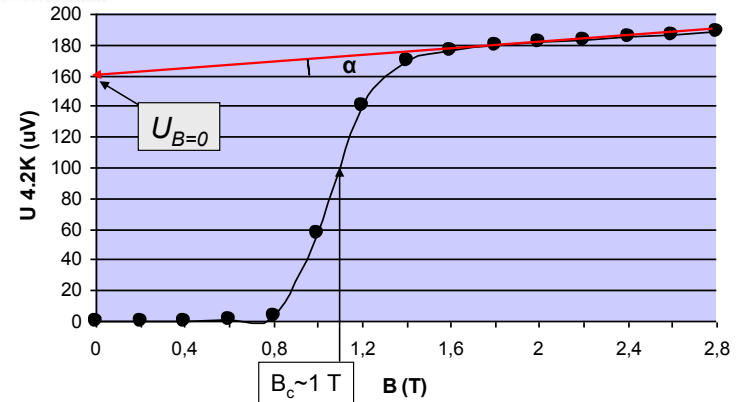
Material Purity: Electrical resistivity of metals at low temperatures is an excellent tool to determine impurity concentrations. The residual resistivity at $T = 0\text{K}$ is caused mainly by scattering of electrons on impurities.

Residual Resistivity Ratio

$$RRR = \frac{\rho(295\text{K})}{\rho(4.2\text{K})} \quad \rho(T) = \rho_{res} + \rho_{ideal}(T)$$



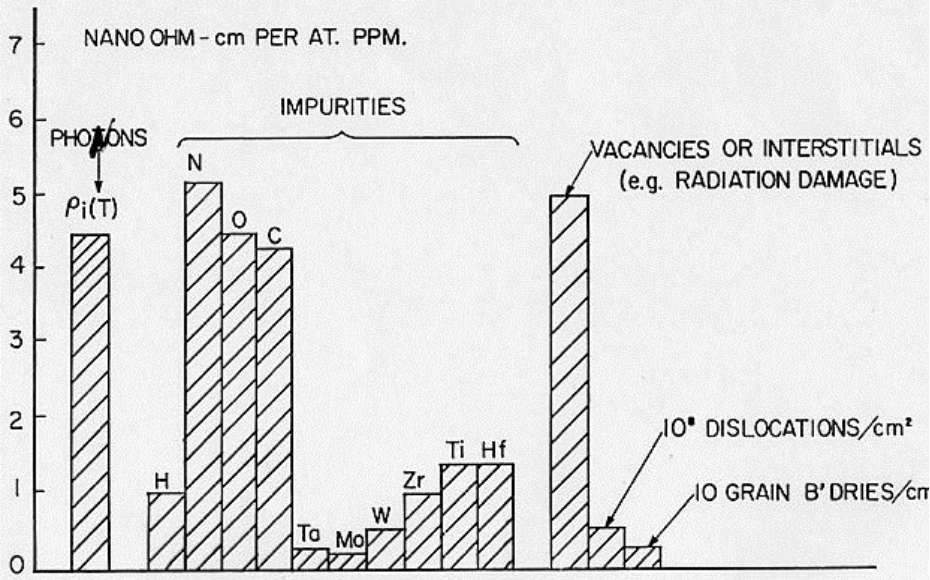
RRR DC determination by extrapolation of $U(T)$ curve



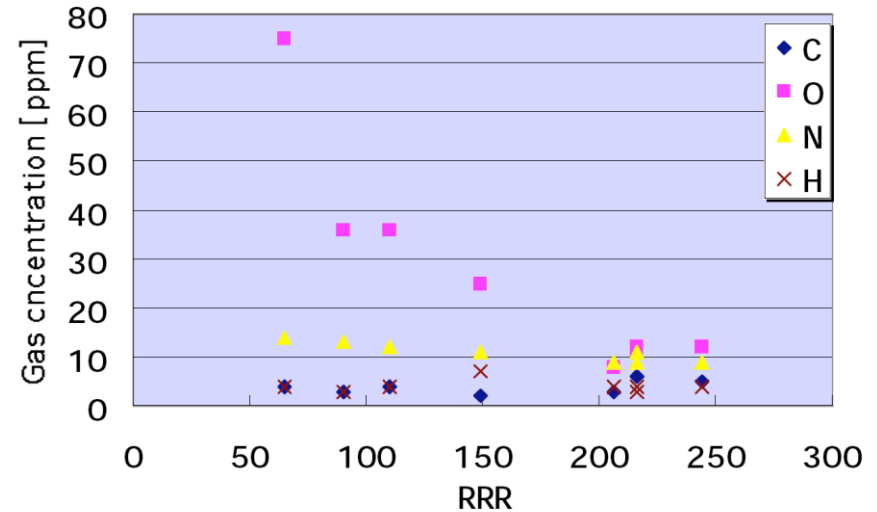
RRR determination by extrapolation of $U(B)$ curve

Influence of impurities on RRR

EFFICIENCY OF VARIOUS SCATTERING MECHANISMS



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



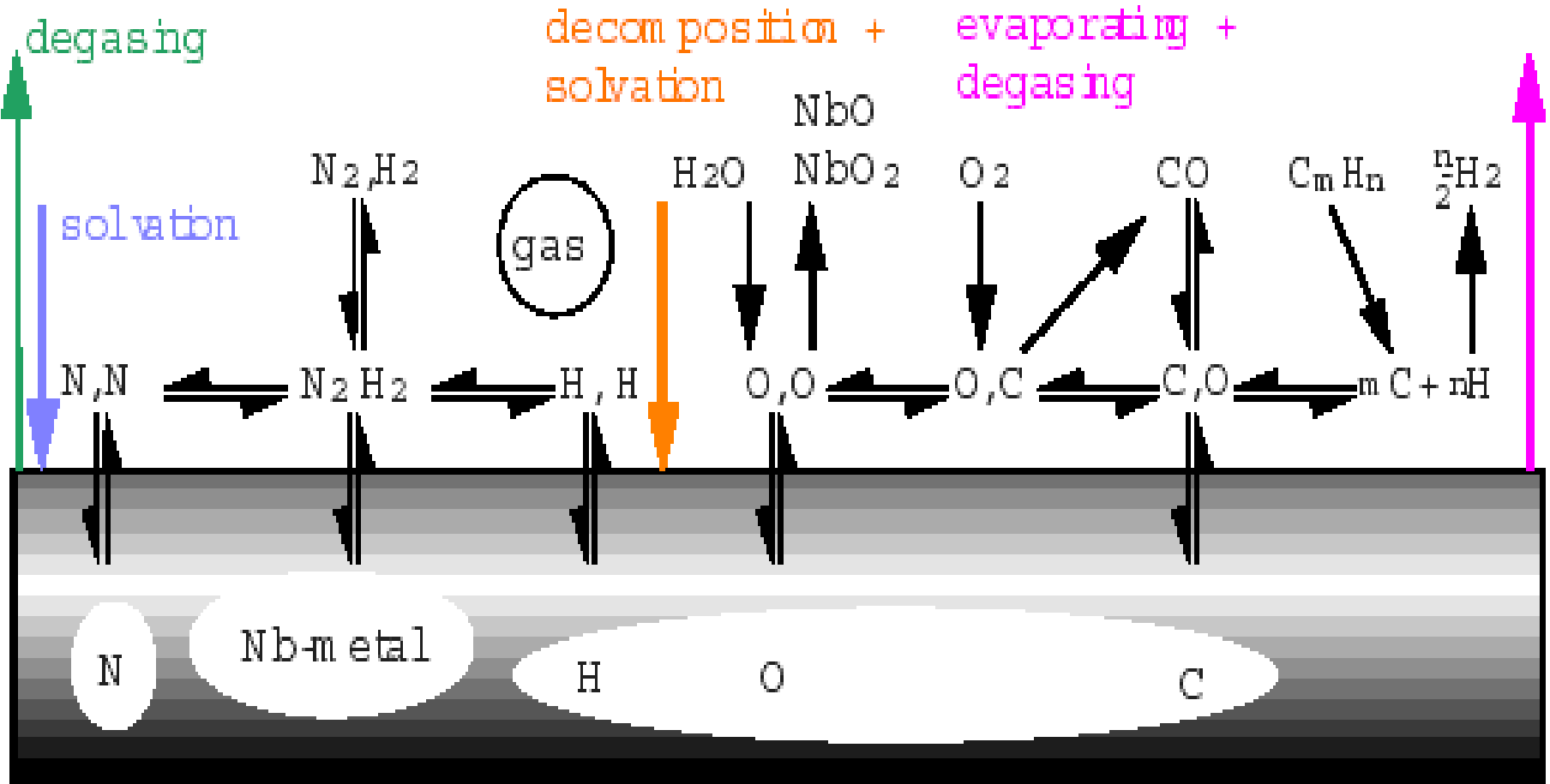
Contribution of different defects in the scattering mechanism (Schulze)

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

$R(300K) = 1,46 \cdot 10^{-5} \Omega \text{ cm}$, $R(10K) = 8,7 \cdot 10^{-9} \Omega \text{ cm}$, $C = 1$ wt. ppm

Relationship between RRR and nonmetallic impurities measured by Tokyo Denkai

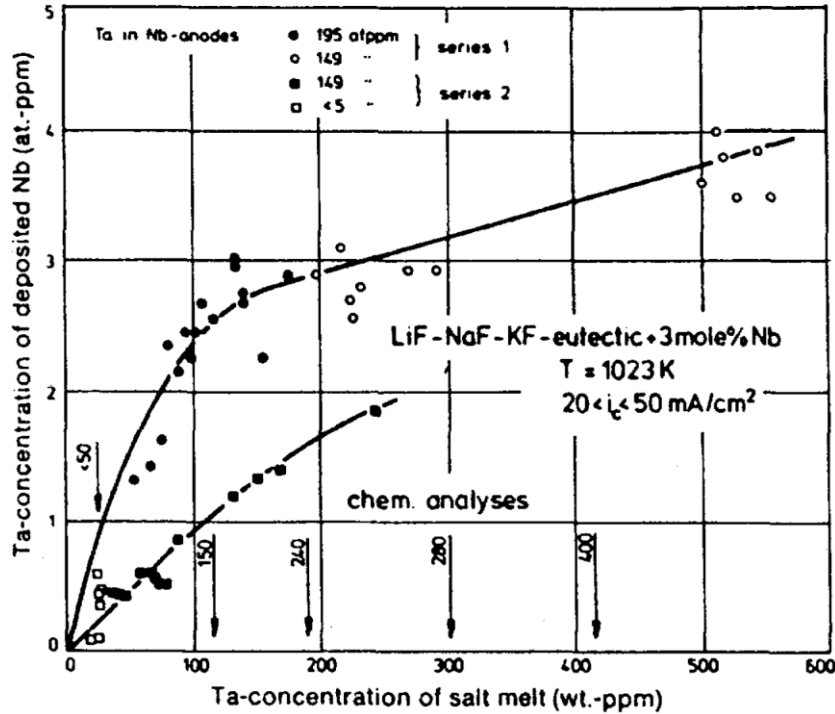
Nb Purification during EB melting



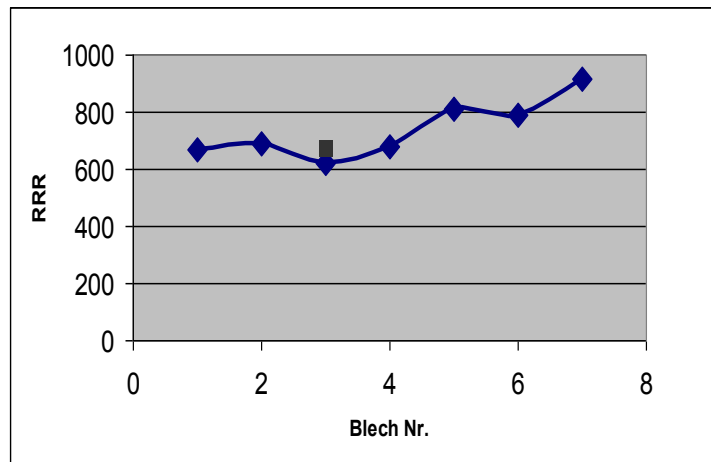
The melting temperature is a compromise between the maximization of purification and minimization of the material losses by evaporation.

RRR=300-500 are reachable currently

Nb-Purification by Electrolysis in Molten Salts



Fundamental investigations of the **electrodeposition of Nb-** from LiF-NaF-KF melts containing K_2NbF_7 , at $T = 1000\text{ K}$ have shown that this electrolyte was suited for the the material refining;
Nb become extremely pure especially concerning of Ta

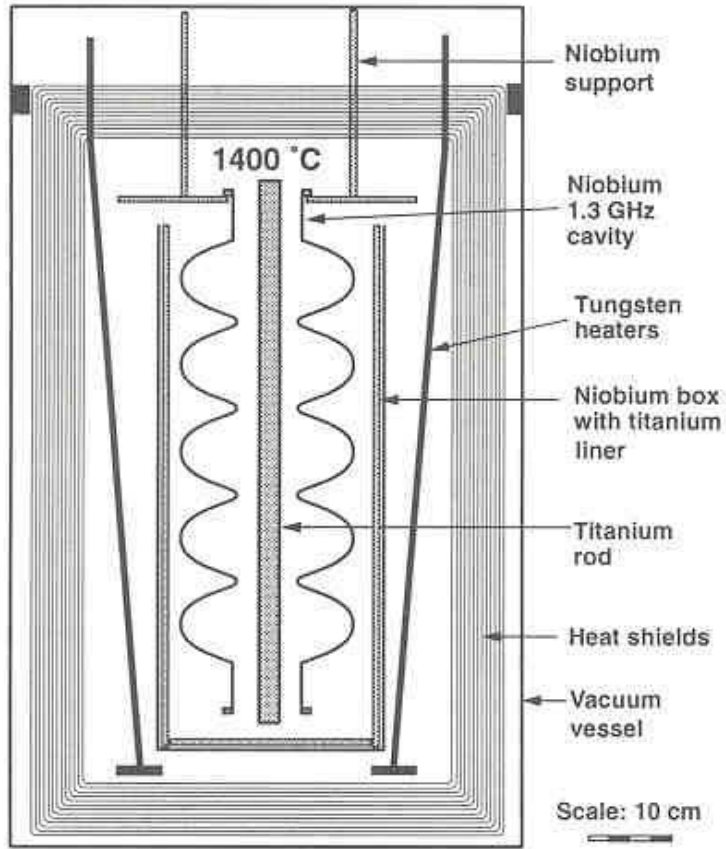


RRR up to 1000

Chemical analysis:

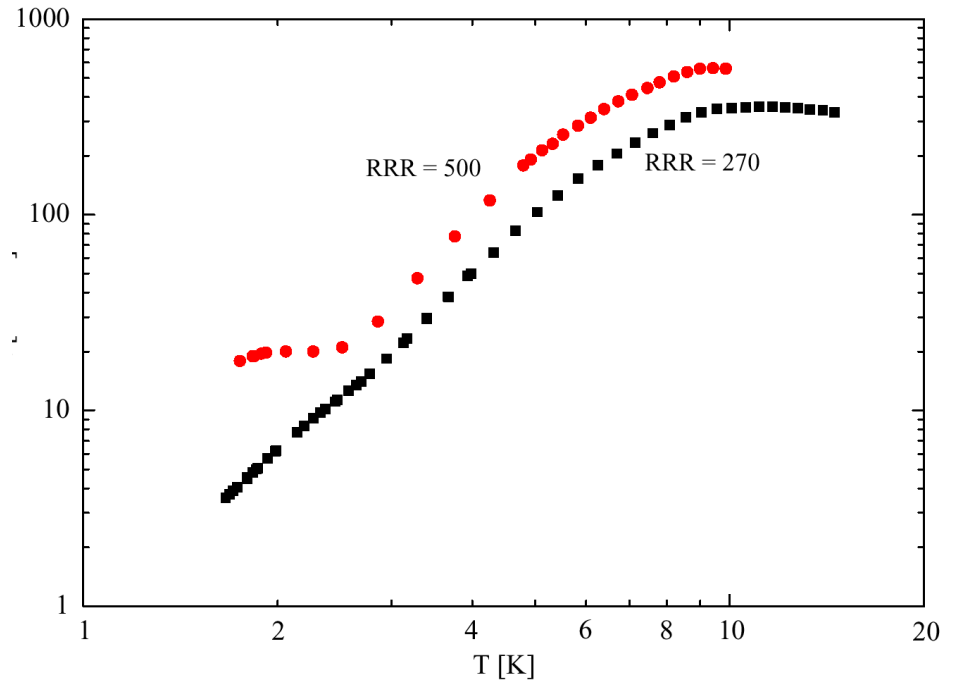
Ta = 6 wt. ppm,
 N = 1 wt. ppm, O = 5 wt.
 ppm,
 W, Ti, Fe, Si, Mo, Ni < 5 wt.
 ppm all together

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 °C heat treatment (in red)



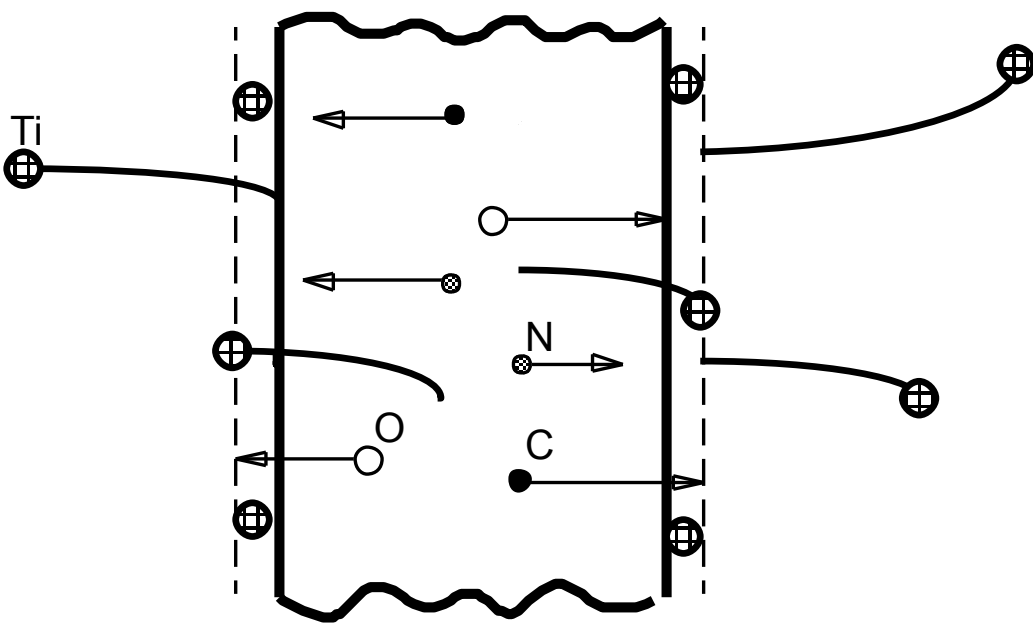
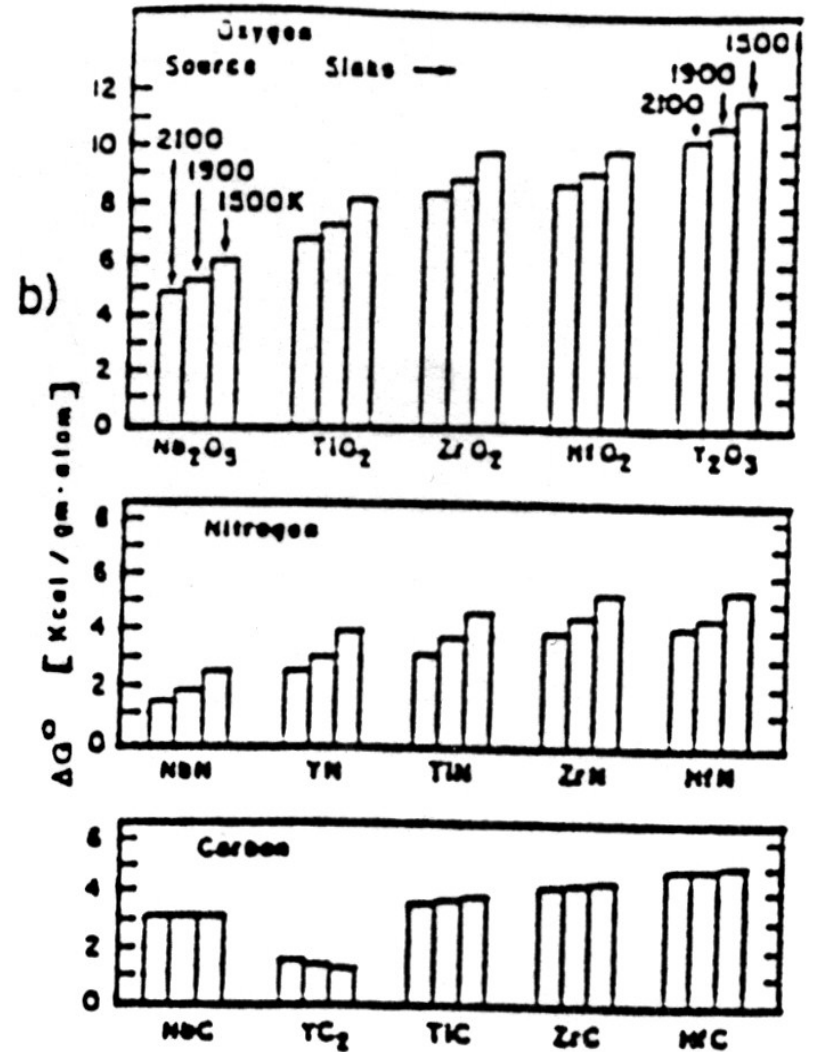
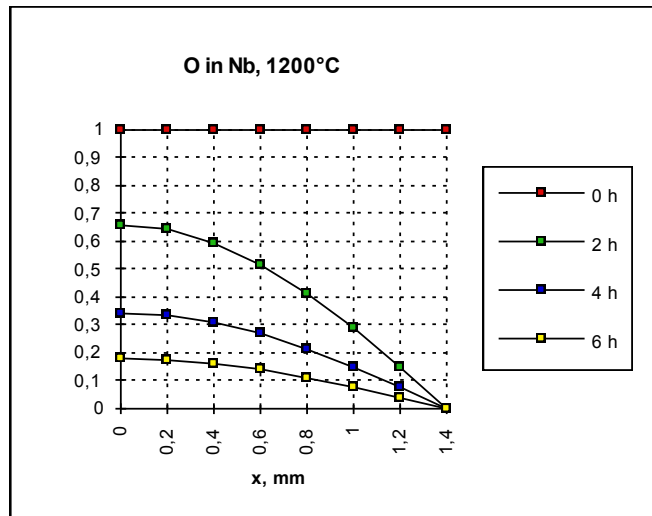
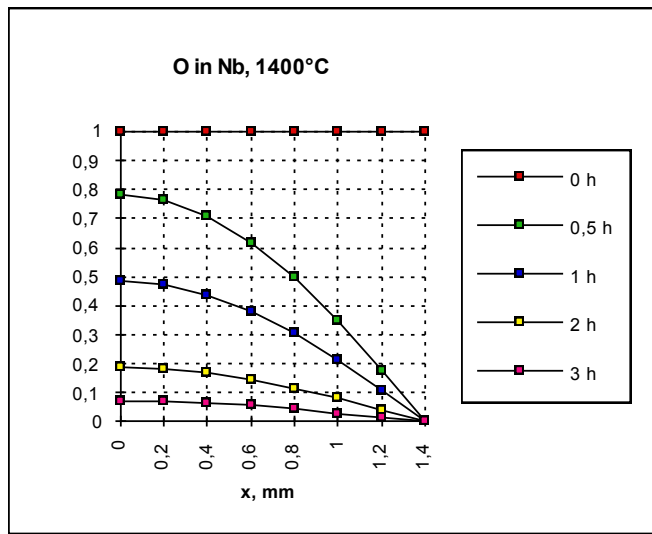


Fig. 1 Scheme of the Nb refining by high temperature gettering

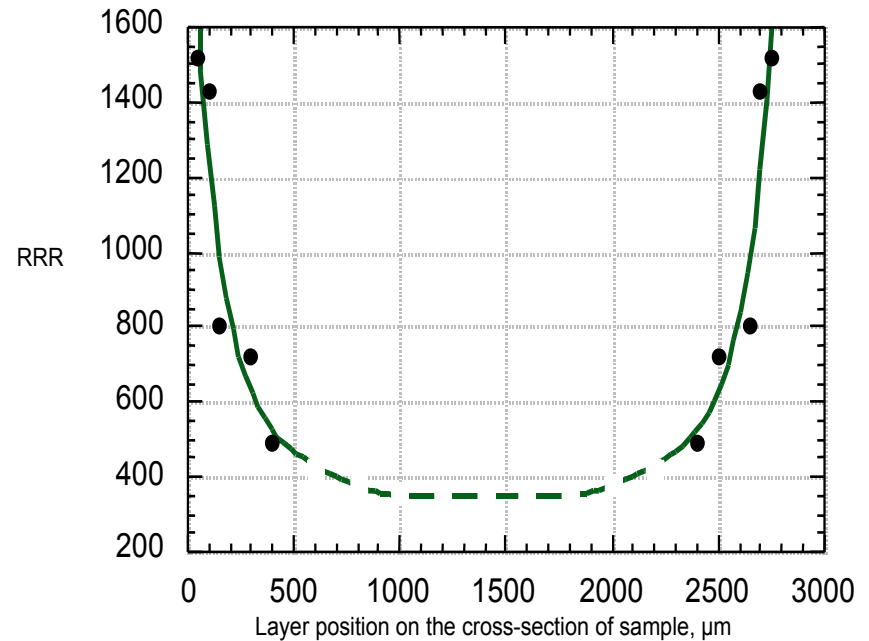
During refining the interstitial impurities O, N, C move to the surface and build compounds with Ti, because the affinity of Ti to O, N and C is higher as of Nb. The concentration gradient of interstitial impurities between surface and inside of Nb keep the refining. On the other hand the Ti diffuse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



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



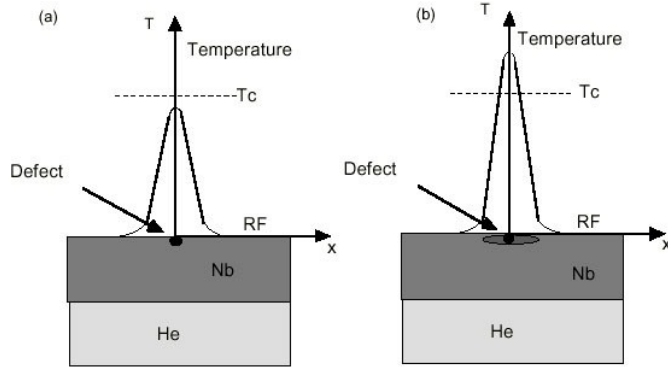
$$\frac{C}{C_0} = \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \text{EXP}\left(-\frac{D\pi^2 t(2n+1)^2}{4l^2}\right) \cos \frac{(2n+1)\pi x}{2l}$$



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 T_c (H. Padamsee)

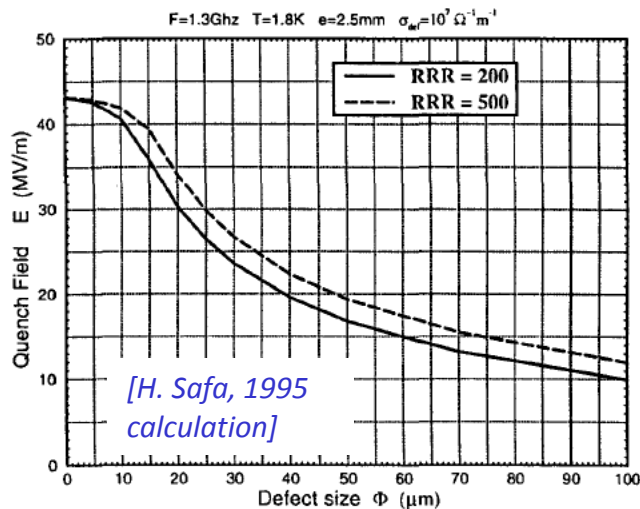
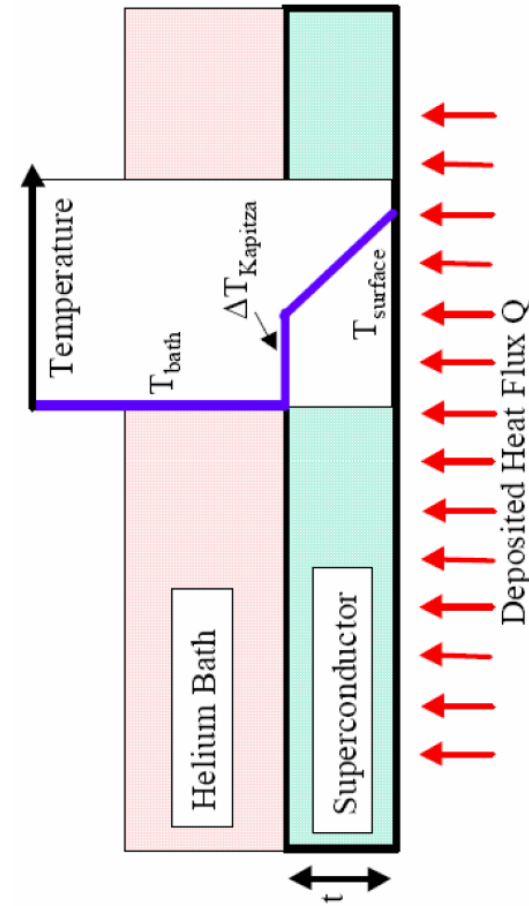


Figure 8- Quench field as a function of defect size.

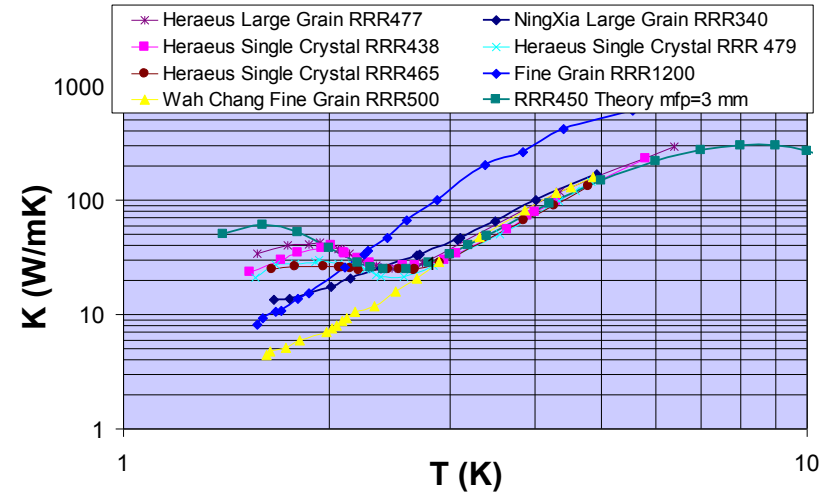
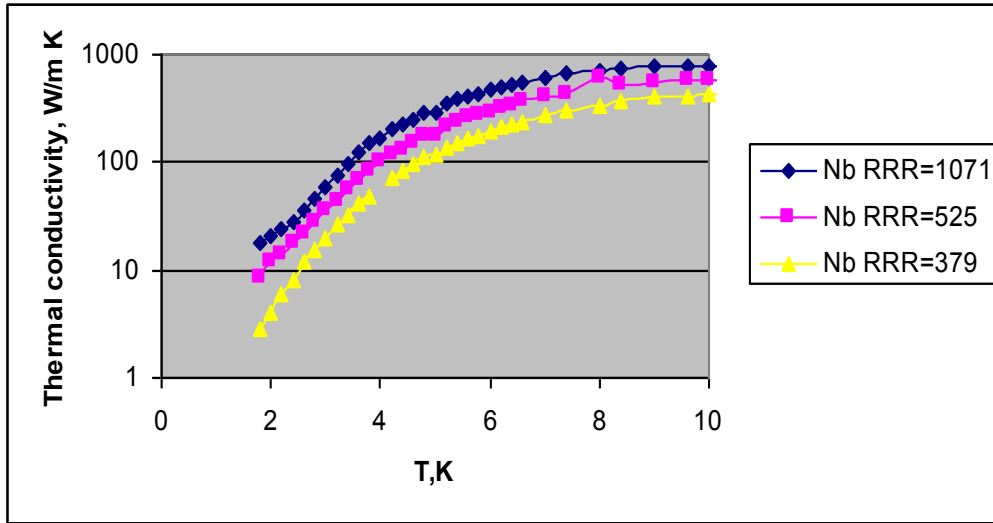
Defect of 50-100 μm caused quench field of < 15-20 MV/m:



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.

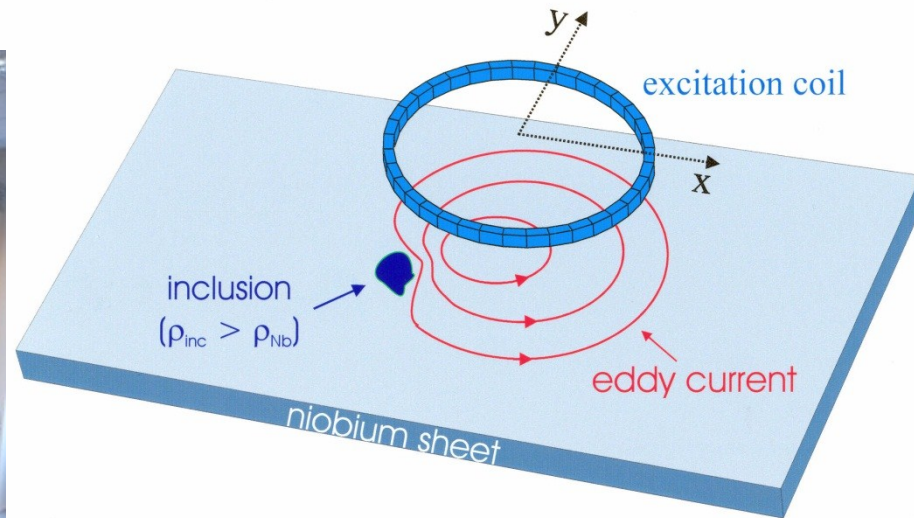
Rule of thumb $\lambda(4,2K) = C \cdot (W/m \cdot K) \cdot RRR$
 $C \approx 0,25 \div 0,14$

$\lambda_T \approx RRR \approx \text{purity (restricted)}$

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

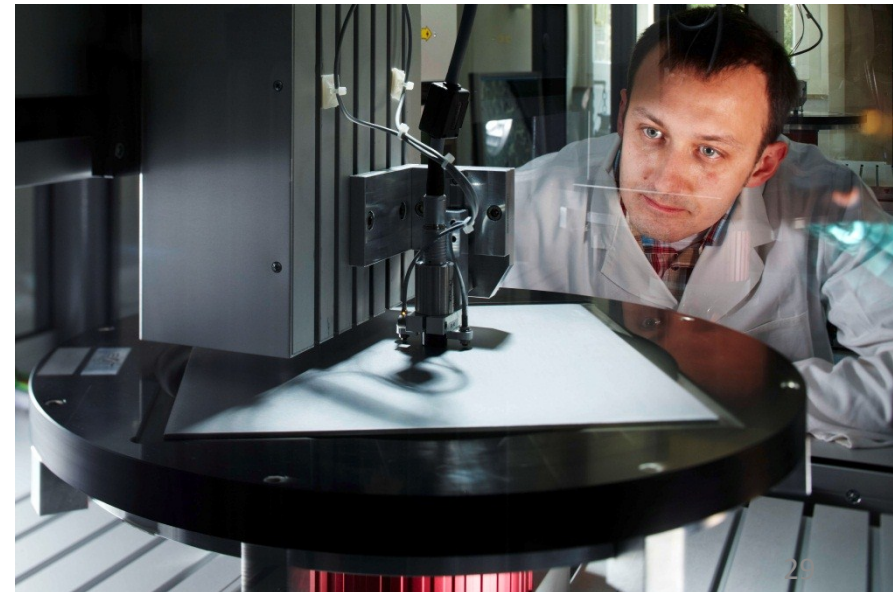
First term: scattering of electrons on impurities, lattice defects and scattering of electrons on phonons. Second term: scattering of phonons on electrons, scattering of phonons on grain boundaries

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

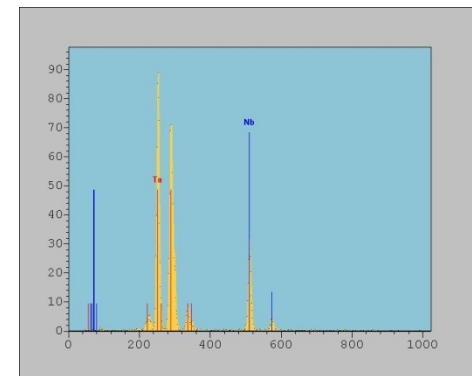
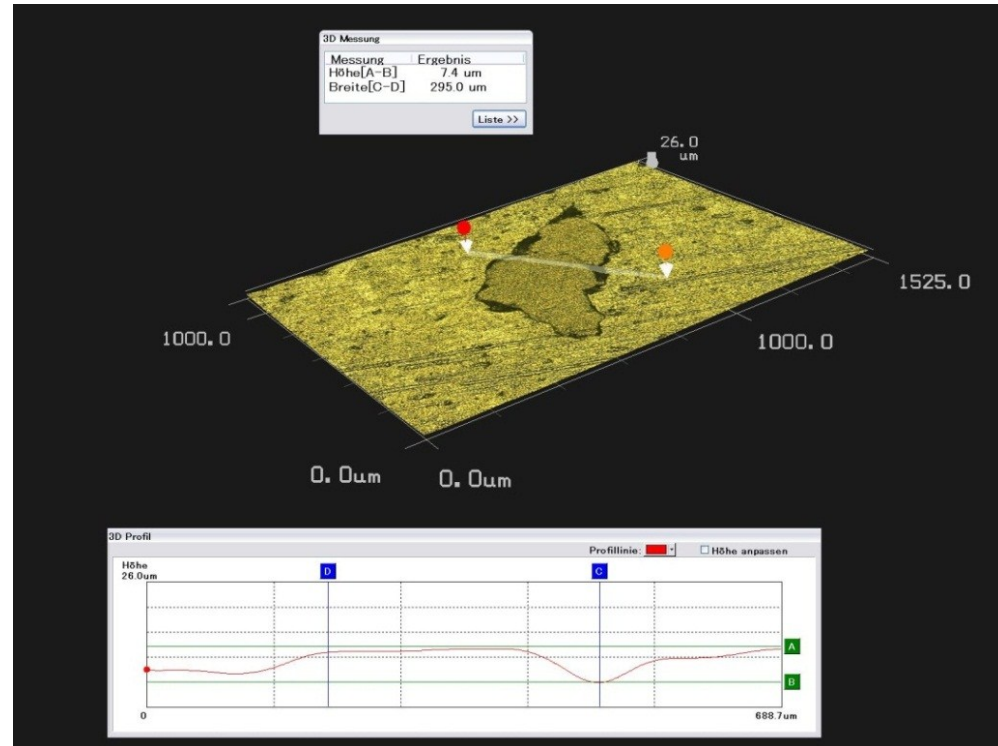
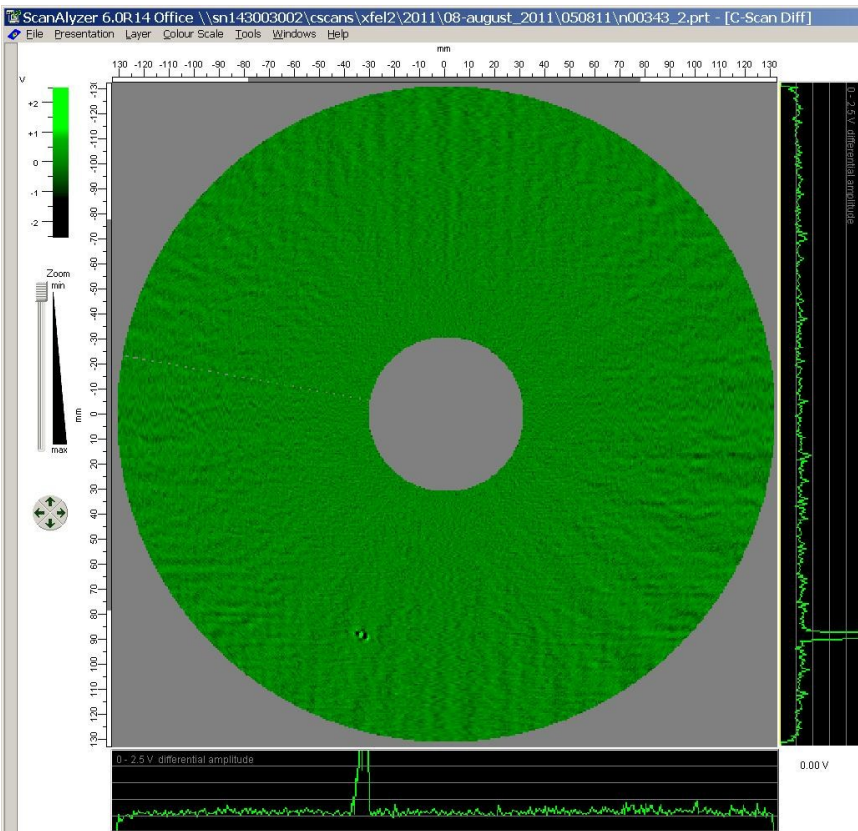


Principle of eddy current measurement

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**

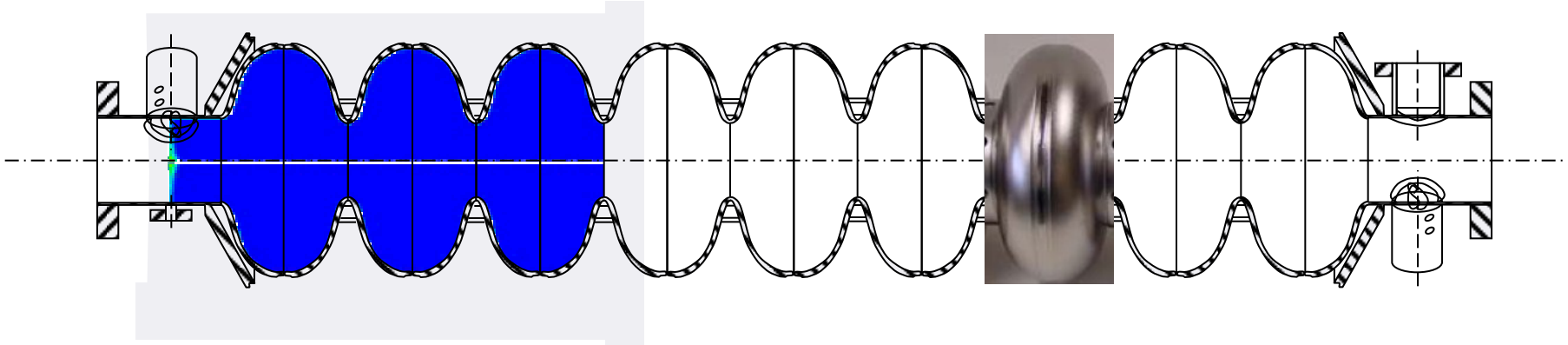
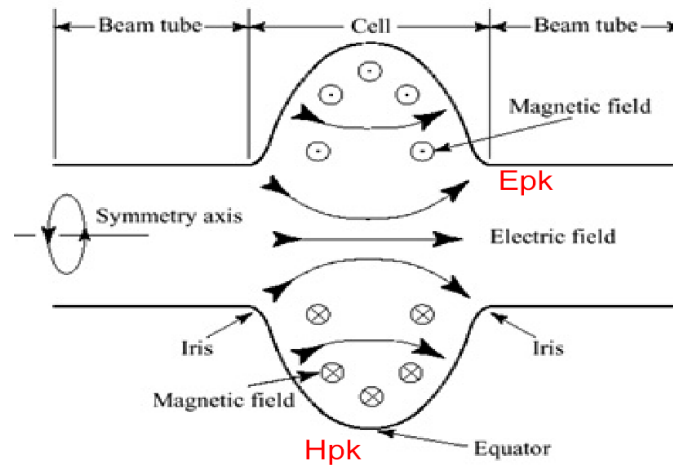


One example of foreign material inclusion (Ta) detected in the Nb sheets



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

Fabrication



Frequency 1.3 GHz

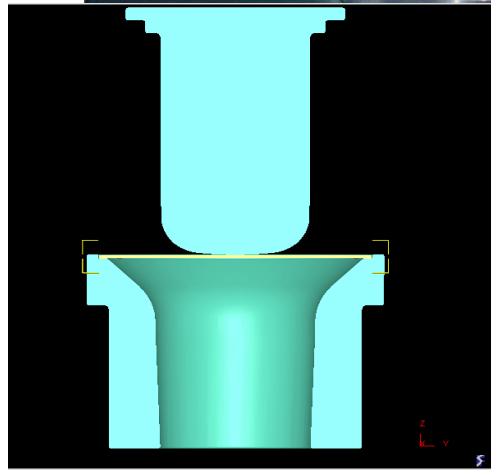
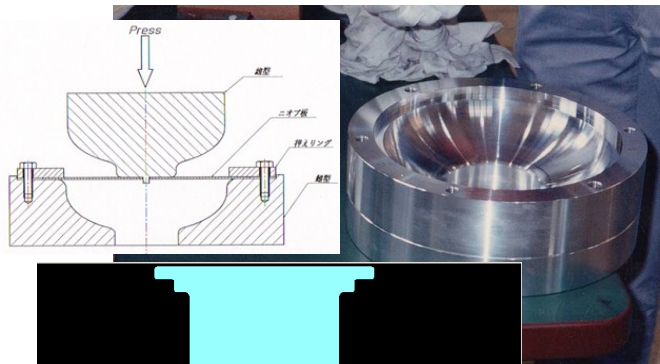
High purity niobium RRR 300

Deep drawn from sheets

Welding with electron beam

Operating temperature 2K

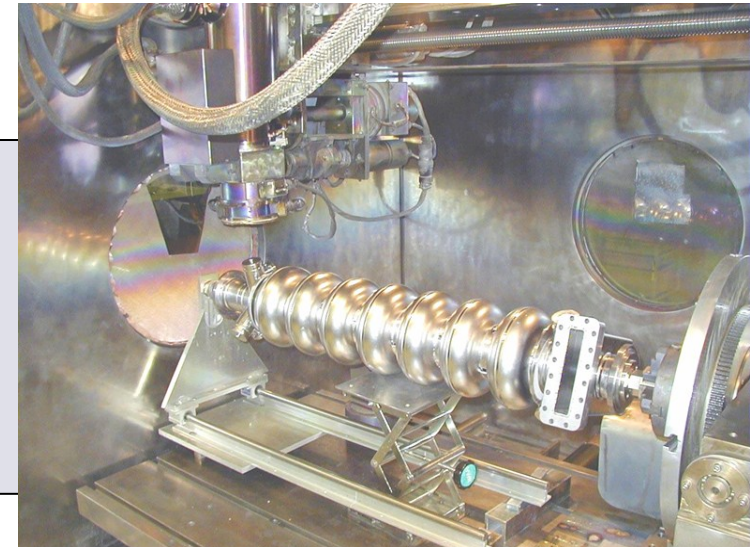
Experiences of ca. 30 years of industrial cavity fabrication by deep drawing and EB welding are available



Half cells are shaped by deep drawing.

Dumb bells are assembled 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

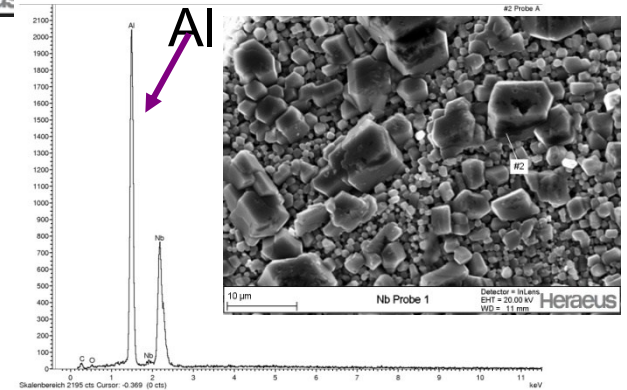
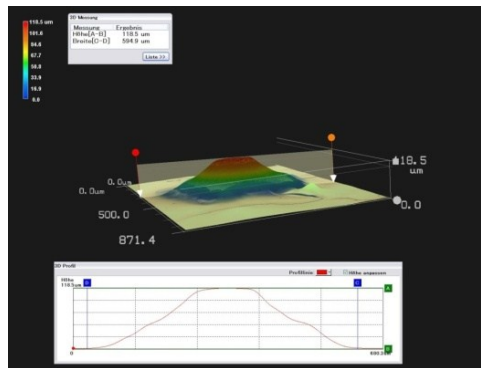
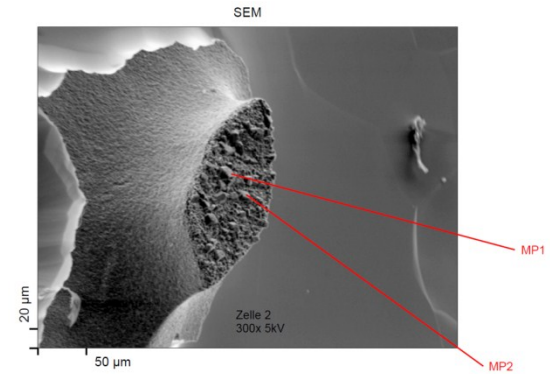
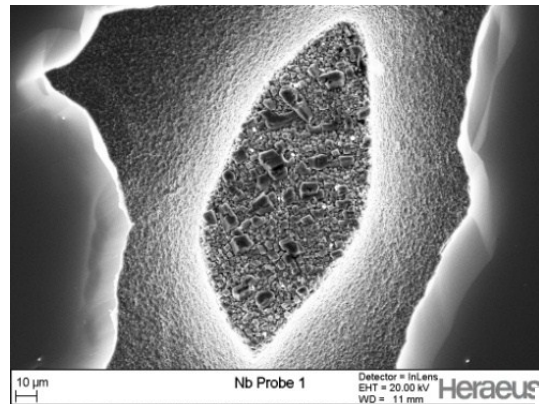
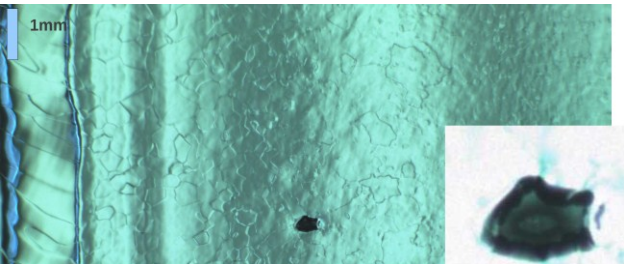
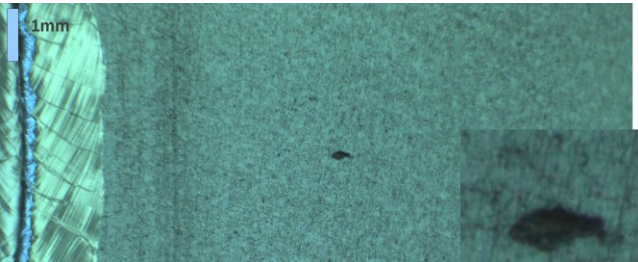
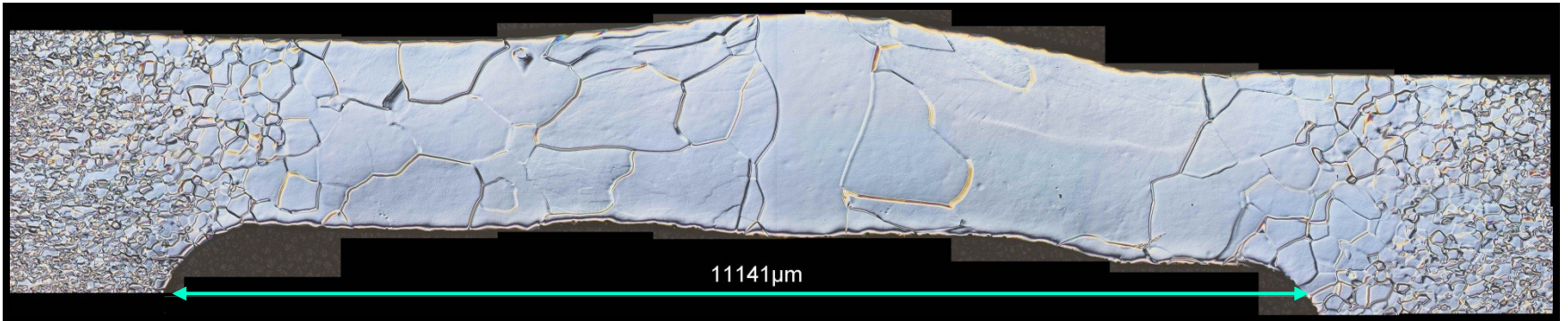


Image of high resolution camera done on the cavity Z161 as delivered (top) and after EP (bottom)

3D microscope, SEM Images and EDX analysis of samples

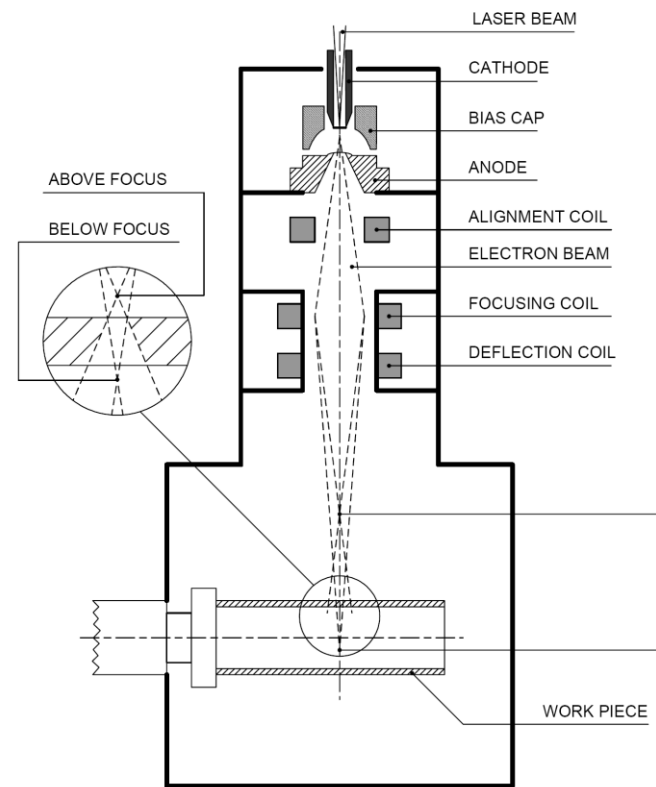
Particle adhered during welding and did not disappear after electropolishing

Electron Beam Welding EBW



Microstructure of the EB welding area. The grain size
 $G=50 \div 2000 \mu\text{m}$

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

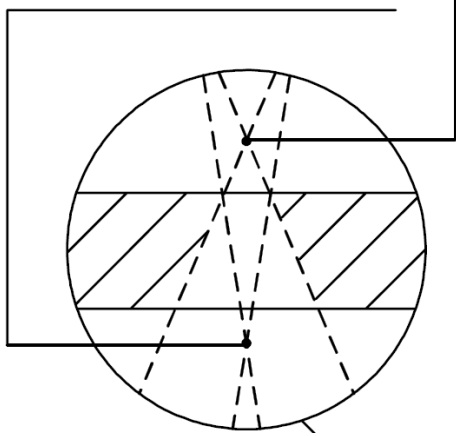
Chamber size: 3300mm x 1400mm x 1600mm (ca. 7,4 m³)

Vacuum: > 5x10⁻⁶ mbar (ca. 2x10⁻⁸ mbar)

Pumping time: ca. 20 min = 3x10⁻⁶ mbar

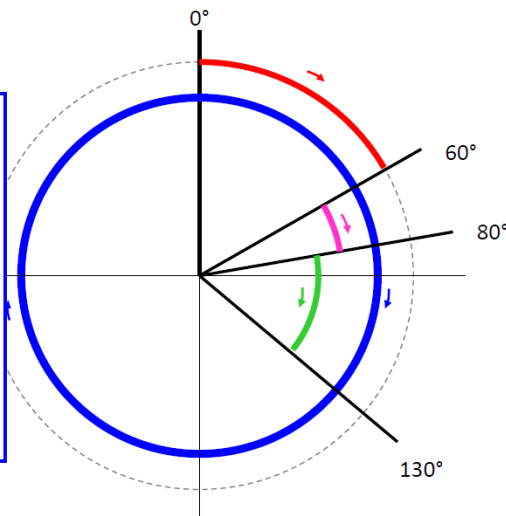
2 Cryogenic - Pumps: ca. 2 × 10.000 l/s

Displacement along the X-Axes ca. 1400 mm

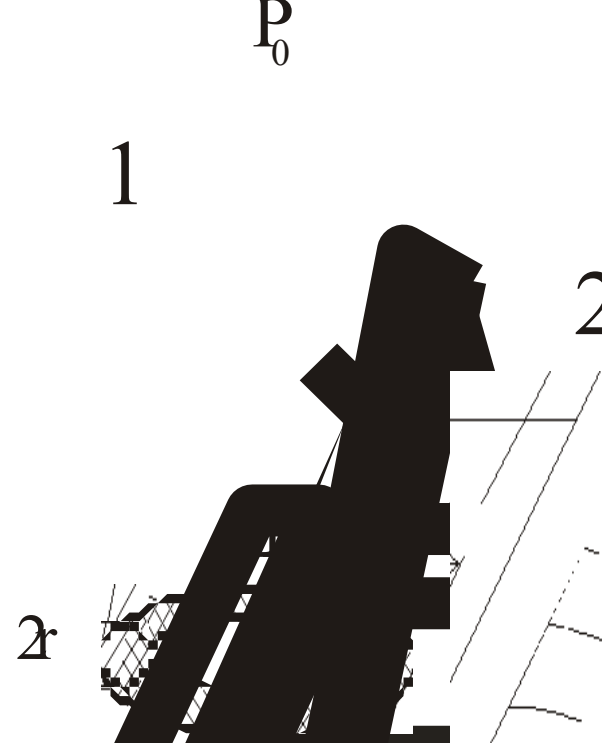


Focusing possibilities (above focus; below focus)

- **Slope up**: start at 0°
 - (60° slope up)
- **Weld**: start at 60°
 - (360° weld)
- **Overlength**: start at 60°
 - (20° overlength)
- **Slope down**: start at 80°
 - (50° slope down)



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

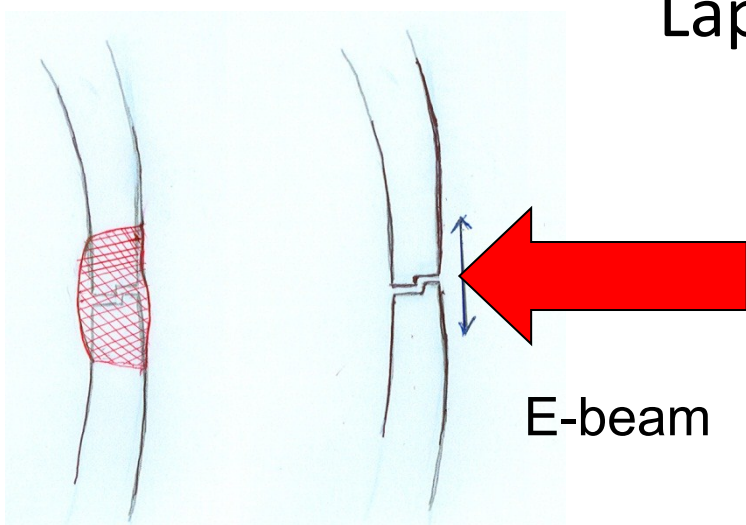


Welding Scheme (circular raster)

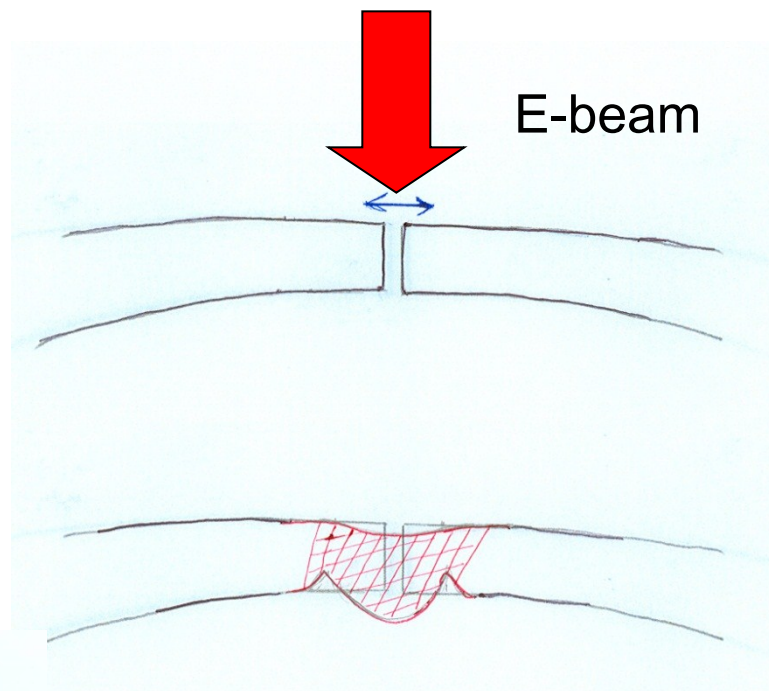
1-Electorn beam (P_0 -power of the beam, r - spot radius on the surface, L - scanning amplitude, V - velocity of the beam movement), 2-Nb sheet, 3- melting zone (z -depth of the melting zone).

EBW with vertical or horizontal positioning of cavity?

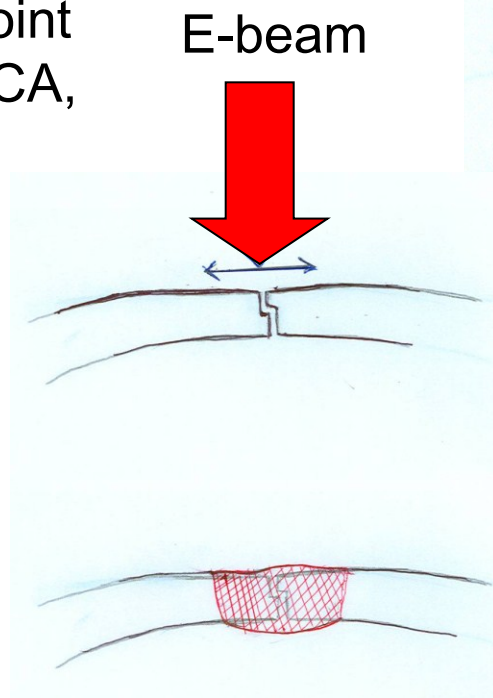
Lap or butt joint?



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

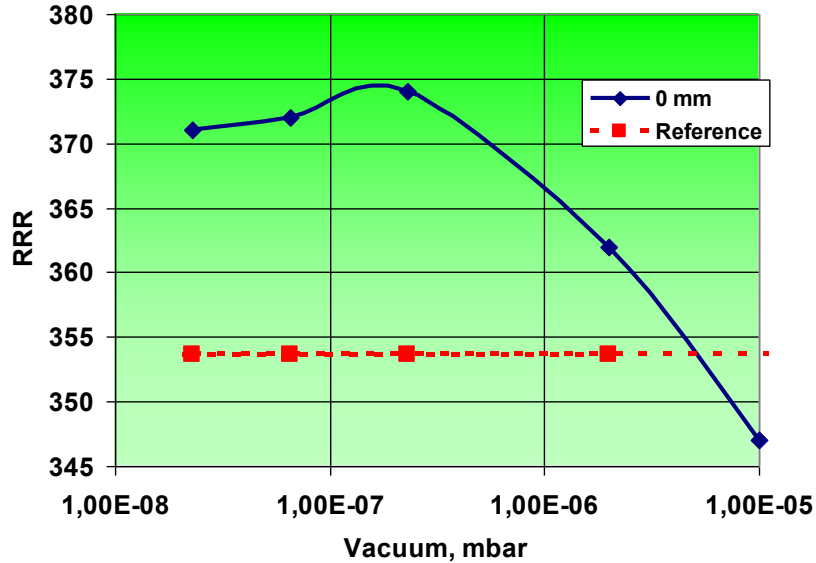


EBW: butt joint (e.g. JLab, PAVAC)



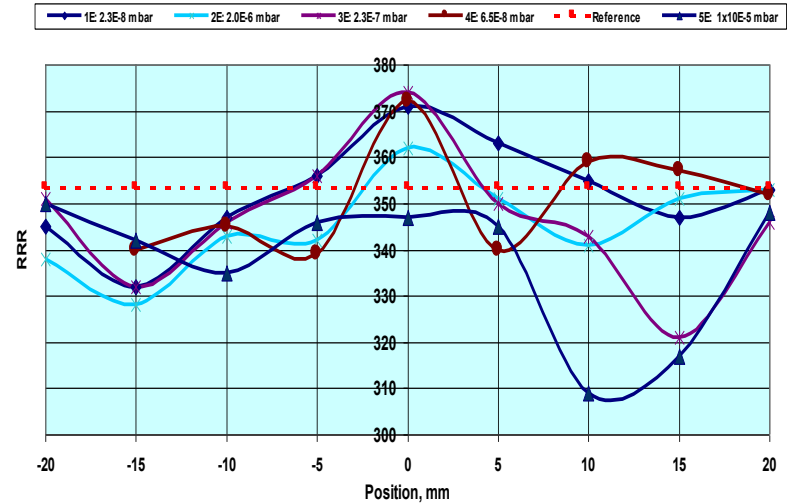
Horiz. Pos. EBW: lap joint (recess) DESY, AES, E.Zanon

RRR degradation during EB welding

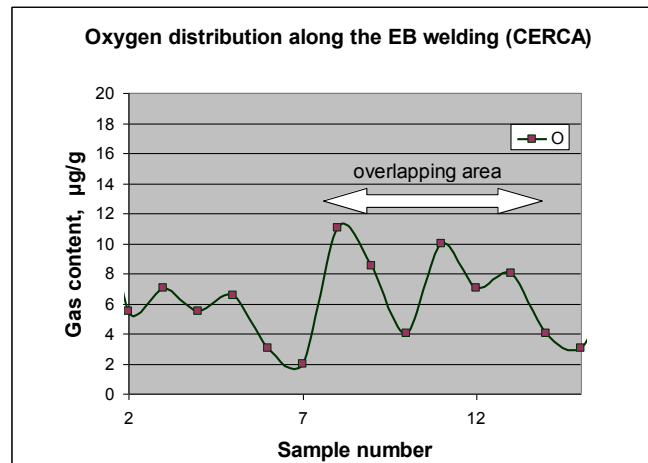


RRR in the welding seam versus pressure in the welding chamber

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



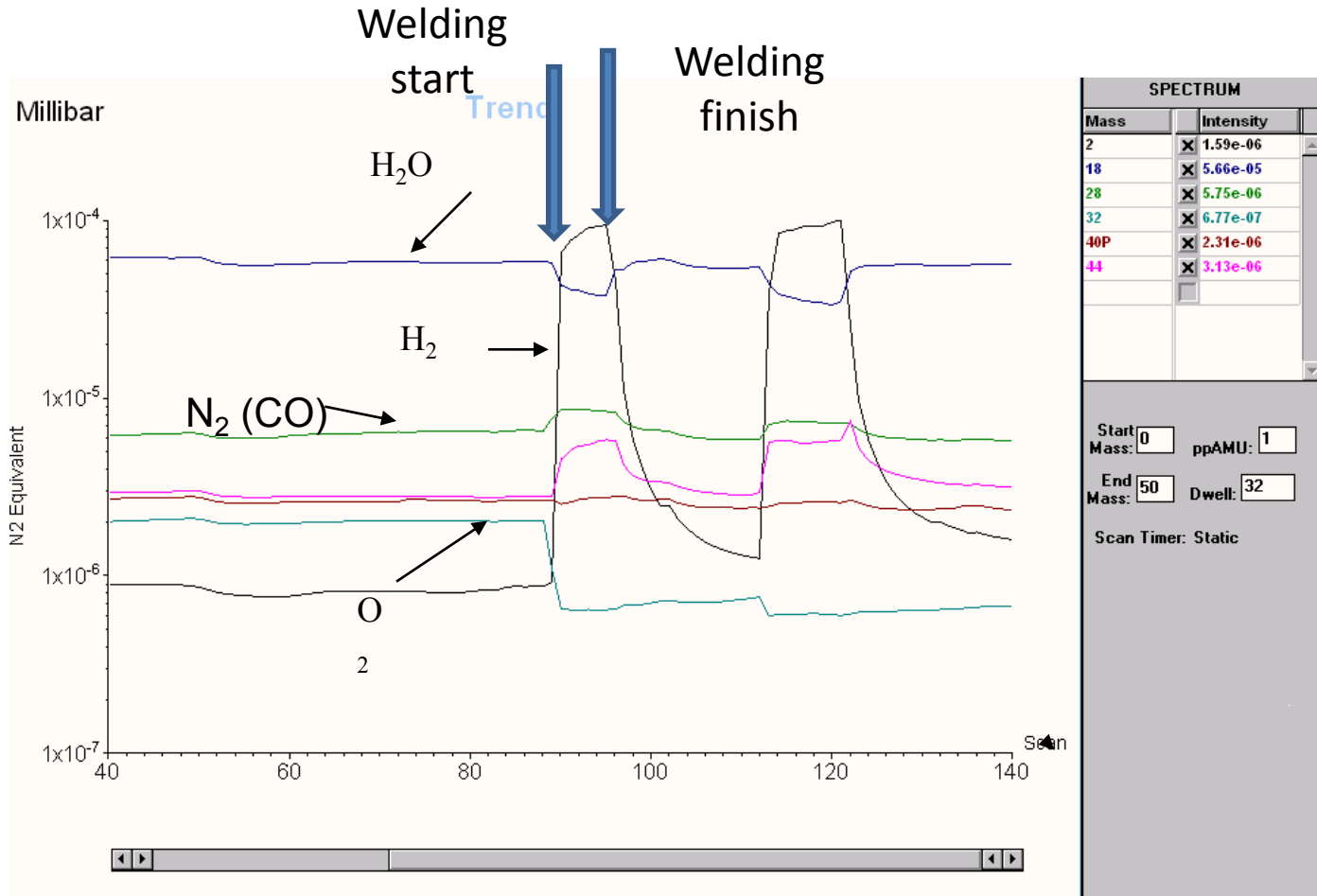
RRR in the EB welding area versus distance from the welding seam at different pressures of DESY EB facility



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.

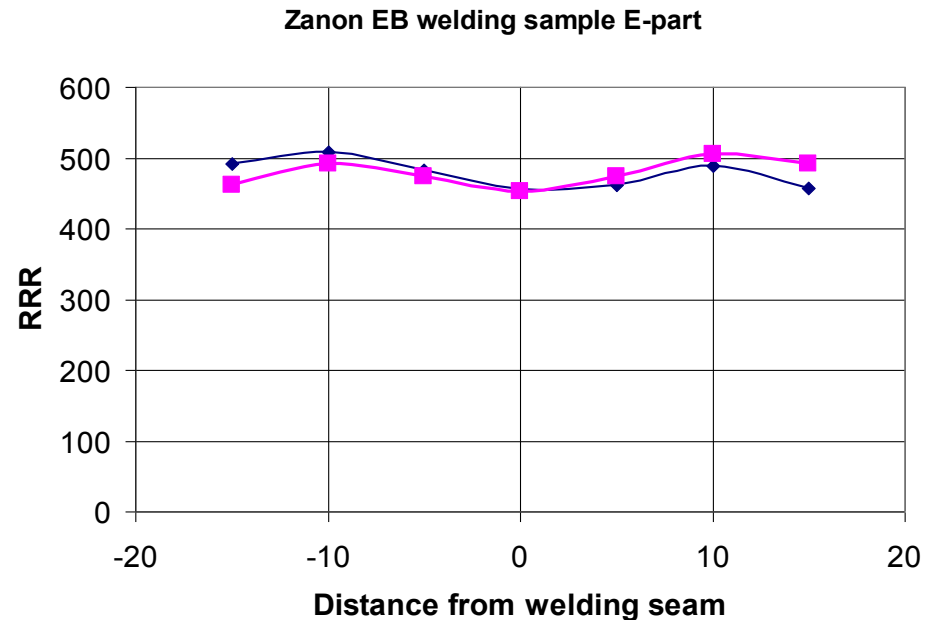
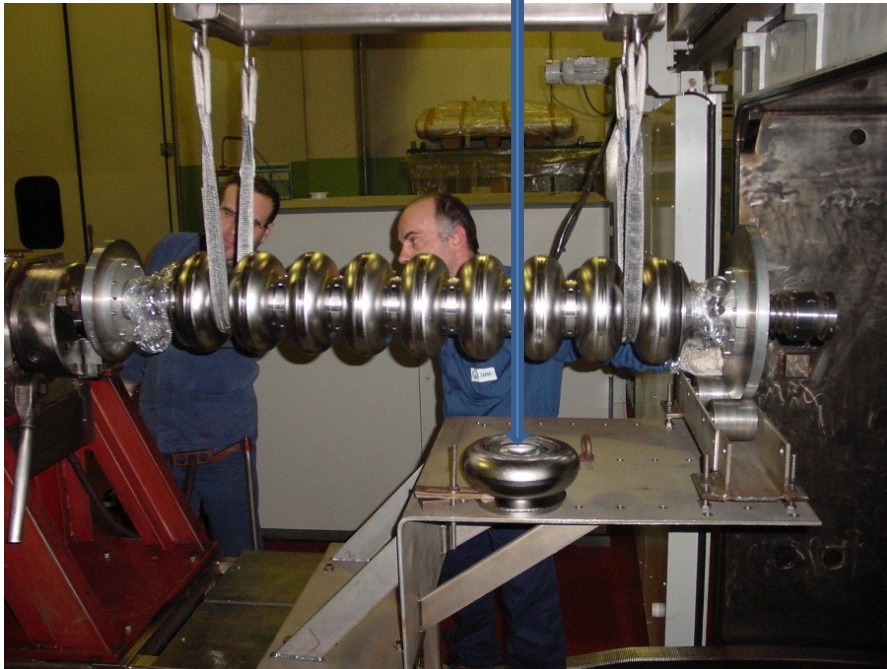
Partial pressure in the EB chamber during tack welding of Nb300



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

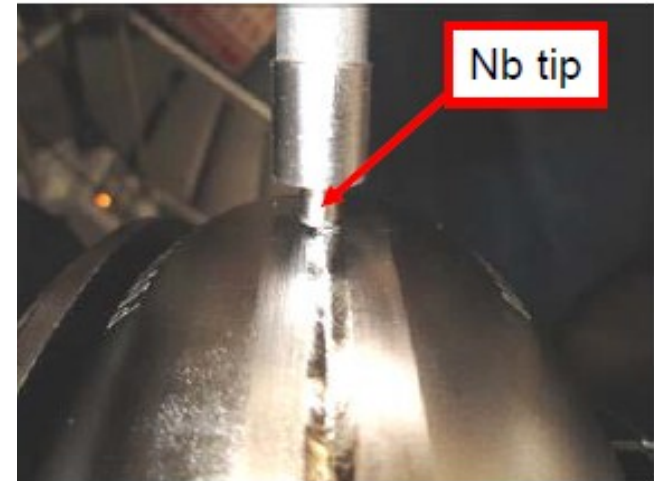
Temporal changes of gas partial pressure in vacuum chamber during the EB welding process.

The RRR degradation can be avoided by Nb evaporation with electron beam before start the welding



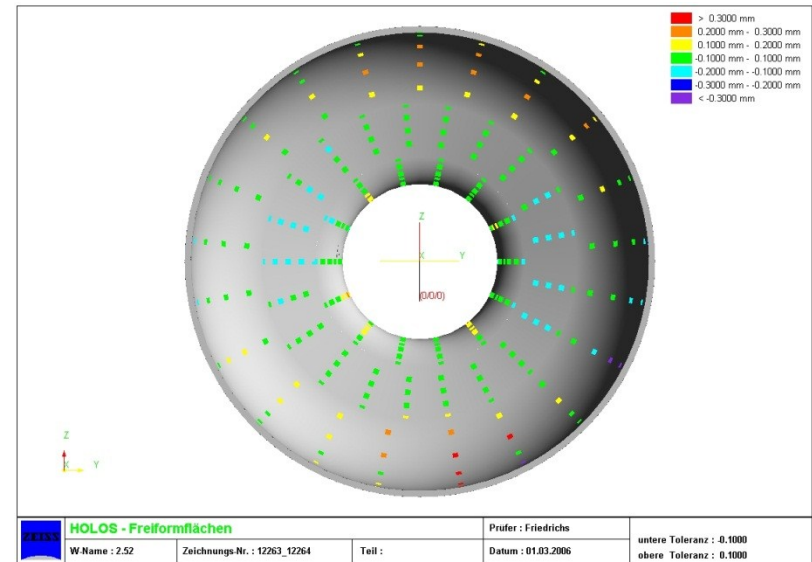
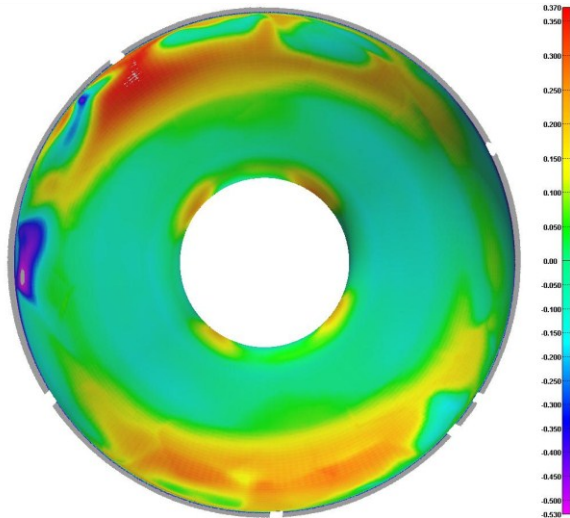
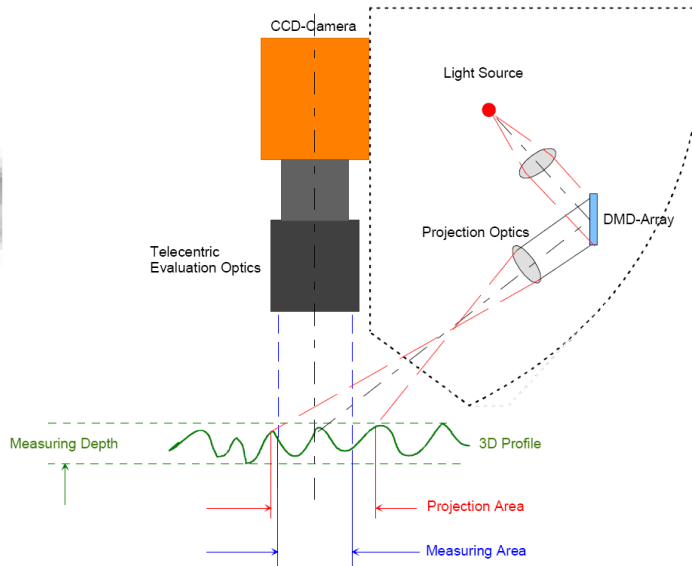
RRR in the welding seam of the two welded samples with RRR=485

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 3D measurement of the half cell shape

Frequency and length adjustment

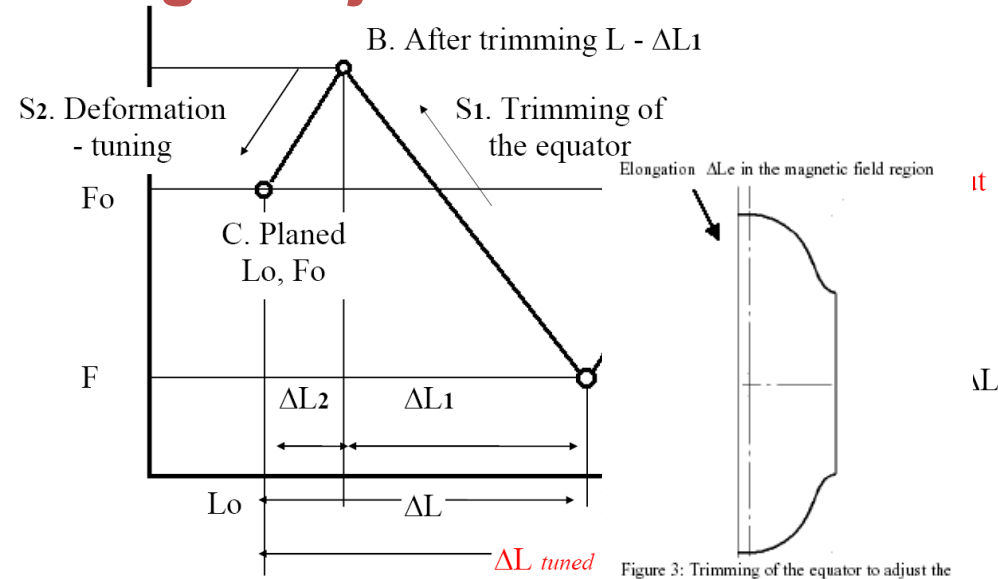
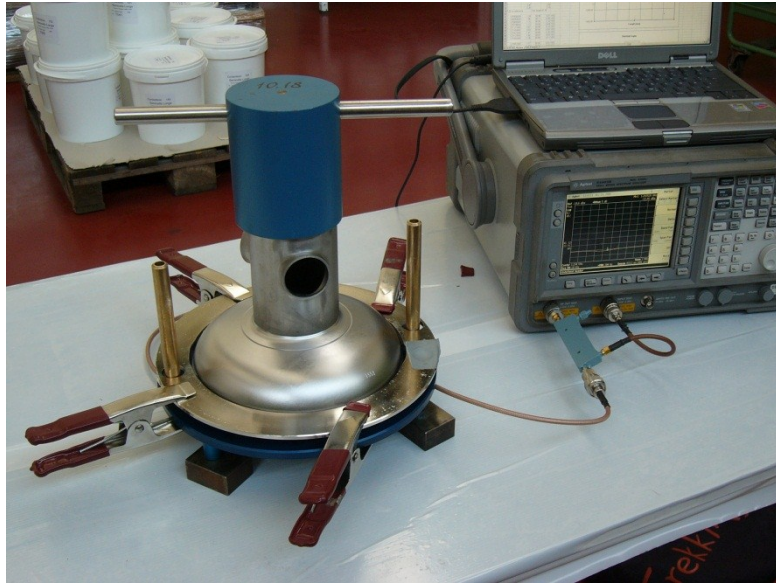
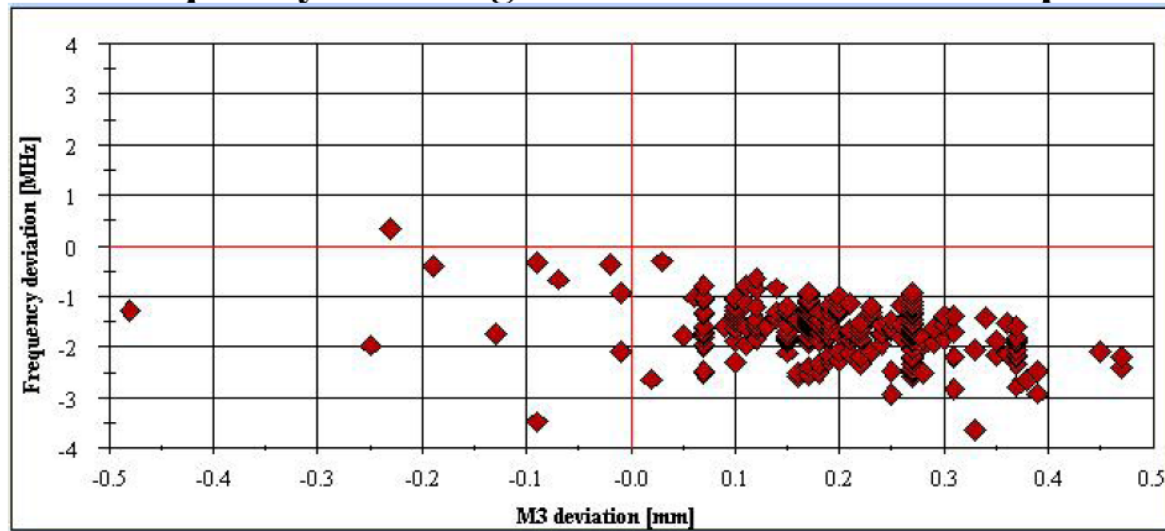


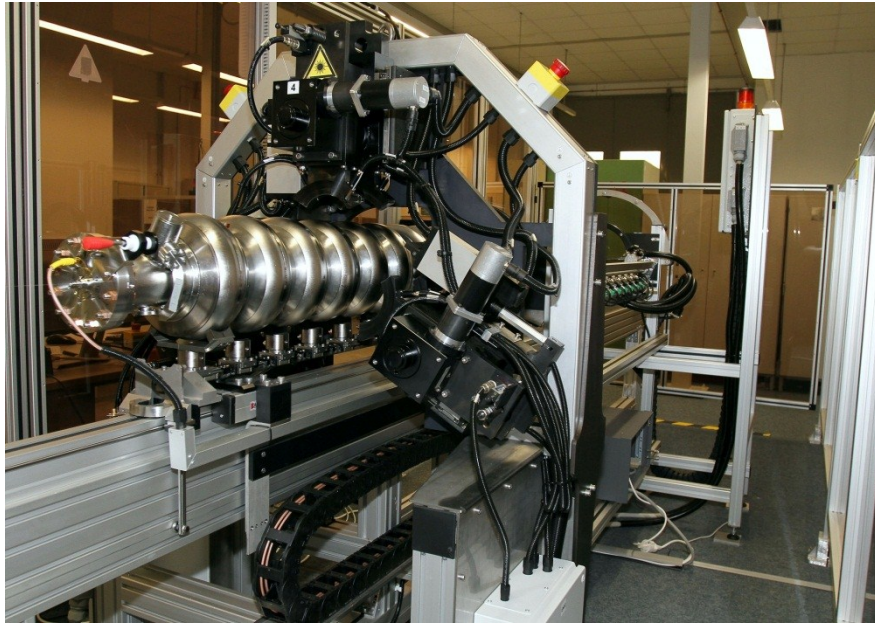
Figure 3: Trimming of the equator to adjust the elongation at the equator

Frequency and length deviation of middle cups

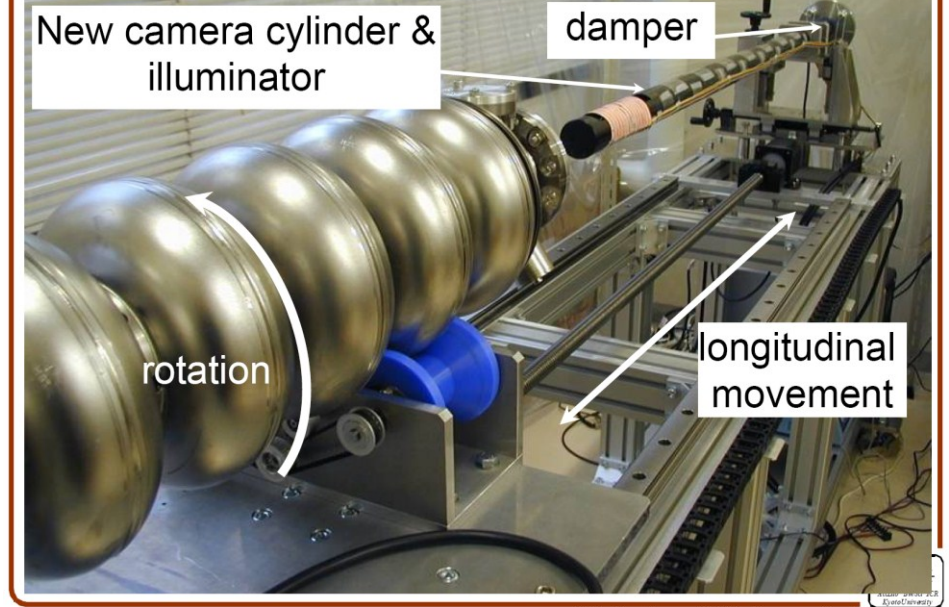


Wah Chang (EDMS-DB)

Cavity inspection



Frequency and eccentricity measurement

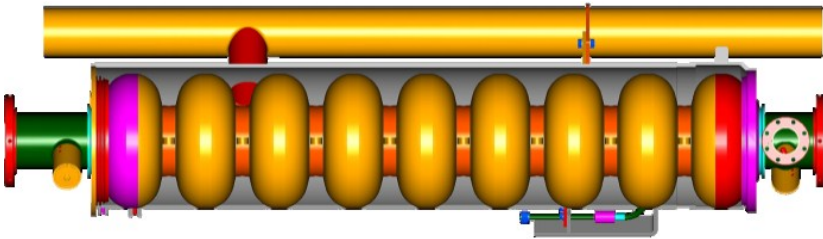


Optical control by high resolution camera



Dimensions check by 3D arm ⁴⁴

Trend: Complete Industrialization (not only mech. fabrication)



Example: EXFEL cavity

- Mechanical fabrication
- **Prior surface treatment.**

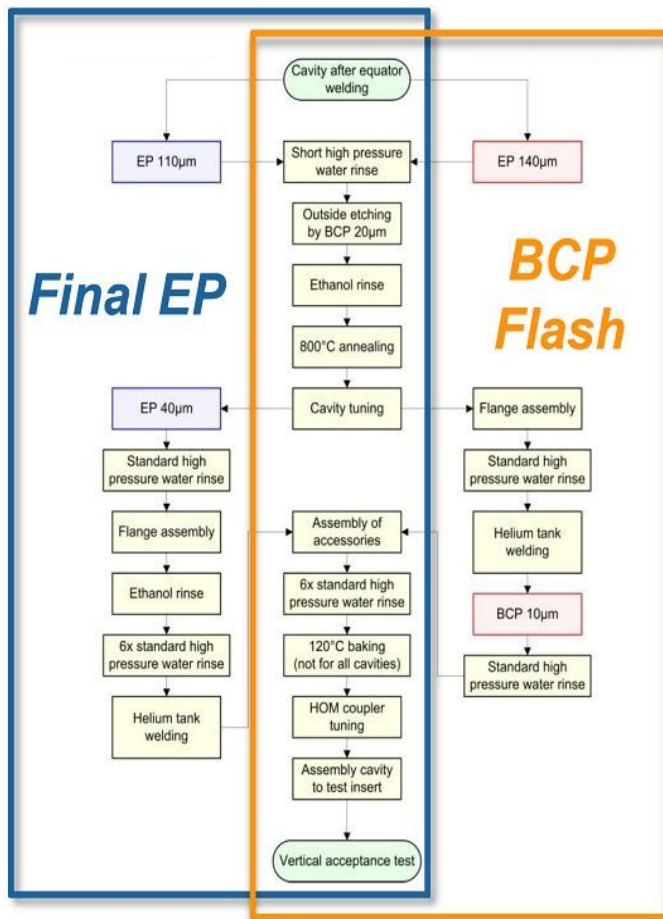
EP 110-140 μm (main EP), ethanol rinse, outside BCP, 800°C annealing, tuning

- **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)

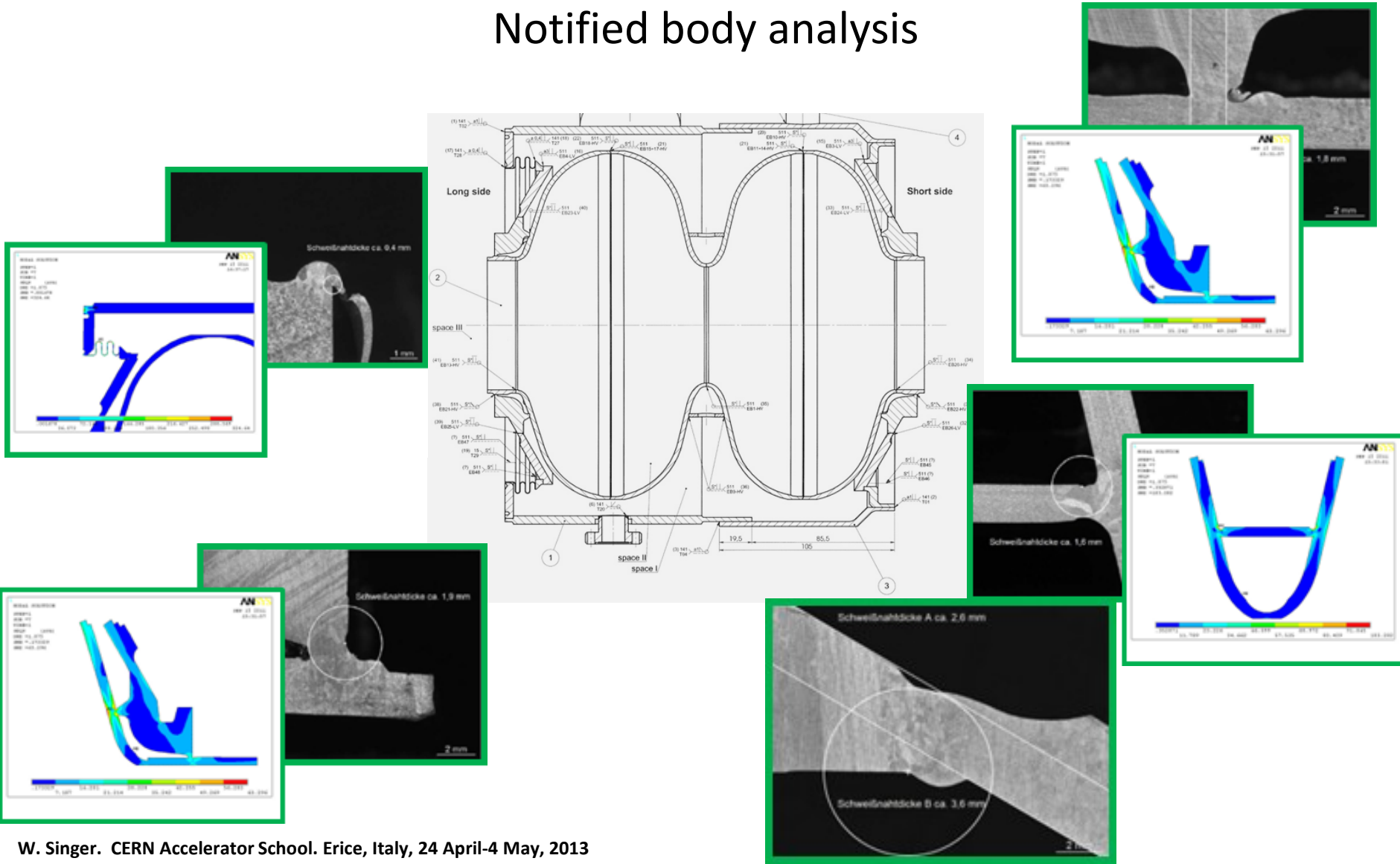
- examination of design, FEM calculation
- qualification of welding processes
- qualification of another PED relevant processes (annealing, deep drawing, forming)
- **production of test pieces 2 pieces/Fa**
- destructive tests on test pieces
- supervising the production qualification on pre-series cavities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



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

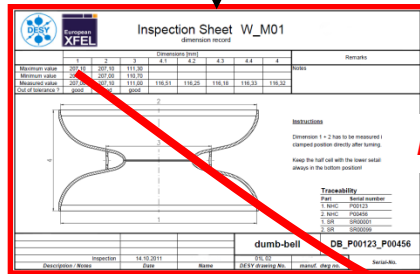
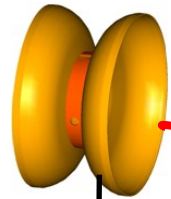
- For each completed cavity, a **traceability report** is to be prepared, in which the serial numbers of all incorporated semi-finished products and manufacturing groups are stated in the form of a parts list, including position information.
- It must be possible to reconstruct the development history 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.

XFEL –Production: EDMS for document management Database for statistics

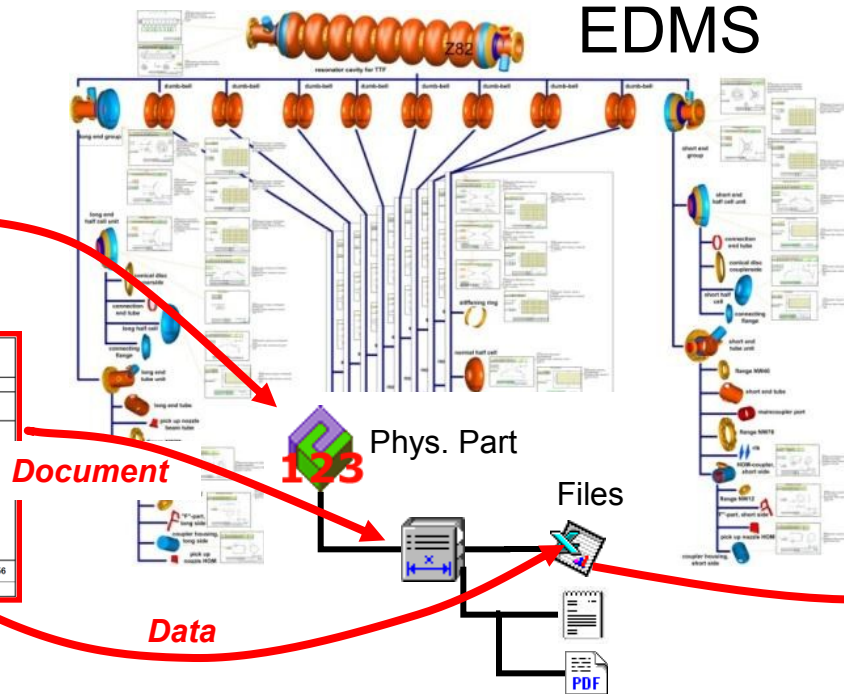
Fabrication



Inspection sheet

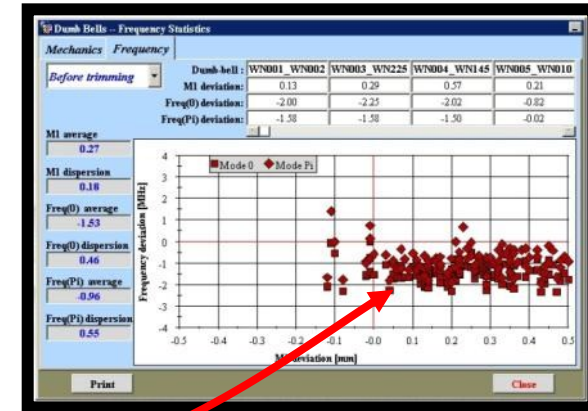
Inspection sheets for QM documentation

- 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)



Fabrication structure.
Subassembly parts related.
Procedure related

Cavity-DB



Statistical analysis

Alternative Fabrication

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



Proposed

by

G.Rao,

P.Kneisel,

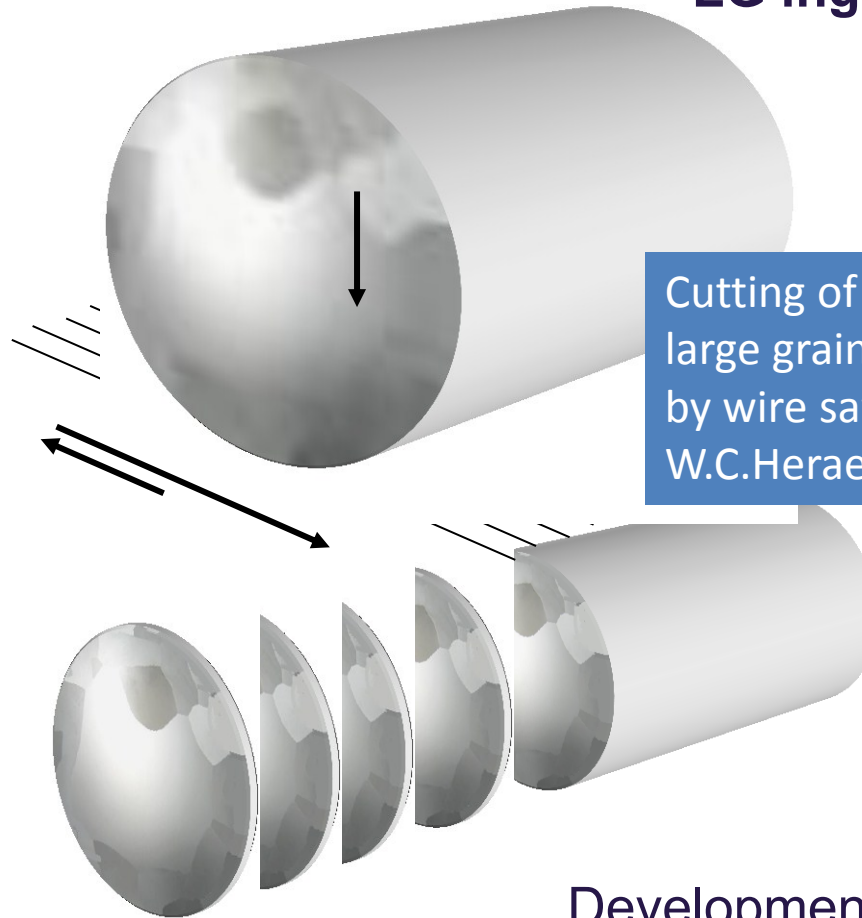
T.Carneiro

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**

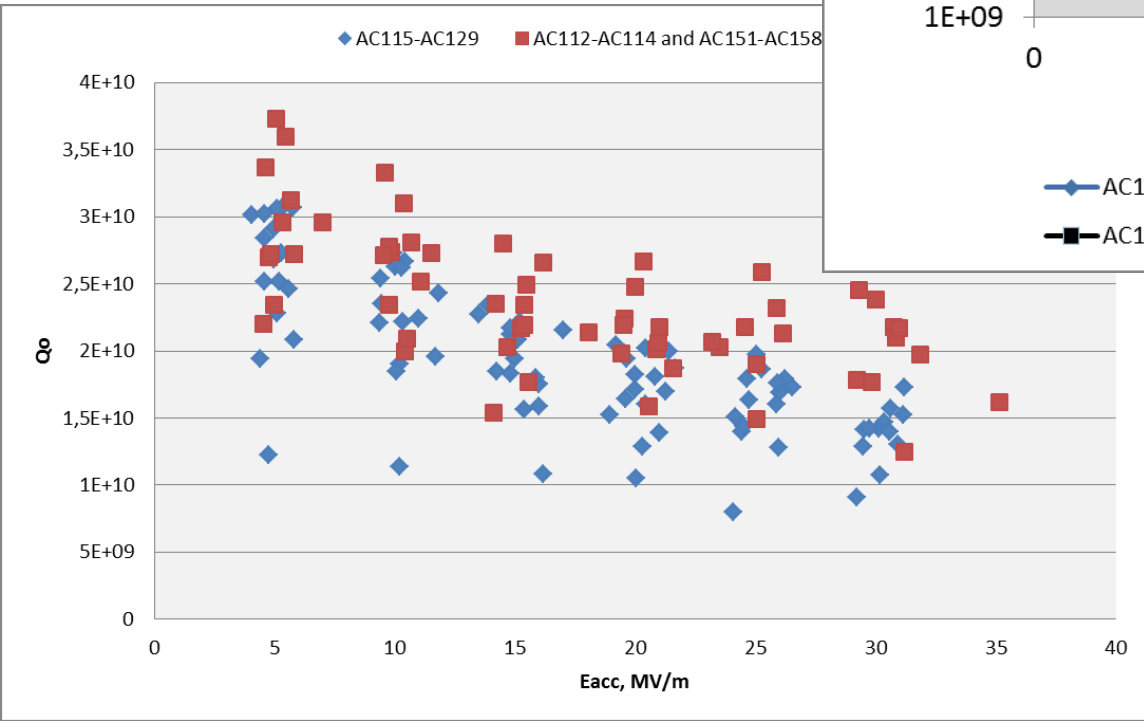
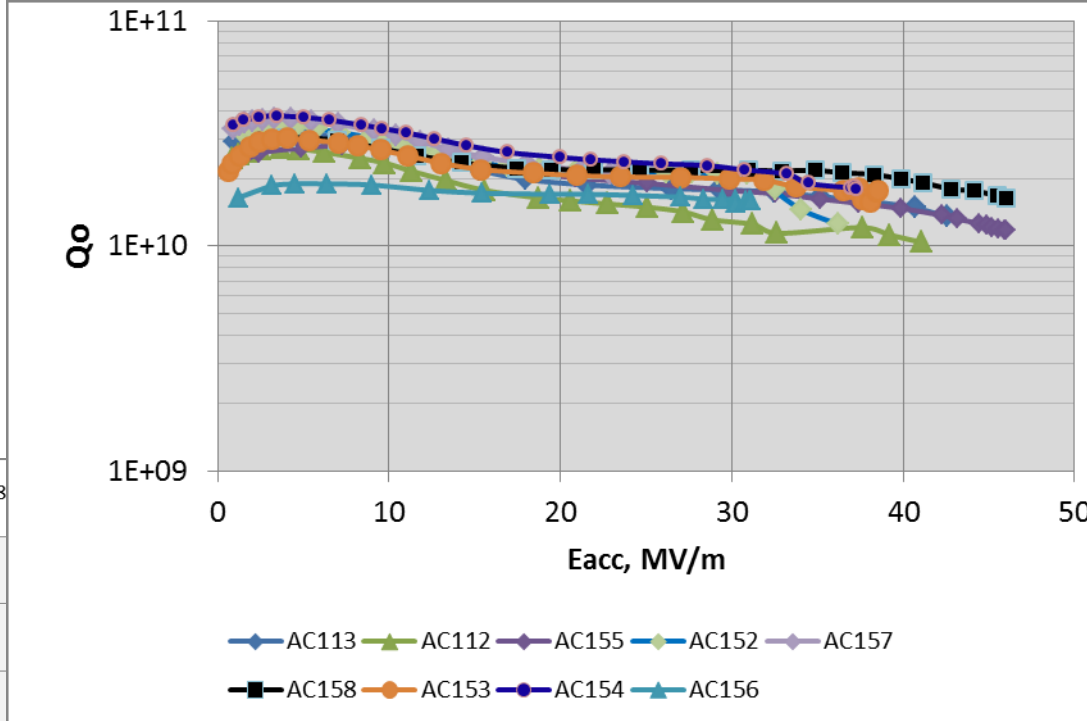


- Very smooth (shiny) surface in grain areas after BCP
- the steps at grain boundaries are more pronounced as in polycrystalline material

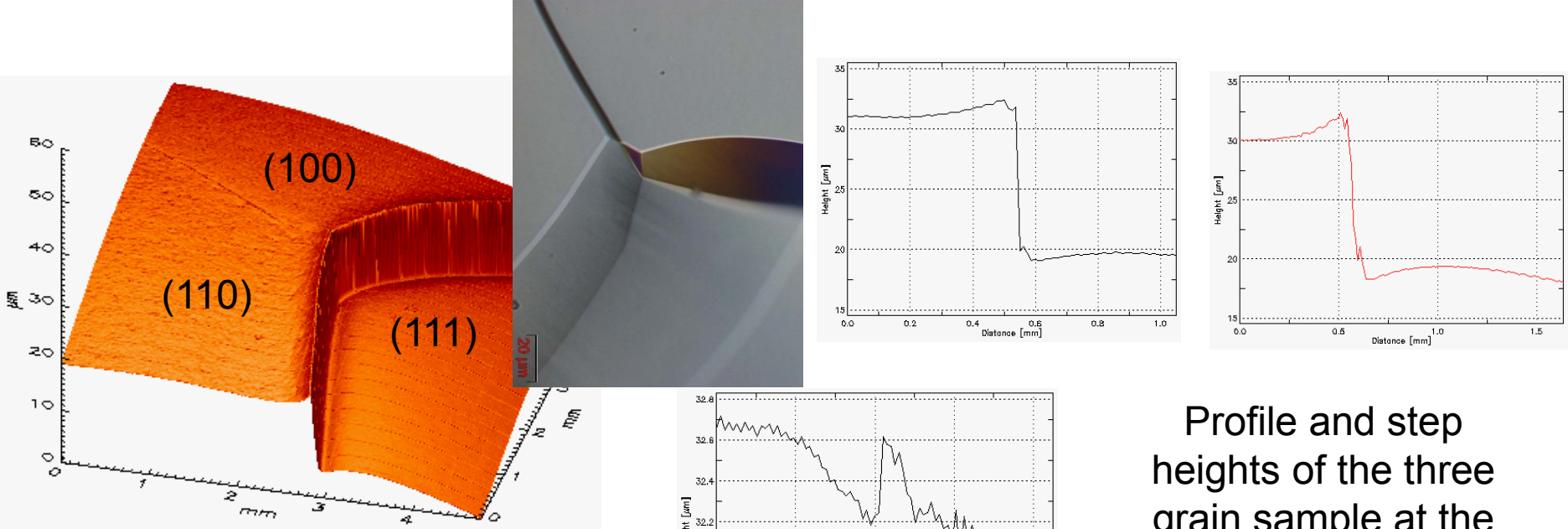
Alternative Fabrication R&D: Large grain LG cavity

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

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

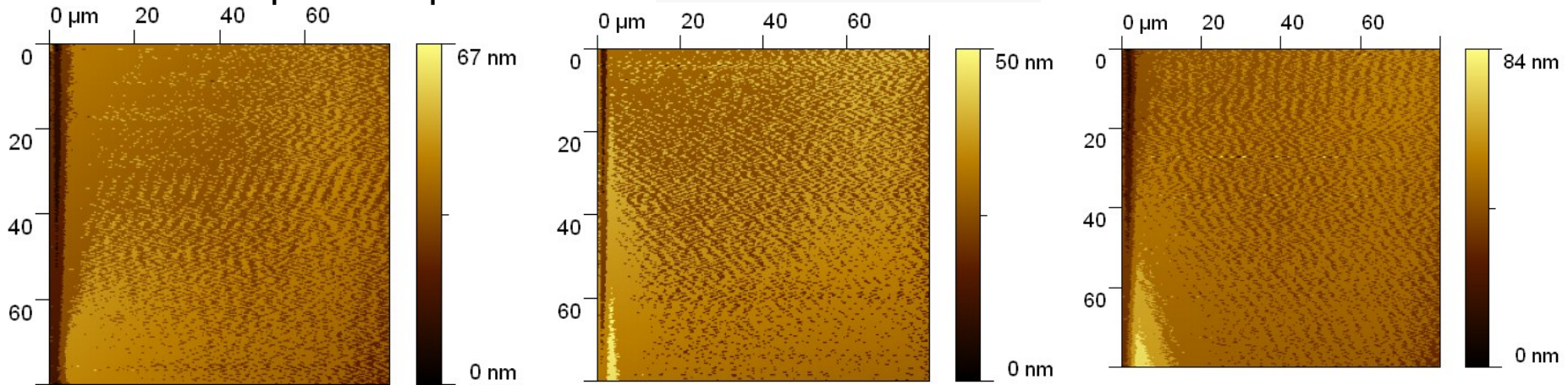


Comparison of unloaded quality factor Q_0 at 2K for 11 EP treated LG cavities with Q_0 at 2K of XFEL prototype cavities



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

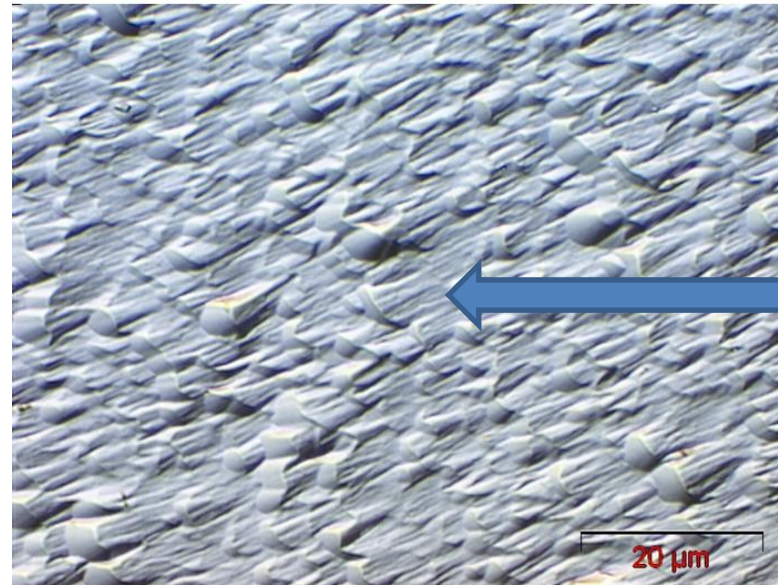
Single Crystal Option

Better not to have the grain boundaries at all

Fabrication of TESLA shape single crystal cavities at DESY.

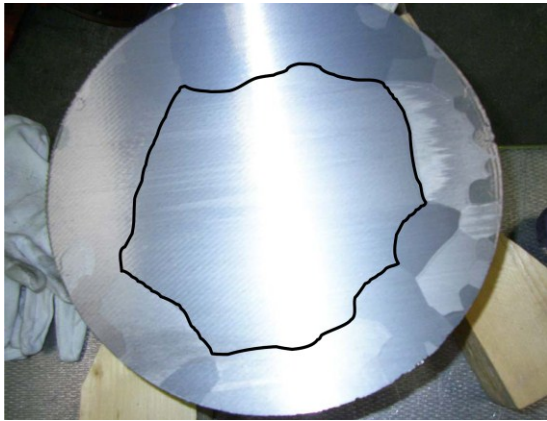
- Definite enlargement of the discs diameter is possible without destroying the single crystal structure in an existing state.
- Appropriate heat treatment will not destroy the deformed single crystal
- The single crystals keep the crystallographic structure and the orientations after deep drawing and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

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

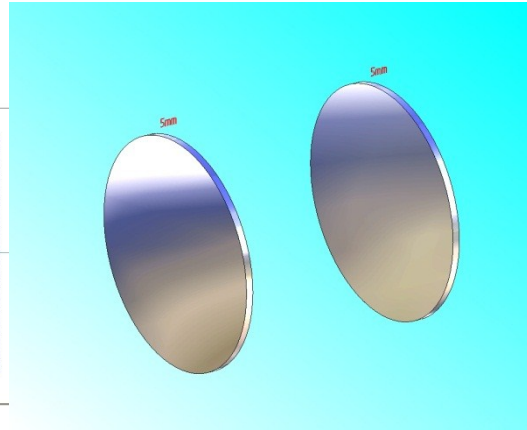


EB
welding
area

Single crystal cavity fabrication (DESY- JLab)



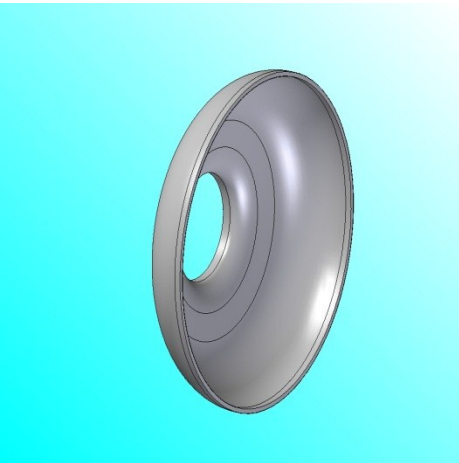
1. Take out central single crystal of definite thickness



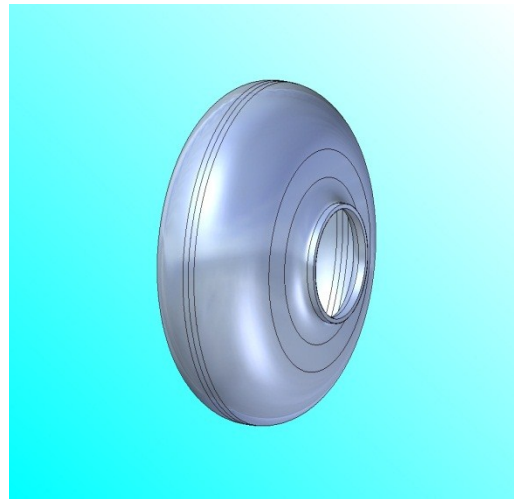
2. Cutting through the disc



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



4. Deep drawing



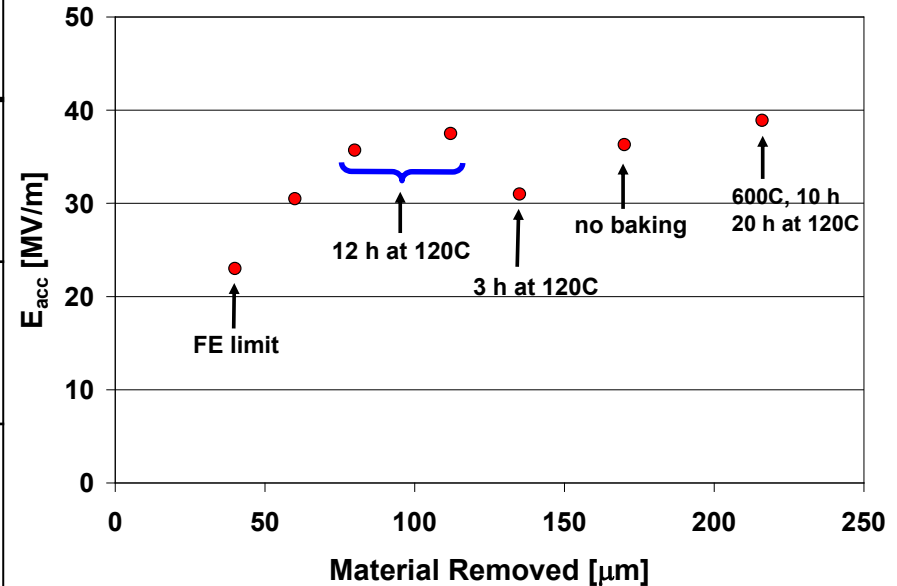
5. EB welding by matching the crystal orientation



Single Crystal Cavities with three different crystal orientation

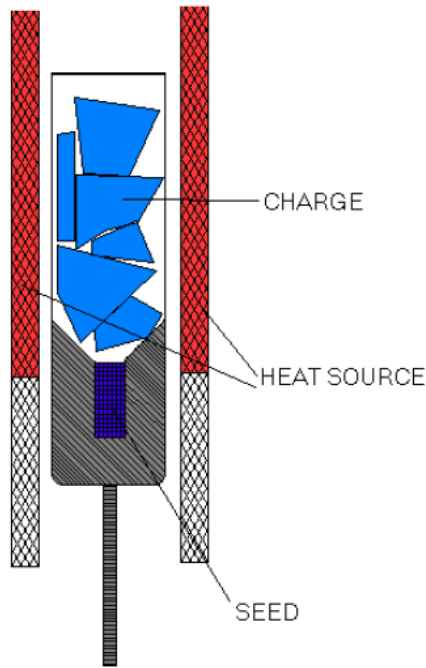
One large grain (single crystal) is a promising option that allows stably reach very high gradient by simple BCP treatment

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



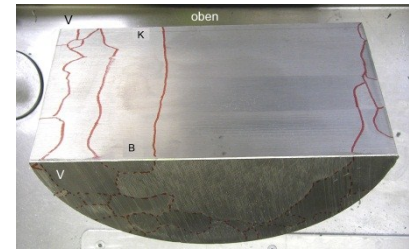
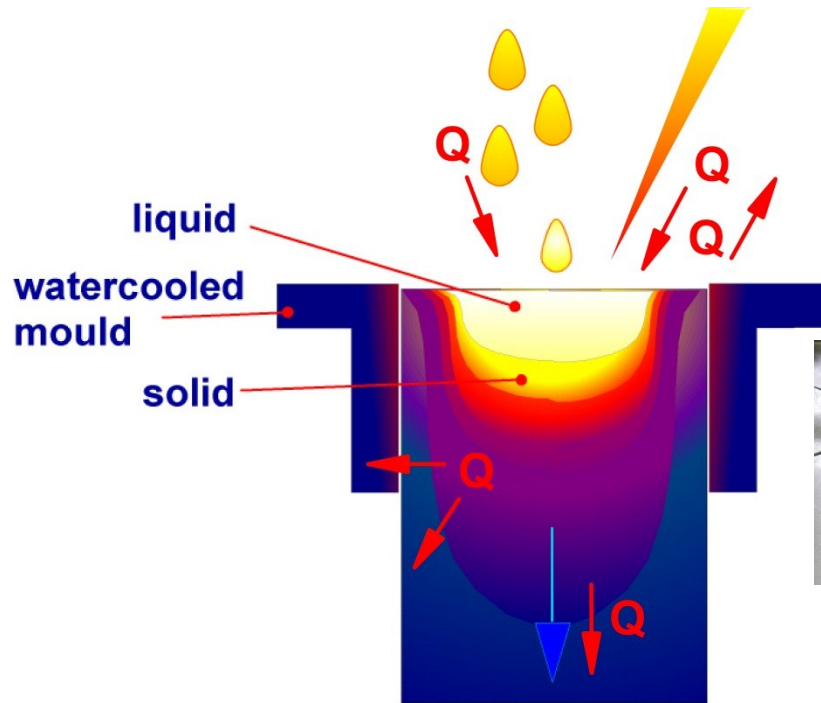
Evaluation of maximum E_{acc} with material removal: best performance after $\sim 216 \mu$ m removal by BCP

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

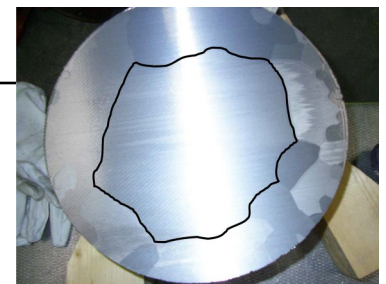


Vertical Bridgman procedure for single crystal grow

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



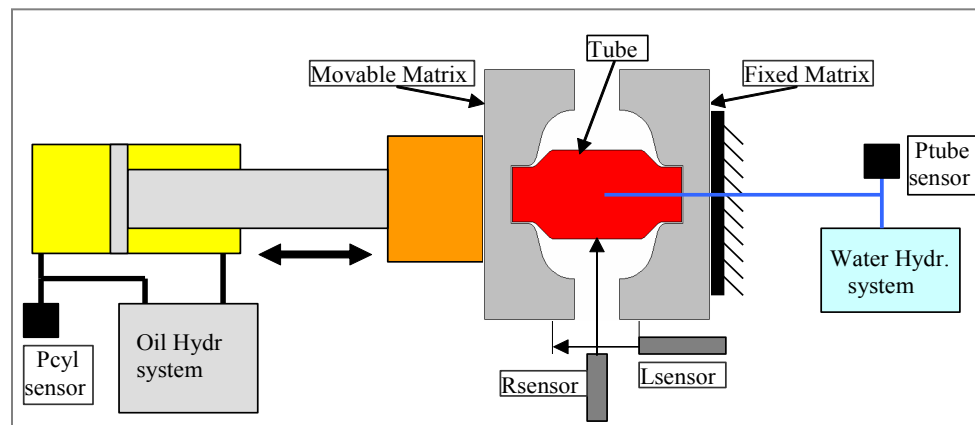
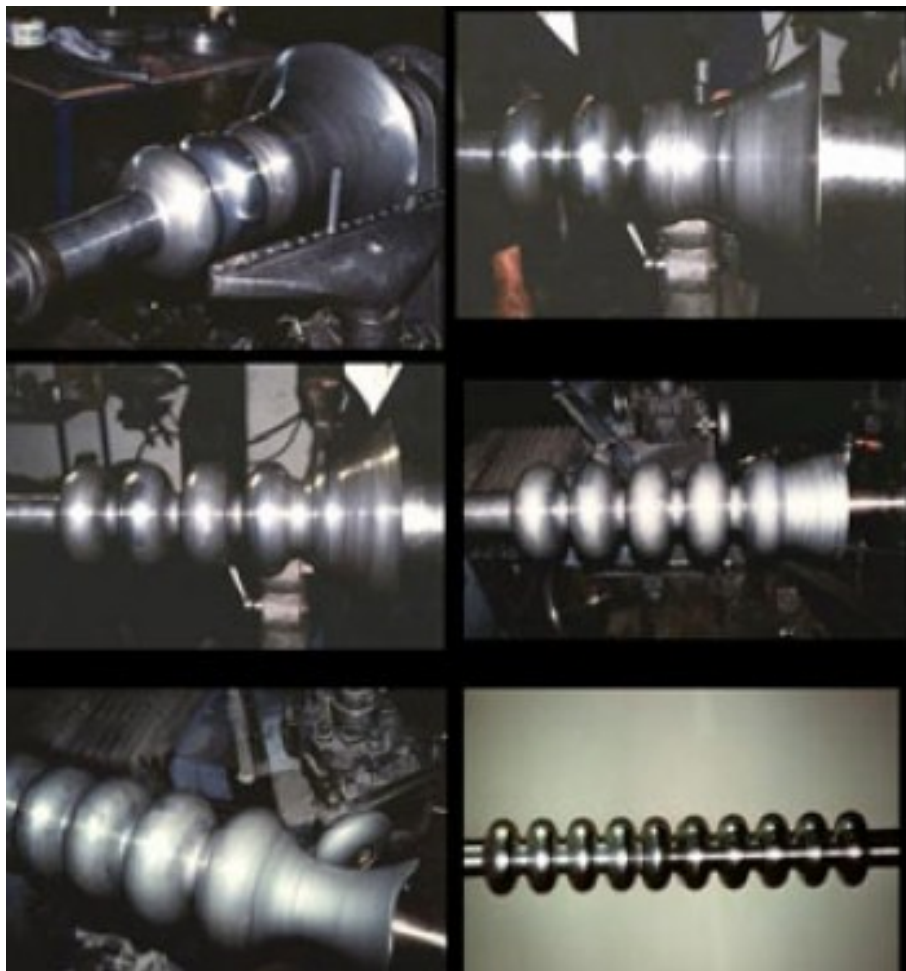
Electron beam melting principle

Challenge for the industry

Fabrication R&D: Seamless fabrication

Hydroforming, DESY, KEK, MSU

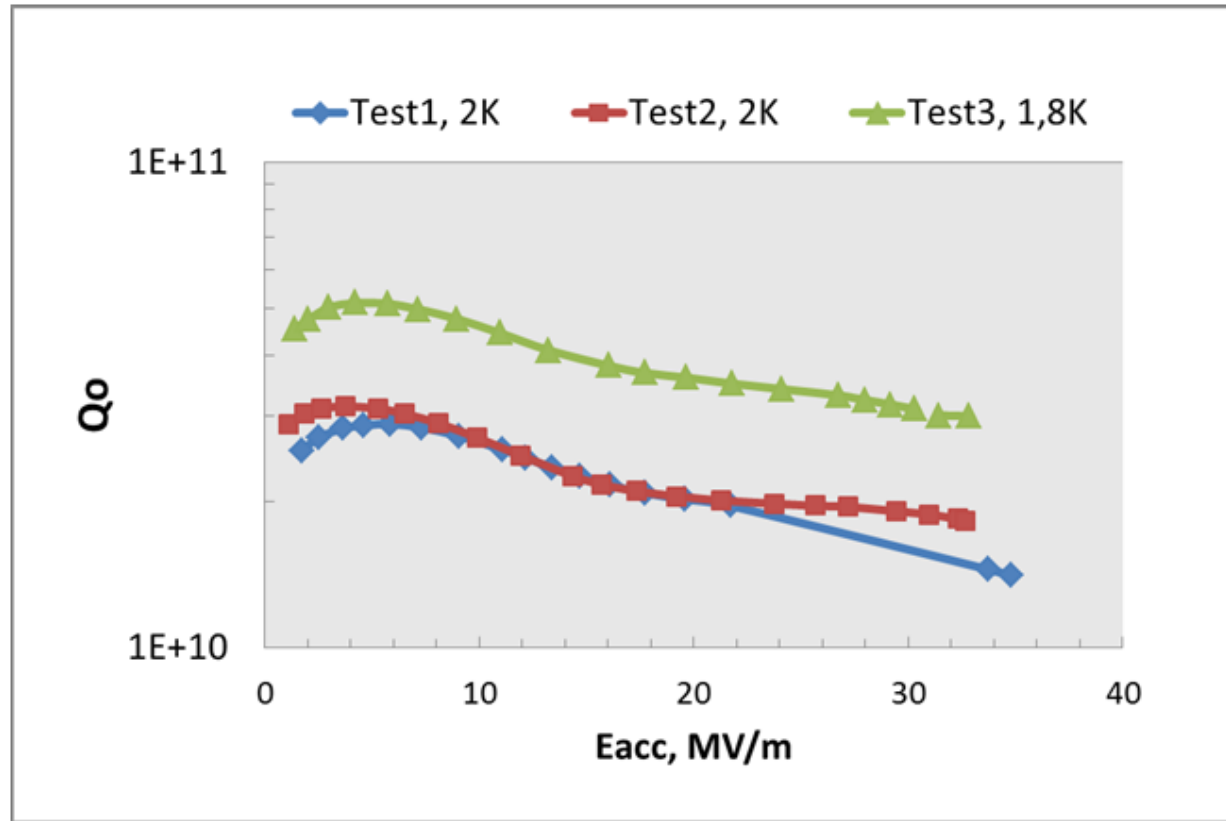
Spinning (V.Palmieri, INFN Legnaro)



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 9-cell cavity of TESLA shape fulfilled the ILC requirement

After 50 μm BCP, HT 800 C, 144 μm EP, 800 $^{\circ}\text{C}$; 48 μm EP, baking at 130 $^{\circ}\text{C}$ 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

Acknowledgement

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

C. Antoine, SACLAY
S. Calatroni, CERN
R. Edinger, PAVAC
R. Graham, Wah Chang
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X. Singer, DESY
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Recommended Literature

1. H. Padamsee, J. Knobloch, T. Hays. RF Superconductivity for Accelerators. Wiley – WCH Verlag, 2008, 521 p.
2. Niobium. Proceedings of the International Symposium, November 8-11, 1981, San Francisco, USA,
3. Burt, R.O. (1999) Research, Innovation and Reality — the Second Richard Moziey Memorial Lecture. Proc. 31st Annual Meeting of the Canadian Mineral Processors. Ottawa CIM ppl 36-148.
4. S.V. Vonsovsky, Yu.A. Izymov, E.Z. Kurmaev. Superconductivity of Transition Metals. Springer-Verlag, 1982, 562 p.
5. J. Schlewitz. Niobium and Niobium Compounds. Reprint. Wah Chang. 1996, 67 p.
6. W. Singer. SC Cavities; Material, Fabrication and QA (Tutorial), Proceedings of the 13th International Workshop on RF Superconductivity, Peking University, Beijing, China 2007.
7. W. Singer. Seamless RF Cavities. Proceedings of the 13th International Workshop on RF Superconductivity, Peking University, Beijing, China 2007.

8. Schulze, K. K. Preparation and Characterization of Ultra-High Purity Niobium. *Journal of metals*, May, 1981, pp 33–4.
9. Umformtechnik. In 4 Bands. Springer-Verlag, 1993, 815 p.
10. Proceedings of International Symposium on Tantalum and Niobium. October 22-25, 2000, San Francisco, USA, 374 p.
11. G. F.J. Humphreys. M. Hatherly. Recrystallization and Related Annealing Phenomena. Elsevier, 2004, 628 p.
12. H. Padamsee. RF Superconductivity. Science, Technology and Application. Wiley – WCH, 2009, 448 p.
13. W. Singer. SC Cavities; Material, Fabrication and QA (Tutorial), Proceedings of the 14th International Workshop on RF Superconductivity, September 20-25, 2009, Berlin-Dresden, Germany
14. C. Antoine. Material and surface aspects in SRF technology (Tutorial). Proceedings of the 15th International Workshop on RF Superconductivity, 21-23 July 2011, Chicago, USA