DESY Experiences in Hydroforming of Elliptical RF Cavities

W. Singer

- Introduction
- Hydroforming technique (necking, expansion)
- Nb tubes for hydroforming
- Examples of RF performance

Introduction

Advantages of seamless cavity fabrication

• no RRR degradation in the welding seam, in the heat affected zone HAZ and in the weld overlapping

• no risk of equator weld contamination due to not sufficiently clean preparation for welding

• no problem with pits in the HAZ, that are intensively in discussion last time

• lower cost of fabrication can be expected, especially for large series.

• less scattering in performance statistic of seamless cavity compare to welded cavities is to expect .

Hydroforming technique

Hydroforming consists of two steps:

a) reduction of diameters at ends of tubes and iris areas (necking)

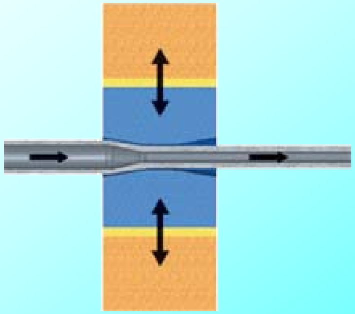
b) tube expansion at the equator

Step 1: necking

Several necking methods were check out before the current necking procedure was established

- spinning
- necking by profile ring
- hydraulic necking
- electromagnetic strike necking,
- verjungen (diameter reduction by push the tube end through the set of rings of smaller diameter)
- rotary swaging (rundkneten)

Principle of rotary swaging



Step 1: necking

- necking by spinning

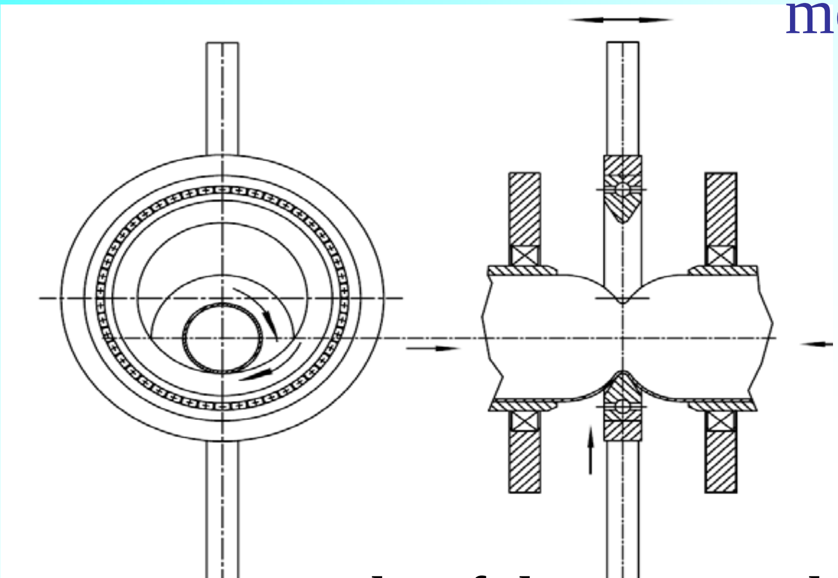
Not uniform necking at the iris area of tube end done at company HTI by spinning (hole appeared during centrifugal barrel polishing).

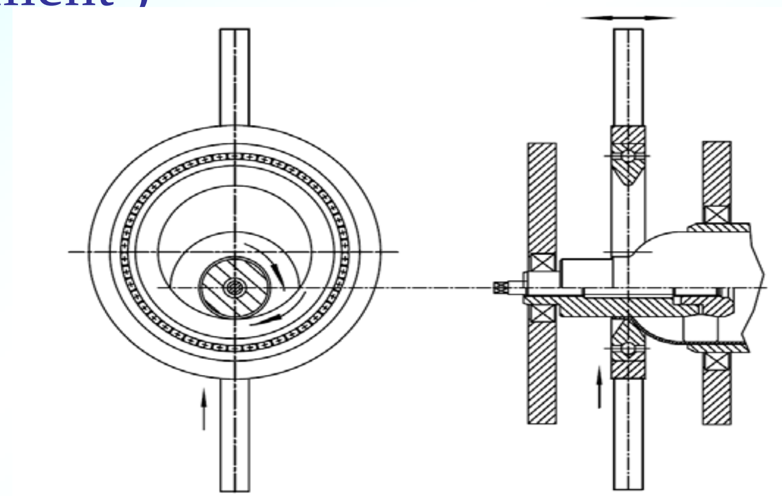
KEK necking machine
(successful on Cu-tubes)

In principle it works

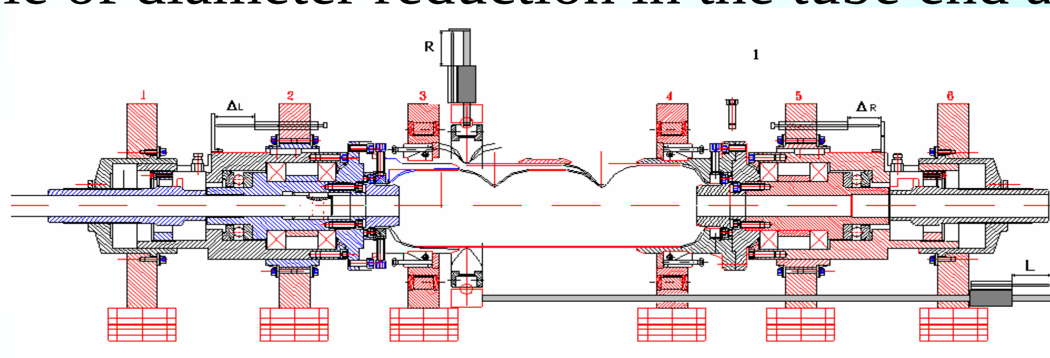
Step 1: necking (by profile ring)

Improvement of the necking procedure and development of DESY necking equipment provided the success (combination of radial and axial movement)





Principle of diameter reduction in the tube end and iris area

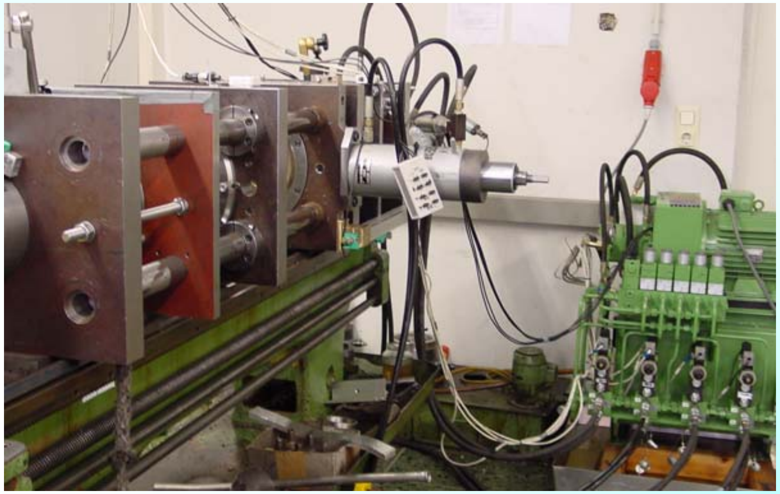


Principle of DESY necking equipment

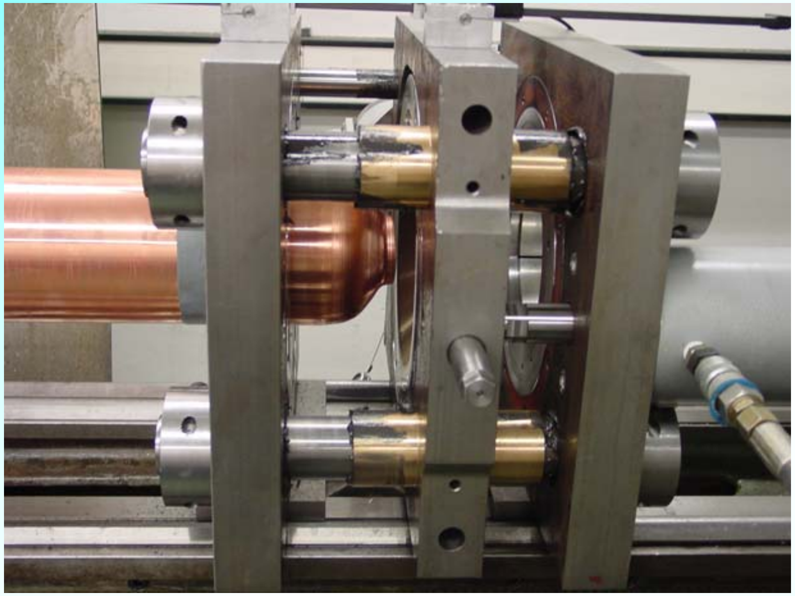
Step 1: necking (by profile ring)

Seamless technique by hydroforming: step 1- necking

DESY developed necking equipment (by profile ring)



DESY Necking machine: new PC controlled necking procedure



Reduction mechanism.

Tubes after reduction in the iris areas

Conclusion to necking:

• spinning: works (essential wall thickness reduction close to iris, probably this can be improved by parameter optimization)

• necking by profile ring: works (best results)

• hydraulic necking: does not work (not round shape)

• electromagnetic strike necking: works for Cu, can work on Nb only for bimetallic NbCu tubes (resistance of Nb is to high), the shape is not sufficiently under control due to single strike

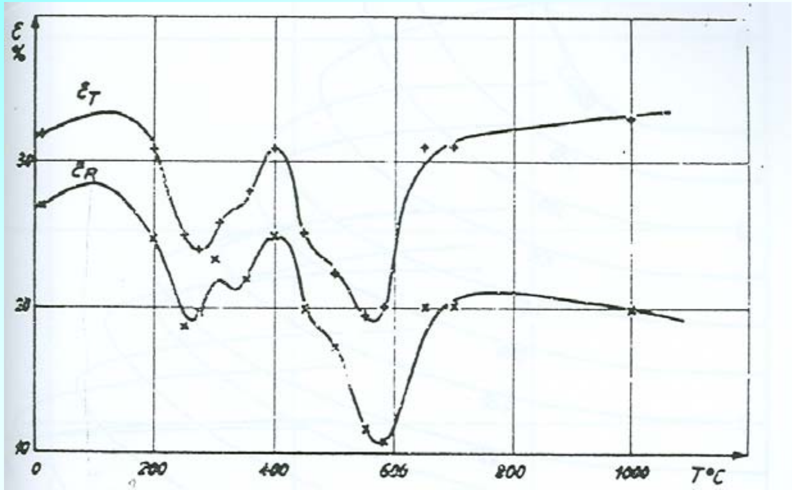
• verjungen: works only for single cells (time consuming due to many rings, not optimal shape of the necking)

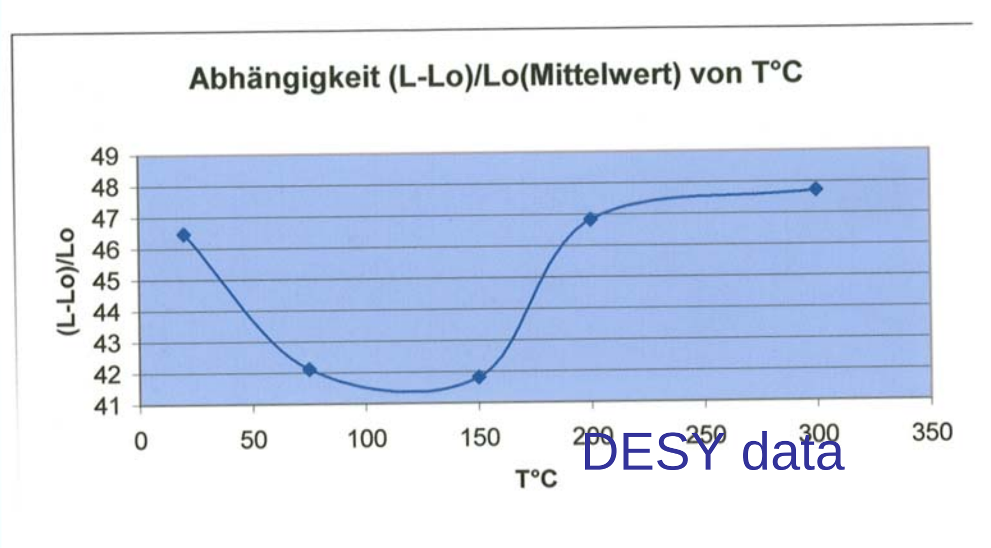
• rotary swaging (rundkneten): works (damaging of the surface, significant work hardening)

Step 2: Expansion (Hydroforming)

First question. Hydroforming conditions ,parameters?

Is the room temperature appropriate for hydroforming? Yes

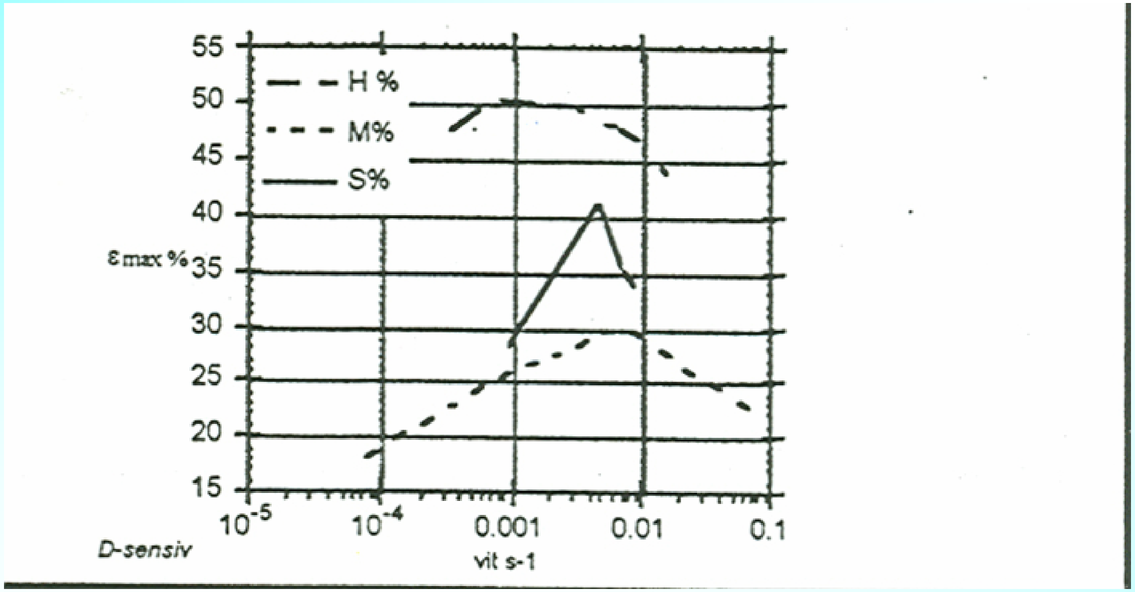




Dependence of the elongation on temperature. It make sense to perform hydroforming of niobium at room temperatures

How fast to perform the deformation (hydroforming)?

Strain rate $\dot{\varepsilon} = \frac{\partial \varepsilon}{\partial t}, \mathrm{sec}^{-1}$



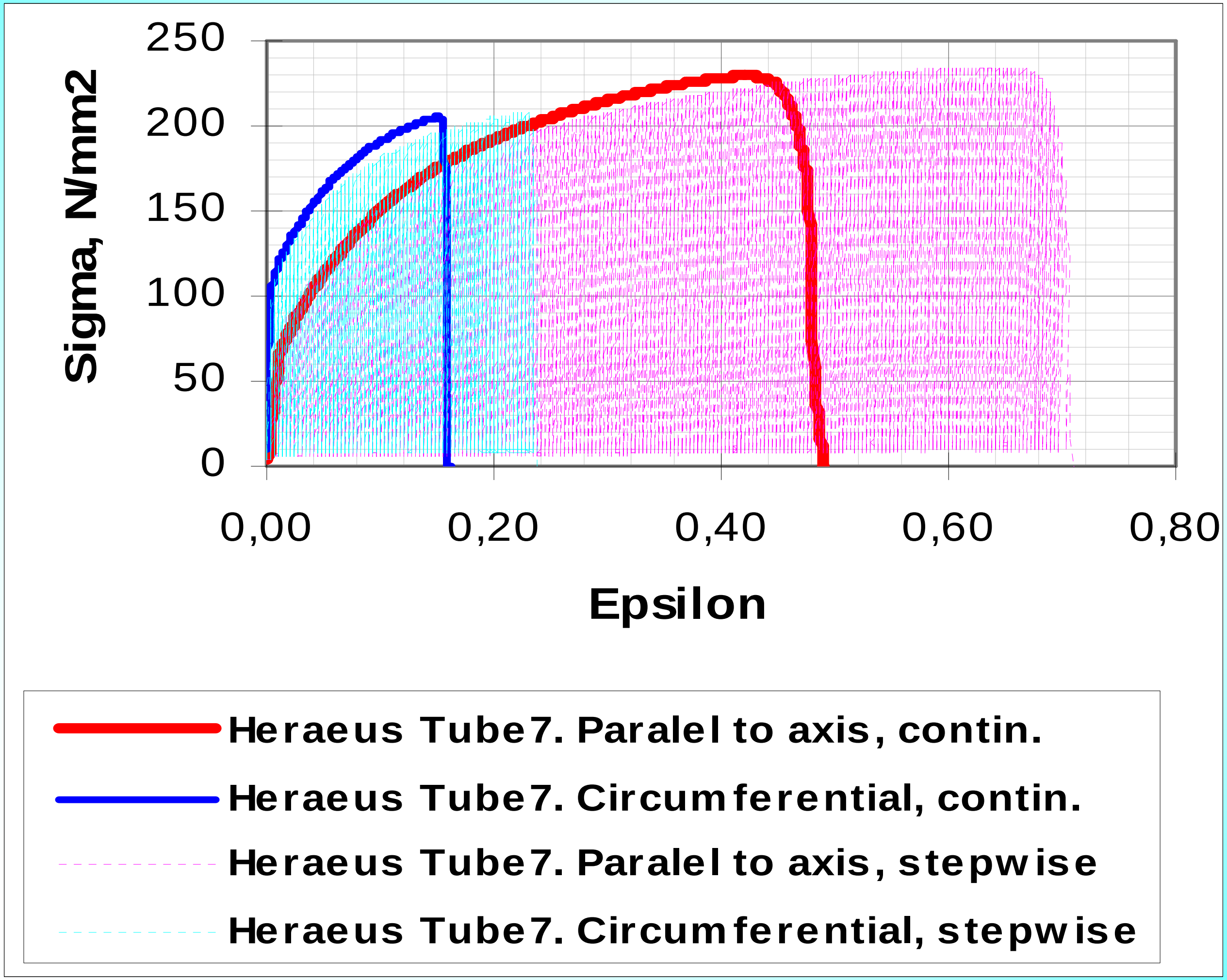
Dependence of maximum elongation of niobium versus strain rate (H, M, S different literature data).

Correct strain rate should be chosen for hydroforming

Chosen strain rate is between 0.01 sec-1 and 0.001 sec-1

Compilations of C. Antoine

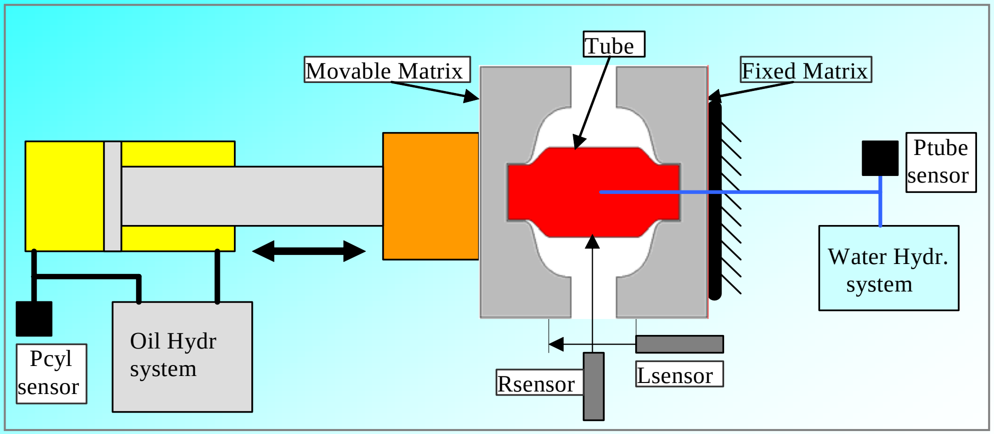
Pulsing of the pressure during hydroforming helps



Comparison of the tensile test in continues and pulse regime

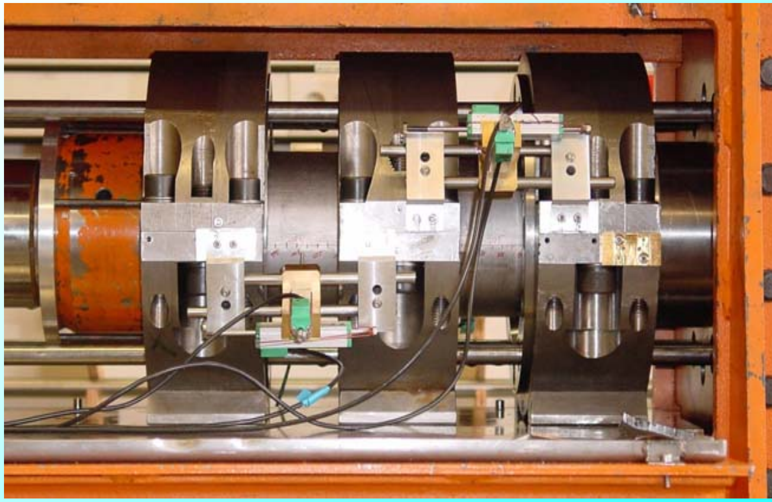
The strain before necking can be increased by using a periodic stress fluctuation (pulse regime). Probably the pull-release regime of the deformation artificially increases the work-hardening of Nb in low-yield strength regions and therefore shift the break to higher elongations.

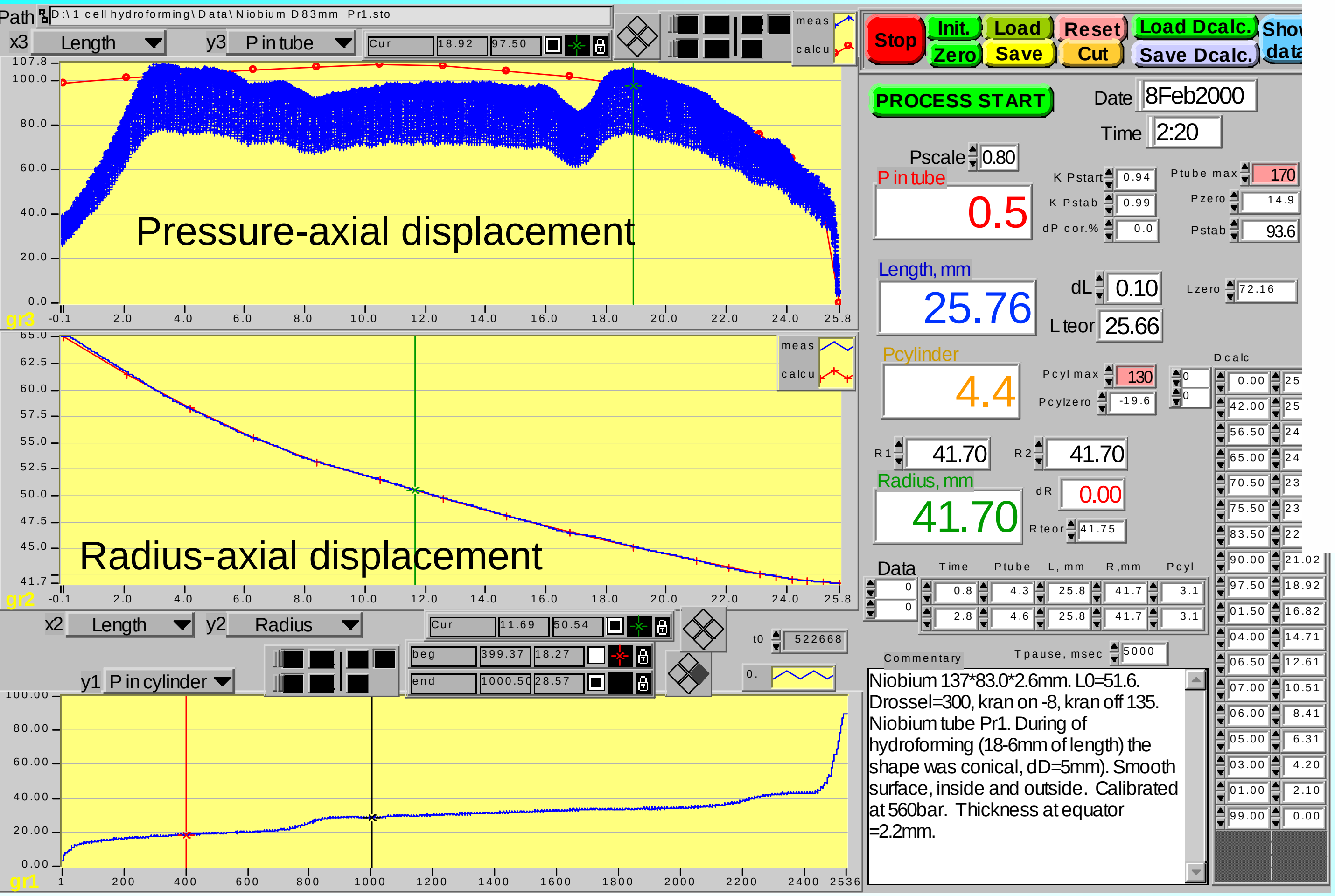
Principle of hydroforming

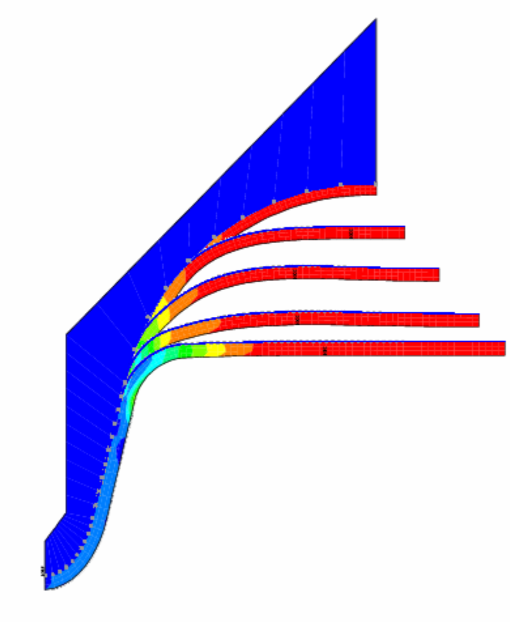


DESY hydroforming machine

- Designed and build in Russia (INR, Troitsk)
- Equipped with hydraulic systems and software at DESY
- From dimension is in position to produce only units of 3 cells







FEM Simulation of the hydroforming

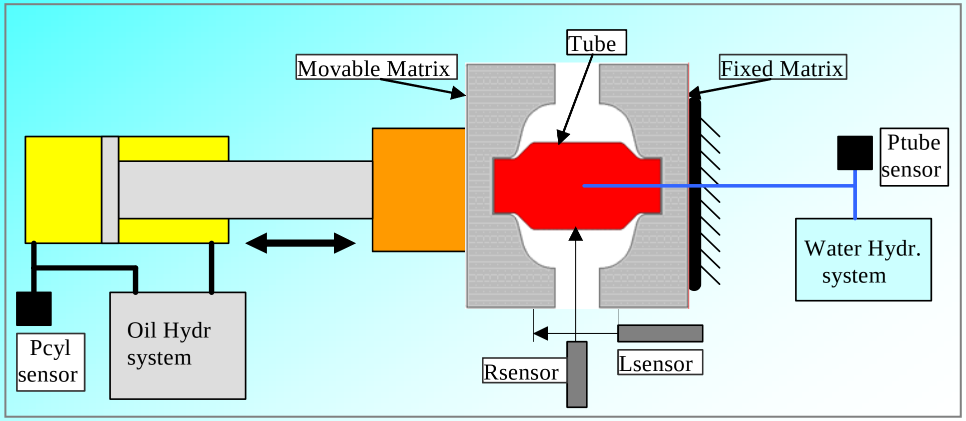
Front panel of the software for hydroforming - machine

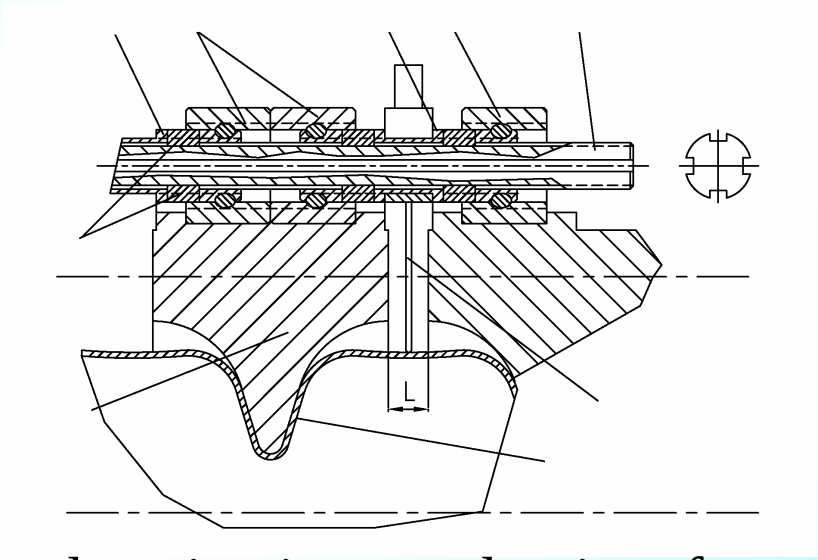
PC control allows reproducibly repeat the forming parameters

All steps of hydroforming optimized and checked on the Cu dummies

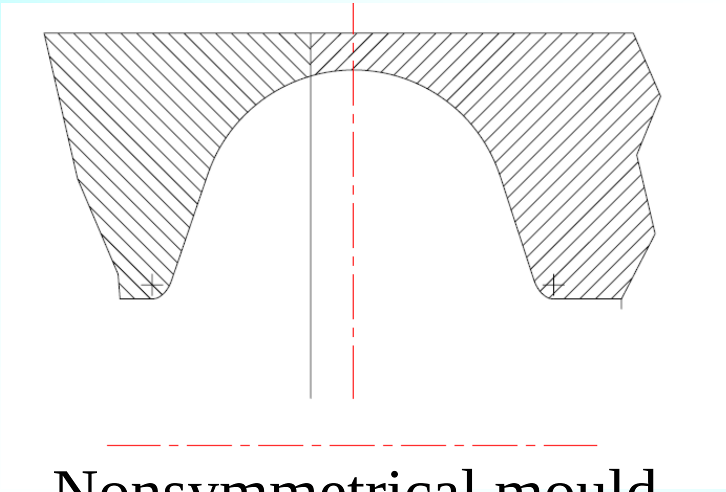
Hydroforming of cells can be done or as three cells simultaneously or cell by cell (hydroforming of the 9-cells from one tube piece can be done on the same way)

Some ideas contributed to hydroforming success





Synchronization mechanism for multi cell fabrication by hydroforming

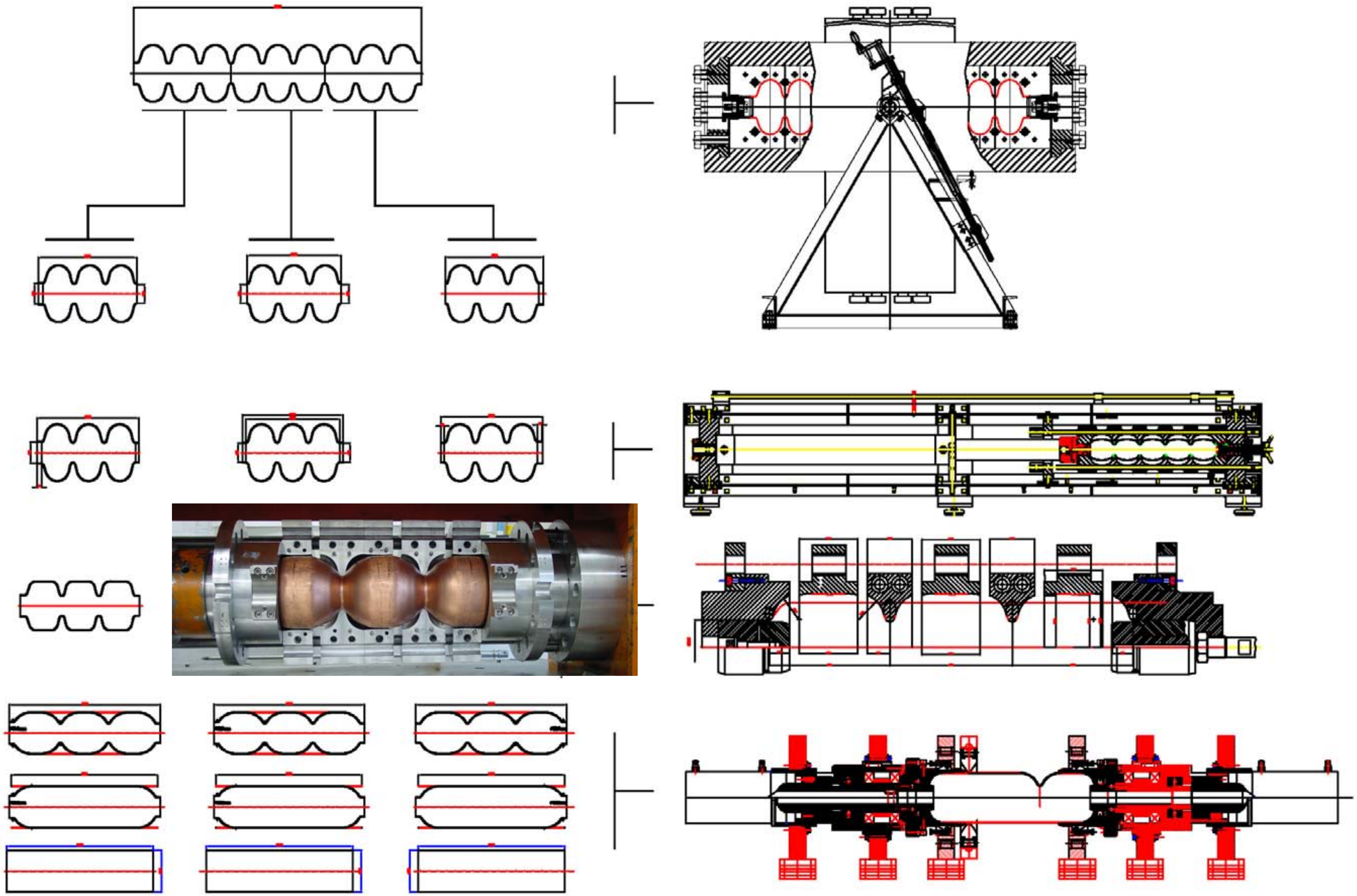


Nonsymmetrical mould for hydroforming

Developed ideas summarized in the patent.

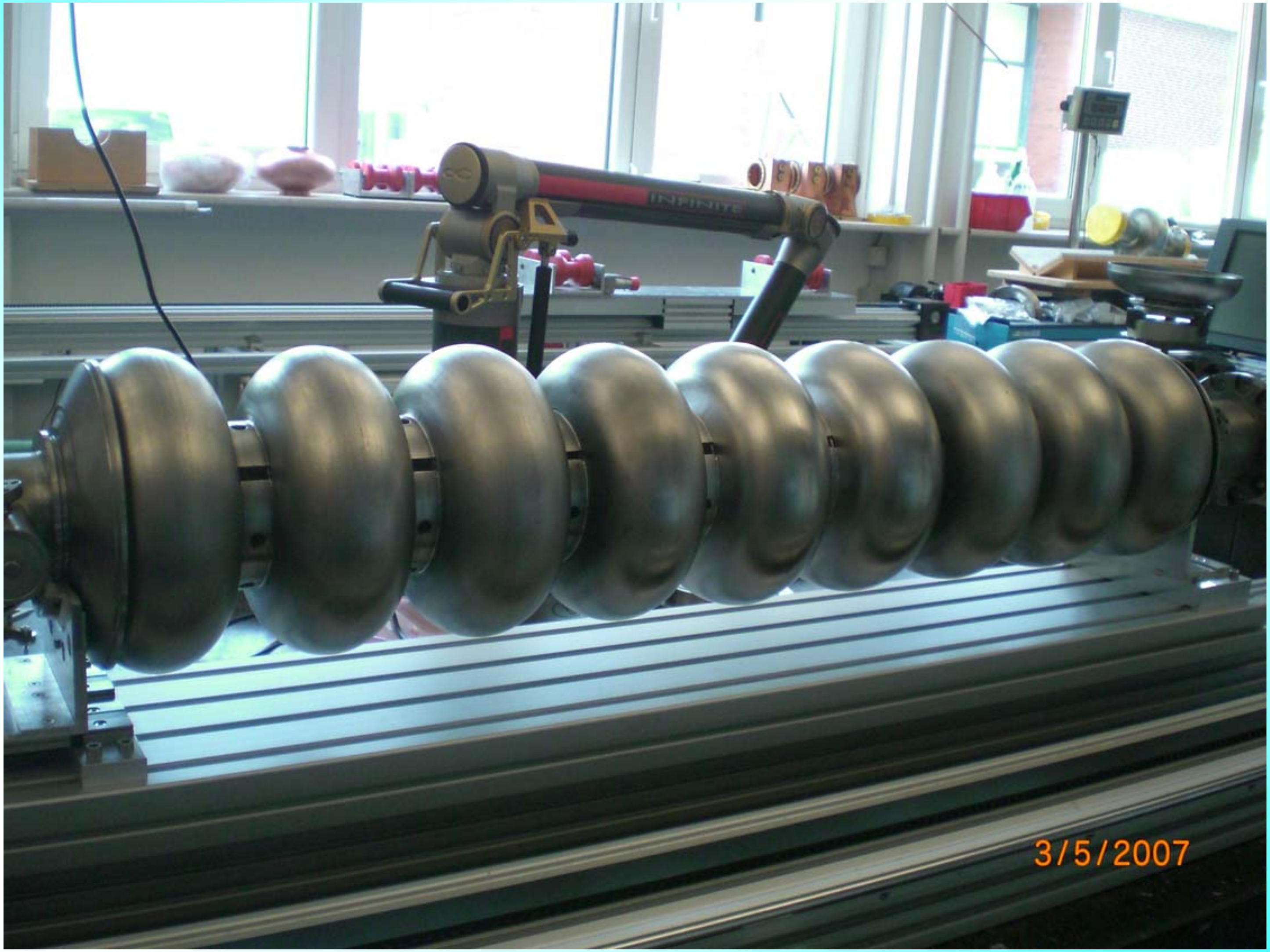
W.Singer, I.Jelezov; No. 10 2007 037 835 ; 18 September 2008

Fabrication steps of 9 cell cavity by hydroforming as option 3x3



Z145: 9-cell as 3x3 cell cavity hydroformed at DESY, completed at E.ZANON (reached ca. 30 MV/m).

Two new 9-cell cavities are currently in completing at E.ZANON



Conclusion to hydroformimng

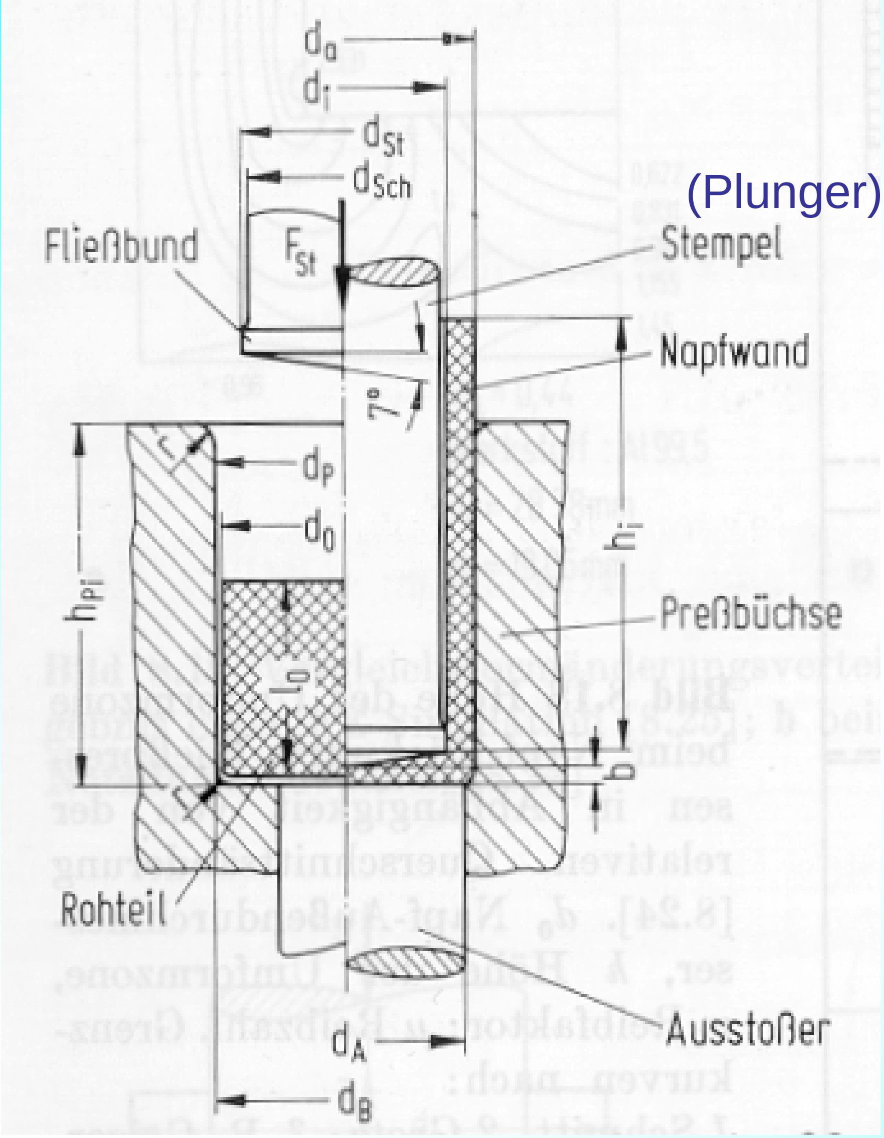
- Hydroformig of 9-cell cavity from one tube-piece is feasible
- Dimensions of a new machine have to be foreseen for that.
- DESY machine is a laboratory equipment. For industrial equipment more moulds (intermediate constraints), less sensors for parameter measurements has to be foreseen
- Experiences of INR (Russia) designers would be reasonable to use
- Computer simulations are helpful on the starting stage
- PC controlled hydraulic allows to optimize and reproduce the forming parameters

Bulk Nb tube fabrication.

Several techniques of the tube fabrication have been taken into consideration at DESY

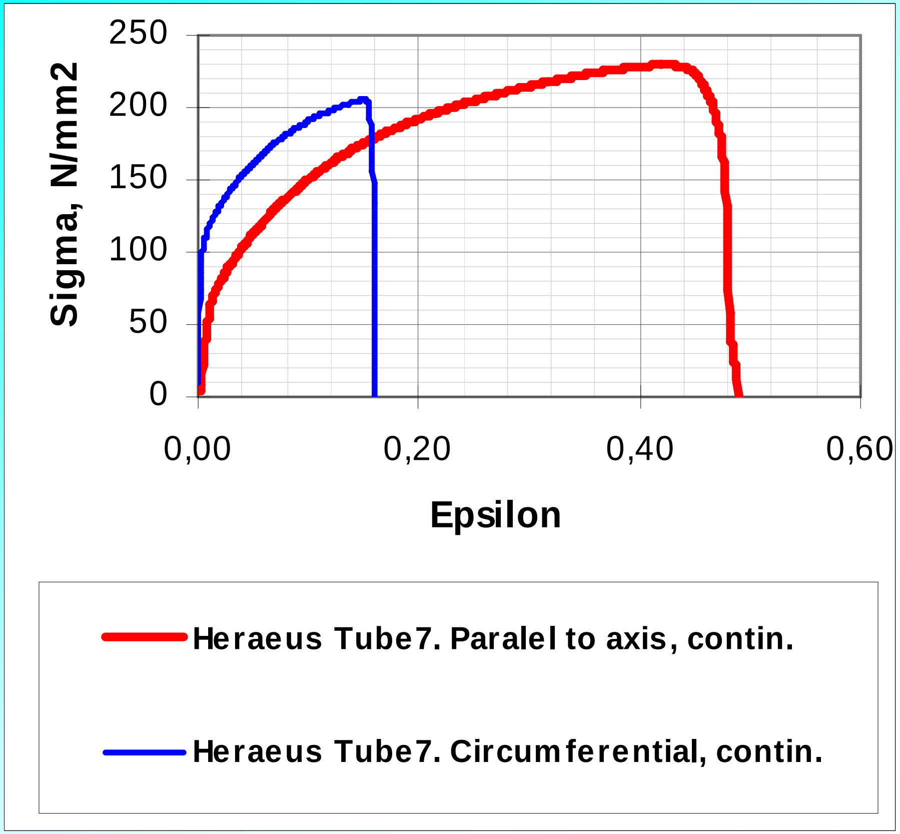
- Tube production by back extrusion from the ingot part:
- Tube production by spinning
- Tube production by deep drawing
- Tube processing by flow forming
- Welded Nb tubes.
- Seamless Nb tubes produced on powder metallurgical way

• Seamless tubes: back extrusion (W.C. Heraeus)

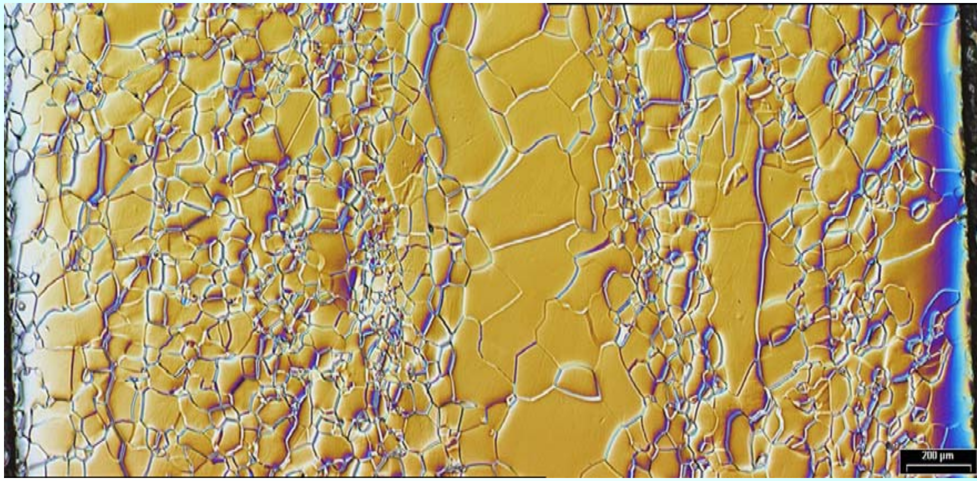


Principle of seamless tube fabrication by back extrusion

Different tubes with covers from Nb1% Zr produced by back extrusion at the company W.C. HERAEUS (Germany)



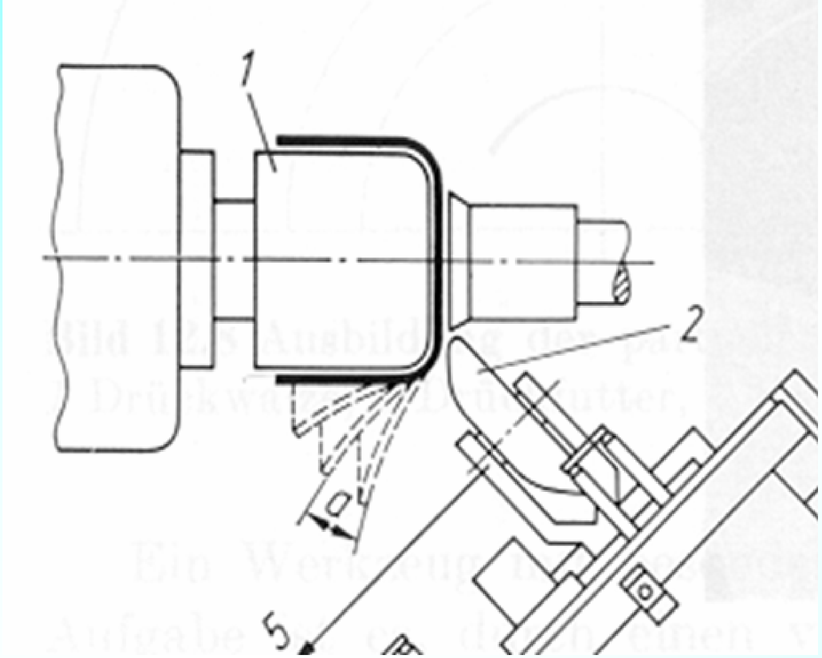
Strain - stress curve of of back extruded Nb tube (drawback: anisotropic properties)



Microstructure of back extruded Nb tube produced from a pill taken from ingot

Only small cavities (ca. 3,9 GHz) have been successfully hydroformed from back extruded tubes

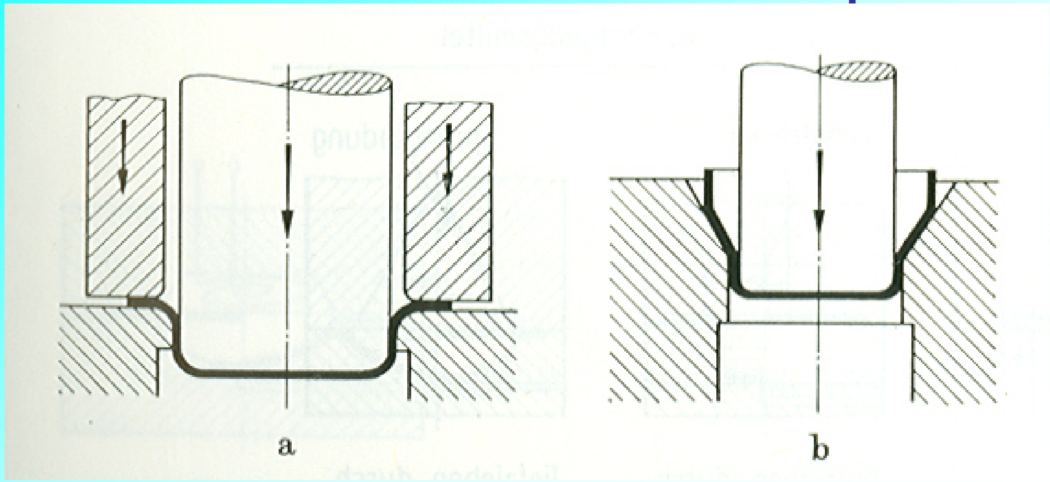
- Spinning



Cavities hydroformed from spun tubes (reached up to 42 MV/m)

Fabrication of the seamless pot from Nb plate by spinning is possible without intermediate annealing

• Deep drawing



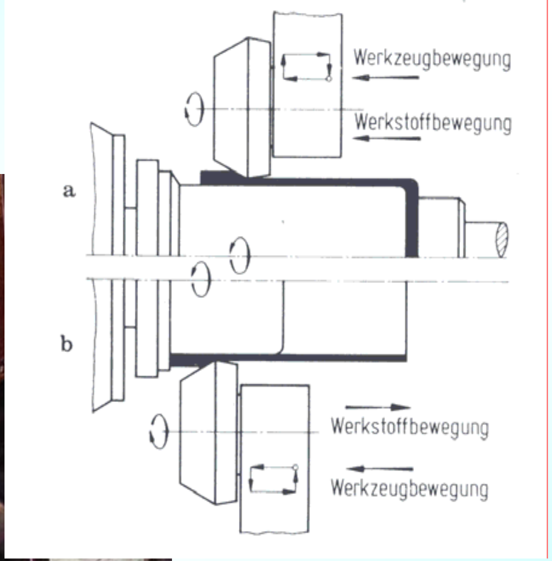
Principle of deep drawing; a-first step, b-second and further steps

Successful tube fabrication by collaboration of Fa. Bravo and INFN Legnaro

Single cell cavity fabricated at Fa. Butting (Germany) in collaboration with DESY from deep drawn tube produced at the company B.J. Enterprise (USA) (reached 39 MV/m

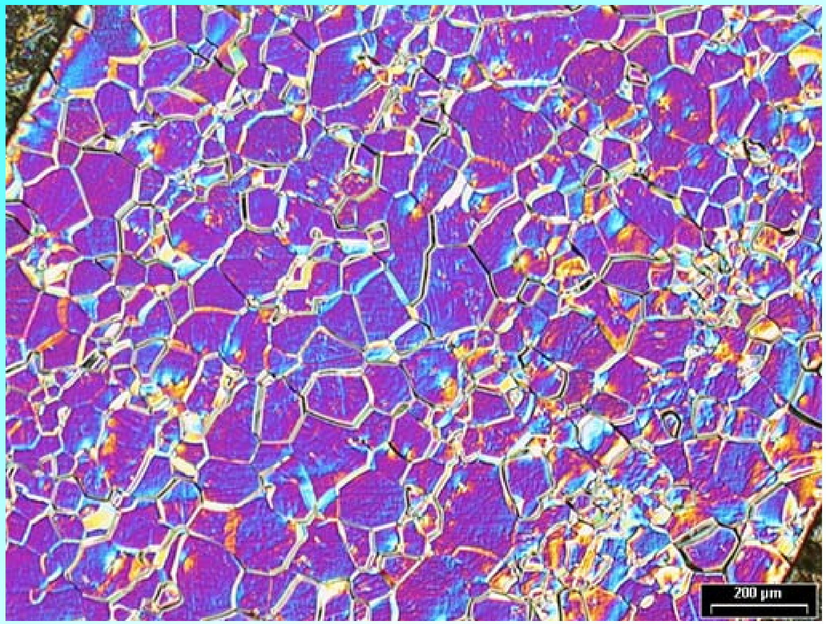
In some cases bad inside surface of tubes (cracks, removed by machining)

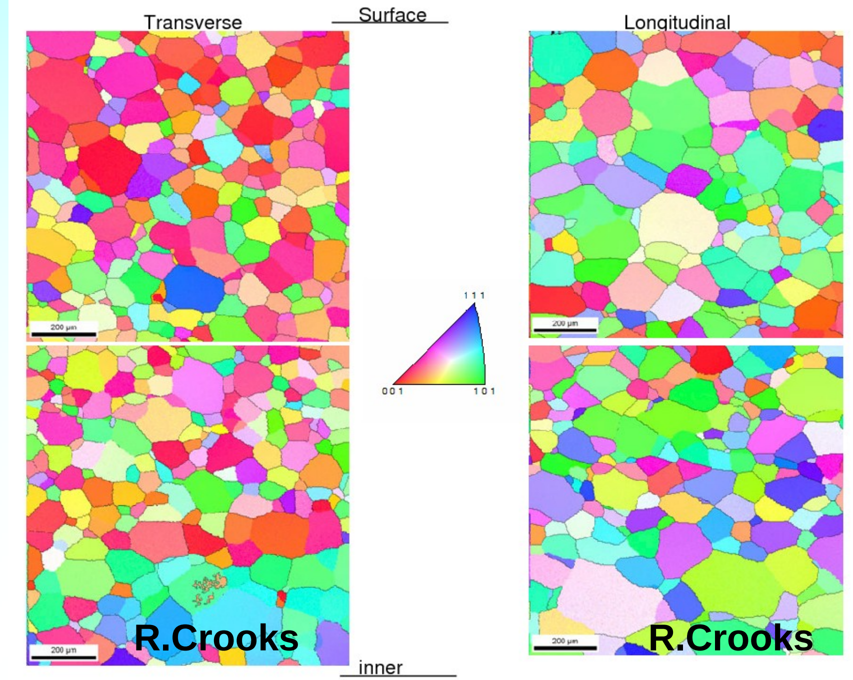
• Flow forming



Flow forming of niobium spun tubes at MSR (Germany). Precise wall thickness after flow forming. Tolerances within of +/- 0,1 mm

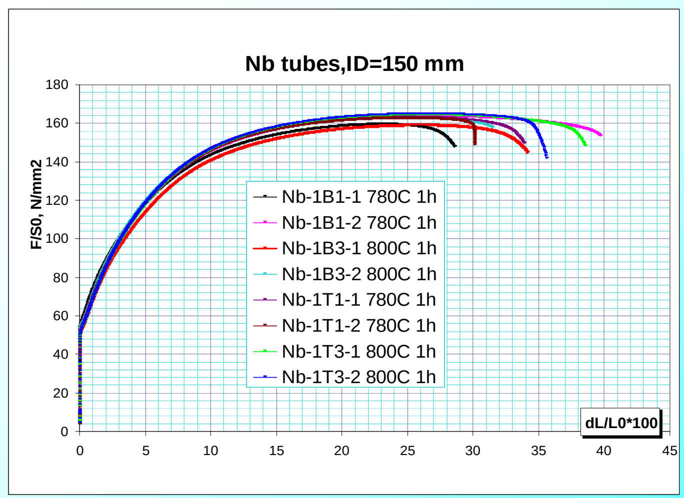
Best result was achieved by combination of spinning (or deep drawing) with flow forming: appropriate microstructure and mechanical properties



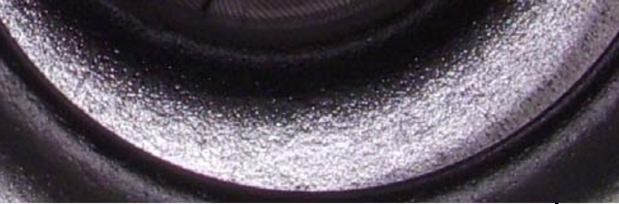


Microstructure and texture of Nb tubes produced by combination of spinning and flow forming

Stress-strain curves and microstructure of Nb tubes produced by combination of spinning and flow forming. Tensile tests done in circumferential direction



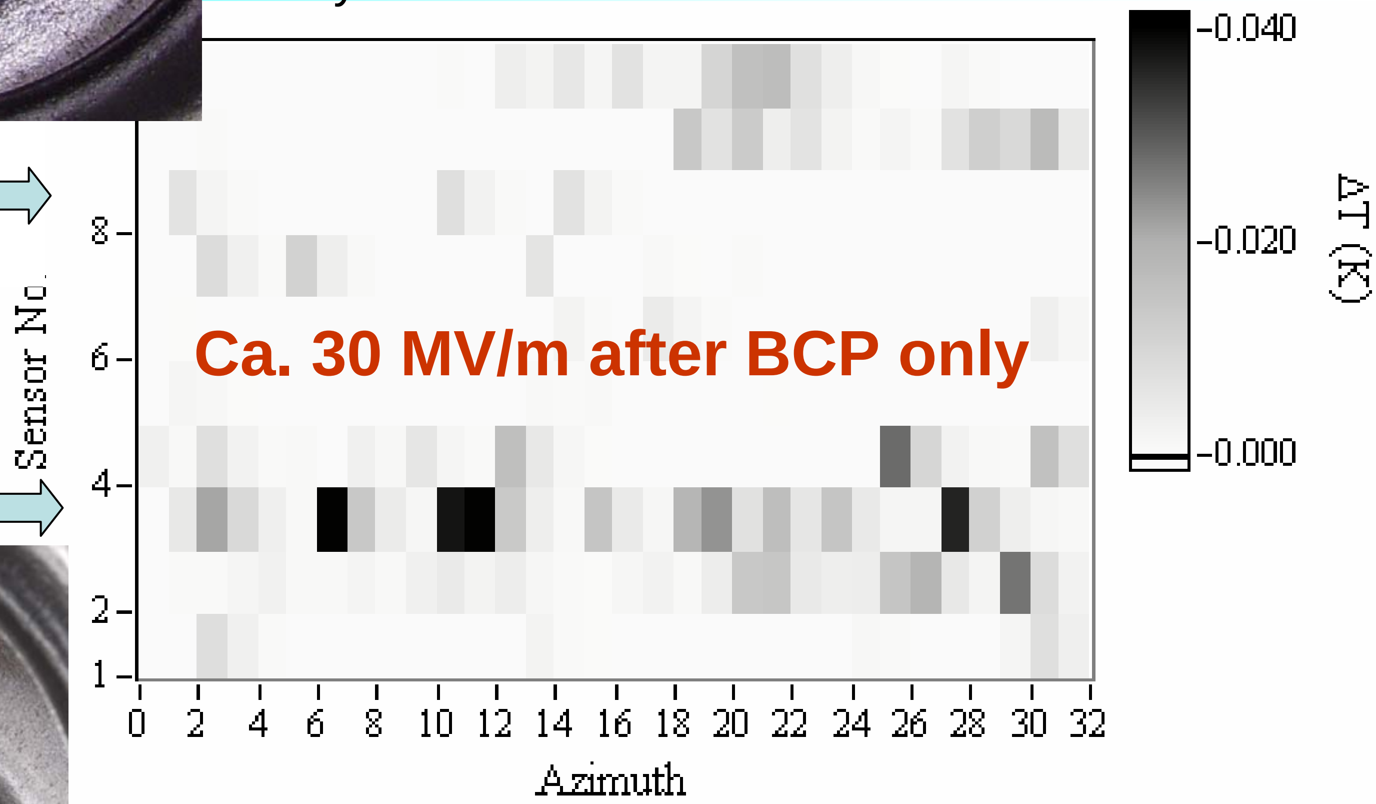
Such tubes used for fabrication of multi cell cavities



Cavity inside surface

(Tube bottom)
Bottom cell

Top cell
(tube top)



Cavity inside surface

Tube after spinning

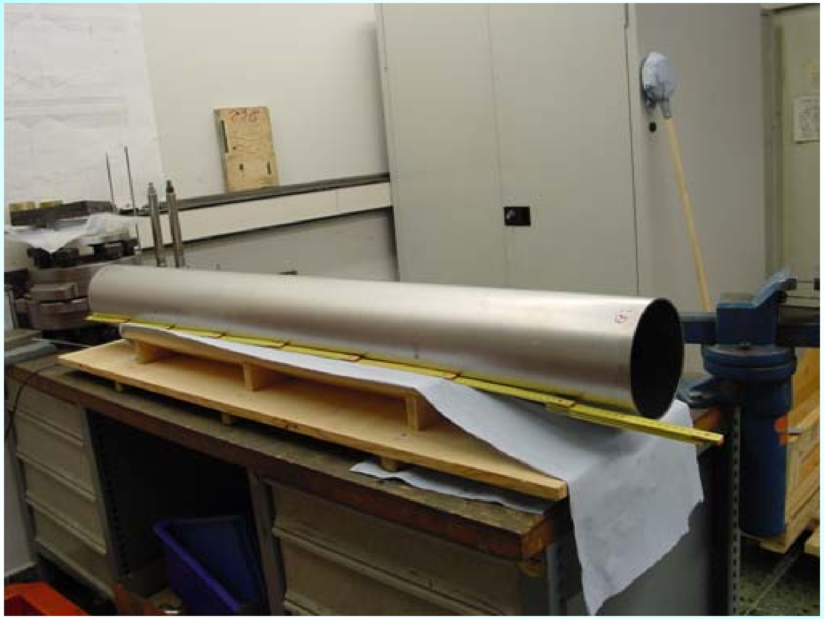
T-map on 3-cell hydroformed cavities from spun+ flow formed tubes at E_{acc} = 27 MV/m, (**JLab**) indicating several hot-spots in the equator area, mostly on the top cell (relation to the tube fabrication method).

Tubes: Roy Crooks: Black Laboratories, L.L.C., Newport News, VA

High purity Nb tube production developed and coordinated with ATI Wah Chang

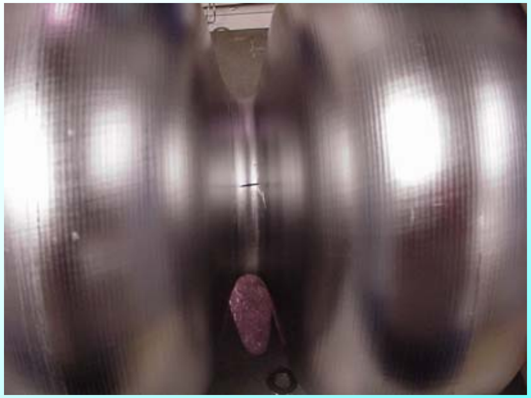
Heavily deformed billet, processed for fine grain structure

Shaped by forward extrusion and flow-forming (more in presentation of Roy Crooks)



Black Lab. Tubes.

1,3 GHz cells hydroformed at DESY from Black Lab tubes

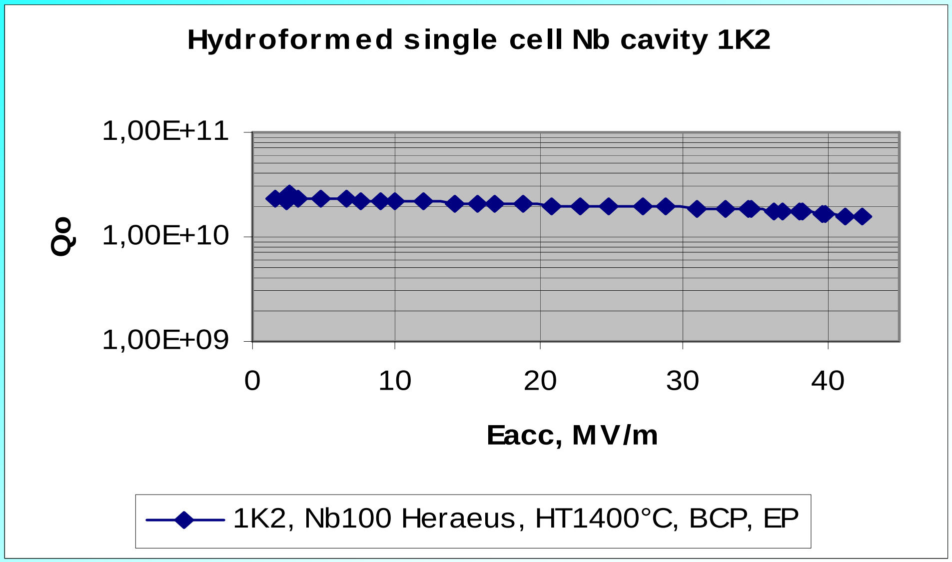


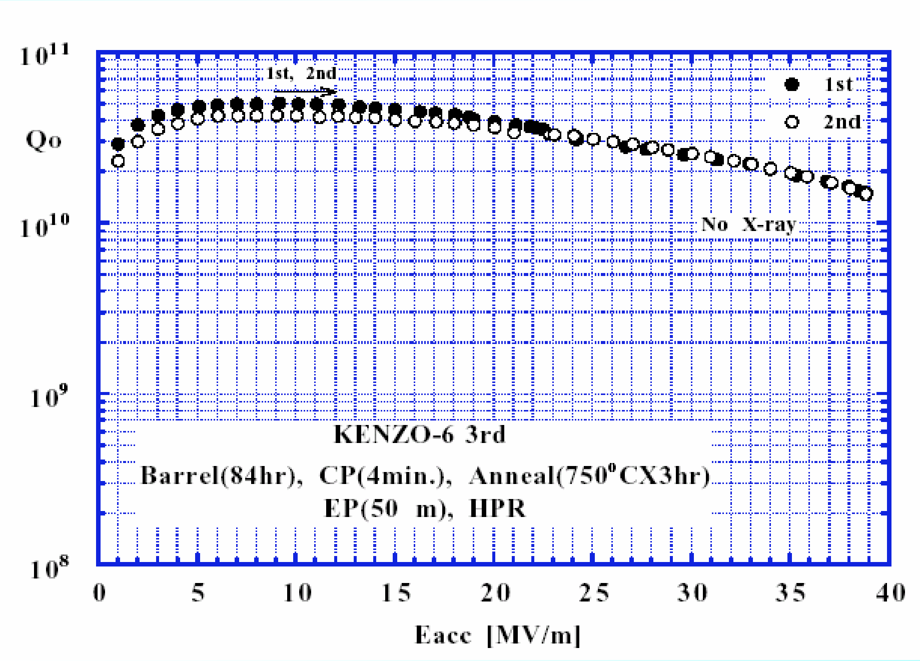
Cracks in few cells at the iris

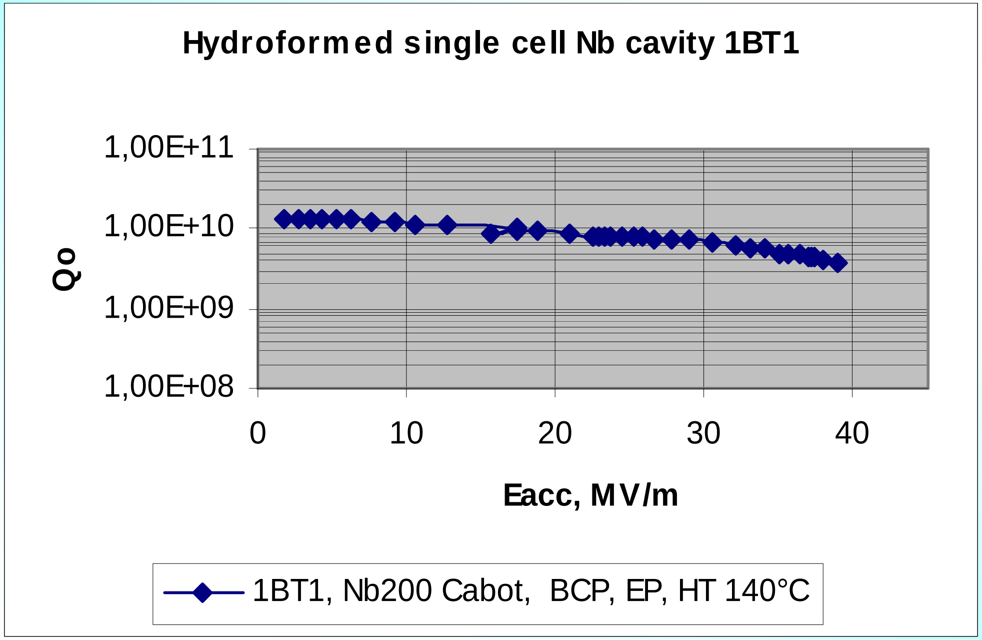
Conclusion to tube fabrication

- Back extrusion from the ingot part: does not work (do not provide the required mechanical properties)
- Spinning: works for short tubes (small cracks on the top part of the tube)
- Deep drawing: works (DESY experiences, in some cases cracks on the inside surface. Good experiences of E. Palmieri)
- Flow forming: works well in combination with spinning, deep drawing, extrusion. Best DESY tubes
- Welded Nb tubes. Does not work (ruptures at the HAZ)
- Powder metallurgical tubes: does not work (not sufficient purity, porosity)
- Fabrication of long tubes for 9-cell cavities is proven by Black Lab (Roy Crooks presentation)

Examples of RF performance: single cells

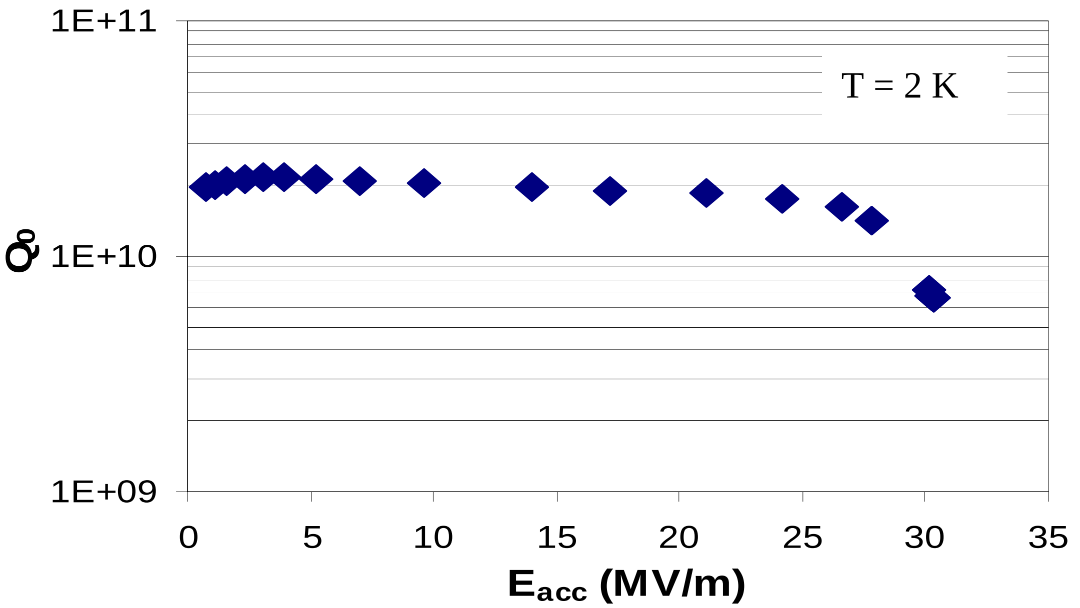






Some best seamless single cell cavities. Preparation and RF tests: K.Saito, P.Kneisel

Examples of RF performance: 9-cell cavity



Surface treatment at DESY: 40 µm BCP, 800 °C heat treatment, tuning; 170 µm electropolishing (EP), ethanol rinsing, 800 °C heat treatment; 48 µm EP, HPR, assembly and evacuation

Mode limits of cavity Z145 measured on 23-Jul-2008 13:08

	Pi	8/9 Pi	7/9 Pi	6/9 Pi	5/9 Pi	4/9 Pi	3/9 Pi	2/9 Pi	1/9 Pi	Max Field	Limit.
Cell 1&9	*30.29*	*27.34*	*29.67*	*28.39*	*26.26*	*25.39*	*17.62*	*8.21*	*5.95*	***30.29***	***bd***
Cell 2&8	*30.29*	*24.05*	*15.79*	*.00*	*17.14*	*34.21*	*35.24*	*20.79*	*17.15*	***35.24***	***bd***
Cell 3&7	*30.29*	*17.85*	*5.48*	*28.39*	*32.21*	*13.51*	*17.62*	*23.64*	*26.27*	***32.21***	***pwr***
Cell 4&6	*30.29*	*9.50*	*24.19*	*28.39*	*5.95*	*38.91*	*17.62*	*15.43*	*32.22*	***38.91***	***pwr***
Cell 5	*30.29*	*.00*	*31.57*	*.00*	*34.28*	*.00*	*35.24*	*.00*	*34.29*	***35.24***	***bd***
Limit	***bd***	***bd***	***bd***	***bd***	***pwr***	***pwr***	***bd***	***pwr***	***bd***		

Conclusions

• High accelerating gradient up to 40 MV/m can be achieved in hydroformed cavities

• Fabrication of the 9-cell cavities (3x3 units) of TESLA like shape is proven.

• The main remaining task is industrialization of the fabrication technique.

ACKNOWLEDGMENTS

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Many thanks to A. Matheisen, B. van der Horst, G. Kreps, H. Wen and A. Ermakov for support in our work.

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