SRF CAVITY FABRICATION BY ELECTRO-HYDRAULIC FORMING AT CERN

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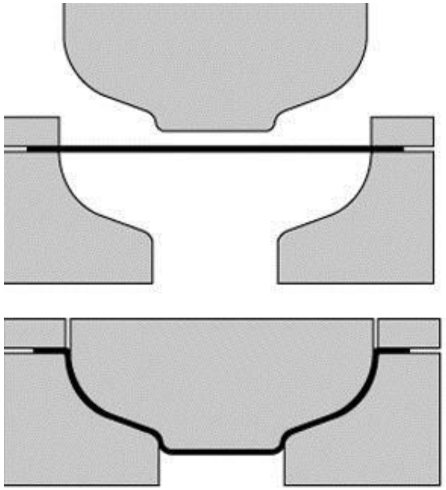
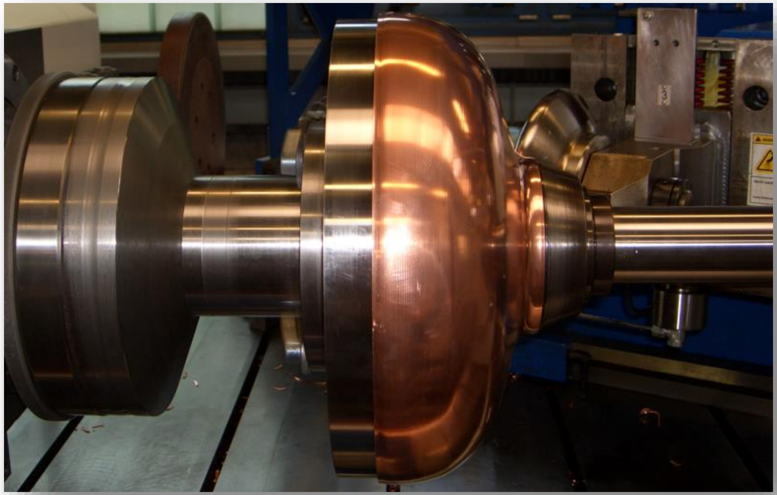
STATE OF ART FORMING OF SRF CAVITIES

➢ Deep-drawing of half-cells



➢ Spinning of copper half-cells



- Requires high tonnage hydraulic press for large cavities;
- A coining step is necessary to obtain the curvature at the iris;
- Spring-back of niobium is an issue;
- Damaged layer left on the surfaces (100-200 μm)

- Multiple steps required to shape blank into final profile without defects;
- Many parameters to be adjusted: Feed ratio, Roller path, Roller design, Spinning ratio;
- Intermediate annealing steps (ok for copper, very difficult for Nb);

MOTIVATION

- Investigate new forming processes which simplify the forming of symmetric and asymmetric SRF cavities (i.e. CRAB);
- High Shape Accuracy;
- Reduce post-processing cost and time;
- Reduce cost and time of forming

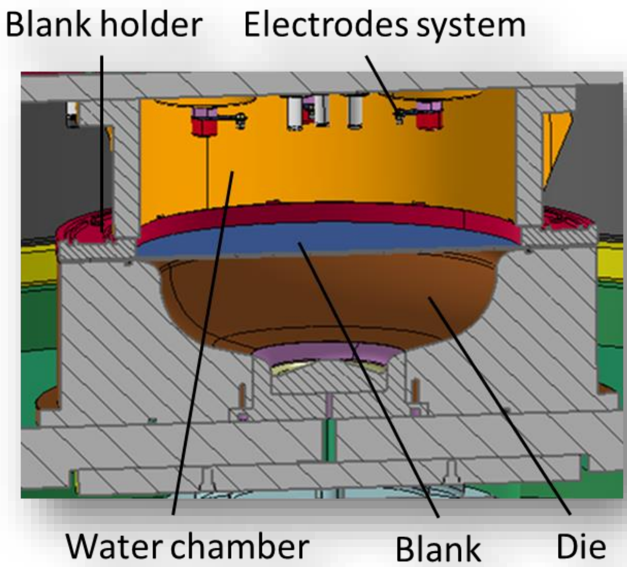
High strain-rate forming processes can help in satisfying the above requirements:

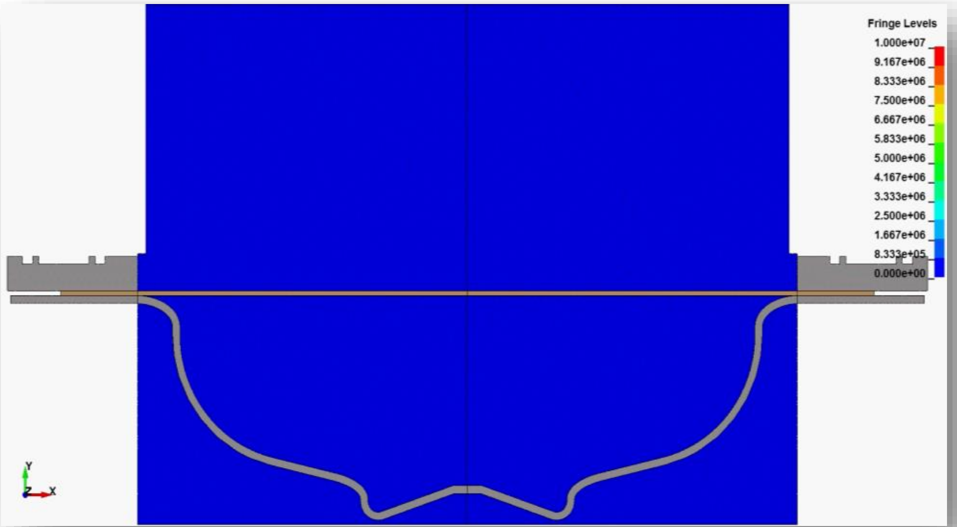
- Increase in metal formability;
- Reduced springback;
- High reproducibility;
- Reduced manufacturing cost;

Collaboration CERN/BMAX to produce symmetric SRF cavities by using electro-hydraulic forming

ELECTRO-HYDRAULIC FORMING

ELECTRO-HYDRAULIC FORMING





Parameters to be considered during EHF:

- Position of electrodes;
- Input energy magnitude;
- Number and duration of pulses;
- Chamber geometry;
- Type of material to be formed (thickness);

$$E=1/2(CV^2)$$

ELECTRO-HYDRAULIC FORMING

- 3 half-cells from 3 mm OFE-Cu sheets;
- 3 half-cells from 3.6 mm Nb sheets;

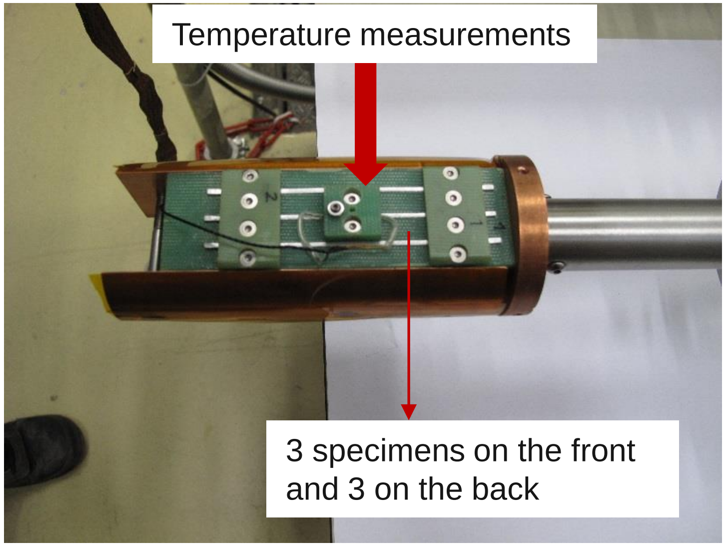
CHARACTERIZATION OF THE STARTING NIOBIUM SHEET

RRR measurements:

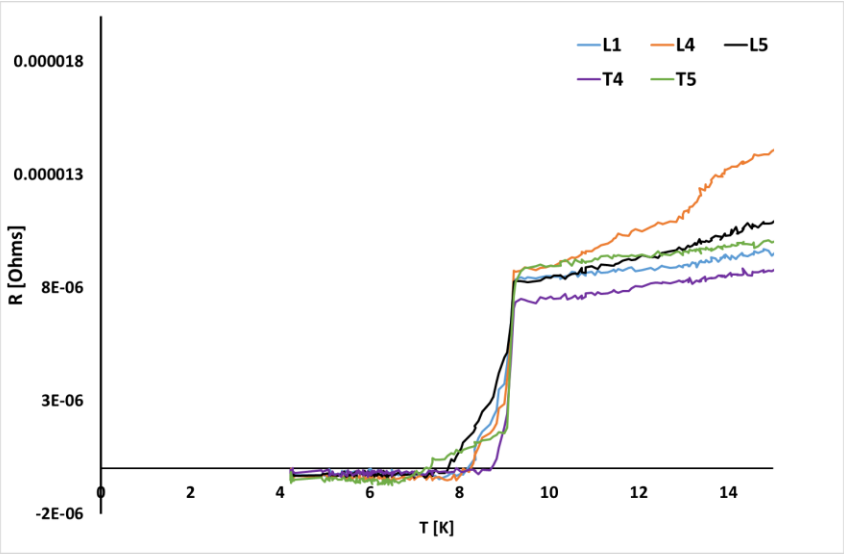
- 5 specimens cut in longitudinal direction of the Nb sheet;
- 5 specimens cut in transversal direction of the Nb sheet;

Raw Dimensions: 2mm x 2mm x 100mm

- Specimens were degreased and chemically attacked to remove 300 µm;



Resistivity versus temperature curves



- Applied current 5 A;
- Warm-up and cool-down procedure performed by using liquid He;

CHARACTERIZATION OF THE STARTING NIOBIUM SHEET

RRR Measurements:

- Results obtained by regression of the resistivity vs temperature curves in the range 9.3K up to 17-20K;

Longitudinal Specimen	RRR	Transversal Specimen	RRR
L1	401	T1	375
L2	412	T2	358
L3	399	T3	373
L4	556 (*)	T4	351
L5	390	T5	318 (*)
Average Removing (*)	401	Average Removing (*)	364
STD	9	STD	12

$$RRR = \frac{R(295K)}{R(4.2K)}$$

✓ Values of RRR are > 300 along both directions (according to SRF cavities requirements);

CHARACTERIZATION OF THE STARTING NIOBIUM SHEET

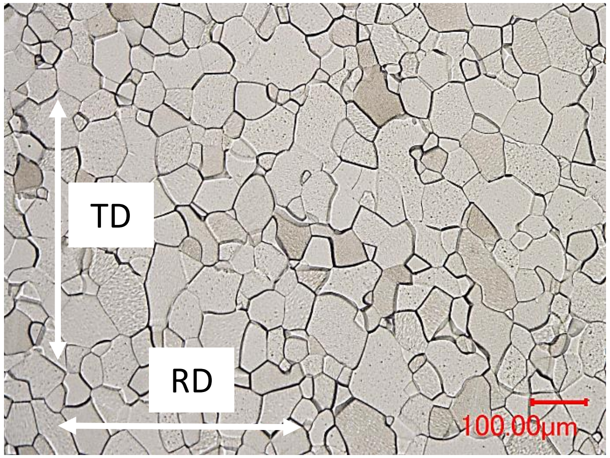
- Vickers Hardness HV10 should be max. 60 according to SRF requirements;

Average HV 10	STD
51	3

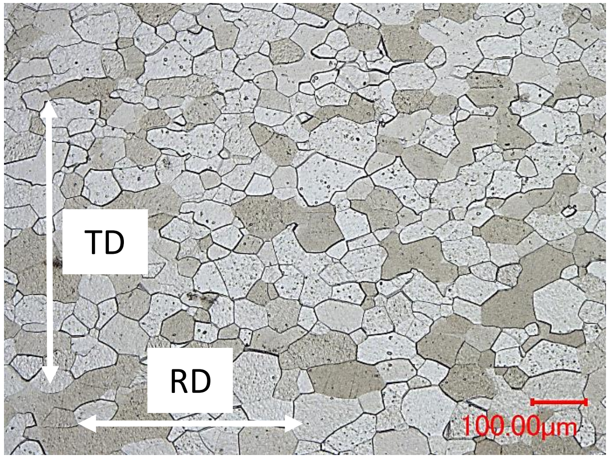
✓ (average values declared by supplier: 47-52);

- Vickers Hardness HV0.2 through thickness: average value 57 and STD ± 4;

Microstructure on surface



Microstructure through thickness

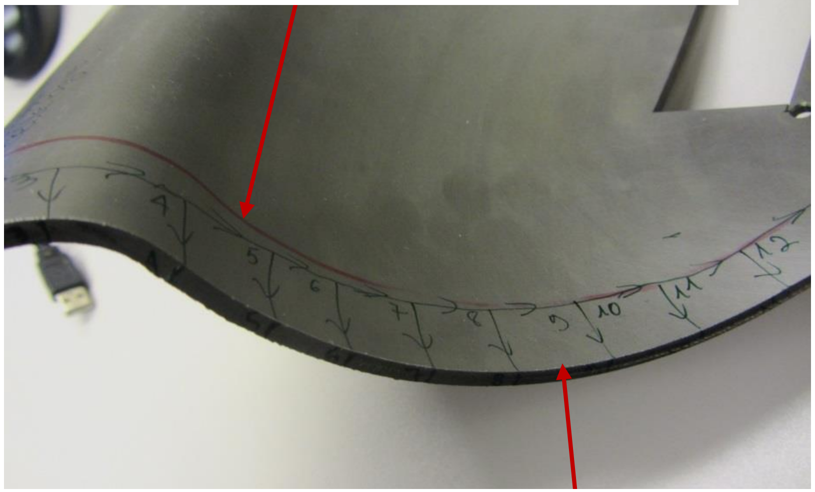


Average grain size number: 5.5 (Ø of grains 53 μm) (ASTM E112-96(2004)).

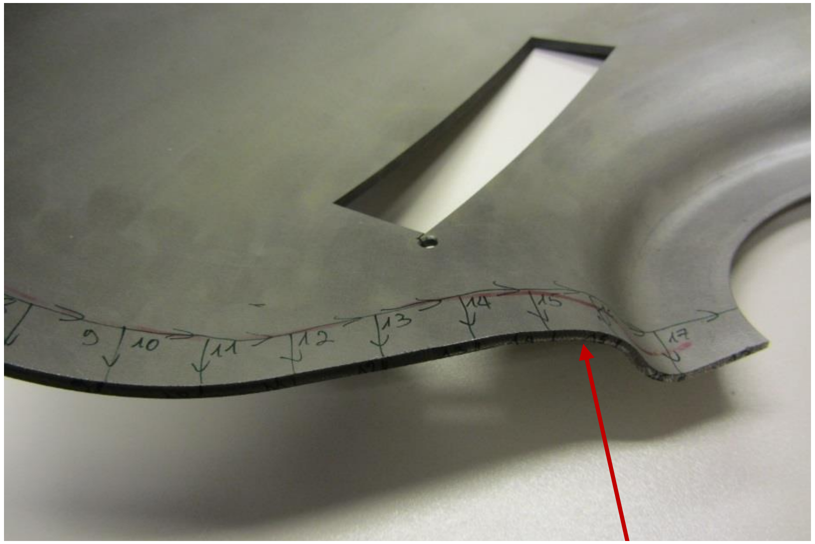
COMPARISON BETWEEN EHF AND SPINNING

- After forming of the metal, the dislocation density is increased
- Dislocation density is related to hardness;
- Specimens were cut along the profile of the two formed cavities and a number was assigned to them based on their position;

Specimen 5 – (close to the equator)



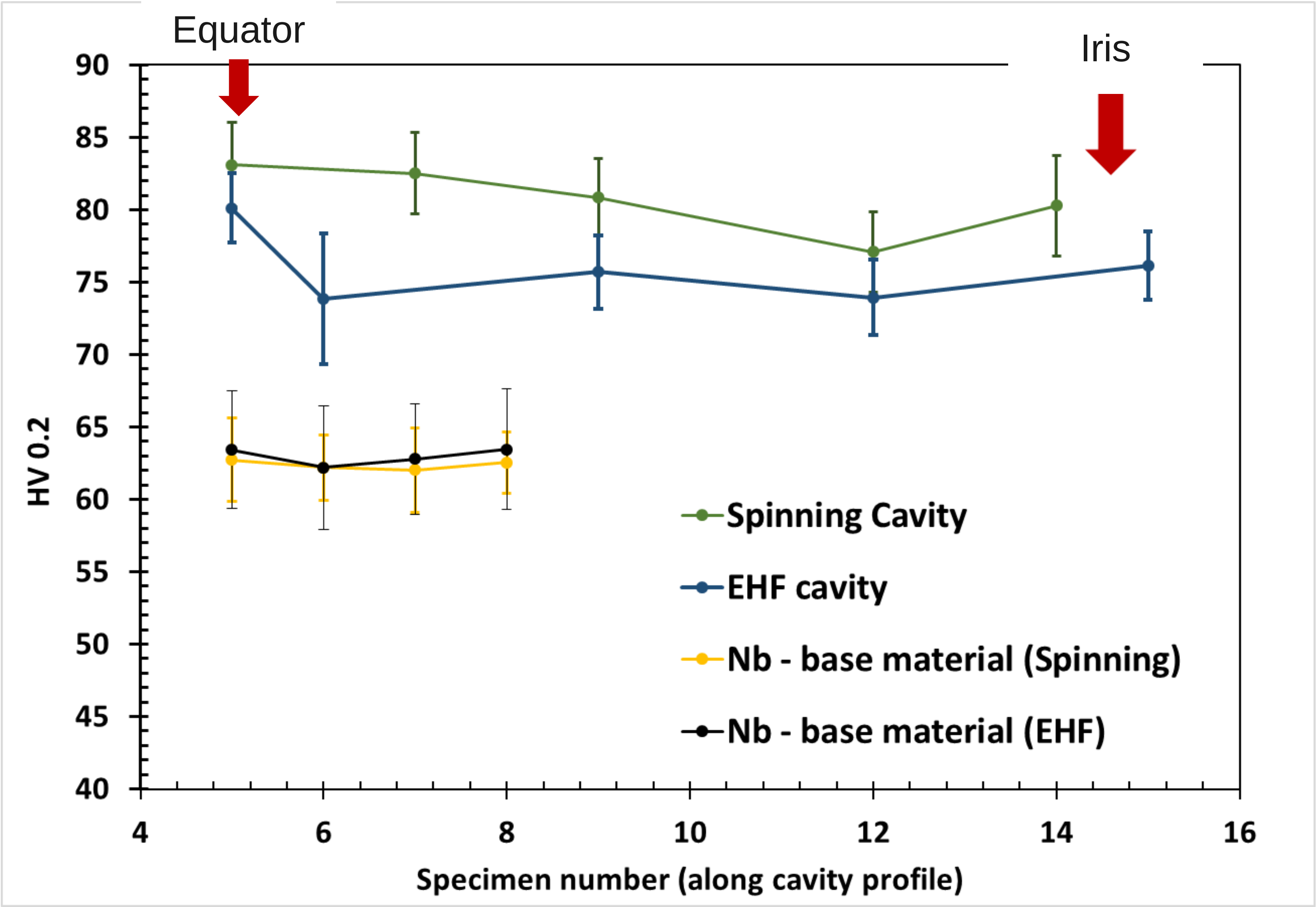
Specimen 9 –
(middle of the cavity profile)



Specimen 15 –
(close to iris of the cavity profile)

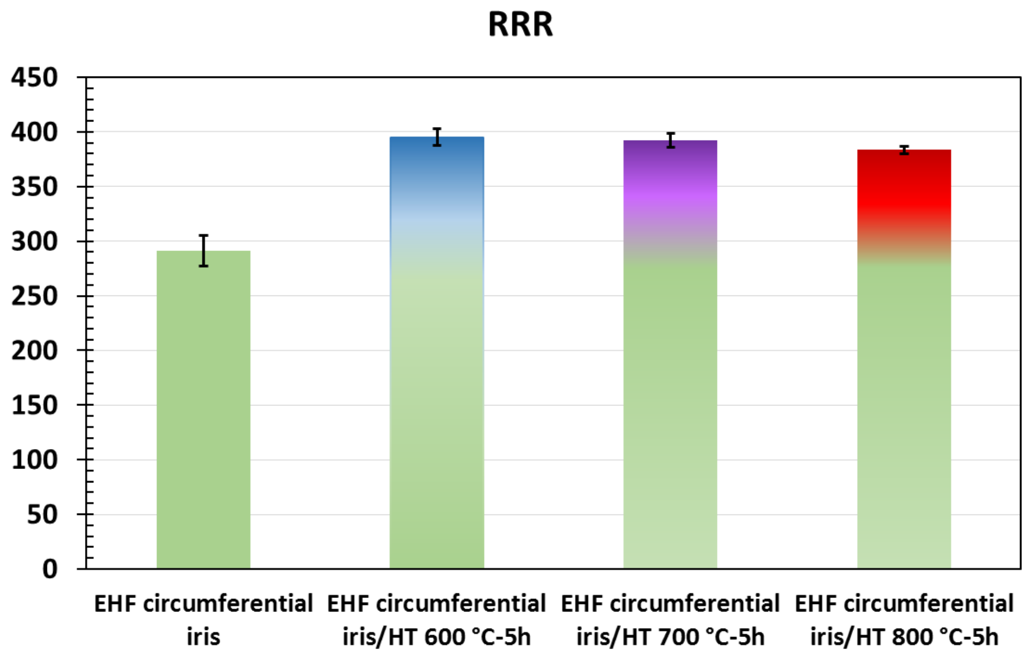
- Surface Vickers Hardness (HV 10) and Vickers Microhardness (HV 0.2) were compared for both forming techniques;

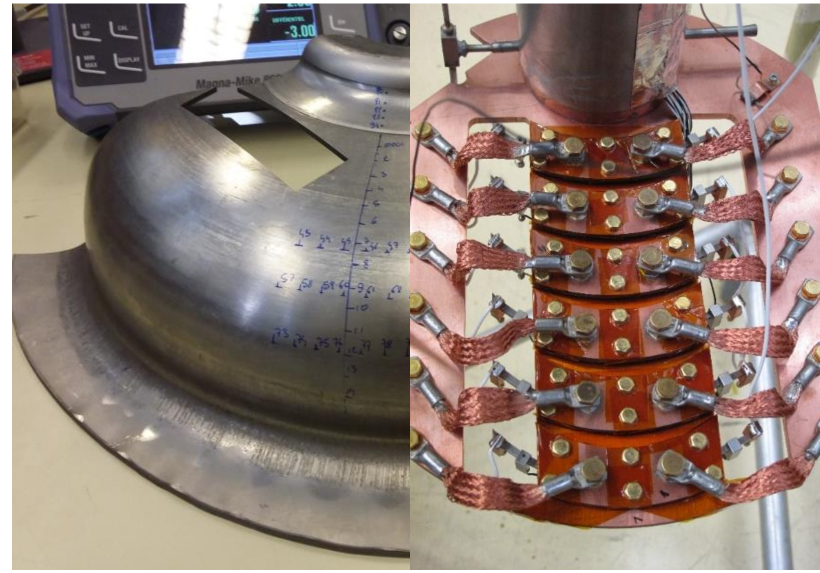
COMPARISON BETWEEN EHF AND SPINNING



RRR OF ELECTRO-HYDRAULIC FORMED HALF CELLS

- RRR value is related to the density of dislocations





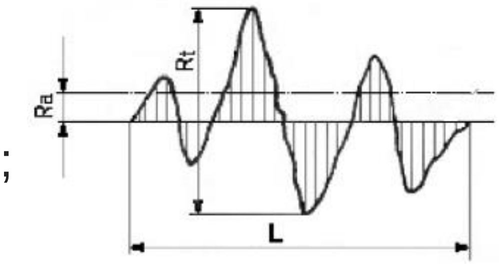
- RRR specimens extracted in circumferential direction close to the iris;
- RRR specimens annealed at 600 °C/700 °C and 800 °C for 5h in vacuum (10^{-6} mbar);

Annealing	Average RRR
600 °C – 5h	395
700 °C – 5h	393
800 °C – 5h	384

} Recovery of RRR values and recovery of dislocations;

SURFACE FINISH OF ELECTRO-HYDRAULIC FORMED CAVITY

- R_a arithmetic average of roughness absolute values;
- R_t distance from the highest peak to the deepest valley;



OFE Cu RF surface

Nb RF surface

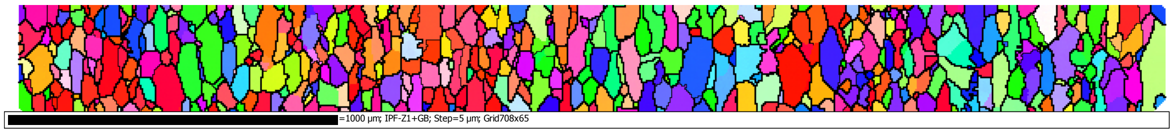
OFE Cu outer surface

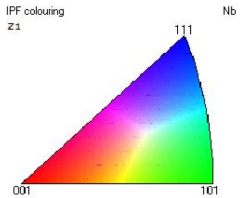
Id	Ra sheet (µm)	Rt sheet (µm)	Ra EHF (µm)	Rt EHF (µm)
OFE	0.2	3.5-5.8	0.2	2-12
Nb	0.8-0.9	7-11	0.9-1	8-11

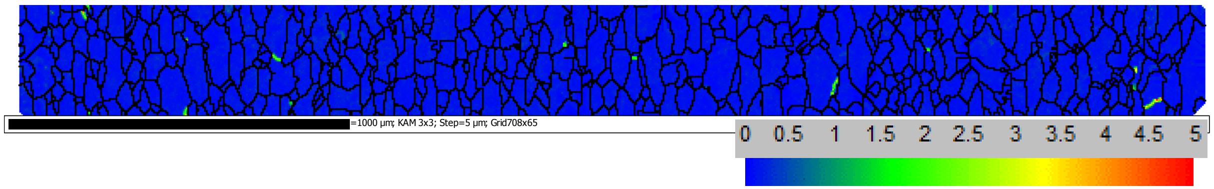
- Conservation of surface roughness;
- Shape Accuracy: ± 200 µm for Nb, ±150 µm for Copper against ± 600 – 800 µm for deep-drawing and spinning;

EBSD OF ELECTRO-HYDRAULIC FORMED CAVITY

➤ **Not Deformed**

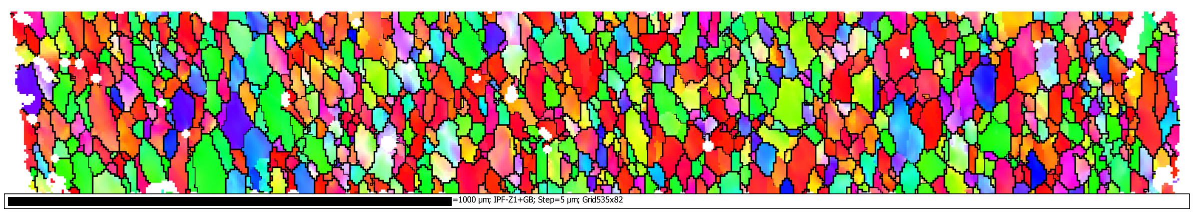


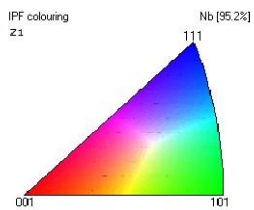


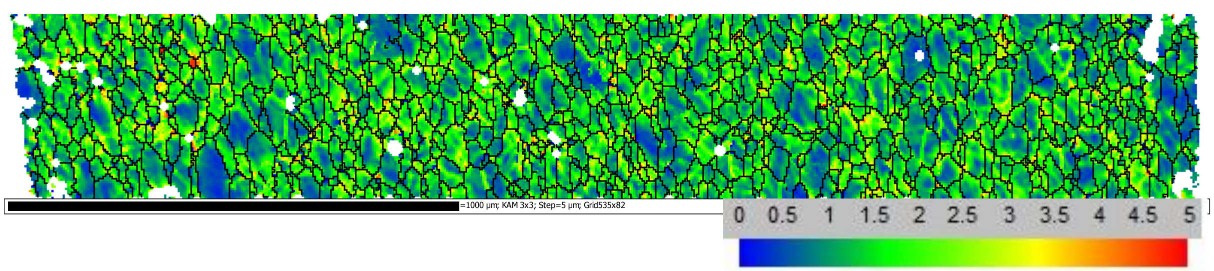


➤ No plastic strain present through thickness;

➤ **Deformed close to iris**

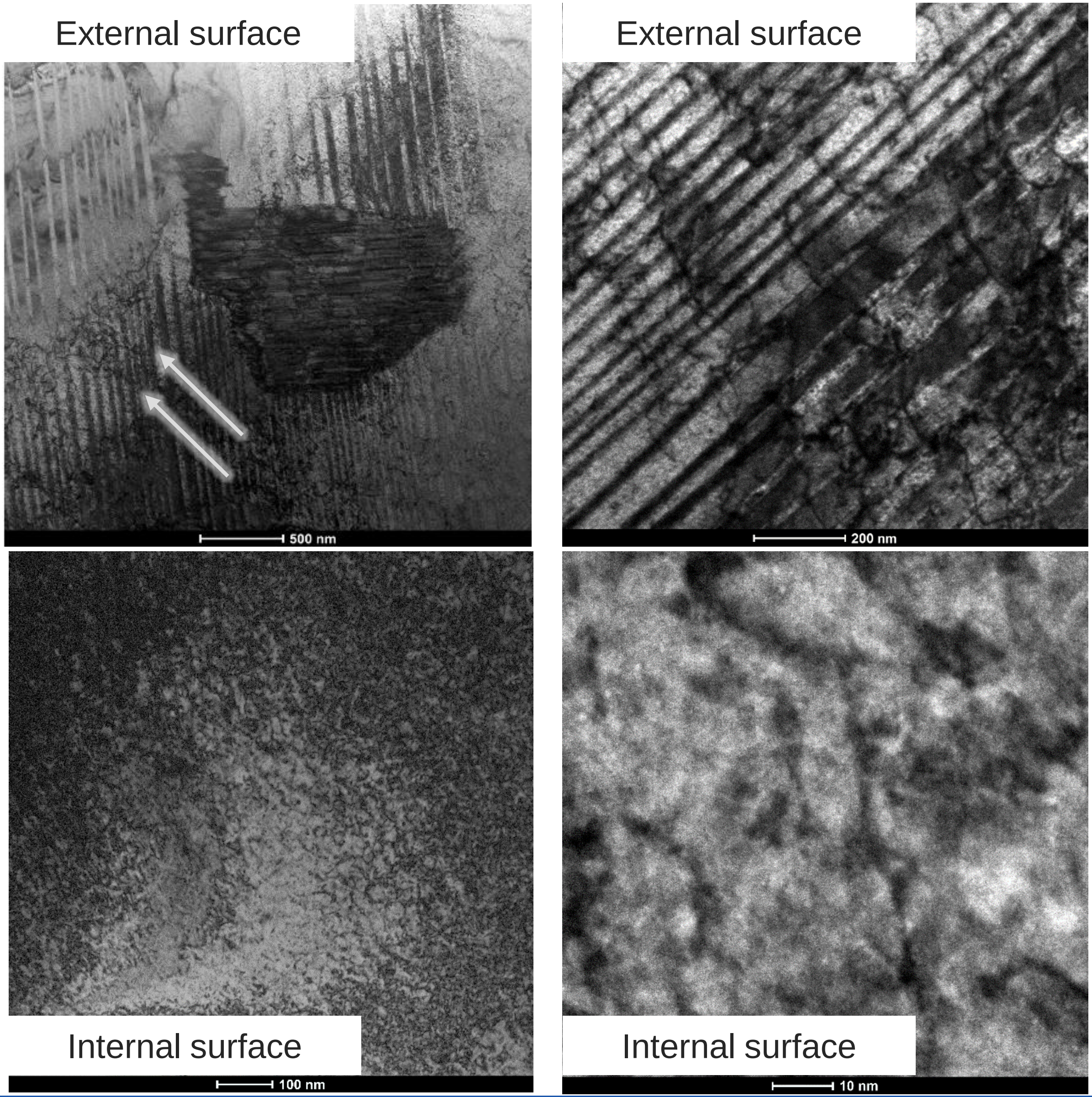


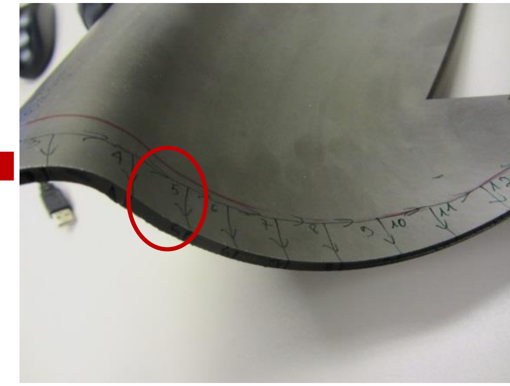




➤ Uniform distribution of plastic strain through thickness;

TEM OF ELECTRO-HYDRAULIC FORMED CAVITY





- External Surface: Twins present in whole grains;
- Internal Surface: NO twins but presence of bundles of dislocations;

(Results obtained in collaboration with ETH Zürich)

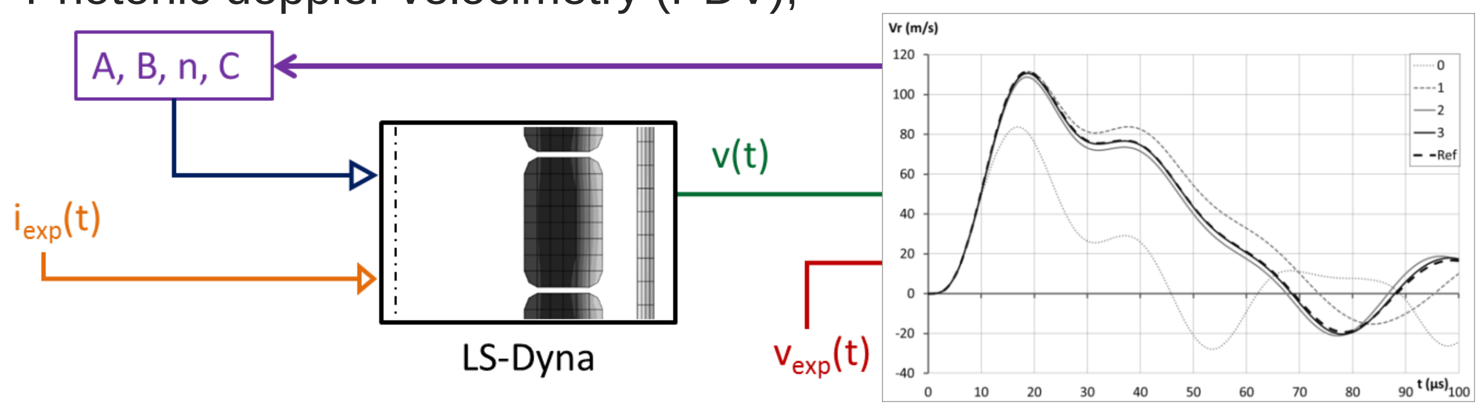
BMAX NIOBIUM CHARACTERIZATION

- FEM modelling of EHF: isotropic yield function + Johnson-Cook rate dependent model;

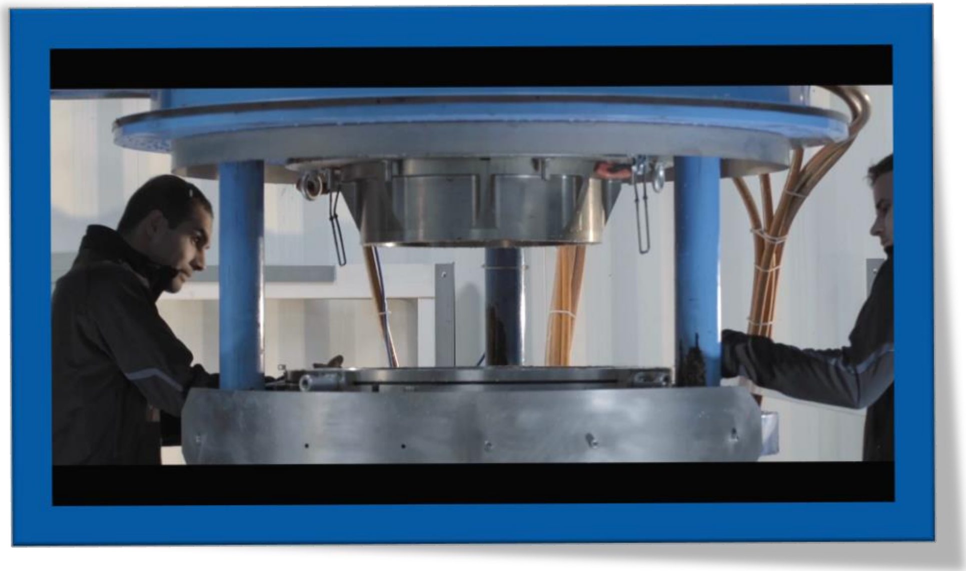
$$\sigma = [A + B \cdot \overline{\varepsilon_{pl}}^{\,n}] \cdot \left[1 + C \cdot ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right]$$

Uniform strain-hardening | Strain-rate sensitivity | Temperature sensitivity

- High speed testing in industrial manufacturing conditions:
  - Testing by magnetic pulse forming (tube expansion test);
  - Rogowski coil (measurement of pulse electrical current);
  - Photonic doppler velocimetry (PDV);



Conclusions and Future Work



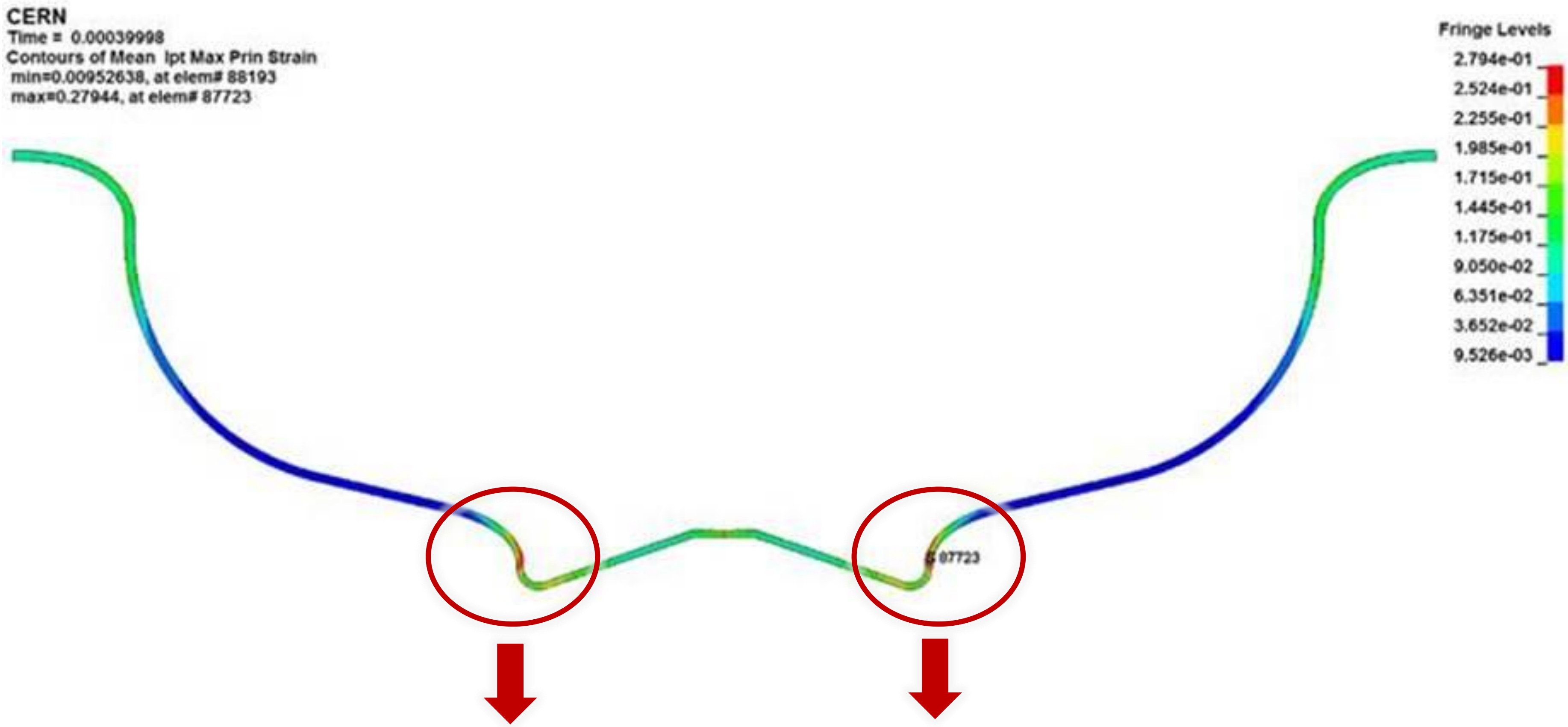
- Electro-hydraulic forming is a promising technique to form axial symmetric SRF cavities;

- The damage caused inside the material (density of dislocations) is lower compared to spinning processes;

- The conservation of surface roughness, low wall thickness variation and lower damage compared to spinning, could lead to an important reduction of post forming related surface treatment, as buffered chemical polishing (BCP) and electropolishing (EP).

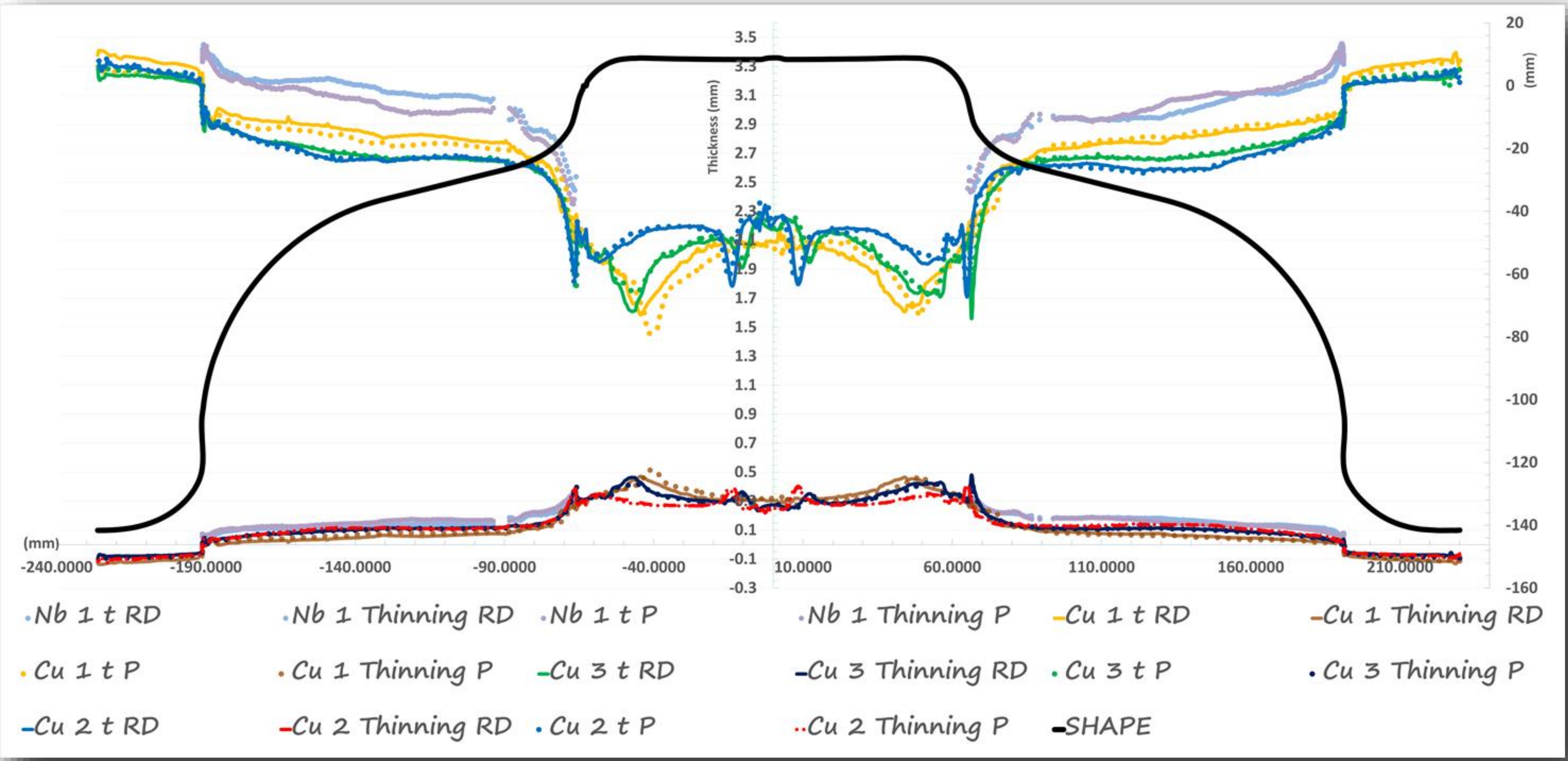
THANK YOU FOR YOUR ATTENTION

DISTRIBUTION OF STRAIN FROM EHF SIMULATIONS



Highest strain at the iris

THINNING OF ELECTRO-HYDRAULIC FORMED CAVITY



MICROSTRUCTURE

Not-deformed

Equator

Middle of profile

Iris