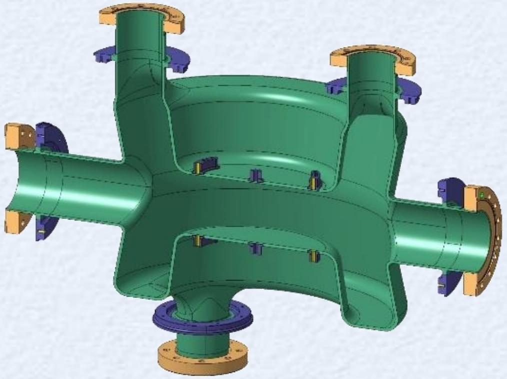
First Results of SRF Cavity Fabrication by Electro-Hydraulic Forming at CERN

S. Atieh

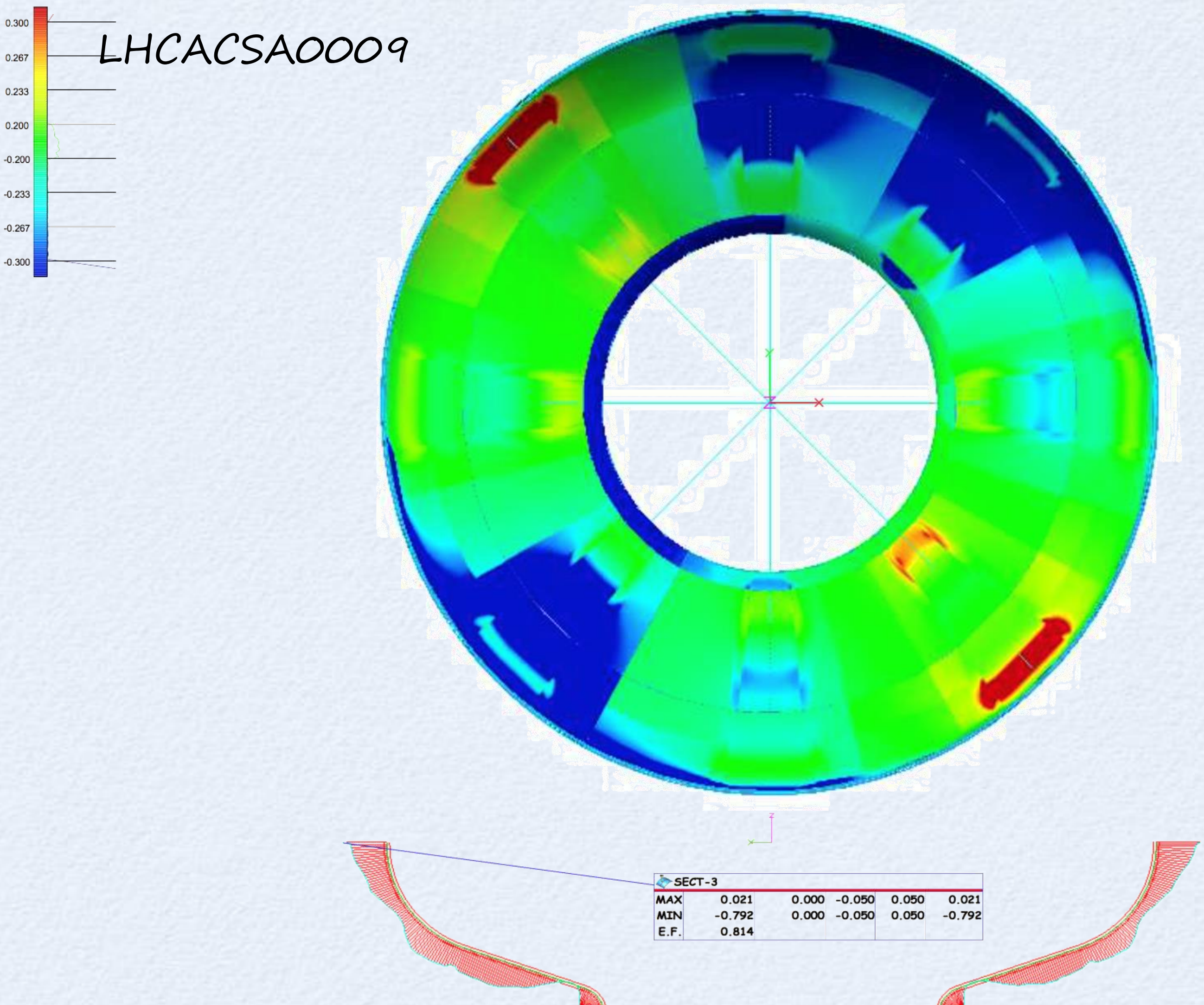
Many thanks to
A. Amorim Carvalho, I. Aviles Santillana, F. Bertinelli, R. Calaga, O. Capatina, G. Favre,
M. Garlasché, F. Gerigk, S.A.E. Langeslag, K.M. Schirm, N. Valverde Alonso,
CERN,
G. Avrillaud, D. Alleman, J. Bonafe, J. Fuzeau, E. Mandel, P. Marty,
A. Nottebaert, H. Peronnet, R. Plaut
Bmax,
And many others

Motivation

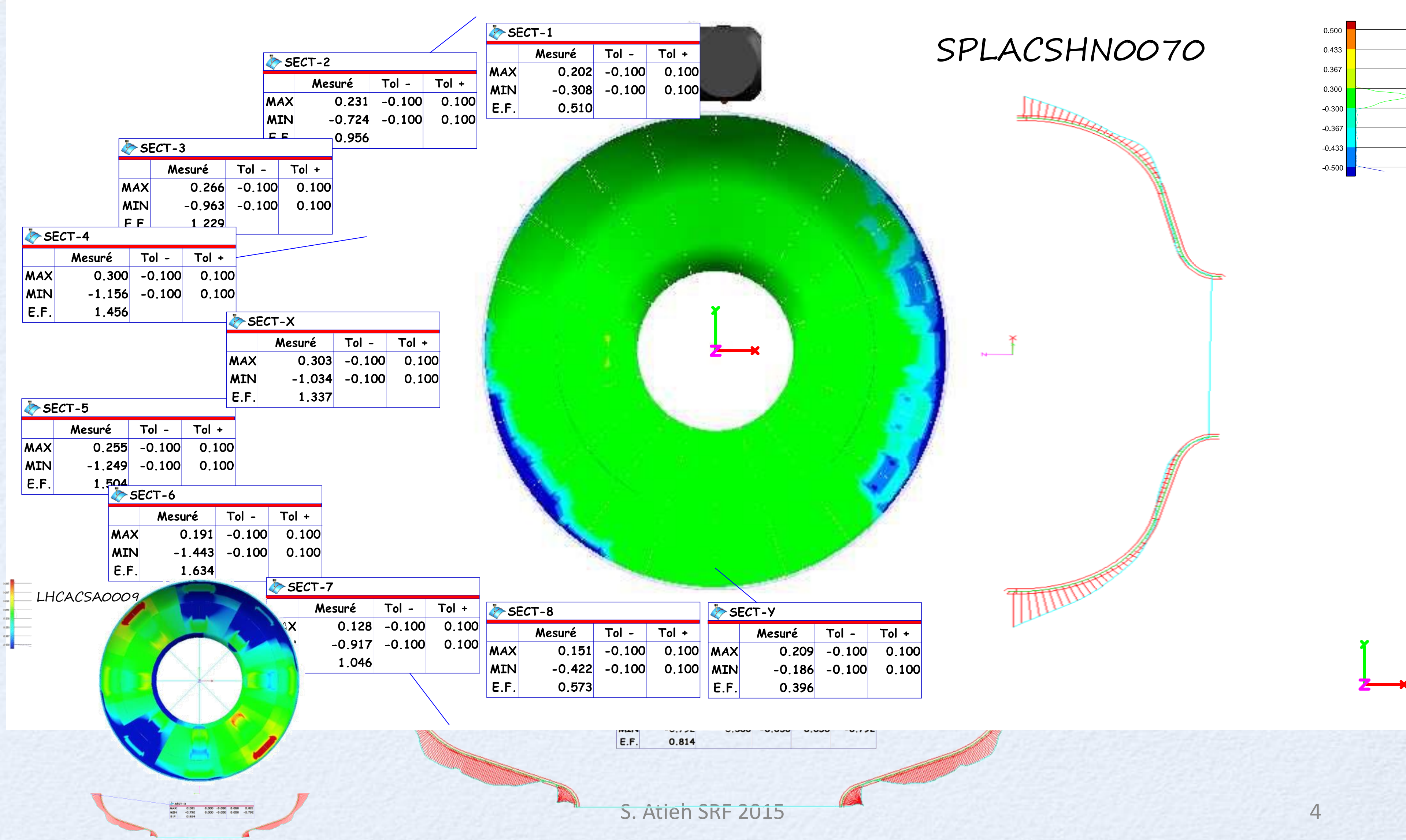
- CERN is widening its competence towards the state-of- the-art SRF Nb technology to be prepared for next generation accelerator projects,
- CERN is upgrading its facilities to be able to perform relevant R&D and help prepare future SRF technology,
- Thin-film technologies are again in focus "but not limited to",
- Developments of new or spare superconducting RF cavities, LHC consolidation, Superconducting Proton Linac (SPL), LHC High Luminosity upgrade (HL-LHC), and the Future Circular Collider (FCC) studies.



Motivation


0.300
0.267
0.233
0.200
-0.200
-0.233
-0.267
-0.300
LHCACSA0009
SECT-3
MAX 0.021 0.000 -0.050 0.050 0.021
MIN -0.792 0.000 -0.050 0.050 -0.792
E.F. 0.814

Motivation



SECT-1

	Mesuré	Tol -	Tol +
MAX	0.202	-0.100	0.100
MIN	-0.308	-0.100	0.100
E.F.	0.510		

SECT-2

	Mesuré	Tol -	Tol +
MAX	0.231	-0.100	0.100
MIN	-0.724	-0.100	0.100
E.F.	0.956		

SECT-3

	Mesuré	Tol -	Tol +
MAX	0.266	-0.100	0.100
MIN	-0.963	-0.100	0.100
E.F.	1.229		

SECT-4

	Mesuré	Tol -	Tol +
MAX	0.300	-0.100	0.100
MIN	-1.156	-0.100	0.100
E.F.	1.456		

SECT-X

	Mesuré	Tol -	Tol +
MAX	0.303	-0.100	0.100
MIN	-1.034	-0.100	0.100
E.F.	1.337		

SECT-5

	Mesuré	Tol -	Tol +
MAX	0.255	-0.100	0.100
MIN	-1.249	-0.100	0.100
E.F.	1.504		

SECT-6

	Mesuré	Tol -	Tol +
MAX	0.191	-0.100	0.100
MIN	-1.443	-0.100	0.100
E.F.	1.634		

SECT-7

	Mesuré	Tol -	Tol +
MAX	0.128	-0.100	0.100
MIN	-0.917	-0.100	0.100
E.F.	1.046		

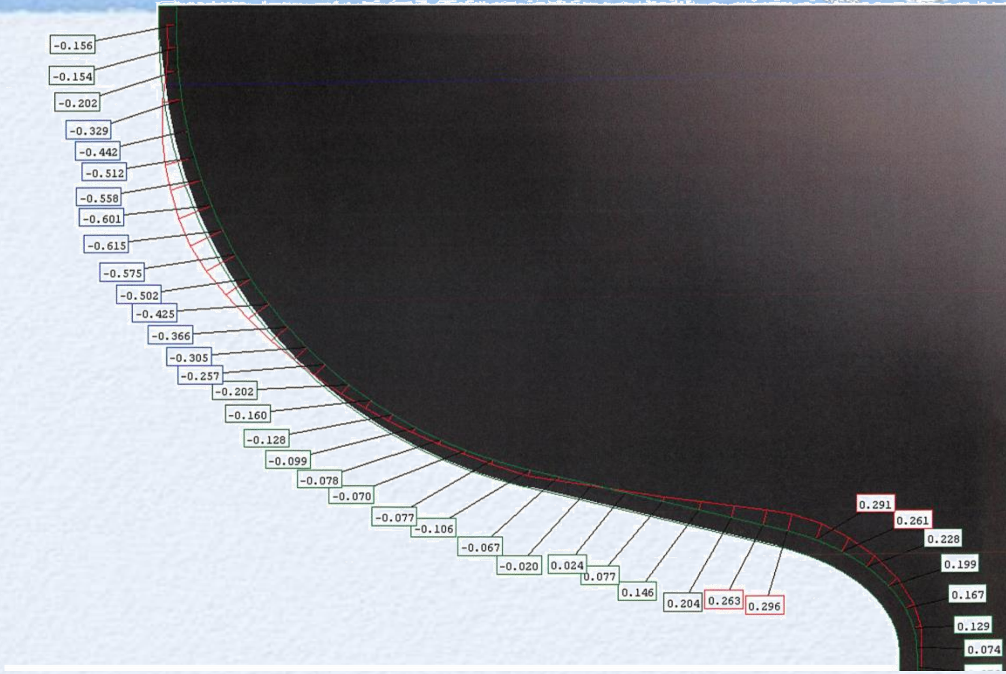
SECT-8

	Mesuré	Tol -	Tol +
MAX	0.151	-0.100	0.100
MIN	-0.422	-0.100	0.100
E.F.	0.573		

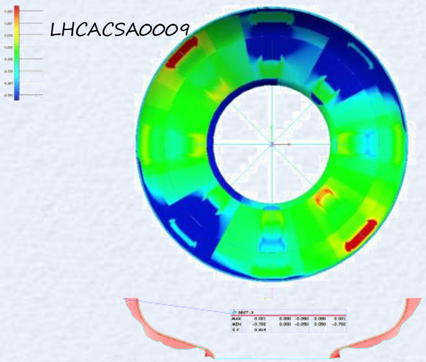
SECT-Y

	Mesuré	Tol -	Tol +
MAX	0.209	-0.100	0.100
MIN	-0.186	-0.100	0.100
E.F.	0.396		

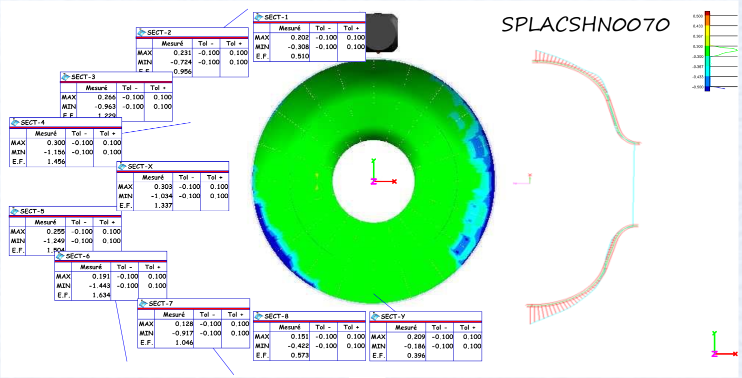
Motivation



-0.156
-0.154
-0.202
-0.329
-0.442
-0.512
-0.558
-0.601
-0.615
-0.575
-0.502
-0.425
-0.366
-0.305
-0.257
-0.202
-0.160
-0.128
-0.099
-0.078
-0.070
-0.077
-0.106
-0.067
-0.020
0.024
0.077
0.146
0.204
0.263
0.296
0.291
0.261
0.228
0.199
0.167
0.129
0.074

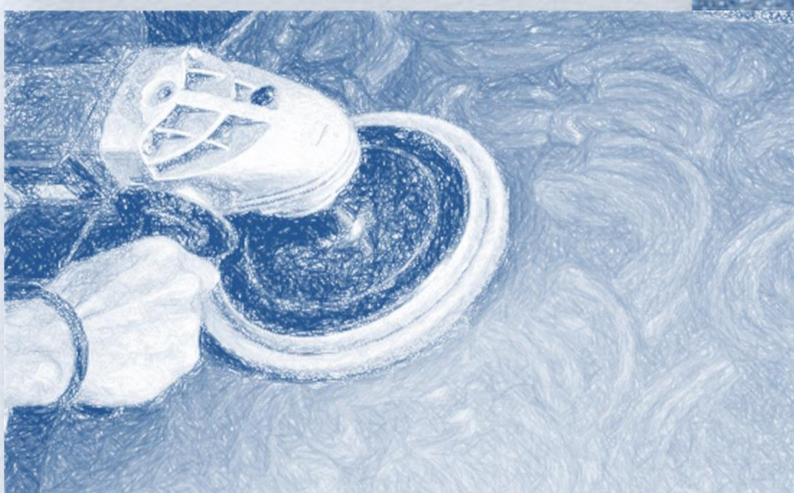


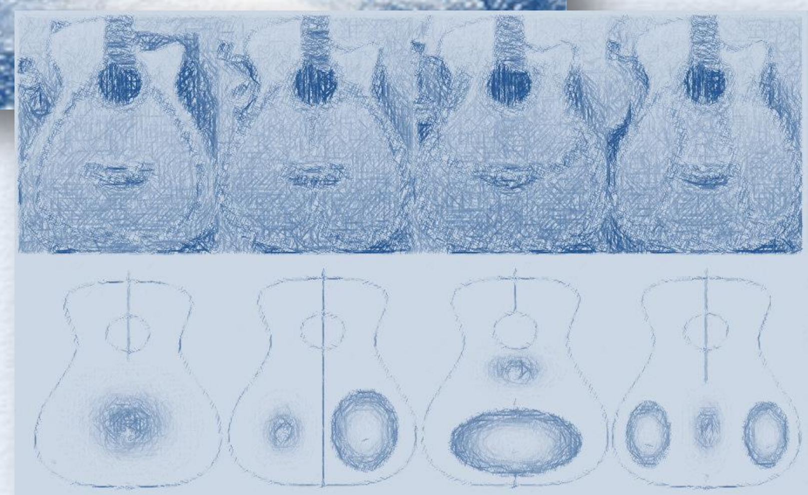
LHCACSA0009



SPLACSHN0070

Motivation

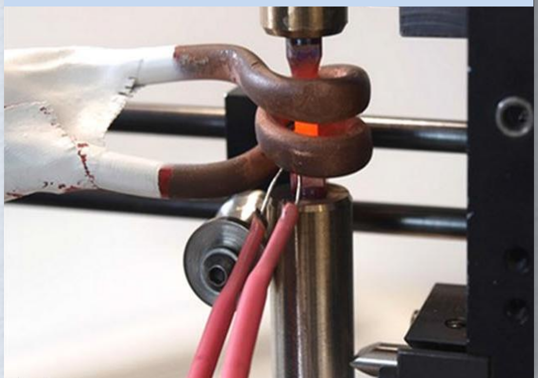




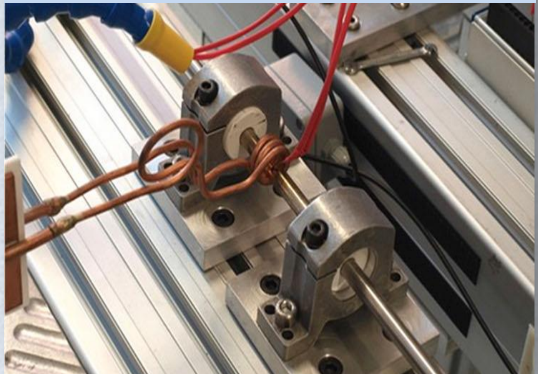
GLIDCOP® LHC collimators

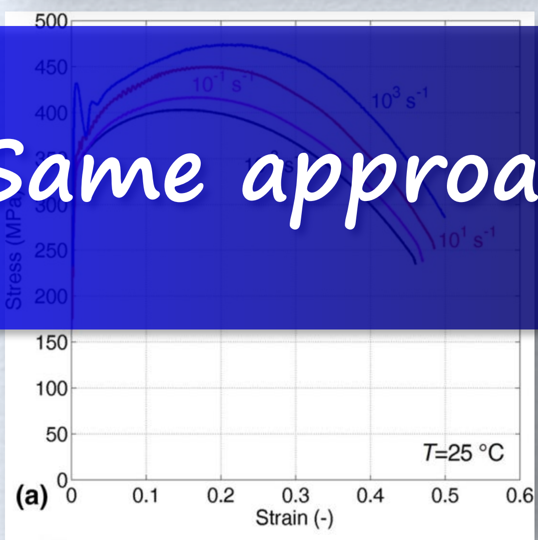
Tensile tests at different strain rate (room temperature)

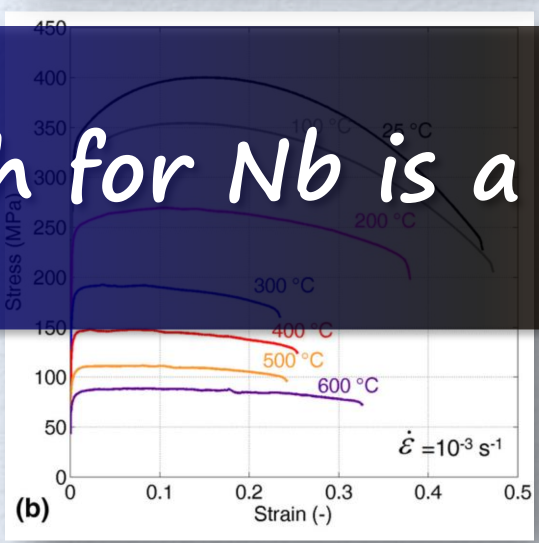
Quasi-static tensile tests at different temperatures

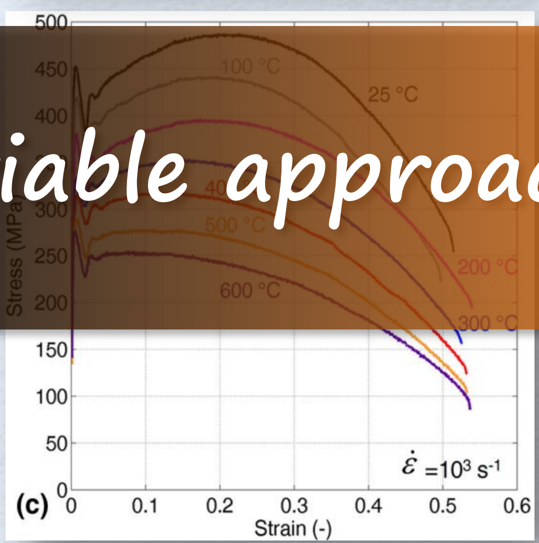


Tensile tests at high strain rate and different temperatures









Same approach for Nb is a viable approach

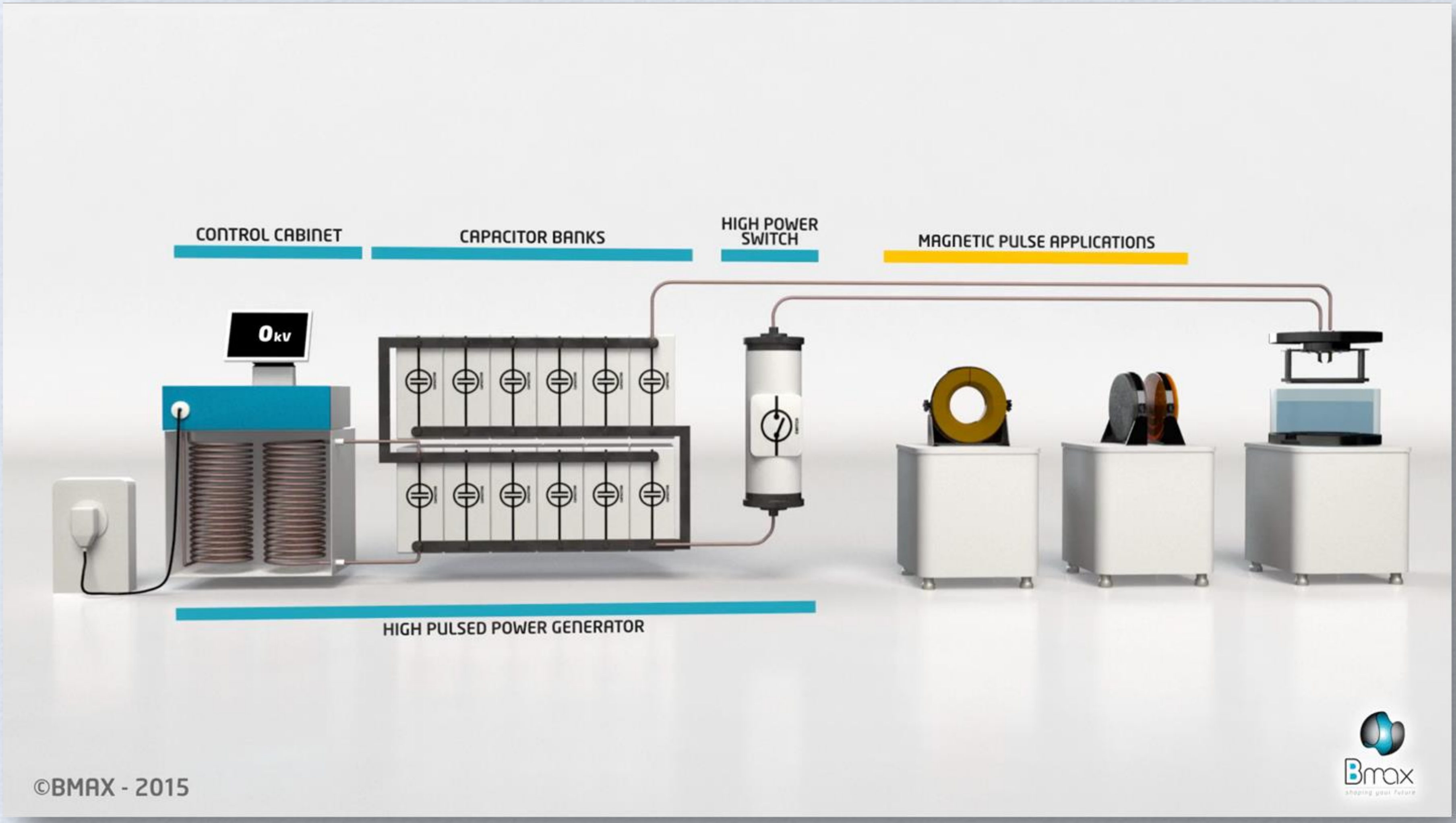
Motivation

Beneficial effects of high strain rates:

- Increase in metal formability,
- Reduced wrinkling,
- High pressure impact for imposing surface details, or conserve it,
- Reduced springback,
- Reduced manufacturing cost.

A collaboration between CERN and Bmax

Electro-Hydraulic Forming principles courtesy Bmax



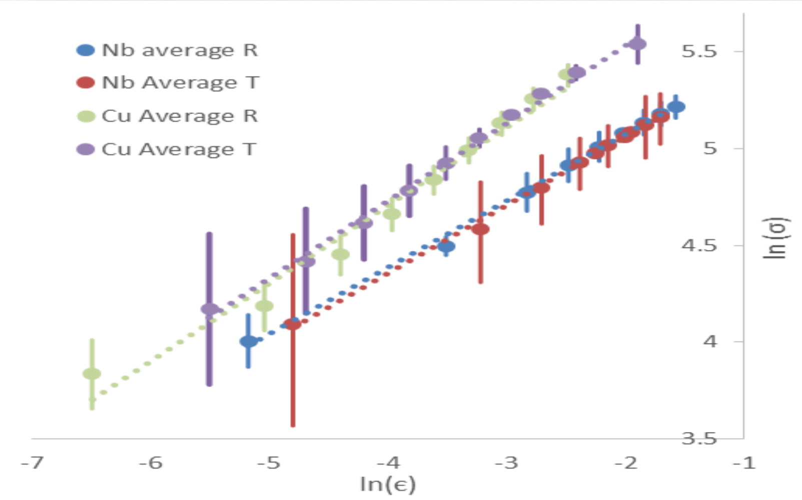
Behaviour at high strain rates

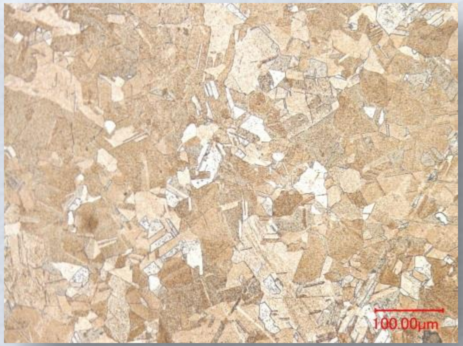
- Proper description of material behaviour at high strain rate requires suitable constitutive material models;
- One of the most used is the Johnson-Cook which includes thermal softening.

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

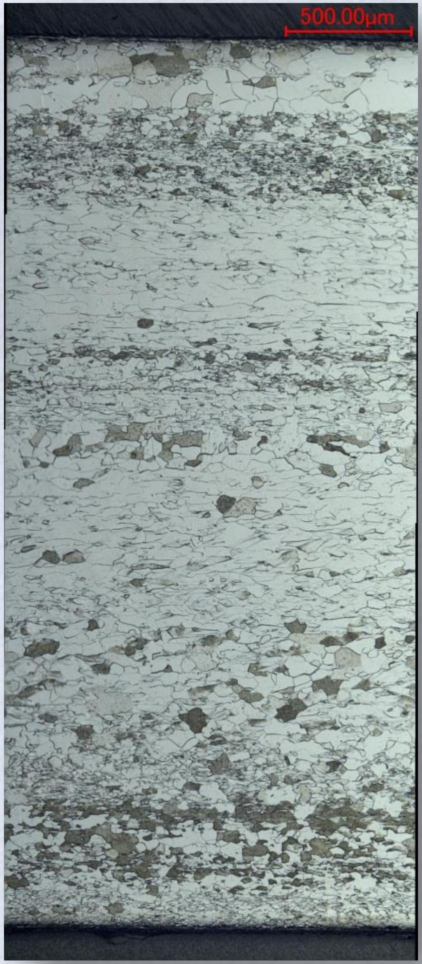
Initial yielding strength and strain hardening	Strain-rate hardening	Thermal softening

Behaviour under Quasi-static loading





Material	OFE Copper	Niobium
Rp0.2 (MPa)	51.5 ± 0.5	122.0 ± 7.0
UTS (MPa)	224.3 ± 3.2	203.8 ± 1.2
A %	52.8 ± 0.0	46.7 ± 3.6



True stress vs true strain in log – log scale for Nb and Cu plates:

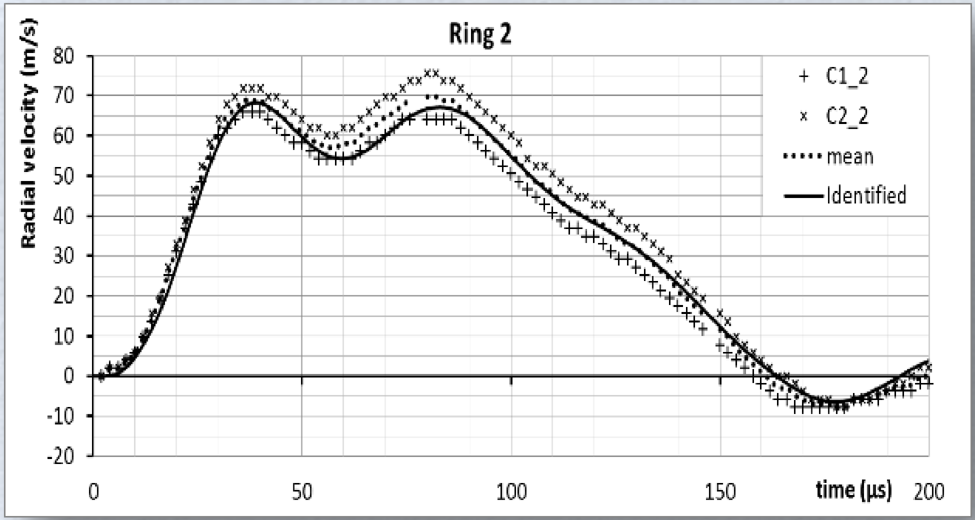
Nb n = 0.40 in Rd and n = 0.35 in T

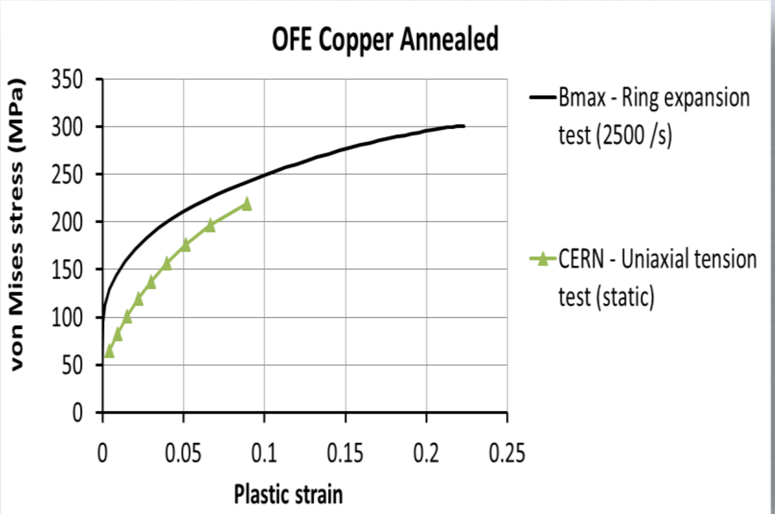
OFE Cu n = 0.35 in Rd and n = 0.40 in T

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

Initial yielding strength and strain hardening

Behaviour at high strain rates $\dot{\varepsilon} > 10^3\ s^{-1}$





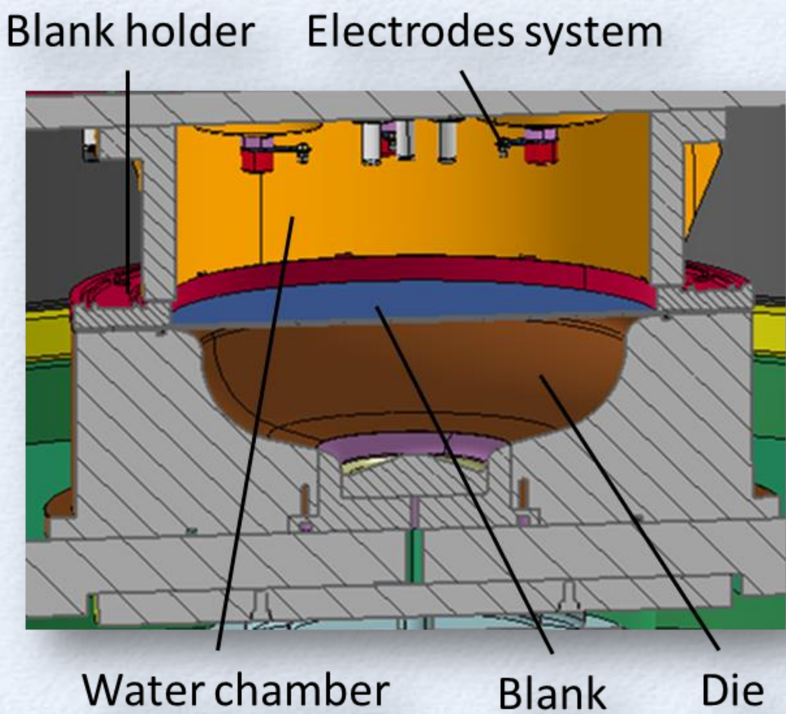
For copper only, to be done for niobium.

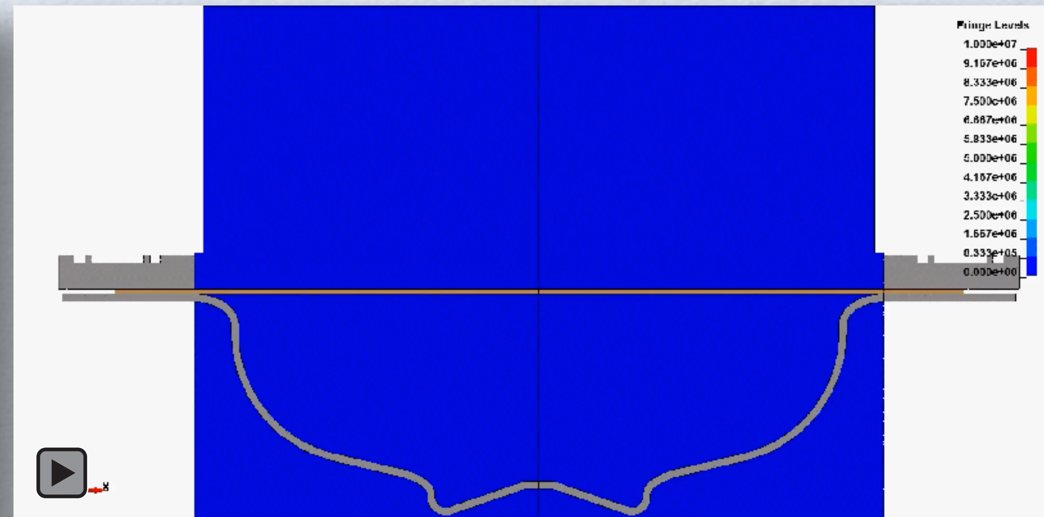
- Measured ring expansion velocities (dots) and identified curves (lines).
- Stress-strain relation comparison for OFE copper between static and dynamic conditions.

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

Strain-rate hardening

Geometry and simulation of the EH Forming





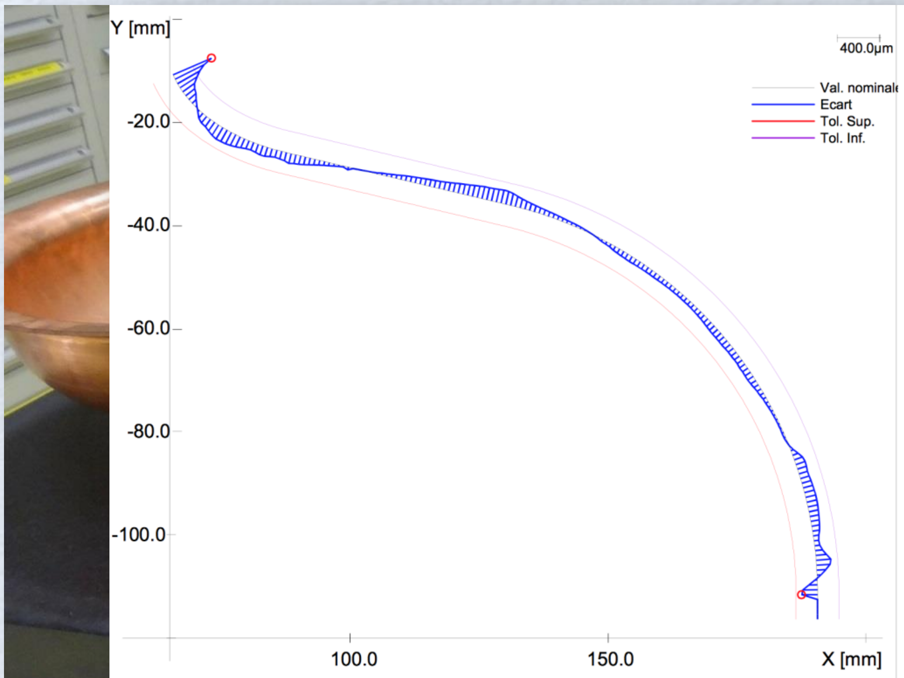
Simulations is used to define the number and position of discharges and to select the energy level.
It allows the optimization of the chamber (mold) geometry, which has a large influence on process efficiency, as typically two thirds of the forming effect comes from reflected waves.

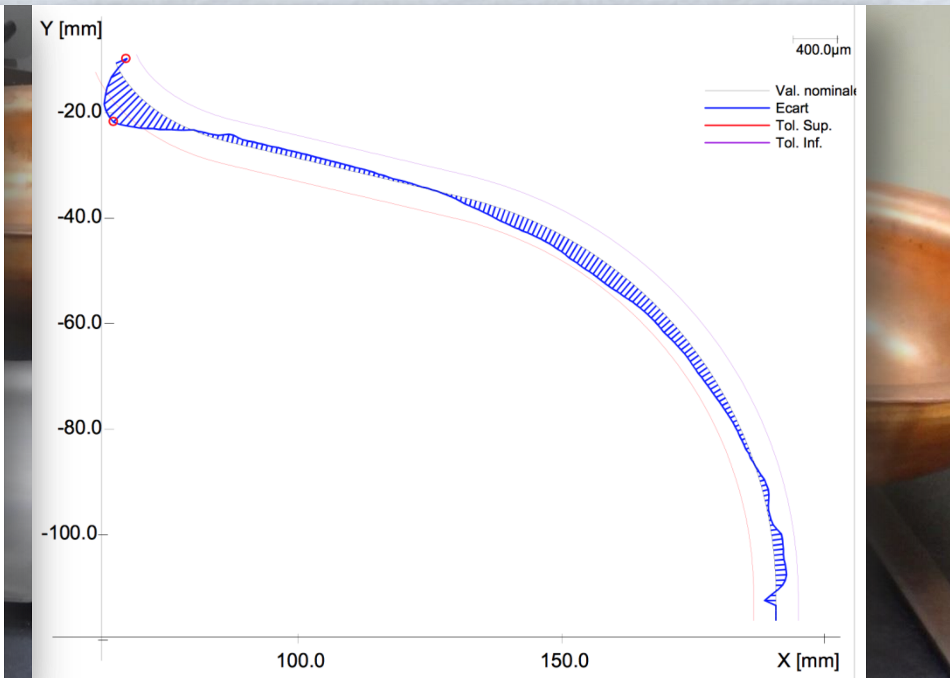
courtesy Bmax

Exp. results: shape accuracy

- 3 OFE half-cells formed
- Good fit in between the experimental results and the simulation
- Achieved shape accuracy: ± 200 µm
- Good reproducibility

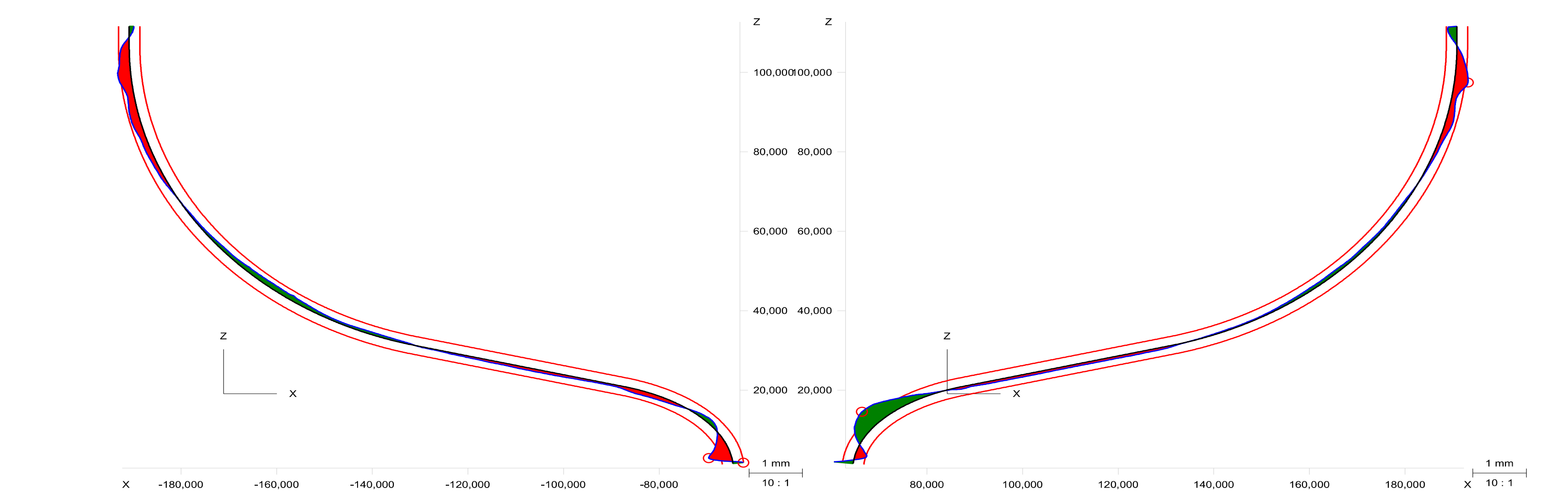
Exp. results: shape accuracy





- 3 OFE half-cells formed
- Good fit in between the experimental results and the simulation
- Achieved shape accuracy: ± 200 µm
- Good reproducibility

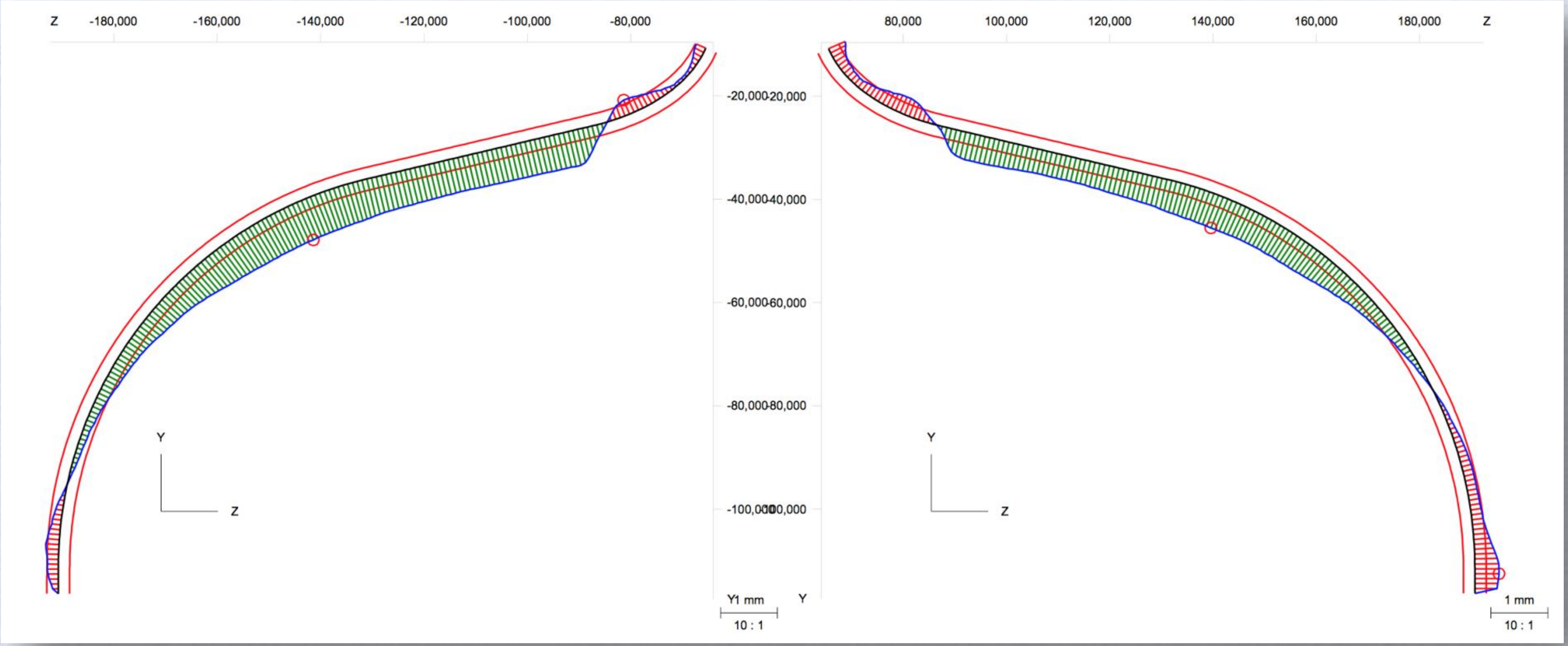
Exp. results: shape accuracy



No	Désignation	Sigma [mm]	Forme [mm]	Nombre Pts	Tol. Inf. [mm]	Tol. Sup. [mm]	MinInd	Ecart Min. [mm]	MaxInd	Ecart Max. [mm]	Résultat de balancement	X [mm]	Y [mm]	Z [mm]		X	Y	Z
1	Ecarts de forme Courbe 180°	0,100	0,614	992	-0,200	0,200	977	-0,418	992	0,196	Translation	0,330	0,000	18,607	Rotation	0.000	-0.355	0.000
2	Ecarts de forme Courbe 0°	0,112	0,645	992	-0,200	0,200	75	-0,254	931	0,391	Translation	0,840	0,000	18,497	Rotation	0.000	-0.171	0.000

- 3 OFE half-cells formed
- Good fit in between the experimental results and the simulation
- Achieved shape accuracy: ± 200 μm
- Good reproducibility

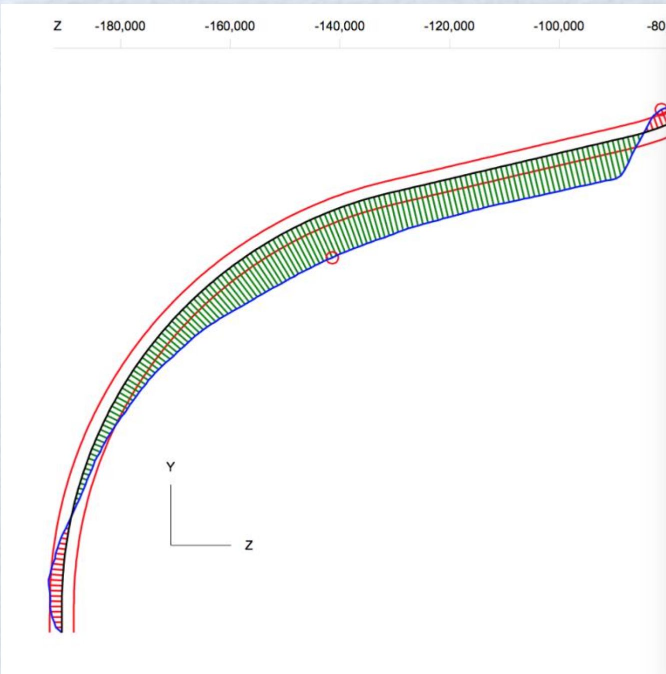
Exp. results: Nb 1st trial



Sheet average hardness 64 HV10

- *Behaviour at high strain rate to be performed at CERN and Bmax;*
- *Parameters to be re-defined;*
- *New power generator by end of year.*

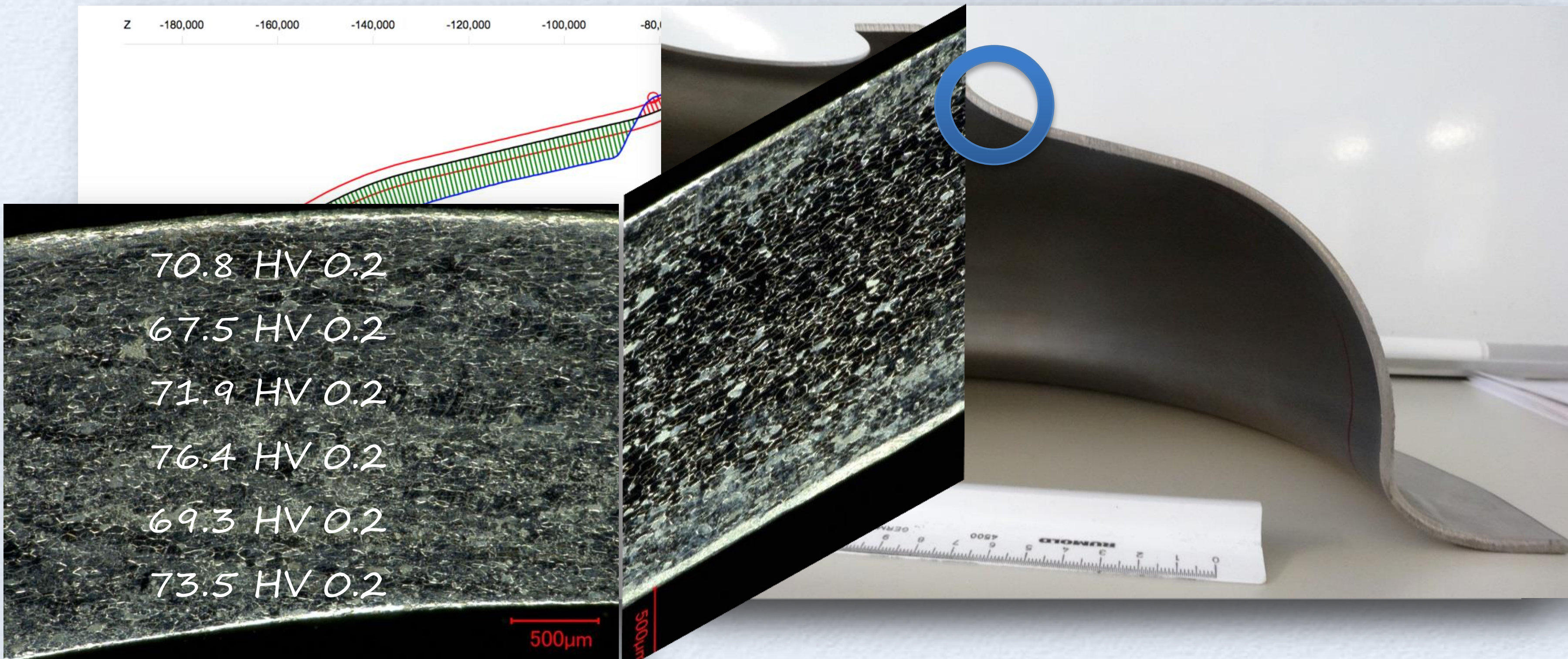
Exp. results: Nb 1st trial



Sheet average hardness 64 HV10

- *Behaviour at high strain rate to be performed at CERN and Bmax;*
- *Parameters to be re-defined;*
- *New power generator by end of year.*

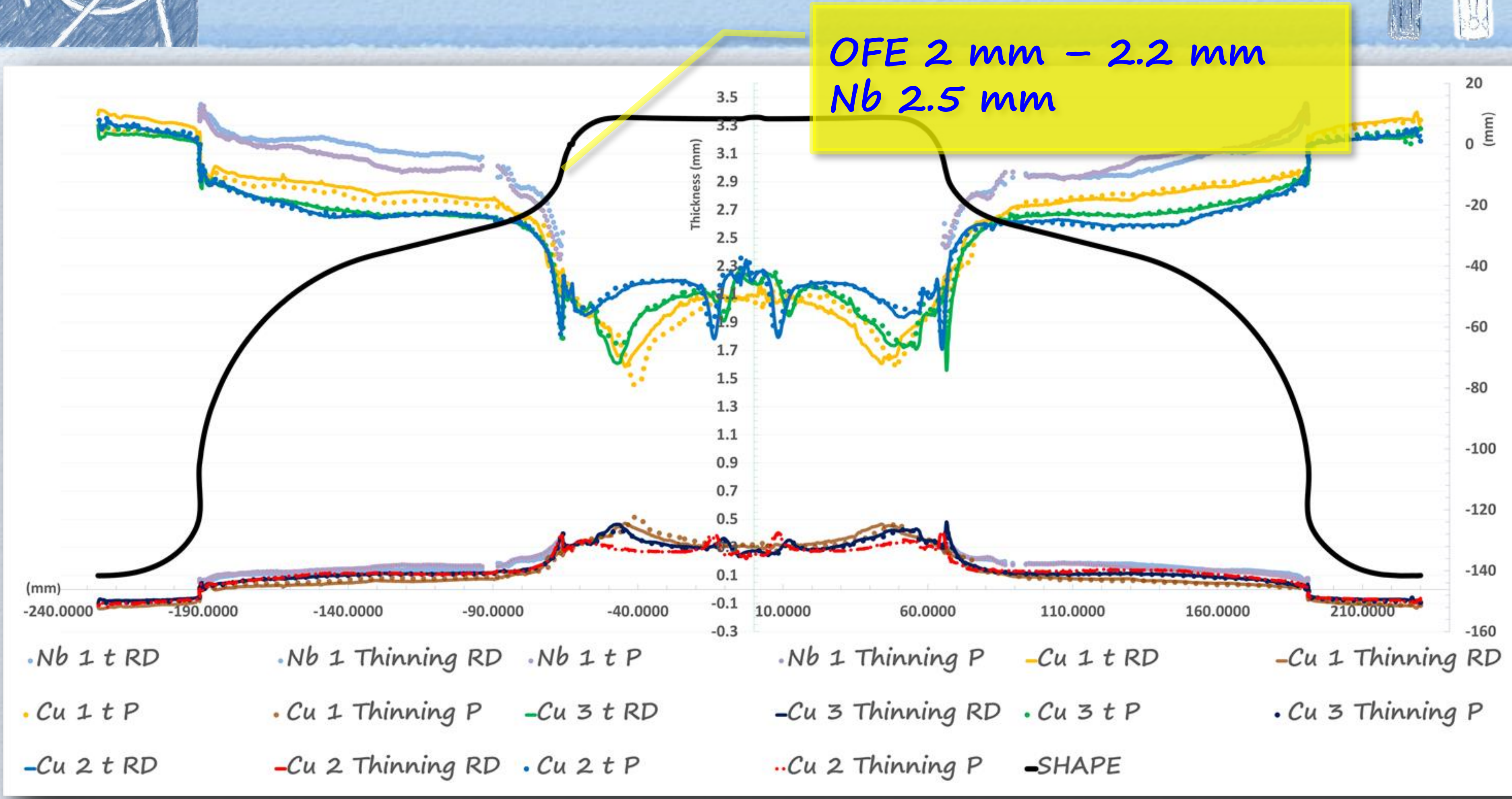
Exp. results: Nb 1st trial



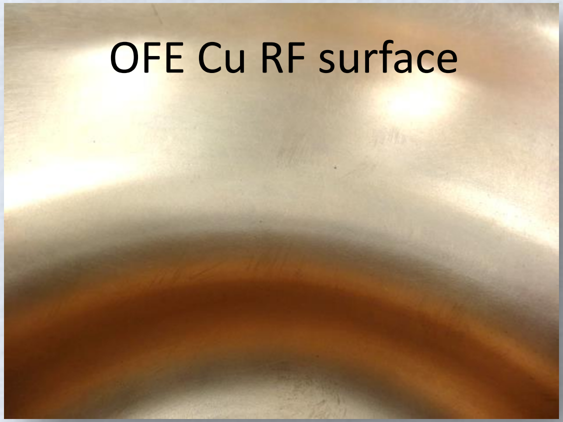
Sheet average hardness 64 HV10

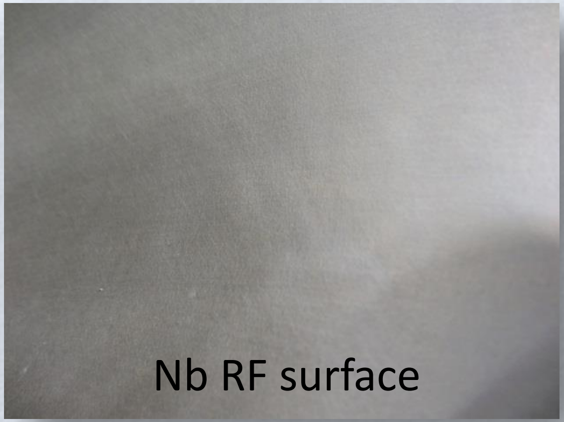
- Behaviour at high strain rate to be performed at CERN and Bmax;
- Parameters to be re-defined;
- New power generator by end of year.

Exp. results: thinning



Exp. results: roughness

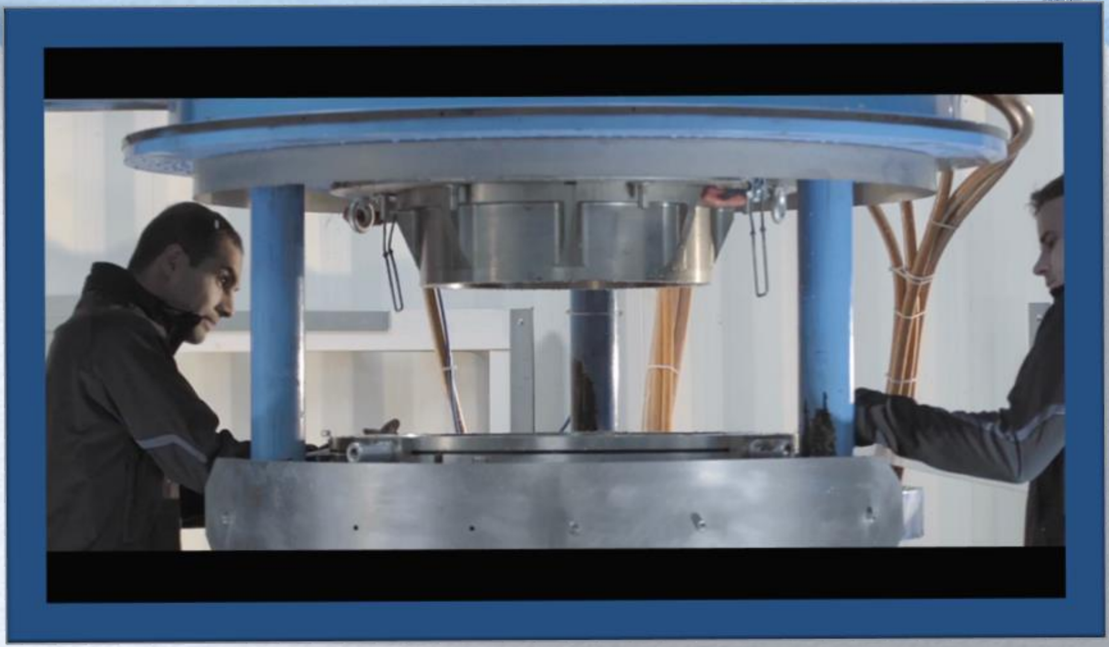




Id	Ra sheet (µm)	Rt sheet (µm)	Ra HEF (µm)	Rt HEF (µm)
OFE	0.2	3.5-5.8	0.2	2-12
Nb	0.8-0.9	7-11	0.9-1	8-11

Conservation of surface roughness

Summary



- Good agreement in between simulation and achieved shape accuracy,
- Reduced springback,
- The conservation of surface roughness and low wall thickness variation, could lead to an important reduction of post forming related surface treatment, as buffered chemical polishing (BCP) and electropolishing (EP).

Future plans

- High-velocity forming is potentially an alternative process.
- Geometrical precision, reproducibility, suitability for economic, small & large series production.
- Characterisation to be performed:
  - Typical raw materials: orthotropic and non-linear behaviour at quasi-static and high-strain rate regimes.
  - The development of material microstructure and of physical (e.g. RRR) and mechanical properties induced.
  - The influence of the main process parameters will be evaluated in terms of cavity performance (2 LHC 400 MHz) and one SPL 704 MHz).
- At a later stage, the technology could be applied to cavities with much more complex shapes, such as the crab cavities for the future upgrade of the LHC.

Thank you for your attention