CEC/ICMC 2013, Cryogenic Engineering Conference and International Cryogenic Materials Conference, Anchorage, June 17-21, 2013

Selection and properties of structural materials for cryogenic applications

Stefano Sgobba
EN-MME-MM
CERN

Outline

- The construction and operation of LHC and its experiments: an almost unique selection ground and testing bench for structural materials
- LHC, examples of successful innovative solutions
  - *The LHC beam screen*
  - *The 2500 near net shaped HIPed PM end covers*
- LHC experiments, the CMS example
  - *Reinforcement of the CMS Al-stabilized conductor produced in continuous 2.5 km lengths*
  - *Al-alloy end flanges of the 6.8 m diameter external cylinder of the 4 T superconducting solenoid*
- Ongoing developments
  - *Innovative materials for conductors of future particle experiments*
  - *Selection and characterization of structural materials for fusion magnets*
- Conclusion
  - *Materials to be identified together with a suitable manufacturing process at an early stage of a project*


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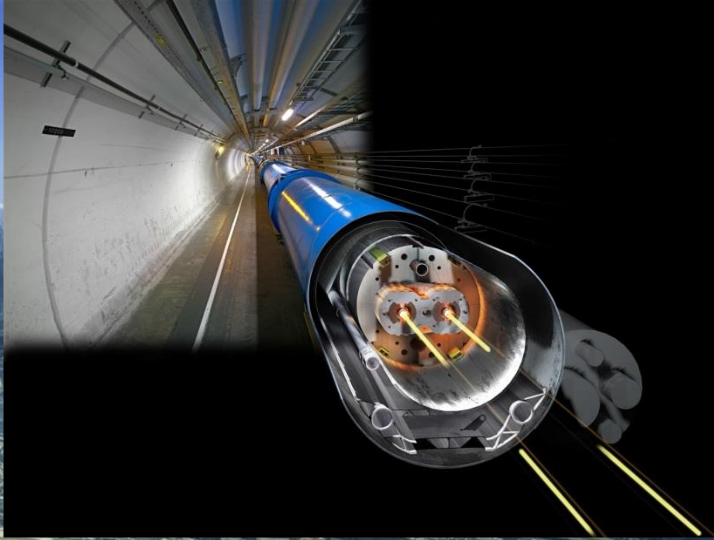
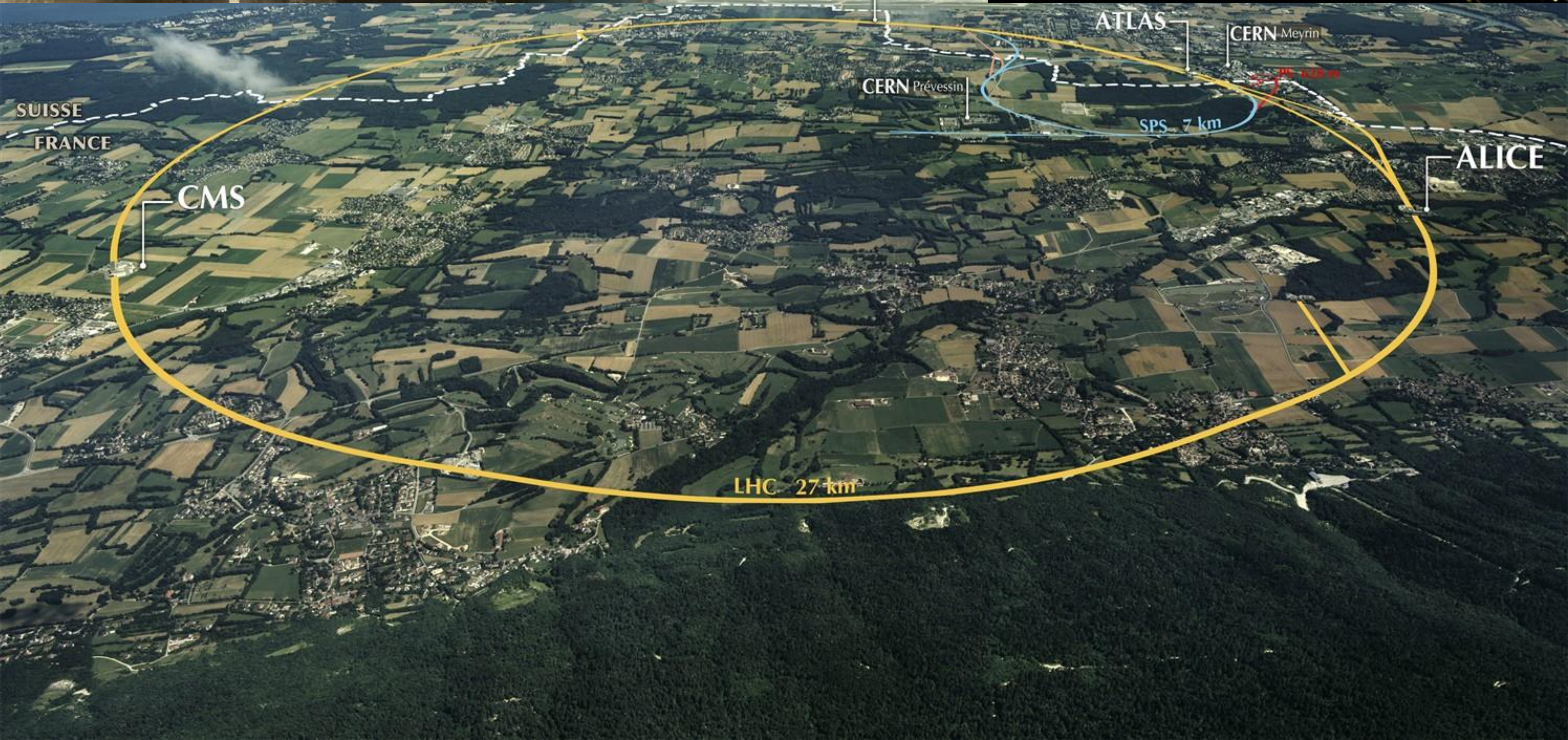
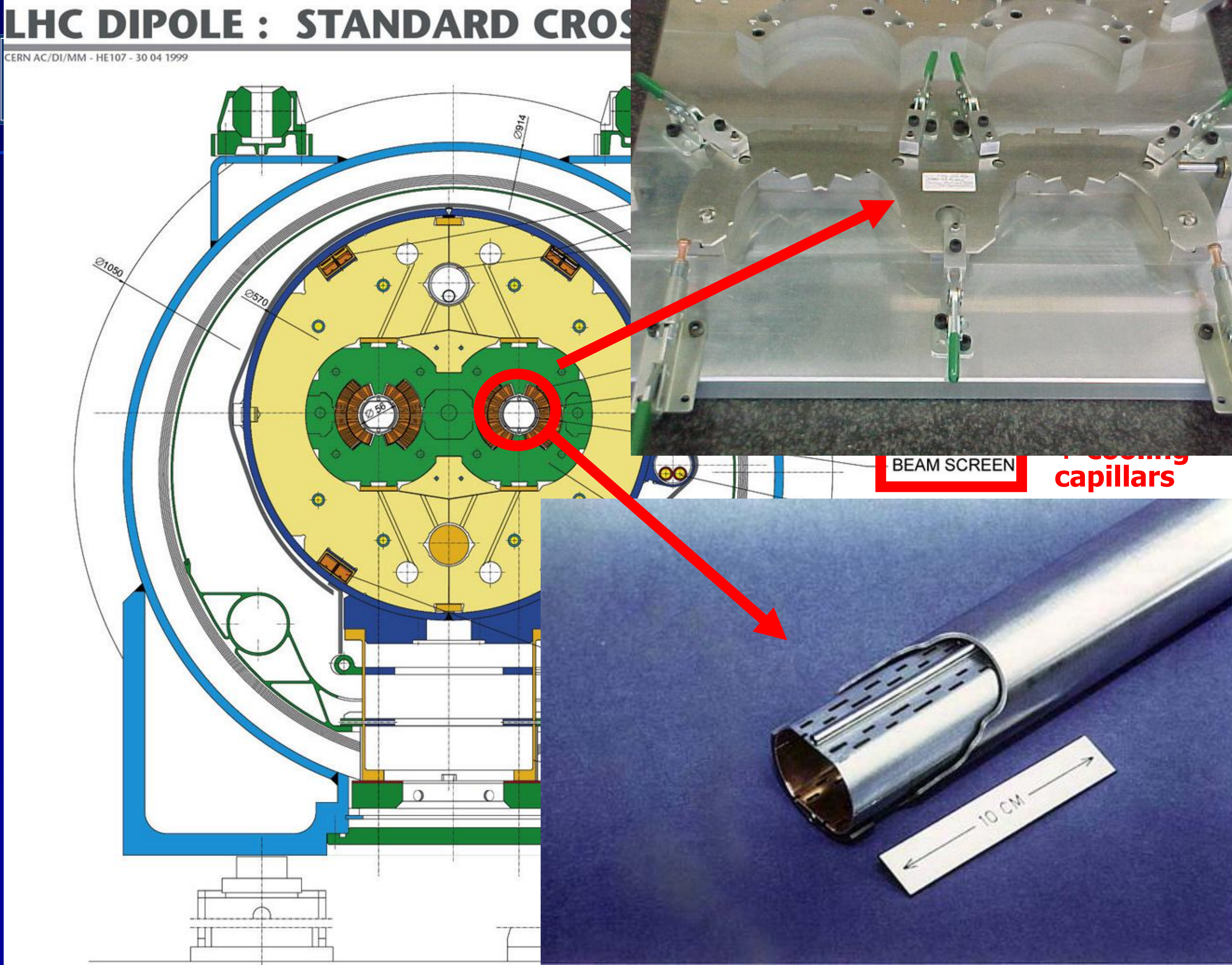
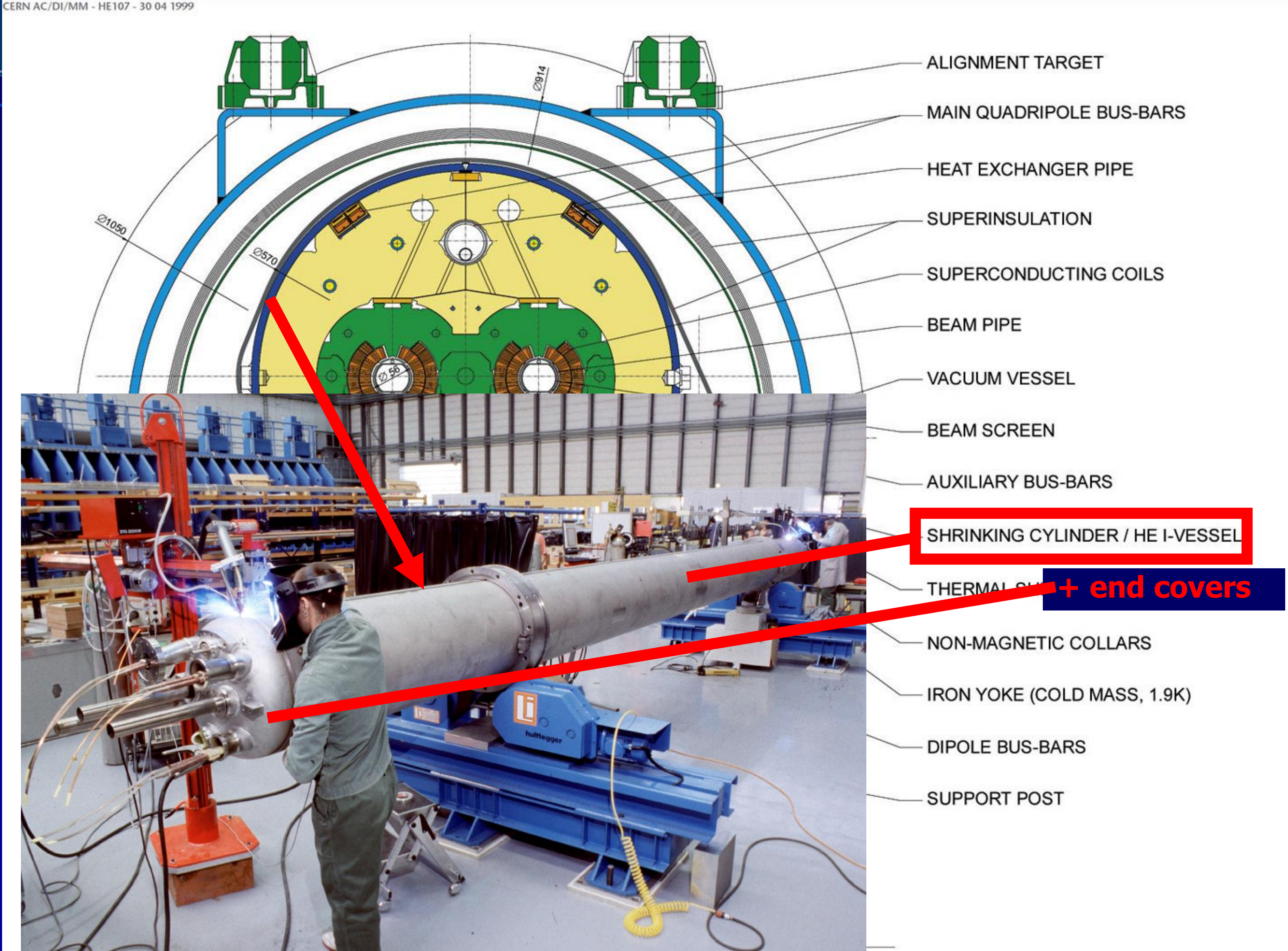



LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

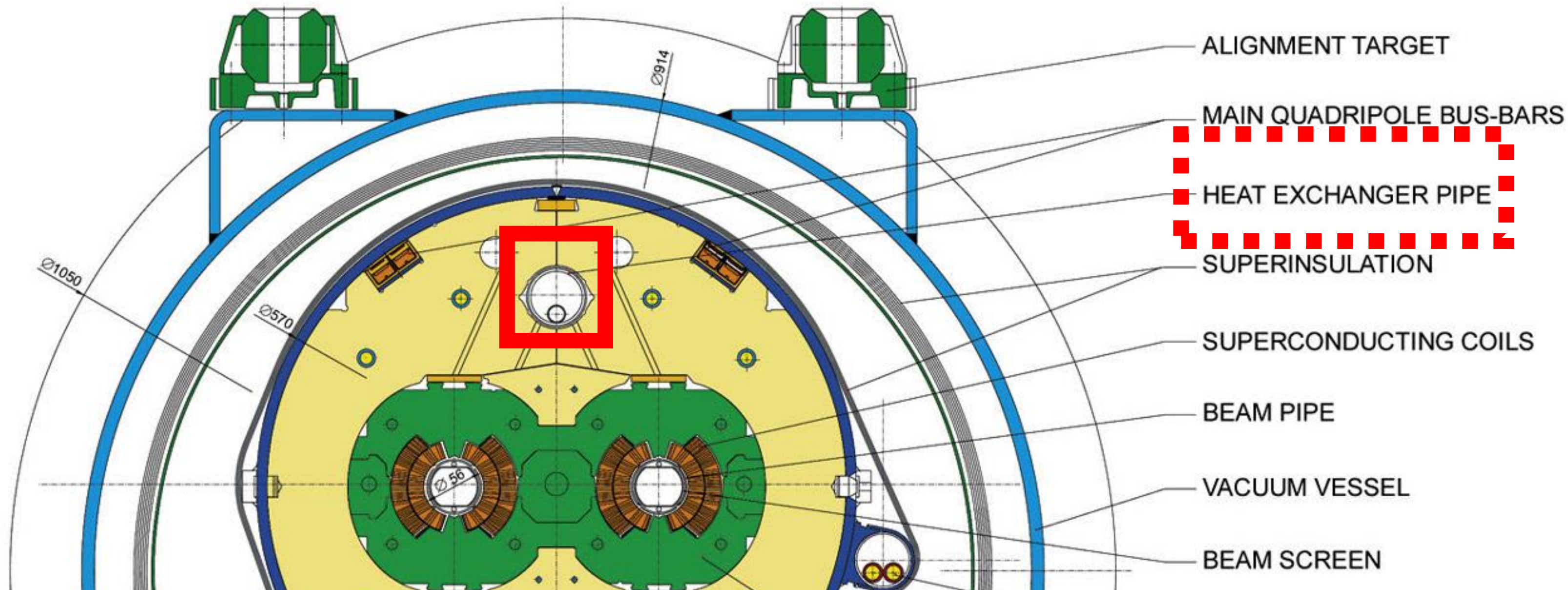

LHC DIPOLE : STANDARD CROS
CERN AC/DI/MM - HE107 - 30 04 1999
Ø914
Ø1050
Ø570
Ø 56
BEAM SCREEN
capillars
10 CM

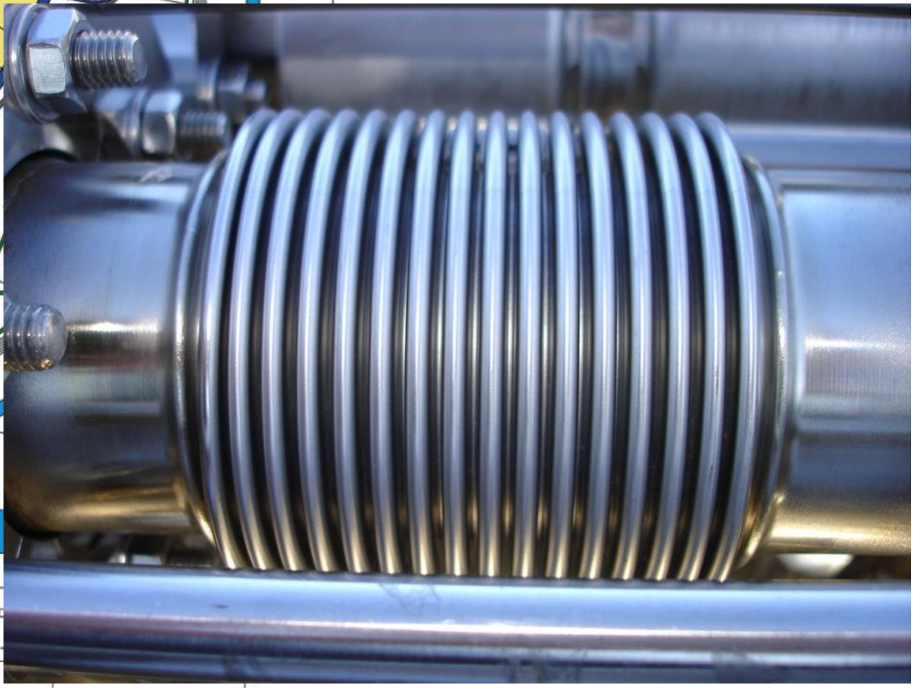
LHC DIPOLE : STANDARD CROSS-SECTION

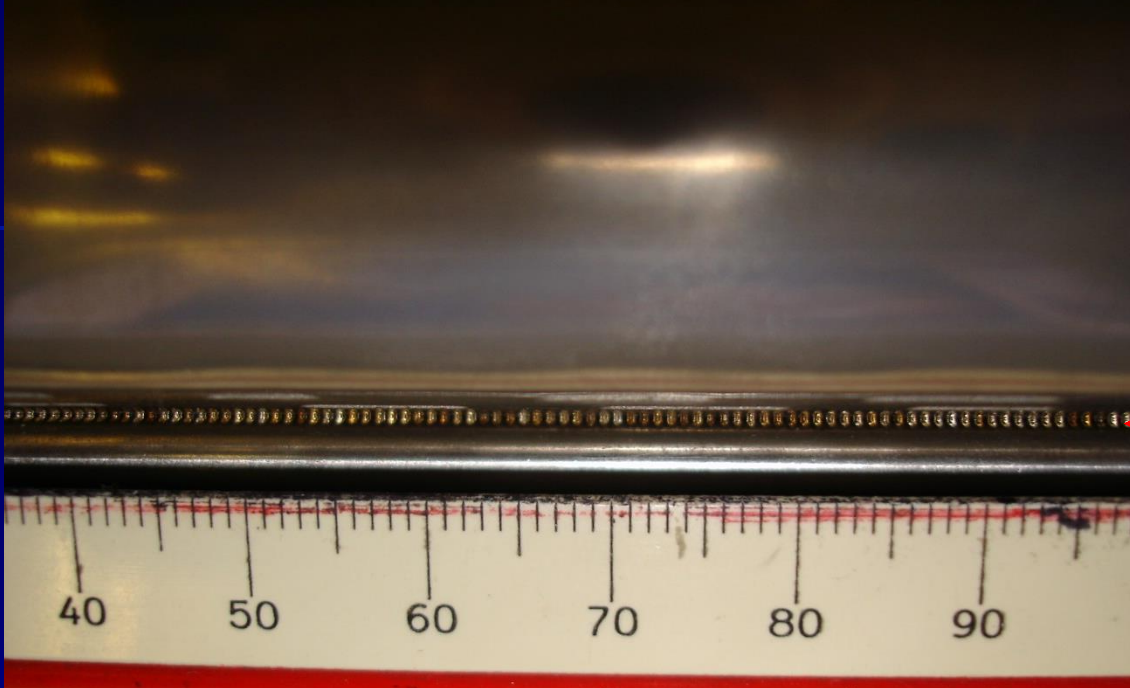


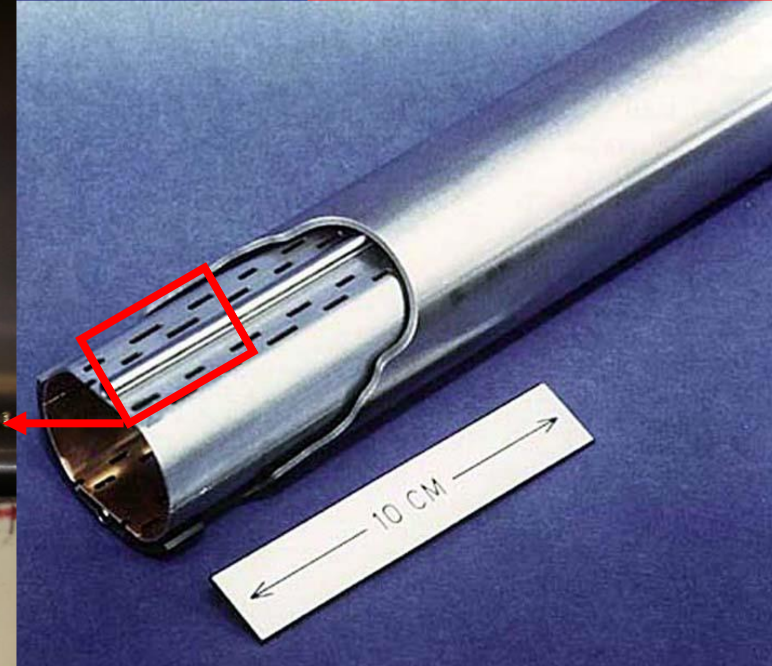
LHC DIPOLE : STANDARD CROSS-SECTION

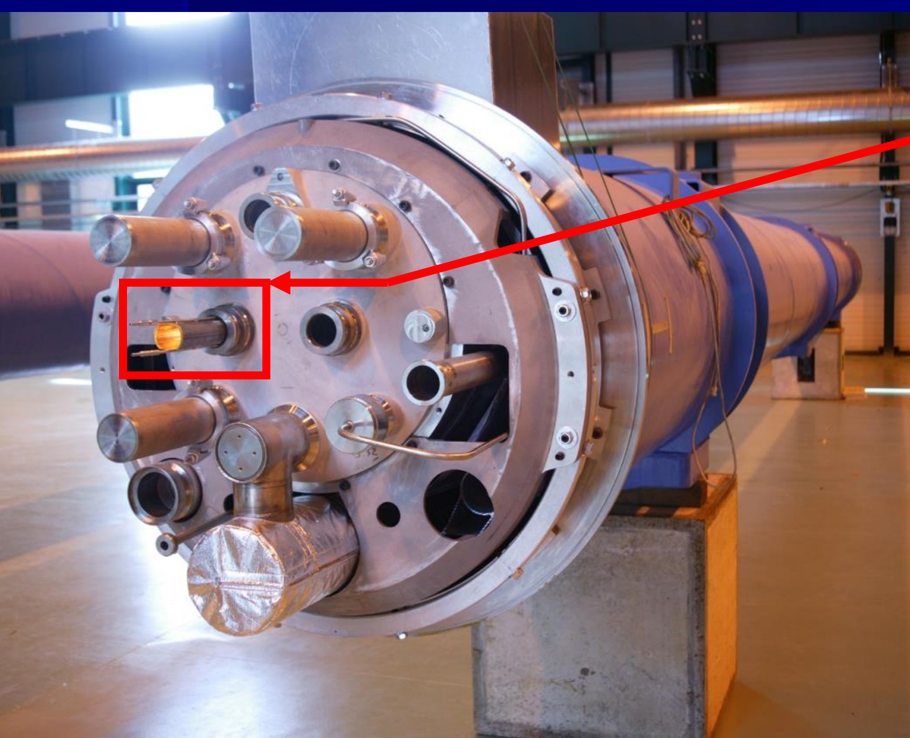
CERN AC/DI/MM - HE107 - 30 04 1999









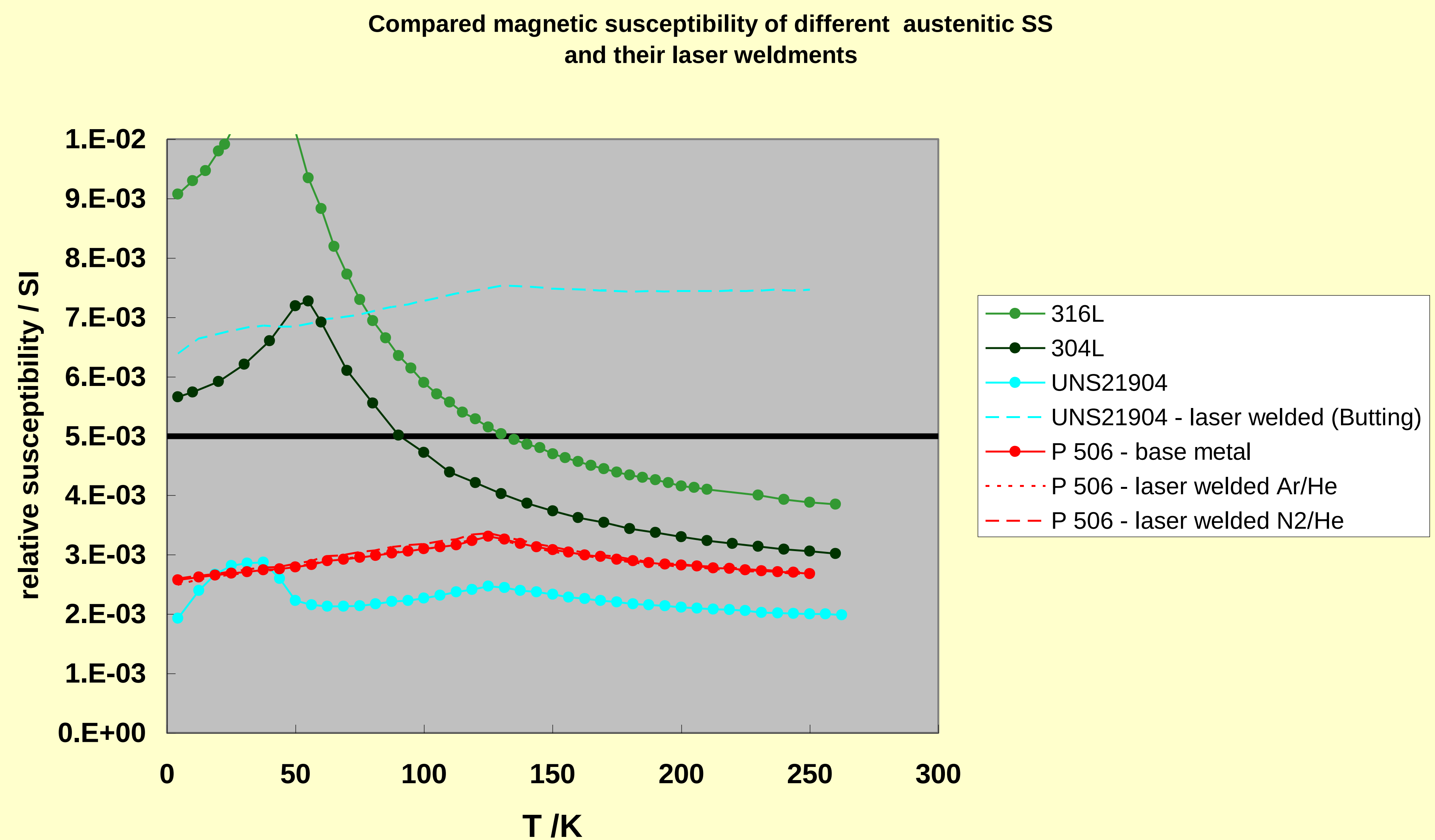


Development of a new stainless steel for the LHC beam screen and the cooling capillaries

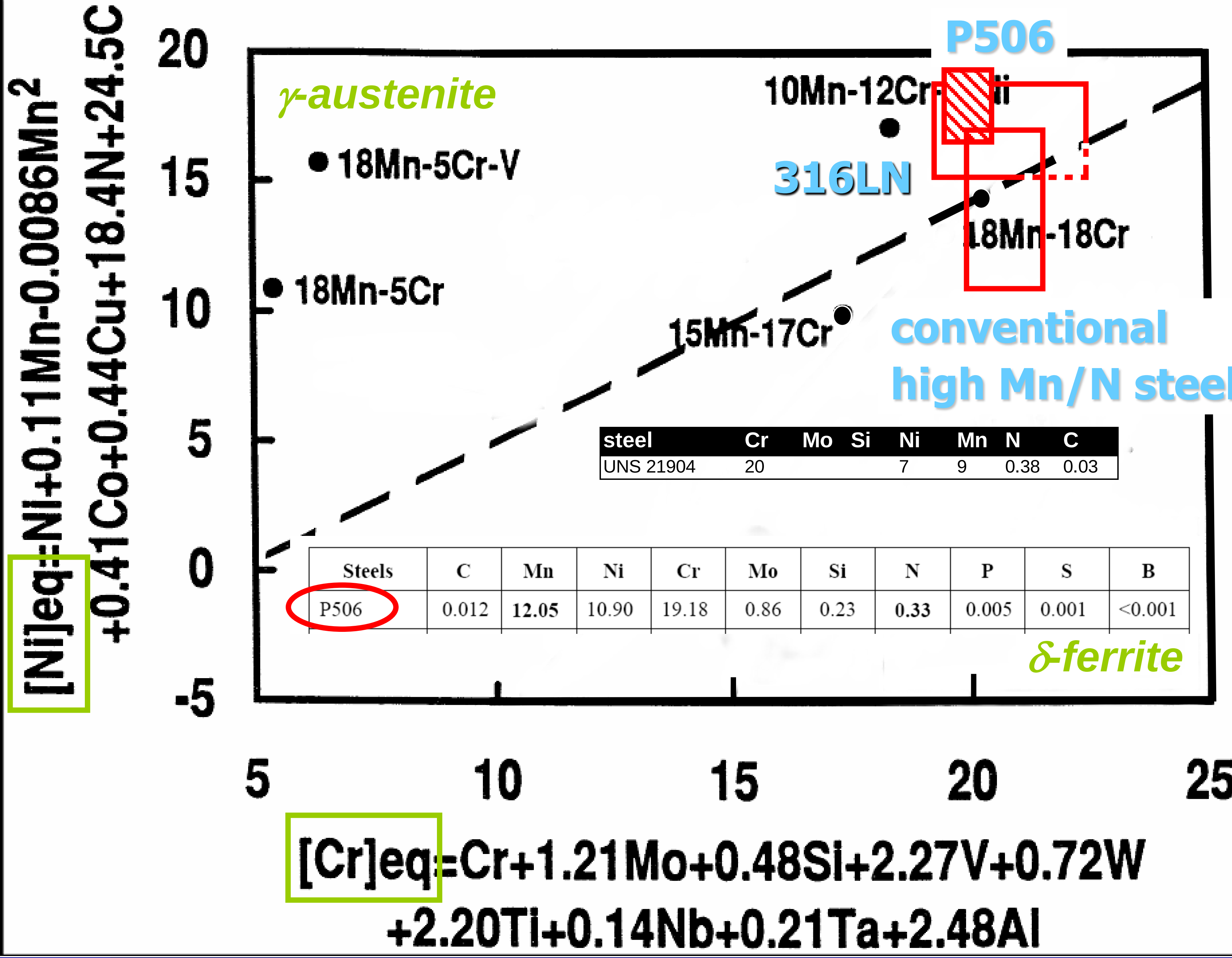
Challenging scope:

- Magnetic susceptibility $\leq 5 \cdot 10^{-3}$ at operating T in weld and parent material
- Fully stable
- Millions of laser welding points fully leak tight
- Absence of hot cracking
- High strength and toughness (> 200 J)
- Thermal contraction not far from 316LN
- Corrosion behaviour $\approx$ 304L, 316LN
- Affordable price (several tens of km…)

Examples of innovative solutions: LHC beam screen

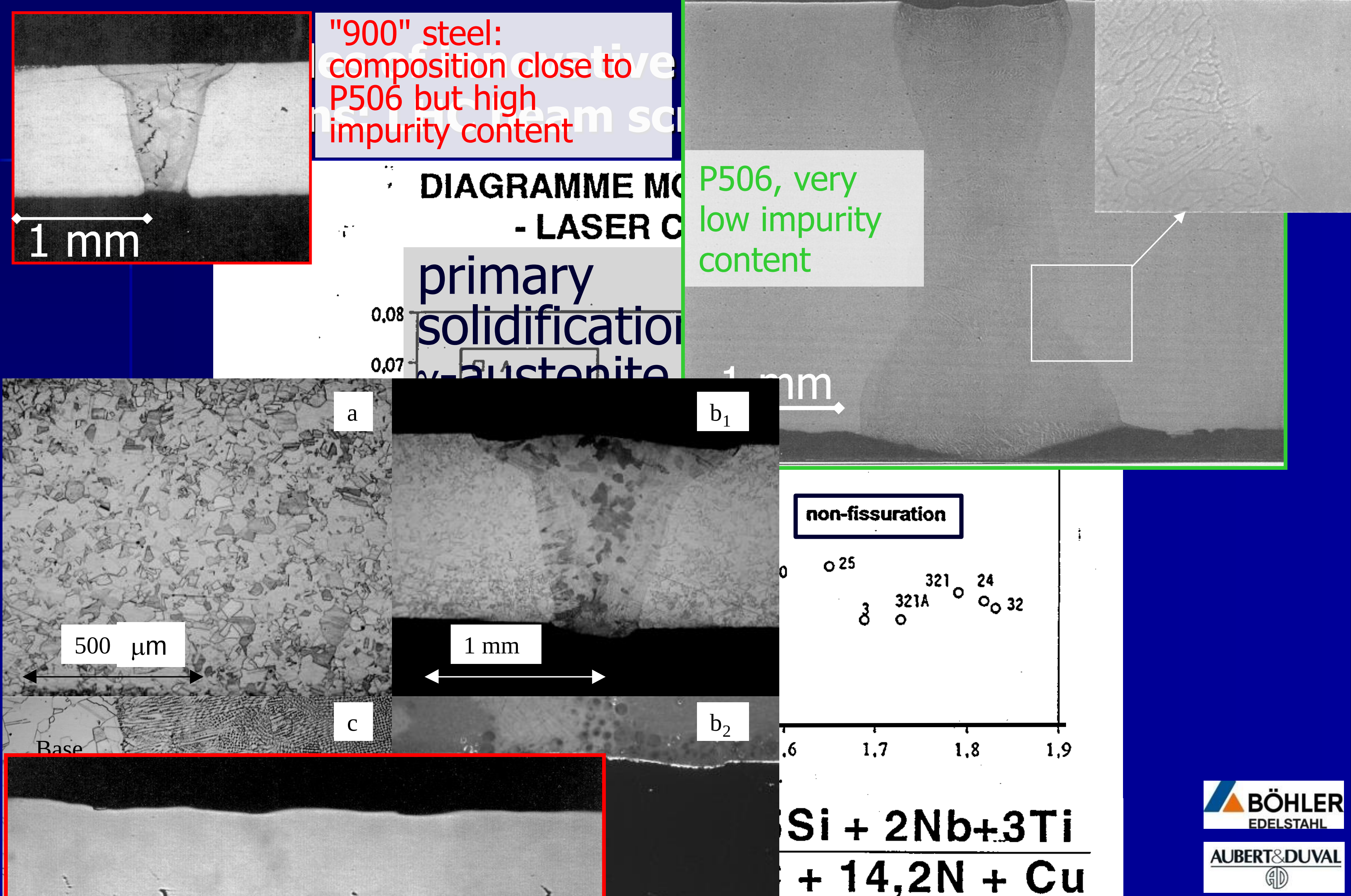


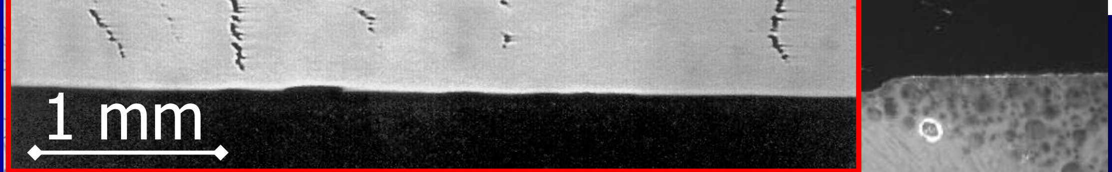
S. Sgobba and G. Hochoertler: *A New Non-Magnetic Stainless Steel for Very Low Temperature Applications,* Proc. Int. Congress Stainless Steel 1999: Science and Market, Chia Laguna /IT, 6-9 June 1999, **2**, p. 391-401



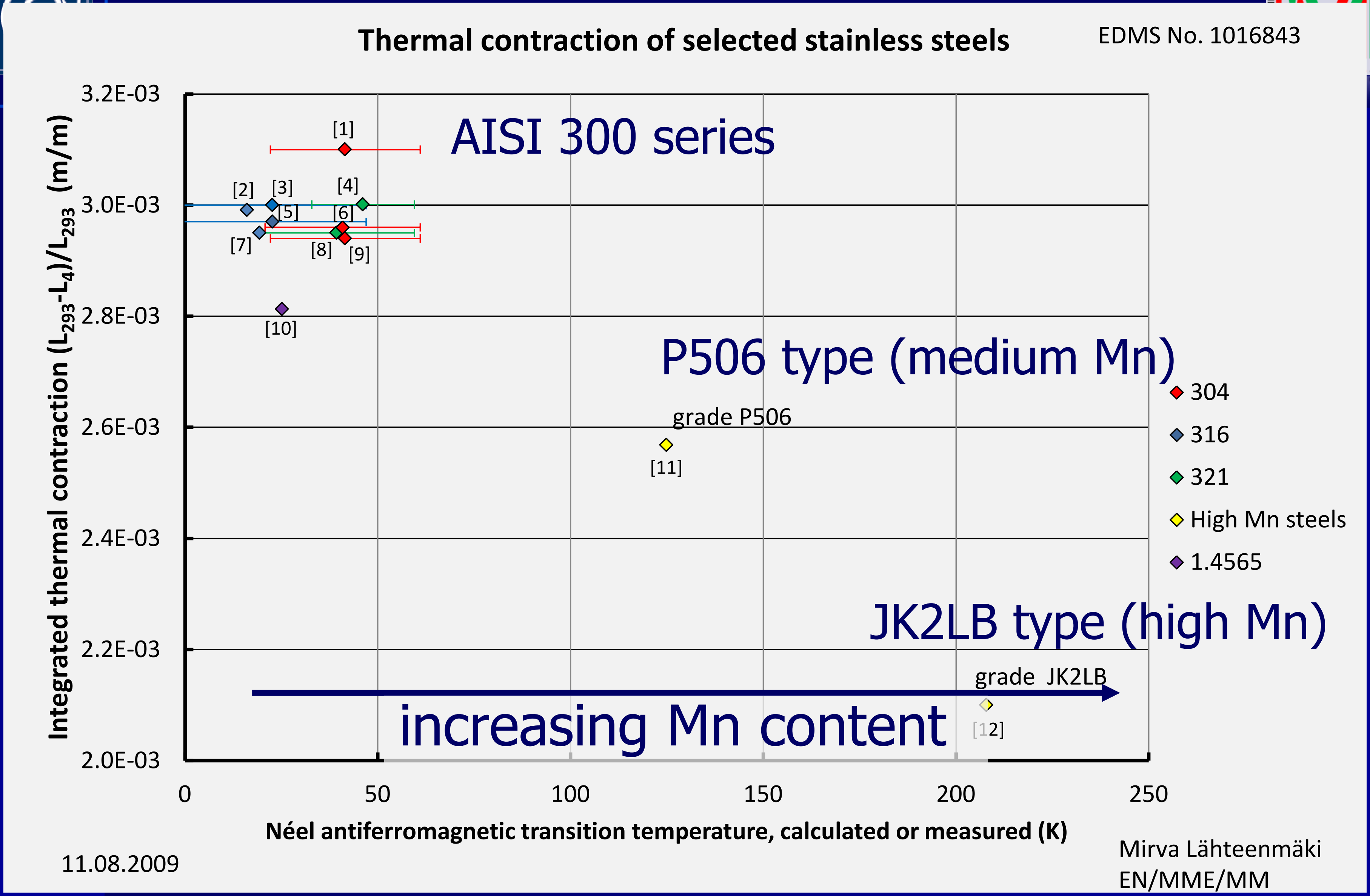
steel	Cr	Mo	Si	Ni	Mn	N	C
UNS 21904	20			7	9	0.38	0.03

Steels	C	Mn	Ni	Cr	Mo	Si	N	P	S	B
P506	0.012	**12.05**	10.90	19.18	0.86	0.23	**0.33**	0.005	0.001	<0.001

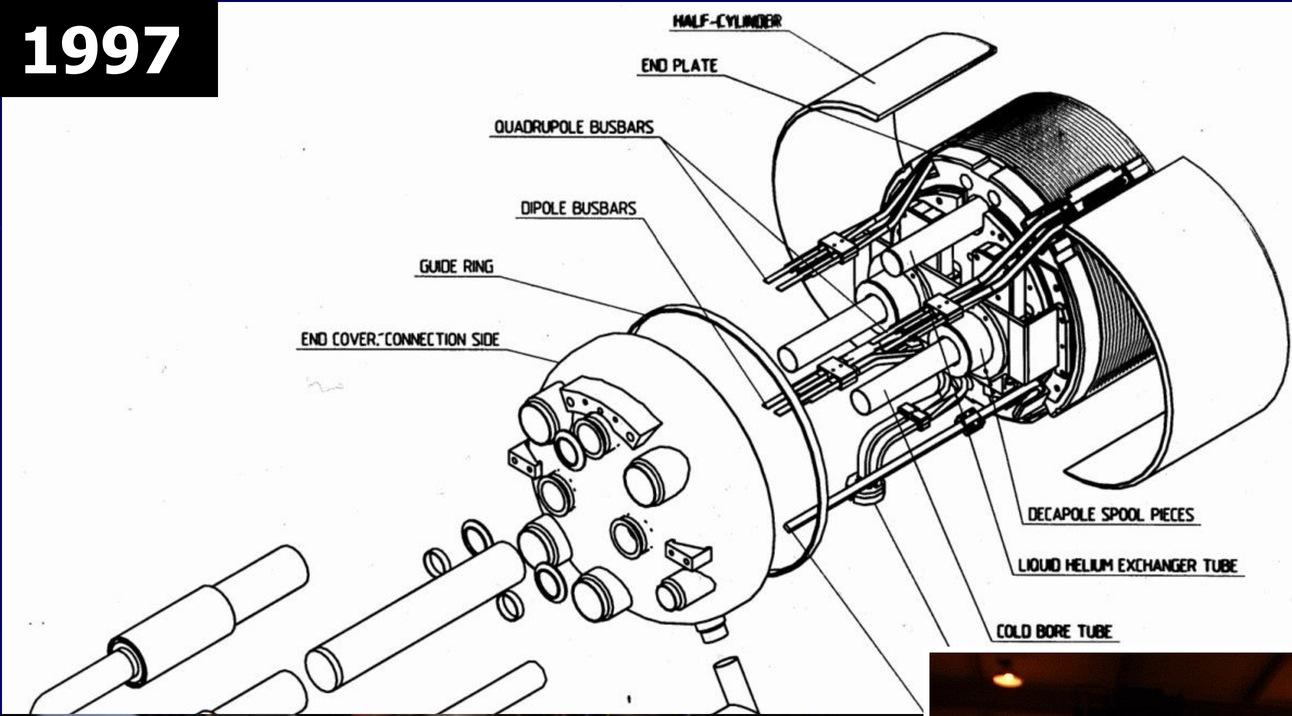


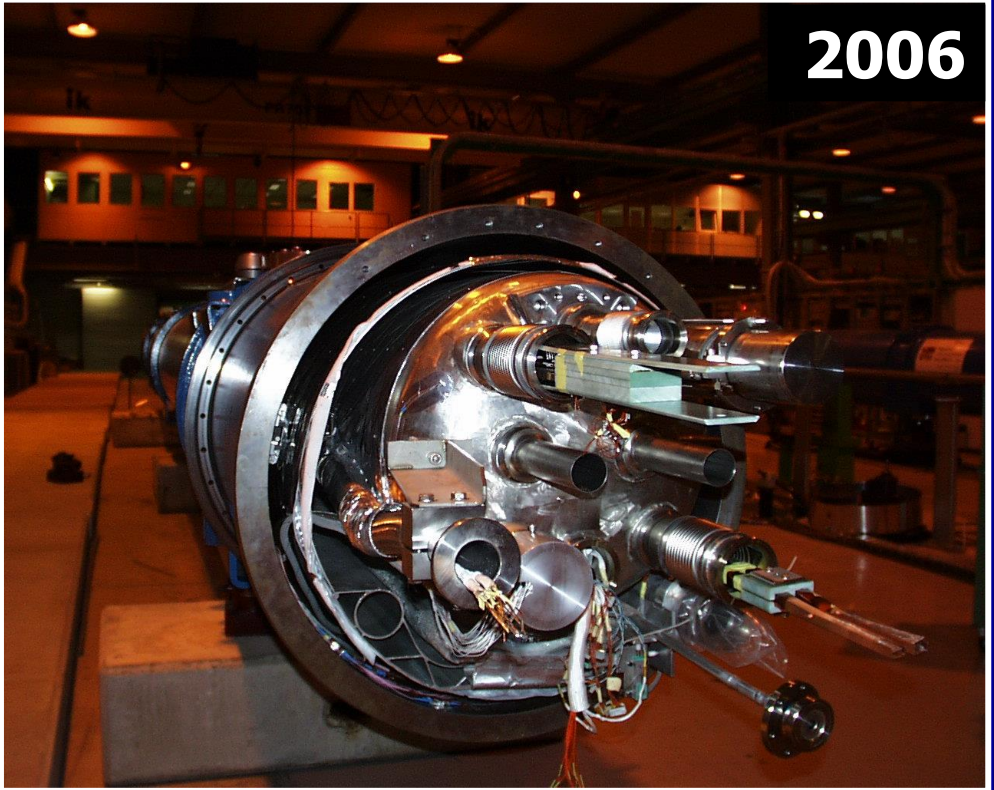


Boudot, Matériaux et Techniques **95**, n°11-12, p. 23 (1997);
Sgobba, Bulletin du Cercle d'Etude des Métaux, **XVI**, p. 13.1 (1995);
S. Sgobba: proc. Cycle Métaux et Procédés, 1996, p. 8/1-10


Thermal contraction of selected stainless steels
EDMS No. 1016843
3.2E-03
3.0E-03
2.8E-03
2.6E-03
2.4E-03
2.2E-03
2.0E-03
Integrated thermal contraction (L_{293}-L_4)/L_{293} (m/m)
AISI 300 series
[1]
[2]
[3]
[4]
[5]
[6]
[7]
[8]
[9]
[10]
P506 type (medium Mn)
grade P506
[11]
JK2LB type (high Mn)
grade JK2LB
[12]
increasing Mn content
304
316
321
High Mn steels
1.4565
0
50
100
150
200
250
Néel antiferromagnetic transition temperature, calculated or measured (K)
11.08.2009
Mirva Lähteenmäki
EN/MME/MM

LHC magnets, PM HIPed end covers

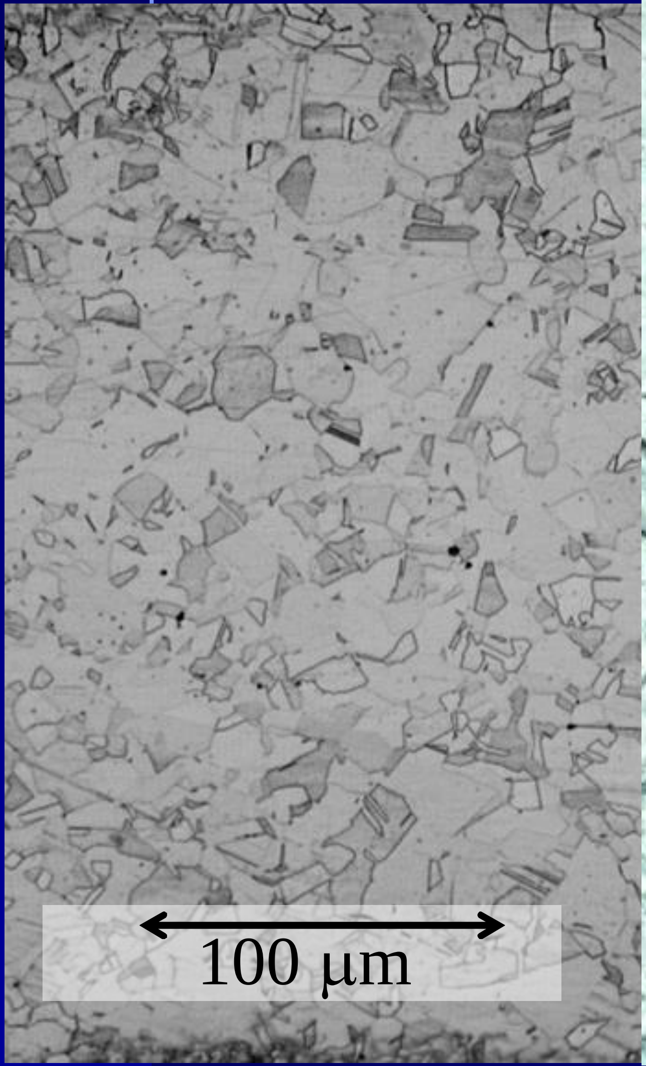


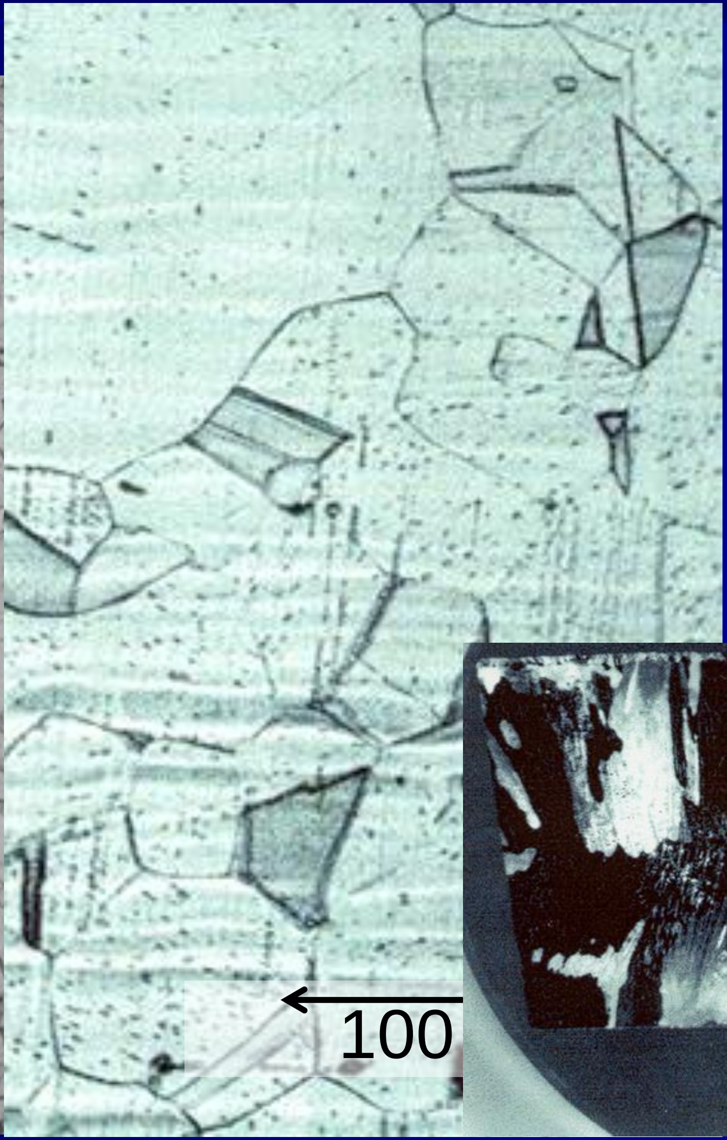


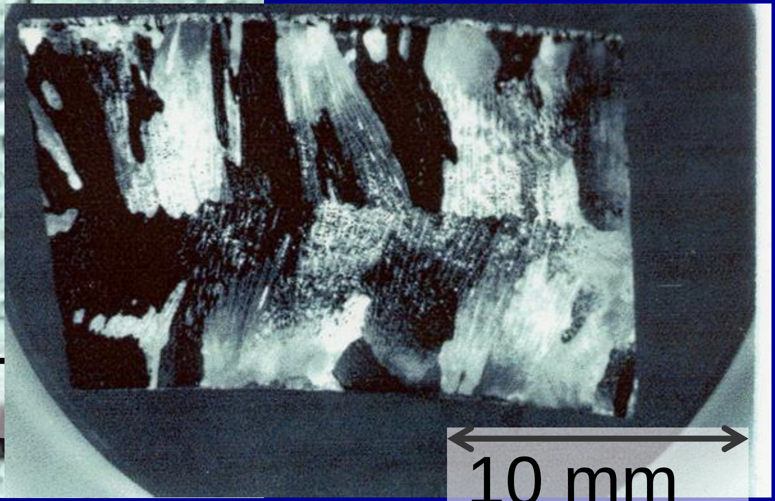
LHC magnets, PM HIPed end covers

After capsule removal by pickling and solution annealing, before machining

LHC magnets, PM HIPed end covers







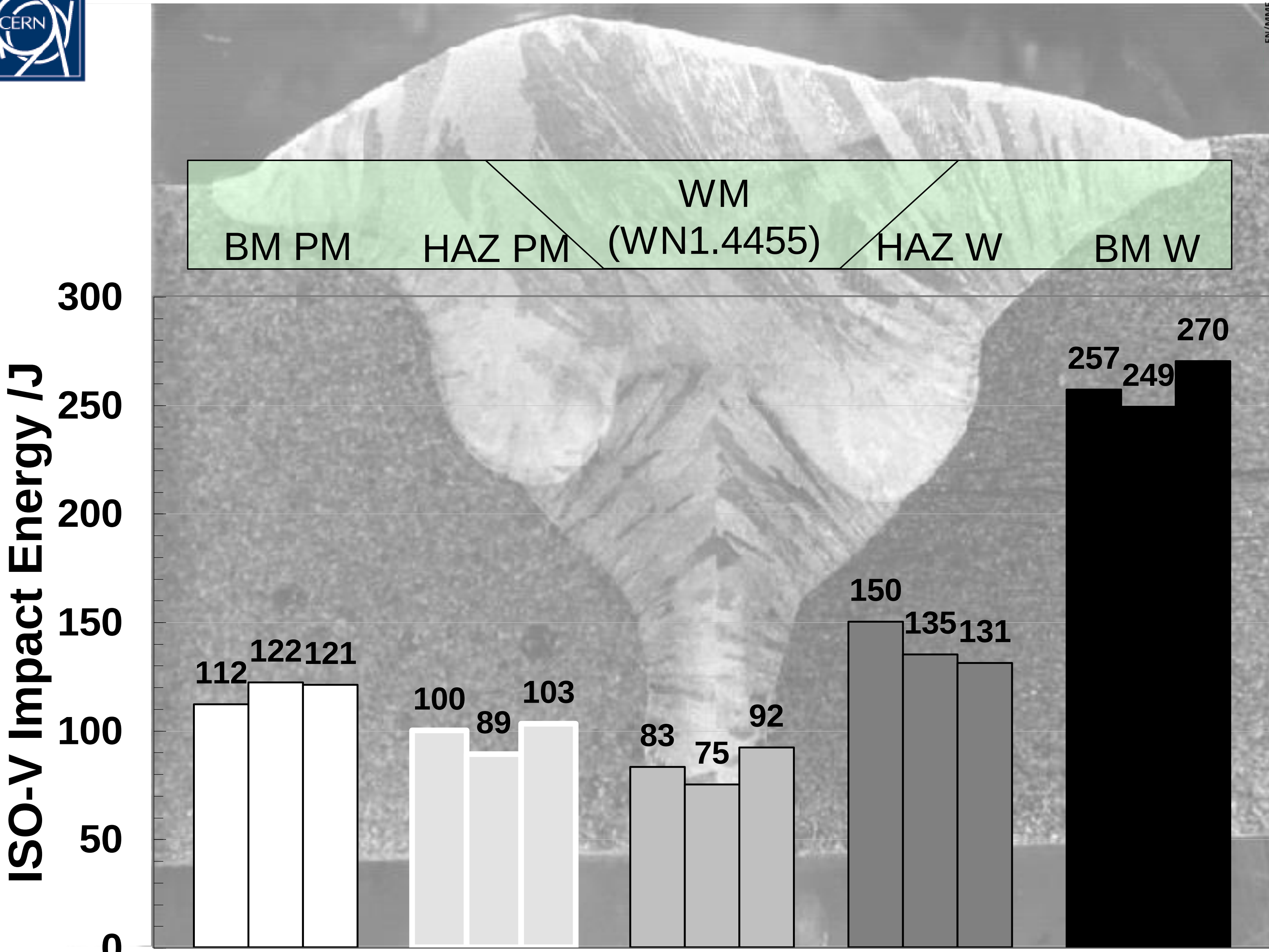
Price competitive compared to wrought and cast

LHC magnets, PM HIPed end covers

HIPed PM 316LN		Metso	CERN Specification	
		H 6277	*Min.*	*Max.*
Composition (w%)	C	**0.017**		0.030
	Si	**0.59**		1.00
	Mn	**0.71**		2.00
	S	**0.005**		0.015
	P	**0.012**		0.040
	Ni	**13.07**	12.00	14.00
	Cr	**16.98**	16.00	18.00
	Mo	**2.53**	2.00	3.00
	O	**0.011**		
	N	**0.185**	0.15	0.20

Typical Oxygen levels

in 316LN:	Couturier et al. (1998)	**200 ppm**
	Dellis et al. (1996)	**195 ppm**
in 304L:	Appa Rao and Kumar. (1997)	**400 ppm**
in aust. SS	Zou and Grinder (1982)	**300 to 4500 ppm**
in 304L	Dunkley (1981)	**1200 to 7800 ppm**

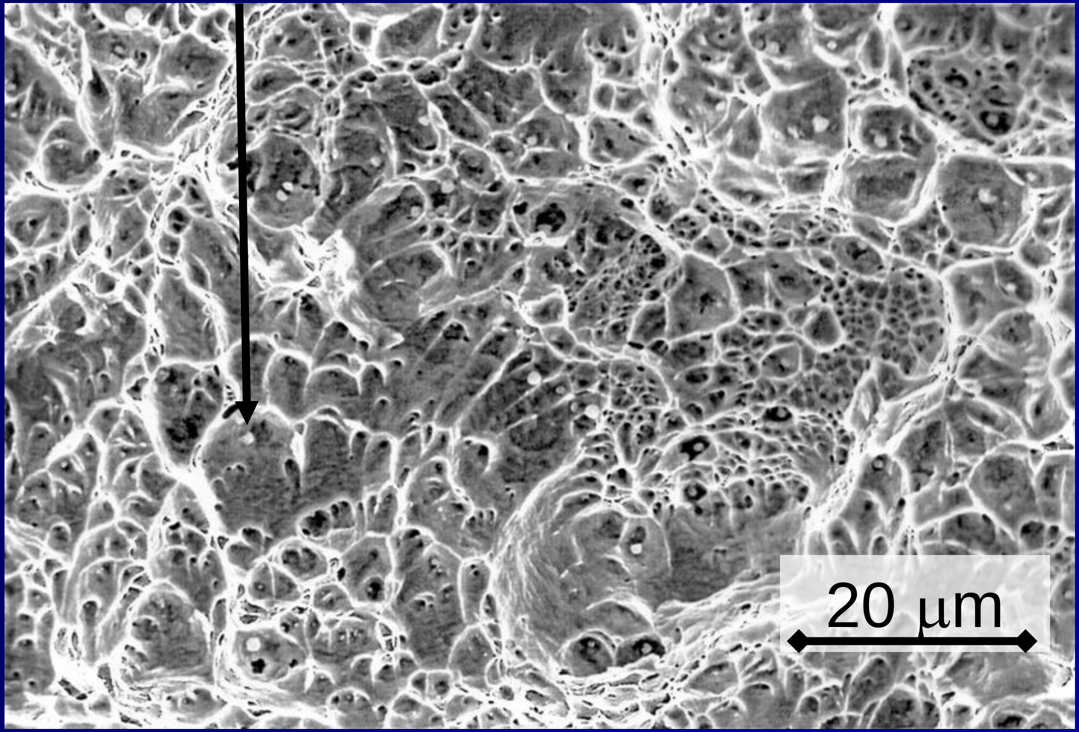


WM
(WN1.4455)
BM PM
HAZ PM
HAZ W
BM W
ISO-V Impact Energy /J
300
250
200
150
100
50
0
112
122
121
100
89
103
83
75
92
150
135
131
257
249
270

LHC magnets, PM HIPed end covers

Fractographic analysis

Oxides within dimples



Localized ductility (Couturier 99)

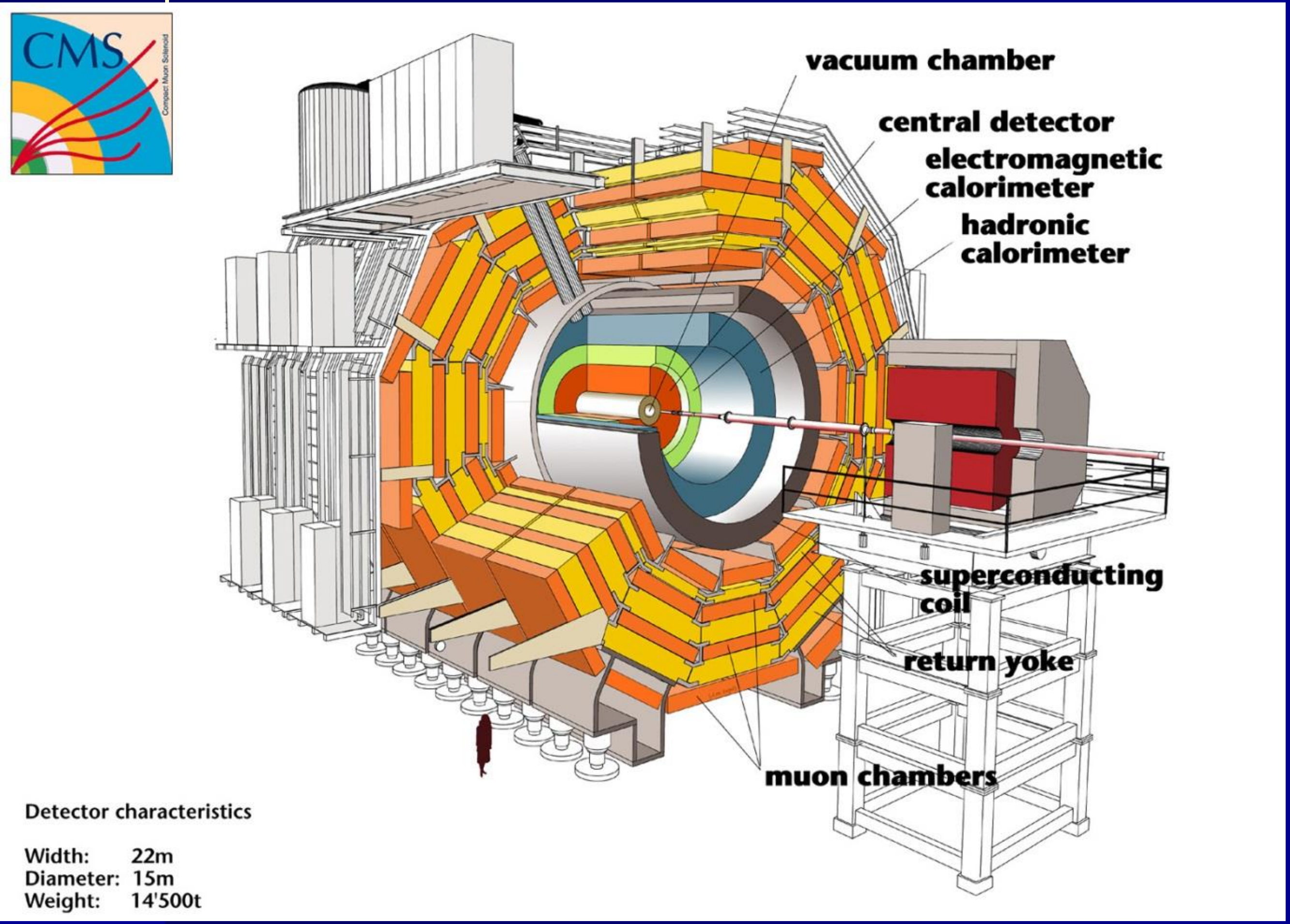
PM Design Competition Award Winner

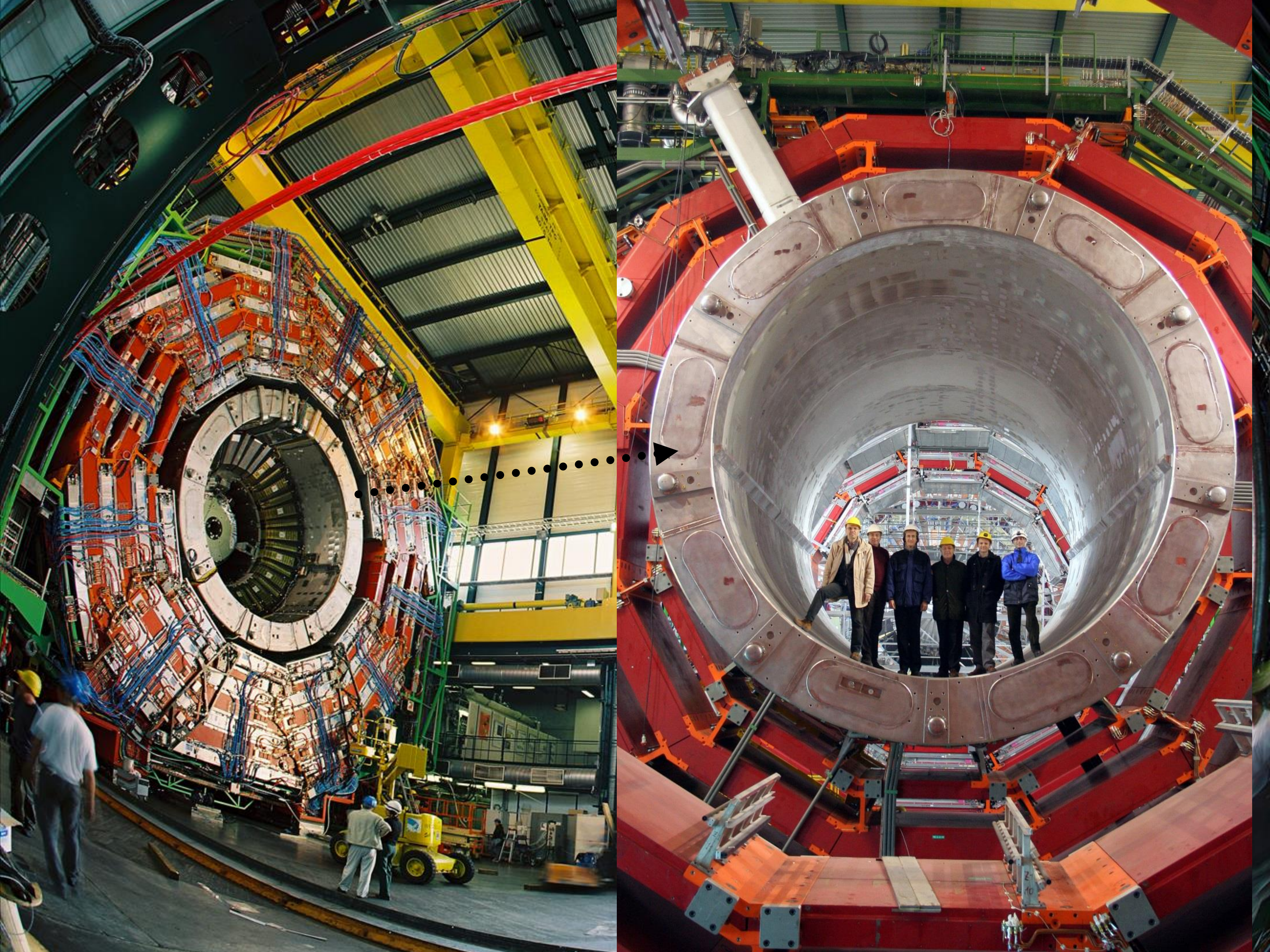
Award: Grand Prize
Year: 2007

Description:
The award was given to an end cover is used in the Large Hadron Collider, the world's largest and highest energy sub-atomic particle accelerator. Made from 316LN stainless steel powder, the part is hot isostatically pressed to full density. The superconducting dipole cryomagnets operate in a cryogenic environment at minus 450°F. As HIPed to a near-net shape of 253.5 pounds, the finished end cover weighs 153.3 pounds. The fabricator incorporated finite element analysis, computer aided design, numerically controlled sheet metal cutting technology, and cutting-edge robotic welding and part manipulation to produce the end covers. This resulted in a more-than-50-times increase over the typical production rate of fully-dense HIPed PM near-net shapes, an unprecedented breakthrough in productivity. About 2,700 end covers have been delivered to CERN. The design of the part features several complex configurations. For example, both the inner and outer surface of the broad face is radiused with the inner surface approximately parallel to the outer surface. The exterior of the curved surface has either eight or 10 projections, depending upon which version of the part is produced. The design differs slightly depending on which side of the dipole magnet it is located. The PM HIPed part meets the equivalent mechanical properties of 316LN wrought stainless steel, including internal toughness and high ductility.

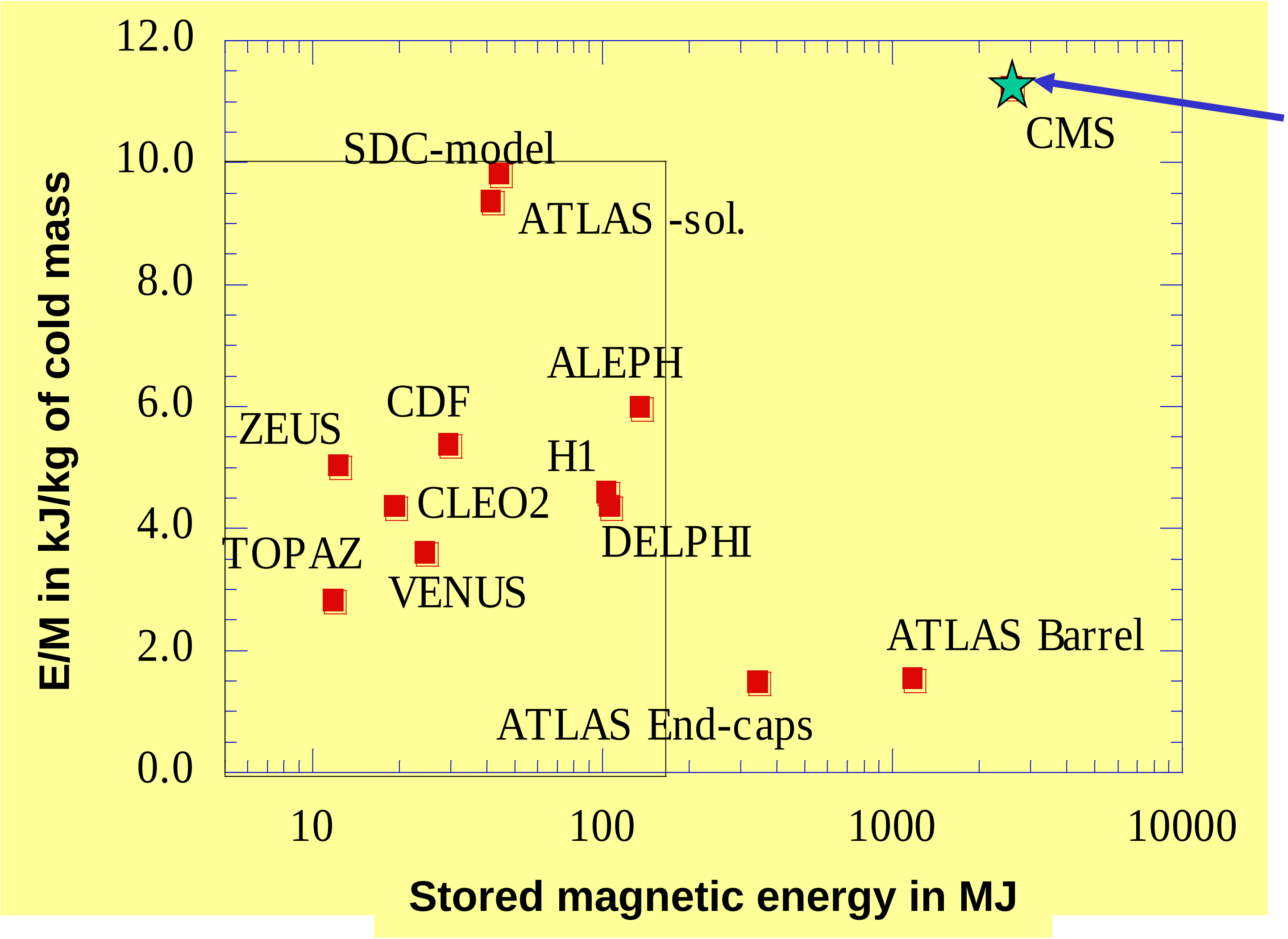
Part: Dipole Cryomagnet End Cover
Fabricator: Bodycote HIP-Surahammar
End User: Metso Materials Technology Oy for CERN

LHC experiments, the CMS example:
reinforcement of the Al-stabilized conductor



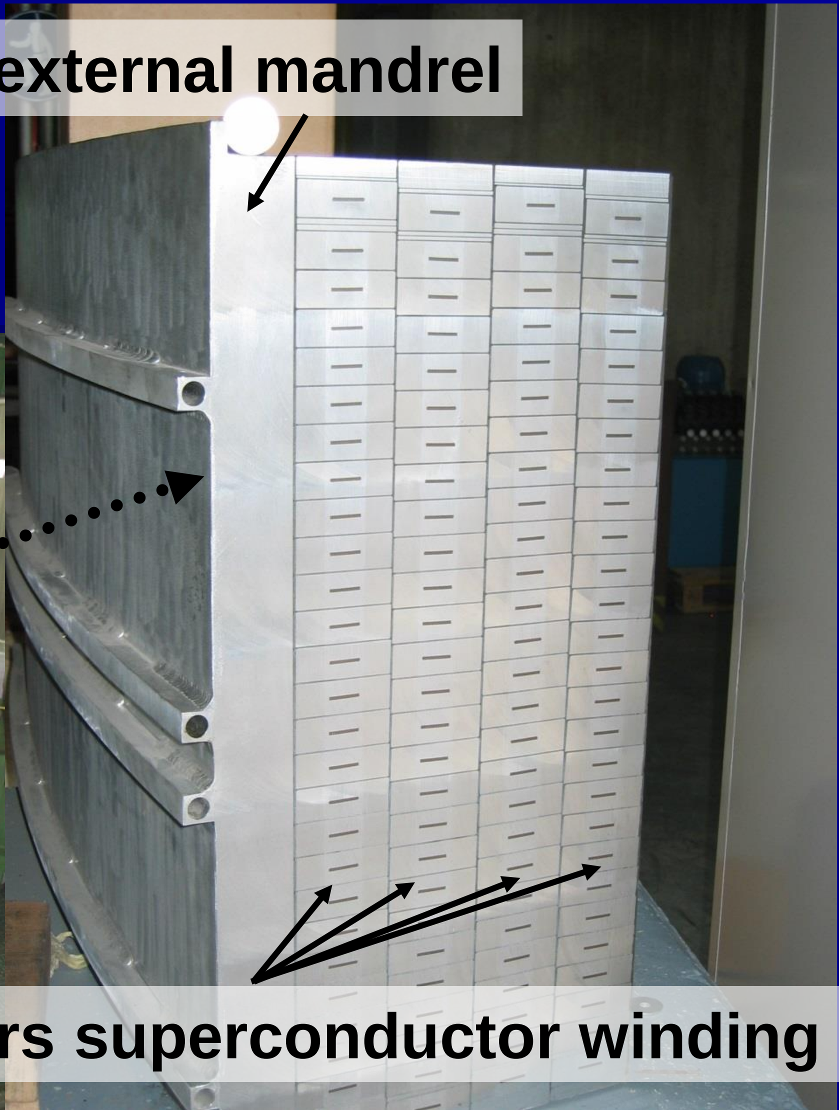


E/M ratio vs. E for several solenoids

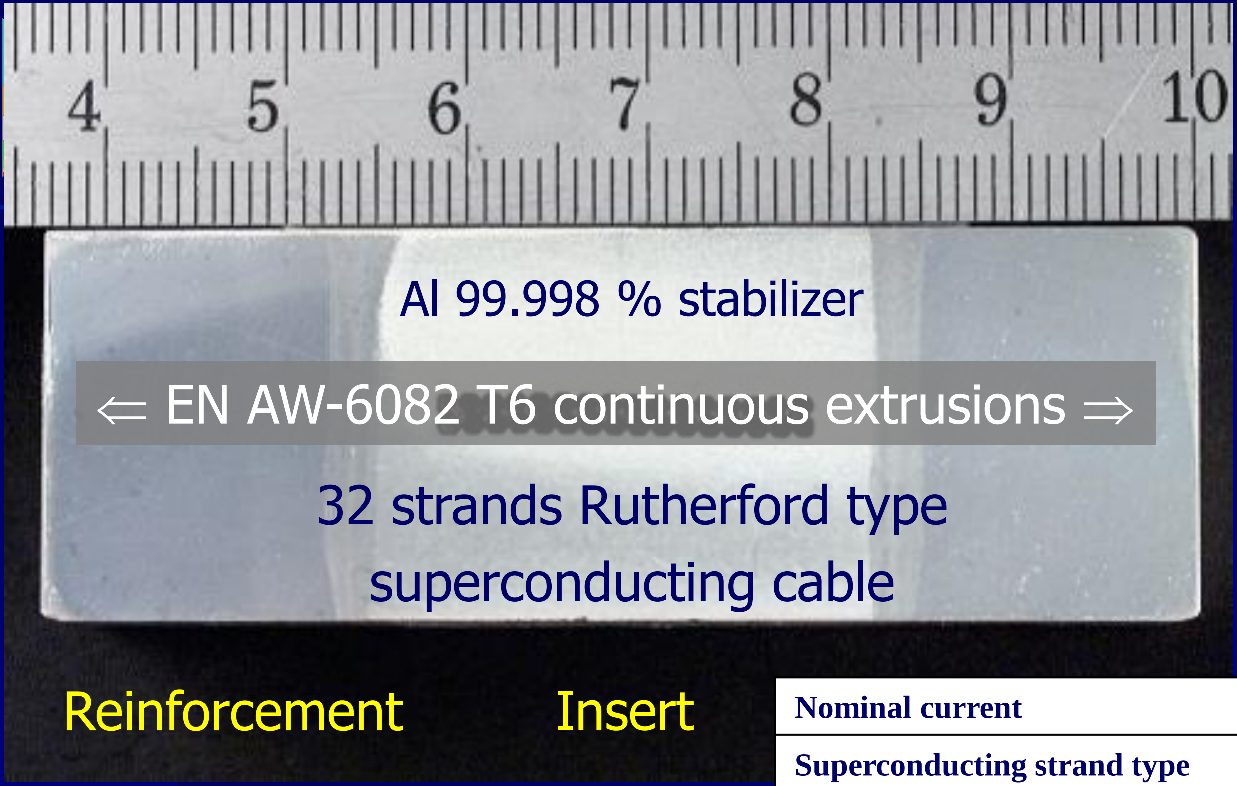


This 'anomalous' positioning meant that innovative solutions were needed to face this challenge

LHC experiments, the CMS example:
reinforcement of the Al-stabilized conductor



LHC experiments, the CMS example: reinforcement of the Al-stabilized conductor



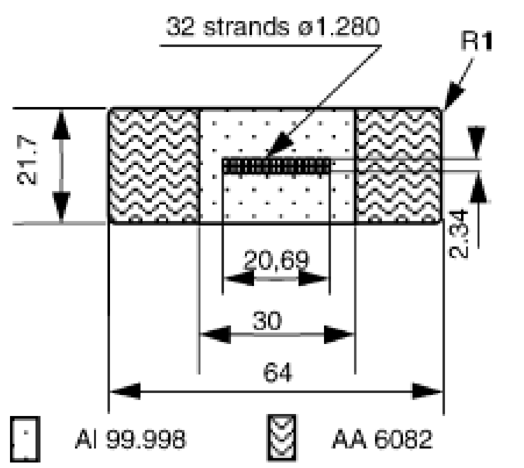
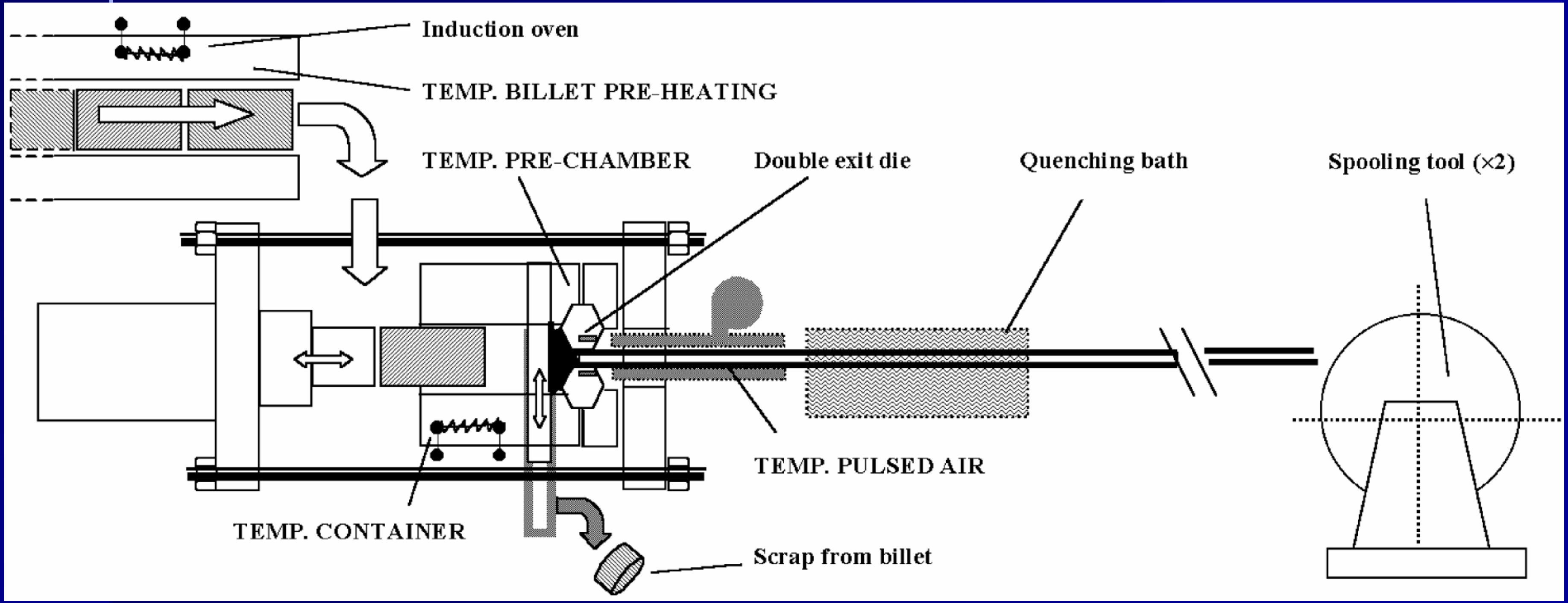


Fig. 1. Cross-section of the conductor.

structural materials

Nominal current	20 kA
Superconducting strand type	NbTi- Cu stabilized
Strand Cu/SC ratio	1.1
Number of strands	32
Strand diameter	1.28 mm
Rutherford cable cross section	20.68 mm x 2.34 mm
Insert cross section	30 mm x 21.6 mm
High Purity Aluminum stabilizer	Al 99.998 %
RRR aluminum at 0 T, annealed	> 1500
Reinforcement material	EN AW-6082
Conductor cross section	64 mm x 21.6 mm
Quantity produced	21 lengths x 2600 m

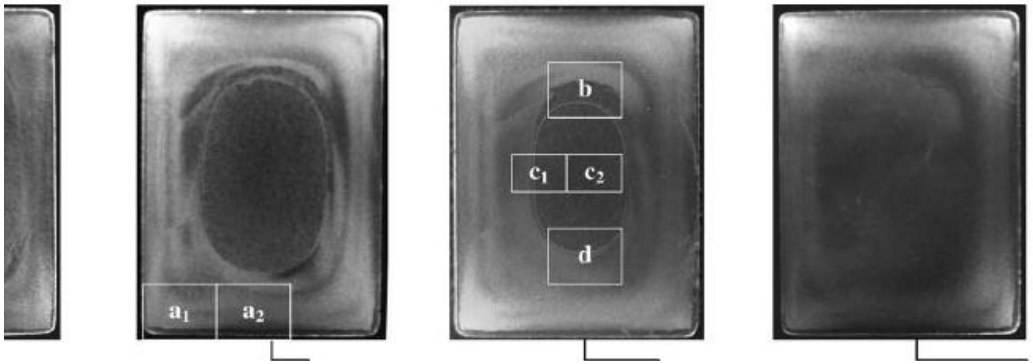
LHC experiments, the CMS example
billet on billet extrusion of the reinforcement

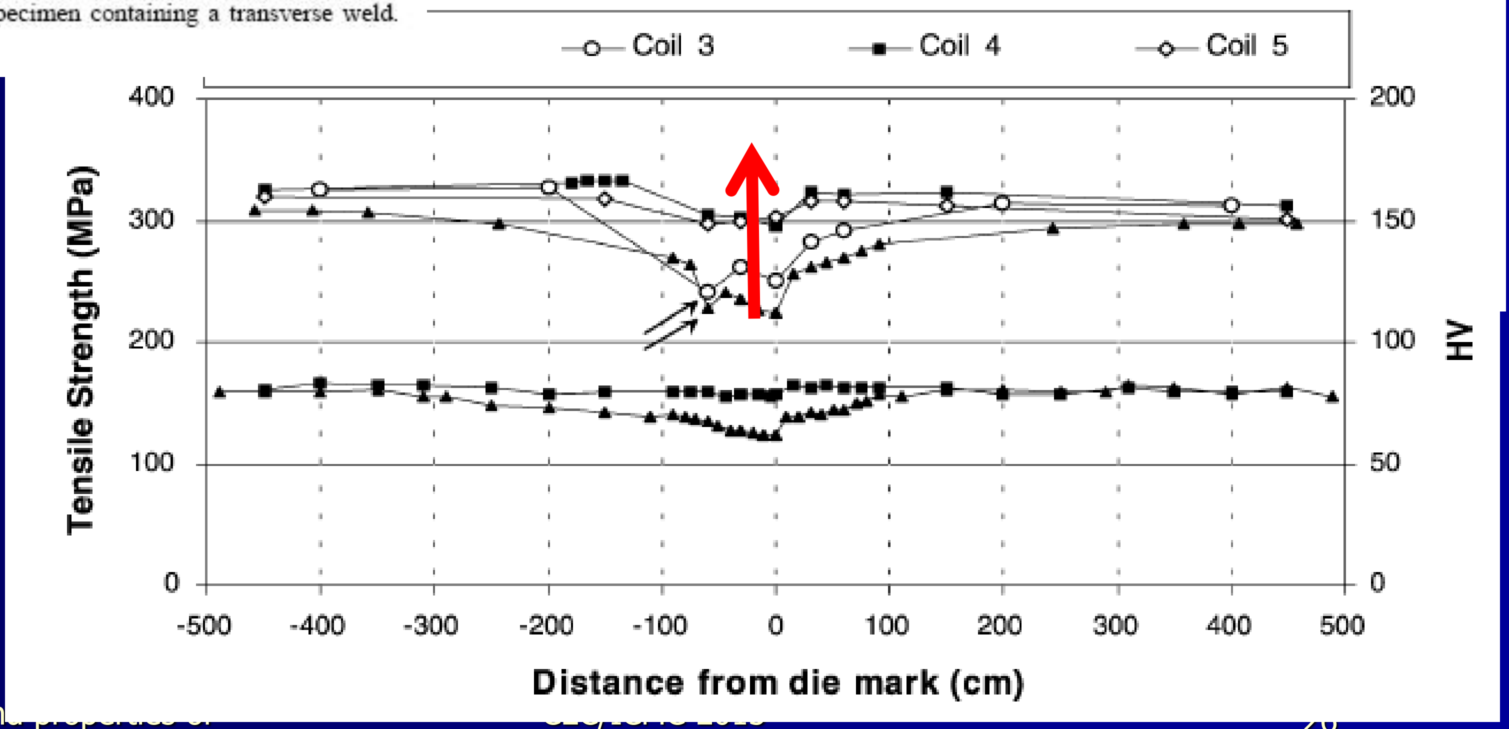


Schematic representation of the extrusion line (S. Sequeira Tavares, S. Sgobba, *An improved billet on billet extrusion process of continuous aluminium alloy shapes for cryogenic applications in the Compact Muon Solenoid experiment*, J. of Mat. Proc. Technology 143–144 (2003) 584–590)

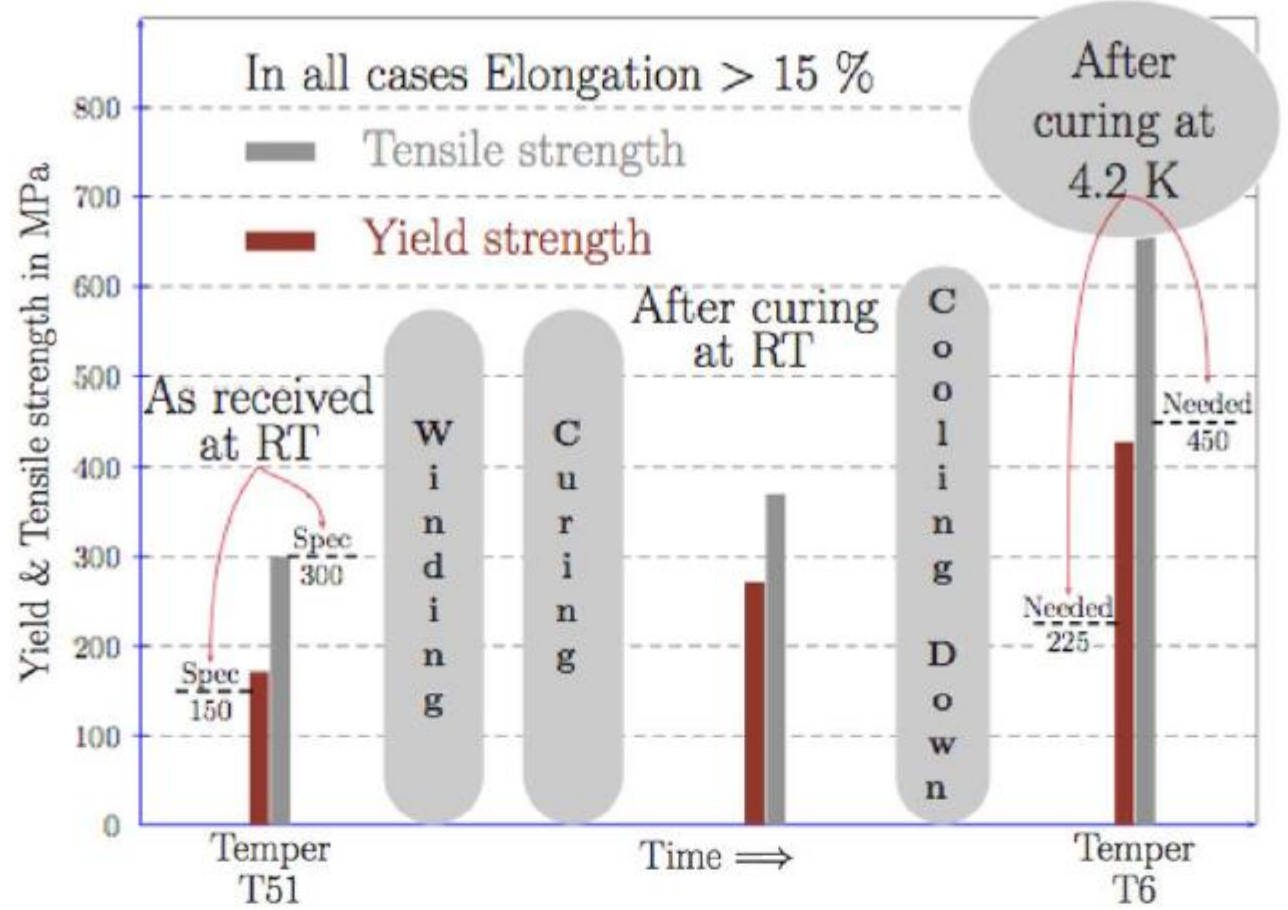
LHC experiments, the CMS example
billet on billet extrusion of the reinforcement

Fig. 8. Fracture of a tensile specimen containing a transverse weld.





LHC experiments, the CMS example
billet on billet extrusion of the reinforcement

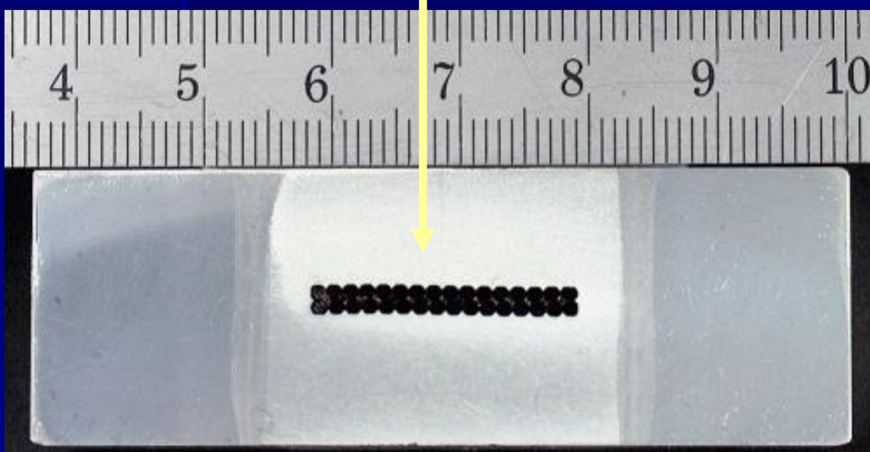


Alain Hervé et al., MT20 in Philadelphia, 27 August 2007

Evolution of the mechanical properties of the alloy 6082 selected for the reinforcement of the conductor, from state T51 to T6 at RT and 4.2 K.

Candidate alloy:

- Al99.998 ⇒ Al-0.1wt%Ni
- developed for the ATLAS thin solenoid superconductor
- maintains $Rp_{0.2}$ = 85 MPa at 4.2 K after thermal cycle

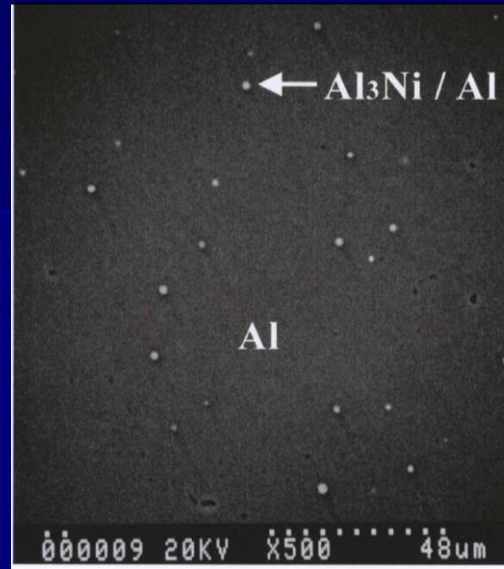


A. Yamamoto et al., Nuclear Physics B 78 (1999), pp. 565-570;
Wada et al., *IEEE Trans. Appl. Superconduc.*, vol. 10, pp. 373-376, March 2000

T or 6 T,

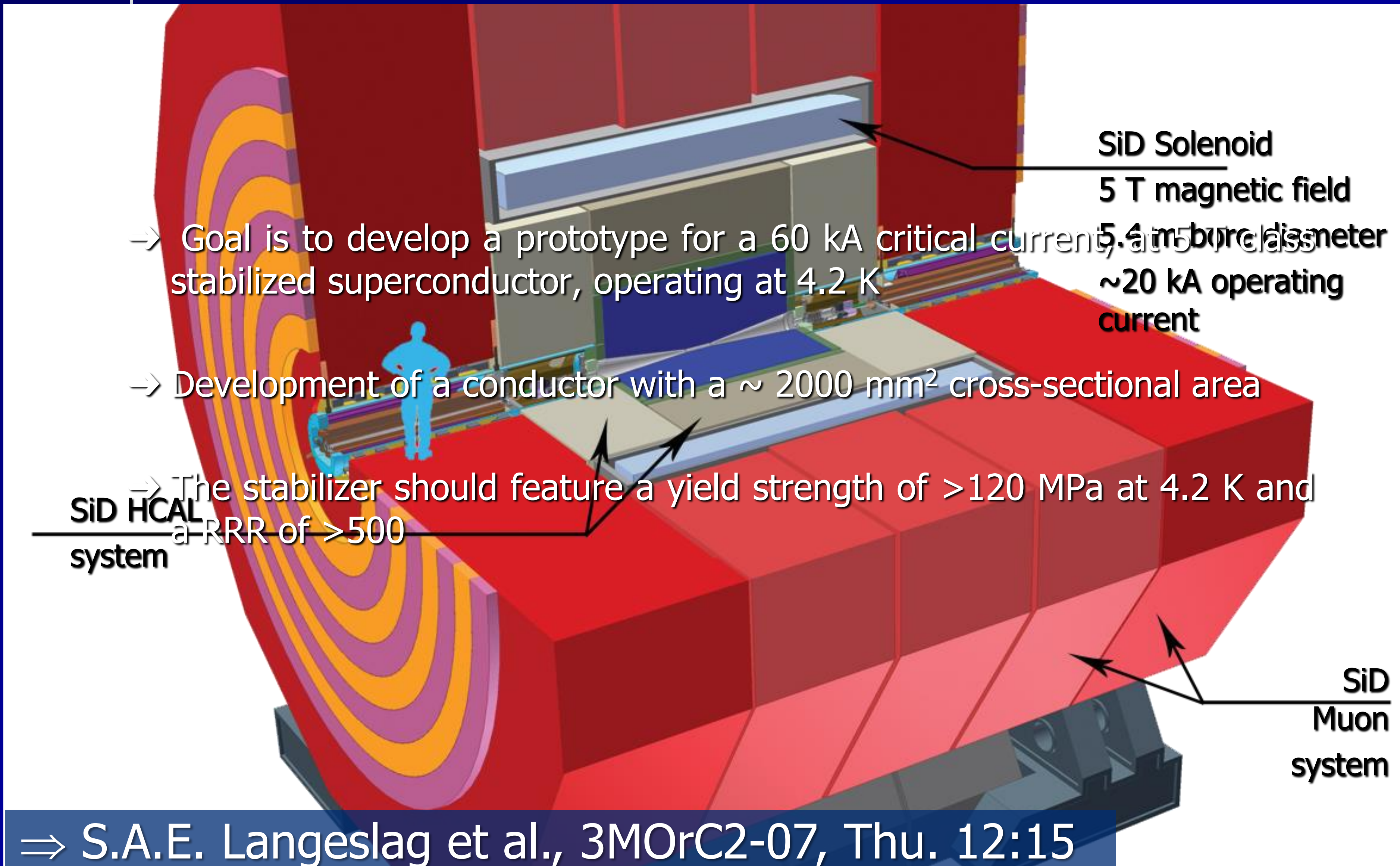
s:

50 MPa ⇒



S. Sgobba et al., *IEEE Trans. Appl. Superconduc.*, vol. 16, p. 521, June 2006

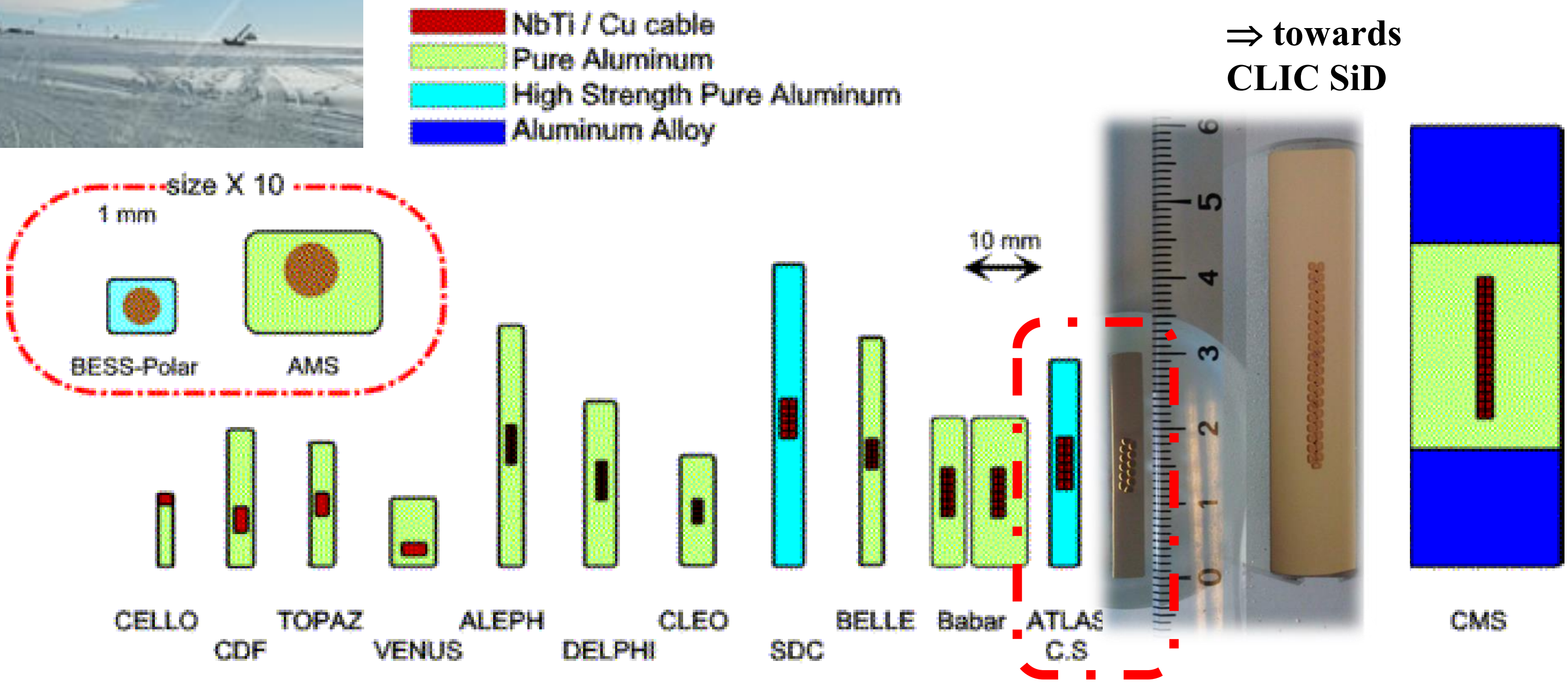
Ongoing developments:
innovative materials for conductors of future particle experiments



- → Goal is to develop a prototype for a 60 kA critical current, at 5 T class stabilized superconductor, operating at 4.2 K
- → Development of a conductor with a ~ 2000 mm^2 cross-sectional area
- → The stabilizer should feature a yield strength of >120 MPa at 4.2 K and a RRR of >500

⇒ S.A.E. Langeslag et al., 3MOrC2-07, Thu. 12:15

gress of Al-stabilized SC



A. Yamamoto, "Advances in Superconducting Magnets for Particle Physics", *IEEE Trans. Appl. Superconduc.*, vol. 14, no. 2, pp. 477-484, June 2004.

⇒ S.A.E. Langeslag et al., 3MOrC2-07, Thu. 12:15

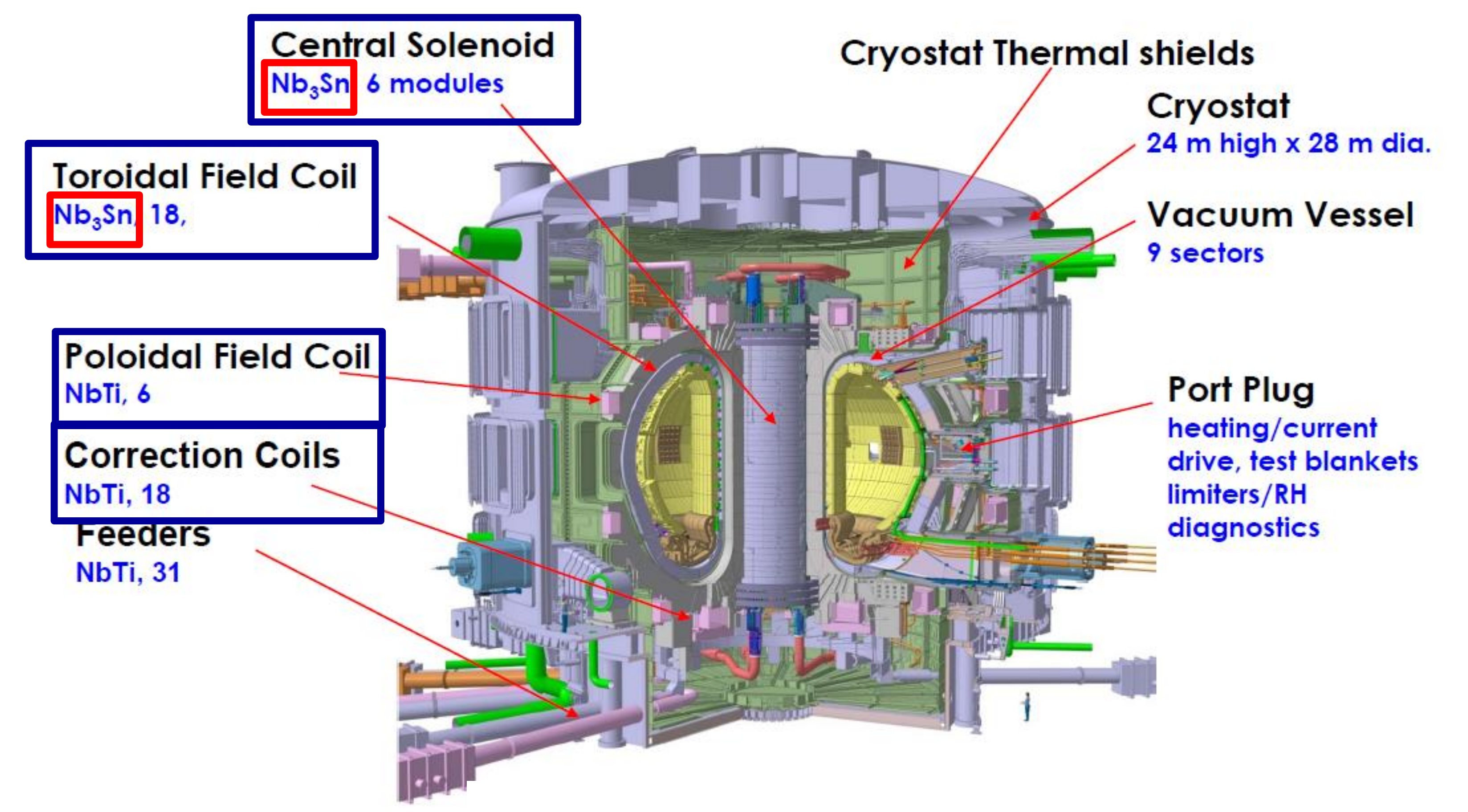
LHC experiments, the CMS example: external cylinder

Flanges, including shoulders

Welded shell

$\sigma_{4.2\,K} = 209$ MPa

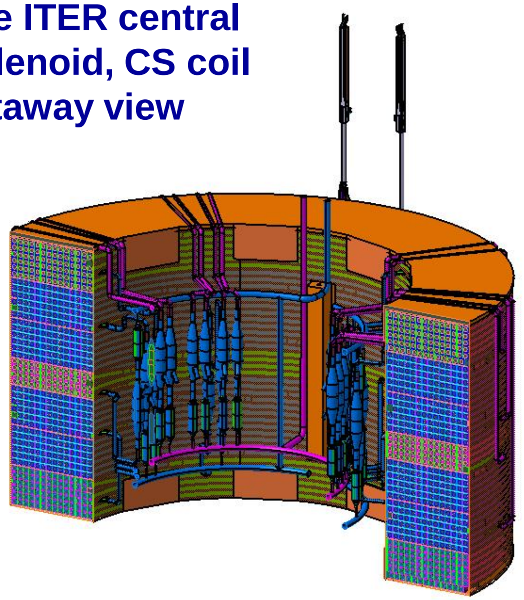
Ongoing developments: selection and characterization of structural materials for fusion magnets



N. Mitchell, A. Devred, P. Libeyre, B. Lim, F. Savary and the ITER Magnet Division The ITER Magnets: Design and Construction Status, presentation at MT-22, Marseille,13 Sept 2011. See also: N. Mitchell et al., The ITER Magnet System, IEEE Trans. Appl. Superconductivity **18** (2008) 435.

Selection and characterization of structural materials for fusion magnets

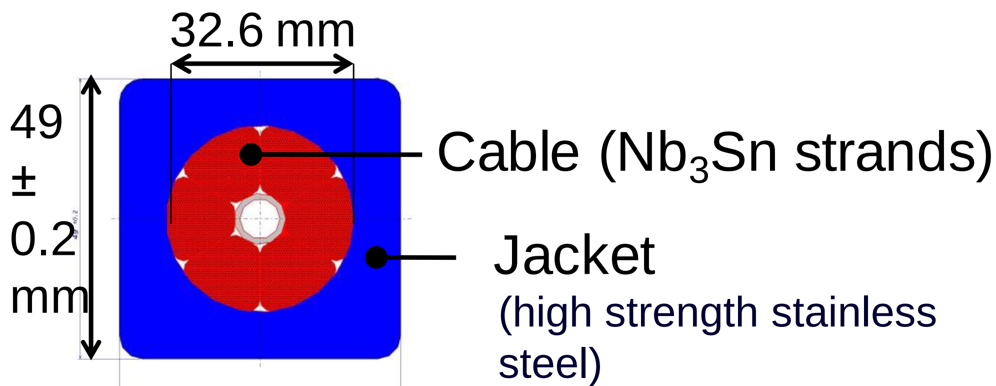
The ITER central Solenoid, CS coil cutaway view



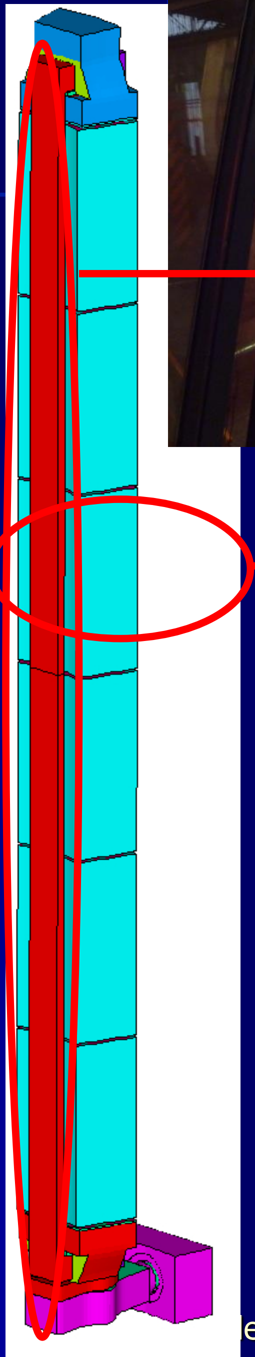
ITER CS includes six identical coils called modules

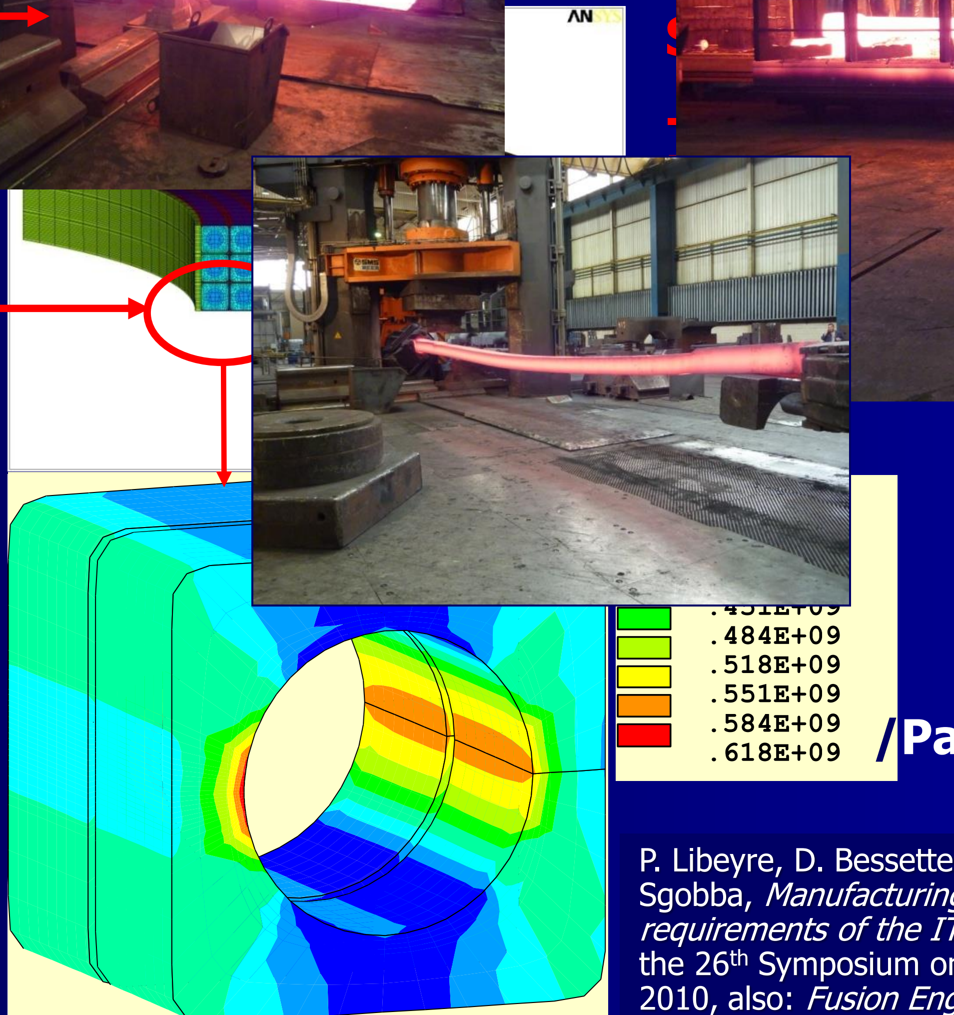
Use a superconducting 40 kA Nb_3Sn cable-in-conduit conductor operating up to 13 T, stacked upon each other and surrounded by a vertical precompression structure

Pulsed operation: 60 000 cycles !



CS conductor cross-section





Stainless steel grades considered for prototype production:

316LN, ITER grade

JK2LB, high Mn grade

P. Libeyre, D. Bessette, A. Devred, C. Jong, N. Mitchell, S. Sgobba, *Manufacturing development to meet the mechanical requirements of the ITER Central Solenoid Coils*, Proceedings of the 26th Symposium on Fusion Technology (SOFT), Porto (PT), 2010, also: *Fusion Eng. Des.* **86** (2011), 1553–1557.

NDT by Phased Array Ultrasonic Testing (PAUT) procedure for testing almost 95 % of the volume of the jackets

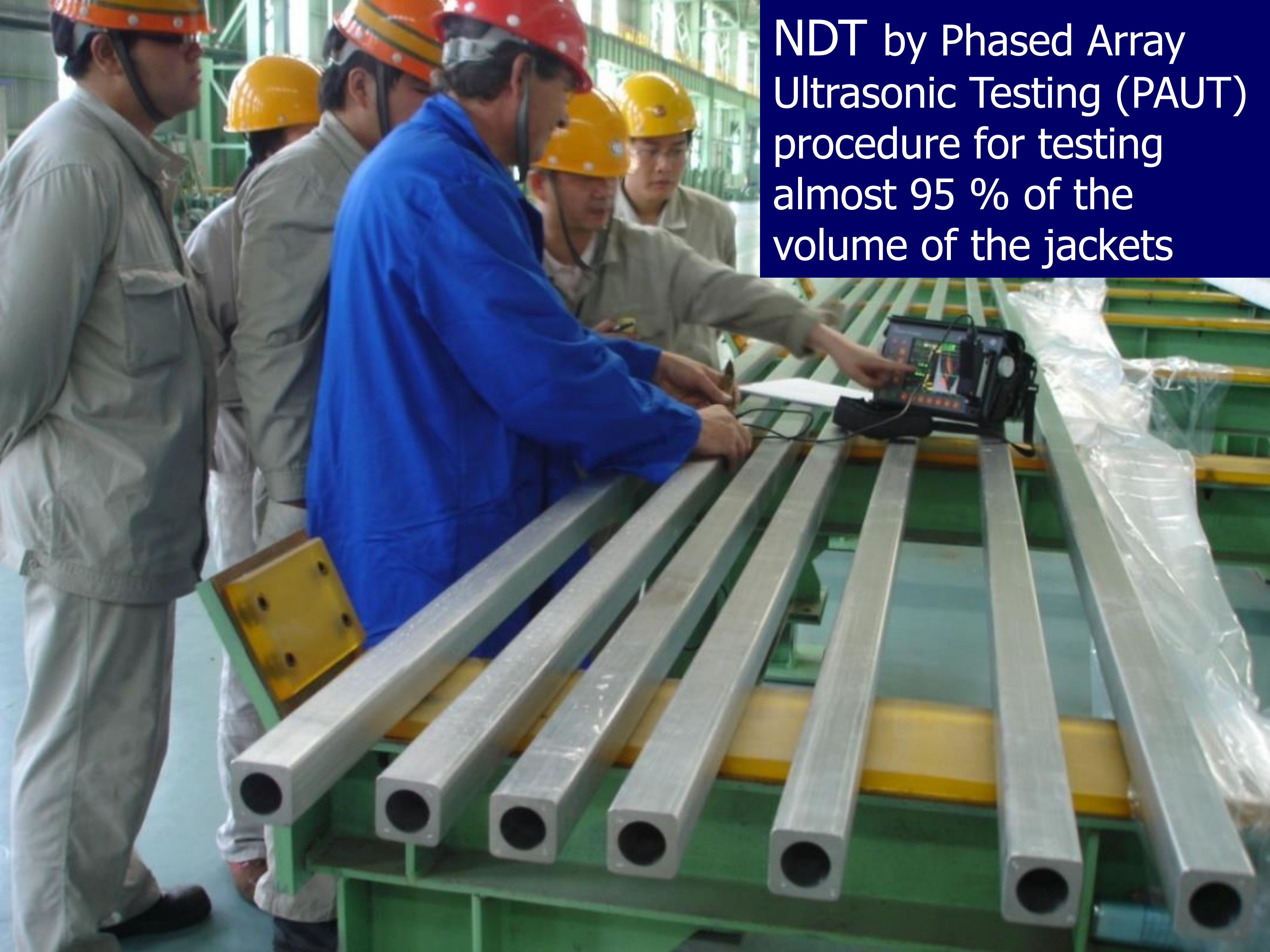
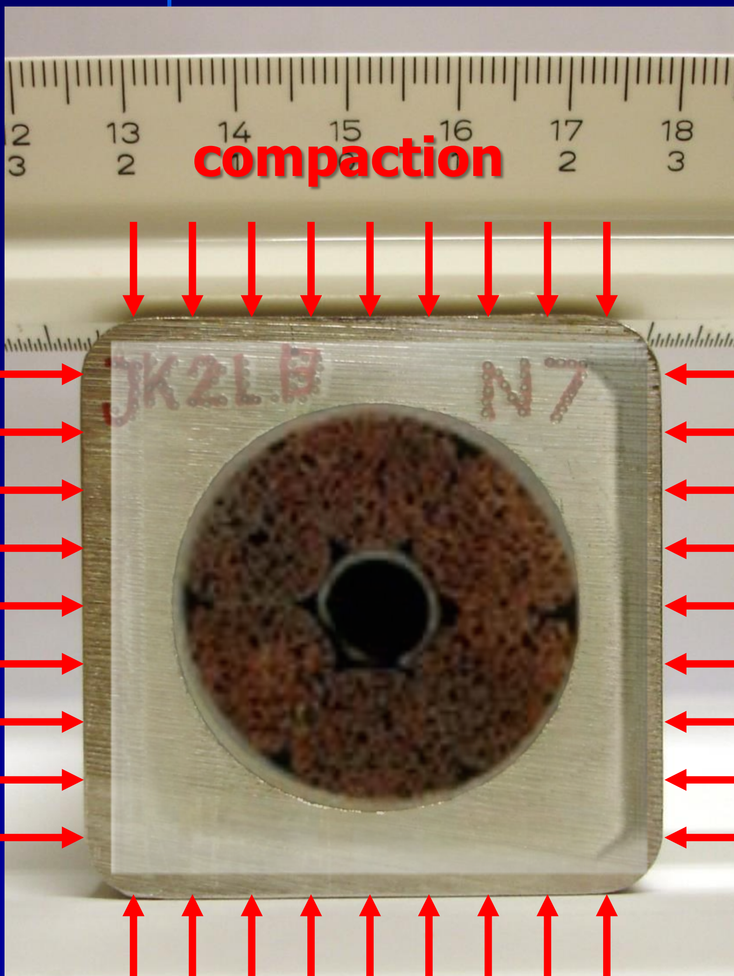


Table 1a. Chemical composition of JK2LB

Element (wt%)	C	Si	Mn	P	S	Cr	Ni	Mo	N	Co	B
JK2LB	≤0.030 (Target <0.025)	≤0.50 (target< 0.28)	20.5 - 22.5	≤0.015 (target <0.008)	≤0.015 (target <0.008)	12.0 - 14.0	8.0 -10.0	0.5 - 1.5	0.09 - 0.15	< 0.1	0.001-0.004

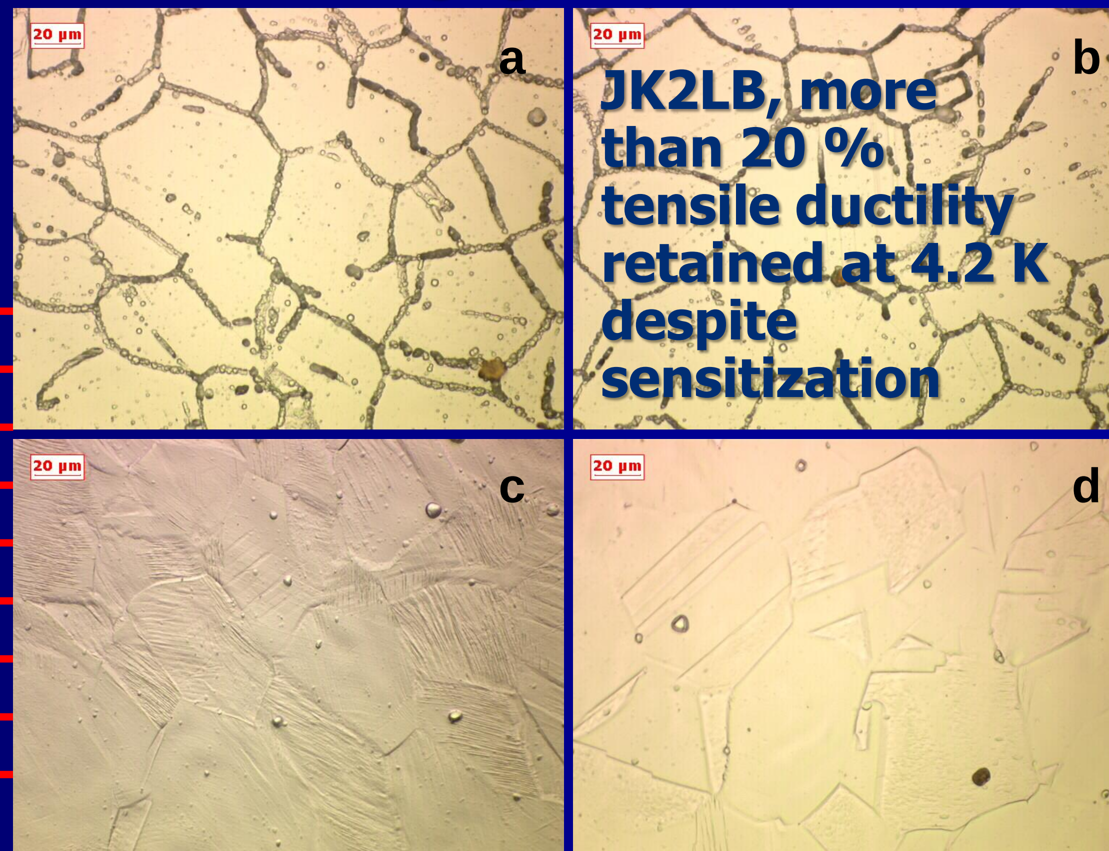
S. Sgobba, et al., Fusion Eng. Des. (2013), http://dx.doi.org/10.1016/j.fusengdes.2013.05.002

S. Sgobba et al., IEEE Transactions on Applied Superconductivity, **22**, 2012, p. 7800104



followed by aging 650 °C – 200 h

after aging, sensitization

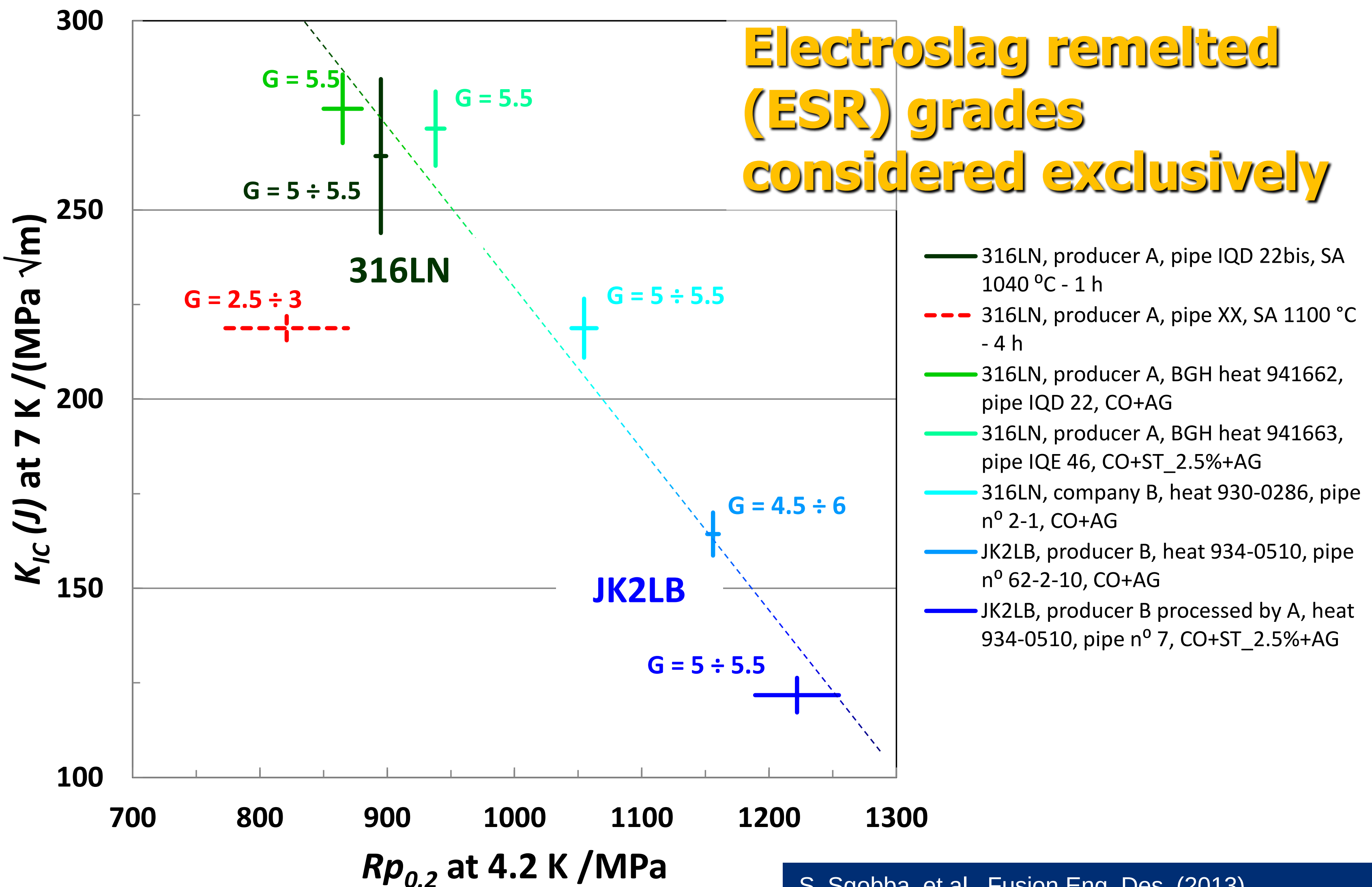


JK2LB, more than 20 % tensile ductility retained at 4.2 K despite sensitization

reference, before aging

Selection and characterization of structural materials for fusion magnets

Electroslag remelted (ESR) grades considered exclusively



S. Sgobba, et al., Fusion Eng. Des. (2013), http://dx.doi.org/10.1016/j.fusengdes.2013.05.002

Selection and characterization of structural materials for fusion magnets:
TF He-inlet developments

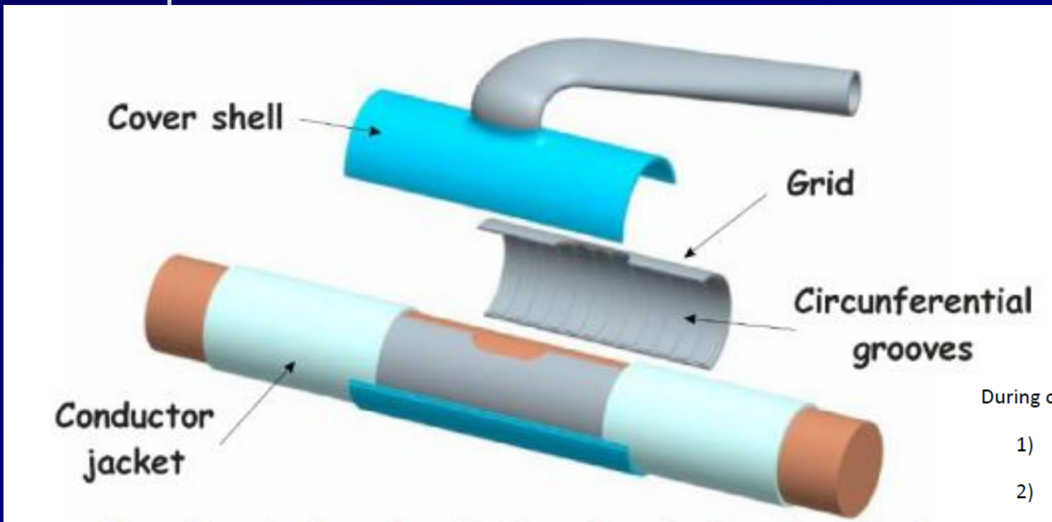


Fig. 3. TF-IN4 mock-up before test (lef

During operation, it will be submitted to

1) static loads (translated into strain of the order of 12 x 10^{-4})

2) Cyclic loads (translated into strain of the order of +/- 2.3 x 10^{-4})

The critical part of this inlet is the filet weld that joins the cover shell to the conductor jacket. There is a stress concentration at the toe of the filet weld that makes it critical from a fatigue point of view.

The picture shows what happened during a fatigue test carried out at FzK in 2005.

Breakdown after 476117 cycles, test under stress control, local stresses up to 550 MPa

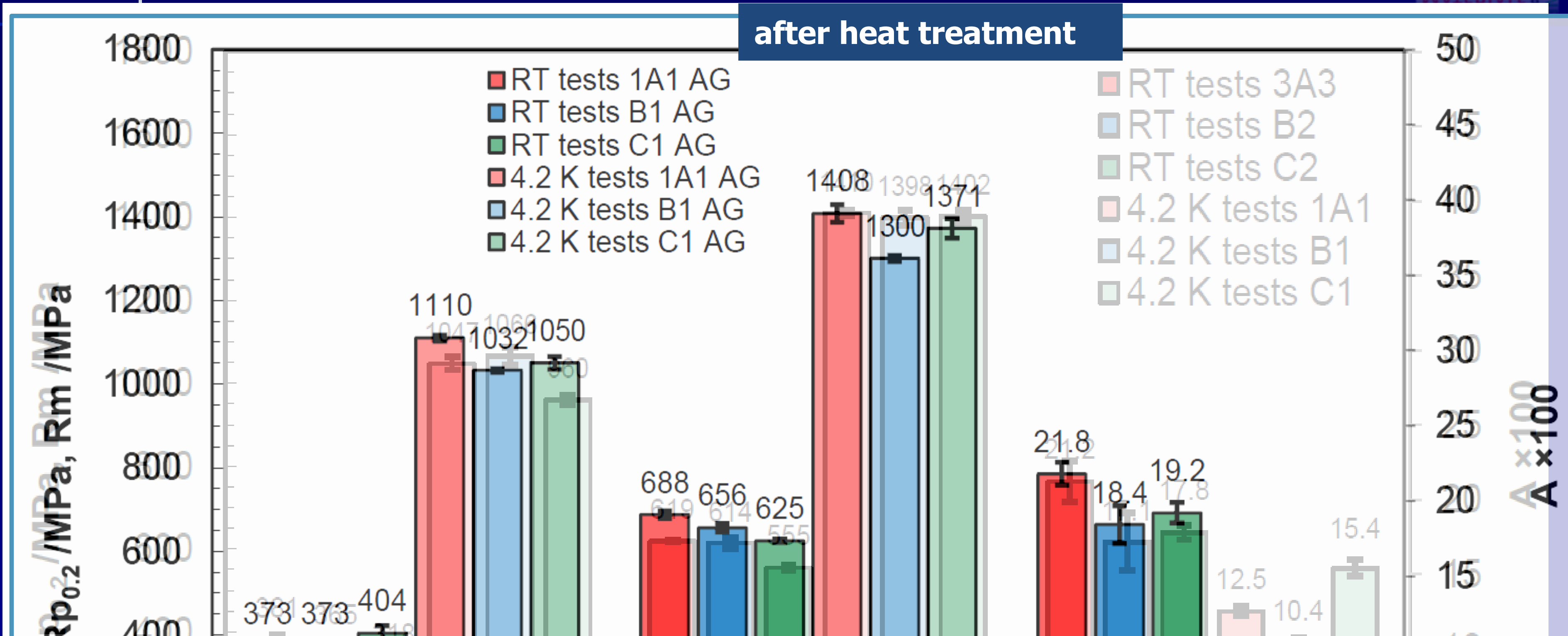
876 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 16, NO. 2, JUNE 2006

Design and Qualification of ITER CS and TF Cooling Inlets

P. Decool, H. Cloez, S. Nicollet, A. Nyilas, and J. P. Serries

TF He-inlet developments, weld qualification and effects of sensitization

Tensile test at RT and 4.2K, 316 LN welds with different weld schedules



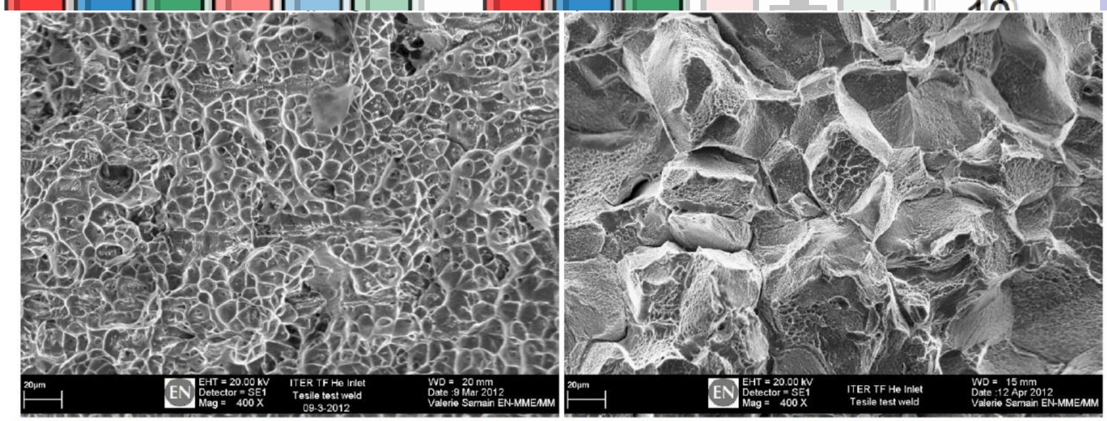
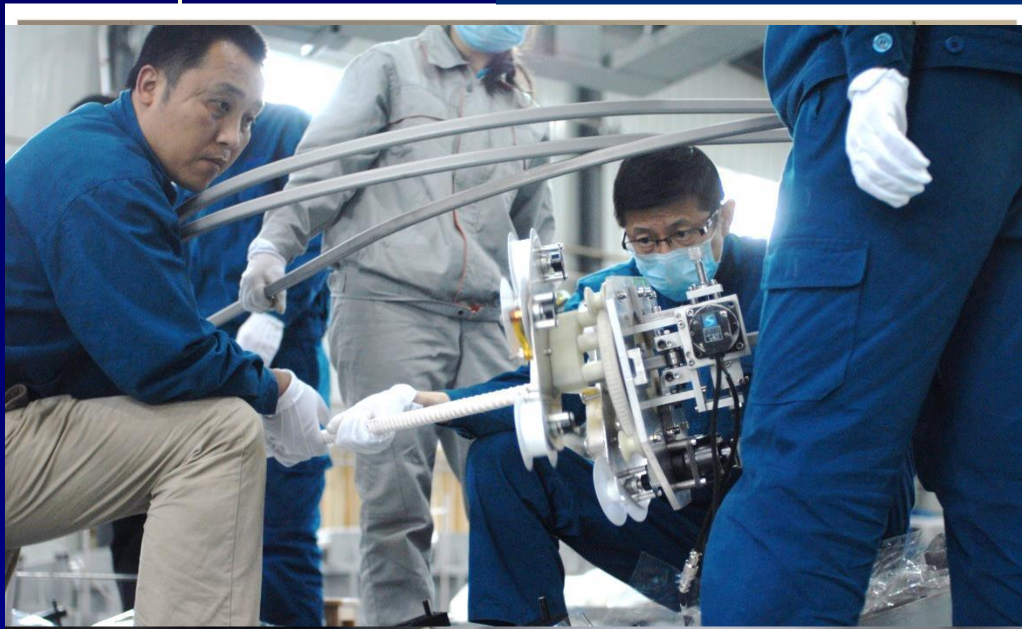
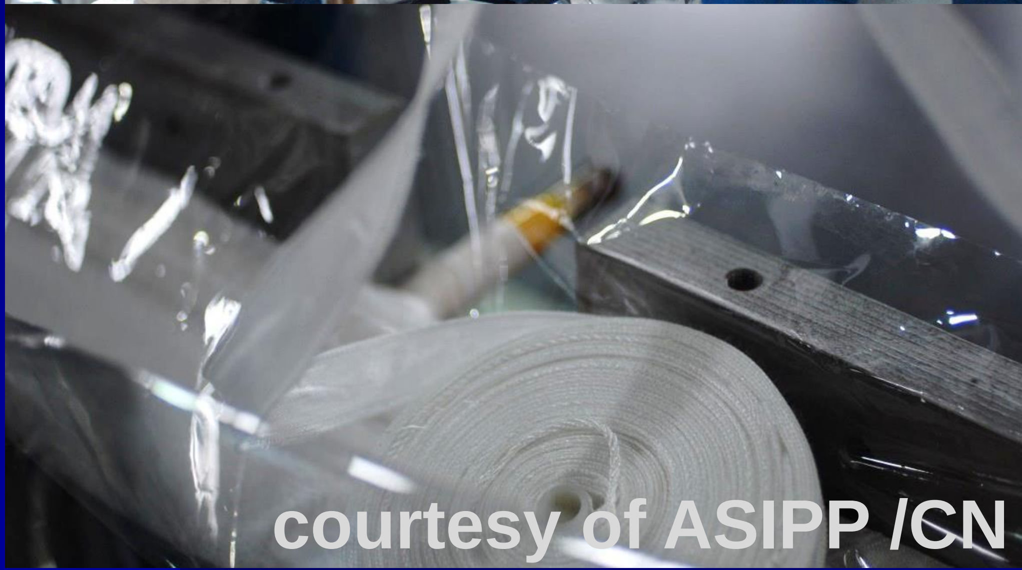


Figure 18: SEM on specimen without filler material (C1_C6 and C1_C12) after tensile test at 4.2K, magnification 400x: before (left, fracture in the weld bead) and after heat treatment (right, fracture between HAZ and the weld bead).

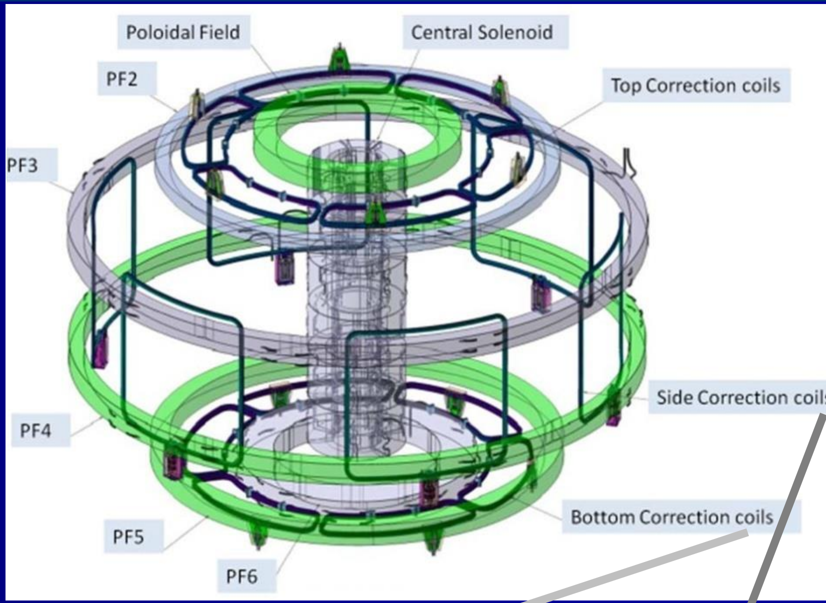
CERN EDMS report n° 1193170, 1208068

Selection and characterization of structural materials for fusion magnets:
additional He-inlet studies, ITER CC





courtesy of ASIPP /CN

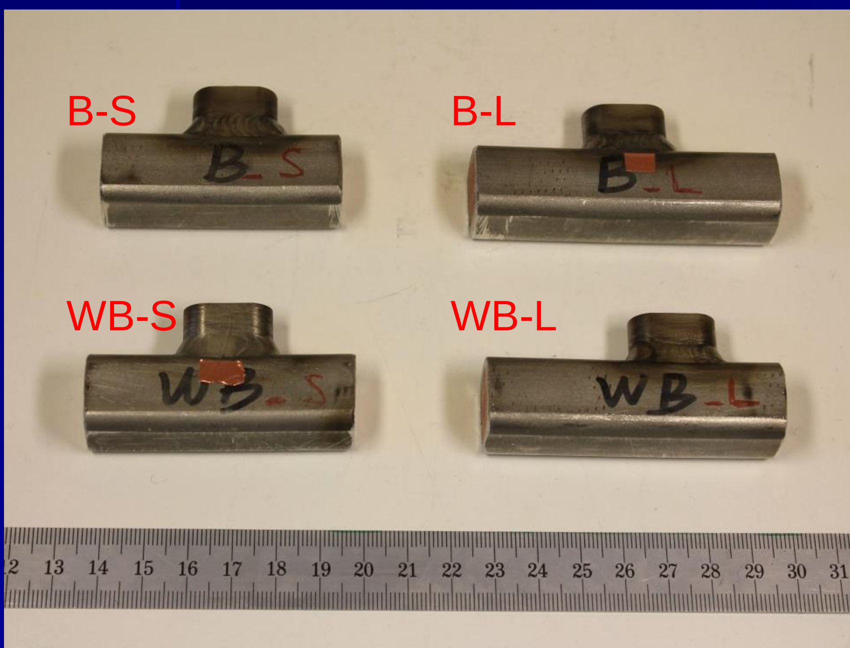


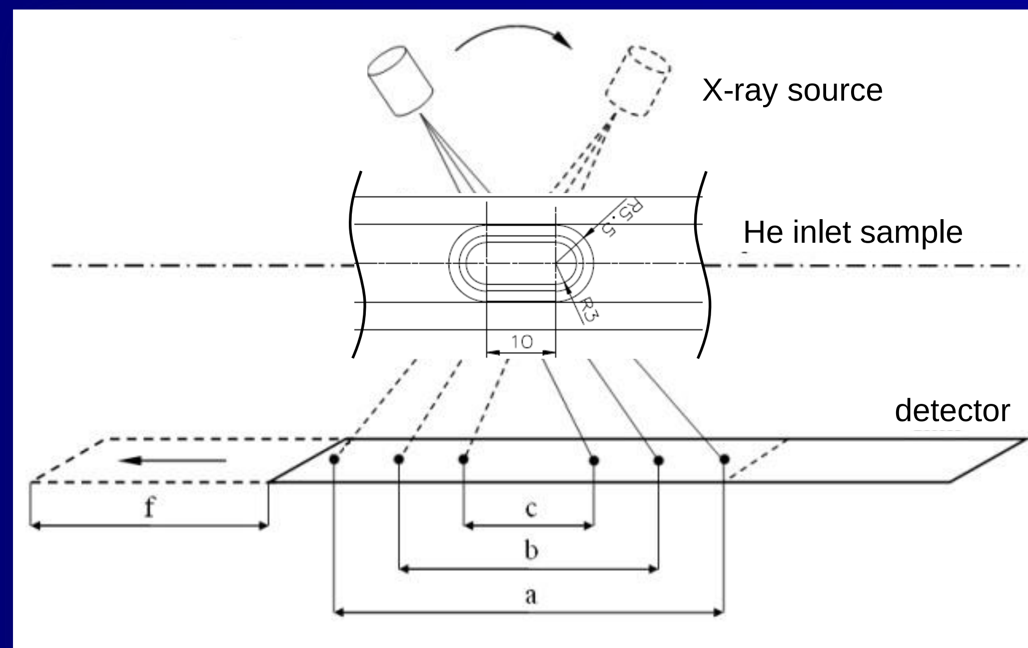
BCC /TCC

SCC

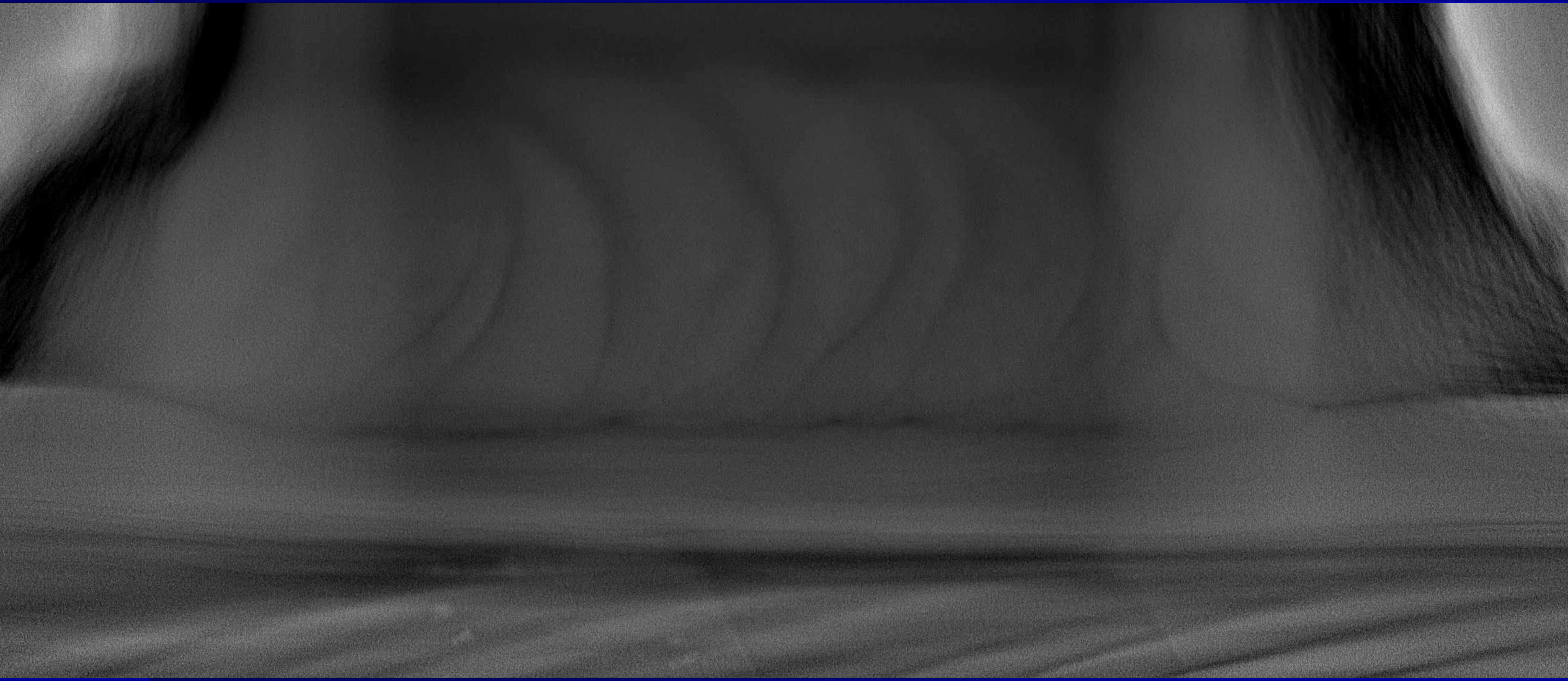
Selection and characterization of structural materials for fusion magnets:
additional He-inlet studies, ITER CC

- **Laminography (planar tomography) by RX Solutions /FR**
- **Classification following ISO 6520-1 and judged with respect to EN ISO 5817 - level B**





Laminography weld WB-S



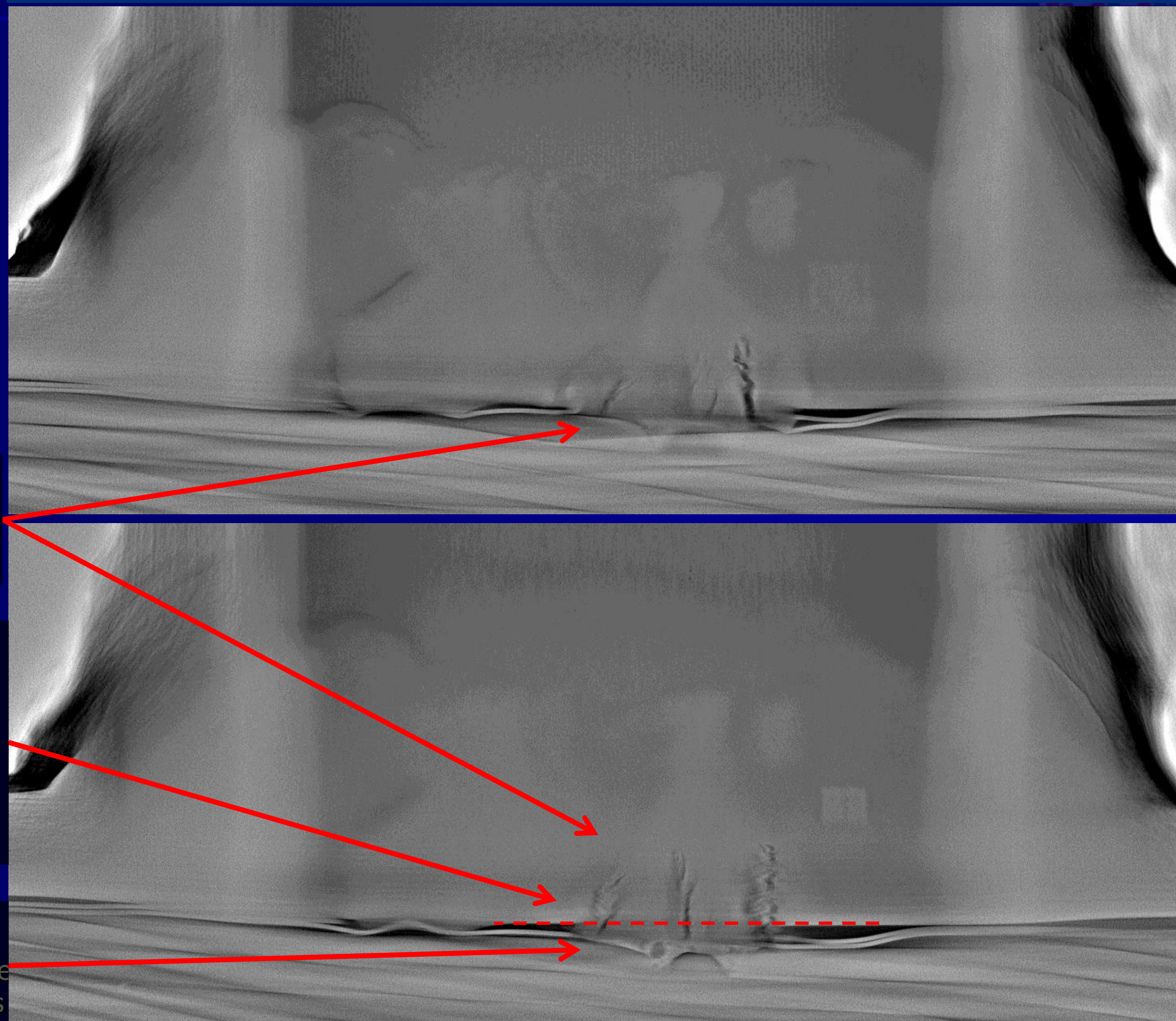
Selection and characterization of structural materials for fusion magnets: additional He-inlet studies, ITER CC

Laminography weld WB-S

Cracks (ref: 401) unacceptable to ISO 5817 level B

Excessive penetration and melt through (ref: 504) acceptable to ISO 5817 level B (h ≤ 1 mm + 0.1 b, where b is a width of weld reinforcement)

Wrap welded with the jacket and possibly with the superconductor



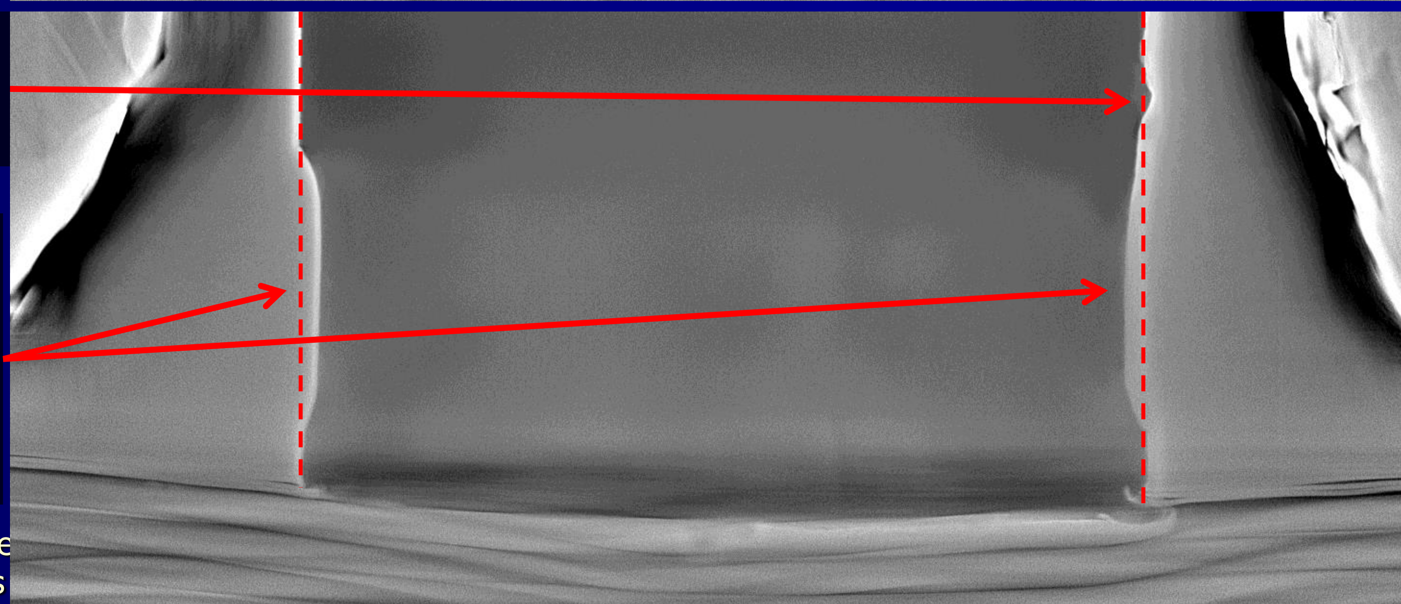
Selection and characterization of structural materials for fusion magnets: additional He-inlet studies, ITER CC

Laminography weld WB-S

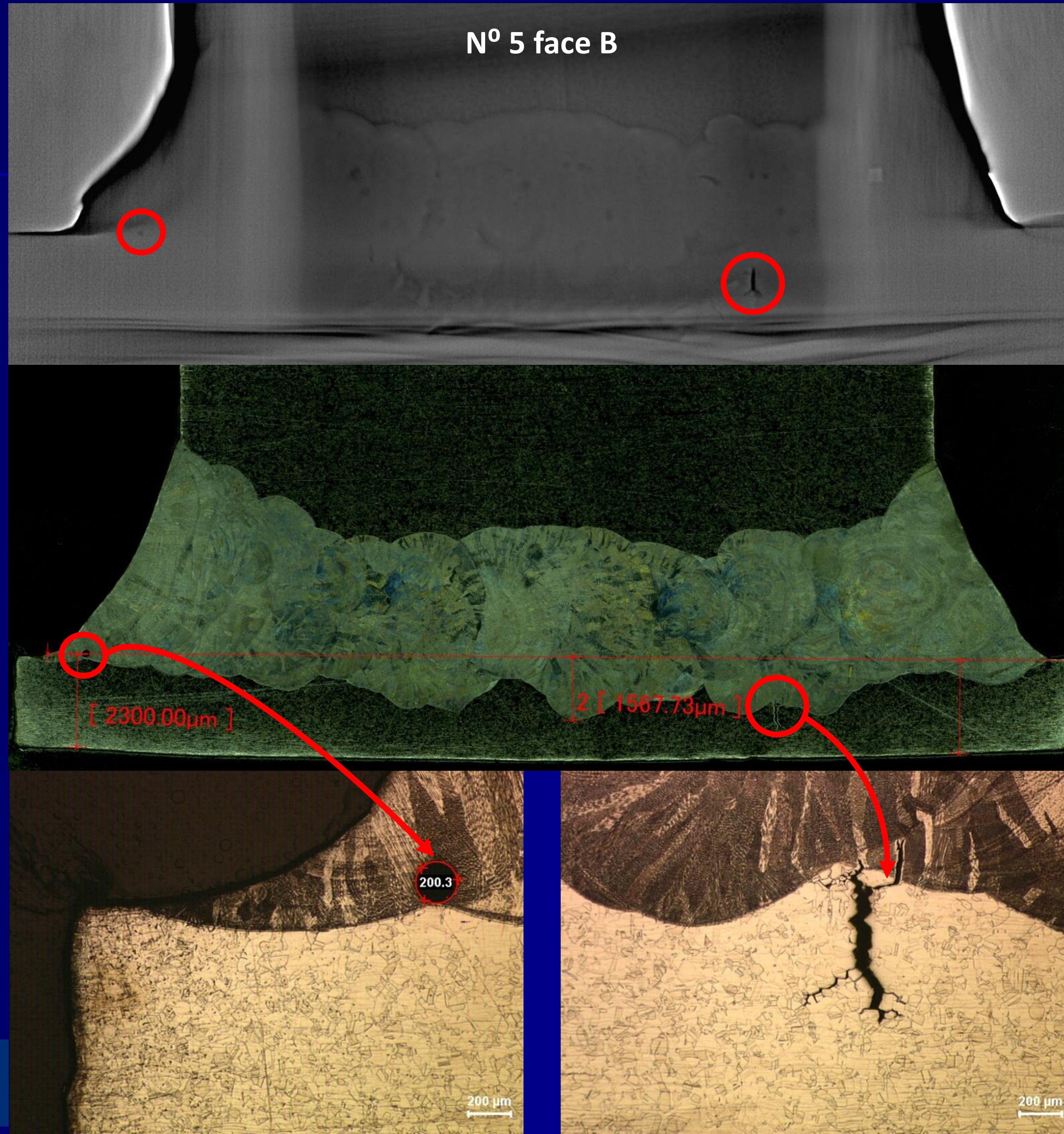
Tungsten inclusion (ref: 6021) according to ISO 5817 level B acceptance depends on application

Shrinkage grooves (ref: 5013) not acceptable to ISO 5817 level B

Excessive penetration (ref: 504) acceptable to ISO 5817 level B ($h \leq 1$ mm + 0.1 b, where b is the width of weld reinforcement)



Laminography: impressive correspondence between XR tomography and microoptical observations



CERN report EDMS n° 1244255

Conclusions

- A structural material for a cryogenic application is not a mere "chemical composition" or a designation

Stainless steels

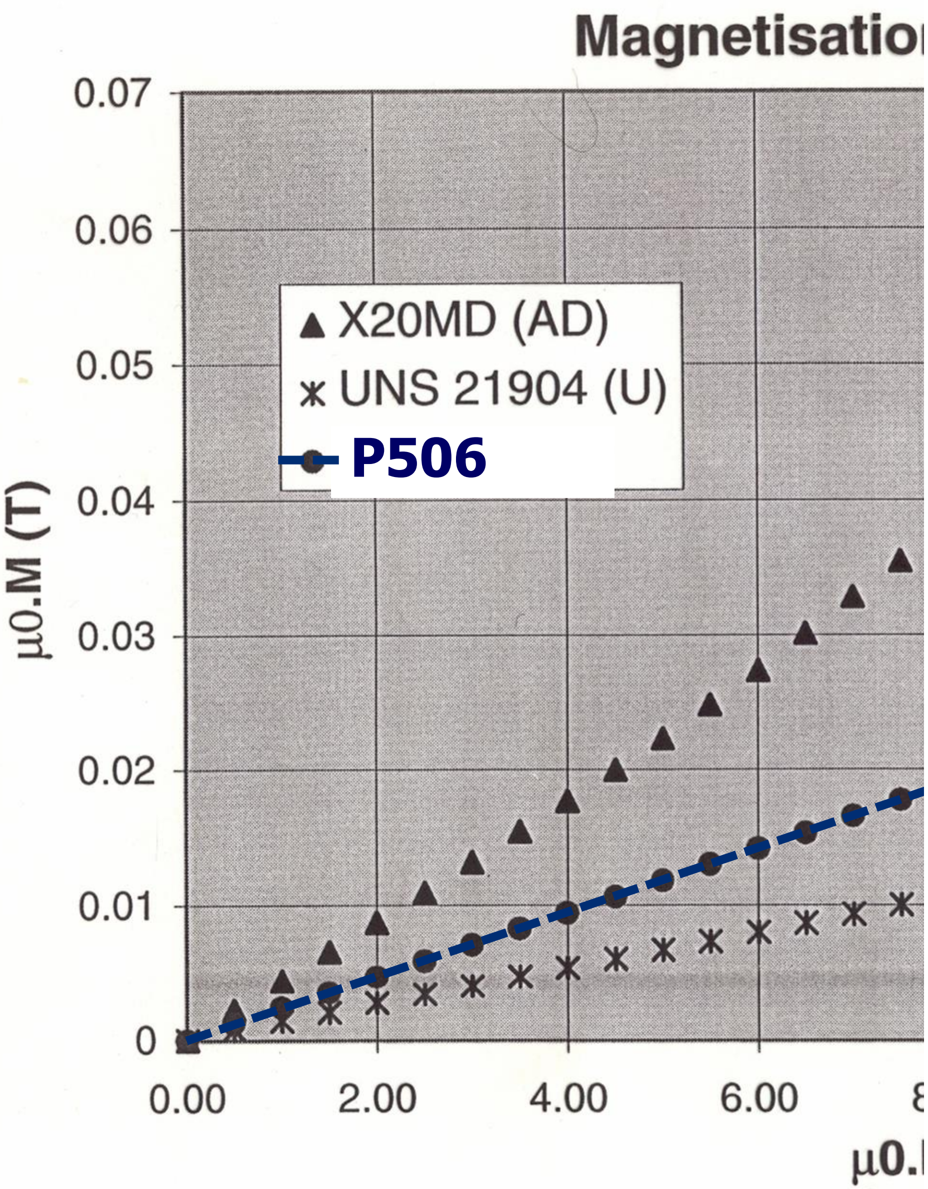
- 304L, general purpose ⇒ 7 $/kg
- 304L, vacuum/cryogenic application ⇒ 15 $/kg
- 316LN, as above ⇒ 20 $/kg
- 316LN, blanks ⇒ 60 (up to 150) $/kg
- P506, 316L convolutions for bellows ⇒ 50-100 $/kg

Al alloys

- plates EN AW 1050 ⇒ 6 $/kg
- special forgings ⇒ 30-35 $/kg
- 5N pure Al ⇒ 100 $/kg (medium quantities)
- Al-0.1%Ni ⇒ 100 $/kg (depends on quantities)

- Material selection (and procurement) to be operated at the beginning of a project

* bolts, braces



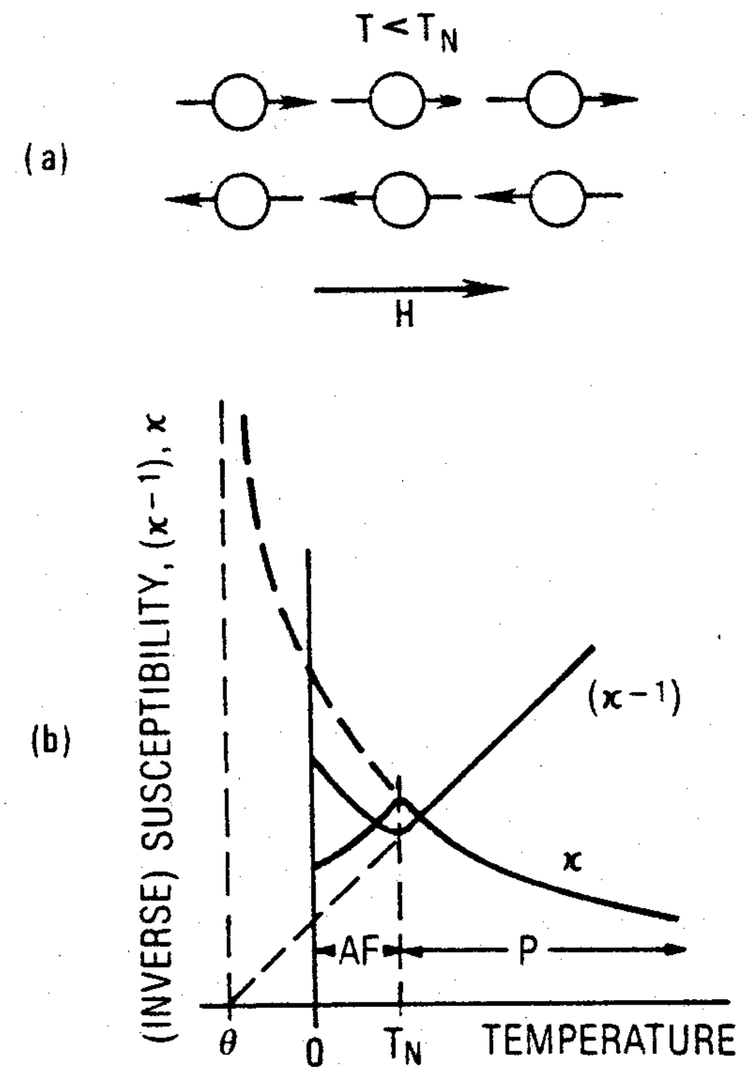


Figure 6.8 (a) Antiferromagnetic alignment of atomic magnetic moments. (b) Susceptibility and reciprocal susceptibility vs. temperature showing antiferromagnetic (AF) and paramagnetic (P) intervals.

Examples of innovative solutions: LHC beam screen, stability against martensitic transformations

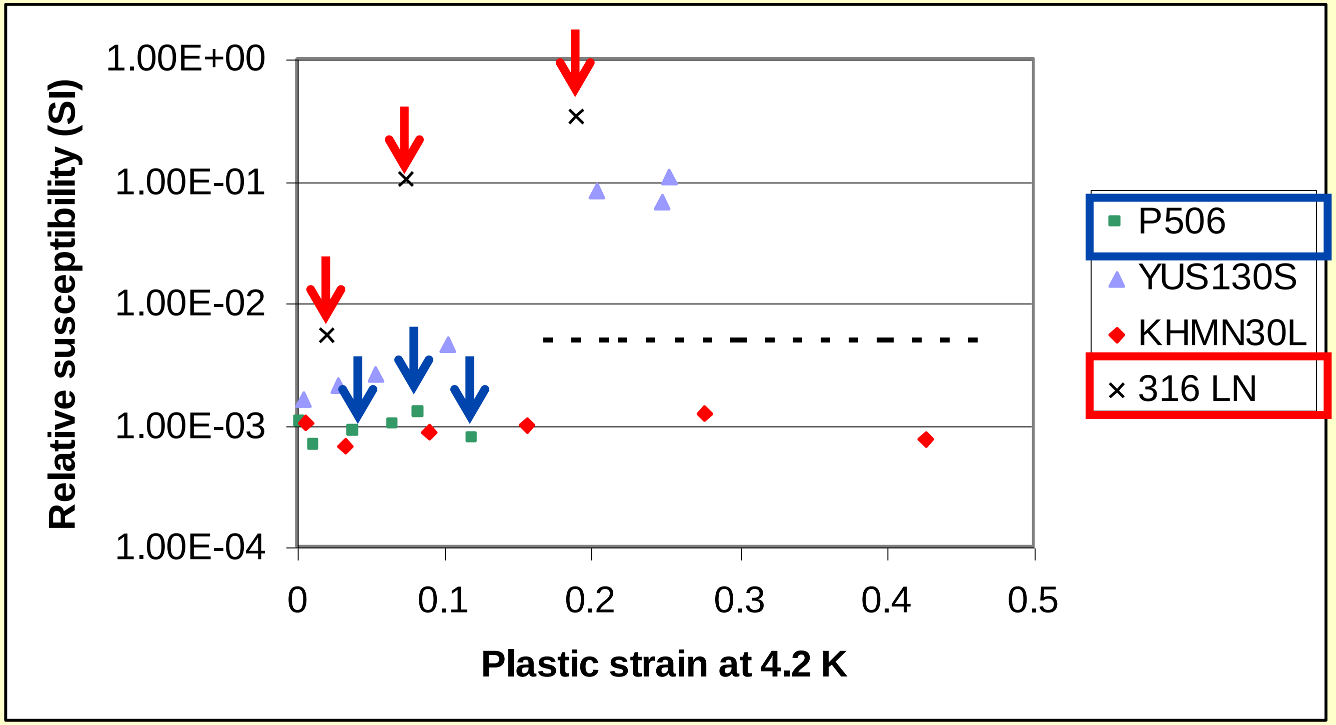
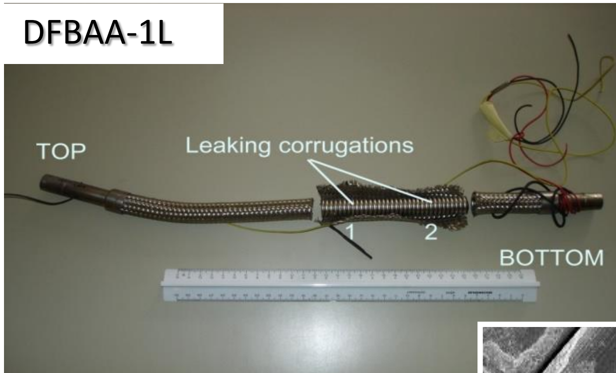
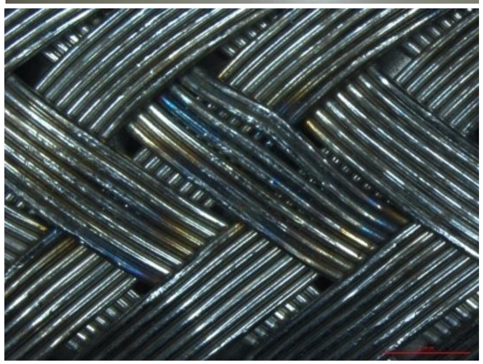
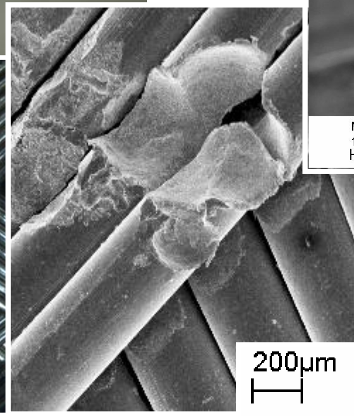


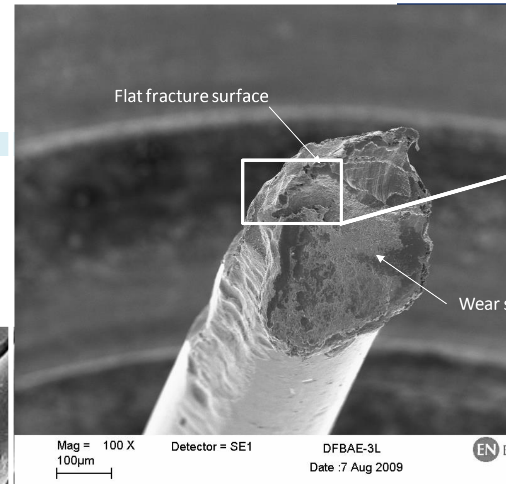
Figure 2: Evolution of room temperature relative magnetic susceptibility with plastic strain at 4.2 K. Values are average values on three tests performed for each plastic strain level. For comparison, values for standard 316 LN stainless steel are also given. The dashed line corresponds to a value of $\chi_r = 5{\cdot}10^{-3}$.

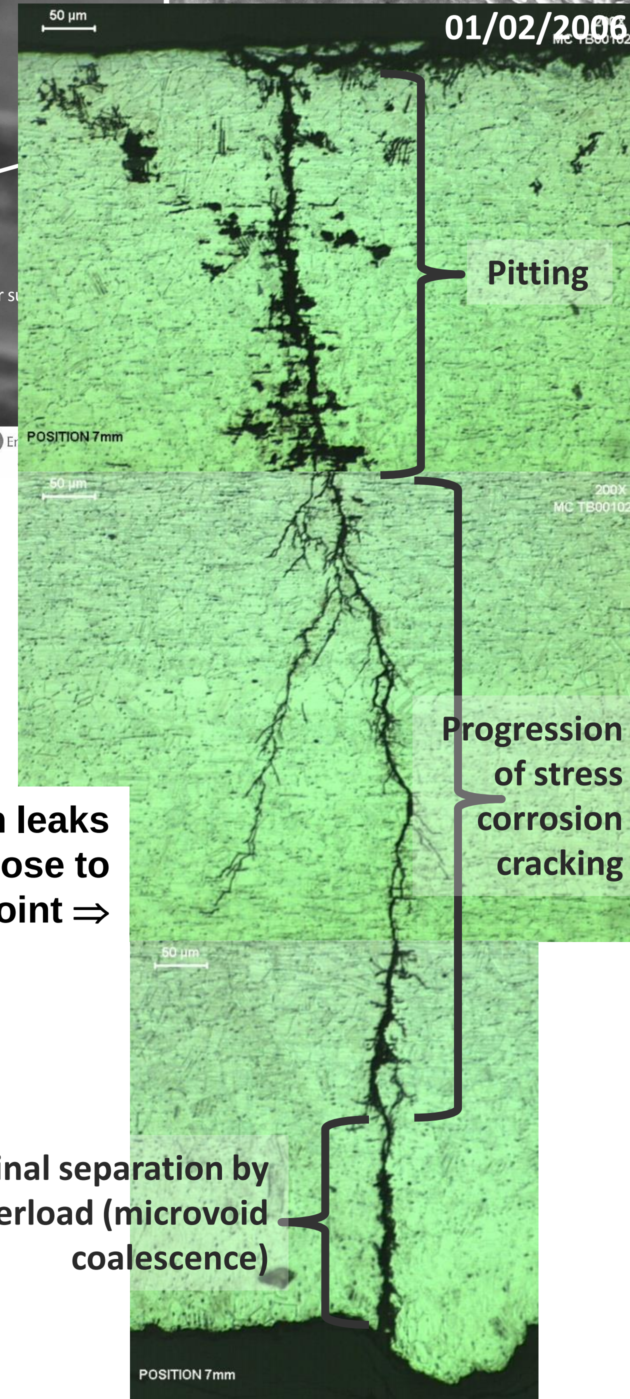
K. COUTURIER, S. SGOBBA, Phase Stability of High Manganese Austenitic Steels for Cryogenic Applications, Proceedings of the "Materials Week" European Conference, Munich, Germany, September 25-28, 2000 http://www.proceedings.materialsweek.org/proceed/mw2000_432.pdf



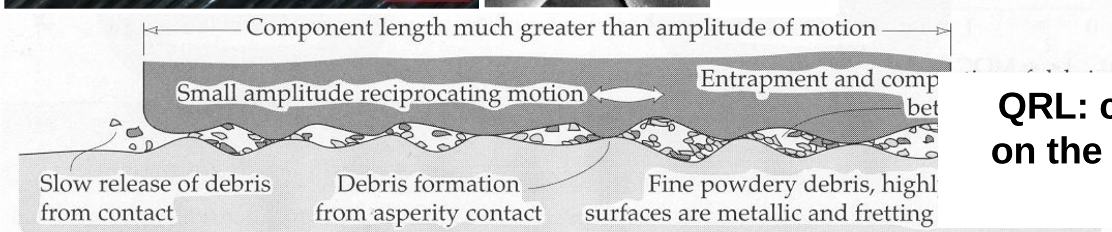






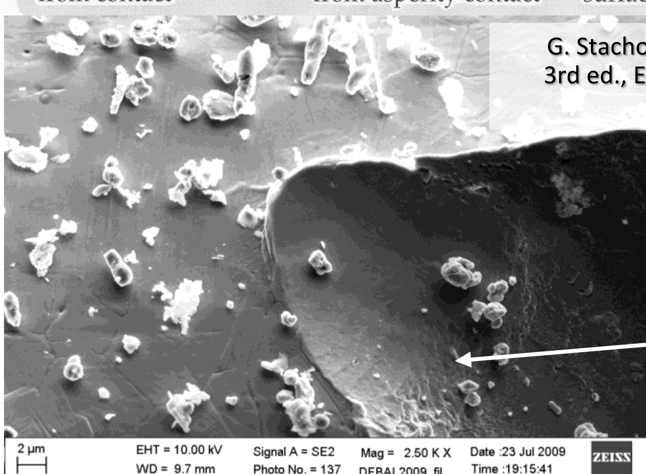


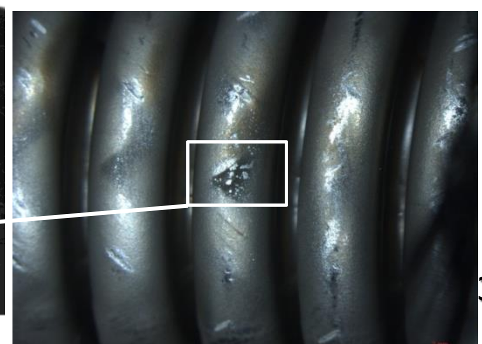
⇐ **Failure analysis of DFBA flexible metal hoses, 01/09/2009**



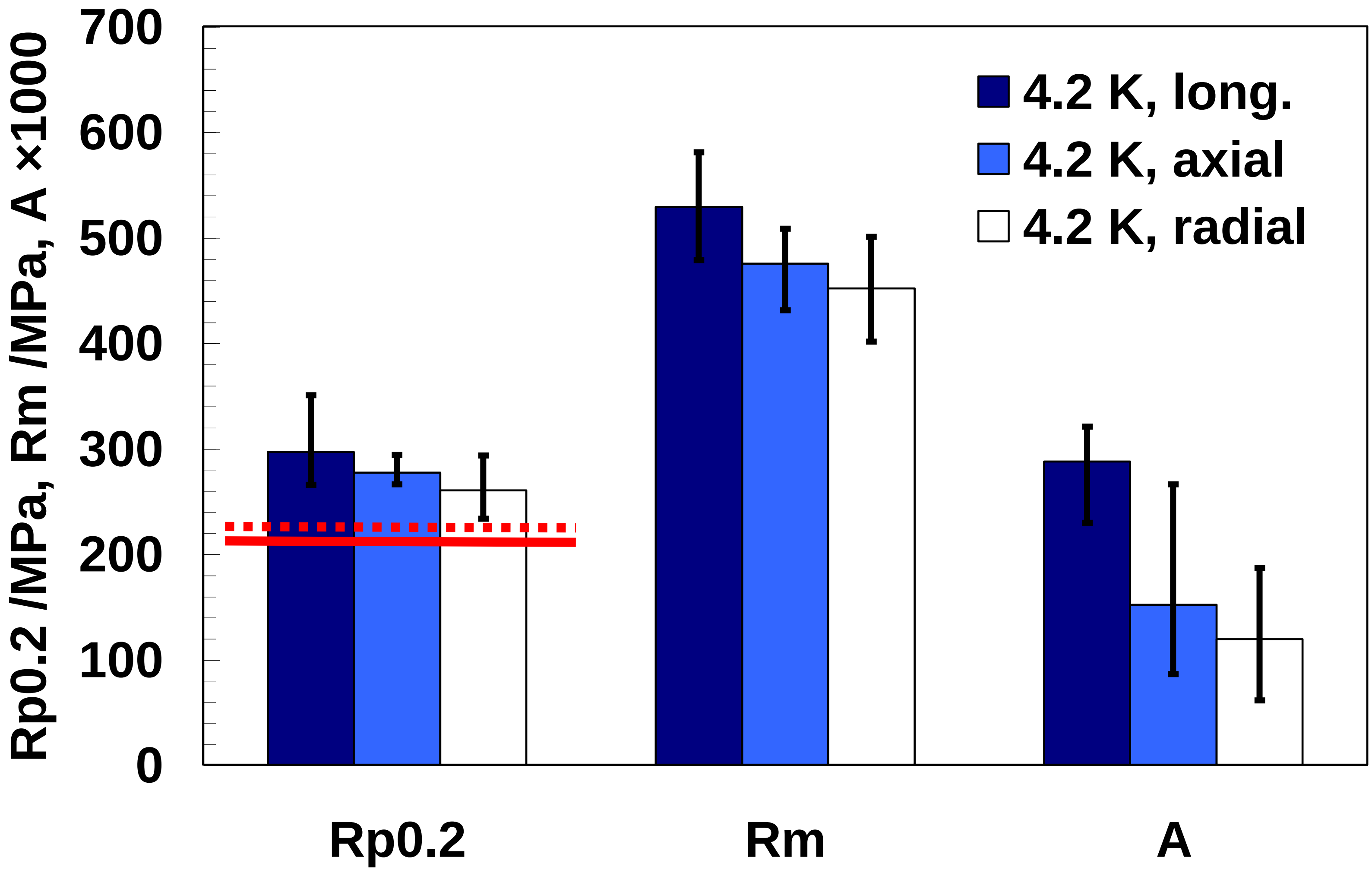
QRL: corrosion leaks on the tube F close to the fix point ⇒

G. Stachowiak, A.W. Batchelor, Engineering Tribology, 3rd ed., Elsevier Butterworth-Heinemann, Amsterdam (2005)





LHC experiments, the CMS example: manufacturing of a seamless ring



S. Sgobba et al.: *Mechanical performance at cryogenic temperature of the modules of the external cylinder of CMS and quality controls applied during their fabrication,* IEEE Transactions on Applied Superconductivity - IEEE TRANS APPL SUPERCONDUCT , vol. 14, no. 2, pp. 556-559, 2004