DE LA RECHERCHE À L'INDUSTRIE

Madmax: Large Dipole Dectector for Dark Matter

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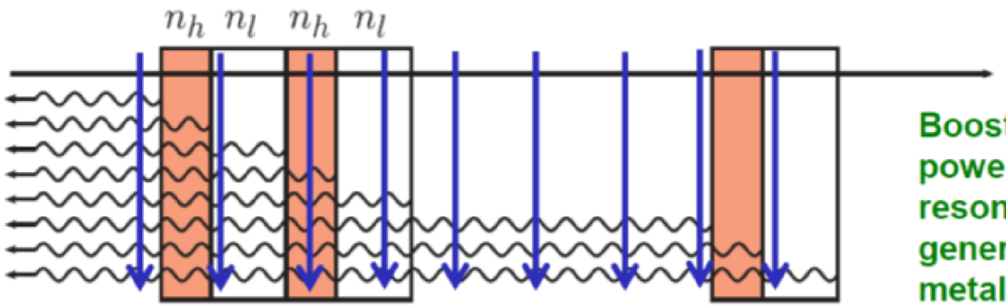
(Werner-Heisenberg-Institut)

BILFINGER NOELL GMBH

Many surfaces → resonator → "photon boost"

J. Jaeckel and J. Redondo, Phys. Rev. D 88 (2013) *115002 [arXiv:1308.1103]*



Boost factor: power generated in resonator/power generated on single metallic ($\varepsilon_r=\infty$) surface

$$P_\gamma(\nu) = \beta^2(\nu)\, P_{\gamma,0} = 1.1 \times 10^{-22}\,\mathrm{W} \left(\frac{\beta^2(\nu)}{5\times 10^4}\right)\left(\frac{A}{1\,\mathrm{m}^2}\right)\left(\frac{B_e}{10\,\mathrm{T}}\right)^2\left(\frac{\rho_a}{0.3\,\mathrm{GeV/cm}^3}\right) C_{a\gamma}^2$$

β : Boost factor, depends on:
frequency (axion mass), ε of materials, number of surfaces, displacement between surfaces, etc.

$$\mathrm{FoM} = \frac{1}{L}\int_A \int_0^L B(x,y,z)^2 dz dx dy$$

TARGET:

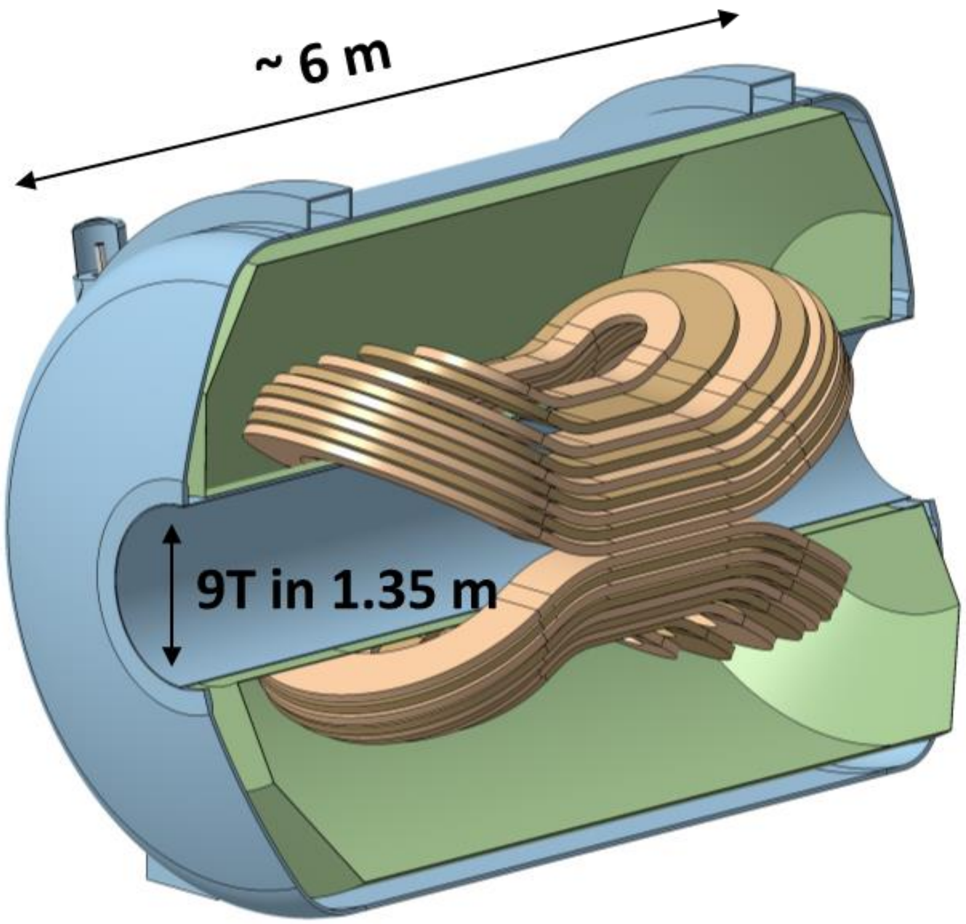
~ 100 T²m² → ~ 10 T in 1 m²

Courtesy of Max Planck Institue (B. Majorovits)

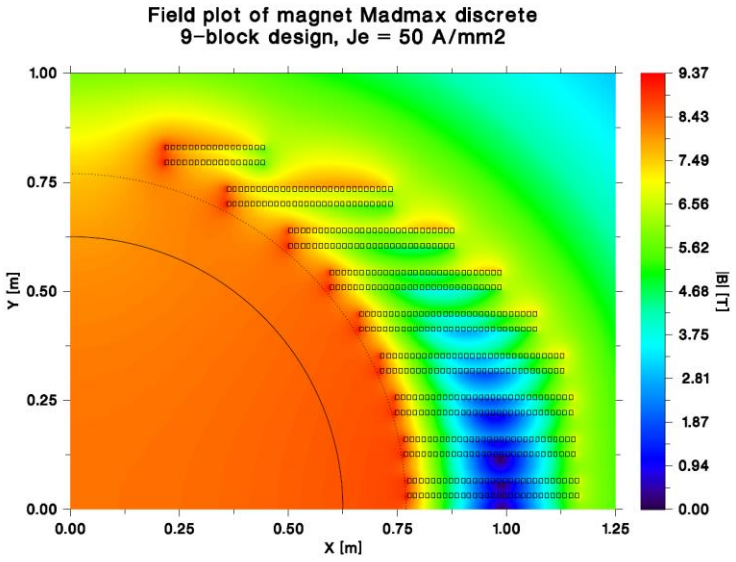
General specification of the magnet

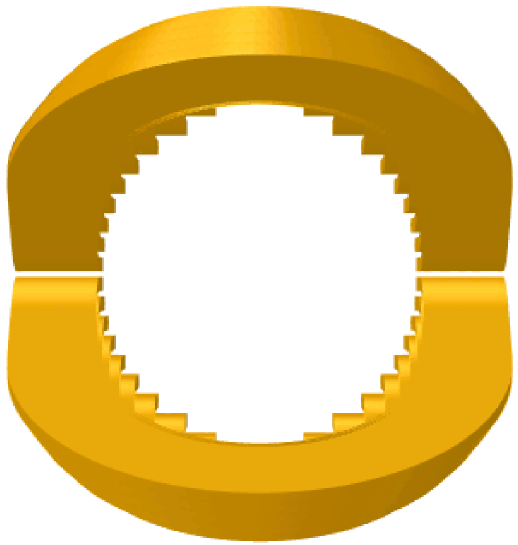
Physics specification	Value
"Ideal" FoM	~ 100 T^2m^2
Booster length 'L_b'	1.3 m
Bore diameter	1.35 m
Dipole Field	~ 9 T
Homogeneity (z=0)	± 10%
Maximum overall length	6.9 m
Maximum overall weight	200 t

Magnet specification	Value
Superconductor	NbTi
Operating temperature	1.8 K
Load Line margin	10 %
Temperature margin	1 K
Allowable VM stress	180 MPa
Hot spot	100 K
Discharge voltage	± 1 kV
Maximum current	30 kA



- 2 x 9 independent blocks made of one Double Pancake each
- 2D analytical harmonics optimization of the blocks shape to minimize peak field and volume
- 3D numerical optimization of the block heads to minimize peak field, volume and cost





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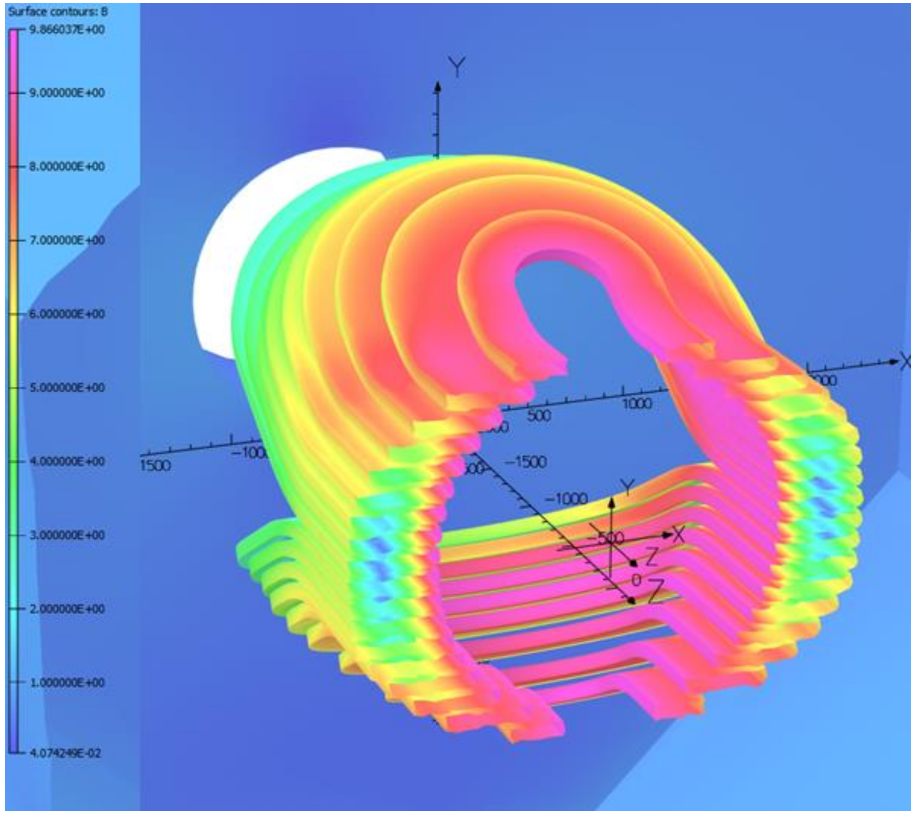
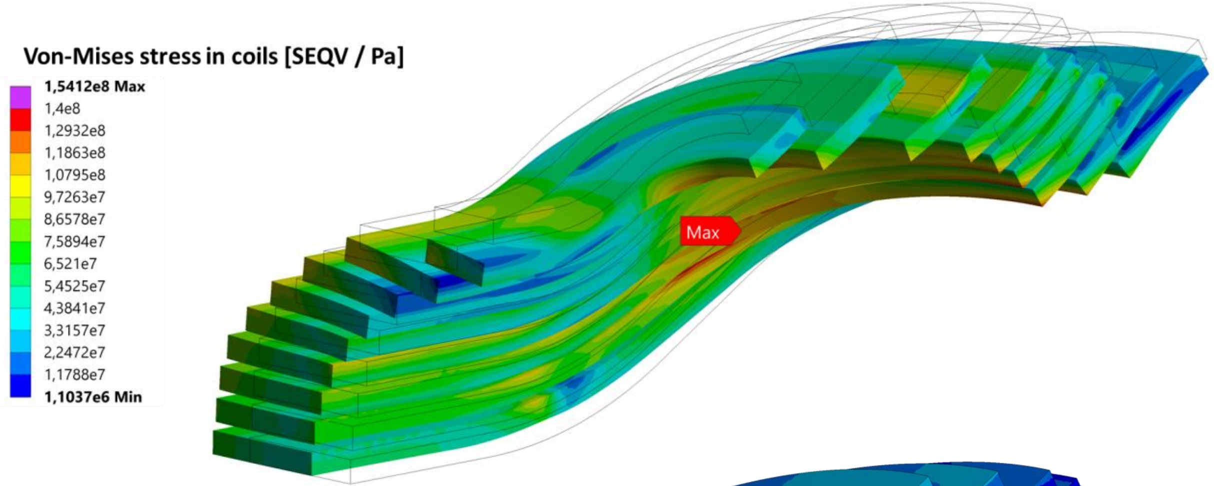
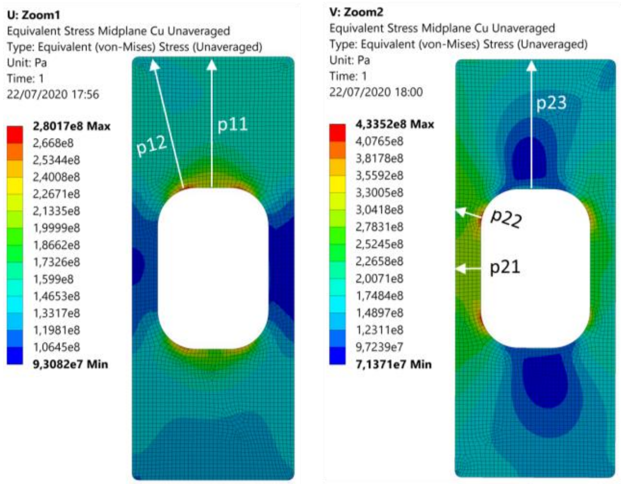


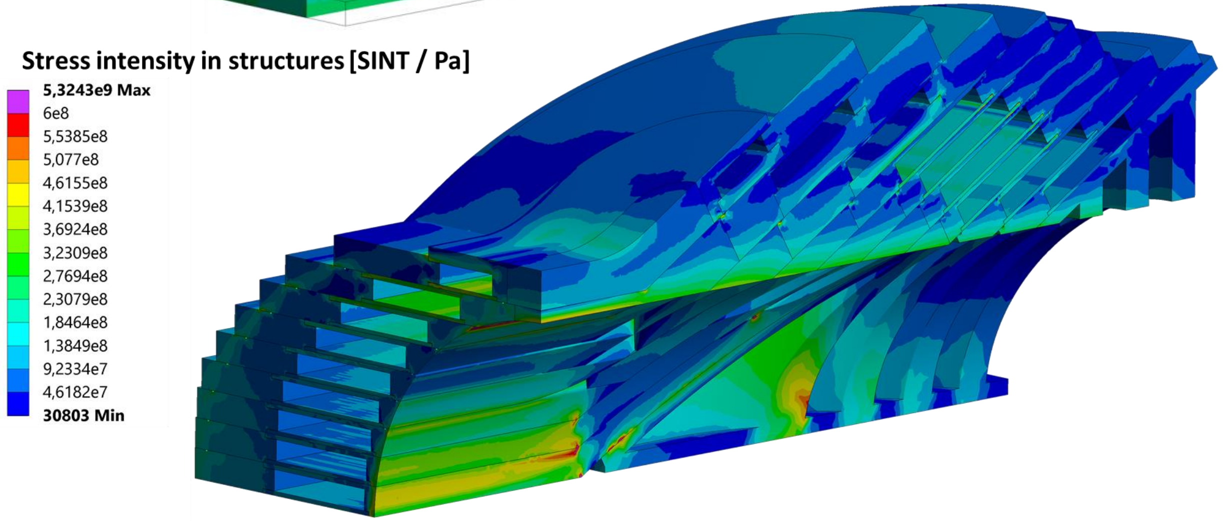
Parameter	Results
J_E	50 A/mm²
By (0,0,0)	-8.82 T
Bpeak (x,y,0)	9.85 T
Bpeak	**9.87 T**
Overfield (B_{peak}/B_0)	11.8 %
FoM	**94.4 T²m²**
H+ / H- (Z = 0.0 m)	-0.9 % / 5.0 %
Energy	**482 MJ**
Volume	**4.435 m³**
Length	**5.0 m**

Mechanical design

- 2 x 9 independent casings to ease manufacturing, reduce pieces weigh and cost
- Mechanical stress in the conductor compatible with ITER/LHD criteria
- Mechanical stress in the casings compatible with 304 L performances







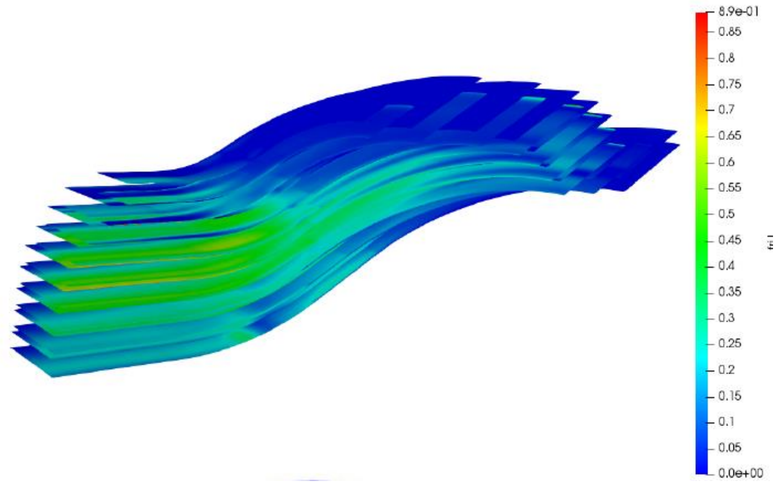
Conductor design

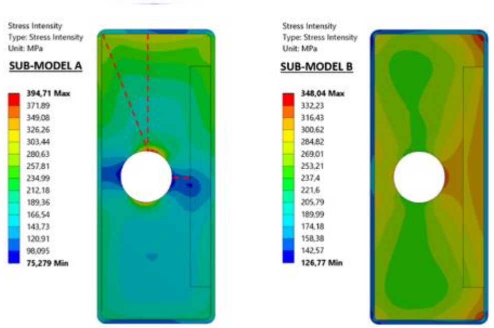
Design
- Magnetic design
- Mechanical design
- **Conductor design**

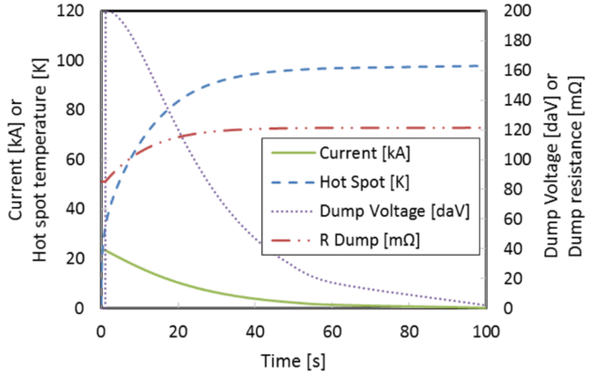
Manufacturing aspects
- Winding issues
- Casing issues

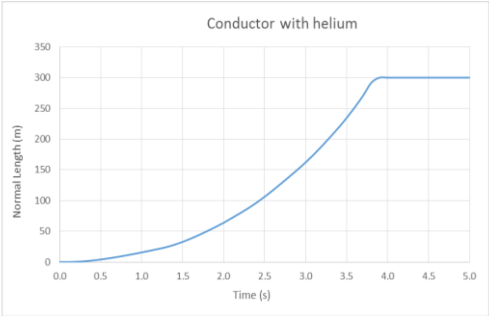
Conductor R&D
- Copper profile shape
- Cold work

Quench propagation R&D
- Design
- Manufacturing & integration
- Test results





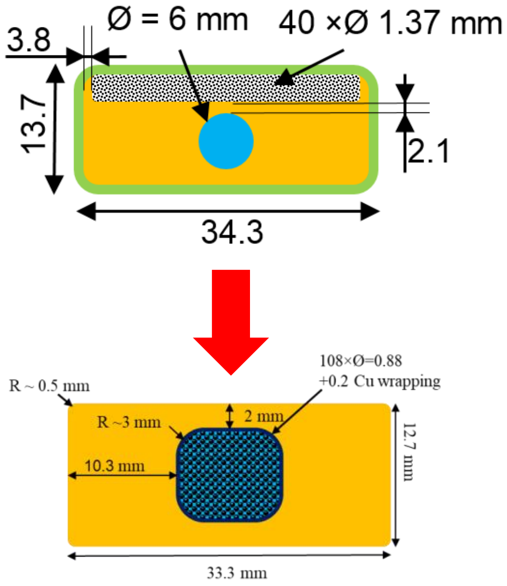




Heat deposition by motion & cryostability

Local stress in copper

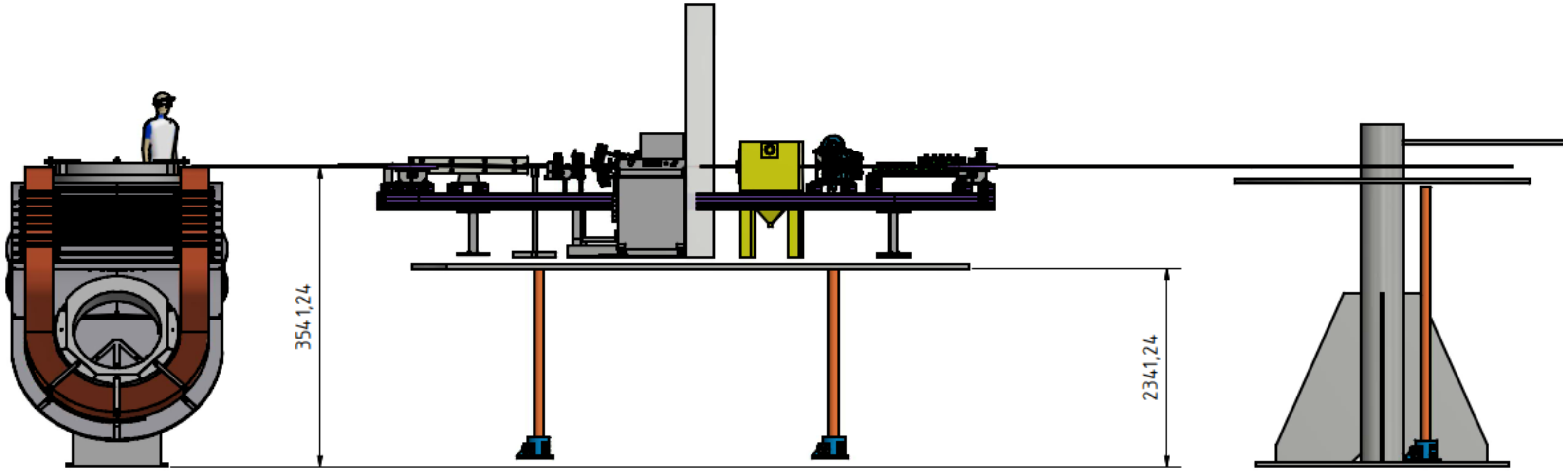
Quench velocity + 100 K hot spot + ±1 kV voltage



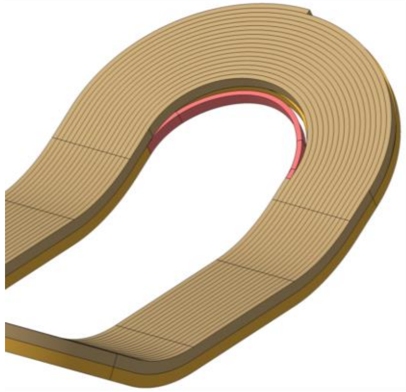
Parameters	Values	Units
Nominal current	23.5	kA
Max. field	10.4	T
Conductor length	9.6	km
Section of Cu	362	mm²
NbTi secion	29	mm²
Helium section	28	mm²
Cu/Sc cond.	12,6	
Coil weight	34	tons
Self	1.8	H

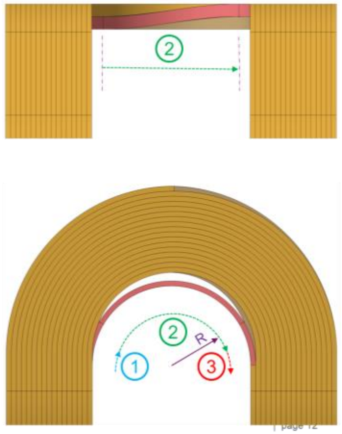
Winding issues

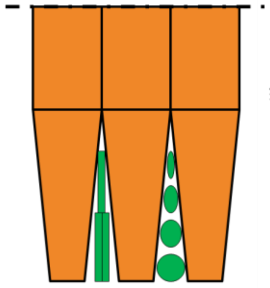
- Tooling and manufacturing process definition
- Points under study: Layer jumps, key stoning, insulation, inner joints, terminals, etc.



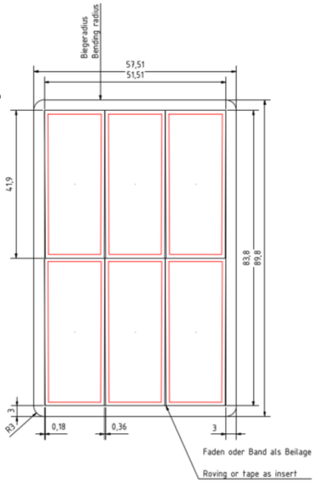
Courtesy of Bilfinger Noell (A. Hobl)

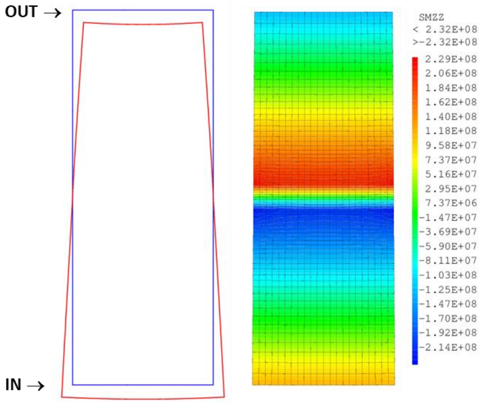






Filling the gaps with glass tape or roving/braid during winding, before impregnation





Deformed X20 (released)

Szz (released)

Casing insertion, closing and impregnation issues

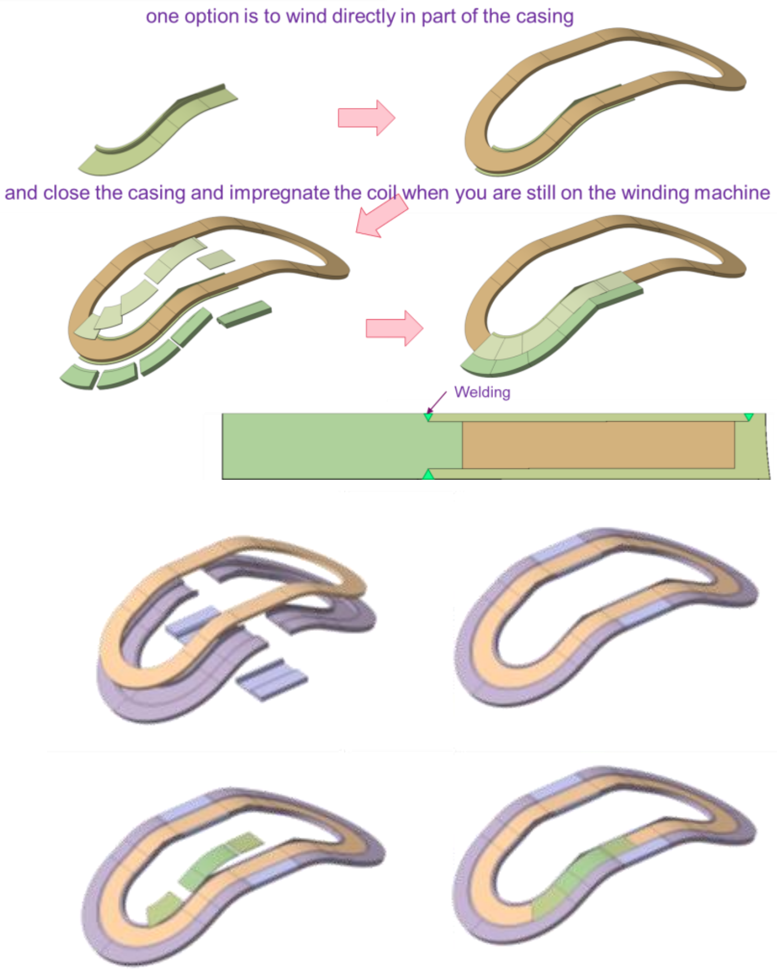
Design
- Magnetic design
- Mechanical design
- Conductor design

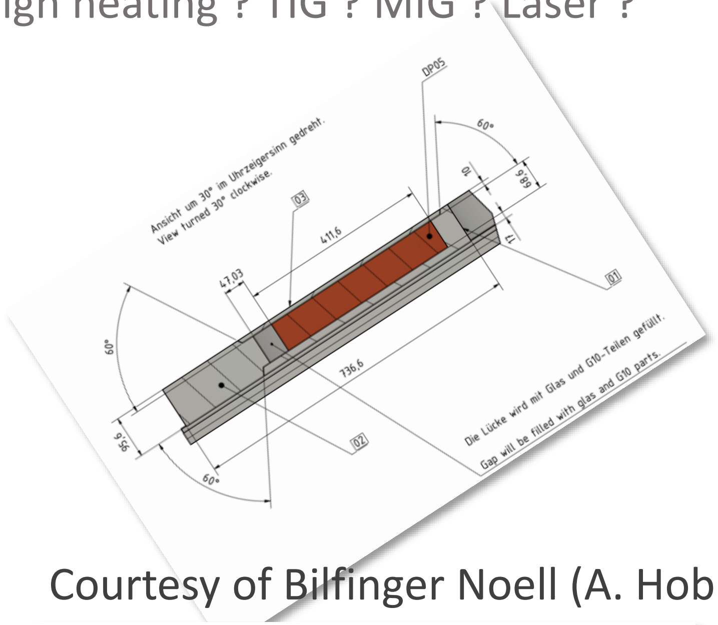
Manufacturing aspects
- Winding issues
- **Casing issues**

Conductor R&D
- Copper profile shape
- Cold work

Quench propagation R&D
- Design
- Manufacturing & integration
- Test results

- Wind the coils on a mandrel or directly on casing parts ?
- Impregnate the coils on specific molds or directly in casings ?
- How to close casings without damaging the coils by high heating ? TIG ? MIG ? Laser ?





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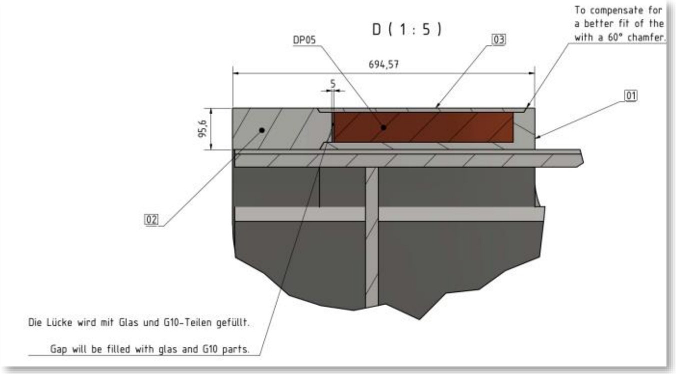
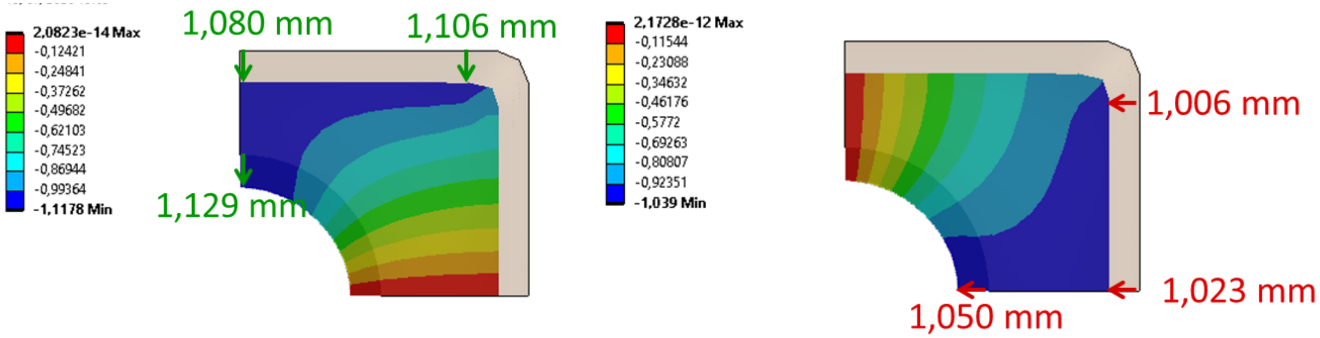
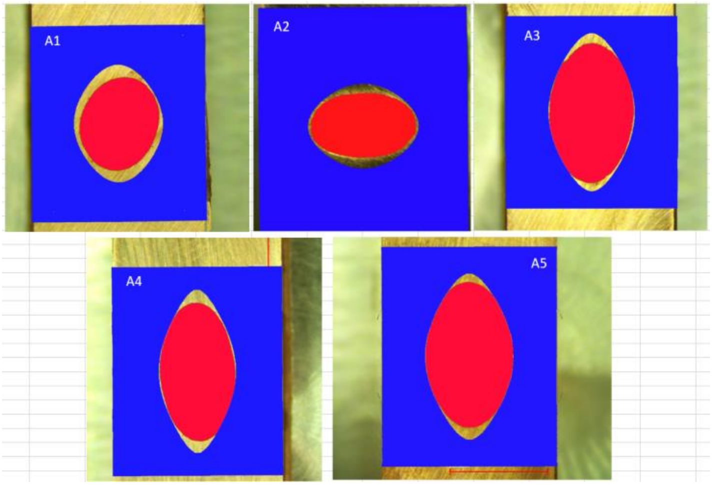
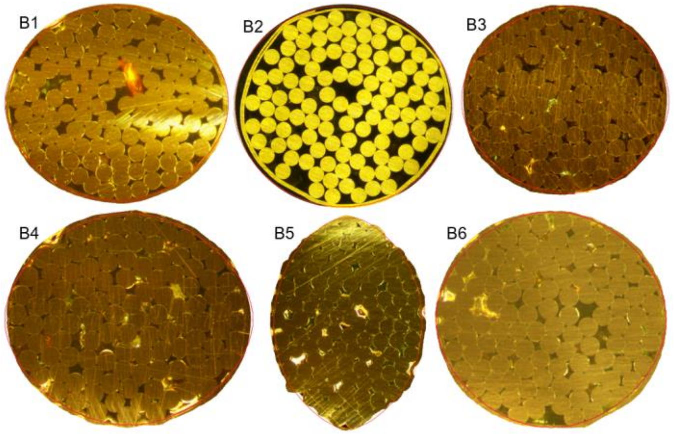


Conductor R&D: a reverse engineering problem

- Initial copper shape to obtain final conductor after insertion + compaction ?
- FEM computations + measurements done on bare copper profile & CICC

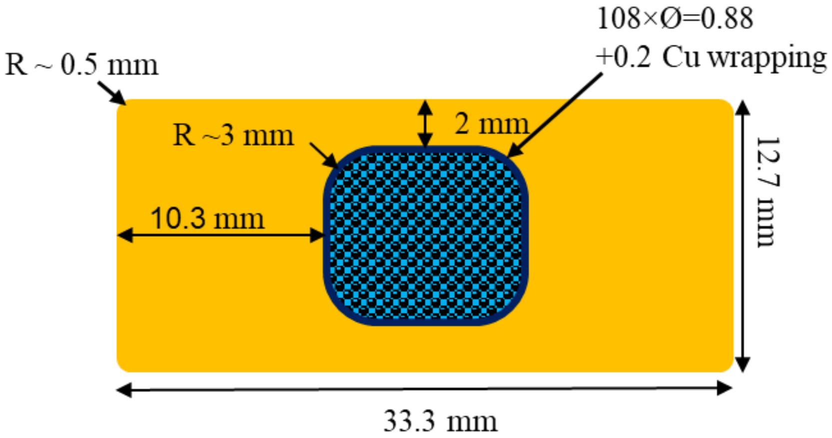


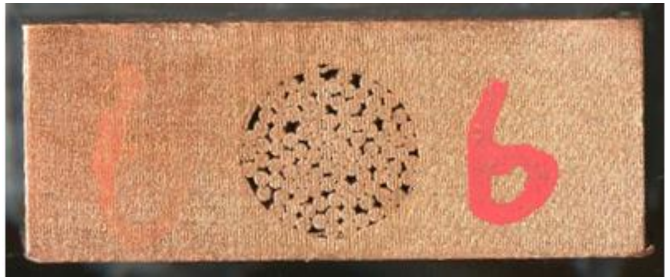


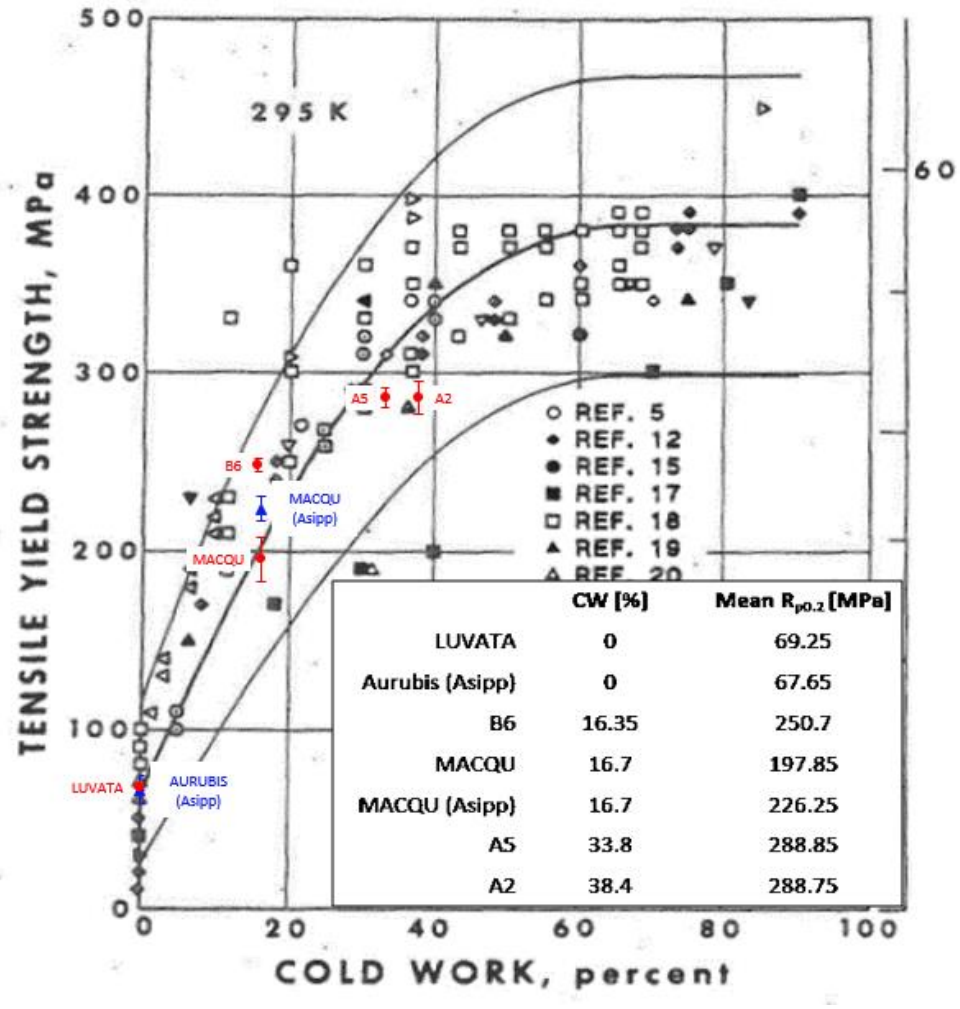


Conductor R&D: a reverse engineering problem

- Cold work needed to obtain the required Yield Strength on copper profile ?
- Compaction trials of soft tempered profiles and mechanical measurements



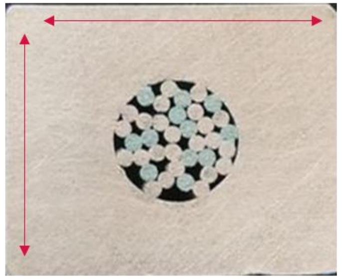




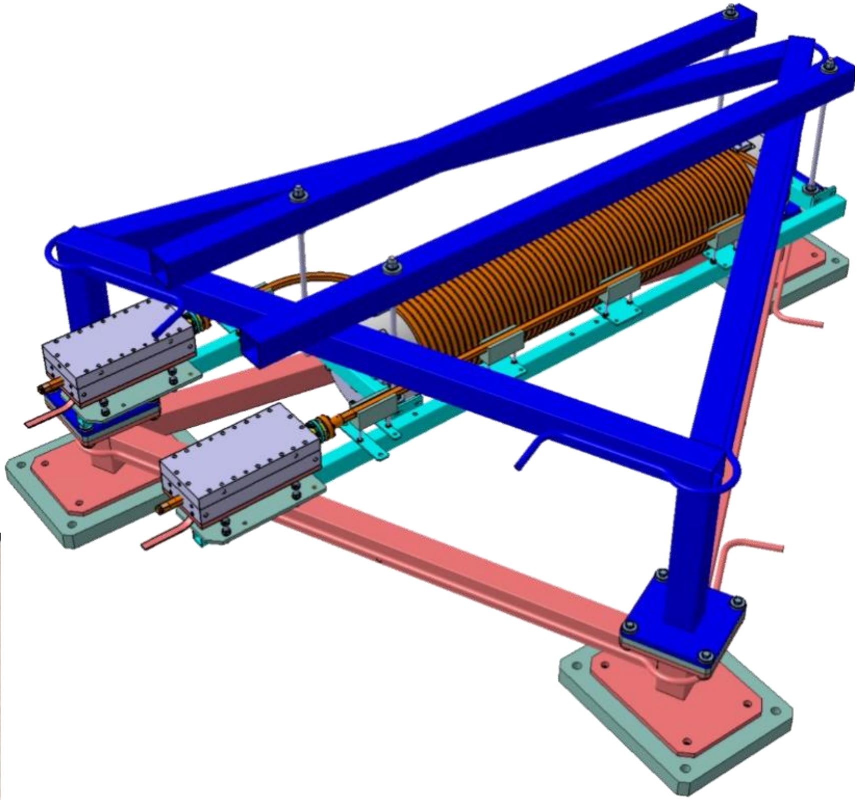
	CW [%]	Mean $R_{p0.2}$ [MPa]
LUVATA	0	69.25
Aurubis (Asipp)	0	67.65
B6	16.35	250.7
MACQU	16.7	197.85
MACQU (Asipp)	16.7	226.25
A5	33.8	288.85
A2	38.4	288.75

- No state of the art + very big uncertainties on models: Shajii ~ 3 cm/s VS THEA ~ 17-50 m/s
- Design, manufacturing and experimental tests on a prototype magnet for quench studies

Parameters	Values	Units
Nominal current	21.6	kA
Max. field	2.30	T
RRR	60	
Conductor length	50	m
Section of Cu	175	mm²
Number of strands	12 Sc / 24 Cu	
Cu/Sc	1.105	
Coil weight	100	kg
Self	0.19	mH
Stored energy	43.5	kJ
Discharge voltage	130	V

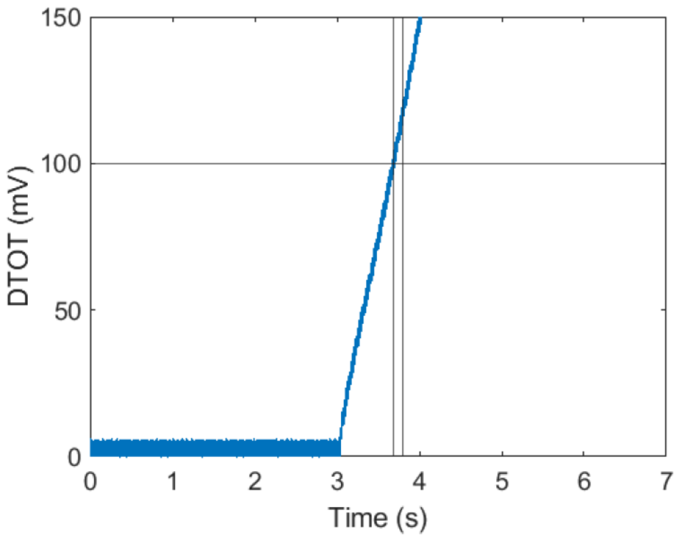


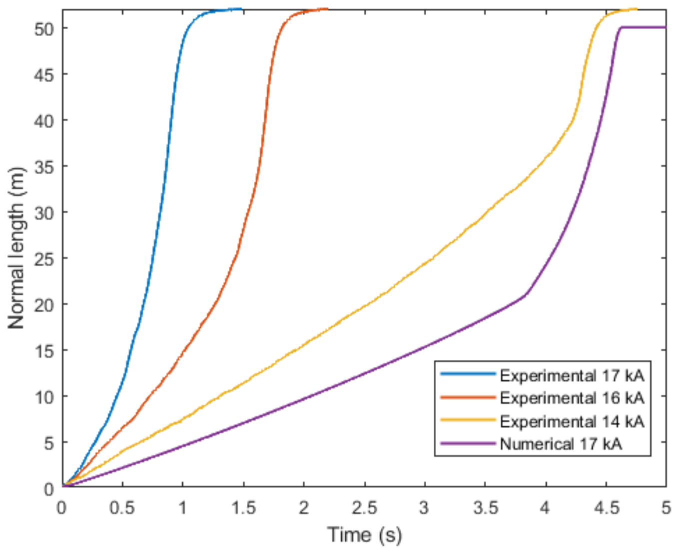
MACQU profile with cable inside

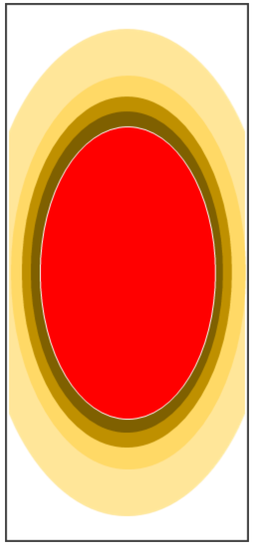


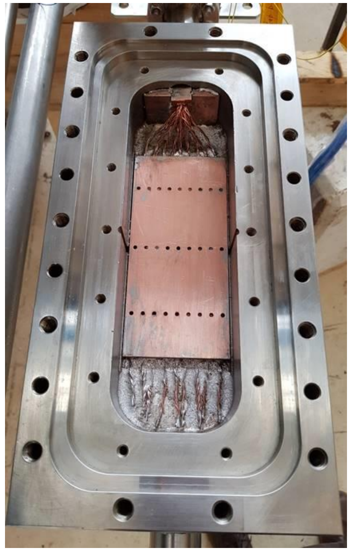
Main Quench R&D results

- **Quench velocity order of magnitude: a few m/s up to tens of m/s → MADMAX Safety Fully OK**
  - Able to detect quench in less than 800 ms with a threshold of 100 mV → done 60 times
- **Same qualitative behavior between models and experiment but experimental quench faster**
  - Good deep understanding of the quench physics thanks to the code equations
  - Assumption and modelling of current diffusion time in copper → increases joule effect and speed
- **Other important results not directly linked to quench:**
  - Current limitation in the W7X terminals → Lessons learned and specific design to be done for Madmax
  - Thermal behavior of a static CICC 1.8 K magnet cooled with no bath
  - Extra trials of 2 K forced flow in the CICC → Interesting pressure drop measurements







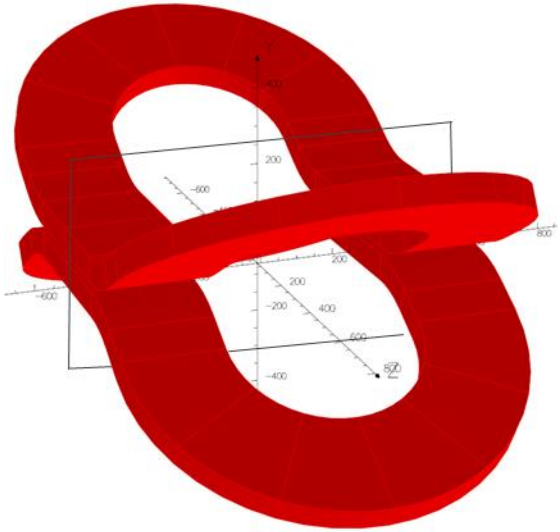


Conclusion

- Conceptual design finished and validated
- Open points on the manufacturing design under study and discussion with industry

- 1st Conductor R&D successfully demonstrated that a copper profile CICC can be manufactured in specifications
- 2nd Conductor R&D on going to study a “rectangular hole” behavior and unexpected issues
- Quench R&D successfully demonstrated that a quench can be “classically” detected in the Madmax case
- For those interested in more details: 7 papers to be published by the end of the year

- Next 3 years: design, manufacture and cold test a real “skateboard shape” demonstrator coil of the Madmax magnet including:
  - Demonstration of the main Madmax critical performances: 90% on the LL, mechanics, thermal cryostability
  - Development of a specific optimized joint concept for Madmax
  - Qualification of the main critical manufacturing issues: final conductor, winding, impregnation, casing insertion and closing impregnation process



Many thanks to the Madmax team! Questions ?

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Thank you for your attention !

Walid ABDEL MAKSOUD