MADMAX detector magnet: technology concepts

Clément Lorin, 26 sep 2024 at CERN

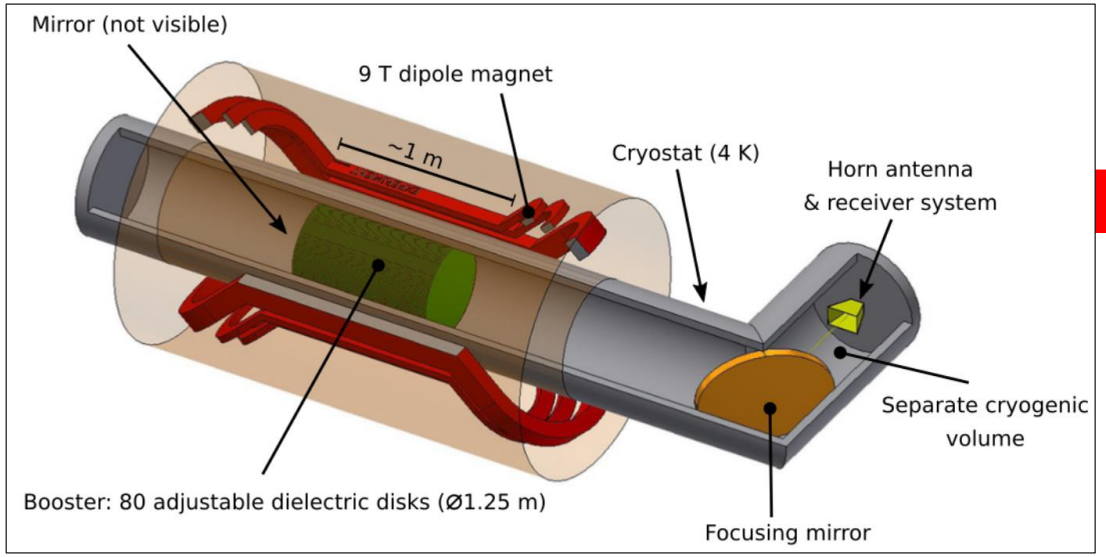
Walid Abdel Maksoud, Jerome Allard, Christophe Berriaud, Valerio Calvelli, Loic Denarie, Guillaume Dilasser, Thomas Donga, Yannick Drouen, Unai Duranona, Thibault Genestier, Pascal Godon, Romain Godon, Quentin Guihard, Antoine Guinet, Stephane Jurie, François-Paul Juster, Jean-Pierre Lottin, Jean-Francois Millot, Frederic Molinié, Francois Nunio, Theophile Pontarollo, Ricardo Correia-Machado, Loris Scola, Leo Segrestan, Nicolas Solenne, Francesco Stacchi (DRF-Irfu)

Context: innovation partnership with MPI around Dark Matter Axion physics

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

BILFINGER
BILFINGER NOELL GMBH

MAgnetized Disk and Mirror Axion eXperiment:



$$P = P_0 \cdot \beta^2(\nu) = 1.1 \times 10^{-22}\ \mathrm{W} \left(\frac{\beta^2(\nu)}{5 \times 10^4}\right) \left(\frac{A}{1\ \mathrm{m}^2}\right) \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm}^3}\right) C_{a\gamma}^2$$

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

TARGET:

~ 100 T²m² → ~ 10 T in 1 m²

Madmax collaboration, “A new experimental approach to probe QCD axion dark matter in the mass range above 40 μeV”, Eur. Phys. Jour. C, 2019
Madmax collaboration, “MADMAX: A dieletric haloscope Experiment” Journal of Physics: Conference Series, 2020
B. Majorovits et al., “MADMAX: A new dark matter axion search using a dieletric haloscope”, arXiv:1611.04549v1, 2016

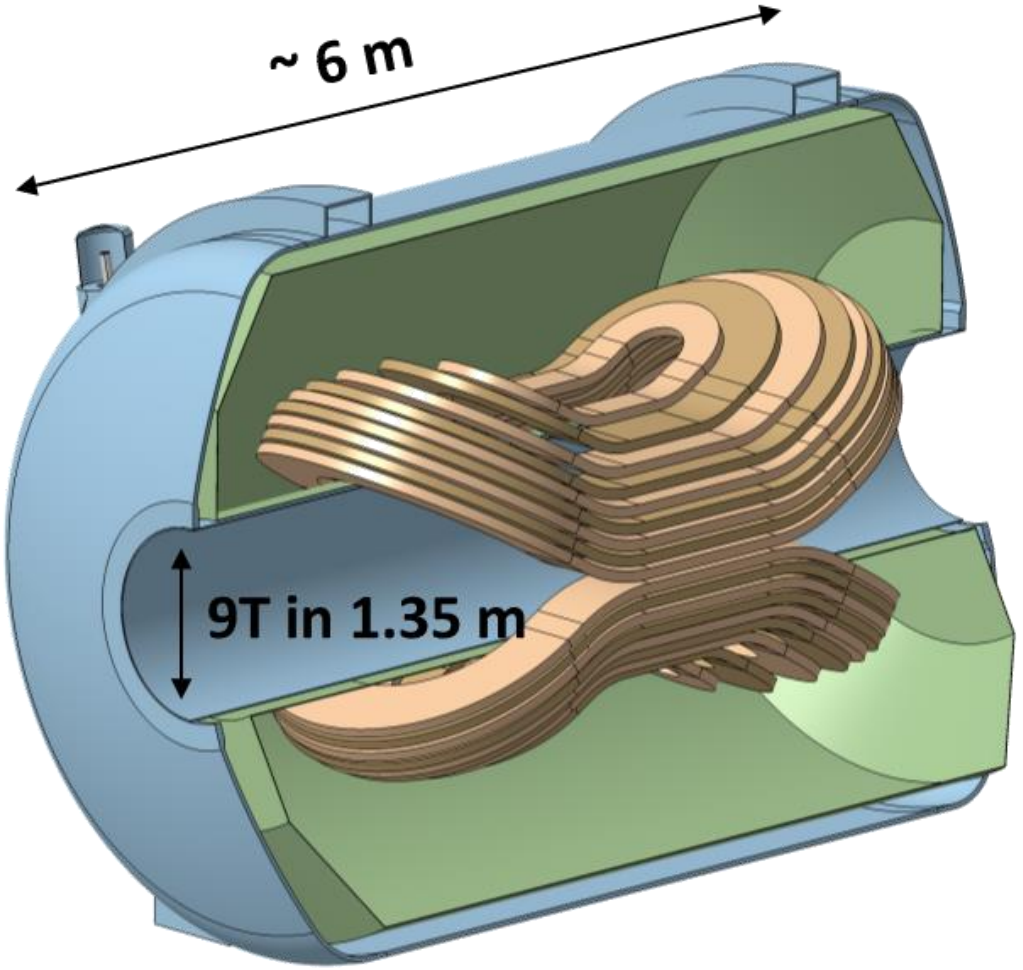
General magnet parameters

MADMAX design overview
- Magnetic design
- Mechanical design
- Conductor design

MADMAX main risk
- Conductor R&D
- Quench R&D
- Next demonstrator

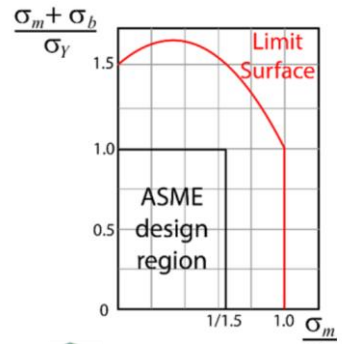
Coming years activities

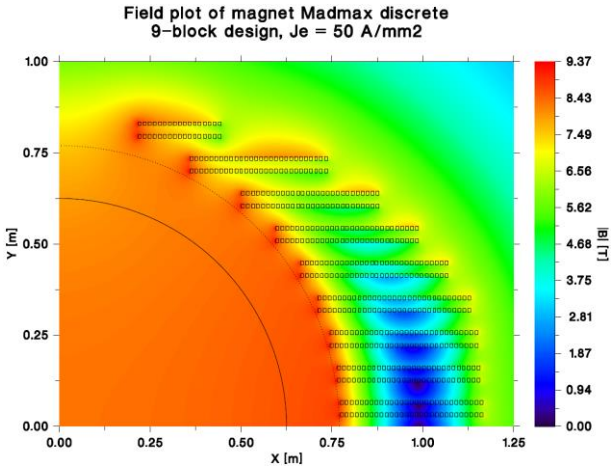
Quantity/parameter	Data
FoM	~ 95 T^2m^2
Peak fields	10.3 T
Superconductor	Nb-Ti
Operating temperature	1.8 K
Nominal current	23.5 kA
Energy	482 MJ

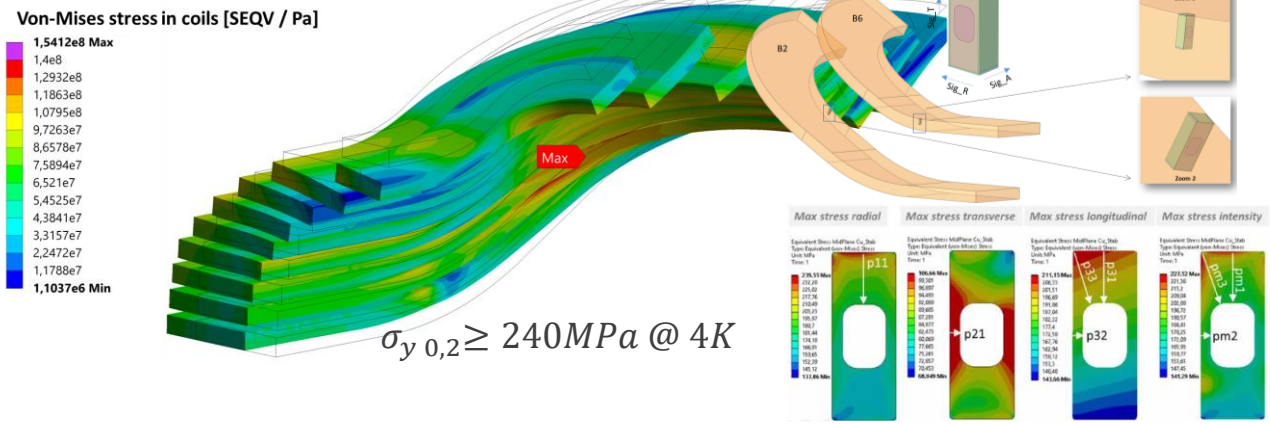


Magnetic and mechanical designs

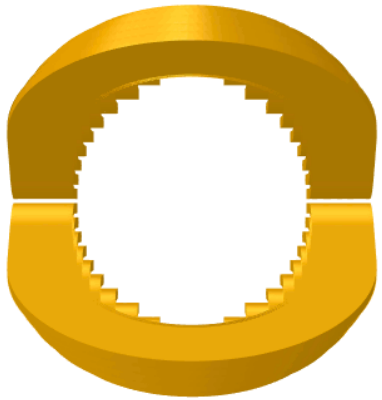
- 2 x 9 casings: one Double Pancake in each one
- 2D/3D emag optimization (minimize peak field and Lorentz forces)
- 3D mech numerical model (conductor sub-modelling (SLC) + casing technological design)

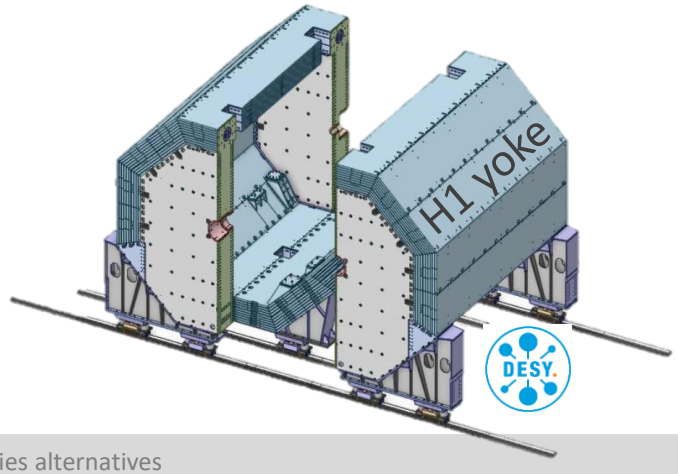


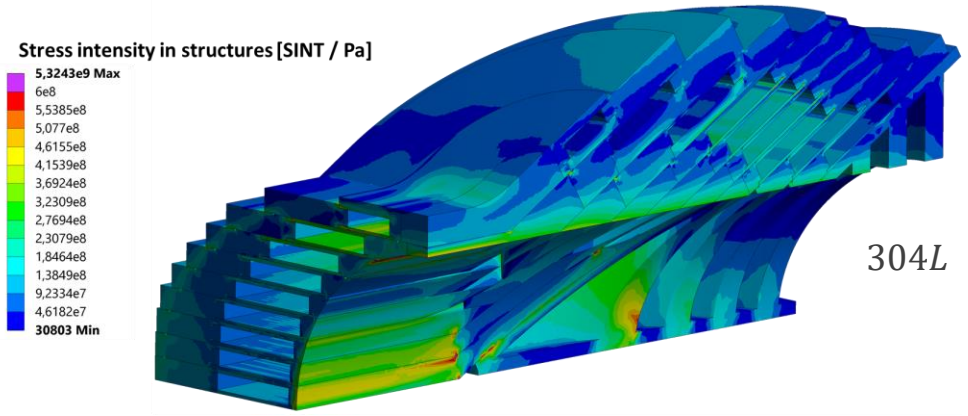




$\sigma_{y\,0,2} \geq 240MPa\ @\ 4K$







$304L$

Conductor design

- **MADMAX design overview**
  - Magnetic design
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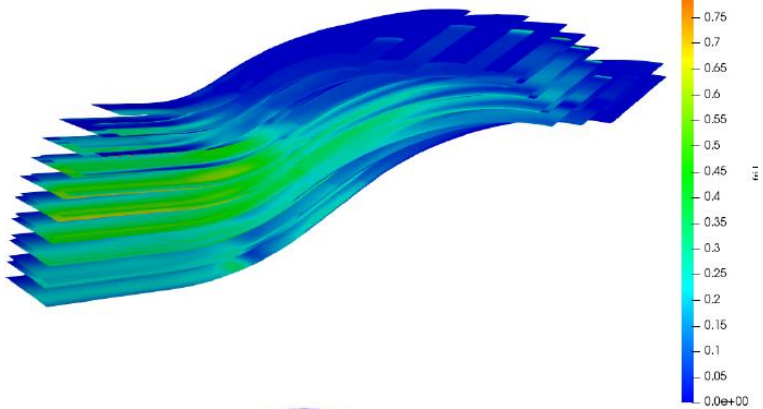
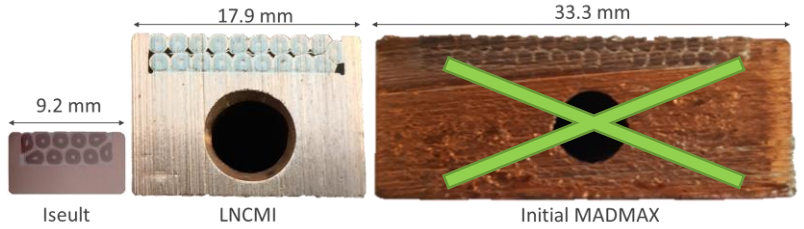
- **MADMAX main risk**
  - Conductor R&D
  - Quench R&D
  - Next demonstrator
- **Coming years activities**

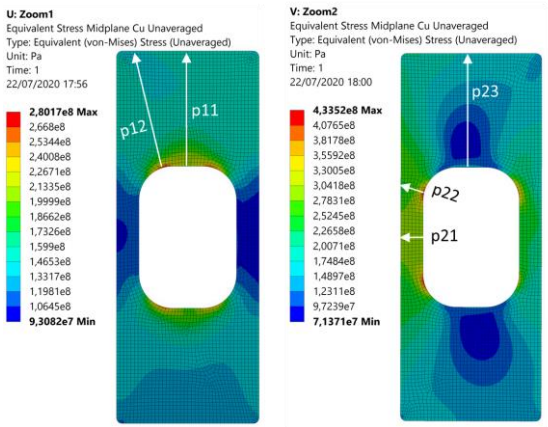


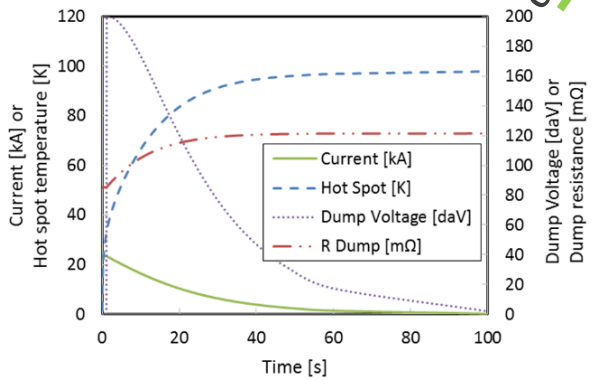


Heat deposition by motion & cryostability

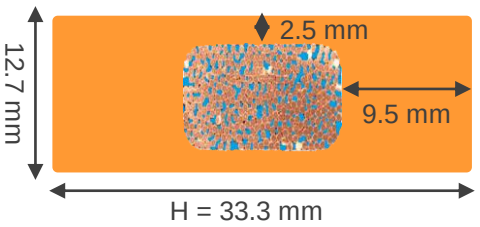
Local stress in copper

Quench velocity + 100 K hot spot + ±750 V voltage





CICC « JT60-like »



Parameters	Values	Units
Conductor length	10	km
Section of Cu	321	mm²
Nb-Ti section	30	mm²
Helium section	28	mm²
Insulation	0.5	mm
Coil weight	35	tons

MADMAX Development Risk and Mitigation Plan

Four levels of risks “with hands” :

- **Having no conductor so no magnet…** ⟹ Conductor R&D
  - Risk: no industry able to manufacture a conductor for MADMAX
  - Mitigation plan: develop and qualify a copper CICC concept of conductor for MADMAX
- **Having a magnet but burnt…** ⟹ Quench R&D: MACQU
  - Risk: too slow not detectable quench
  - Mitigation plan: experimentally measure quench velocity on a MADMAX like coil prototype
- **Having a working magnet but underperforming… (less FoM)** ⟹ Next demonstrator
  - Risk: not achieving the nominal current and field
  - Mitigation plan:
    - Evaluate the main reasons for which this could happen
    - Design, manufacture and test demonstrator(s)/mockup(s) proving that the nominal conditions are achievable on MADMAX and risks under control
- **Having a working and performing magnet but with high cost and schedule deviations…**
  - Risk: loosing to much time and money for solving manufacturing non conformities, learning curve…
  - Mitigation plan: limit full success oriented strategy: tooling and processes qualification, dummy samples/mockups/coils manufacturing, improve CEA team know-how

Conductor R&D (with ASIPP-China)

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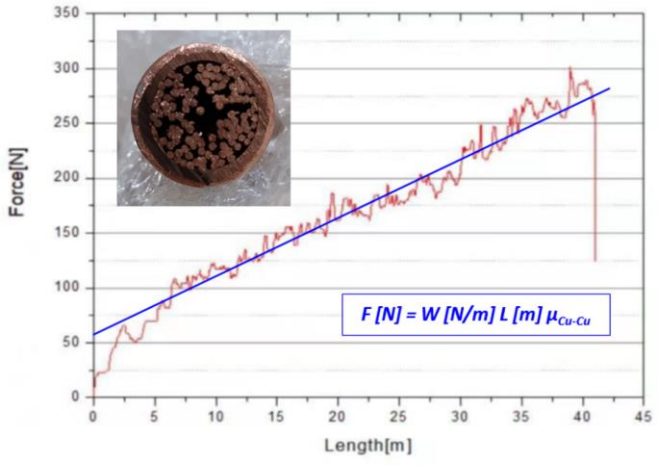
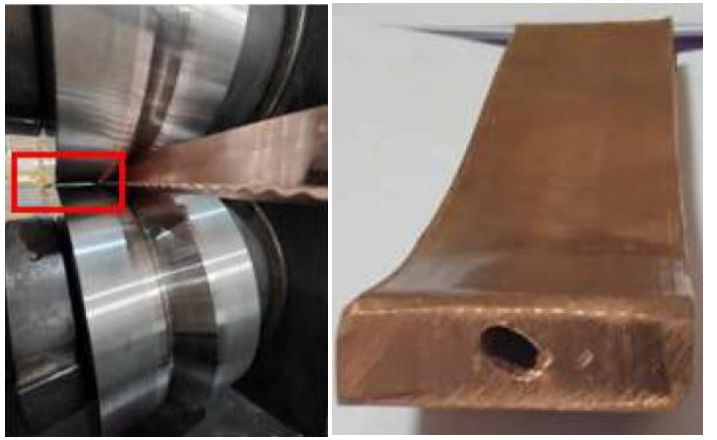
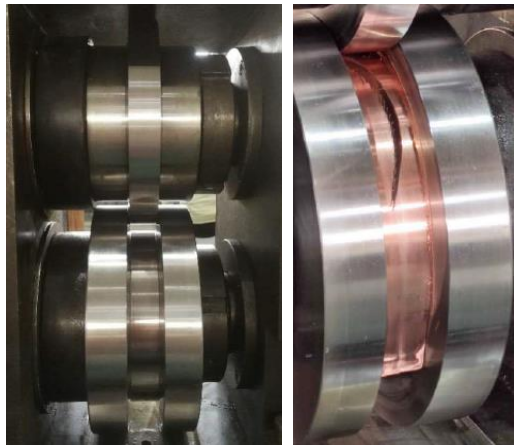
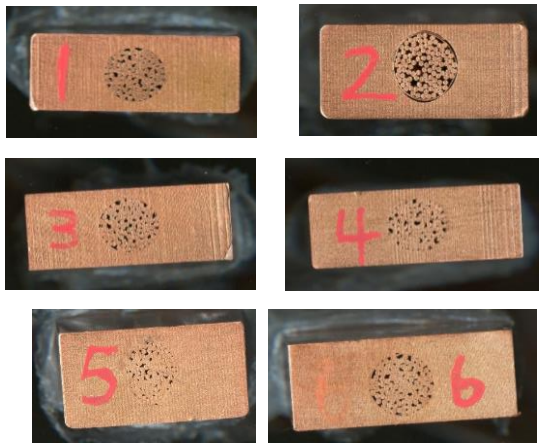
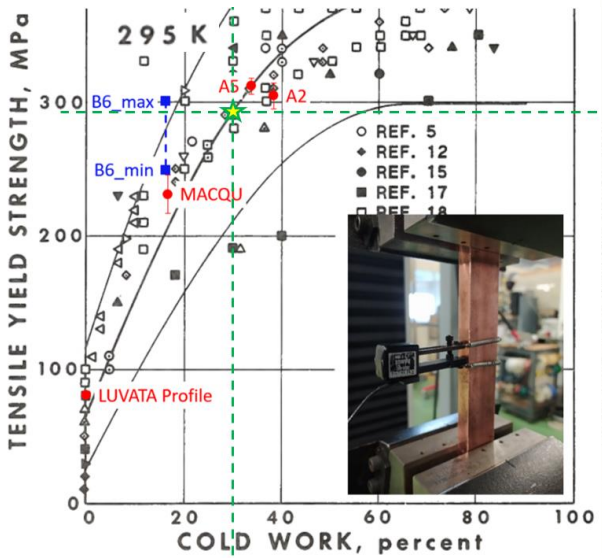
Trials: insertion, compaction method, cold work/RRR vs yield strength, shaping vs model

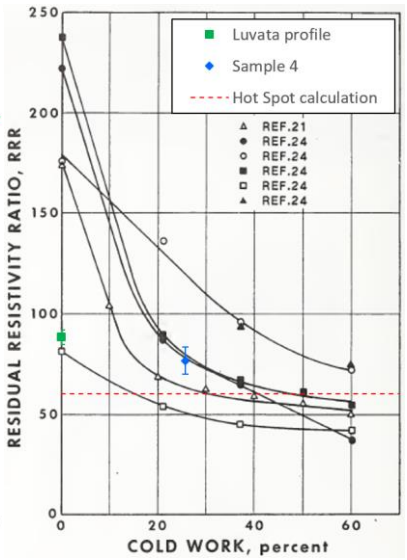


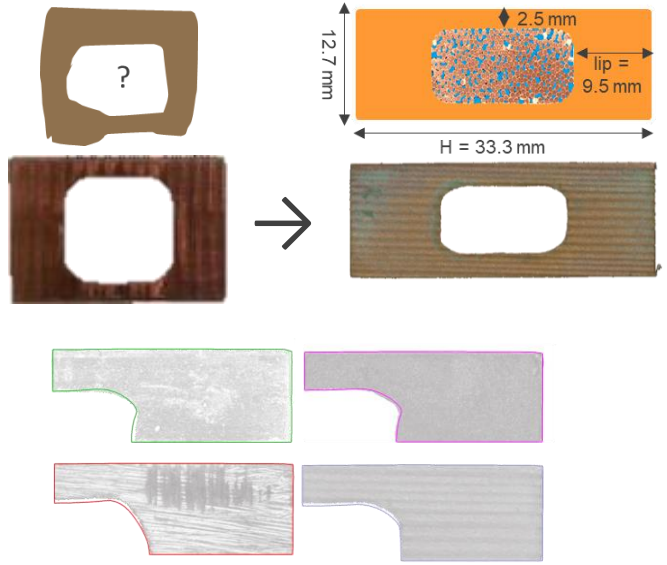












Quench R&D: MACQU design

- MADMAX design overview
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  - Quench R&D
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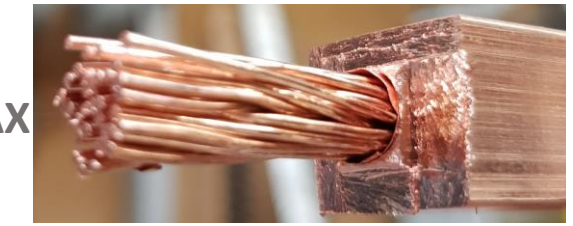
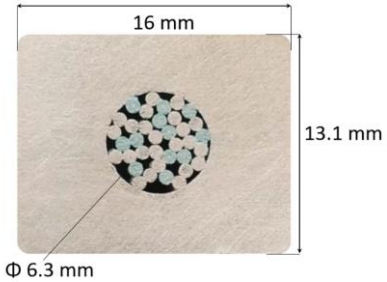
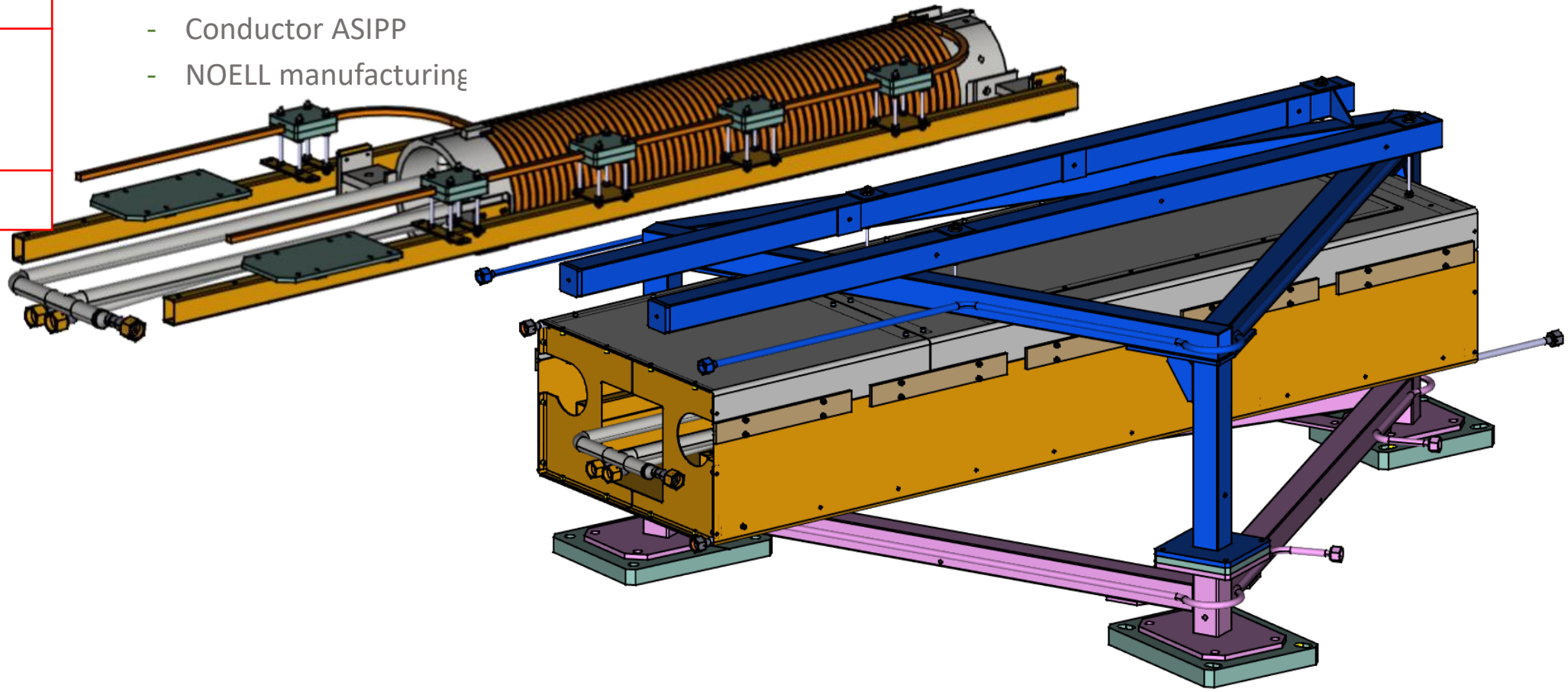
- Coming years activities

- **MADMAX Coil for Quench Understanding**
- **Make sure that quench is detectable in MADMAX**
  - MADMAX_like conductor, cooling, Joule heating
  - CEA design – CAD
  - Conductor ASIPP
  - NOELL manufacturing







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MADMAX Coil for Quench Understanding

Quench R&D: MACQU is a success but…

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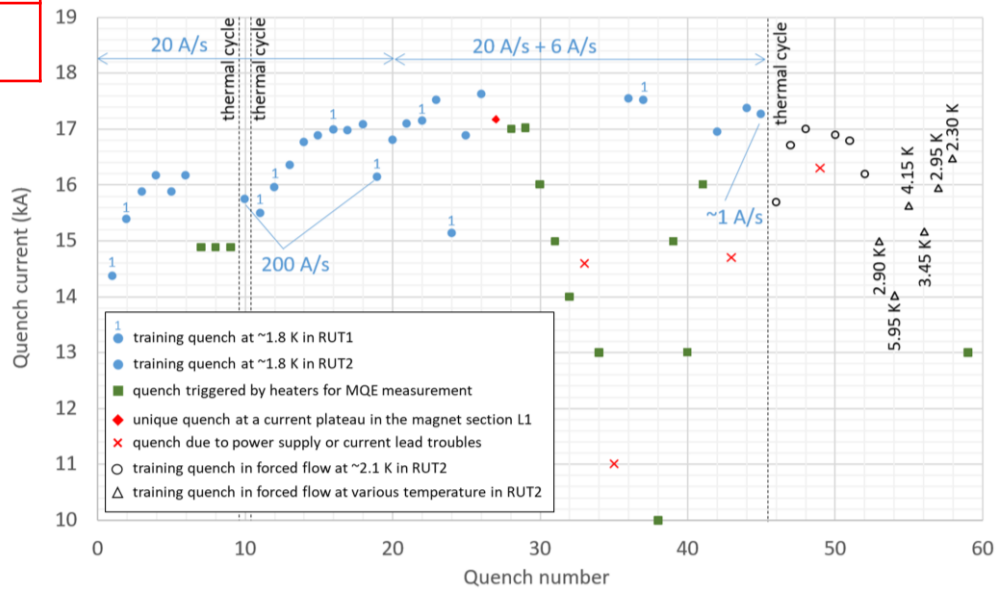
Coming years activities

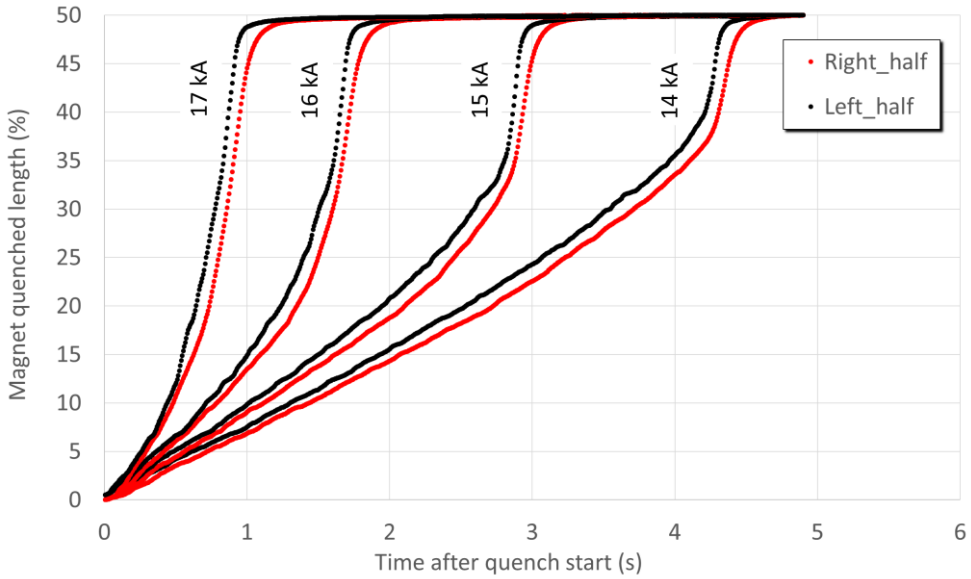
▶ Project objective: Detection/Protection OK

- ~60 quenches in MACQU
- Quench front velocity detectable
- But: Operation ~10 % lower than nominal:
  - terminals limitation



▶ Scientific objective: Observation of the THQB

- **First observation in superfluid helium**
- But: Bad match in terms of velocity between MACQU & simulation



Quench R&D: MACQU is a success but…

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MADMAX main risk
- Conductor R&D
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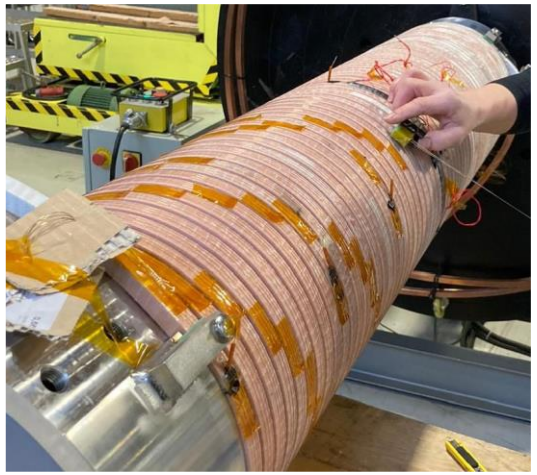
- Next demonstrator

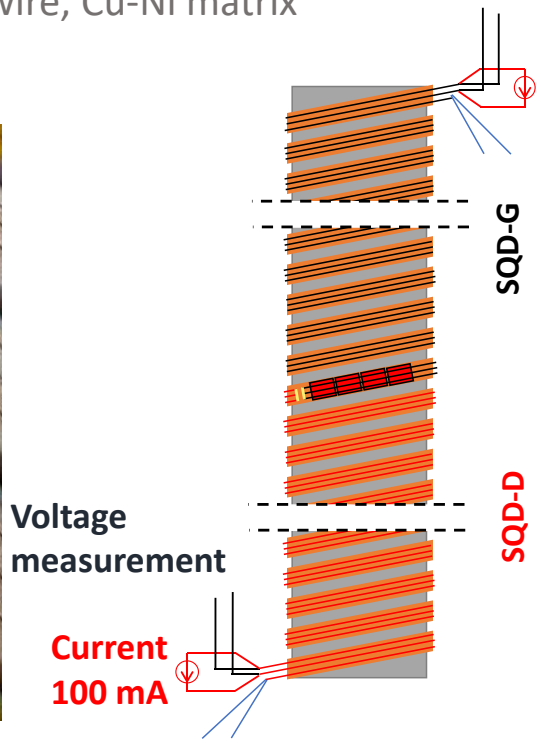
Coming years activities



Courtesy NOELL

▶ Superconducting Quench Detector (SQD)

- 0.3 mm Nb-Ti wire, Cu-Ni matrix
- Bifilar winding



MACQU technological aspects:
C. Lorin *et al.*, "Development, Integration, and Test of the MACQU Demo Coil Toward MADMAX Quench Analysis," in *IEEE TAS*, 2023

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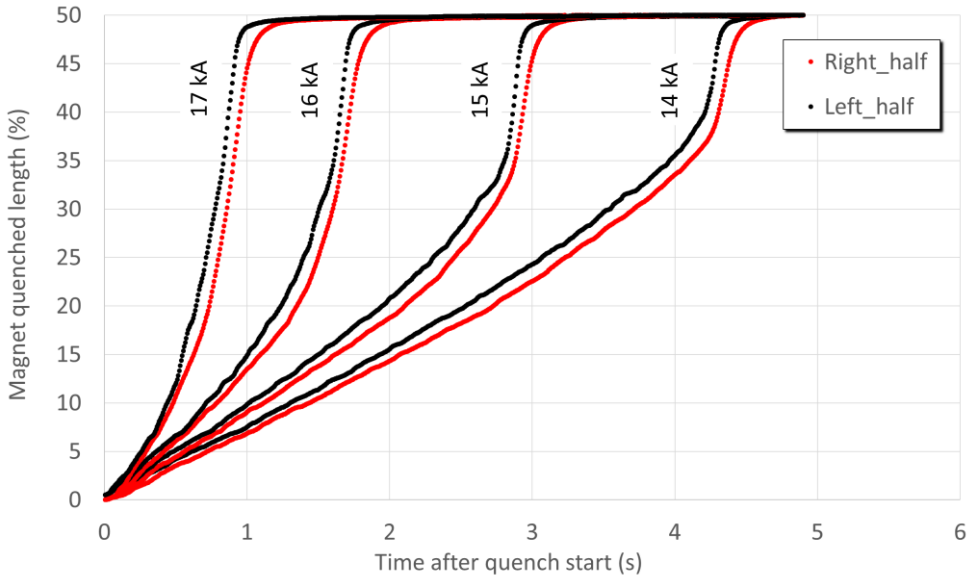

Next demonstrator: Macumba

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  - Conductor design
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  - Conductor R&D
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  - Next demonstrator
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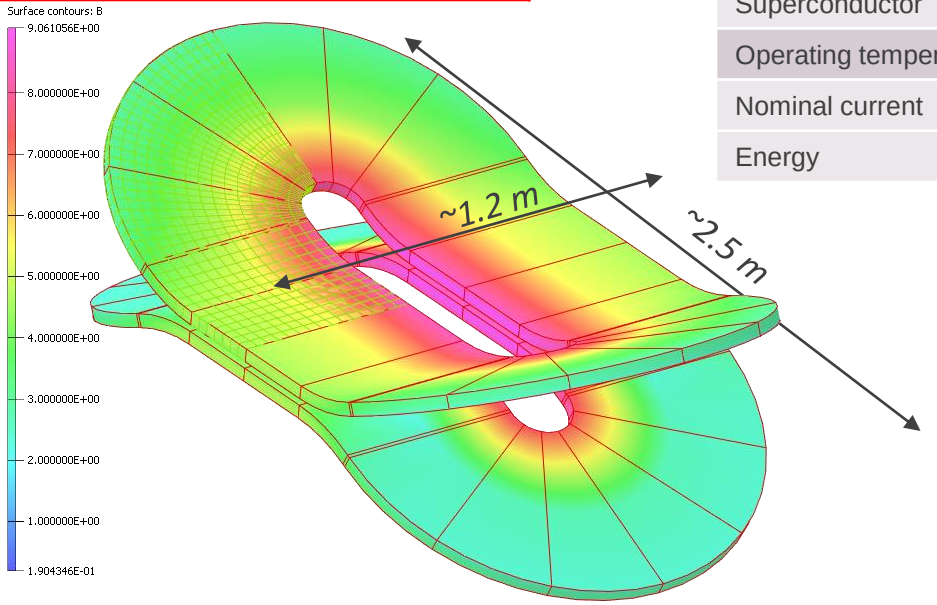
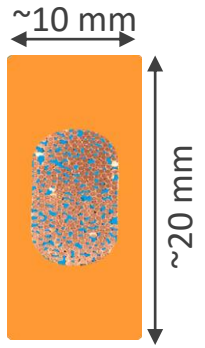
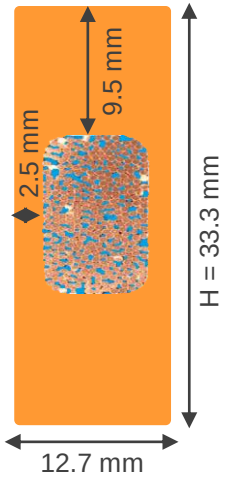
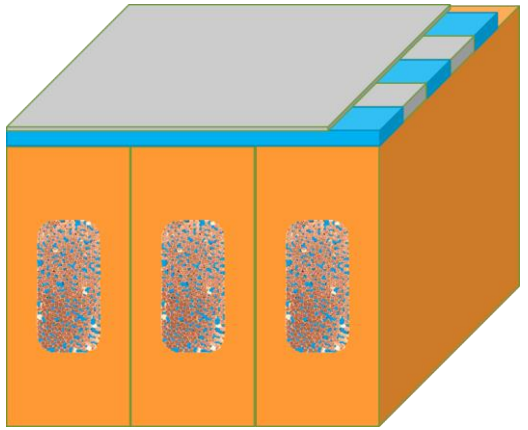
- **Level 2 risks mandatory performances**:
  - **90% of the load line (nominal current)**
  - **Thermal stability as MADMAX**
- **Level 1 risks mandatory requirements: (manufacturing process qualification)**
  - Madmax “like”

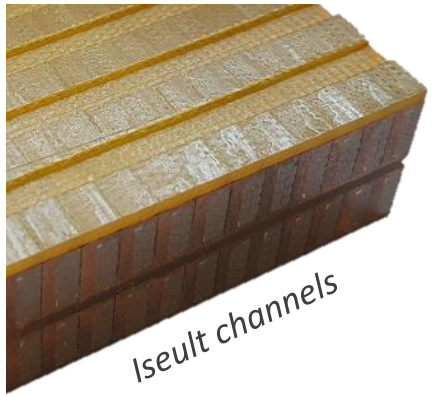
Quantity/parameter	Data
Peak fields	~8 T
Superconductor	Nb-Ti
Operating temperature	1.8 K
Nominal current	~20 kA
Energy	~15 MJ

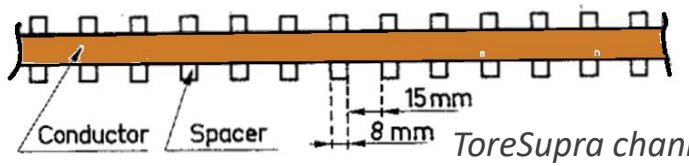








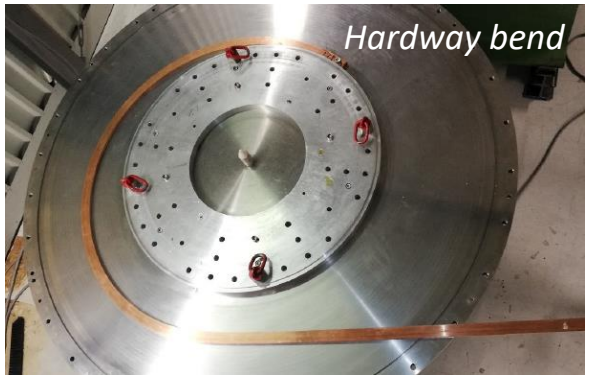


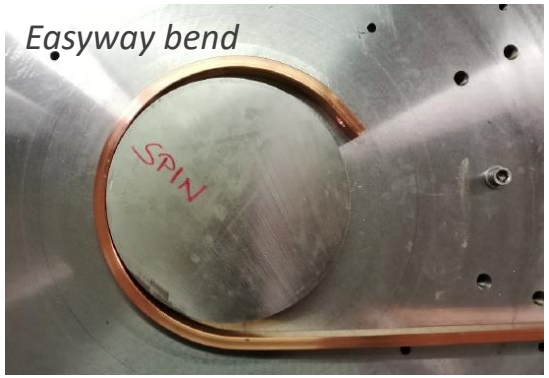


*R. Aymar et al., GLOBAL TEST OF THE CONDUCTOR FOR "TORE SUPRA" UNDER ACTUAL WORKING CONDITIONS, IEEE Trans. On Magn., 1981

Next demonstrator: Fabrication

- **Fabrication challenges**:
  - **Winding springback**
    - **Objective: over-bending to get stress free coils to ease handling, impregnation, insertion**
    - **Springback illustration on a copper bar (MADMAX conductor like)**





Courtesy NOELL

  - **Past ideas (**“The 62 MJ MHD Italian dipole”**)**

Courtesy ASG

Next demonstrator: Test in MATTRICS (ex-JT60)

- **Test at CEA saclay at ~20 kA, 1.8 K in the MAgnet Testing Technology Research InfrastruCtureS**
  - Move from one building to another (starting T4 of 2021, commissioning expected in T1 of 2025)

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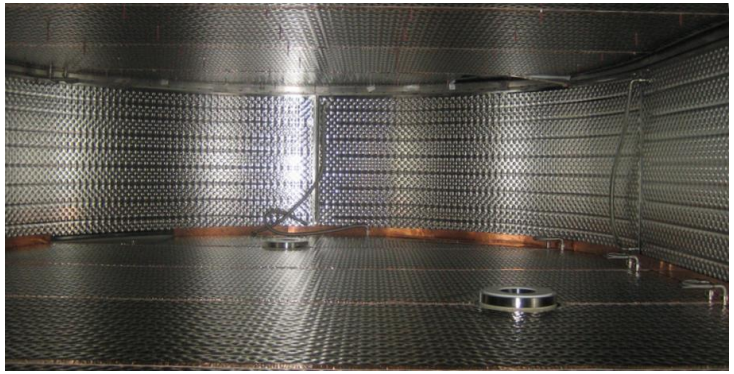
Coming years activities

~45 T

~25 T



1.9×6×10 m^3 from LN2 shield to shield

Conclusion

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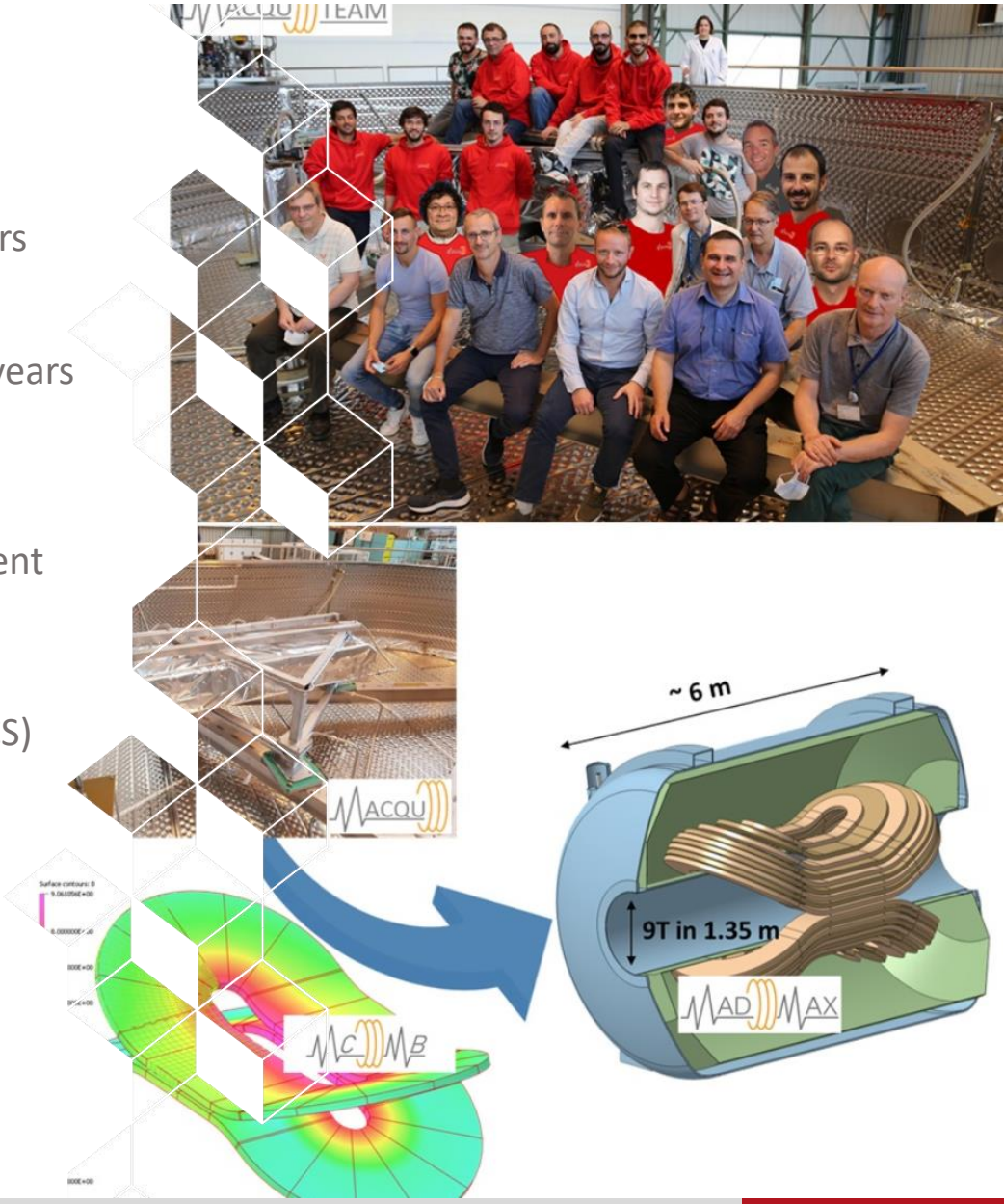
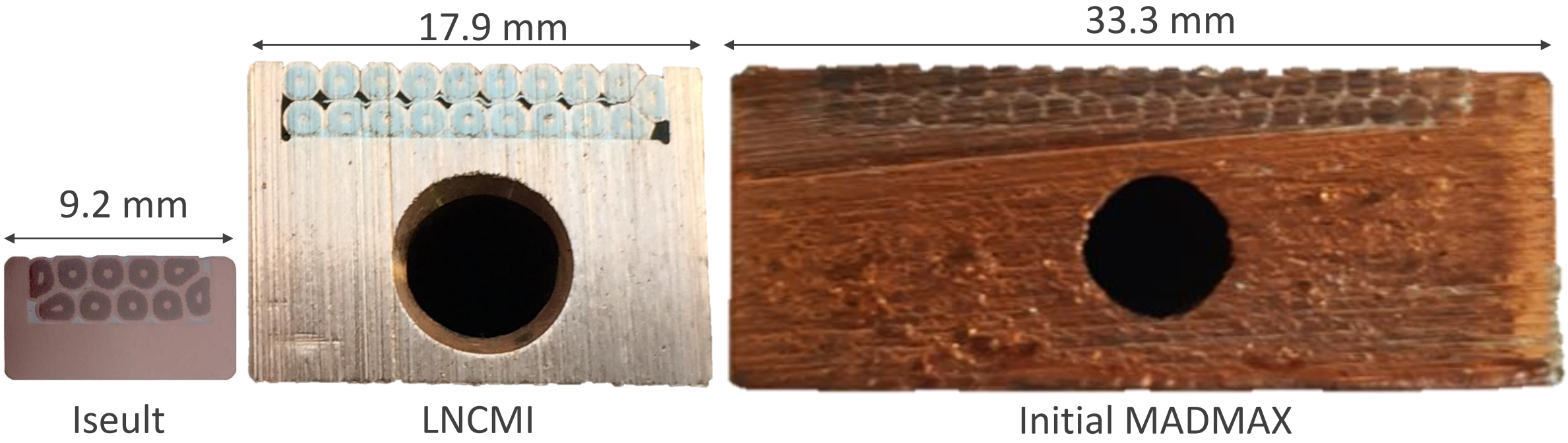
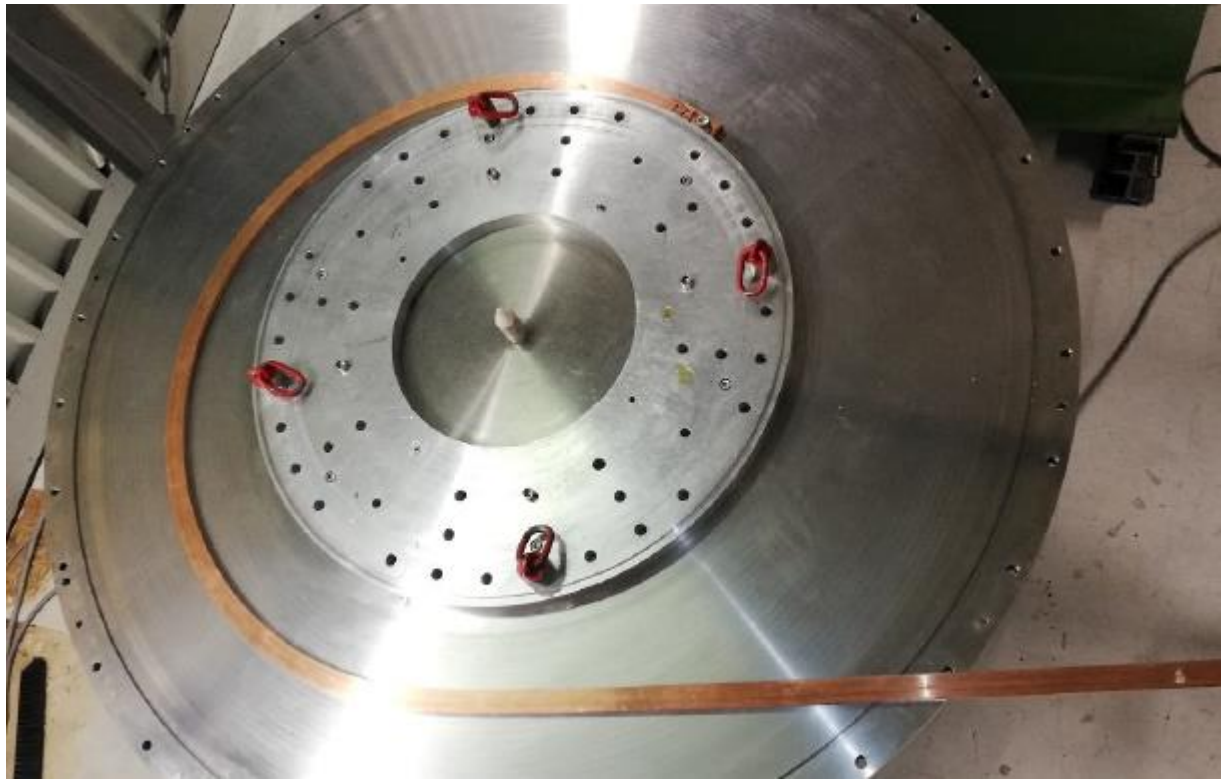
Coming years activities

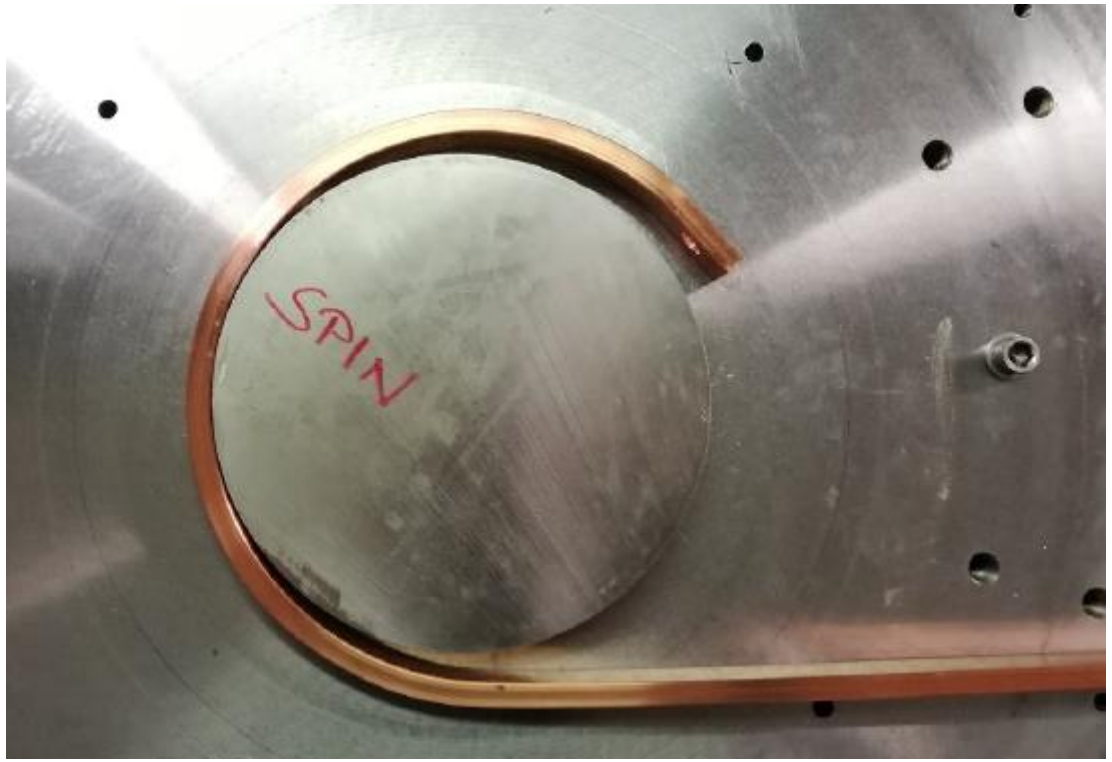
- **Innovation partnership signed end of 2017**
  - MADMAX final magnet design during 2-3 years
- **R&D development plan in phase 1**
  - Conductor and Quench R&D (MACQU) for 3 years
- **Next 6 years to built MACUMBA:**
  - 2024 magnet design
  - 2025 NbTi strand & copper profile procurement
  - 2025/2026 conductor manufacturing
  - 2027/2028 coil manufacturing
  - 2029 integration and test @ Saclay (MATTRICS)

Thank you for your attention !




17.9 mm
33.3 mm
9.2 mm
Iseult
LNCMI
Initial MADMAX

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