Roberto Iuppa

New technologies for superconducting magnets in space

Roberto Iuppa[1,2], William J. Burger[2], Rita Carpentiero[3], Enrico Chesta[4], Magnus Dam[5], Gijs de Rijk[6], Lucio Rossi[7,5]

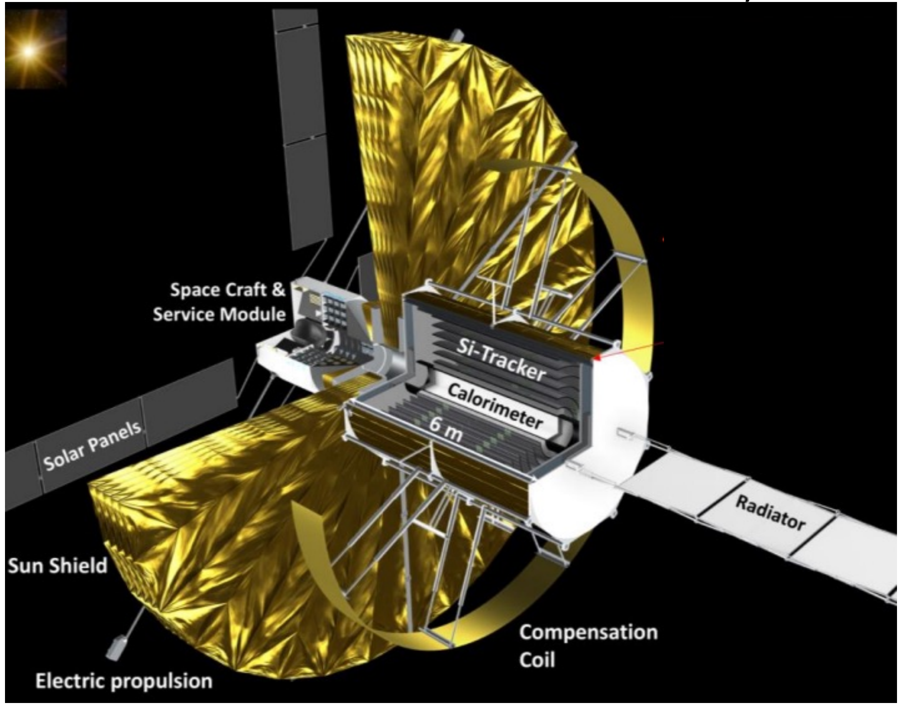
(1) Università di Trento, (2) INFN TIFPA – Trento, (3) Agenzia Spaziale Italiana, (4) CERN, (5) INFN Milano, (6) Retired, formerly CERN, (7) Università di Milano

INFN

UNIVERSITAS STUDIORUM ATHESINA

“ future CR detection in space “

see solicited talk by S. Schael

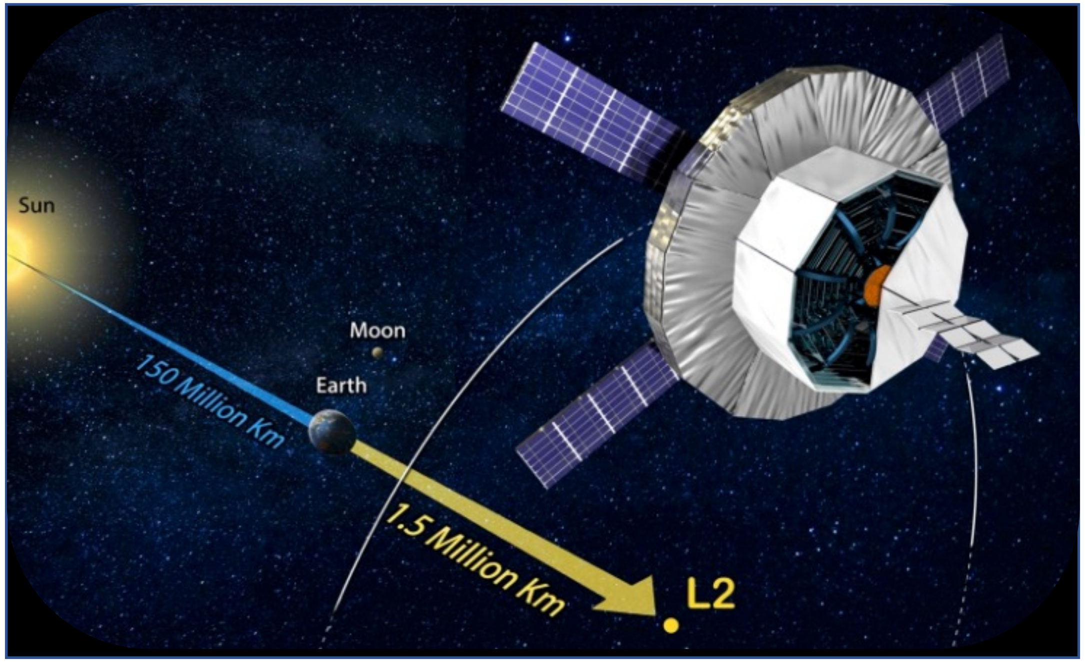


AMS-100: The next generation magnetic spectrometer in space – An international science platform for physics and astrophysics at Lagrange point 2

S. Schael [a], A. Atanasyan [b], J. Berdugo [c], T. Bretz [d], M. Czupalla [e], B. Dachwald [e], P. von Doetinchem [f], M. Duranti [g], H. Gast [a], W. Karpinski [a], T. Kirn [a], K. Lübelsmeyer [a], C. Maña [c], P.S. Marrocchesi [h], P. Mertsch [i], I.V. Moskalenko [j], T. Schervan [k], M. Schluse [b] ... J. Zimmermann [k]

https://doi.org/10.1016/j.nima.2019.162561

see solicited talk by B. Bertucci



Open Access | Feature Paper | Article

Design of an Antimatter Large Acceptance Detector In Orbit (ALADInO)

by Oscar Adriani [1,2], Corrado Altomare [3], Giovanni Ambrosi [4], Philipp Azzarello [5], Felicia Carla Tiziana Barbato [6,7], Roberto Battiston [8,9], Bertrand Baudouy [10], Benedikt Bergmann [11], Eugenio Berti [1,2], Bruna Bertucci [12,4], Mirko Boezio [13,14], Valter Bonvicini [13], Sergio Bottai [2], Petr Burian [11], Mario Buscemi [15,16], Franck Cadoux [5], Valerio Calvelli [17,†], Donatella Campana [18], Jorge Casaus [19], Andrea Contin [20,21], +
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https://doi.org/10.3390/instruments6020019

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solenoids

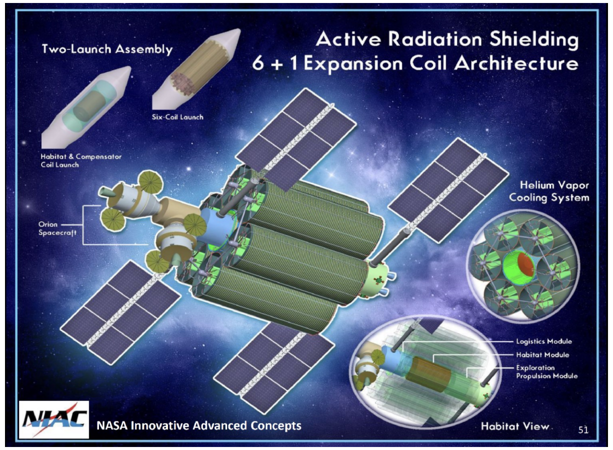
[Y. Makida et al., IEEE Transactions on Applied Superconductivity, TASC.2009.2017946]

A thin superconducting solenoid for BESS-Polar I (2004, 8.5 days) and II (2009, 25 days ultra-thin). Technological breakthrough.

TABLE I
SOLENOID PARAMETERS

Magnet Parameters	2nd solenoid	1st solenoid
Coil nominal diameter (m)	0.9	Same
Coil Length (m)	1.4	Same
Coil Thickness (center/notch) (mm)	3.4 / 3.7	Same
Coil Weight (kg)	43	Same
Cryostat (outer dimension) (m)	ϕ 1.06× L3.2	Same
(Inner bore) (m)	ϕ 0.80	Same
Central magnetic field (T)	0.8 (~ 1.0)	Same
Magnetic uniformity (%)	≤ ± 9	Same
Current (A)	380 (~ 476)	Same
Turns	2829	Same
Inductance (H)	3.49	Same
Stored Energy (kJ)	252 (~395)	Same
E/M Ratio in coil (kJ/kg)	5.9 (~ 9.2)	Same
Material @half-wall (g/cm^2)	2.52	Same
LHe Capacity (ℓ)	520	400
LHe Life Time (day)	21	10
Magnet weight (kg)	450	410
Conductor Parameters		
Type	Al clad NbTi/Cu monolith	
Overall size with insulation (mm^2)	0.9 × 1.2	Same
NbTi / Cu core diameter (mm)	0.60	Same
Critical current (A) @2.5T, 4.2 K	> 750	Same
Area ratio (NbTi/Cu/Al)	1/0.81/3.9	Same
Insulation (μm)	Kapton 2 × 20	Same
Additive into Al stabilizer	Ni (5000 ppm)	Same
Al clad process	Co-extrusion	Same
RRR (Al stabilizer, Cu, over all)	286, 55, 116	Same
Yield strength (NbTi/Cu @RT) (MPa)	580	Same
Yield strength (Al @4.2 K) (MPa)	100	Same
Yield strength (over all @4.2 K) (MPa)	240	Same

solenoids



NIAC, S. Westover, MAARSS, 2012

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Yield strength (Al @4.2 K) (MPa)	100	Same
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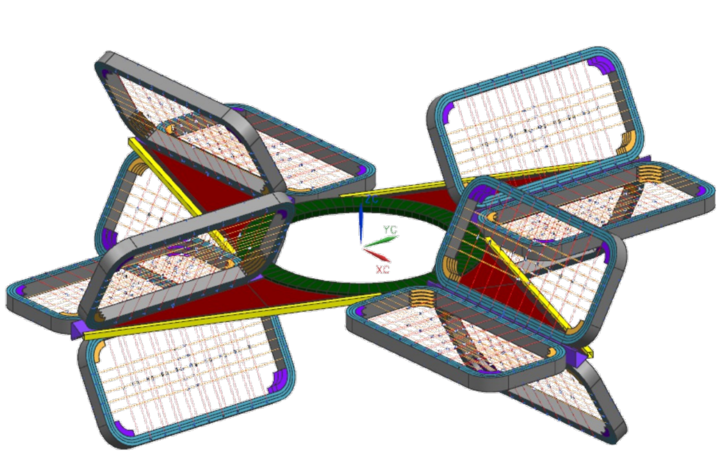
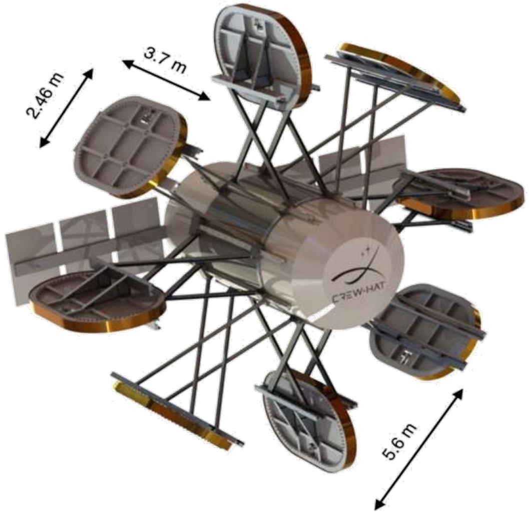
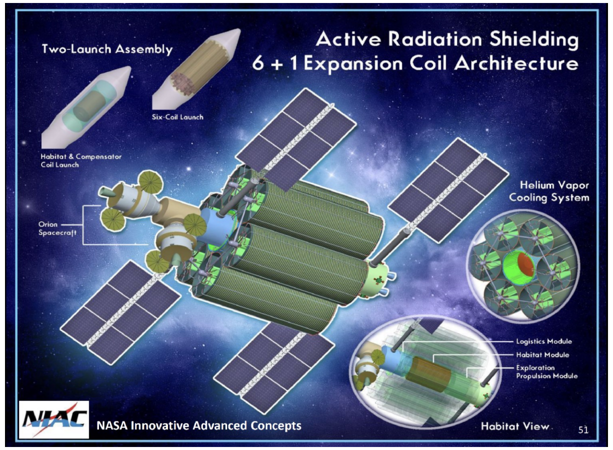
magnetic shields to protect astronauts



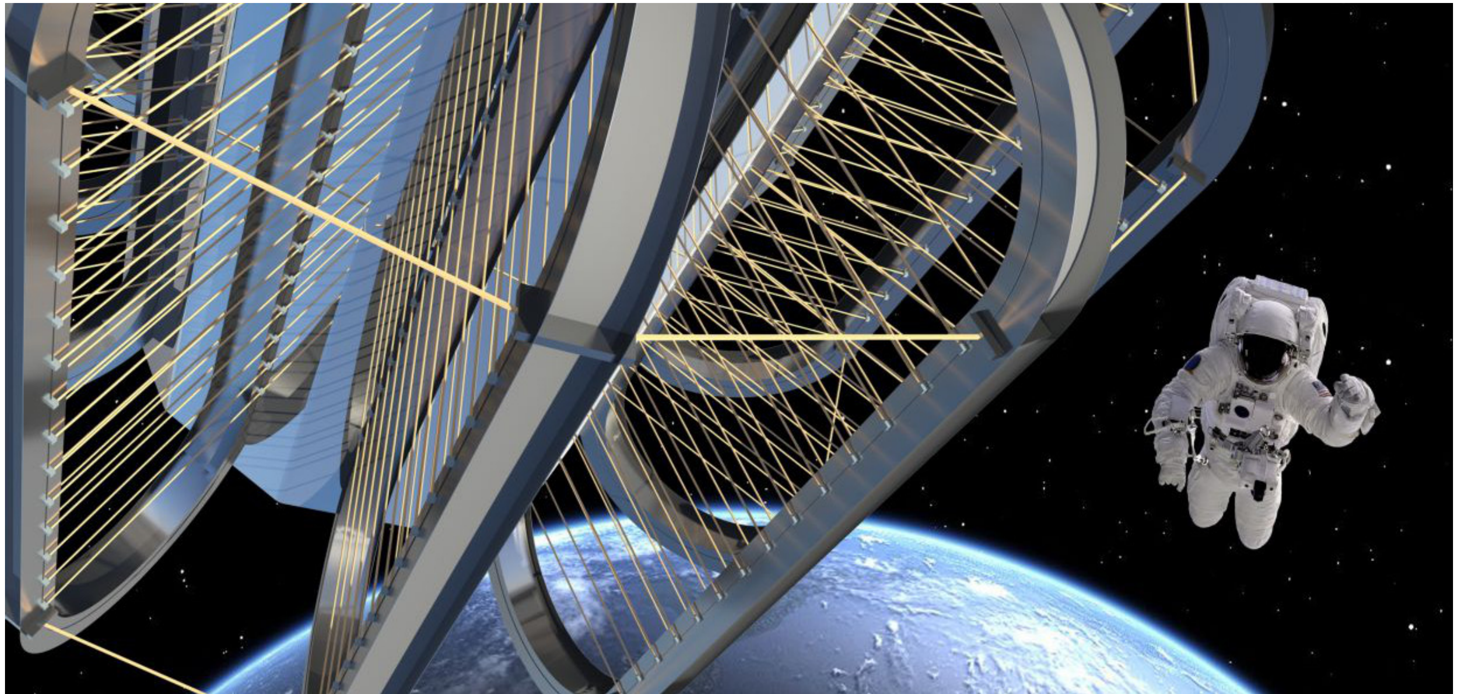
[Pumpkin configuration - SR2S project (Battiston 2016)](#)



[NIAC, E. D'Onghia, Crew-HaT (Halbach torus), 2022](#)



[NIAC, S. Westover, MAARSS, 2012](#)



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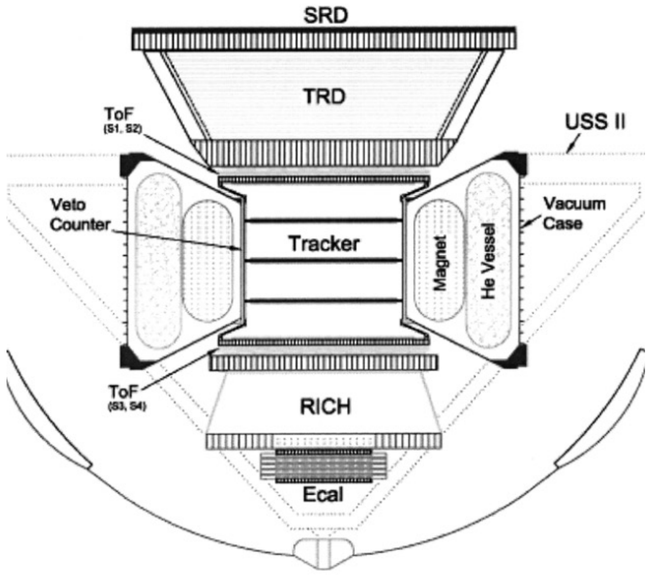
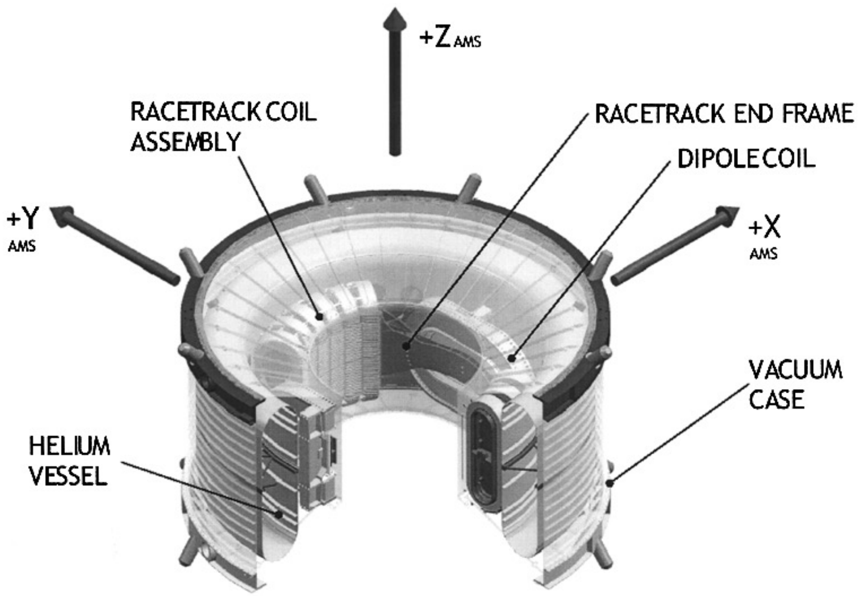
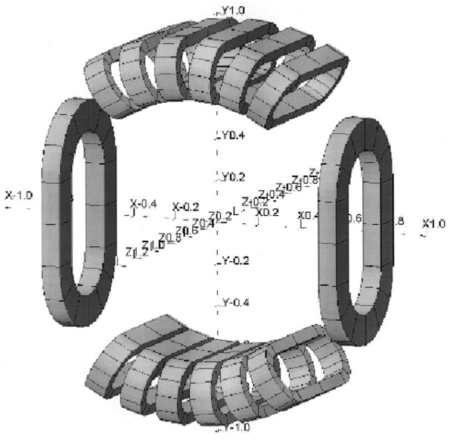
AMS-02 superconducting magnet



The AMS-02 detector in the cargo bay of the space shuttle for the flight to ISS



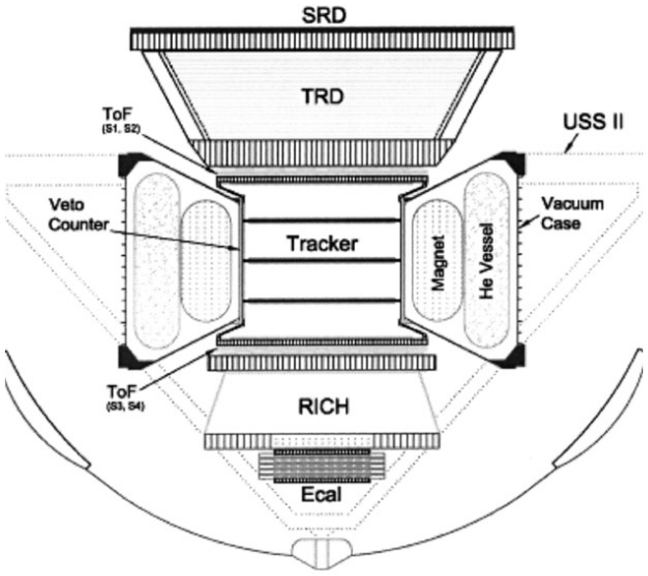
3-D artist view of the AMS-02 magnet system.



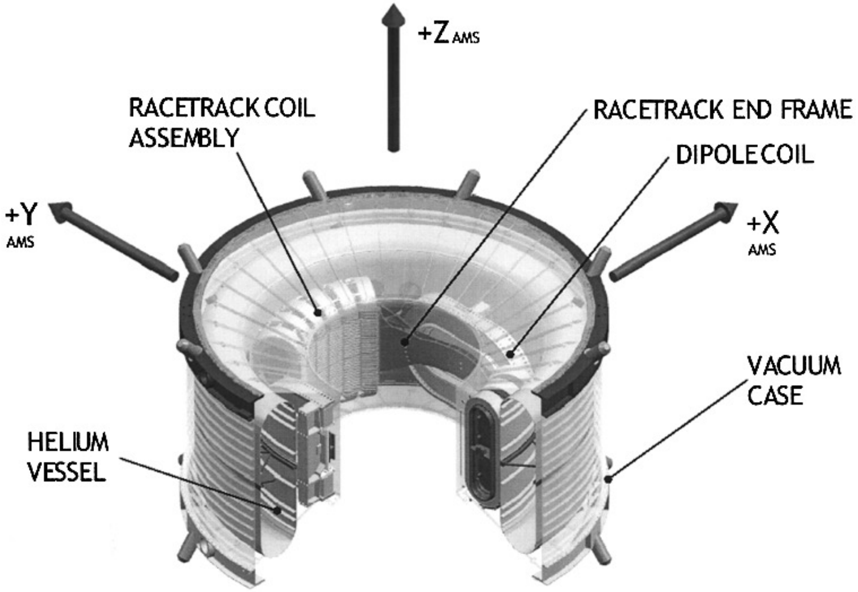
AMS-02 magnet configuration producing a dipole field

B. Blau *et al*., "The superconducting magnet system of AMS-02 - a particle physics detector to be operated on the International Space Station," in *IEEE Transactions on Applied Superconductivity*, vol. 12, no. 1, pp. 349-352, March 2002, doi: 10.1109/TASC.2002.1018417.

AMS-02 superconducting magnet



The AMS-02 detector in the cargo bay of the space shuttle for the flight to ISS



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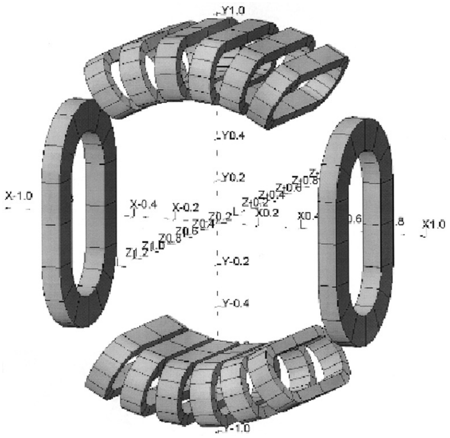

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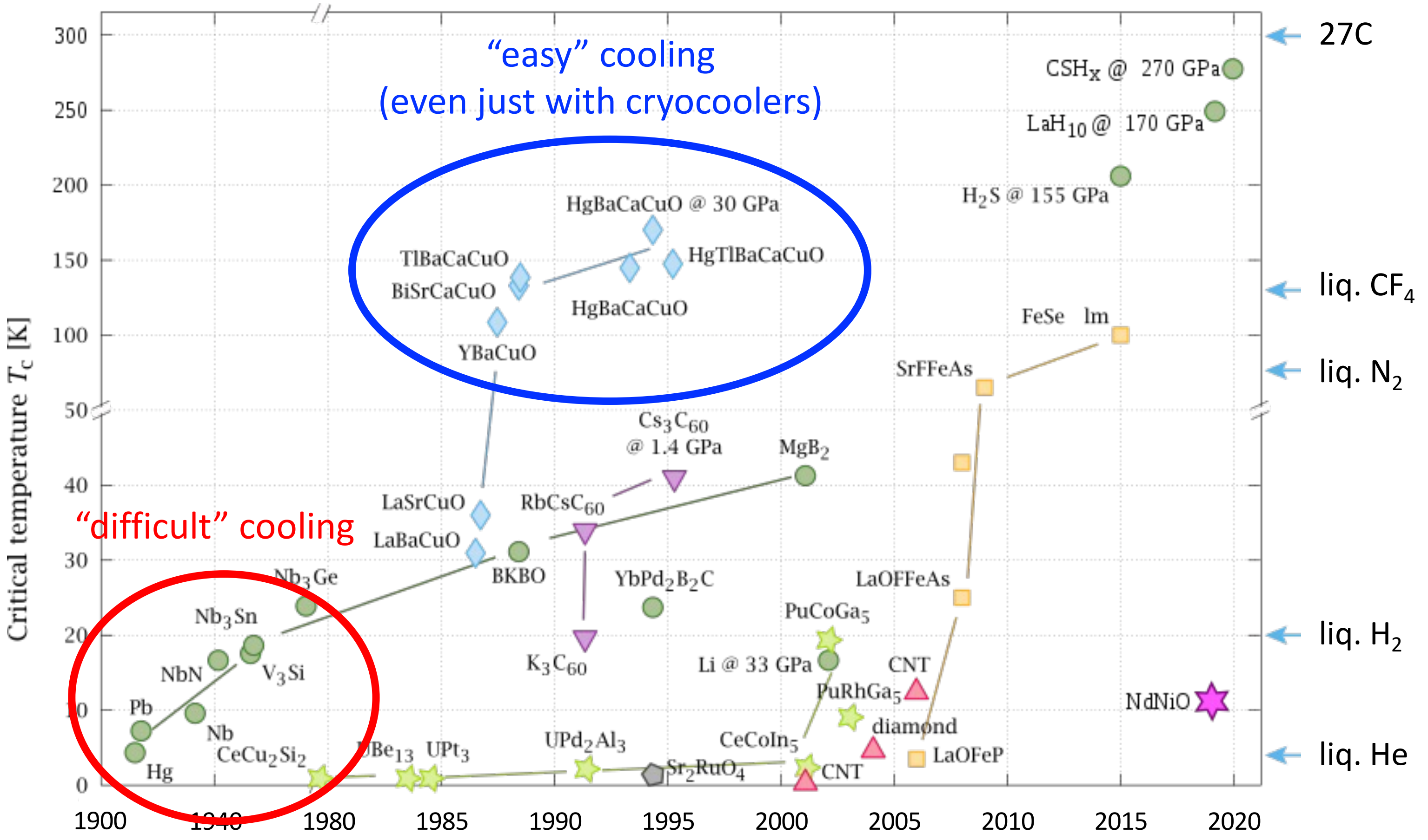
''Since the magnet design is optimized with respect to very low heat losses, the magnet is intended to be operated for 3 years without refilling.''

B. Blau et al., NIMA (2004) 518,139-142, https://doi.org/10.1016/j.nima.2003.10.043.

''With Obama administration plans to extend International Space Station operations beyond 2015, the decision was made by AMS management to exchange the AMS-02 superconducting magnet for the non-superconducting magnet''

https://en.wikipedia.org/wiki/Alpha_Magnetic_Spectrometer, link visited on July 10th 2022

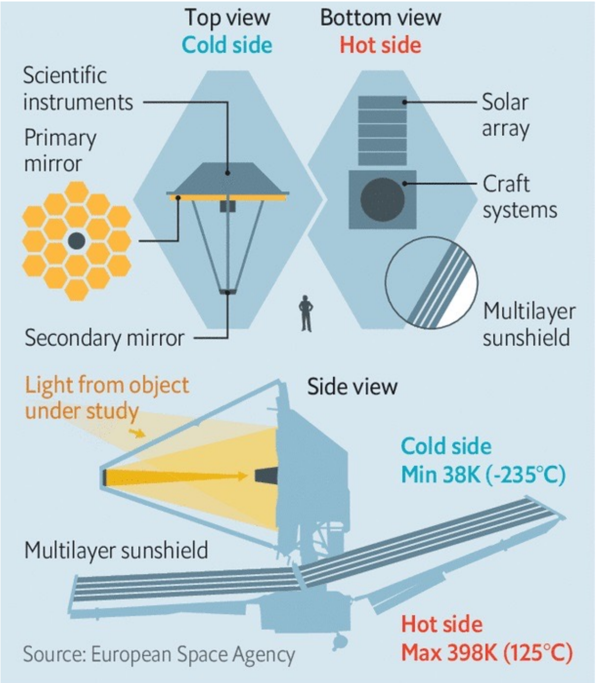
”High-temperature”



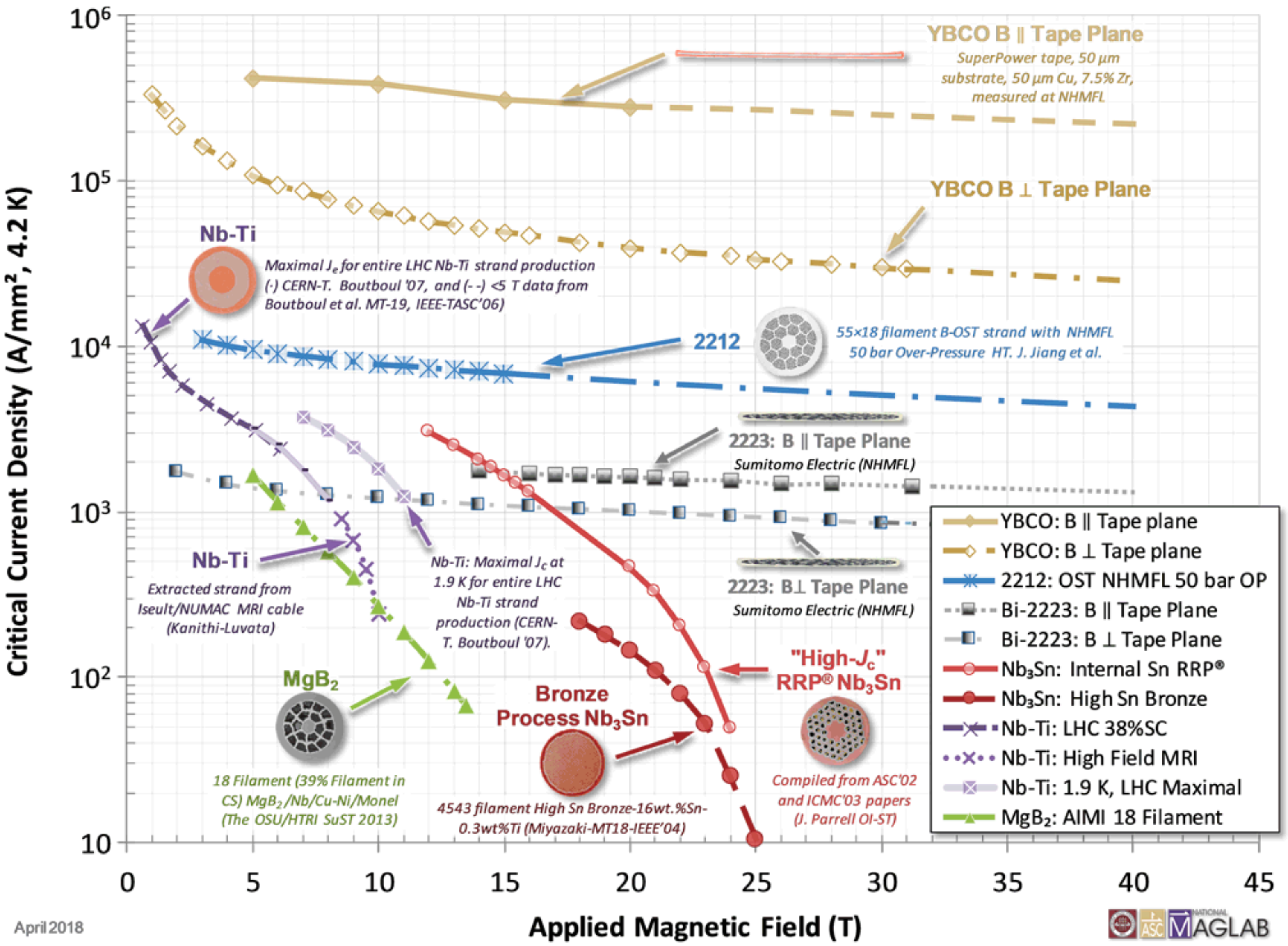
Readapted from https://en.wikipedia.org/wiki/High-temperature_superconductivity, visited on July 10th, 2022

Robustness, efficiency and lifetime of the cooling system are among the most limiting requirements for the use of SC magnets in space. They all depend on the difference T_{env}-T_{op}.

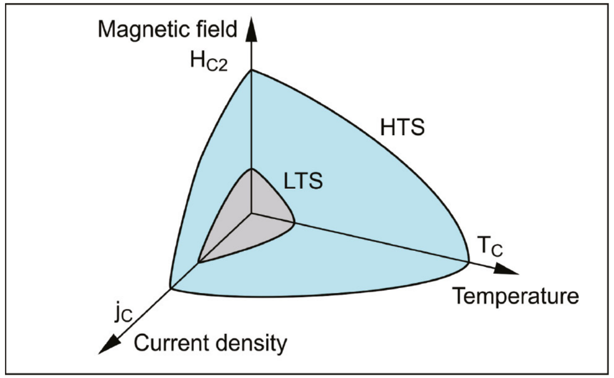
James Webb hot/cold sides at L2



High-Temperature Superconductors



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots, link visited on July 10th, 2022



Zeitschrift für Naturforschung B, vol. 75, no. 1-2, 2020, pp. 3-14. https://doi.org/10.1515/znb-2019-0103

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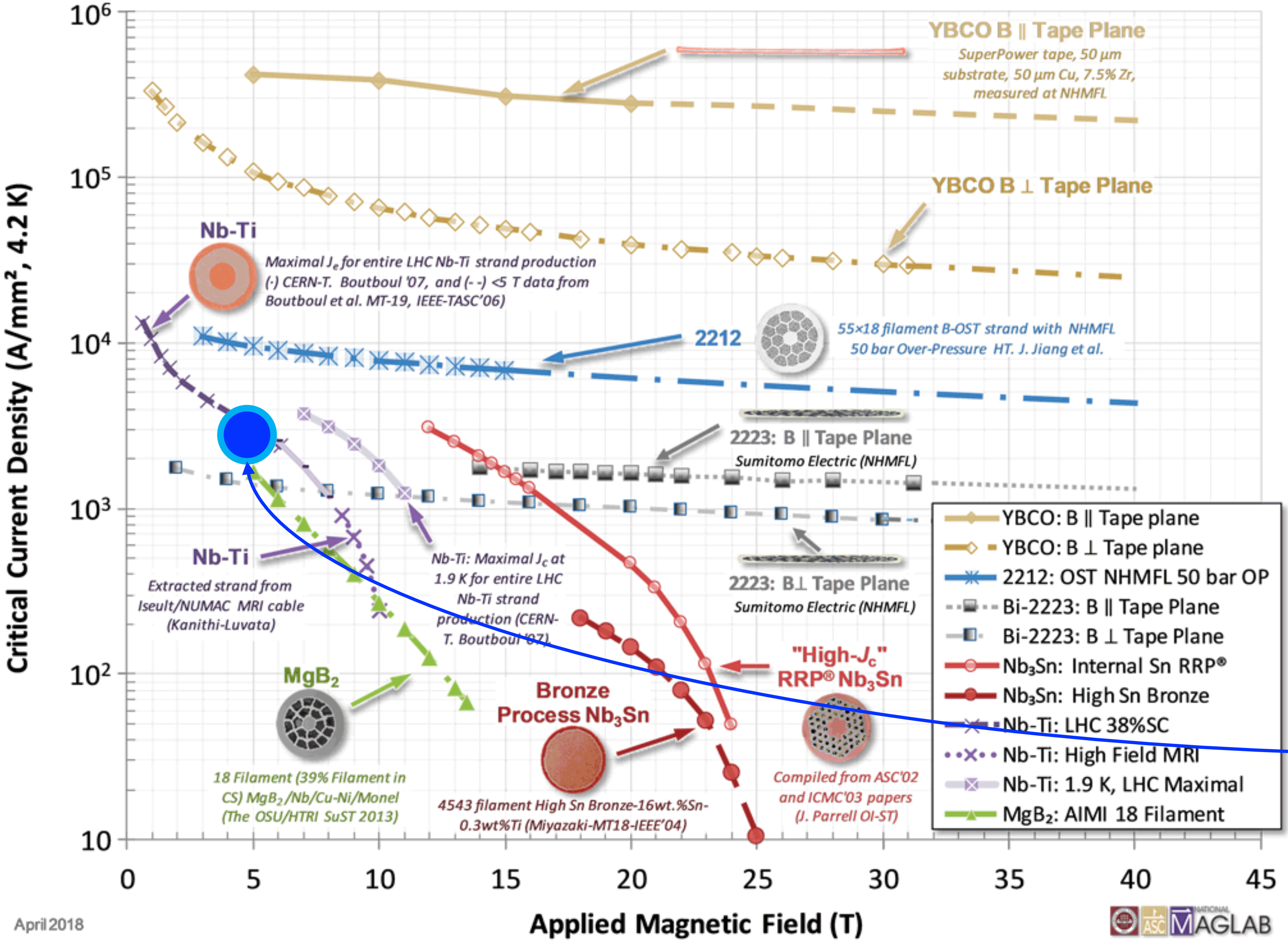
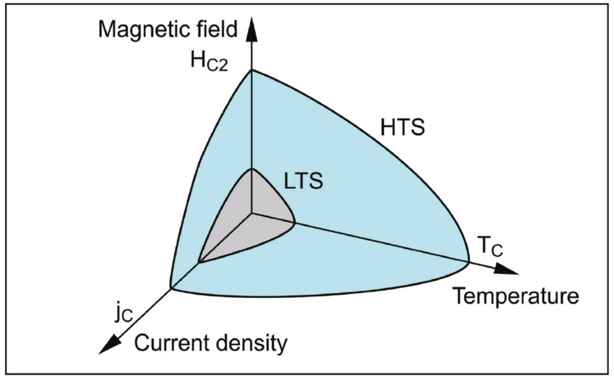
High-Temperature Superconductors



AMS-02
Nb-Ti/Cu
3000 A/mm2
at 5T at 4.2K
(specs from doi:10.1109/TASC.2002.1018417)



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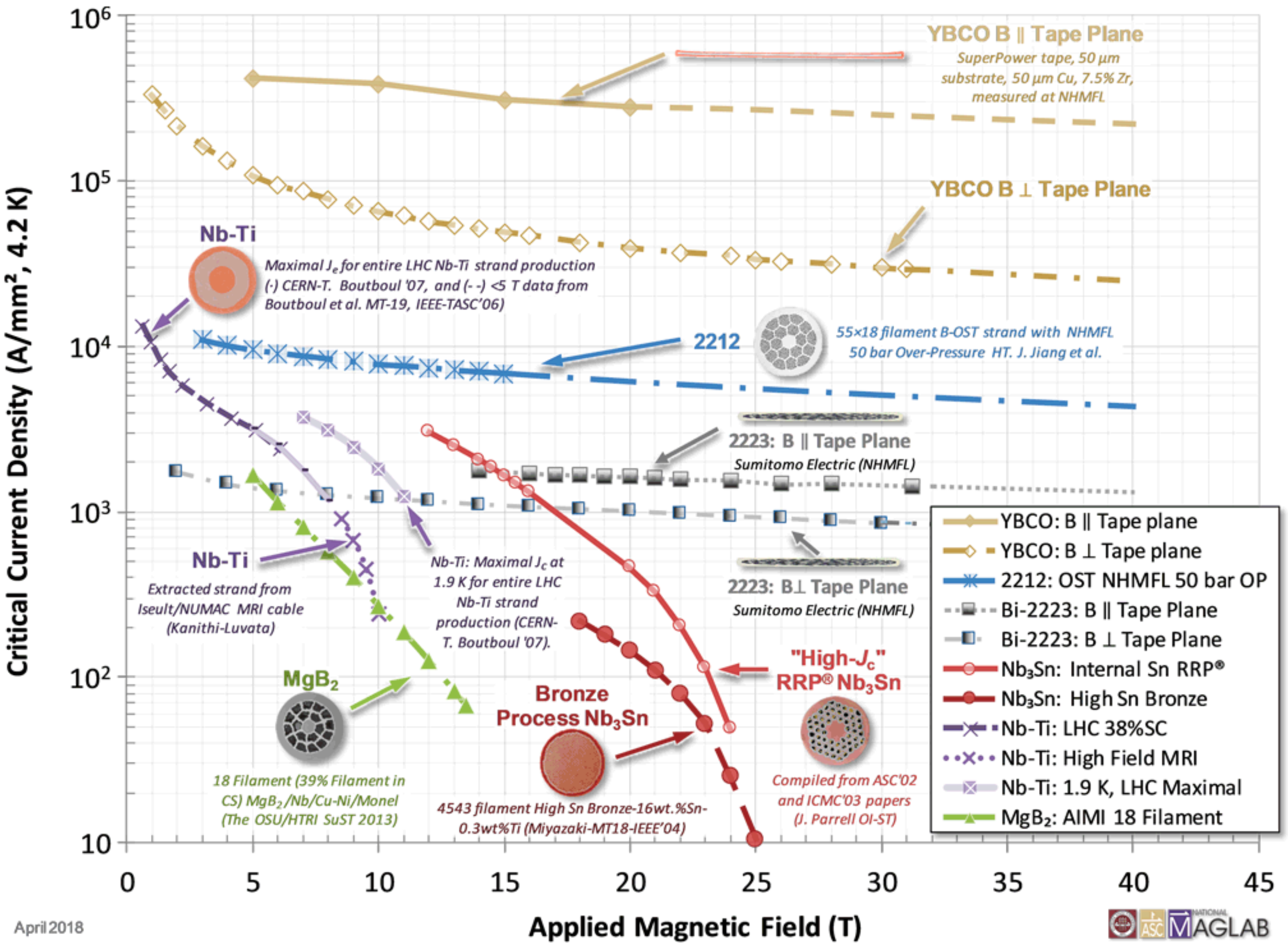

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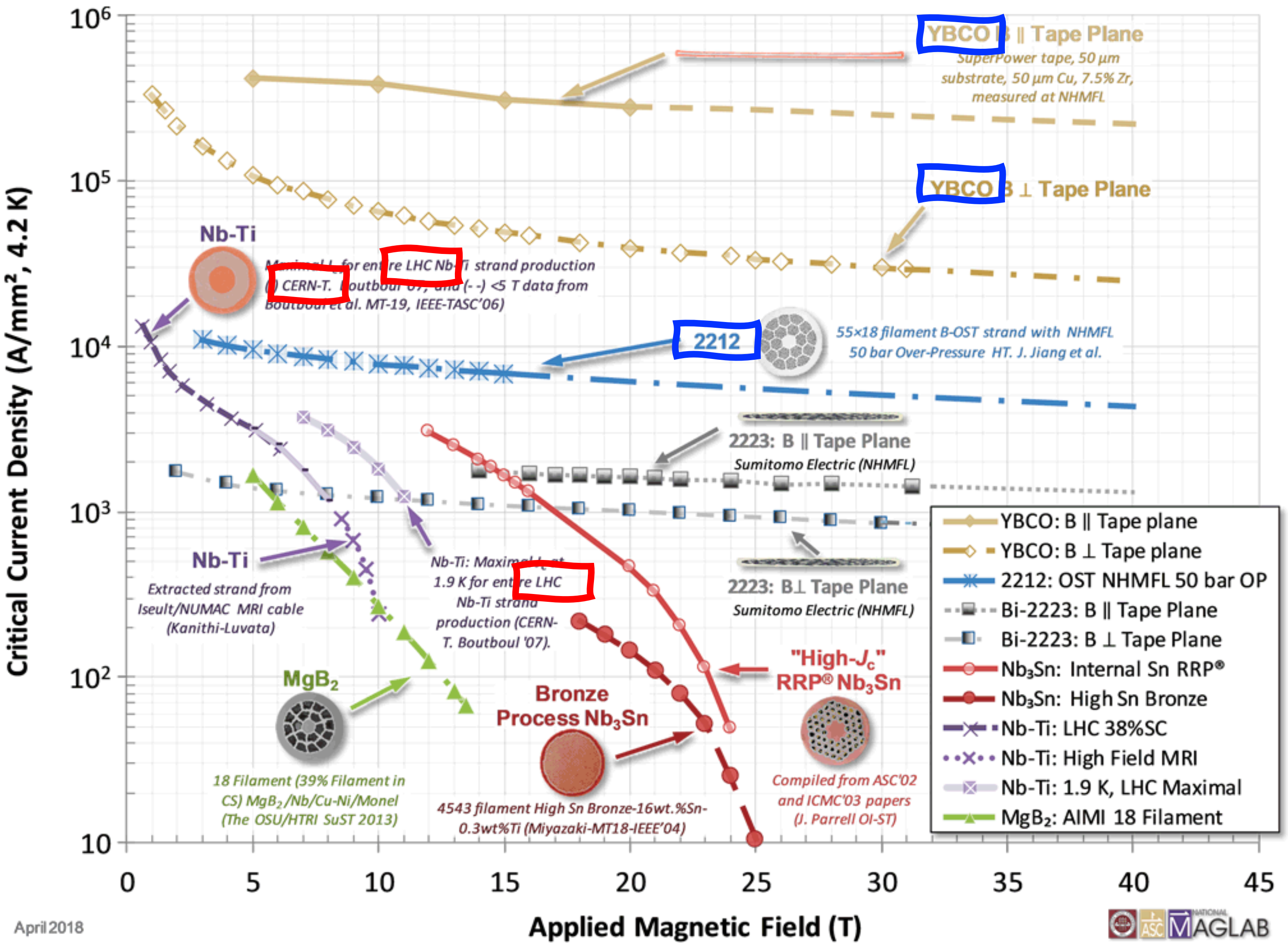

https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots, link visited on July 10th, 2022

EuCARD-2 is co-funded by the partners and the European Commission under Capacities 7th Framework Programme, Grant Agreement 312453

WP10 Future Magnets for post-LHC colliders (study, test and design solutions using Bi-2212 and YBCO for HTS dipole magnets)

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Advances in Space AstroParticle Physics - 2023

June 20th

HTS Demonstrator Magnet for Space (HDMS)

Agenzia Spaziale Italiana | UNIVERSITÀ DI TRENTO | CERN | INFN Istituto Nazionale di Fisica Nucleare | UNIVERSITÀ DEGLI STUDI DI MILANO

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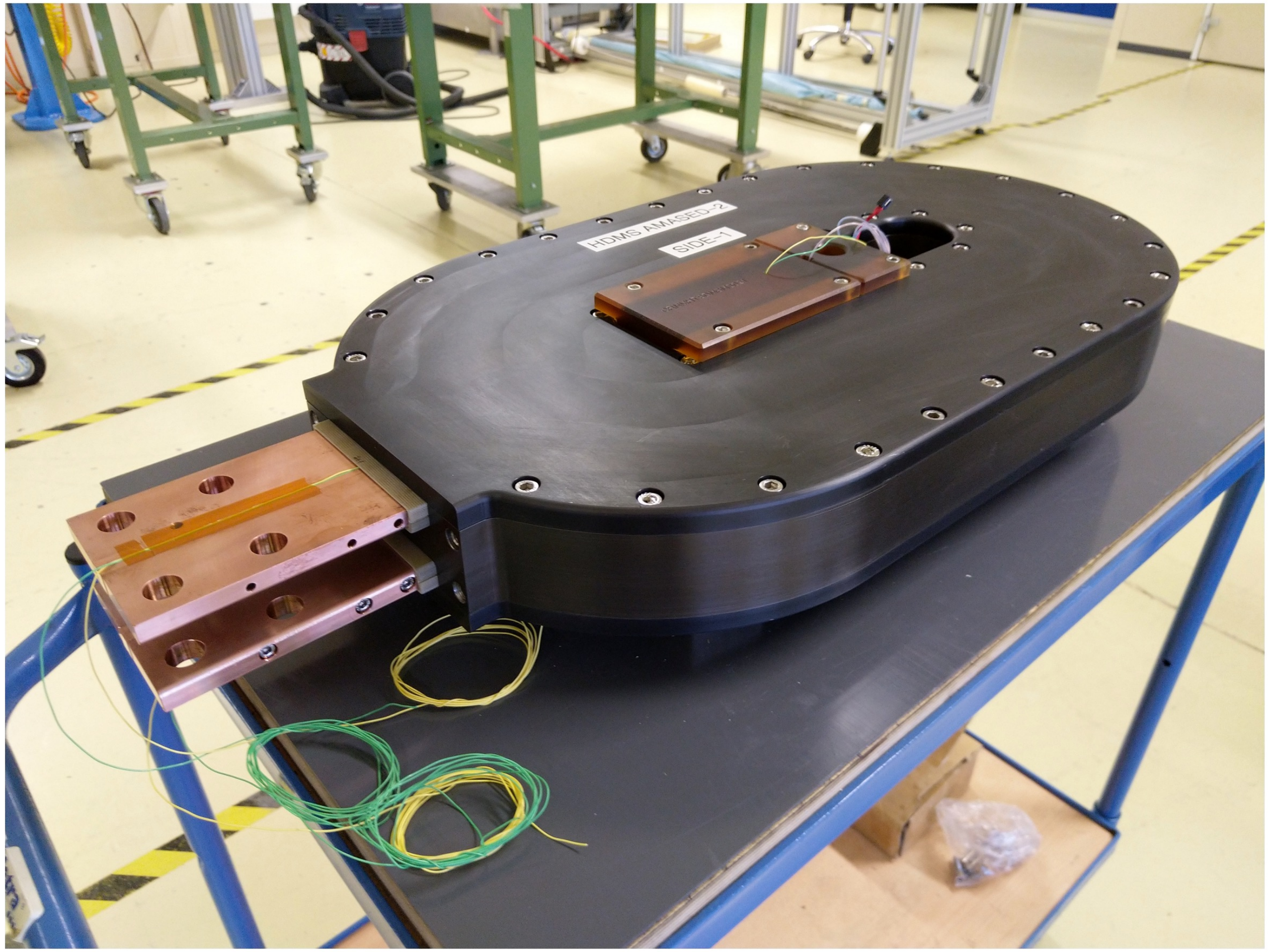

HDMS project goals (Jun. 2018- Feb. 2022)

- Conceptual design of a toroidal HTS magnet for a spectrometer in space
- Design and manufacture a demonstrator coil for the toroidal magnet
- Test and make it ready up to TRL 6

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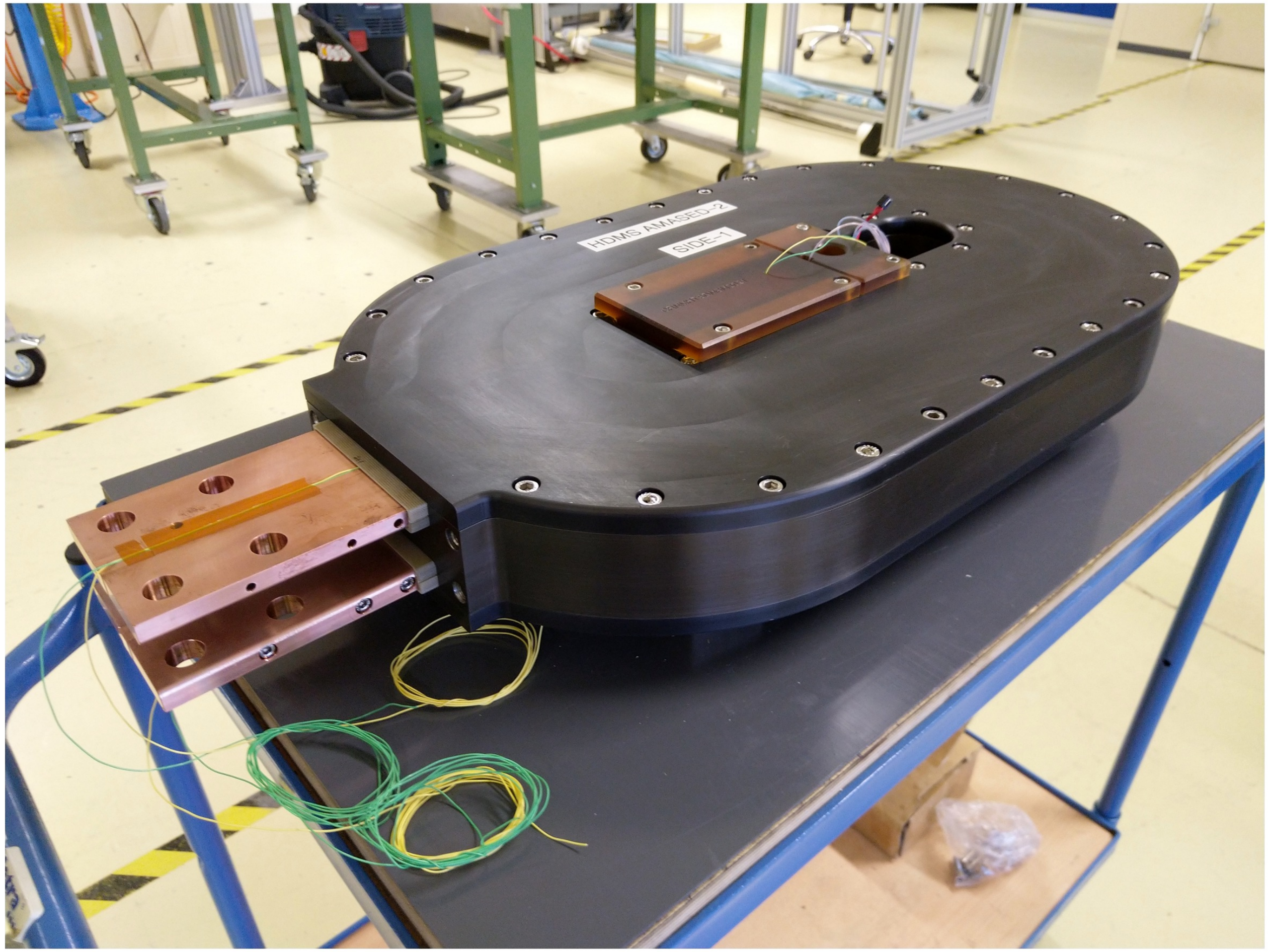

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IOP Publishing
Superconductor Science and Technology
Supercond. Sci. Technol. 33 (2020) 044012 (12pp)
https://doi.org/10.1088/1361-6668/ab669b

Conceptual design of a high temperature superconducting magnet for a particle physics experiment in space

Magnus Dam[1], Roberto Battiston[2,3], William Jerome Burger[3], Rita Carpentiero[4], Enrico Chesta[1], Roberto Iuppa[2,3], Gijs de Rijk[1] and Lucio Rossi[1,5]

[1] CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland
[2] Department of Physics, University of Trento, I-38122 Trento TN, Italy
[3] TIFPA, Trento Institute for Fundamental Physics and Applications, I-38123 Povo TN, Italy
[4] ASI, Italian Space Agency, I-00133 Rome RM, Italy
[5] On leave from: Department of Physics, University of Milan, I-20133 Milano MI, Italy

E-mail: magnus.dam@cern.ch

Supercond. Sci. Technol. 33 044012 (2020)

HTS Demonstrator Magnet for Space (HDMS)

Agenzia Spaziale Italiana | UNIVERSITÀ DI TRENTO | CERN | INFN Istituto Nazionale di Fisica Nucleare | UNIVERSITÀ DEGLI STUDI DI MILANO

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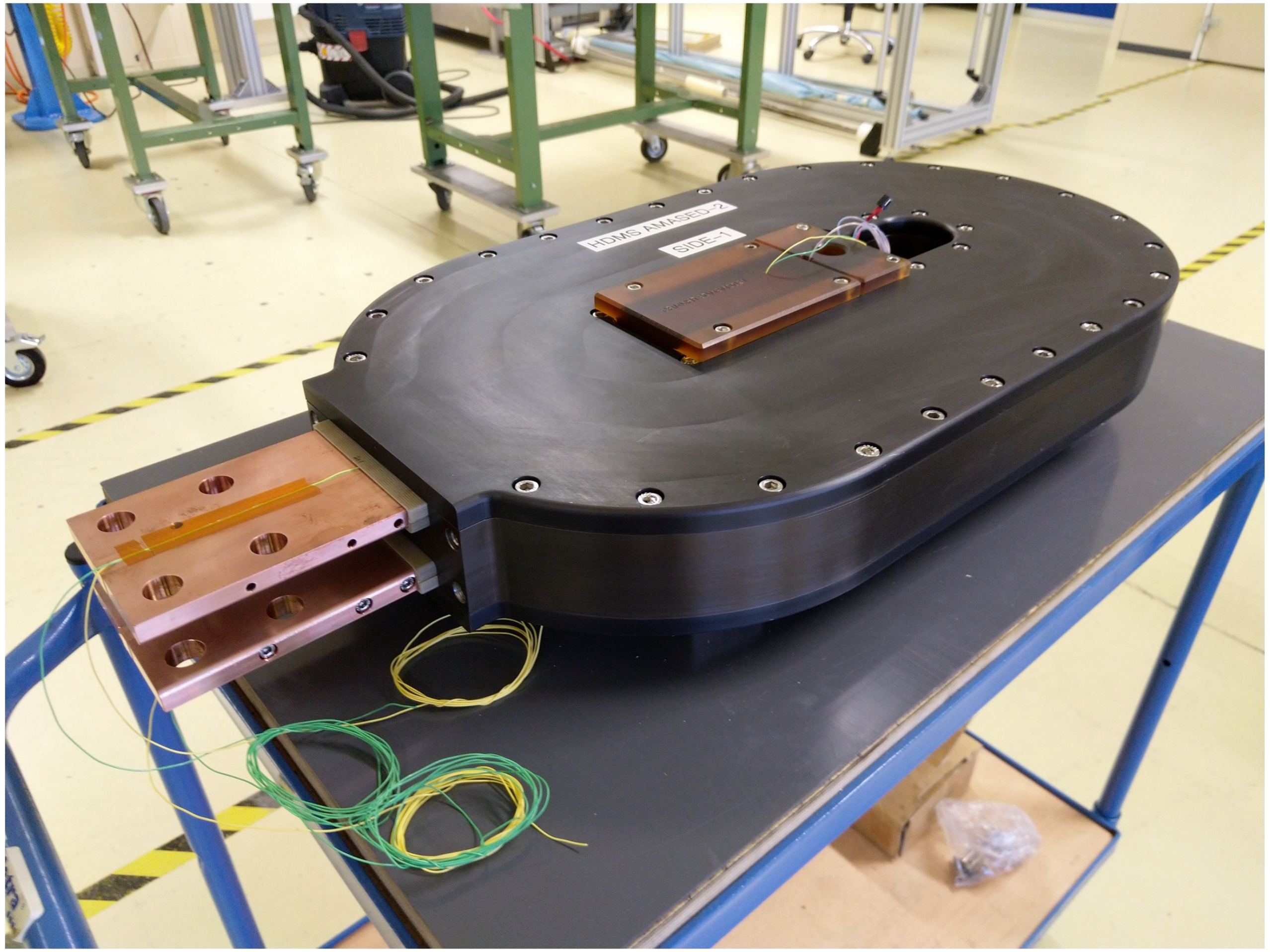

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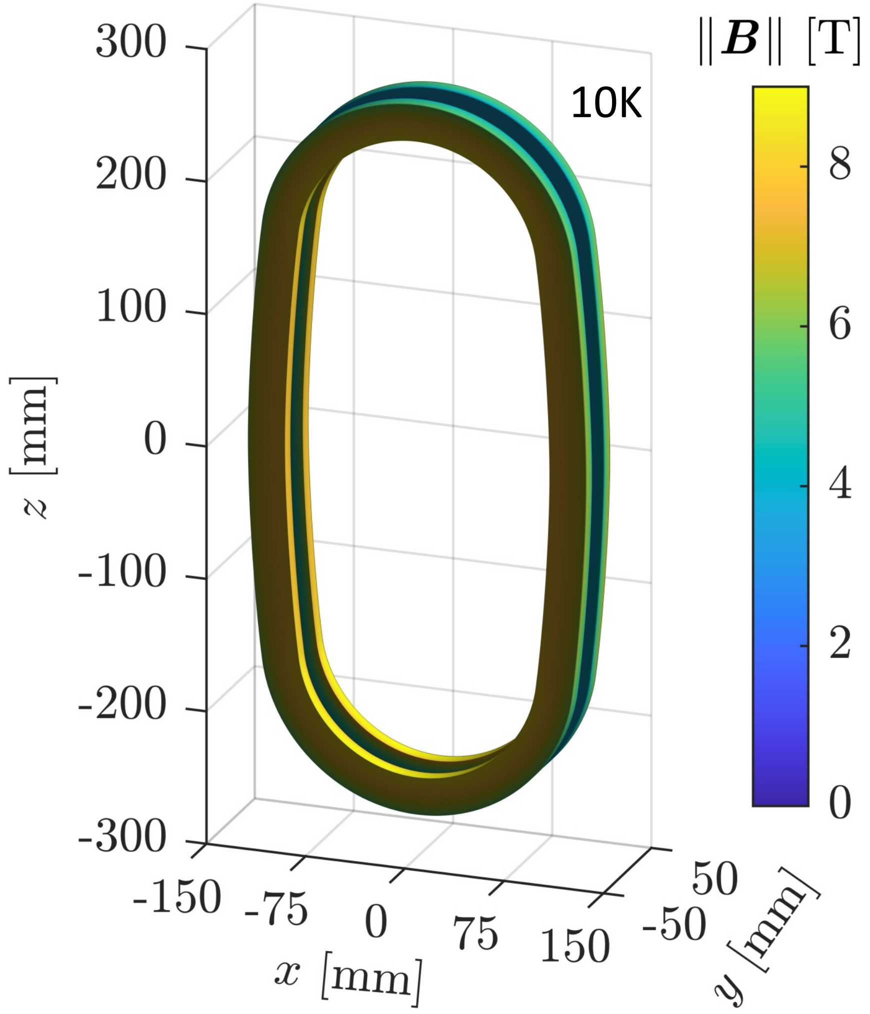
- Focus of the next part of this presentation
- Other useful links:
  - https://knowledgetransfer.web.cern.ch/aerospace/hdms
  - M. Dam et al., PoS ICRC2021 498 (2021)

AMaSED:
Advanced Magnetic Spectrometer Experimental Demonstrator

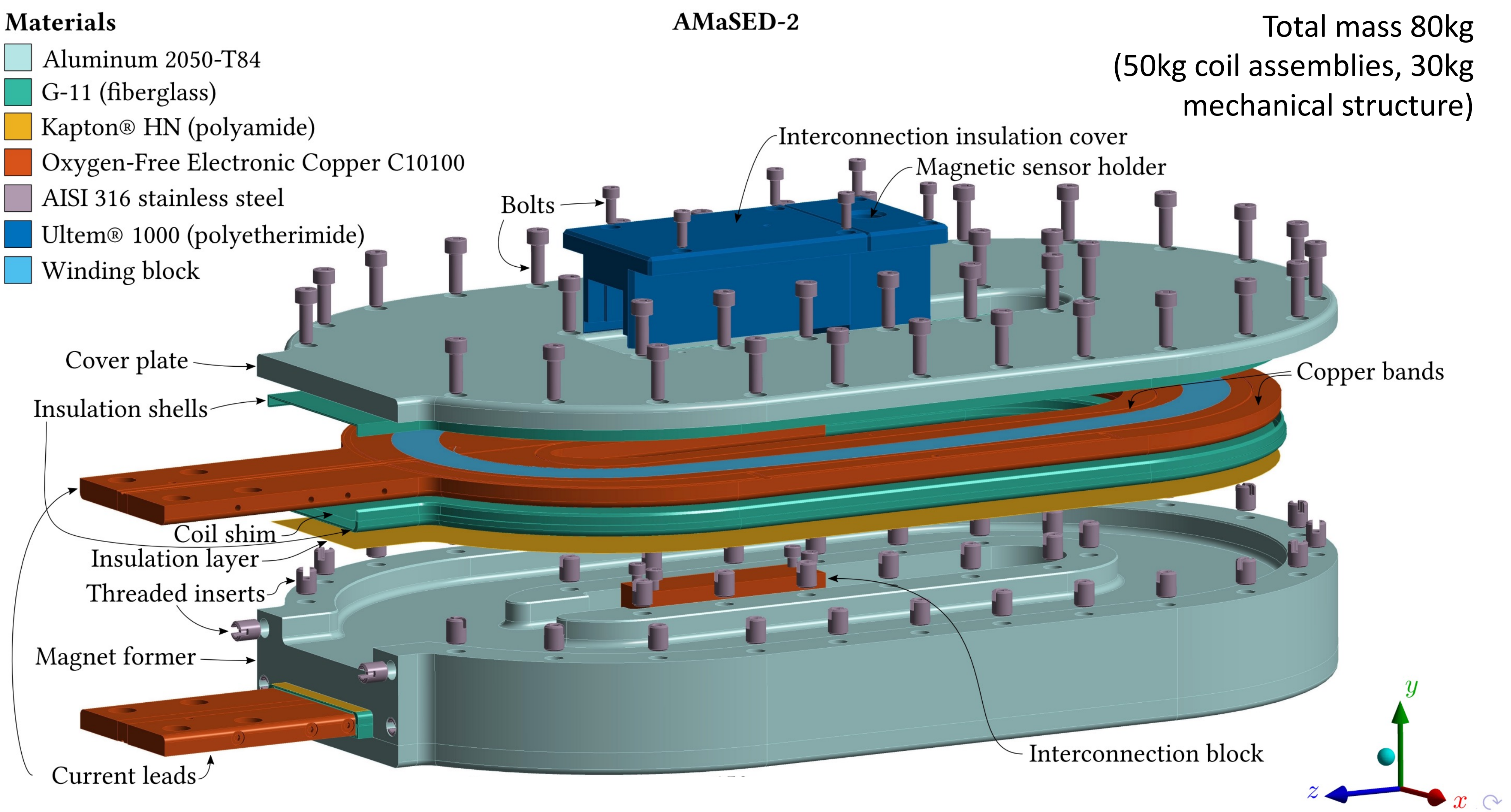
Roberto Iuppa

Coil design

- Two pancake coils
- Racetrack-like shape
- No-insulation coil
- Two-tape-stack SuperPower HTS cable (face-to-face)
- Tape width: 12 mm
- Total HTS tape length: 724 m
- Inductance: L = 46.6 mH
- Center magnet constant: α_0 = 1.125 T/kA
- Peak magnet constant: α_m = 3.75 T/kA



AMaSED full design



Total mass 80kg
(50kg coil assemblies, 30kg mechanical structure)

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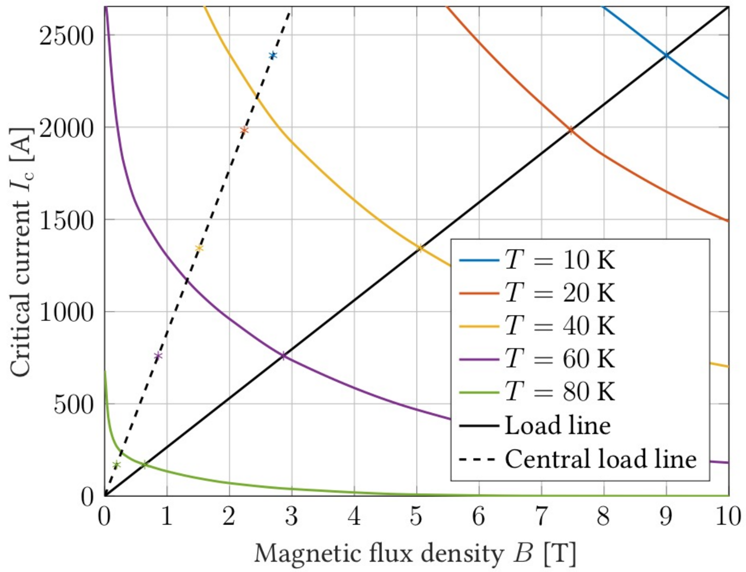
Advances in Space AstroParticle Physics - 2023

June 20th

Conductor and cable configuration

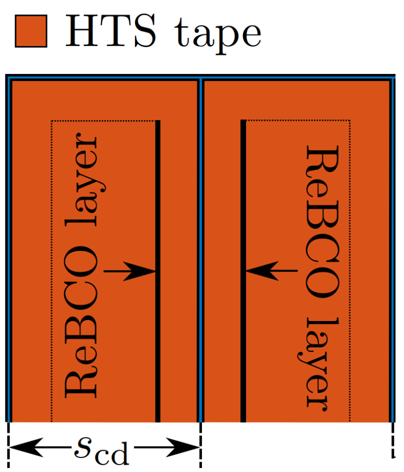
SuperPower 2G HTS tape

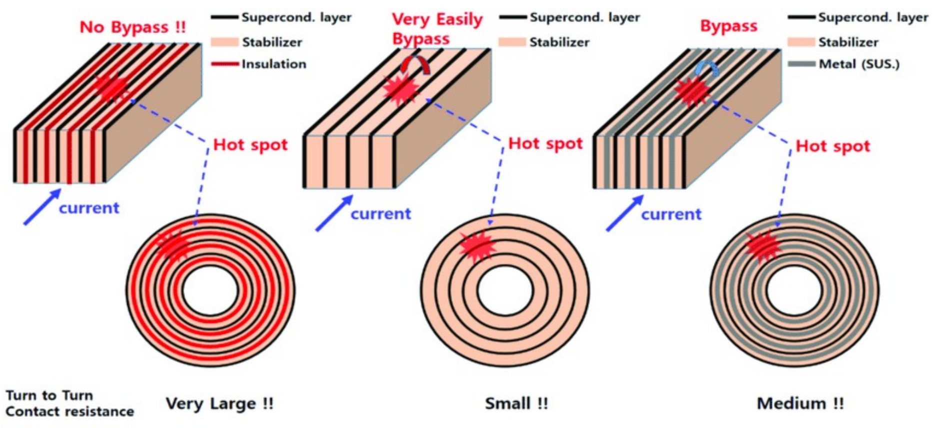
Description	Value	Unit
Tape width	12	mm
Tape thickness	97	µm
Hastelloy substrate thickness	50	µm
ReBCO thickness	1.6	µm
Silver thickness	3.8	µm
Copper stabilizer thickness	40	µm
I_c at 77 K, self-field	0.4	kA



Cable configuration

- No-insulation winding technique
- Two-tape stack
- Dry wound with first and last turns soldered





ins. winding	no ins. winding	metallic ins. winding

Appl. Sci. 2021, 11(7), 3074

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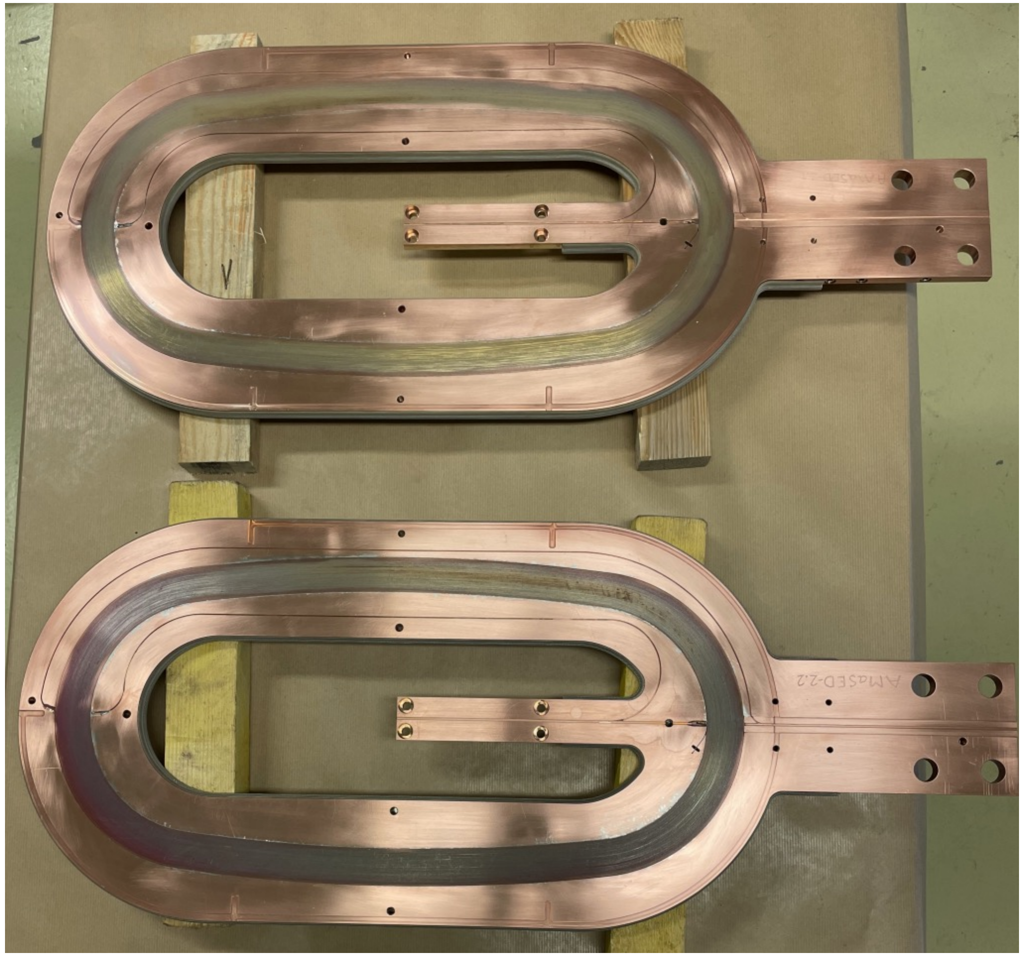
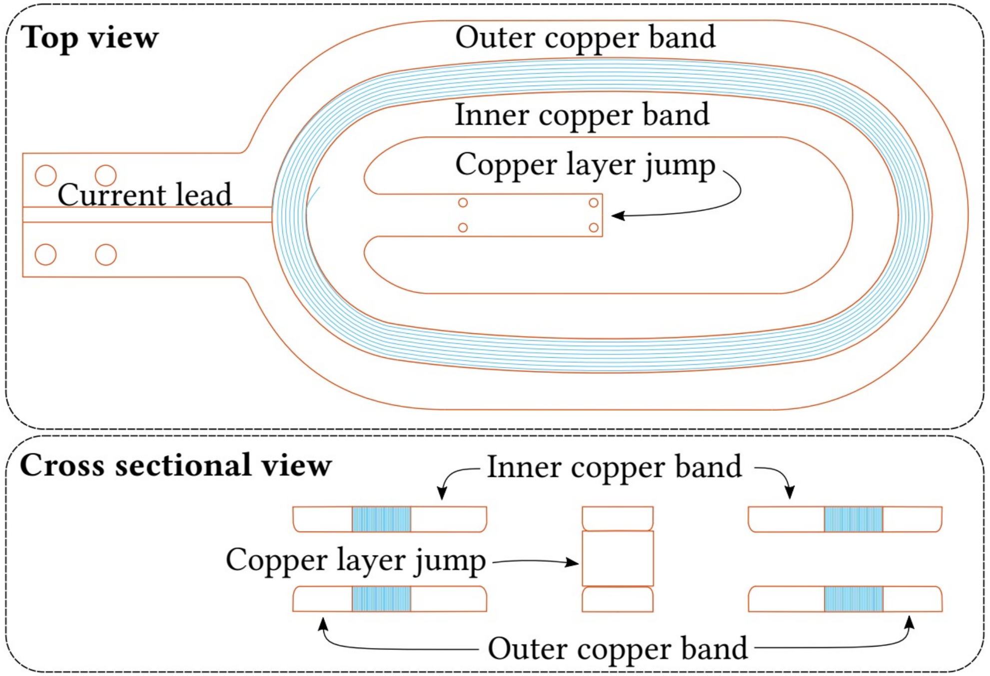
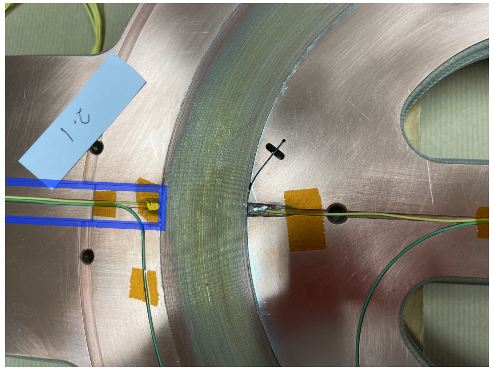
Coil assemblies

Inner and outer copper bands





Opening in outer copper band and clamping.



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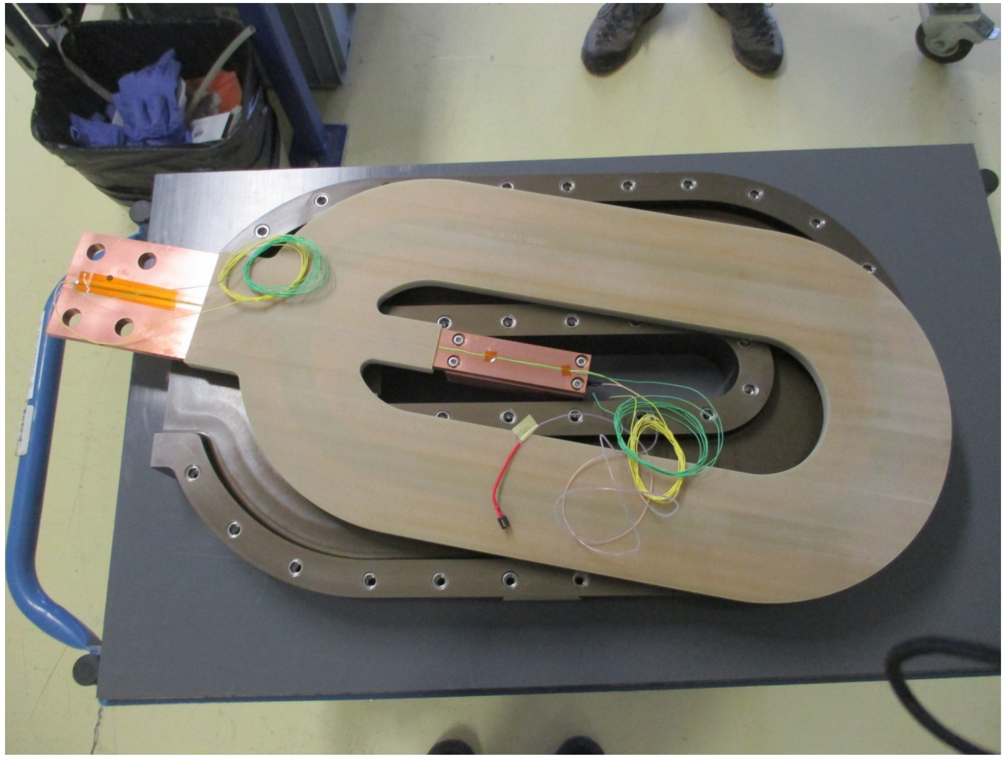
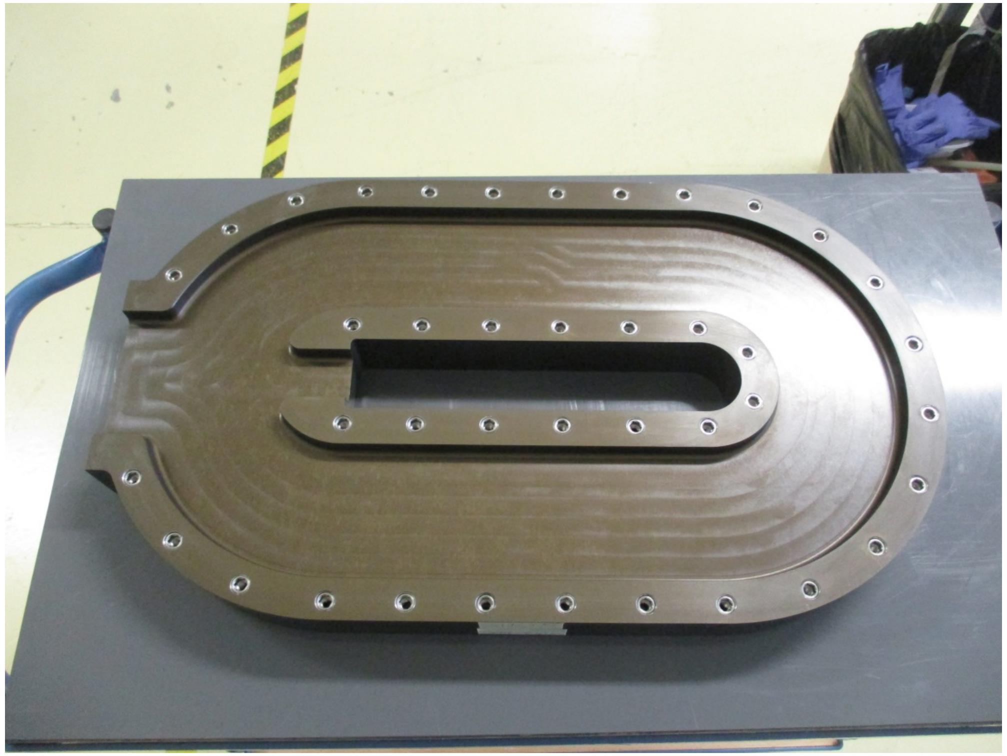
Coil insulation and mechanical structure





- 1.5 mm–3 mm thick G11 fiberglass
- Break down voltage greater than 1000 V (largest voltage measured over coil was 0.1 V).

Single-piece magnet former in Aluminum 2050-T84

Magnetic critical current measurements

Supercond. Sci. Technol. 36 (2023) 014007

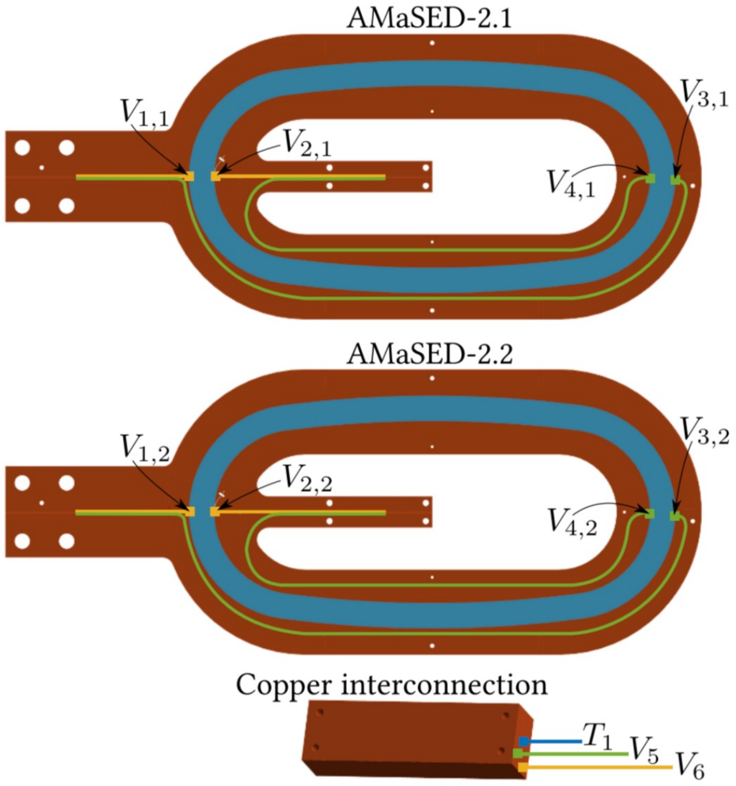


Figure 3. Locations of temperature sensor and voltage taps on coil assemblies and interconnection block.

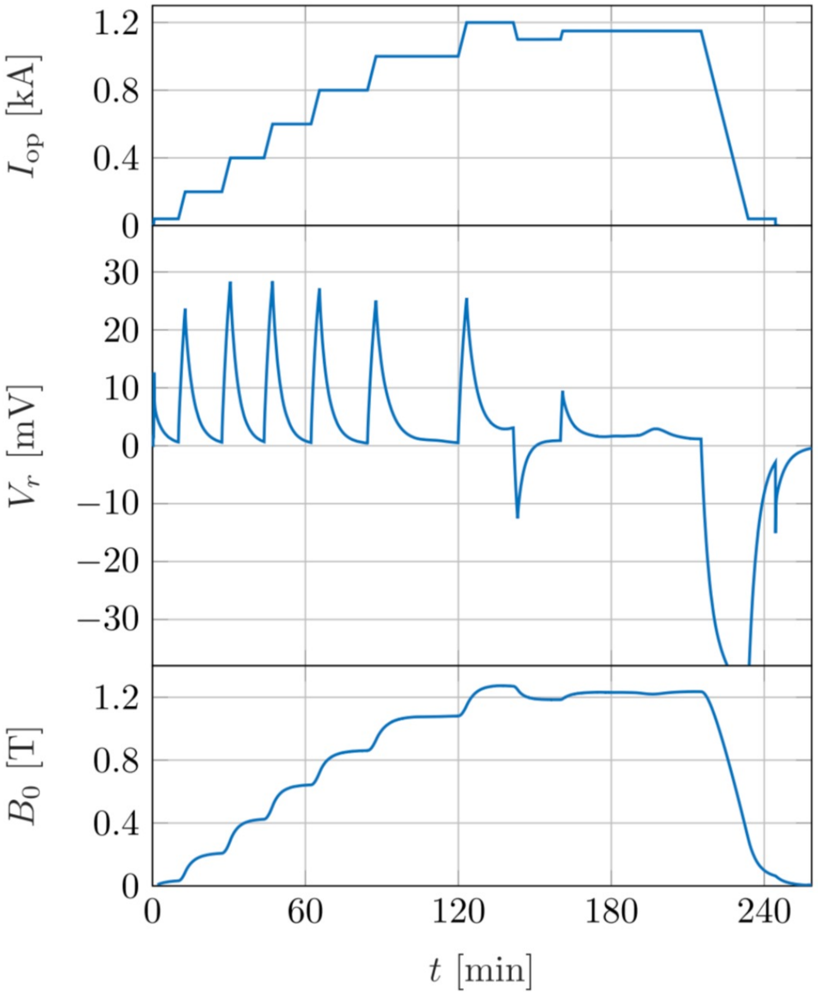


Figure 4. Measurement for $T_{op} = 40\,K$ where we increased the operating current I_{op} in steps until we approached the magnet critical current I_{mc}.

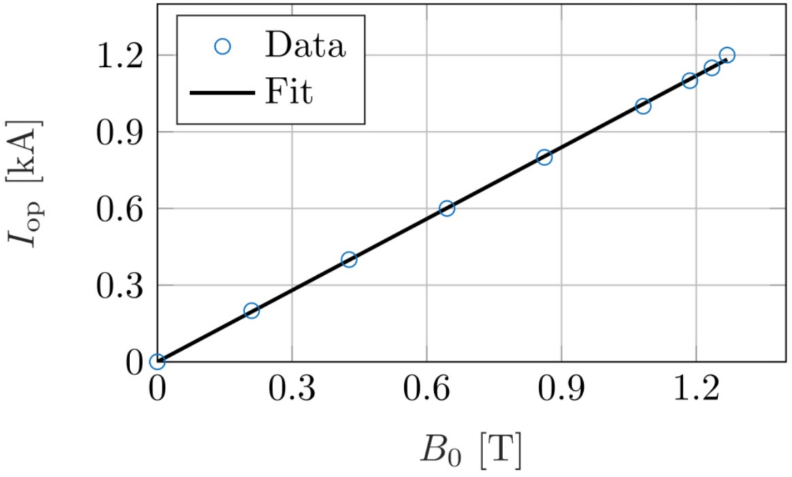


Figure 5. The operating current I_{op} as a function of the convergence value of the central magnetic flux density B_0 for $T_{op} = 40\,K$.

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Coil parameter estimation

Supercond. Sci. Technol. 36 (2023) 014007

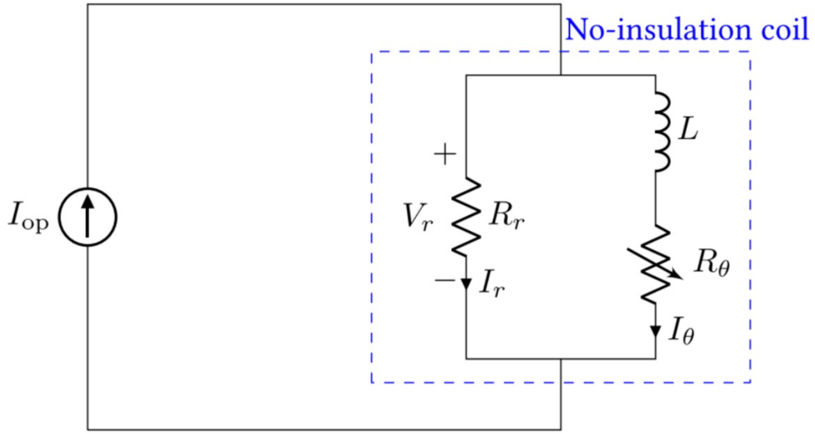
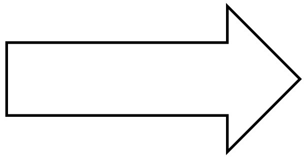
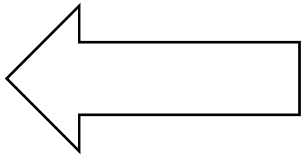


Figure 6. Circuit diagram for the model of a no-insulation coil.



Symbol	Description
α_0	Center magnet constant
α_m	Peak magnet constant
τ	Magnet leftging time constant
R_r	Radial resistance
I_{mc}	Magnet critical current
$\max I_\theta$	Maximum achieved I_θ
$\max B_0$	Maximum achieved B_0
$\max B_m$	Maximum achieved B_m



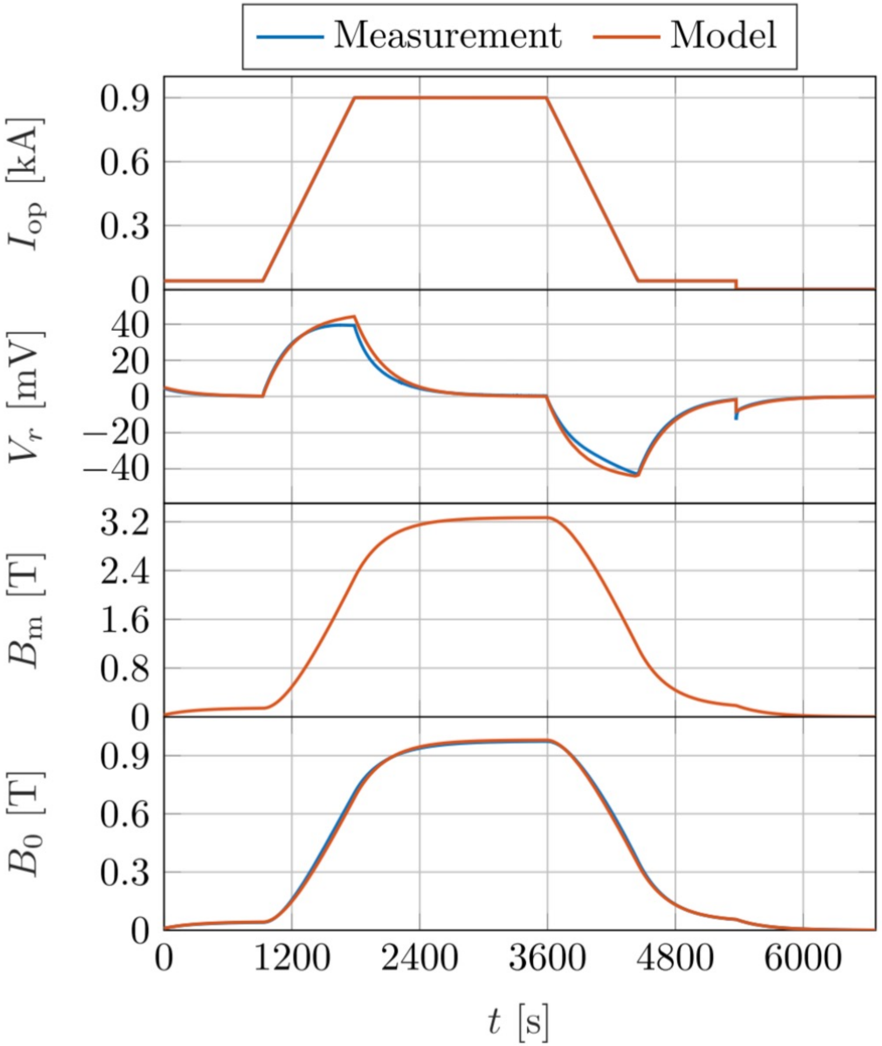


Figure 7. Comparison of simulation results with measurement data for $T_{op} = 40$ K when the identified parameters are used in the model. No measurement data is available for B_m.

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Achieved performance for AMaSED-2

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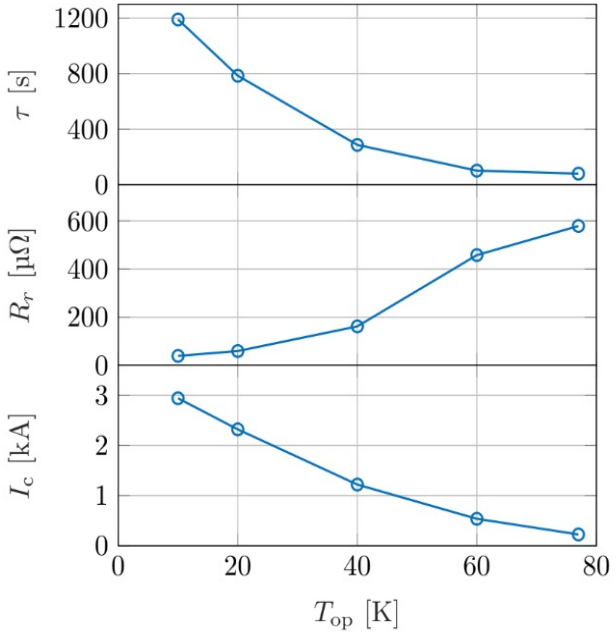


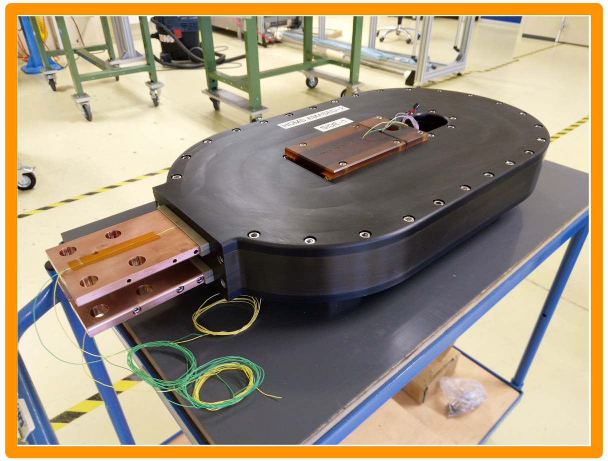
Symbol	Description	Value at 77 K	Value at 60 K	Value at 40 K	Value at 20 K	Value at 10 K	Unit
α_0	Center magnet constant	1.09	1.08	1.09	1.05	1.03	T/kA
α_m	Peak magnet constant	3.63	3.60	3.63	3.50	3.43	T/kA
τ	Time constant	80.4	102	287	785	1190	s
R_r	Radial resistance	579	458	162	59.4	39.3	μΩ
I_c	Critical current	0.226	0.537	1.22	2.32	2.94	kA
max B_0	Maximum achieved B_0	0.226	0.537	1.27	2.32	2.91	T
max B_m	Maximum achieved B_m	0.755	1.79	4.22	7.73	9.71	T

Next steps

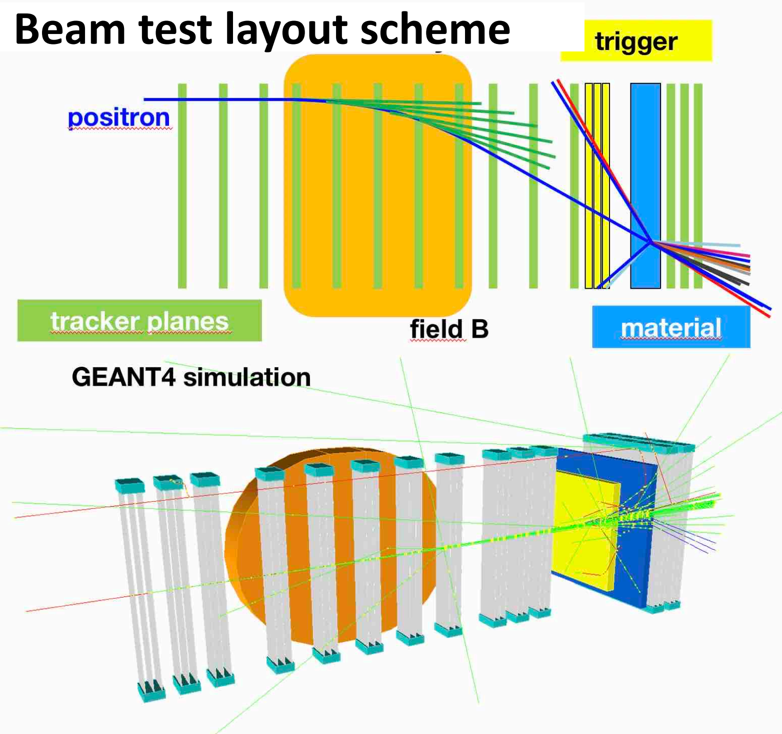
ASTROTOR project just funded by Italian ministry for research, targeting:

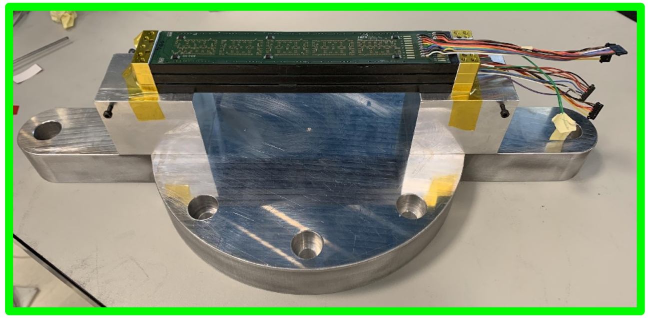
- thermal design of a toroidal magnet for different scenarios (ball. pathfinder/LEO mission /L2 mission)
- possibly very high-field beam tests

MUR PRIN
Portale dei bandi PRIN della Direzione Generale della Ricerca del MUR



HDMS – AMASED coil





CSES – HEPD-02 tracking module

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Conclusions

- Large acceptance and long operation time spectrometers require HTS magnets
- The HDMS team constructed and successfully tested an HTS demonstrator magnet for space
- AMaSED-2 features important innovations:
  - No-insulation winding technique
  - Self-protection against quenches
  - Copper-bands to transfer current
- AMaSED-2 performs better than expected in the range 10-77K
- All solutions adopted are space-compliant and immediately scalable
- Cooling system design not been addressed by the HDMS team
- HDMS delivered the most advanced HTS magnet prototype for space applications, an essential starting point for any future enterprise to detect high-rigidity antimatter in cosmic rays.

Roberto Iuppa

- Magnus Dam, William Jerome Burger, Rita Carpentiero, Enrico Chesta, Roberto Iuppa, Glyn Kirby, Gijs de Rijk, and Lucio Rossi. ***Manufacturing and testing of AMaSED-2: a no-insulation high-temperature superconducting demonstrator coil for the space spectrometer ARCOS***, Supercond. Sci. Technol. 36, 014007 (2022).
- Magnus Dam, William Jerome Burger, Rita Carpentiero, Enrico Chesta, Roberto Iuppa, Gijs de Rijk, and Lucio Rossi. ***Design and modeling of AMaSED-2: A high temperature superconducting demonstrator coil for the space spectrometer ARCOS***, IEEE Trans. Appl. Supercond. 32, 4500105 (2022).
- Magnus Dam, William Jerome Burger, Rita Carpentiero, Enrico Chesta, Roberto Iuppa, Gijs de Rijk, and Lucio Rossi. ***A high temperature superconducting demonstrator coil for ARCOS: a novel toroidal magnetic spectrometer for an astroparticle physics experiment in space***, PoS Proc. Sci. 394, 498 (2021).
- Magnus Dam, Roberto Battiston, William Jerome Burger, Rita Carpentiero, Enrico Chesta, Roberto Iuppa, Gijs de Rijk, and Lucio Rossi. ***Conceptual design of a high temperature superconducting magnet for a particle physics experiment in space***, Supercond. Sci. Technol. 33, 044012 (2020).

backup slides

courtesy of M. Dam

Central magnetic field

$$B_0 = \alpha_0 I_\theta$$

The center magnet constant α_0 must be determined from measurements. Differentiation yields:

$$\dot{B}_0 = \frac{R_r + R_\theta}{L}\left(\alpha_0 \frac{R_r}{R_r + R_\theta} I_{\text{op}} - B_0\right)$$

In the limit $R_\theta \to 0$ we get the approximation

$$\dot{B}_0 = \frac{\alpha_0}{\tau} I_{\text{op}} - \frac{1}{\tau} B_0, \qquad \tau = \frac{L}{R_r} \tag{1}$$

Rewrite to vector notation:

$$\dot{B}_0 = \begin{bmatrix} I_{\text{op}} & B_0 \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix}, \qquad \xi_1 = \frac{\alpha_0}{\tau}, \quad \xi_2 = -\frac{1}{\tau} \tag{2}$$

Insert the measurement data:

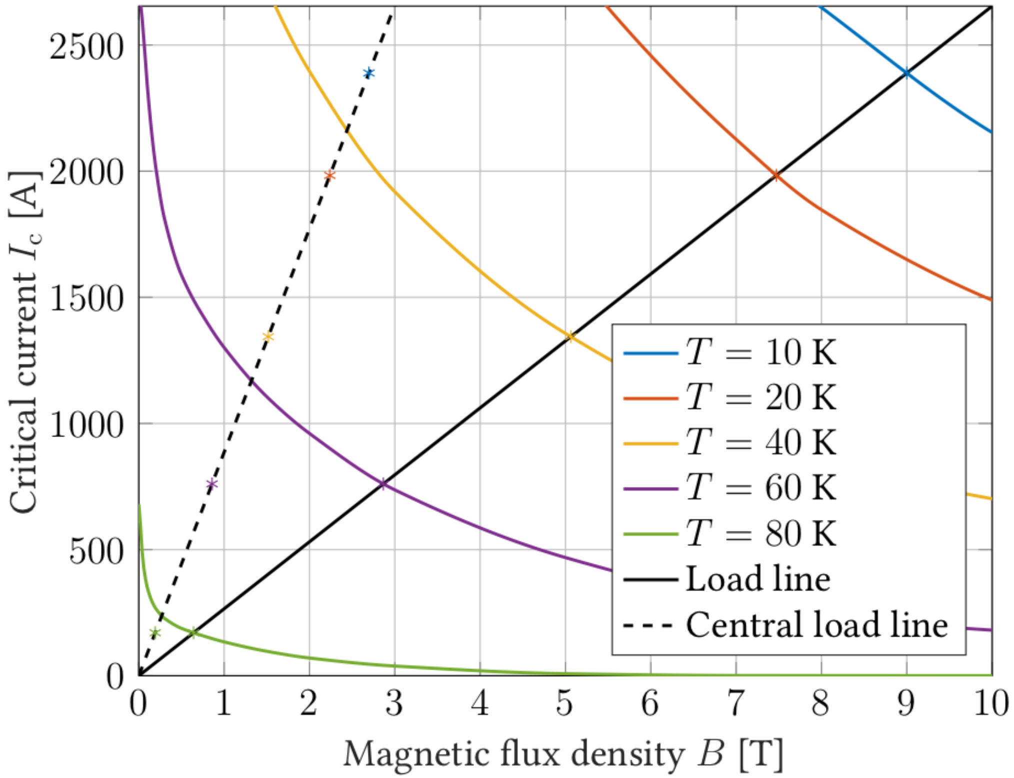
$$\begin{bmatrix} \dot{B}_0(t_1) \\ \dot{B}_0(t_2) \\ \vdots \\ \dot{B}_0(t_m) \end{bmatrix} = \begin{bmatrix} I_{\text{op}}(t_1) & B_0(t_1) \\ I_{\text{op}}(t_2) & B_0(t_2) \\ \vdots & \vdots \\ I_{\text{op}}(t_m) & B_0(t_m) \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} \tag{3}$$

This is an regression problem that can be solved for ξ_1 and ξ_2.

courtesy of M. Dam

SuperPower HTS ReBCO tape:

- 12 mm wide, 97 µm thick
- Angle dependence: worst case conditions (we conservatively assume B-field perpendicular to tape surface)
- Field dependence: Robinson Research Institute HTS Wire database, extrapolated to lower temperatures and higher flux densities



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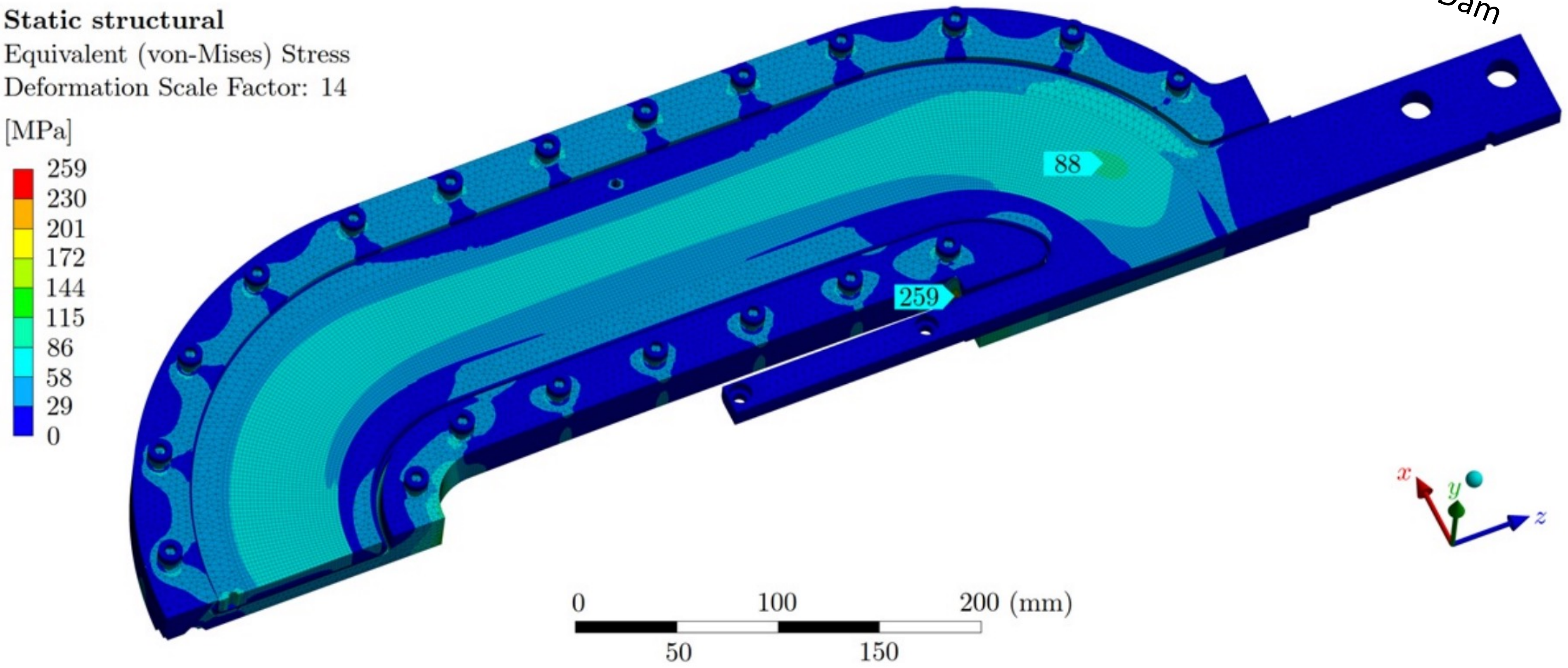

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