Does the shift to HTS magnets for compact fusion reactors call for the development of a new generation of numerical tools?

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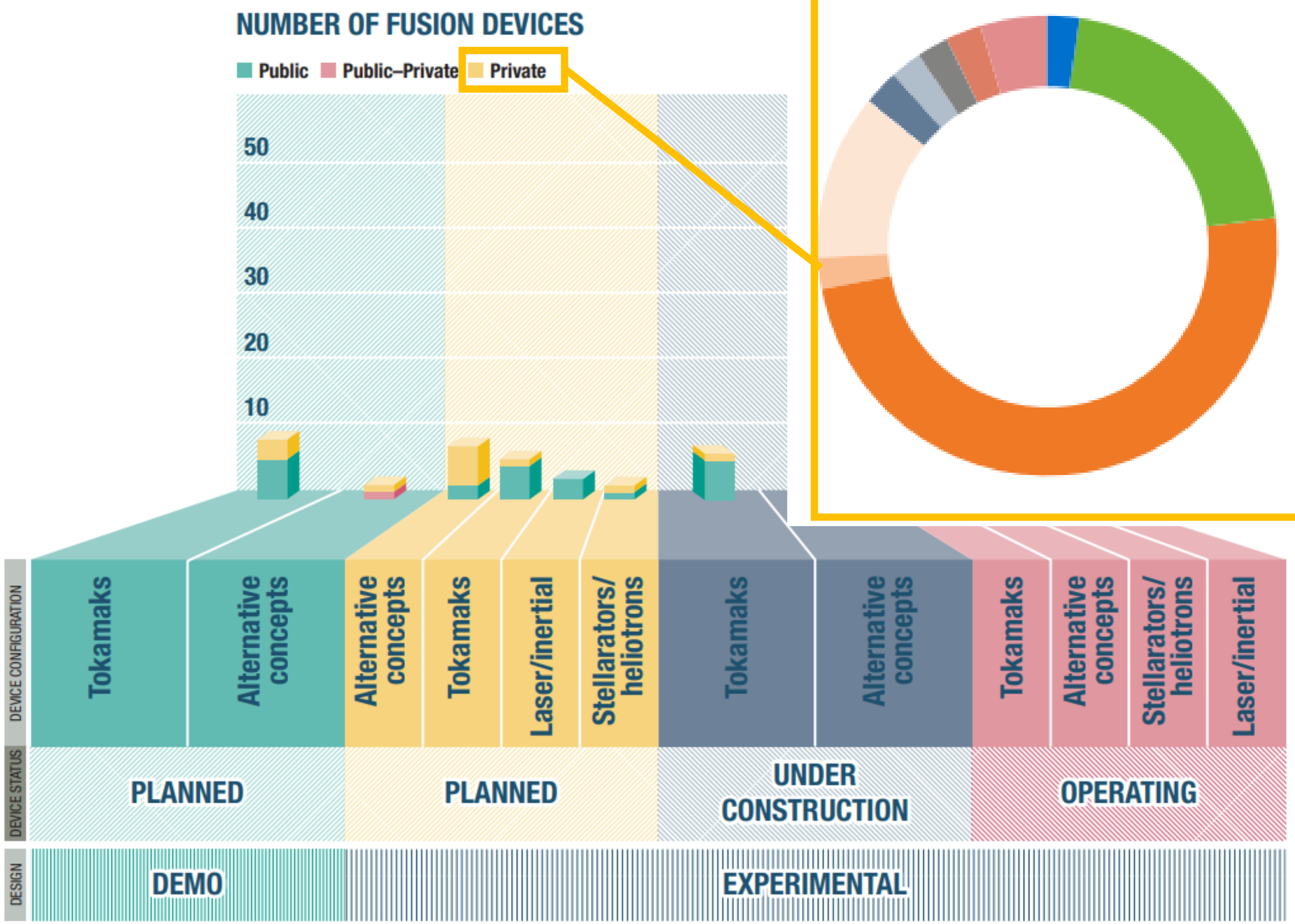
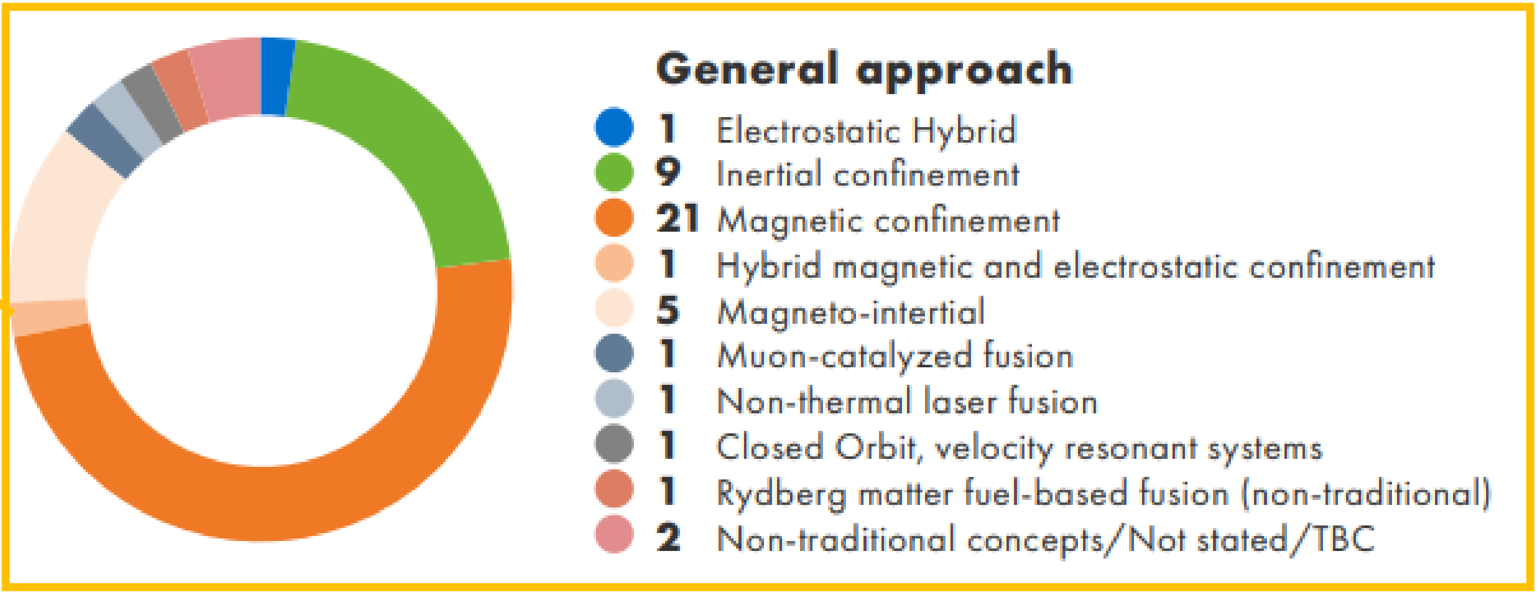
Outline

- HTS in the paths to fusion and to advanced particle physics
- Aim of the presentation
- New challenges: irradiation, mechanical, electro-magnetic, thermal-hydraulic behavior
- Take-home message

Paths to fusion (I)

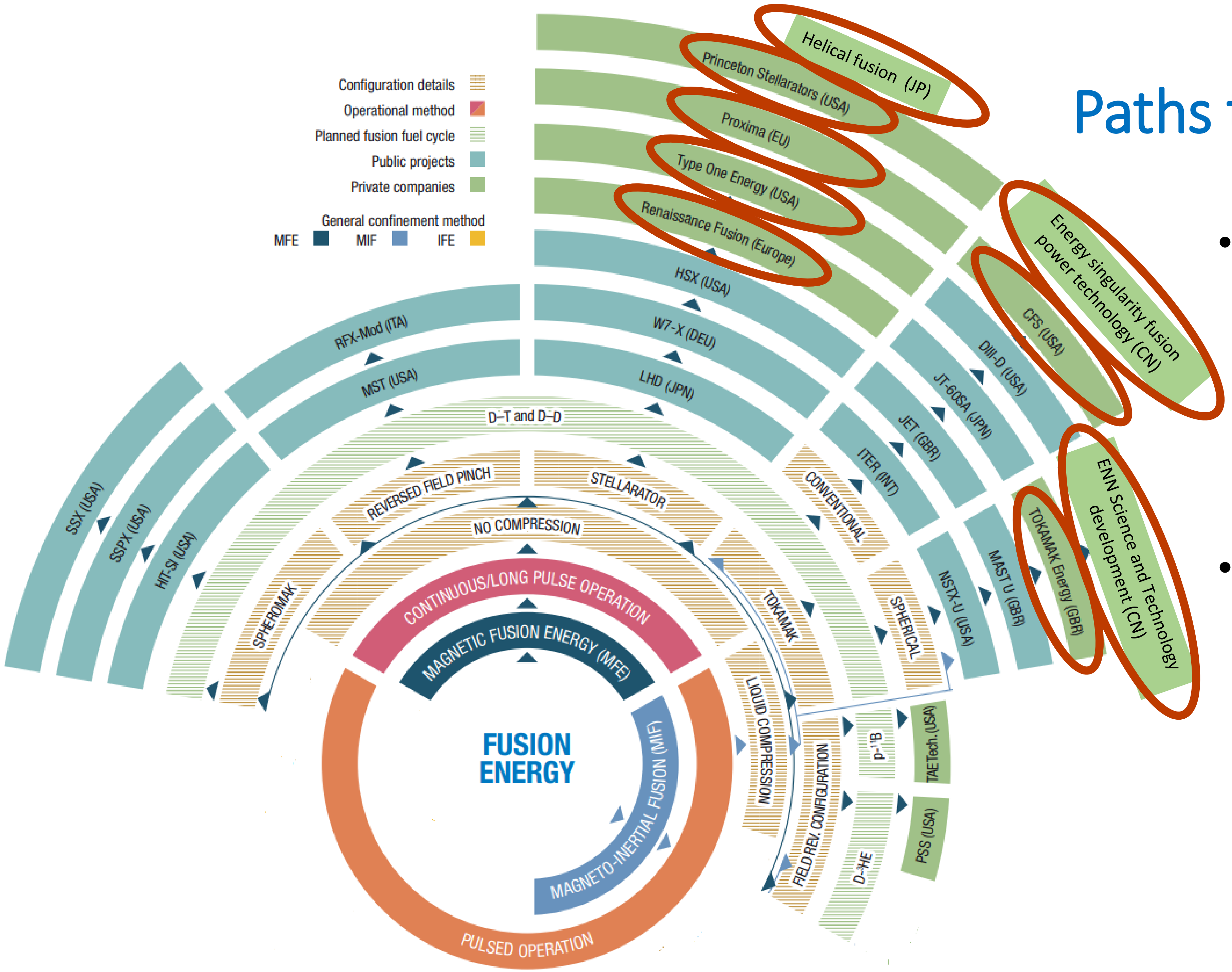




["The global fusion industry in 2023", Fusion Industry Association]

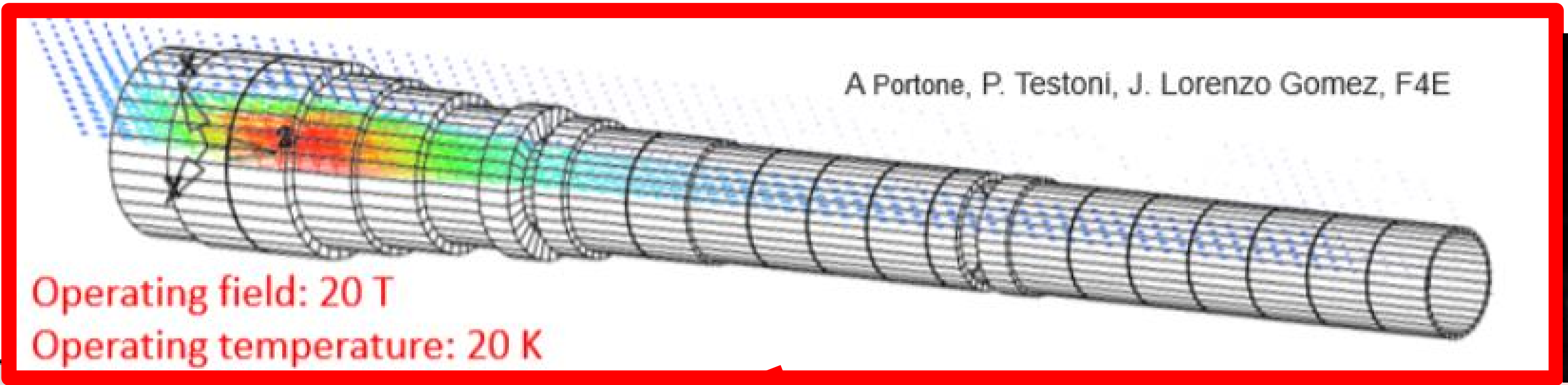
[IAEA, Fusion Outlook 2023]

Paths to fusion (I)



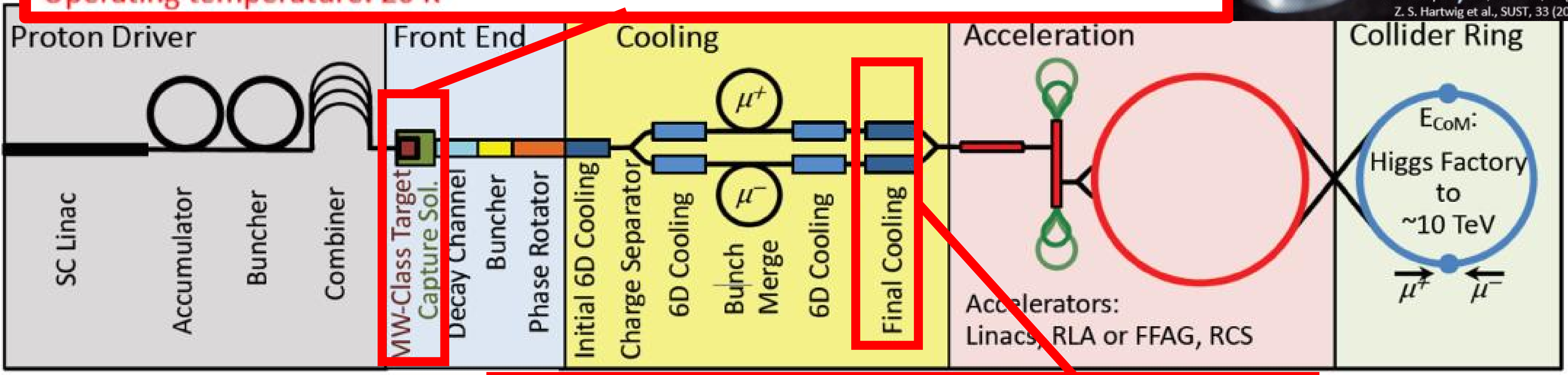
- HTS magnets are in the plans of almost all the MFE projects by public/private companies
- Benefit from what particle physics community has already understood

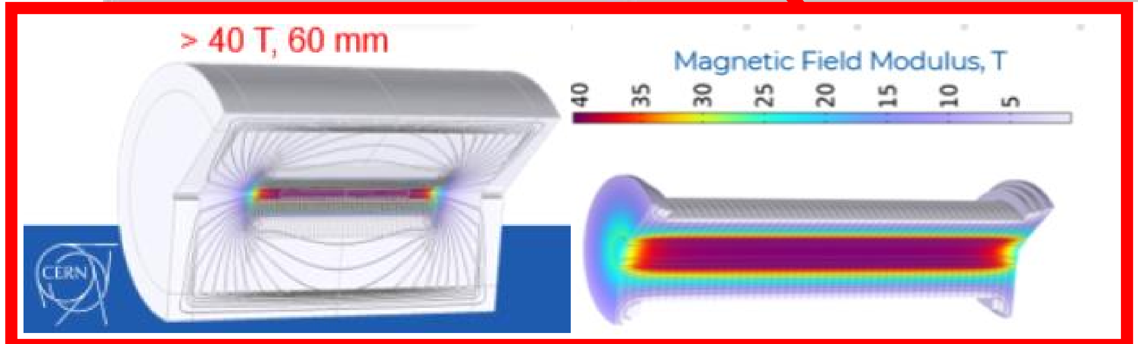
Paths to high-physics particles: the Muon Collider @CERN



Target and capture solenoid

Large bore (1.2 m) , large heat (4.1 kW), and radiation (80 MGy)





Final cooling magnets

[Courtesy of B. Bordini]

Non-insulated HTS modular solenoid

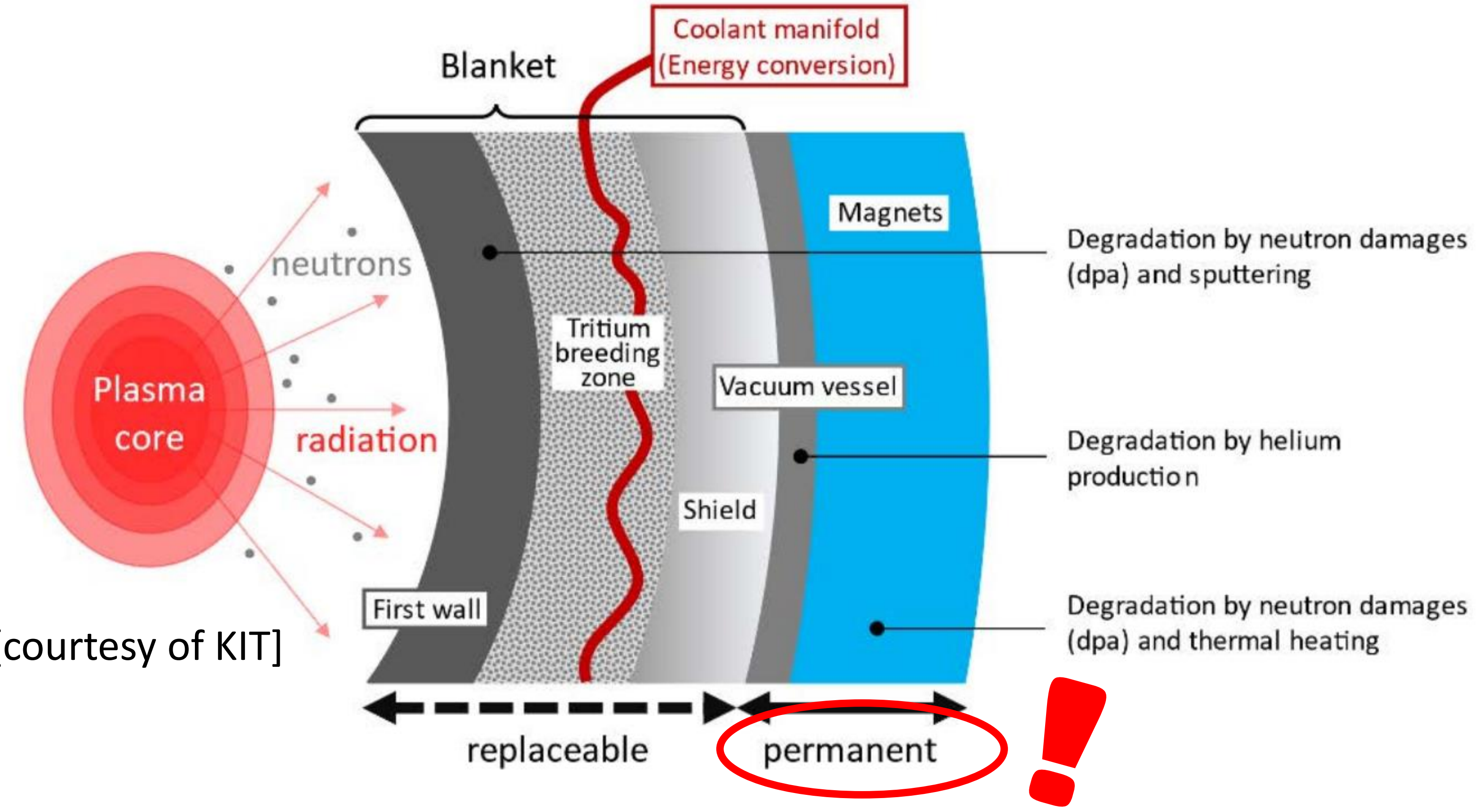
HTS magnets for fusion: a perspective

New paradigms are emerging for HTS magnets:

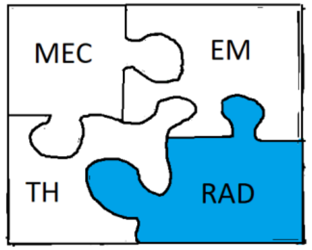
- Not only Cable-in-Conduit concept (as for LTS magnets)
- Not only internal forced flow cooling (as for LTS magnets)
- Non-insulated tape layouts
- Increasing operating temperatures ($\geq$ 20 K):
  1) higher energy efficiency
  2) different material properties (higher heat capacity of solids, lower cryogen inventory)

Which are the new challenges that cannot be ignored in the behaviour (→ modelling → design) of the future HTS magnets?

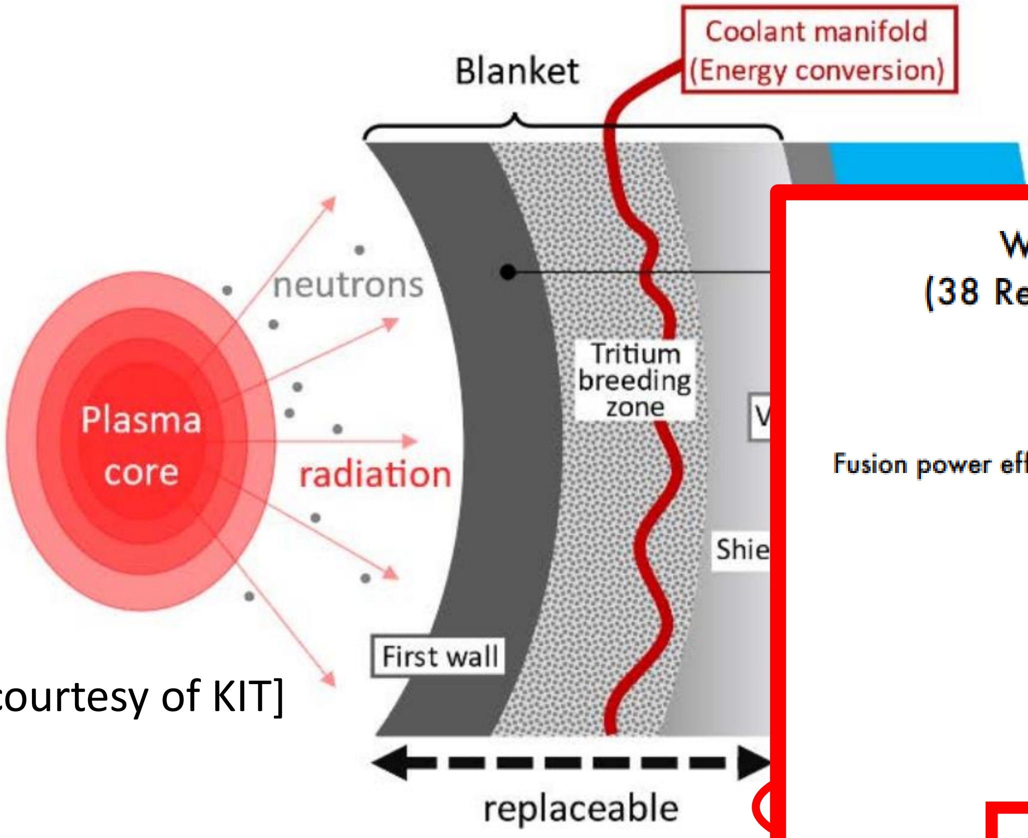
Particle-material parasitic interactions: fusion machines…



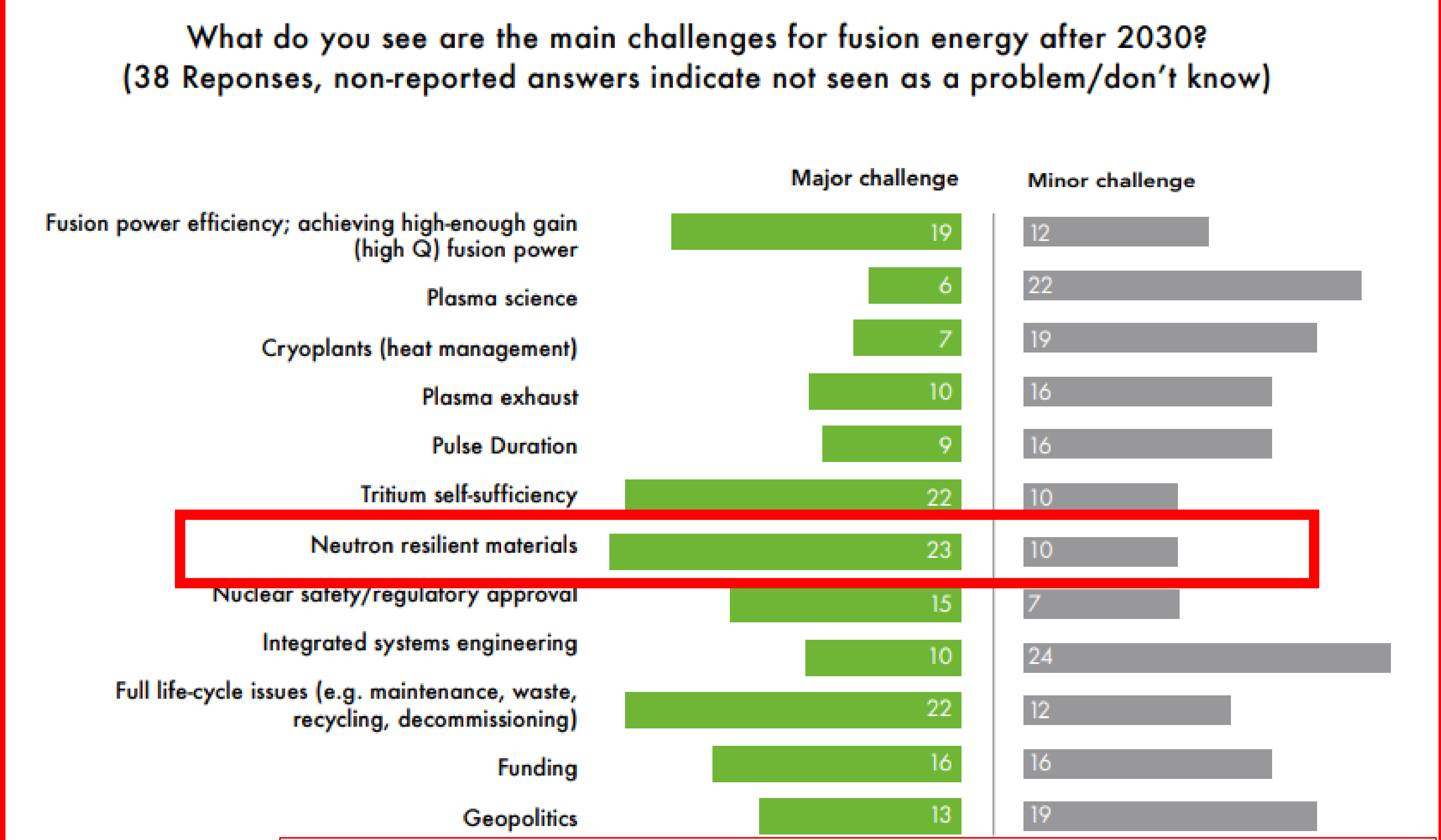
[courtesy of KIT]



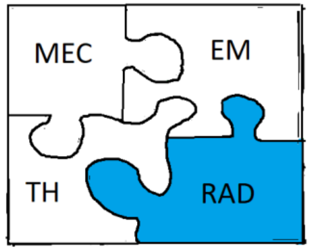
Particle-material parasitic interactions: fusion machines…



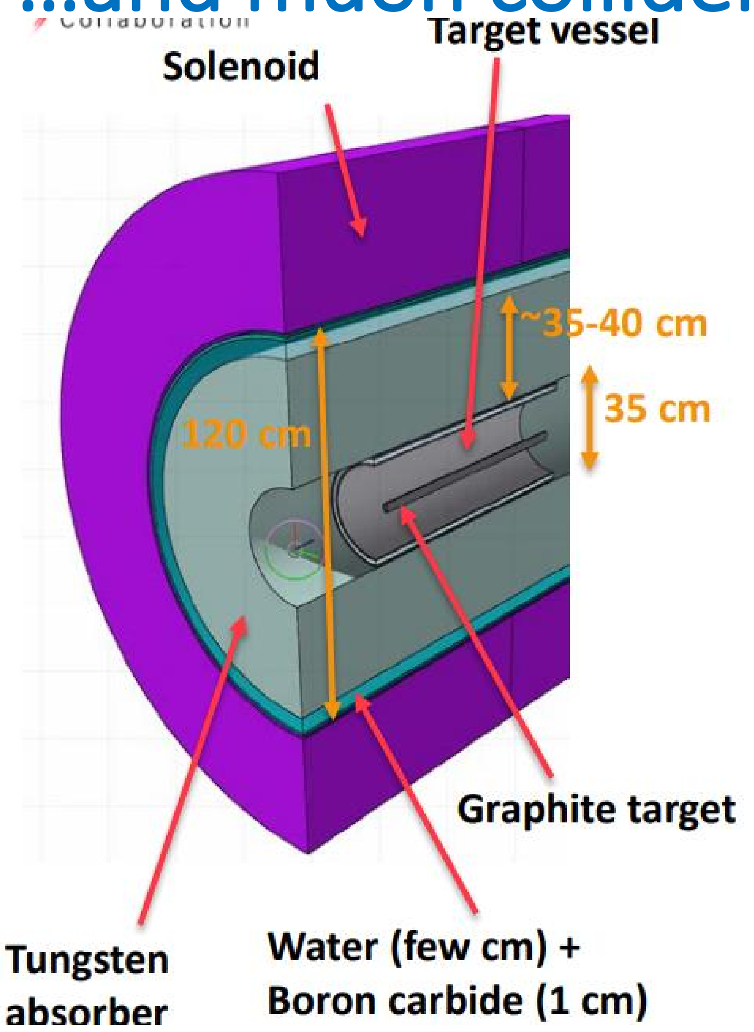
[courtesy of KIT]



["The global fusion industry in 2023", Fusion Companies Survey by the Fusion Industry Association]

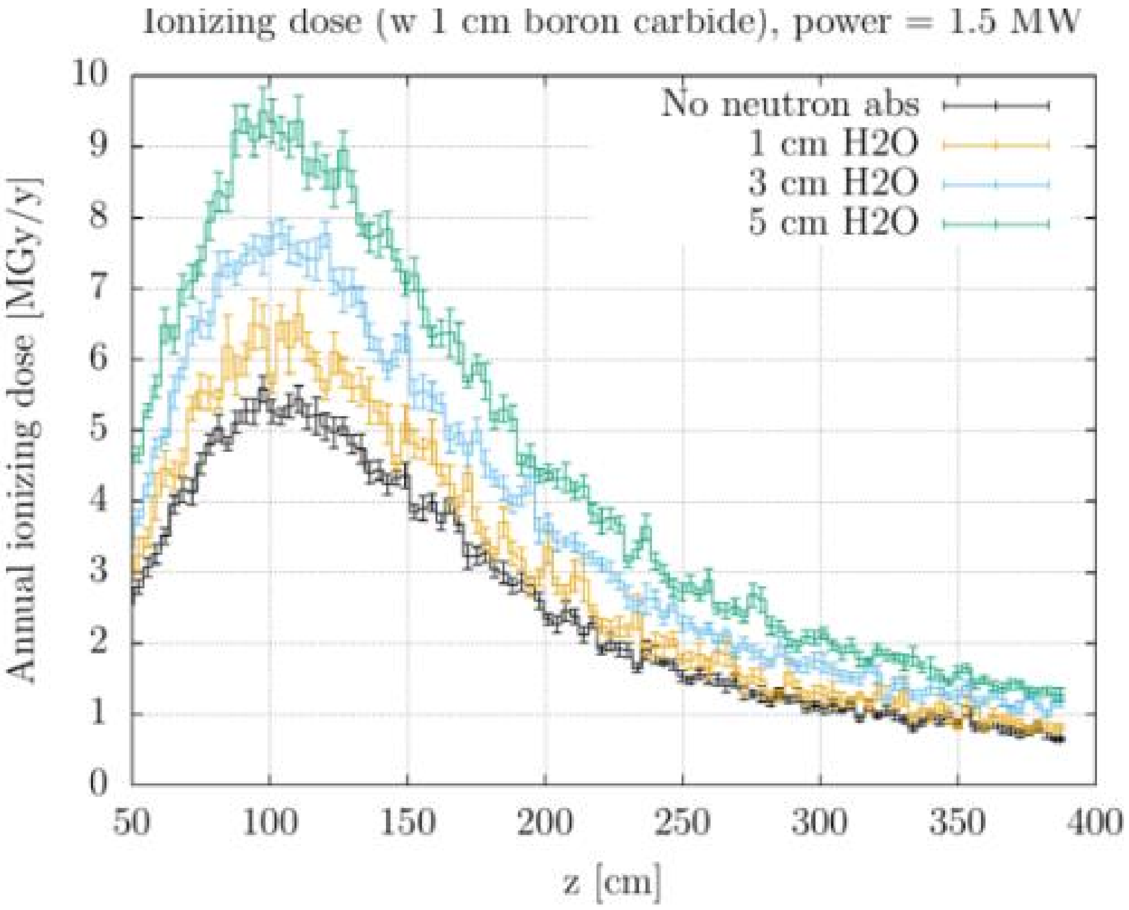


…and muon collider



With a beam power of 1.5 MW

- All HTS coil (in the straight part): 4.1 kW (the most loaded gets 1.5 kW)
- Very high dose on HTS → requires shielding



MEC EM TH RAD

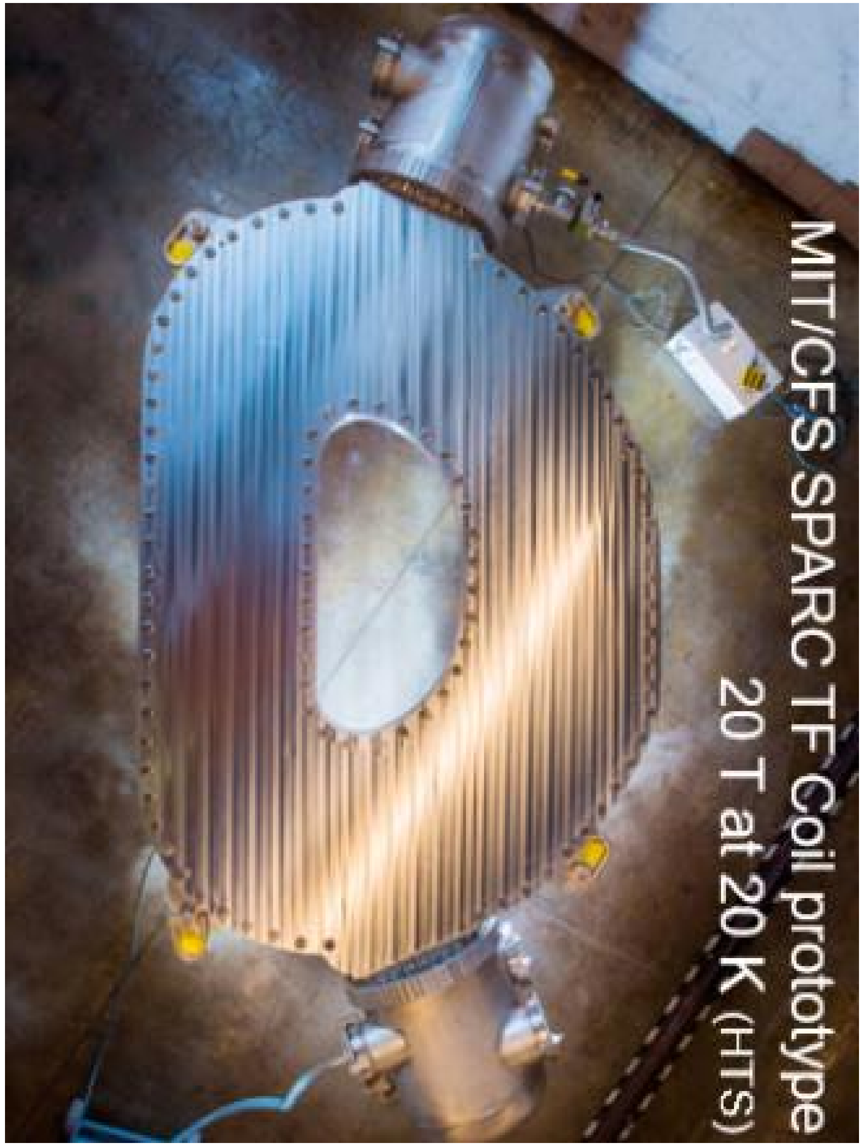
[A. Lechner, D. Calzolari et al., 2023]

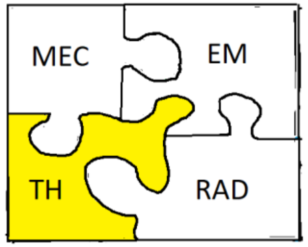
Thermal (hydraulic?) behavior

- Beyond CICCs: Cooling paths (if any) not necessarily follow the ampere-turn paths (transport current direction not necessarily related to flow pattern)
- For SS, Cu: $c_{p@20K} \sim 10 \times c_{p@4.5K}$
- GHe @ 20K: operation at higher pressure to reduce pumping power, but higher ΔT

$$\dot{q}_{pump} \approx \left(\frac{\dot{q}}{\Delta T}\right)^3 \left\langle\frac{T}{p}\right\rangle^2$$

- Emphasis shifting from cryogens to solids

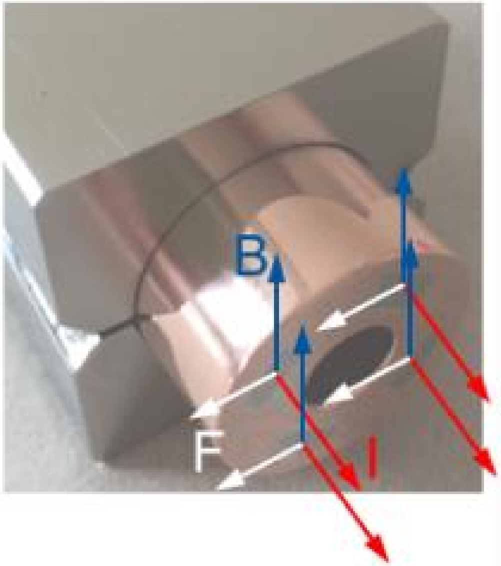


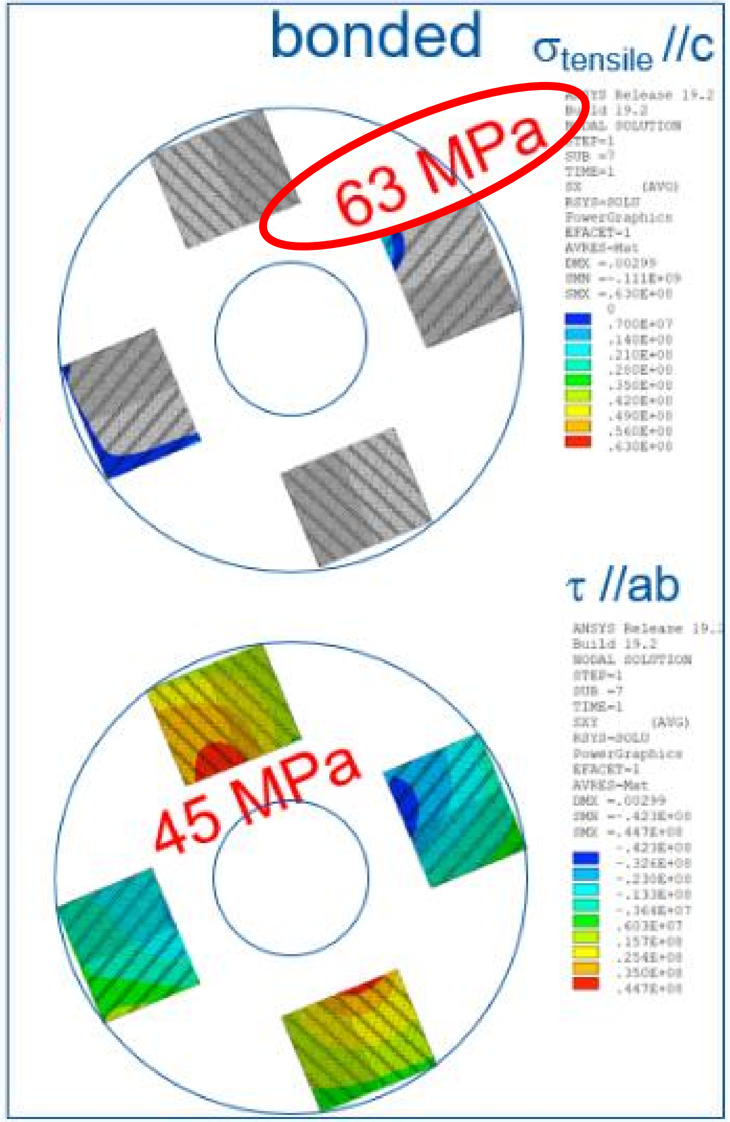


Mechanical behavior

More complex analysis due to:

1) HTS tapes are fragile – tension & delamination to be controlled
2) HTS tapes are anisotropic → need to compute and check principal stress components – not Von Mises - at the tape level

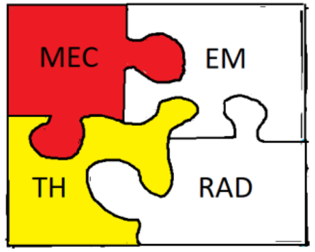




- **Mechanical stresses** producing **irreversible I_c reduction**
  - **Tensile longitudinal strain > 0.4 %**[1] (600-800 MPa depending on the Hastelloy fraction)
  - **Compressive** stress in **thickness** direction **> 400 MPa**[1]
  - **Compressive** stress in **width** direction **> 100 MPa**[1]
  - **Tensile** stress in **thickness** direction: 10-100 MPa[3]
  - **Shear** stress **> 19 MPa**[3]
  - **Cleavage/Peel** stress[3] (tensile at tape extremities)**<1 MPa**[3]

[B. Bordini et al, EUCAS 2023]

[L. Bottura, CHATS 2023]

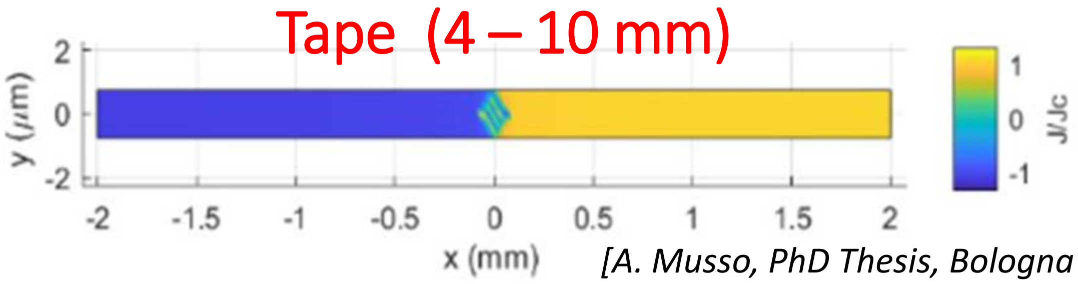


2) Thermal gradients due to conduction cooling?

Electro-magnetic behavior

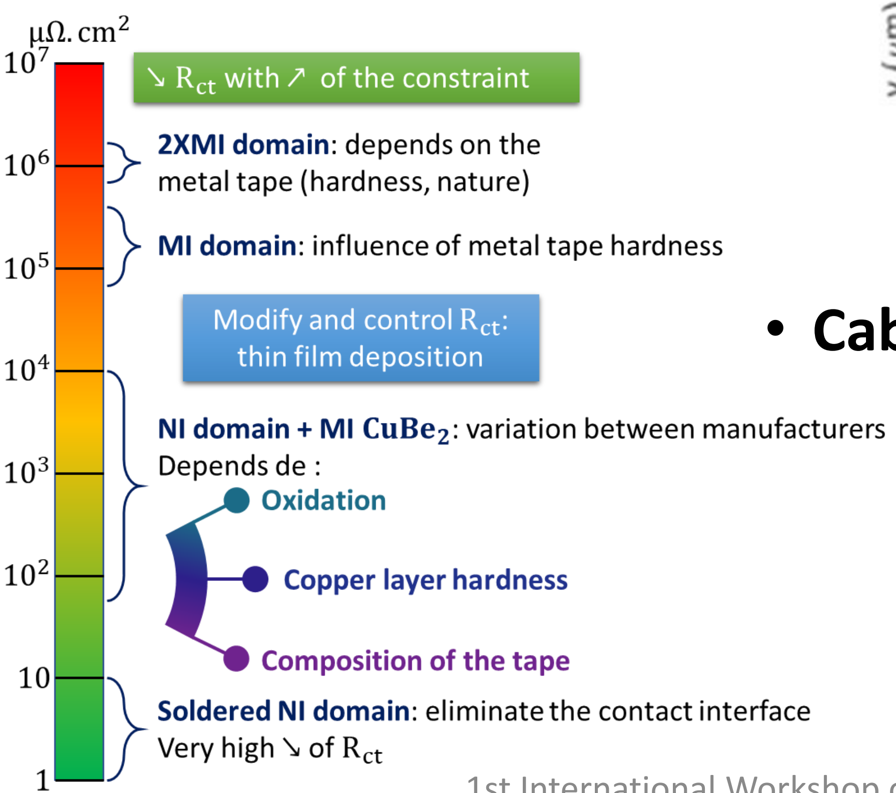
- **Tape/strand level**

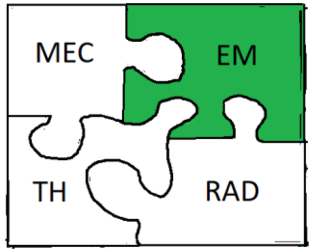
HTS tapes (in particular ReBCO tapes) exhibit different magnetization current pattern with respect to LTS wires. In LTS wires, filaments magnetization currents in filament coupling → 3-50 μm. In 2[nd] generation HTS tapes the currents flow over the whole tape width (4-12 mm).



[A. Musso, PhD Thesis, Bologna 2021]

[C. Genot, PhD Thesis, CEA Saclay 2022]

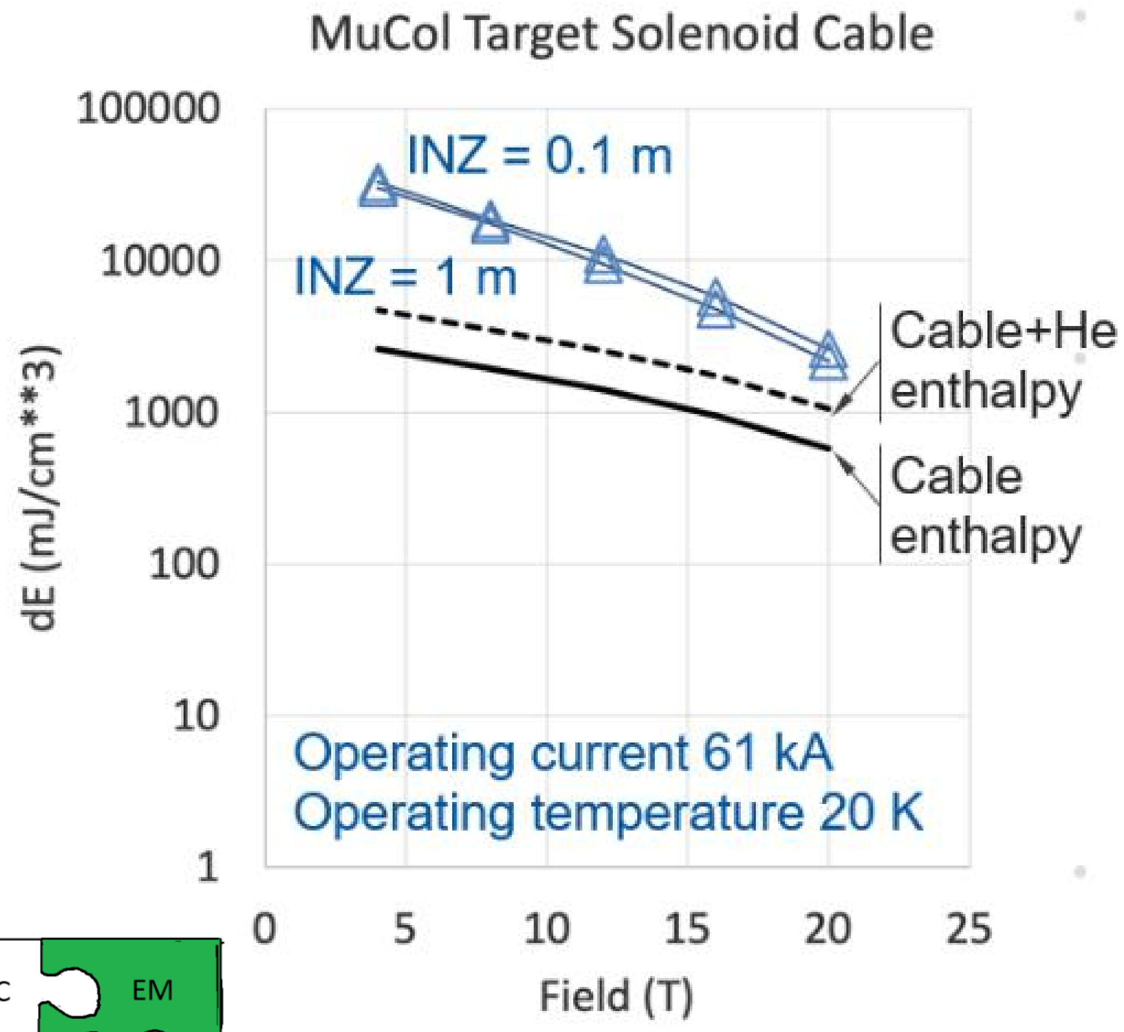




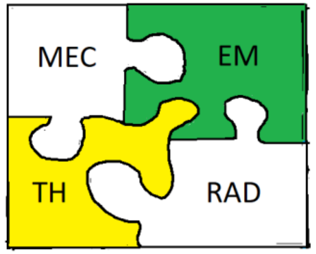
- **Cable/coil level**

The current transfer between HTS tapes in a cable or coil normally occurs over <u>lengths</u> and <u>times</u> >> between strands in LTS cables. Measured contact resistances between HTS tapes span over many orders of magnitude (depending on the application).

Electro-thermal behavior

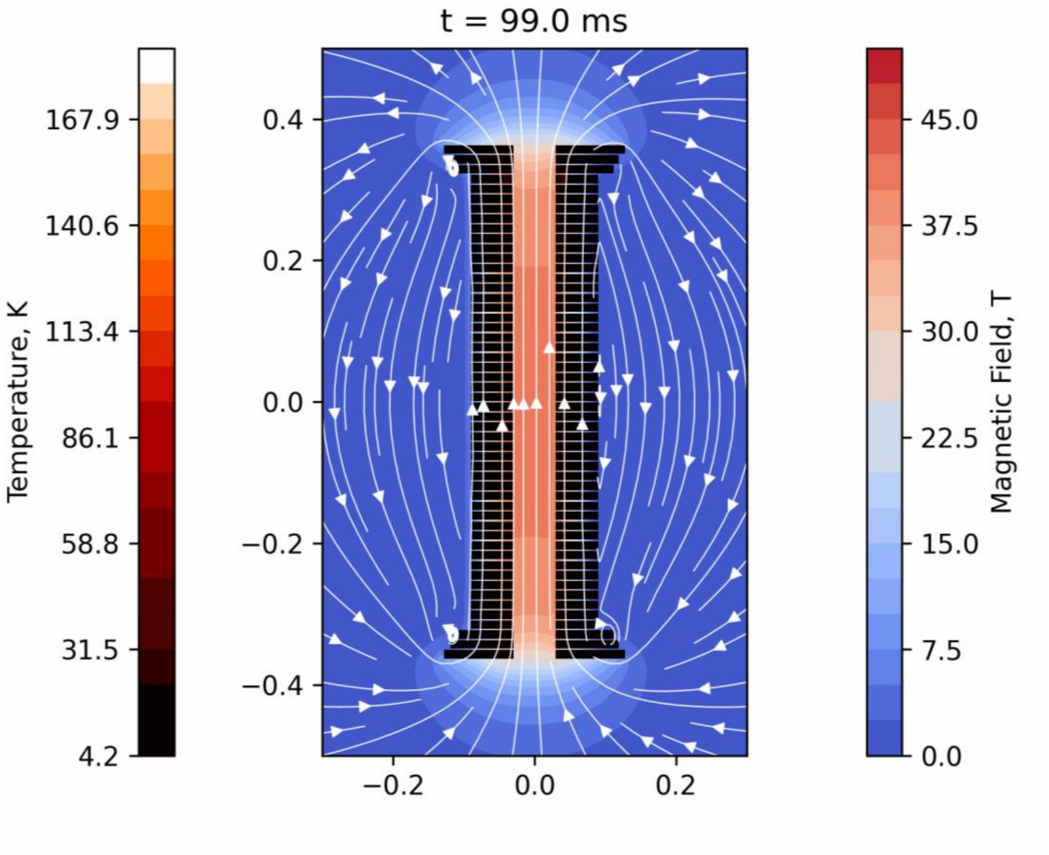


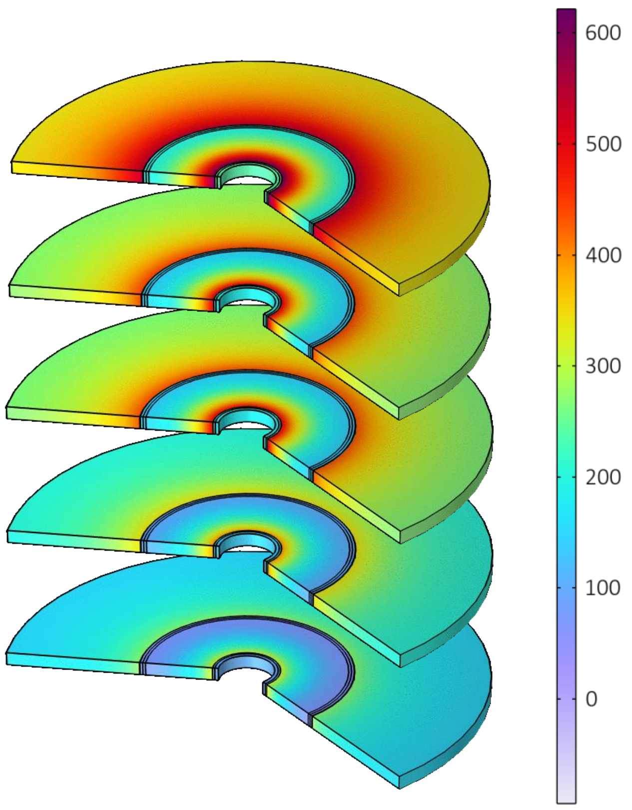
- HTS tapes/cables have very large enthalpy margin → high stability
- Low quench propagation velocity → More destructive damage in case of quench / complex detection with V measurements
- No practical use of quench heaters (high stability)
- Coil protection is much more challenging than for LTS magnets



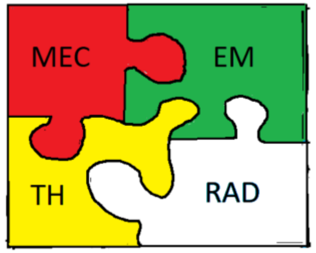
Electro-thermal-mechanical behavior

[courtesy of T. Moulder]





[courtesy of G. Vernassa]

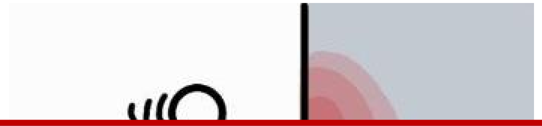


- **NI** coils (beyond the CICC concept) seem a good option for quench management → need for a full 3D analysis of the current (re)distribution, with very long timescales
- Stress assessment needed

→ Aggressive program on solenoid model coils ongoing for the MC final cooling magnet will provide high and ultra-high field characterization of the HTS critical surface and quench detection and protection solutions in a new regime

Particle-material parasitic interactions

Flux effects

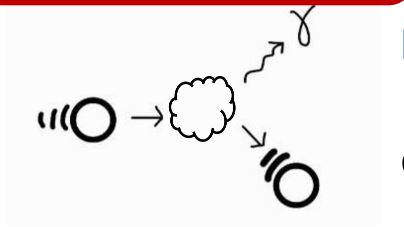


Neutrons exchange kinetic energy, converting it into thermal energy, which is then as **heat in the superconductor**

Cooling

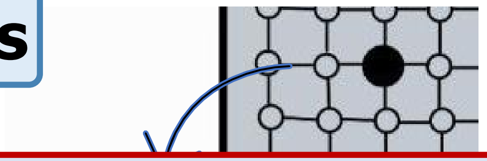
MACROSCOPIC SCALE
within the entire nuclear reactor core or a significant portion of it

Secondary gammas



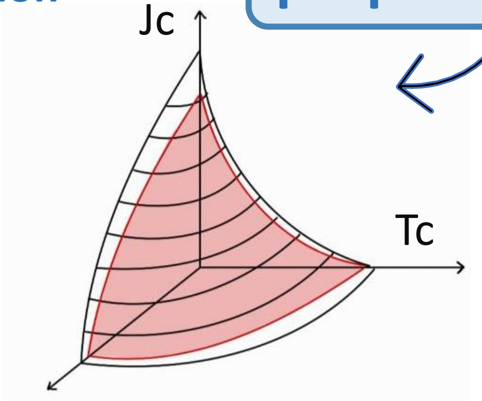
Neutron-Nucleus interactions can generate Bremsstrahlung losses or $\gamma -$ radiations after nucleus excitation

Fluence effects

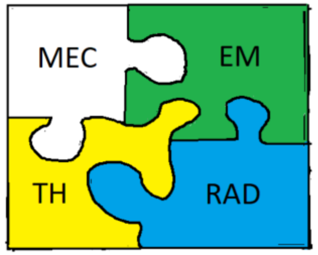


Changes in the superconductive properties result from the cumulative effects of **radiation damage**

SC properties

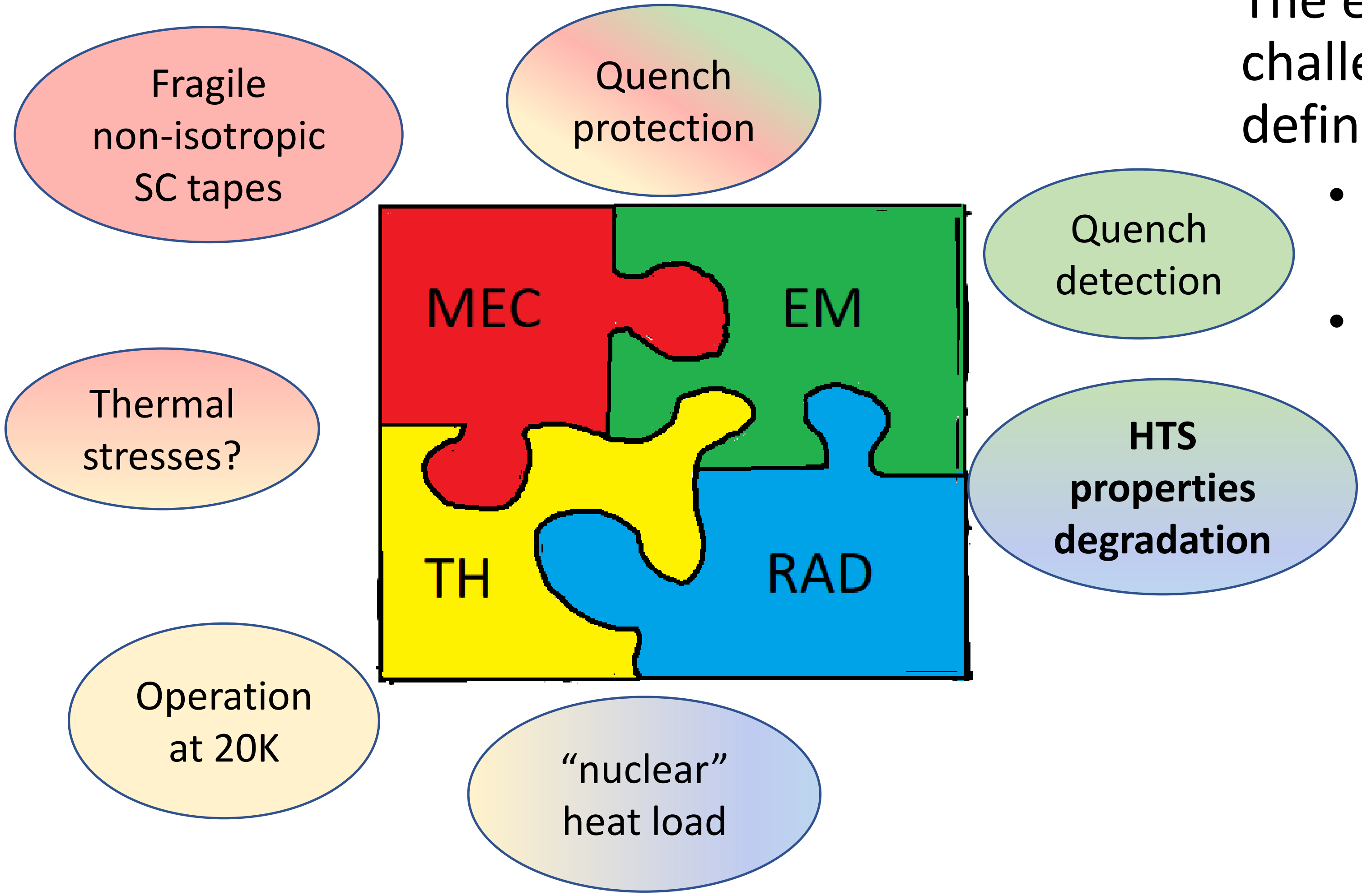


MICRO/MESO SCALE
within specific regions of the reactor or within the single cable



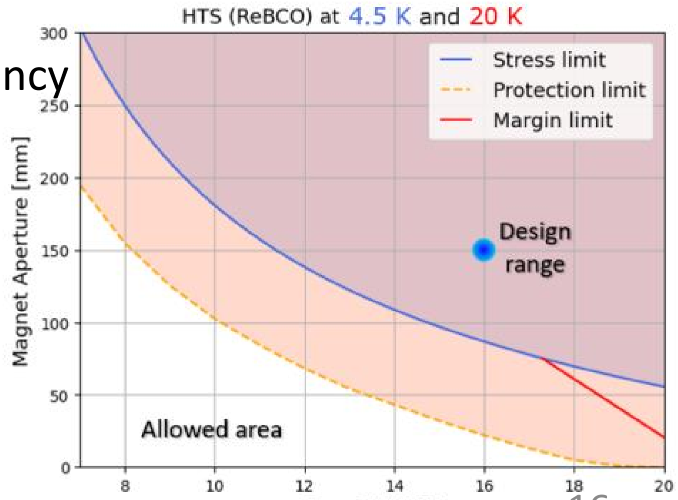
[courtesy of M. Casciello]

HTS magnets in compact fusion reactors



The early consideration of all the challenges in a whole should allow defining what we miss:

- Material props (Jc) as a function of the fluence
- A realistic operational space for HTS high-field magnets, accounting for constraints from:
  - Mechanics
  - Protection
  - Energy efficiency
  - …



[D. Novelli et al, EUCAS 2023]

Beyond the tools for LTS magnets?

- Based also on what is already clear for the particle-physics community, the design of new high-field HTS magnets is not just incrementally based on the LTS magnet design → **requires additional R&D**
- The design approach requires to account for multi-physics aspects:
  - particle-material interaction and mechanical analysis at the tape level (it was mainly at coil level for LTS),
  - electro-magnetic, thermal-hydraulic analysis at coil level (it was at strand/cable level for LTS)
- Maybe the more relevant question becomes then:

Does the shift to HTS magnets for compact fusion reactors call for the development of a new design approach?


THANK YOU!