



Modelling superconducting magnets for fusion applications

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Myself in a nutshell



- BSc in Energy Engineering (Politecnico di Torino, 2008)
- MSc in Energy and Nuclear Engineering (Politecnico di Torino, 2010)
- PhD in Energetics (Politecnico di Torino, 2014)
- EUROfusion Fusion Research Fellowship on magnet modelling (2014-2016)
- EUROfusion Engineering Grant in Work Package MAG 2016-2019
- Assistant professor at Politecnico di Torino since April 2016
- Recipient of the IEEE Council on Superconductivity Graduate Study Fellowship in Applied Superconductivity (2014)
- Research topics:
 - modelling of magnet system for tokamak fusion reactors
 - modelling of tritium transport in fusion reactors
 - thermal-hydraulic modelling of high heat flux components for fusion reactors
 - multi-physic modelling of Gen-IV fission reactors



Outline



- Introduction: SC magnets
- The need for modelling
- Thermal-hydraulics
- The 4C code
- Conclusions & perspective

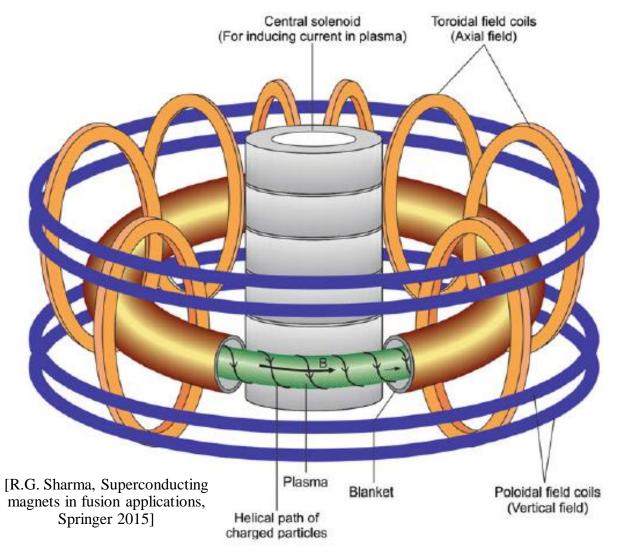
Acknowledgements:

Prof. R. Zanino, prof. L. Savoldi, Dr. A. Brighenti, Dott. A. Zappatore



Introduction

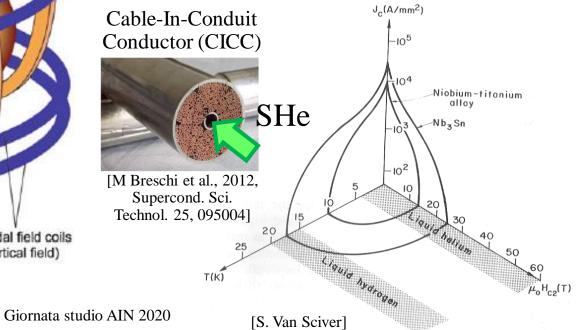




Tokamak

TRANSFORMER PRINCIPLE → PULSED OPERATION!

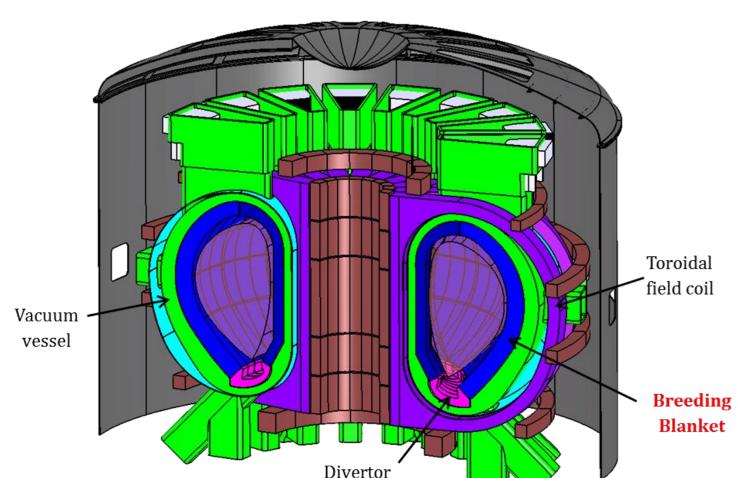
- Magnet system (CS, PF and TF)
- B > 10 T, I_{op} ~ 10-100 kA → SC magnets!





Superconducting tokamaks: the challenge of temperature gradients





From ~10⁸ K (plasma core) to 4.5 K (SC coils) in few m → the issues of heat removal is of paramount importance!



NEED for MODELING!

- Interpretation
- Design

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Case A



Pieces of physics to be considered

Depend on the domain (type of magnet) and transient

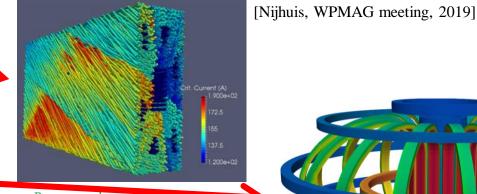
considered

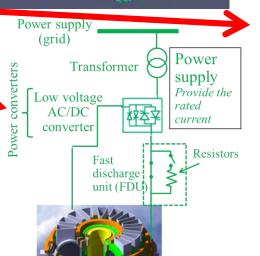
- Electro-mechanics
 - static
 - dynamic (fatigue)
- Electro-magnetics
- Electrical

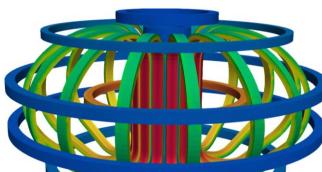
shield

TF coils

- Neutronics 1
- Thermal-hydraulics
- + Safety and RAMI analyses





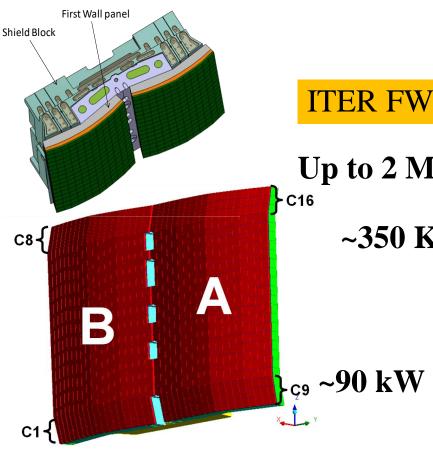


[Boso, WPMAG meeting, 2019]



Why cryo-temperature components are critical?





ITER FW panel

Up to 2 MW/m²

~350 K

Heat flux

(Coolant) temperature ITER TF coil

 $< 100 \text{ W/m}^2$

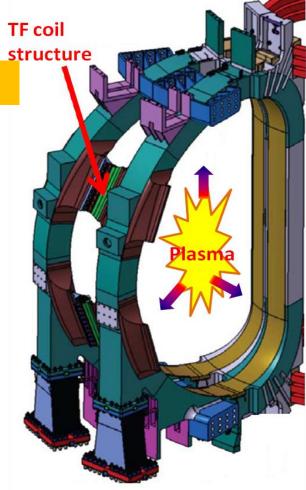
~5 K

Exergy of the heat flow

$$E = Q \left(1 - \frac{T_0}{T} \right)$$

~70 kW

Critical load margin (= Critical load / heat load)



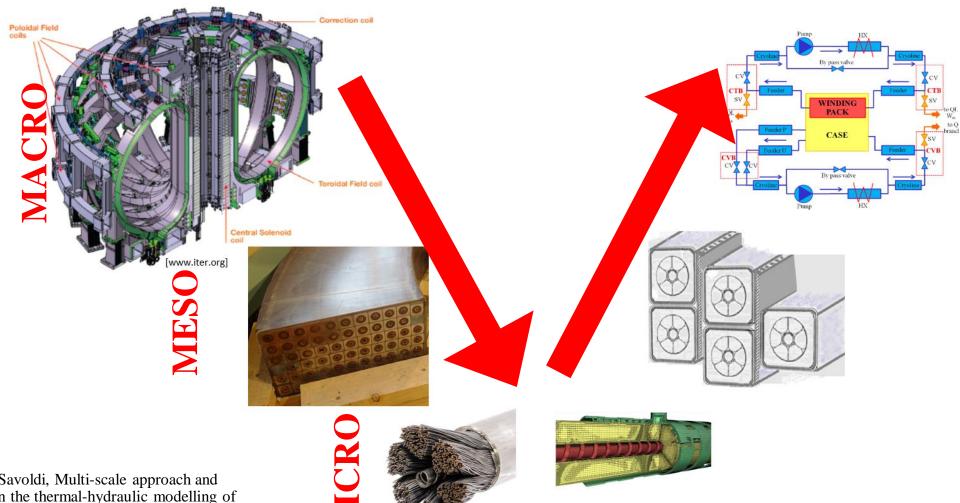


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Thermal-hydraulic modeling



Courtesy of ENEA]

[R. Zanino and L. Savoldi, Multi-scale approach and role of validation in the thermal-hydraulic modelling of the ITER superconducting magnets, IEEE TAS 2013]



Background and motivation



- Magnet system is very complex
- Different transients are expected to take place
- Strict requirements for a safe and cheap operation of the cryoplant
- Thermal-hydraulics (TH) is a key issue in a fusion reactor design
- → develop suitable **system codes** able to **predict the dynamic behavior** of the entire magnet system

Politecnico di Torino Energy Department



(Cryogenic Circuit, Conductor and Coil)
4C code

• "Supplement and backup to existing codes" (e.g. Vincenta)

→ state-of-the-art tool



Architecture of the 4C code



Circuit module [Modelica]

0D pumps, thermal buffers, manifolds, valves, 1D pipes

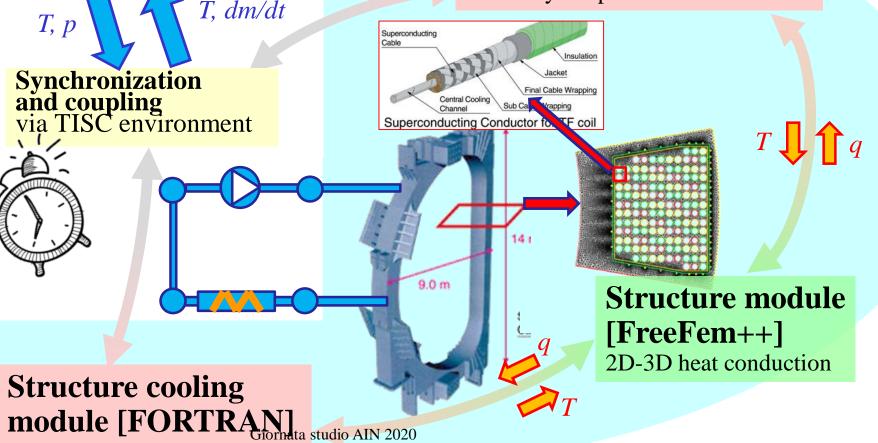
> T, dm/dtSynchronization and coupling via TISC environment

> > **Structure cooling**

[L. Savoldi et al., Cryogenics, 50, 2010, pp. 167-176]

Winding module [FORTRAN]

1D conductors (two-fluid + solids), thermally coupled in transverse 2D





4C code roadmap so far























INCLUDES PARAMETER ESTIMATION AND CALIBRATION

Benchmark

Predictive validation



BLIND TESTS: EXPERIMENTAL EVALUATION OF PREDICTIVE ACCURACY

Application









[www.enea.it]

V&V approach consistently pursued

Verification exercise







Terminology from [1], Roadmap from [2]

Development

[1] W.L.Oberkampf and C.L. Roy, V&V in scientific computing, Cambridge up 2012

[2] R. Zanino and L. Savoldi, Multi-scale approach and role of validation in the thermal-hydraulic modelling of the ITER superconducting magnets, IEEE TAS 2013

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• Normal-operation

- Cooldown
- Pulsed plasma operation
- Faulted operation
 - Quench
 - Energy discharge
 - Plasma disruption
 - Loss of flow / coolant accident

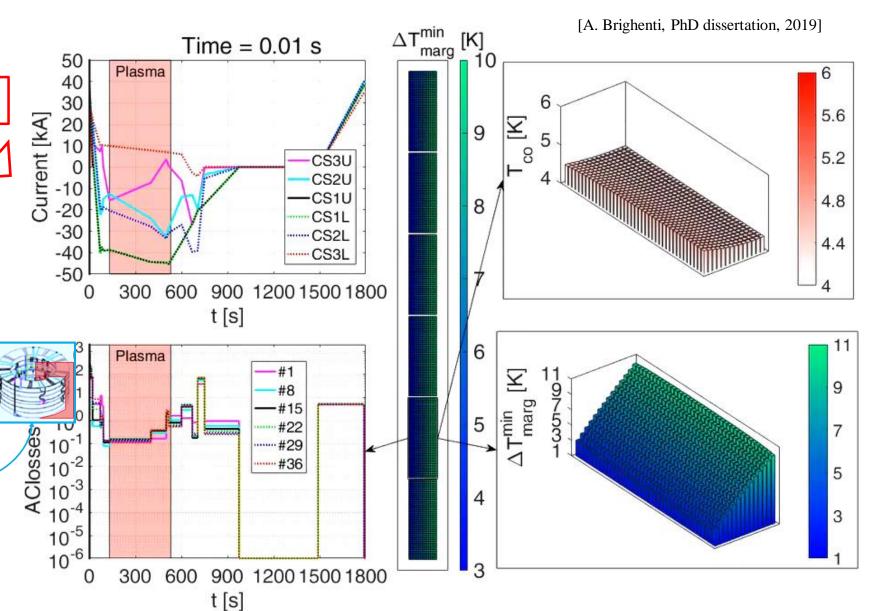
Upper modules

Lower modules

CS2U

CS1U

- ...
- Testing/conditioning
- Maintenance







Conclusions, perpectives...

- Many different thermal-hydraulic aspects of fusion SC magnets addressed @ PoliTo, NEMO group, in the past 25 years
- \rightarrow development of a state-of-the-art tool 4C code (V&V approach pursued)

• <u>NEXT?</u>



- TH analysis in support of design and operation of future tokamaks (EU-DEMO, JT-60SA, DTT)
- Include analysis of HTS conductors
- Include other pieces of physics (mechanics, electromagnetics, ...)
- Issue of interface between different subsystems (magnets/cryoplant, ...)



...and opportunities



Fusion Engineering is experiencing a magic moment:

- JT-60SA first plasma this year in Japan
- DTT is being designed (first call for tenders this year) in Frascati, Rome
- ITER build up is accelerating
- SPARC at MIT, EU-DEMO ...
- Development of HTS conductor prototypes, and related testing

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Thank you for your kind attention