Ricerca sulla fusione nucleare al Politecnico di Torino

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Overview

- Physics (D. Grasso, et al.)
- RF plasma heating (R. Maggiora, G. Vecchi, et al.)
- Materials (M. Ferraris, M. Salvo, et al.)
- Plasma-Wall Interactions (F. Subba, R. Zanino, et al.)
- Superconducting coils (L. Savoldi Richard, R. Zanino, et al.)
- Formazione

Burning Plasma Research Group
Politecnico di Torino, Italy

- magnetic reconnection
- simulation of MHD activity in tokamaks
- behavior of energetic charged particles in magnetic fusion experiments
- basic issues in stochastic motion and turbulent behavior in magnetically confined plasmas

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Introduction

- In ideal MHD regimes, plasma elements initially connected by a field line remain connected by the same field line as they move into their new position.
- In a non-ideal plasma, the frozen-in law is not valid anymore and the magnetic field lines can break and reconnect

ideal plasma

$\vec{E}+\vec{v}\times\vec{B}=0$

non-ideal plasma

$\vec{E}+\vec{v}\times\vec{B}\neq 0$

Approach and reconnection of field lines

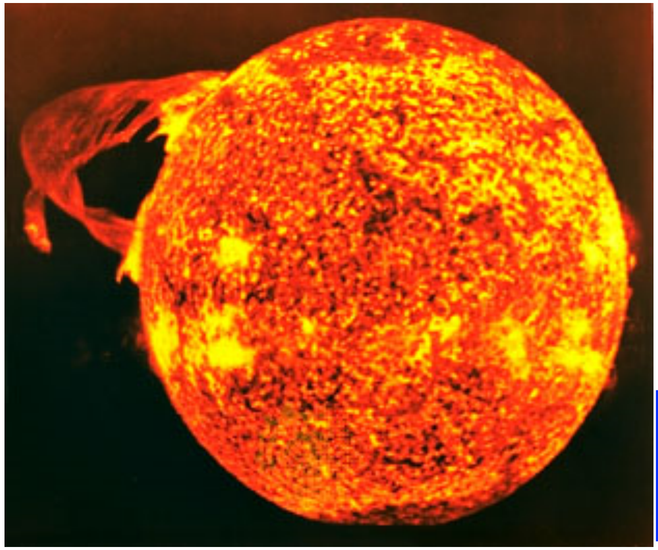
- This change of the magnetic field topology is called magnetic reconnection and is due to non-ideal terms in the generalized Ohm's law

$$\vec{E}+\vec{v}\times\vec{B}=\eta\vec{J}+\frac{1}{ne}\left(\vec{J}\times\vec{B}-\nabla\cdot\vec{p}_e\right)+\frac{m_e}{ne^2}\frac{\partial\vec{J}}{\partial t}$$

resistivity:

$$\eta = m_e \nu_{ei} / ne^2 \propto T^{-3/2}$$

Phenomenology

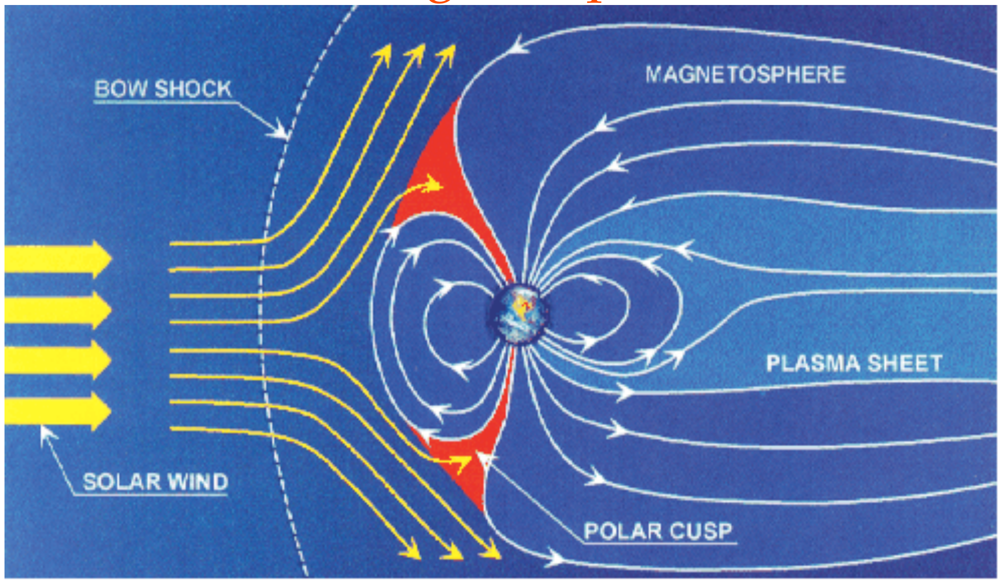


- The magnetic energy stored in the solar corona is the most probable source for the energy released during large solar flares, the largest explosions in the solar system.

The Sun, photographed by NASA's Skylab 4.
Source: http://www.chm.bris.ac.uk

- Interplay between the solar wind and the Earth’s magnetosphere.

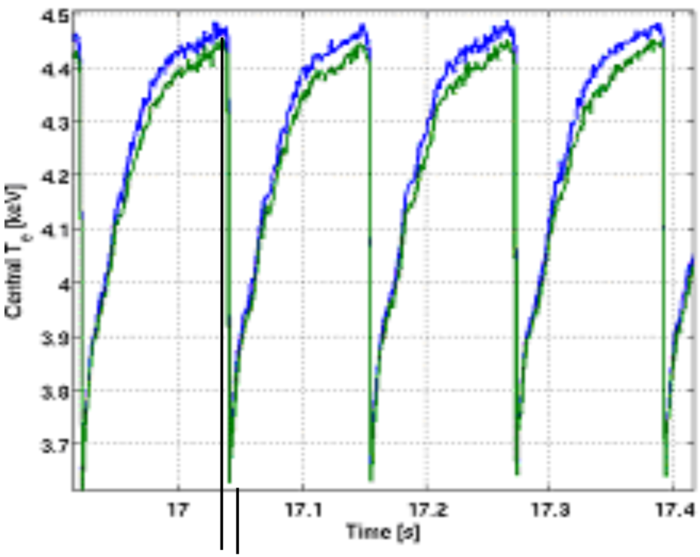
The Earth's magnetic field connects with the Sun's impinging field. These connected field lines are swept to the nightside of the Earth, where they reconnect in an area called the magnetotail.



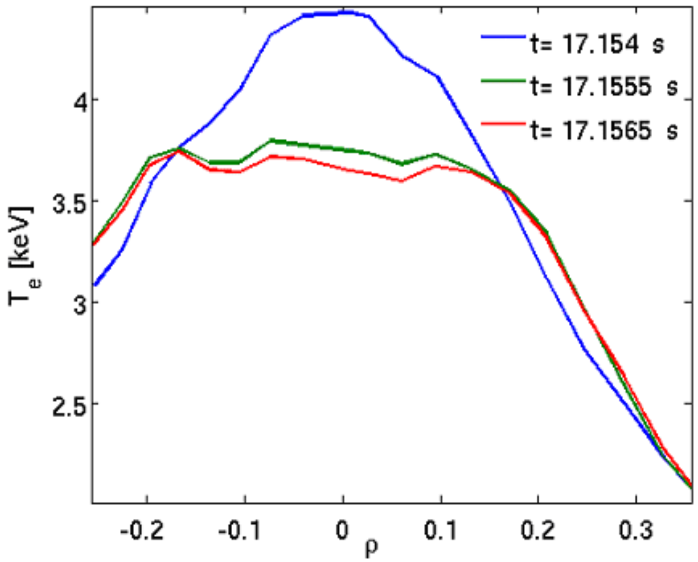
Source: http://smsc.cnes.fr

Magnetic reconnection in Tokamaks: sawtooth oscillations and disruptions

- Sawteeth are internal relaxation oscillations of the central temperature and density of the plasma, causing an abrupt loss of energy confinement.



$\Pi \lfloor 100 \quad s$



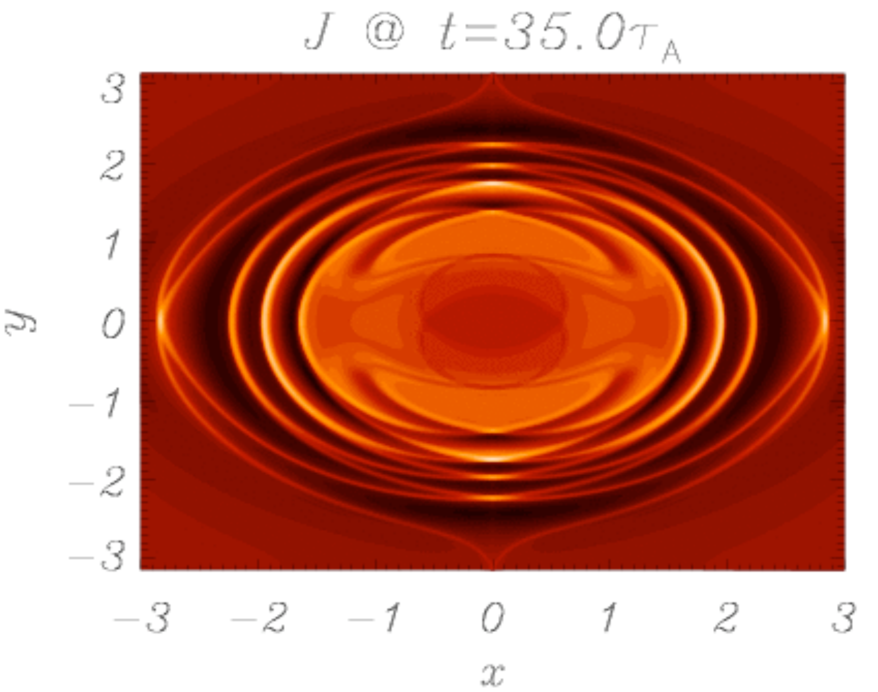
Central temperature profiles vs time and vs the radial coordinate in the Tore Supra tokamak.
(Courtesy of F. Turco, PhD thesis, (2008)).

- Disruptions are characterized by a sudden relaxation of the equilibrium in which the central temperature collapses followed by a decay of the plasma current. Unlike sawtooth oscillations, disruptions may lead to the destruction of the plasma confinement.

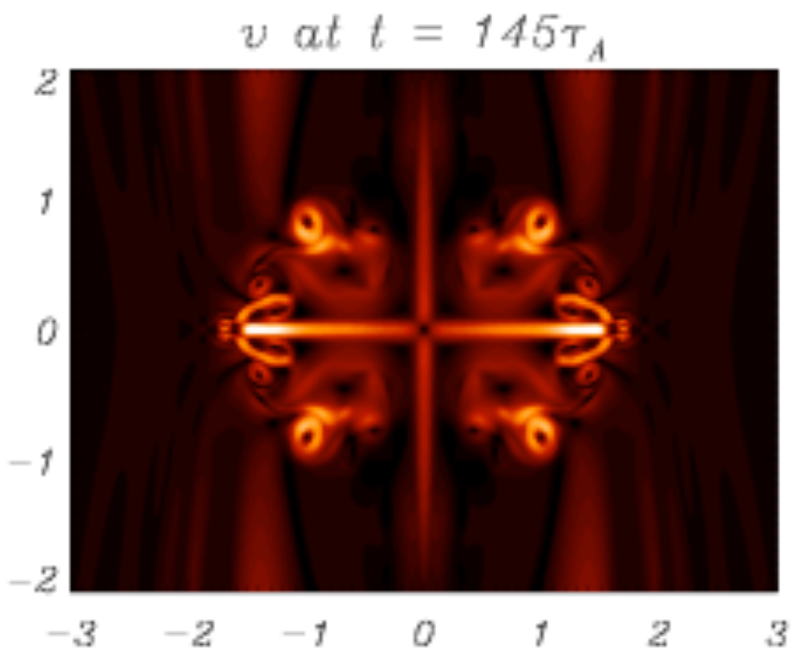
Basic features of magnetic reconnection (2D)

- Laminar or turbulent regimes may develop during reconnection processes.
- Occurrence of secondary hydrodynamic (Kelvin-Helmholtz) instability can lead to turbulence causing disruptions of current density and vorticity layers.

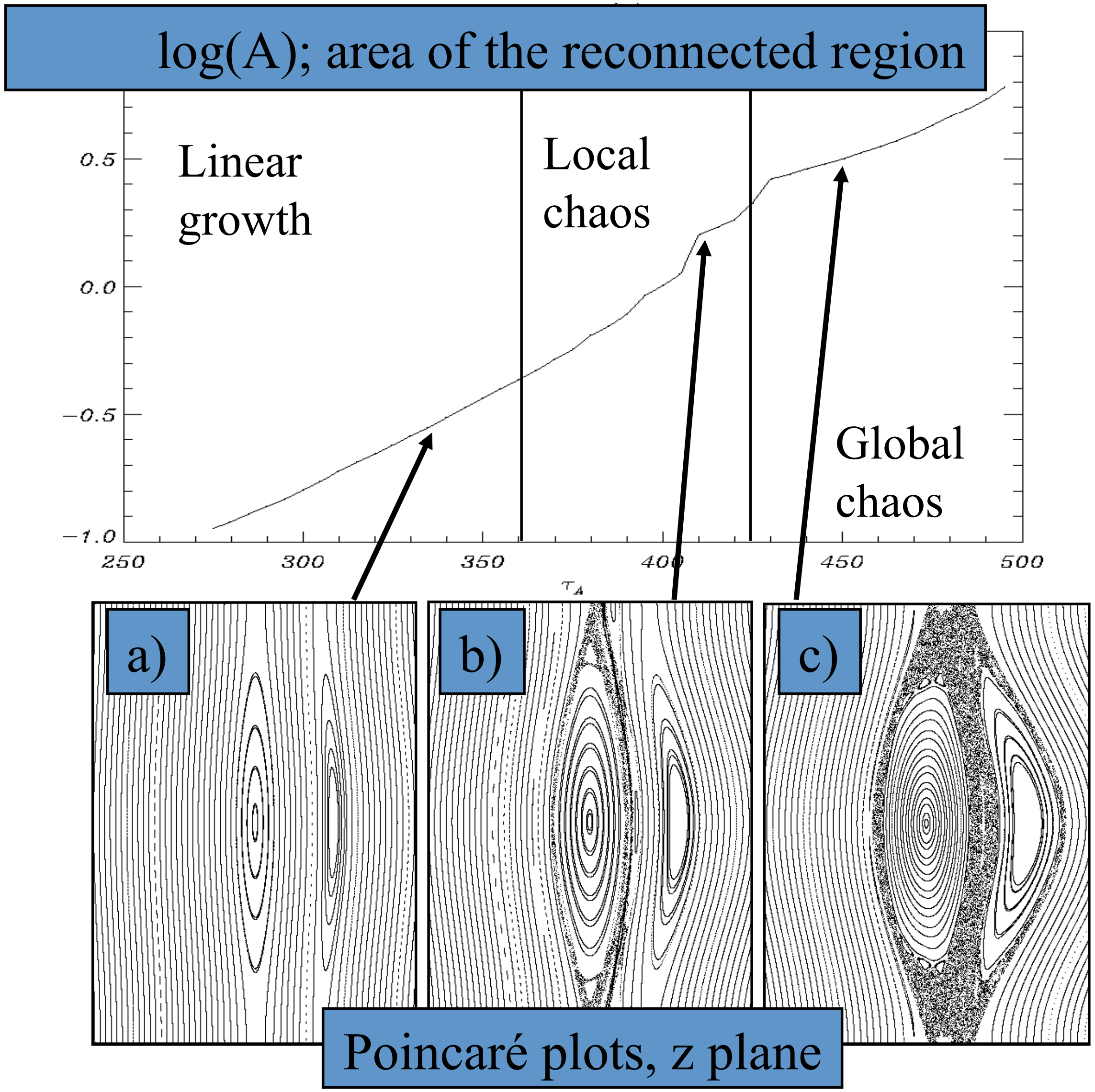
Current density in laminar regime



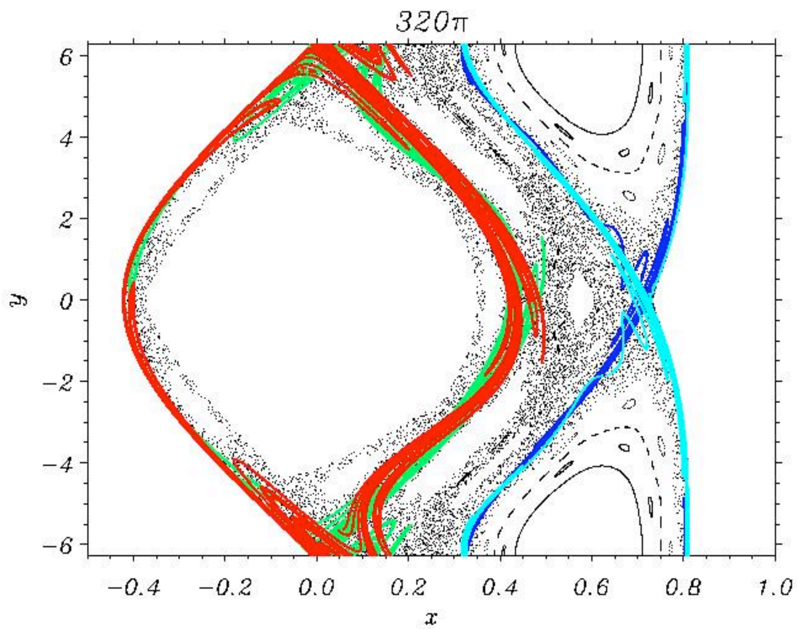
Velocity in turbulent regime



Basic features of magnetic reconnection (3D)



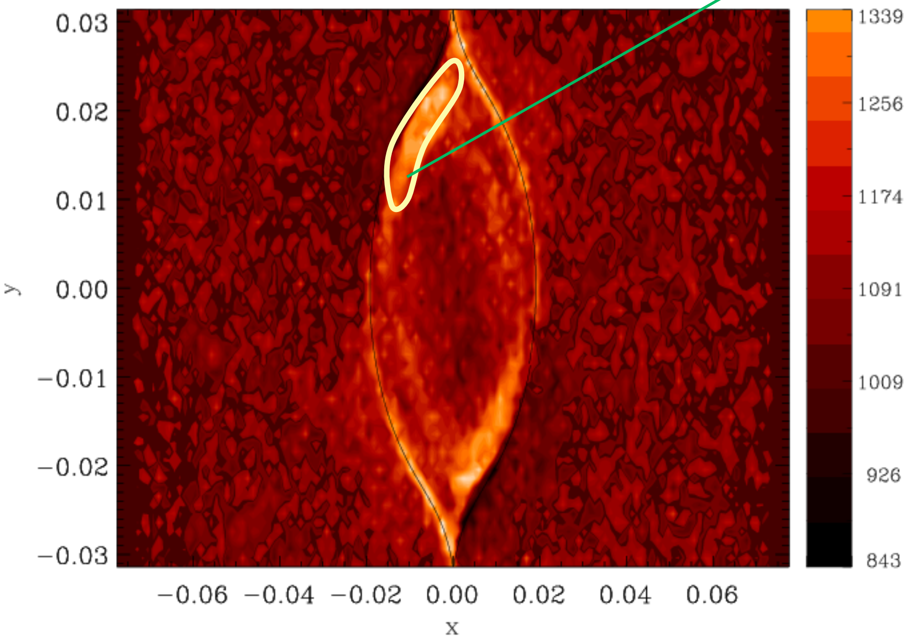
Chaotic behavior of magnetic field lines and formation of transport barriers.



Energetic electron generation: electron distribution function

One of the most characteristic features of magnetic reconnection is the conversion of part of the stored magnetic energy into heating of the plasma and particle acceleration.

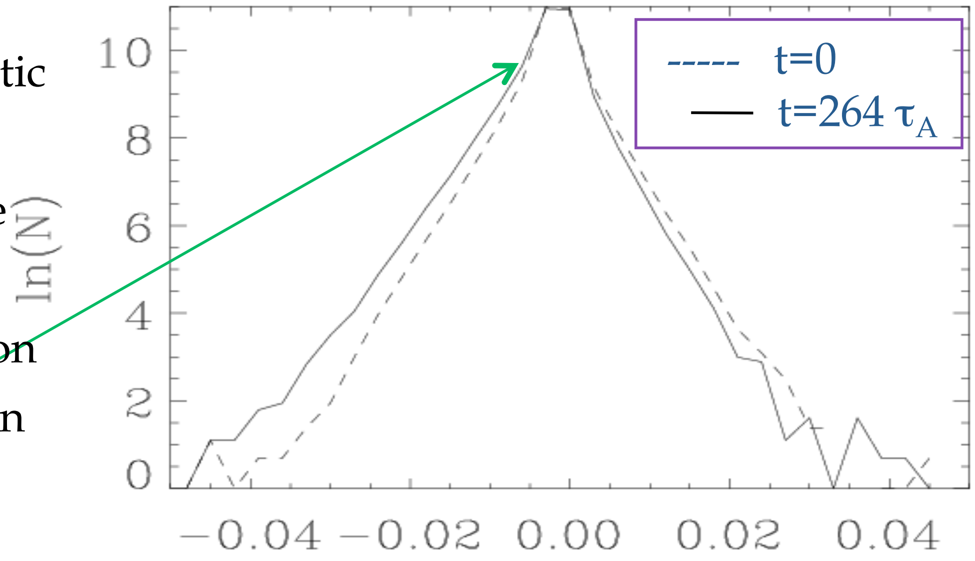
Energetic electrons during magnetic reconnection have been observed in Earth's magnetotail and in laboratory tokamak experiments.

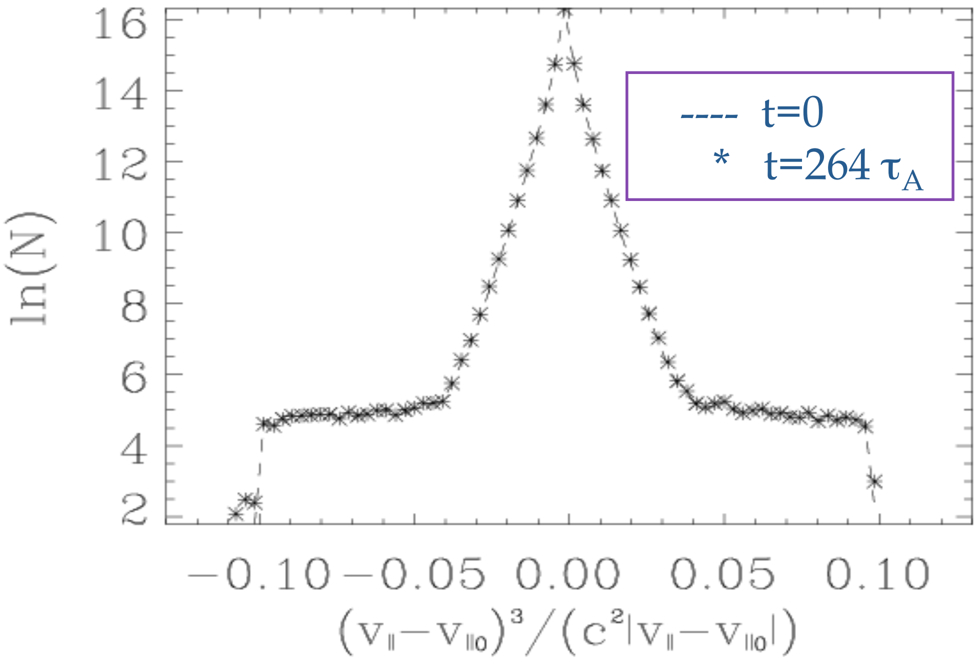


Global distribution in Tokamaks:

<u>No energetic nor 'runaway' electrons!</u>

Local distribution:





TOPICA/TOPLHA/TOPCYL

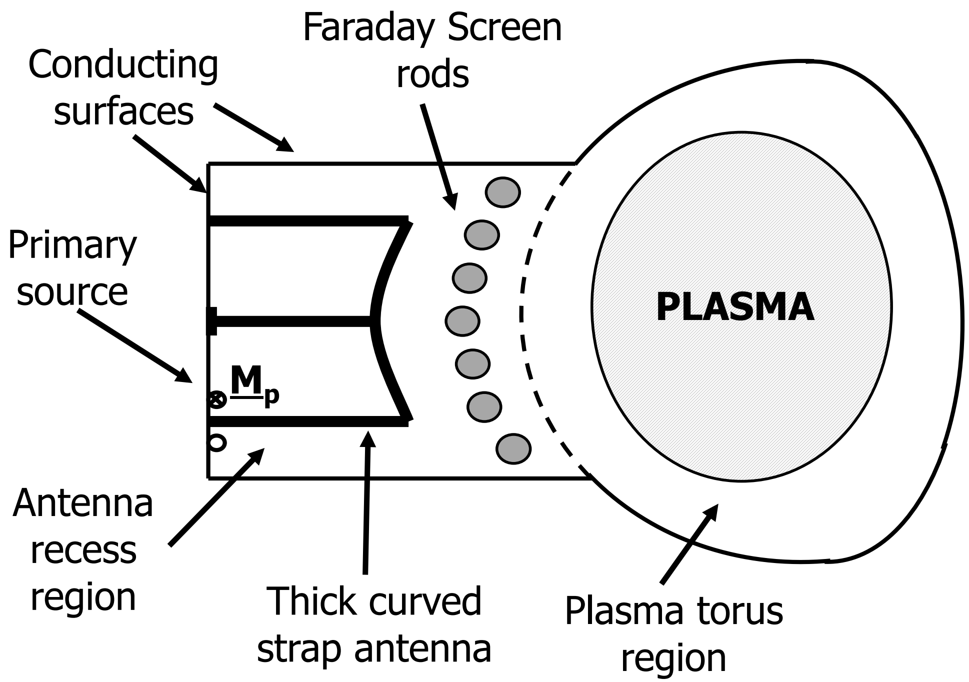
A Predictive and Design Oriented Simulation Tool for ICRF and LH Antennas

• The plasma facing antennas group of Department of Electronics @ POLITO started the development of this tool in **1995**.

• Today this is the only simulation tool capable of simulating a **realistic antenna geometry in front of a plasma**.

•The tool capabilities extend from the **ion cyclotron** range of frequencies to the **lower hybrid** range of frequencies and to the the possibilities of having **slab** plasma model and **cylindrical** plasma model.

Strategy and Formulation



Full-wave and self-consistent procedure (starting from Maxwell's equations and without assuming any known distribution of electric current on conductors)

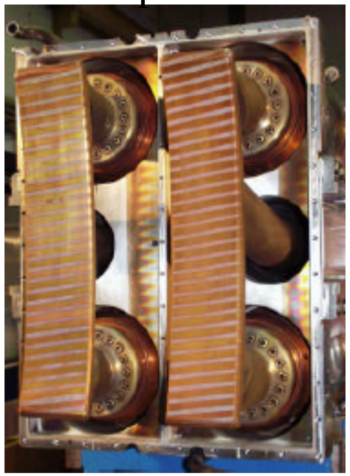
Coupling to assessed codes (FELICE/ FELHS/…) that describe the plasma

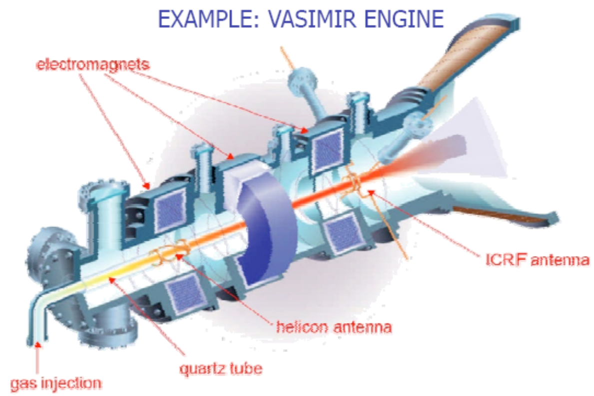
Numerical efficiency and parallelization

Examples of Antennas simulated

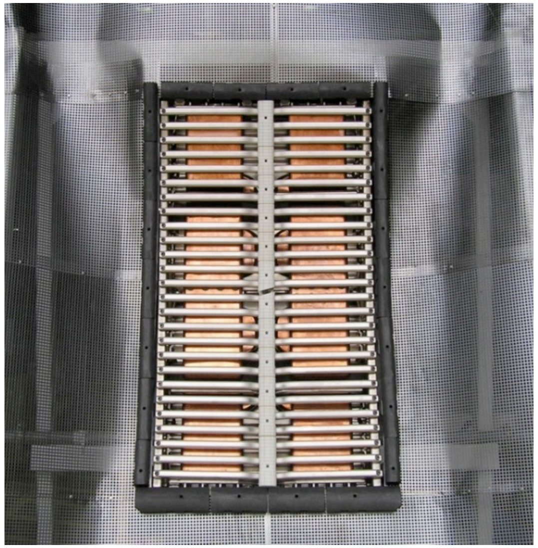
CMOD ICRF

Tore Supra ICRF



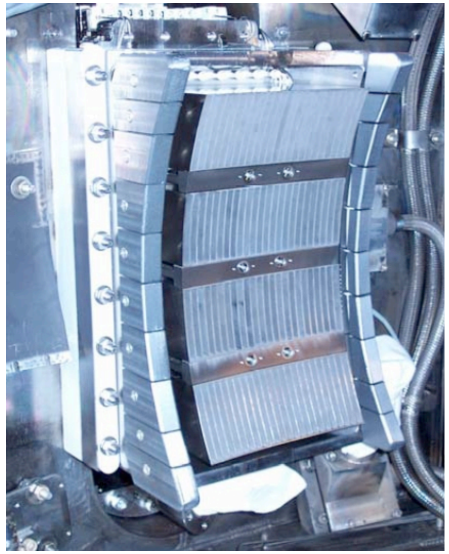


JET ICRF

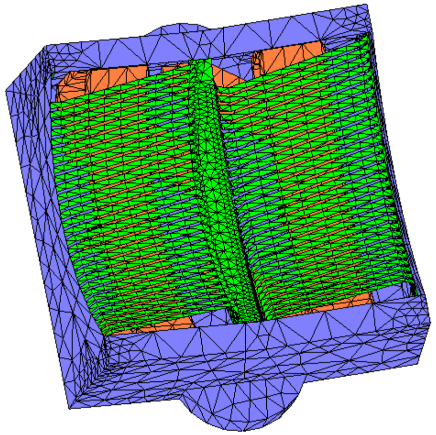


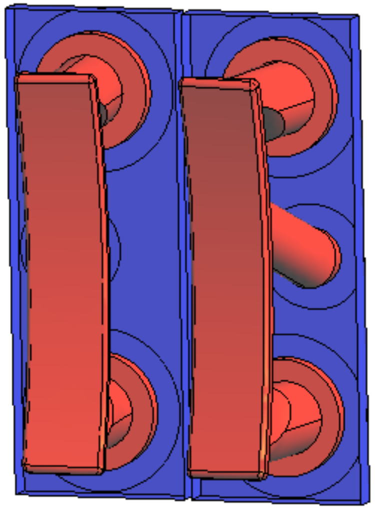
DIII-D ICRF

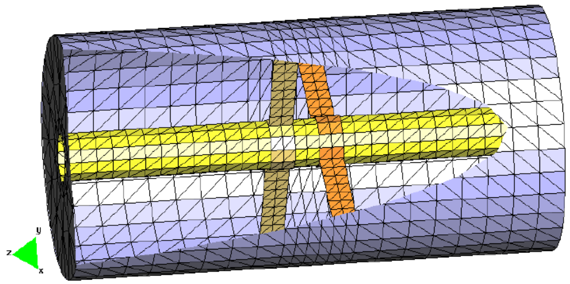
CMOD LH

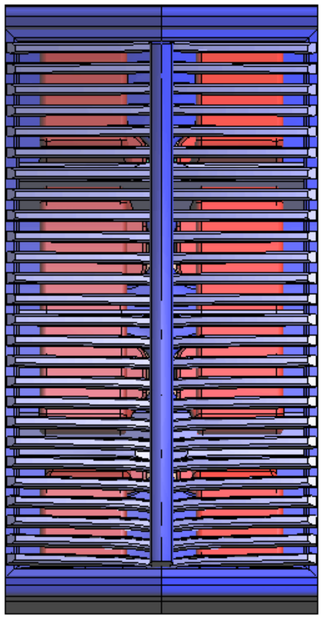


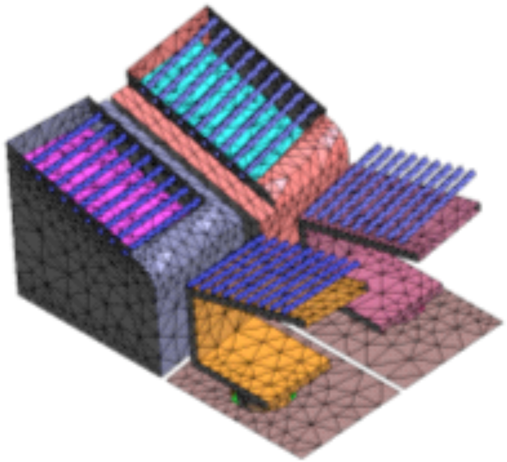
Corresponding Models

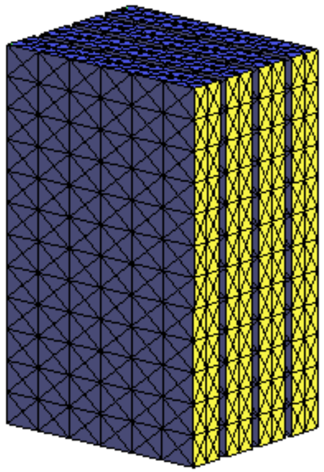




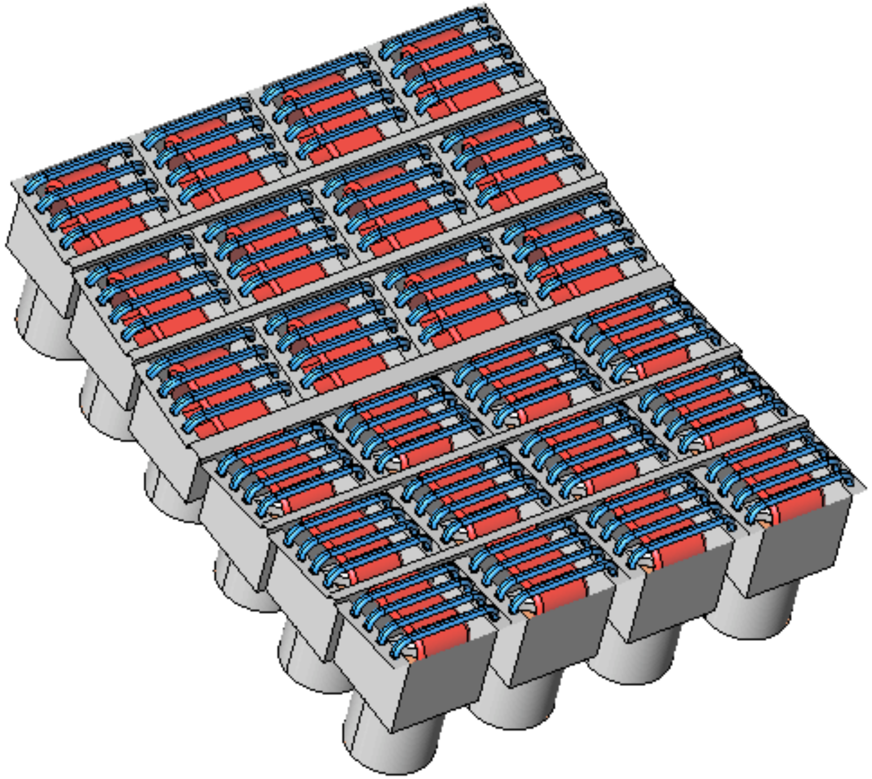


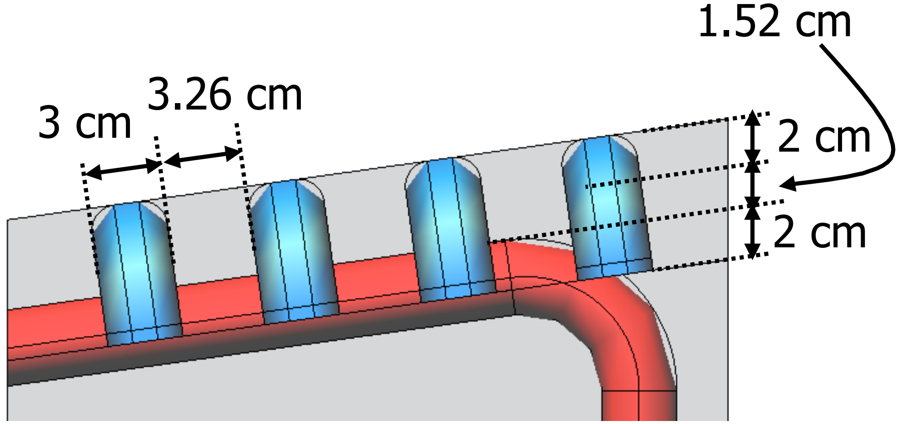


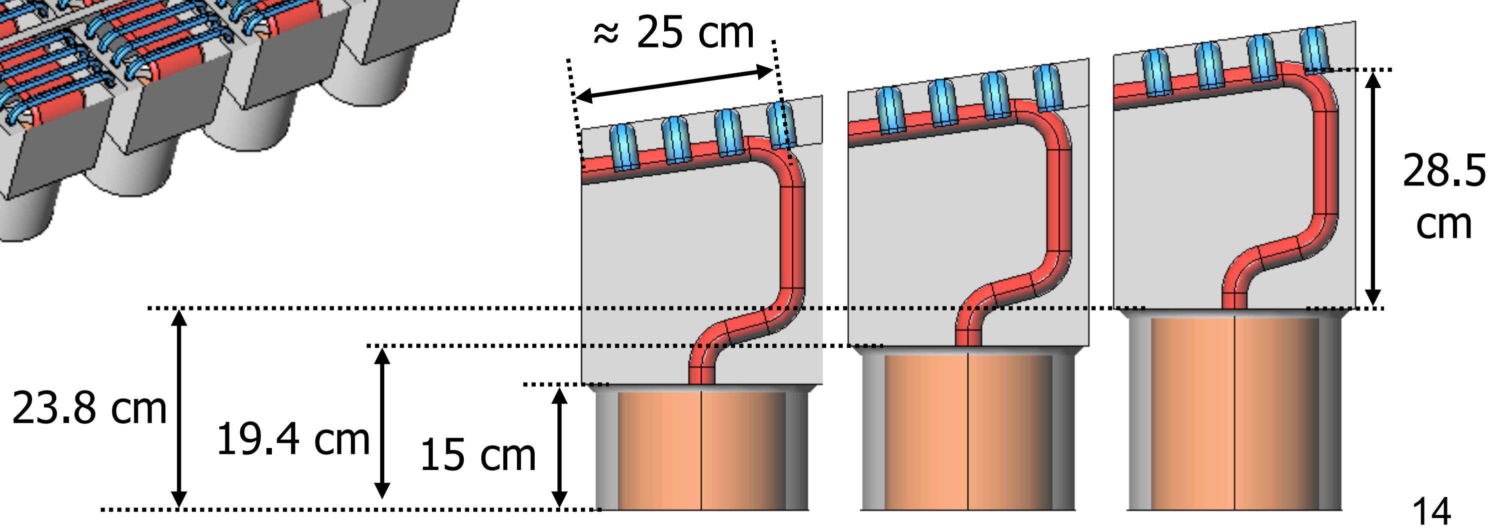




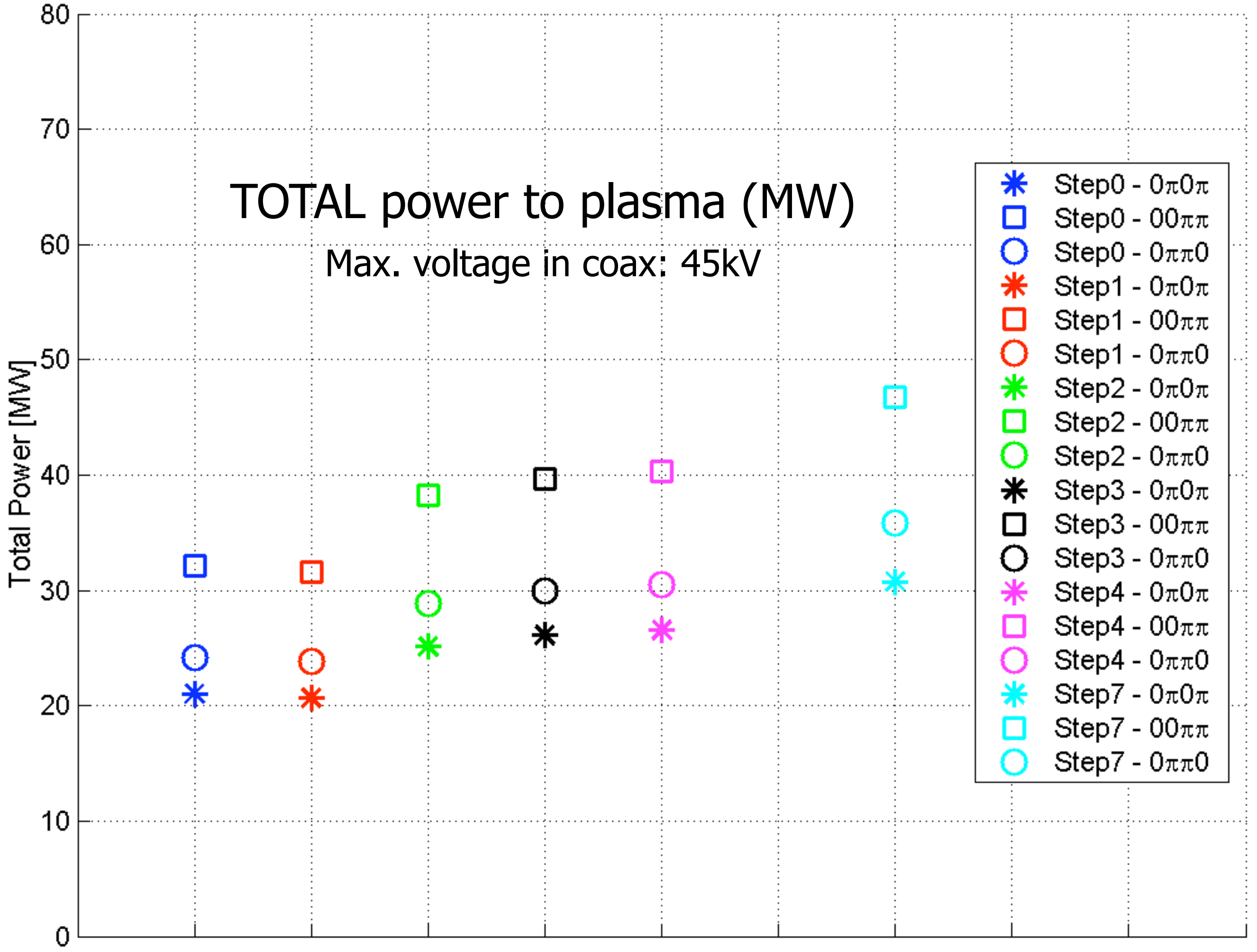
ITER ICRF Antenna Model for design







ITER ICRF Antenna Optimization



A significant increase in the antenna performances has been reached by optimizing some geometrical details

Collaborations

TOPICA code has been installed and is currently used in the following labs:

- Plasma Science and Fusion Center (MIT), Cambridge (USA)
- Oak Ridge National Laboratory, Oak Ridge (USA)
- Commissariat à l'Energie Atomique, Cadarache (France)
- Max-Planck-Institut für Plasmaphysik, Garching (Germany)
- Ecole Royale Militaire, Brussels (Belgium)
- FOM Institute for Plasma Physics Rijnhuizen, Utrecht (Netherlands)
- Universidade Estadual de Santa Cruz, Ilhéus (Brazil)
- United Kingdom Atomic Energy Authority, Culham (England)
- Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Frascati (Italia)

Most of the research groups dealing with plasma facing antennas has adopted TOPICA as their only RF design tool

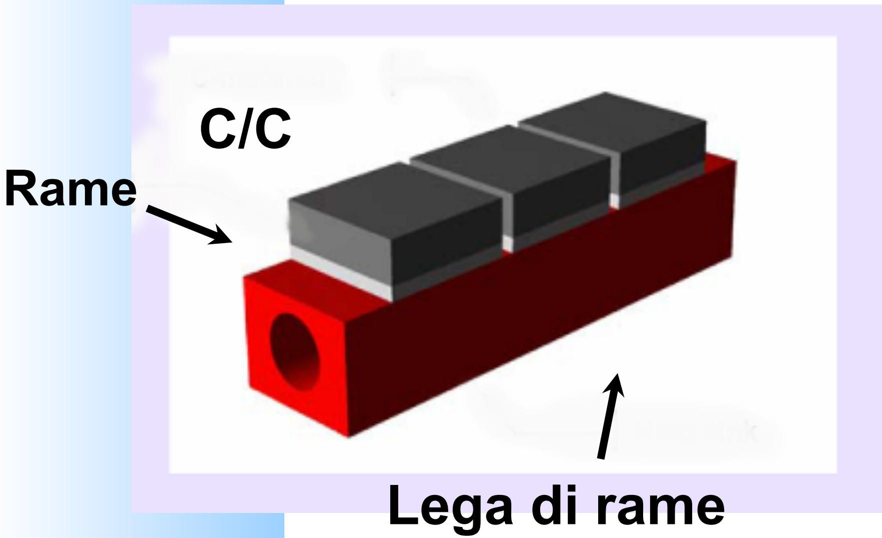
Joining of C/C composites and SiC-based materials for nuclear energy applications

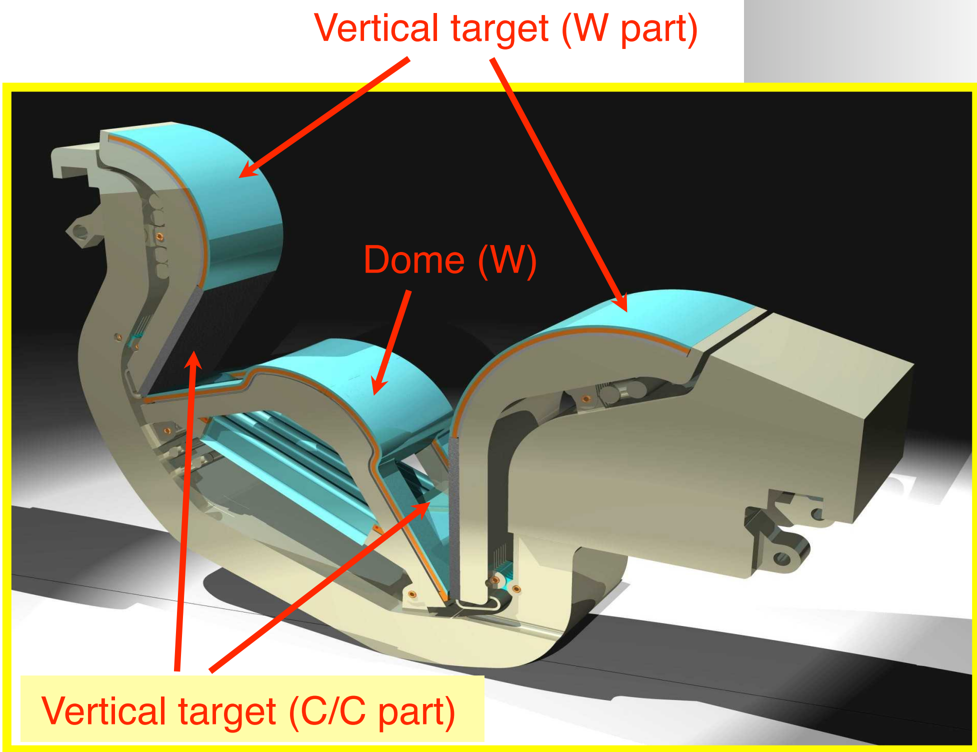
- To join C/C to copper for ITER Divertor
- to design and test reliable **low activation materials to join** SiC and SiC/SiC
- to find a test suitable to measure **shear strength** of joined SiC and SiC/SiC **before and after neutron irradiation**

Funds: PRIN, VI FP (KMM-NoE, Extremat), VII FP (FEMAS-CA).

Web page: http://www.composites.polito.it/

GIUNZIONE TRA COMPOSITO C/C E LEGA DI RAME PER IL DIVERTORE DI ITER

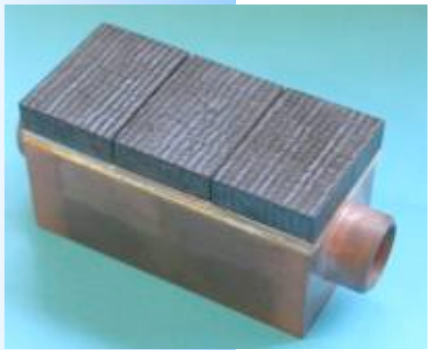


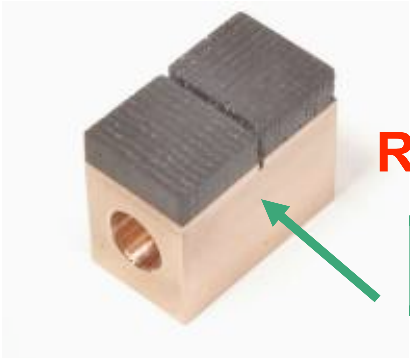


<u>Brevetto</u>: FERRARIS M, CASALEGNO V, SALVO M. (2005). Process to join carbon based materials to metals and its applications. WO2005037734. Politecnico di Torino.

monica.ferraris@polito.it

GIUNZIONE TRA COMPOSITO C/C E LEGA DI RAME PER IL DIVERTORE DI ITER REALIZZATI AL POLITECNICO-*DISMIC*

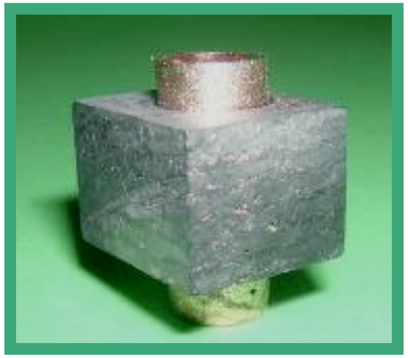




Configurazione “flat-tile”

Screening tests : 50 cycles at 9.8 MW/m^2 and 30 cycles at 14.35 MW/m^2

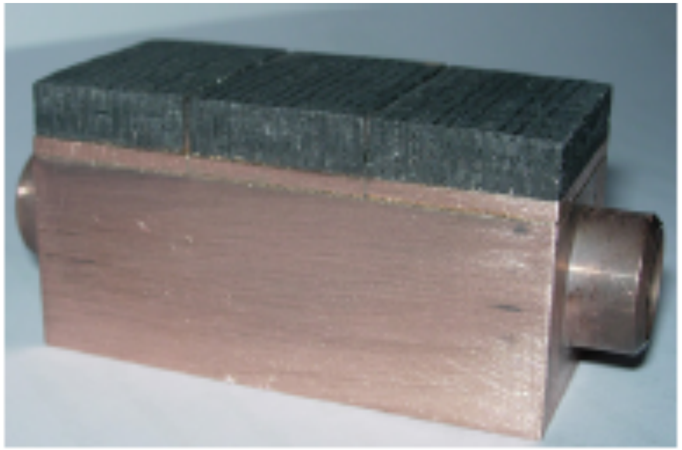
Configurazione “monoblock”

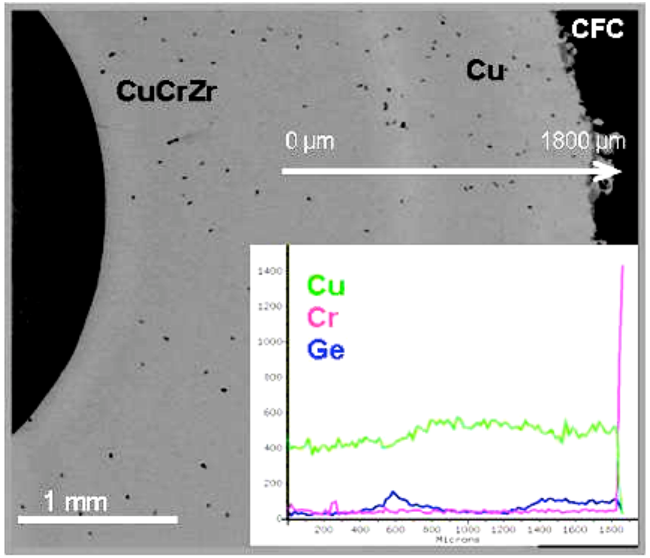


M. Salvo, V.Casalegno, S.Rizzo, F.Smeacetto, M.Ferraris, M. Merola, **One-step brazing process to join CFC composites to copper and copper alloy**, Journal of Nuclear Materials, in press, doi: 10.1016/j.jnucmat.2007.07.010 *monica.ferraris@polito.it*

Joining of CFC/Cu/CuCrZr for ITER divertor

- Direct copper casting on surface modified CFC*
- One-step brazing of CFC/Cu/CuCrZr
- Mock-up (flat-tile and monoblock) production and test in collaboration with Forschungszentrum Juelich



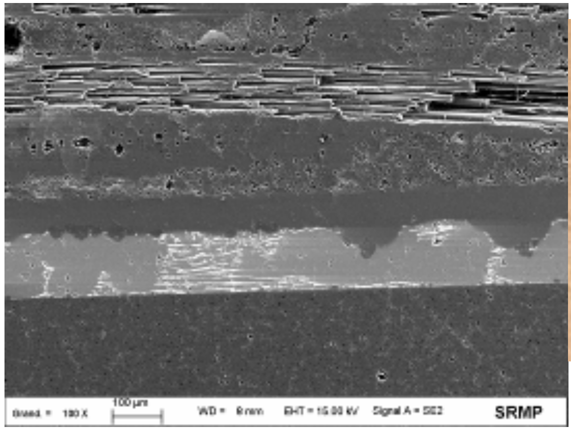


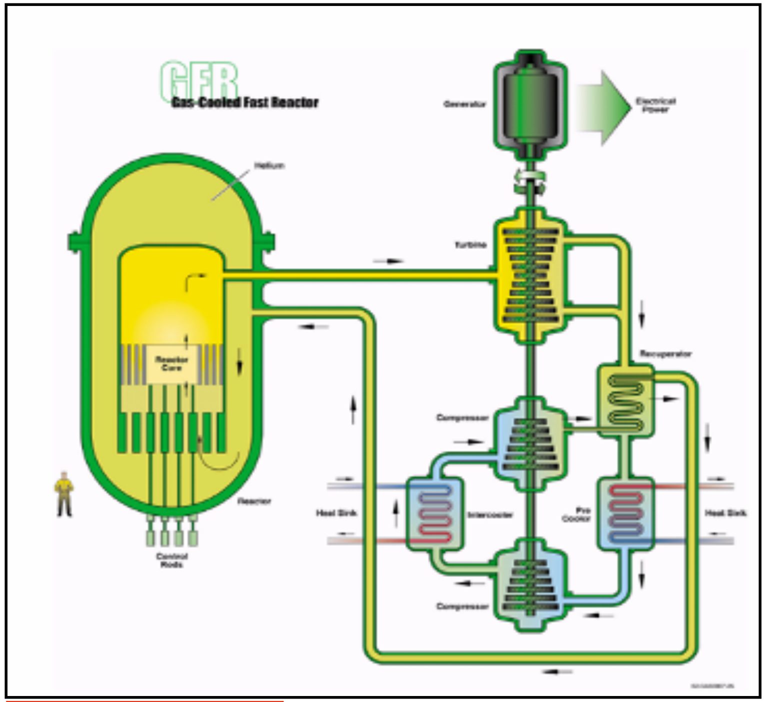
*Patent "Process to join carbon based materials to metals and its applications" PCT/EP2004/011202 (2004) M. Ferraris, M.Salvo, V. Casalegno. Politecnico di Torino

Why Joining SiC-based materials… ?
(cross-cutting issue fusion-fission ….)

SiC/SiC Composite Materials for Structural Application
- Present Status and Road Map for the Future-EFDA
7-8 May 2009 , Garching - Germany

« …Robust bond between two composites, stable during operation…. »





Gas Fast Reactor

Laurent Chaffron – CEA, France

Examples of Potential Materials and Techniques for Joining SiC-based Materials for Radiation Services

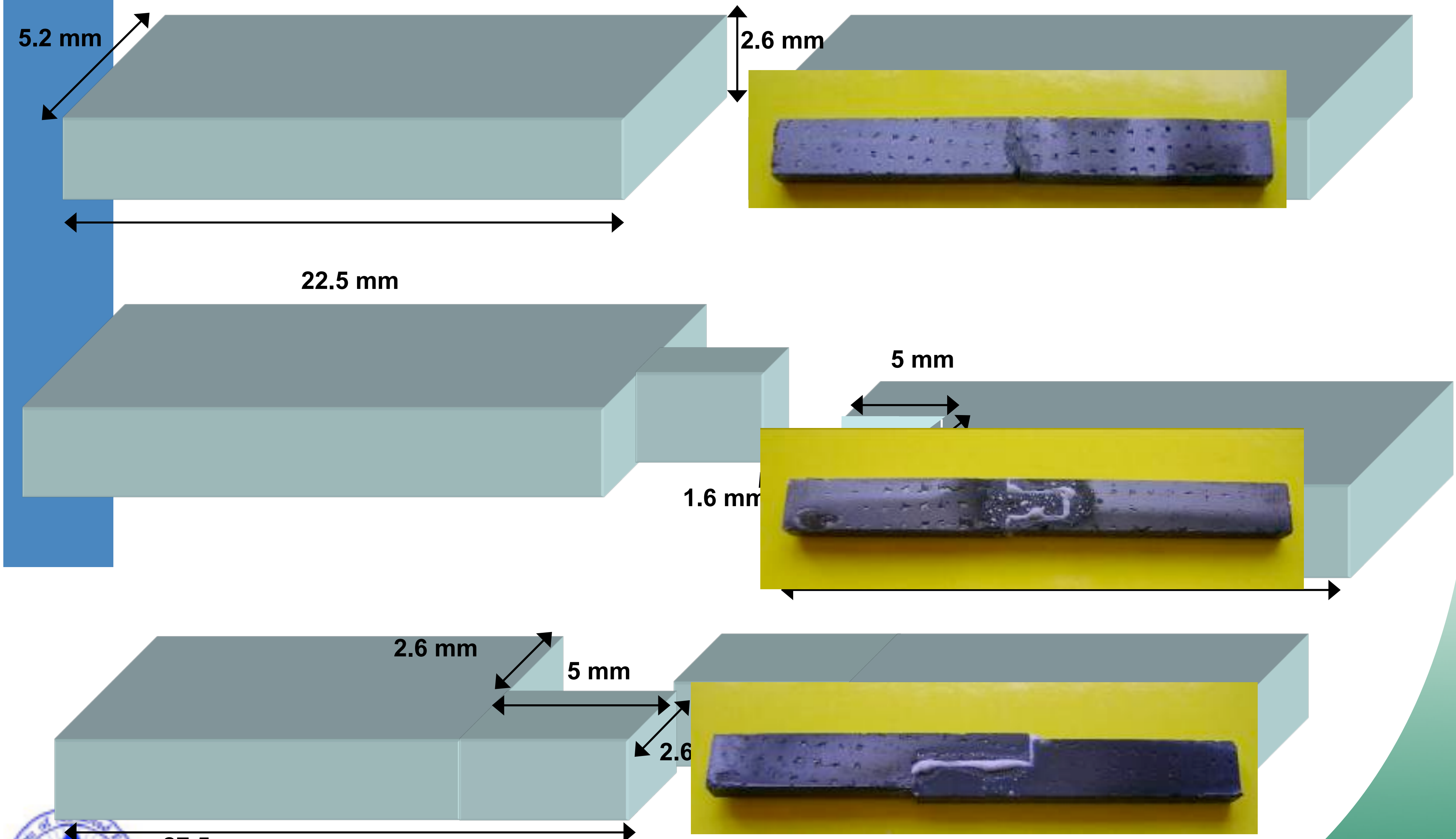
Method	Typical strength	Radiation performance	On-going / recent R&D
Diffusion bonding w/ metallic inserts	>~150 MPa shear	Expectedly good with adequate insert materials	NASA, Bettis, EU fusion
Transient eutectic-phase joining	~250 MPa tensile	Expectedly good with process optimization	Kyoto U., Dresden, etc.
Glass-ceramics Joining	~50 MPa apparent shear	Positive result from EU Extremat program	Politecnico di Torino
Brazing	N/A	Generally poor	Snecma, ENEA,
Reaction bonding (SiC+Si)	~200 M		
Reaction bonding (TiSiC)	50		
Polymer joining	~10 MP		
Transient Liquid Phase Metal Joining	N		
Selective area CVD	N		

- •Several joining materials for SiC
- •joined SiC will be tested with the same mechanical test (shear)
- •Mechanical tests before and after neutron irradiation

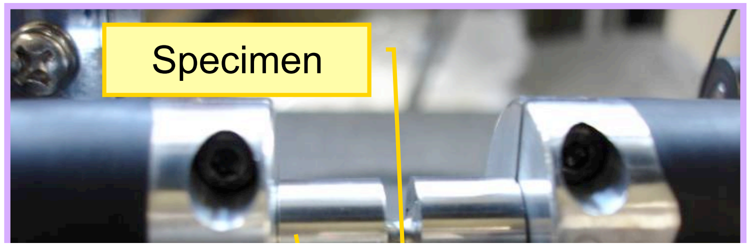
US/Japan TITAN CollaborationTask 2-2 SiC/SiC Joining and Coating

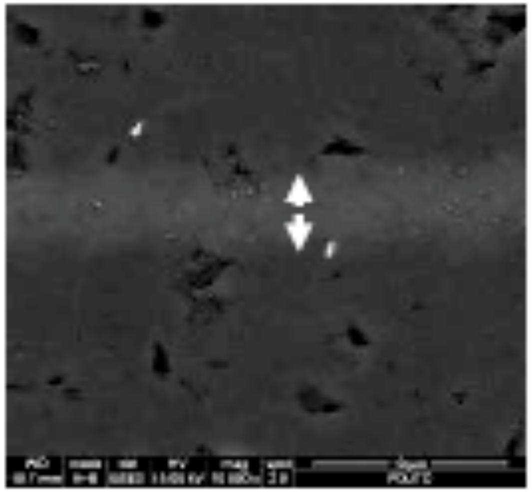
Y. Katoh (Oak Ridge National Laboratory, USA) et al. -- 33rd International Conference on Advanced Ceramics and Composites January 2009 Daytona Beach, Florida (USA)

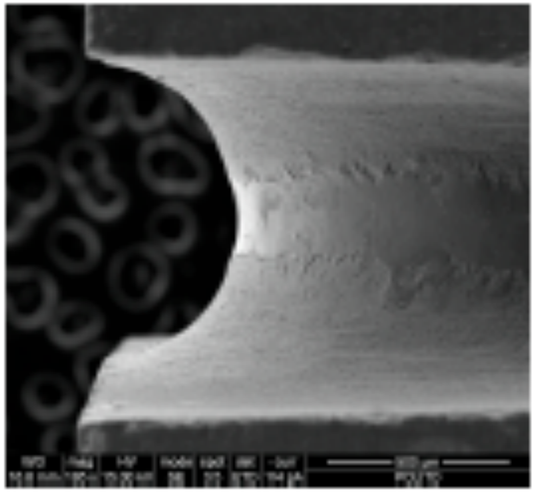
Mechanical & sealant joints for SiC/SiC

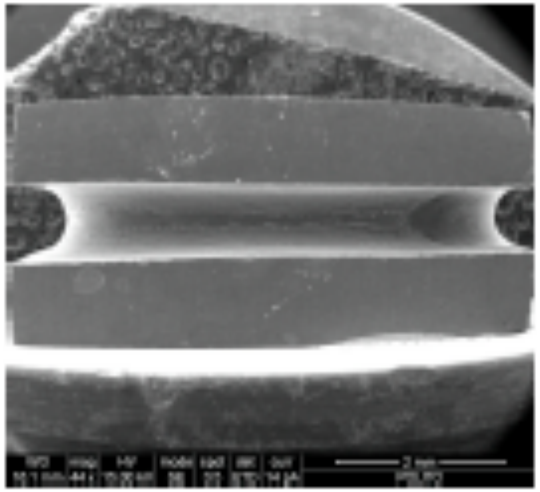


Torsion Test Setup at Politecnico di Torino and at Kyoto University









Gla… cross-section, left) and join… ts (center and right)

In collaboration with Y. Katoh
Oak Ridge National Lab., USA

H.C. Jung, T. Hinoki, A. Kohyama
Kyoto University, Japan

Oak Ridge National Laboratory

PWI know-how @ PoliTo

- Many years experience in:
  - Modeling edge plasma for various specific tasks, e.g.
    - Self-consistent impurity modeling for FTU [1]
    - Various collaborations with the IGNITOR project
    - ELMs modeling for JET [2]
  - Development of sophisticated 2D fluid modeling tools, based on
    - Finite Elements (FE) [3]
    - Finite Volumes (FV) [4]
    - Control Volume Finite Elements (CVFE) [5]

[1] Zanino, Ferro, et al., Self-Consistent Impurity *Modeling in the Frascati Tokamak Upgrade*, JNM (1999).

[2] Subba et al., *Modeling JET ELMs with the SOLPS edge plasma code*, EPS (2003)

[3] Zanino, *Advanced Finite Element Modeling of the Tokamak Plasma Edge*, J. Comput. Physics, (1997)

[4] Subba and Zanino, *2D fluid model of the scrape-off layer (SOL) using adaptive unstructured finite volumes*, JNM, (2001)

[5] Subba, Zanino et al., *Development of a computational tool for limiter edge plasma modeling with application to IGNITOR*, JNM, (2007)

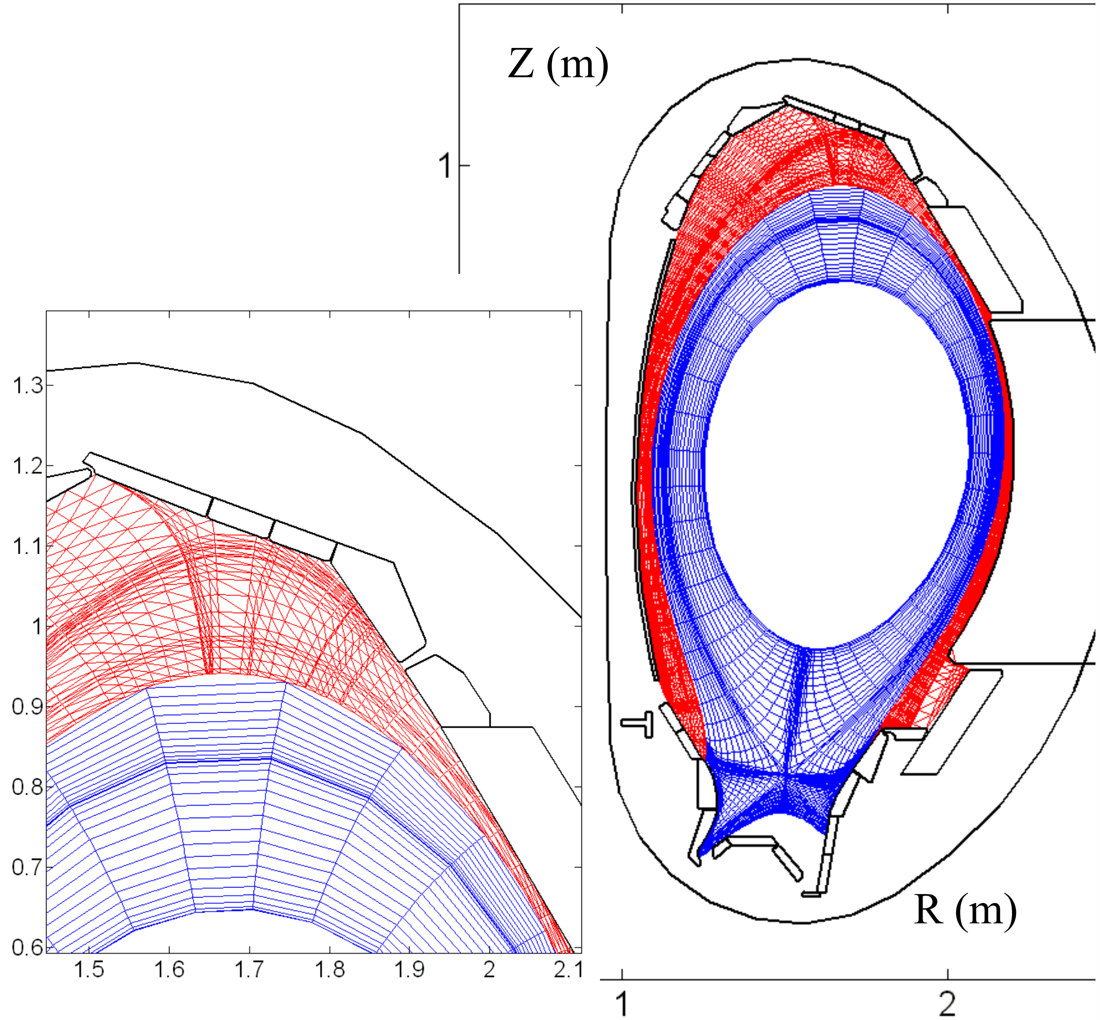
Currently Used Tools

- SOLPS (most used in Europe). A complete suite of codes. Principal components are:
  - B2: a multi-fluid edge plasma solver. A number of versions now around: we are familiar with the most used one (B2.5)
  - EIRENE: a Monte-Carlo neutral gas solver
    - A version is usually shipped integrated with B2
    - A more recent version may be obtained as stand-alone if needed
  - CARRE: the standard mesh generation tool for B2
- ASPOEL (developed at PoliTo)
  - ASPOEL: single fluid edge plasma solver
    - Developed to extend the model to the far-SOL
    - Simplified physics

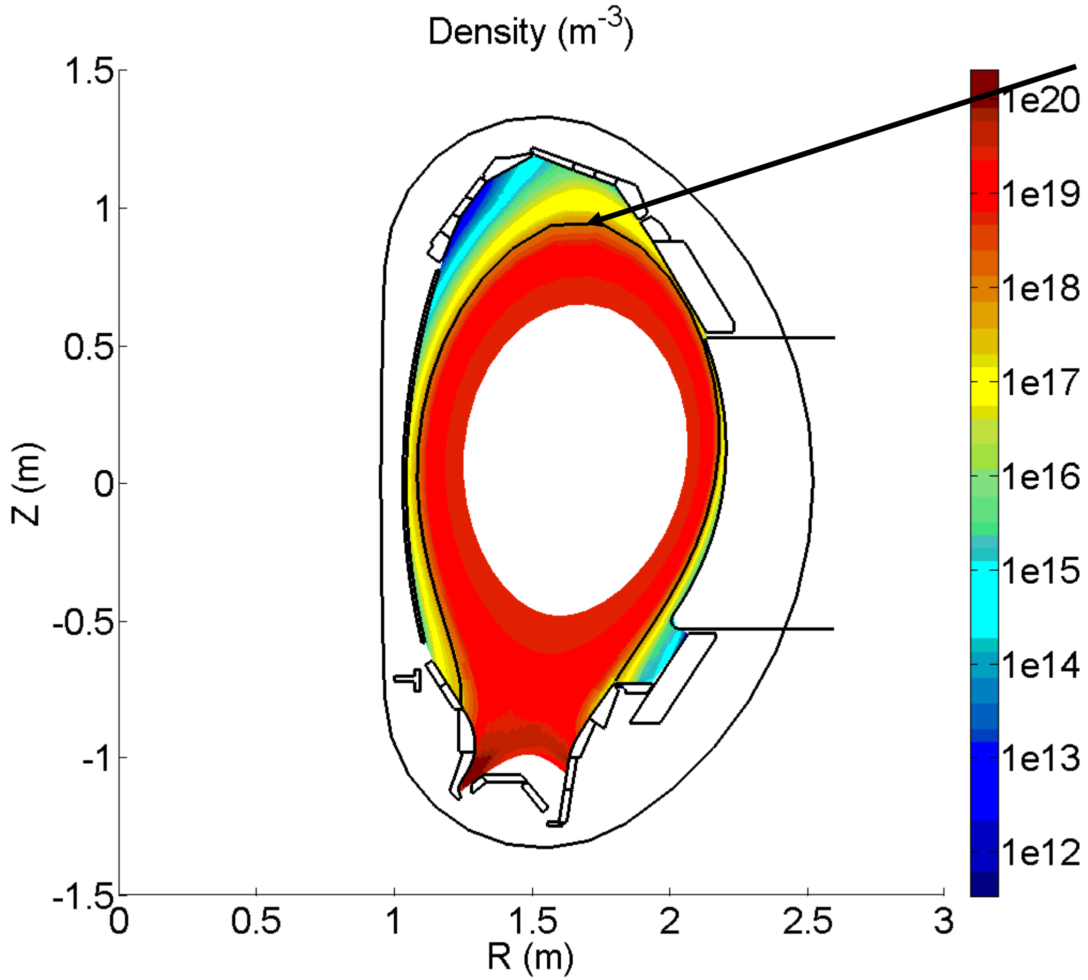
Coupled B2-ASPOEL Mesh (ASDEX- Upgrade)

- B2
- Fills the near SOL
- ~ 3700 cells
- Quadrilateral
- FV scheme

- ASPOEL
- Fills the far SOL
- ~ 6000 elements
- Triangular
- CVFE scheme



Application: ASDEX Upgrade

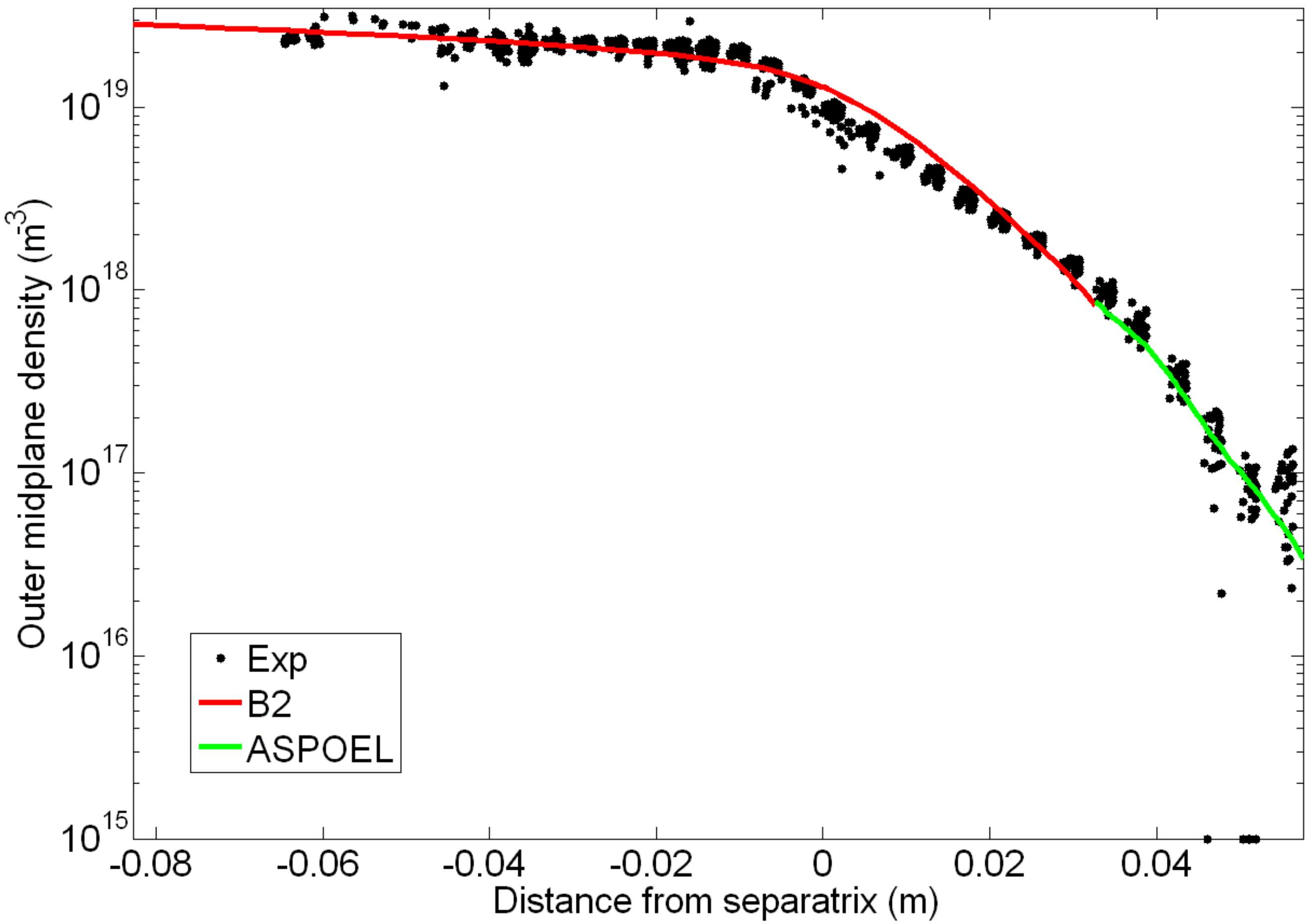


Near-far SOL interface

Very low density/ vacuum in the farthest regions

Validation: ASDEX Upgrade

Density profile @ outer mid-plane



Excellent agreement with experimental data

Modeling of Superconducting Coils for ITER

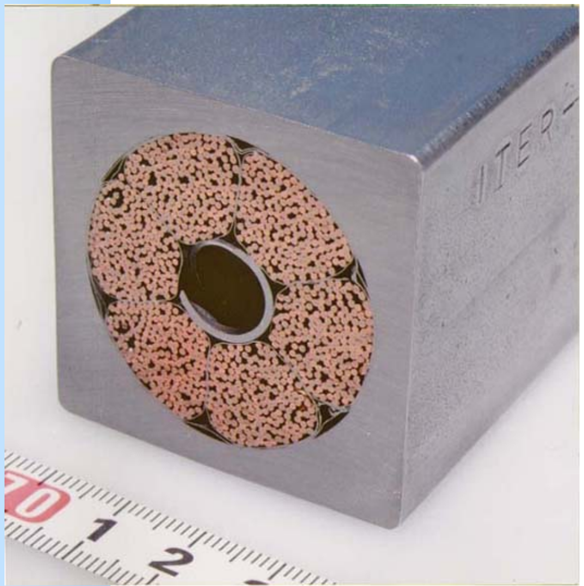
- Micro-scale: Local CtFD modeling of transverse transport processes in cable-in-conduit conductors (CICC); heat exchangers for HTS components COMMERCIAL CODES (FLUENT, STAR-CD)
- Meso-scale: Global CtFD modeling of longitudinal transport processes in CICC CODE DEVELOPMENT
- Macro-scale: Conductor, structures and cryogenic circuit CtFD modeling CODE COUPLING

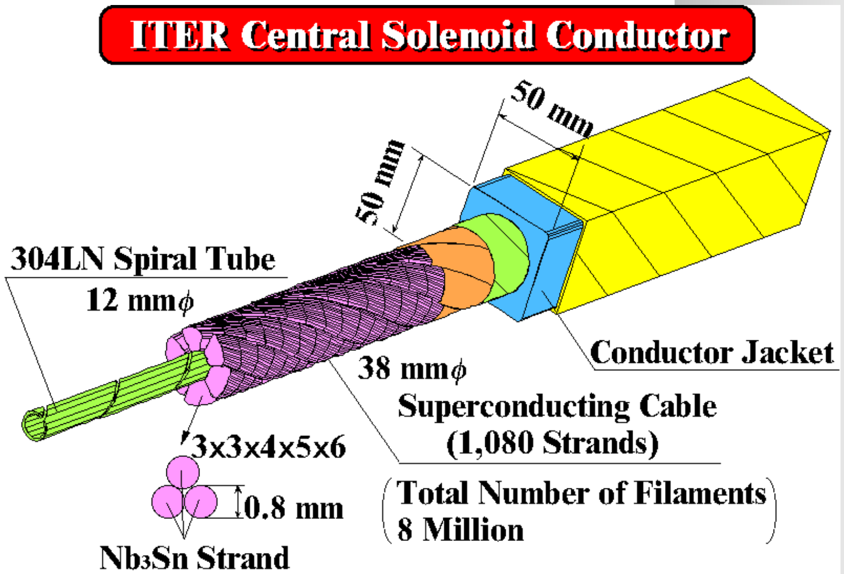
- Multiphysics EM-TH COUPLING

CICC for ITER superconducting coils

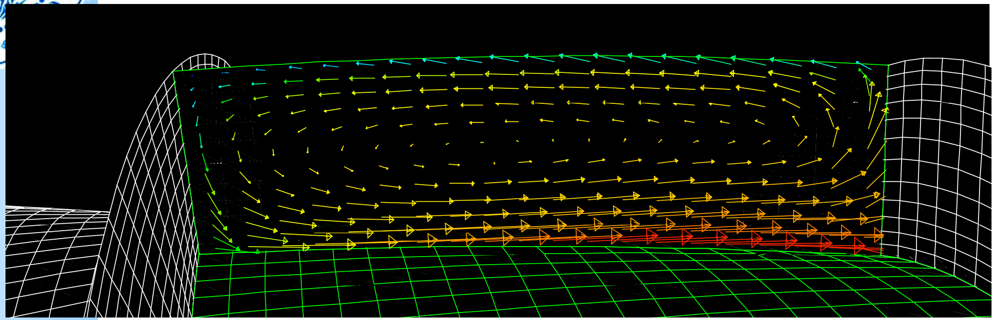
SC coils for fusion applications (e.g., ITER) carry <u>high currents</u> (up to ~ 70-80 kA) to generate <u>high magnetic fields</u> (up to ~ 13 T)

<u>Low critical temperature</u> SC (e.g., Nb_3Sn or NbTi) are used in multi-stage **cable-in-conduit conductors** (CICC) cooled by supercritical He @ ~ 5 K and 0.5 MPa



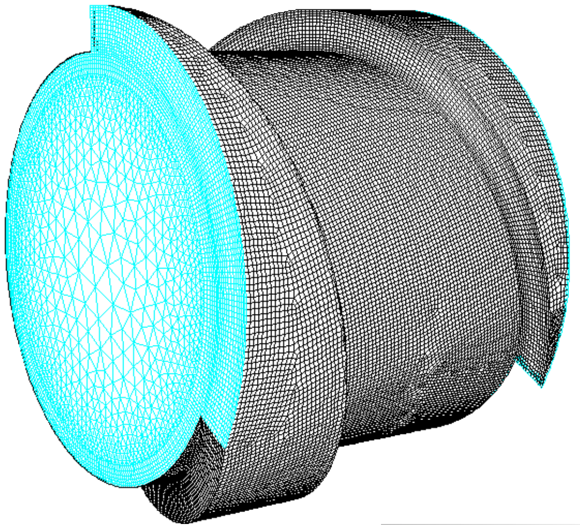


Micro-scale

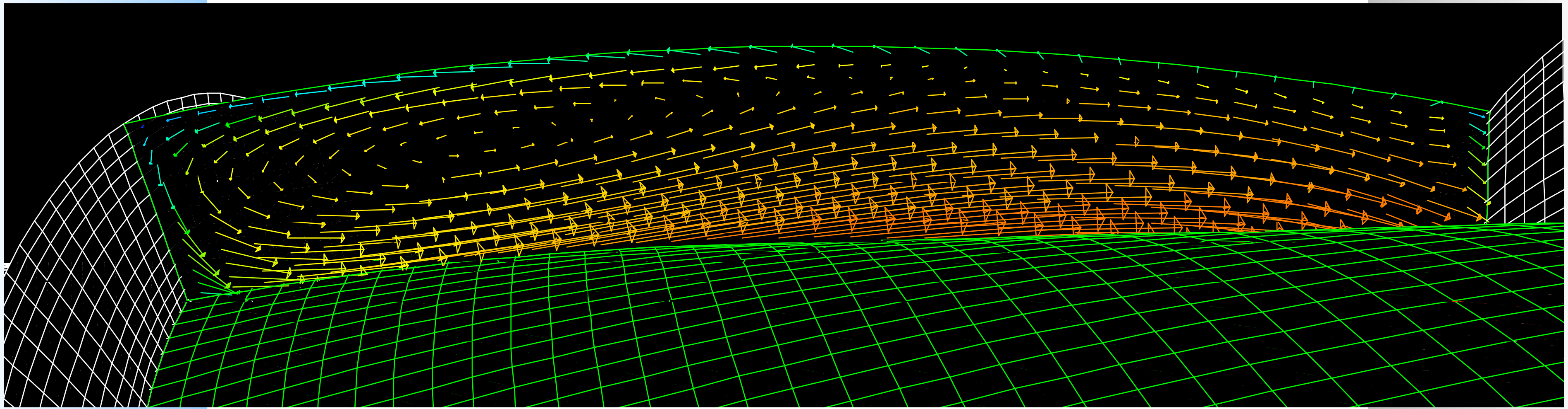


g/h = 4 ➔ RECIRCULATION

Main/core flow

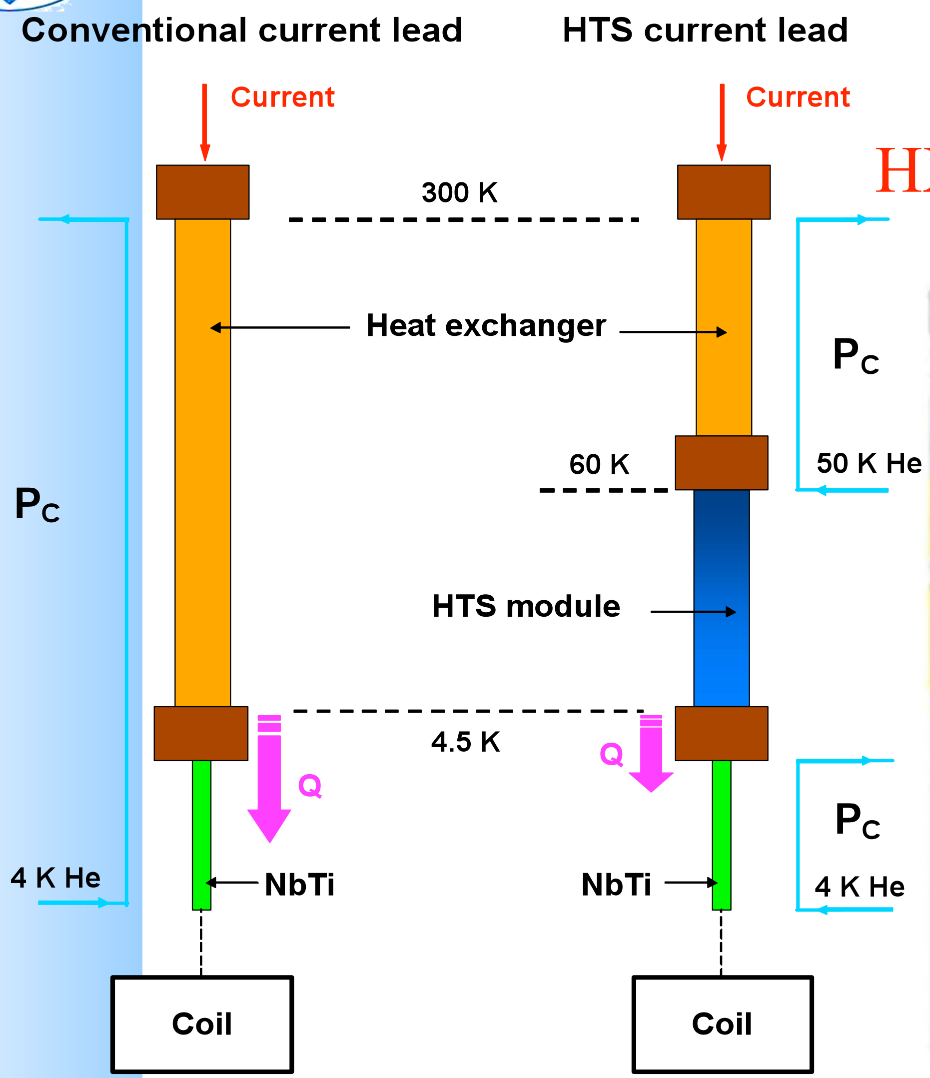


g/h = 8 ➔ RE-ATTACHMENT

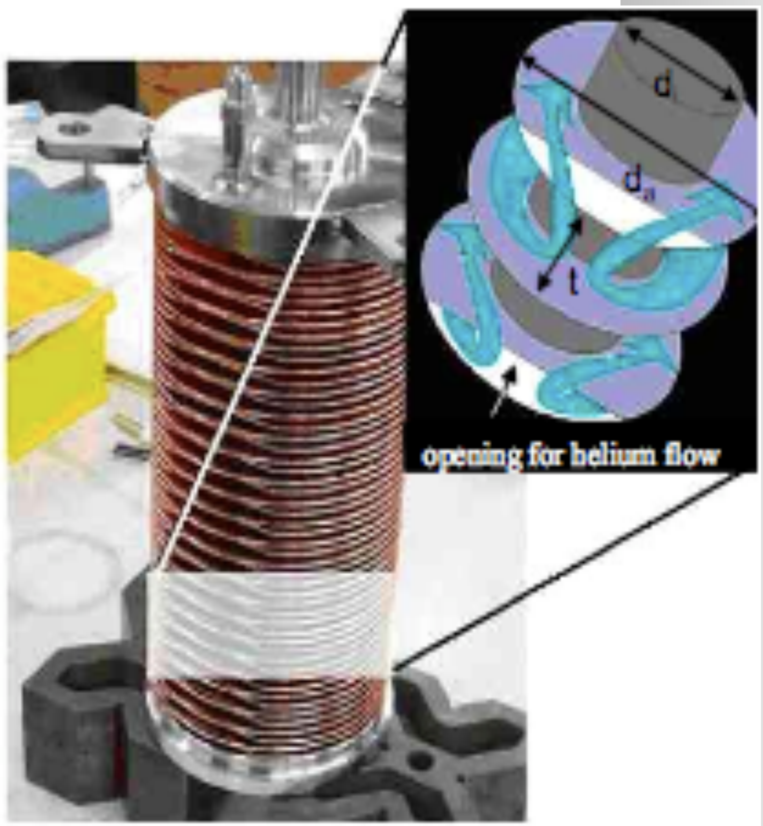


2D effect [Webb et al., *IJHMT* (1971)] recovered in 3D!

High Tc superconducting current leads for ITER



HX CERN design adopted by FZK



HX CtFD modeling with StarCD

CICC for ITER : Single-conductor model

(Mithrandir code)

$$
\begin{cases}
\dfrac{\partial v}{\partial t} + v\dfrac{\partial v}{\partial x} + \dfrac{1}{\rho}\dfrac{\partial p}{\partial x} = \dfrac{1}{\rho}\left[\Lambda_v - v\Lambda_\rho\right] \\[2ex]
\dfrac{\partial p}{\partial t} + \rho c^2\dfrac{\partial v}{\partial x} + v\dfrac{\partial p}{\partial x} + \rho c^2\dfrac{v}{A}\dfrac{\partial A}{\partial x} = \phi\left[\Lambda_e - v\Lambda_v - \left(w - \dfrac{v^2}{2} - \dfrac{c^2}{\phi}\right)\Lambda_\rho\right] \\[2ex]
\dfrac{\partial T}{\partial t} + \phi T\dfrac{\partial v}{\partial x} + v\dfrac{\partial T}{\partial x} + \phi T\dfrac{v}{A}\dfrac{\partial A}{\partial x} = \dfrac{1}{\rho c_v}\left[\Lambda_e - v\Lambda_v - \left(w - \dfrac{v^2}{2} - \phi c_v T\right)\Lambda_\rho\right]
\end{cases}
$$

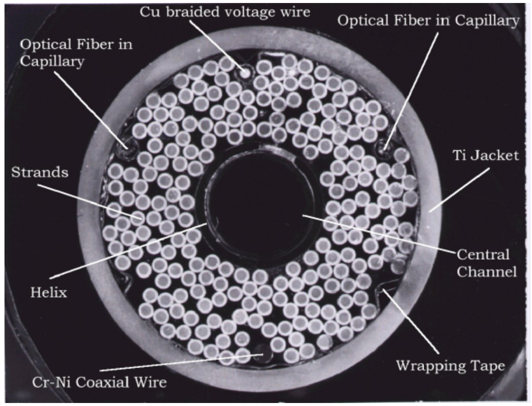
RHS **sources/sinks** (← interaction with solids and other channels) include **constitutive relations** which require transport coefficients (**friction factors, heat transfer coefficients**) ← Local 3D models

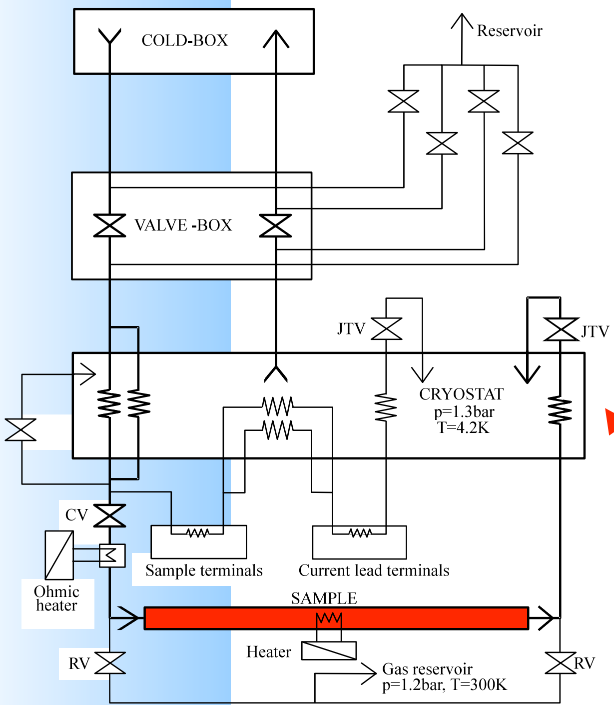
$$\phi = \frac{\alpha K_T V}{C_v}$$

$$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$$

$$K_T = -V\left(\frac{\partial P}{\partial V}\right)_T$$

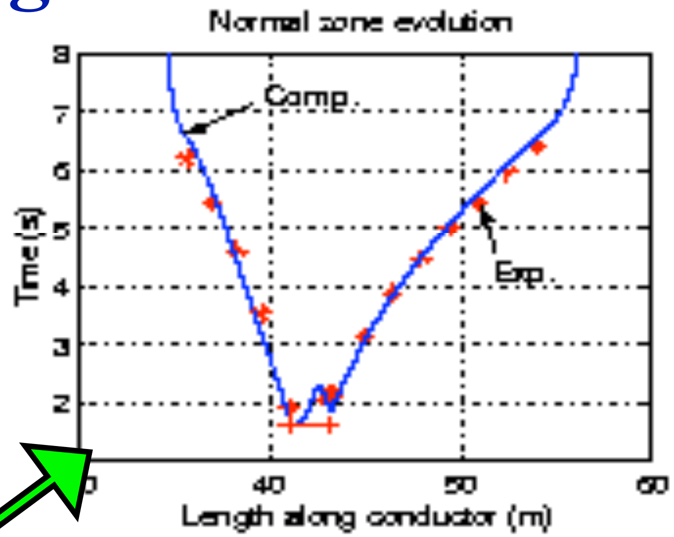
Meso scale (I)
Quench propagation in single conductor

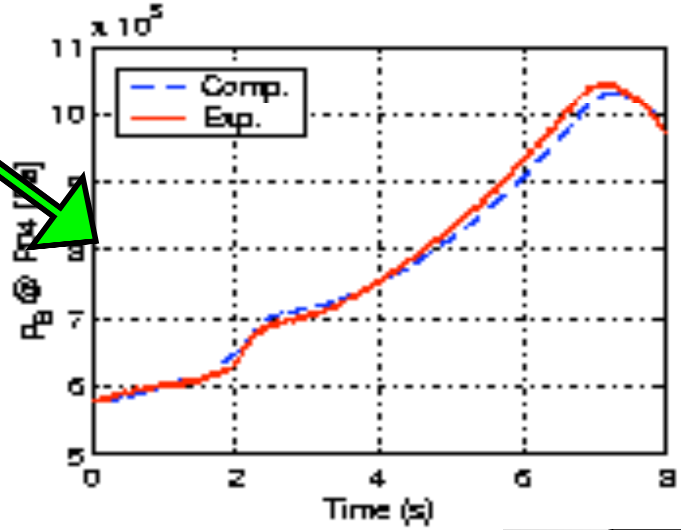




Cryogenic circuit

Quench propagation

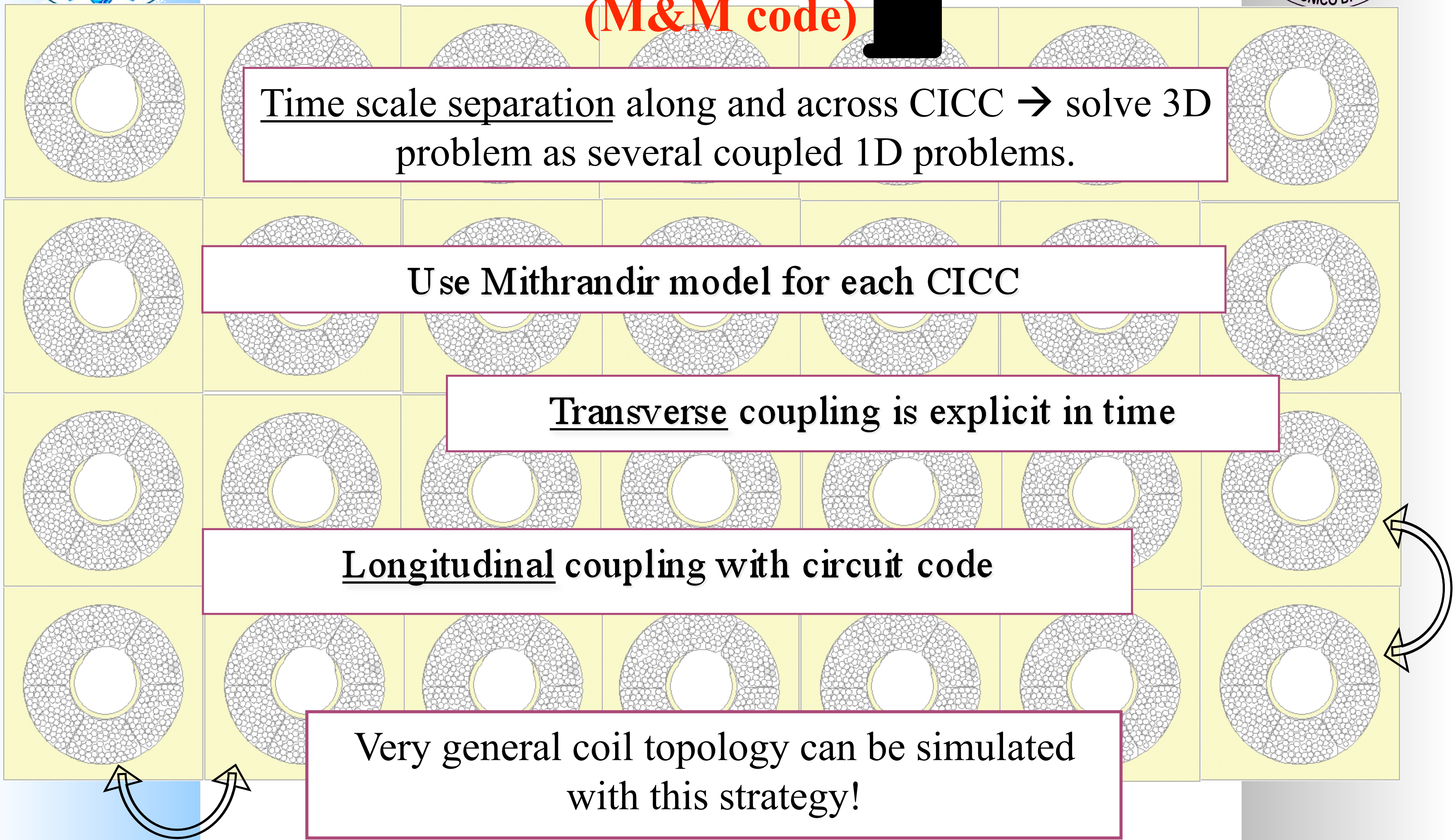




Nb_3Sn conductor test&analysis (1997)

CICC for ITER : Multi-conductor model

(M&M code)



Time scale separation along and across CICC → solve 3D problem as several coupled 1D problems.

Use Mithrandir model for each CICC

Transverse coupling is explicit in time

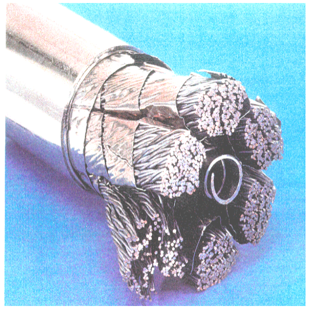
Longitudinal coupling with circuit code

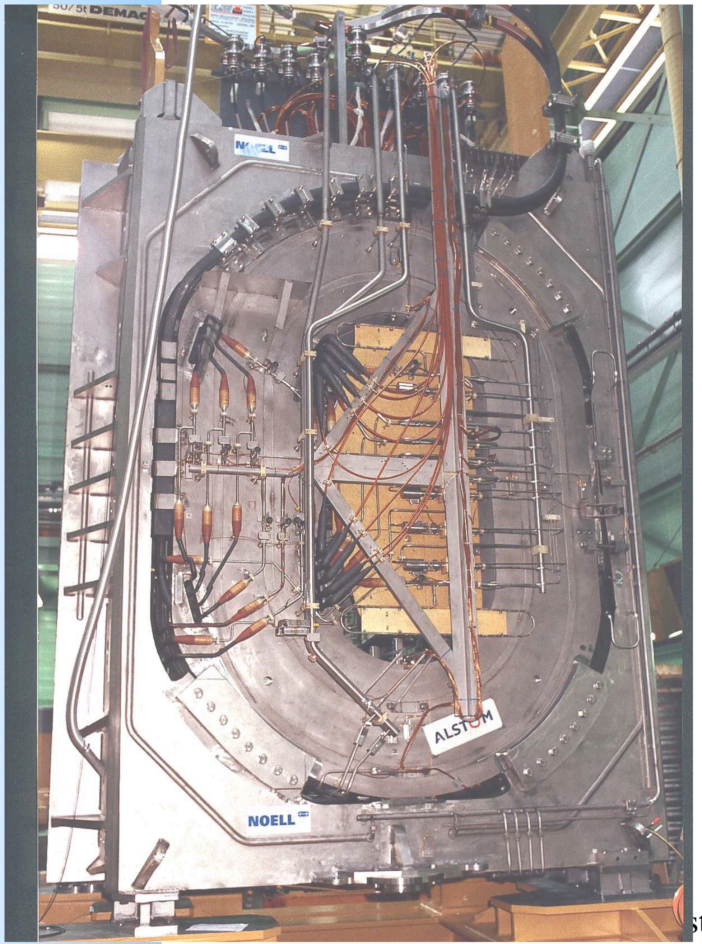
Very general coil topology can be simulated with this strategy!

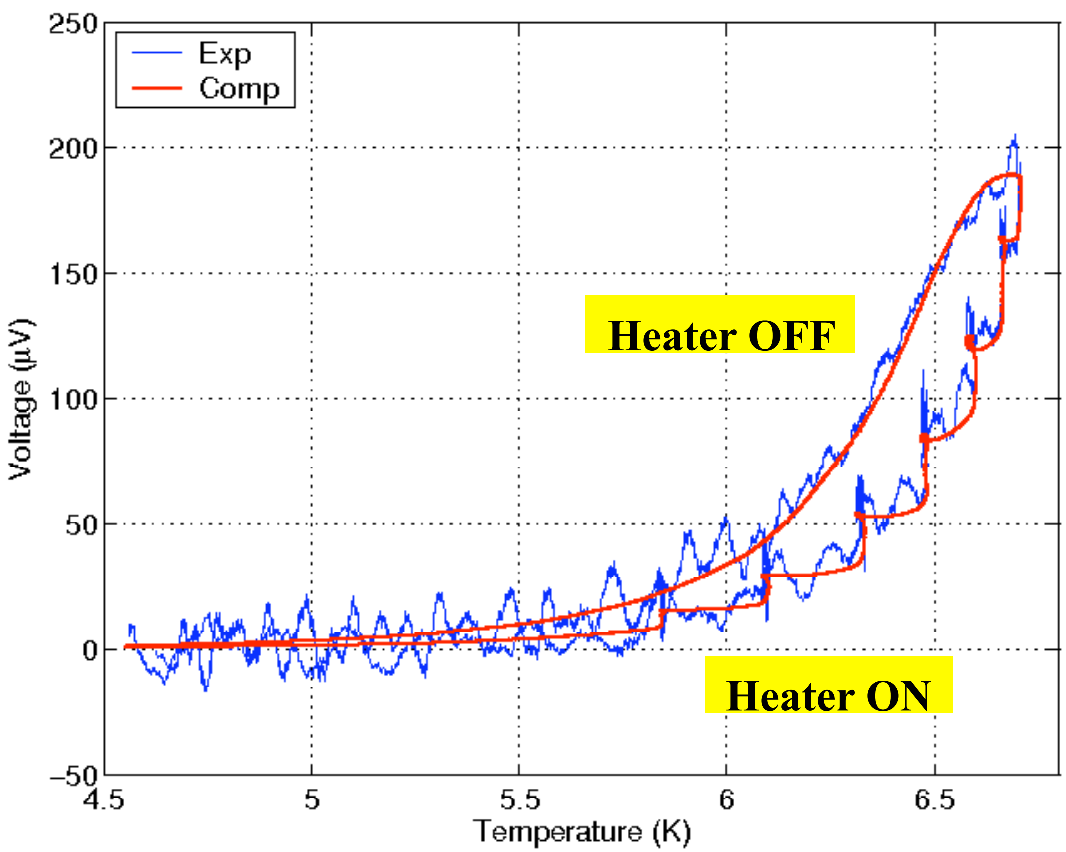
Meso scale (II)
Performance assessment in coil

(Nb_3Sn) Toroidal Field Model
Coil test&analysis

(2001-2002)



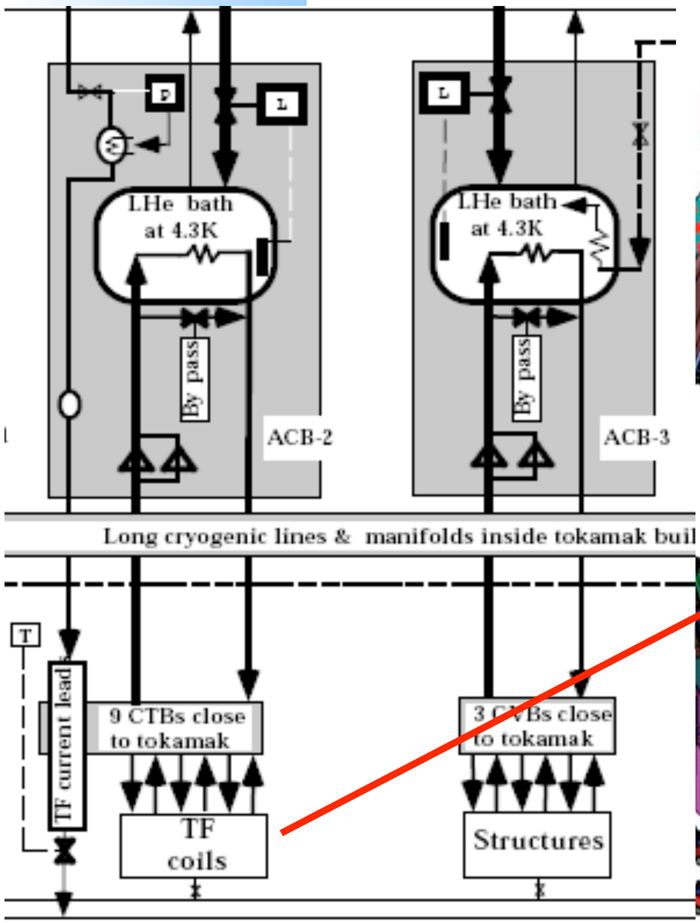


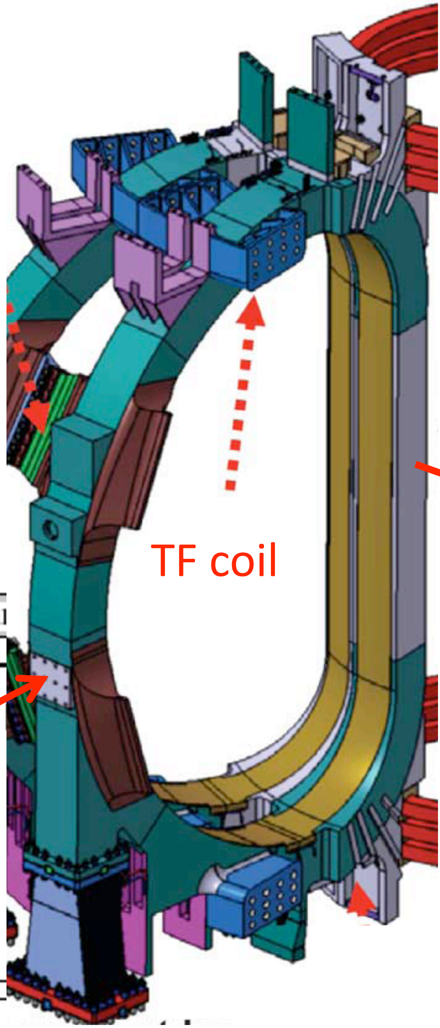


stiv

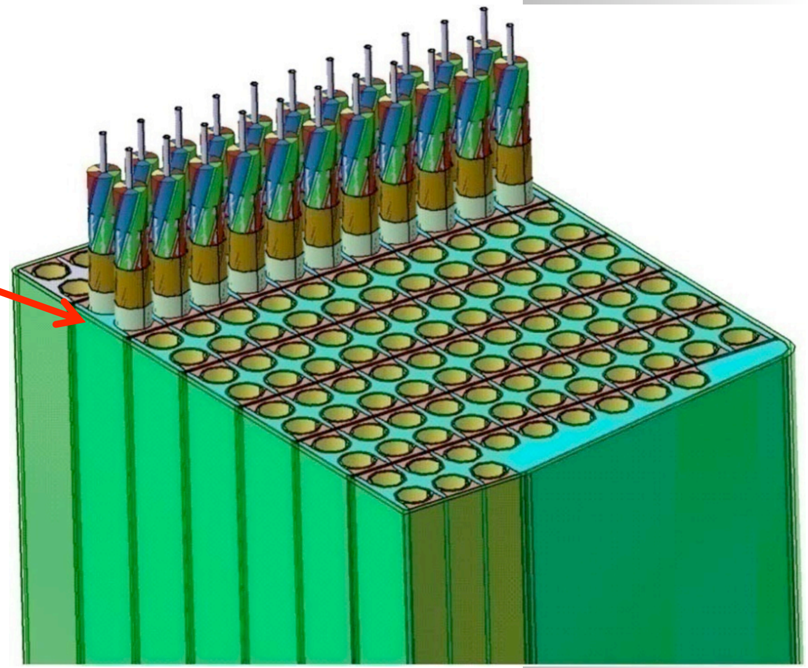
Macro scale
ITER TF coils

TF coil and case cooling circuit



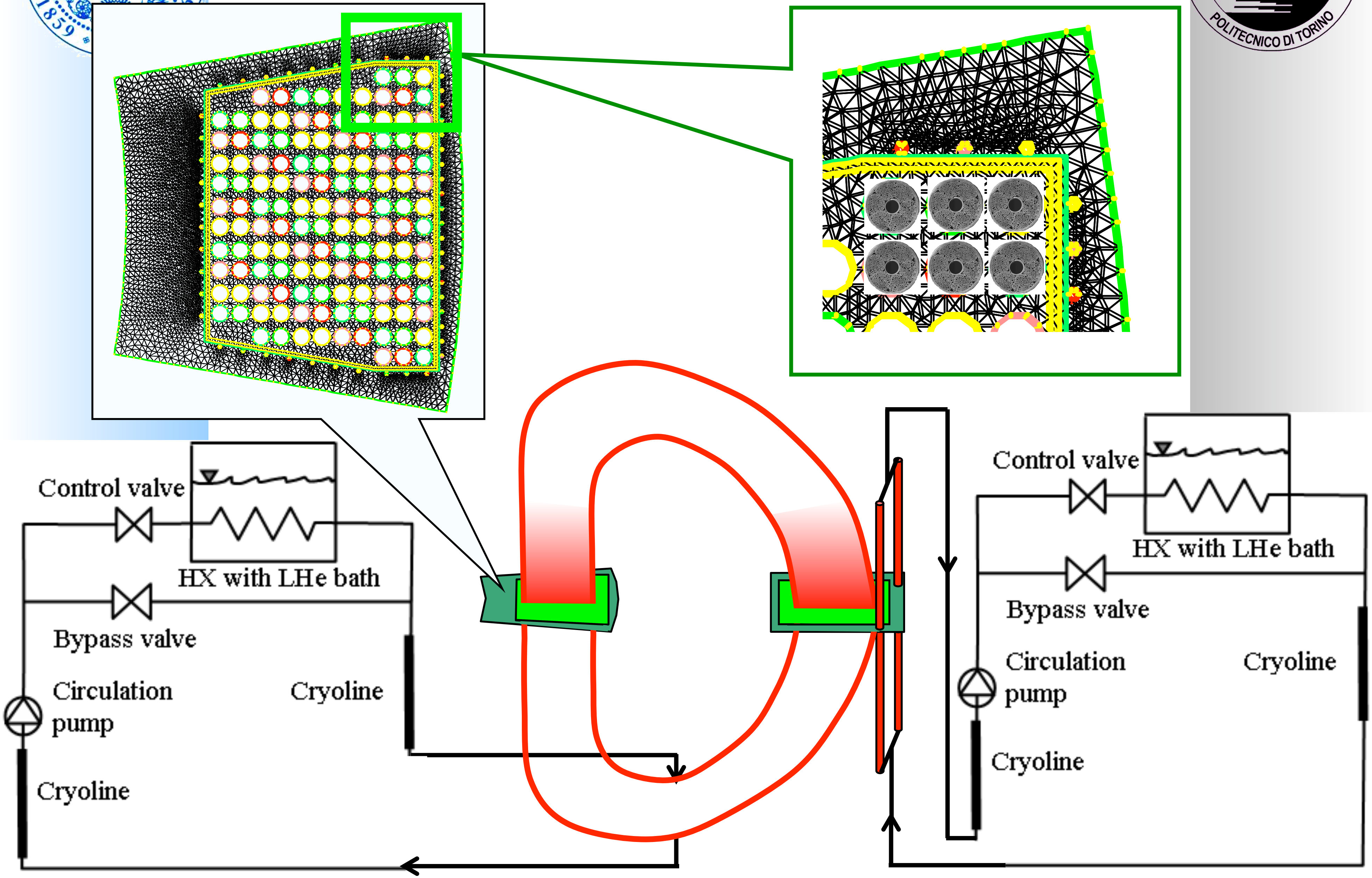


TF winding



[www.iter.org]

4C model

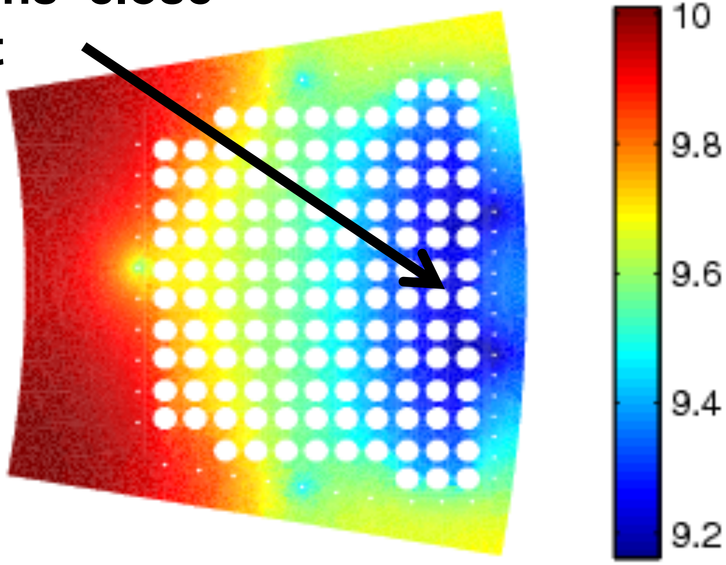


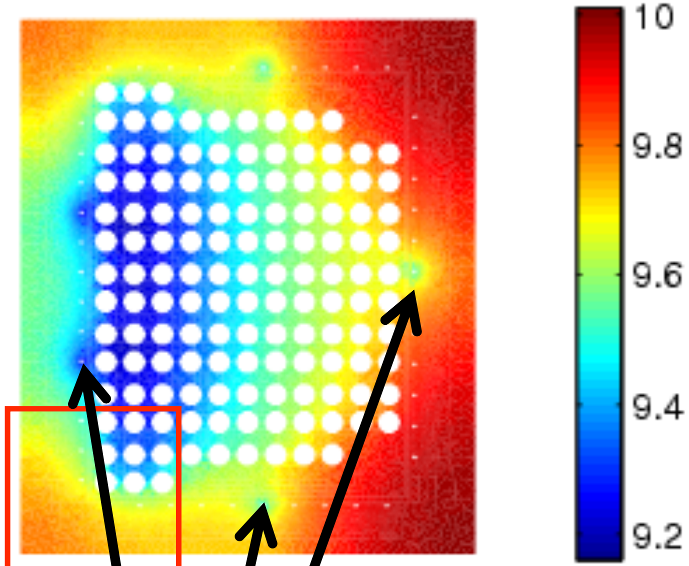
Control valve
HX with LHe bath
Bypass valve
Circulation pump
Cryoline
Cryoline
Control valve
HX with LHe bath
Bypass valve
Circulation pump
Cryoline
Cryoline

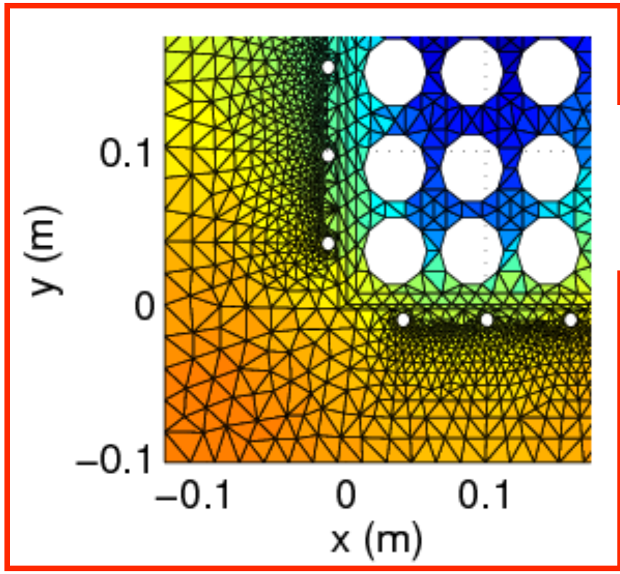
"Cooldown" test case

t ~ 7000 s = middle of cooldown transient

Colder turns close to He inlet

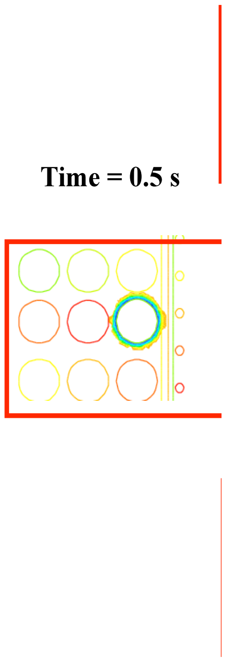


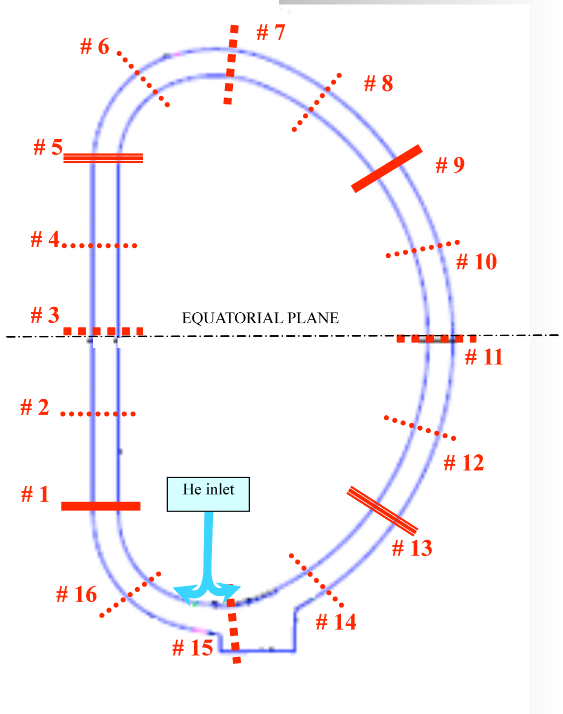




Effect of case cooling channels

3D temperature evolution in structures during TF quench

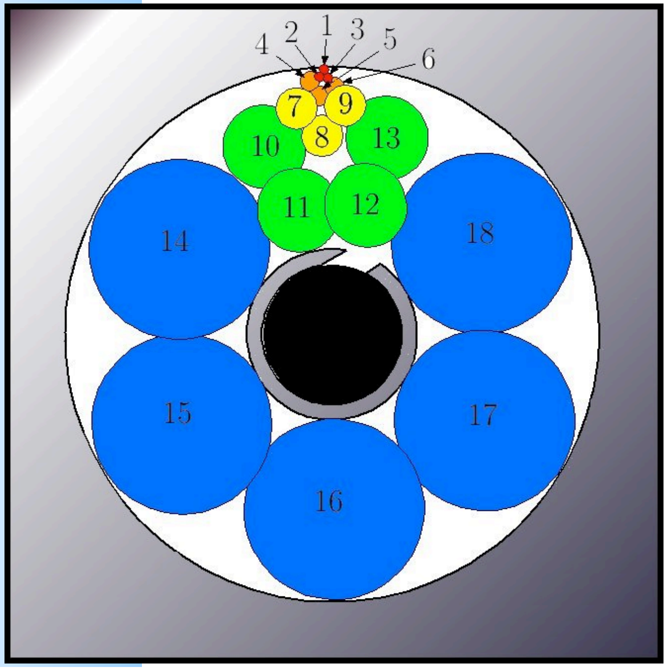




Multiphysics

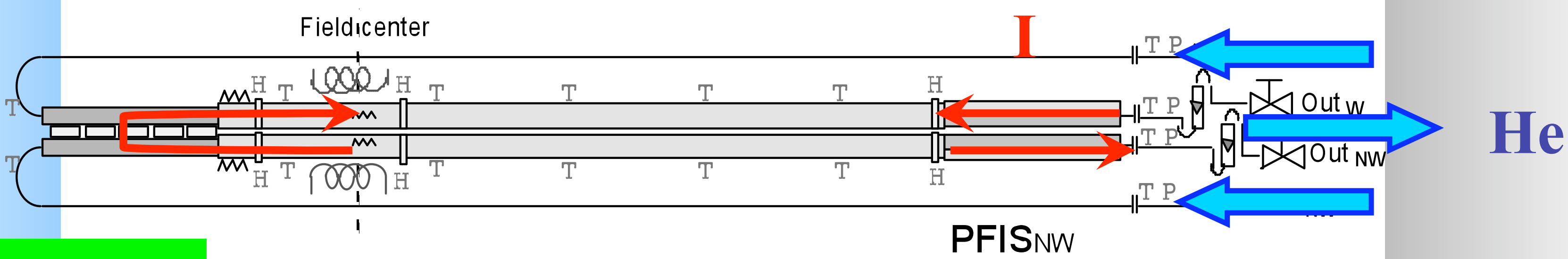
• Thermal-Hydraulics of CICC is only part (and sometimes not even the “most important” one) of the story

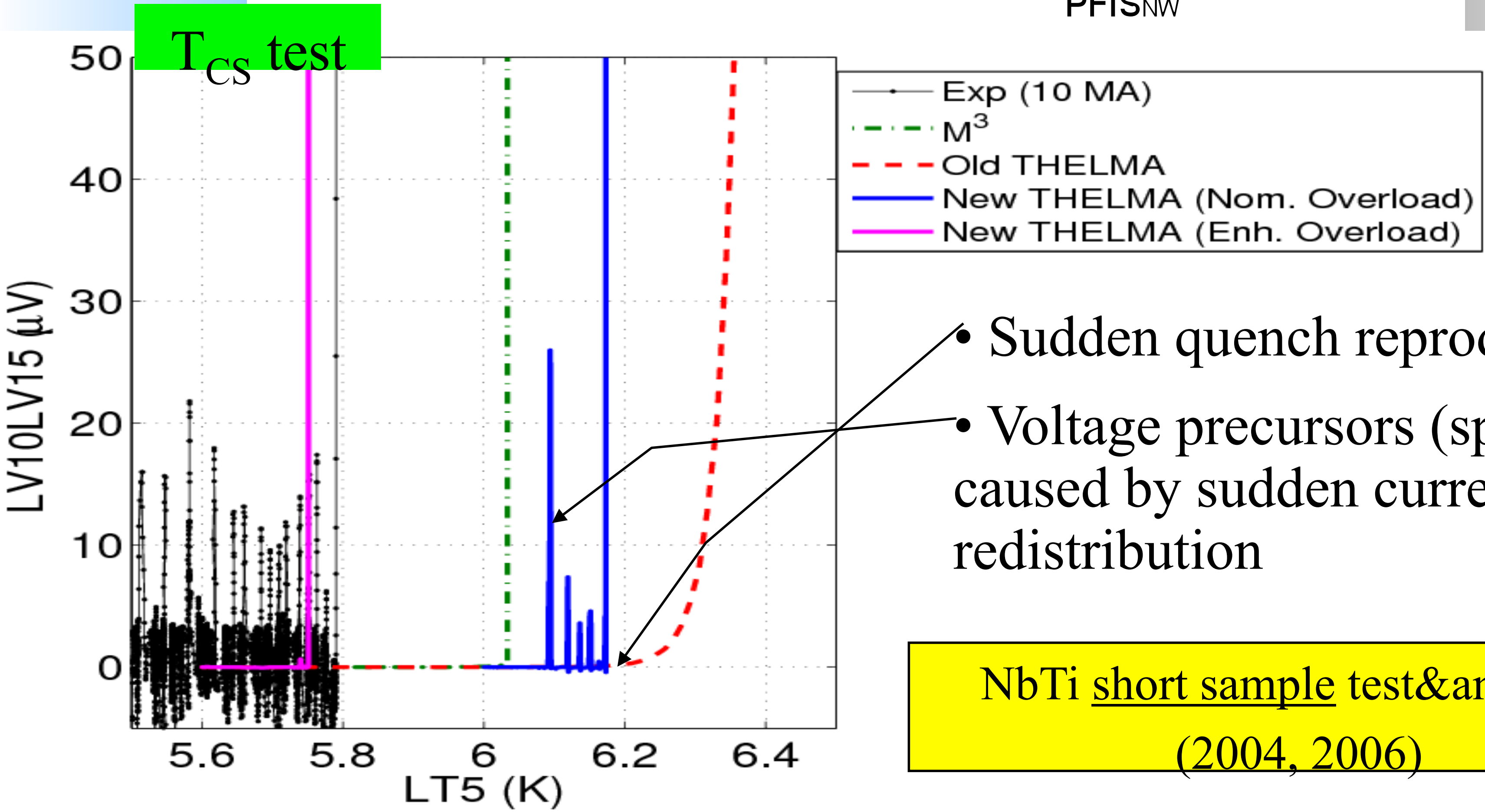
• CICC performance depends on **current distribution** among the strands, which may be non-uniform because of non-uniform contacts at joints → EM model of cable (and joints) [Bologna U., Udine U.] requires the temperature of the different cable elements → **THELMA code**



Discretize cable cross section nested down to single strand

DC performance assessment





- Sudden quench reproduced
- Voltage precursors (spikes) caused by sudden current redistribution

NbTi short sample test&analysis (2004, 2006)

Formazione

- Dal 1992 due corsi a PoliTo per Ingegneri Nucleari (laurea magistrale) su
  - "Fisica dei Reattori a Fusione" ANCHE NEI PROGRAMMI MFN UniTO DAL 2009
  - "Ingegneria dei Reattori a Fusione"

- > 50 Tesi di Laurea, > 20 dottorati a PoliTo nel campo della fusione (Energetica&Nucleare, Ing. Elettronica , Ing. Chimica, Ing. Aerospaziale)