Agenzia nazionale per le nuove tecnologie,
l'energia e lo sviluppo economico sostenibile

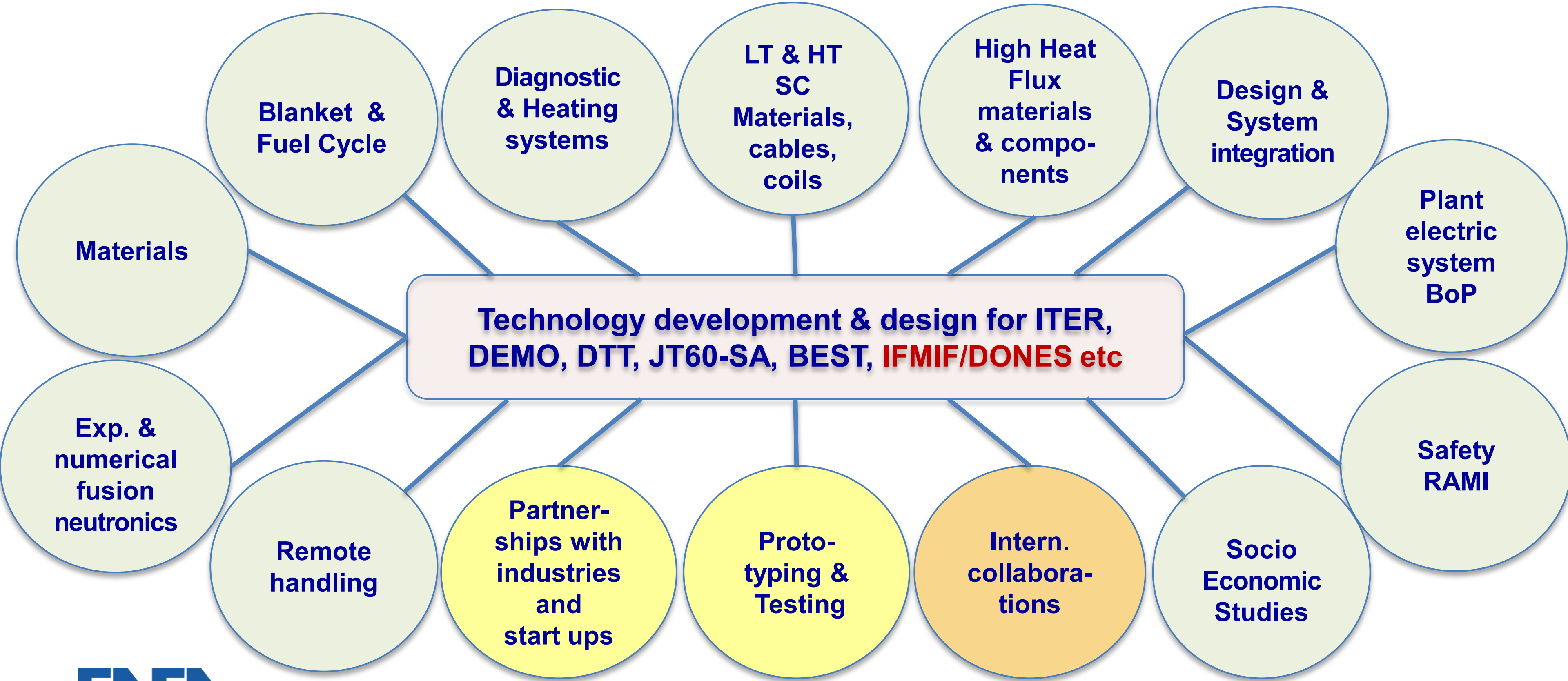
Overview of physics and technology of magnetic fusion in Italy

Fusion technology

Paola Batistoni
ENEA, Nuclear Department

1ª Conferenza Italiana sui Plasmi (CIP), Frascati, 3.2.2026

Fusion technology activities in Italy

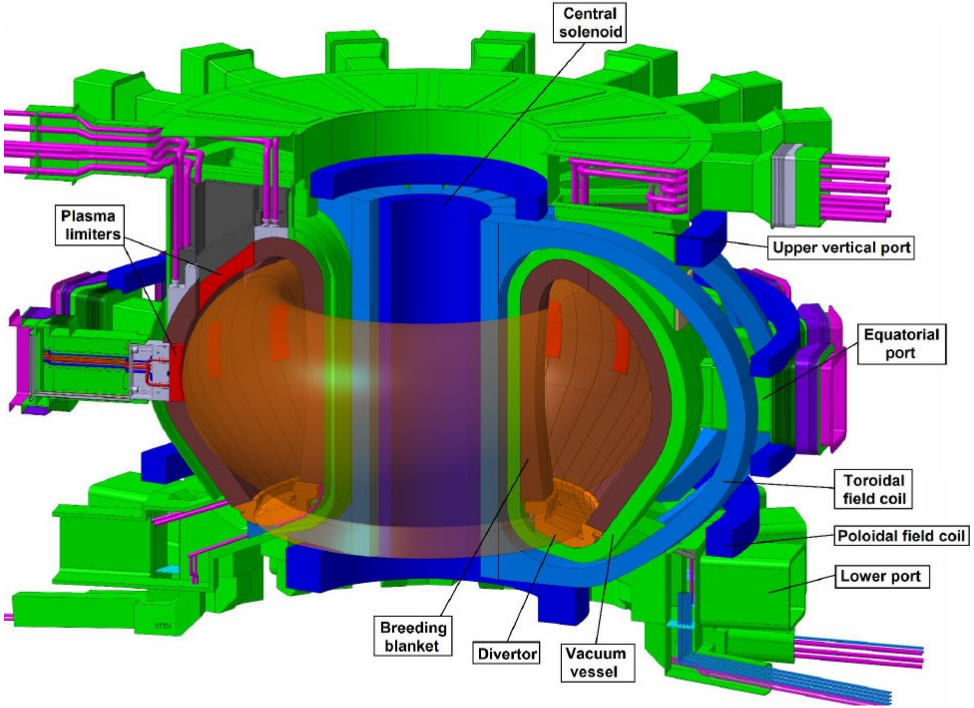


Italian Fusion Network (EUROfusion)

- Second most important contributor to **Eurofusion Consortium**
- ENEA is the Program Manager
- 22 partners including:
  - universities, national research labs and consortia
  - several industries and the major Italian energy company, ENI

Outline

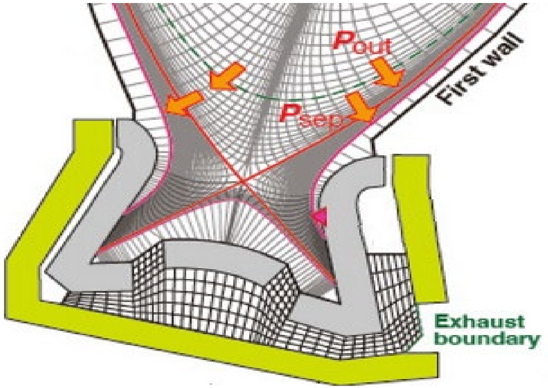
- Reactor technologies & components
  - Plasma facing components (Divertor)
  - Tritium breeding blanket & Fuel Cycle
  - Magnet system
  - Neutronics
  - Materiali (IFMIF/DONES)



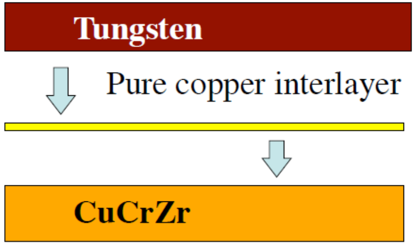
European DEMOnstration fusion reactor (DEMO)

Divertor technology

- **Divertor functions:**
  - remove heat produced by particle bombardment, radiation(~10 – 20 MW/m^2) and nuclear heating (~MW/m^3).
  - Direct He ‘ash’ and unburnt fuel to pumping ports for exhausting

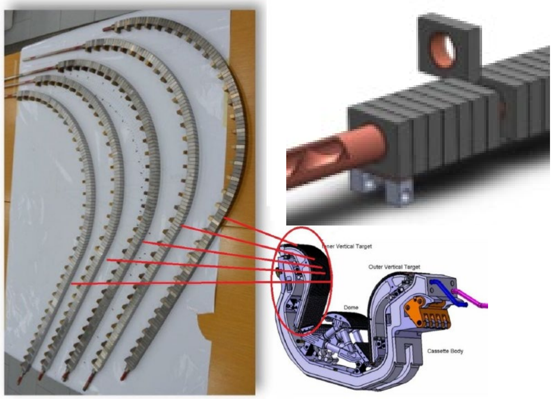


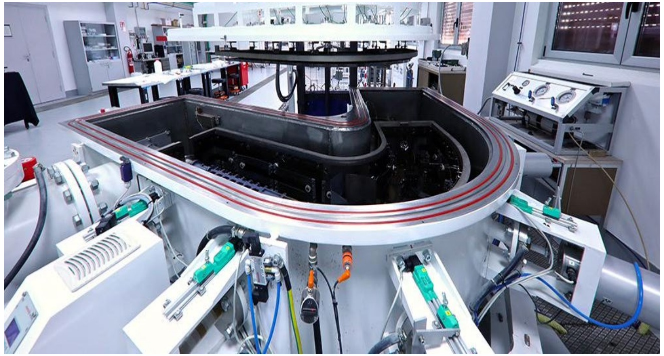
- **ITER Divertor technology**
  - **W** monoblock as **sacrificial armour material on targets (**physically compatible with the plasma) to protect the **CuCrZr cooling pipes**
  - A pure Cu interlayer is used between armour and tube to smooth thermo-mechanical stresses during operation.
  - Good wetting of Cu on W required to prevent the formatic of bubble in the cast Cu



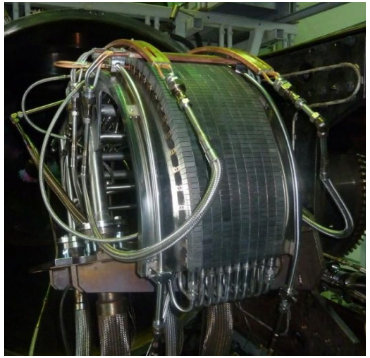
Divertor: ITER technology

ENEA junction technology
Hot Radial Pressing (Diffusion bonding)

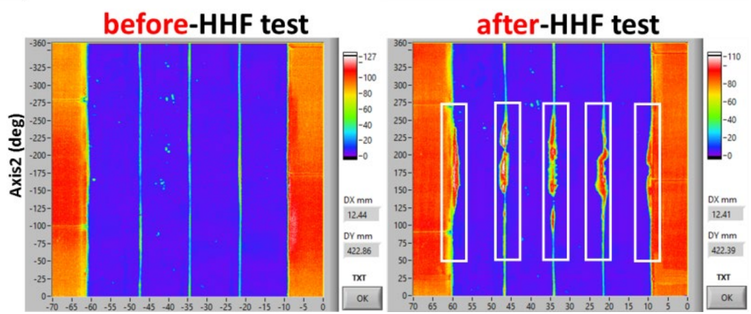


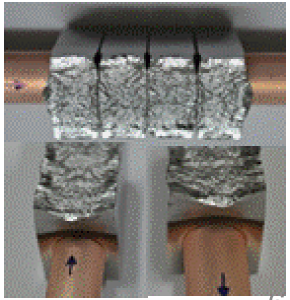


ENEA patent oven for the manufacturing of the PFU of ITER Inner Vertical Target



***ANSALDO-ENEA** ITER IVT successfully qualified*





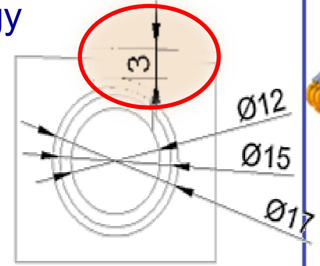
PFU mock up before and after 1600 cycles at 25 MW/m² with hot water (105°) and NDT control by Ultrasonic Testing

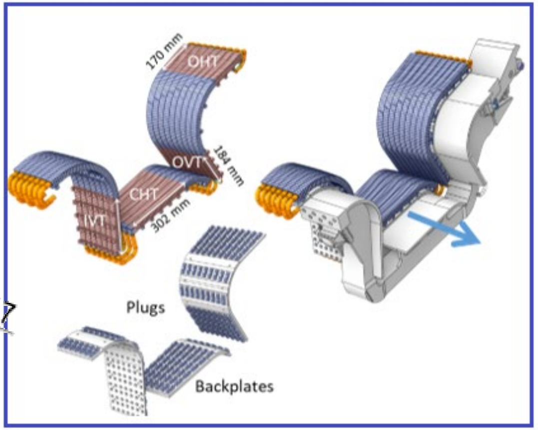
ENEA

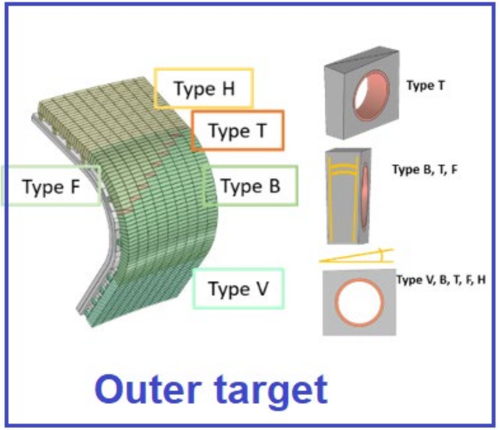
DTT divertor design and prototyping

Design

- ITER-like monoblock technology with a reduced thickness of armour (3 mm) to increase the permissible thermal load

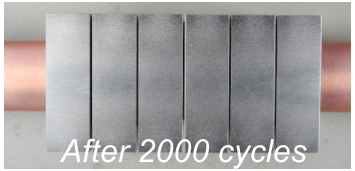






Experimental assessment

- HHF testing in GLADIS: up to 2000 cycles at 20 MW/m^2; hot water (130°C)
- No damage, no cracks or surface plastic deformation
- Permissible load up to 20 MW/m^2 stationary in DTT



S. Roccella et al.,IEEE Transactions on Plasma Science,2024

Prototyping

- New oven for DTT PFU full scale prototype fabrication

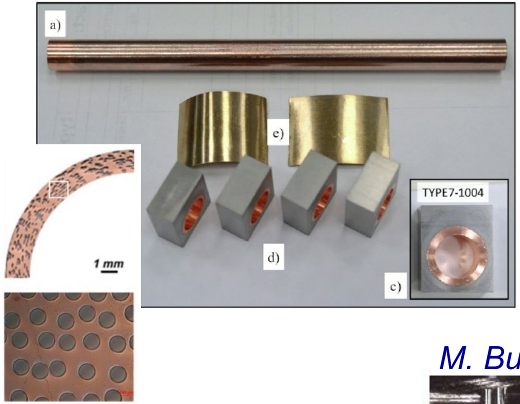
DEMO divertor technology

Fabrication and testing of DEMO divertor target mock-up

- W reinforced with W fibres (W_f/W) to overcome the intrinsic brittleness of W & increase mechanical fatigue resistance.

F. Crea et al., Fus. Eng. Design Volume 215, June 2025, 115025

- W fibre-reinforced Cu (W_f/Cu) to provide higher thermal conductivity and strength of CuCrZr up to 500 °C - less prone to neutron damage.

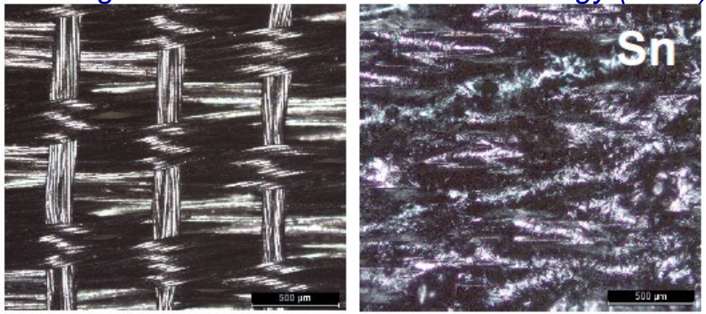


P. Lorusso et al.,Nuclear Materials and Energy 46 (2026) 102045

Liquid metal divertor

- Liquid Sn-based divertor design and R&D
- Corrosion Barrier for W
- Modelling and PWI simulations (SOLPS)

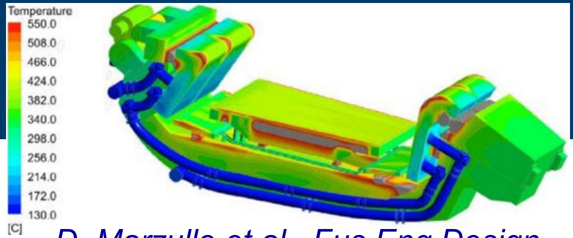
M. Bugatti et al. Journal of Fusion Energy (2025)



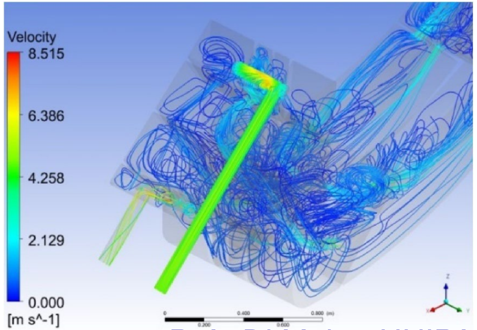
W yarn woven in herringbone pattern not wet (L) and wet (R) by liquid Sn

Divertor design & technology in Italy

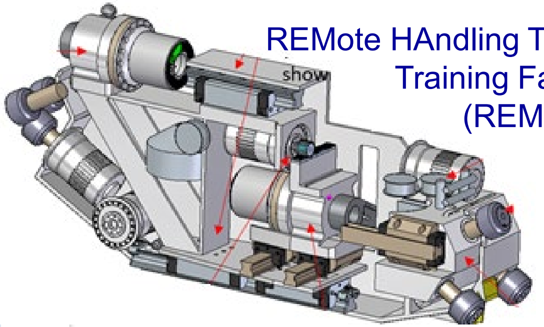
ENEA	Divertor technology R&D , design, testing - LMD
CREATE	System Engineering & architectural design, structural & em analyisis, cassette fabrication technology, RHEMAT
CSM/RINA	Nuclear safety, waste, recyclying, coatings
Uni Tor Vergata	Structural & FEM analysis, coatings & cassette fabrication technology
Uni Palermo	Thermo-fluid dynamics
Uni Tuscia	W lattice studies, PWI
Uni Trieste	em analysis
Uni Napoli	Remote Handling (RHEMAT)
LTCalcoli	FEM analysis of limiters, structural analysis
ENI	PWI simulations and valudation
Uni Sapienza	Liquid metals limiters modelling: capillarity, MHD modelling
PoliTO	LMD materials, PWI modelling (SOLPS)
PoliMI	LMD limiters: corrosion barriers, W coatings
CNR - ISTP	LMD experiments



D. Marzullo et al., Fus Eng Design, 46, 2026



P. A. Di Maio - UNIPA

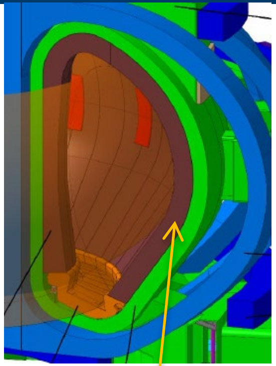


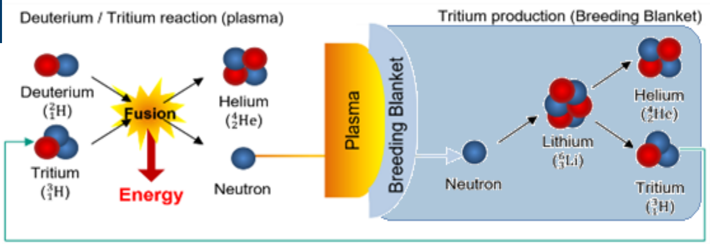
REMote HAndling Test & Training Facility (REMHAT)

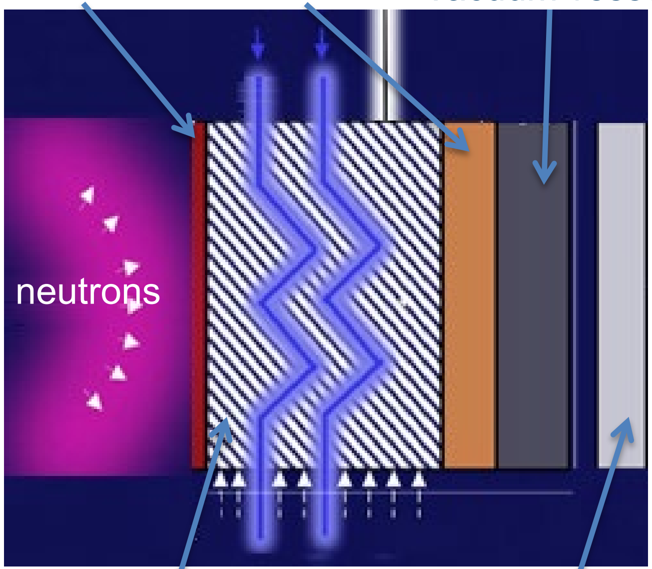
Tritium breeding blanket

Three main functions:

- Production and efficient extraction of tritium minimizing its losses
  → *T consumption* *55.6 kg / GW_{fus} /y*
  (~150 g / GW_{fus}/ day)
  → *Self sufficiency* ***TBR=T/n > 1*** *(1.05 – 1.15)*







- Absorbing ~80% of fusion power deposited by neutrons and converting it in thermal power suitable for power generation systems
  → *high power conversion efficiency > 40%*
- Contributing to providing neutron shielding to permanent components (vacuum vessel, superconducting coils)
  → *good shielding properties*

ENEA

Multi physics problem

European blanket concepts

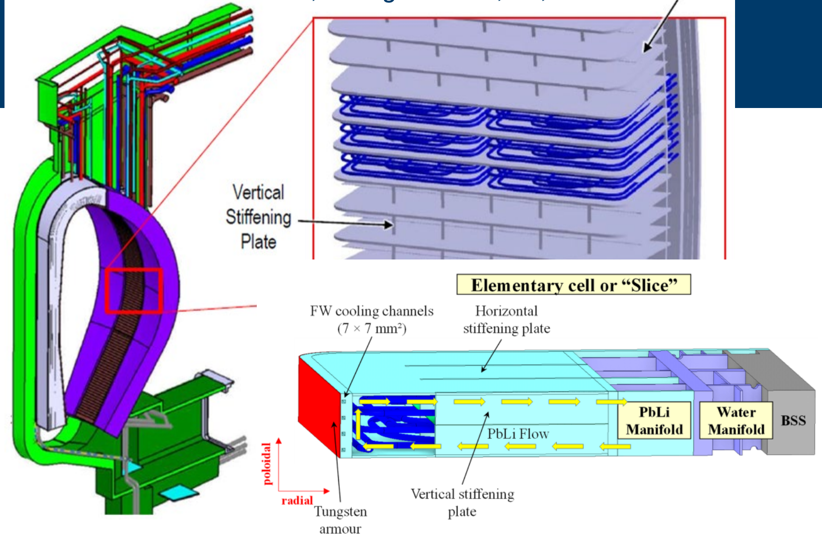
- **European Water Cooled Lithium-Lead (WCLL)**

Breeder & Neutron Multiplier

Pb-Li(16%) eutectic (liquid metal, 90%^{6}Li)

Coolant: Water 15,5 MPa, T_{in}= 295°C, T_{out}= 325°C

Arena et al., Energies 2023, 16, 2069



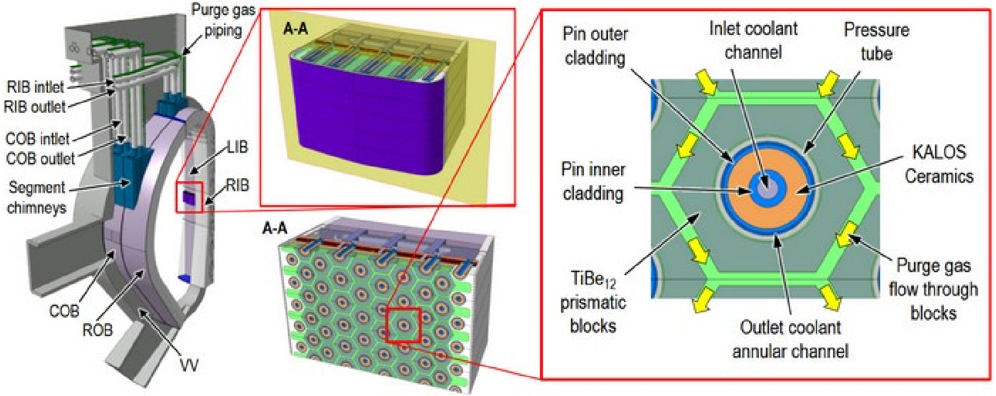
- **European He Cooled Pebble Bed (HCPB)**

Breeder pebble bed:

65% Li_4SiO_4 - 35% Li_2TiO_3 (60% ^{6}Li)

Neutron Multiplier: **$TiBe_{12}$ block**

Coolant: He 8 MPa, T_{in}= 300°C, T_{out}= 520°C



- **Other explorative concepts e.g. WLCB**

Li_4SiO_4 - 35% Li_2TiO_3 Pb as multiplier

Blanket & Fuel Cycle R&D

- **TPbLi & tritium technologies**

– Development of sensors for monitoring the H isotopes concentration in LiPb

– H isotopes extraction from PbLi -Testing of Gas Liquid Contactor, Permeator Against Vacuum (GLC & PAV)

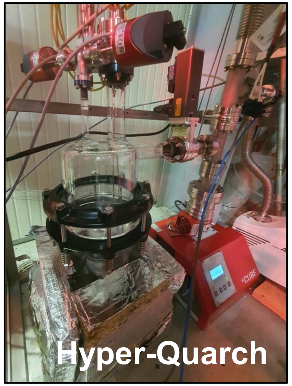
– Measurements of T permeation in water in DEMO conditions

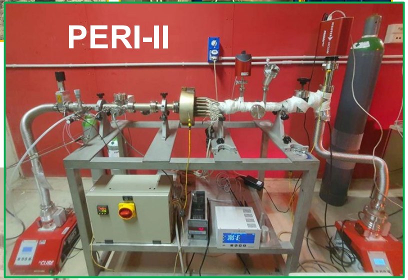
– Development and demonstration of anti-permeation Al- based coatings to reduce the T permeation from PbLi to coolant and environment

– Tests on PbLi/water interaction

– Concept design of the DEMO fuel cycle - Processing of all tritiated streams before their release into environment.

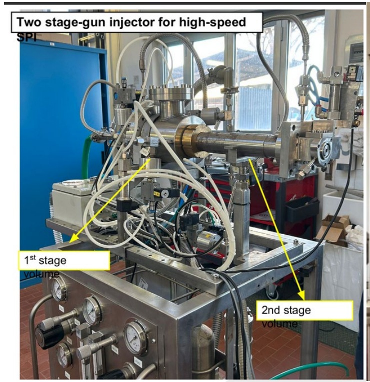
– High speed pellet injection





Facilities at ENEA Brasimone

and Frascati

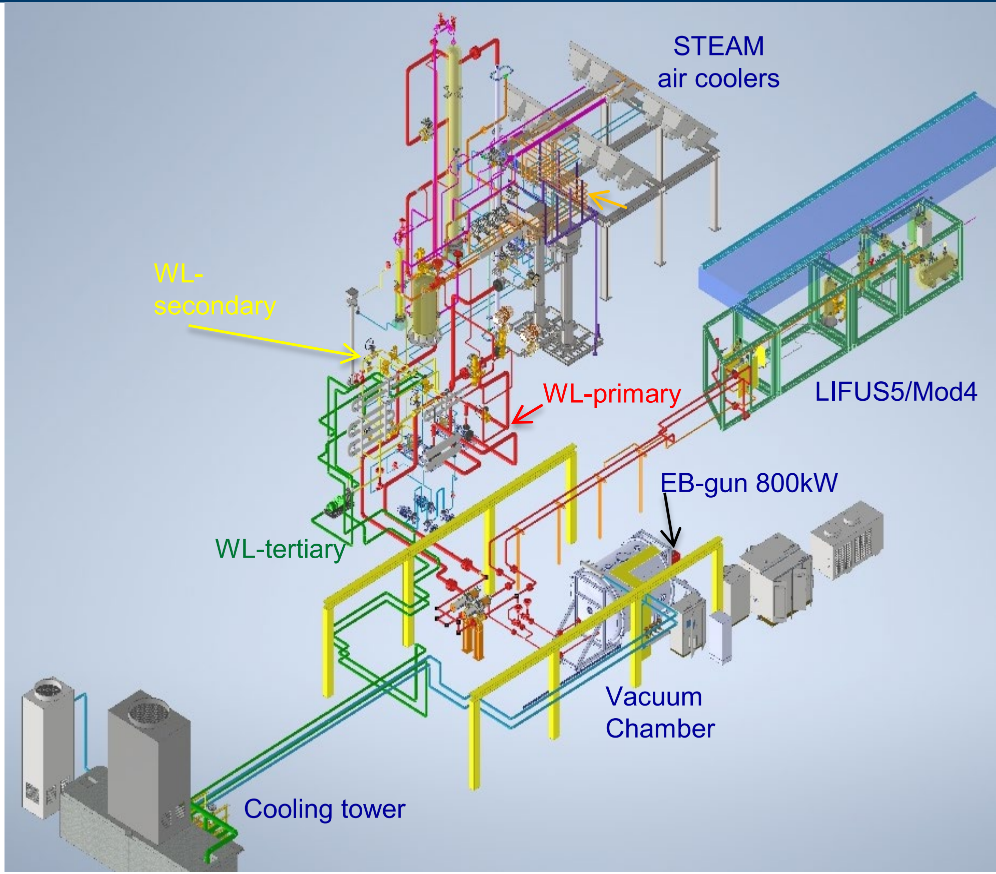


Blanket Technology & BoP

W-HYDRA WCLL Test Bed

- ✓ WL facility able to provide water at PWR conditions (15.5 MPa, 295 °C–328 °C)
- ✓ 800 kW Electron Beam (EB)
- ✓ STEAM Generator test facility for pulsed operating conditions
- ✓ LIFUS5/Mod4 PbLi/water reaction accident scenarios

- Thermo-hydraulic testing on prototypical mock-ups under relevant working conditions (first wall, manifold, steam generator)
- Testing of PbLi/water interaction.
- Qualification and validation of numerical models and codes, and safety procedures



W-HYDRA platform under construction in ENEA Brasimone

Blanket design & technology in Italy

ENEA Blanket design, PbLi technology development, testing and qualification, T technology, Fuel cycle

CREATE Architectural design, em analyisis

Uni Palermo Thermo-fluid dynamics, neutronics

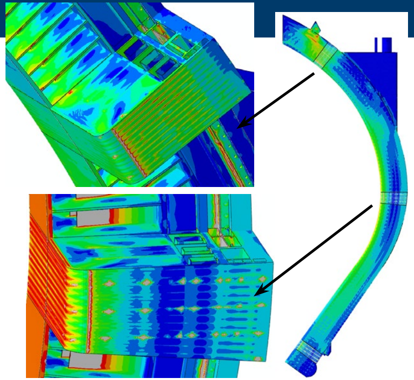
Uni Pisa Thermo - hydraulic analysis, PbLi – water interaction

PoliTO T extraction, PAV, T permeation studies, ACP, Neutronics, Safety

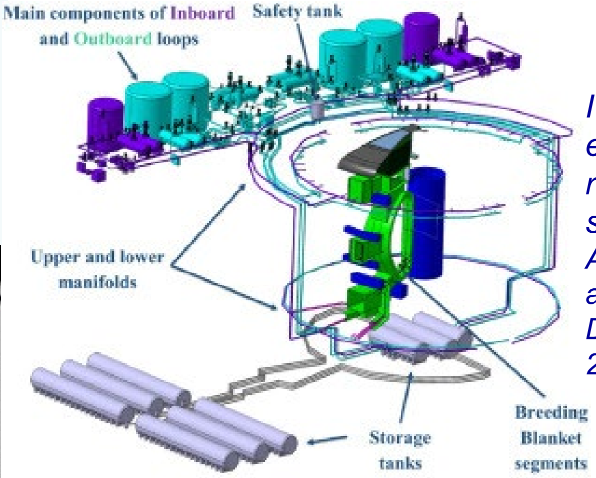
PoliMI Thermo - hydraulic analysis, T extraction

Uni Basilicata Remote handling

CM/RINA Water chemistry, Eurofer corrosion, materials
ENI Technology developement, regulatory framework

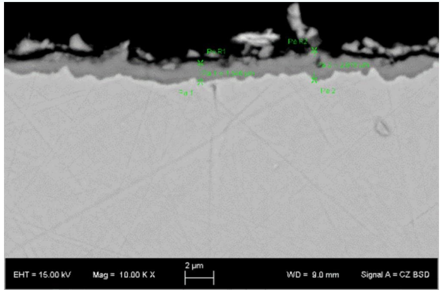


Von Mises stress in DEMO WCLL blanket
P. A *Di Maio*



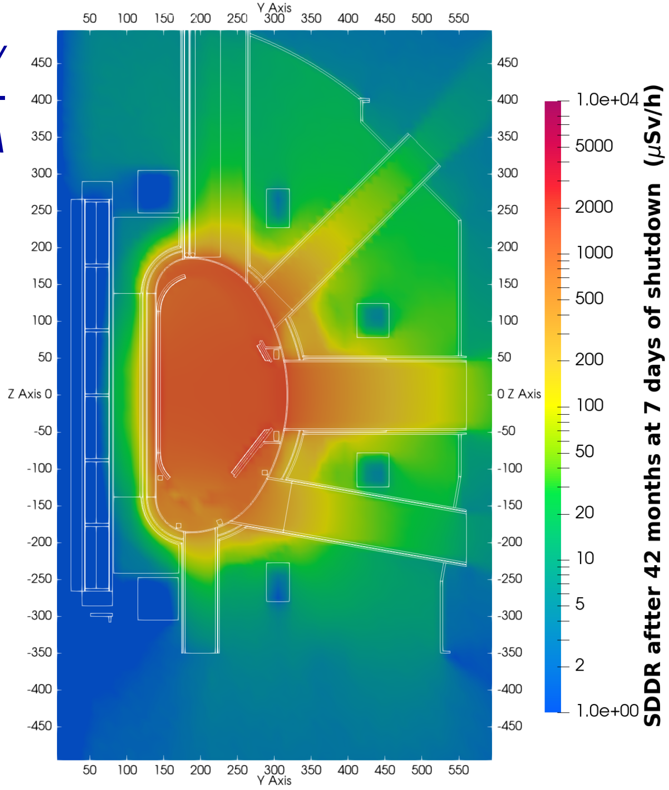
ITER Tritium extraction & removal system
A. Venturini et al.,Fus. Eng. Design, 216, 2025

Corrosion products in Eurofer
M. Molinari et al., Nucl Mat and Energy 41, 2024

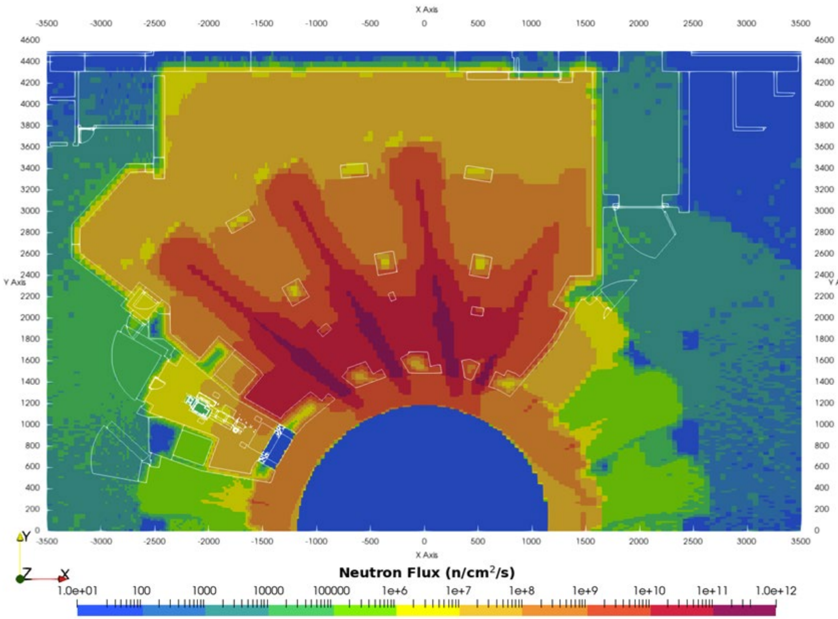


Neutronics code development and analyses

Shutdown doserate in DTT by
***AD1S coupled neutron transport – activation code** fully developed in ENEA*



Neutron fluxes in ITER NBI ducts integrated in Tokamank building



ENEA

Experimental neutronics

Frascati Neutron Generator (FNG)

14 MeV neutron source of medium intensity (10^{11} n/s) using T(d,n)α reaction

- Measurements and validation of nuclear data for fusion
- Fusion benchmark experiments
  - ✓ Shielding, shutdown doserate, nuclear heating, tritium production, activation of water, ACPs …
- Tests of radiation hardness
- Detectors' calibration and characterization

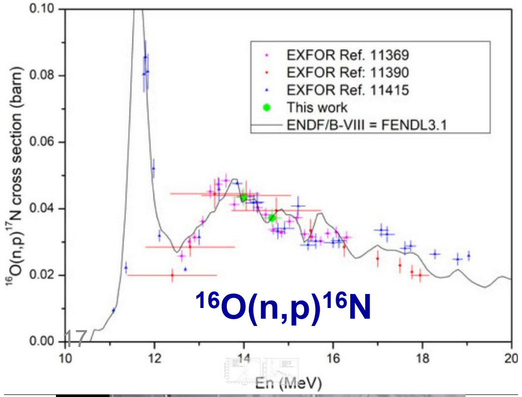
Experimental neutronics

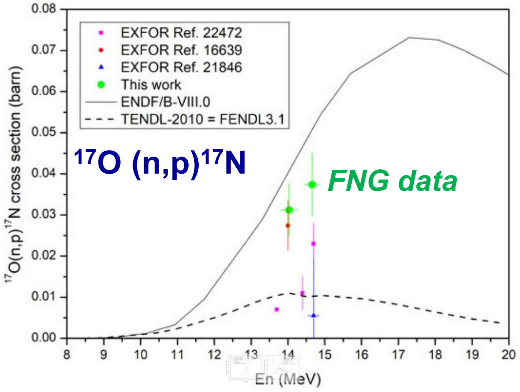
FNG Water activation experiment

Measurement of Oxygen activation cross sections

$^{16}N \rightarrow {}^{16}O \rightarrow {}^{16}O + \gamma$ (6.1 MeV), $T_{1/2}$ = 7.1 s

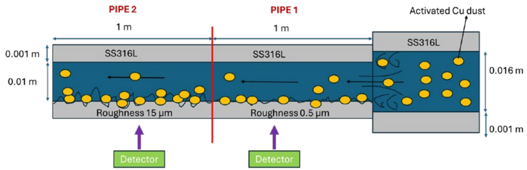
$^{17}N \rightarrow {}^{17}O \rightarrow {}^{16}O + n$
(E_n= 0.386, 1.16,1.69 MeV), $T_{1/2}$ = 4.2 s

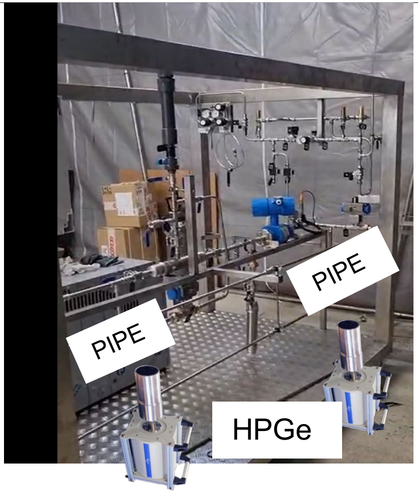


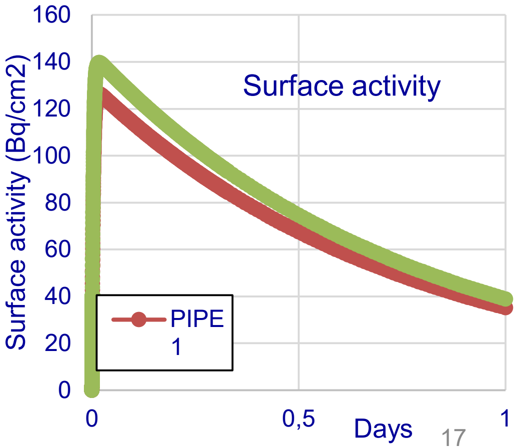


FNG Activated Corrosion Products (ACP) Experiment (ENEA, UKAEA, KIT, JSI)

- Testing fundamental water chemistry & corrosion products transport mechanisms for ITER.
- Validation of ACP simulation code (e.g., CEA OSCAR-Fusion).

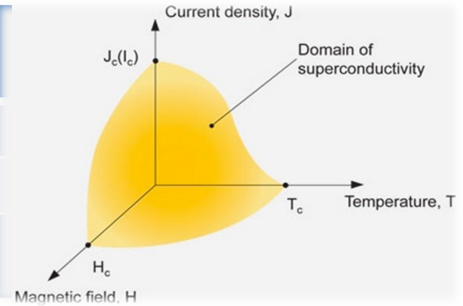






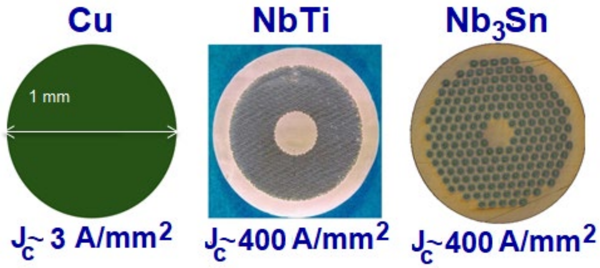
Magnets: Superconductivity

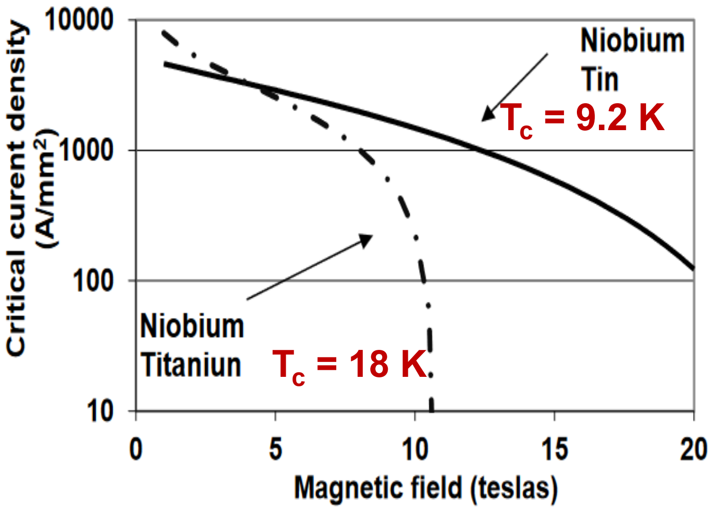
Material	T_c(K) @B=0T	H_c(T) @T=0K	Practical use for fusion	Features
NbTi	9.2	15	Up to 7T @4.5K	Ductile alloy
Nb_3Sn	18	27	7-15 T @4.5K	Intermetallic compound - brittle
REBCO*	93	➢ 100	> 15 T @ 4.5 - 20K	$REBa_2Cu_3O_{7-x}$ - brittle



*Rare-earth: Yttrium, Lanthanum, Samarium, Neodymium, Gadolinium, Europium

ITER's and DEMO's requirements for B >10 T necessitated the use of Nb_3Sn for both the TF and CS systems

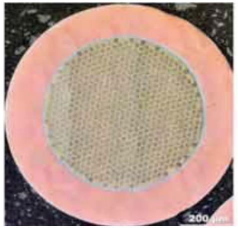


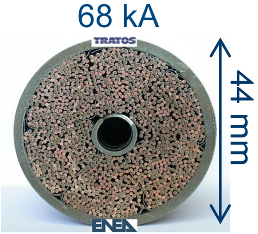


LTS magnets: ITER technology

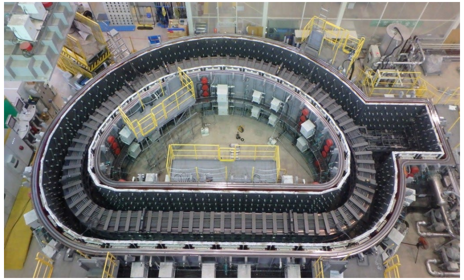
Nb_3Sn wind & react W&R (ITER):

- The formation of the crystallographic structure of Nb_3Sn requires heat treatment in several stages
- When reacted, Nb_3Sn becomes very brittle and cannot be manipulated.
- Unit lengths of conductor are wound into a D-shaped double spiral called "**double pancake**"
- Each pancake is heated @650°C,>100h.
- Pancakes are unwound slightly to be insulated and transferred into **radial plates**.

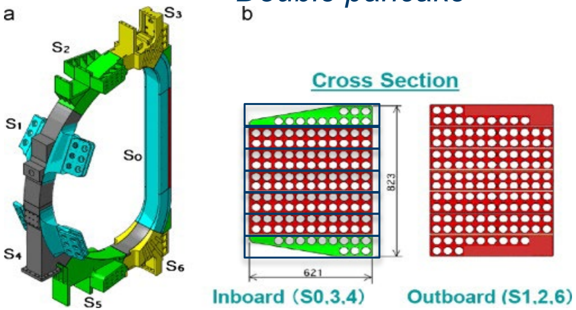




Double pancake



Heat treatment oven

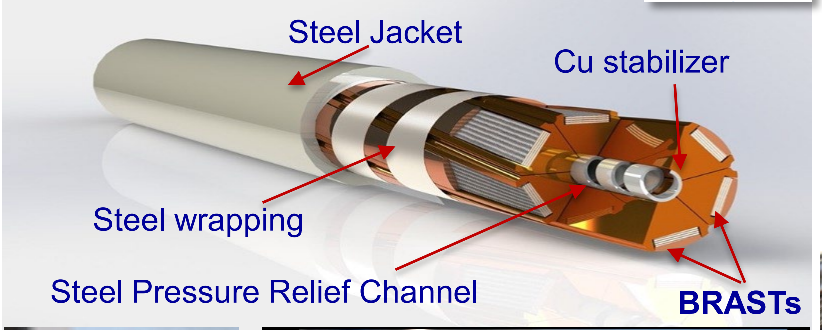


Radial plate

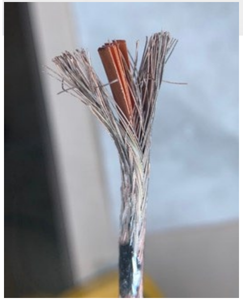
HTS conductors (REBCO)

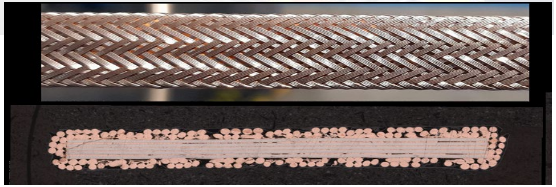
- To enhance magnets flexibility → higher magnetic field, operating temperature, temperature margin, etc.

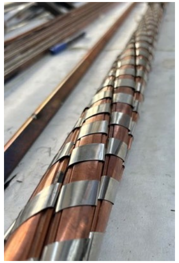
SECtor ASsembled ***(SECAS)*** Conductor



60 kA
@4.5 K
18 T

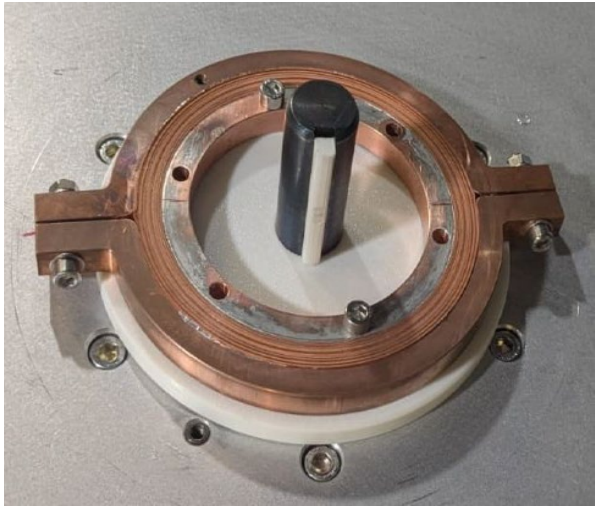






BRAided STAcks ***(BRAST)*** of REBCO tapes

L. Muzzi et al. 2023, IEEE TAS 33 (5) 1-6

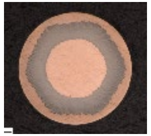


HTS TRUST-like PF1 coil
Università Tuscia - ASG
Internal Radius: 45 mm
Windings: 50 turns, 100 A/turn
Operating Temperature: 77 K

DTT magnet system

Design of the entire DTT superconducting magnet system.

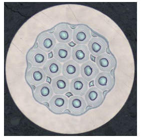
PF



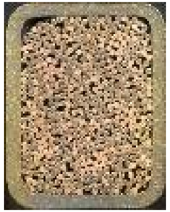
NbTi wire

Conductor

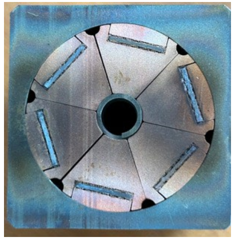
TF



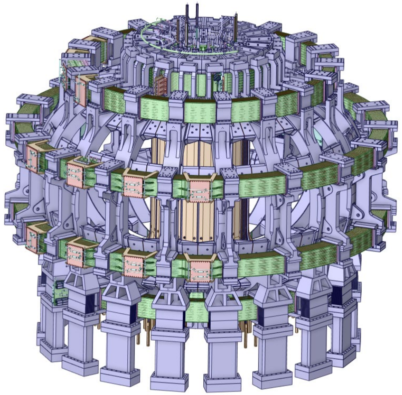
Nb_3Sn wire

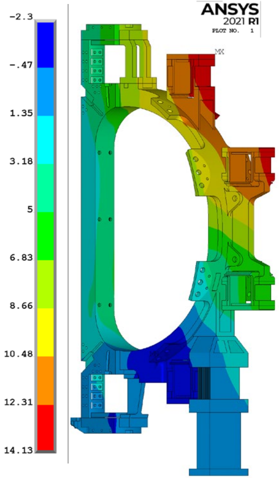


Conductor



SECAS Prototype for **CS Insert Coil**

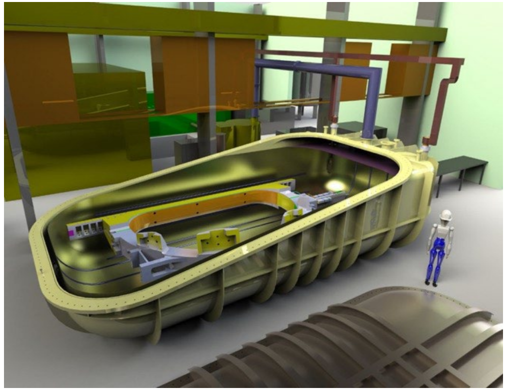


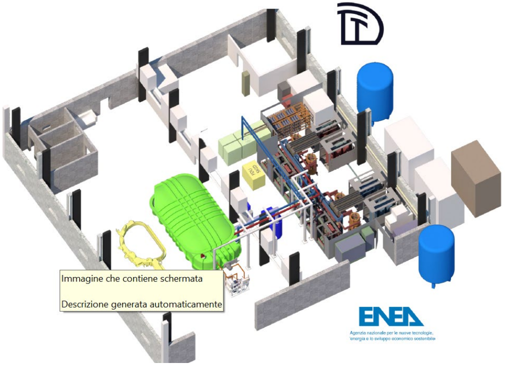


Frascati Coil Cold Test Facility

All DTT Nb_3Sn coils will be tested at max current for electrical integrity at 4.2 K, SC performances, thermal-hydraulic, joints behaviour and resistance values

- 100 ml^3 large cryostat
- TF power supply 4.2 MVA, 42.5 kA
- Cryo system 500W @ 4.2K Linde Refrigerator





Magnet design & technology in Italy

ENEA LTS and HTS materials, cables, magnets design & technology development

RFX Magnet structures design

PoliTO Thermo – hydraulic analysis, quench analysis, RAMI, Radiation damage modelling, experimental testing

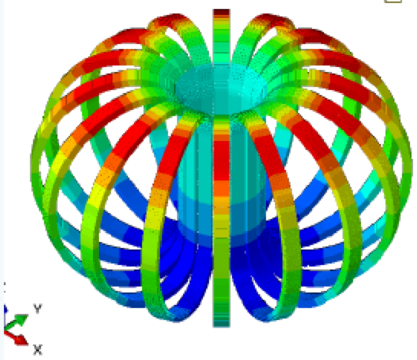
Uni Tuscia HTS materials and magnets

Uni Tor Vergata feeder design

CM/RINA Mechanical testing on stainess steels and conductors

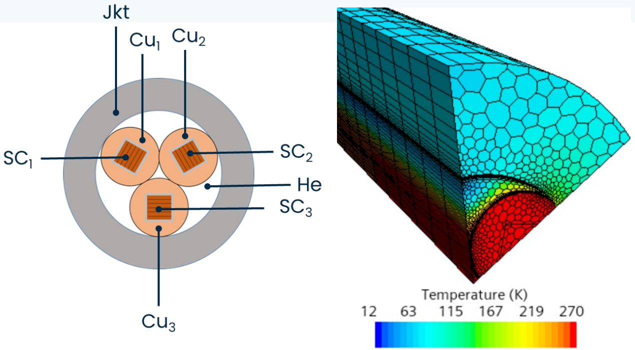
CREATE Current scenarios and magnet operations

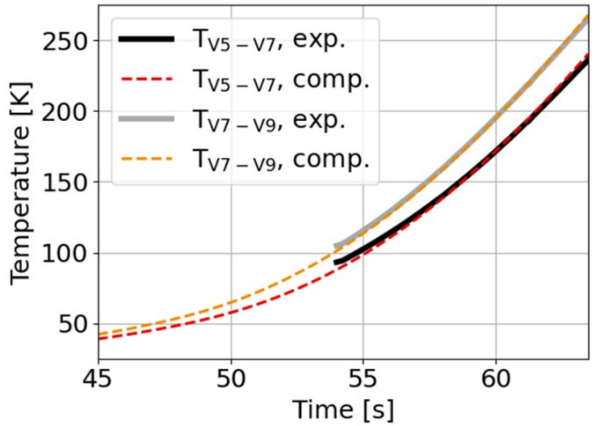
ENI Magnet industrialization



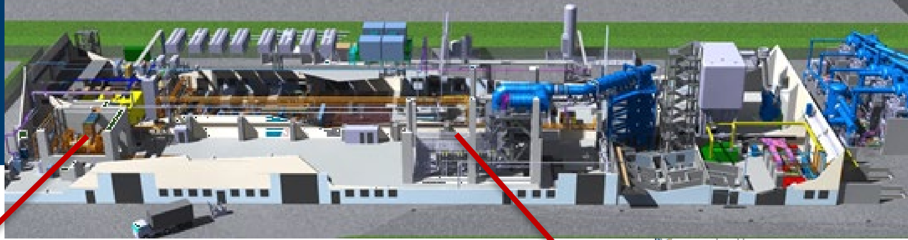
SULTAN experiment to validate 3D CFD models of quench propagation in sub-scale (15 kA) REBCO conductors

A. Zappatore, SuST, 2024



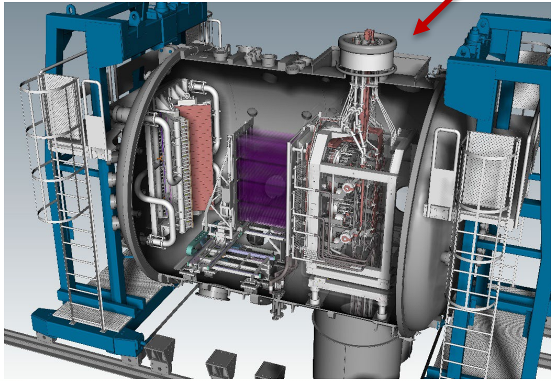


Heating systems

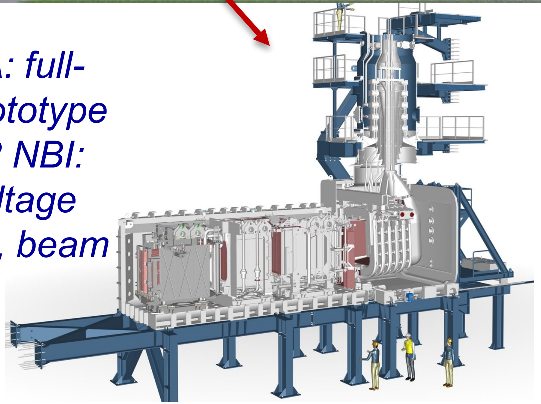


Neutral Beam Test Facility (NBTF, RFX Padua)

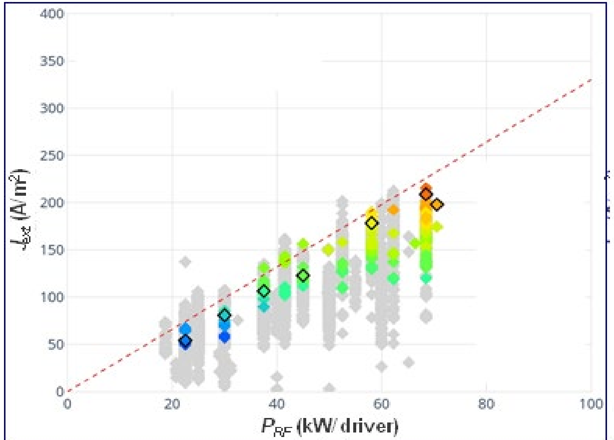
Development of the ITER HNB prototype design, procurement follow-up, integration commissioning and operation

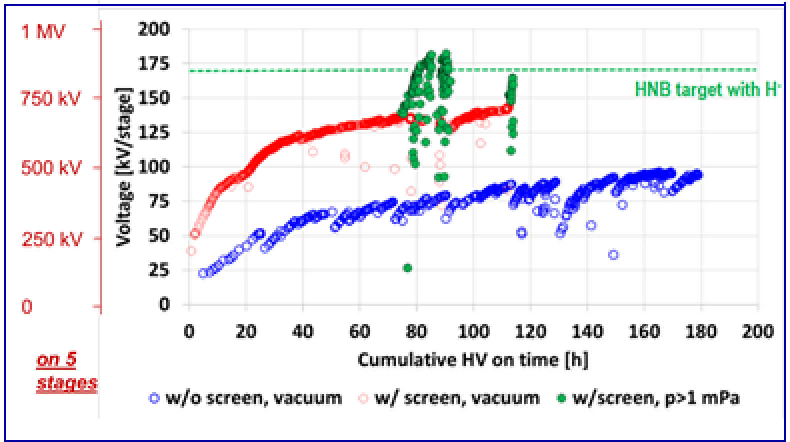


MITICA*: full-size prototype of ITER NBI: high voltage holding, beam optics*



SPIDER*: optimisation of ion source: current density, uniformity, stability*





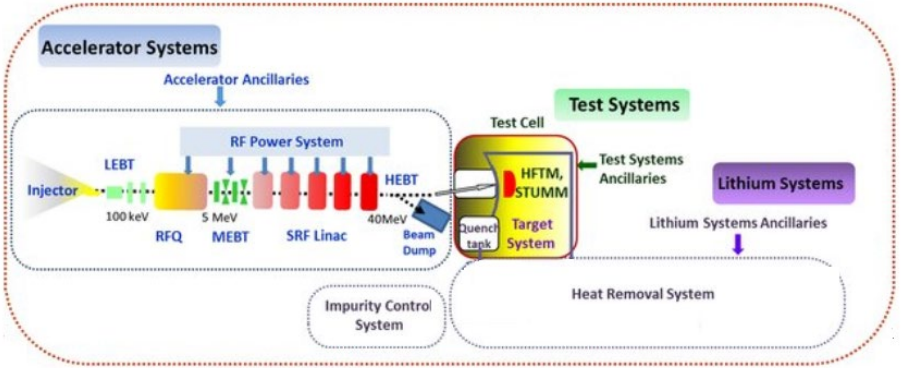
A Pimazzoni, this conference, 5th February

ENEA

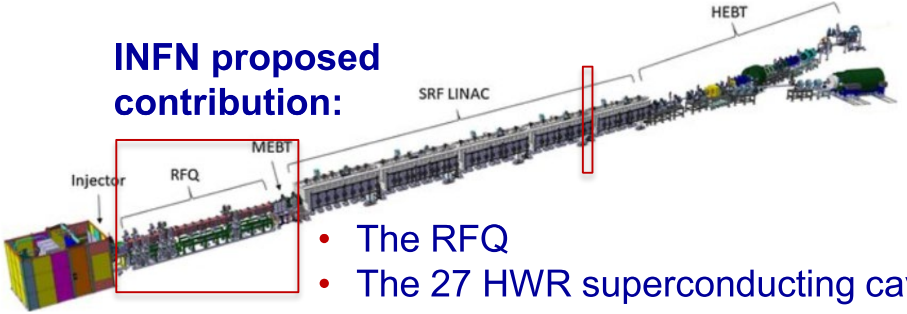
Fusion Materials Irradiation Facility (IFMIF/DONES)

Intense neutron source for the qualification of fusion materials based on Li(d,xn) stripping reactions in a liquid Li target (15 m/s, 300 °C)

- E_d = 40 MeV, I_d= 125 mA
- Neutron flux up to 5 × $10^{18}/(m^2\ s^1)$,
- Dose rate up to ~20dpa/fpy



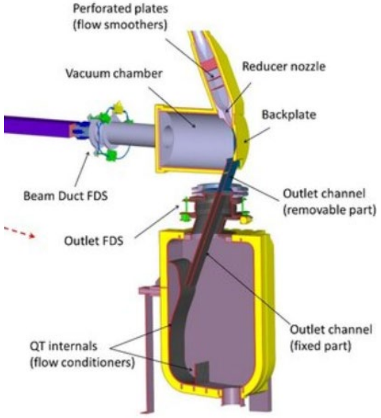
INFN proposed contribution:



- The RFQ
- The 27 HWR superconducting cavities
- A general contribution to computer control, installation, commissioning and management of the accelerator

ENEA proposed contribution:

- Lithium Systems
- Control system & management



ENEA

Thanks for your attention

paola.batistoni@enea.it