DE LA RECHERCHE À L'INDUSTRIE

GROWING SYNERGIES BETWEEN FISSION AND FUSION RESEARCH TOWARDS DEMONSTRATION PLANTS

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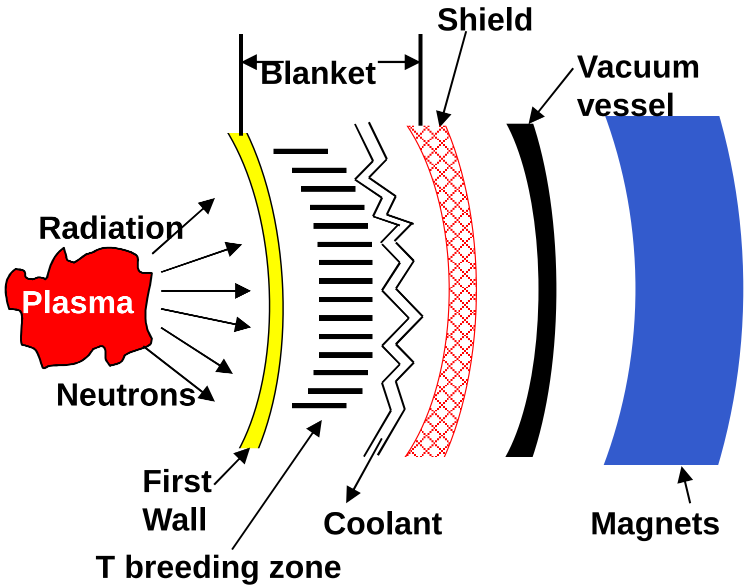
FUSION REACTION

D + T→ ^{4}He (3.5 MeV) + n (14.1 MeV)

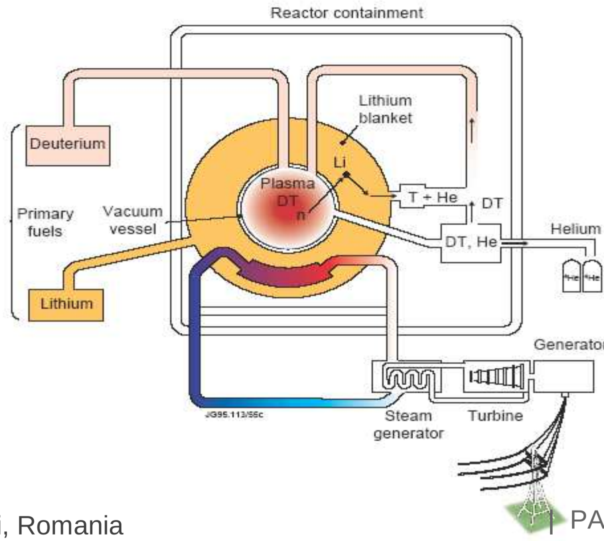
- **Deuterium** can be extracted from natural water: Standard mean ocean water contains 0.016% D
- **Tritium must be bred internally from lithium**
  - ~150 kg tritium is required per GWe year of fusion power
  - About 100 g tritium is produced per year in a standard CANDU reactor
  - Breeding reactions in a fusion reactor

n + ^{6}Li → T + ^{4}He

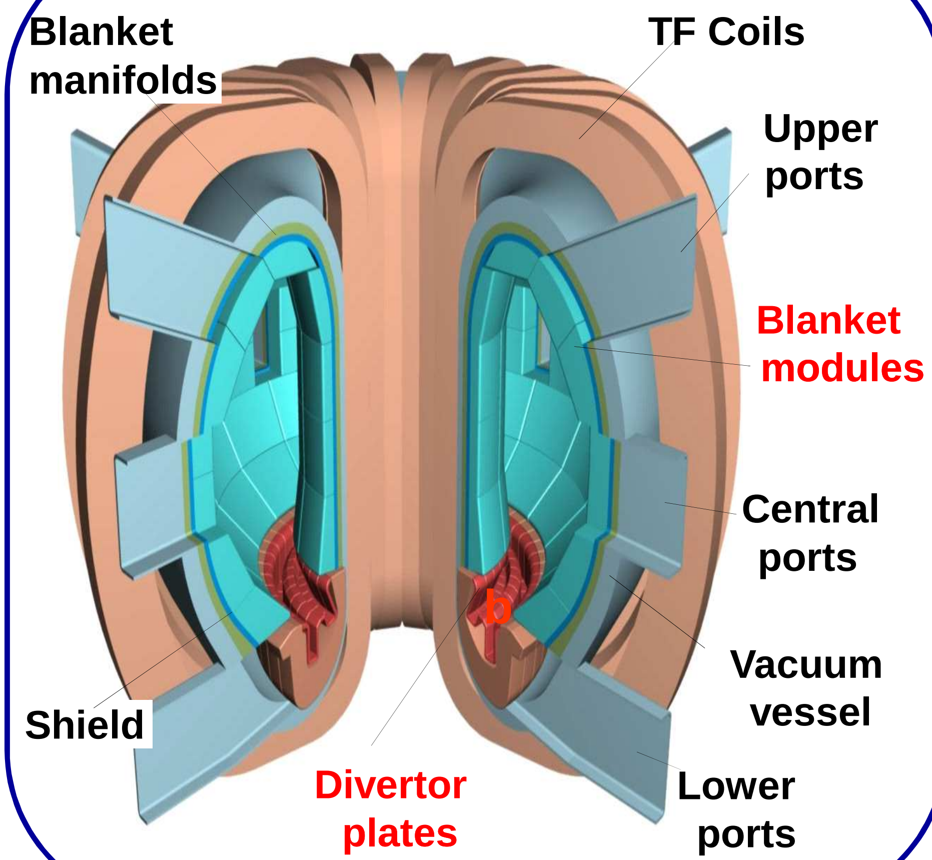
n + ^{7}Li → T + ^{4}He + n



(Source ENEA, I. Ricapito, Nov 2006)



SYNERGIES BETWEEN FISSION AND FUSION ENERGY



1 – Design methods and codes for plasma facing components and tritium breeding blankets *(structural materials, manufacturing, reliability, lifetime…)*

2 – Safety approach & licensing *(safety regulation, licensing procedure…)*

3 – Materials & Systems Technology *(high temperature, neutron damage)*: **AFMA, ODS, C-C, SiC_f-SiC…** and design rules

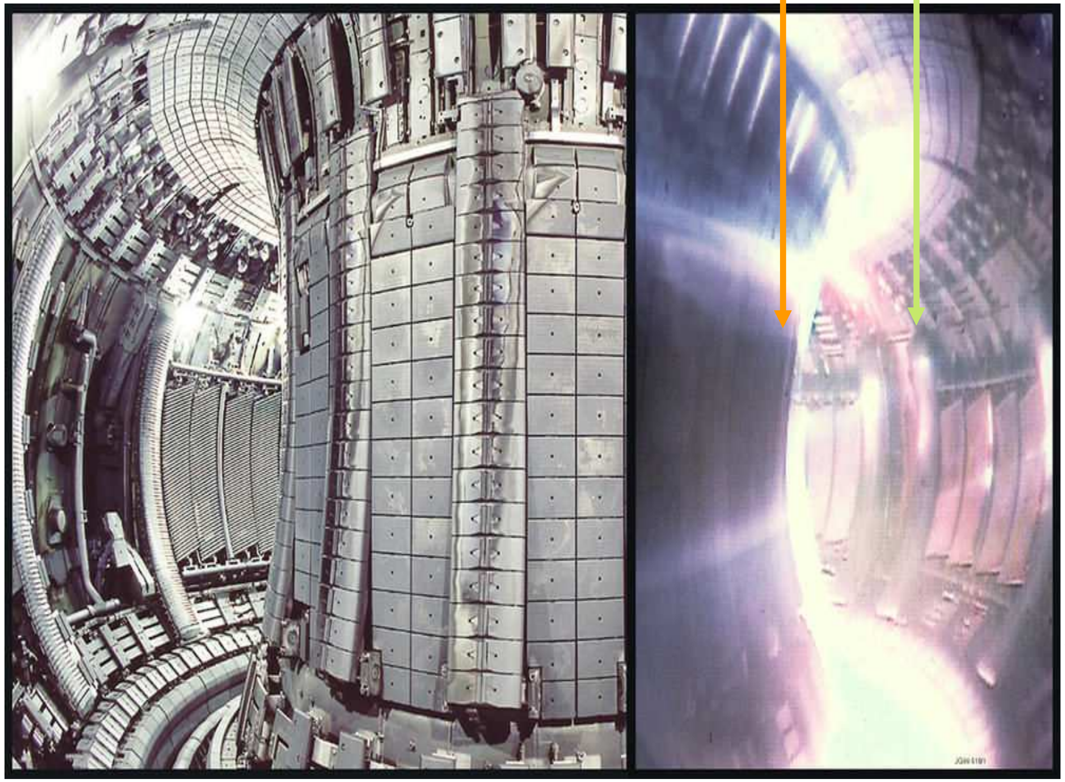
4 – In service inspection, decom-missioning & waste management

5 – Tritium breeding & Production of initial load

IN-VESSEL COMPONENTS & BREEDING BLANKETS

100 000 000 °K (centerline)

1 000 °K (first wall)



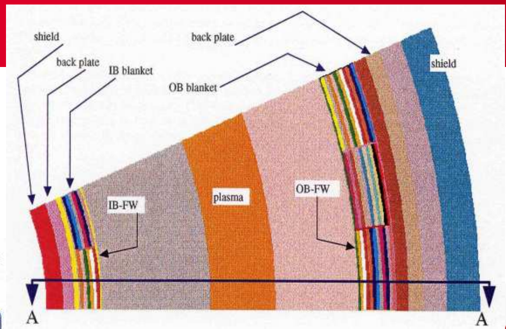
Very severe operating conditions & requirements

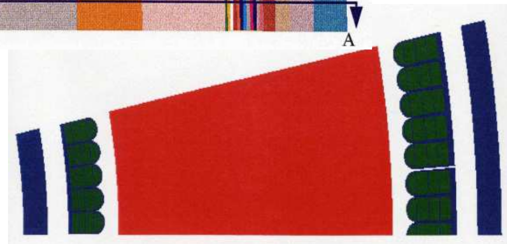
- **High surface heat flux**
  0.5 (FW) ➔ 15 MW/m² (divertor)
- **High neutron wall loading (FW)**
  ~2.5 MW/m², ~150 dpa (Fe)
- **Operation under void (plasma), complex torus geometry**
  ➔ Low coolant leakages
- **High magnetic field (~7 Tesla)**
  (high MHD effects)

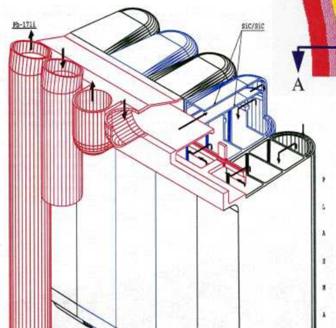
Moreover: Remote access in high radiation field
(maintenance, inspection, repairs, diagnostics,…)

(Source CEA, JF. Salavy, Nov 2006)

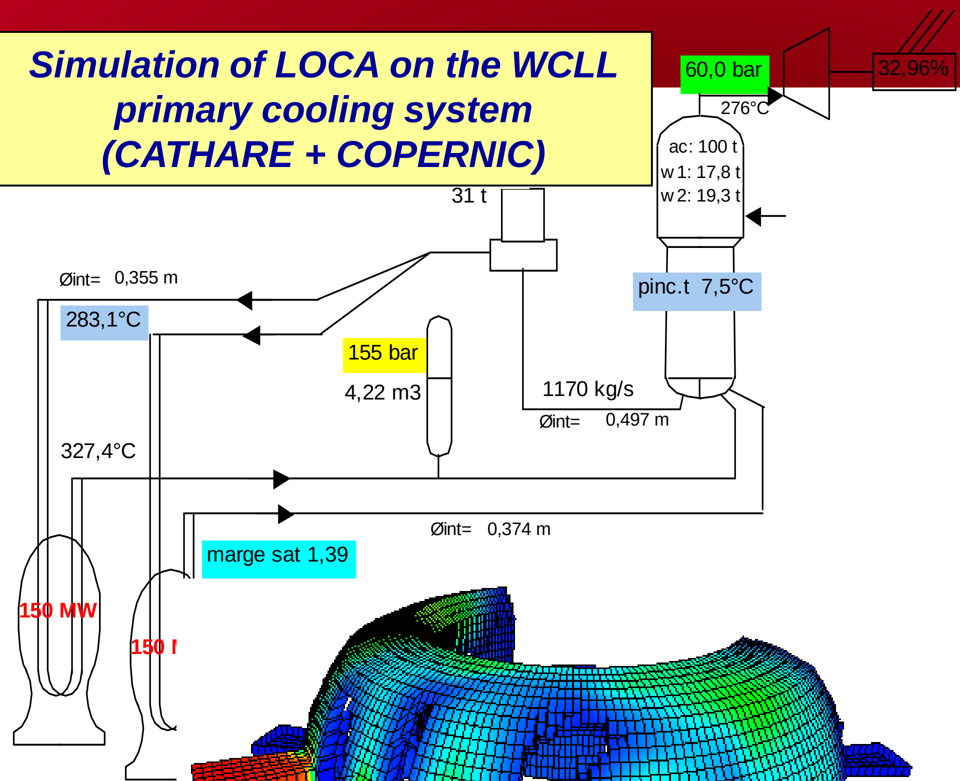
DESIGN AND SAFETY CODE SYSTEM



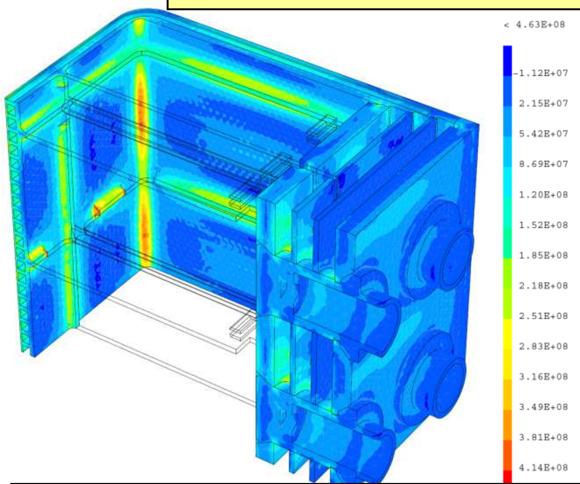




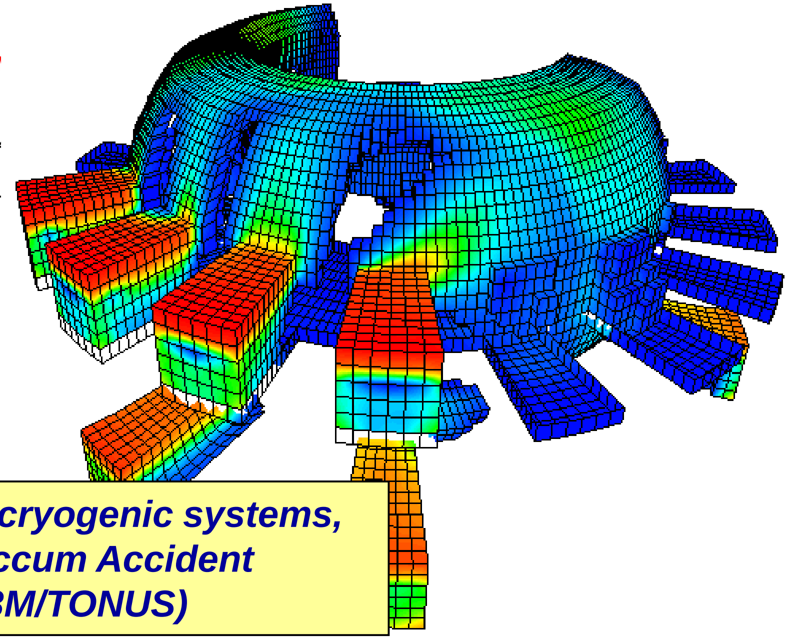
Evaluation of Tritium Breeding Ratio (TBR) with TRIPOLI-4



Simulation of LOCA on the WCLL primary cooling system (CATHARE + COPERNIC)



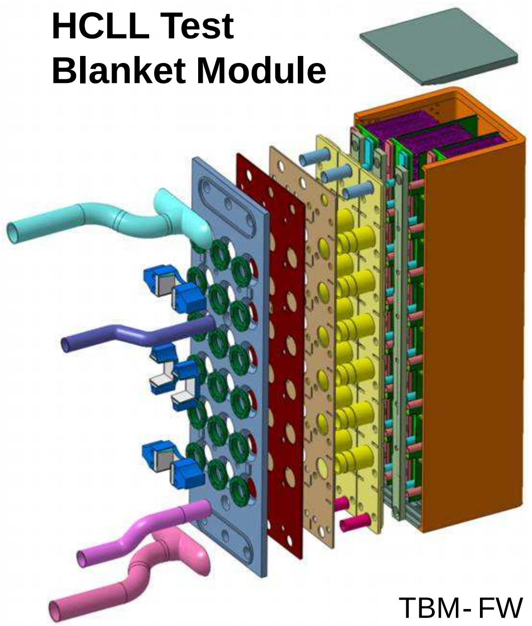
Thermo-mechanical Analysis of HCLL Blanket Module (CAST3M)



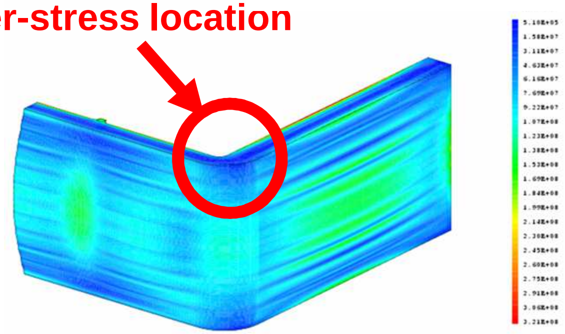
H_2 release from cryogenic systems, Loss of Vaccum Accident (CAST3M/TONUS)

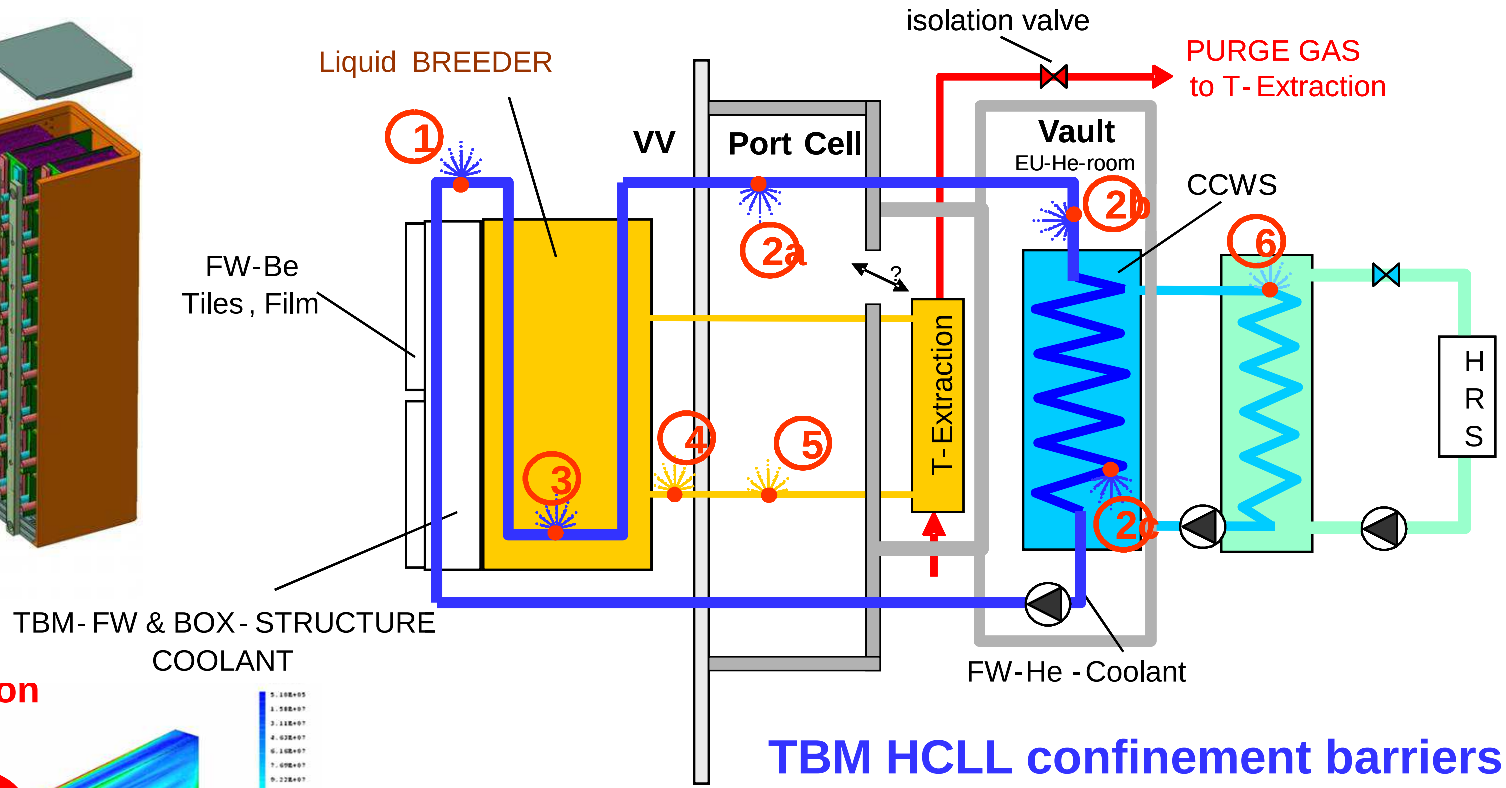
Analysis with CASTEM of thermal and mechanical loading of ITER-TBM *(HCLL concept)* in LOCA conditions

HCLL Test Blanket Module



Over-stress location





TBM HCLL confinement barriers

Standard CAST3M with implementation of specific materials properties (Be, Pb-Li, helium)

SAFETY ANALYSIS & LICENSING PROCESS

Specific aspects of D-T Fusion Tokamak reactors

- **Inherent safety of plasmas**
- **Production of radioactive nuclei by activation only**
- **Low decay heat**
- **Pulsed operation & Control of plasma disruption**
- **Large energy stored in the magnetic configuration**

Common features with fission reactors

- **Confinement of radioactive materials: large Tritium hold-up, activation products in the system** *(Mn, Fe, Co, Ni, Mo in steels + Cu, Co, Zn in copper alloys)*
- **Removal of power (in operation and at shutdown)**

Safety and licensing

- **Adaptation of Fission safety demonstration to Fusion experimental devices → Safety case of ITER and DEMO**

MATERIALS FOR FISSION & FUSION SYSTEMS

	Present Generation		Next Generation	
	Fission (Gen. II&III)	**Fusion (ITER)**	**Fission (Gen. IV)**	**Fusion (Reactor)**
T_{max} (structural material)	<300°C	<300°C	500-1000°C	**550-1000°C**
DPA max (internal components)	~1 dpa	~3 dpa (TBM)	~30-100 dpa	**~150 dpa**
He Production	~0.1 appm	~30 appm	~3-10 appm	**~1500 appm**
He/dpa	~0.1	~10	~0.1	**~10**
Structural material	***Austenitic steels, Zircaloy***	***Austenitic steels***	***Ferritic steels, Superalloys ? SiC-SiC ?***	***Ferritic martensitic steels, SiC-SiC ?***

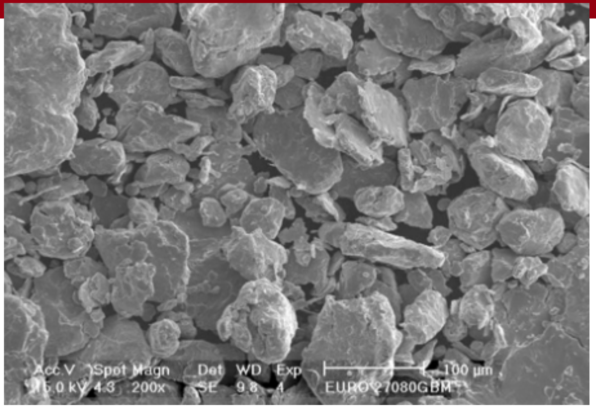
*Comparable service conditions : **high temp.** (>500°C) & **high dpa** (>100 dpa)*

ADVANCED STRUCTURAL MATERIALS FOR FUSION REACTORS

Options considered

- **Low activation martensitic steel**
  - → **Replace elements subject to activation**

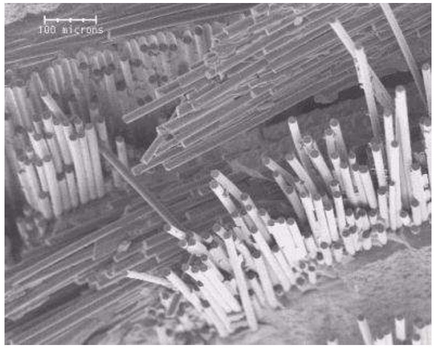
    Ni, Mo… → Mn, W…
  - → **Low activation martensitic steel EUROFER**
    - Operating conditions 500-650°C ***(ODS)***
    - Several tonnes already manufactured

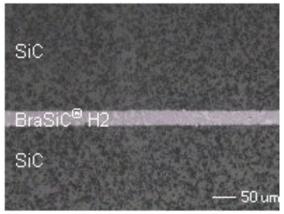


Powder of EUROFER strengthened with 0.2% Y_2O_3

- **Vanadium alloys or SiC composite ceramics**
  - → **Heat resisting materials with fast des-activation**
  - → **Less known materials → Longer term use**
    - Operating conditions
      - 700°C ***(V)***
      - 1000°C ***(SiC-SiC)***

SiC/SiC



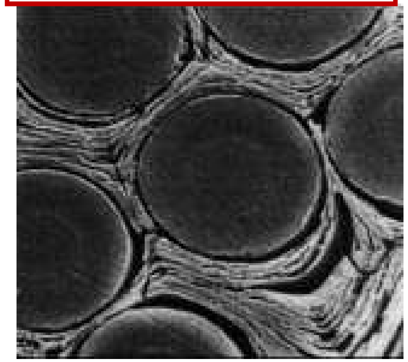


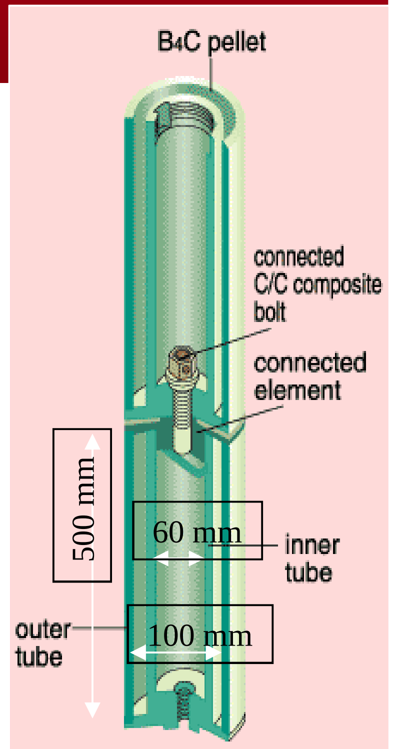
Assembling SiC/SiC and SiC/W

C/C & SiCf/SiC composites

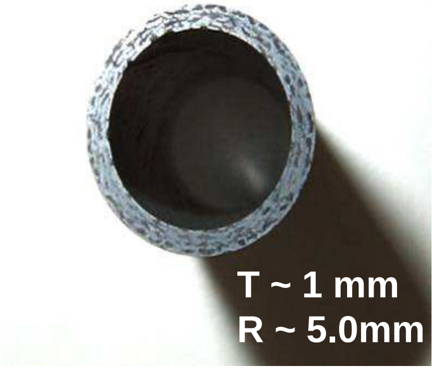
→ **Manufacturing:** 2D & 3D woven fibres (C, Hi-Nicalon S), interphases, CVI or pitch densification, anti-oxidation coating (Si, B)…)
→ **Technical file for codification** of design Standards

ORNL (L. Snead)

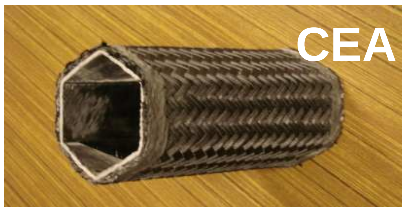


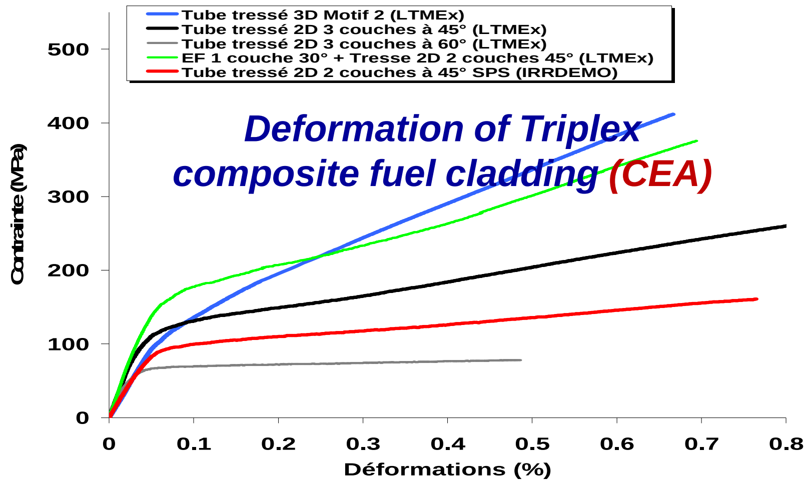


Fuel Pin Cladding
Nite Process
Kyoto University

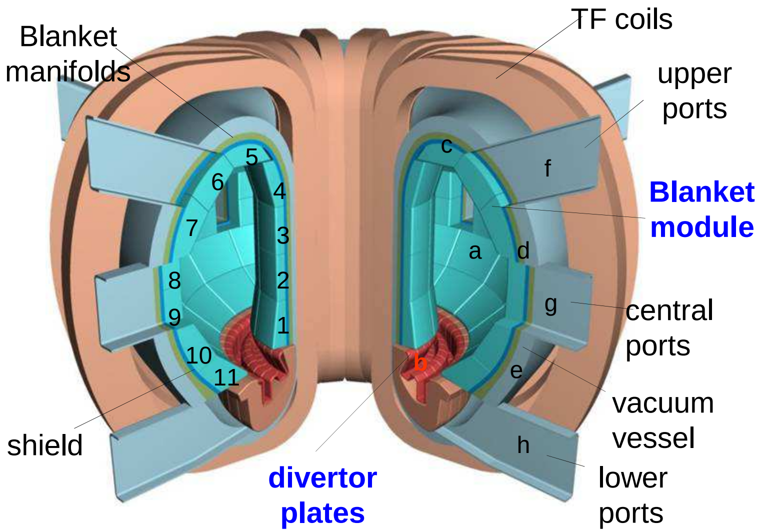


Hexagonal wrapper tube for SFR subassembly





MATERIALS CONSIDERED FOR FUSION REACTORS



Breeding Blankets (DEMO ➔ Reactor)

- **Structural materials: EUROFER, EUROFER ODS, SiC_f/SiC** (+ beyond EU: other M/FS, V alloys)
- **Tritium breeder materials:** $LiPb_{eu}$, Li_2TiO_2, Li_4SiO_4 (+ beyond EU: Li_2O, Li)
- **Functional materials:** Be (neutron multiplier), permeation barrier & corrosion, electric insulators in **SiC_f/SiC**, shielding PP (W)
- **Coolants**: He, $LiPb_{eu}$ (+ beyond EU: Li, water SP)

Divertor (DEMO ➔ Reactor)

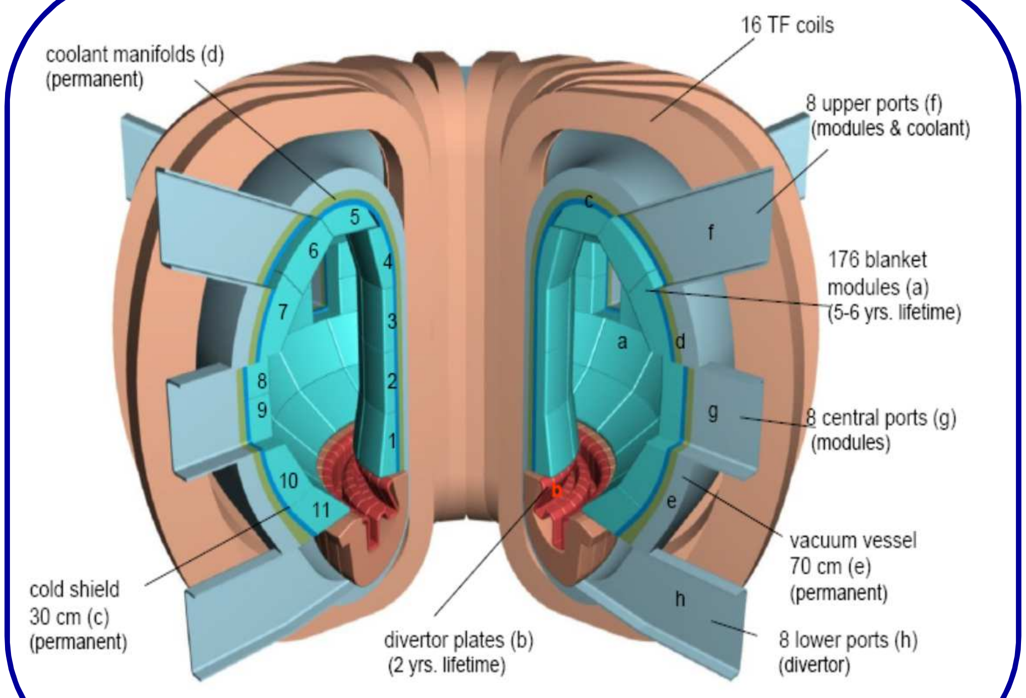
- **Structural materials: W alloys**, **Eurofer (+ interface in C), Eurofer ODS, SiC_f/SiC** (+ brazing?) (+ beyond EU: other M/FS, V alloys)
- **Shielding materials: Ceramics** or W tiles
- **Coolants:** He, pressurized water, $LiPb_{eu}$ (+ beyond EU: Li)

R&D needs (measurements & improvements)

- Behaviour under irradiation (mechanical, thermal, neutronic, electrical, …)
- Irradiation behaviour
- Modelling
- Compatibility between materials
- Fabrication (ex.: **CIC**, particle bed..)
- Assembly (ex.: interface, weldings…)
- Low long term activation

DESIGN & TECHNOLOGY OF BREEDING BLANKET (1/2)

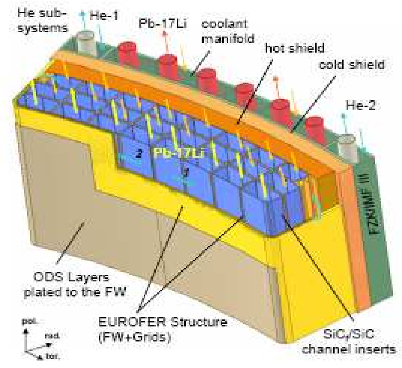
Typical Tokamak Configuration T-Breeding Blanket: Dual Coolant Lithium Lead



Fusion Power Reactor Dual-Coolant T-Blanket

He, 80 bars	**Pb-17Li, ~**bar
300, 480 ^{0}C	480-700 ^{0}C

Dual-Coolant T-Blanket



Martensitic Steels (550 ^{0}C)

ODS Ferritic steels (700 ^{0}C)

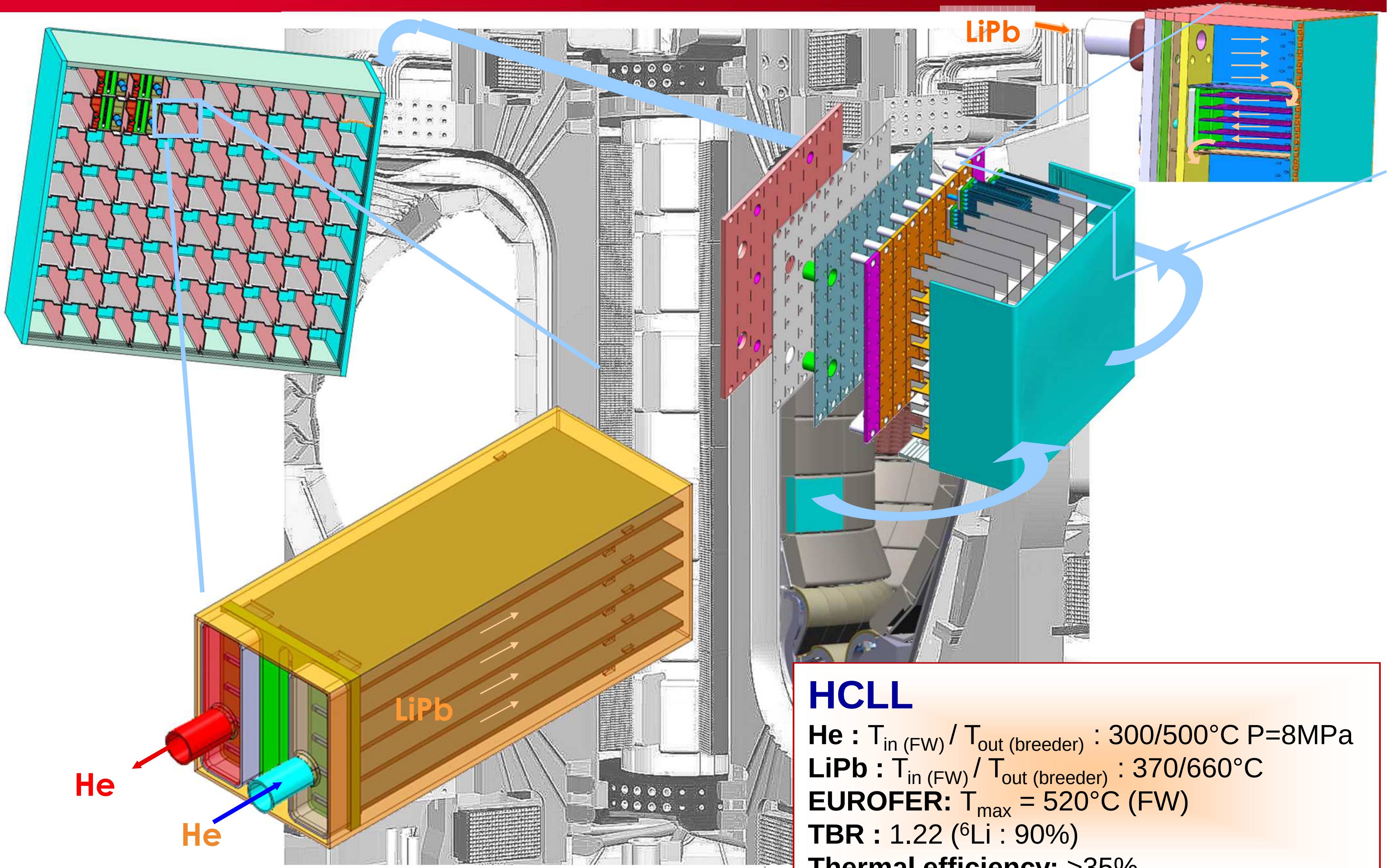
SiC$_f$-SiC th. & elect. insulator

F W: T max= 625 ^{0}C

Channel : Tmax= 500 ^{0}C

Insert : Tmax~1000 ^{0} C

DESIGN & TECHNOLOGY OF BREEDING BLANKET (2/2)

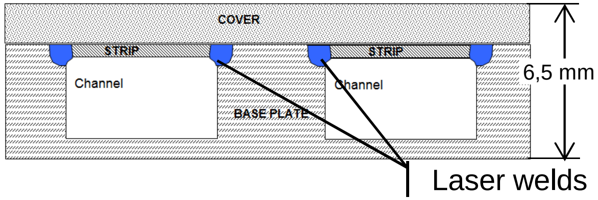


HCLL

He : $T_{in\ (FW)}$ / $T_{out\ (breeder)}$: 300/500°C P=8MPa
LiPb : $T_{in\ (FW)}$ / $T_{out\ (breeder)}$: 370/660°C
EUROFER: T_{max} = 520°C (FW)
TBR : 1.22 (^{6}Li : 90%)
Thermal efficiency: >35%

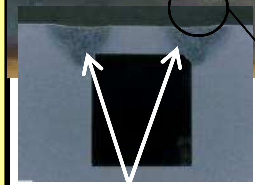
Fabrication of He Cooling Plate and Stiffeners for HCLL TBM

Manufacturing technology
(CEA patent)

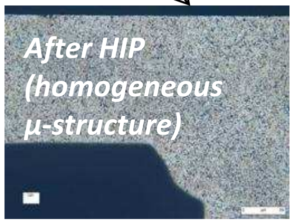


Before welding

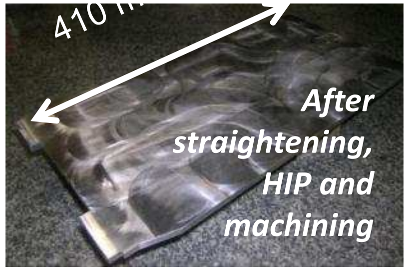
After laser welding

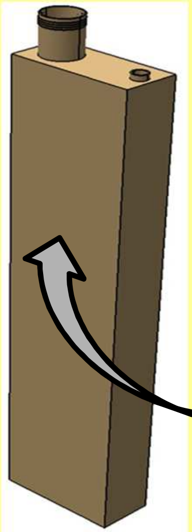


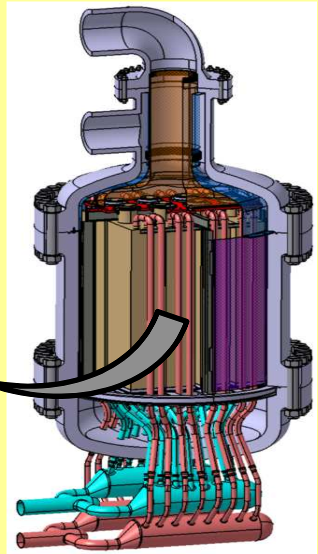
Melt Zone (laser welds)



After HIP cycle





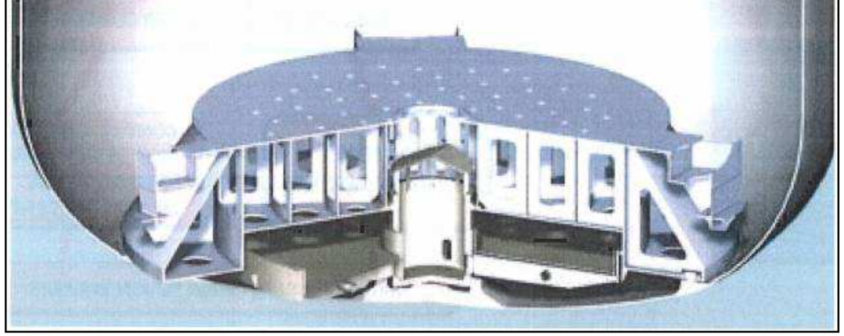


DIADEMO ***mockup for SFR of sodium /gaz heat exchanger***

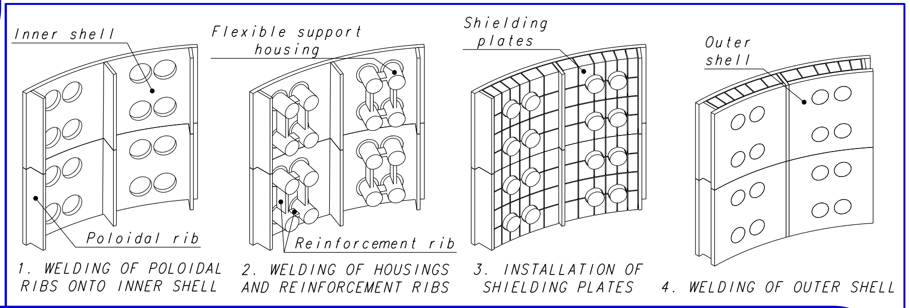
ANALYSIS OF COMPONENT INTEGRITY & DESIGN RULES

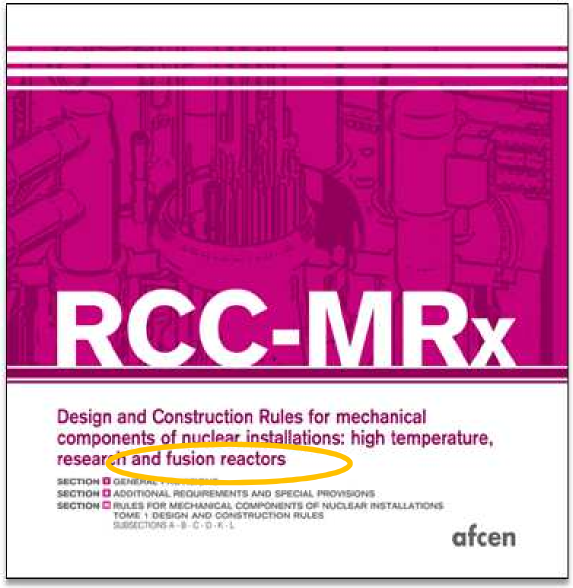
- **RCC-MR, developed for Sodium Cooled Fast Reactors in Europe (EFR, Phenix lifetime extension), has been selected for the design & construction of ITER Vacuum Vessel** (high temperature and low pressure operation, "box" structure, 316 L(N) steel, fabrication, weldings…)
- Huge R&D at European level to **develop and characterize Eurofer steel**

EFR core support with strongback resting on the main vessel bottom



ITER Vacuum Vessel box structure

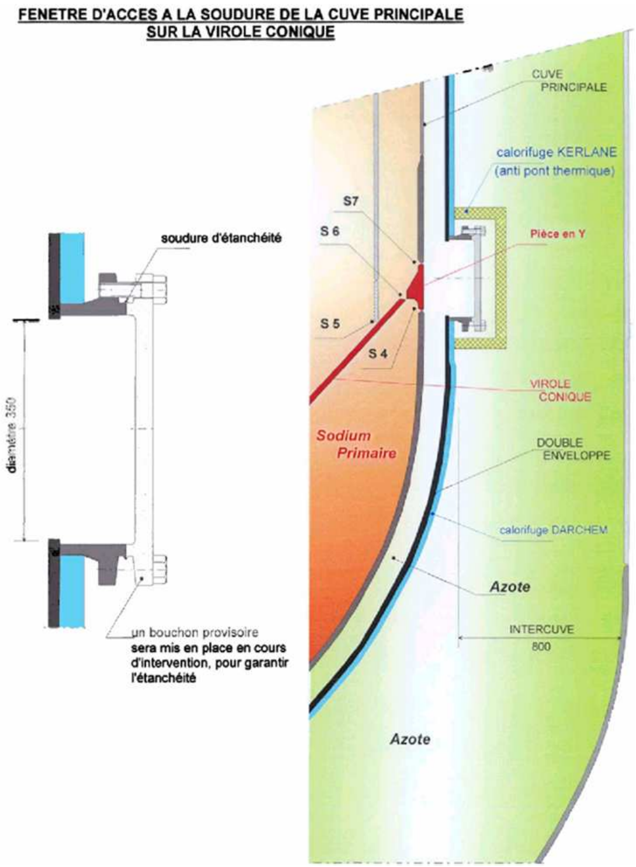


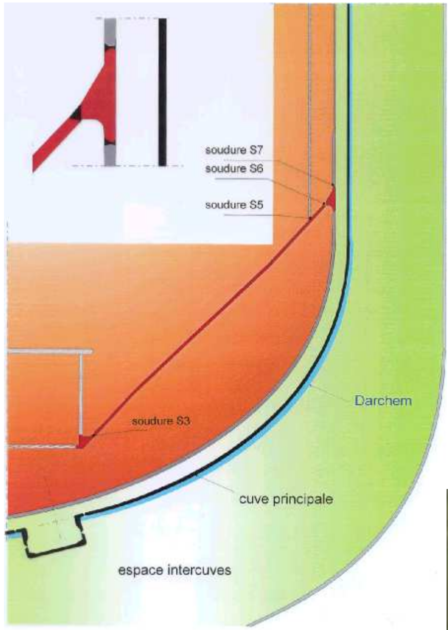


- Introduction of **Eurofer97 in the French RCC-MRx** design and construction code
- **RCC-MRx is selected** for the design and construction of the **test blanket module (TBM) for ITER**. The code will continue to be developed within the framework of the TBM program for fusion relevant aspects

IN-SERVICE INSPECTION OF PHENIX CORE SUPPORTING STRUCTURES

Control of Phenix Core Supporting Structure Weldings

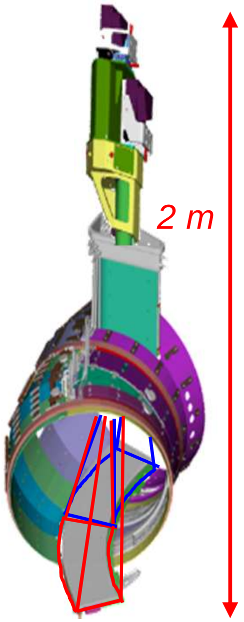




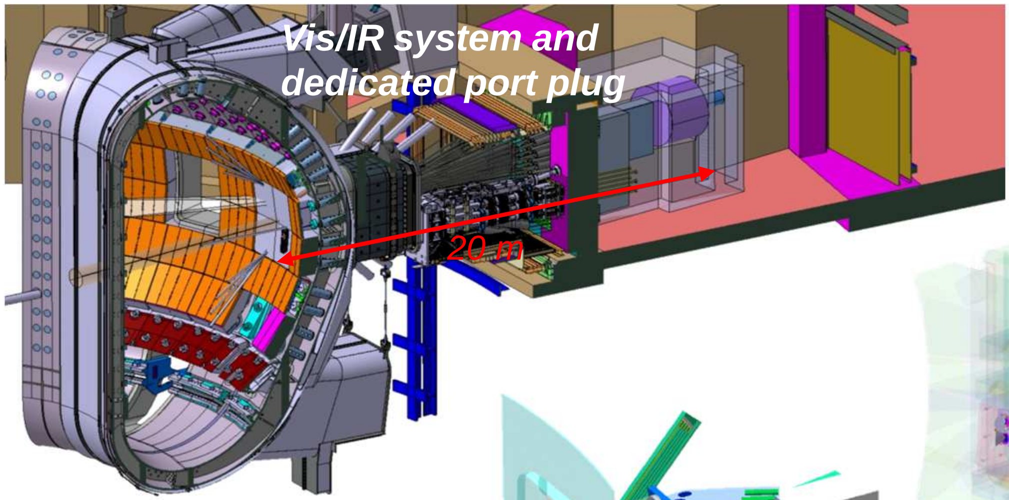
Intervention sur la virole conique

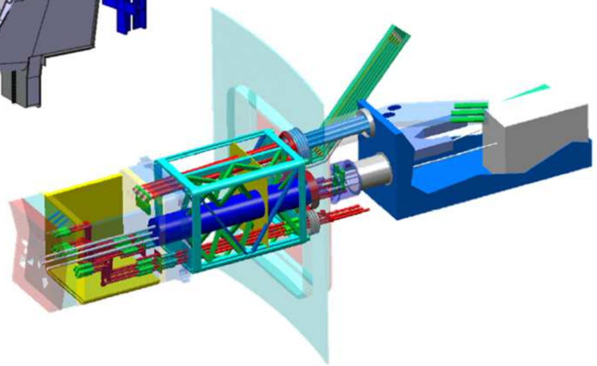
- ***Ultrasonic sensors***
- ***X-Tomography***

GEN-IV FISSION & FUSION REACTORS: A HIGH LEVEL OF INTEGRATION

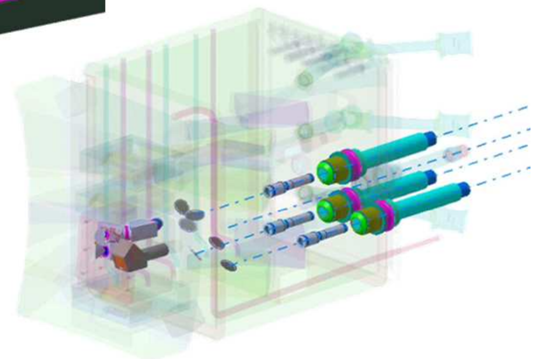


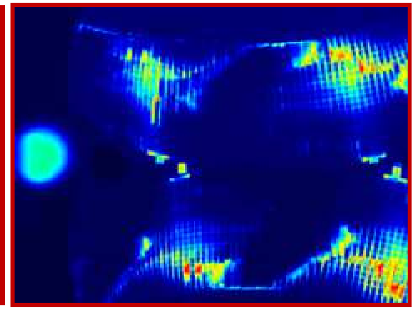
InfraRed endoscope in Tore Supra





Integration studies of ITER IR diagnostic in equatorial port plug n°1





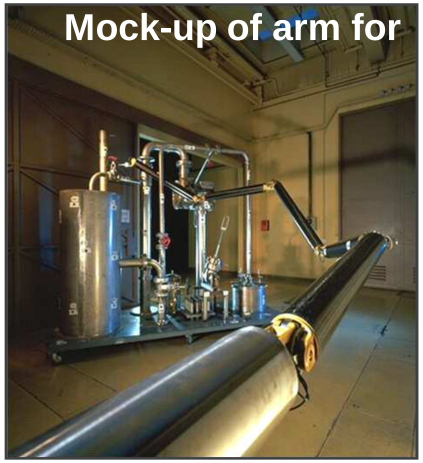
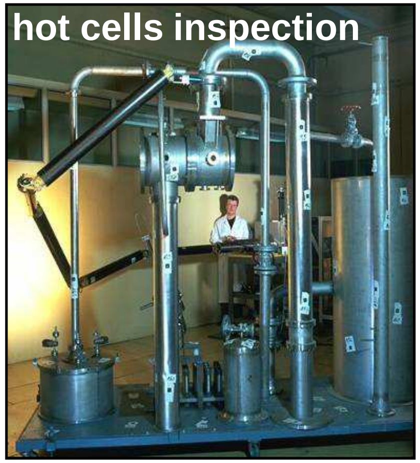
- ***ITER is a major step for fusion***
- ***ITER = integration of both present fusion and nuclear constraints***

New engineering tools

REMOTE MAINTENANCE TOOLS FOR INSPECTION IN HARSH ENVIRONMENT

CEA robotic developments of long reach arm for hot cells inspection

(1kg payload capacity, 6 segments 11 axis, L=7.2m, atmospheric pressure, ambiant T°)

Mock-up of arm for hot cells inspection

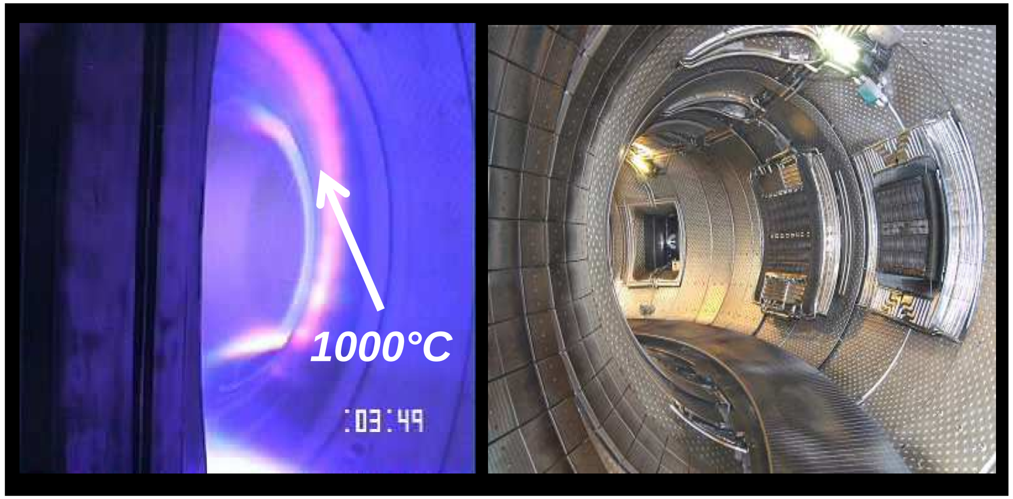
CEA development for Tokamak in-situ inspection : Articulated Inspection Arm (AIA)

(10 kg payload, 9,5 meters total length, Ultra High Vacuum (10^{-6} Pa) and 120°C)

AIA is a versatile arm able to plug different tools (camera, leak detection, diagnostics...)

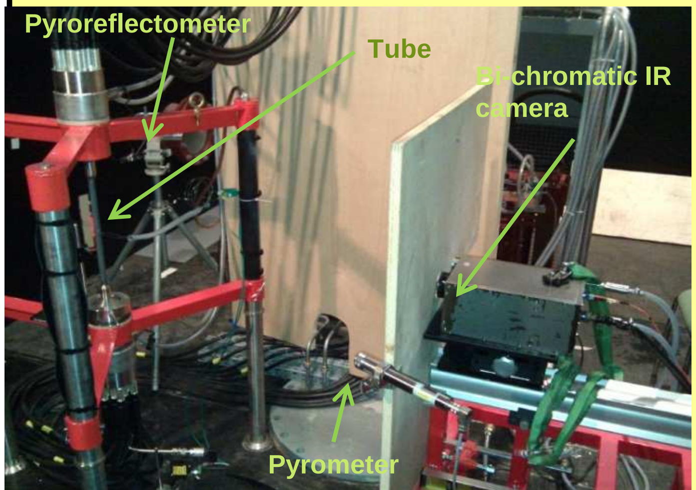
AIA operation inside the CEA WEST tokamak vacuum vessel

FUSION DIAGNOSTICS APPLICABLE TO FISSION



In-situ IR monitoring during plasma shot in fusion device

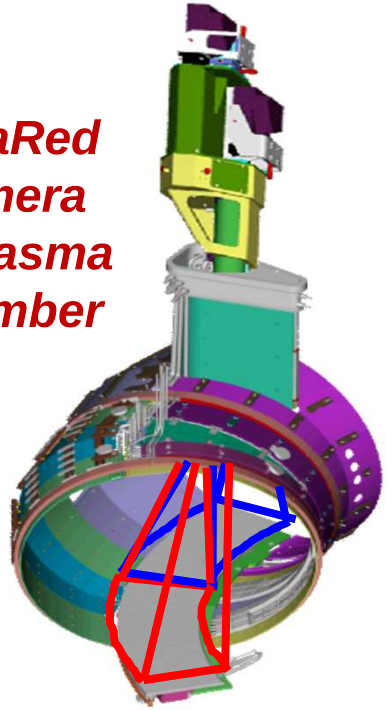
- ***First wall monitoring in fusion devices***
  - **Temperature measurement by Infra-Red camera**
  - **Measurement of erosion by confocal microscopy**



- ***Infra-Red monitoring of steam generator tube temperature to detect abnormal conditions***

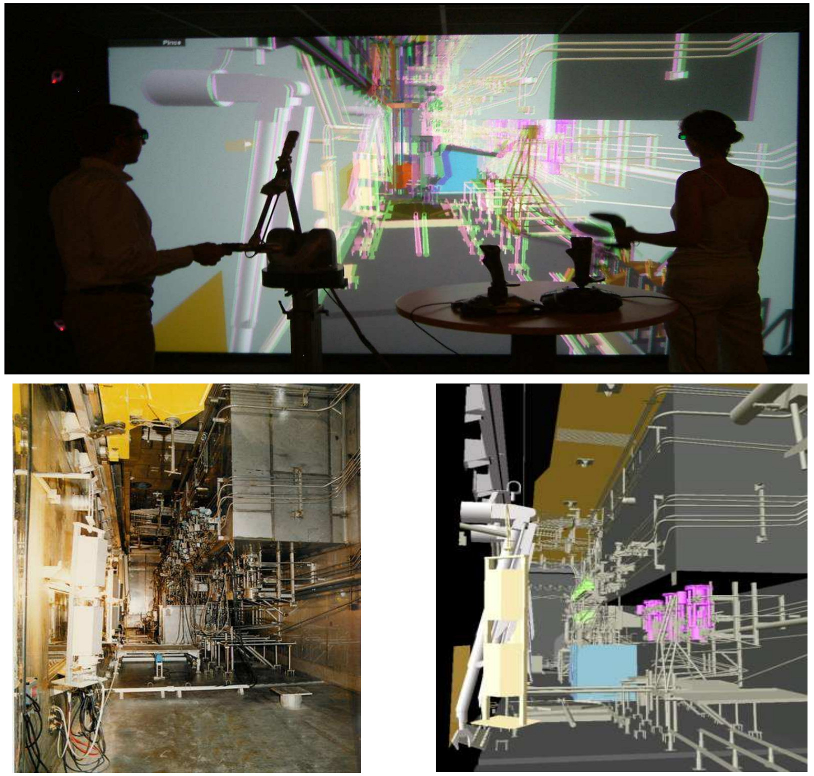
Bi-chromatic IR camera for temperature monitoring

InfraRed camera in plasma chamber

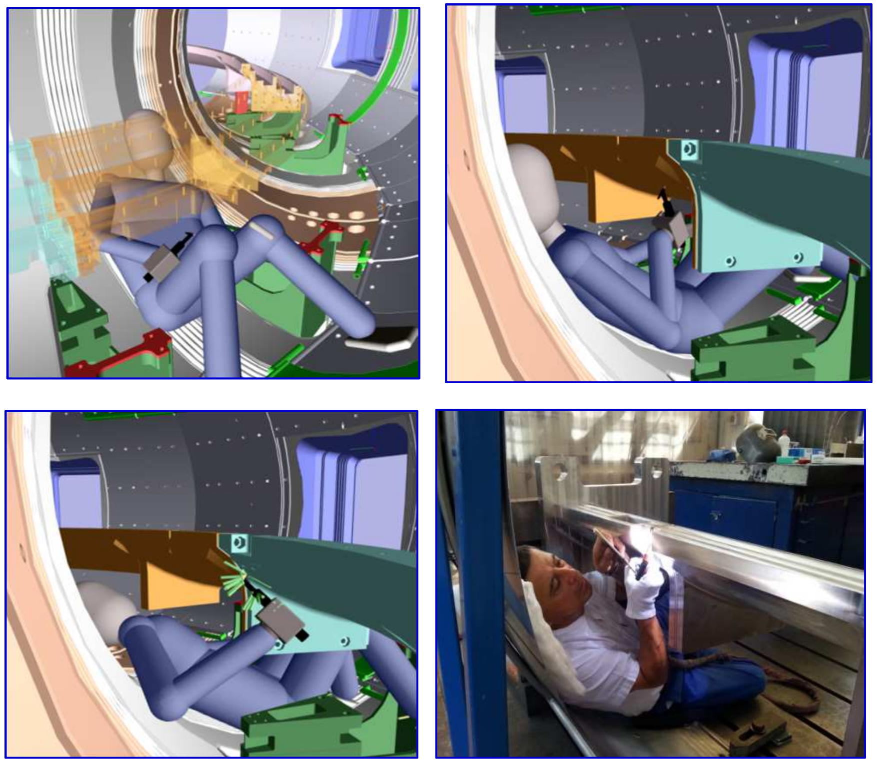


FISION REACTOR DISMANTLING: VIRTUAL REALITY FOR INTERVENTIONS IN COMPLEX ENVIRONMENTS

➤ ***Virtual Reality for dismantling fission reactors & Fuel cycle plants***



Dismantling scenario qualification (CEA/Marcoule)



Accessibility studies for in situ manufacturing (CEA/WEST project)

Close collaboration between Fusion and Fission teams for the development of Virtual Reality instruments

LASER INDUCED BREAKDOWN SPECTROSCOPY

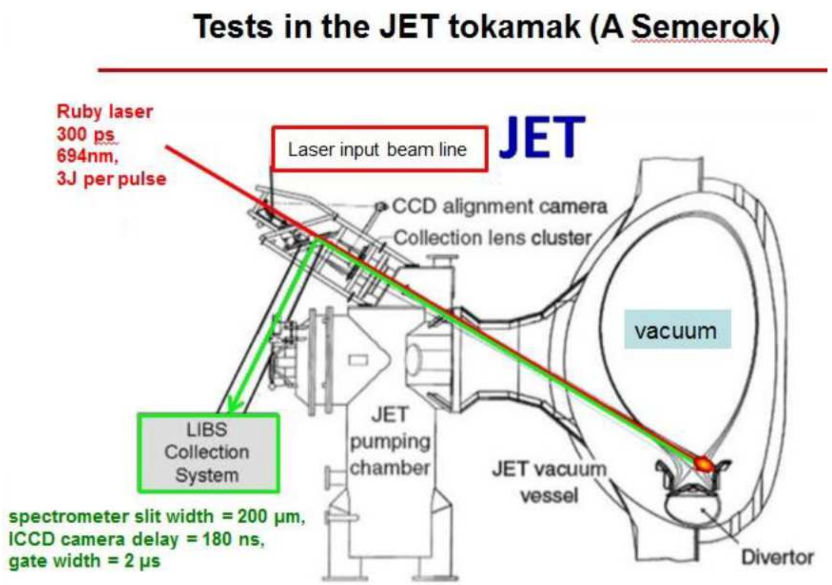
Laser Induced Breakdown Spectroscopy (LIBS) developed for real-time analyses (sample composition) in severe environment

Laser induced breakdown spectroscopy application in Joint

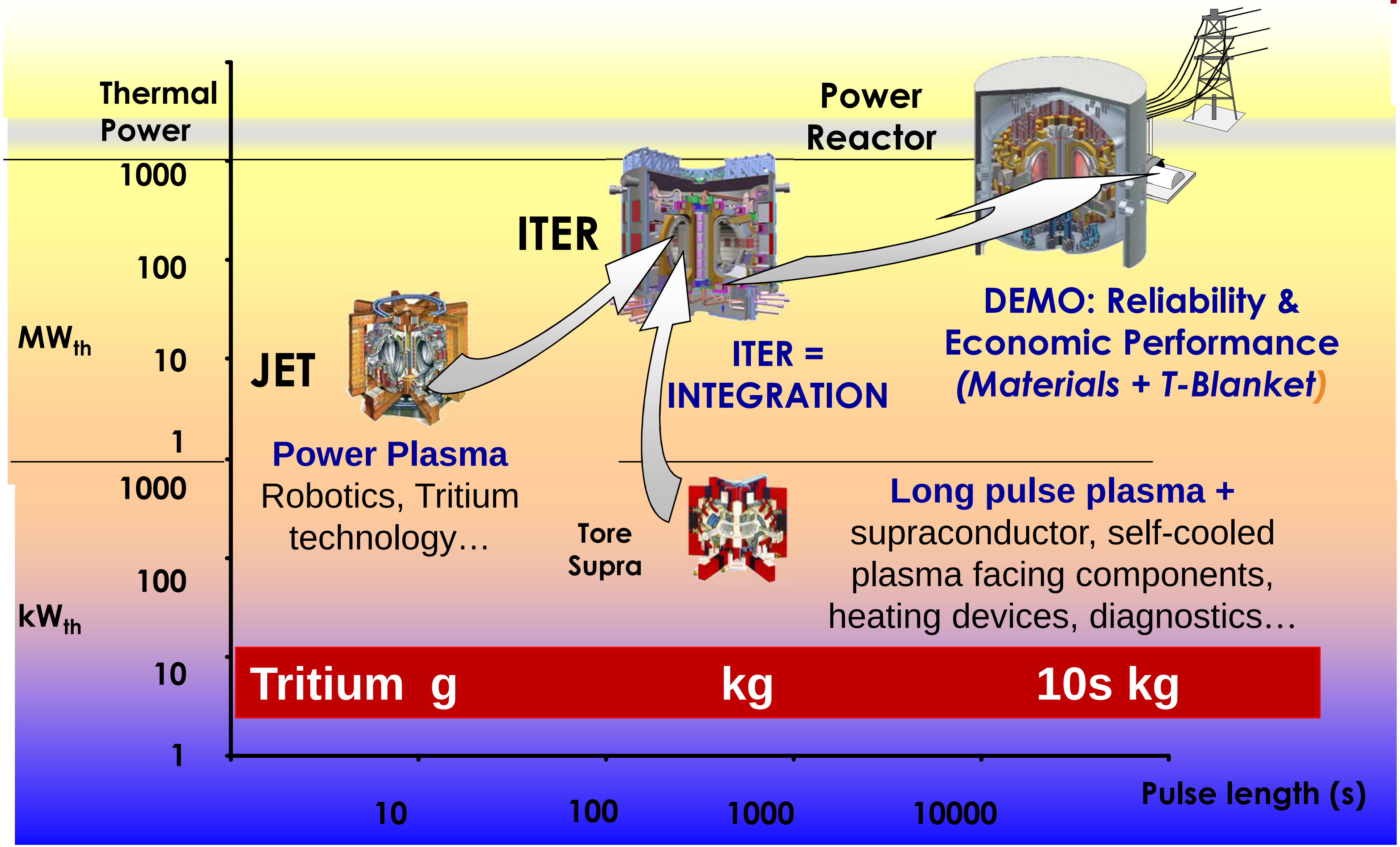
European Torus (JET)

[A. Semerok et all, Spectrochimica Acta Part B 123 (2016) 121–128]

Development of LIBS (ps) for both quantitative detection (composition and profilometry) of tritium retention in Tokamak.



ITER & MAGNETIC FUSION DEVELOPMENT PATHWAY



TRANSAT: A TRANSVERSAL ACTION FOR TRITIUM

- **TRANSAT, a European H2020 project focused on Fission-Fusion commonalities on tritium** (CEA as coordinator, 8 EU countries involved, 2018-2021)

TRANSAT
TRANSversal Actions for Tritium
http://transat-h2020.eu/

- Cross-cutting support to **improved knowledge on tritium management in fission and fusion facilities**
  1. Tritium permeation control
  2. Assessment of the tritium inventory using state-of-the-art modelling tools
  3. Engineering solutions for detritiation techniques and waste management
  4. Refinement of the knowledge on outgassing, radiotoxicity, radioecology, radiobiology, dosimetry and metrology of tritium

- **First International School on Tritium organised in Ljubljana (Slovenia, 25-28/03/2019)**

SYNERGIES BETWEEN FISSION AND FUSION NUCLEAR ENERGY

Summary

- **Nuclear Design and Technology**
  - Codes and design methods
  - High temperature and neutron resistant materials
  - Gas, water or liquid metal cooled systems technology
  - In service inspection, maintenance in hostile environment
  - Dismantling and waste management
- **Safety approach and licensing**
- **Increased synergies for the Fusion DEMO reactor**
  - Optimization of blanket design for energy and tritium production
  - Demonstration of full tritium breeding and recovery
  - Production of initial tritium load
- **Education in nuclear physics and engineering**
  - Attraction of young scientists in the fields of nuclear energy
  - Stimulation of education and training in nuclear physics and engineering
- **Towards more integrated Fusion and Fission programs**