FUSERO: JHR's applicability to fusion research by neutron irradiation experiments

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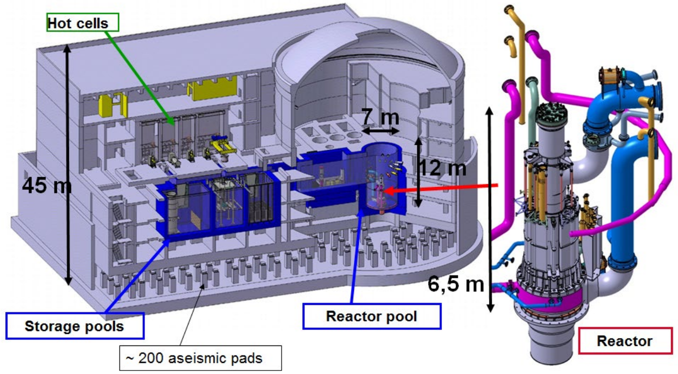
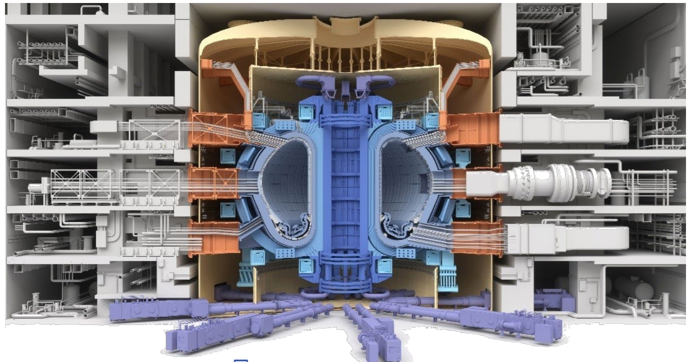
FUSERO: JHR's applicability to fusion research by neutron irradiation experiments

1. Context
   Experimental irradiations in MTR, JHR, FUSION needs
2. FUSION irradiation programs
3. FUSERO A
   Functional materials for diagnostic or current drive systems windows
4. FUSERO B
   Cryogenic testing for irradiation of magnet materials
5. FUSERO C
   Thermo-Mechanical Fatigue (TMF) for first wall and divertor materials
6. Conclusions





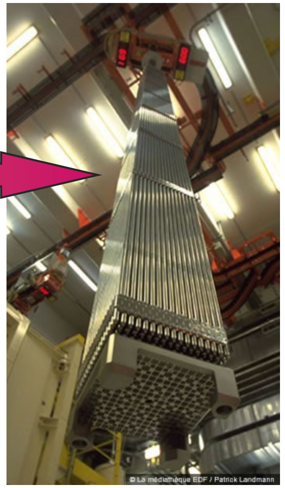
1. Context

Experimetal irradiations in MTR, JHR,

Fusion needs

Fuel & materials irradiation needs in the nuclear industry

Selection → **Characterisation** → **Qualification** →



Selection

- Main objectives
  - ✓ Basis irradiation of several innovative products under similar conditions
- Main requirements
  - ✓ High embarking capacity
  - ✓ Few instrumentation
  - ✓ Post irradiation examination

Characterisation

- Main objectives
  - ✓ Measurement of physical properties under neutron flux
  - ✓ Investigation of: Burn-up effect / Fission gas release / Pellet-Clad interaction / Chemical effect / Creep phenomena …
- Main requirements
  - ✓ High instrumentation
  - ✓ Accurate control of environment conditions (steady or transient)
  - ✓ Single effect experiments

- Parametric irradiations
  - ✓ ex: Microstructure effect experiments

Qualification

- Main objectives
  - ✓ Reproduction of environment conditions of power reactors in normal and off-normal situations
  - ✓ Envelope situations targeted
- Main requirements
  - ✓ Good representativity of power reactor (steady and transient states)
  - ✓ Long term or short term irradiations

The figure shows the three stages of a research program necessary to bring new materials, or fuel, into a nuclear environment.

JHR facility & experimental capacity

A 100 MW High Performances Research Reactor

~20 simultaneous experiments

In reflector
Up to 3.5E14 n/cm².s (th)

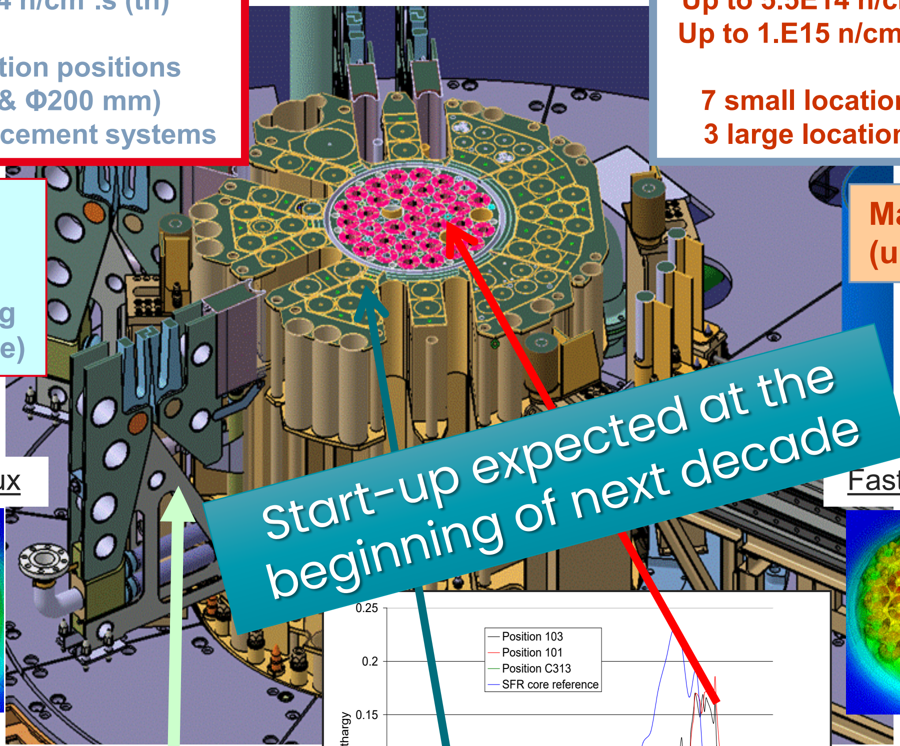
Fixed irradiation positions
(Φ100 mm & Φ200 mm)
and on 6 displacement systems

In core
Up to 5.5E14 n/cm².s (E> 1 MeV)
Up to 1.E15 n/cm².s (E> 0.1 MeV)

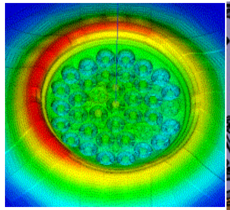
7 small locations (Φ ~ 32mm)
3 large locations (Φ ~ 80mm)

LWR fuel experiments
+
Material ageing
(low ageing rate)

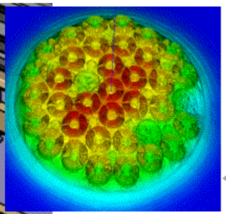
Material ageing
(up to 16 dpa/y)

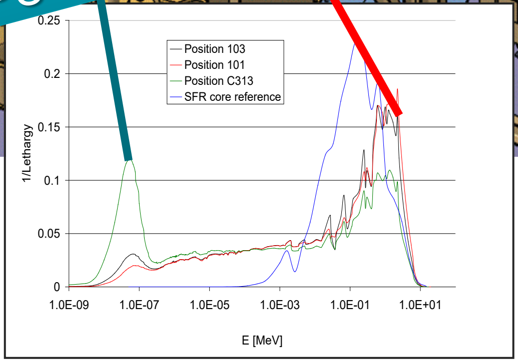


Thermal neutron flux



Fast neutron flux





Reliable Displacements Systems for Power adjustment, Power transient tests…

- New Material Test Reactor (MTR): **Jules Horowitz Reactor**
- @CEA **Cadarache**, France
- Under construction: start-up expected at the **beginning of next decade** (2030-2035)
- To perform **experimental neutron irradiations** in well controlled environment
  - Up to around 12 dpa/an
  - 6 cycles/year
  - 25 days/cycle
- Combined with Hot Laboratories to perform PIE (Post Irradiated Exams) on Material for full service
- **Pre-JHR era opportunities**

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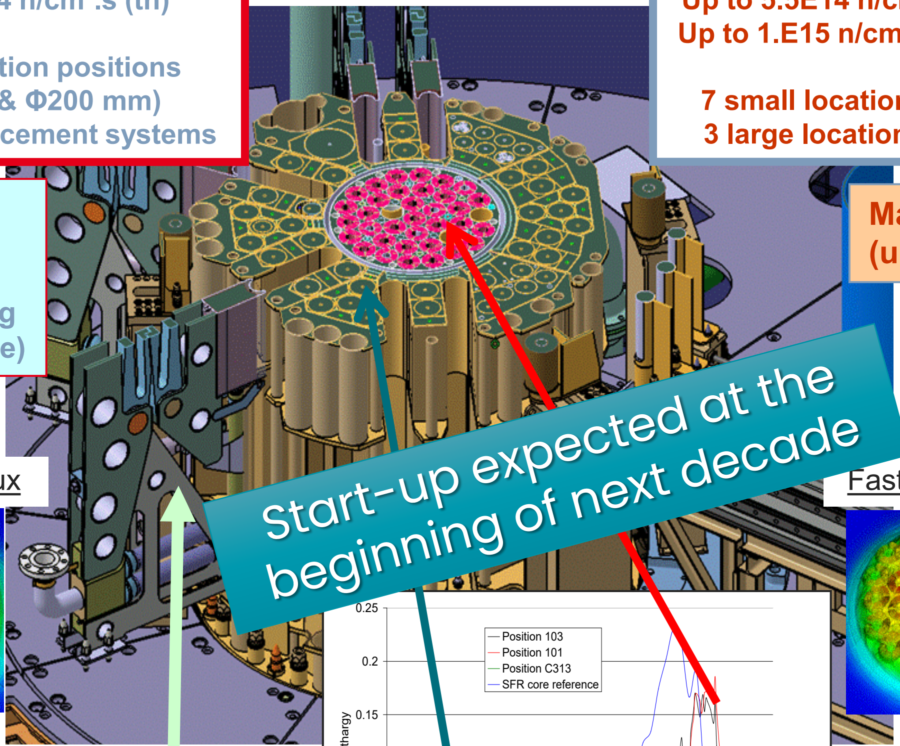
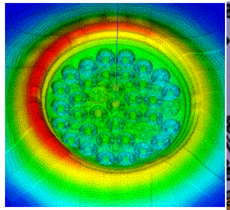
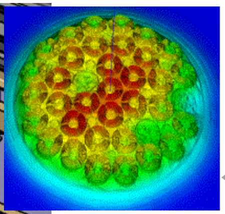


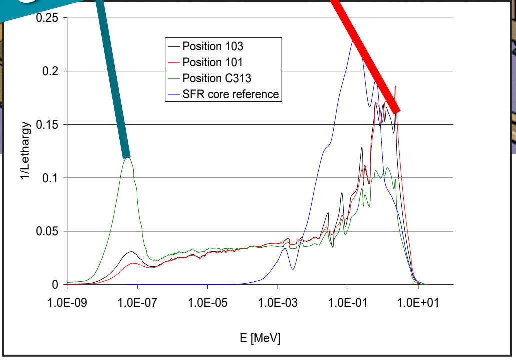
Start-up expected at the beginning of next decade

Thermal neutron flux



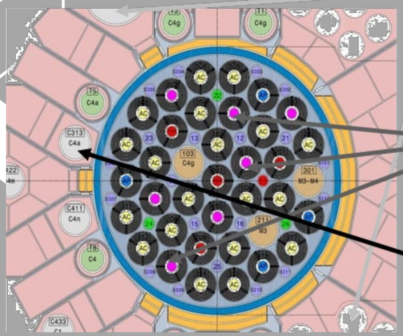
Fast neutron flux



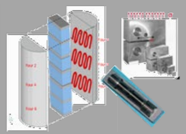


Reliable Displacements Systems for Power adjustment, Power transient tests…

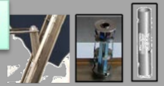
First fleet of irradiation material devices



OCCITANE



MICA / CALIPSO



CLOE

- Zr alloy corrosion
- IASCC studies

LORELEI (fuel)

Topic	Objective	Material	Instrumentation	Flux ($n.cm^{-2}.s^{-1}$)	Fluence ($n.cm^{-2}$) / dpa	Temp. (°C)
RPV	Dose accumulation	Low alloyed steels	Loading	$10^{11} – 10^{13}$	$< 2.10^{20}$	240 – 320
Internals	Dose accumulation	Stainless steels, Ni-based alloys		$10^{12} – 10^{14}$	10 – 80 dpa	320 – 390
	Environment effect		Loading, displacement meas.			
	Mechanical testing		Loading, displacement meas.			
Cladding	Mechanical properties	Zr-alloys SS	Loading, displacement meas.	$< 3. 10^{14}$		< 400°C
	Accident tolerance					

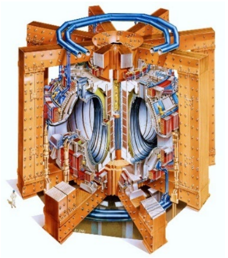
What is FUSERO?

Question: How can we exploit the JHR (or MTR) to help design future fusion reactors?

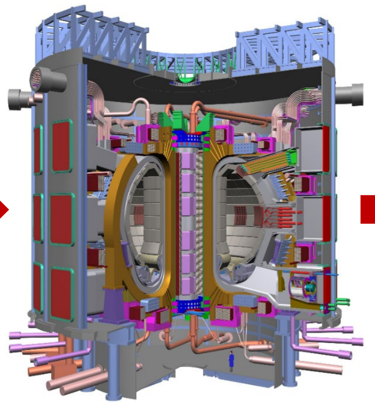
An international collaboration between
UKAEA-CCFE (Oxford, UK) and CEA-JHR (Cadarache, FR)

- Since 2014
- Secondees, apprentices, trainee @CCFE and @CEA

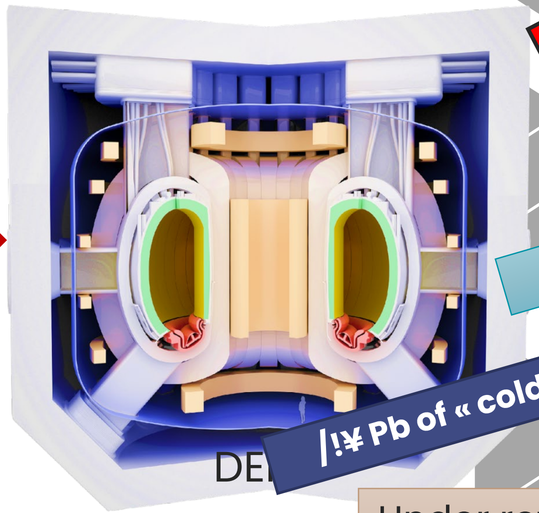
⇒ **Feedback from EUROfusion call and survey (2014, 2024) sent to both the "fusion and fission" communities**



JET
CCFE UKAEA



ITER



DE

Answers

Selection
Irradiation types

- Cook'n look irradiations in MTR
  - Selection stage
    (= many samples
    + few instrumentation)

⇒ **1st fleet of JHR irradiation devices**
(MICA, OCCITANE,…)

Characterisation
Irradiation types

Qualification
Irradiation types

- Highlighted 3 major areas for development
  - Characterization and qualification stages
    (= few samples
    + high instrumentation)

⇒ **FUSERO A, B, C**

/!¥ As a part of the vessel

/!¥ Pb of « cold » PIE facilities ?!

- A. Functional materials for diagnostic or current drive systems windows
- B. Cryogenic testing
- C. Thermo-mechanical fatig… for first wall and divertor ma…

/!¥ Interest of both communities fusion+fission

Under reflexions: FUSERO D, E,…
(ex. « Tritum » materials, PbLi loop under irradiation, conductivity…)

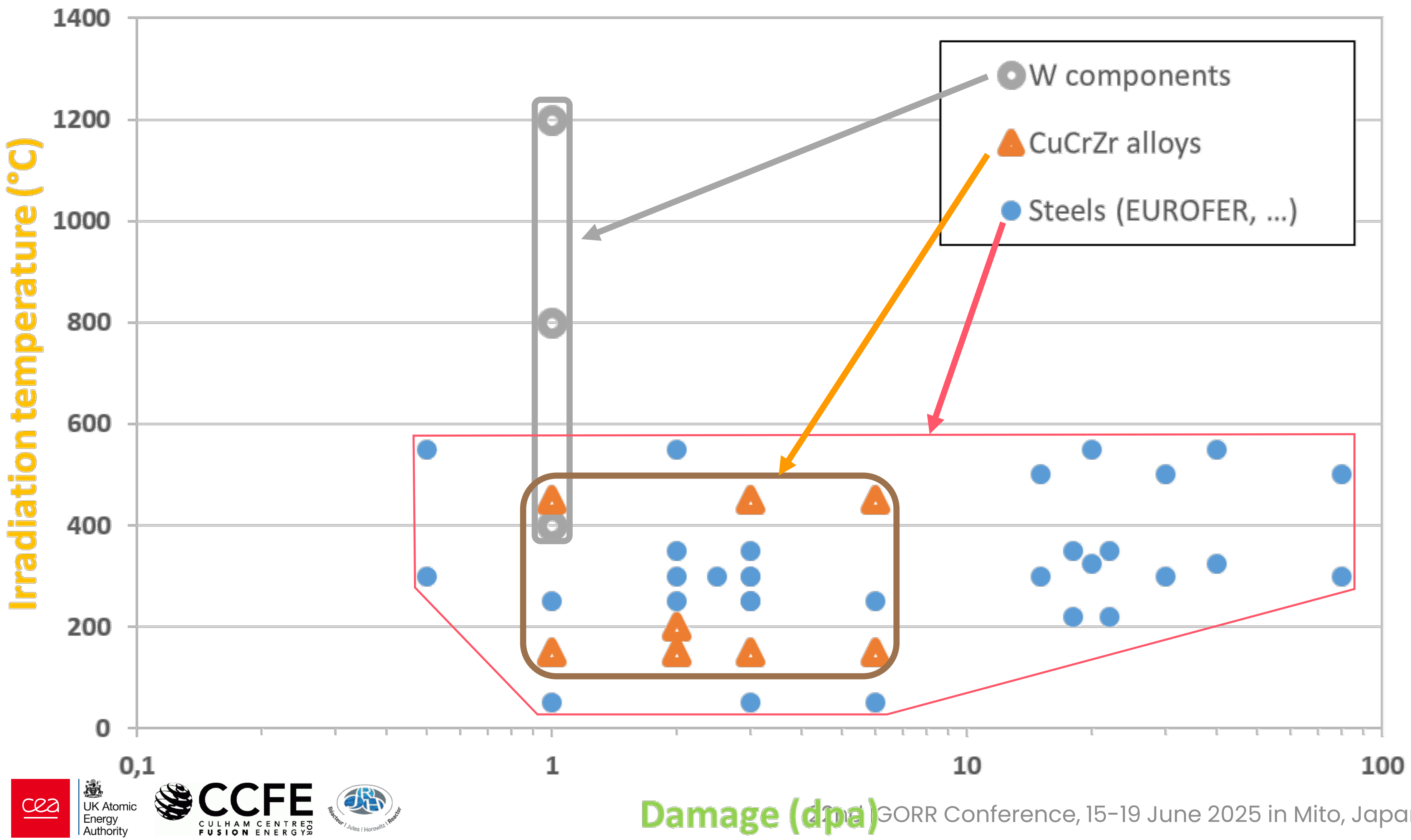
cea | UK Atomic Energy Authority | CCFE CULHAM CENTRE FOR FUSION ENERGY | JHR Réacteur Jules Horowitz Reactor

2. FUSION needs

Overview on current, future and prospective experimental irradiation programs

Contributions to the Fusion Roadmap

OVERVIEW of the **current programs** in MTR (BR2, LVR15,...)



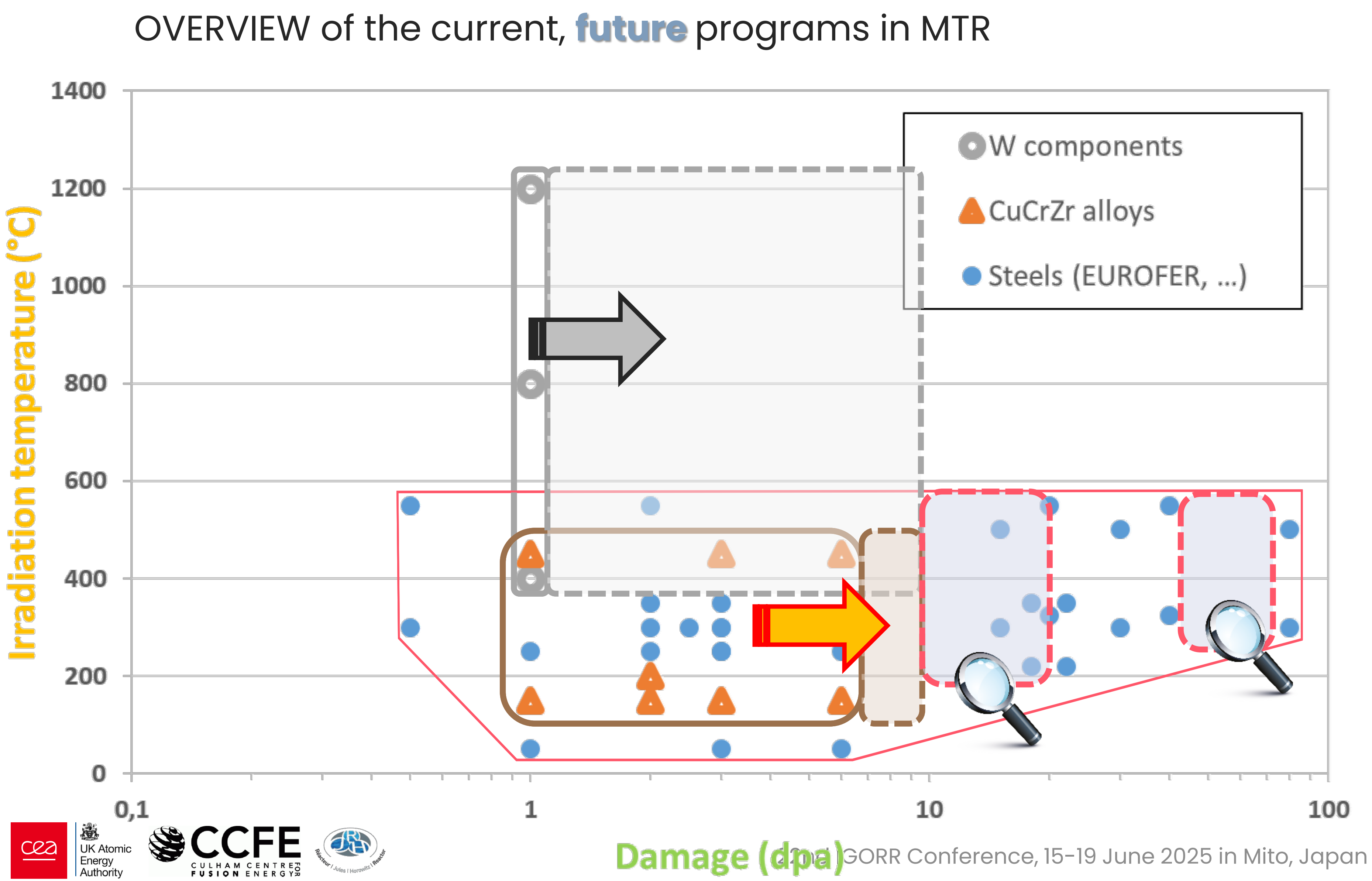
Selection Irradiation types

The figure resumes the different neutron irradiation current programs around EUROFusion umbrella, in a simplied manner Irradiation temperature vs damage.

Here, all of them correspond to Selection Irradiation types ("cook'n look"), in slide n°4.

3 main domains for 3 different materials family.

Contributions to the Fusion Roadmap

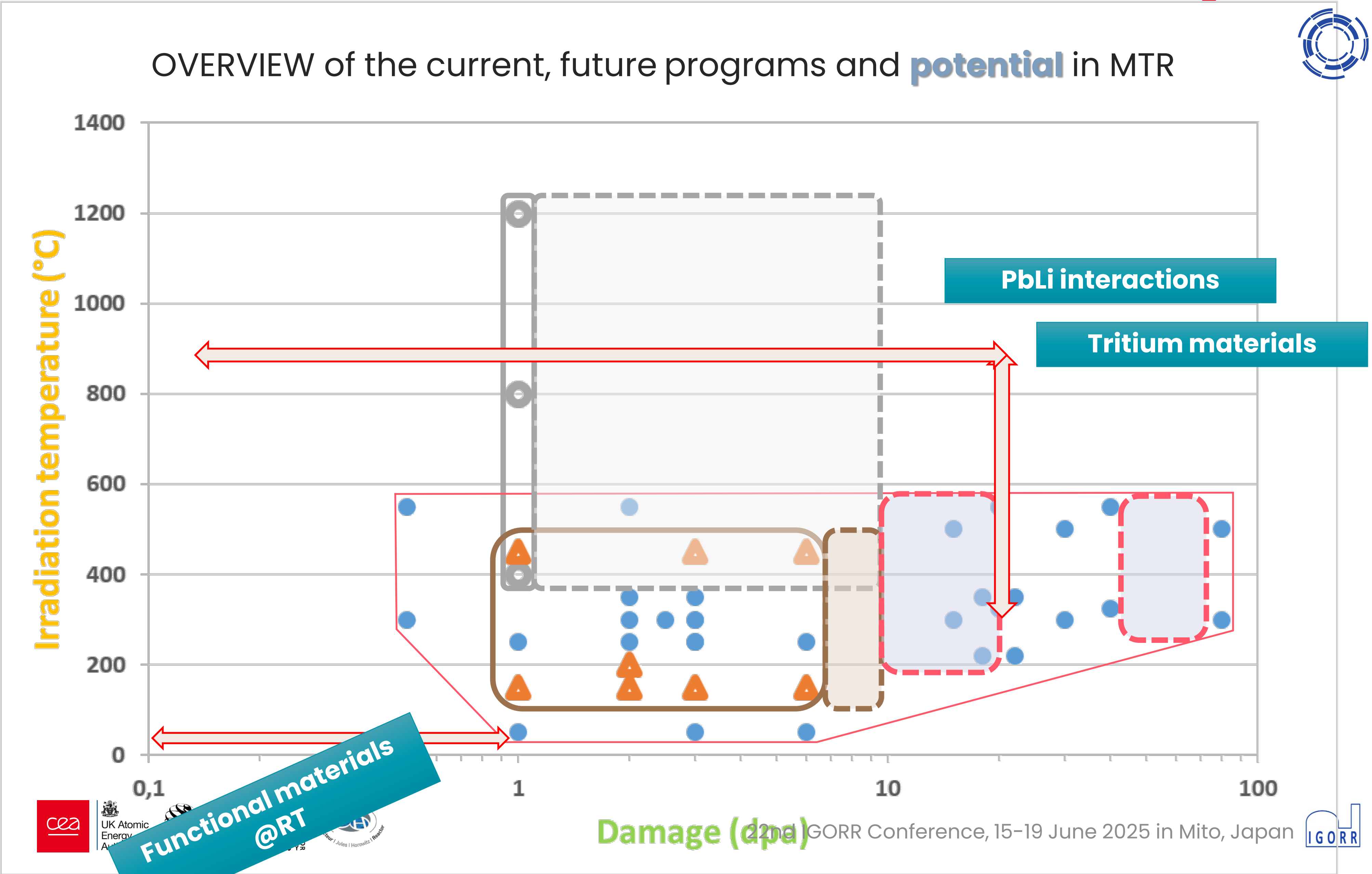


Selection Irradiation types

The figure completes the previous one with the anticipated future irradiation programs.

All of them correspond to Selection Irradiation types ("cook'n look") , in slide n°4

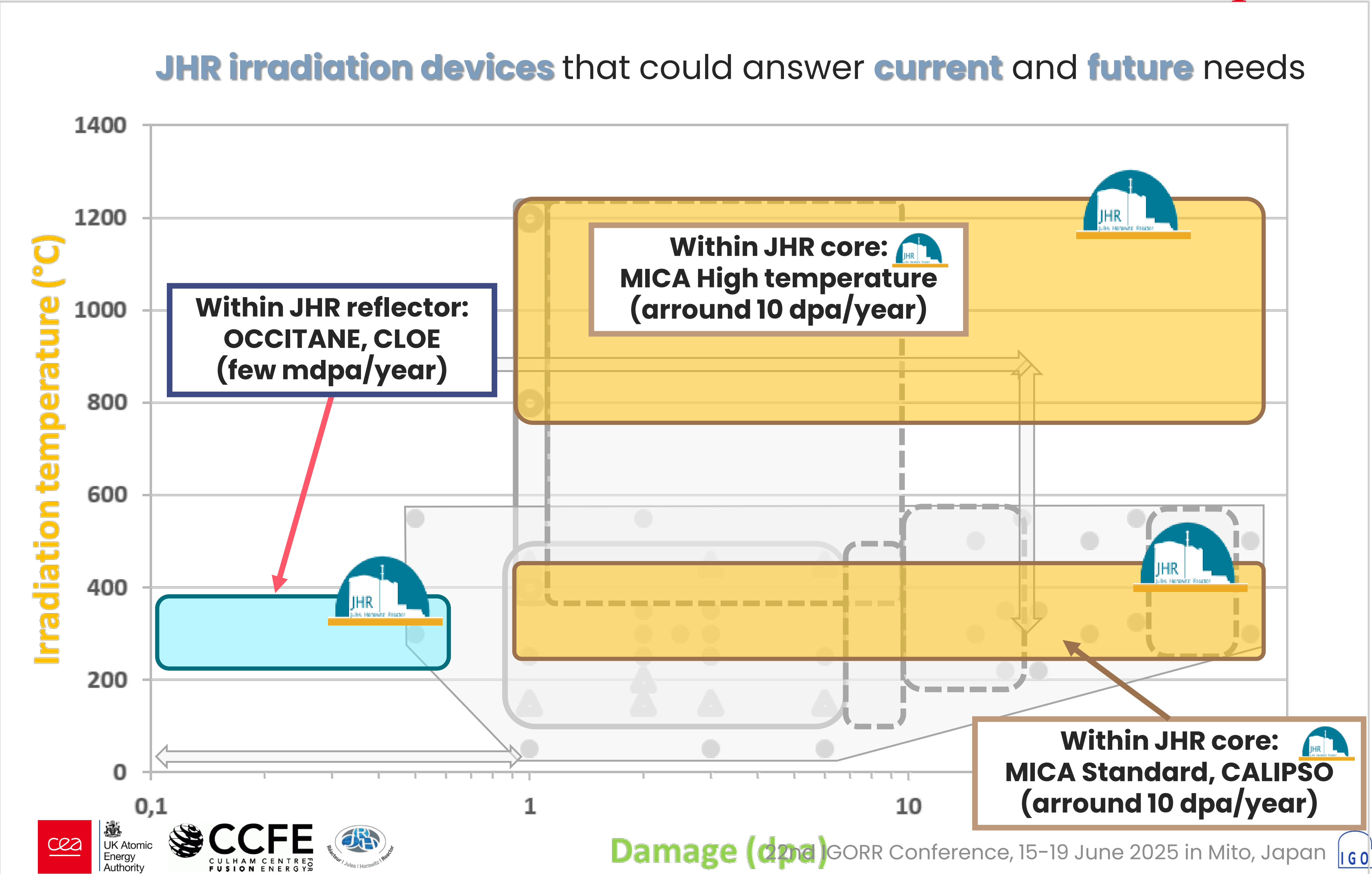
Contributions to the Fusion Roadmap



The figure completes with the anticipated potential irradiation programs.

These potential irradiations correspond to each type of irradiation: Selection, Characterisation, Qualification types, in slide n°4.

Contributions to the Fusion Roadmap



Selection Irradiation types

Characterisation Irradiation types

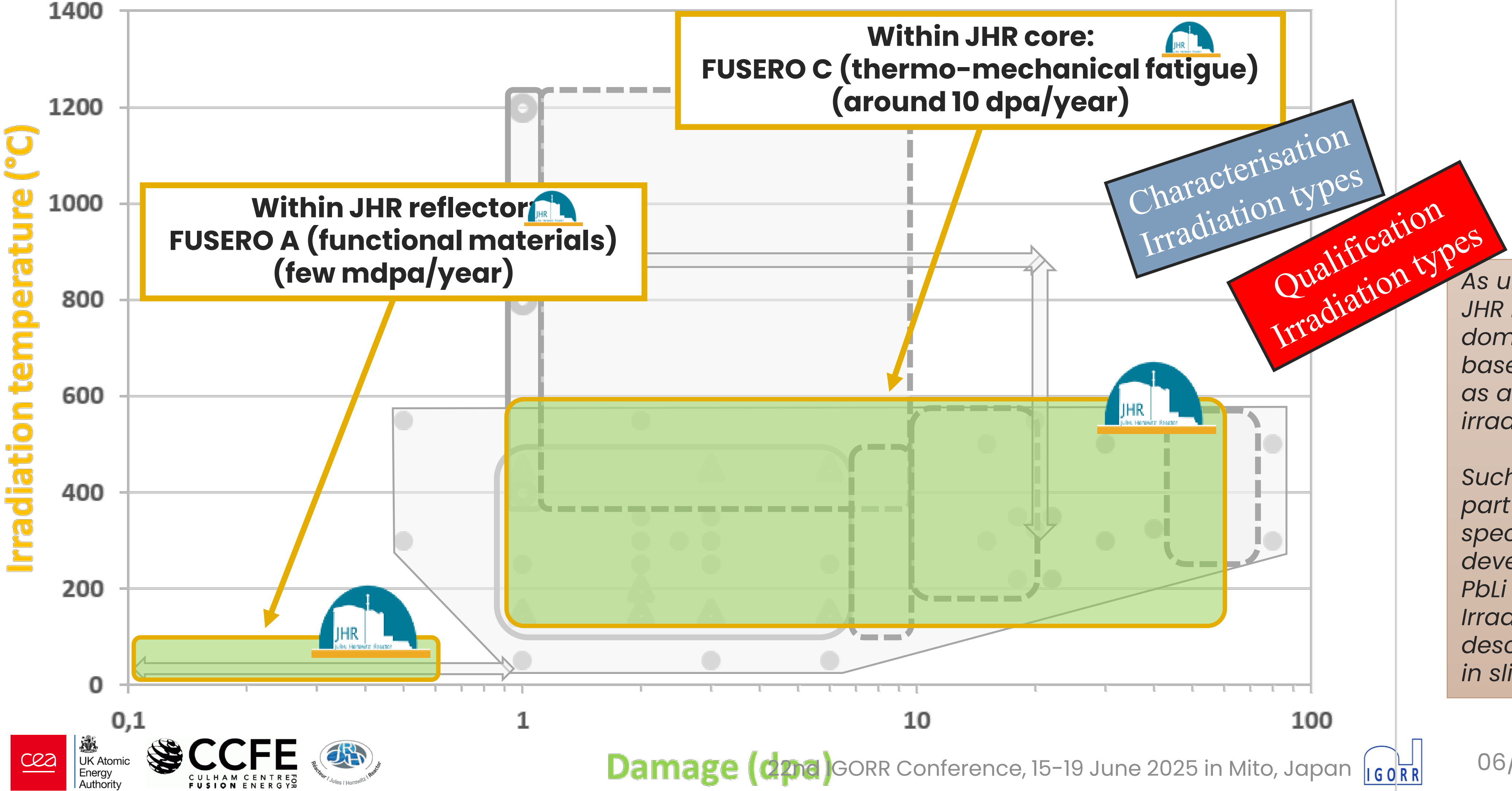
Qualification Irradiation types

As important contributions, the JHR irradiation devices domain are underline here, based on the previous figure, as an answer of the current and future irradiation programs.

Irradiation devices are described in slides n°6 and annex

Contributions to the Fusion Roadmap

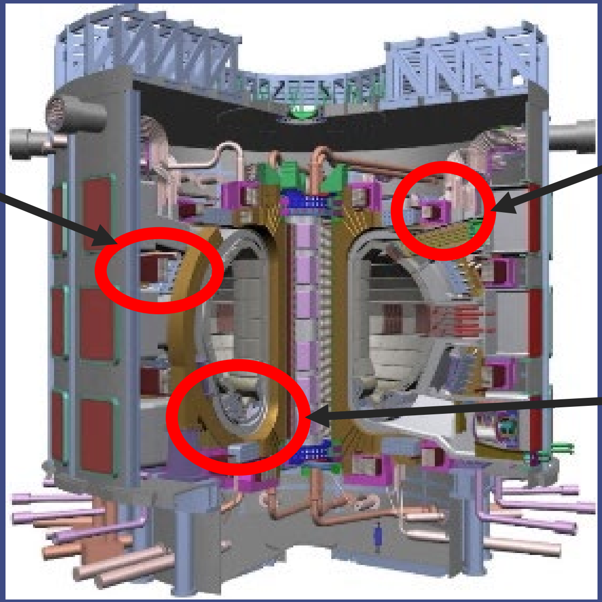
JHR irradiation devices that could answer **potential** needs



As unique contributions, the JHR irradiation devices domain are underline here, based on the previous figure, as an answer of the potential irradiation programs.

Such specific devices are a part of FUSERO project. Other specific devices could be developed (tritium materials, PbLi material interactions). Irradiation devices are described in slides n°6 and annex

FUSERO A: Functional materials for diagnostic or current drive systems **windows**



FUSERO B: Cryogenic testing for irradiation of **magnet** materials

FUSERO C: Thermo-mechanical fatigue for **first wall** and **divertor** materials

3. FUSERO A

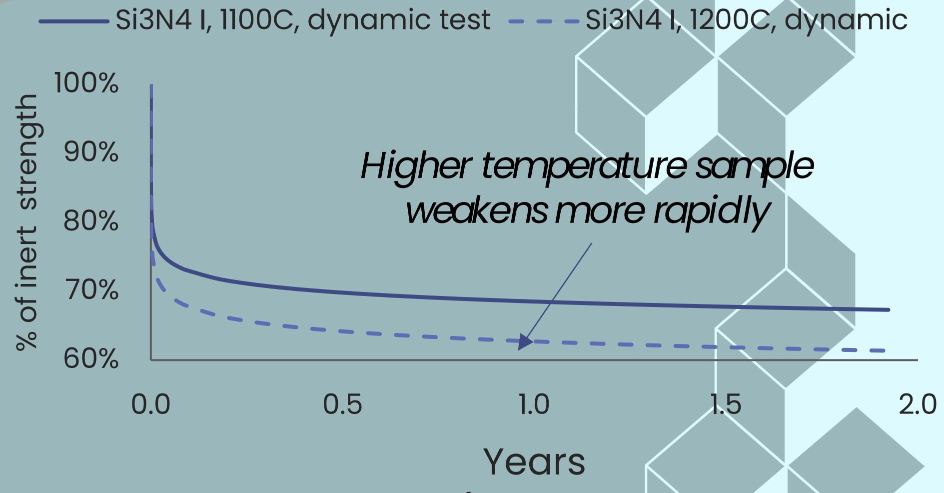
Functional materials for diagnostic or current drive systems windows

FUSERO A

Functional materials for diagnostic or current drive systems windows

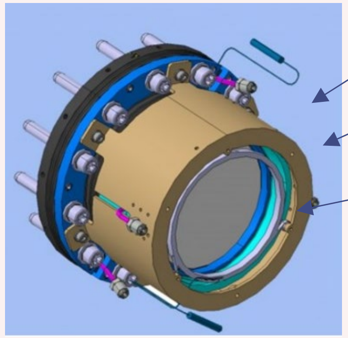
Hypothesis: **Subcritical crack growth** could be a significant failure mechanism in **diagnostic windows** for future fusion reactors.

Subcritical crack growth in glasses and ceramics



- Material **weakens over time** under sustained application of a below-critical stress, as chemical bonds at the crack tip react with polar molecules in the environment.
- Speed of crack growth typically **increases** with raised **temperatures,** humidity **and stress.**
- *What about in **radiation** and **vacuum** conditions?*

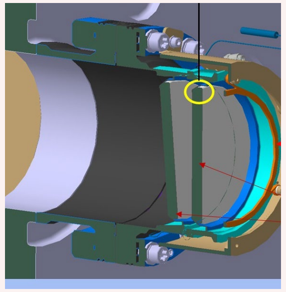
Diagnostic windows



Typically, fused silica

25-160 mm diameter

100s of windows in vacuum vessel



- Glass fails from brittle fracture; flaws cannot be managed in the same way as metal components.
- Must withstand **stress** from 0.5 bar vacuum pressure, **radiation** (10^9 neutrons/cm^2/s) and **raised temperature** (<300°C)
- Must last **working lifetime** of device

Aim: Develop a test rig to characterise subcritical crack growth rate under **irradiated** and **heated** conditions in the Jules Horowitz Materials Test Reactor.

FUSERO A

Testing Roadmap: increasing complexity

Aim: Develop a test rig to characterise subcritical crack growth rate under **irradiated** and **heated** conditions in the Jules Horowitz Materials Test Reactor.

TODAY

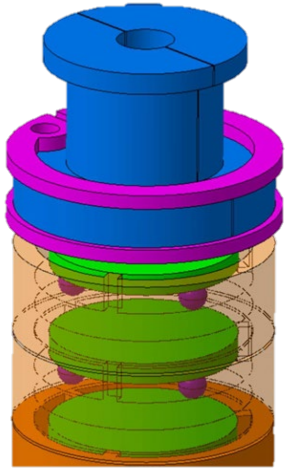
surface polish + Mechanical loading

- Room temperature
- Standard geometry

Uniaxial loading 4-point bend test: Standard BS EN 843-3 *for determination of subcritical crack growth parameters*

\+ Representative geometry

- Room temperature
- Representative geometry



JHR tests

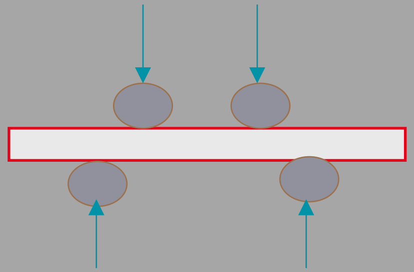
\+ Temperature + Radiation

- Temperature
- Radiation
- Representative geometry

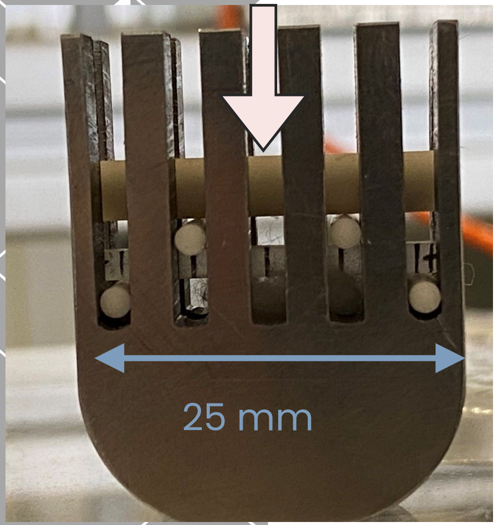
Biaxial loading ball-on-ball support
Emily Organ, 'A Prototype Device to Test Subcritical Crack Growth in Biaxially Stressed Ceramics', 2019

FUSERO A

Experimental method: dynamic 4-point bend test



180 samples of fused silica manufactured, chamfered and polished.



Keep broken samples for microscope analysis

Problem:

No commercial test rig available to apply suitable loads:

1. The strength of glass follows a **probability distribution**, so **multiple samples** need to be tested at each stress rate.
2. **5 stress rates** need to be tested across **4 orders of magnitude.**
3. The samples are **very small**, so will fail at low loads

➔ The rig needs to apply **low, constant stress rates** over **hours or days.**

➔ Tests may need to be repeated for **100s of samples.**

Solution:

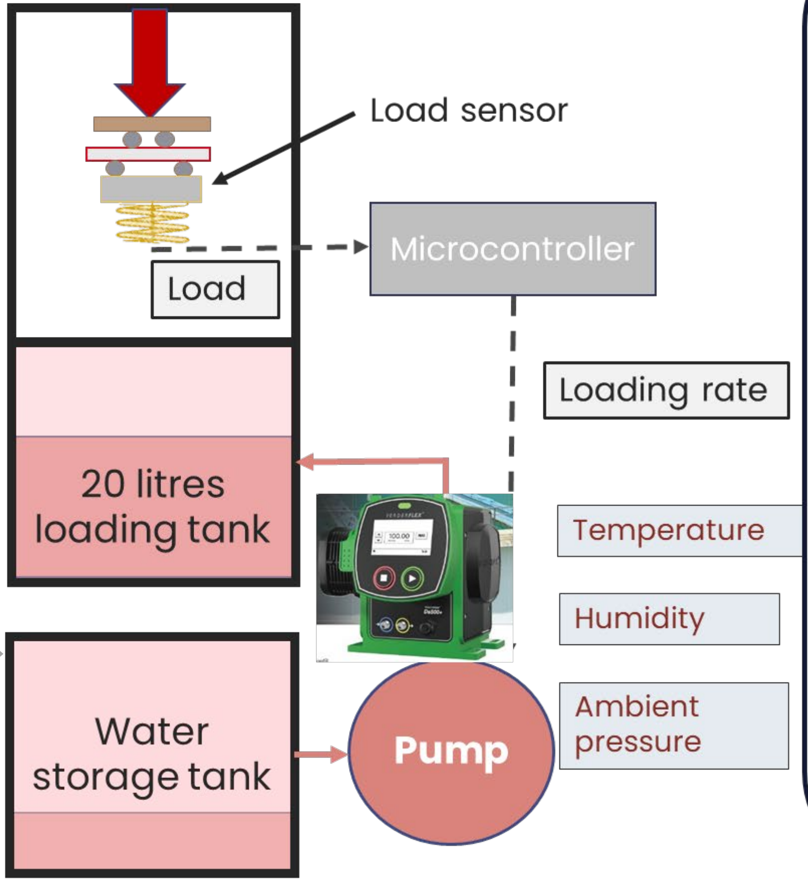
Use water as a **'deadweight'** load:

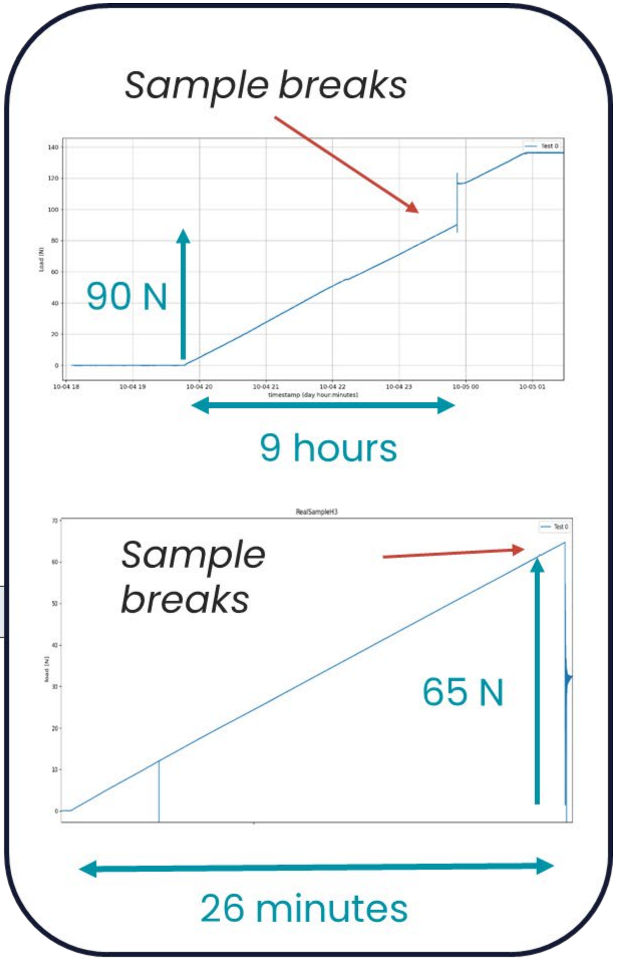
1. **Constant, reliable** load over **long durations**
2. Can achieve **low load rates** with a **pump.**
3. Relatively low-cost to build several rigs and **test in parallel.**

FUSERO A

Experimental bench: controlled loading rate

Laboratoire de Mécanique et d'Acoustique, Marseille





AMJE Aix en Provence

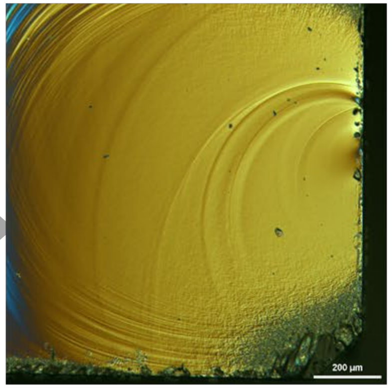
FUSERO A
Some results

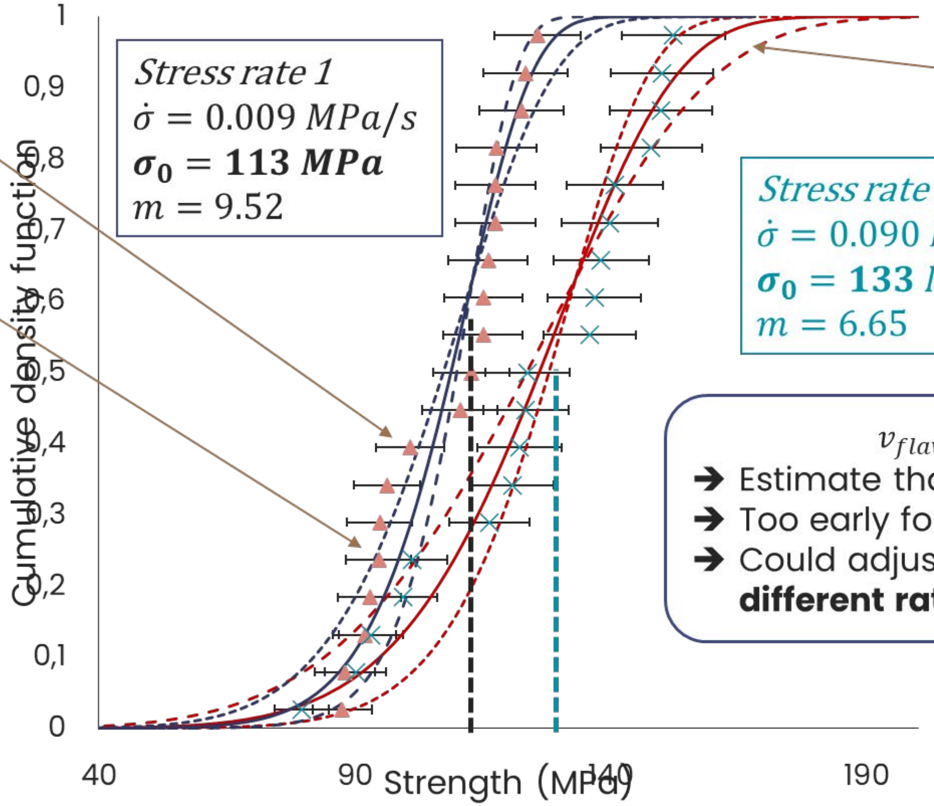
- 2/5 stress rates tested.
- 1/4 orders of magnitude covered.
- 19 samples at each rate were fitted to a **Weibull distribution**.

→ Observed an **increase in strength** when load rate increased - first indication of **subcritical crack growth** in fused silica.

Experimental uncertainty: +-6.6 MPa

Fractography to validate failure



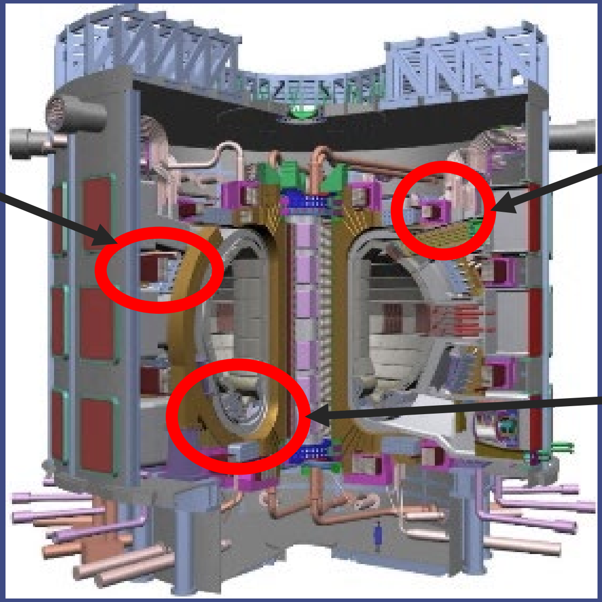


*Uncertainty of fitting parameter m to a **finite number** of samples*

$v_{flaw} \sim (\sigma_{applied}\sqrt{a})^n$

- ➔ Estimate that **n=13** from two rates.
- ➔ Too early for conclusive results.
- ➔ Could adjust **the same rig for different rates** using a lever.

FUSERO A: Functional materials for diagnostic or current drive systems **windows**



FUSERO B: Cryogenic testing for irradiation of **magnet** materials

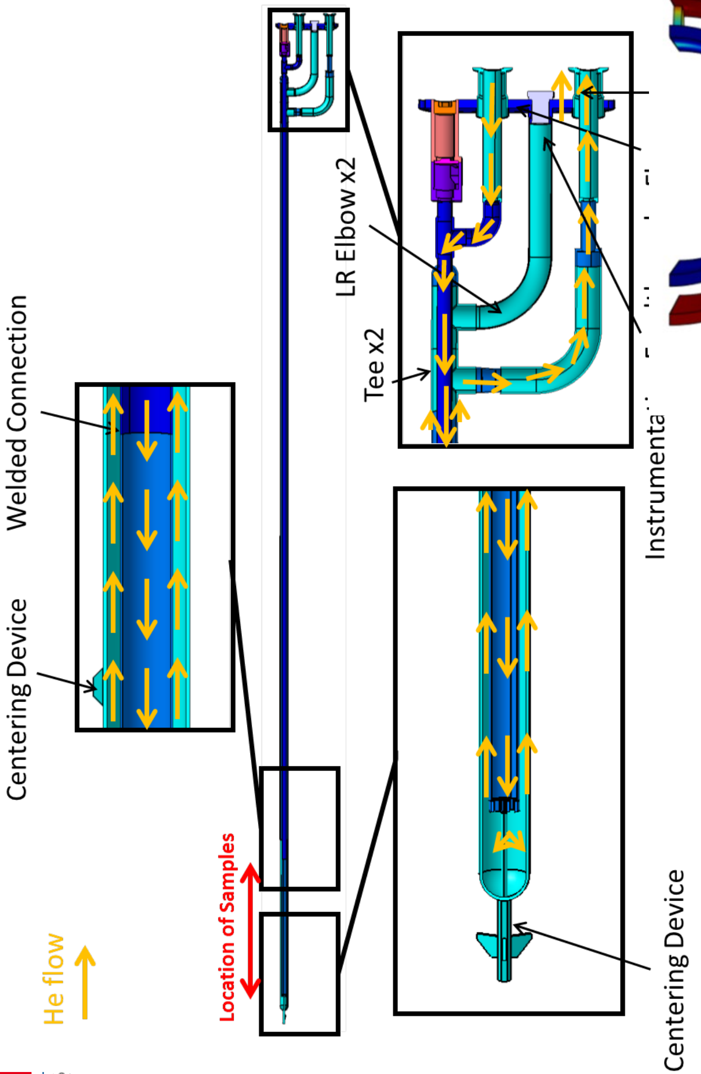
FUSERO C: Thermo-mechanical fatigue for **first wall** and **divertor** materials

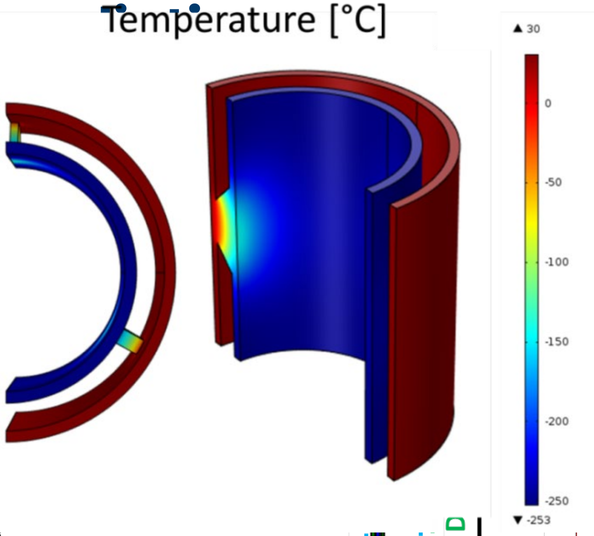
4. FUSERO B

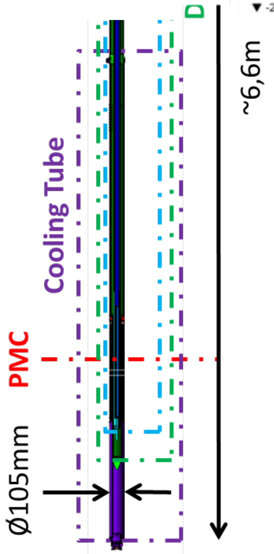
Cryogenic testing for irradiation of magnet materials

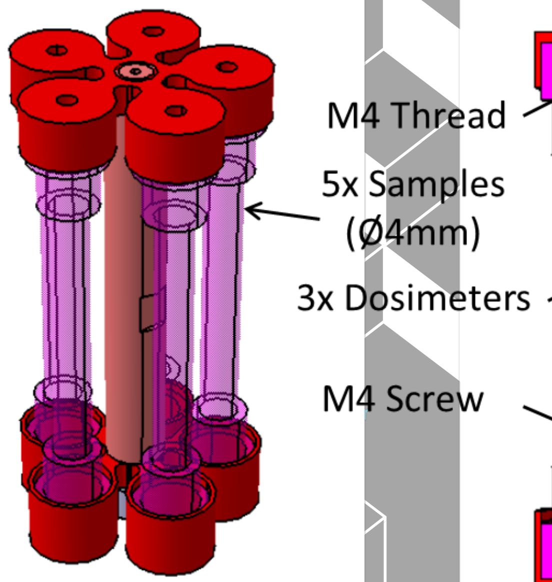
FUSERO B

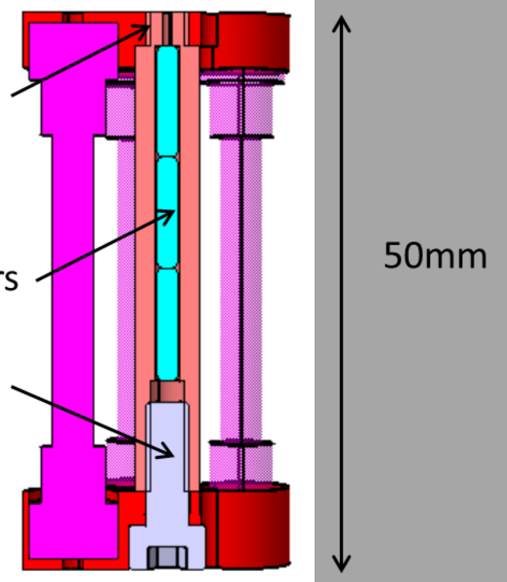
Cryogenic testing for i… of magnet materials

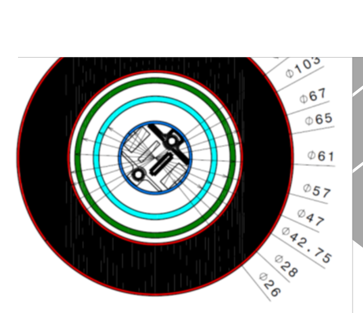


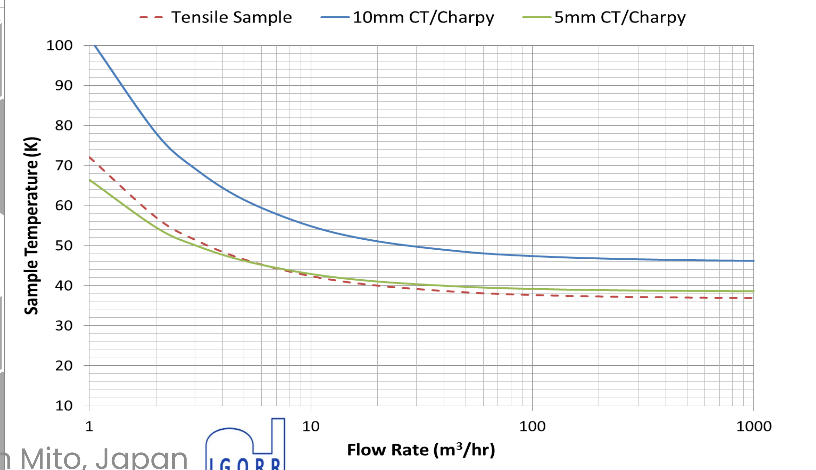




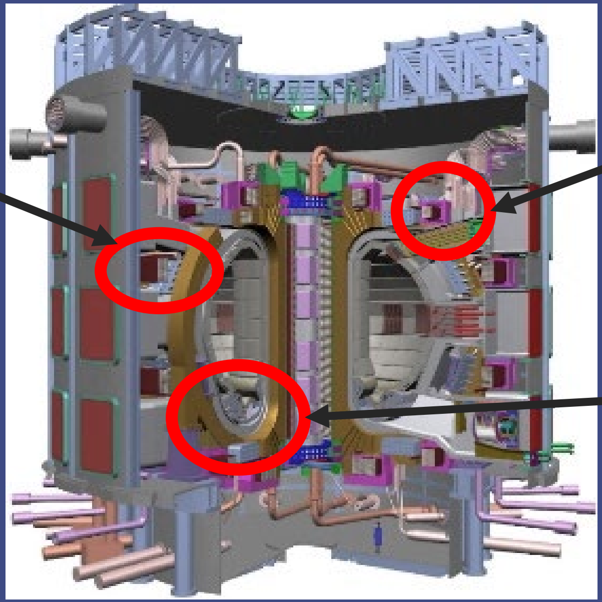








FUSERO A: Functional materials for diagnostic or current drive systems **windows**



FUSERO B: Cryogenic testing for irradiation of **magnet** materials

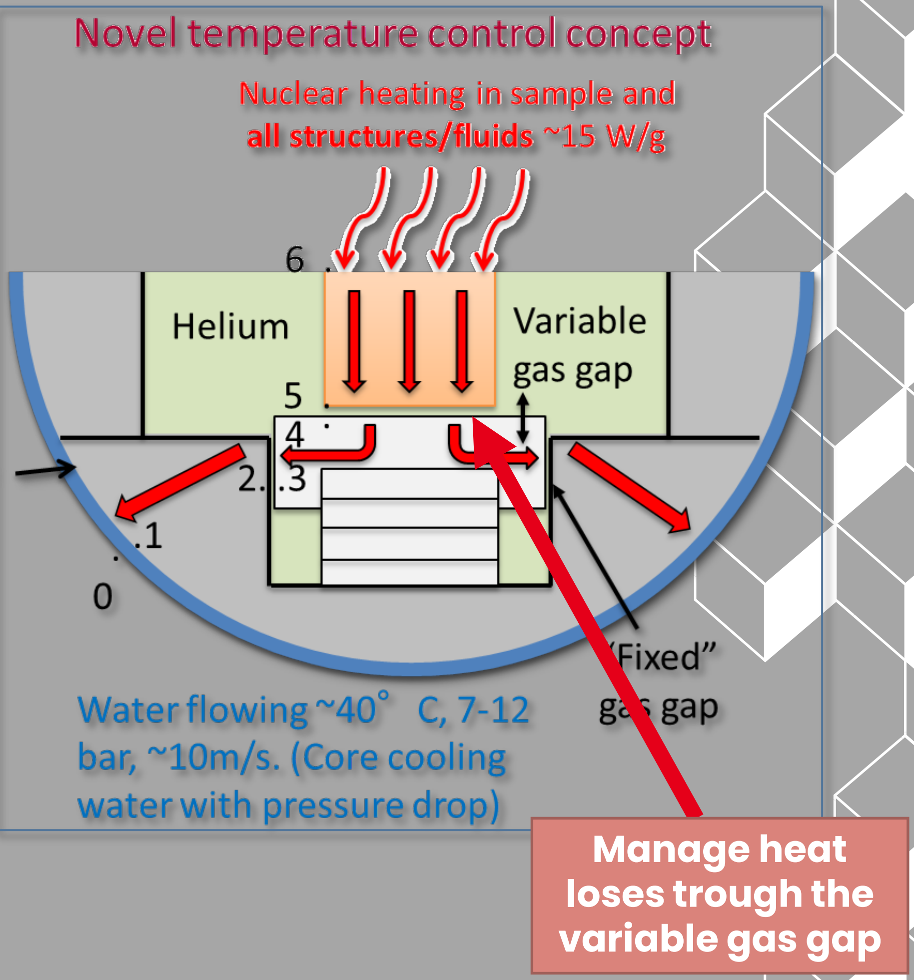
FUSERO C: Thermo-mechanical fatigue for **first wall** and **divertor** materials

5. FUSERO C

Thermo-Mechanical Fatigue (TMF) for first wall and divertor materials

FUSERO C

Thermo-mechanical fatigue TMF for first wall and divertor materials



- Design an irradiation device/sample holder in-situ low-cycle thermomechanical fatigue
  - Specifications: to achieve cycling of
  - Stress (200MPa)
  - Temperature (150-600°C)
  - Under irradiation
  - With online temperature / displacment measurements

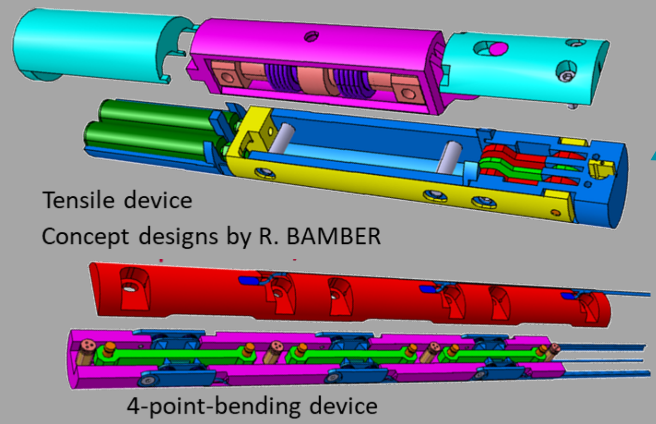
/!¥ Interest of both communities fusion+fission

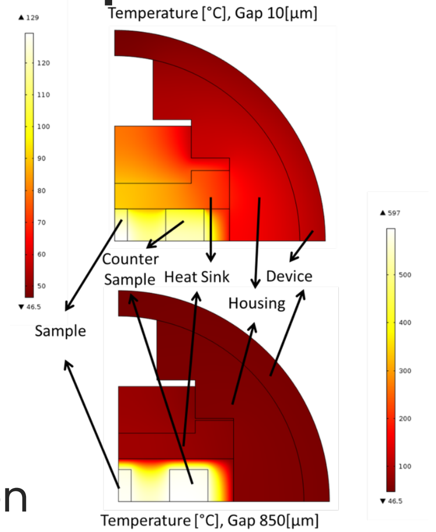
⇒ **New… challenging… temperature control concept**

- Conceptual design
- 2D FEM Calculations

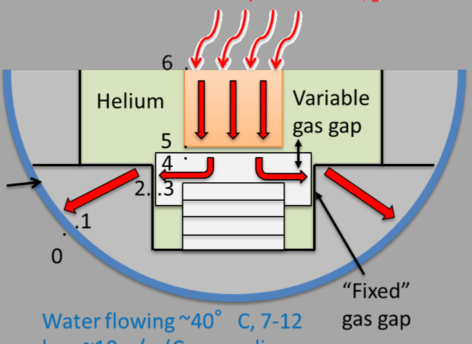
⇒ **Need to check this "technological brick"**

- **PASTIS** mock-up
- Design, calculations
- Specifications
- Manufacture, commissioning, qualification





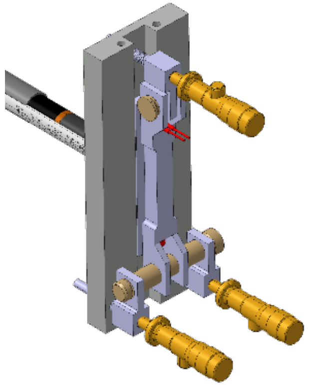
Novel temperature control concept

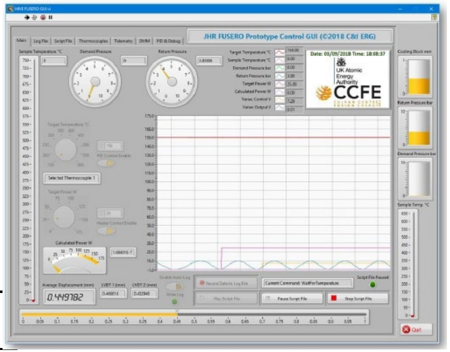


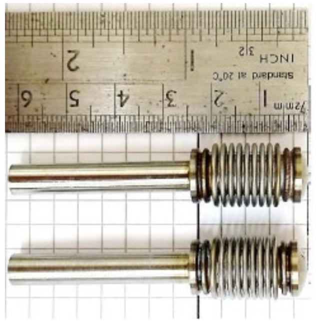
FUSERO C

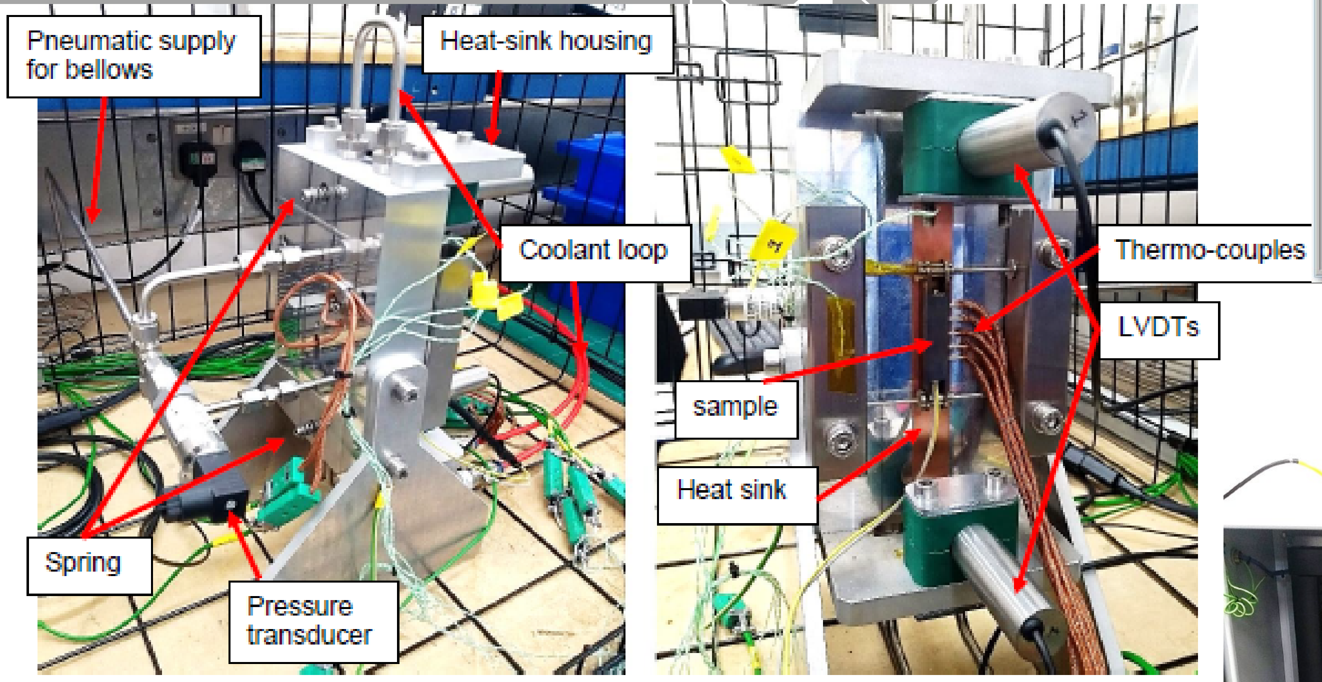
Thermo-mechanical fatigue TMF for first wall and divertor materials

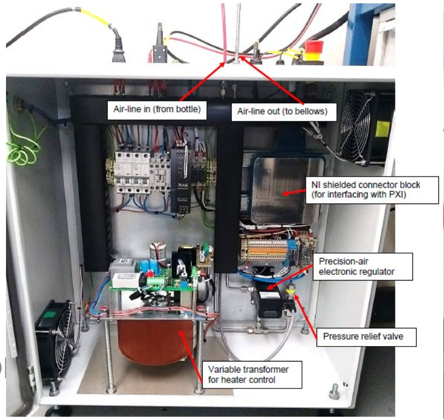
PASTIS Mock-up

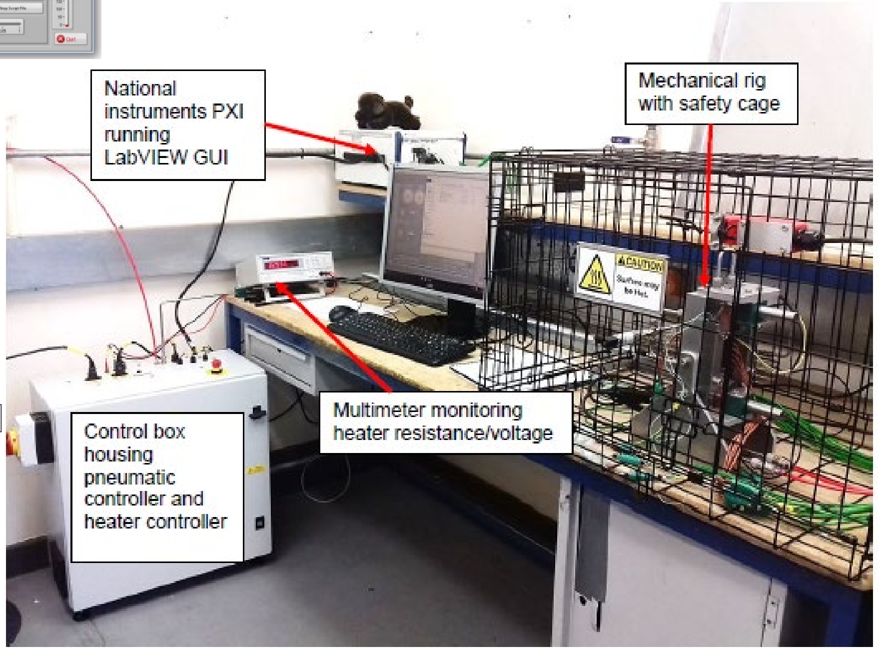










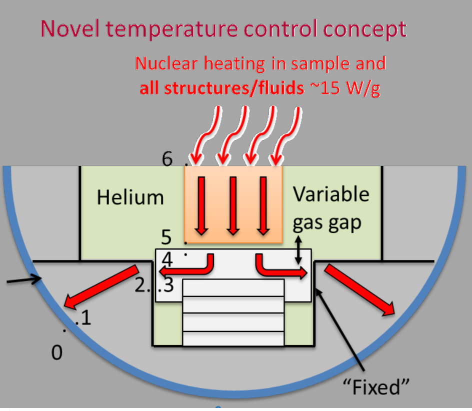


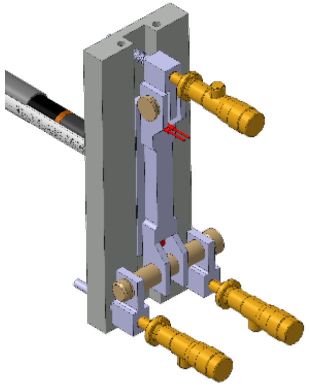
CCFE
CULHAM CENTRE FUSION ENERGY

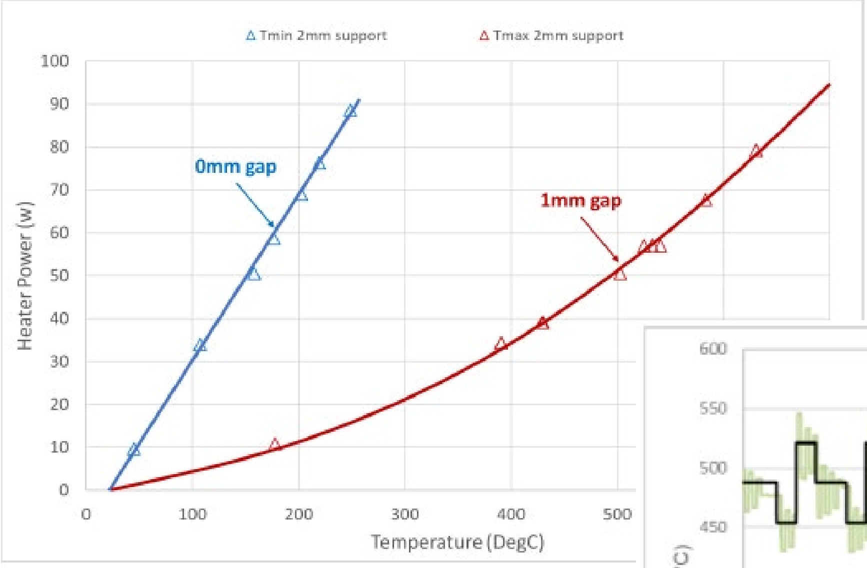
FUSERO C

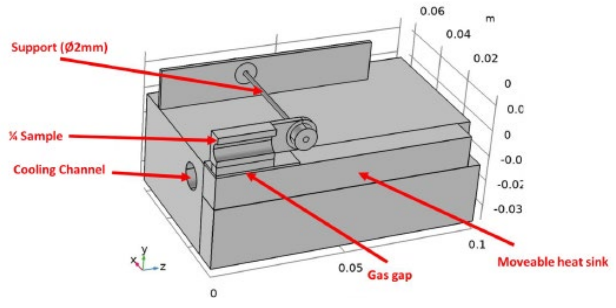
Thermo-mechanical fatigue TMF for first wall and divertor materials

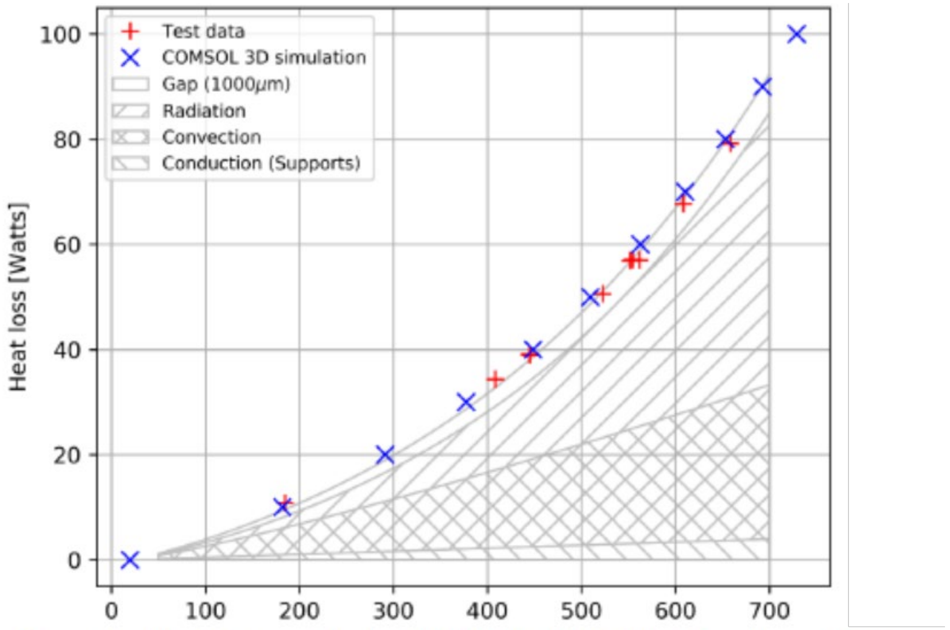
PASTIS Mock-up



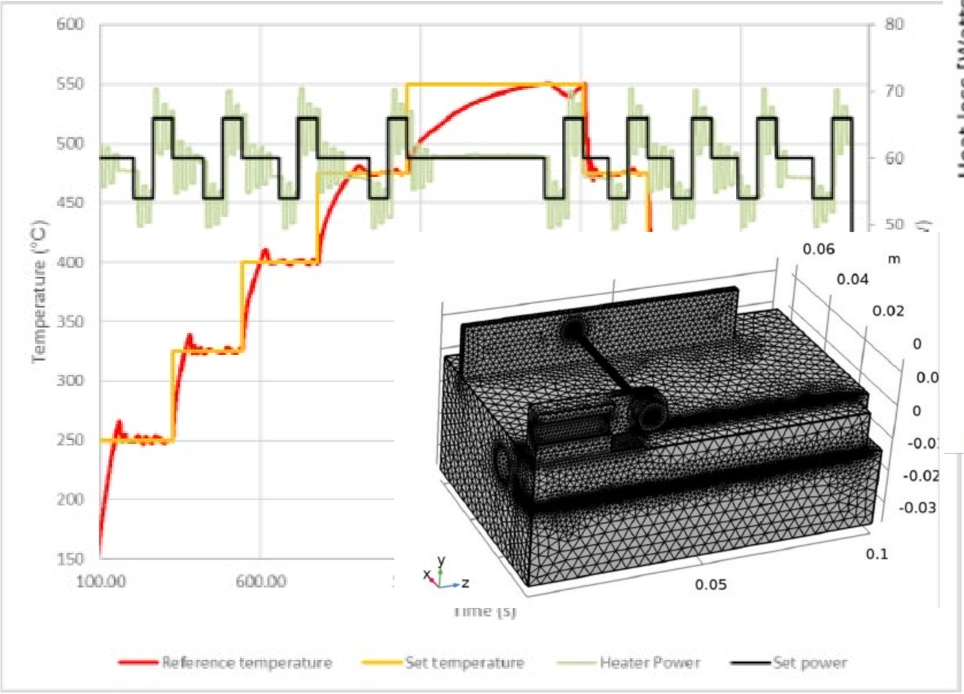








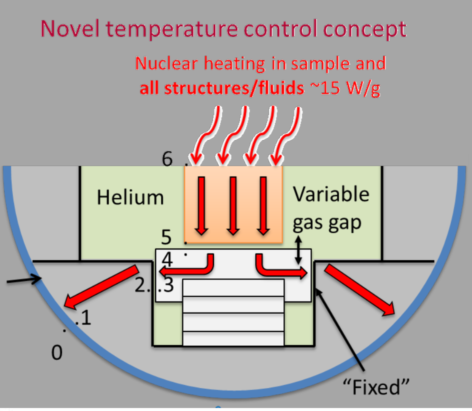
Comparison between measured and modelled steady state heat loss for maximum gap size (~1mm) with heat transfer mechanism contribution from 1-D (python) script.

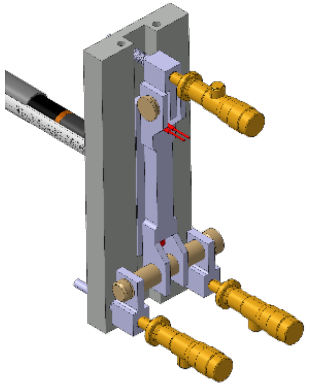


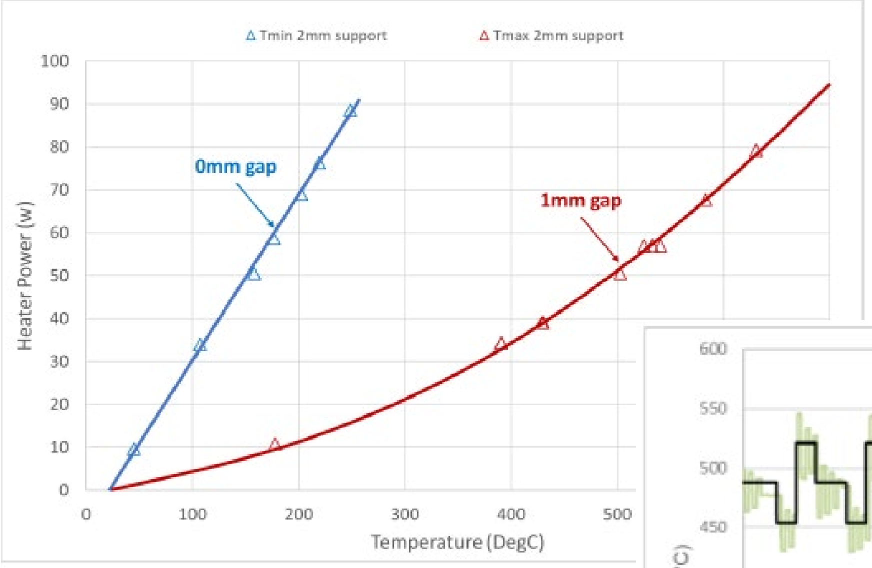
FUSERO C

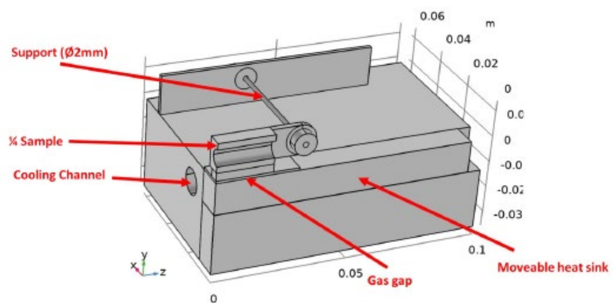
Thermo-mechanical fatigue TMF for first wall and divertor materials

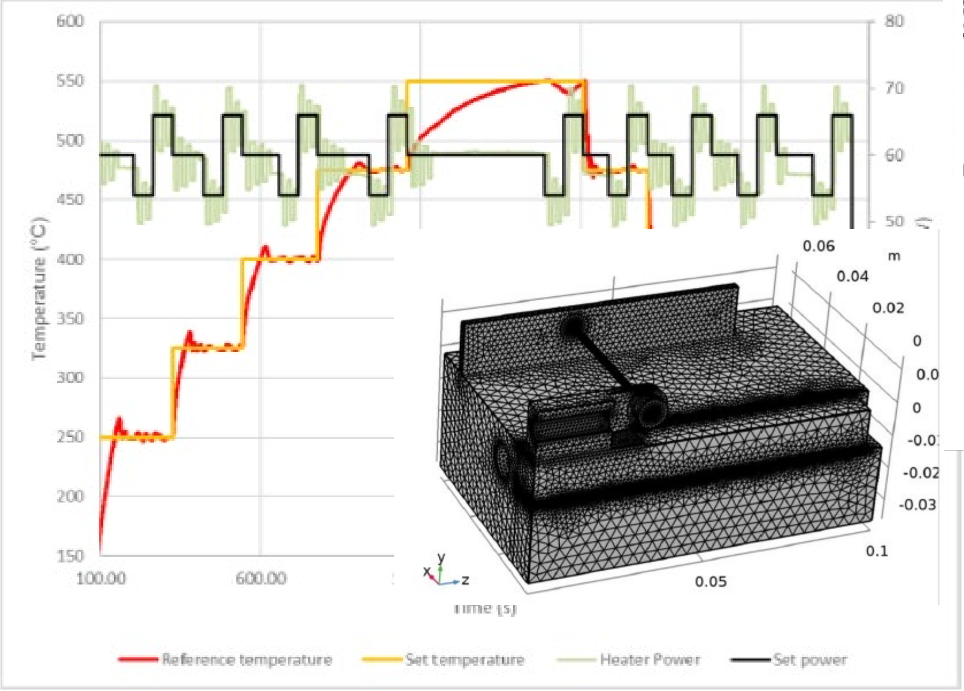
PASTIS Mock-up

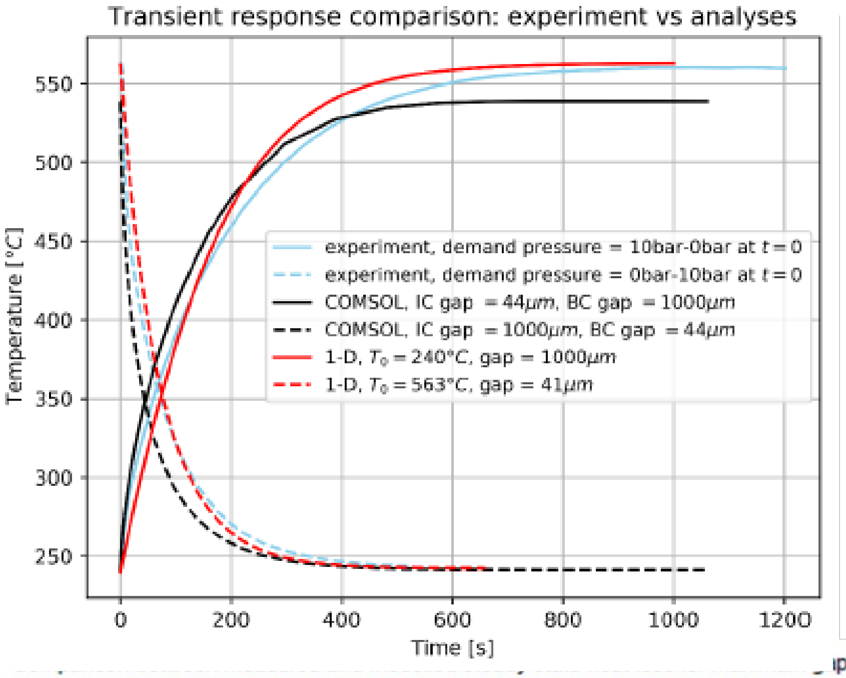












...ıp size (~1mm) with heat transfer mechanism contribution from 1-D (python) script.

6. CONCLUSIONS

6. CONCLUSIONS

Question: How can we exploit the JHR (or MTR) to help design future fusion reactors

- An international collaboration between
  UKAEA-CCFE (Oxford, UK) and CEA-JHR (Cadarache, FR)
- Feedback from EUROfusion call and
  survey sent to both the "fusion and fission" communities:
  - Cook'n look irradiations in MTR
    ⇒ 1st fleet of JHR irradiation devices
  - Highlighted 3 major areas for development
    ⇒ FUSERO A, B, C
    - A. Functional materials for diagnostic or current drive systems windows
      - Feasibility studies, calculations+design+prototypes
    - B. Cryogenic testing
      - Feasibility studies, standy
    - C. Thermo-mechanical fatigue TMF for first wall and divertor materials
      - Feasibility studies, calculations+design+prototypes

Under reflexions: FUSERO D, E,...
(ex. « Tritum » materials, PbLi loop under irradiation, conductivity...)

6. CONCLUSIONS

FUSERO long term roadmap

- A well established collab.
- For « all » FUSERO
- Trainee, Apprentices, Secondee oportunities

Studies
- Specifications
- Feasibility studies
- Detailed design

Qualifications
- Mock-up (s)
- Device construction (# years…)
- Pre-JHR area Irradiation prog ???
- PIE

JHR Irradiations
- Specifications
- Manufacturing : device + I&C + sample holder
- … IRRADIATIONS …
- Transportation
- PIE (CEA, MRF,… ?)

Increase confident (vs standard?)

Increase confident

A very well qualified irradiation device

⇒ NO doubt of irradiation performances

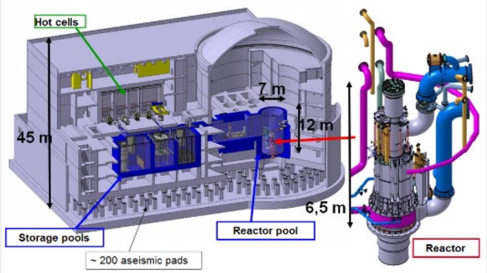
⇒ NO doubt in PIE results

6. CONCLUSIONS

Resources involved

- **Jules Horowitz Reactor:**
  - New MTR:
  - @CEA **Cadarache**, France
  - Under construction: start-up expected at the **beginning of next decade** (2030-2035)

- Resources are not yet finalized and will be available later



- However, estimate durations to **develop a new equipment** are as follows:
  - **around 5 years for a "sample-holder"** to be implemented in a existing equipment (order of magnitude of investment **5M€**)
  - **around 8-10 years for a "whole equipment" from scratch** (order of magnitude of investment **10M€**)

- **Need of « fusion » community involvement**
  - To **specify the irradiation needs**,
  - To check the adequacy with the current studies (for example: low irradiation temperature?)
  - To development specific equipment in FUSERO project (for examples: functional materials, thermo-mechanical fatigue, tritium materials, PbLi material interactions,…)

FUSERO: JHR's applicability to fusion research by neutron irradiation experiments

C. Colin[a,b], C. Hardie[c], A. Aleska[c], J. Allison[c], R. Bamber[c], B. Edwards[c], A. Gabieli[b], J-M John[c], S-F Legry[b], E. Organ[c], S. Tan-Ya[c], G. Bignan[b]

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Thank you, どうもありがとう, Merci

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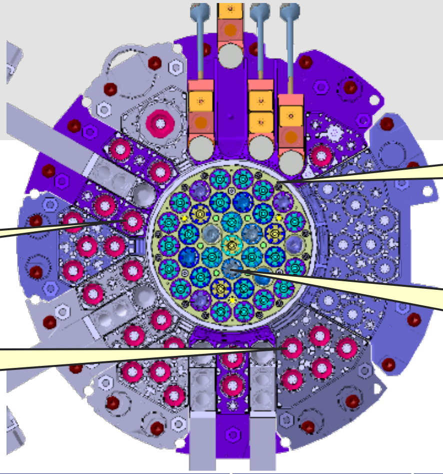
JHR Technical capabilities

Foreseen equipments that will be implemented in JHR



CLOE
Corrosion loop for "Zr alloy Corrosion" and "Irradiation Assisted Stress Corrosion Cracking"

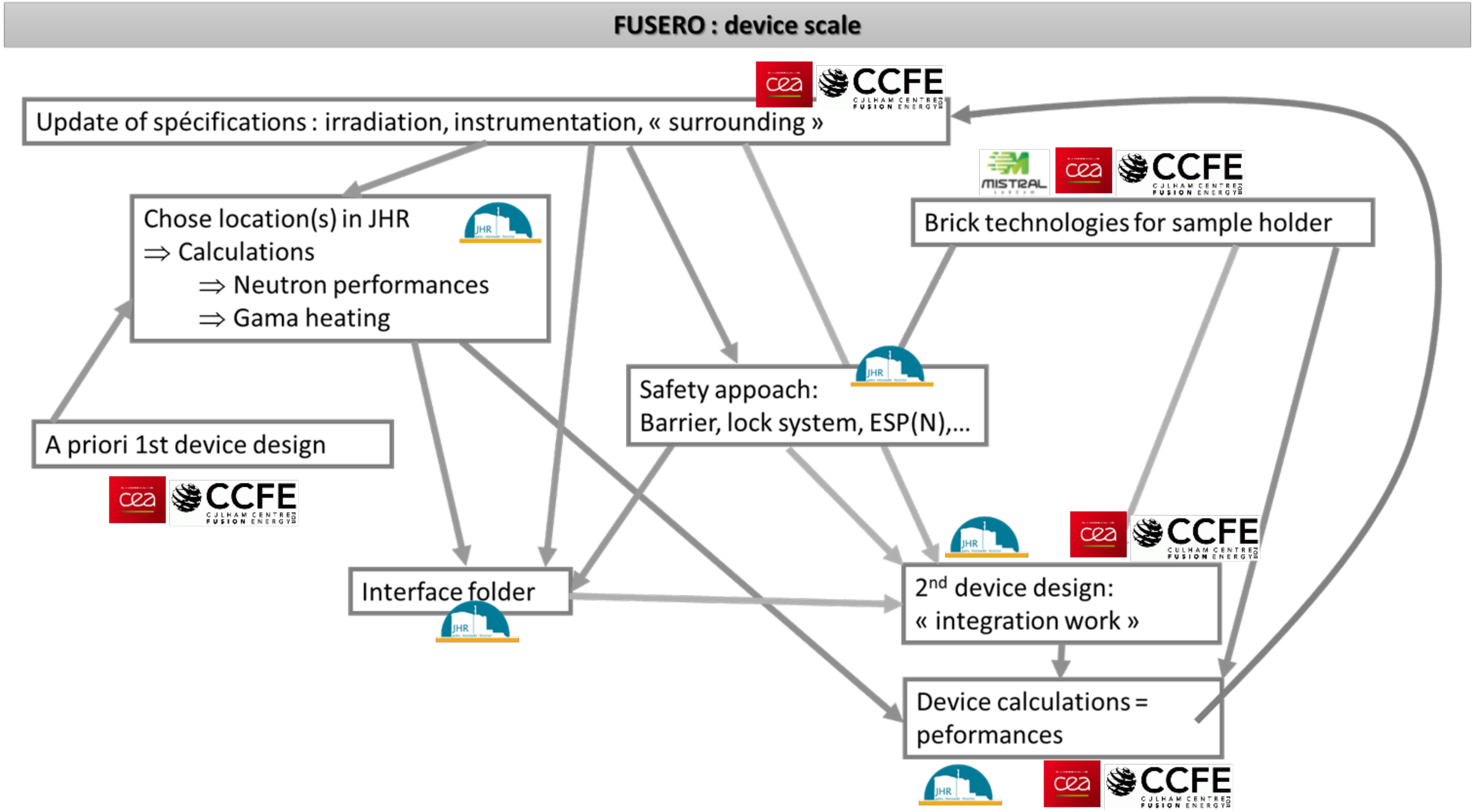
OCCITANE
For Reactor Pressure Vessel steel testing

MICA
For material testing under high dpa

CALIPSO
For material testing under high dpa and accurate temperature control

Equipment	Topic	Associated scientific program	Location	Nb. max. of equipment Samples volumes.	Damage (dpa/year)	Temperature (°C)	Coolant
MICA Standard	Internals, cladding	Dose accumulation, Post-irradiation Examinations, Mechanical testing	Core	2-3 equ./cyle # 350 cm³	12	250-450	Static NaK
MICA HT	Internals, cladding	Dose accumulation, Post-irradiation Examinations, Mechanical testing	Core	1-2 equ./cyle # 350 cm³	12	800 – 1200	Static Helium
CALIPSO	Internals, cladding	Dose accumulation, Post-irradiation Examinations, Mechanical testing	Core	1 equ./cyle # 350 cm³	12	250-450 (low thermal gradient)	Dynamic NaK
CLOE	Internals, cladding	Corrosion loop for "Zr alloy Corrosion" and "Irradiation Assisted Stress Corrosion Cracking"	Reflector	1 equ./cyle # 1000 cm³	0,1	< 360	LWR conditions
OCCITANE	Reactor vessel	Dose accumulation, PIE	Reflector	2 equ./cyle # 1000 cm³	0,1	230-300	Static Helium
FUSERO	Under développent	A. Functional materials for diagnostic or current drive systems windows B. Cryogenic testing C. Thermo-mechanical fatigue for first wall and divertor materials	Reflector Reflector Core	Under developent		RT BT 150 – 600°C	Helium Helium Helium
UK Atomic Energy Authority	Under investigation	D. « Tritum » materials E. PbLi loop under irradiation …	**Depending on « fusion » community needs**				

How to design…



Neutron spectra …