THE IFMIF-DONES TEST BLANKET UNITS

Technical Meeting on Tritium Breeding Blankets and Associated Neutronics
Vienna, September 4th , 2025

David Rapisarda
Fusion Technologies Division
National Fusion Laboratory
CIEMAT

On behalf of:
D. Rapisarda, P. Arena, F. Arranz, S. Becerril, B. Brañas, C. Caballero, A. Ibarra, F. Mota, M.I. Ortiz, A. Serikov, G. Zhou

OUTLINE

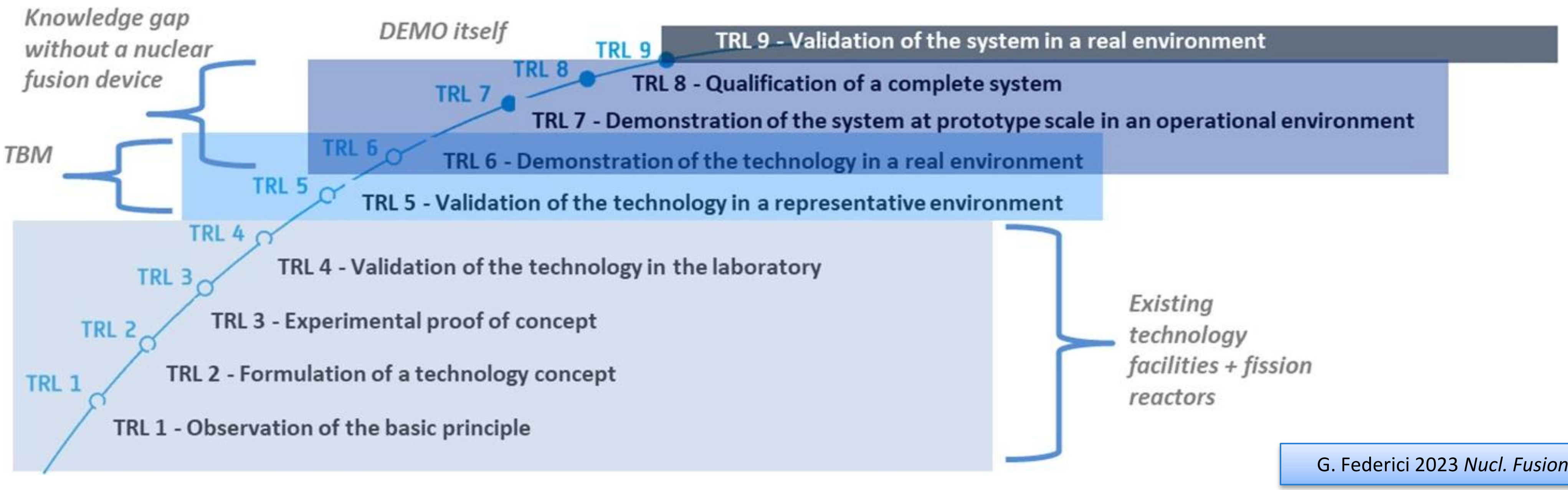
- ❑ Motivation
- ❑ IFMIF-DONES and tritium technologies validation
- ❑ DONES Test Blanket Units
- ❑ The HCPB-TBU: preliminary results
- ❑ The WCLL-TBU: preliminary results
- ❑ Capabilities of DONES to test the TBU
- ❑ Summary & Conclusions

MOTIVATION

- Despite the importance of the BB, feasibility concerns and uncertainties exist in all explored concepts.
- Significant research and development are needed to address these issues.

The Role of Different Facilities for the Nuclear Qualification of the BB, G. Aiello, this WS

- BB maturity level is still very low → measured through the Technology Readiness Level (TRL).
  - Application to BB development and qualification → as proposed by G. Federici



G. Federici 2023 *Nucl. Fusion* **63** 125002

MOTIVATION

- Efforts put on the ITER-TBM program and VNS → looking for **BB integrated testing** alternatives, as transferring this task to DEMO will limit and postpone DEMO performance

> Progress in the Concept Development of the VNS - A beam-driven Tokamak for Component Testing, I. Moscato, this WS

- Evaluate other alternative neutron sources → Working Group on BB and Fuel Cycle Development (2022)

Some findings of the group:

- Prior to integrated testing and qualification of a breeding blanket, either in a VNS or in DEMO, **single and combined effect characterization** will be necessary, along the timeline of the availability of neutron sources
- The overall need for neutron irradiations, in order to accelerate the development and the informed selection of design choices, is quite huge, and **a wide range of facilities has to be considered** to fulfil the capacity needs
- Focussed pre-qualification campaigns, prior to the availability of either a VNS or DEMO, have to be performed with **high-grade spectrum sources** like IFMIF-DONES (~ 10 years to availability)

MEMBERS:

- Klaus Hesch (KIT) – chair
- Alessandro Spagnuolo (PMU) – secr.
- Alessandro Del Nevo (ENEA)
- Philippe Magaud (CEA)
- Amanda Quadling (UKAEA)
- David Rapisarda (CIEMAT)
- Dmitry Terentyev (SCK-CEN)
- Ladislav Vala (CV Řež)
- Sandor Zoletnik (CER)

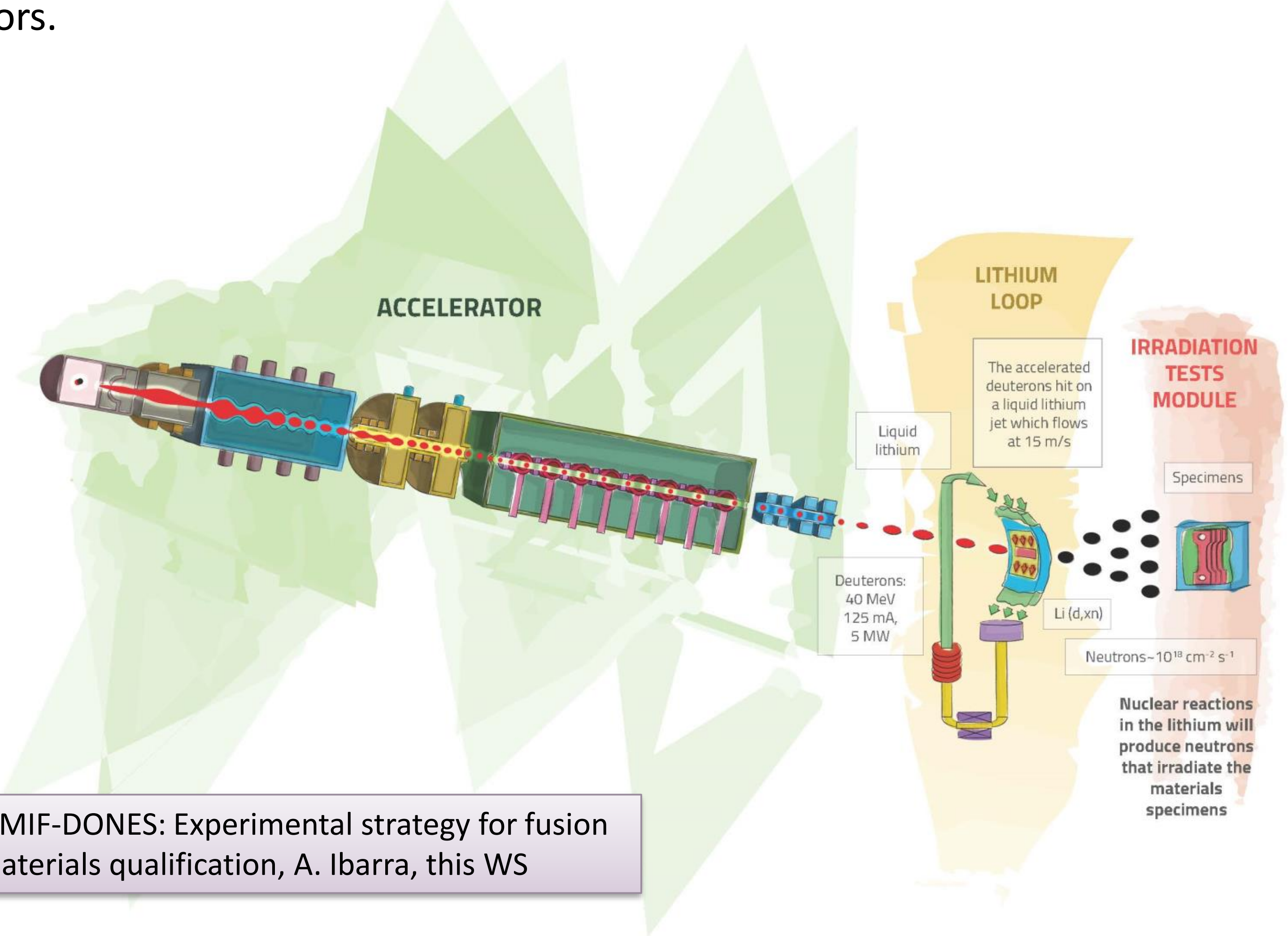
DONES Schedule seems compatible with ITER and VNS schedules: feasible, quick, cheap → important outcomes to both programs

OUTLINE

- ❑ Motivation
- ❑ IFMIF-DONES and tritium technologies validation
- ❑ DONES Test Blanket Units
- ❑ The HCPB-TBU: preliminary results
- ❑ The WCLL-TBU: preliminary results
- ❑ Capabilities of DONES to test the TBU
- ❑ Summary & Conclusions

IFMIF-DONES facility

- Main objective → to simulate as closely as possible the irradiation conditions of the structural materials of nuclear fusion reactors.



- Users Community → propose experiments
  - HFTM
  - Tritium Technologies Validation
  - Nuclear physics
  - …

IFMIF-DONES: Experimental strategy for fusion materials qualification, A. Ibarra, this WS

IFMIF-DONES: Tritium technologies validation

- Some modules where explored in the past (IFMIF 2 x accel.):
  - **HFTM** (high flux area)
  - **LBVM** (medium flux area) – Liquid Breeder Validation Module
  - **TRTM** (medium flux area) – Tritium Release Test Module
  - **CFTM** (medium flux area)
  - **LFTM** (low flux area)
  - **STUMM** (characterization of the irradiation parameters-codes validation)

- EUROfusion (WPENS) works in using the available space in the Test Cell to propose **other irradiation modules**

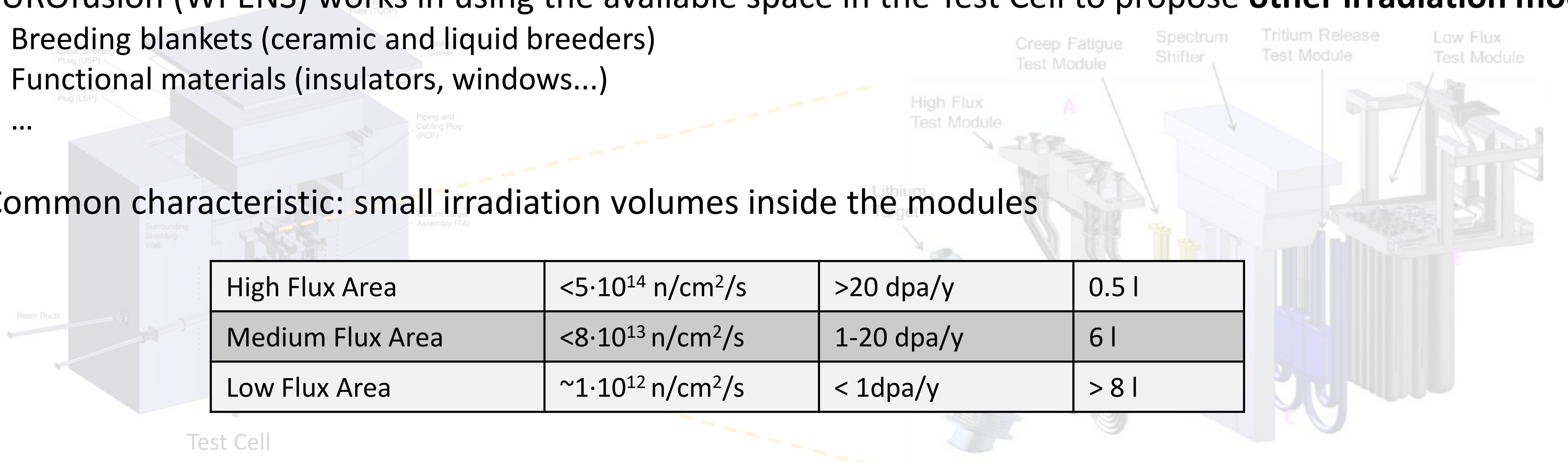
  Breeding blankets (ceramic and liquid breeders)

  Functional materials (insulators, windows...)

  …

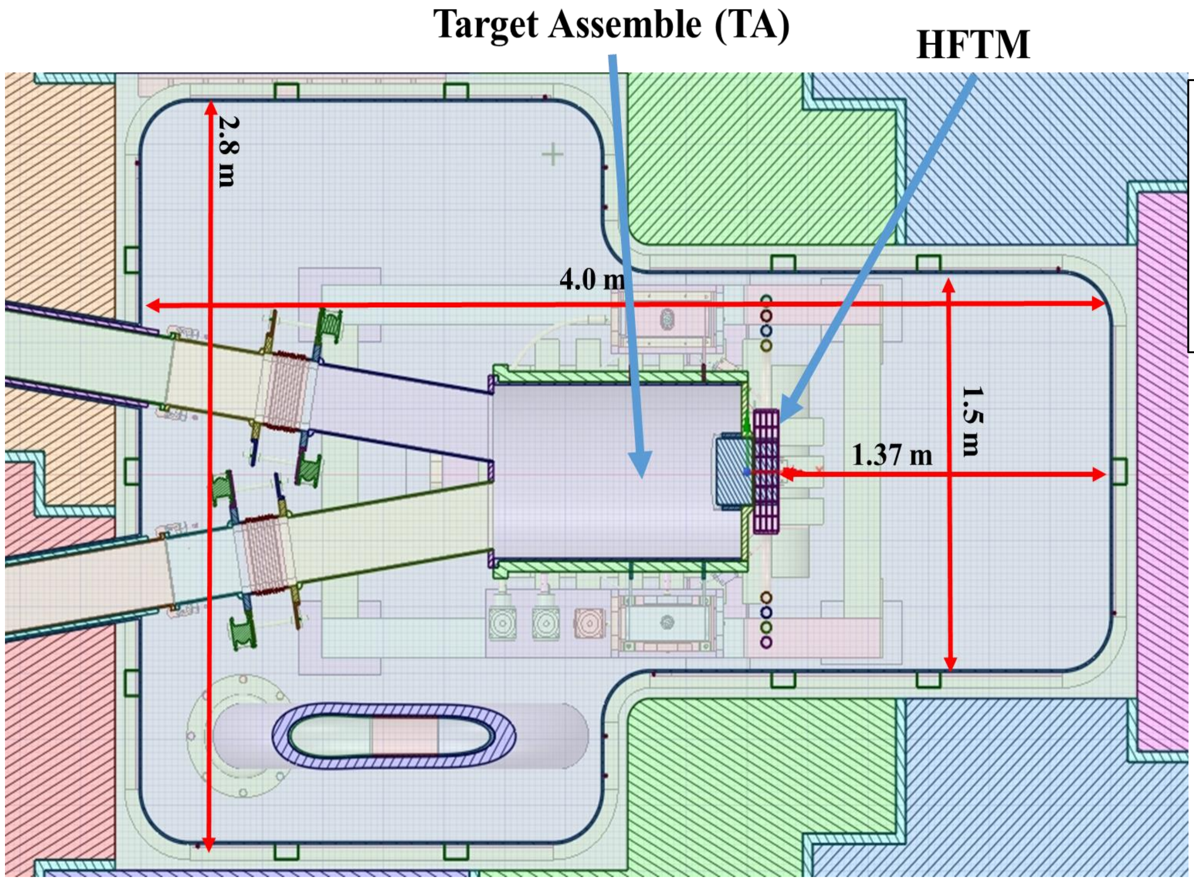
- Common characteristic: small irradiation volumes inside the modules

High Flux Area	$<5\cdot10^{14}$ n/cm²/s	>20 dpa/y	0.5 l
Medium Flux Area	$<8\cdot10^{13}$ n/cm²/s	1-20 dpa/y	6 l
Low Flux Area	$\sim1\cdot10^{12}$ n/cm²/s	< 1dpa/y	> 8 l



IFMIF-DONES test area

- Available irradiation volume in DONES is huge and represents an important benefit → large margin to propose new experiments.



x-axis: 1.37 m in the direction of the beam (excluding the HFTM)
y-axis: 4 m in the vertical direction
z-axis: 1.5 m in the horizontal direction

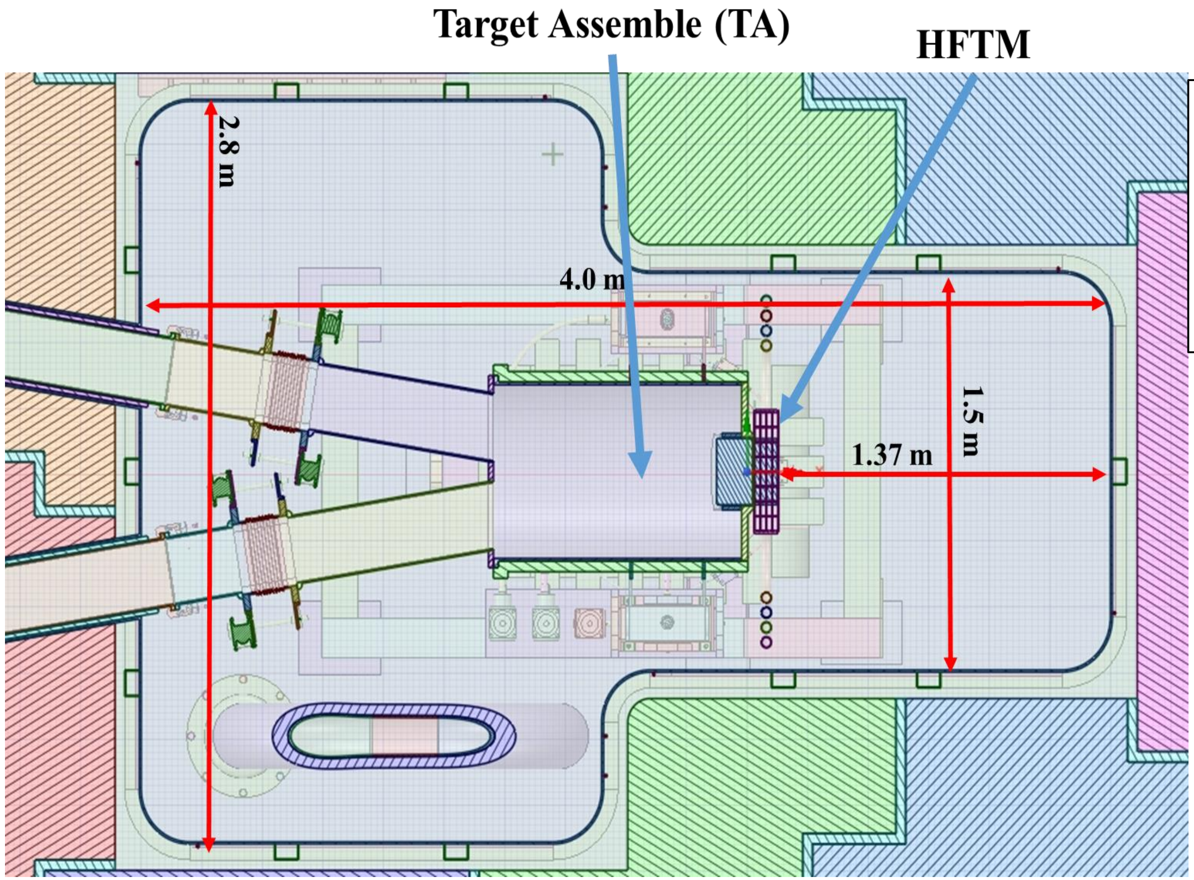
Characteristics of IFMIF-DONES:

- Large irradiation volume

- Strong gradients…
  - compared to DEMO, and depending on the direction

IFMIF-DONES test area

- Available irradiation volume in DONES is huge and represents an important benefit → large margin to propose new experiments.



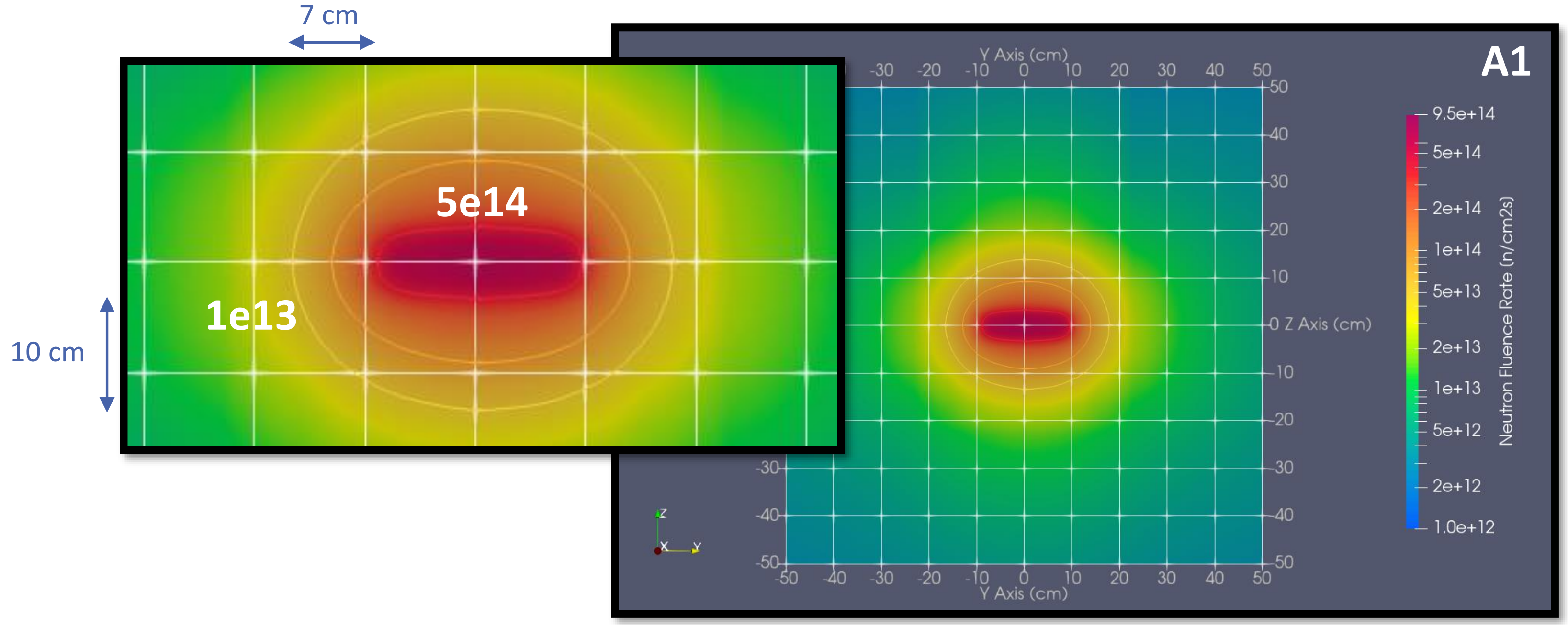
x-axis: 1.37 m in the direction of the beam (excluding the HFTM)
y-axis: 4 m in the vertical direction
z-axis: 1.5 m in the horizontal direction

Effective irradiation volume

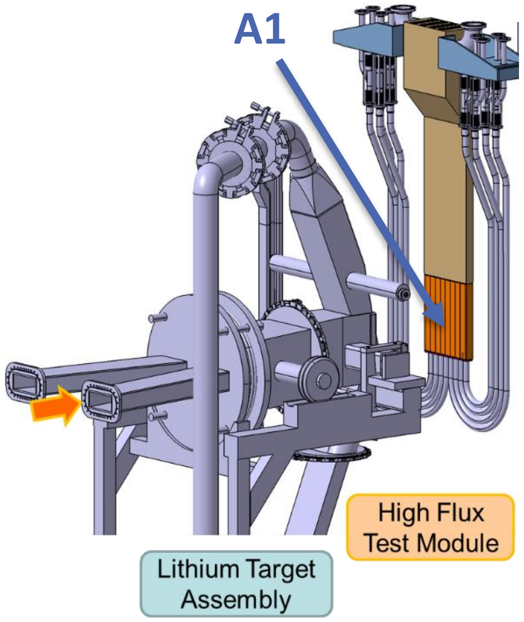
- The volume where the experiments can be relevant for the BB testing
- As in any other neutron source, depending on the used materials and components, the irradiation field could be modified
- **Specific calculations are needed**

IFMIF-DONES test area

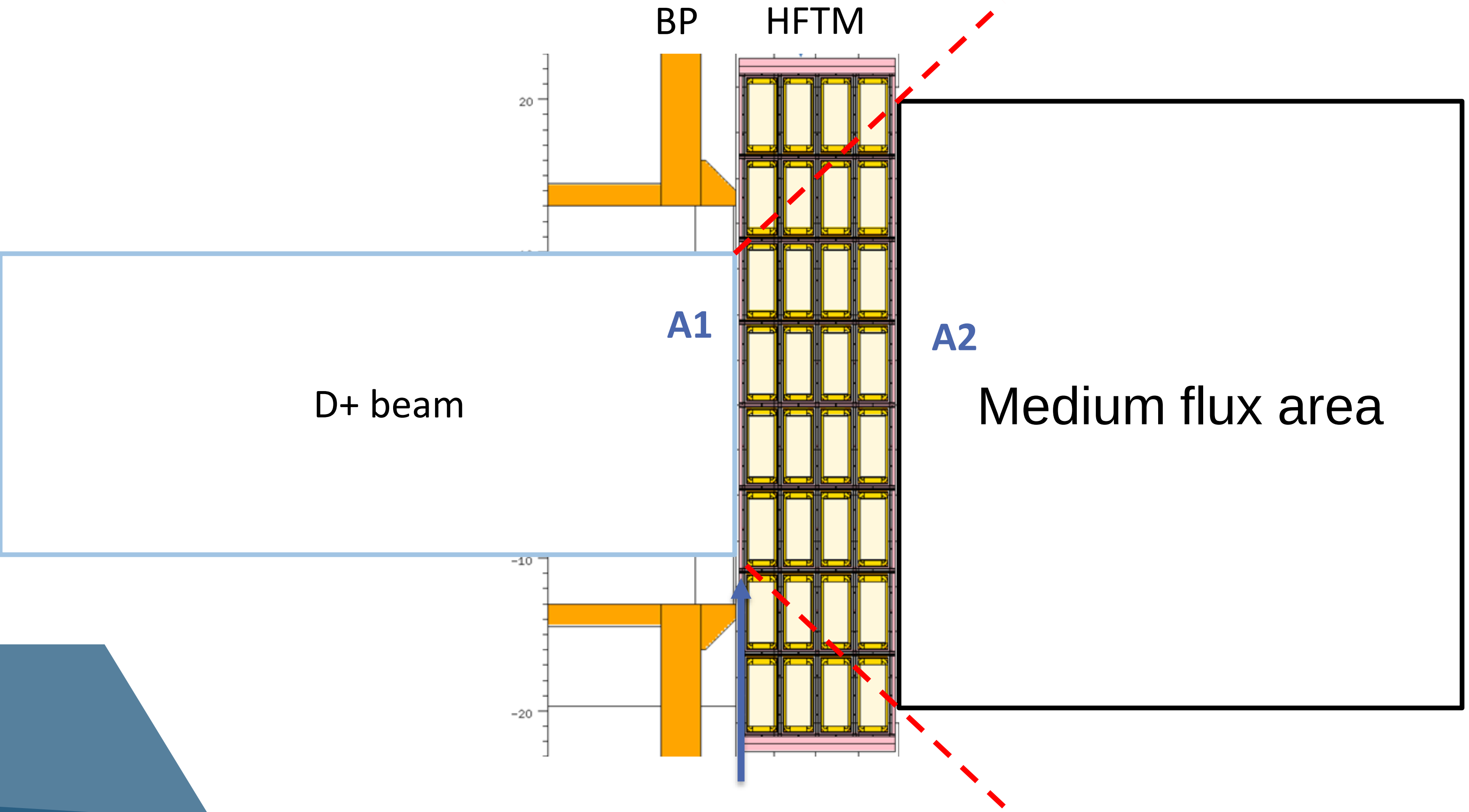
- Most of people think on this kind of neutron distribution → this is the footprint just immediately behind the BP (or the front of the HFTM). Focused in dpa

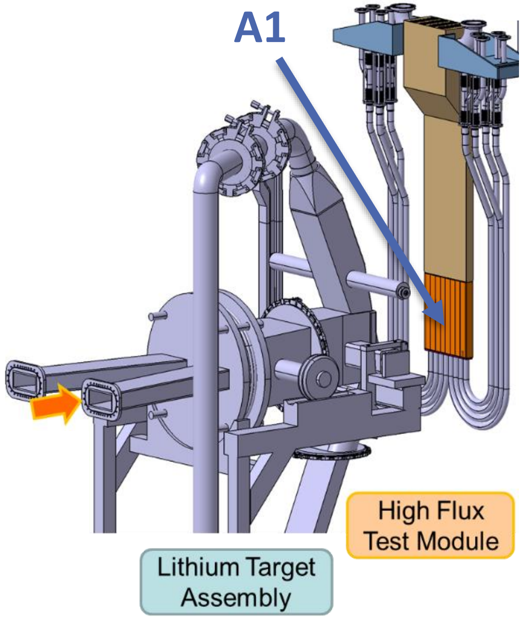


'footprint'
20 x 5 cm^2

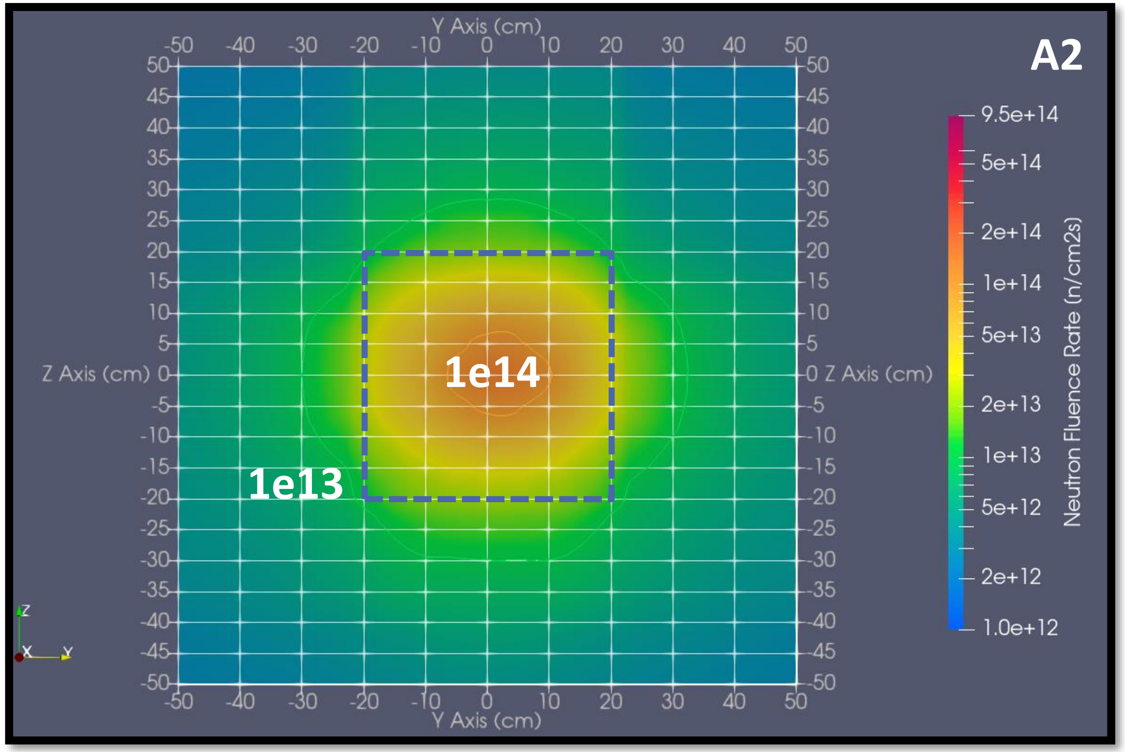


- However, the neutron field presents dispersion through the HFTM (distance ~10 cm) that results in a more homogeneous rad field at the beginning of the MF area

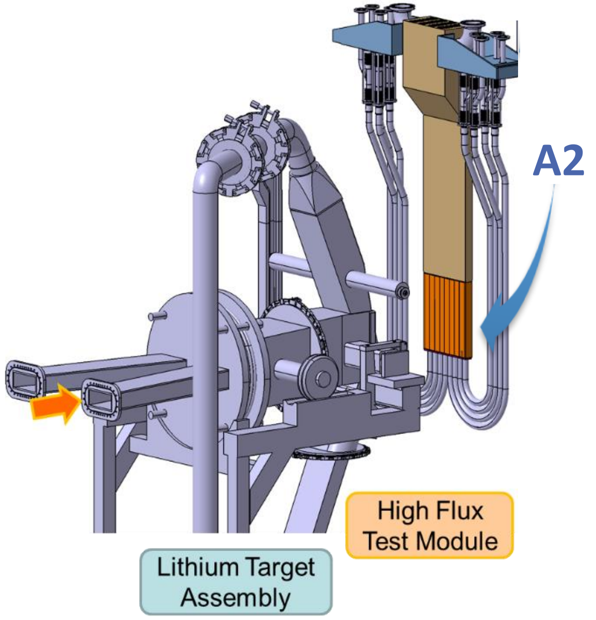




- However, the neutron field presents dispersion through the HFTM (distance ~10 cm) that results in a more homogeneous rad field at the beginning of the MF area



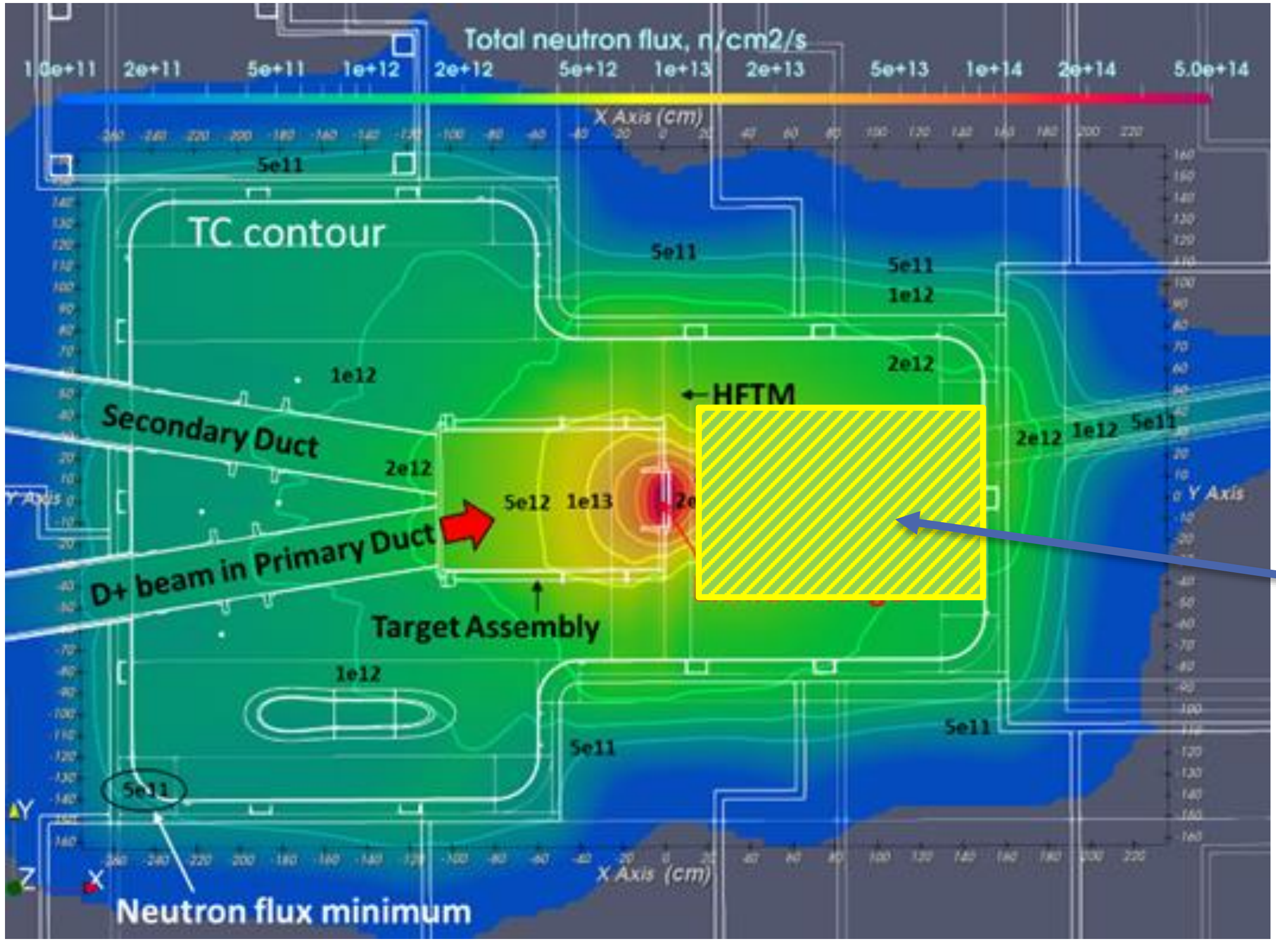
‘footprint’
40 x 40 cm^2



Behind the HFTM → ‘effective area’ from 100 cm^2 to 1600 cm^2

IFMIF-DONES test area

- Neutron flux distribution over the TC volume (neutrons/cm^2/s)

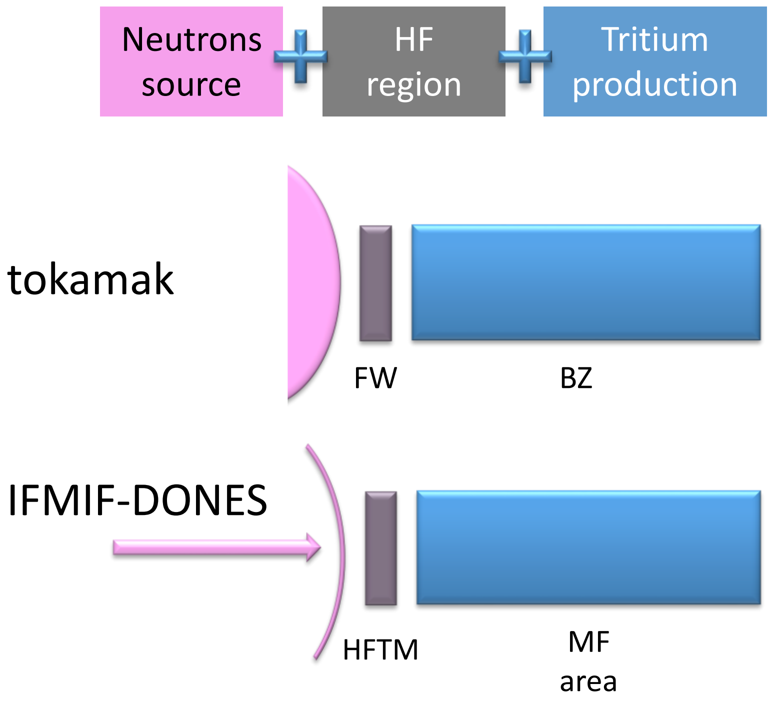


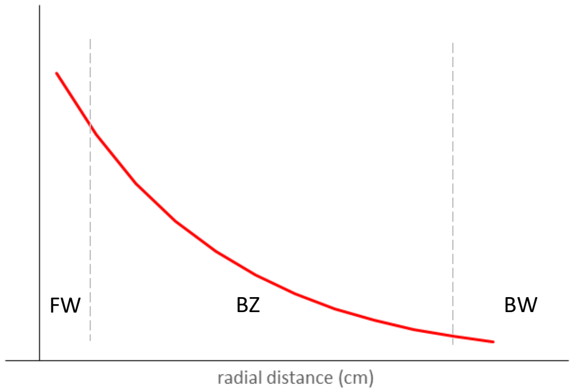
Minimum value: 2×10^{12} n/cm^2/s
Maximum value: $\sim 1 \times 10^{14}$ n/cm^2/s

Large and empty space to allocate new experiments

IFMIF-DONES test area

❑ What about the axial gradients?





❑ Neutron axial gradient similar to the one in DEMO → results coming in the next slides

❑ The DONES medium flux area constitutes a perfect test bench for the BB

OUTLINE

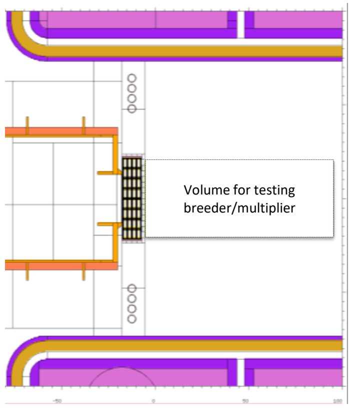
- ❑ Motivation
- ❑ IFMIF-DONES and tritium technologies validation
- ❑ **DONES Test Blanket Units**
- ❑ The HCPB-TBU: preliminary results
- ❑ The WCLL-TBU: preliminary results
- ❑ Capabilities of DONES to test the TBU
- ❑ Summary & Conclusions

The DONES-TBU

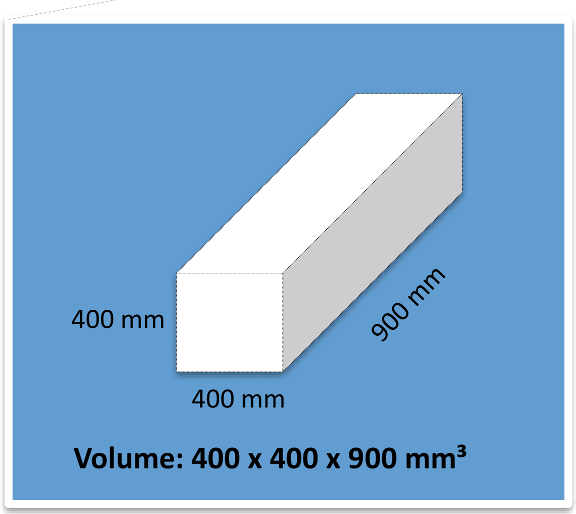
- Tritium technologies validation in IFMIF-DONES
  - Maintain dedicated experiments to test the basic physics → OIM (TRTM, LBVM)
  - Scaling up the system to test relevant-sized blanket mock-ups

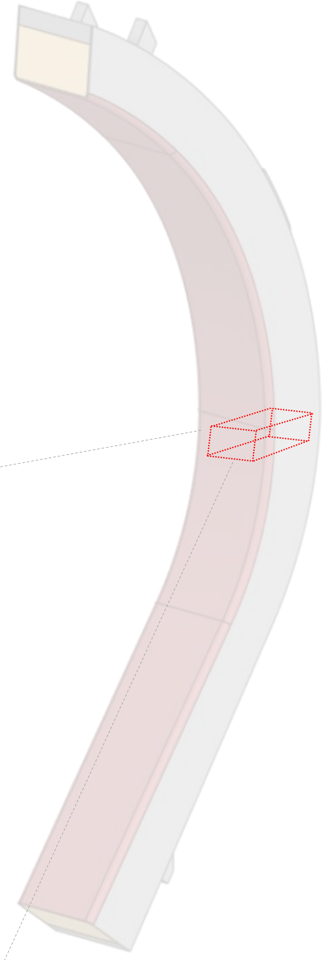
- **Test Blanket Unit** (TBU):
  - A BB fraction, considered representative (in some way) of a whole segment
  - Medium flux area → effective irradiation volume that can accommodate the TBU
  - Offers screening experiments before introducing the complexity of the EM loads

- Activity that involves experts in neutronics, thermal-hydraulics, thermo-mechanics, materials… → BB + DONES



Volume for testing in Test Cell of IFMIF-DONES





The DONES-TBU

- What can we expect from this kind of experiments

  - Validation of different numerical models adopted for the BB design (e.g. neutronics, tritium transport and production, activation, etc.)
  - Materials behavior (breeder, coating, etc.)
  - Breeder/Structure thermo-mechanical interactions (e.g. stress and strain in the structure, cracking and redistribution in the breeder, overall deformation…)
  - Weld performances under high radiation fields, gradients, stresses…
  - Diagnostics development → integration in the TBU (similar to BB)
  - Heat Transfer Experiments (e.g. HCPB, to address heat transfer in realistic fuel-breeder pin geometry)
  - DWT behavior and impact of irradiation on coatings (specific WCLL)

- This comprehensive approach is crucial for several reasons:

a) Verifying the tritium production rate to ensure the blanket meets the necessary efficiency for fuel breeding.

b) Demonstrating effective temperature control of the breeder blanket to maintain operational stability and safety.

c) Testing the bonding quality between tungsten and EUROFER to ensure the structural integrity and durability of the materials used in the blanket.

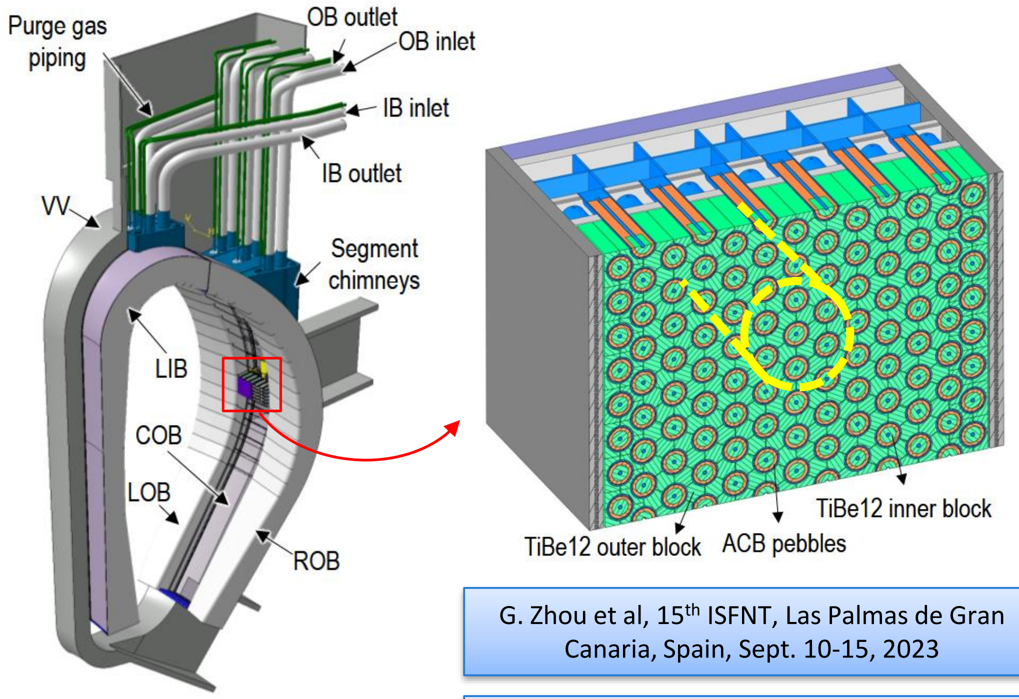
d) …

Exercise with two EU breeding blanket

- Helium Cooled Pebble Bed - HCPB
- Water Cooled Lead Lithium - WCLL

EU Breeding Blanket Concepts

❑ The **HCPB** breeding blanket → sequential distribution



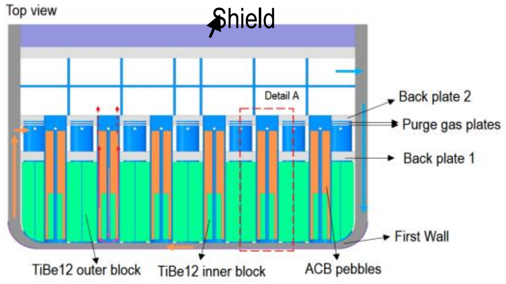
G. Zhou et al, 15th ISFNT, Las Palmas de Gran Canaria, Spain, Sept. 10-15, 2023

G. Zhou et al., Energies 16(14) (2023) 5377

Design status of the European DEMO Helium Cooled Pebble Bed breeding blanket, G. Zhou, this WS

Main characteristics

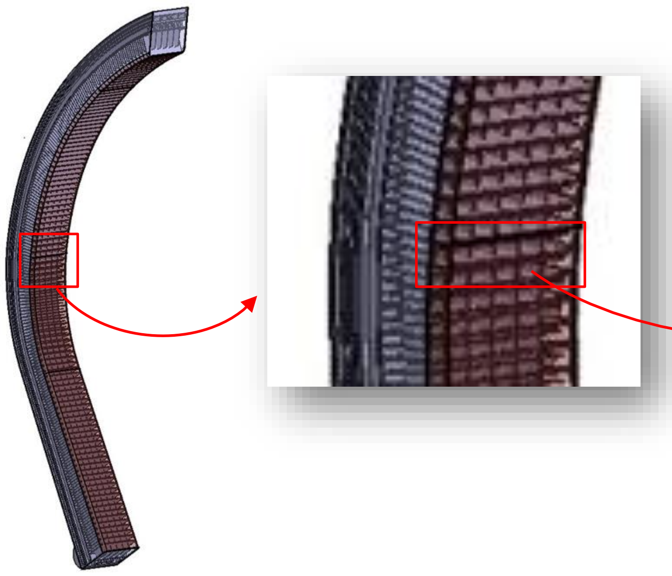
- Eurofer as structural material
- Coolant: He @80 bar, 300-520°C
- Fuel-breeder pins contain advanced ceramic breeder (ACB) pebble
- Beryllide neutron multiplier of **triangular prism** with lateral edges filleted
- T-extraction: He + 200 Pa H2 @80 bar
- FW and critical structure thicker + cooled by fresh coolant
- Inner beryllide block inside ACB pebble

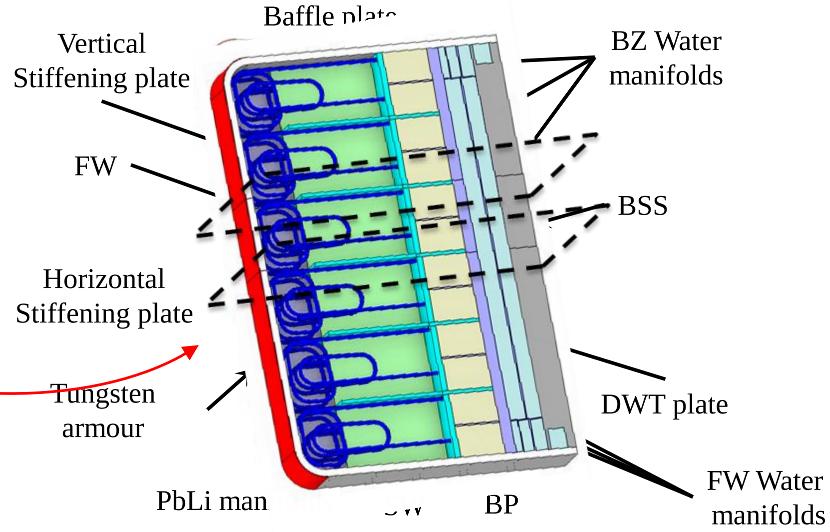


❖ A possible HCPB BB test section could be represented by just one or a set of fuel-breeder pins → the TC effective volume allows to accommodate up to 7 pins

EU Breeding Blanket Concepts

❑ The **WCLL** breeding blanket → sequential distribution





Helical shaped DWT

Main characteristics

- Eurofer as structural material, tungsten coating in plasma facing surfaces
- Water in PWR conditions as coolant: 15.5 MPa, 295-328°C
- Dedicated water coolant circuits for FW (channels) and BZ (DWTs)
- Eutectic PbLi alloy as neutron multiplier (Pb), tritium breeder (^{6}Li at 90% enrichment) and tritium carrier
- Single segment structure with elementary cell (slice) approach

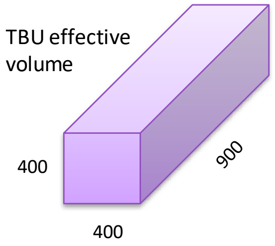
P. Arena et al., 33rd Symposium On Fusion Technology, Dublin, Ireland, Sept. 22-27, 2025

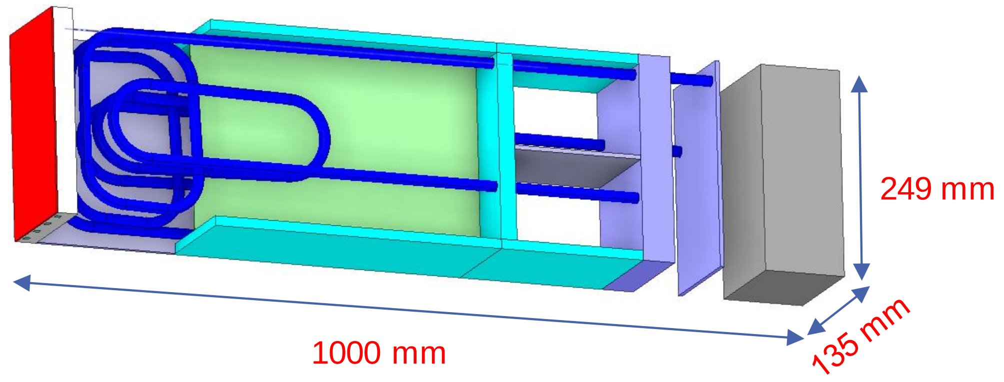
P. Maccari et al., Fusion Engineering and Design 199 (2024) 114134

❖ A possible WCLL BB test section could be represented by the area enclosed between two consecutive horizontal and vertical stiffening plates → slice

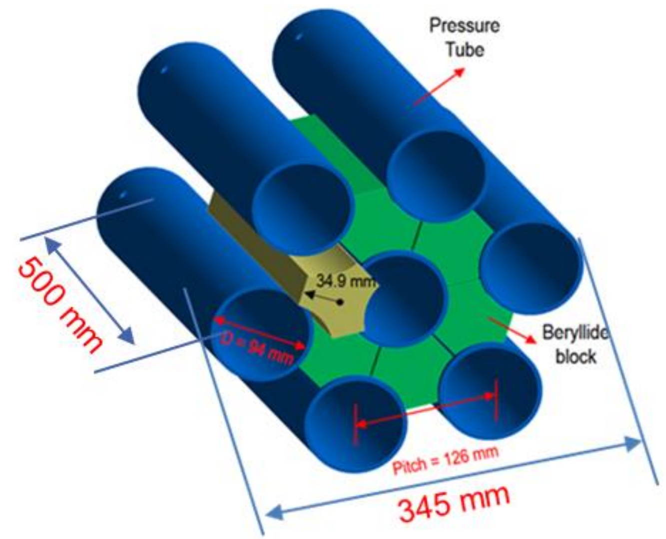
- TBU for the WCLL and HCPB → basic elements

Volume: 400 x 400 x 900 mm³





Dimensions of WCLL blanket BZ + manifold



Dimensions of HCPB blanket breeder zone

ENEA
ENTE PER LE NUOVE TECNOLOGIE, L'ENERGIA E L'AMBIENTE

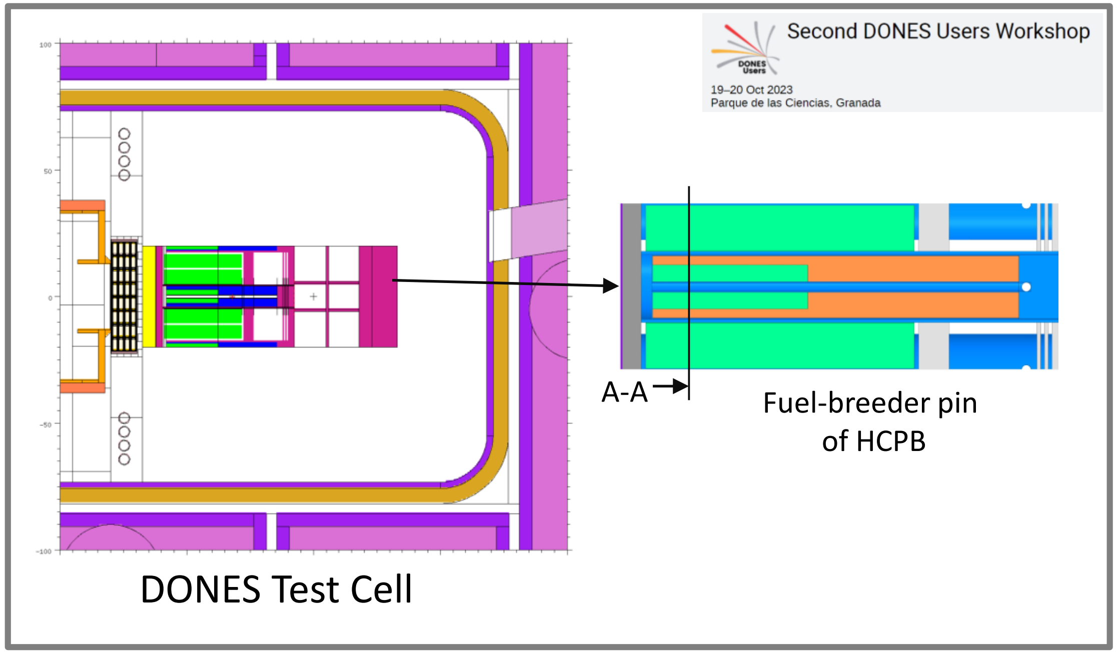
KIT
Karlsruher Institut für Technologie

OUTLINE

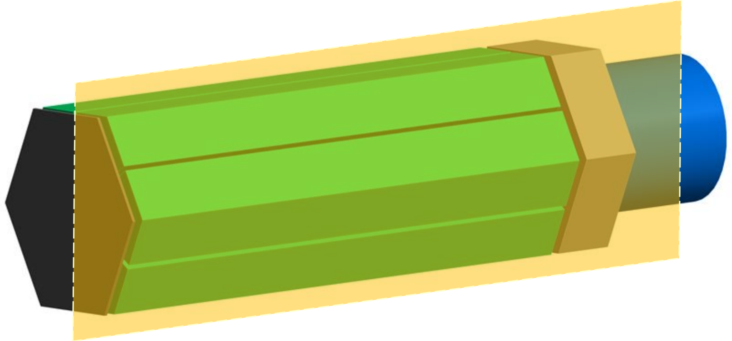
The HCPB-TBU: preliminary results

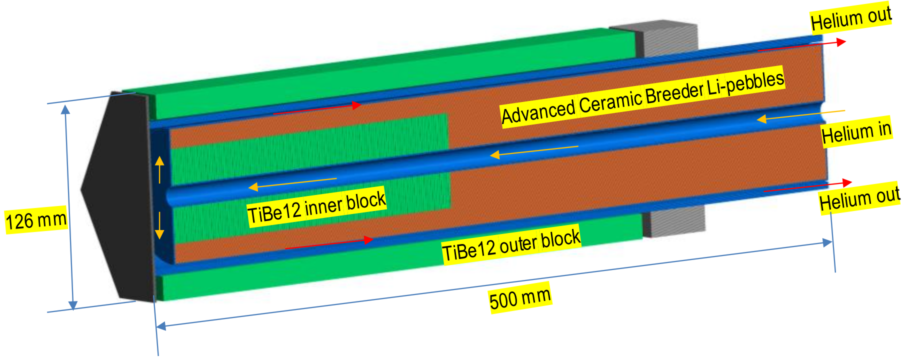
- Preliminary model → developed 2023

  1 unique fuel-breeder pin



G. Zhou et al., Second DONES Users Workshop, Oct 19-20, 2023, Granada, Spain

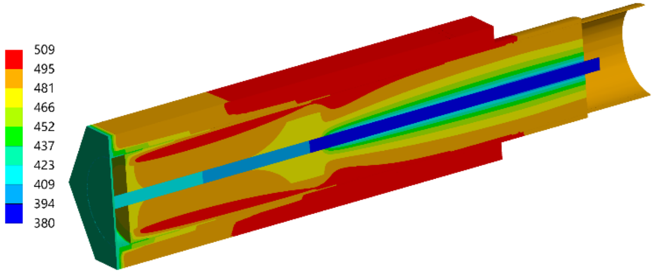




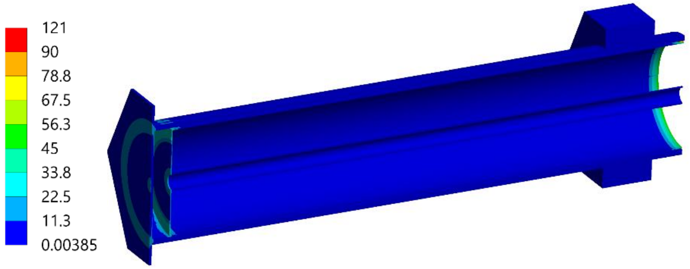
The HCPB-TBU: preliminary results

- Preliminary NX calculations:

1 Thermal analysis: temperature field



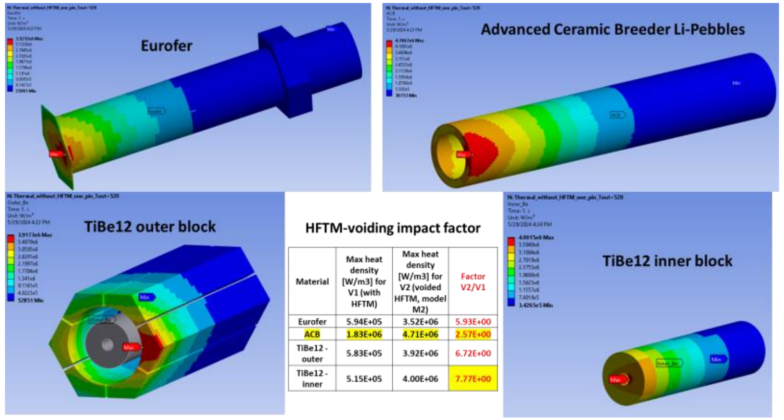
3 Von-Mises Stress field [MPa]



Stress with pressure and temperature field

- … and ANSYS → structural analysis

2 Nuclear heating in the different materials



HFTM-voiding impact factor

Material	Max heat density [W/m3] for V1 (with HFTM)	Max heat density [W/m3] for V2 (voided HFTM, model M2)	Factor V2/V1
Eurofer	5.94E+05	3.52E+06	5.93E+00
ACB	1.83E+06	4.71E+06	2.57E+00
TiBe12 - outer	5.83E+05	3.92E+06	6.72E+00
TiBe12 - inner	5.15E+05	4.00E+06	7.77E+00

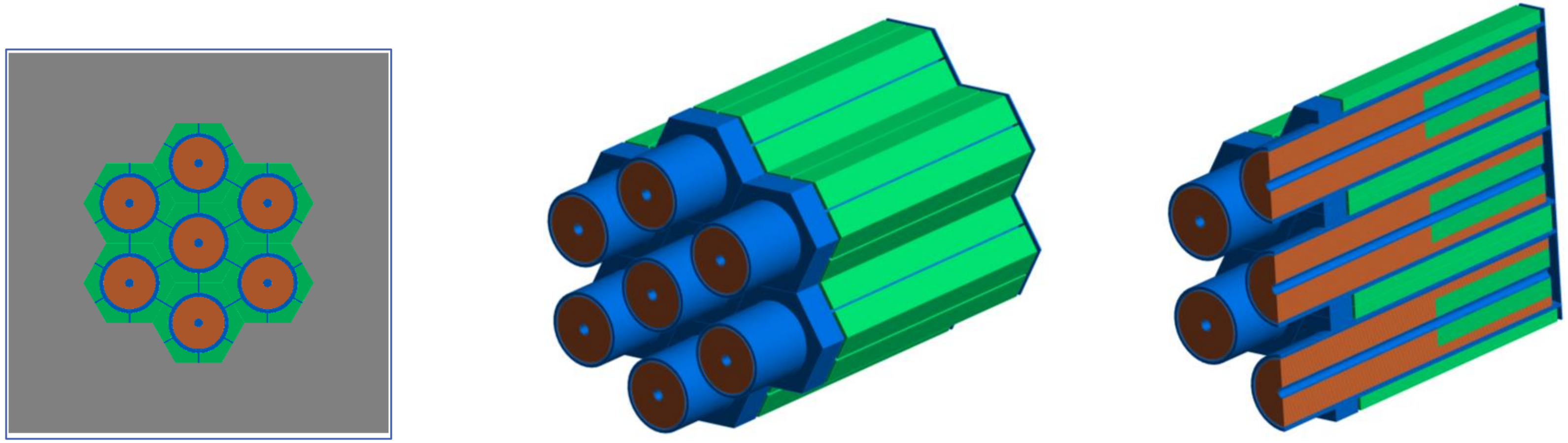
4 Tritium production rate

model	Tritium production [per pin]
DEMO HCPB BB	3.3 mg/day
HCPB-TBU	0.34 mg/day

Laboratorio Nacional de Fusión Ciemat

Karlsruher Institut für Technologie

- More advanced model (2024) → 7 fuel-breeder pin

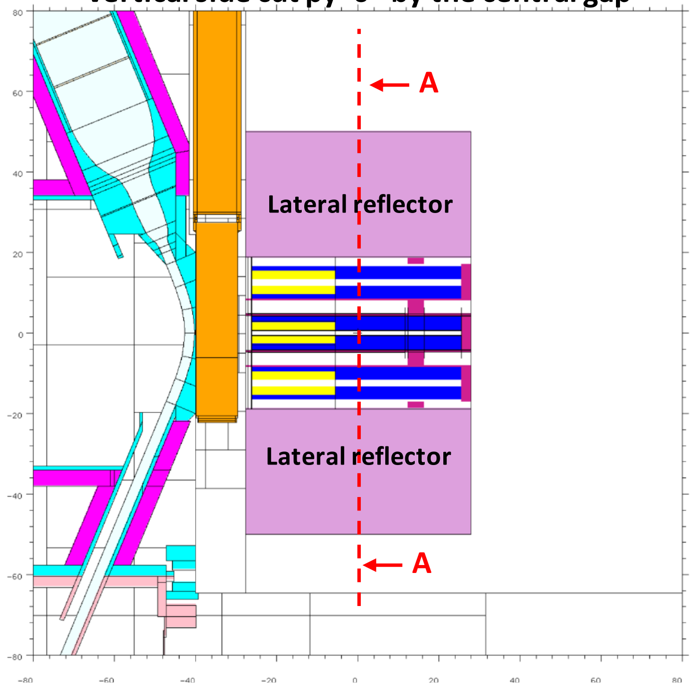


G. Zhou et al., Third DONES Users Workshop, Oct 1-2, 2024, Zagreb, Croatia

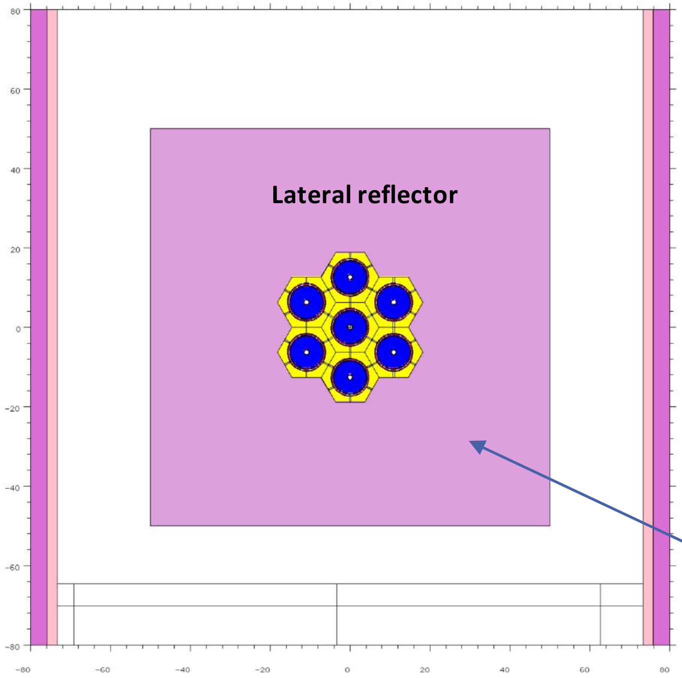
The HCPB-TBU: preliminary results

- More advanced model (2024) → 7 fuel-breeder pin
- Neutronics model

Vertical side cut py=0 –by the central gap



Cross-cut A-A



Calculated and compared :
1) Neutron fluxes
2) Nuclear heat for the different materials
3) T-production in Li-ceramics ACB
4) Neutron damage (DPA/FPY)

The model includes reflectors surrounding the TBU

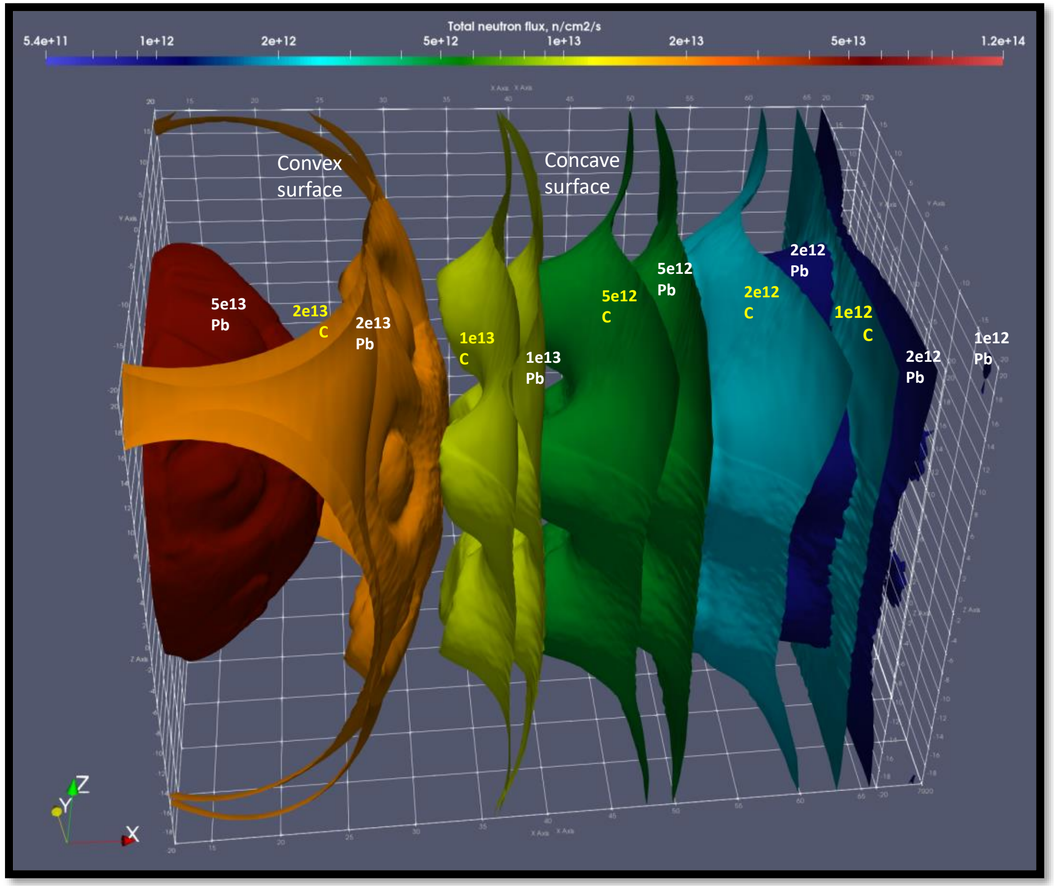
A. Serikov et al., Third DONES Users Workshop, Oct 1-2, 2024, Zagreb, Croatia

- More advanced model (2024) → 7 fuel-breeder pin

- Includes neutron lateral reflectors: prevent neutron leakage from the lateral sides

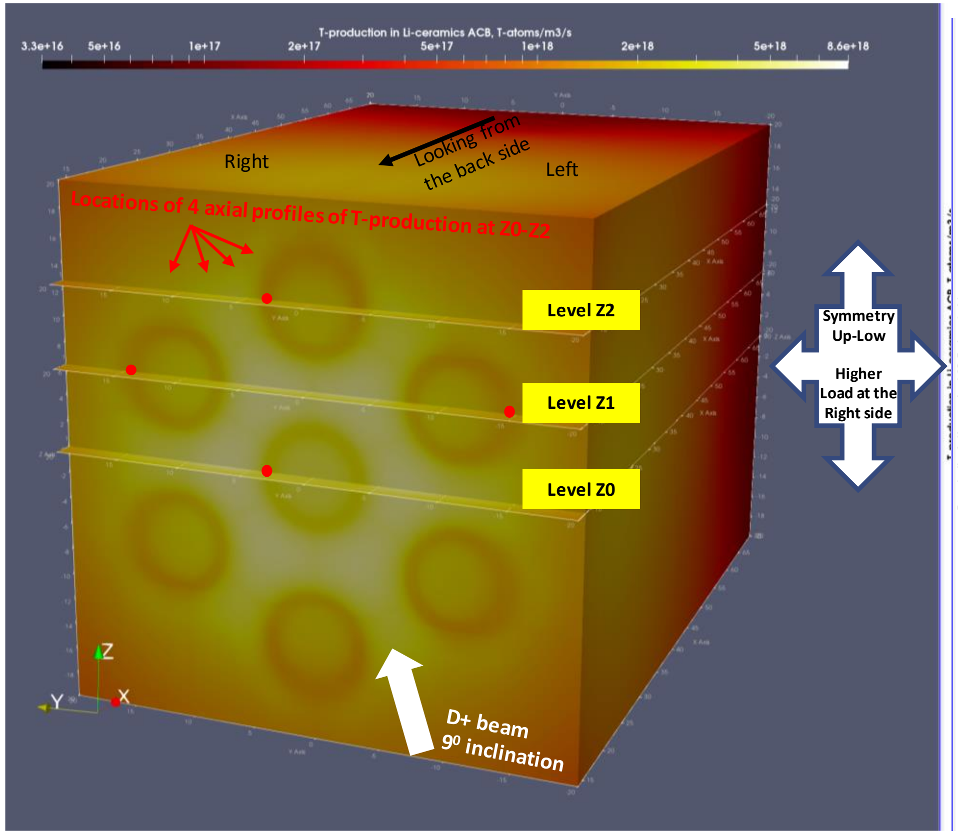
Options: graphite (C) or lead (Pb)

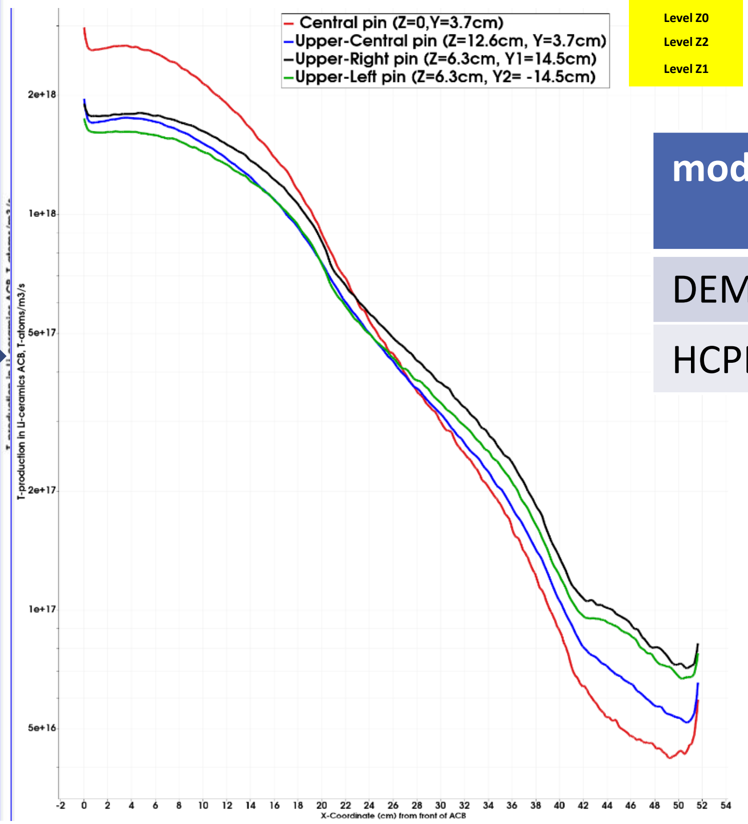
- Pb → preferable shape of the neutron flux distribution
  - shape is flatter
  - it allows to breed tritium with ~2 times higher flux



The HCPB-TBU: preliminary results

- Tritium production estimation in Li-ceramics ACB (Pb-reflector)



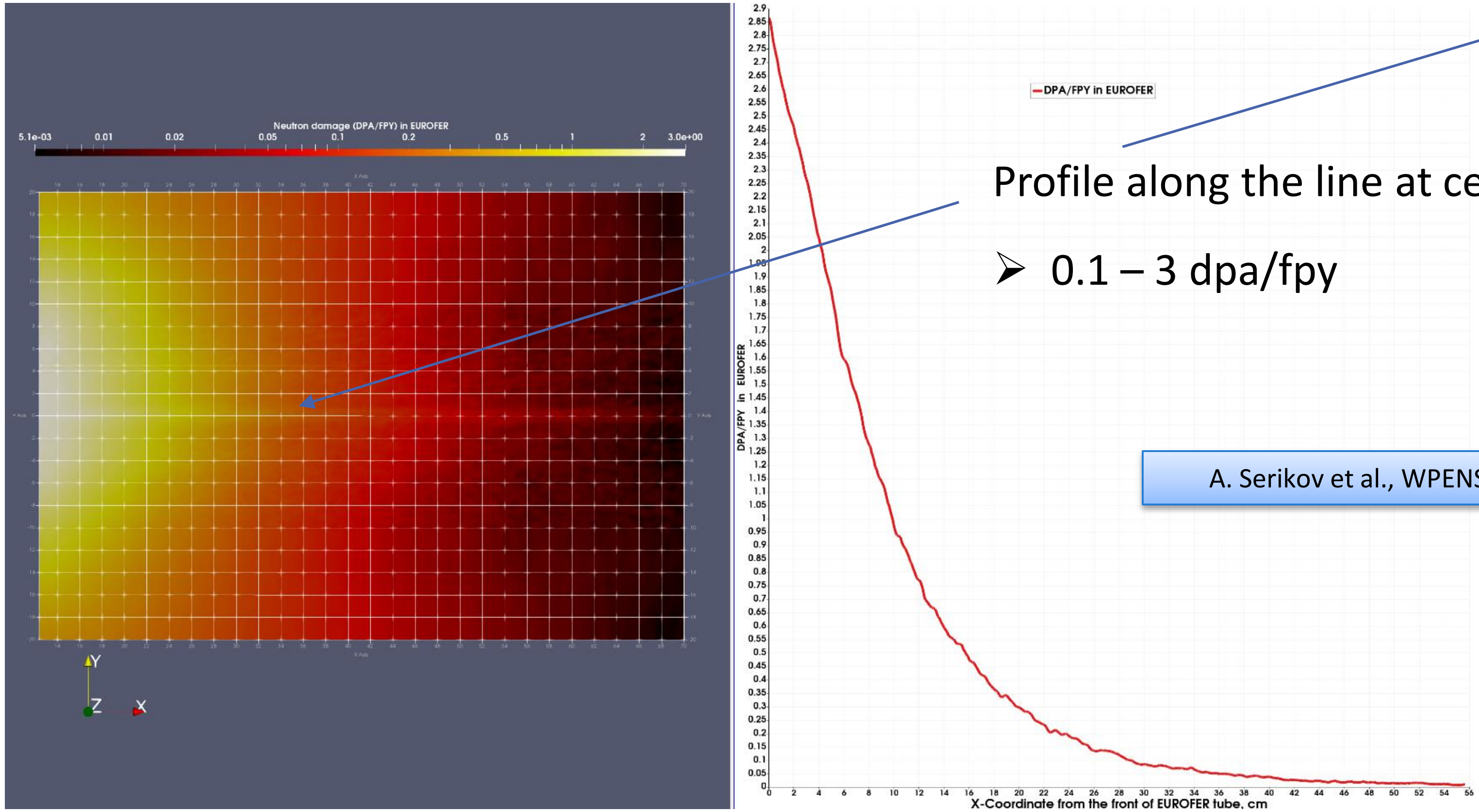


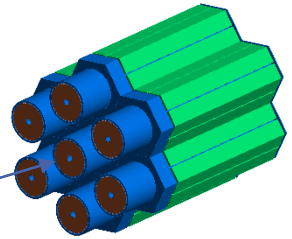
model	Tritium production [per pin]
DEMO HCPB BB	3.3 mg/day
HCPB-TBU-7	0.52 mg/day

3.64 mg/day in 7 pins

The HCPB-TBU: preliminary results

- Neutron damage (DPA/FPY) in EUROFER (Pb-reflector)





Profile along the line at central pin

- 0.1 – 3 dpa/fpy

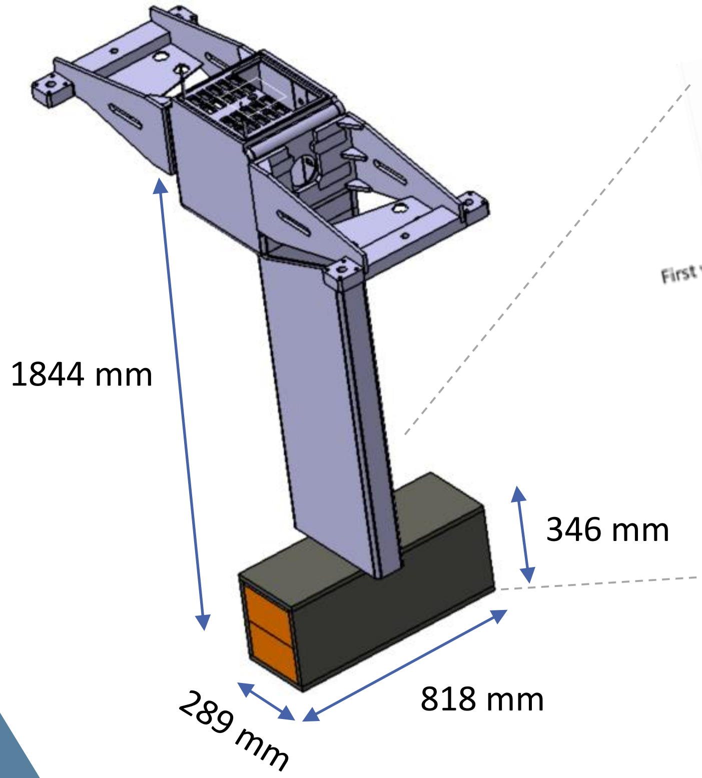
A. Serikov et al., WPENS TM#18, Nov 27, 2024, Madrid

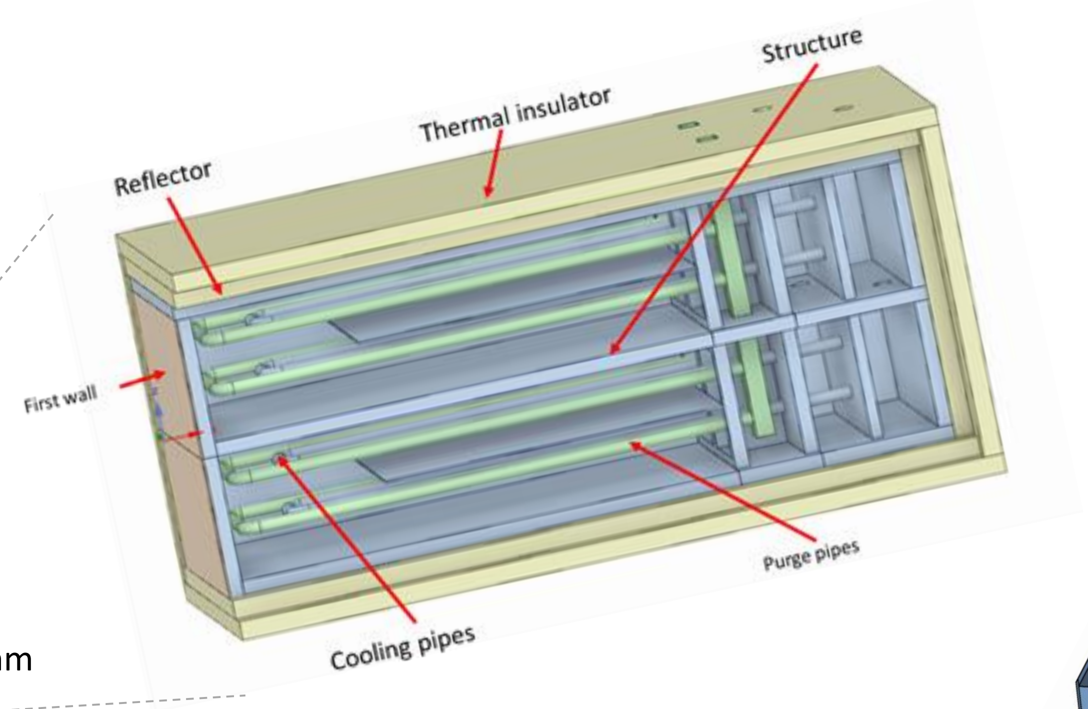
OUTLINE

- ❑ Motivation
- ❑ IFMIF-DONES and tritium technologies validation
- ❑ DONES Test Blanket Units
- ❑ The HCPB-TBU: preliminary results
- ❑ The WCLL-TBU: preliminary results
- ❑ Capabilities of DONES to test the TBU
- ❑ Summary & Conclusions

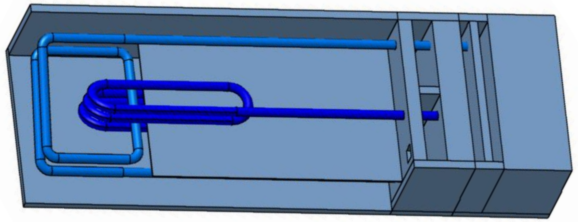
The WCLL-TBU: preliminary results

- CATIA design of the WCLL-TBU already available



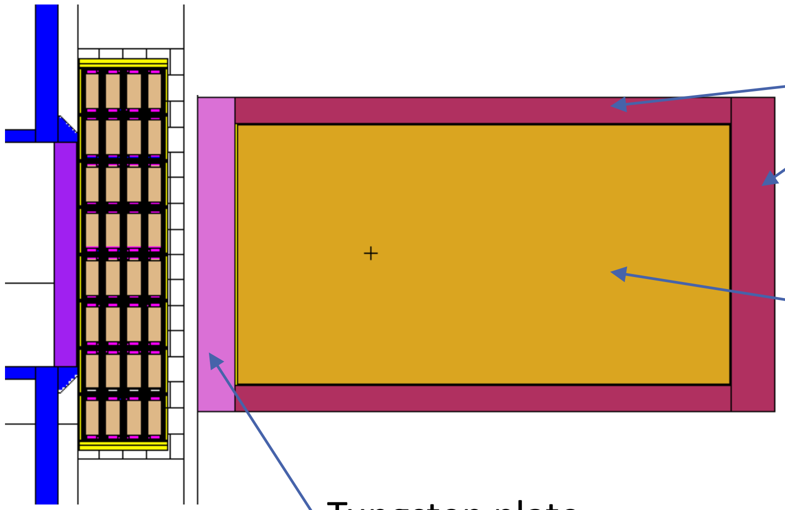


- Tungsten plate
- Graphite reflectors (grey color box)
- 2 slices (one on top of the other)
- Same support than HFTM (first iteration)

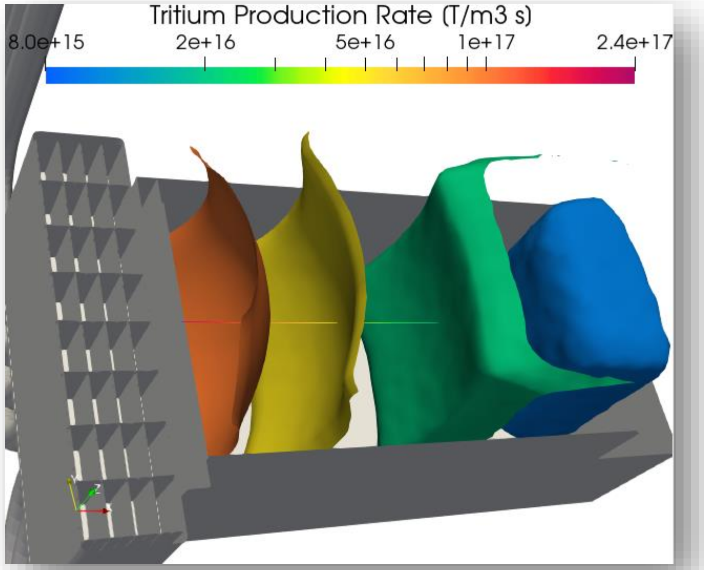


The WCLL-TBU: preliminary results

- Simplified NX model for preliminary estimations



- 1 unique box
- Dimensions: 30x30 cm^2
- 60 cm length
- Stagnant PbLi
- No DWT

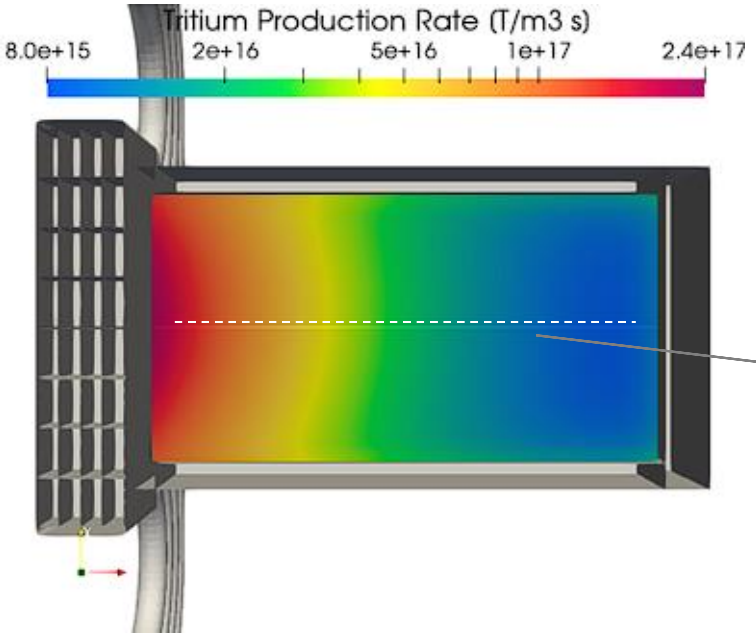


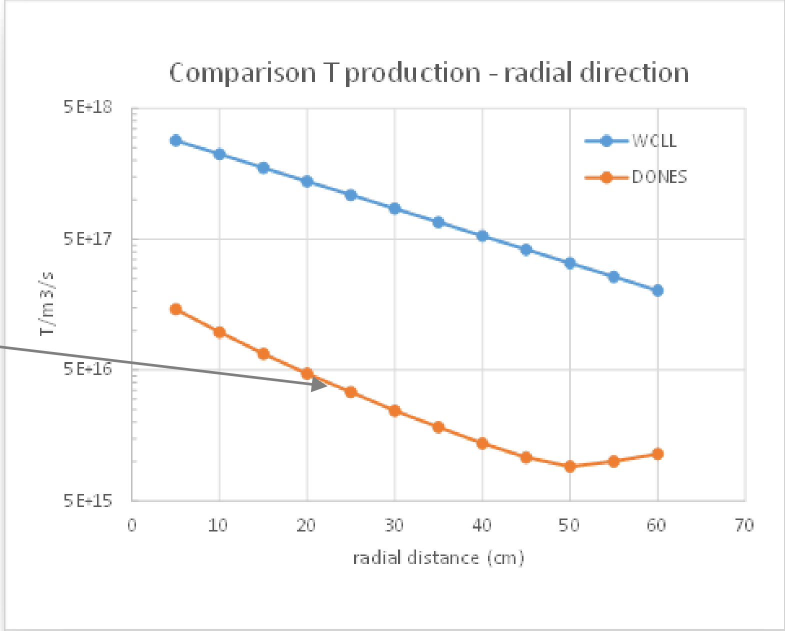
Effect of reflectors:
almost flat profiles in ZY plane

MI Ortiz et al., Third DONES Users Workshop, Oct 1-2, 2024, Zagreb, Croatia

The WCLL-TBU: preliminary results

- Simplified NX model for preliminary estimations: tritium production

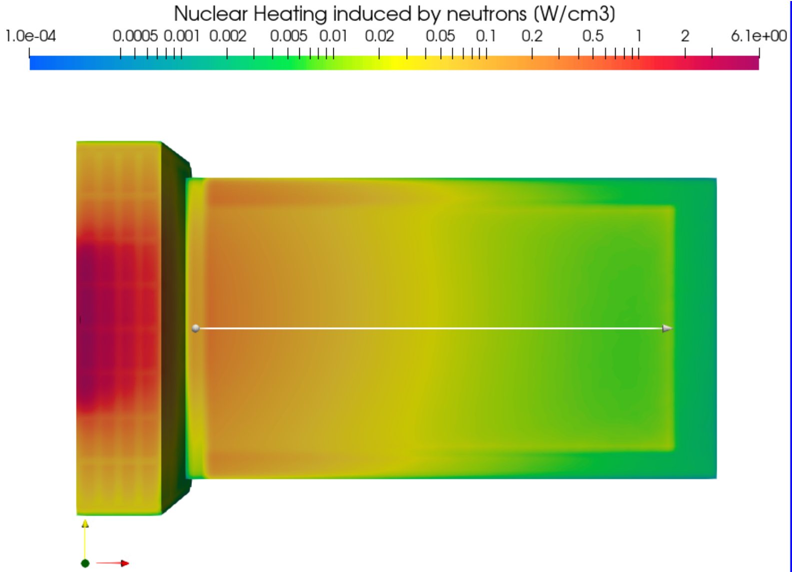


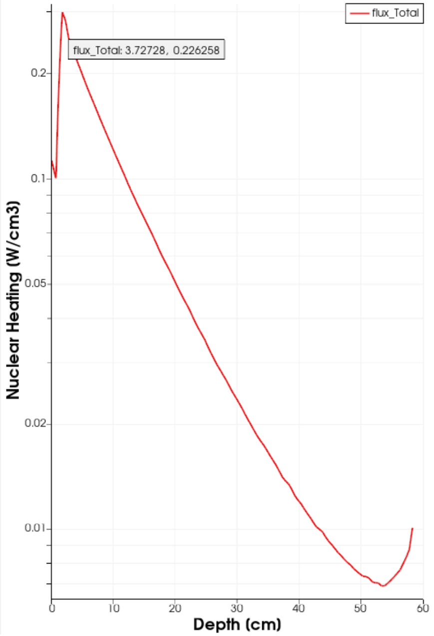


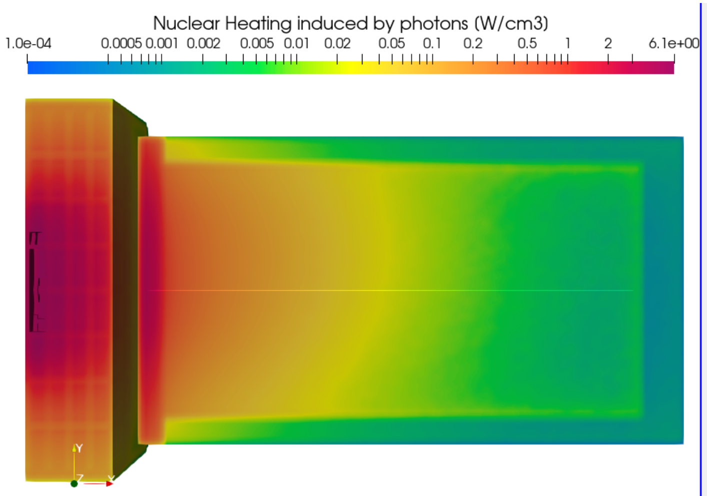
- Tritium production in the WCLL-TBU → one order of magnitude lower than WCLL-BB
- Total production WCLL-TBU ~ 1 mg/day

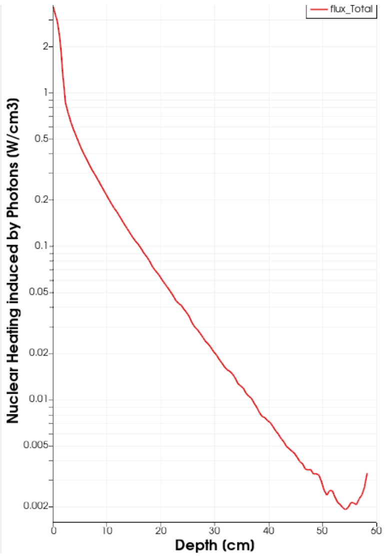
Laboratorio Nacional de Fusión
Ciemat

- Simplified NX model for preliminary estimations: nuclear heating









- Nuclear heating results →

model	Nuclear Heating
WCLL (OB Eurofer)	~ 0.02 – 0.6 kGy/s
WCLL-TBU	~ 0.01 – 0.2 kGy/s

OUTLINE

DONES Capabilities (TBU): safety issues

- Stored and mobilized tritium is governed and licensed by the national regulator

Tritium: IFMIF-DONES considers an amount of tritium produced (mainly from the Li loop) of 3.6 g/year.

TBU: 1 full campaign (11 months @full power) ~1 g

→ no strong limitations on this parameter.

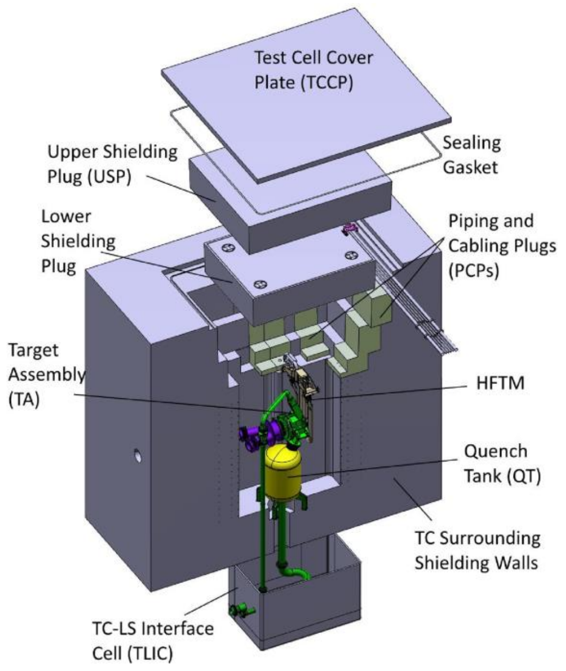
Tritium in Process: subjected to maximum release in the event of an accident. More restrictive values: 0.3 g

TBU: 10 mg/day → exceeds the estimated value in the current TBU designs

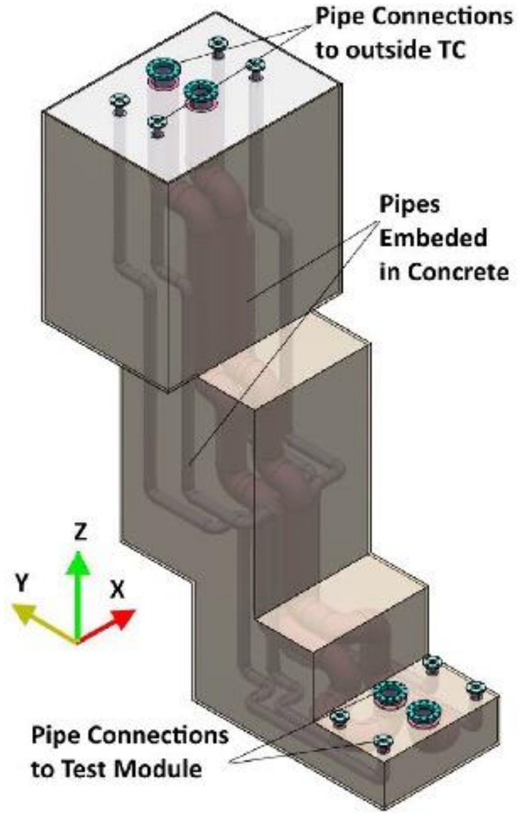
→ no strong limitations on this parameter.

DONES Capabilities (TBU): integration TC

- A critical point involves the penetrations required in the irradiation area



PCPs (piping and cabling plugs): concrete block, several horizontal and vertical steps in all three directions to minimize neutron streaming during operation.



K. Tian et al., Fusion Engineering and Design 136 (2018) 628-632

- Each experiment (TBU) would have a specific PCP tailored to its requirements.
- Presently, there are three dummy PCP available for TBU

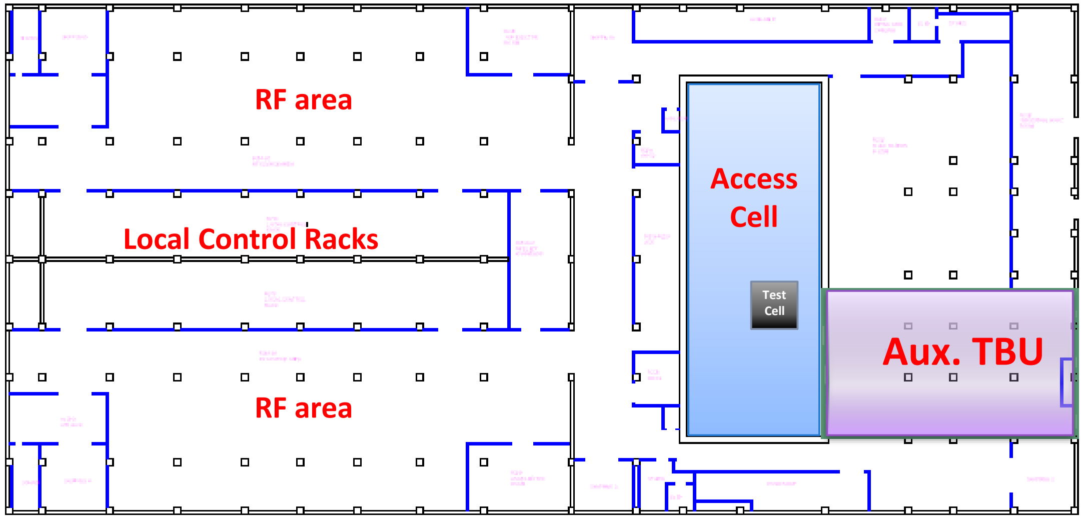
DONES Capabilities (TBU): Auxiliary Systems

- The experiments proposed need additional auxiliary systems:
  - Power supply
  - Tritium extraction/storage
  - Gas supply
  - …

- IFMIF-DONES has a dedicated area: space covers ~800 m², height of 6.5 meters

  - Access to the TC is provided through the Access Cell, located on the upper floor.

  - The area designated for auxiliaries is an adjacent room to the Access Cell → minimize the distance for tritium transport.



2nd floor – top view

OUTLINE

- ❑ Motivation
- ❑ IFMIF-DONES and tritium technologies validation
- ❑ DONES Test Blanket Units
- ❑ The HCPB-TBU: preliminary results
- ❑ The WCLL-TBU: preliminary results
- ❑ Capabilities of DONES to test the TBU
- ❑ **Summary & Conclusions**

SUMMARY & CONCLUSIONS

- The **IFMIF-DONES** facility constitutes a perfect scenario for BB testing, offering neutrons (and gammas) of high energy and fluence, comparable with the radiation loads to be reached at the future fusion reactors

- The capabilities of IFMIF-DONES to qualify **tritium technologies** within the medium flux area have been presented → neutron axial gradient similar to the one in DEMO, fluence rate same order of magnitude

- The concept of **DONES-TBU** has been introduced, and the main objectives of the mockups have been established and presented (first iteration, to be discussed and improved).

- **Preliminary designs** of TBU are proposed for the HCPB/WCLL, and specific calculations show the feasibility of the mock-up.

SUMMARY & CONCLUSIONS

- Ongoing activities:
  - ✓ CFD, ancillary systems requirements, interfaces with the TC…
  - ✓ EcosimPro modeling for tritium transport and inventories
  - ✓ More advanced designs are being studied to include electrical heaters, instrumentation…
  - ✓ Definition of essential auxiliaries: tritium measuring and accountancy system

  (New conceptual designs → under development at CIEMAT: DCLL, WLCB)

- IFMIF-DONES (TBU modular validation) can constitute a **complementary program** to ITER TBM (adding EM loads) and Volumetric Neutron Source (VNS, integrated validation)