IFMIF-DONES: Experimental strategy for fusion materials qualification

L. Monasterio-Guillot, A. Ibarra and the DONES Join Team

Technical Meeting on Tritium Breeding Blankets and Associated Neutronics
September, 2-5th 2025

Outline

- Introduction
- The Test Cell Area
- Materials Irradiation Capabilities
- Materials Irradiation Experimental Programme
- Where we are?
- Summary

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- **Introduction**
- **The Test Cell Area**
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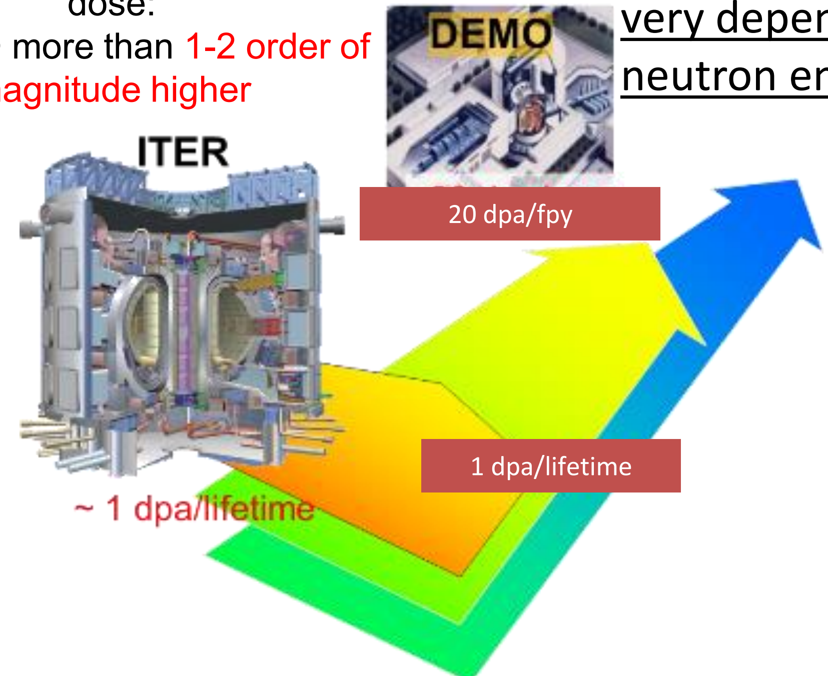
- **Where we are?**
- **Summary**

Why IFMIF-DONES?

One of the main differences between **ITER** and **DEMO** (or any fusion power plant) is the radiation dose:
at DEMO more than 1-2 order of magnitude higher



Radiation damage processes and effects are very dependent on the neutron energy spectrum

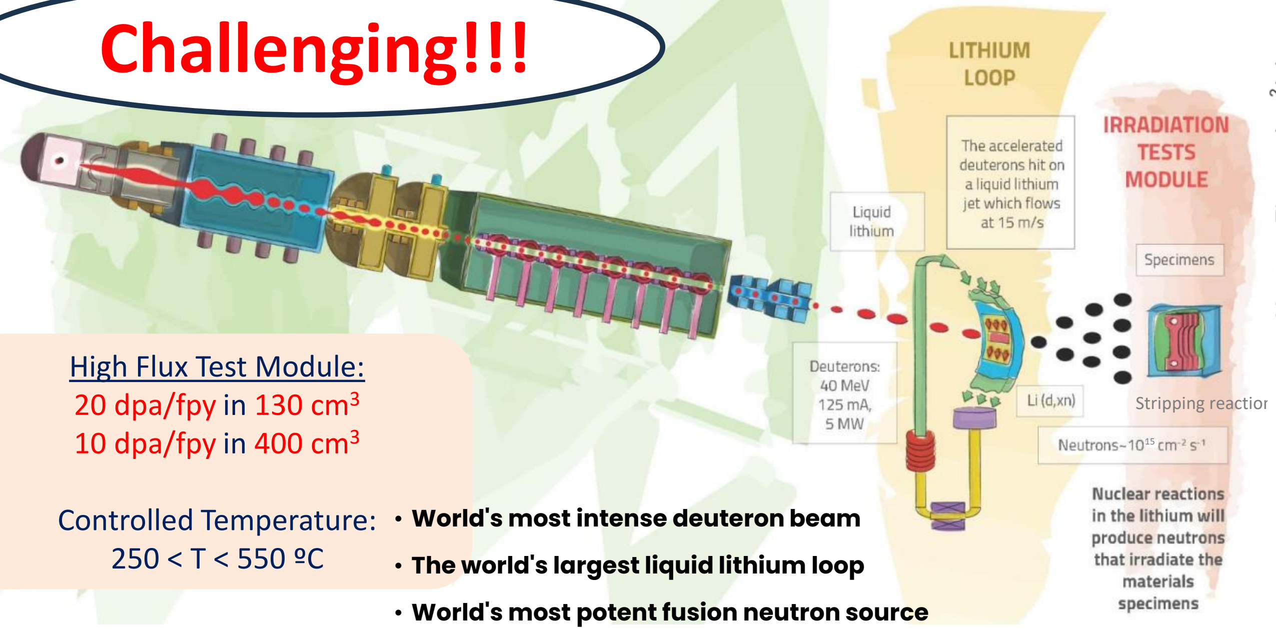
Fusion neutrons spectrum differ significantly from the ones of Fission Reactors

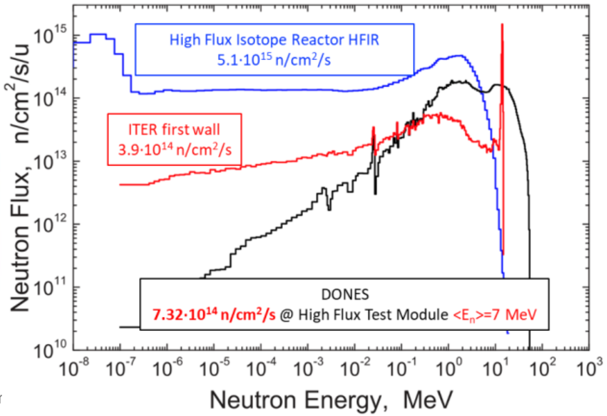
An intense fusion-like neutron source is needed to validate fusion materials and components!!!

What is IFMIF-DONES?

An accelerator based fusion-like neutron source required for the qualification of the materials to be used in the DEMO reactor

Challenging!!!





High Flux Test Module:
20 dpa/fpy in 130 cm^3
10 dpa/fpy in 400 cm^3

Controlled Temperature:
250 < T < 550 ºC

- **World's most intense deuteron beam**
- **The world's largest liquid lithium loop**
- **World's most potent fusion neutron source**

A neutron flux of ~ 10^{15} n/cm²/s is generated with a neutron spectrum up to 55 MeV energy

Identified as high priority in the EU Fusion Roadmap
Included in the ESFRI Roadmap as a EU strategic facility

What is IFMIF-DONES?

An accelerator based fusion-like neutron source required for the qualification of the materials to be used in the DEMO reactor

Challenging!!!

It will be the only facility able to reach EoL of DEMO-like reactor components in the near (20 years?) future

High Fl...

Controlled Temperature:
250 < T < 550 ºC

- **World's most intense deuteron beam**
- **The world's largest liquid lithium loop**
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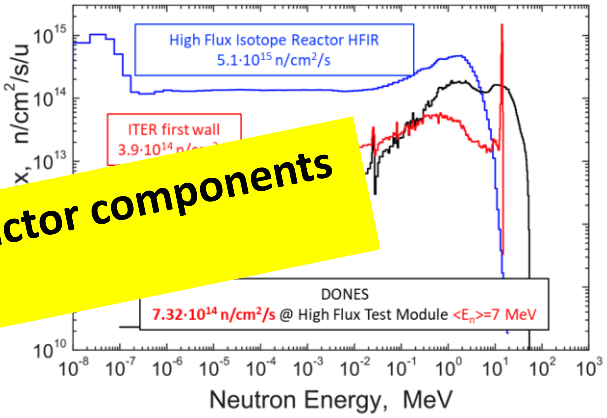

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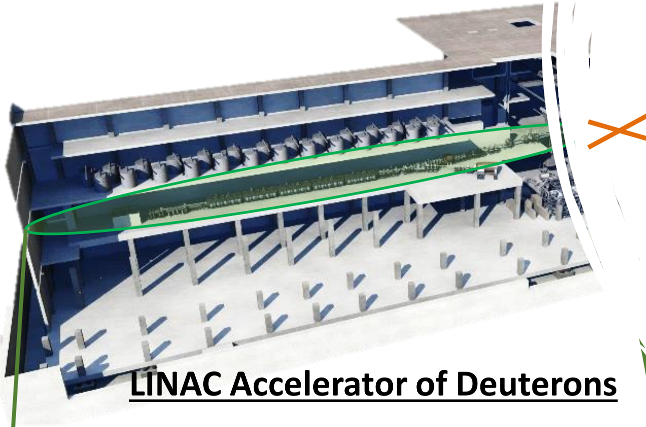
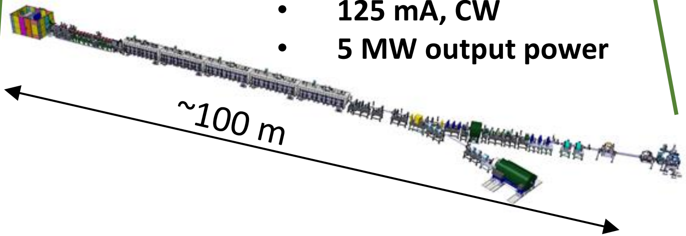
The IF… Facility

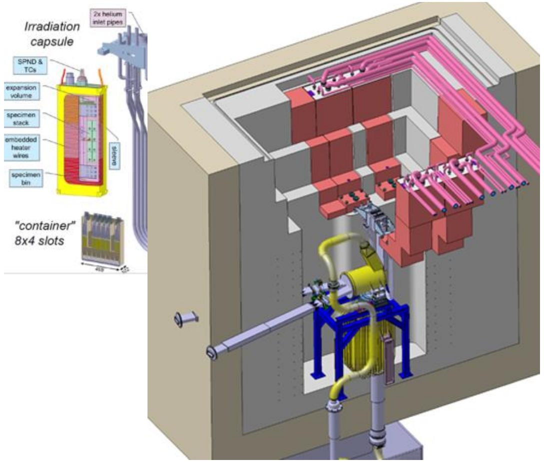
Li Target, Irradiation Modules and Test Cell



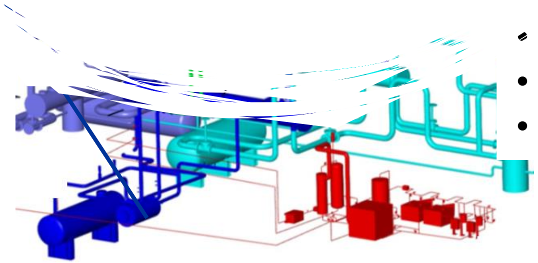
LINAC Accelerator of Deuterons

- 40 MeV
- 125 mA, CW
- 5 MW output power



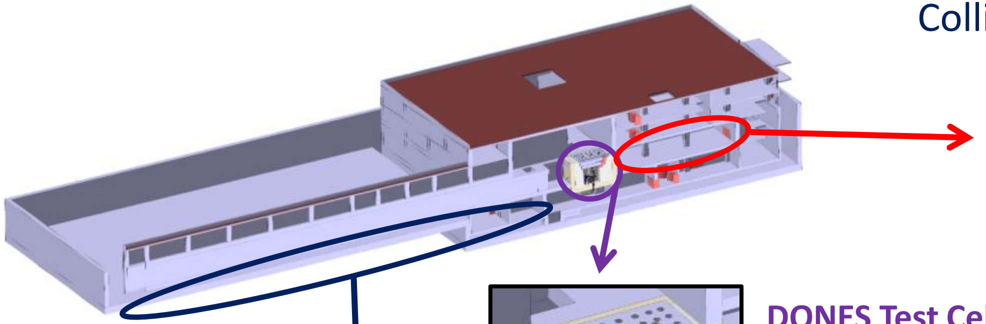


… Oil Cooling …

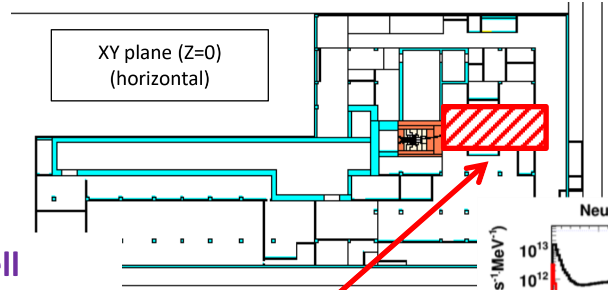


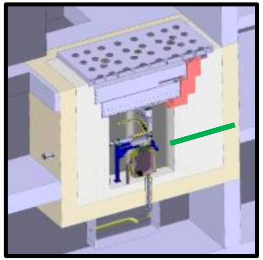
- 100 l/s Li
- Strict Li Purity Control
- ~15 m3 of Li

IFMIF-DONES Experimental capabilities



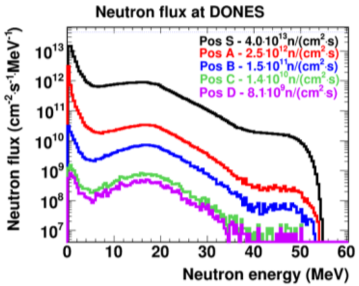
Collimated neutron beam facility – behind the Test Cell

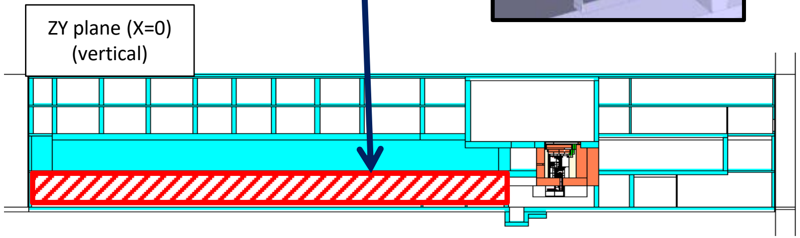




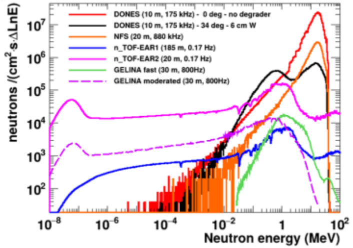
DONES Test Cell
(highest neutron flux)

Experiments with continuous neutron beam





Experiments with pulsed deuteron & neutron beams
(one level below the accelerator vault) E.g. nTOF



IFMIF-DONES Experimental capabilities

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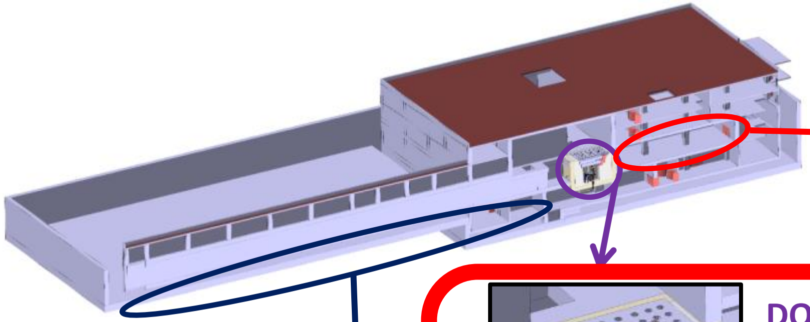

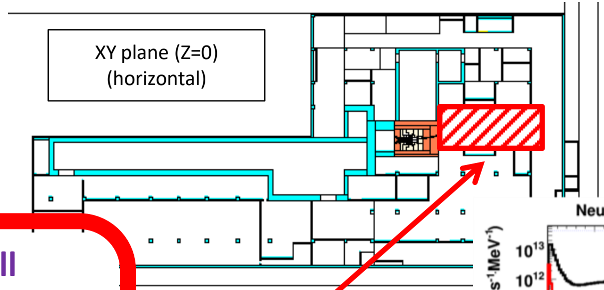

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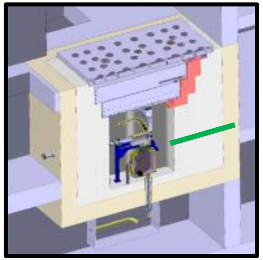

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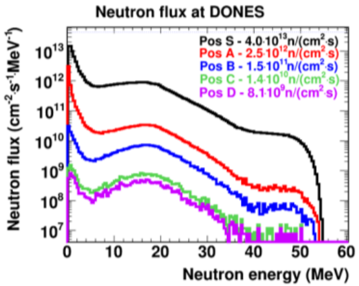

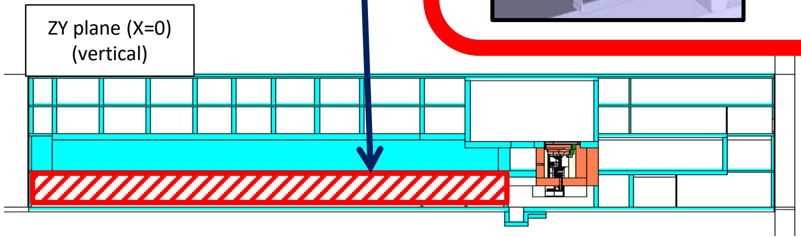

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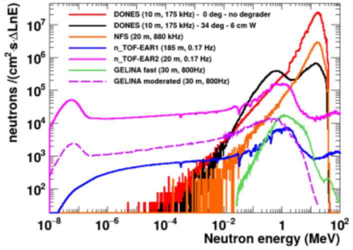

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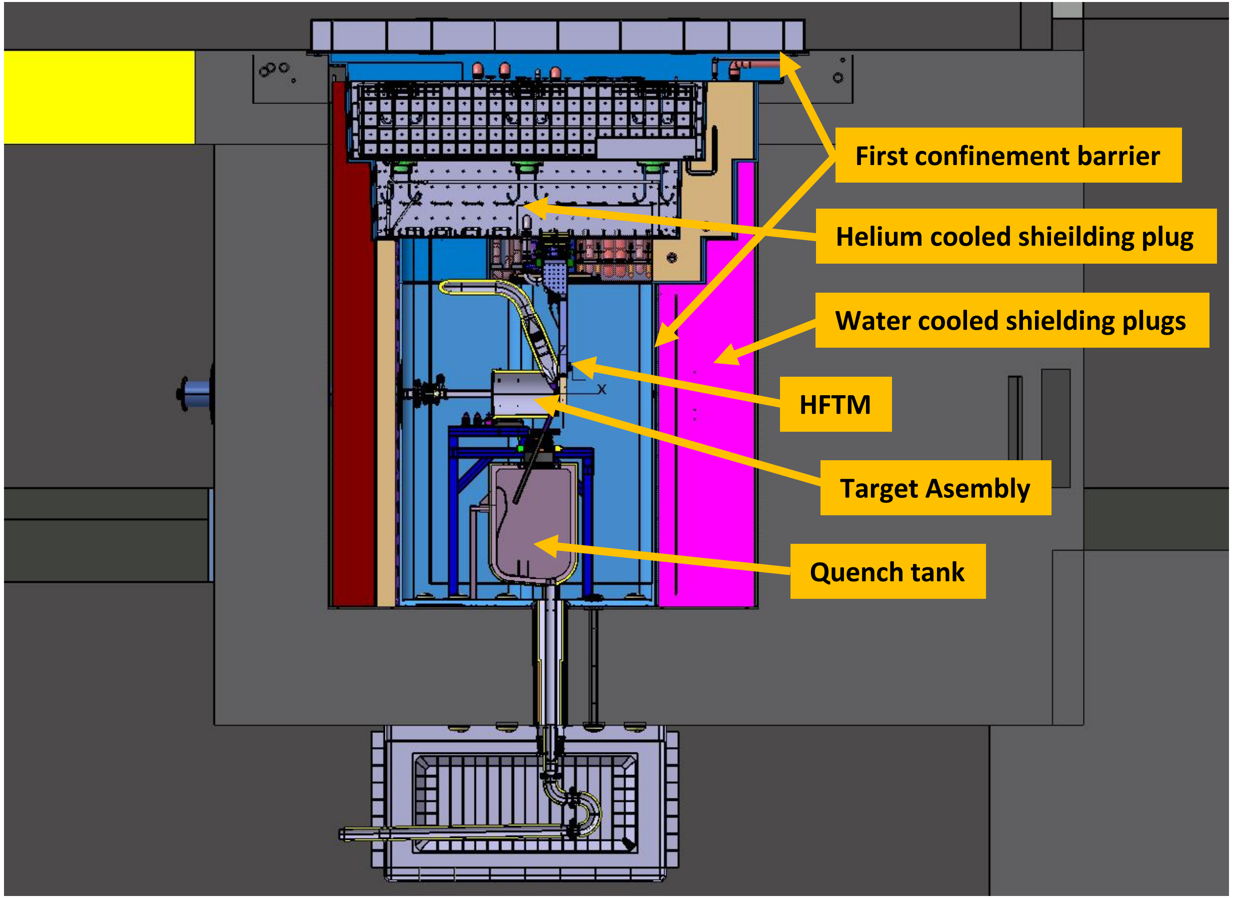
Test Cell Description



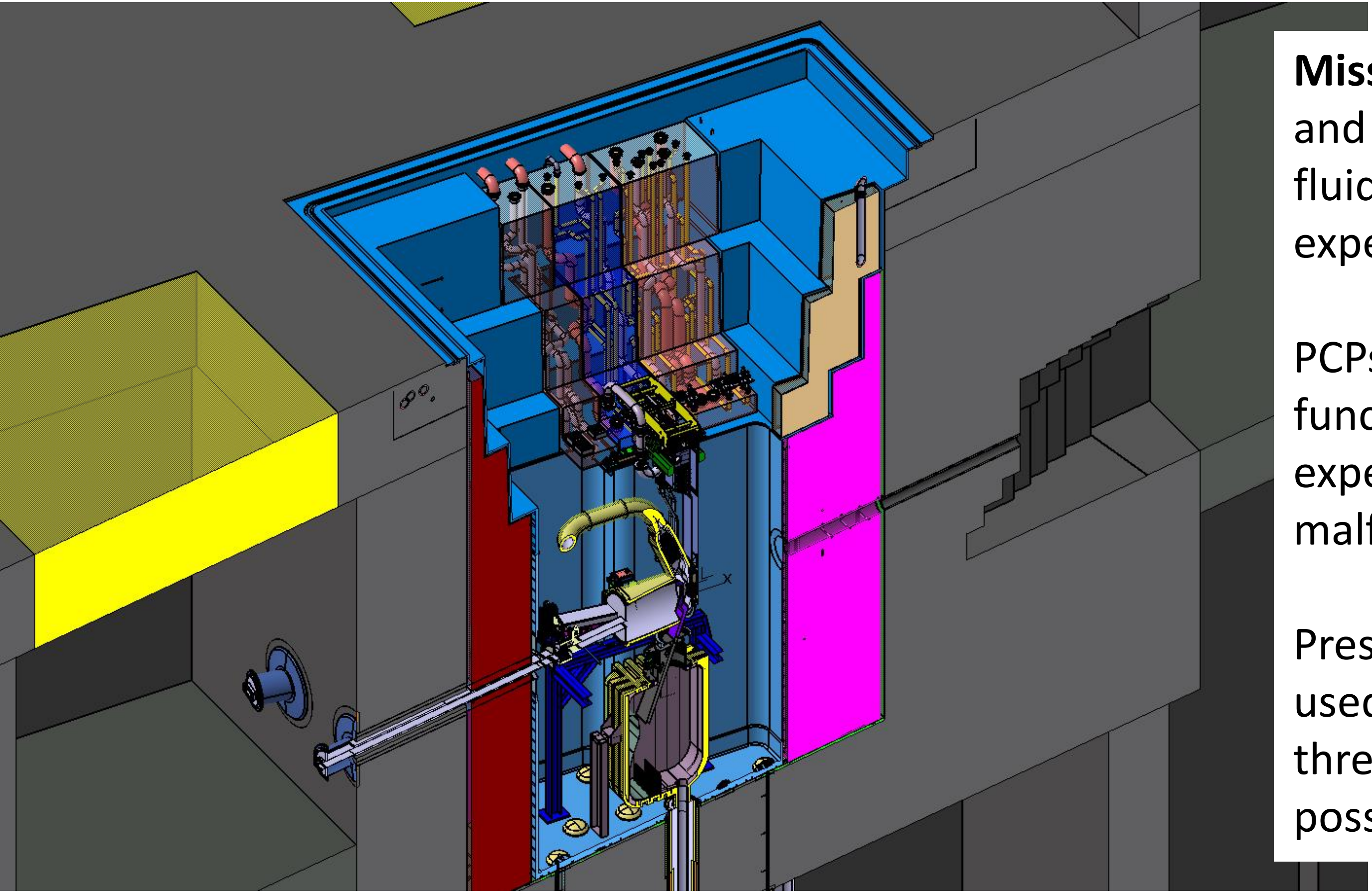
Key component

Some Constrains (conservative):

- Helium atmosphere during irradiation
- Argon atmosphere during maintenance
- No water inside First Confinenemet Barrier

Present baseline: only one irradiation module (but there is room for others)

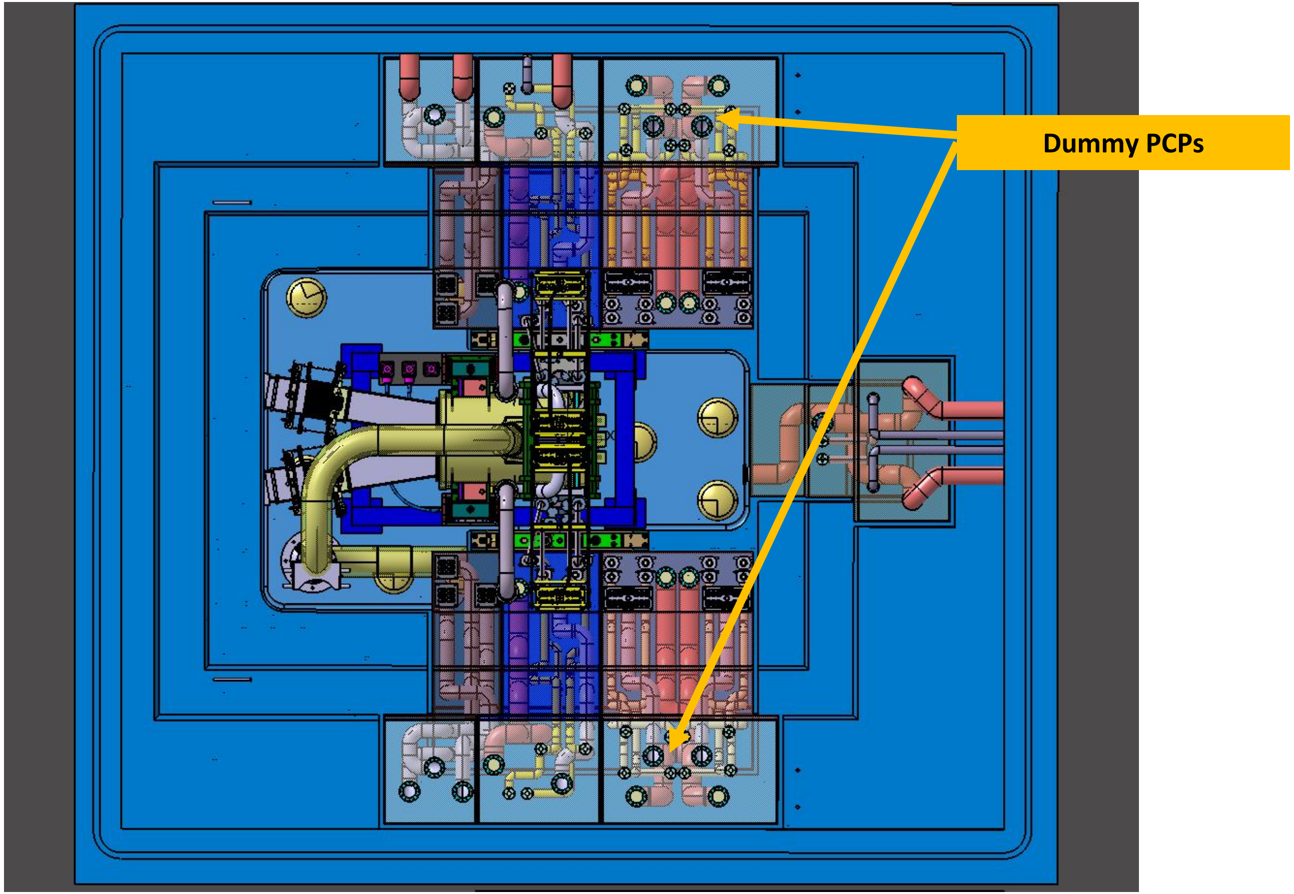
PCPs



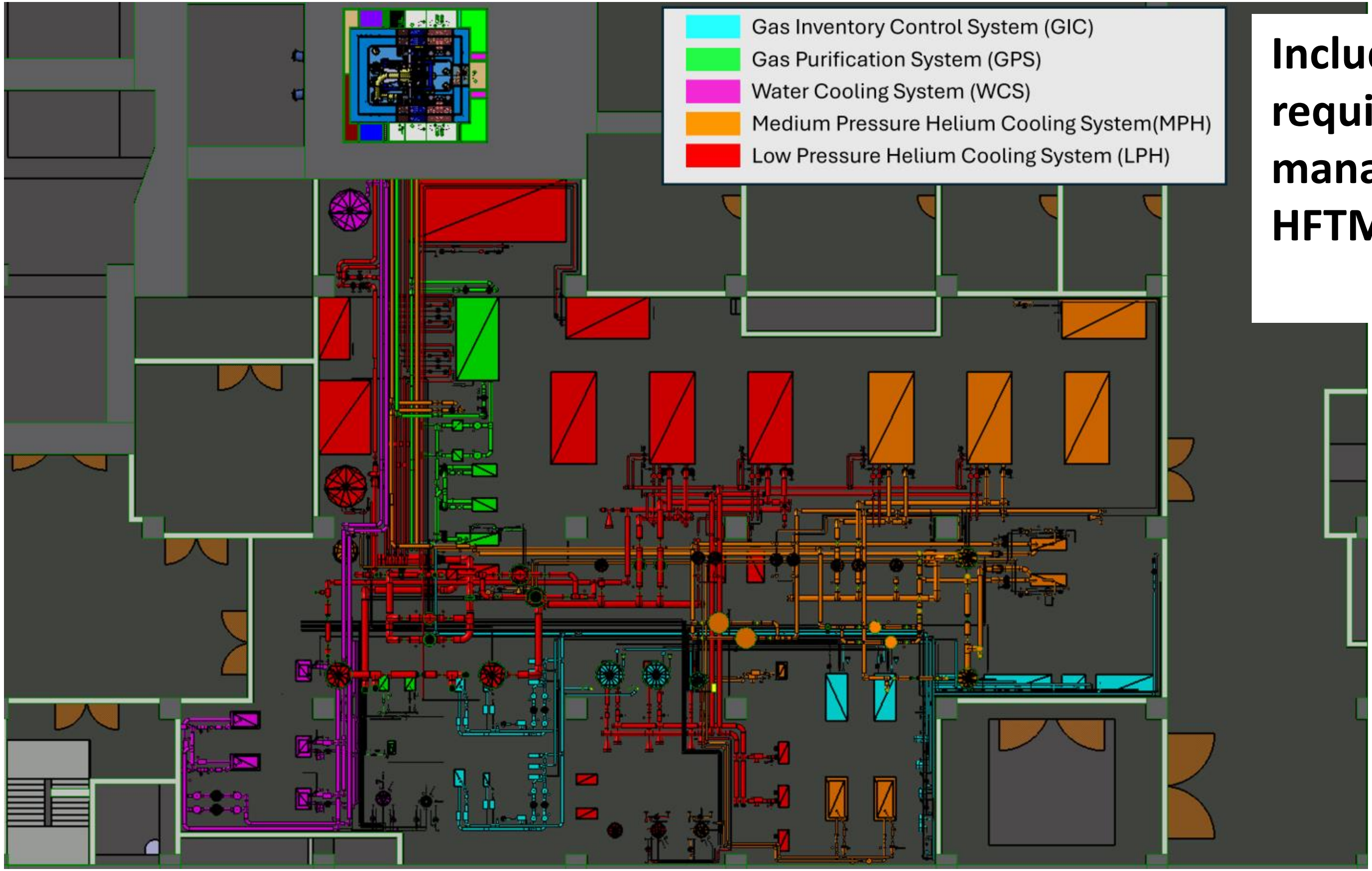
Mission of PCPs: input and output of signals and fluids linked to the TC and experiments management

PCPs can be replace as a function of the experiment and/or malfunctioning

Present baseline: Three used for TA and HFTM, three more dummy for possible future use

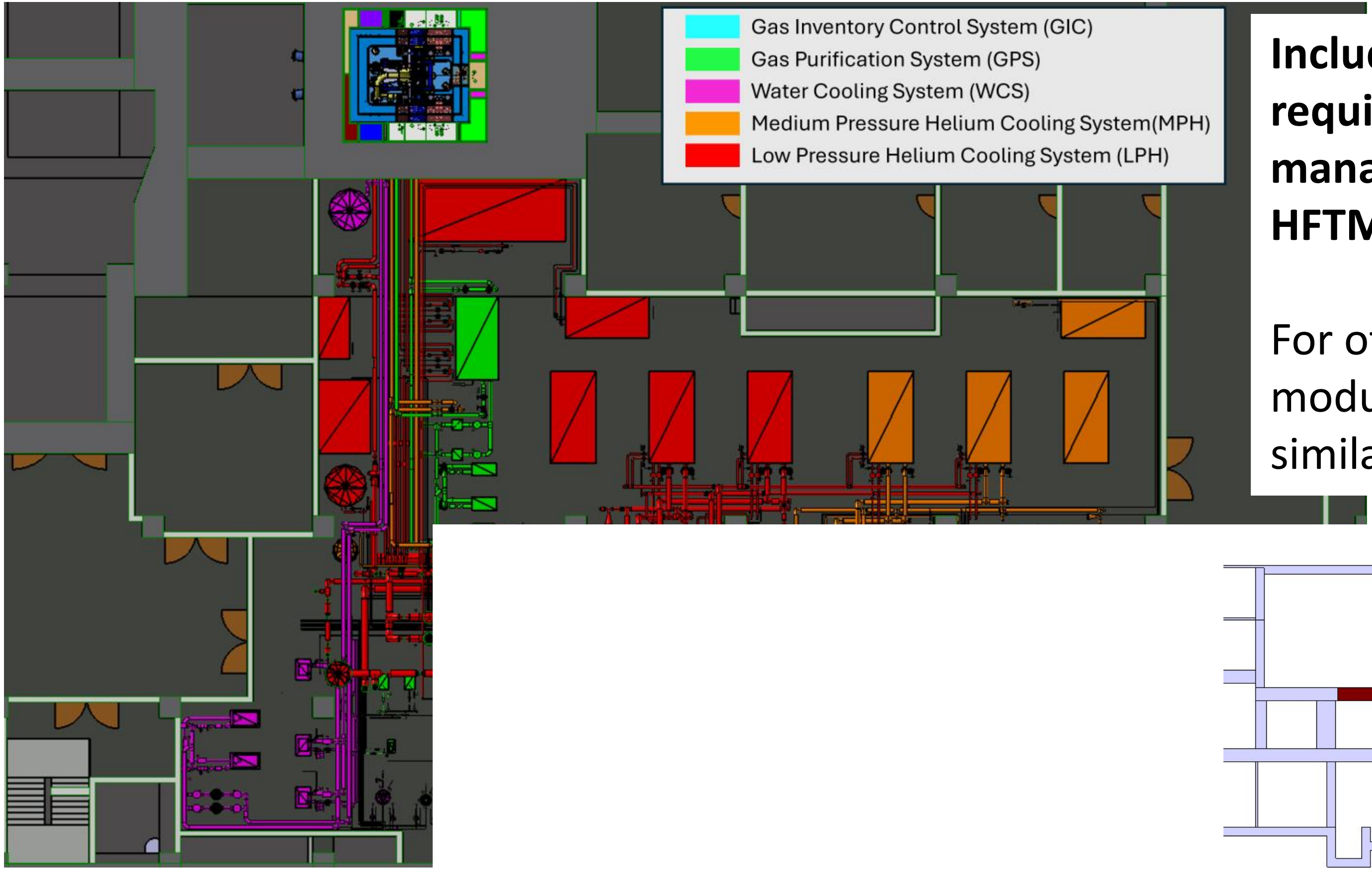

Dummy PCPs

TS Auxiliaries Room



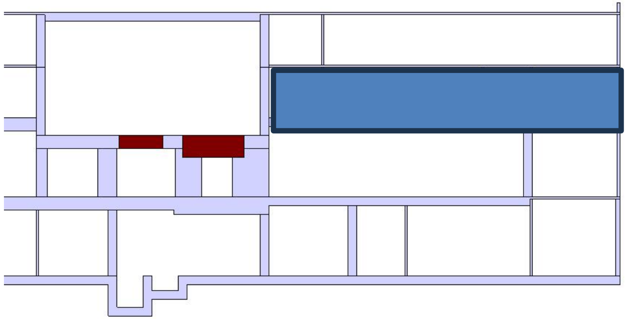
Includes the Auxiliaires required for the TC management as well as the HFTM one

TS Auxiliaries Room



Includes the Auxiliaires required for the TC management as well as the HFTM one

For other irradiation modules (if any) reserved a similar room in the upper



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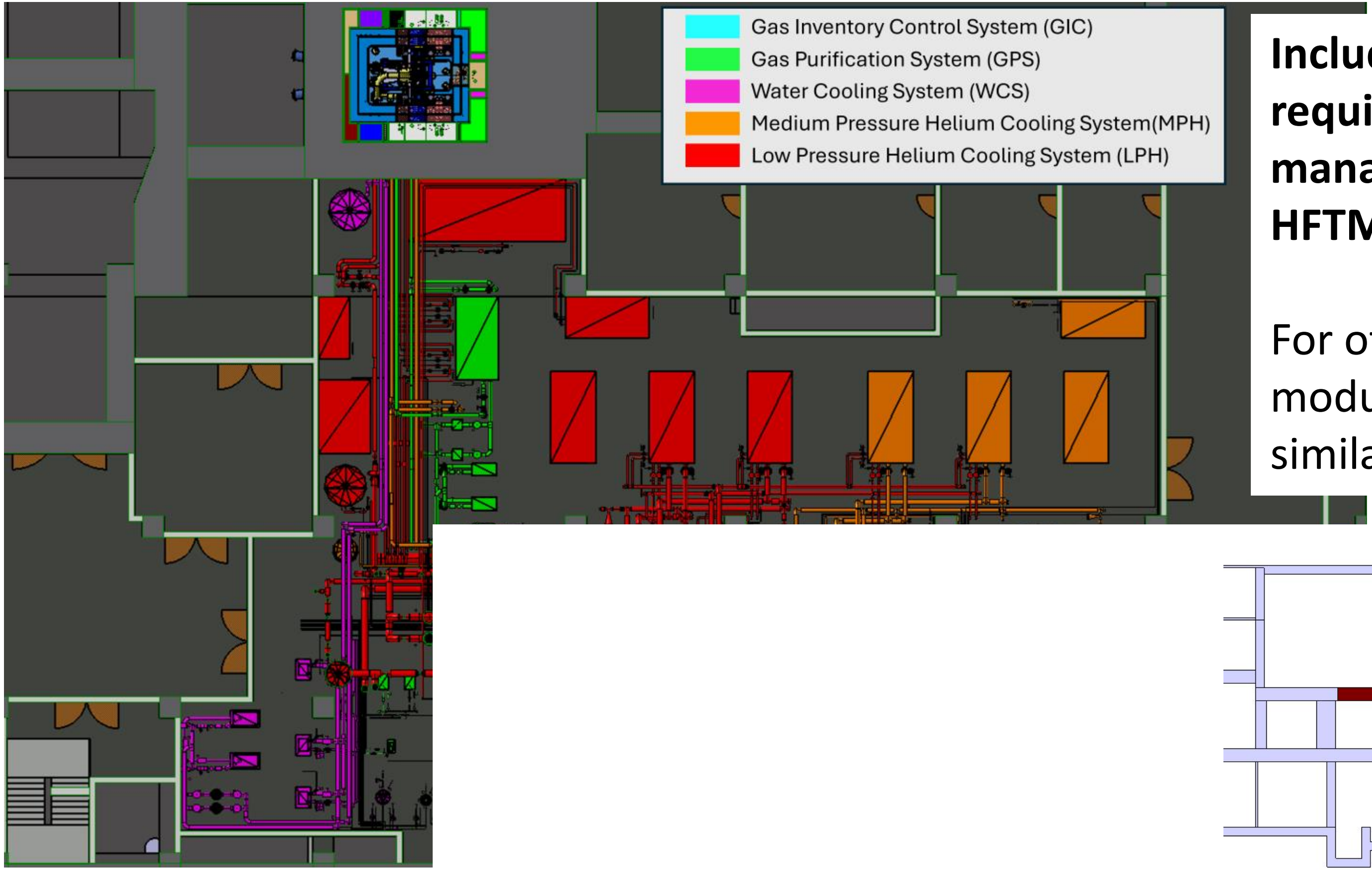

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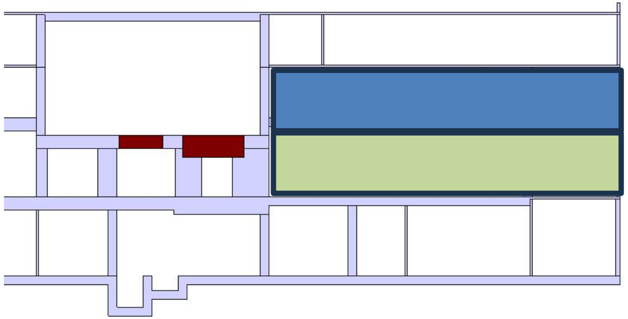

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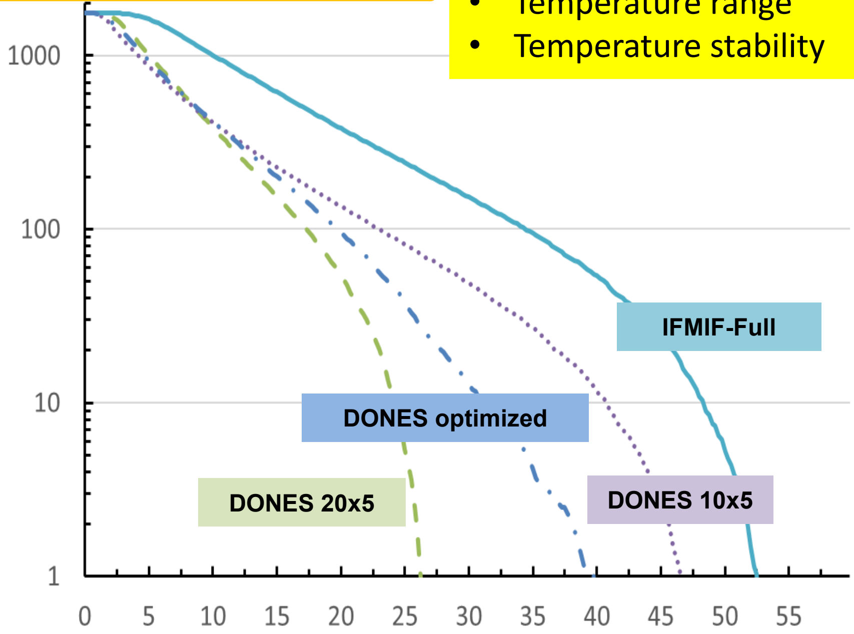
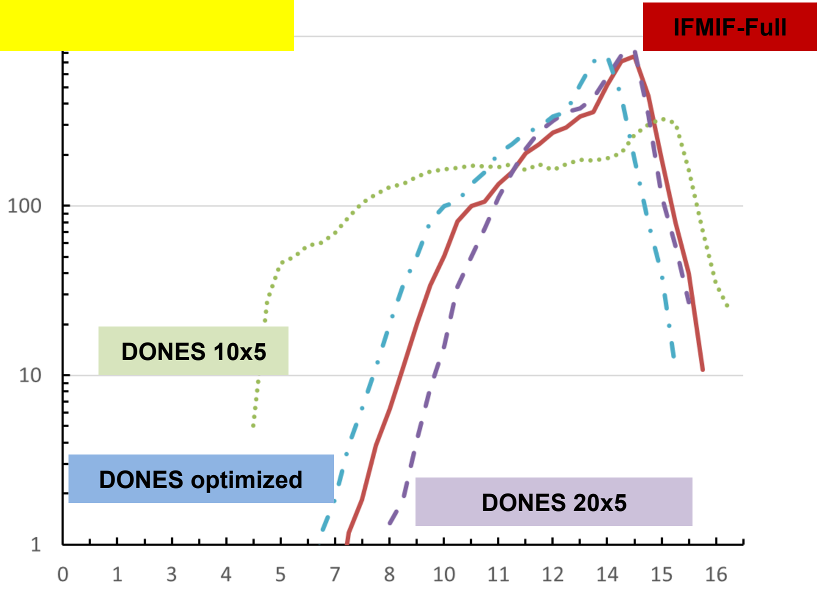
Irradiation capabilities

Key parameters for the different irradiations:
- Total neutron dose (EoL of the material under study)
- Dose rate
- He and H transmutation rate (He/dpa and H/dpa ratios)
- Temperature range
- Temperature stability

Available Irradiation Volume (cm³) vs DPA (dpa/fpy)

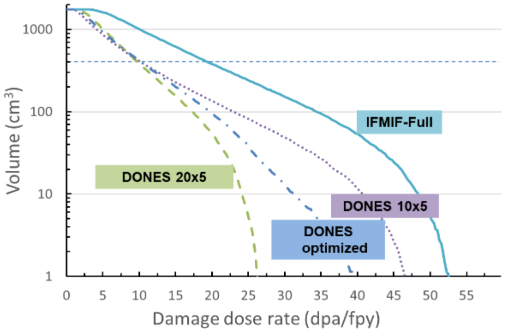


Available Irradiation Volume (cm³) vs He/dpa ratio (HE appm/dpa)

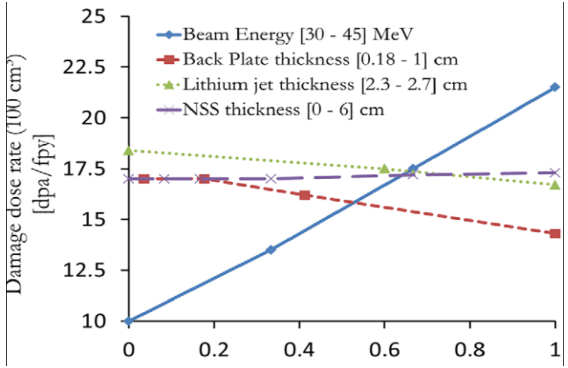


Irradiation capabilities: flexibility

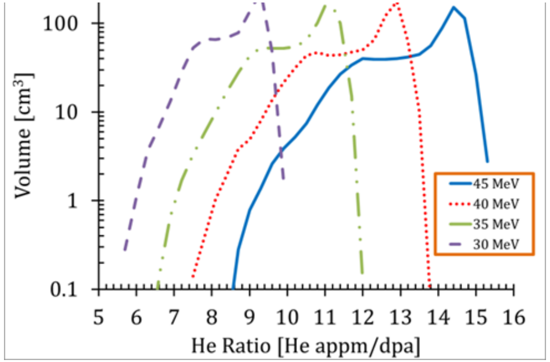
IFMIF-DONES design is **flexible**, in order to accommodate for different irradiation conditions



Variation of the damage dose rate of the central part of the HFTM for different IFMIF-DONES parameters



Available irradiation volume of the central part of the HFTM vs He appm/dpa for different IFMIF-DONES D energy



Flexibility on:

- Continuous or pulsed irradiation
- Dose rate (beam current and shape)
- Neutron spectra (i.e. He/dpa and H/dpa ratios)
- Temperature range
- Irradiation modules

HFTM for materials qualification

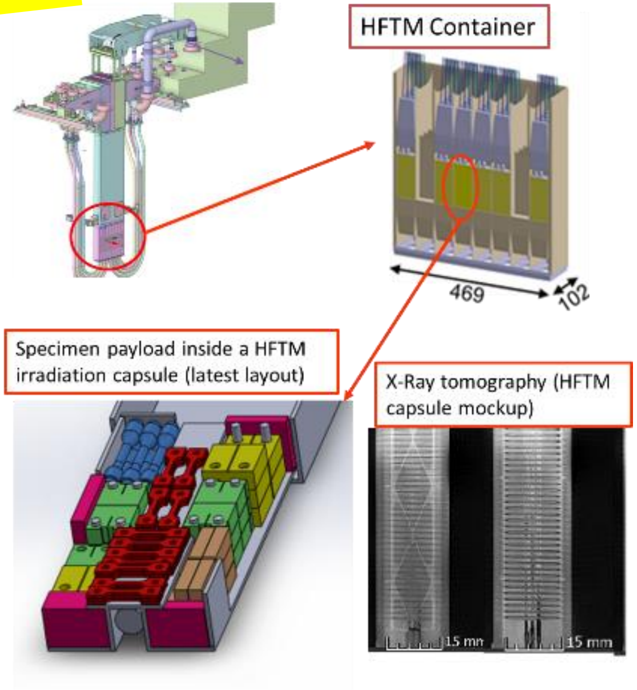
Present baseline focuses on the High Flux Test Module (HFTM) for high-priority structural materials irradiation

Objective: to irradiate a large volume of SSTT samples in the high flux region of DONES

First-to-be-installed irradiation experiment (critical path).

Fusion relevancy studied in detail in a recent paper: J. Marian et al (2025)

- Heating: Nuclear **2.3 W/g peak**, 17 kW tot., 1.5 kWe per capsule
- Cooled by **low pressure helium** gas (0.3MPa, 50°C), **Sodium** heat transfer filler
- Lifetime: 1year / 2.5 years (**53 dpa**). Body made from **316LN** (acc. RCC-MRx)
- Masses: Total 680 kg, 40 kg irradiation capsules with specimens



Steel irradiation

- 13-35 dpa/fpy up to 300 cm³ (22-50 dpa/fpy with two accelerators)
- 10-15 appm He / dpa, 45-55 appm H / dpa.
- 250 – 550 °C, sodium immersed specimens

Copper irradiation (divertor heat sink)

- 5–30 dpa/fpy
- 6–8 appm He/dpa is (~DEMO), 48–50 appm(H)/dpa (~1.4x DEMO)
- >100°C, helium immersed specimens

Tungsten irradiation (armor)

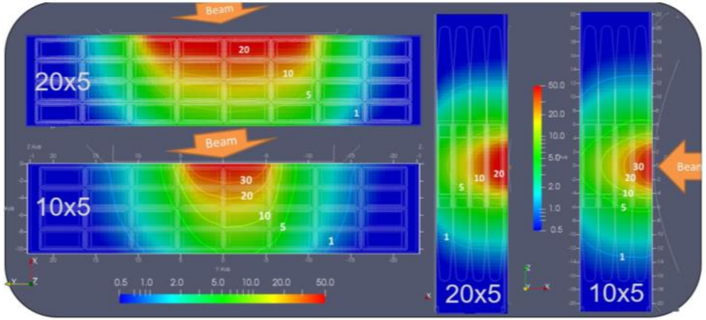
- Up to 800°C, assisted by self-heating
- 8x20 cm³ (cylindrical HT capsules)
- 1–3 dpa/fpy in W
- 9–10 appm He / dpa, (2x of DEMO), 20–29 appm H / fpy, (3x of DEMO)

Adaptation for ODS-Steels and vanadium materials can be easily implemented

HFTM for materials qualification-II

High Flux Test Module (HFTM) in the area just behind the target backplate

Condensed from I. Alvarez et al @2nd DONES Users Ws (2023)



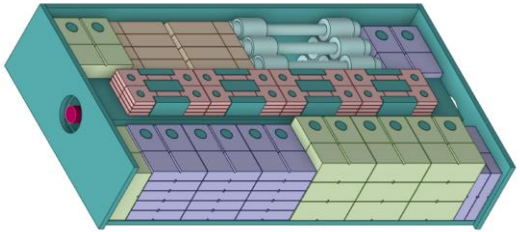
DPA (dpa/fpy) distribution

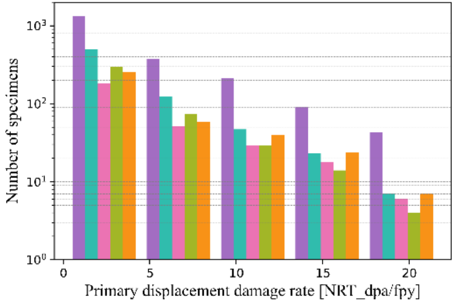
i.e. for a specific beam configuration

Mean (per rig) yearly dpa (assuming an availability of 70%)

0,35	2,1	10,5	14	14	10,5	2,1	0,35
0,35	1,4	7	8,4	8,4	7	1,4	0,35
0,35	1,4	3,5	5,6	5,6	3,5	1,4	0,35
0,35	0,7	1,4	1,4	1,4	1,4	0,7	0,35

i.e. with a specific rig loading configuration





Strong gradients!

They are not relevant inside the sample but they are relevant from sample to sample

each sample will be different

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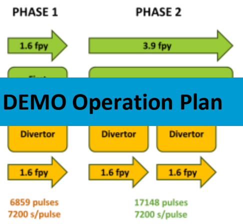
Summary of materials irradiation needs

From G. Pintsuk et al @3rd DONES Users Ws (2024)

- **RAFM&ODS steels**
  - **HIGH priority**: Bulk material and joint properties: high dose (20-50 in DEMO, >50 for FPP), in particular He-effects
  - **MEDIUM/HIGH priority**: Tungsten/EUROFER-joints: "no serious problem" statement requires confirmation at high dose
- **Tungsten (based materials)**
  - **MEDIUM priority**: Bulk material mechanical and thermo-physical properties: high dose effects (incl. H/He) with low Re-transmutation at medium to high temperature
- **CuCrZr (Cu-based materials)**
  - **MEDIUM/HIGH priority**: Influence of fast neutron induced H/He transmutation in CuCrZr on basic properties
  - **MEDIUM/HIGH priority**: Hardening / swelling of the pure Cu interlayer by neutron damage and H/He transmutation
- **Tungsten/Cu/CuCrZr joints**
  - **MEDIUM/HIGH priority**: Determination of interface properties essential for design by analysis
  - Irradiation of mock-ups for benchmarking and validation of modelling heat exhaust technologies for FPP
- **Optical and dielectrial materials**
  - **MEDIUM priority**: Bulk material: high dose, He and H effects
  - **MEDIUM priority**: Testing of mock-up sensors in conditions very close to operational ones
  - **LOW priority**: Can insulators can be used closer to the First Wall?

DONES Experimental Plan

Condensed from M. Rieth @3rd DONES Users Ws (2024)



DEMO Operation Plan

Load conditions for the different materials

Cond.	Component	Location	Temperature [°C]	Damage [dpa/fpy]	He [appm/fpy]	appm He/dpa
1	WCLL / HCPB First wall	in front of channels	330-470 / 450-500	11	121	11
2		fillets and rear side of cooling channels	330-400 / 400-450	10	100	10
6	Divertor shielding liner	heat sink	400-450	5.0	94	18.8
7	Divertor cassette body	upper part	400	~2.0	~20	~10
8		lower part	<250	~0.1	~1	~10
9	Divertor PFC support		400-450	0.9-5.1	10-58	~11

Irradiation parameters (T, dose, He/dpa, when)

Temperatures [°C]	Doses [dpa]	Rounded doses [dpa]	appm He/dpa	Cond.	Materials	Comments
330, 400, 450, 470, 500	18	20	11	1, 2	EF97	1st blanket
400, 450	1.5, 8	2, 10	11	9	EF97	divertor PFC support
400	3.2	5	10	7	EF97	upper part of divertor cassette body
300, 350	1.6	2	2	4	EF97	1st blanket, low He content
300, 350	3.9	5	2	4	EF97	advanced 2nd blanket, low He content

- Mechanical
  - Tensile (UTS, YS, UE, TE, RA, ...), 3 specimens per test temperature, Ttest=RT+Tirr → 6 spec.
  - Charpy (USE, DBTT, FATT, ...), 8 specimens for a test series
  - Fracture toughness (T0, J1c, K1c, ...), 6-8 specimens for a master curve series
  - Hardness, can be tested on samples with flat surfaces (e.g., tensile or Charpy)
  - Low cycle fatigue (strain controlled, symmetric load, recording min/max stress per cycle), min. 8 specimens for a series with different strain amplitudes
  - Fatigue crack growth (stress controlled, recording of crack growth rate da/dN), min. 8 specimens for a series
  - Annealing of irradiation damage, tested by tensile, Charpy, and/or fracture toughness
- Microstructure
  - Base materials, 1-2 samples or extracted from tested specimens
  - Joints (welds, brazes, ...), 1-2 samples
  - Interlayers (coatings, joints), 1-2 samples
  - Surfaces (fractures, plasma interaction, corrosion, ...), 1-2 samples

Properties of interest and mínimum number of simples required

SSTT technologies & HFTM loading capabilities

→ Material data must comply with existing standards

→ Standardization required to exploit irradiated material data: tensile, fracture toughness, fatigue, creep, ...

Experimental Plan!

Dose [dpa (steel)]	Temperature [°C]	appm He/dpa	Specimen type	Number of specimens		Comments
20	300	<2	Tensile	6	W	Tensile properties, Ttest = RT, Tirr
			KLST	8	W	Charpy test series, DBTT
			FT	8	W	Master curve series, T0
	330	11±1	Tensile	6	EF97	Tensile properties, Ttest = RT, Tirr

Dose [dpa (steel)]	Temperature [°C]	appm He/dpa	Specimen type	Number of specimens		Comments
15	250	<2	Tensile	6	W	Tensile properties, Ttest = RT, Tirr
			KLST	8	W	Charpy test series, DBTT
			FT	8	W	Master curve series, T0
		6±1	Tensile	6	CuCrZr	Tensile properties, Ttest = RT, Tirr
10	400					
	450					

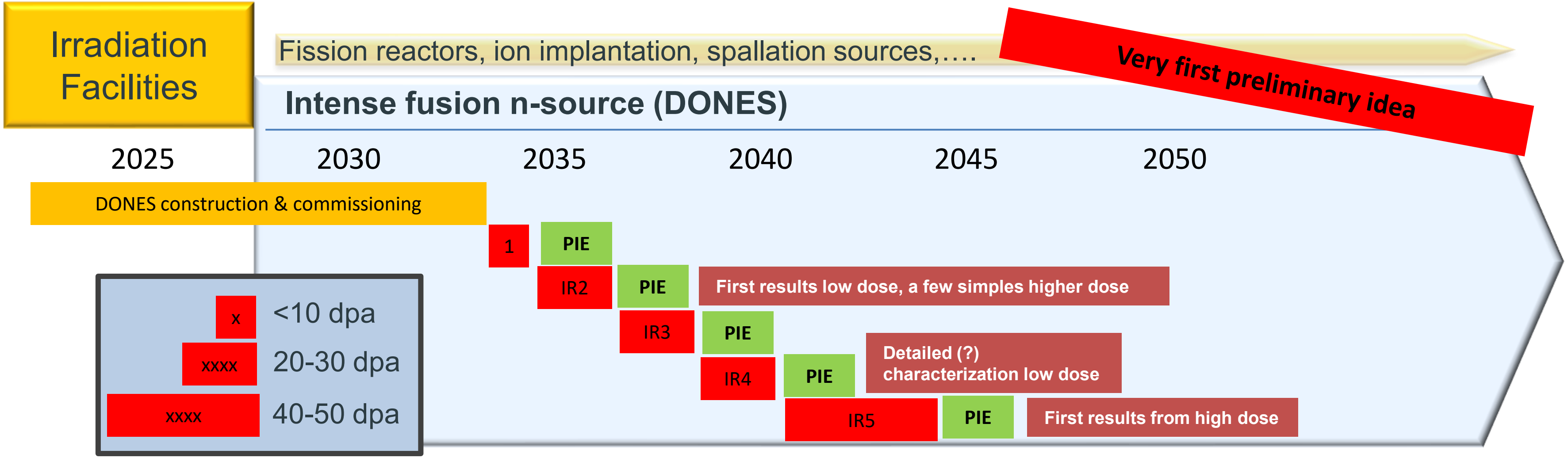
						Comments
						Tensile properties, Ttest = RT, Tirr
						Charpy test series, DBTT
			FT	8	CuCrZr	Master curve series, T0
	300	11±1	Tensile	6	EF97	Tensile properties, Ttest = RT, Tirr
			KLST	8	EF97	Charpy test series, DBTT
			FT	8	EF97	Master curve series, T0
			Tensile	6	CuCrZr	Tensile properties, Ttest = RT, Tirr
				8	CuCrZr	Charpy test series, DBTT
				8	CuCrZr	Master curve series, T0
			Tensile	6	EF97	Tensile properties, Ttest = RT, Tirr
						Charpy test series, DBTT
						Master curve series, T0
	400					Tensile properties, Ttest = RT, Tirr
						Charpy test series, DBTT
						Master curve series, T0
2	300	11±1	Tensile			Tensile properties, Ttest = RT, Tirr
			KLST	8		Charpy test series, DBTT
			FT	8	EF97	Master curve series, T0
	350	11±1	Tensile	6	EF97	Tensile properties, Ttest = RT, Tirr
			KLST	8	EF97	Charpy test series, DBTT
			FT	8	EF97	Master curve series, T0
	400	11±1	Tensile	6	EF97	Tensile properties, Ttest = RT, Tirr
			KLST	8	EF97	Charpy test series, DBTT
			FT	8	EF97	Master curve series, T0
	450	11±1	Tensile	6	EF97	Tensile properties, Ttest = RT, Tirr
			KLST	8	EF97	Charpy test series, DBTT
			FT	8	EF97	Master curve series, T0

Preliminary conclusions: work still to be developed:
A draft Experimental Plan to issued in the near future

- Close to 700 specimens! (186 tensile, 248 KLST, 248 FM)
- Around 300 specimens with doses higher than 20 dpa (84 tensile, 112 KLST, 112 FT)
- Around 150 specimens with doses higher than 35 dpa (42 tensile, 56 KLST, 56 FM)

Several irradiations campaign will be needed!!!

DONES Experimental Plan-II



Several irradiations campaign will be needed!!!
Priorities to be defined
Loading flexibility will be important
Reloading capability will be also implemented

Is it posible to speed up?

- Most effective way: add second Accelerator (x2 faster from 2035)
- Some improvement: additional paralelization of the construction and comissioning phase
- Some improvement: Implementation of some optional upgrades

Summary of IFMIF-DONES experimental capabilities

- # Materials qualification

Experiments to be developed in the irradiation area with the highest neutron flux are managed by specific irradiation modules that can be replaced (and modified) after each irradiation campaign

Present baseline design activities focuses on the High Flux Test Module (HFTM) for high-priority structural materials irradiation

Steel irradiation

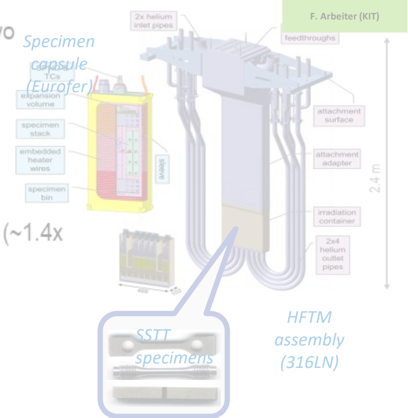
- 13-35 dpa/fpy up to 300 cm³ (22-50 dpa/fpy with two accelerators)
- 10-15 appmHe/dpa, 45-55 appmH/dpa.
- 250 – 550 °C, (~ 1000 specimens)

Copper irradiation (divertor heat sink)

- 5–30 dpa/fpy
- 6–8 appm He/dpa is (~DEMO), 48–50 appmH/dpa (~1.4x DEMO)
- >100°C, helium immersed specimens

Tungsten irradiation (armor)

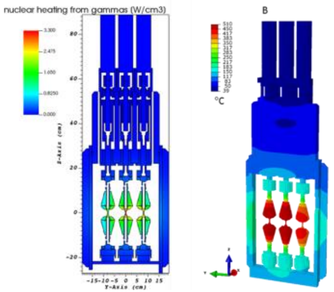
- Up to 800°C, assisted by self-heating
- 8x20 cm³ (cylindrical HT capsules)
- 1–3 dpa/fpy in W
- 9–10 appm He / dpa, (2x of DEMO), 20–29 appm H / fpy, (3x of DEMO)



Adaptation for ODS-steels and vanadium materials can be easily implemented

Prospective irradiation modules for other materials properties characterization are feasible and proposed

- **In-Situ Creep Fatigue Test Module (ICFTM)**



In-situ creep/fatigue/crack-growth loading & measurement

Temperature range 250 – 550 °C in the high flux zone

Base materials, welds, dissimilar welds; optionally multiaxial loads

- **In-Situ Irradiation Module for Diagnostics (IIMD)**
- **In-situ Irradiation Module for Superconductor materials** (probably outside of Test Cell)
- **In-situ Irradiation Module for corrosion testing in flowing media**

Summary of IFMIF-DONES experimental capabilities

- ## Materials qualification

Experiments to be developed in the irradiation area with the highest neutron flux are m… odules that can be replaced (and modified) after each irradiation campaign.

Also irradiation modules for breeding blankets (see D. Rapisarda talk) and divertor components validation are feasible

Present baseline design activities f… (HFTM) for …

Steel irradiation

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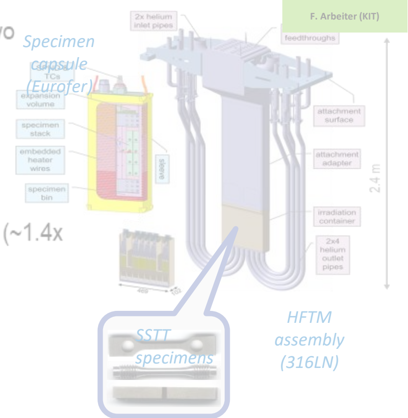

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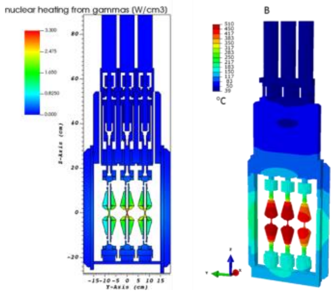

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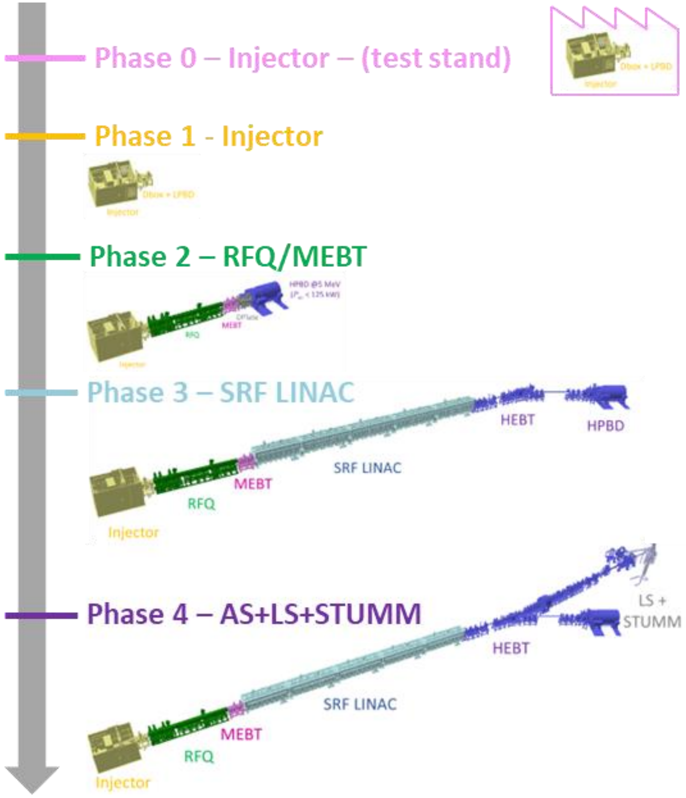
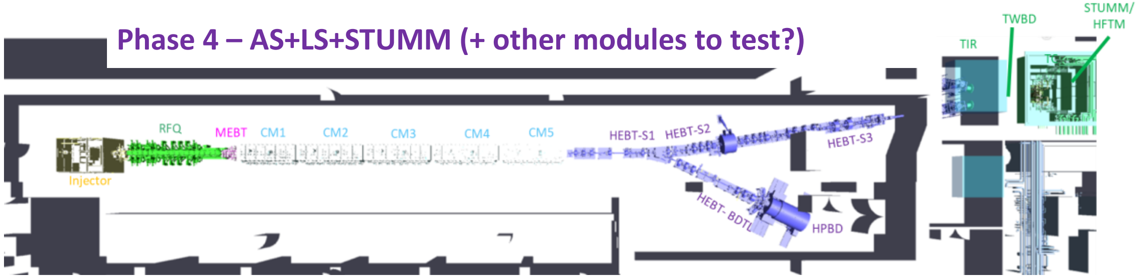
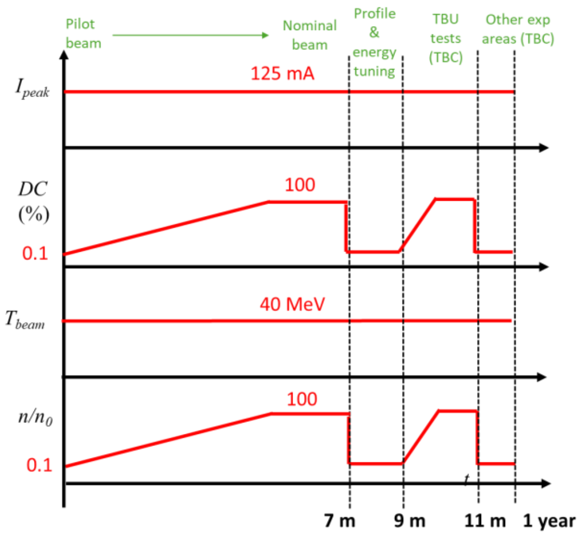
Summary of IFMIF-DONES experimental capabilities

Another possibility: Experiments during commissioning @ BOT phase



Phase 4 – AS+LS+STUMM (+ other modules to test?)





BOT devoted to:

- Tune and optimize the beam **transport** and **profile**
- Characterize the **beam-lithium** interaction
- Reach nominal **BOT** (125 mA/40 MeV/5 MW) → 2-3 months expected at full power **(~1 dpa)**
- Characterize the **neutron field** with nominal beam
- Test **other configurations** such:
  - **Variable profile for optimization** of material irradiation in the High Flux areas: changes in the horizontal dimensions
  - **Variable profile for optimization** of TBU's in the lower flux areas → **~50 mg of T @** WCLL-TBU (D. Rapisarda, EF WS, Granada, 2025)
  - **Variable energies** (30-40 MeV)

Summary of IFMIF-DONES experimental capabilities

- **Materials qualification**

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Also irradiation modules for breeding blankets (see D. Rapisarda talk) and divertor components validation are feasible

Present baseline design activities f... (HFTM) for ...

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Steel irradiation

- 13-35 dpa/fpy up to 300 cm³ (22-50 dpa/fpy with two accelerators)
- 10-15...
- 250–...

Specimen capsule

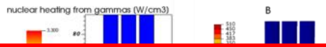
Copper irrad...

- 5–30...
- 6–8 a... DEMO)
- >100...

Tungsten irr...

- Up to...
- 8x20...
- 1–3 d...
- 9–10... 20–29 a...

- **In-Situ Creep Fatigue Test Module (ICFTM)**



In-situ creep/fatigue/crack-growth ... – 550 °C in the ... ...ssimilar ... ...al loads

... (IIMD)

...ctor

- **In-situ Irradiation Module for corrosion testing in flowing media**

It is important to clarify that **present baseline ONLY includes 1 acelerator and the HFTM experiment**

As explained here a number of additional experimental capabilities has been identified and they are being developed but, for the moment, has not been implemented in the baseline

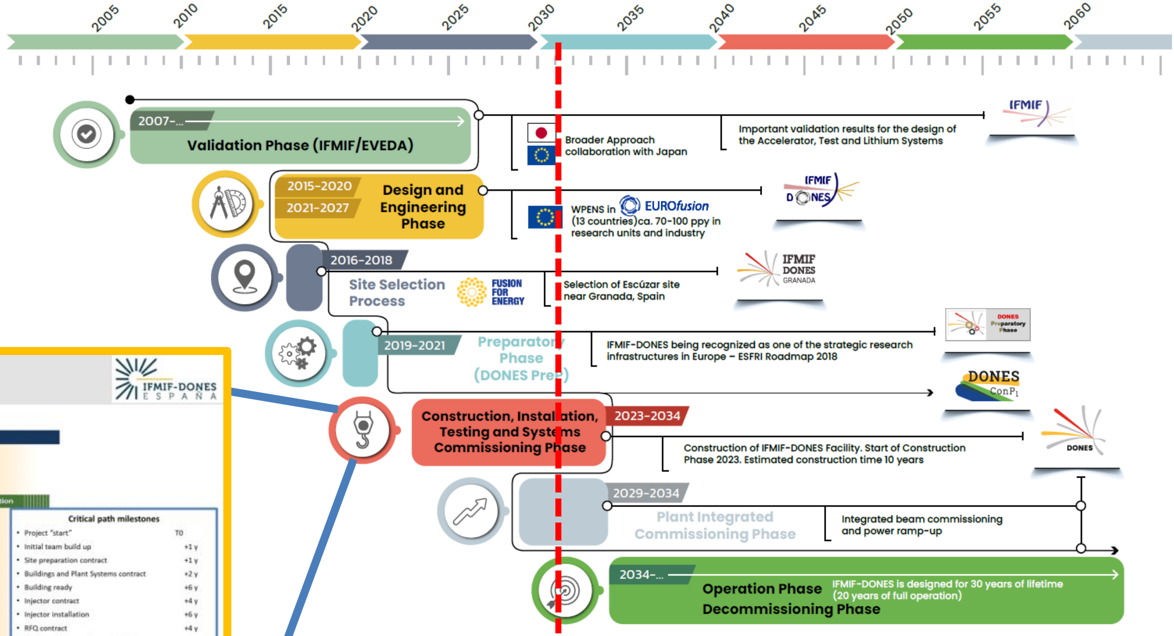
Anyhow, **engineering design of the building and all the related system is develop in such a way these additional experimental capabilities can be added at any momento**

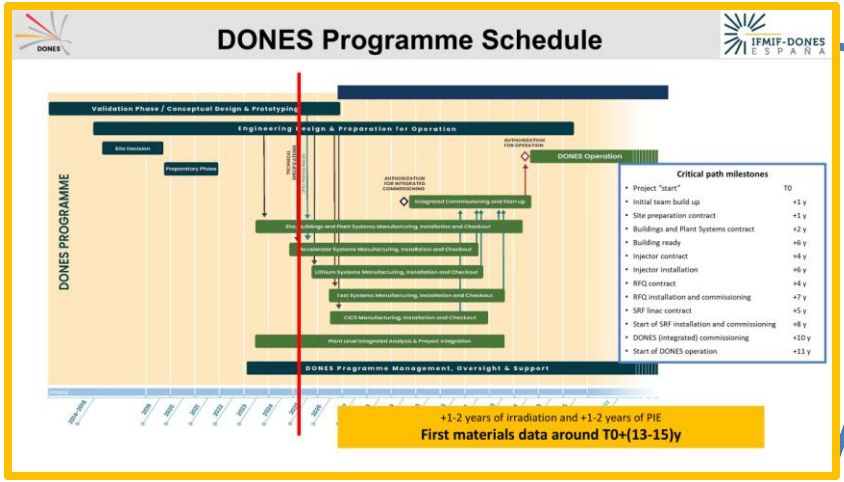
Outline

- Introduction
- The Test Cell Area
- Materials Irradiation Capabilities
- Materials Irradiation Experimental Programme
- Where we are?
- Summary

DONES Programme Phases

The objective of the DONES Programme is not only for building the IFMIF Facility... but also to operate and to exploit it!!





Site Status

DONES

On-site experimental prototypes & tests

MuVACAS

STUMM-PROTO

LITEC for developing lithium impurities trapping technologies

Quick Disconnecting System (QDS): To validate RH connection system at the target

Activities @DONES Site

- The team in Granada is growing up (around than 80 people end of the year from esDONES & F4E).

- The handover of engineering responsibility to the Programme Team is made

- A number of contracts for the building construction as well as some Accelerator components are already runing (or will be running very soon) for a value around 250 M€

- Key members of the international consortium recently joined (Japan & F4E). Additional ones are shortly expected <u>assuring funding for 100% of the present baseline</u>

Outline

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Summary

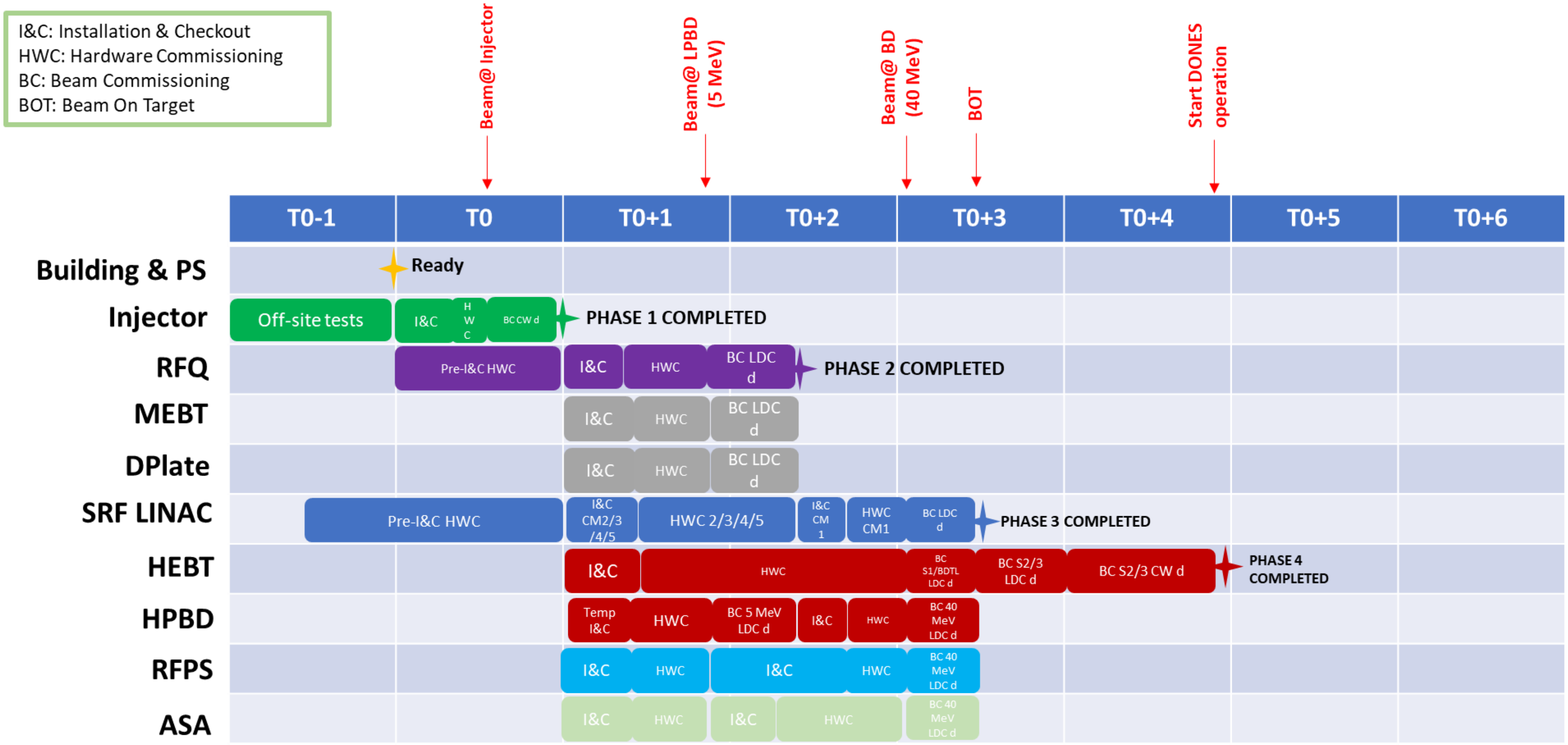
- The **DONES Programme** has entered into its **Construction Phase…** including formal engagement of several countries in such a way entire contribution for the construction of the **IFMIF-DONES Facility** is granted**!!**

- The IFMIF-DONES Facility is unique and, as a consequence, its experimental capabilities are very relevant:
    - for fusion
        - different type of materials qualification
        - some tritium technologies validation
        - Could also be of interest for ITER?
    - non-fusion communities

- Present baseline only includes HFTM irradiation module. Several additional opportunities are identified that, with a relatively small investment, will significantly increase IFMIF-DONES capabilities


EUROfusion
FUSION FOR ENERGY
DONES
IFMIF-DONES ESPAÑA
Junta de Andalucía
Consejería de Universidad, Investigación e Innovación
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Integrated commissioning Plan



What about if we install a 2nd Accelerator?

Example with DONES operation (HFTM) of one year between commissioning of both accelerators

Still not optimized for first accelerator
IFMIF operation after T0+7/8 could be possible

Impact on target+tests systems commissioning being analyzed