Accelerator-Based Materials Irradiation Facilities

J. Knaster (IFMIF-EVEDA Project Team), **A. Ibarra** (CIEMAT)

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

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Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Outline

- Materials irradiation needs
- Ion irradiation sources
- Accelerator-based neutron sources
- Summary

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Primary radiation effects

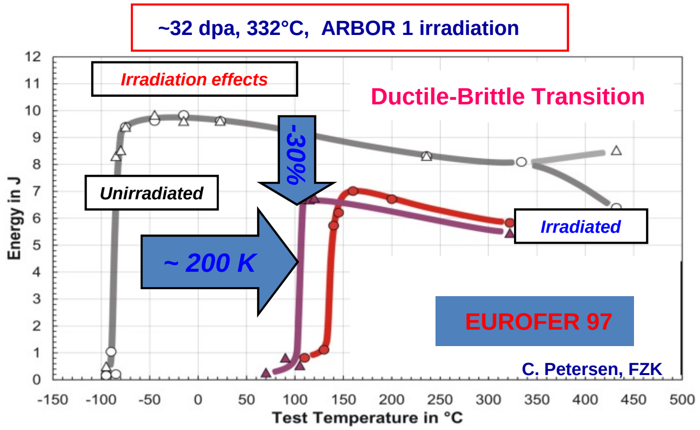
- Transmutation
  - Due to nuclear reactions, new ions appear inside the materials, giving rise to new impurities (main ones are H and He, but others can be also relevant)
  - It can induce also the activation of the material (some of these new impurities can be radioactive isotopes). This is the main reason for the development of low-activation materials.
  - The amount and specific new ions is a function of the type of incident particle, its energy and the target ion. If enough information of the target material (impurities can be very relevant) is available, usually it is feasible to make a rough stimation

- Point defects (holes and interstitials)
  - It is a complex function of the incident particle, its energy, the materials characteristics and temperature
  - After their creation, they can move around being trapped in previous defects or on new ones giving rise to extended defects (dislocations, bubbles, loops, precipitates,...)
  - If dose/dose rate is high enough, it can be produced strucutral changes in the material (amorphization, new cristalline phases, new compounds,...)

Macroscopic radiation effects

- Both the dose, dose rate and the shape of the energy spectra of the incident particle, have important consequences in the materials properties and on the design of an irradiated component.

- Main changes in mechanical properties of interest for irradiated components design:
  - Increased hardening
  - Decreased ductility
  - Decreased heat conduction
  - Swelling
  - Embrittlement
  - Blistering
  - ...



- Consequences to be taken into account in the design of irradiated components:
  - Changes in the mechanical properties of structural materials
  - Changes in physical properties (corrosion, diffusion, conductivity, luminescence,...)
  - Welding, joins,... must be evaluated
  - Systems behaviour under radiation (radiation enhanced phenomena)
  - Remote Handling
  - ...

Main materials irradiation needs

Materials irradiation needs are coming from very different fields:

- **Fission reactors** (specially for GenIV development)
  - Very high doses of (quasi) thermal neutrons.
  - Main concern are effects on mechanical properties

- **Fusion reactors**
  - Very high doses of 14 MeV neutrons and/or low energy charged particles
  - Main concern are effects on mechanical properties (but also physical ones) and/or surface degradation

- **Spallation sources and other accelerator-related machines**
  - Window and/or target lifetime evaluation
  - Main concers are effects on mechanical properties and in the case of the liquid alternative cavitation and corrosion effects

- **Space applications**
  - Fluxes of charged particles up to very high energy.
  - Integrated dose not very high
  - Main concern are effects on physical properties

- **Medical applications**

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Irradiation sources

Very different irradiation sources can be used, as a function of the issues to be investigated

(note that the use of a irradiation source different to the "original" one assumes the capability to extrapolate between different irradiation conditions –something that is not obvious at all-): role of modelling and the use of normalized samples

A materials irradiation facility should be able to provide control of different irradiation parameters (dose, dose rate, temperature, …)

Irradiation sources

Types of irradiation sources:

- **Ionizing radiation sources**

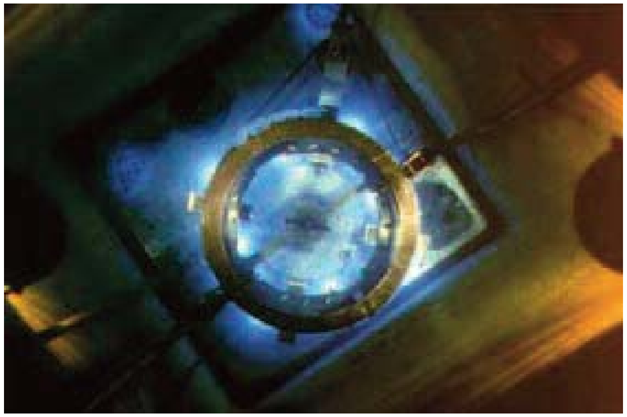
- Displacement damage sources.
  - **Ion accelerators (ion irradiation)**
  - **Nuclear reactors**
  - **Accelerator-based neutron sources**
    - **Spallation sources**
    - **Stripping**
    - **Others (DT sources)**

Irradiation sources

Types of irradiation sources:

1) Ionizing radiation sources: gamma sources, electron accelerators or ion accelerators (using the electronic excitation region)

- *Many different ones all around the world*
- *Typicaly used to investigate **in-beam effects** on physical properties (RIC, RID, OL, OA, permeation,…)*
- *Very high localized power density is feasible, but usually not very high power beams and, no beam window is needed, so no significant target issues*



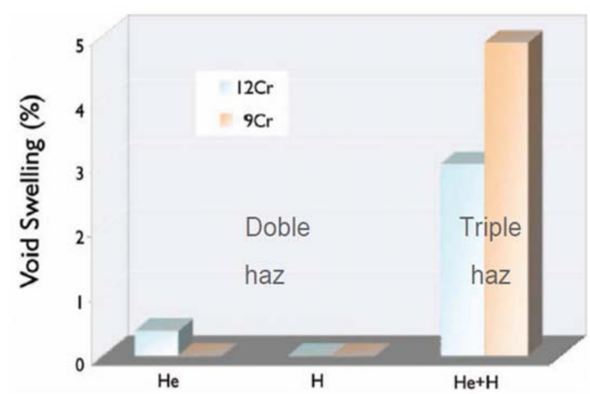
Irradiation sources

2) Displacement damage sources. **Ion accelerators (ion irradiation):**

<u>Single and multi-ion beam facilities</u>

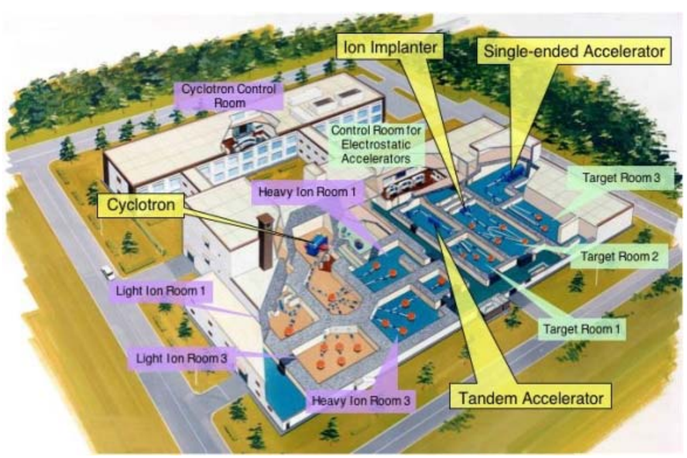
- *Wide range of particles and energies*
- *Main advantage: high damage rate (accelerated testing), adjustable He/dpa and H/dpa ratio, no activation, very high flexibility*
- *Main drawbacks: high damage rate, limited range (microns), recoil energy spectrum*
- Many single/dual ion facilities
- Main triple beam facilities: TIARA (JA), JANNUS (FR), Michigan Univ. (US)

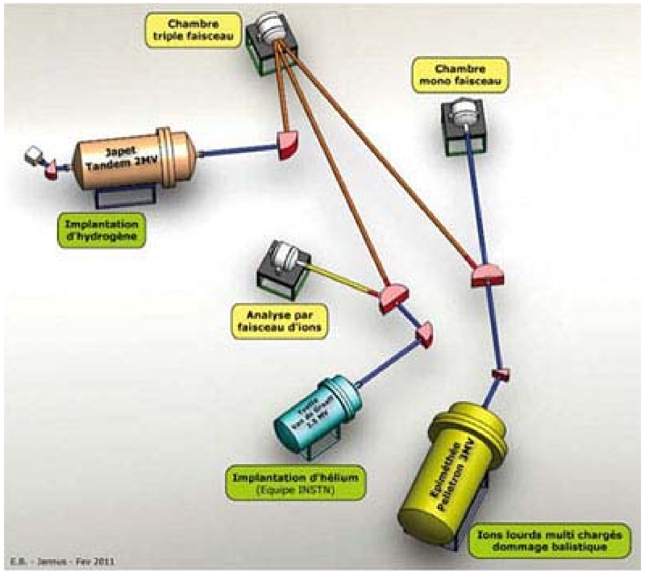
Swelling measured after Fe irradiation, combined with simultaneous H and/or He irradiation



T.Tanaka, 2003

Figure 1. The synergistic effect of He and H was shown clearly in the triple ion (Fe^{3+} + He^{+} + H^{+}) irradiation of an FeCr steel.[3]





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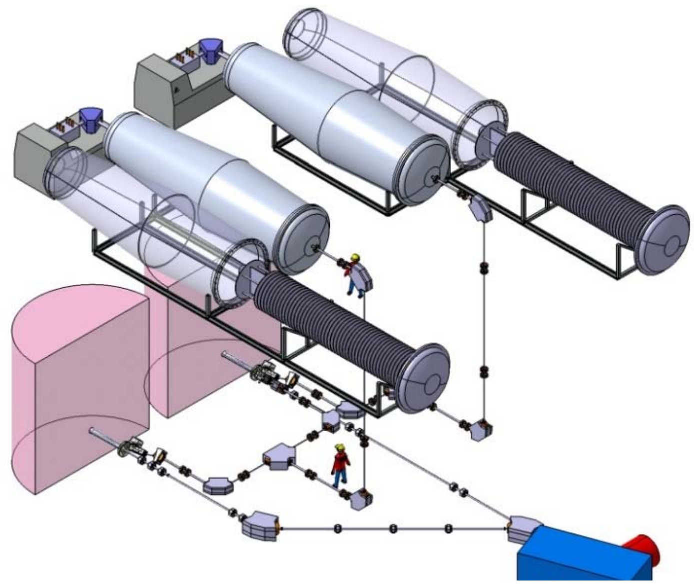
CIEMAT proposal:
TF-triple beam facility

Presently in standby, but conceptual design is finished and available

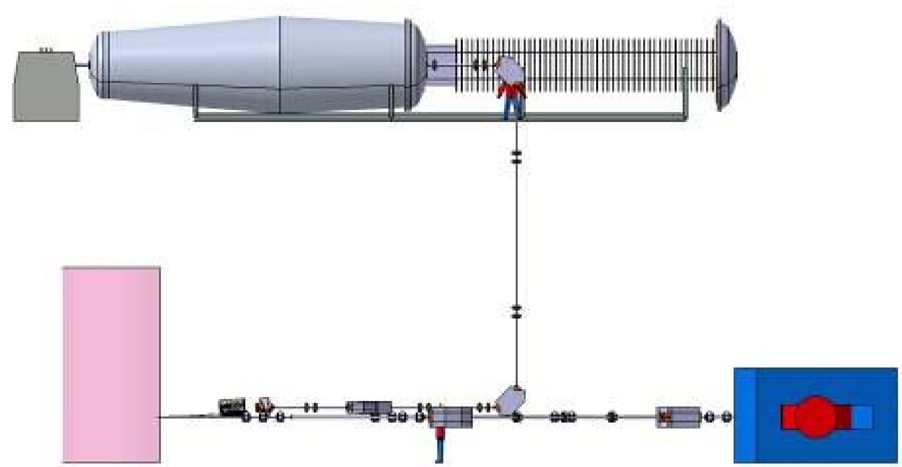
A Facility to contribute to the evaluation of radiation effects on fusion materials

Three simultaneous ion accelerators will emulate the neutron irradiation effects



Includes:

- **Two light ions tandem-type, electrostatic accelerators (mainly for He and H irradiation)**
- **One heavy ion cyclotron (isochronous type) accelerator (Fe -400 MeV-, W -400 MeV-, Si -300 Me , C -100 MeV-, … and k = 110)**
- **Also experiments under high-field magnet**



<u>Irradiation volume up to tens of microns – relevant for volume effects-</u>

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Irradiation sources

3) Displacement damage sources. **Nuclear reactors**

- Mixed neutron spectra: HFIR –ORNL-, HFR –Petten-, BR2 –Mol-. Most important future project: JHR (France)
  Fast spectra: SM3 –Rusia-, JOYO –Japan-, BOR60 –Rusia-
- *Main advantages: volumetric irradiation, "high" volume*
- *Main drawbacks: only relatively low energy neutrons available (low He/dpa ratio), limited flexibility, long irradiations, activation of materials*

Up to now the most important neutron sources used for materials irradiation (also He effects using isotopically tailored or B doped materials)

Irradiation sources

- Displacement damage sources. **Accelerator-based neutron sources**
  Spallation sources –with materials irradiation facility-
  (nonexhaustive list for low power ones)

  Running: LANSCE, ISIS, SINQ
  Planned: SNS *(TBC)*, MaRIE *(TBC)*, MYRRPHA, JPARC
  Under study: ESS

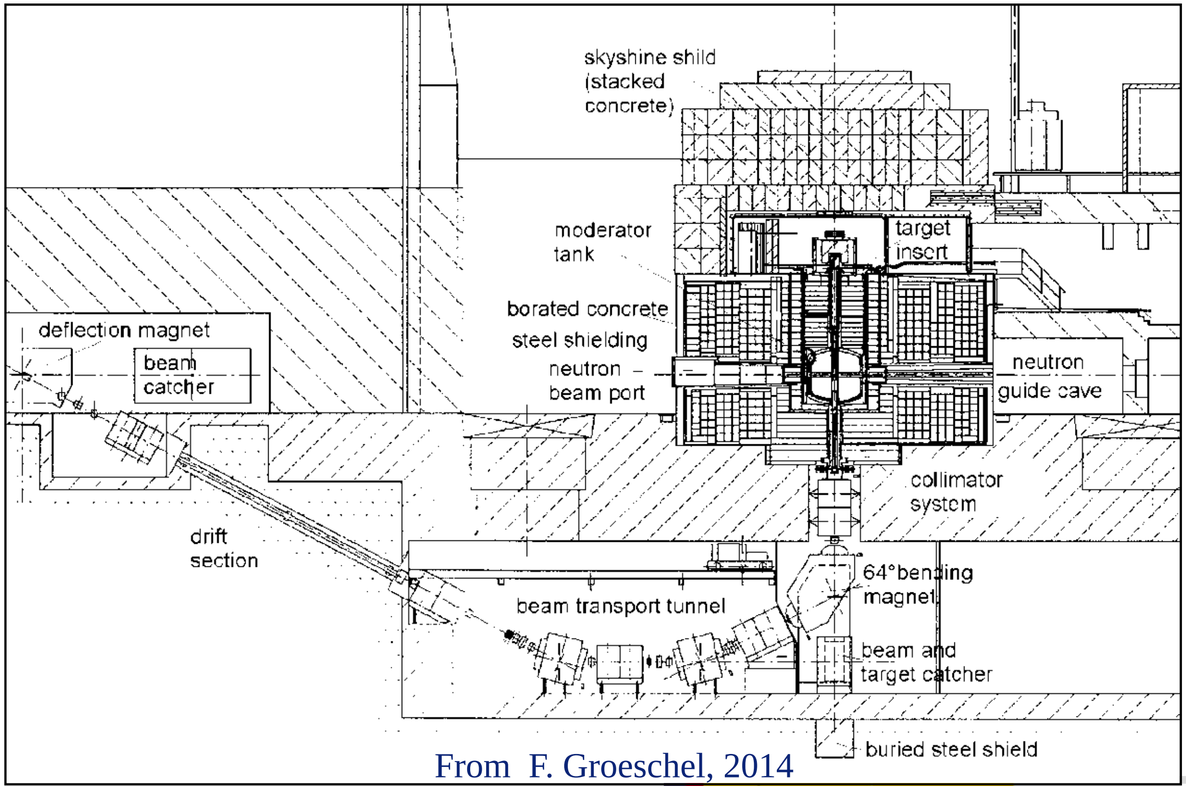
  Main characteristics: Very efficient for producing neutrons, high He and H production, generation of other transmutation products , usually pulsed irradiation, usually mixed proton/neutron damage, materials irradiation usually secondary facility

  - Target can be of a solid one (W for example) or liquid metal (Hg or PbBi). Usually liquid metal case can manage higher power disipation.

  Main target issues: radiation damage effects on materials (synergetic effects by dpa –in some cases mixed p/n spectrum-, He and H production), for liquid metal case: risk of cavitation and corrosion

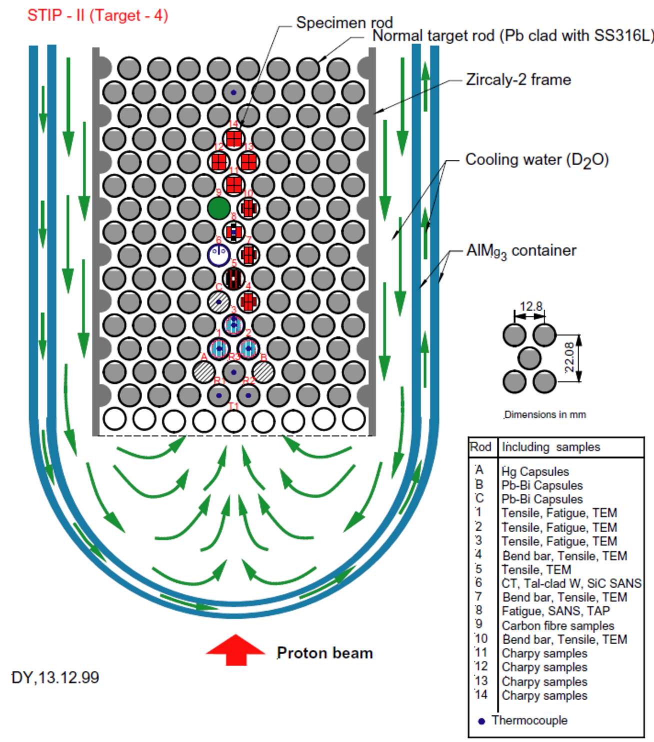
SINQ-MEGAPIE

- Probably the most important materials irradiation facility (excluding nuclear reactors) in the last 10-15 years
- Based on a proton accelerator and two ciclotrons
- Proton energy up to 600 MeV, max power 0.8-1.3 MW, continous source
- Two main programs:
  - STIP
  - MEGAPIE



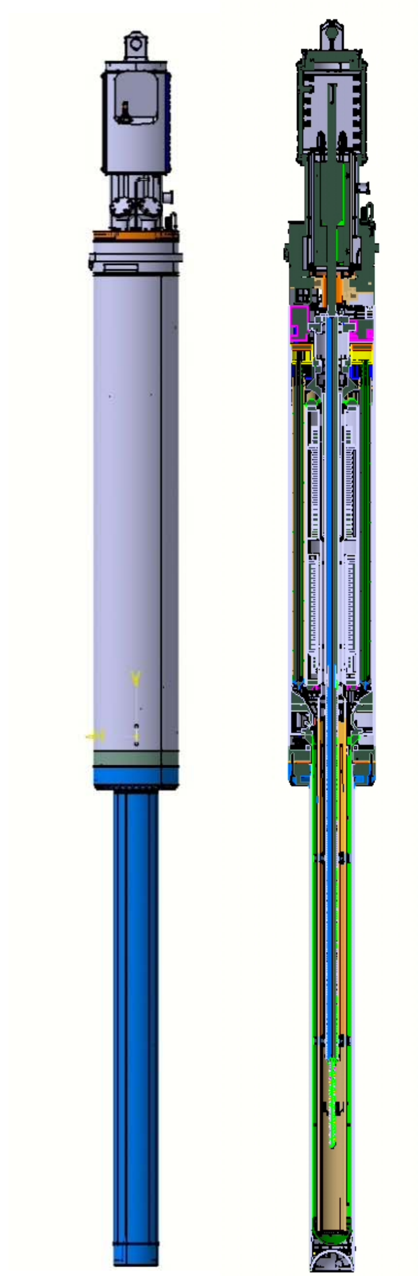
From F. Groeschel, 2014

SINQ-Materials Irradiation (STIP)



Materials	STIP-I	STIP-II	STIP-III	STIP-IV	STIP-V
Austenitic steels	≤ 12 dpa ≤ 400°C	≤ 20 dpa ≤ 400°C	≤ 20 dpa ≤ 400°C	≤ 20 dpa < 400°C	20 dpa 400°C
FM steels (FMS)	≤ 12 dpa ≤ 360°C	≤ 20 dpa ≤ 400°C	≤ 20 dpa ≤ 800°C	≤ 25 dpa < 600°C	20 dpa 400°C
FMS-ODS		≤ 20 dpa < 400°C	≤ 20 dpa ≤ 800°C	≤ 25 dpa < 600°C(?)	20 dpa 600°C

MEGAPIE Target

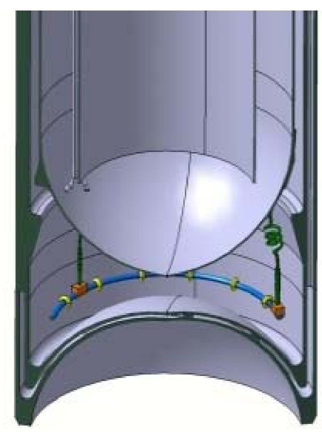


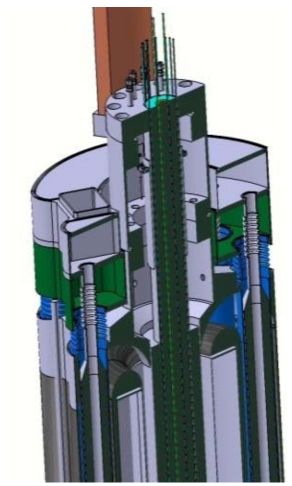
First PbBi cooled irradiation experiment in the MW range
Main objective: Increase of the neutron flux in SINQ

Materials irradiation limited to structural materials: T91 at 230-350 ºC range, 316L, AlMg3

Target: 5.35 m long
LBE. 82 l   T=230 –380°C
575 MeV – 1.74 mA – 1 MW
650 kW thermal power – Diphyl THT oil loop
Cover Gas Pressure 0.5 – 3.2 bar

Beam Windows

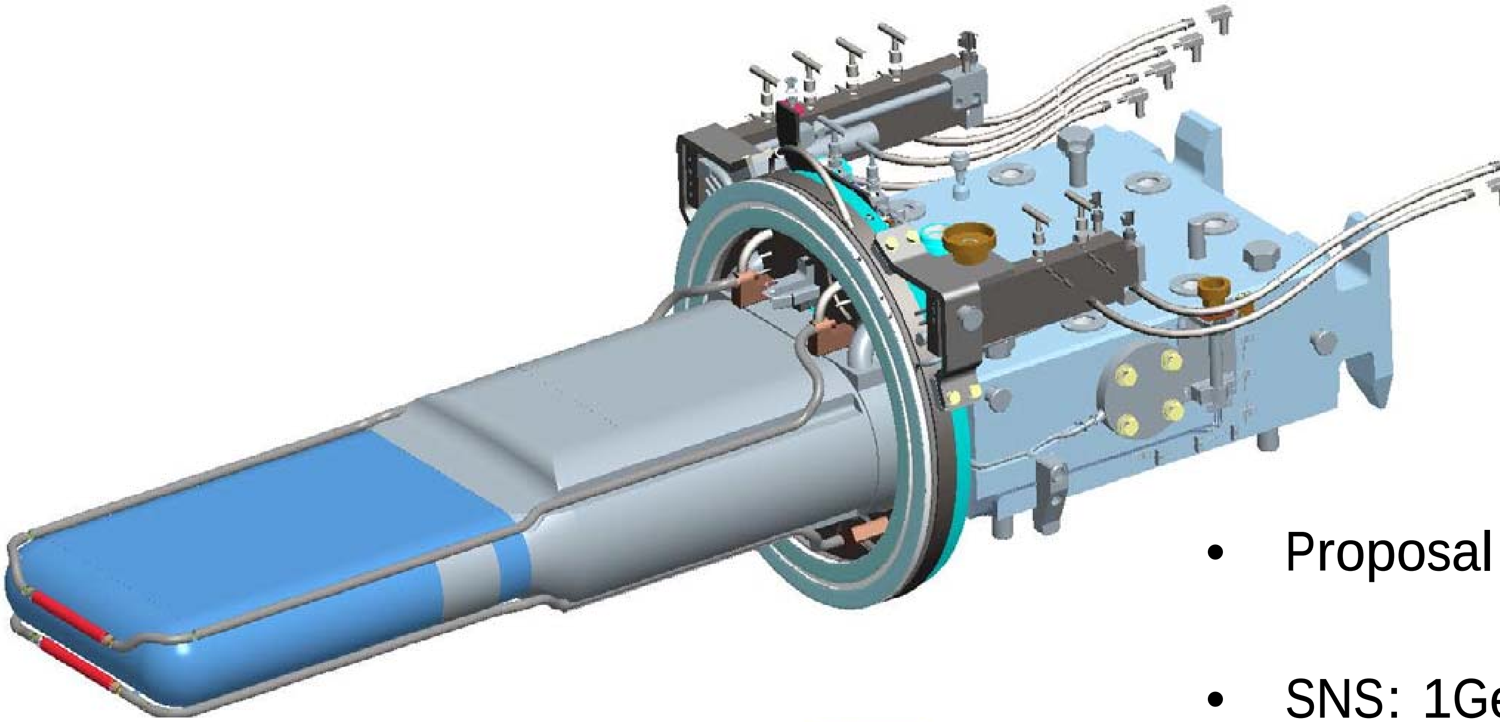


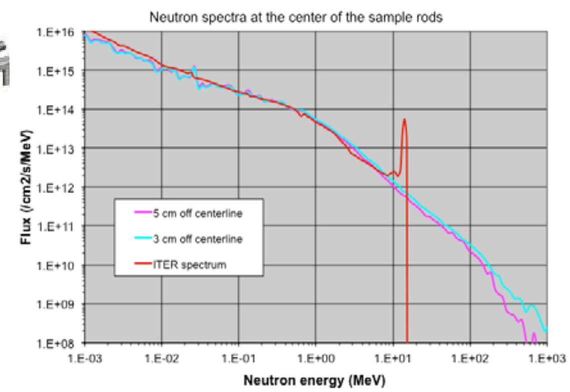


Plenum and Heat Exchanger Inlet

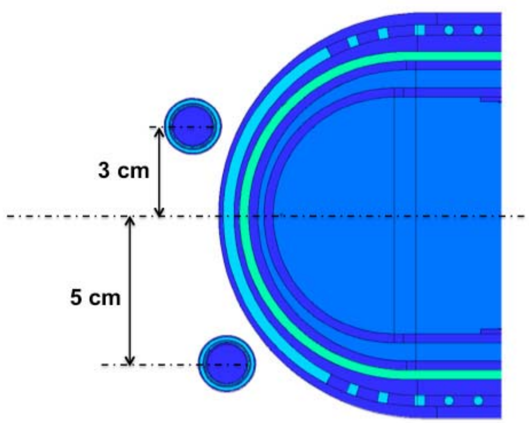
From F. Groeschel, 2014

SNS (FMITS)





- Proposal under study
- SNS: 1GeV protons – 1.4 MW on Hg target. Pulsed operation
- Proton/neutron mixed spectra
- 2-5 dpa/y feasible
- He/dpa ratio 13-75



From W. Lu et al, J. Nucl. Mater. (2014)

JPARC-Transmutation Experimental Facility

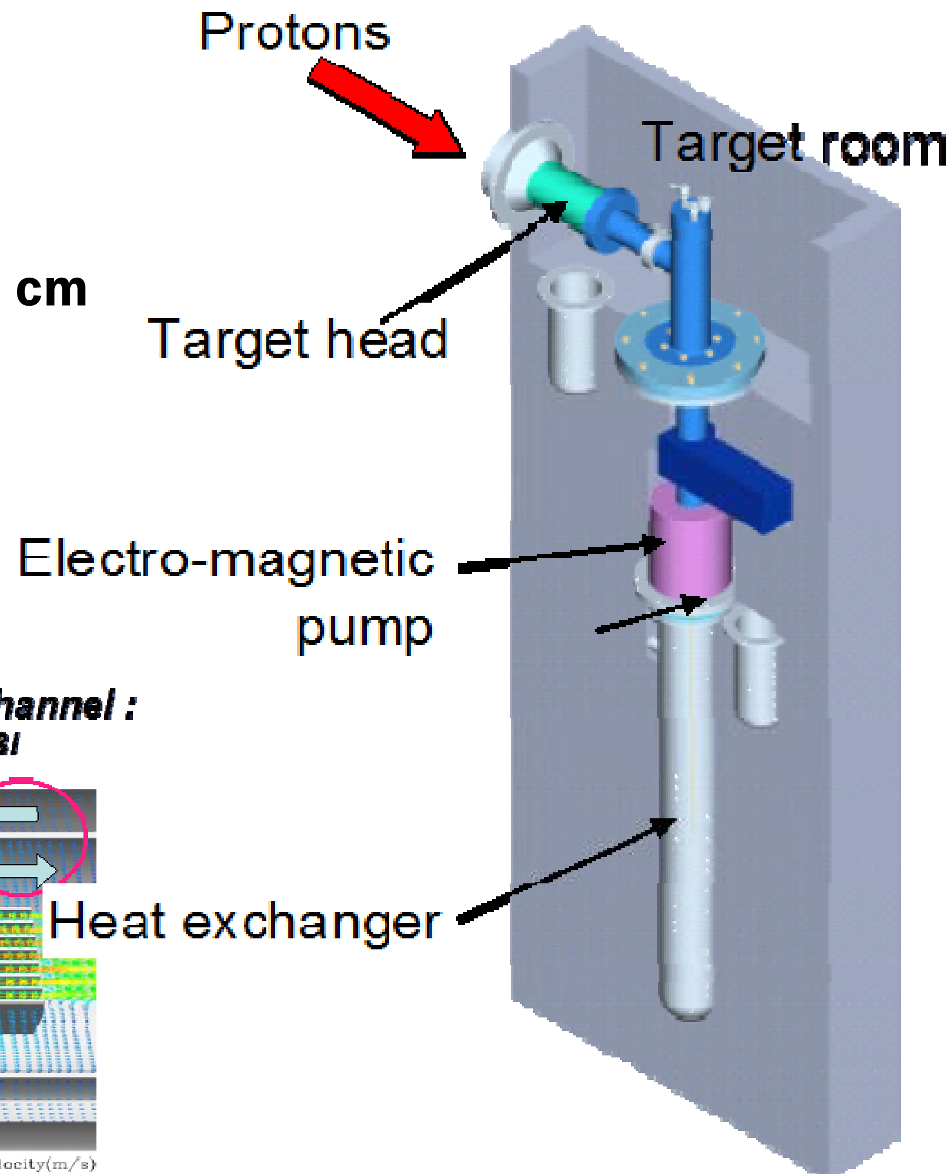
TEF-P:Transmutation Physics Experimental Facility

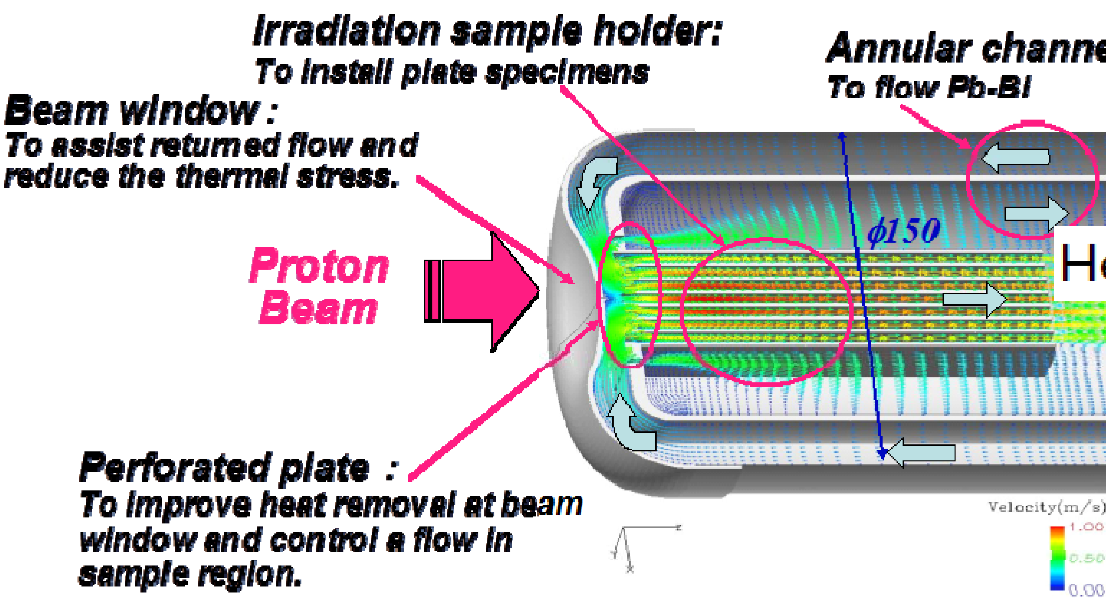
Purpose : Reactor Physics
Category : Critical Assembly
Proton Power : 400MeV-10W
Thermal Output : Less than 500W

TEF-T:ADS Target Test Facility

Purpose : Material Irradiation
Category : Radiation Application
Proton Power : 400MeV-250kW
Target Material : Lead-Bismuth

- **400 MeV p in PbBi target**
- **250 kW irradiation**
- **Dose rate: 10 dpa/y, 400 He ppm/y**
- **Irradiation sample holder: 15 x 4 x 4 cm**





A. Ibarra, 5th HPT Workshop, Chicago, May 2014

MYRRHA - An Accelerated Driven System

Accelerator

(600 MeV - 4 mA proton)

Reactor

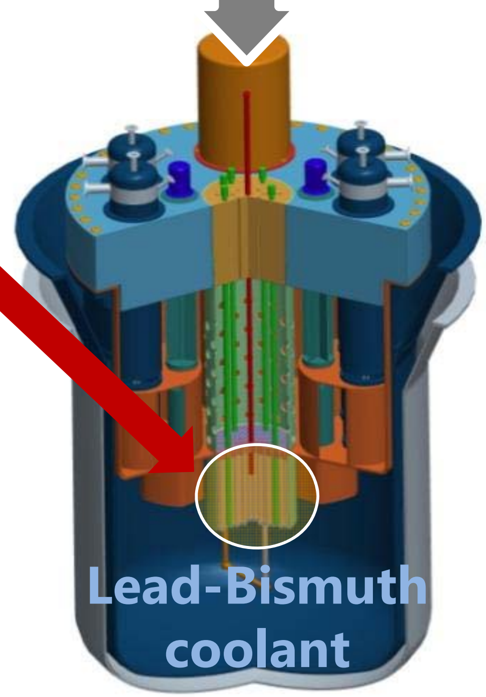
- Subcritical or Critical modes
- 65 to 100 MWth

Innovative & Unique

Spallation Source

Fast Neutron Source

Multipurpose Flexible Irradiation Facility

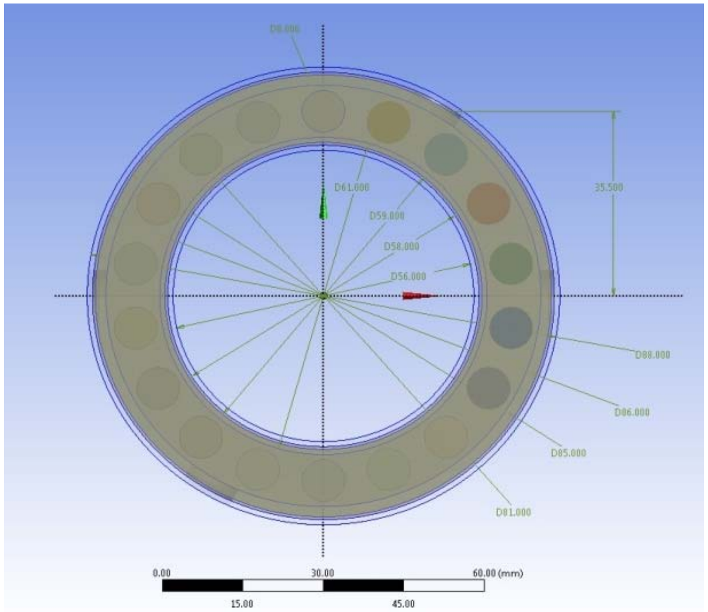


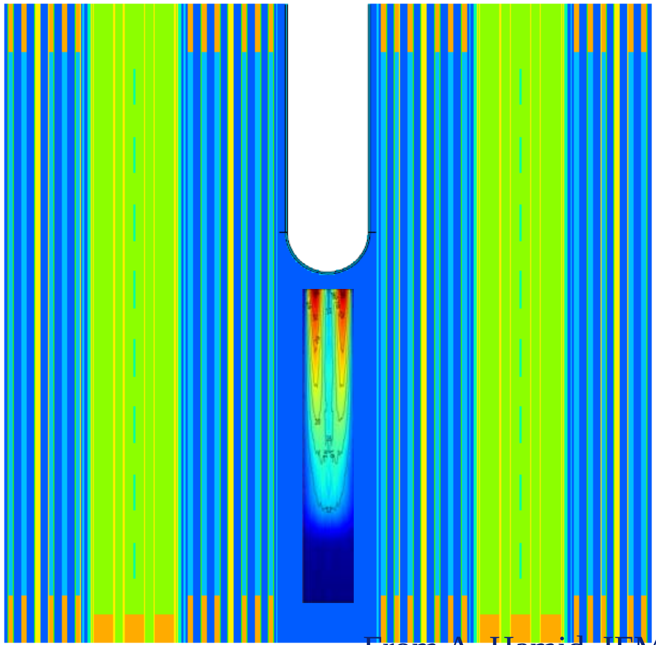
From A. Hamid, IFMIF Workshop Kyoto January 2014

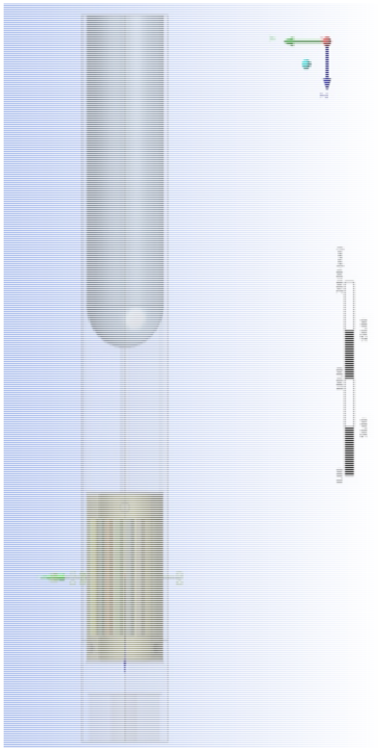
MYRRHA-IMIFF for fusion material
Material samples loaded in the spallation target vicinity

Core lay-out:

- Irradiation in sub-critical mode
- 600MeV proton beam hitting the beam tube, with spallation directly in reactor coolant LBE, creating high energetic neutrons
- A few litters of irradiation volume with 20-30 dpa/fpy and 5-20 He/dpa
- Sample holder cooled by He, temperature range: 200°C – 550°C
- Sample temperature = controlled







From A. Hamid, IFMIF Workshop Kyoto January 2014

Irradiation sources

- Displacement damage sources. **Accelerator-based neutron sources**

Stripping reaction

Planned: LiLiT, IFMIF
Under study: FAFNIR

Main characteristics: *Required ligth ions, Fusion-like He and H production, continous irradiation, materials irradiation main objective*

- Target can be of a solid one (C for example) or liquid metal (Li). Usually liquid metal case can manage higher power disipation.

Main target issues: radiation damage effects on materials , for liquid metal case: risk of cavitation and corrosion

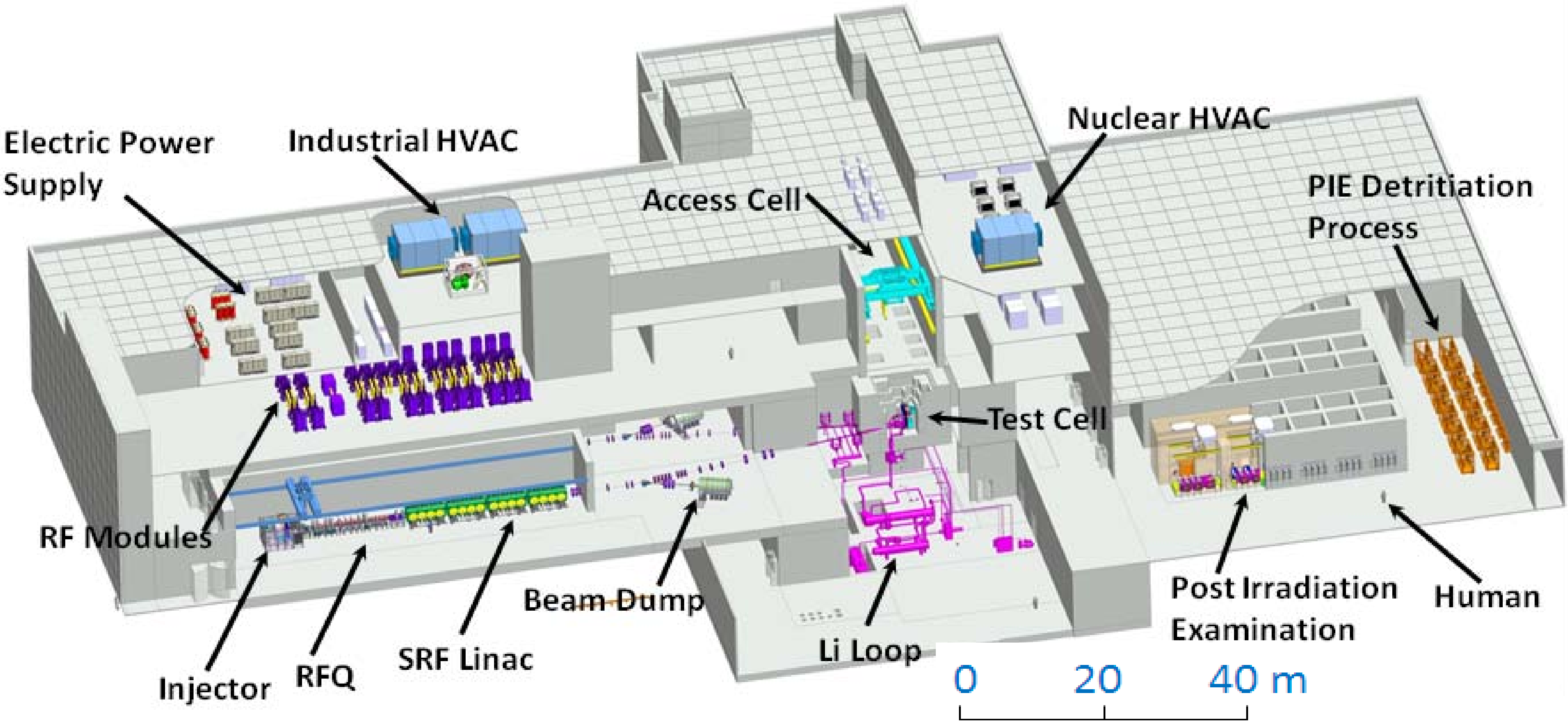
Others (**DT neutron sources**)

Under study: SORGENTINA

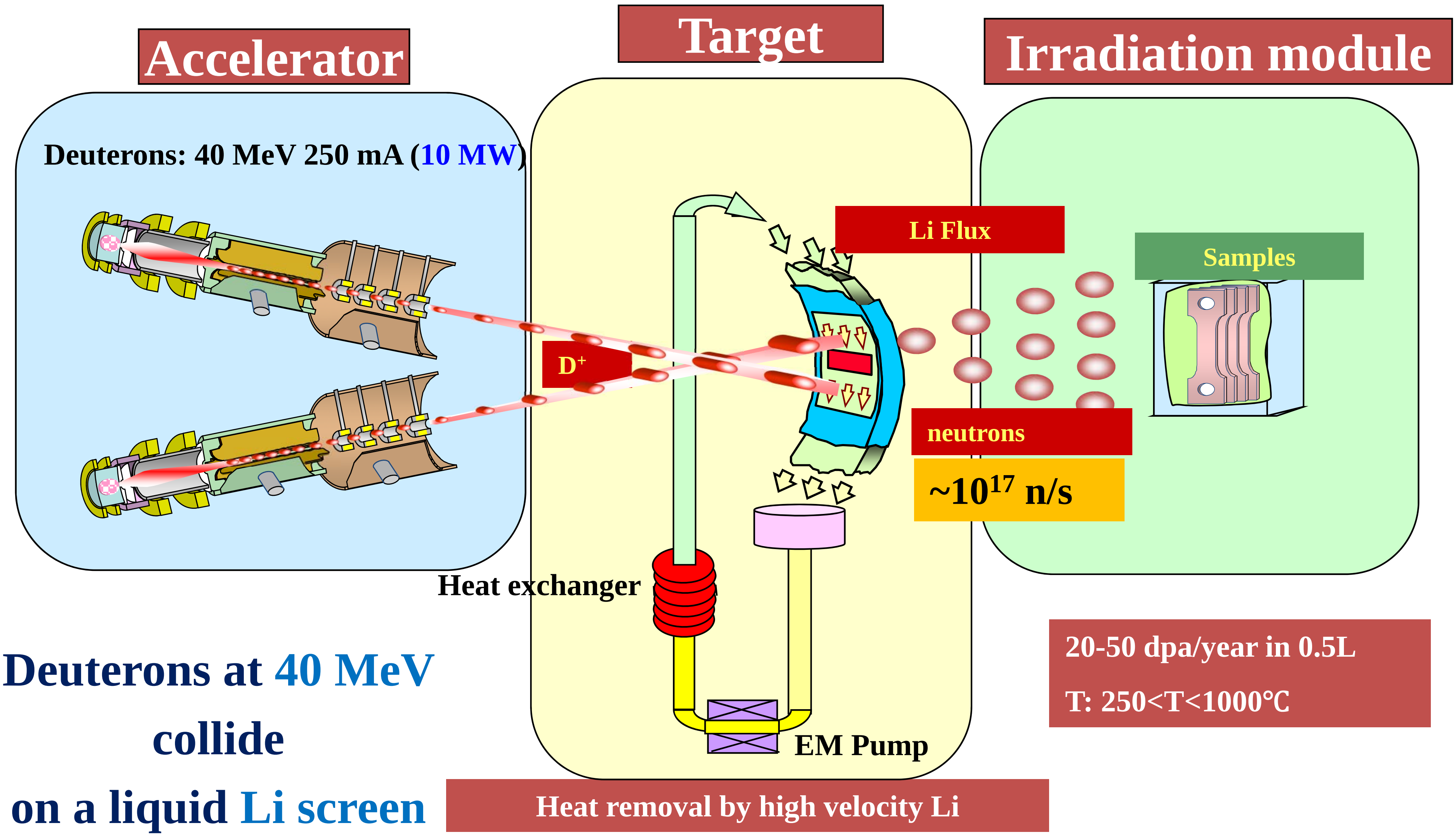
Main characteristics: *Fusion-like neutrons*

IFMIF

IFMIF is an accelerator driven neutron source designed to provide adequate flux at a suitable energy to simulate the neutron induced damage conditions expected in future Fusion Power Plants



IFMIF main elements

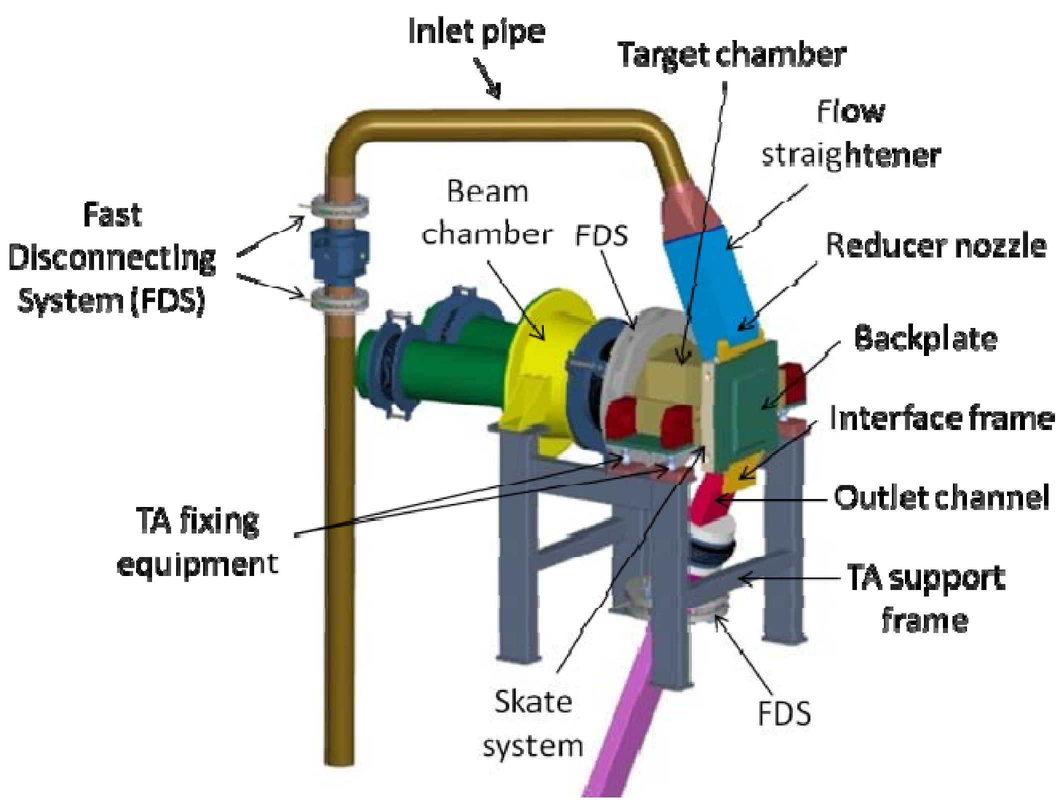


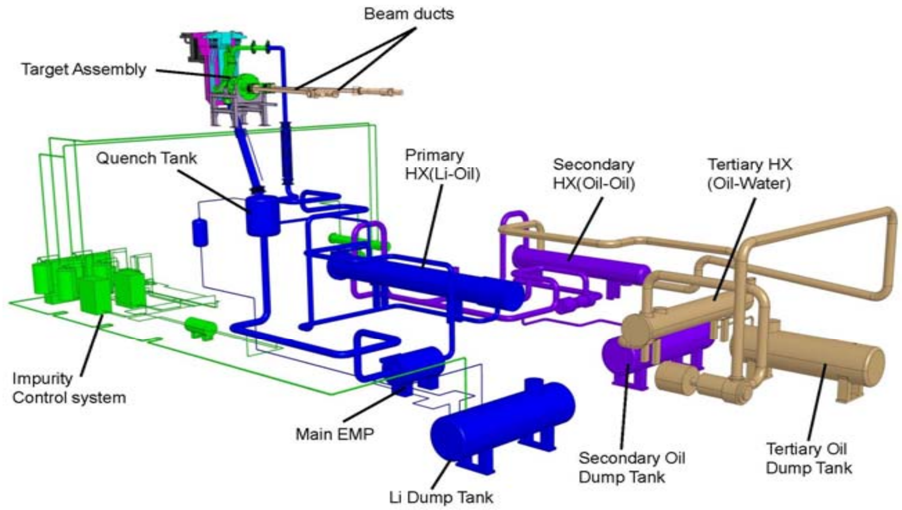
Deuterons at 40 MeV collide on a liquid Li screen flowing at 15 m/s

A flux of neutrons of ~10^{18} $m^{-2}s^{-1}$ is generated with a broad peak at around 14 MeV

A. Ibarra, 5th HPT Workshop, Chicago, May 2014

IFMIF target description-I





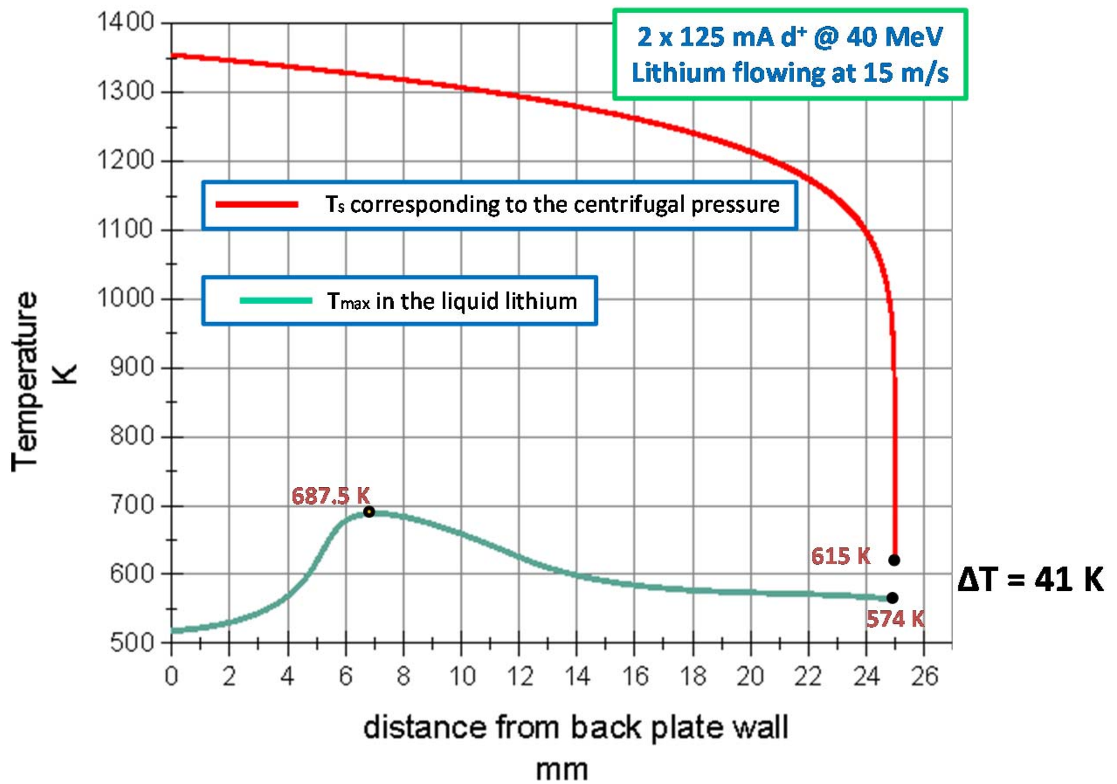
- Beam low energy → Risk of Li evaporation
- Li thermal expansion → Risk of stationary waves; Risk of pressure waves

→ **Target design**

Concave target

high Li velocity

IFMIF target description-II

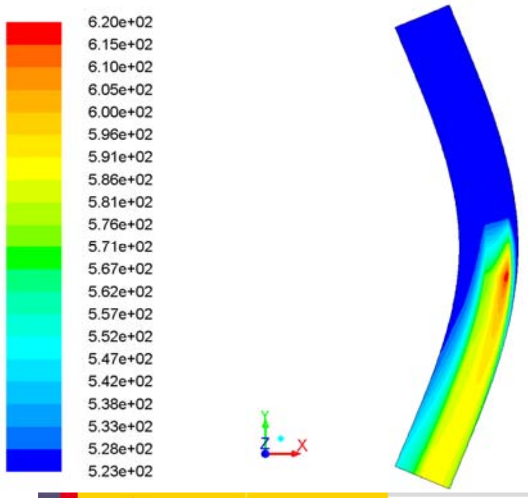


Some numbers

- Concave Li jet generates kPa centrifugal forces (pressure waves amplitude 32Pa)
- Li speed 15 m/s (if V> 0,5 m/s no pressure resonances foreseen) mean 3.3 ms exposure to the beam
- Vacuum near the surface: 10-3 Pa

Main issues (concerns):

- Impurity control required (to avoid corrosion and to reduce evaporation)
- Real vaporization rate (design margin for vaporization near the surface)



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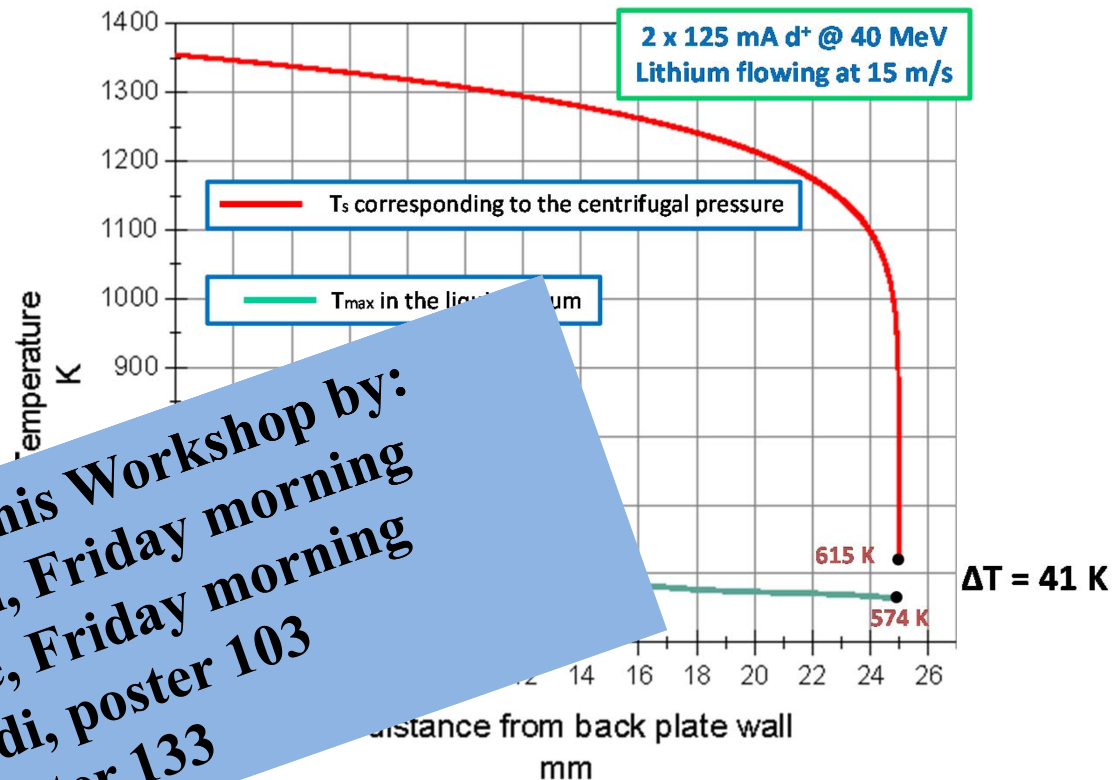
IFMIF target description-II



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More details during this Workshop by:
F. Groeschel, Friday morning
G.Micchice, Friday morning
D. Bernardi, poster 103
F. Nitti, poster 133

Main issues (c

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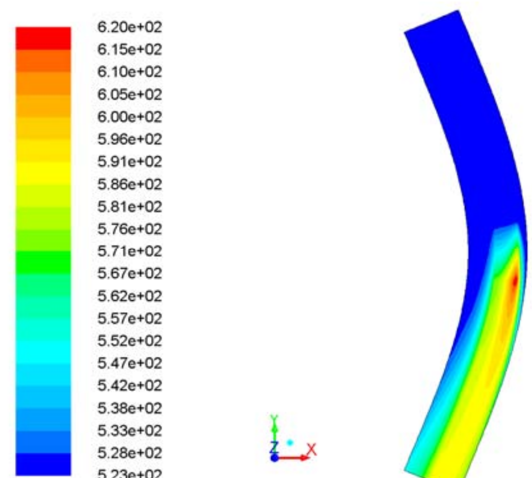

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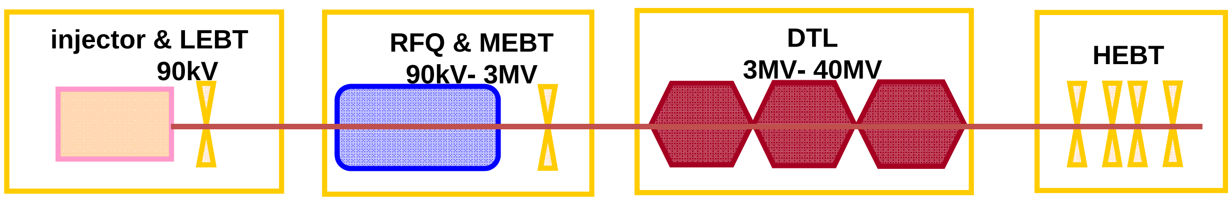
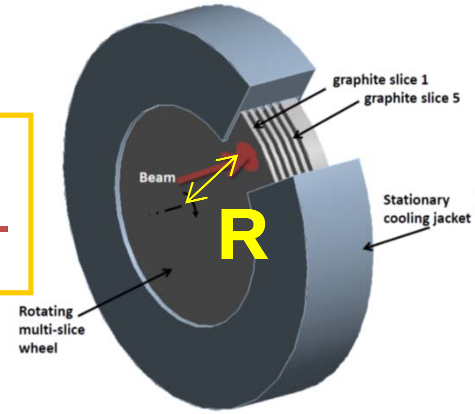
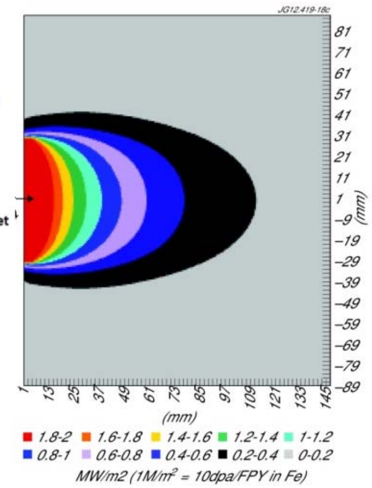
FAFNIR







40 MeV, 5/30 mA D accelerator on C solid rotating target

Beam current	Volume $25cm^3$	Volume $150cm^3$
5mA	4 dpa/fpy	1 dpa/fpy
30mA	20 dpa/fpy	5 dpa/fpy

Main target issues:

- Radiation damage (lifetime 6 months, 2 dpa)
- Heat removal

From E. Surrey, ISFNT-11 Barcelona September 2013

SORGENTINA

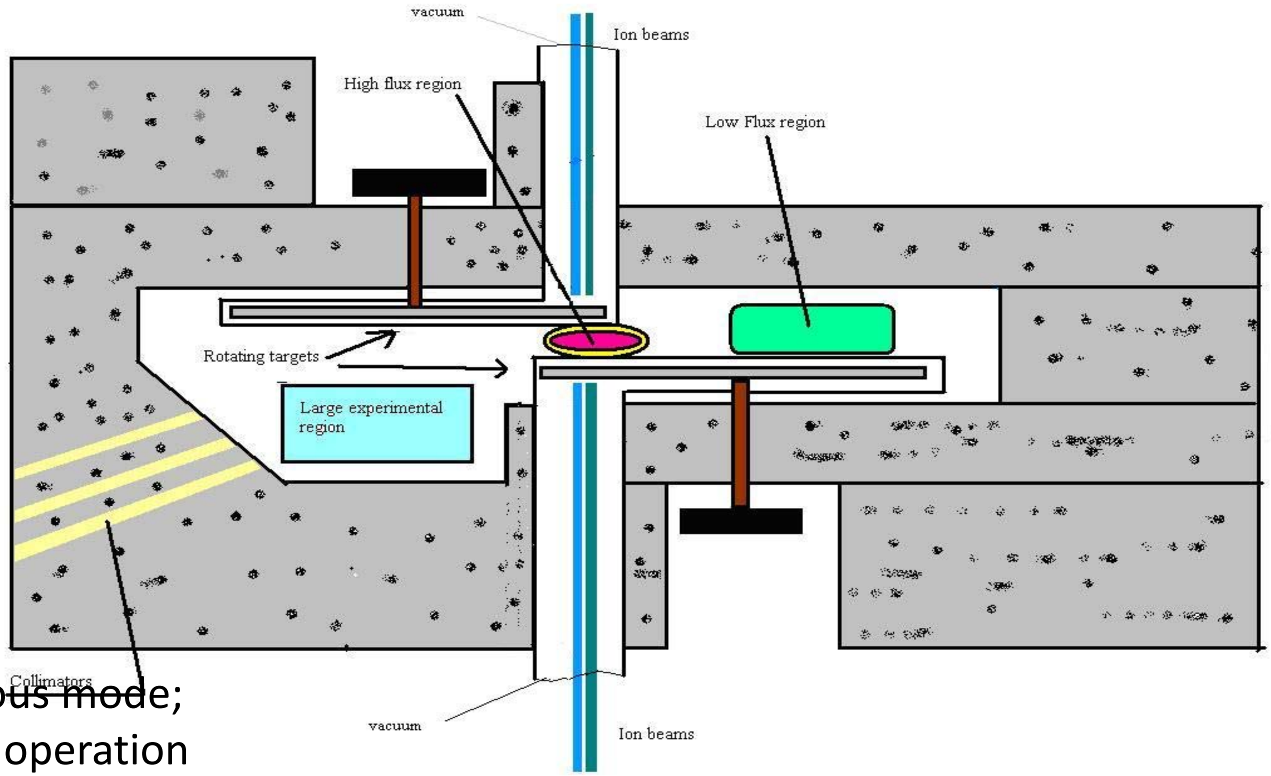
Two intense D-T 14 MeV rotating targets facing each-other

Two beams of 160 kV, 25 A (4 MW) each fire 50-50% Deuterons and Tritons on a 2 m radius rotating target

Deuterium and Tritium are implanted during the beam bombardment on a Titanium layer covering the rotating targets.

The Titanium layer is continuous reformed using a sputtering source

2 x 10^{15} n/s of 14 MeV neutrons
2 dpa/year in 50 cm^3
7 x10^{12} n/cm^2/s in 1200 cm^3



From M. Pillon, ISFNT-11 Barcelona September 2013

Main uncertainties

- ✓ To asses the use of PINI in a continuous mode;
- ✓ reforming the Titanium layer during operation
- ✓ thermo-mechanical and stress analysis
- ✓ heat removal from the target

IFMIF

SORGENTINA

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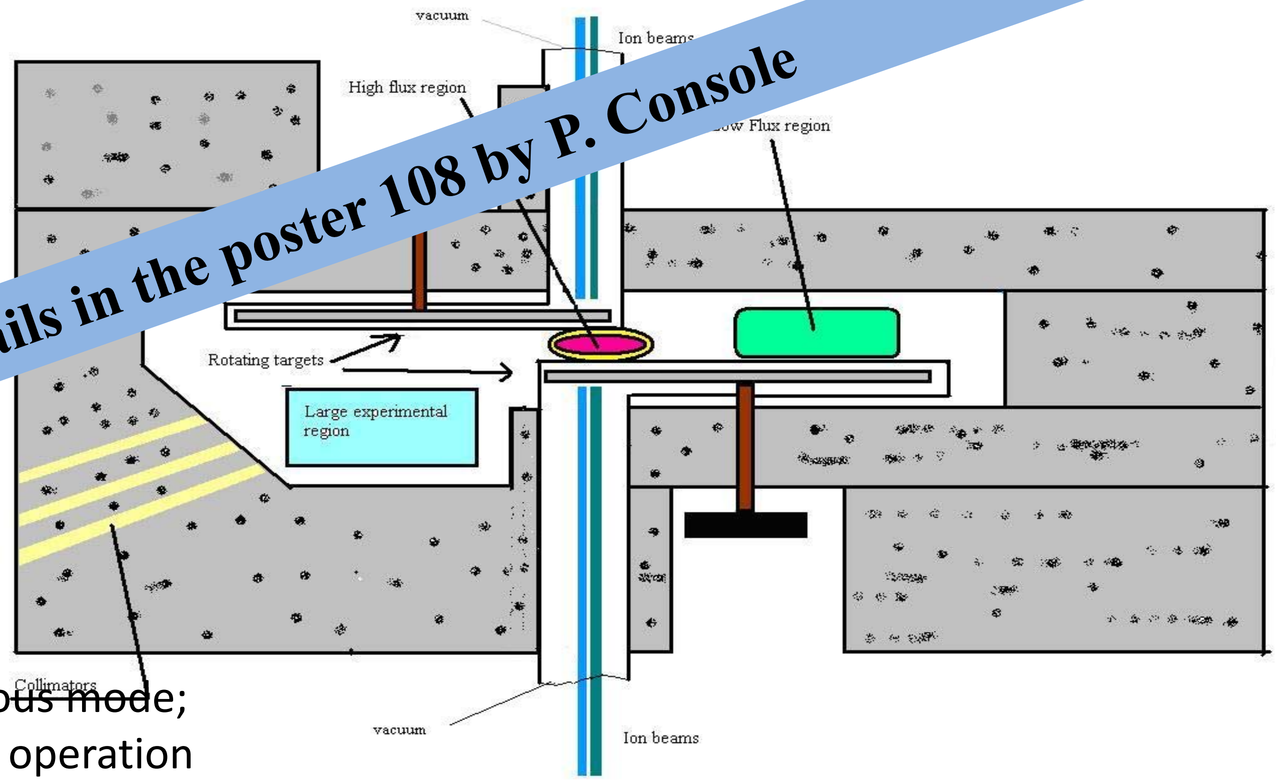
More details in the poster 108 by P. Console



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Comparison criteria

High-dose radiation effects in materials can only be properly understood if many different irradiation sources are used and a proper "common" model is developed.

How they can be compared? (the neutron/particle spectra is not so important: the important thing is the effects on the materials *–NOTE: the effects can be different for different materials-*)

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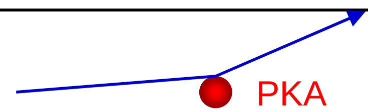
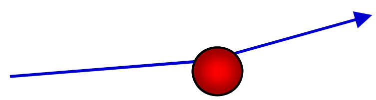
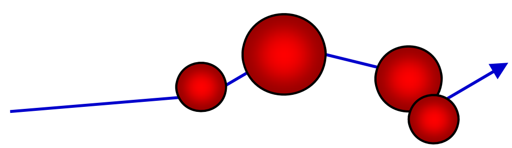
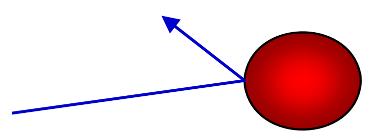
How they can be compared? (the neutron/particle spectra is not so important: the important thing is the effects on the materials –*NOTE: the effects can be different for different materials*-)

Particle type (E_{kin} = 1 MeV)	Typical recoil (or PKA) feature	Typical recoil energy T	Dominant defect type
Electron		25 eV	Frenkelpairs (FP: Vacancy-Insterstitial pair)
Proton		500 eV	
Fe-ion		24 000 eV	Cascades & sub-cascades
Neutron		45 000 eV	

Typical impact on materials properties:
FPs as "freely migrating defects": Alloy dissolution, segregation, irradiation creep
Cascades & sub-cascades: Irradiation hardening, ductility reduction

Comparison criteria

High-dose radiation effects in materials can only be properly understood if many different irradiation sources are used and a proper "common" model is developed.

How they can be compared? (the neutron/particle spectra is not so important: the important thing is the effects on the materials *–NOTE: the effects can be different for different materials-*)

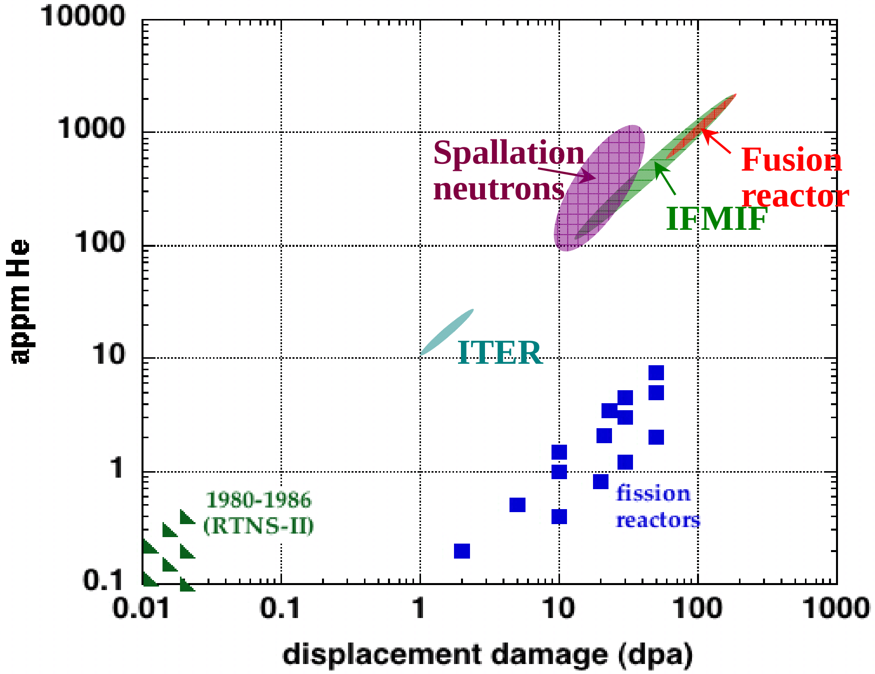
Radiation effects in materials are very complex processes that can strongly depend on many parameters (total dose, dose rate, irradiation temperature, time from irradiation, material characteristics,...).

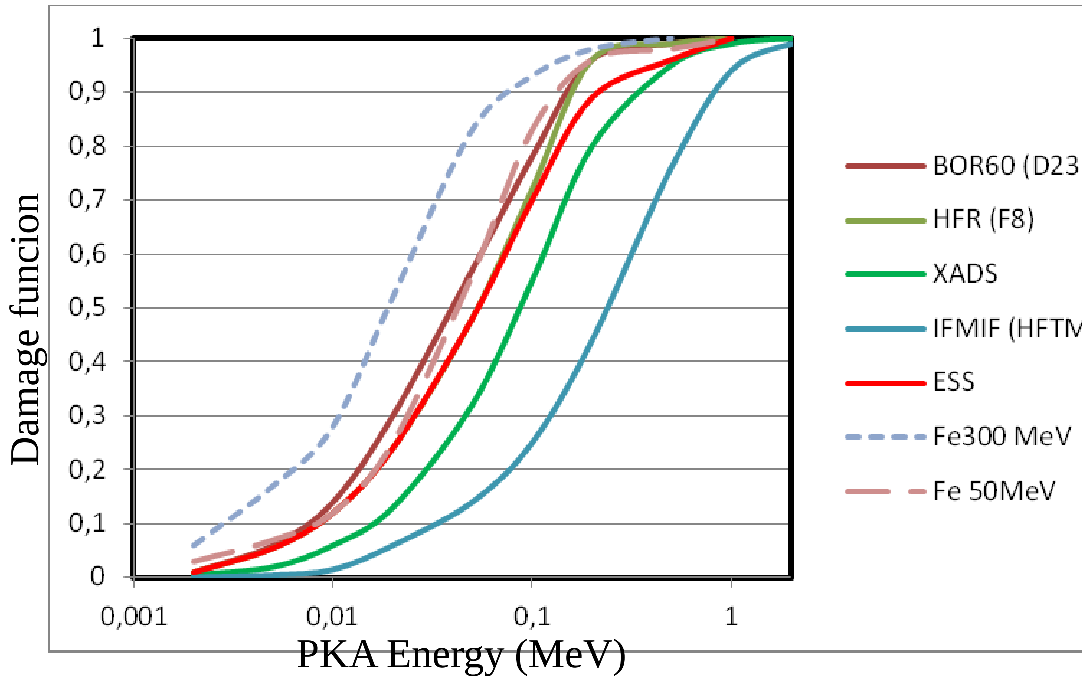
The comparison is based in the initial phases of interaction of radiation particles with the material:

- i) scattering of particles. This is measured with **the parameter "dpa"-total dose and dose rate-** and with **W(T) –damage function-** (a parameter that describes in a qualitative way the "type" of damage in the material)

- ii) Nuclear reactions, giving rise to "new" ions not previously in the matrix. In the case of fusion-like neutrons the main impurities induced are He and H. This is measured with the **He/dpa, H/dpa ratios** and other impurities production.

+ other obvious comparison criteria like **irradiation volume**, **feasible temperature range**,...


10000
1000
100
10
1
0.1
appm He
0.01
0.1
1
10
100
1000
displacement damage (dpa)
Spallation
neutrons
Fusion
reactor
IFMIF
ITER
fission
reactors
1980-1986
(RTNS-II)


Damage funcion
PKA Energy (MeV)
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0,001
0,01
0,1
1
BOR60 (D23
HFR (F8)
XADS
IFMIF (HFTM
ESS
Fe300 MeV
Fe 50MeV

Neutron source type	Short description	Neutron production efficiency (1)	Heat release (1)	Example
Nuclear fission		*1n/fission*	*180 MeV/n*	
Spallation	*800 MeV p on W*	*15-30 n/p*	*30-55 MeV/p*	*SINQ*
Stripping	*40MeV D on Li*	*7 10-2 n/D*	*3500 MeV/n*	*IFMIF*
D-T in solid target		*4 10-5 n/D*	*10000 MeV/n*	*Sorgentina*

Neutron source type	typical dpa/y	He/dpa ratio
Nuclear fission	*<10*	*0.1*
Spallation	*<10*	*20-200 (strong design dependence)*
Stripping	*<40*	*8-15*
D-T in solid target	*<5*	*10*

(1) Claussen (2008)

Conclusions

- An increasing number of applications requires materials irradiation test beds including dedicated high flux accelerator driven neutron sources
- A significant number of Materials Irradiation Facilities is presently proposed and under study. We all hope that the next 10-20 years will show an impressive progress in this area
- Other facilities, like multi beam ion accelerators in the MeV range can also be very useful
- Do not forget efforts for sample size normalization and modelling

Thank you!!!