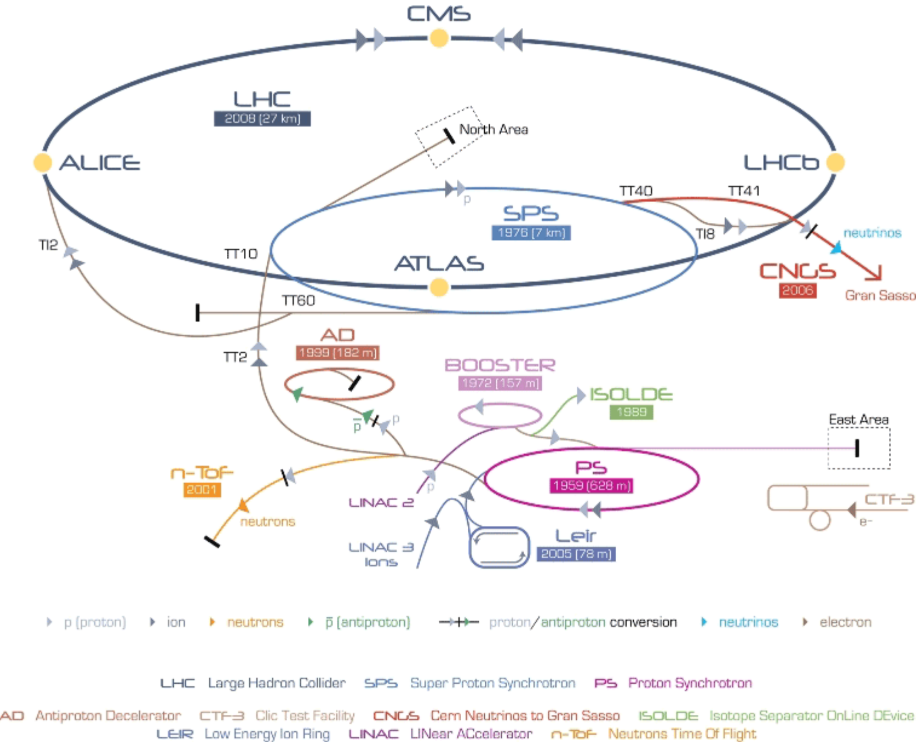
IFMIF-DONES facility: a key accelerator-based neutron source for the design of DEMO

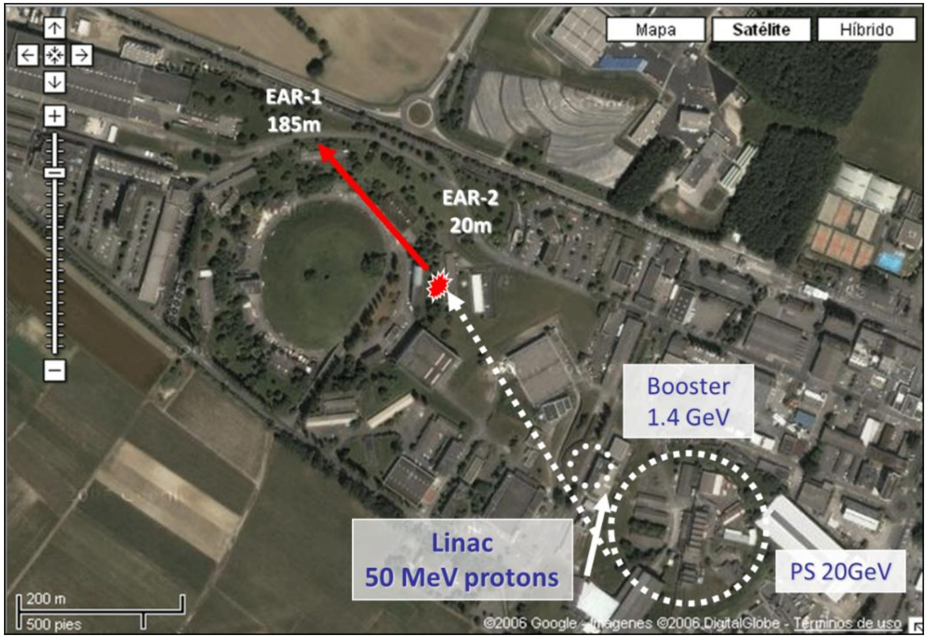
Javier Praena

Profesor Titular, Universidad de Granada (Spain)

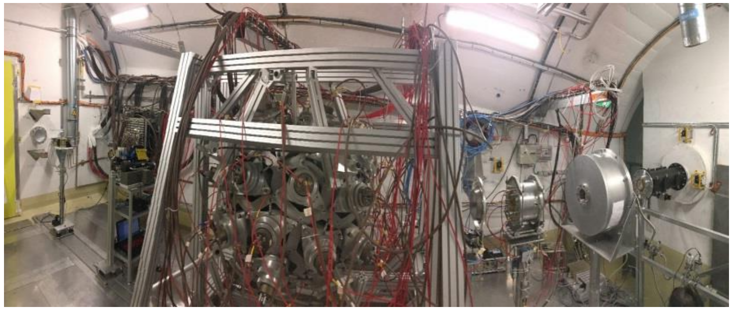
CERN Scientific Associate (EP-SME-62)
n_TOF Physics Coordinator (2020-28/02/2022)

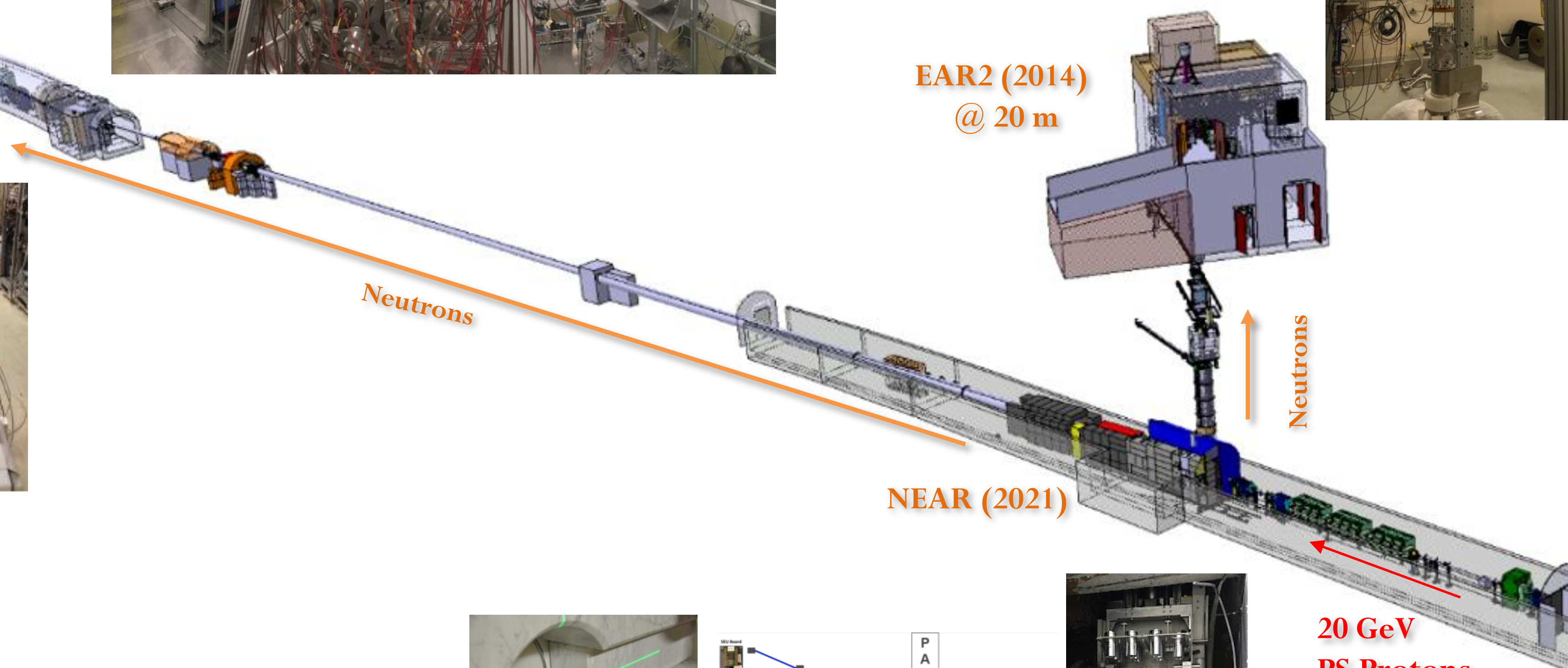
Outlook of CERN facilities

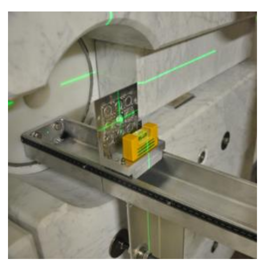


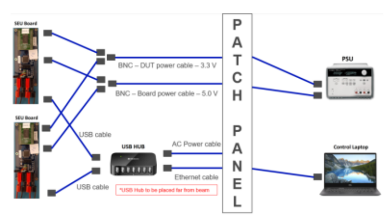


Outlook of the n_TOF facilities

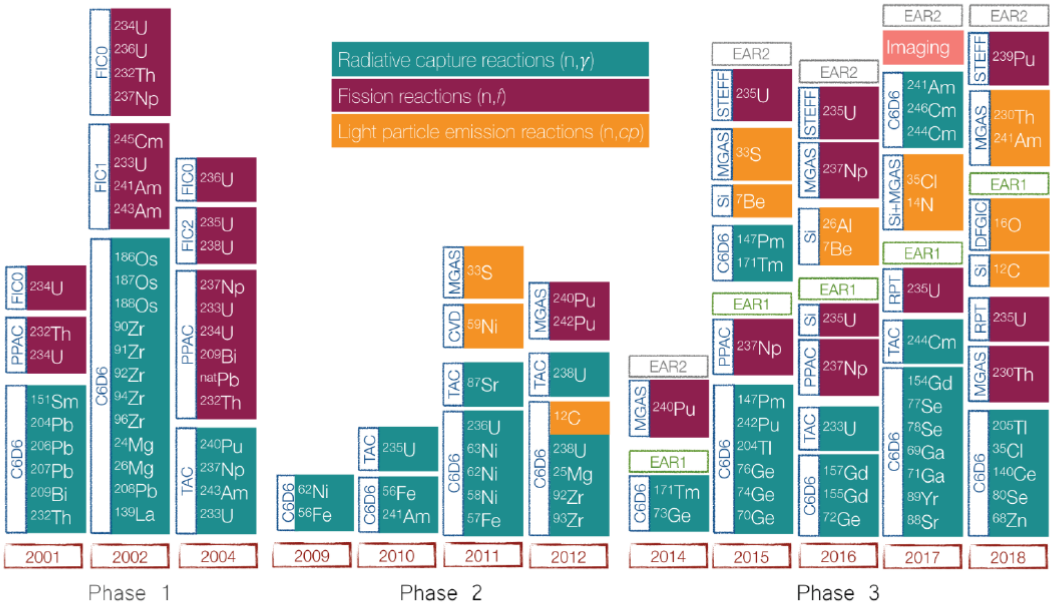








The experiments at n_TOF: cross sections (n,γ) (n,cp) (n,f)

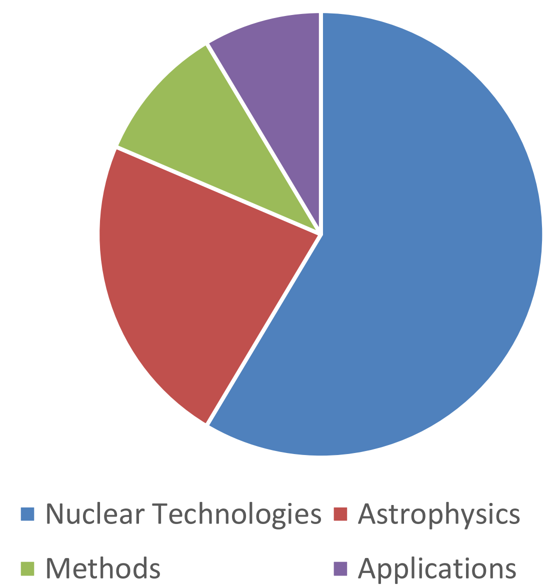


Our expertise is to determine with high accuracy and high resolution neutron induced cross-sections and to use them in differents fields.

The average duration of an experiment is 5 weeks.

220 days/year 24h/day proton beam on the target.

This is our main characteristic for the irradiation of materials and electronics.
A Complementary Program very important for n_TOF.

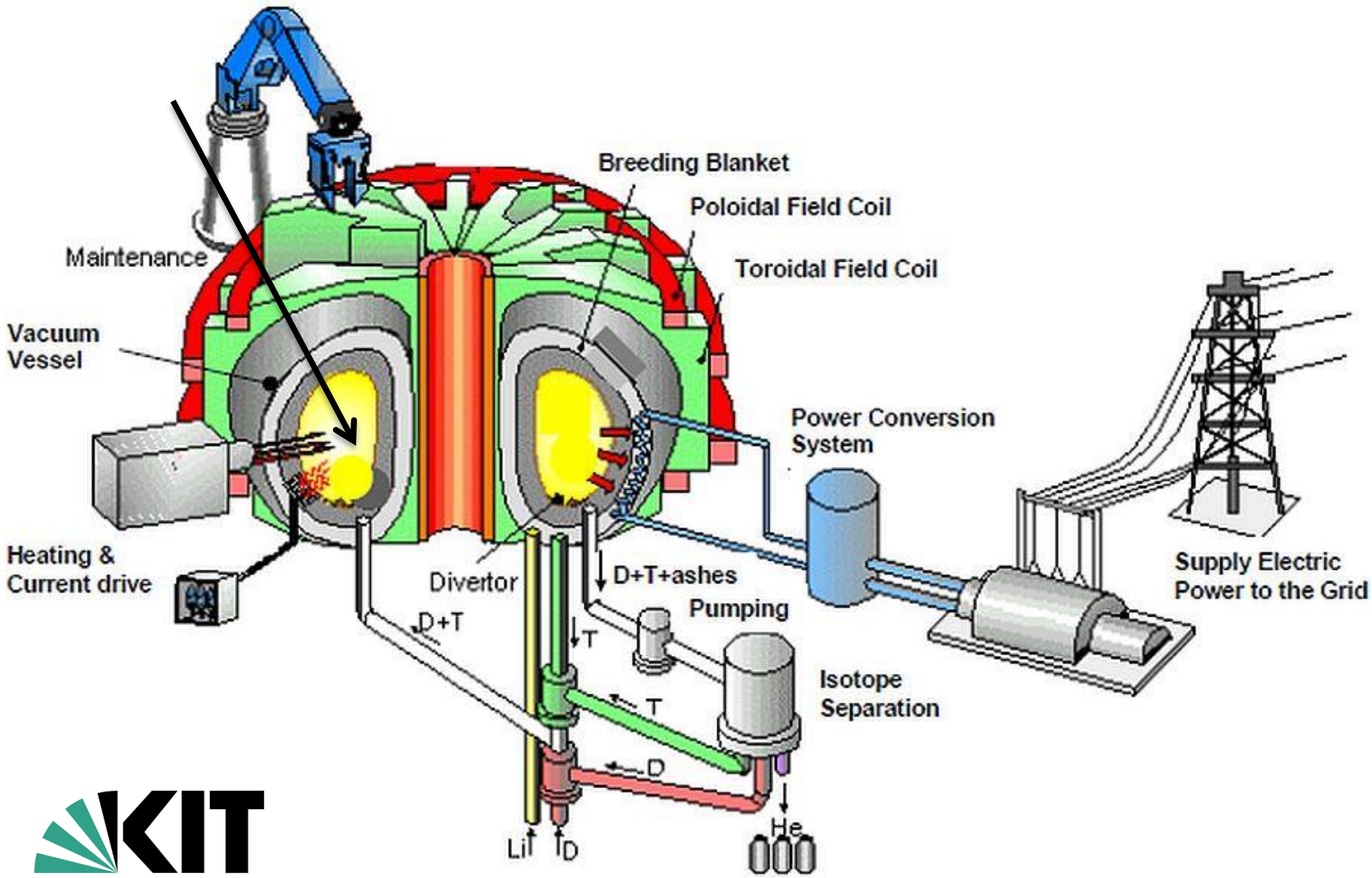


IFMIF-DONES overview

- DONES in the framework of DEMO (future fusion reactor).
- International Fusion Materials Irradiation Facility (IFMIF): long term project.
- Demo Neutron Source (DONES): speed up of IFMIF, urgent need of data.
  - DONES $\sim \frac{IFMIF}{2}$, one accelerator instead two accelerators
- Overview of the DONES building and site.
- Requirements of the IFMIF-DONES facility.
- Key devices: accelerator, Li jet for neutron production and the test facility.
- Complementary Physics Program.

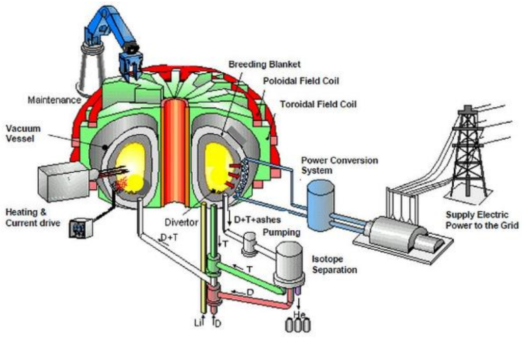
DEMO: Demostration Power Plant

- First fusion reactor supplying electricity to the domestic grid.
- Key task for the design: evaluation of the neutron damage (DONES).
- D + T produces high energy neutrons (14 MeV) with high yield.



Karlsruher Institut für Technologie

Roadmap to DEMO



DEMO

FUSION REACTOR

Larger size 15%?
Denser plasma 30%?

Solution to neutron damage
Materials for the walls

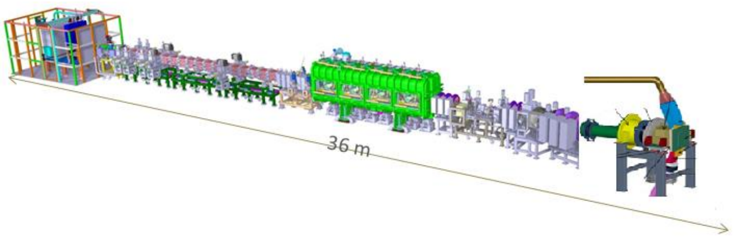
ITER

FUSION REACTOR

Cadarache (France)
No electricity
Superavit
50MW/500MW

IFMIF-DONES

Accelerator-based neutron source

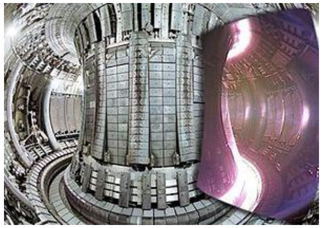


Plasma Volume x 8

JET…

FUSION REACTOR.

Experiments



Oxford (UK)

DONES project framework

The need for a facility of this type was identified long time ago and work has been carried out by using different frameworks

In the last 15 years, key projects are:

- **IFMIF/EVEDA**
- **WPENS –including specific Industry contract- (EUROfusion WP)**
- **DONES-PreP (EURATOM CSA)**
- **DONES-PRIME**
- **DONES-UGR (Spanish funded projects), ….**

- 16 Research Units + UKAEA
- Collaboration with Fusion for Energy (F4E)
- Lead beneficiary CIEMAT
- Many more affiliated entities laboratories
- Industry contribution (both AE and contract)

Since 2018…

ESFRI. Site: Escúzar, Granada (Spain)

Strategy Report on Research Infrastructures
ROADMAP **2018**

Part 1 STRATEGY REPORT | Part 2 LANDSCAPE ANALYSIS | Part 3 PROJECTS & LANDMARKS

International Fusion Materials Irradiation facility - DEMO Oriented NEutron Source

A unique Research Infrastructure for testing fusion materials in realistic conditions

DESCRIPTION

The International Fusion Materials Irradiation Facility - Demo Oriented NEutron Source (IFMIF-DONES) is a single-sited novel Research Infrastructure for testing, validation and qualification of the materials to be used in a fusion reactor. It is based on a unique neutron source with energy spectrum and flux tuned to those expected for the first wall containing future fusion reactors. Materials irradiation data under such conditions are of fundamental interest for the fusion community as those will feed and validate the modelling tools for materials radiation damage phenomena. The IFMIF-DONES will be a major step towards IFMIF as it will develop a unique high-current high-duty cycle accelerator technology, liquid metal target technology and advanced control systems.

IFMIF was first proposed to the ESFRI Roadmap in 2006, but the development of its concept was mostly carried out within the Broader Approach that will deliver the final results in 2020. The IFMIF-DONES will build on the results of the international community by establishing suitable collaboration schemes, whilst bringing back to Europe one important development in the roadmap to fusion energy.

BACKGROUND

TYPE

single-sited

LEGAL STATUS

pending

POLITICAL SUPPORT

European Strategy Forum on Research Infrastructures

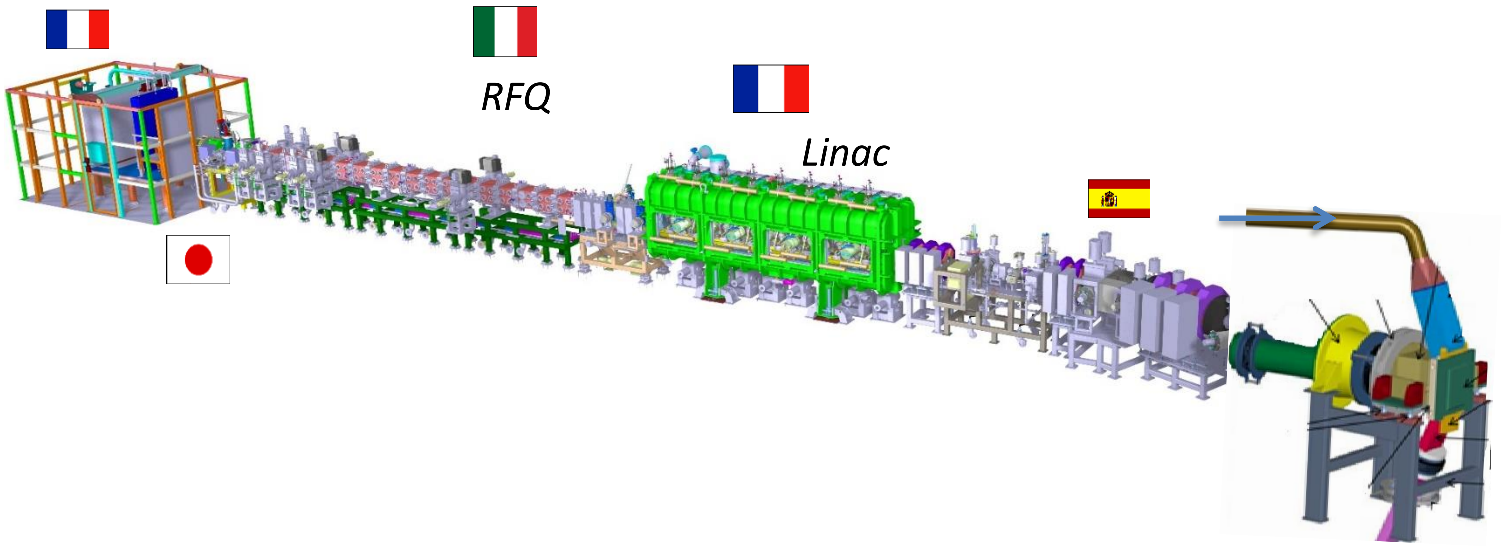
Why Granada?

University of Granada is the 3rd Spanish university (Shangai Rank).

University of Granada, Seven Solution spin off, has been part of the IFMIF-DONES in deep collaboration with CIEMAT (Fusion) (Spain).

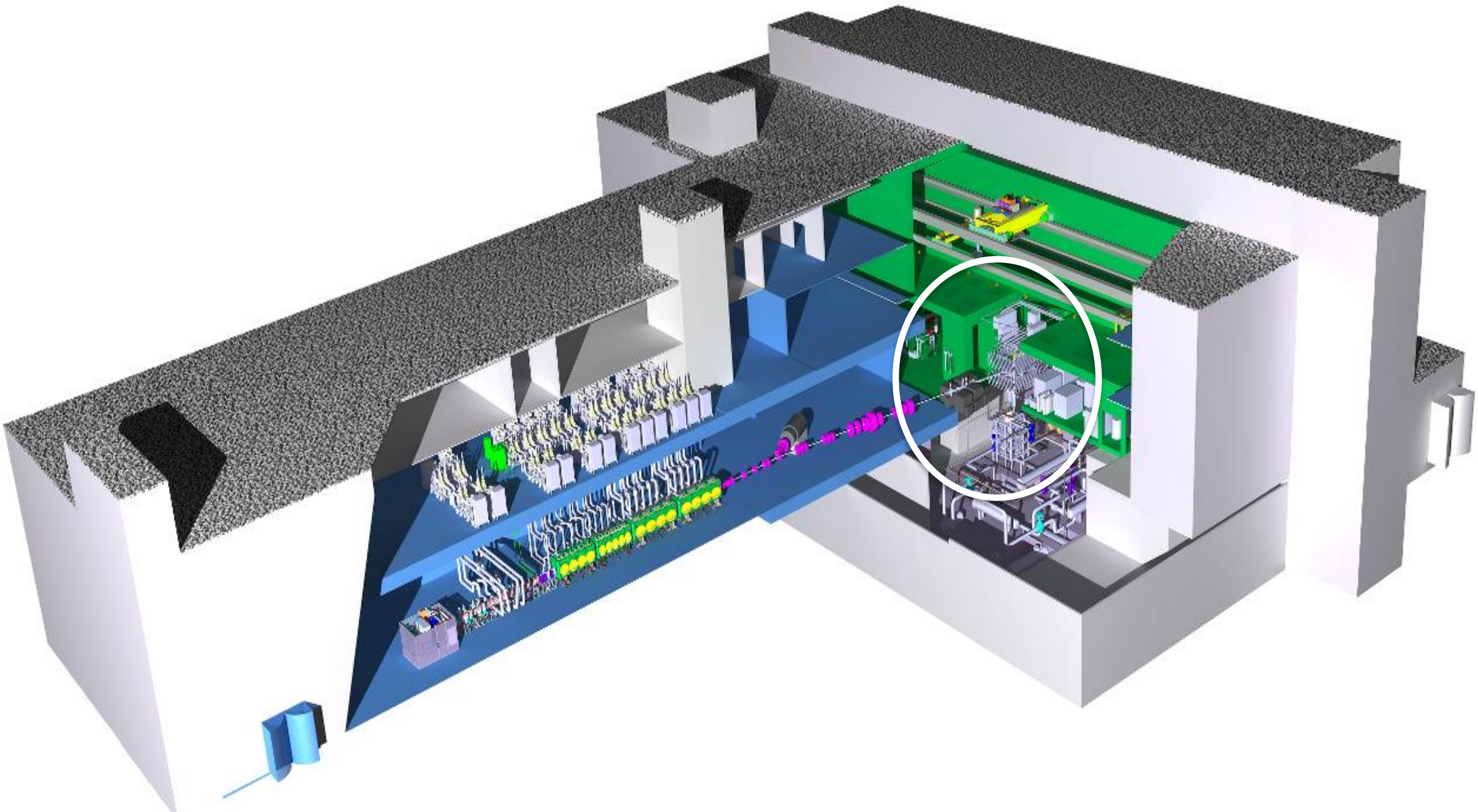
Granada belongs to a region with European Regional Development Fund. ERDF is not funding DONES.

The core of the DONES facility

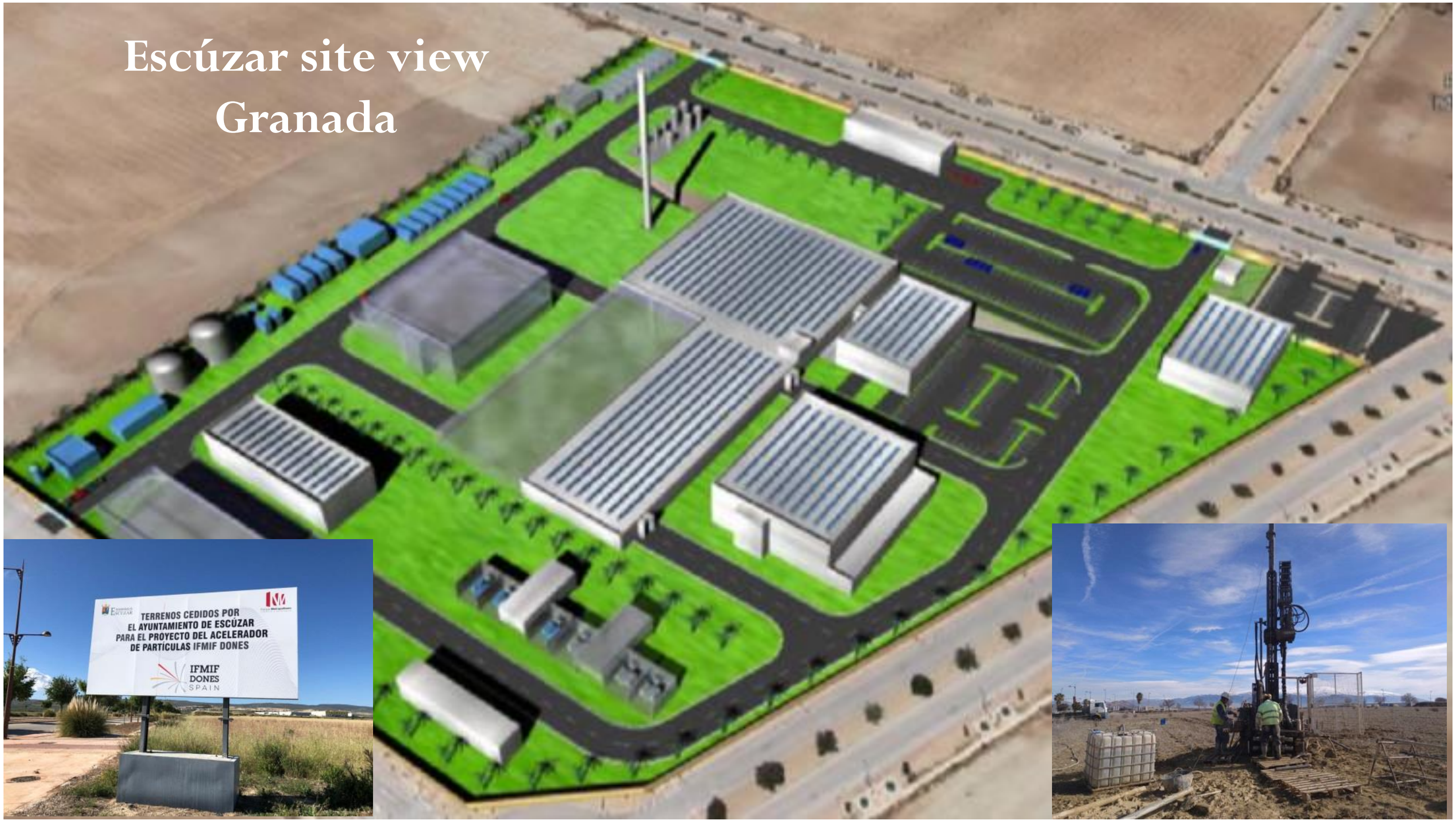


Deuteron Accelerator
Lithium Jet

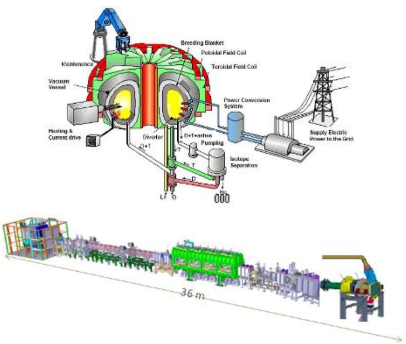
DONES building



DONES site


Escúzar site view
Granada
TERRENOS CEDIDOS POR
EL AYUNTAMIENTO DE ESCÚZAR
PARA EL PROYECTO DEL ACELERADOR
DE PARTÍCULAS IFMIF DONES
IFMIF
DONES
SPAIN

Requirements for IFMIF-DONES



- IFMIF-DONES must provide the information in terms of neutron irradiation for designing DEMO.
- It is not needed to reproduce exactly DEMO conditions but it is needed to generate fusion-like neutrons.

DEMO will probably have two operational phases:

First one: focused on startup and feasibility evaluation (low availability): 20 dpa

Second one: focused on availability increase: 50 dpa

- Intensity large enough to allow accelerated testing compared to DEMO. — **> 10 dpa(Fe)/fpy**
- Damage level above the expected operational lifetime in DEMO. — **20 dpa(Fe) in 1.5 y /50 dpa(Fe) in 3.5 y**
- Irradiation volume large enough to allow the characterization of the macroscopic properties of the materials for DEMO. — **300 cm^3**

IFMIF-DONES is necessary

NATURE PHYSICS DOI: 10.1038/NPHYS3735

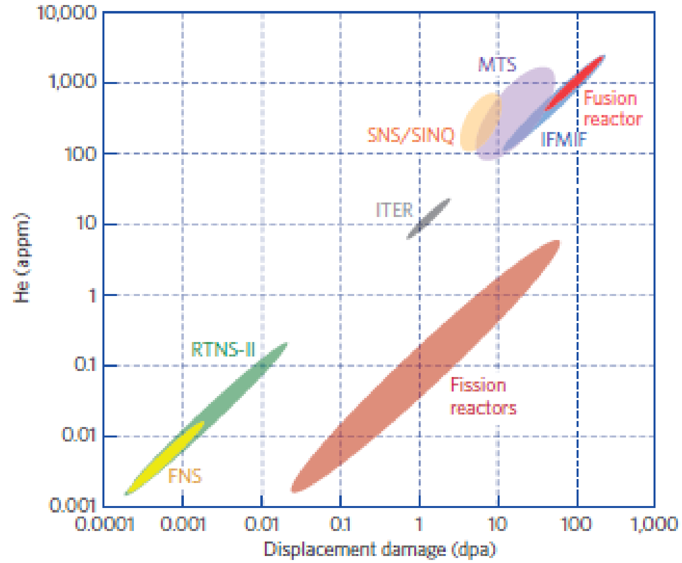
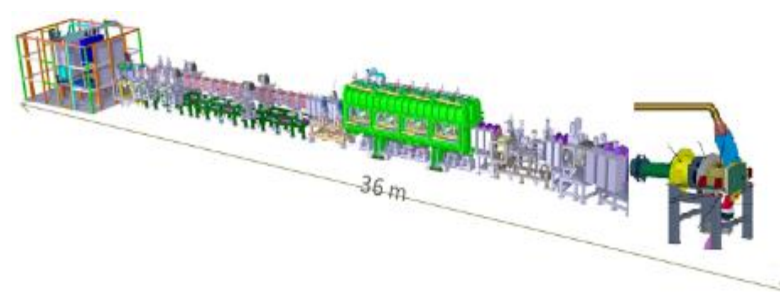


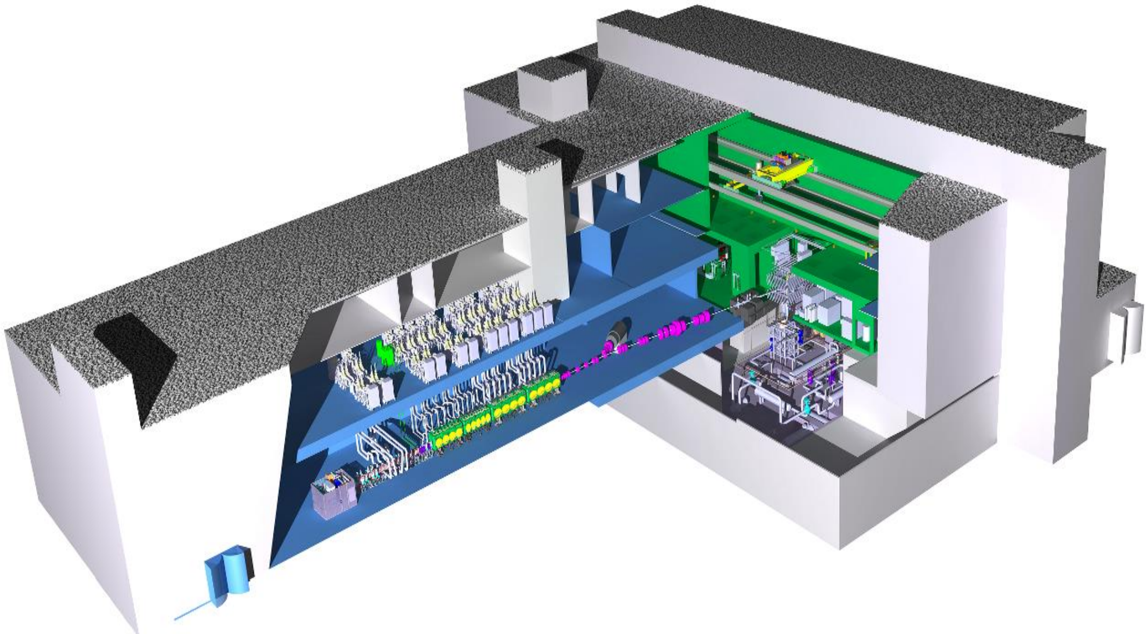
Figure 4 | Graph showing the correlation of dpa_{NRT} versus appm of He generated for the different possibilities of testing materials (alternative and IFMIF) compared with fusion reactor conditions. MTS, Materials Test Station spallation source at Los Alamos National Laboratory; RTNS-II, Rotating Target Neutron Source-II, previously at Lawrence Livermore National Laboratory; SINQ, Swiss Spallation Source at Paul Scherrer Laboratory; SNS, Spallation Neutron Source at Oak Ridge National Laboratory; FNS, Fusion Neutron Source at Japan Atomic Energy Agency. Figure modified from ref. 31, © 2014 Annual Reviews.

The best compromise for achiving the requirements:

- **Neutrons from Li(d,xn) reactions**
- **Deuteron Energy = 40 MeV**
- **Deuteron Current = 125 mA**
- **High power 5 MW: lithium jet**



IFMIF-DONES: key devices

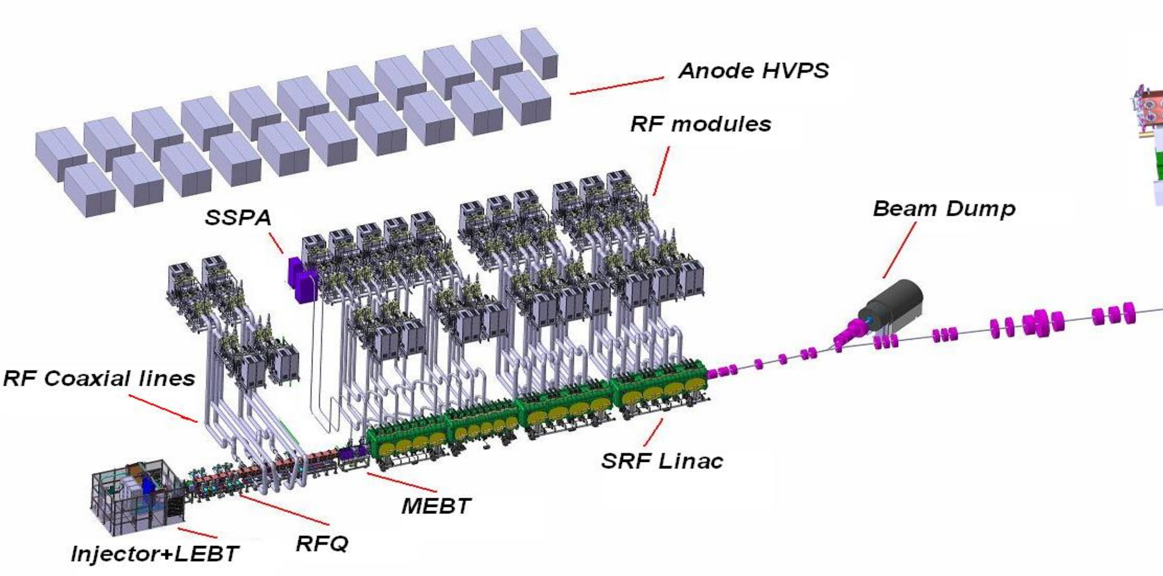


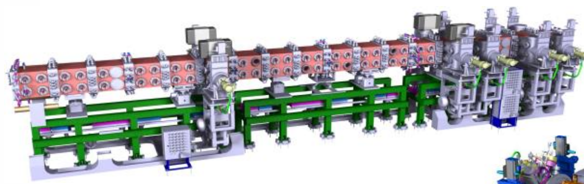
The accelerator

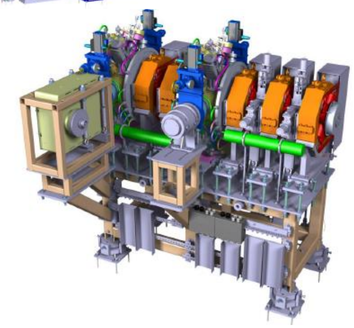
The Lithium Jet, target for neutron production

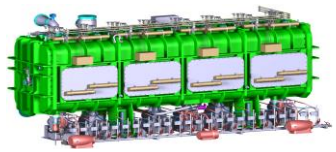
The bunker and the High Flux Test Module

The accelerator

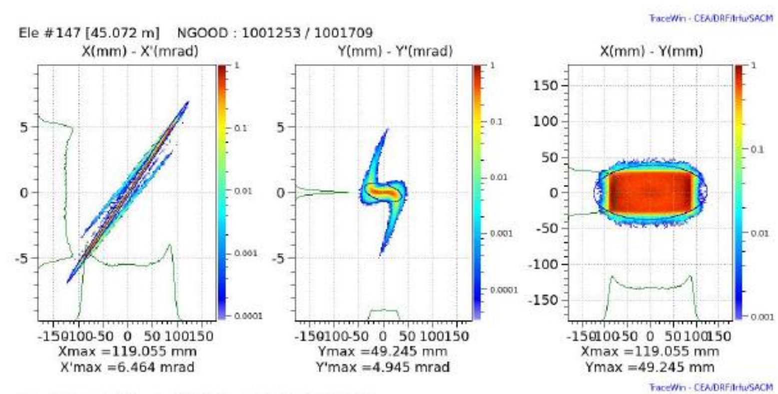




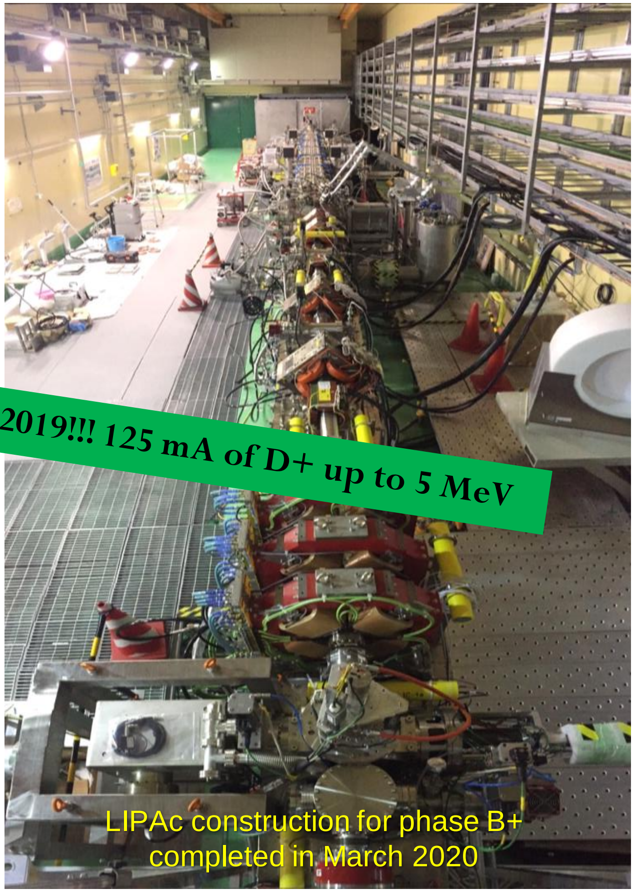




- Deuteron accelerator up to 40 MeV
  - RFQ at 5 MeV
  - Linac up to 40 MeV
- Continuous wave (CW), 100% duty cycle.
- 175 MHz.
- 200 mm x 50 mm beam cross-section.
- Buncher cavity voltage = 350kV
- Quadrupole magnetic field gradient = 25T/m
- Steerers strength = 25 G·m.



The accelerator: status of prototype in Japan

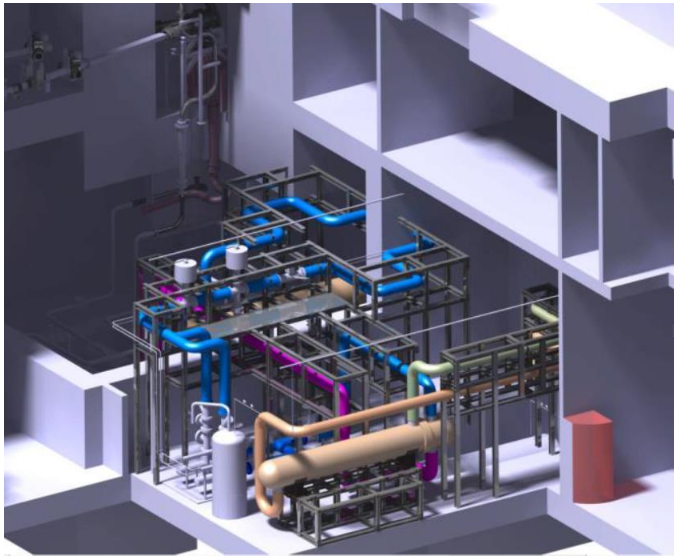


LIPAc construction for phase B+ completed in March 2020

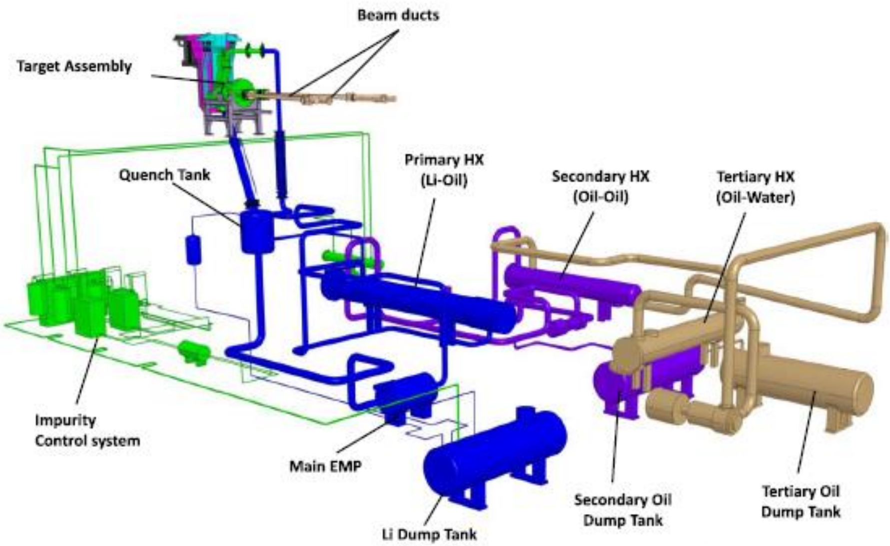
Achieved in 2019!!! 125 mA of D+ up to 5 MeV

Beam Dump

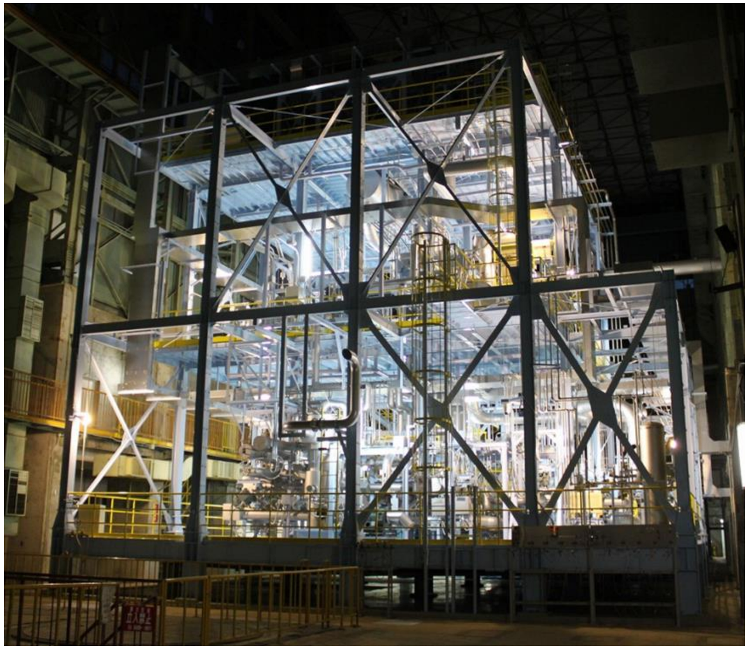
Lithium Jet

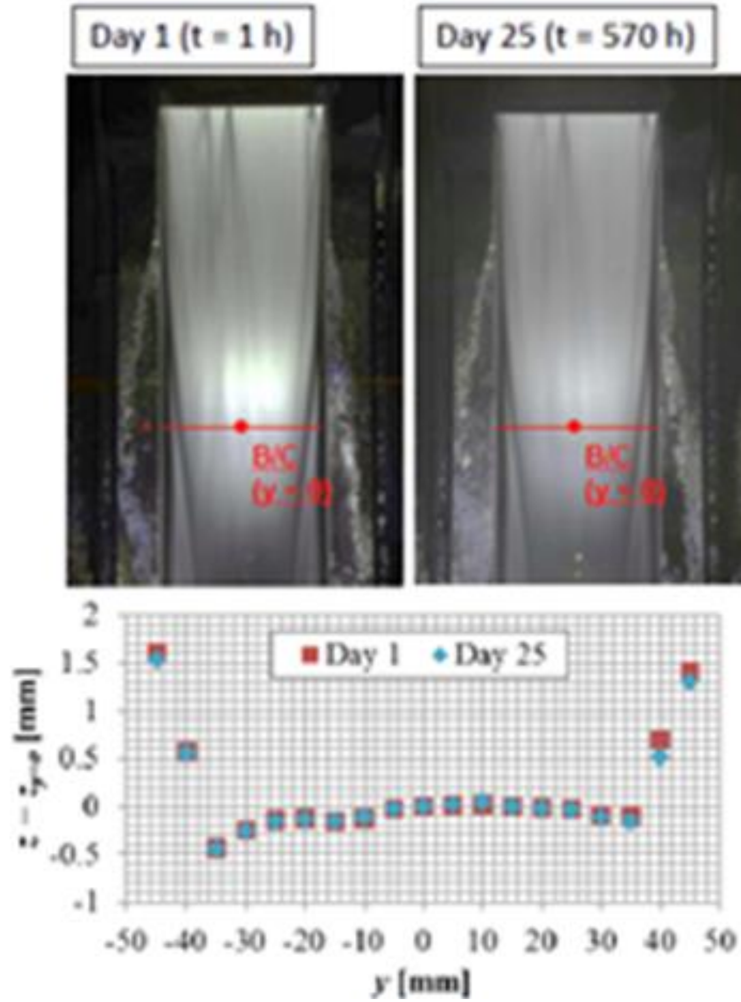


- Lithium objective is to provide the neutrons.
- Extraction based on Li-Oil-Oil-Water
- Impurities are constantely produced, including radioactives.
- Cold trap, H trap and N trap.
- Getter material to be determined (Ti)



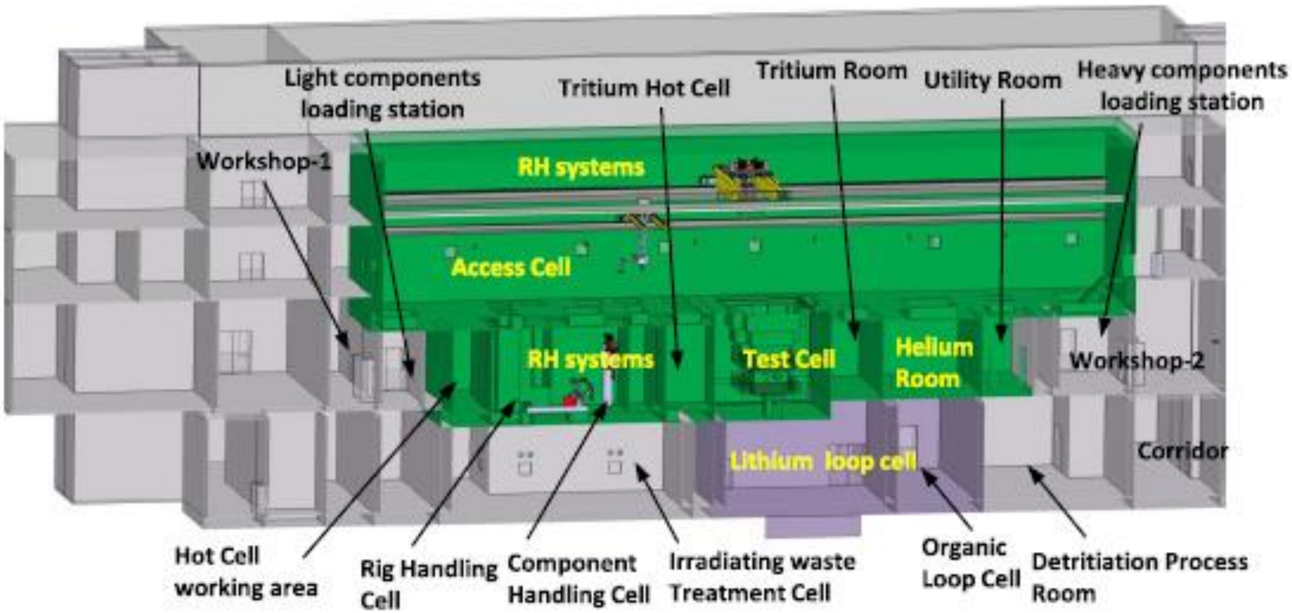
Lithium Jet: status in Japan





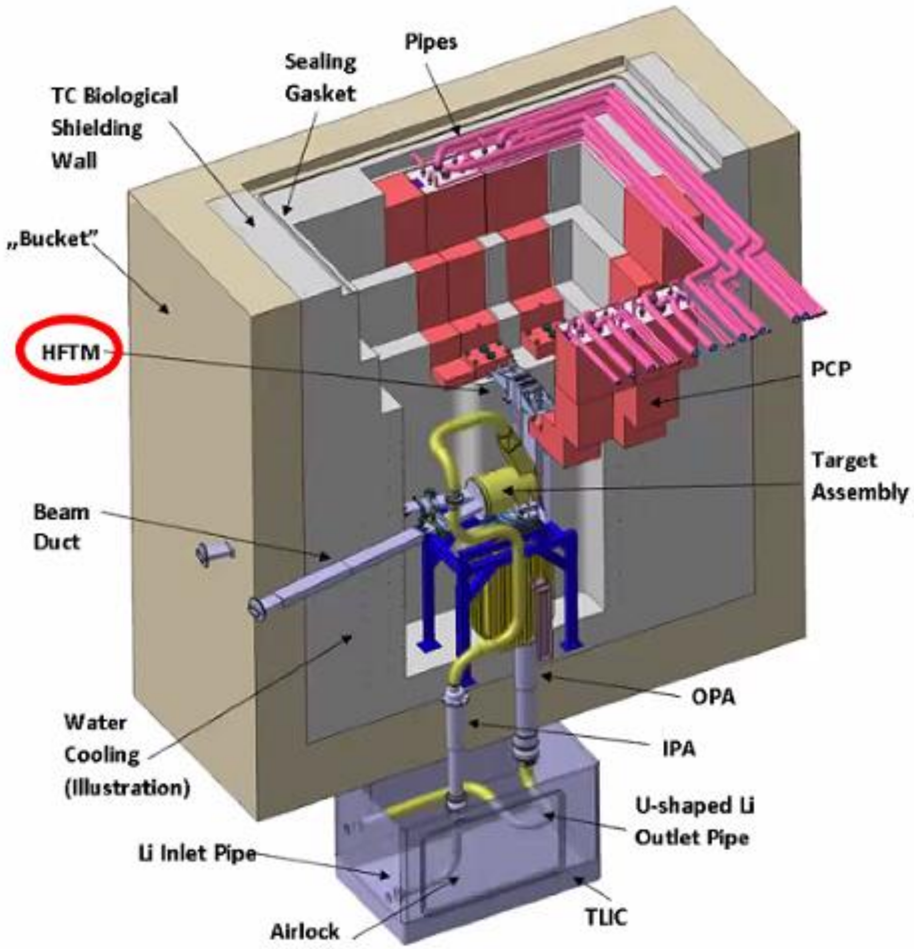
- **Lithium temperature at 250 °C.**
- **10 m^3.**
- **Flow speed at 15 m/s.**
- **Stable flow with ± 1 mm (25 days)**
- **Impurities < 10 ppm.**
- **Life time under irradiation?**

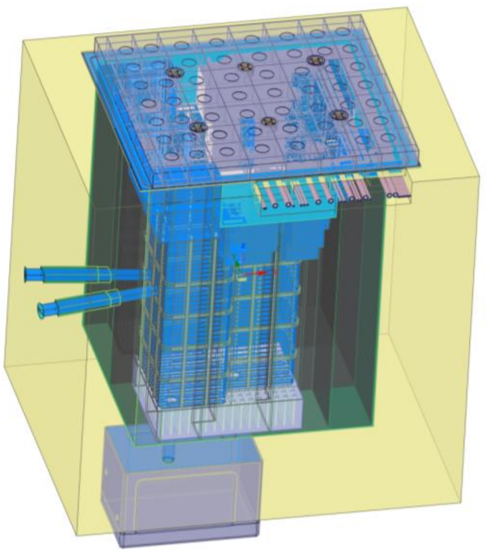
Test Facility: bunker, test cell, remote handly



- Housing Li(d,xn) reactions.
- Disassembling and assembling the test module including insertion and extraction of specimens.
- Replacement of target assembly.
- Transportation of specimens

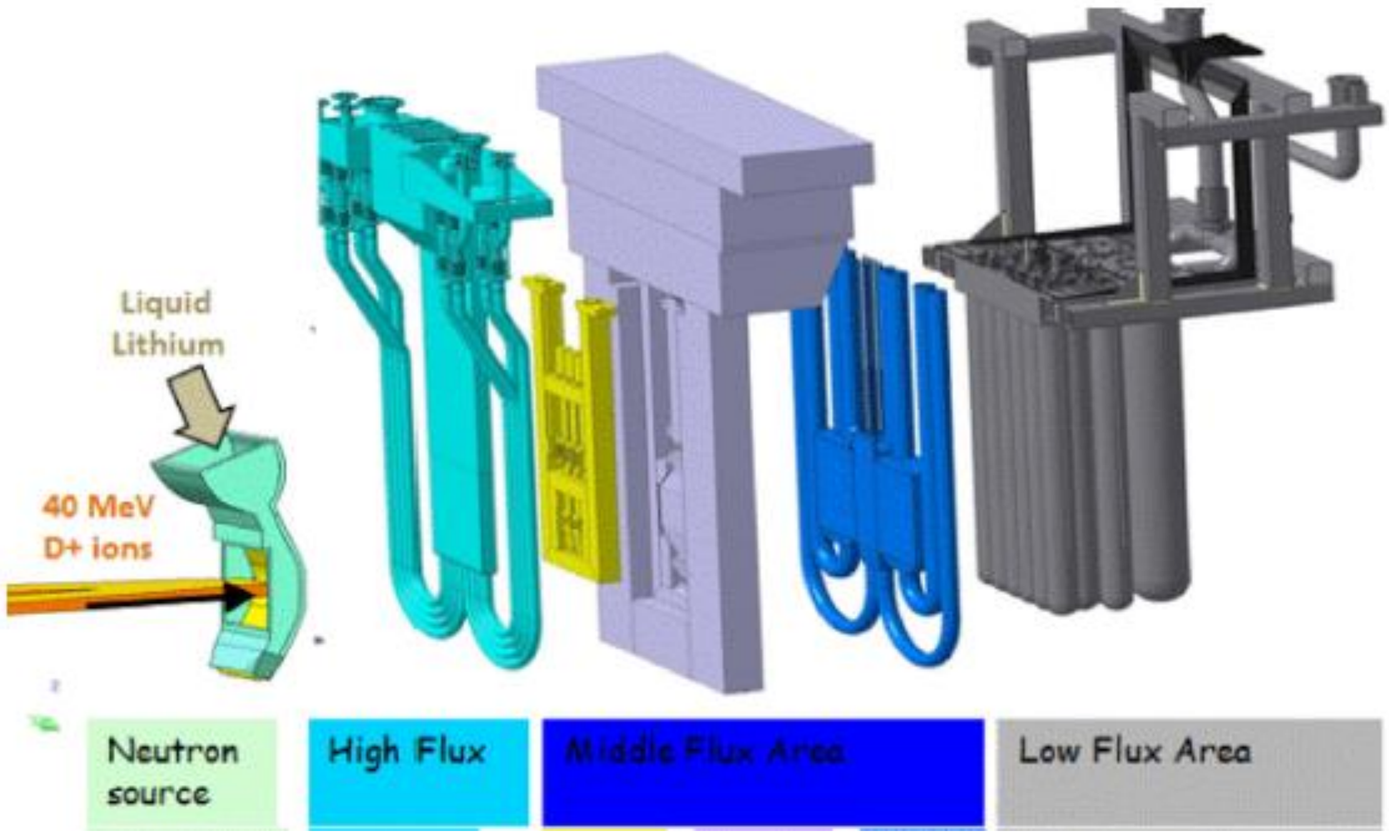
Test Module: bunker and test cell



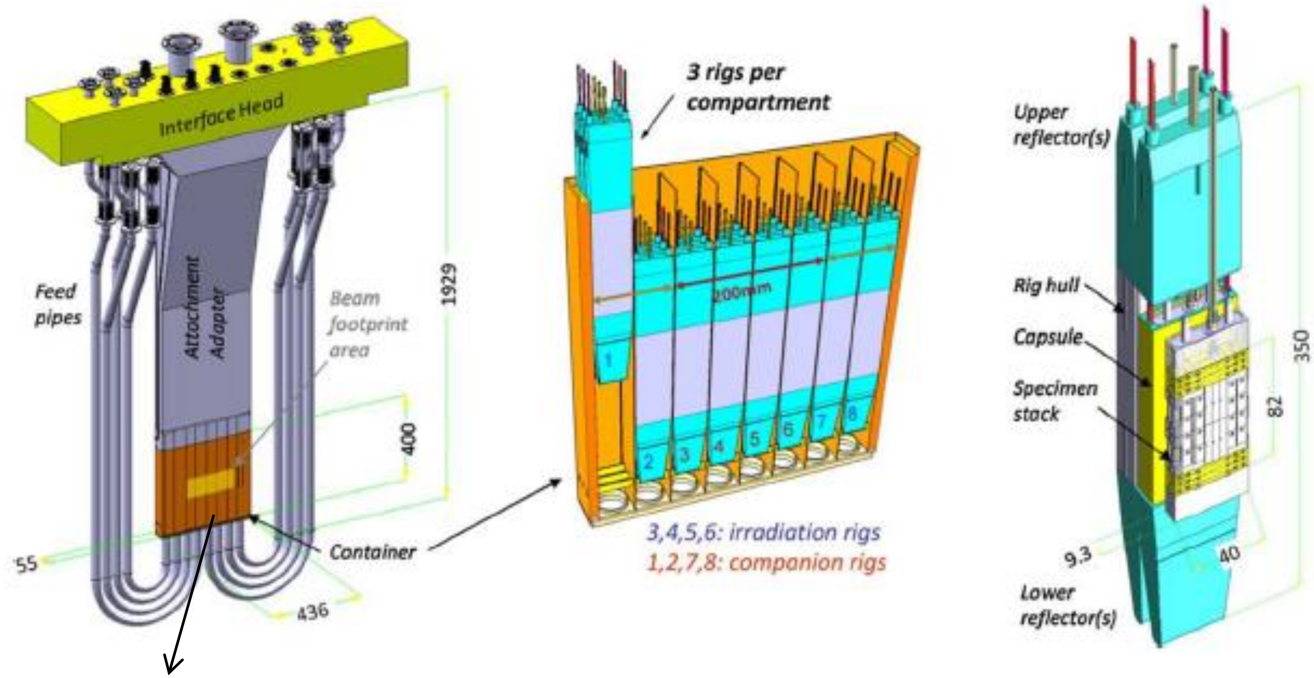


- **$6x6x12\ m^3$.**

- **Three irradiation modules: High, Medium and Low Flux**

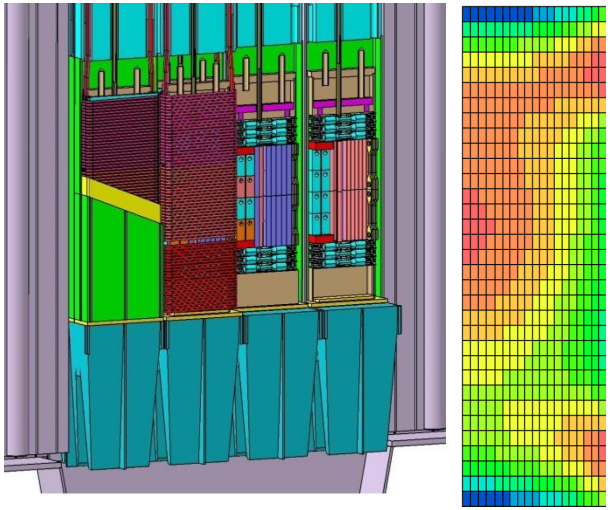


High Flux Test Module



200 mm x 50 mm beam cross-section

Temperature distribution of specimen volume

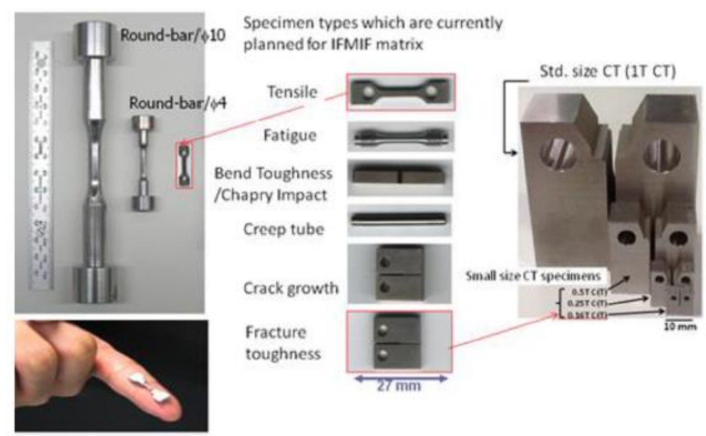


High Flux Test Module: status in Germany

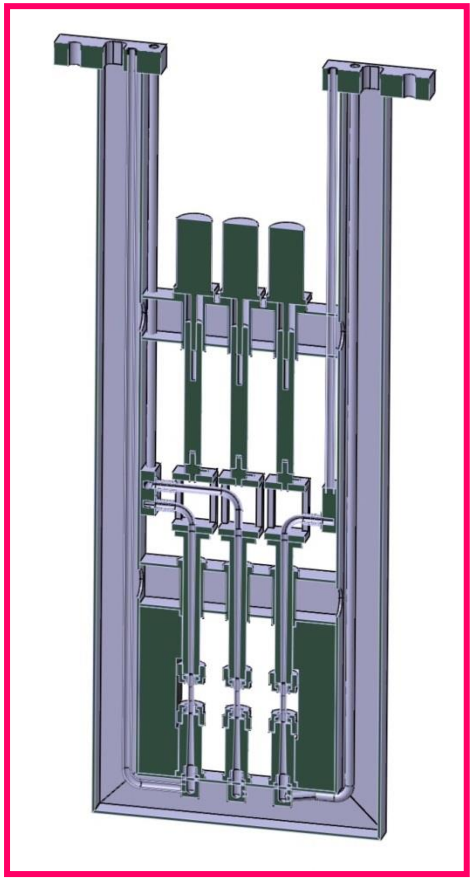
Tested in HELOKA, low pressure He loop test facility.

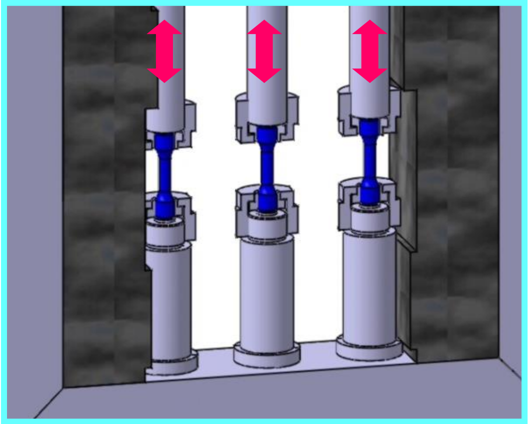
±3% temperature uniformity

Specimens to be irradiated



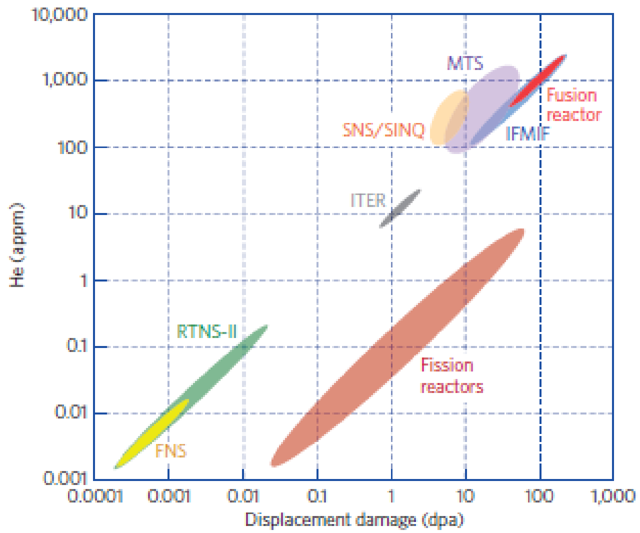
Medium Flux Test Module





IFMIF-DONES: comparison with others facilities

NATURE PHYSICS DOI: 10.1038/NPHYS3735



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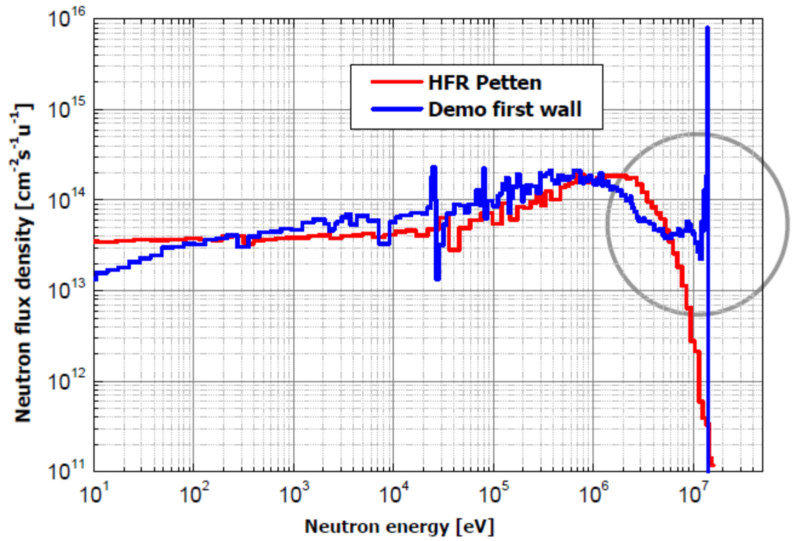
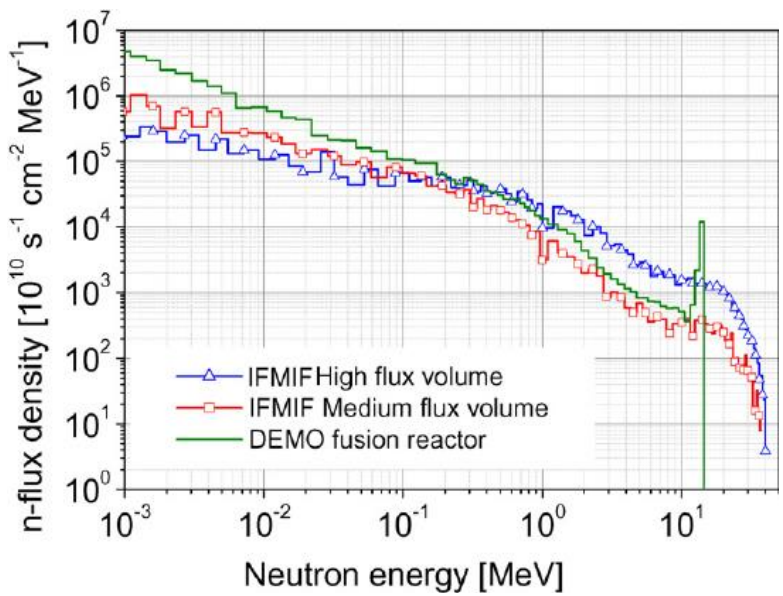




UNIVERSIDAD DE GRANADA

IFMIF DONES GRANADA

NEAR at n_TOF

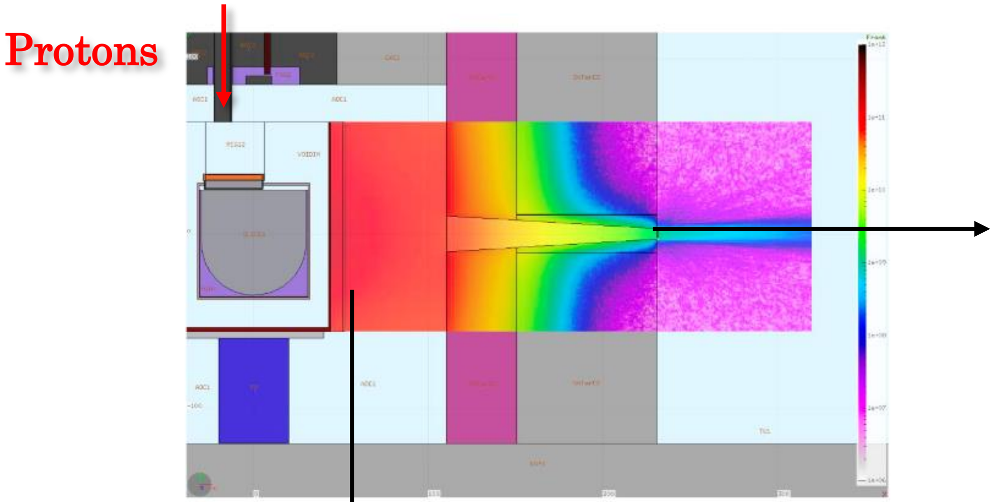
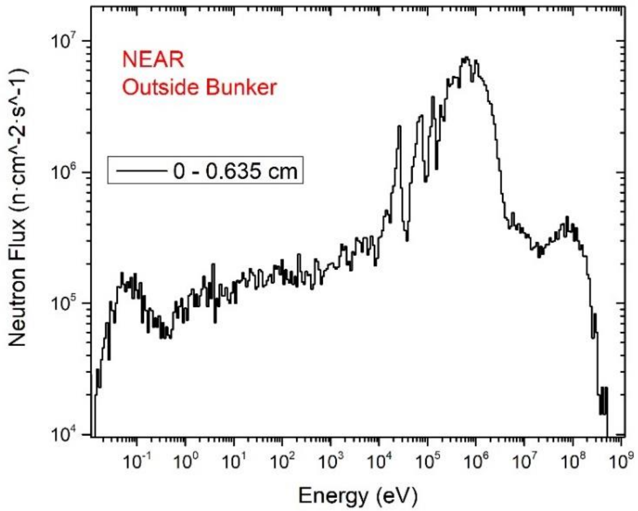
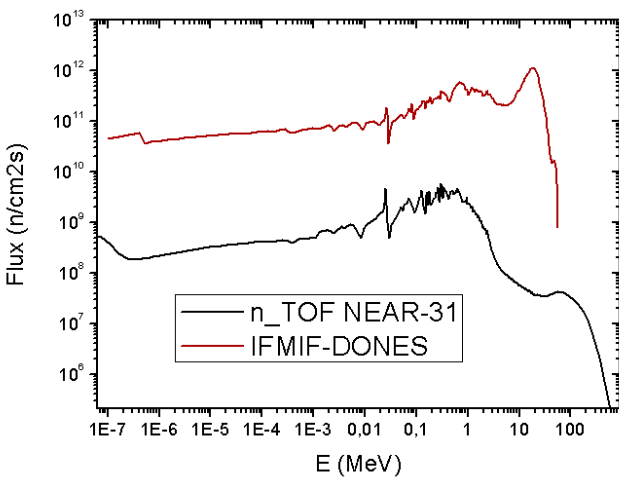
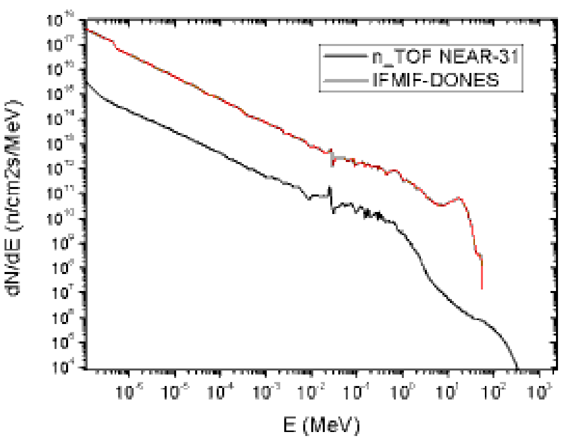


Figure 12. The figure shows a transversal cross section of the n_TOF Target pit and a potential configuration of the modified target shielding, showing the neutron fluence in units of n/cm²/pulse, averaged along the center of the external cone aperture.







NEAR:

8 months with a total dose of 1-1.5 MGy in 1cm^3.

Complementary Physics Program

Several applications can be foreseen for IFMIF-DONES.

- Neutron scattering, Si-doped, neutron time-of-flight facility, studies on electronics devices (SEE…), material science for other applications, astrophysics, production of radioisotopes for fundamental physics and for medicine, boron neutron capture therapy, ISOL facility, explosive detection…

The Henryk Niewodniczański
INSTITUTE OF NUCLEAR PHYSICS
Polish Academy of Sciences
ul. Radzikowskiego 152, 31-342 Kraków, Poland

www.ifj.edu.pl/publ/reports/2016/

Kraków, November 2016

Report No. 2094/PL

White Book
on the Complementary Scientific Programme
at IFMIF-DONES

A. Maj, M.N. Harakeh, M. Lewitowicz,
A. Ibarra, W. Królas

Table of contents

However, the applications to be developed at DONES should be unique and with low impact in the main purpose of the facility:

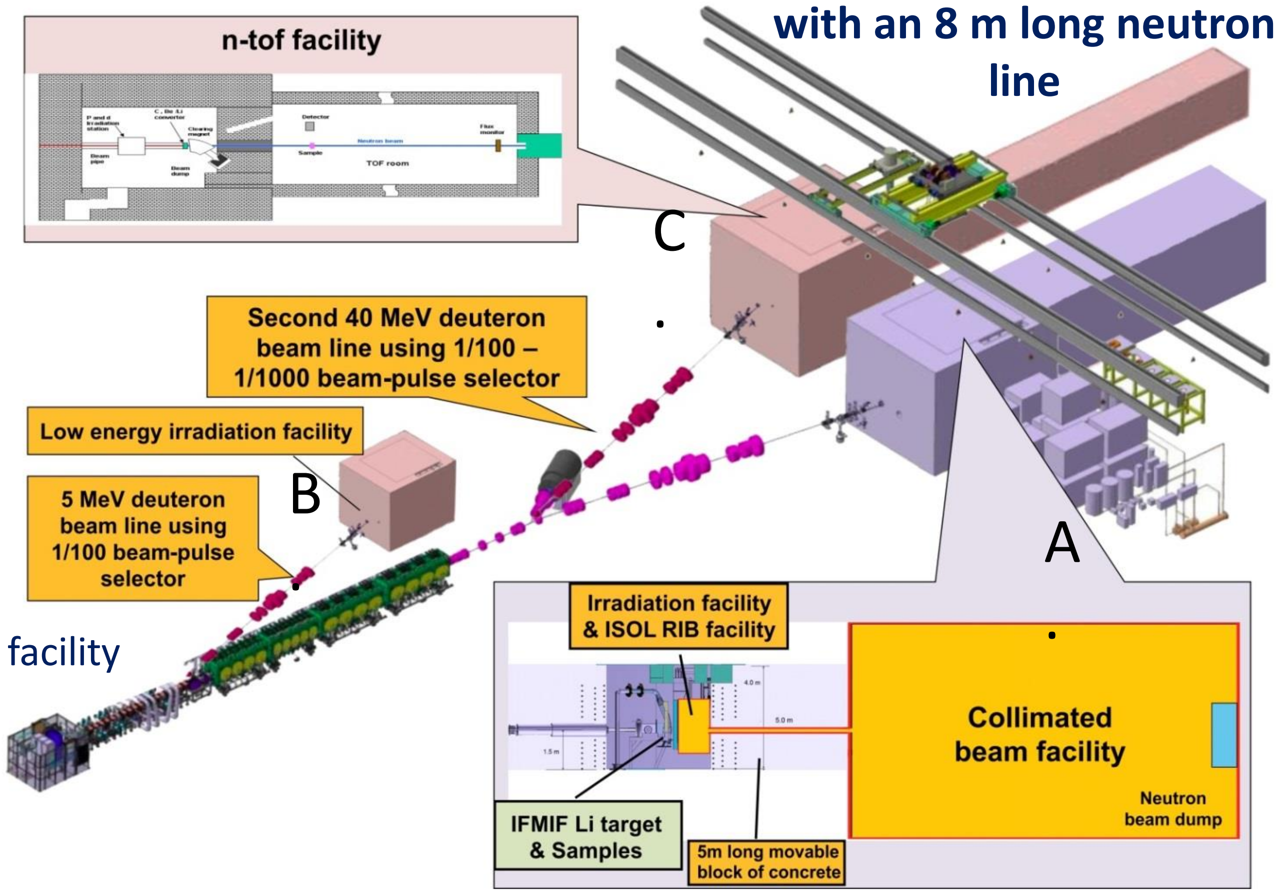
Materials for fusion reactors.

Complementary Physics Program (2016)

White Book
on the
Complementary Scientific Programme
at IFMIF-DONES

Kraków, November 2016

A. Irradiation facility and ISOL RIB facility behind the HFTM;
Collimated beam facility with an 8 m long neutron line

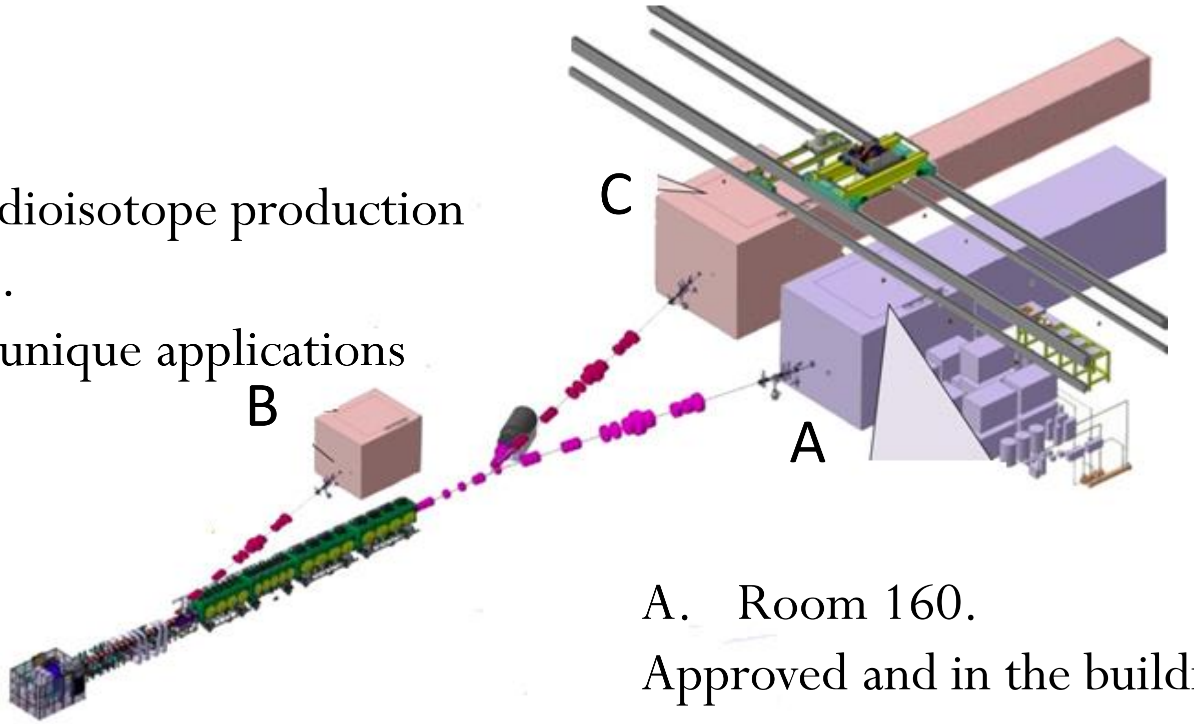


B. A 5 MeV deuteron beam line using 1/100 beam-pulse selector to a low-energy irradiation facility

Complementary Physics Program (UGR)

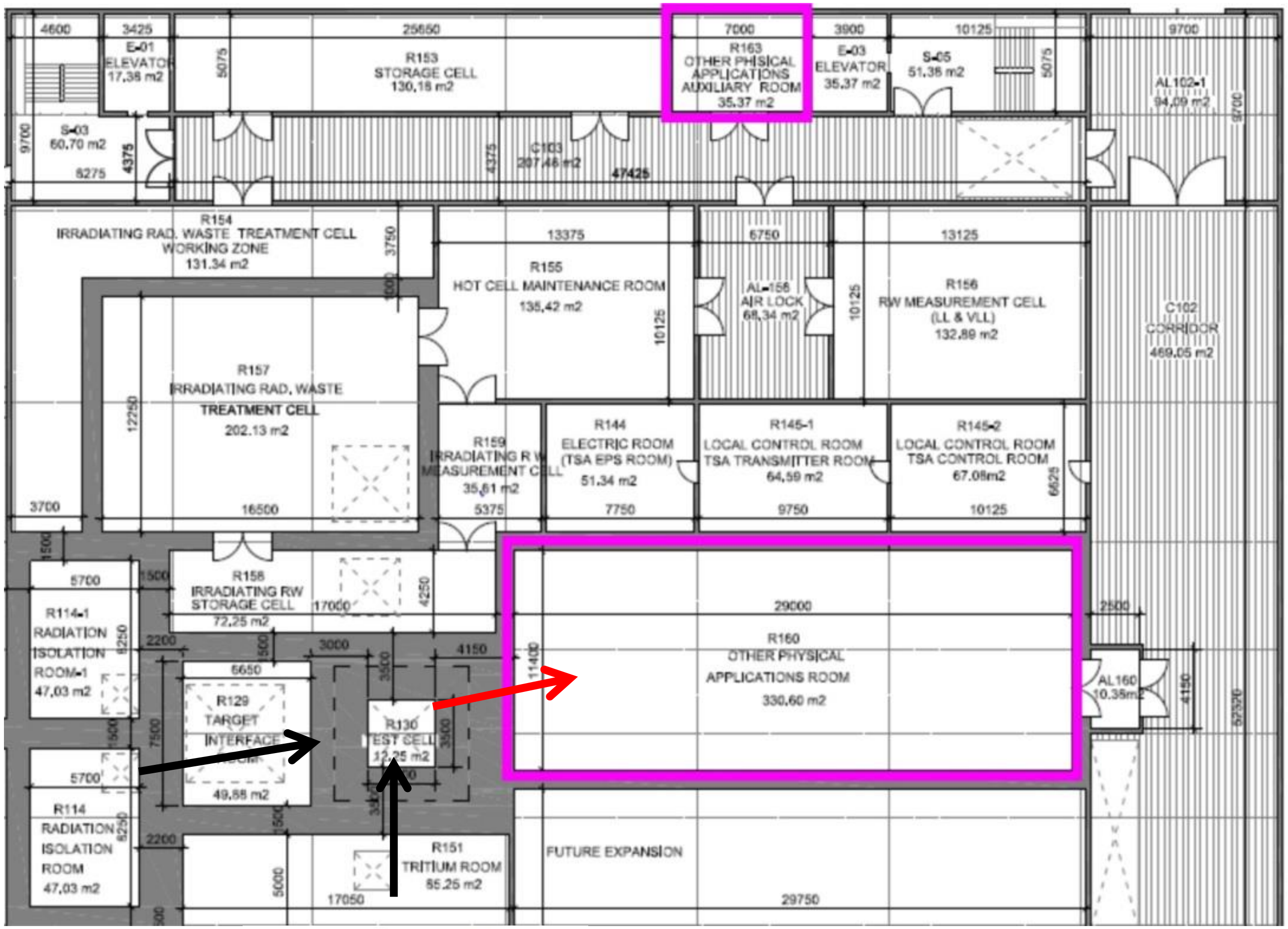
C. Radioisotope production with deuterons, ^{177}Lu.
To deflect 1/100 beam or for a certain time.
To be found unique applications

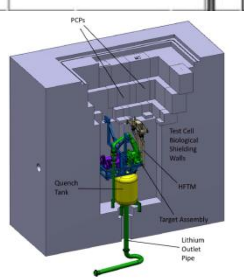
B. BNCT, radioisotope production for medicine.
To be found unique applications



A. Room 160.
Approved and in the building design.

Complementary Physics Program (UGR): Hall A





Hall A is approved:

- **Neutron scattering.**
- **Radioisotope production for diagnosis and therapy.**
- **Doped of semiconductors.**
- **Single Event Effects in electronics devices.**
- **Neutron imaging.**

Complementary Experimental Area

Room **R160**

Dimensions

29.00 m x 11.40 m,

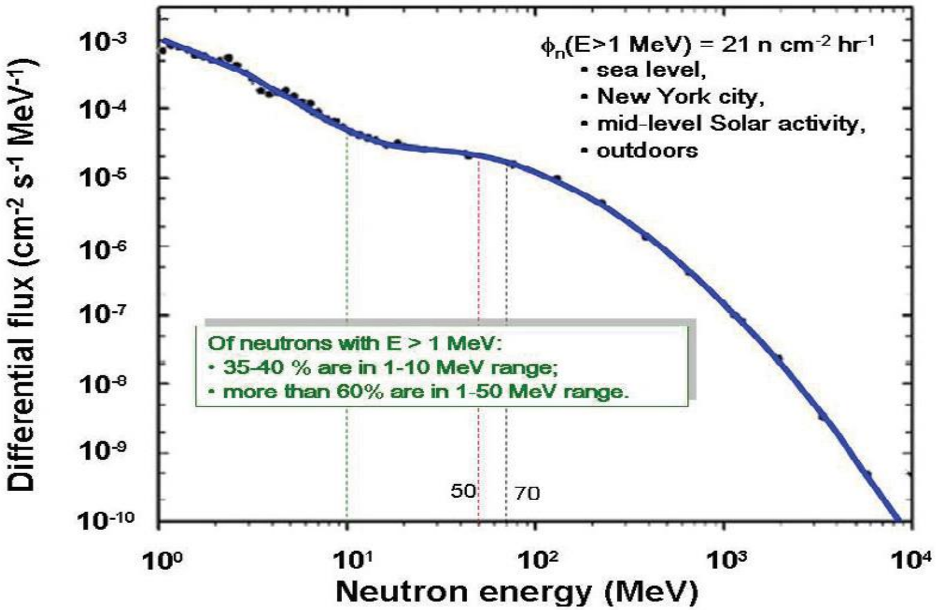
height 8.00 m, 330.60 m^2

Auxiliary Room **R163**

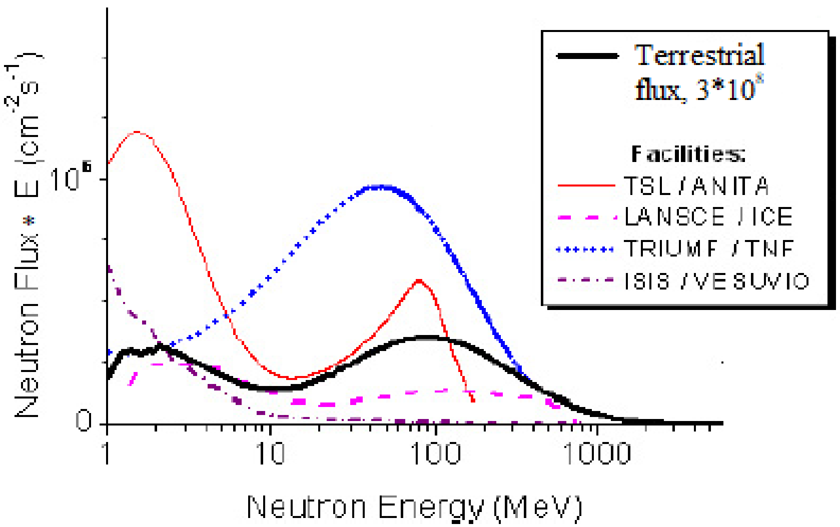
7.00 m x 5.07 m, 35.37 m^2

POSSIBLE EXPANSION

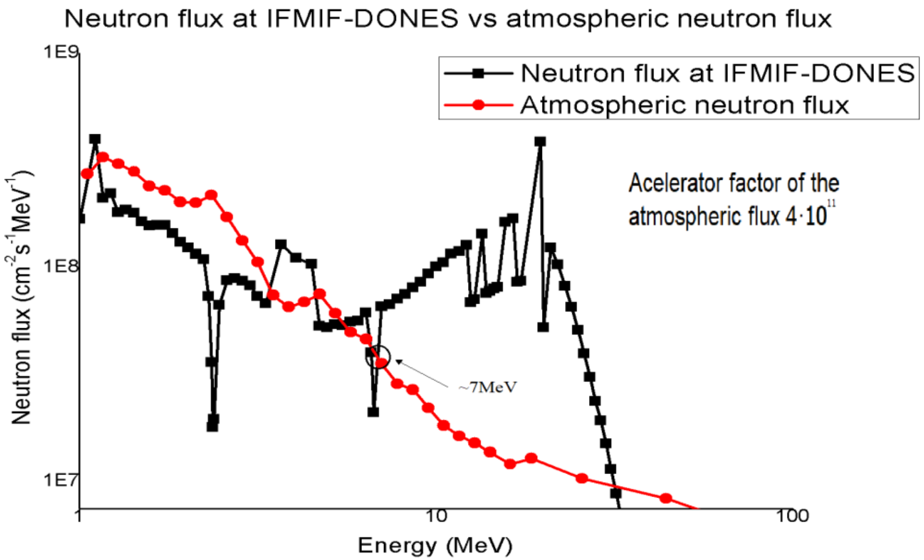
Hall A: irradiation of electronic devices

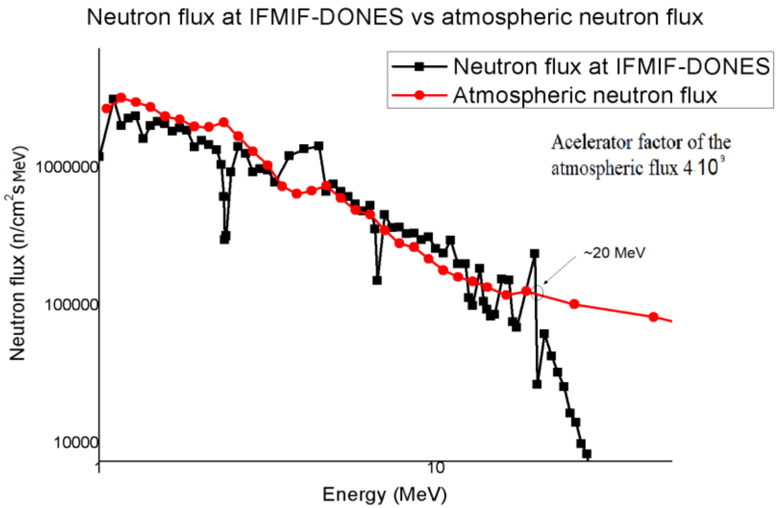


Atmosfheric neutron FLUX



Hall A: irradiation of electronic devices





Hall A: irradiation of electronic devices

DONES will follow the JEDEC STANDARD

A calibration for beam energy and flux shall be run prior to the first test and at the end of the last test.

It is necessary that the flux variation is less than 10% during the experiment.

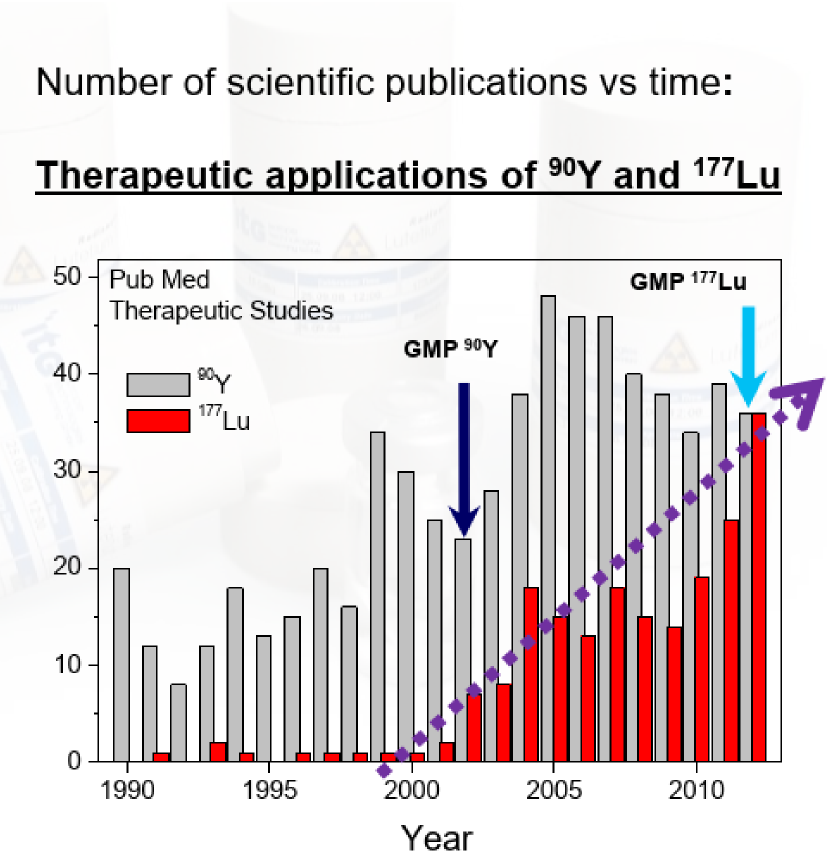
Soft Error Rate test linearity: It is necessary to also run at a lower flux (e.g., 1/10 normal flux) to check for a linear Soft Error Rate flux dependence.

The beam flux is many orders of magnitude higher than the flux at use conditions, i.e., at ground level; Thus the lower flux measurements would be the most useful.

1) Test readiness check for 'golden' part.
2) Beam and setup check for 'golden' part.
3) Collect data for 'golden' part to verify appropriate flux density.
4) Test readiness check for device under test.
5) Collect data on device under test.
6) Final test for device under test.
7) Repeat steps 4-6 for additional parts.

Hall C: apps to be found! ^{177}Lu

- Theragnostic = diagnosis and therapy.
- Versatile radioisotope and one the most important emergent radioisotopes.
- Good good success in gastroentero-pancreatic neuroendocrine tumours [11].
- Currently, Lu177 is under study for several other tumours with good results [12].
- At present, it is produced in nuclear reactors.
- Rising demand radioisotope.



At present, Lu177 is only produced in nuclear reactors.
Last month a demand problem with the Mo99 in the Spanish hospitals.

^{177}Lu production routes at present

"Carrier Added"

^{176}Lu(n,γ) → ^{177}Lu + ^{177m}Lu

Higher production. Lower specific activity.

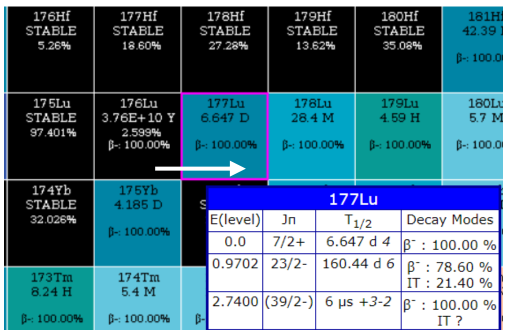
^{177m}Lu is produced (0.05%), 160 days.

"Non Carrier Added"

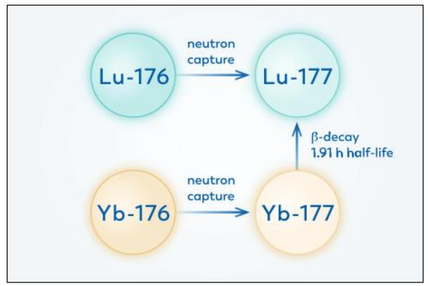
^{176}Yb(n,γ)^{177}Yb (→ ^{177}Lu)

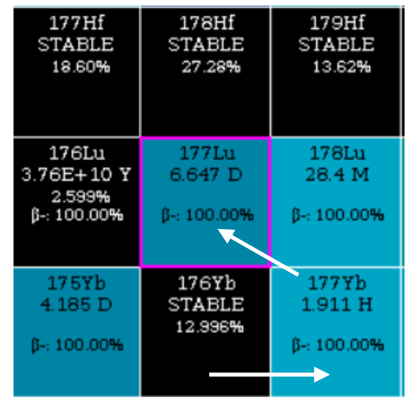
Lower production. Higher specific activity.

^{177m}Lu is negligible (<0.0001%)

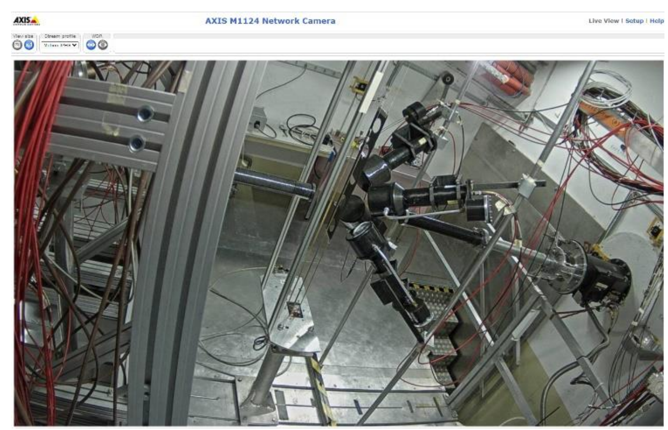


E(level)	Jπ	$T_{1/2}$	Decay Modes
0.0	7/2+	6.647 d 4	β^- : 100.00 %
0.9702	23/2-	160.44 d 6	β^- : 78.60 % IT : 21.40 %
2.7400	(39/2-)	6 μs +3-2	β^- : 100.00 % IT ?



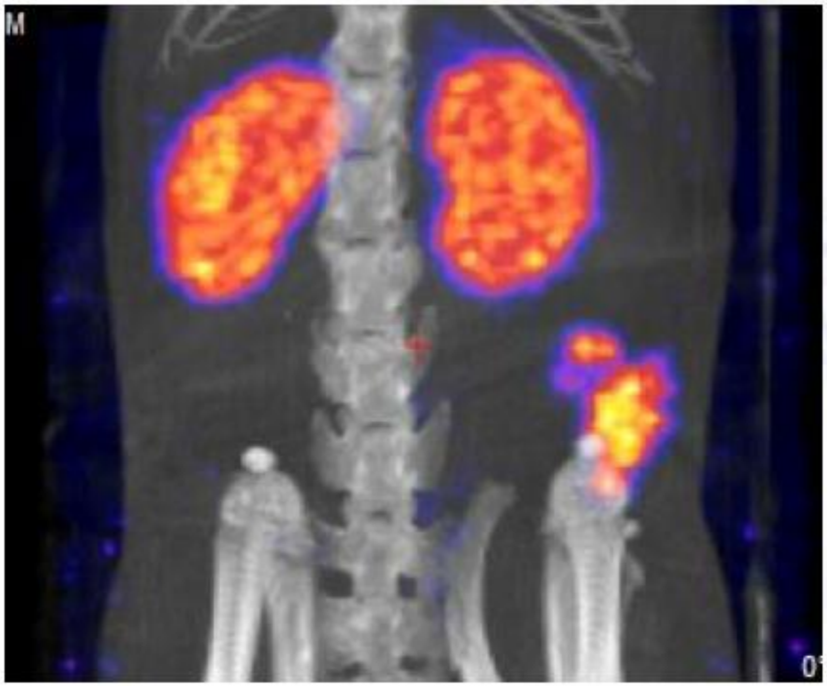


We have performed an experiment in Oct-Nov 2021 at n_TOF EAR1.
Production in DONES.
CERN PhD Francisco Garcia Infantes



Specific activity: impact on tumor uptake

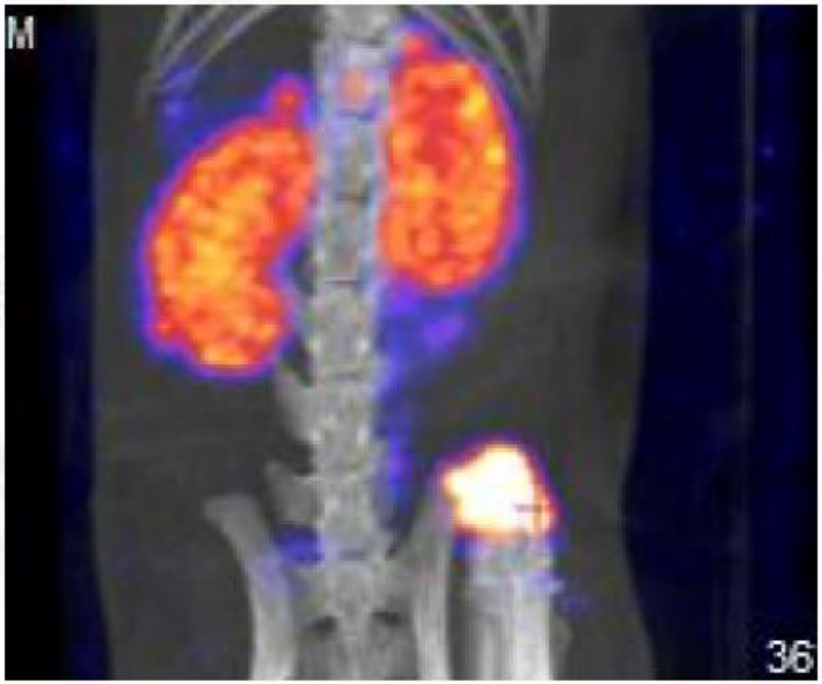
"Carrier Added"



300 MBq of ^{177}Lu c.a.

Dose to tumor - 35 Gy

"Non Carrier Added"

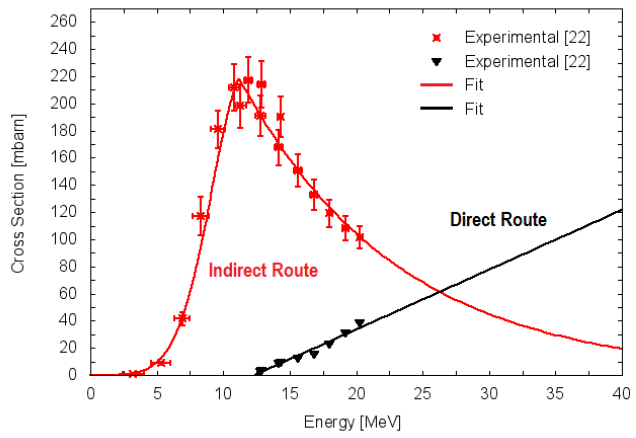


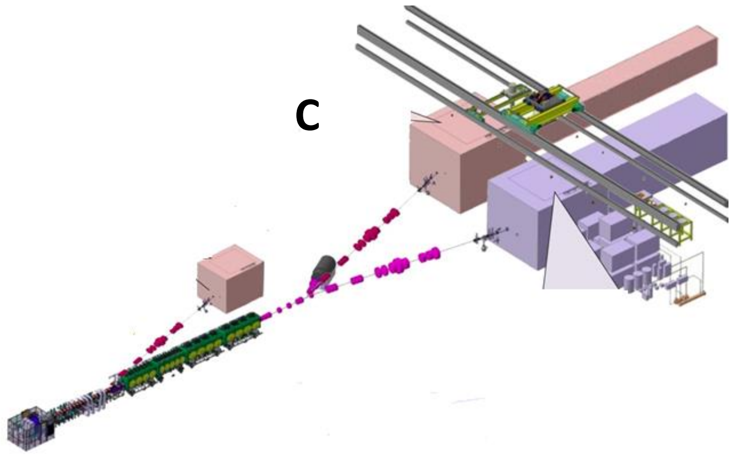
300 MBq of ^{177}Lu n.c.a.

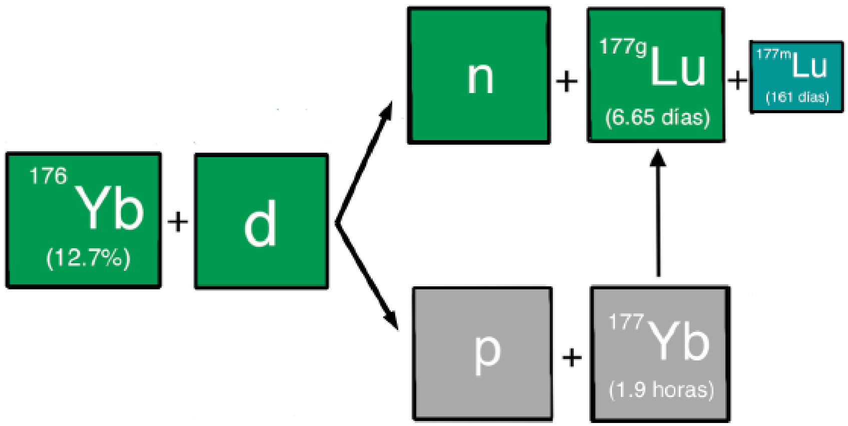
Dose to tumor - 70 Gy

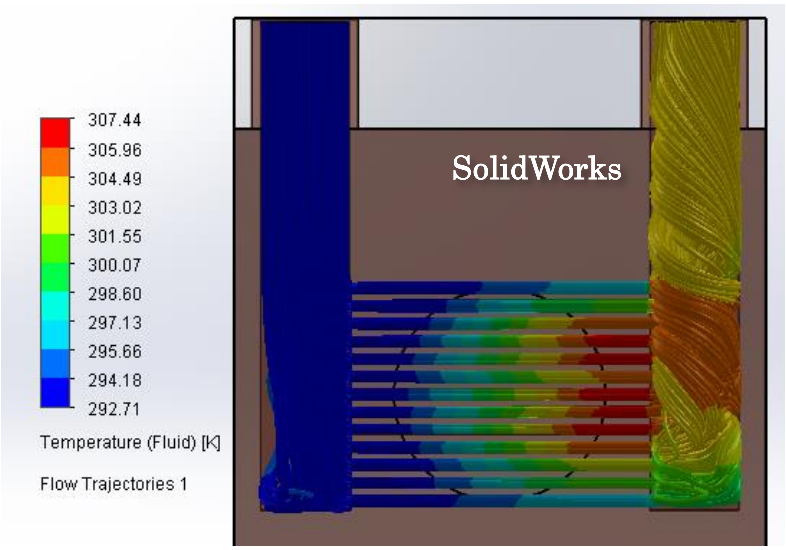
Marion de Jong et al.; 2012 ICTR-PHE

^{177}Lu production with deuterons?

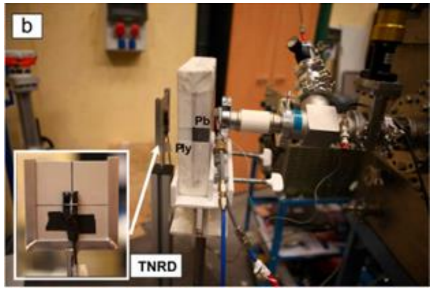




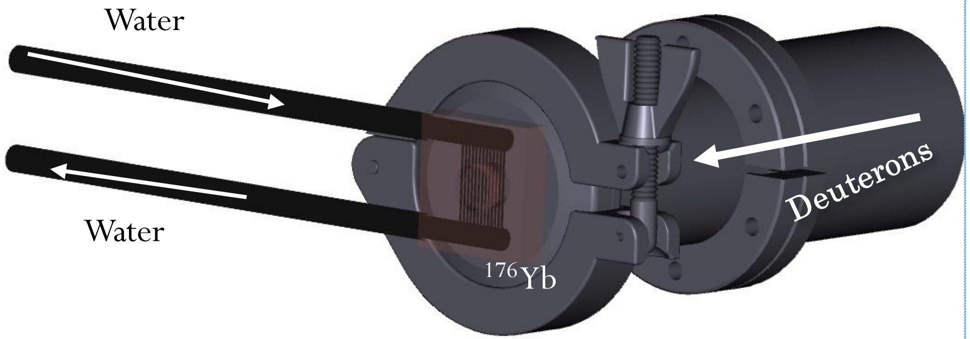


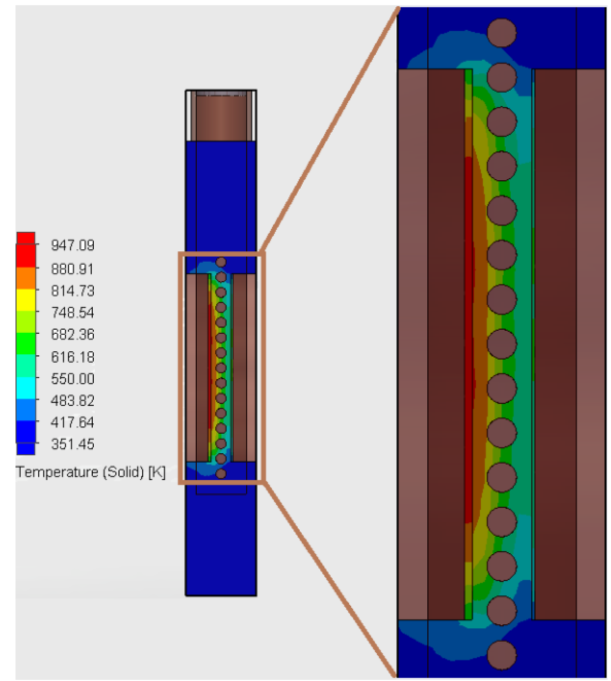


^{177}Lu production: justification for Hall C.



An existing device have been simulated





Reaction	Irradiation time (d)	Activity (GBq)	Specific Activity (GBq/mg)
^{176}Lu(n,γ)$^{177(g+m)}$Lu	8	251	738
^{176}Yb(n,γ)^{177}Yb→^{177}Lu	7	590	1.11
^{176}Yb(d,n)+^{176}Yb(d,p)	7	(1st notch)	
		373	0.52
		(2nd notch)	
		342	0.99

Our results show that the production in DONES would be greater than in nuclear reactors

Summary

- DONES facility is expected to start in around 2028.
- DONES is necessary for fusion material and for the design of DEMO.
- Unique applications without interfering the main purpose of the facility if possible.
- Applications to society as medicine with low impact in the design could be possible.
- A room for other applications has been approved and the design of the collimator and beam shutter is ongoing.

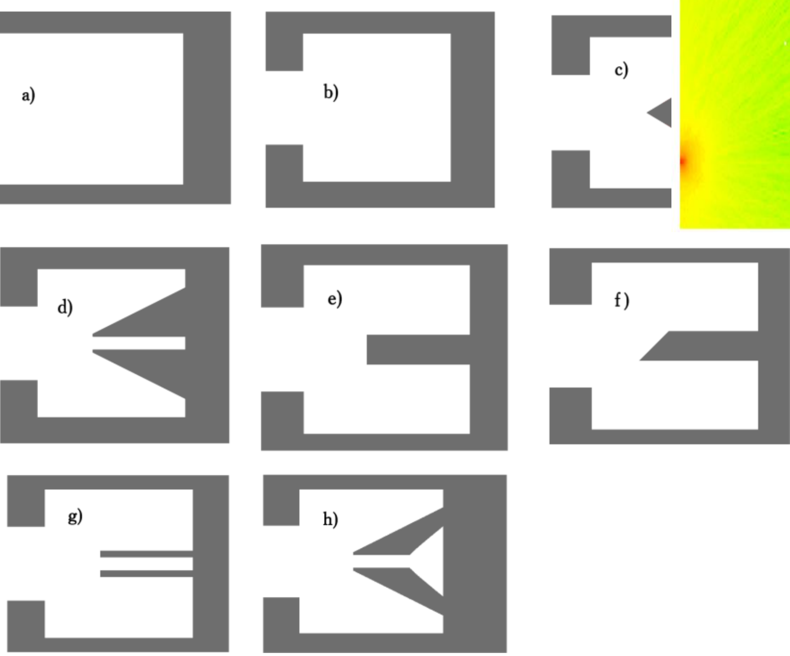
Thank you!

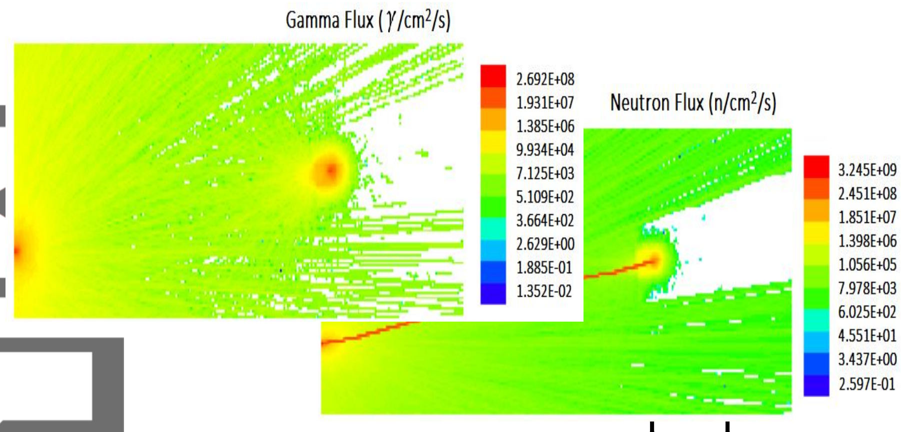
Javier Praena

Complementary Physics Program

Several applications can be foreseen for IFMIF-DONES.

- Neutron scattering, Si-doped, time-of-flight facility, studies on electronics devices (SEE…), material science for other applications, astrophysics, production of radioisotopes for fundamental physics and for medicine, boron neutron capture therapy…

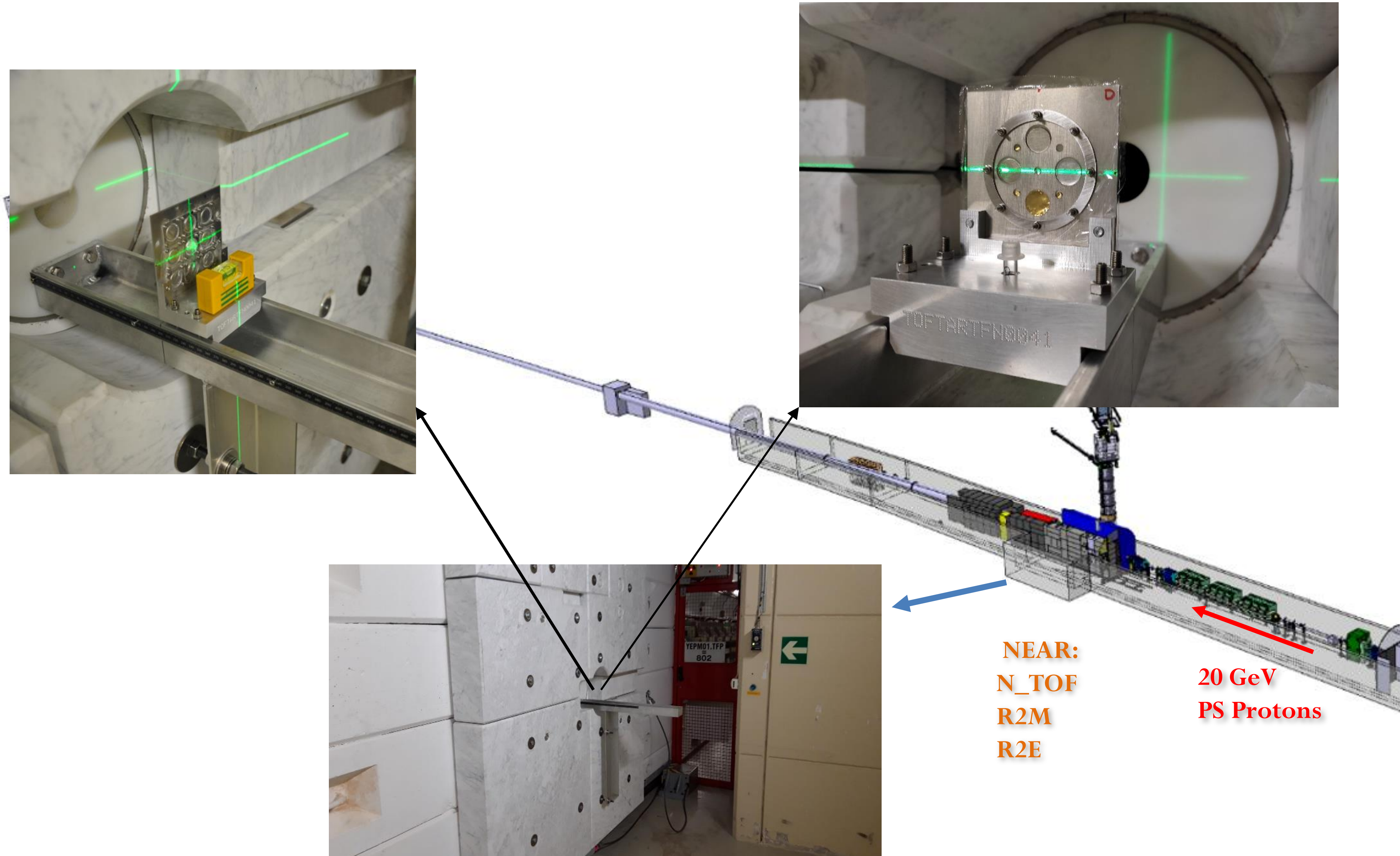




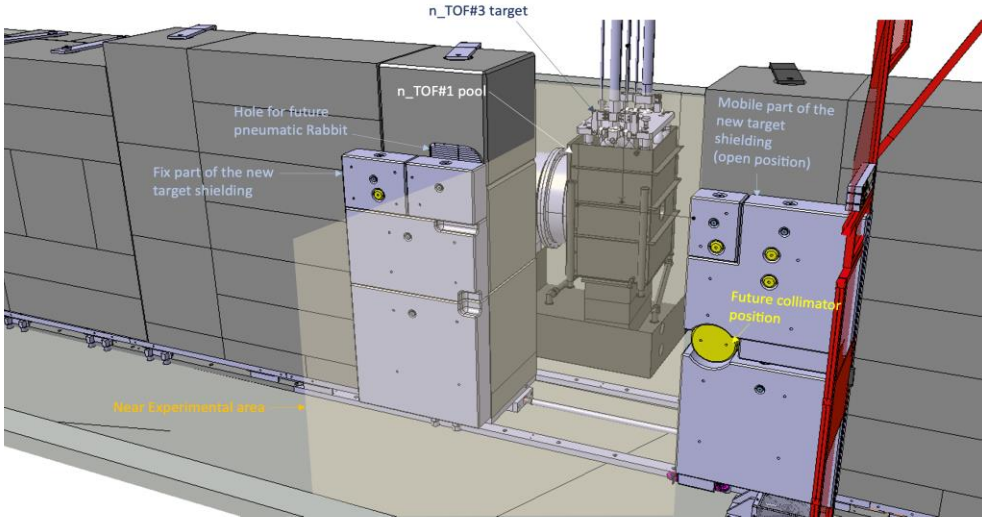
ions to be
should be
mpact in
he facility.

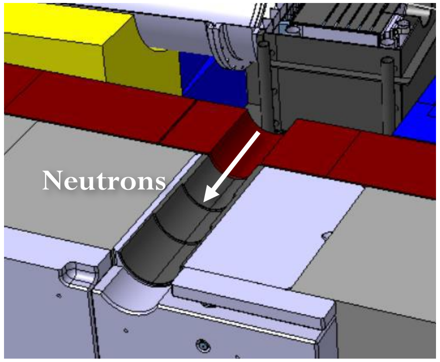
Material for fusion reactors.

NEAR: measurement of the neutron flux outside bunker

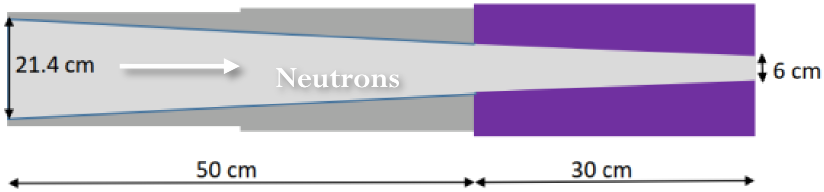


NEAR: outside the bunker.





A collimator based on Fe, borated polyethylene and polyethylene



Linac Modules

Table 4.3.7: SRF Linac System requirements

Requirement	Target value	Comment
Type	Half-Wave Resonators	Superconducting (LHe cooled)
Operating frequency	175 MHz	
Beam A/q	2	
Input energy / Output energy	5 / 40 MeV	
Input beam current	125 mA	
Beam loss	<10 W	<1W/m
Operating Temperature	4.5 K	

Table 4.3.8: Distribution of cavities and solenoid packages in the present reference design

Cryomodules	#1	#2	#3	#4
Number of cavities	1 × 8	2 × 5	3 × 4	3 × 4
Number of solenoid packages	1 × 8	1 × 5	1 × 4	1 × 4
Cryostat length (m)	5.44	5.30	6.50	6.50
Output energy (MeV)	9	14.5	26	40

Table 4.3.9: SRF Linac Cryomodule requirements

Beam Dump

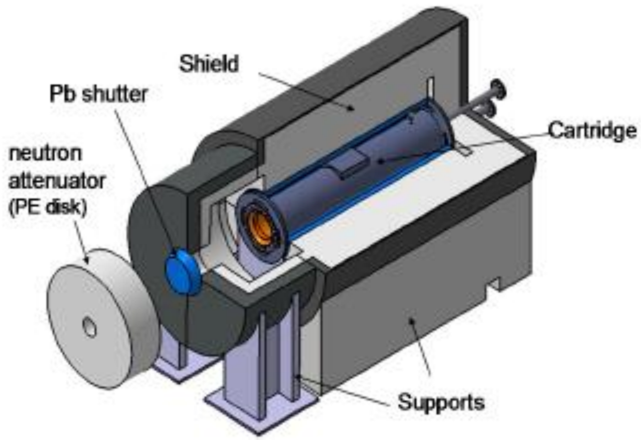


Figure 4.3.11: The DONES Beam Dump

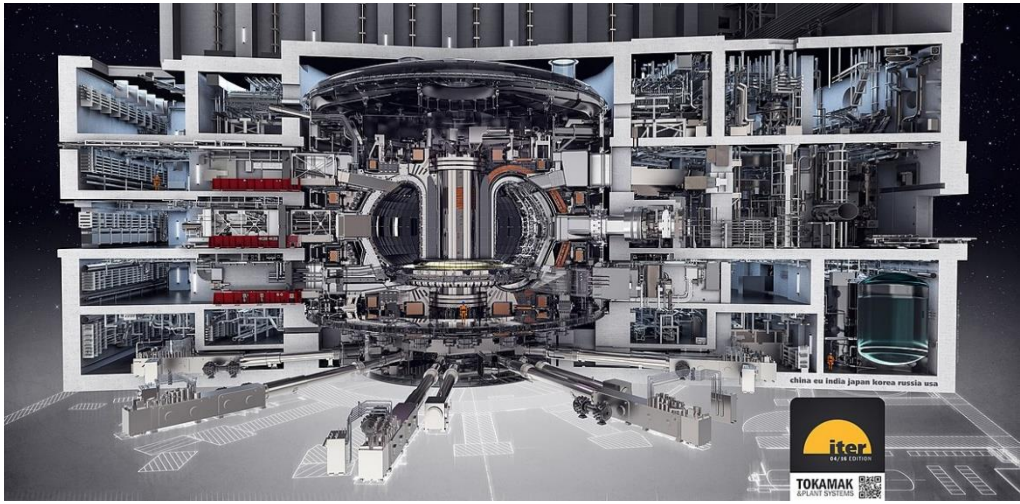
The Beam Dump consists basically of a cartridge, which stops the beam, and a local shielding to attenuate the resulting radiation. The Beam Dump cartridge is composed of three main pieces: the internal cone, the flow shroud and the cylinder. The water coolant flows at high velocity through an annular channel between the internal cone and the flow shroud and returns through the space between the flow shroud and the stainless steel cylindrical casing. The internal cone is the piece that stops the ion beam. A chamfer located at the entrance is absorbing the power deposited by the beam halo.

As a consequence of the radioactivation of the copper cone (mainly Zn65 ($t_{1/2}$: 244 d), Co58 ($t_{1/2}$: 71 d) and Cu64 ($t_{1/2}$: 12.7 h)) by the 40 MeV deuterons, a lead shutter is inserted to the beam tube when the Beam Dump is not operating to reduce the dose rates in the vicinity (mainly due to γ-radiation).

ROADMAP to DEMO

ITER

International Thermonuclear Experimental Reactor



Neutron source requirements

to produce **fusion-like neutrons**

- Intensity large enough to allow accelerated (as compared to DEMO) testing,

> 10 dpa(Fe)/fpy

- Damage level above the expected operational lifetime,

20 dpa(Fe) in 1.5 y/50 dpa(Fe) in 3.5 y

- irradiation volume large enough to allow the characterization of the macroscopic properties of the materials of interest required for the engineering design of DEMO (and the Power Plant)

300 cm3

- **Irradiation conditions (neutron flux, temperature) to be homogeneous for standarised specimens:** Over a gauge volume flux gradient <10% and temperature gradient within ±3% with the long time stability in the same order must be satisfied

T: 250-550ºC

2014 EU Roadmap scenarios

The 2014 EU Roadmap to a Fusion Power Plant In EU (presently under review) is based on a scenario with an early construction of DEMO. That means early selection of DEMO technologies and immediate specific needs for fusion materials database

MAG Report (2012)

DEMO will probably have two operational phases:

- **First one: focused on startup and feasibility evaluation (low availability): 20 dpa**
- **Second one: focused on availability increase: 50 dpa**

A neutron source is needed for materials qualification,

- **Short-term mission and requirements linked to DEMO needs**
- **Long-term mission and requirements linked to the Power Plant needs**

Critical materials to be irradiated for DEMO: Reference steels (as structural material), Cu alloys (as interface material between W and steel) and W (high dpa dose: as first-wall material and structural divertor material.

critical materials: those where a Design Code is needed for design and licensing

DONES overall framework

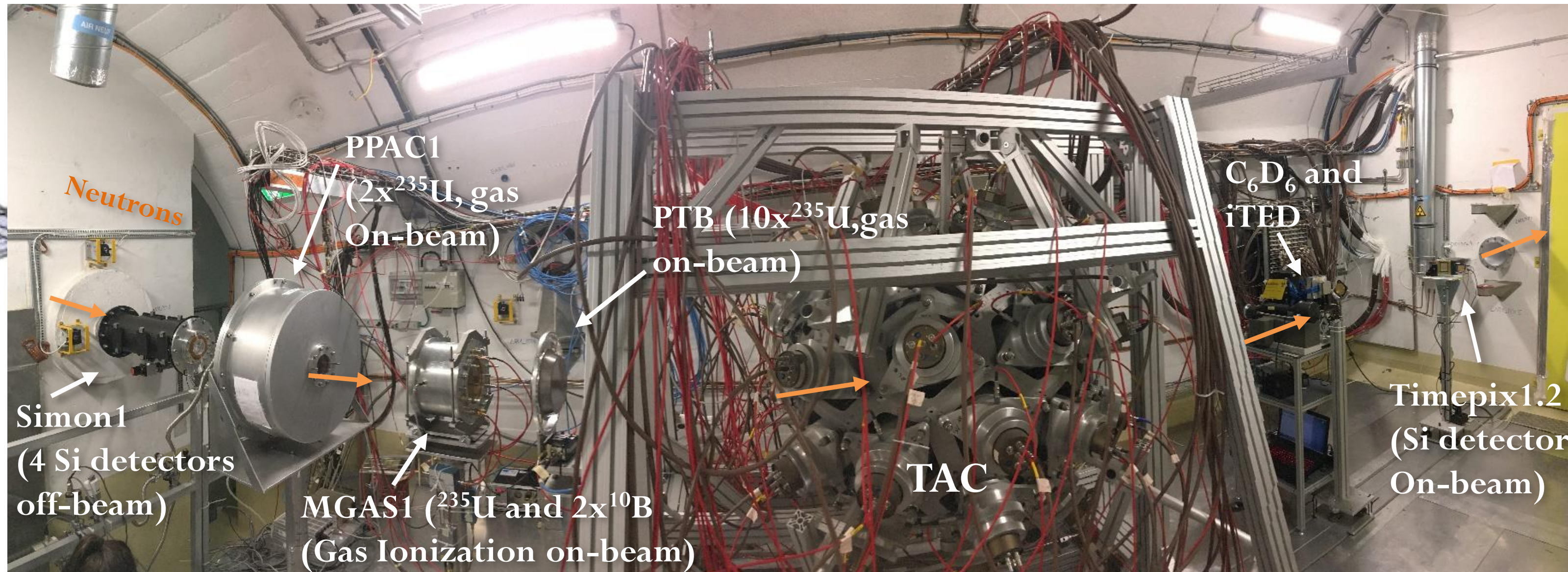
The need for a facility of this type was identified long time ago and work has been carried out by using different frameworks

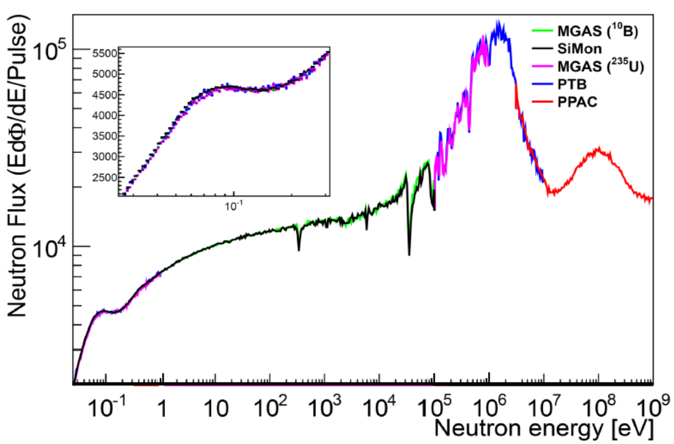
In the last 15 years, key projects are: IFMIF/EVEDA (included in the BA), WPENS –including specific Industry contract- (EUROfusion WP), DONES-PreP (EURATOM CSA), DONES-PRIME and DONES-UGR (Spanish funded projects), ….

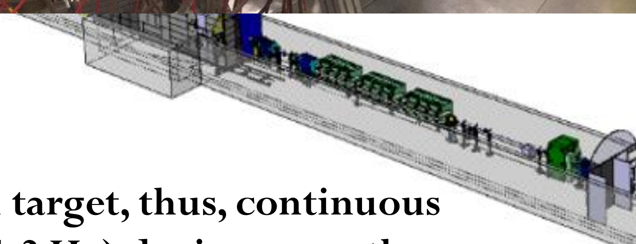
DONES-PRIME
DONES-UGR

Horizontal (185 m) Experimental Area (EAR1): setups.

EAR1
@ 185 m

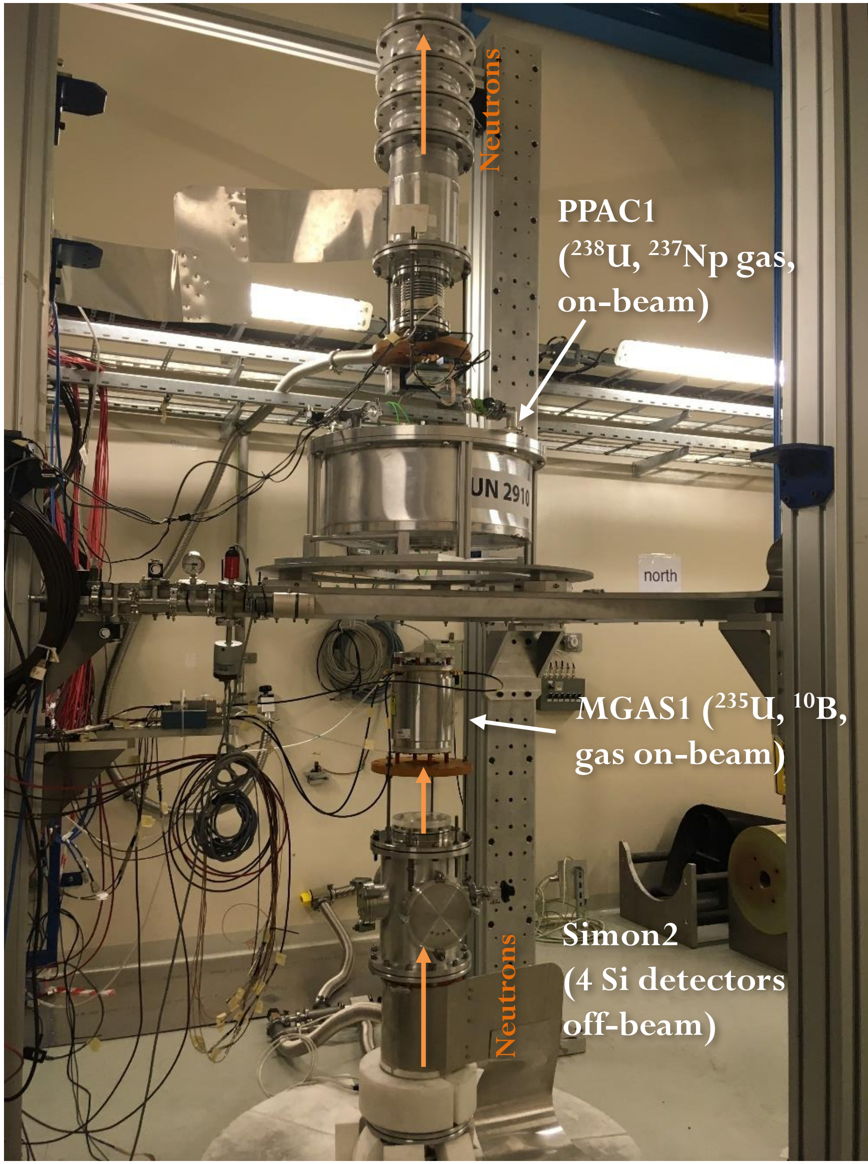




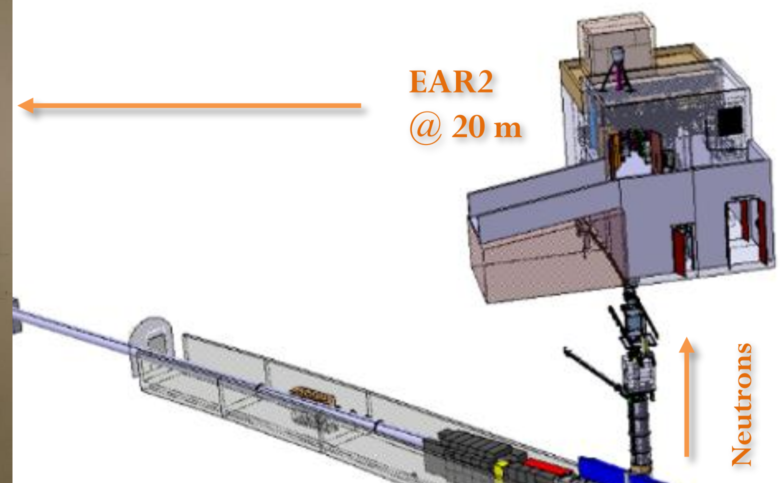


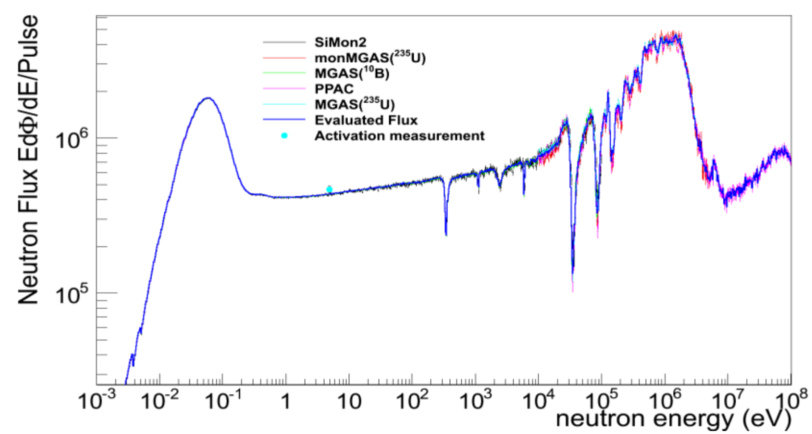
Continuous proton beam on target, thus, continuous neutron beam (pulsed, 6ns, 1.2 Hz) during more than 220 days per year.
Our expertise is to measure neutron induced cross-sections.

Vertical (20 m) Experimental Area (EAR2): setups.



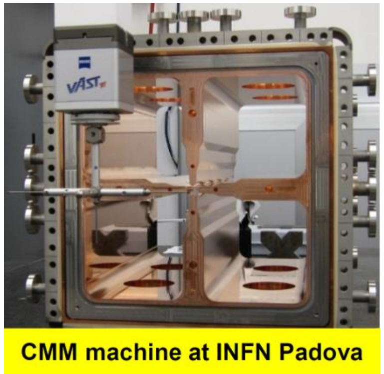
Neutron flux is 50-100 times higher than EAR1

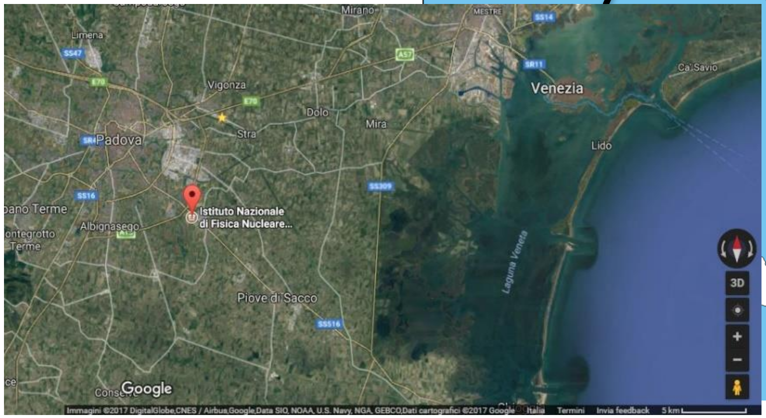




2006-2009 Laboratori Nazionali di Legnaro.

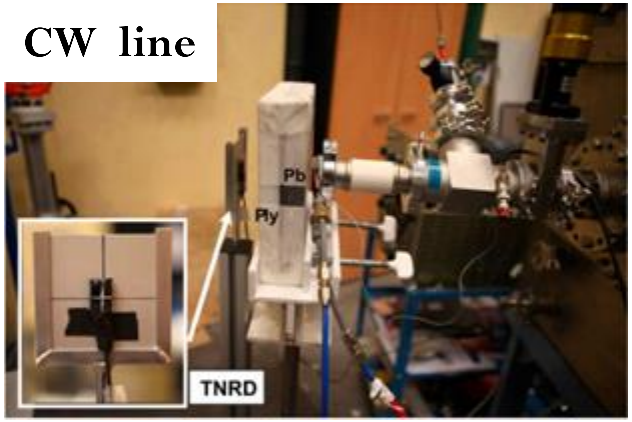
- Italy developed the RFQ the most important part of the IFMIF-DONES accelerator.
- The accelerator purpose is to generate **neutrons** by nuclear reactions.



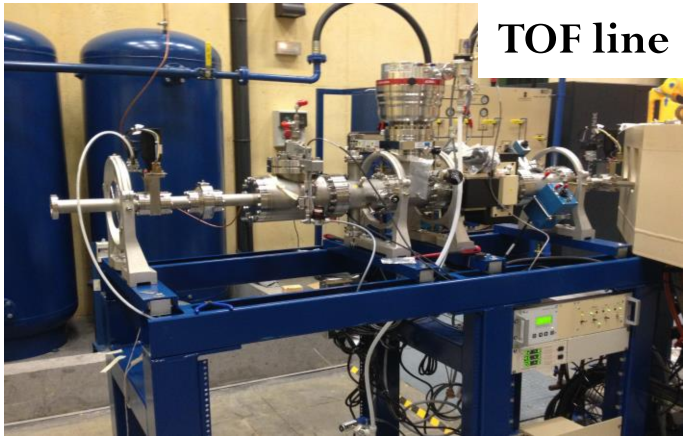


UGR neutron group: Spanish National Lab

CW line



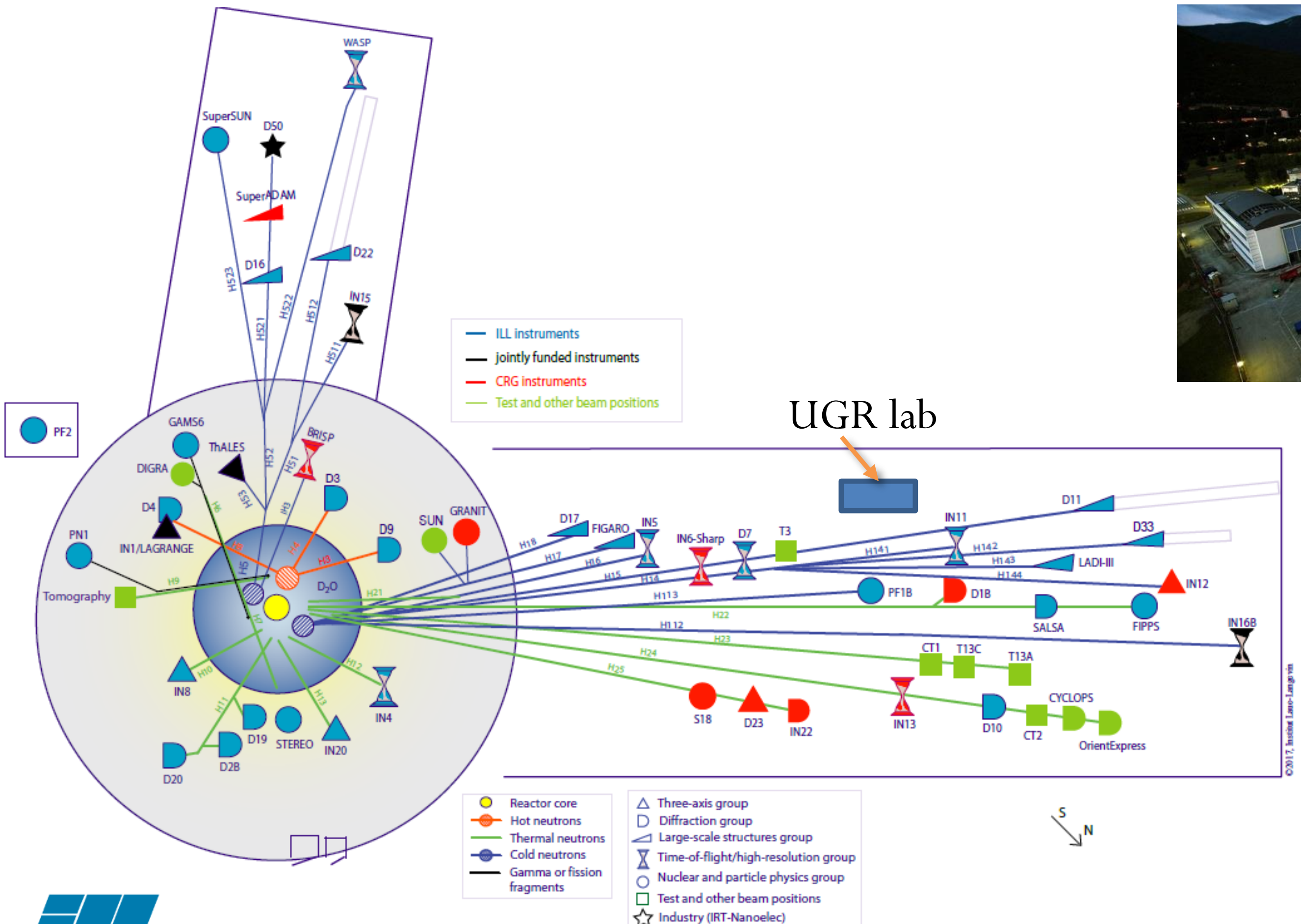
TOF line

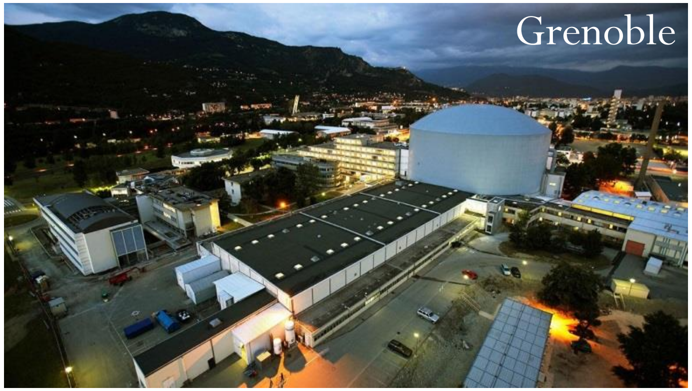


Two lines of the accelerator are dedicated to **neutron** experiments: CW and TOF.

UGR neutron group: Institut Laue-Langevin

- Most powerfull nuclear reactor for science and technology.
- **Neutrons** for: condensed matter, biology, graphene, chemistry, nanotechnology





NEUTRONS FOR SCIENCE

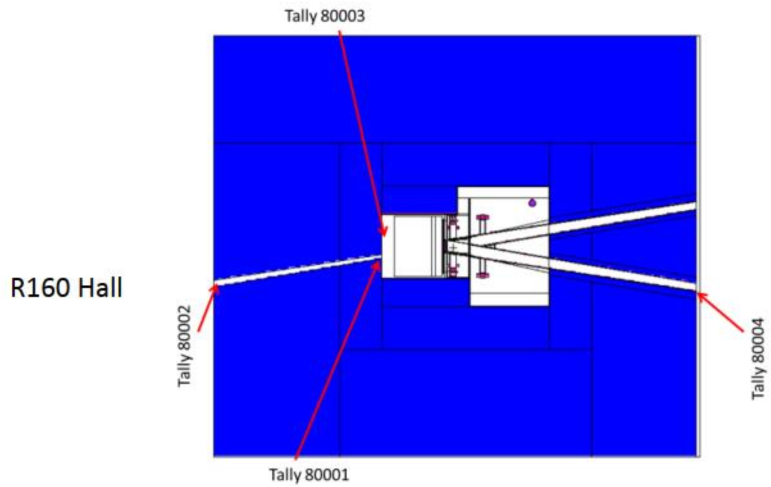


Figure 2.4. Representation of the incidence of the deuteron beam on the test cell, as the neutron outputs generated in the R130.

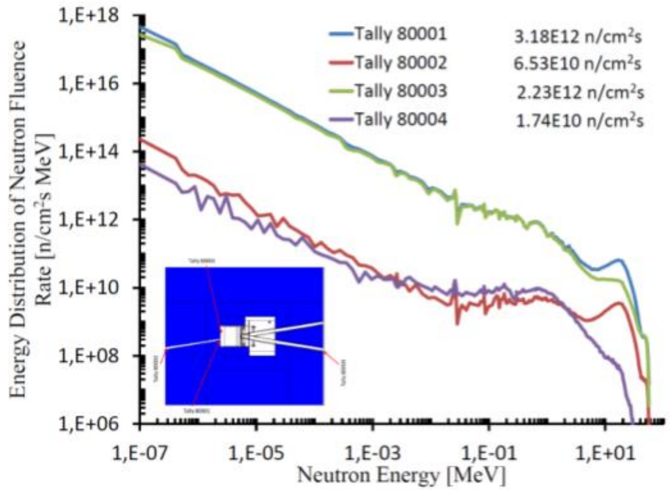
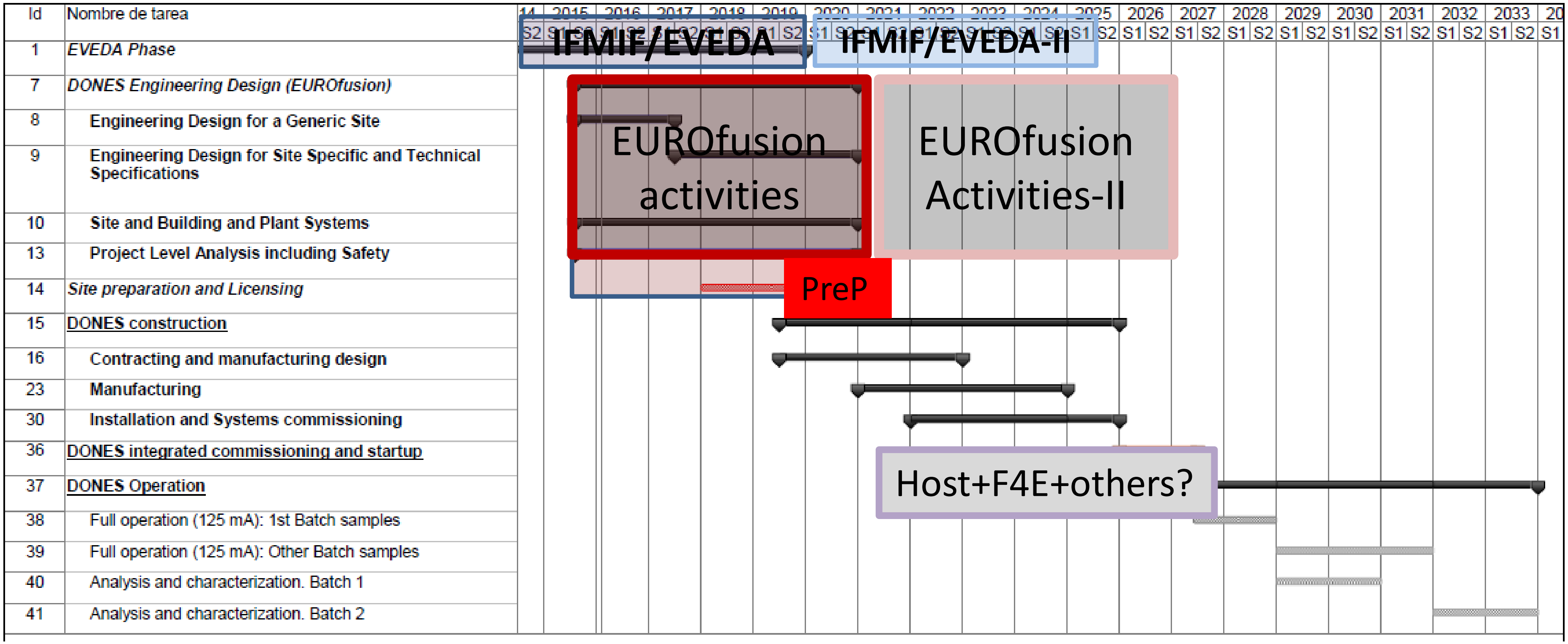


Figure 2.5. The expected energy distribution of neutron fluence rate [n/(cm^{2}sMeV)], for each neutron tally.

IFMIF-DONES Reference Time Schedule

Based on an agreement between F4E and EUROfusion, the ENS Workpackage in the framework of the EUROfusion Consortium will develop the engineering design of DONES -in close collaboration with F4E-.



Objectives of the ENS project (as of the EUROfusion Workprogramme):

To be ready for IFMIF/DONES construction in the early 2020´s