Accelerator-Driven Neutron Sources for Materials Irradiation

Alberto Facco

INFN/LNL, Legnaro, Italy

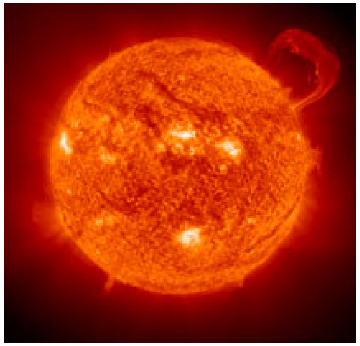
MSU/FRIB, East Lansing, USA

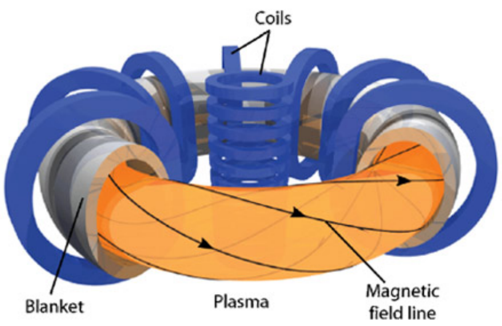
Outlook

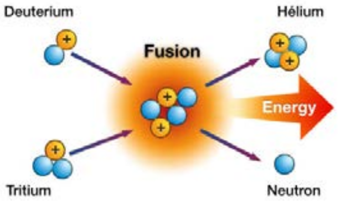
- Materials irradiation for the fusion power production program
- Accelerator-driven neutron source in the Broader Approach roadmap: IFMIF/EVEDA
- New proposal for the next irradiation facility
- Outcome of the “Ad Hoc Group Toward IFMIF”
- Summary and conclusions

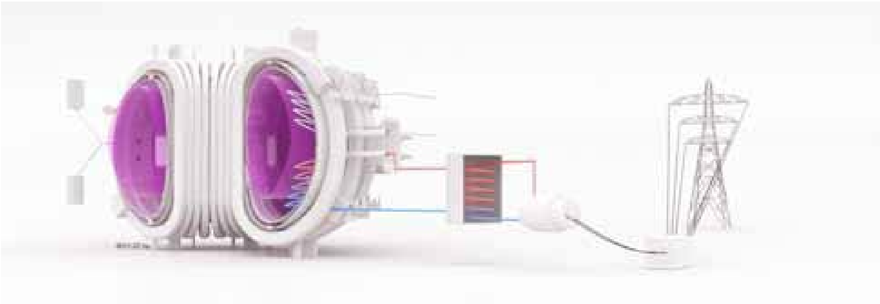
Power from Nuclear Fusion

- Dream: producing energy by means of nuclear fusion, like in the sun
  - No radioactive nuclear waste produced, only He
  - No risk of explosion, no runaway chain reaction
  - No expensive fuel, only H isotopes
  - No radioactive heavy metals
  - Fully acceptable by public
- A large international effort is devoted to achieve this extremely important goal
- Building suitable reactors presents huge technological challenges





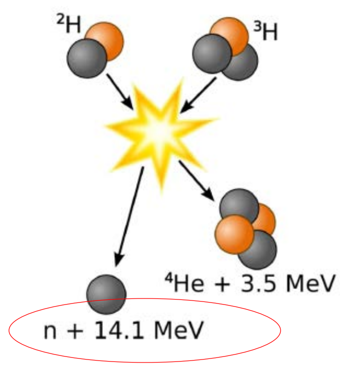




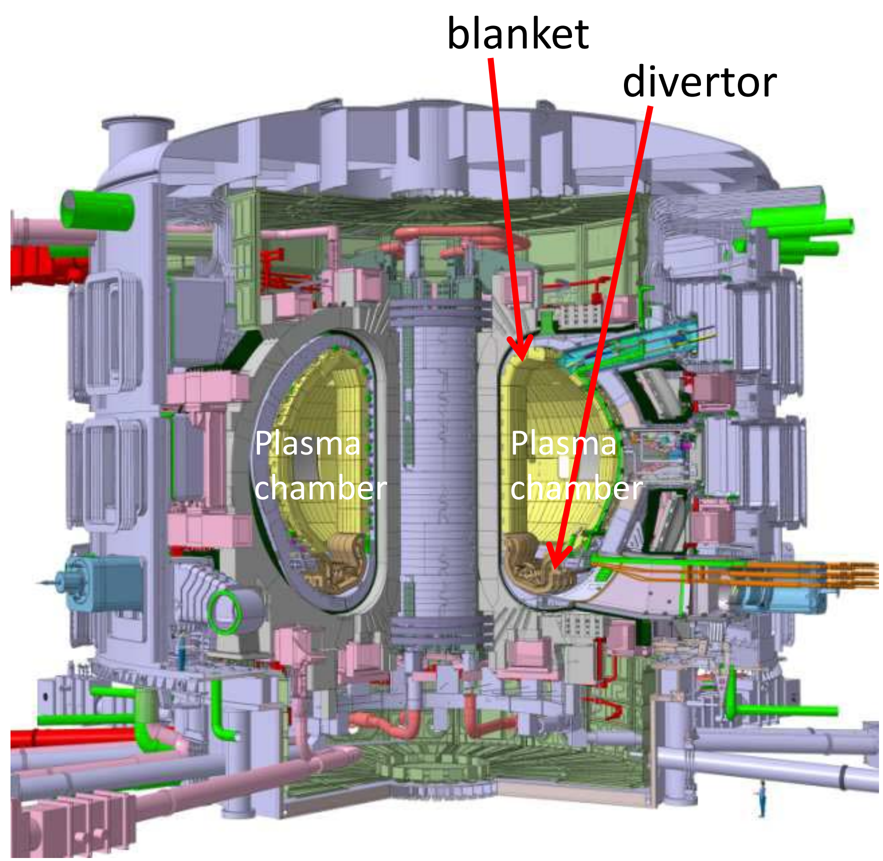
Figures from the Fusion for Energy website
http://fusionforenergy.europa.eu

Major Challenge: Structural Materials

- Mainstream nuclear fusion power plants:
  - Power generated by D-T reactions



  - Most of the power is released to the reactor walls by **14.1 MeV neutrons**
- Even if large fusion reactors are already planned, the **long term** behavior of materials under this type of radiation is still unknown
  - the plasma chamber walls **lifetime** cannot be reliably extrapolated
  - **Licensing** is not yet possible
  - **New materials** need to be developed

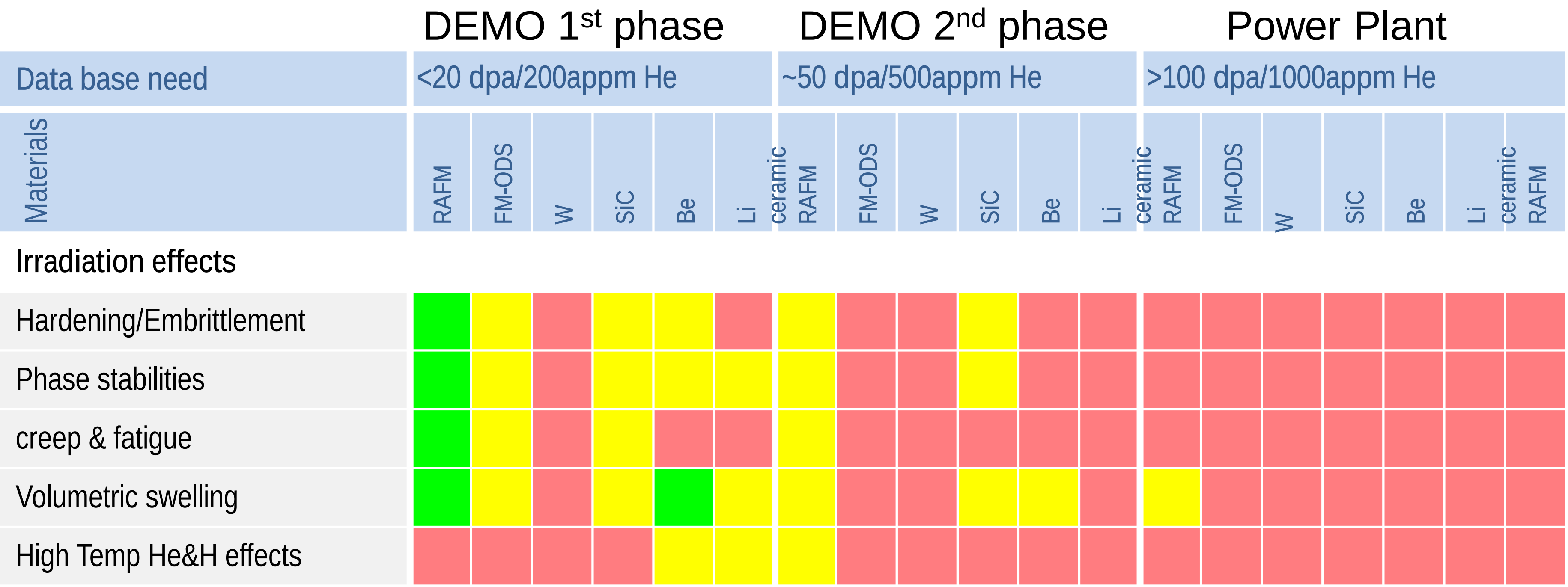


ITER reactor view

Materials Degradation in Typical Fusion Reactor Conditions

- Neutrons interact with the plasma facing walls and with the structural material behind them (Special steels, W, Cu, SiC, Be, Li ceramic, and others)
  - elastic collisions cause displacement of the atoms in the lattice
  - Neutron capture cause transmutation and generation of He and H inside the material
- Macroscopic phenomena observed:
  - Embrittlement, and increase of the Ductile to Brittle Transition Temperature (DBTT)
  - Swelling
  - In general, modification of mechanical properties
- Main parameters determining mechanical properties evolution:
  - **Type of material**
  - **Neutron energy** distribution
  - Average number of **displacements per atom (dpa**) accumulated, and ratio of **appm He/dpa**
  - **Temperature** of the irradiated material
- Experimental data: available at a **few dpa** (sufficient for low duty cycle research reactors) but largely missing for **10-100 dpa** or more, expected infusion power plants (~**150 dpa**)

Required Database for DEMO the Power Plant Reactor Prototype



- Adequate knowledge base exists
- Partial knowledge base exists
- No knowledge base

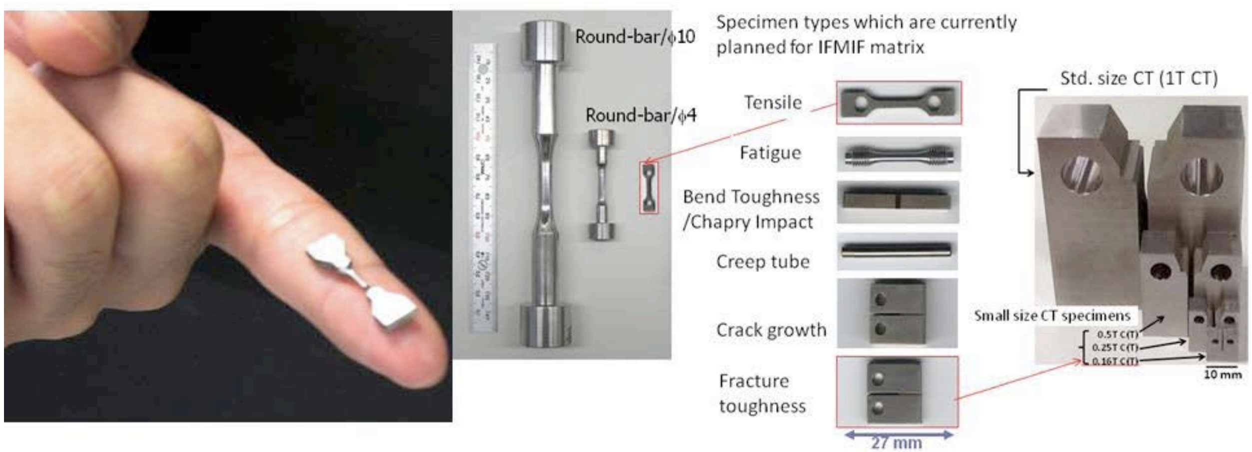
Note: He levels are only for FM steels

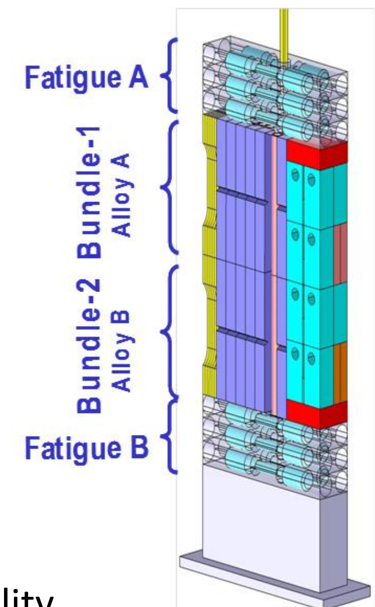
Courtesy of A. Moeslang and A. Ibarra, (In the style of R. Kurtz, ORNL, 2011)

A neutron irradiation facility, closely reproducing the fusion reactor conditions and allowing post-irradiation material analysis, is necessary to the fusion program

Material Testing Techniques

- Samples specially shaped to allow testing of critical mechanical properties for all materials of interest are stacked in special bundles and irradiation modules
- Modules must be placed in volumes with homogeneous and controllable irradiation and temperature conditions
- After irradiation the activated samples are removed and sent to Post-Irradiation Examination (PIE) facilities for testing

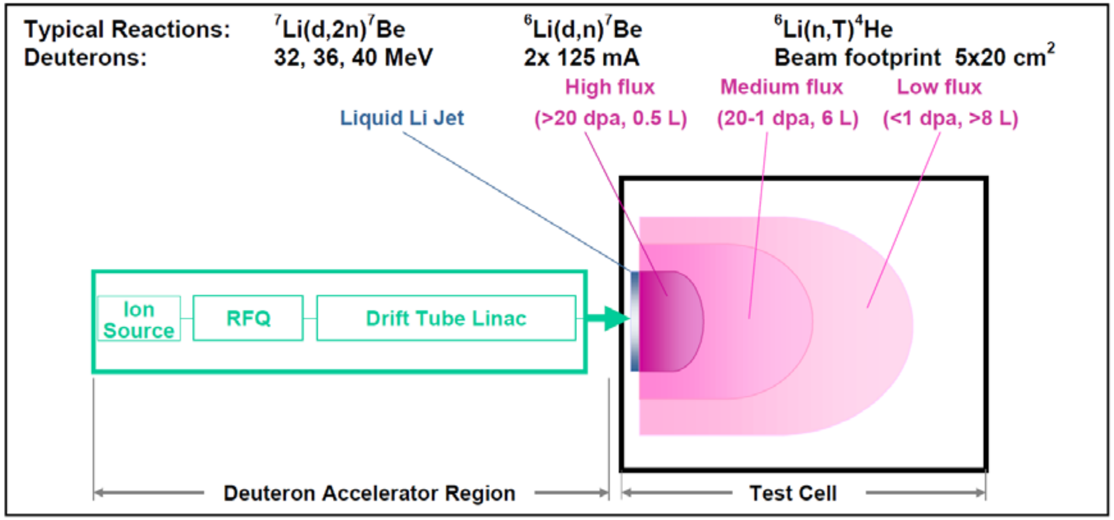




Samples and irradiation modules developed for the IFMIF facility

Accelerator Based Neutron Sources for Material Irradiation

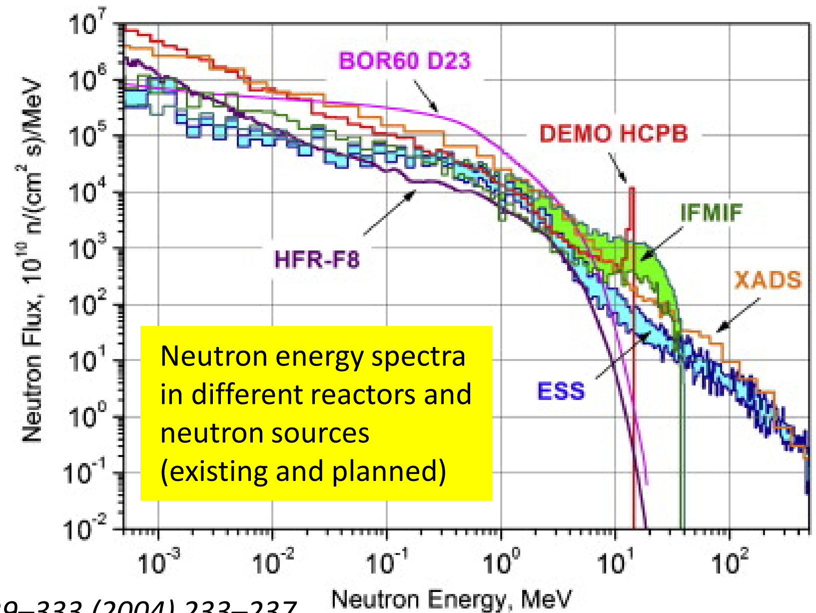
- Accelerator-based n sources using Li(*d, xn*) or C(*d,xn*) reactions can fulfill all requirements for an irradiation facility:
  - Neutron **energy spectrum** 0÷14.1 MeV
  - Neutron **flux** ~ $10^{18} m^{-2} s^{-1}$
  - **dose** : sufficient number of dpa within acceptable irradiation time (1-2 years)
  - **Irradiation volume** with homogeneous characteristics suitable to locate material samples can be created close to the beam target, which must be **thin** and able to **withstand several MW** of beam power



Schematic layout of a Li stripping neutron source

Neutron Sources Comparison

- Fission reactors deliver high flux, but neutrons have too low energy compared to fusion ones
- Spallation neutron sources energy spectrum has a high energy tail which produce different material modifications
- Existing fusion reactors can deliver a similar energy spectrum, but not the dose
- To fulfill fusion reactor program needs a Li stripping n source (IFMIF) was designed



From P. Vladimirov, A. Moeslang / Journal of Nuclear Materials 329–333 (2004) 233–237

Irradiation parameter		Demo power plant W/m²	IFMIF HFTM	ESS	XADS 1 MW	HFR (reactor)	BOR60 (reactor)
Total flux, cm-2 s-1	n	**$1.3\cdot10^{15}$**	**$5.7\cdot10^{14}$**	**$6.5\cdot10^{14}$**	**$1.2\cdot10^{15}$**	**$3.8\cdot10^{14}$**	**$2.3\cdot10^{15}$**
	p	**0**	**0**	$2.5\cdot10^{12}$	$2.7\cdot10^{14}$	**0**	**0**
Damage, dpa/fpy		**30**	**20–55**	5–10	**38**	2.5	**20**
H, appm/fpy		**1240**	**1000–2400**	160–360	16 250	1.9	14
He, appm/fpy		**320**	**250–600**	25–60	1320	0.8	5.8
H/dpa		**41**	**35–54**	**33–36**	430	0.8	0.70
He/dpa		**11**	**10–12**	**5–6**	**35**	0.3	0.29

Displacement damage and gas production in iron for several neutron irradiation environments

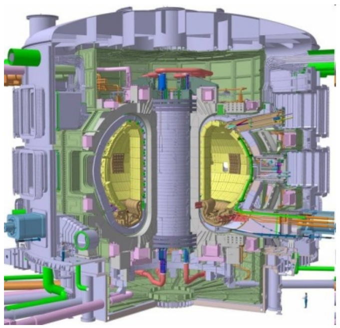
European Contribution to Fusion

" **Fusion for Energy (F4E)** is the **European Union's Joint Undertaking for ITER** and the **Development of Fusion Energy**. The organisation was created under the Euratom Treaty by a decision of the Council of the European Union in order to meet three objectives:

- F4E is responsible for providing Europe's contribution to ITER... together with seven parties that represent half of the world's population – the EU, Russia, Japan, China, India, South Korea and the United States.
- **F4E also supports fusion research and development** initiatives through the **Broader Approach Agreement**, signed with Japan – a fusion energy partnership which will last for 10 years (**till April 2017**).
- Ultimately, F4E will contribute towards the construction of demonstration fusion reactors.
- F4E is established for a period of 35 years from 19 April 2007 and is located in Barcelona, Spain. "

(From F4E web page, http://fusionforenergy.europa.eu)

The Broader Approach Agreement toward Energy Production with Fusion Reactors



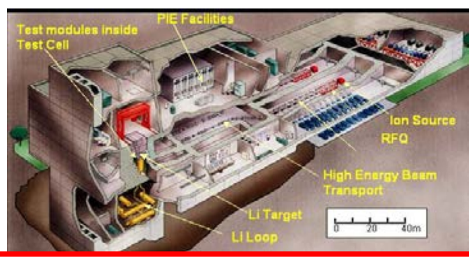
- **ITER**, 500 MW fusion reactor

In Europe

Broader Approach (BA) partners:
- Belgium, France, Germany, Italy, Spain, Switzerland
  - *Represented by **Fusion for Energy** (EURATOM)*
- Japan
  - *represented by **JAEA***

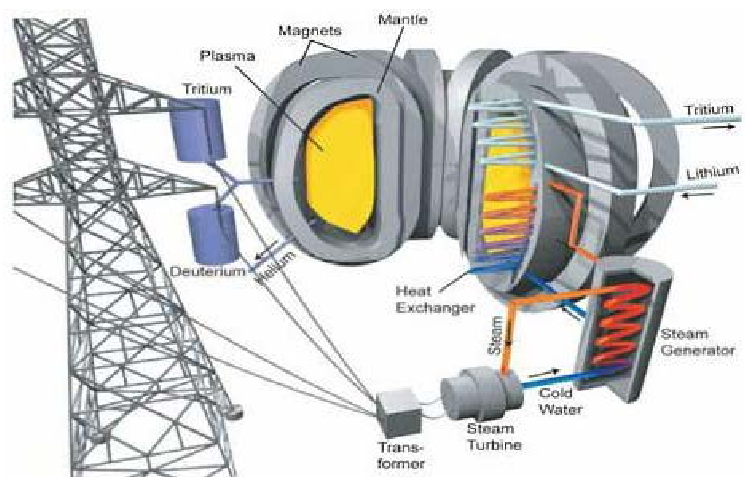
DEMO, 2000 MW fusion reactor

Demonstrator of the reactors for large scale energy production after 2050

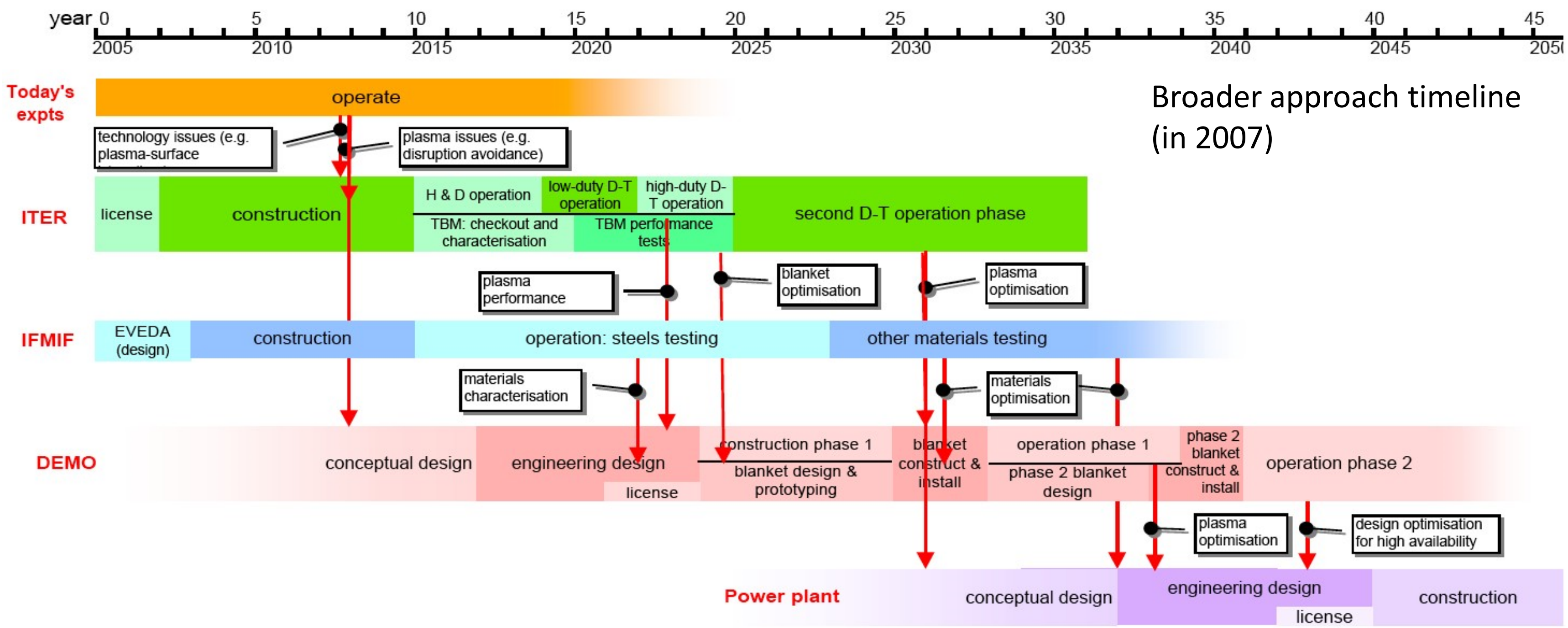


- **IFMIF**: **I**nternational **F**usion **M**aterials **I**rradiation **F**acility
  - 1st step: the EVEDA demonstrator
- **STP** - Satellite Tokamak Programme (JT60)
- **IFERC** - International Fusion Energy Research Centre

In Japan



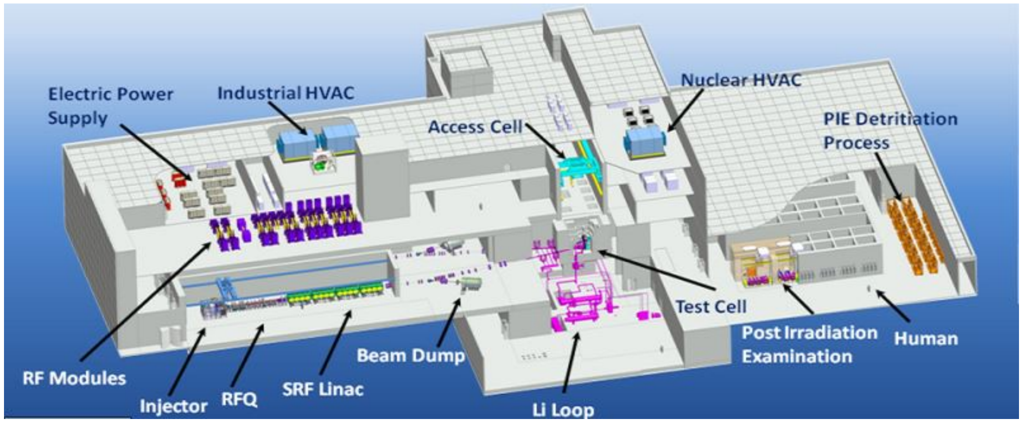
The Broader Approach Roadmap



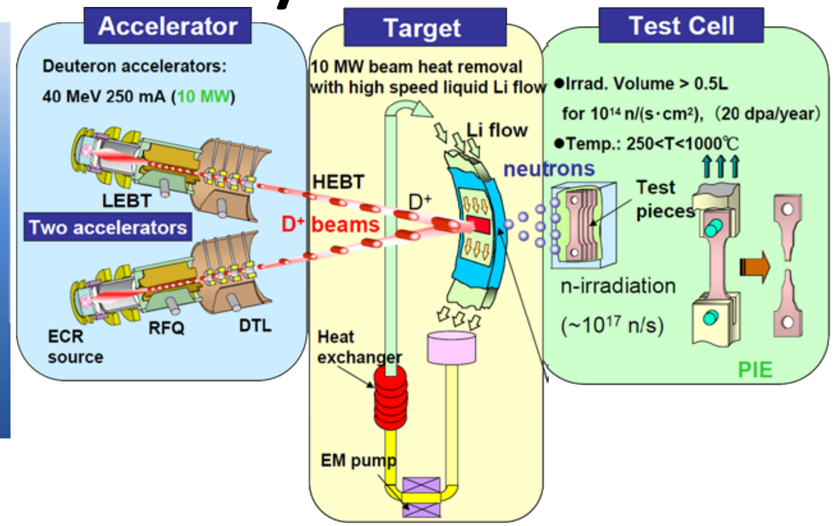
Broader approach timeline (in 2007)

- Material irradiation and testing in parallel with ITER activity
- Material properties database must be available when decision on the DEMO material are taken

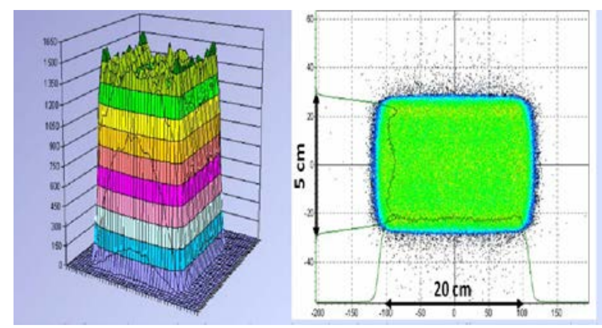
IFMIF - International Fusion Materials Irradiation Facility



IFMIF artist's view

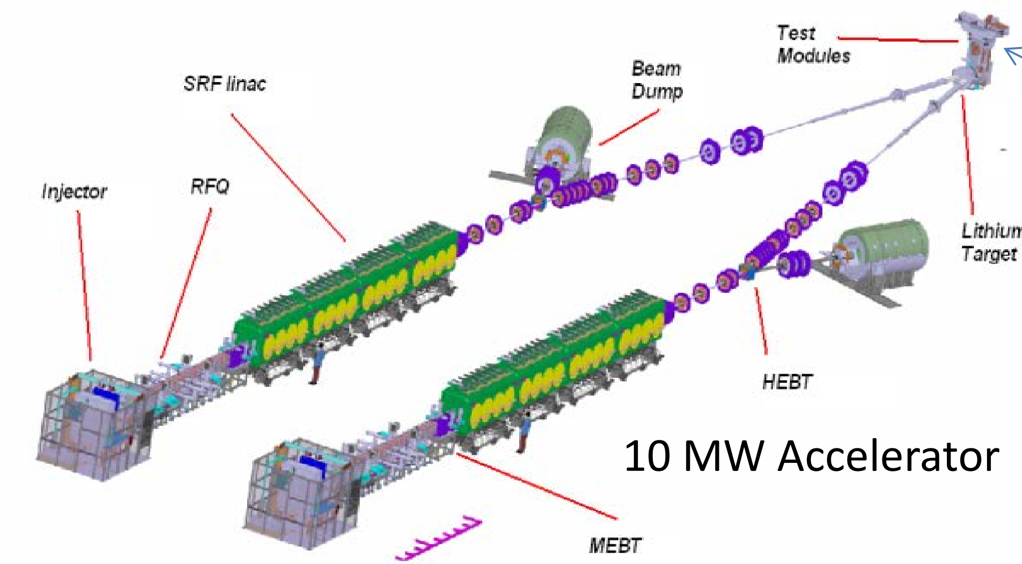


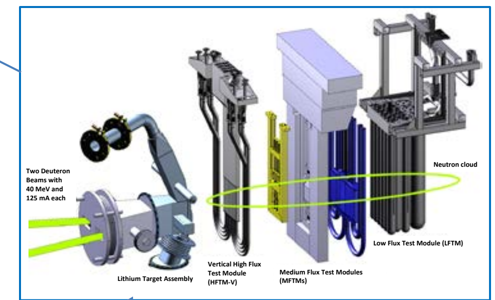
- 2×125 mA CW , 40 MeV Deuteron beams on a liquid Li target
- 200×50 mm beam footprint with uniform density
- Neutron flux with similar shape peaked at 14 MeV:
  - >20 dpa/y in 0.5 liters
  - >1 dpa/y in 6 liters
  - <1 dpa/y in 8 liters
- PIE facility for material analysis



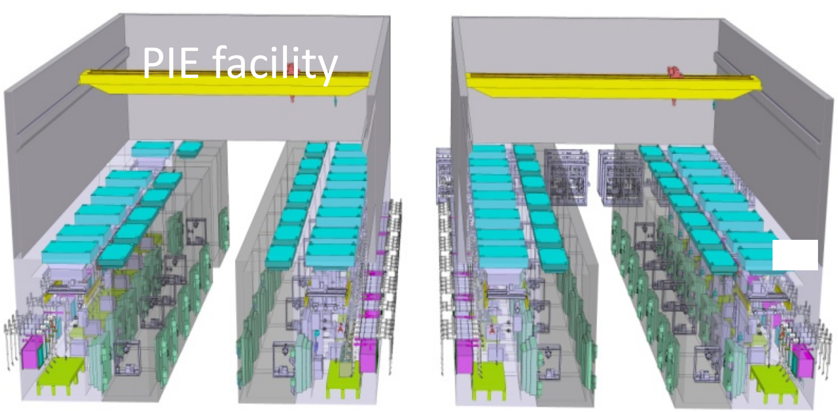
IFMIF Beam distribution on target

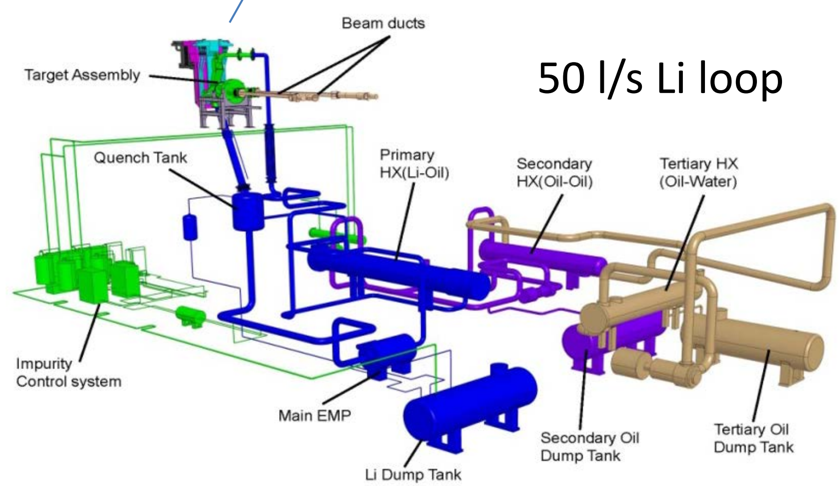
IFMIF Main Subsystems





Test facility





50 l/s Li loop

Some of the IFMIF Major Challenges

Accelerator:

- Extremely high beam power: 125 mA cw Deuteron beam in a ~50 m long, dual accelerator system
- Extremely precise beam distribution on target
- Extremely low beam losses required
- Extremely high reliability in 30 years of operation

Liquid Lithium target:

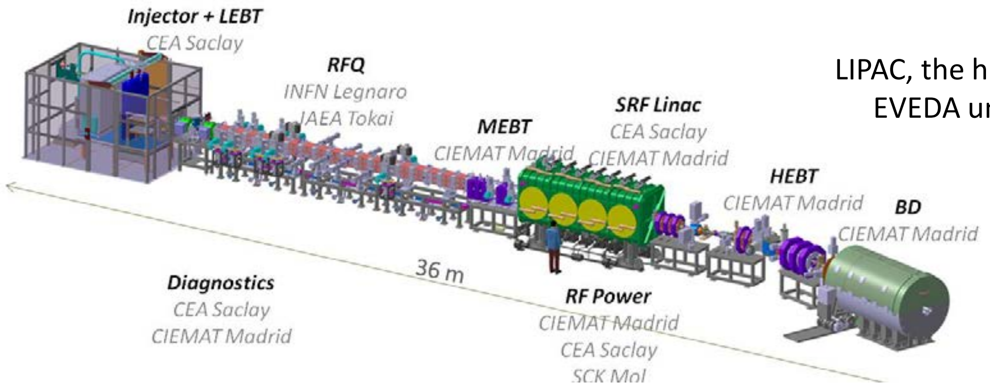
- 50 l/s lithium flow at 15 m/s speed
- Li flow cross section in the target 260×25 mm, with ±1mm uniformity
- Curved Li target for centrifugal acceleration of 90g to eliminate Li boiling under 10 MW bombardment

…And more.

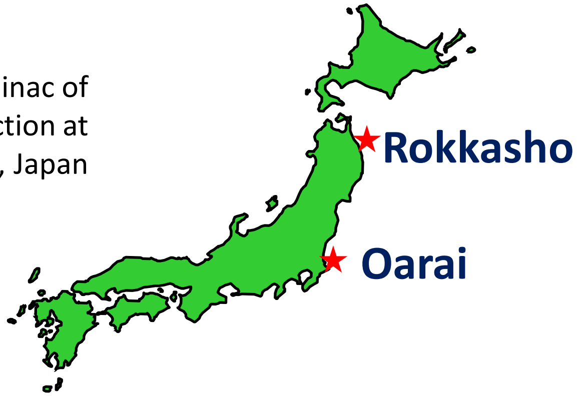
- Technological demonstration required before IFMIF construction

EVEDA, the IFMIF Demonstrator

- EVEDA (Engineering Validation and Engineering Design Activities) for the assessment of the most challenging technology required for IFMIF:
  - 125 mA cw **linac** with all critical components
  - Liquid Li target and related **Li loop**
  - **Test facility** critical items
- The project started in 2007 as as part of the BA agreement between F4E-JAEA
- In-kind contributions from EU and Japan.
- Linac designed and built in EU, installed and operated in Japan (Rokkasho)
- Italy participates through INFN (Linac) and ENEA (Li loop and test facility)
- Now in an advanced stage of construction.



LIPAC, the high intensity linac of EVEDA under construction at Rokkasho, Japan



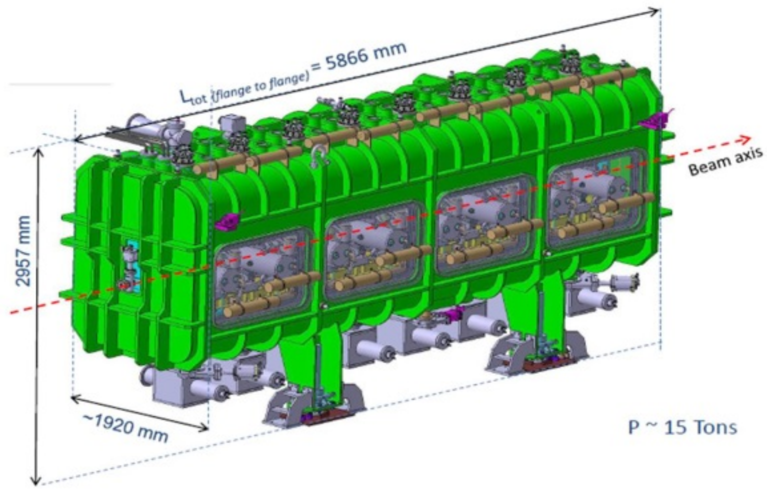
The EVEDA site in Rokkasho

EVEDA construction status [1]

Ion Source and LEBT (CEA Saclay)

- 2.45 GHz ECR
- E = 100 keV, I = 140 mA CW
- Design ε at RFQ input=0.25 π mm·mrad
- **Installed in Rokkasho**
- **Presently under beam commissioning**

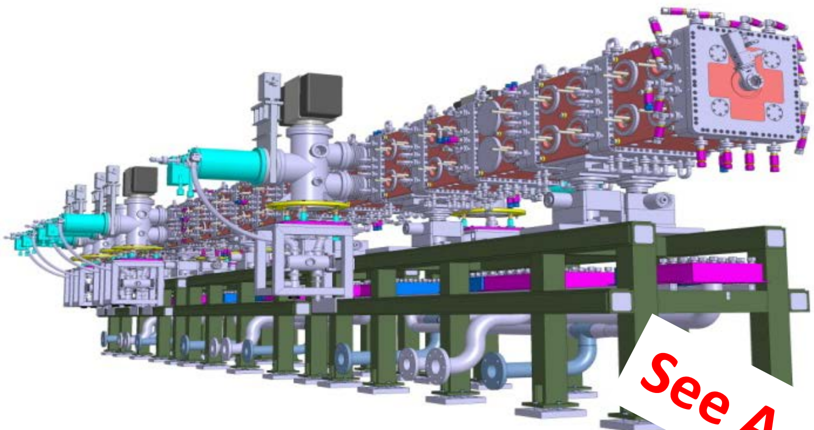
Cryomodule (CEA Saclay)

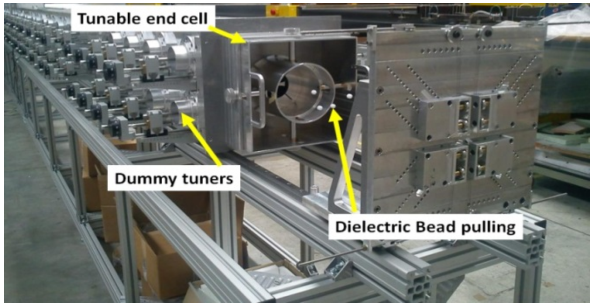


- 175 MHz SC HWR resonators and SC solenoids
- E_{input}= 5 MeV
- E_{output}= 9 MeV
- E_{acc}=4.5 MeV/m
- RF power = up to 70 kW per cavity
- **Cavity performance validated**, construction contracts being launched
- Assembly in Japan of cryomodule being assessed

EVEDA construction status [2]

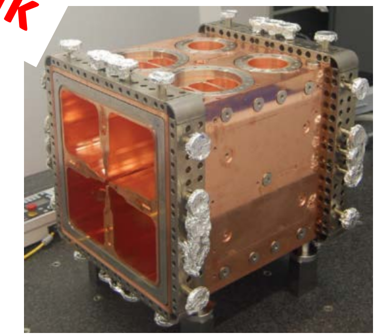
RadioFrequency Quadrupole (INFN Legnaro)





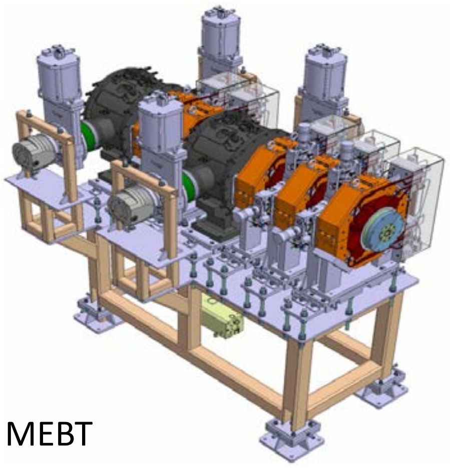
See A. Pisent talk

- 175 MHz CW
- I_{input}= 130 mA
- E_{output}= 5 MeV
- 1.6 MW RF power
- Max surface field 25.2 MV/m (1.8 Kp)
- Under construction, several modules built
- **RF testing at full power ongoing at Legnaro**
- Design field already reached
- **Delivery in Rokkasho scheduled by 2015**

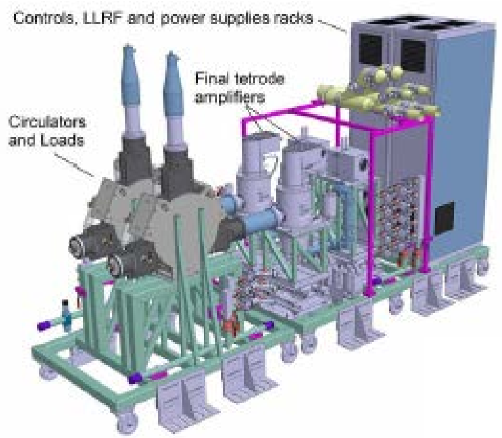


EVEDA construction status [3]

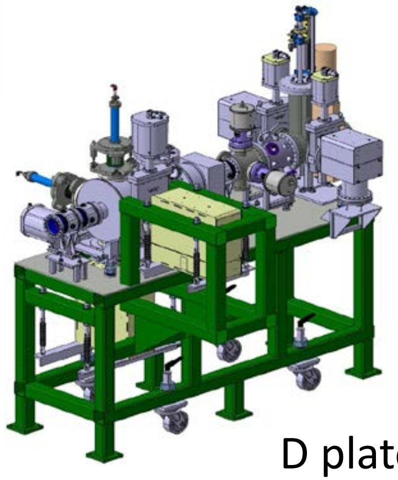
MEBT, RF system, Beam Instrumentation (CIEMAT Madrid)



MEBT



RF amplifier
Prototype successfully tested. Production starting



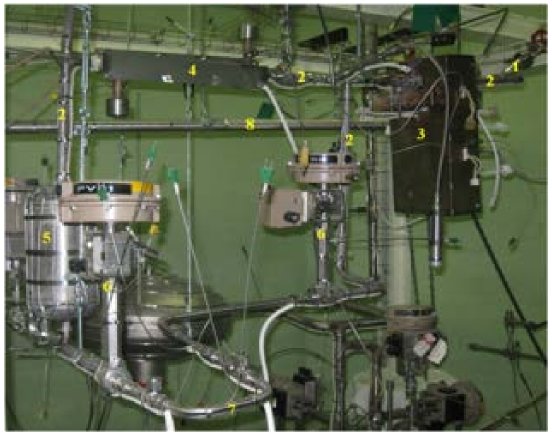
- Under construction
- Delivery in Rokkasho in 2015

D plate

EVEDA construction status [4]

•Li flow operated for 1000h
•20 m/s, 2.250 l/min
•100×25 mm flow cross section in the target
•± 1 mm max wave amplitude

Erosion, corrosion, purification and remote handling (ENEA)




Li Loop (JAEA)

2012: Update of the BA Roadmap

“A dedicated neutron source is needed for material development.
Irradiation studies up to ~30 dpa with a fusion neutron spectrum are needed before the DEMO design can be finalised. While a full performance IFMIF would provide the ideal fusion neutron source, the schedule for demonstration of fusion electricity by 2050 requires the acceleration of material testing. By the end of FP7 *the possibility of an early start to an IFMIF-like device with a reduced specification (e.g. an upgrade of the IFMIF EVEDA hardware) or a staged IFMIF programme should be assessed*.
A selection should be made early in Horizon 2020 of risk-mitigation materials for structural, plasma-facing and high-heat flux zones of the breeding blanket and divertor areas of DEMO, also seeking synergy with other advanced material programmes outside fusion.”

From EFDA roadmap – 2012

(EFDA - European Fusion Development Agreement – signed by 28 European countries to work on an energy source for the future)

Alternate Proposals as Intermediate Steps to IFMIF

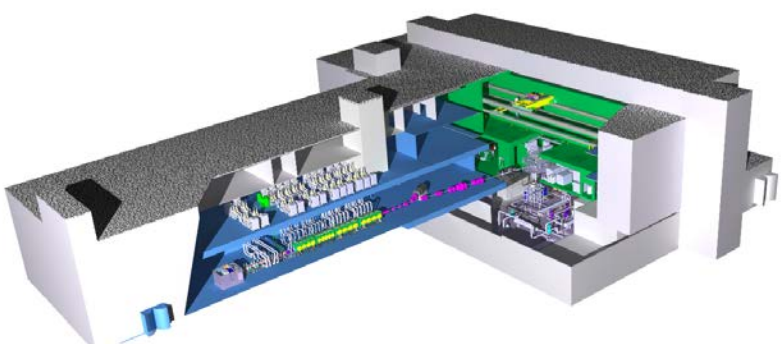
- The IFMIF/EVEDA program is facing some slippage from the planned completion by mid 2017
- The DEMO scope was modified to allow stepped approach
  - 1st phase: up to 20 dpa – early neutron source
  - 2nd phase: up to 50 dpa – early neutron source
  - 3rd phase: > 100 dpa – final IFMIF
- Proposals have been presented for an early neutron source project able to speed up its construction while fulfilling the updated DEMO scope:
  1. DONES (EU contributors to EVEDA)
  2. ENS (JAEA)
  3. FAFNIR (UK)
  4. SORGENTINA (ENEA)
- An “Ad-Hoc Review Group on Options towards IFMIF” was nominated by F4E in 2013 to analyze the proposals

Proposal 1. DONES

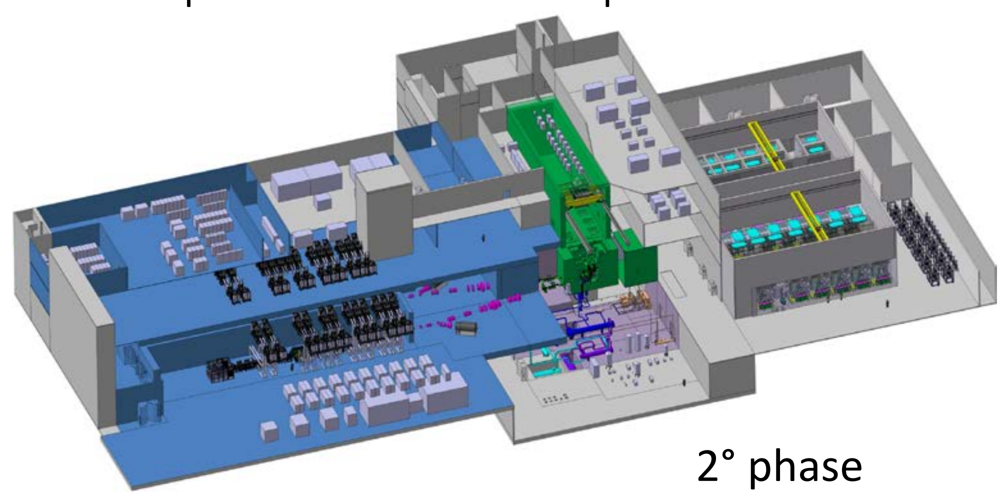
(Demo Oriented Neutron Source)

Staged approach to IFMIF, using most of the IFMIF intermediate engineering design

- 1° phase fitting DEMO phase I and II needs: early completion, reduced cost
  - Only 1 d linac (40 MeV, 125 mA) preserving IFMIF design (including the bent HEBT)
  - Full IFMIF Li loop and test cell, with half cooling
  - Only high flux testing modules (simplified operation)
  - No internal PIE: all radioactive material being processed elsewhere
  - Building prearranged for easy implementation 2° phase
  - Performance similar to the IFMIF ones, but with half irradiation rate
- 2° phase: completion of the IFMIF plant to full performance for DEMO-phase III



1° phase
DONES

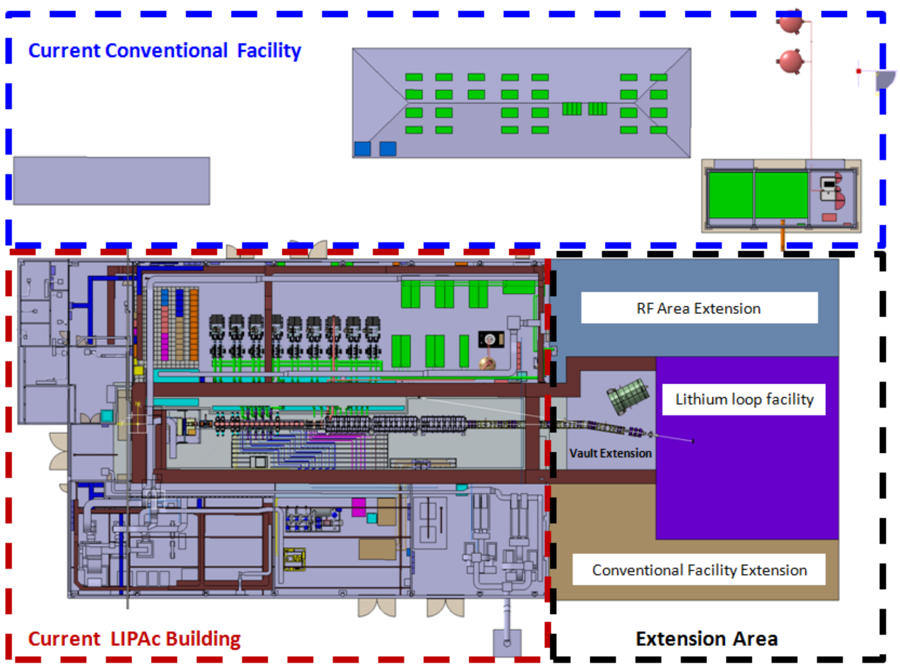


2° phase
Full IFMIF

Proposal 2. ENS
(Elementary Neutron Source)

Upgrade of the existing EVEDA linac in Rokkasho with 2 more cryomodules, to reach **26 MeV** and **125 mA**, and re-use the **EVEDA Lithium loop**

- No change in the neutron spectrum, but neutron yield 15% of IFMIF one
- Smaller beam shape: 10 x 3 cm (to increase the dose rate)
- Test Cell and irradiation module rather small (but based on HFTM design of IFMIF)
- No PIE facility. Irradiated samples to be analyzed elsewhere
- Simplest to build, taking advantage of existing components and infrastructure

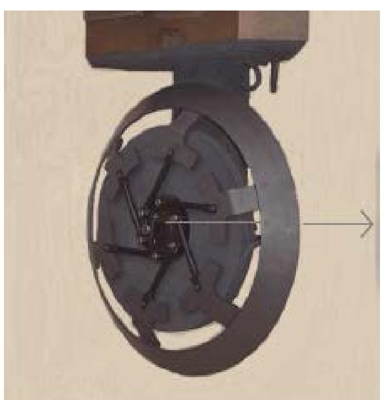


Proposal 3. FAFNIR

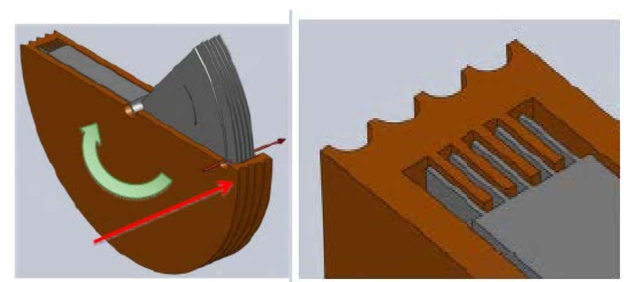
(FAcility for Fusion Neutron Irradiation Research)

Similar concept as DONES 1° phase, but with lower beam power to allow “existing or near term technology”, thus early start and lower cost

- **40 MeV d** linac (SPIRAL2 or LIPAC type)
  - 1° phase **5 mA**, 2° phase **30 mA**. Neutron yeld about 2% and 12% of IFMIF, respectively
- **Rotating wheel C target** instead of liquid Li target:
  - 200 kW (60 kW PSI operating; 100 kW SPIRAL2 and 200 kW FRIB expected on line in a few years)
  - **1.2 MW** planned to be built with limited R&D as an upgrade of the 200 kW design
- Performance in 100 cm^3 volume: 1.5dpa/fpy at 5mA and 7dpa/fpy at 30mA
- C**hallenge: 1.2 MW rotating C target**
- Presently at the conceptual design stage



PSI E-Target (Heidenreich et al.)
Radiation cooled spinning carbon wheel – 60rpm
Diameter – 0.45m
Deposited power - 90kW
Operating Temp - 1427°C
Operation since 1990

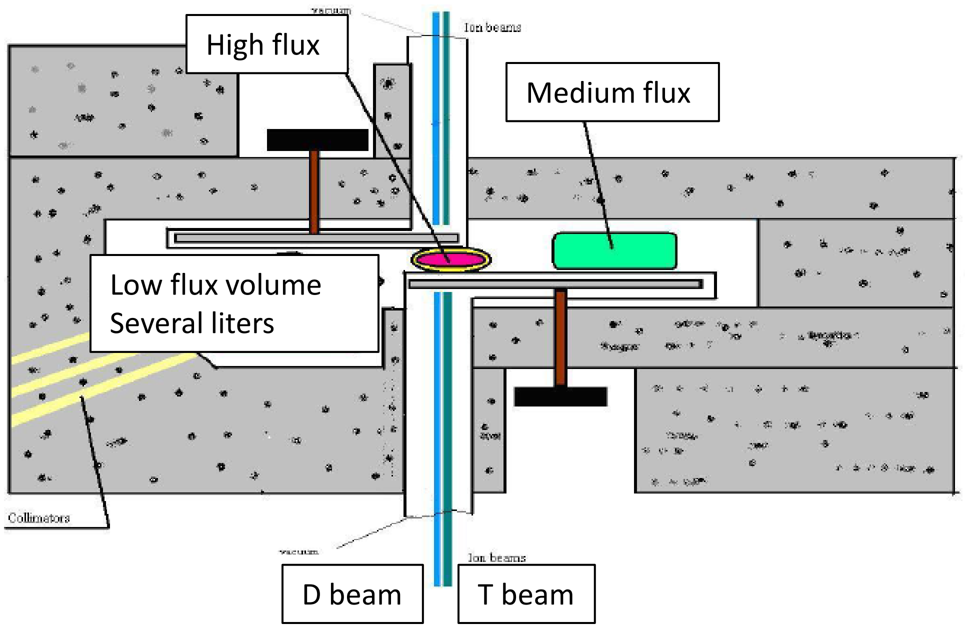


FRIB rotating target multi-foil design to enhance radiation cooling. 50 kW prototype tested

From T. Davenne (RAL), presentation at EuCARD2 Accelerator Applications Network meeting ,CERN 14th June 2013

4. SORGENTINA

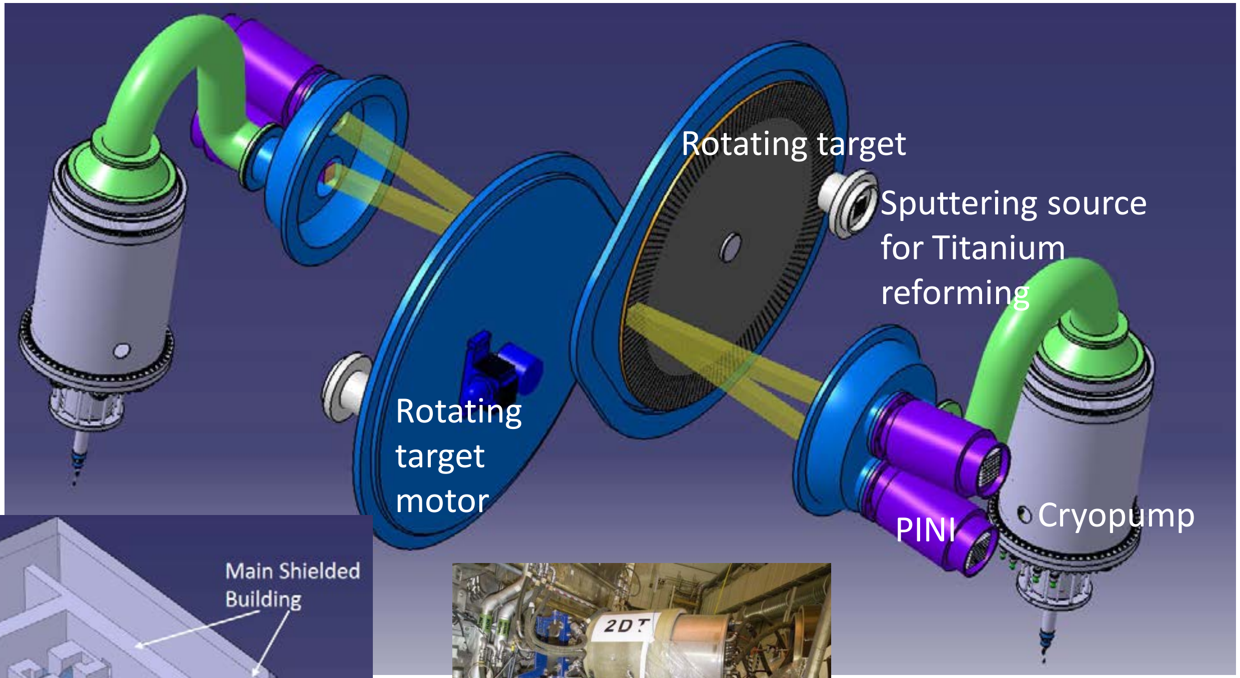
- Based on two Deuterium and Tritium, 2 m diameter, water-cooled rotating targets facing each other, each bombarded by two **200 keV, 20 A *D* and *T* beams (16 MW)**
- D and T are implanted on a Ti layer continuously deposited on the target, and react with the incoming beam D+T → n+α producing 14.1 MeV neutrons
- Well proven JET PINI ion source technology for D and T
- D and T are recycled - T inventory is only 7 g, T consumption 1 g/y
- **Challenge: 16 MW deposited on a thin layer**

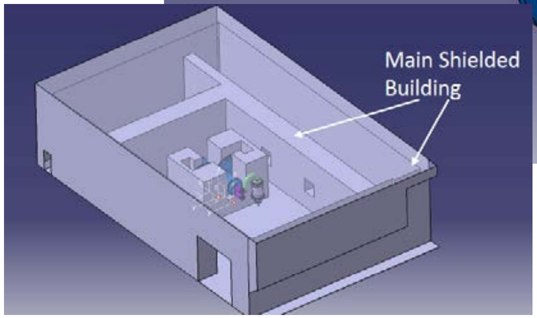


High flux volume	Medium flux volume
~ 150 cm^3	~ 500 cm^3
2.3×10^{13} $n/cm^2/s$	1.5×10^{13} $n/cm^2/s$
2 dpa/fpy	> 1.5 dpa/fpy

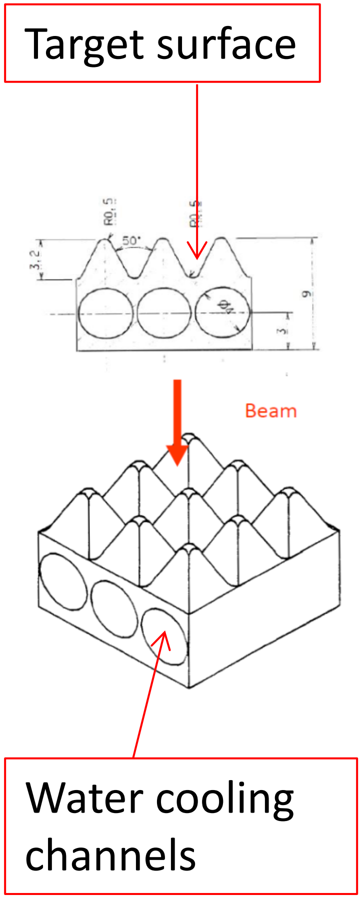
From Mario Pillon presentation at the ERINDA Workshop, CERN, 1-3 October 2013

SORGENTINA [2]





JET PINI sources



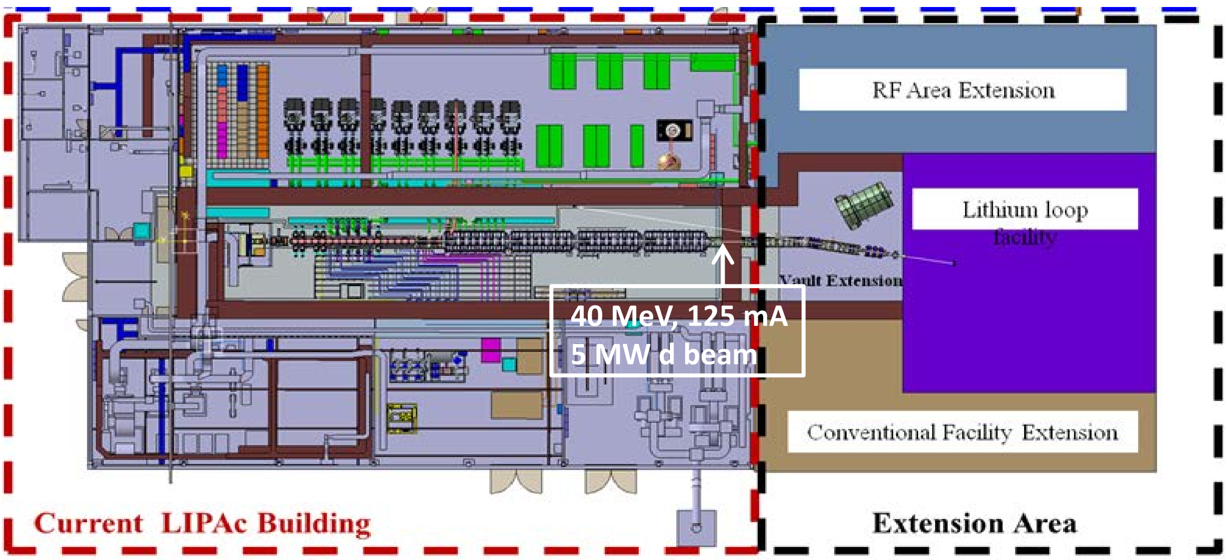
Proposals Performance Comparison

	IFMIF-Full	DONES		ENS	FAFNIR	SORGENTINA
Beam current	2 x 125 mA (Li target)	1 x 125 mA (Li target)		1 x 125 mA (Li target)	1x (2,5/5/30) mA (C target)	2 x 2 x 20 A (Ti target)
Beam energy	40 MeV	40 MeV		26.5 MeV	40 MeV	200 keV
Neutron yield n/(sr.μA.s)	40×10^{10}	40×10^{10}		12×10^{10}		
Total neutron production	10^{18} n/s	5×10^{17} n/s		1.5×10^{17} n/s	$2.5/5/30 \times 10^{15}$ n/s	10^{15} n/s
Beam footprint	20 x 5 cm^2	20 x 5 cm^2	10 x 5 cm^2	10 x 3 cm^2	6x6 cm^2	2 x 20 x 10 cm^2
Typical Damage Rate @ Irradiation volume (*)	40 dpa/fpy @>60 cm^3 + 20 dpa/fpy @>400 cm^3 + 2 dpa/fpy @ >1500cm3	20 dpa/fpy @>60 cm^3 + 10 dpa/fpy @>400 cm^3 + 2 dpa/fpy @ >1100cm3	20 dpa/fpy @>100 cm^3 + 10 dpa/fpy @400 cm^3 + 2 dpa/fpy @ >900cm3	15 dpa/fpy @ 20 cm^3 + 2dpa/fpy @ >600 cm^3	1 dpa/fpy @ 50/150/?? cm^3 + 10 dpa/fpy @ <1/<10/<50 cm^3	2 dpa/fpy @ 10 cm^3 + 1.6 dpa/fpy @ 500 cm^3
Capability of facility	Provide Engineering + Scientific Database for DEMO / Power Plants	Provide Engineering + Scientific Database for DEMO		Provide Reference Data on He-effect + Fusion Neutron spectral effects		

- **DONES appears to be the only alternative** to IFMIF which can fit the DEMO-phase I and -phase II requirements within the planned schedule
- To produce irradiation on a large number of samples at power plant level (150 dpa) **even the full IFMIF might not be adequate**

A Natural Solution for the Next Machine: DONES in Rokkasho as EVEDA upgrade

- The facility which could meet DEMO needs could be made in Rokkasho, using existing hardware, infrastructure and a trained team in continuity with EVEDA
  - An **upgrade to 40 MeV of 125 mA LIPAC** (ENS+ 1 more cryomodule)
  - Upgraded **EVEDA Lithium loop** for 5 MW on target
  - **IFMIF beam footprint and Test Facility**



- Performance: as DONES (IFMIF-like with 50% neutron yeld)
- Minimum cost and construction time at maximum performance expected

Summary and Conclusions

- Powerful neutron sources for material irradiation are a necessary step to the construction of nuclear fusion power plants
- Accelerator-driven, high power sources have shown to be the best choice
- The EVEDA project, supported by a large international collaboration with the aim of demonstrating and validating all required technology, is in an advanced stage of construction
- Discussion on final configuration and site location of the first dedicated facility is ongoing. Its construction is presently scheduled in order to start operation by 2026.
- The high intensity accelerator technology developed in this framework will be ready for new applications in different fields (e.g. compact low energy neutron sources)
- European countries and Italy are on the cutting edge of this research