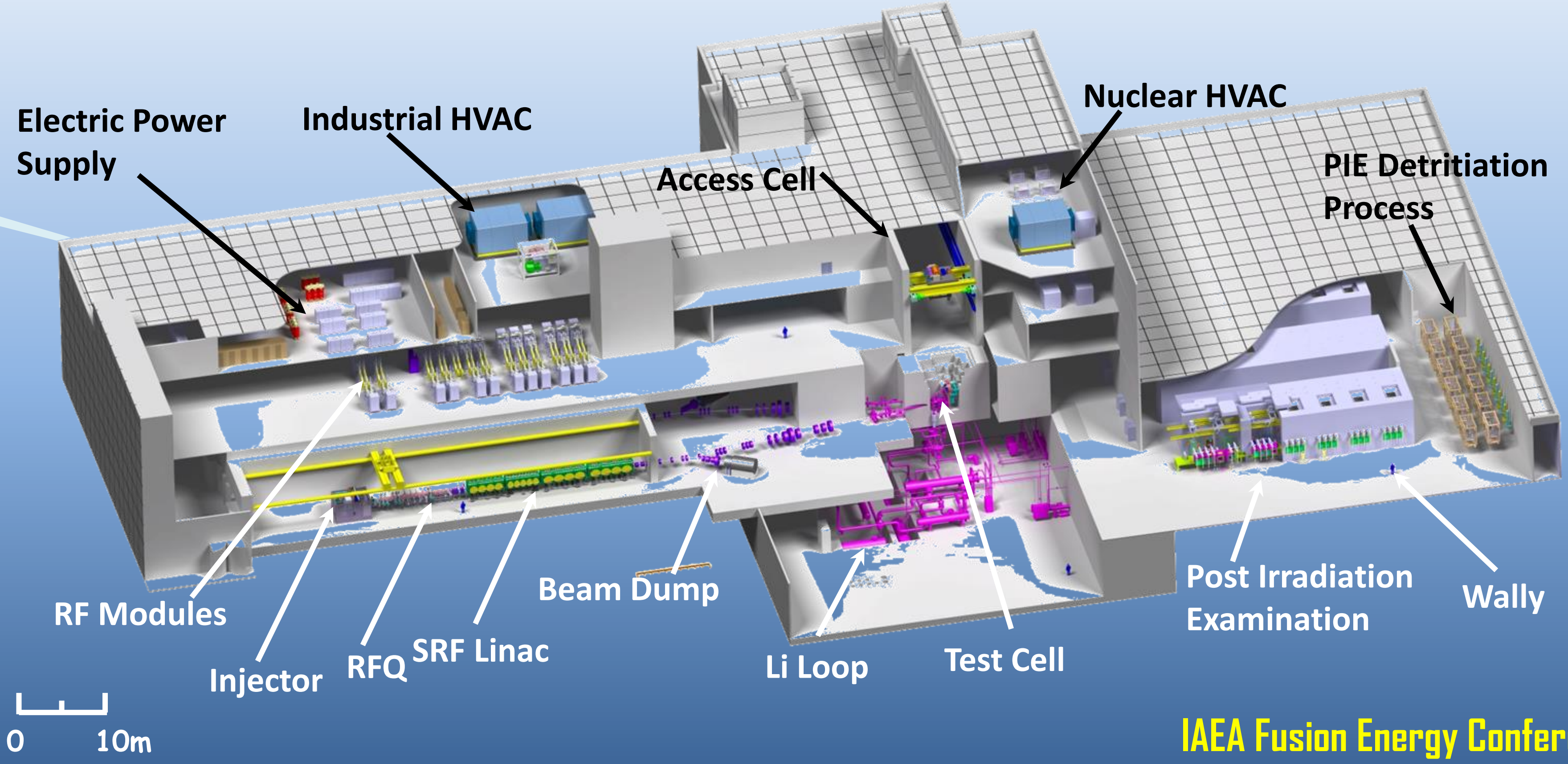
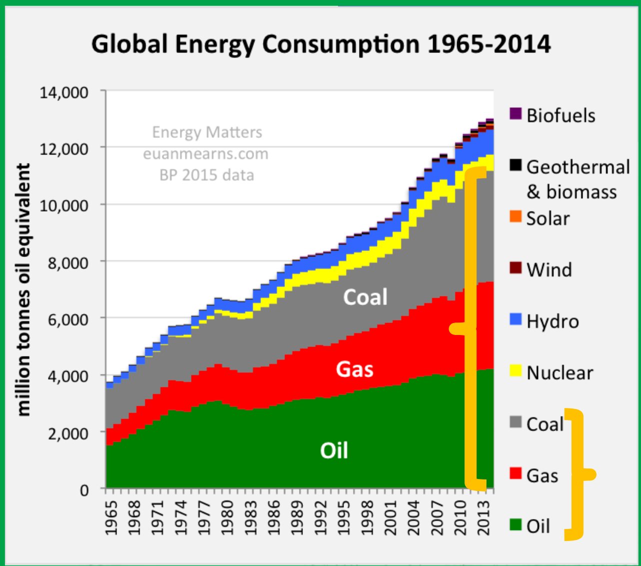
IFMIF

the neutron source for the Fusion Program

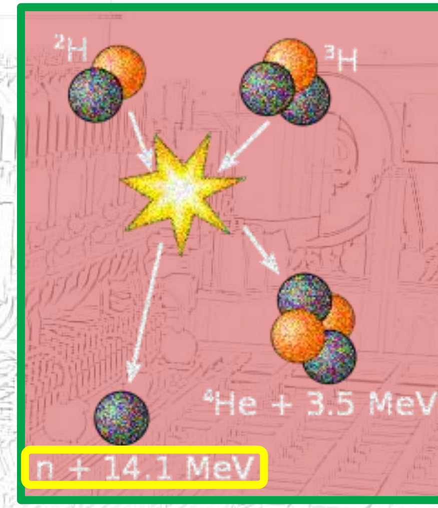
J. Knaster, R. Heidinger and S. O'hira
on behalf of IFMIF/EVEDA team



IAEA Fusion Energy Conference
Kyoto
October 2016



The first wall
of the reactor vessel shall
absorb 14.1 MeV neutrons
product of DT reactions



ITER first wall will present
3 < dpa at the end of its operational life

In a Fusion power plant
~15 dpa per year of operation

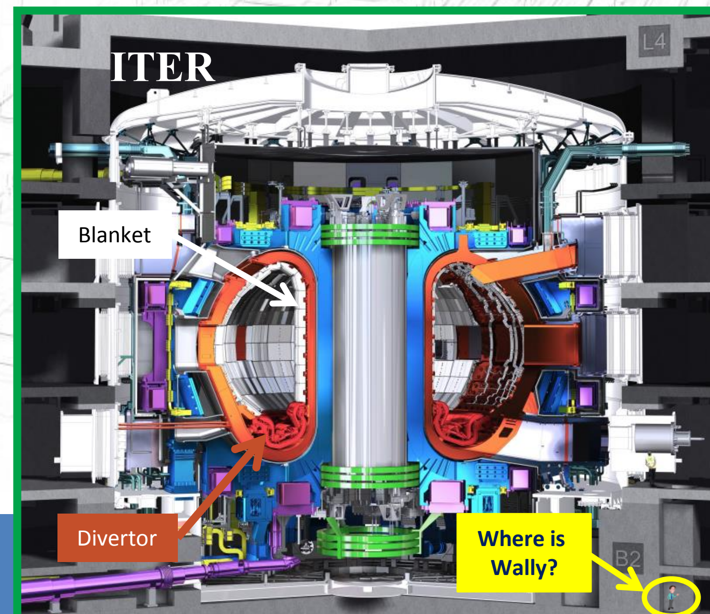
Two transmutation reactions become critical

$^{56}Fe(n,\alpha)^{53}Cr$

and

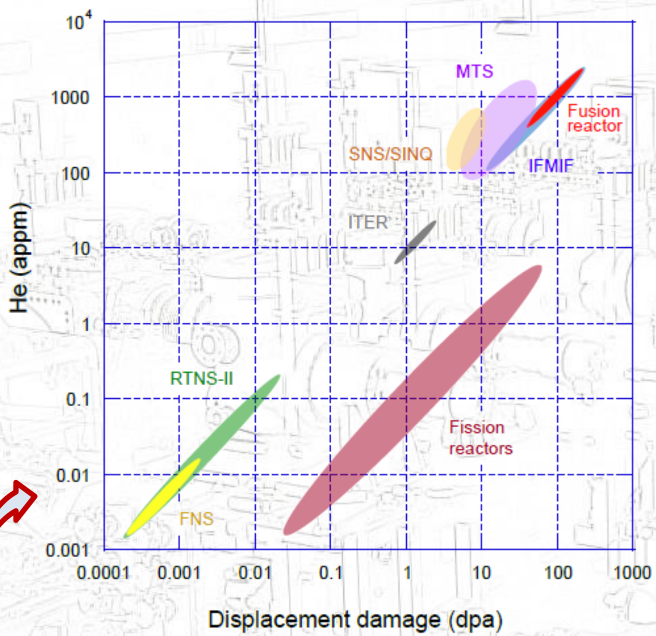
$^{56}Fe(n, p)^{56}Mn$

with **n** threshold energies at **2.9** and **0.9 MeV**



Unique features of fusion materials

Structural Fusion materials are to withstand the combination of

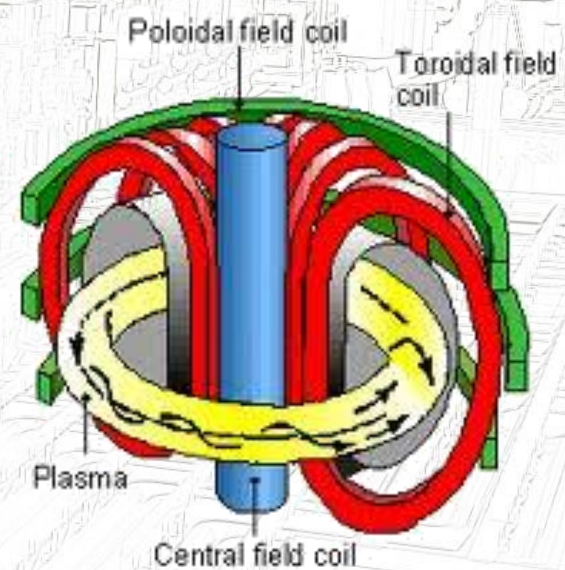


High fluxes (and fluences)
10^{18} n/m^{2}s

Cyclic stresses
$\Delta\sigma > 100$ MPa
(Maxwell stresses)

Thermal loads
>10 MW/m^2
(critical in W based divertor)

He&H generation
~12 appm He/dpa



Neither fission reactors (0.3 He/dpa) nor spallation sources (>50 He/dpa) give needed answers

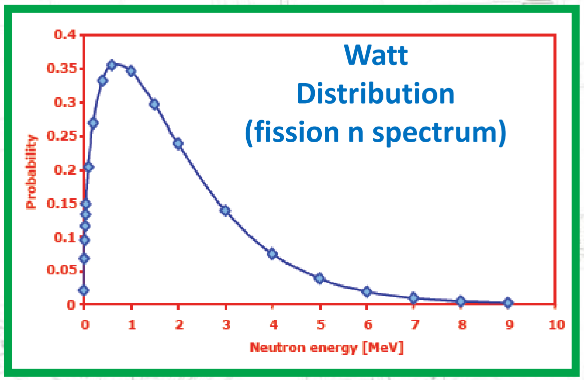

REVIEW ARTICLES | INSIGHT
PUBLISHED ONLINE: 3 MAY 2016 | DOI: 10.1038/NPHYS3735
nature physics

Materials research for fusion

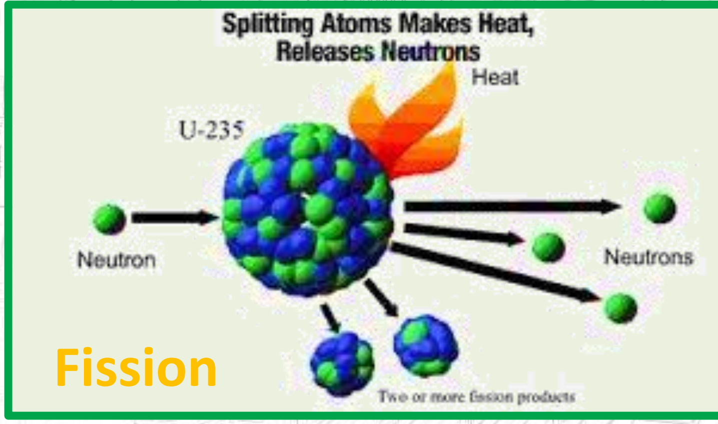
J. Knaster[1]*, A. Moeslang[2] and T. Muroga[3]

Available neutron sources

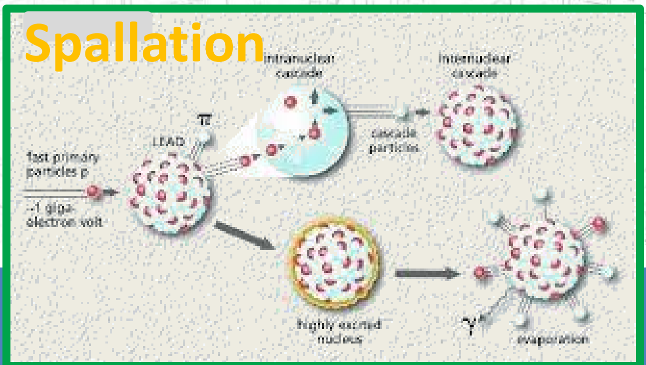
Fission reactors n average energy <2 MeV



No efficient
p^+ or α-particle generation



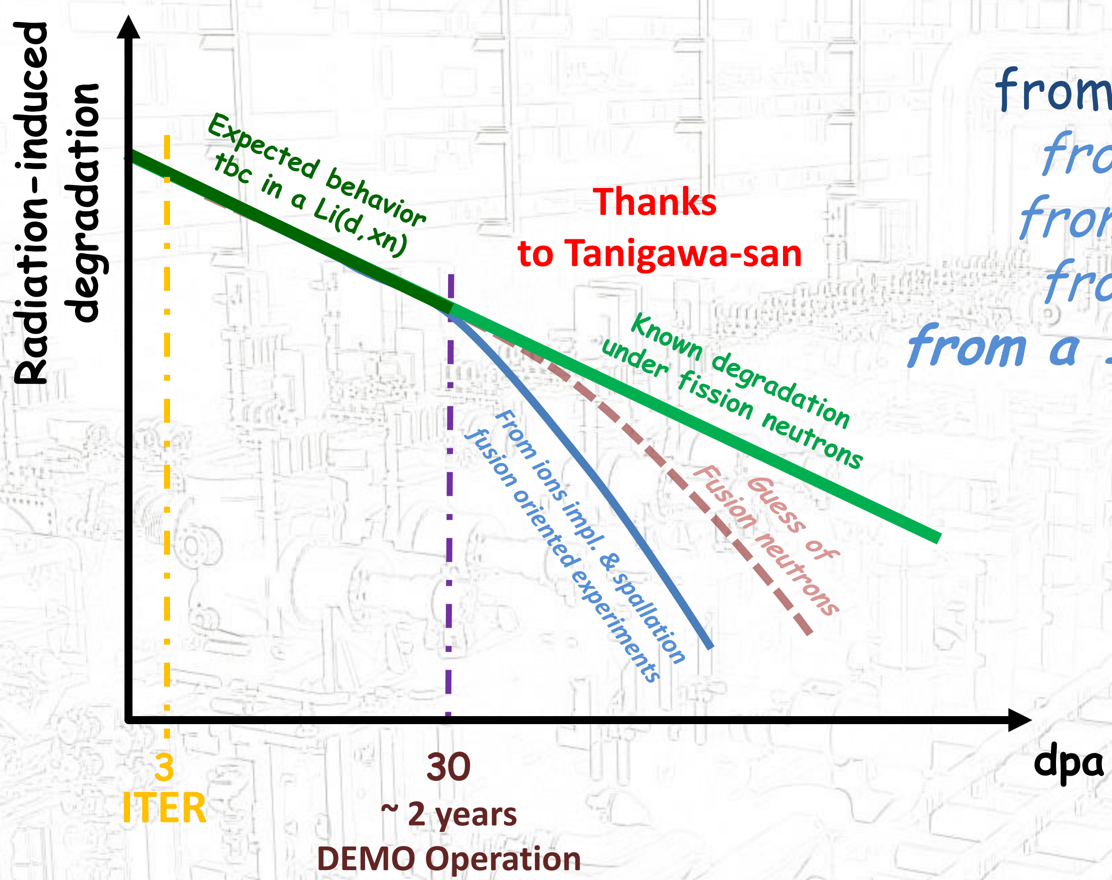
Spallation sources present a wide spectrum with tails reaching impacting particle energy



~20 n per reaction

and are pulsed

Uncertainties (many) present



We need data
from all possible sources
from fission reactors
from spallation sources
from ion implantation
from a 14 MeV neutron source

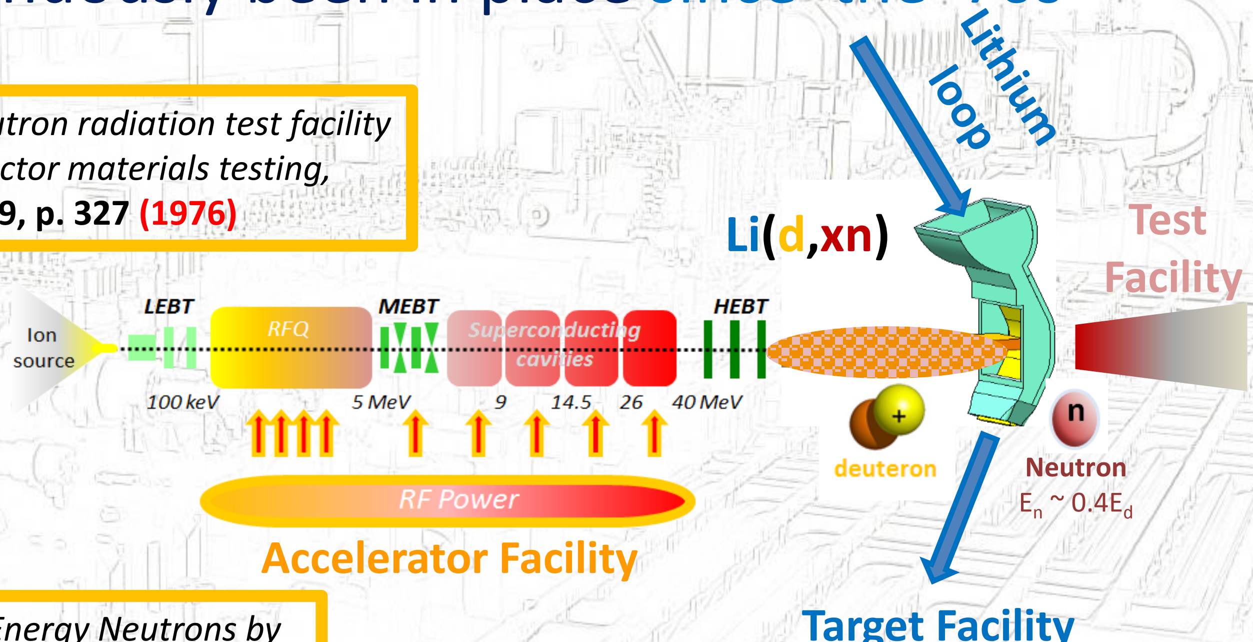
A 2 GW DEMO will reach ITER's expected degradation damage in a couple of months operating at full power

Fusion relevant neutron sources are indispensable

Four decades of work towards a Li(d,xn) facility

A worldwide R&D and design work has continuously been in place since the ‘70s

P. Grand et al., *An intense Li(d,n) neutron radiation test facility for controlled thermonuclear reactor materials testing*, **Nuclear Technology, Vol 29, p. 327 (1976)**



R. Serber, *The Production of High Energy Neutrons by Stripping,* **Phys. Rev. Vol. 72, No 1 (1947)**

FMIT (80s in the US) – ESNIT (90s in Japan)

IFMIF for last 20 years

Initially as a US, RF, JP & EU collaboration up to 2007

Four decades of work towards a Li(d,xn) facility

IFMIF

FMIT

IOP Publishing | International Atomic Energy Agency — Nuclear Fusion

Nucl. Fusion 55 (2015) 086003 (30pp) doi:10.1088/0029-5515/55/8/086003

Special Topic

The accomplishment of the Engineering Design Activities of IFMIF/EVEDA: The European–Japanese project towards a Li(d,xn) fusion relevant neutron source

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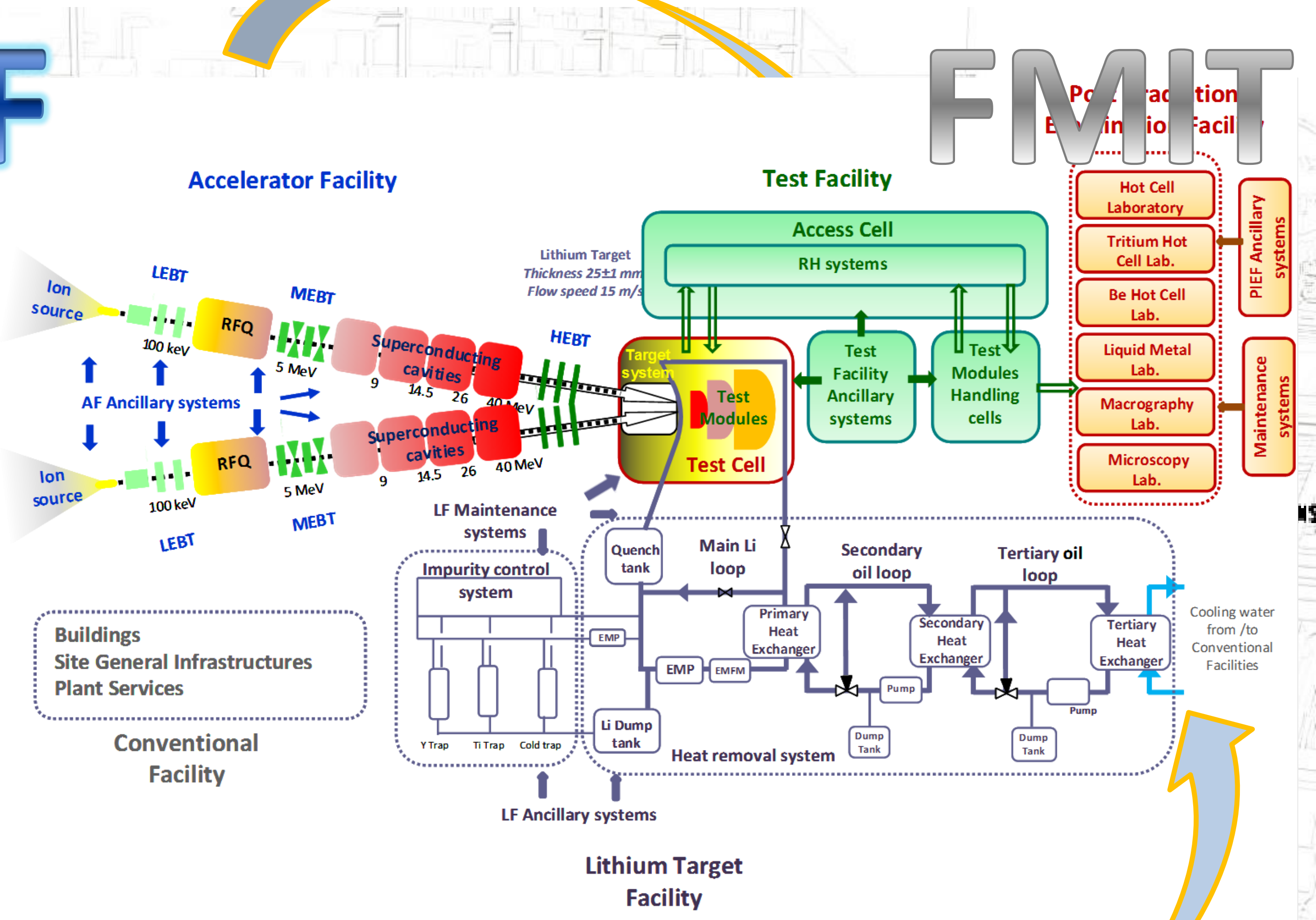
CrossMark

Abstract
The International Fusion Materials Irradiation Facility (IFMIF), presently in its Engineering Validation and Engineering Design Activities (EVEDA) phase under the frame of the Broader Approach Agreement between Europe and Japan, accomplished in summer 2013, on schedule, its EDA phase with the release of the engineering design report of the IFMIF plant, which is here described. Many improvements of the design from former phases are implemented, particularly a reduction of beam losses and operational costs thanks to the superconducting accelerator concept, the re-location of the quench tank outside the

0029-5515/15/086003+30$33.00 1



J. Knaster et al, *The accomplishment of the Engineering Design Activities of IFMIF/EVEDA: The European–Japanese project towards a Li(d,xn) fusion relevant neutron source*, **Nuclear Fusion 55 (2015) 086003**

IFMIF

International Fusion Materials Irradiation Facility

EVEDA

Engineering Validation & Engineering Design Activities

…to produce an integrated engineering design of IFMIF and the data necessary for future decisions on the construction, operation, exploitation and decommissioning of IFMIF, and to validate continuous and stable operation of each IFMIF subsystem

Signed in February 2007

Framed by the Broader Approach Agreement

FUSION FOR ENERGY

QST

cea

Ciemat

Tohoku University

Osaka University

Nagoya University

INFN

ENEA ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

Hachinohe Institute of Technology

Kyushu University

Tokyo University

SCK•CEN

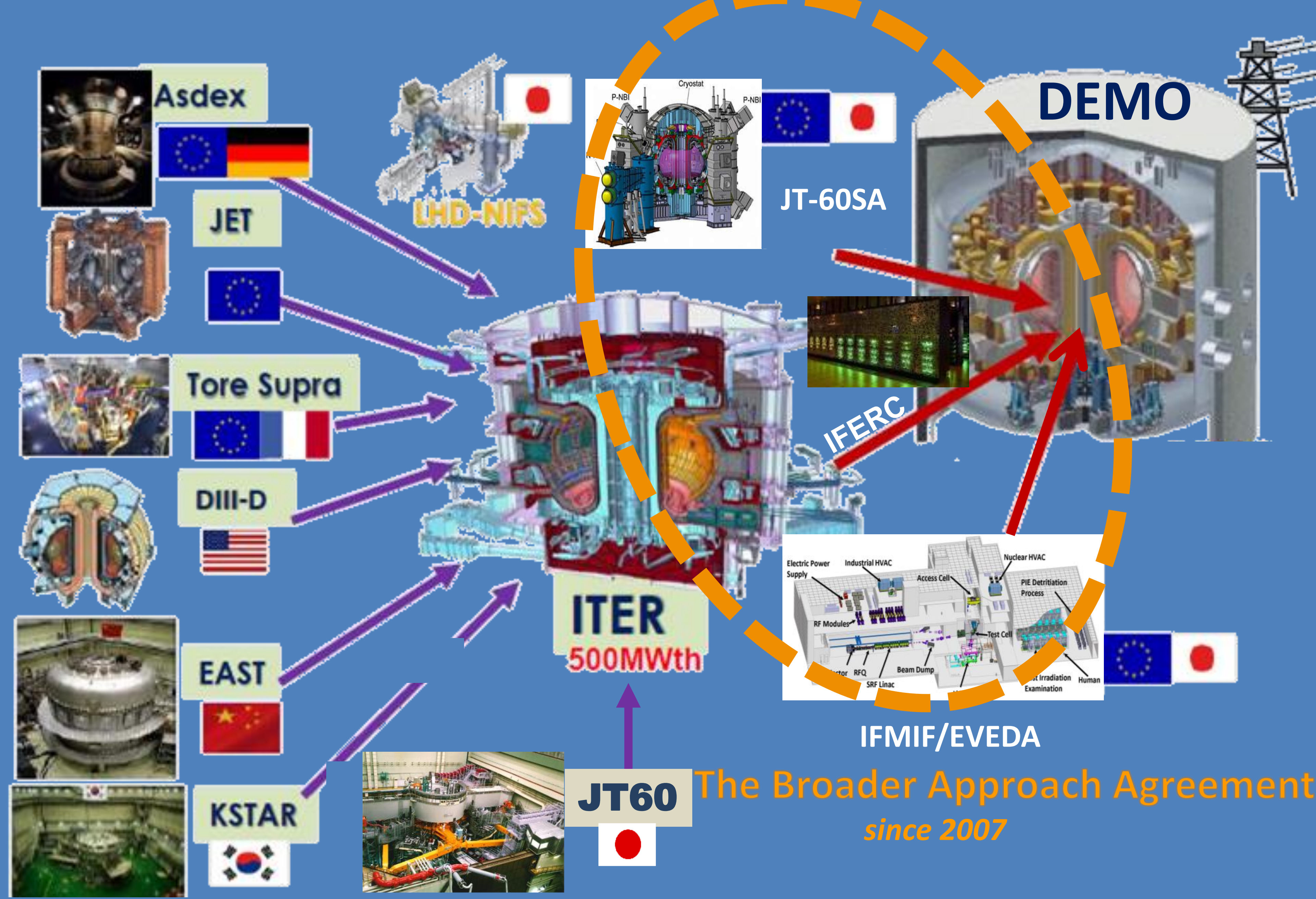
EPFL

KIT

LHD NIFS

Hachinohe National College of technology

KYOTO UNIVERSITY FOUNDED 1897

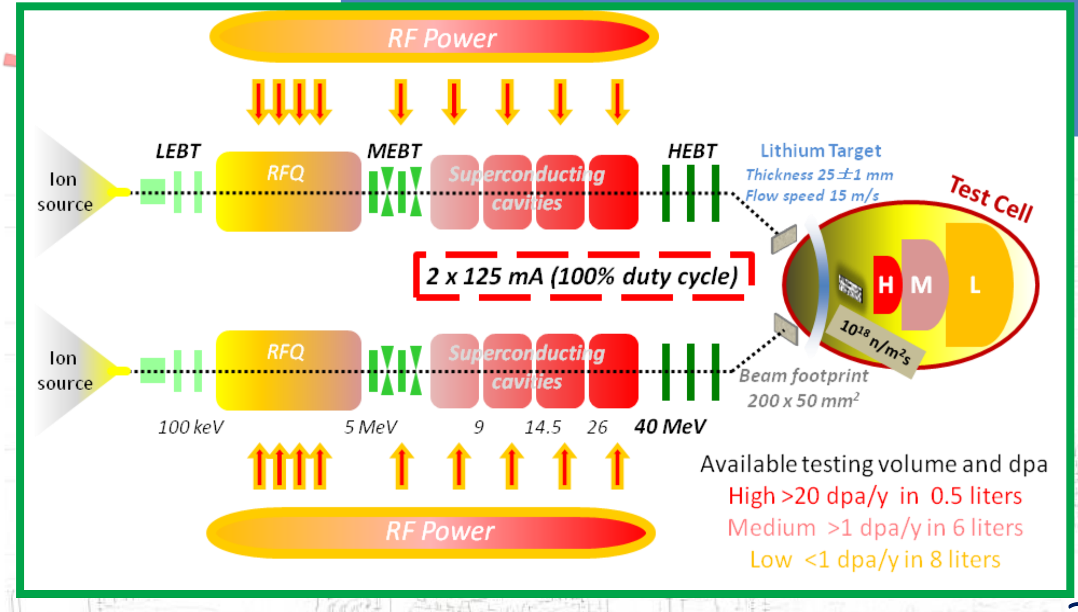


J. Knaster et al.

IAEA Fusion Energy Conference
October 2016

QST FUSION FOR ENERGY

IFMIF concept



Two concurrent

125 mA CW deuterons beam

at 40 MeV

impact with

a beam footprint of 200 x 50 mm^2

on a liquid Li screen

flowing at 15 m/s

A flux of neutrons of ~10^{18} $m^{-2}s^{-1}$

is generated in the forward direction

with a broad peak at

14 MeV

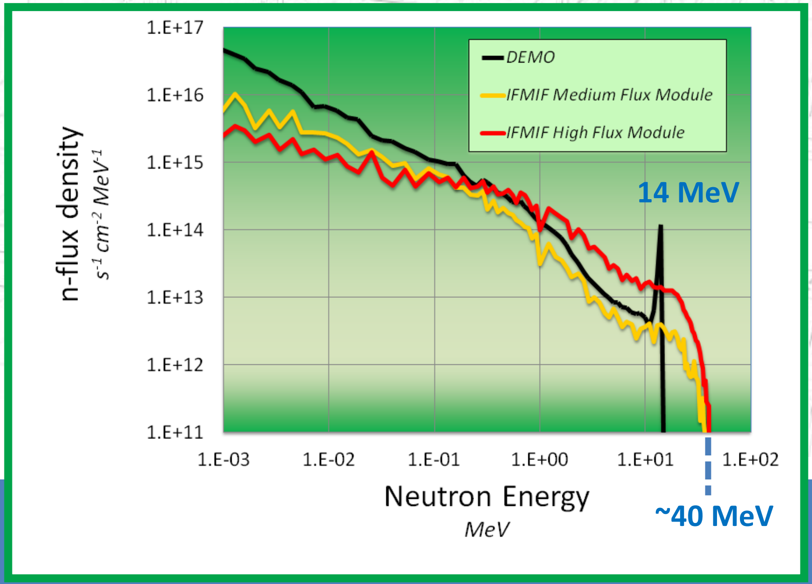
and irradiate three regions

>20 dpa/y in 0.5 liters

>1 dpa/y in 6 liters

<1 dpa/y in 8 liters

Availability of facility >70%



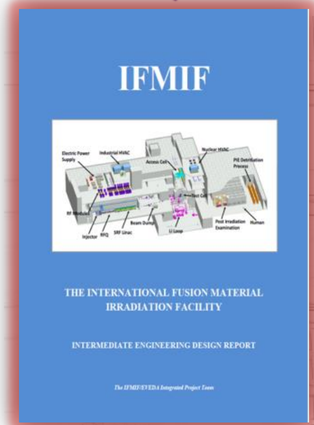
J. Knaster et al.

EVEDA = EDA + EVA Phases

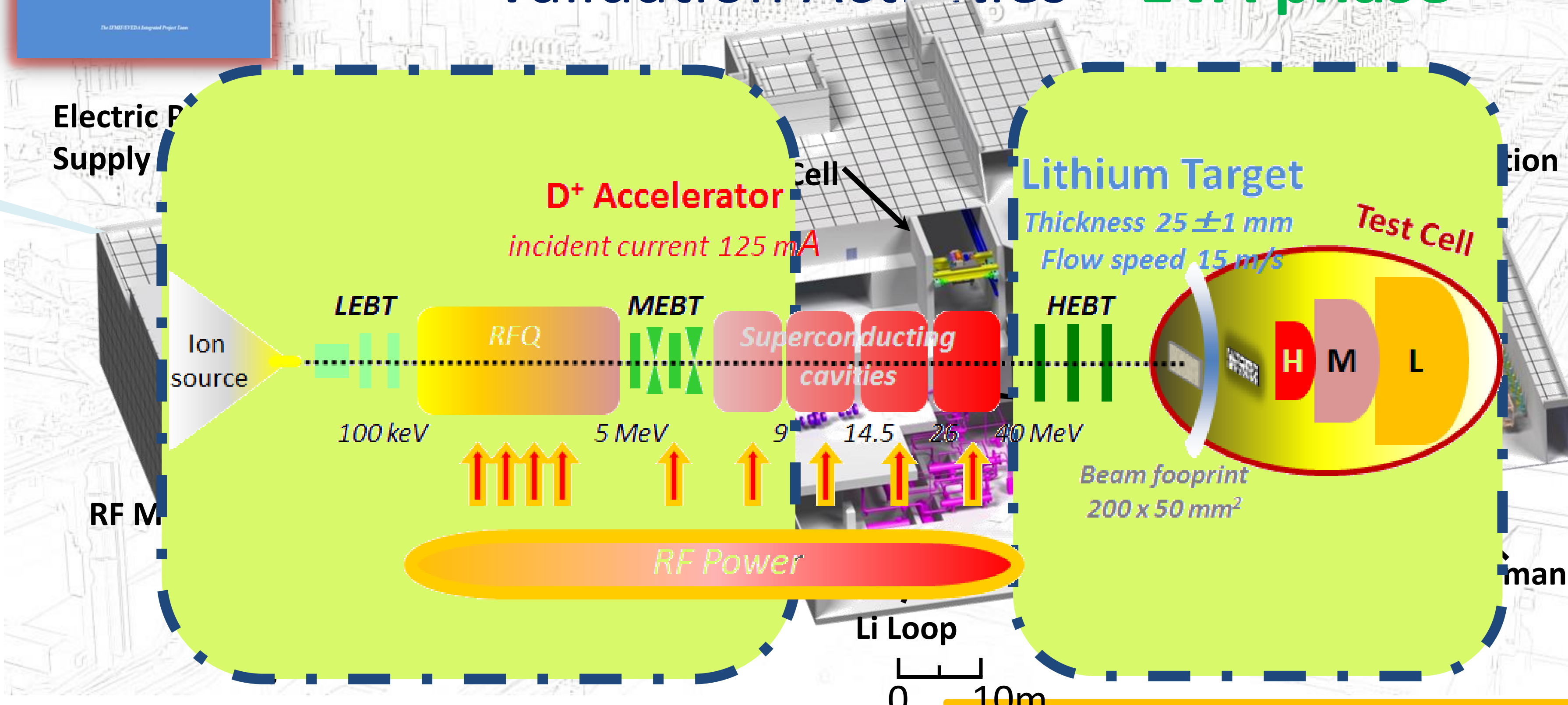
Engineering Design Activities – EDA phase

Successfully delivered on schedule

J. Knaster et al, *The accomplishment of the Engineering Design Activities of IFMIF/EVEDA: The European–Japanese project towards a Li(d,xn) fusion relevant neutron source*, **Nuclear Fusion 55 (2015) 086003**



Validation Activities – EVA phase



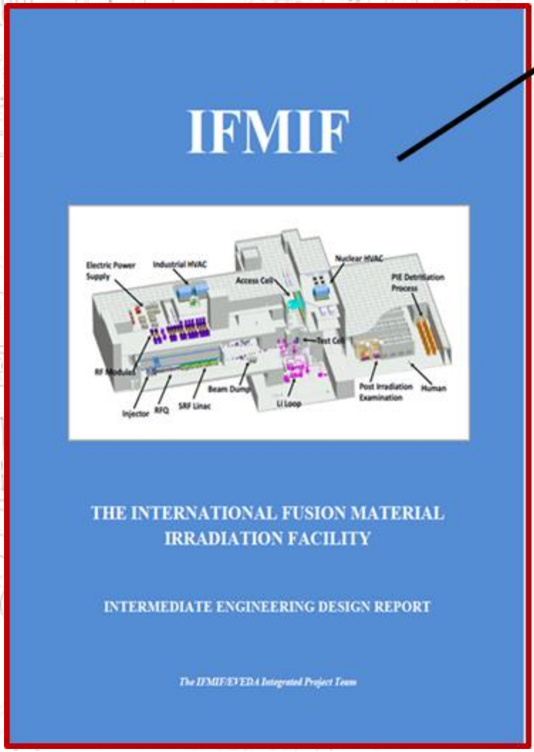
J. Knaster et al., *IFMIF: overview of the validation activities*, **Nuclear Fusion 53 (2013) 116001**

Engineering Design Activities (EDA) Phase

It includes

>100 technical reports

interfaces with thorough 3D models, licensing scenarios, RAMI analysis, nuclear safety studies, beam dynamics, 35 Detail Design Description documents of all sub-systems and cost&schedule



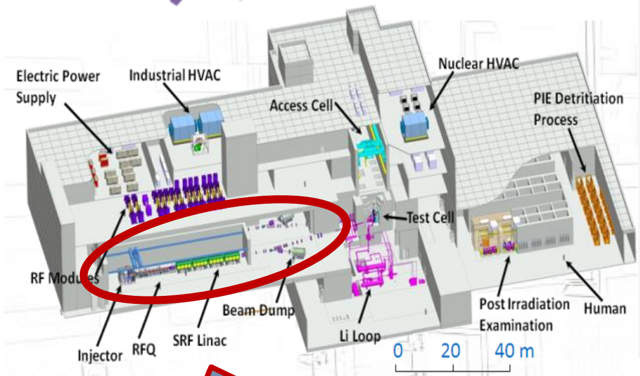
- Executive Summary (this document)
- IFMIF Plant Design Description Document (PDD)
- Cost Estimate Report
- PDD Annexes
  - I. Design Guidelines
    - Annex I.1-CAD Guidelines
    - Annex I.2- EDA ALARA Process Guideline
    - Annex I.3- Fire Protection Guideline
    - Annex I.4- Hazard Evaluation Guideline
    - Annex I.5- Human Factor Approach Design Guideline
    - Annex I.6- IFMIF Generic Site Assumptions Guideline
    - Annex I.7- IFMIF Materials Library
    - Annex I.8- Liquid Metal Handling Guideline
    - Annex I.9- RAM Guidelines
    - Annex I.10- Remote Handling Design Guideline
    - Annex I.11- Safety Specifications Guideline
    - Annex I.12- Tritium Safe Handling Guideline
  - II. PBS and Interface Management System
  - III. 3D MockUp
  - IV. Compilation of Safety-related reports
    - Annex IV.1-Safety Important Class (SIC)
    - Annex IV.2- Confinement Strategy
    - Annex IV.3- Tritium Source Term
    - Annex IV.4- AF Safety Report
    - Annex IV.5- LF Safety Report
    - Annex IV.6- CF Safety Report
    - Annex IV.7- TF FMECA
    - Annex IV.8- TF Safety Requirements
    - Annex IV.9- PIES
  - V. RAMI
  - VI. Licensing Scenarios
  - VII. IFMIF Beam Dynamics

SYSTEM DESIGN DESCRIPTION DOCUMENTS (DDDs)

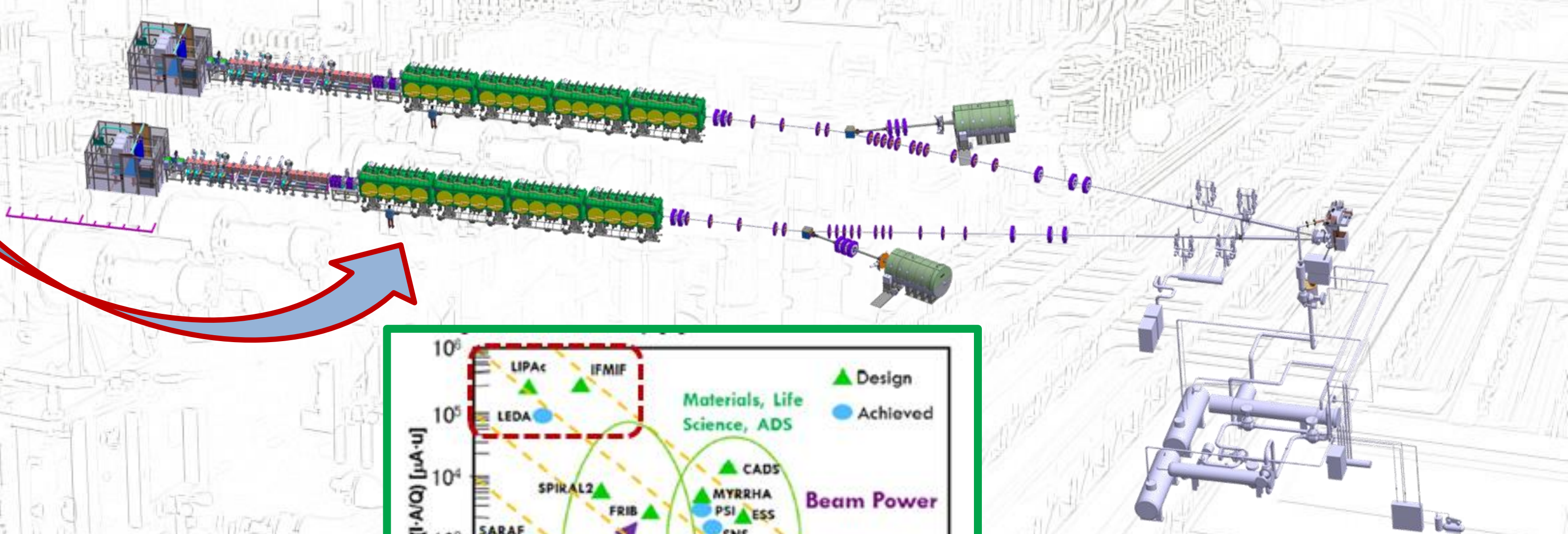
- Test Facility(TF)
  - Test Cell, Access Cell and Test Module Handling Cell
  - TF Auxiliaries
  - TF Remote Handling
  - Test Modules
    - High Flux Test Module (HFTM) - Vertical
    - High Flux Test Module (HFTM) - Horizontal
    - Start-Up and Monitoring Module (STUMM)
    - Creep Fatigue Test Module (CFTM)
    - Tritium Release Test Module (TRTM)
    - Liquid Breeder Validation Module (LBVM)
    - Low Flux Validation Module (LFVM)
- Lithium Facility (LF)
  - Lithium Facility (Integral Target Assembly)
  - Target System - Bayonet Concept
- Accelerator Facility (AF)
  - Injector
  - Radio Frequency Quadrupole (RFQ)
  - Medium Energy Beam Transfer (MEBT)
  - Superconducting RF Linacs
  - High Energy Beam Transfer (HEBT)
  - Radio Frequency (RF) Power
  - Diagnostics
  - Beam Dumps
  - Accelerator Auxiliaries
- Conventional Facility (CF)
  - Building and Site Infrastructure
  - Electrical Power System
  - Heat Rejection System
  - Heating, Ventilation and Air Conditioning System (HVAC)
  - Service Gas System
  - Service Water System
  - Solid Waste Treatment System
  - Liquid Waste Treatment System
  - Exhaust Gas Processing System
  - Fire Protection System
  - Radiation Monitoring System
  - Central Control & Common Instrumentation
  - Access Control & Security System

Figure 3. List of documents of the IIEDR.

EVA Phase – Accelerator Facility



Deuteron beams 2 x 125 mA in CW
40 MeV energy
2 x 5 MW beam power



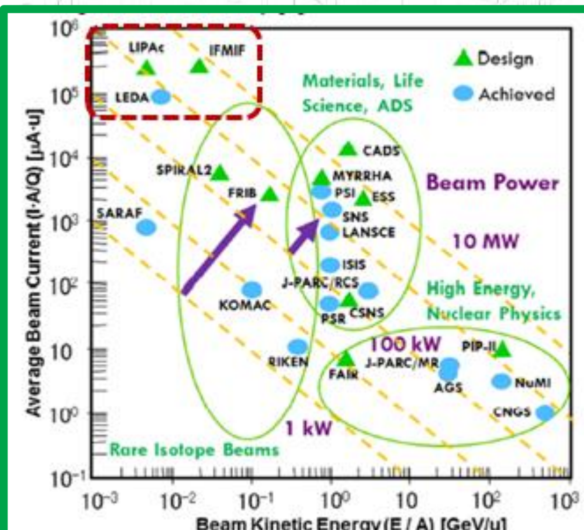
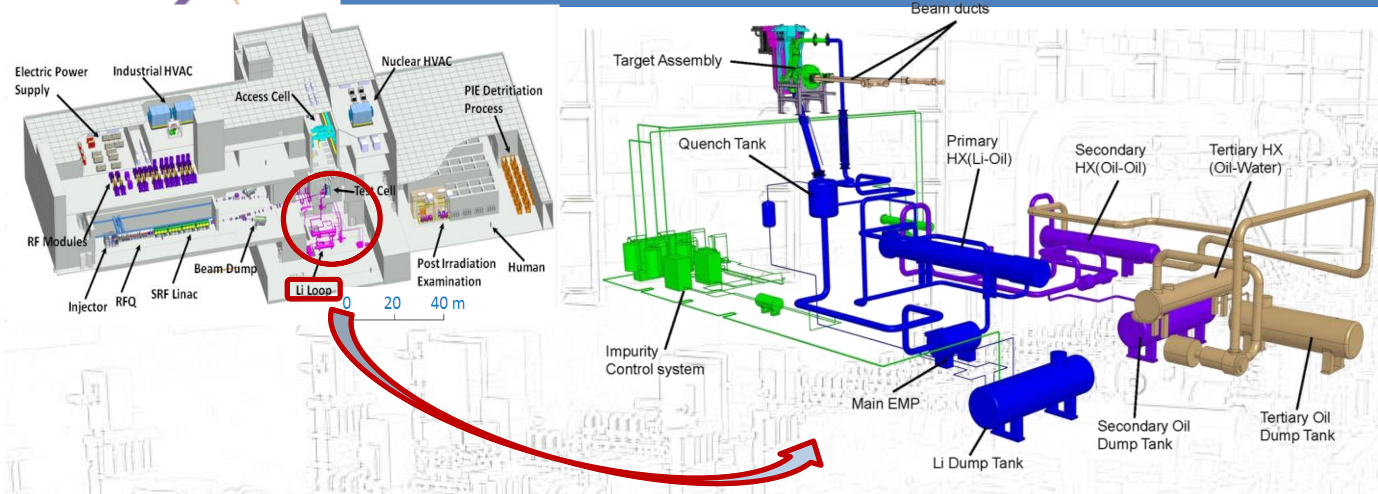


Figure 1: Hadron accelerator power frontier.

J. WEI et al., *The very high intensity future*, ***IPAC 2014*, *Dresde***

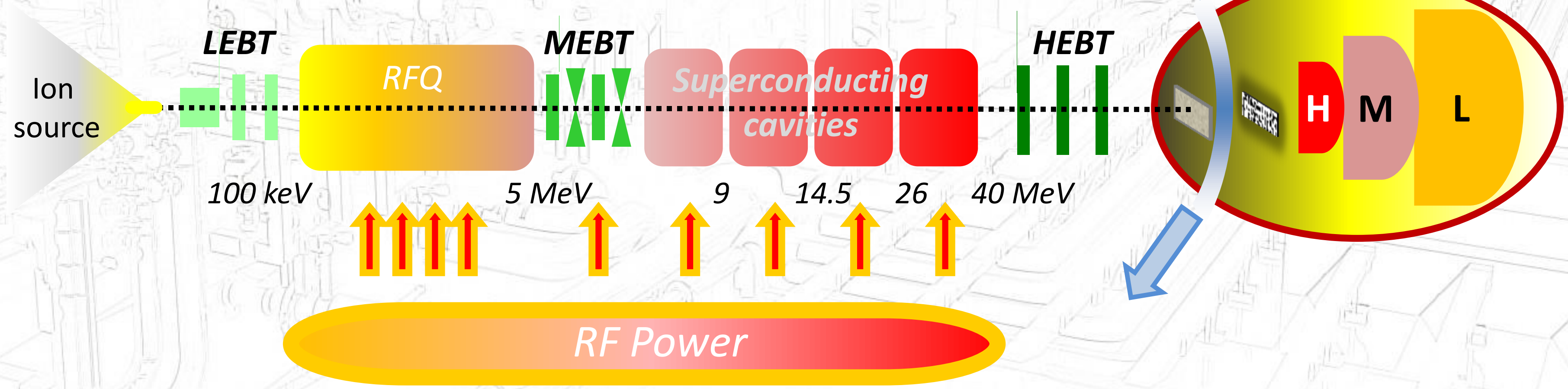
EVA Phase – Target Facility



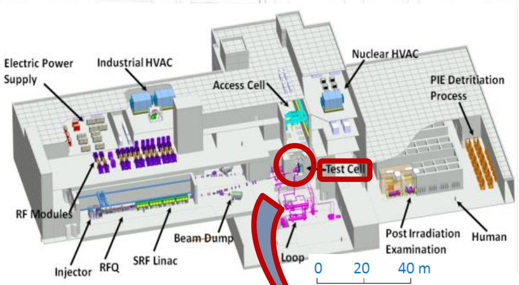
Lithium jet at 250 C
Flow speed 15 m/s
Thickness 25 ±1 mm

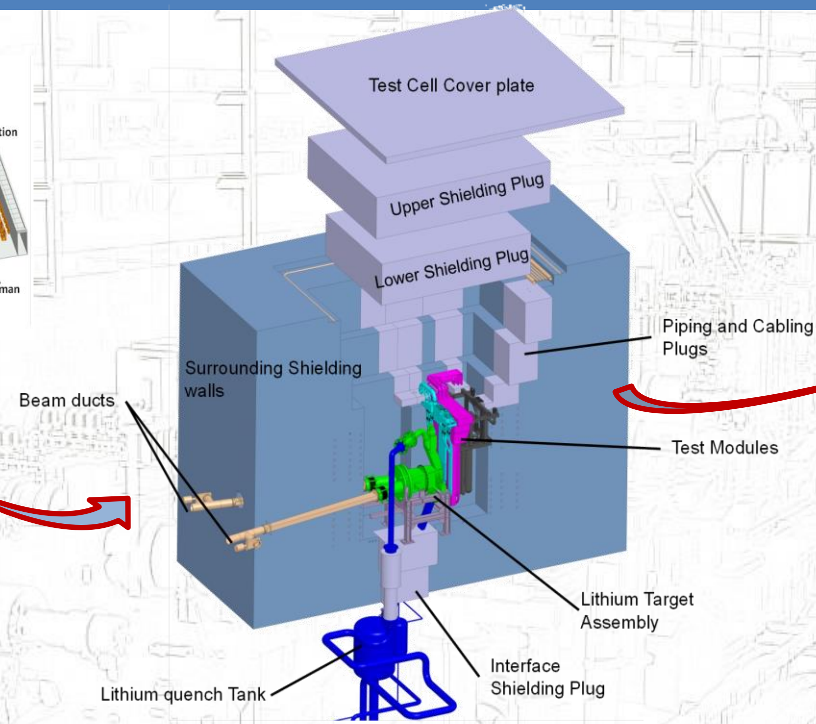
D^+ Accelerator

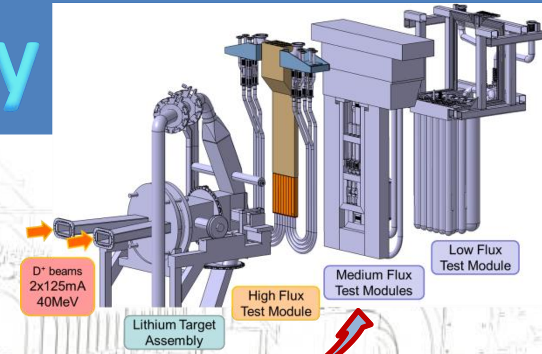
incident current 125 mA



EVA Phase – Test facility







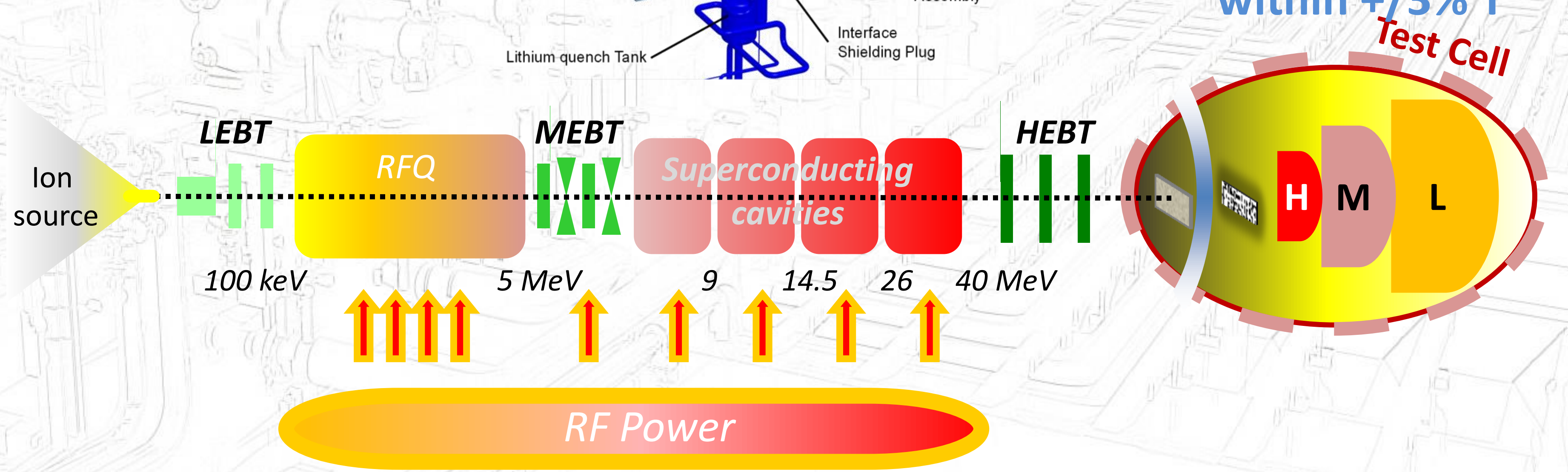
HFTM

20 dpa/y in 500 cm^3

12 x 80 small specimens

independently cooled

within +/3% T



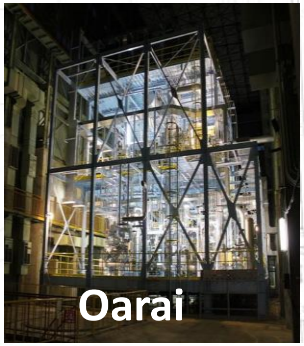
The validation activities covered
a very wide range

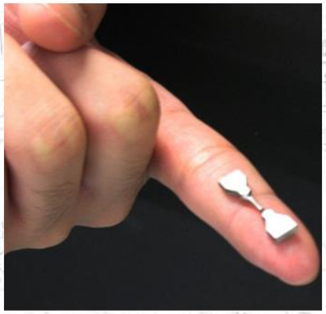
There is no time to cover the full scope
in this talk

J. Knaster et al., *IFMIF: overview of the validation activities,* **Nuclear Fusion 53 (2013) 116001**

I will focus on identifying
those historical main technological challenges
and explain how EVEDA has addressed them

Five major historical technical concerns addressed in IFMIF/EVEDA





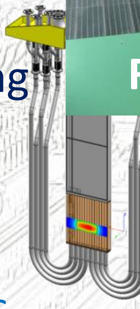
1st concern: D⁺ accelerator of 125 mA CW at 40 MeV
D⁺ prototype accelerator of 125 mA CW at 9 MeV in Rokkasho

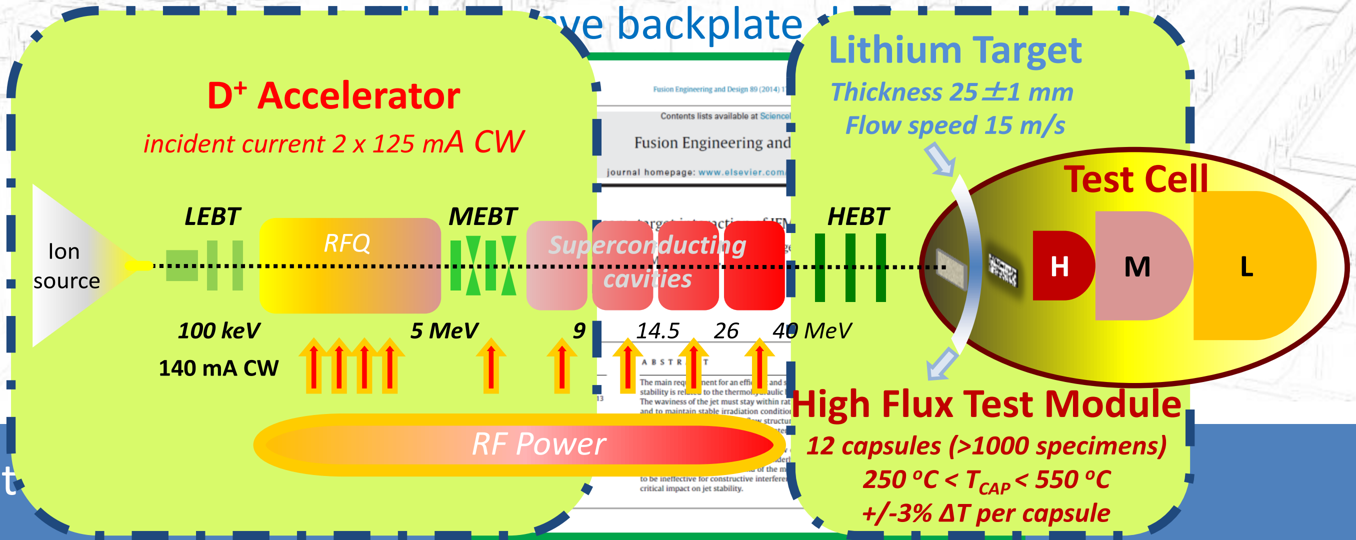
2nd concern: Stable flow of lithium at required performance
Full scale prototype of Li facility in Oarai

3rd concern: Irradiated capsules allowing independent cooling
High Flux Test Module prototype in KIT

4th concern: Small Specimens Test Techniques
Shape validation for pending specimens in Japanese Univers.

5th concern: 2 x 5 MW beam vs target interaction
ve backplate

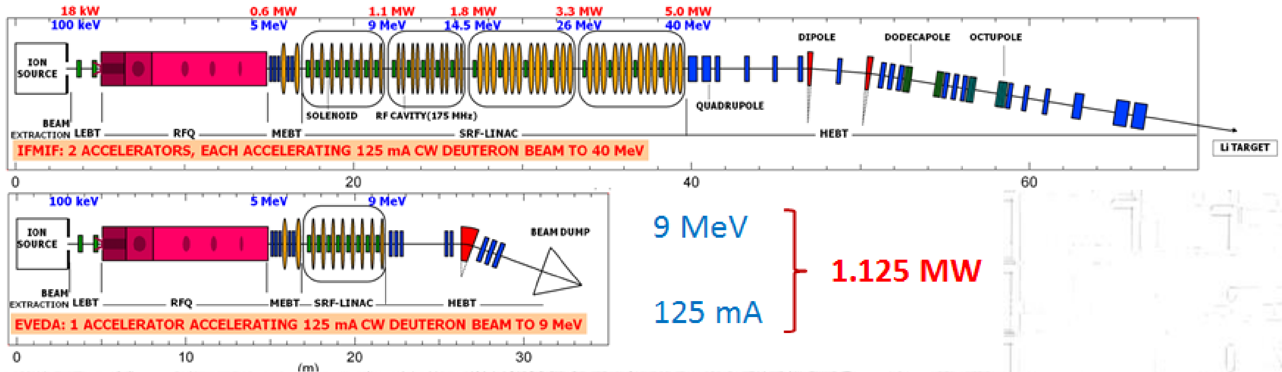




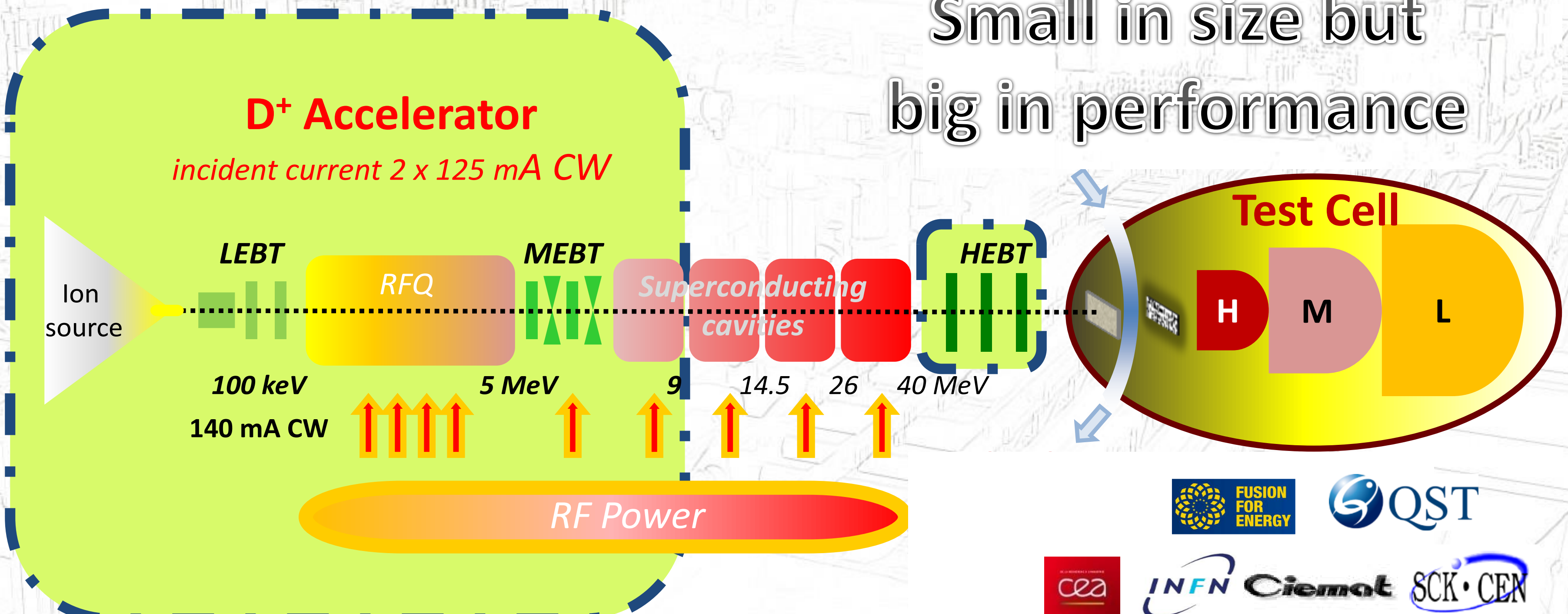
1st concern: D+ accelerator of 125 mA CW

IFMIF

LIPAc

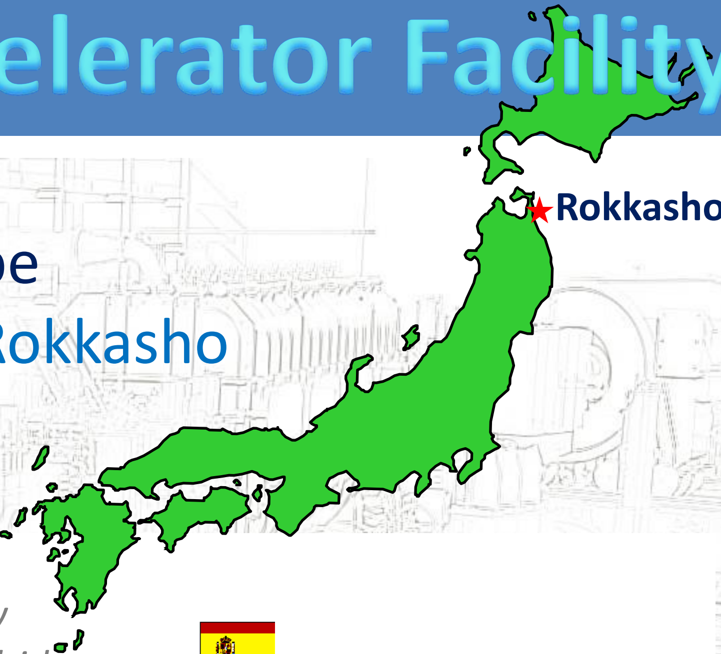


Small in size but big in performance



EVA Phase – Accelerator Facility

Equipment designed
and constructed in Europe
Installed and commissioned in Rokkasho



FUSION FOR ENERGY QST cea Ciemat INFN SCK•CEN

1st concern: D+ accelerator of 125 mA CW

The accelerator of records

LIPAc is very ambitious

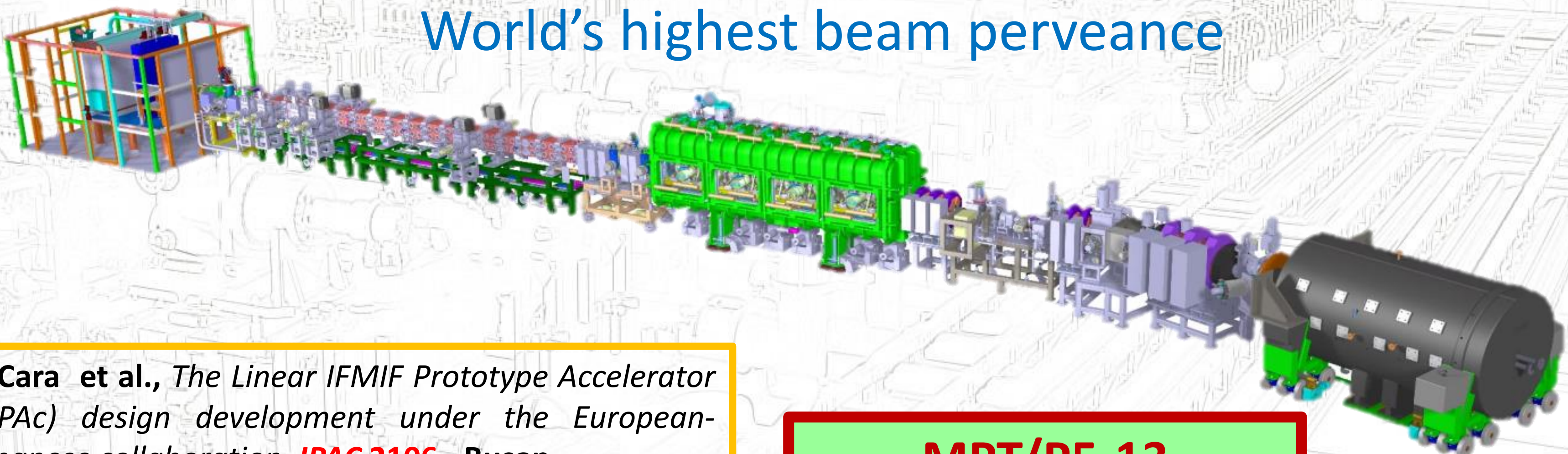
World's highest current linac

World's top H^+&D^+ injector performance

World's longest RFQ

World's record of light hadrons current through SC cavities

World's highest beam perveance



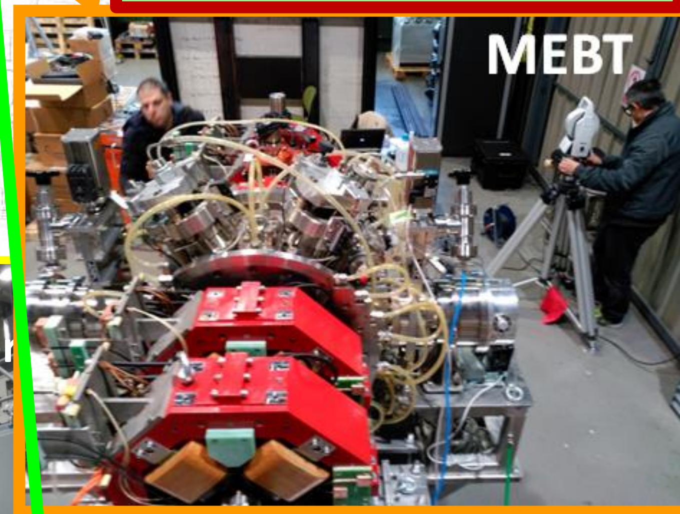
P. Cara et al., *The Linear IFMIF Prototype Accelerator (LIPAc) design development under the European-Japanese collaboration, IPAC 2106* - **Busan**

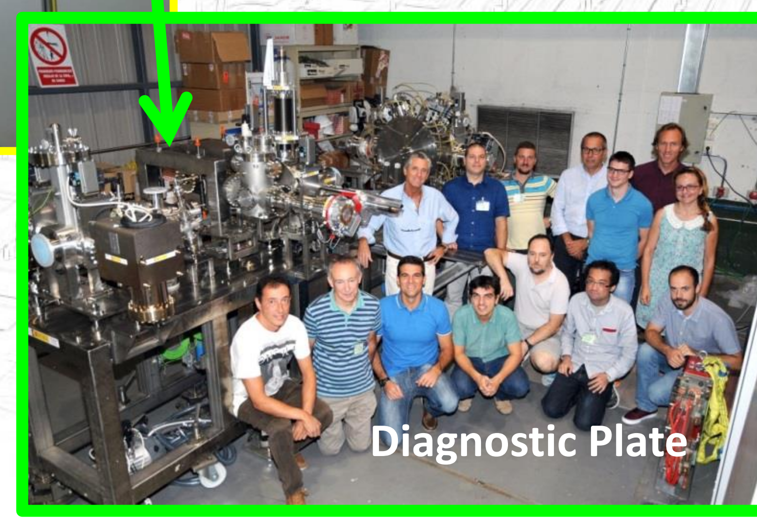
MPT/P5-13

A. Kasugai et al., *Progress on the Development of Linear IFMIF Prototype Accelerator and the Beam Commissioning*

MPT/P5-13

A. Kasugai et al., *Progress on the Development of Linear IFMIF Prototype Accelerator and the Beam Commissioning*





Are we technologically ready for such accelerator?

Evolution of accelerators technology since FMIT

The 1st attempt to run a RFQ in CW was in Los Alamos (LANL) for FMIT accelerator validation exercise

The 'beam halo' was discovered the rough way

80s

W.D. Cornelius, *CW operation of the FMIT RFQ accelerator*, **Nucl. Instr. Meth. Phys. Res. B10/l1 (1985) 859-863**

90s

T. Taylor and J.S.C. Wills, *A high-current low-emittance dc ECR proton source,* **Nucl. Instr. Meth. Phys. Res. A309, (1991)**

Beam quality injected in RFQ was poor

ECR approach was technologically validated for H^+ in Chalk River

1999

L.M. Young et al., *High power operations of LEDA*, **LINAC 2000, Monterey**

LANL successfully operated LEDA

100 mA in CW at 6.7 MeV

with a dual electrodes capacitive/inductive part cooling RFQ tuning

and unraveled beam halo physics the following years

2001

C.K. Allen et al., *Beam-Halo Measurements in High-Current Proton Beams*, **Phys. Rev. Lett. 89, Number 21, 18 Nov. 2002**

2001

Alvarez type accelerating structure (DTL) for beam energies within $0.2<\beta<0.6$ is a difficult challenge for high currents in CW

the feasibility of superconducting resonators for low-β was demonstrated in LANL in 2002

M. Kelly, *Superconducting Radio-Frequency Cavities for Low-Beta Particle Accelerators*, **Reviews of Accelerator Science and Technology 5:185 (2012)**

T. Tajima, et al., *Evaluation and Testing of a Low-β Spoke Resonator*, **PAC 2001, Chicago**

2010

Operation of superconducting HWR cavities in CW

SARAF has operated 176 MHz HWR cavities in CW in 2010

J. Knaster and Y. Okumura, *Accelerators for fusion materials testing*, **Reviews of Accelerator Science and Technology 8, 115142 (2015)**

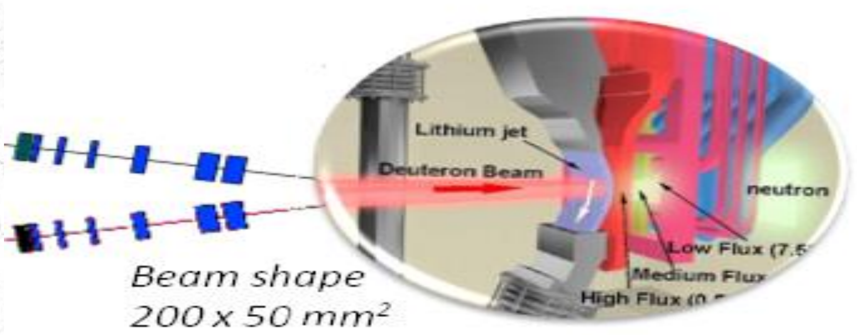
D. Berkovits et al., *Operational experience and Future goals of the SARAF proton/deuteron linac*, **LINAC 2012, Tel-Aviv**

LIPAc implements best possible technologies

2nd concern: Stable flow of lithium at required performance

The mandate was challenging
the demonstration
of the flow operational conditions of IFMIF lithium target

Lithium temperature at 250 °C
Flow speed at 15 m/s
Stable flow with +/- 1 mm amplitude
10^{-3} Pa on free surface
Long term operation stability
Free surface interferometry diagnostics
Feasibility of Impurities in lithium <10 ppm

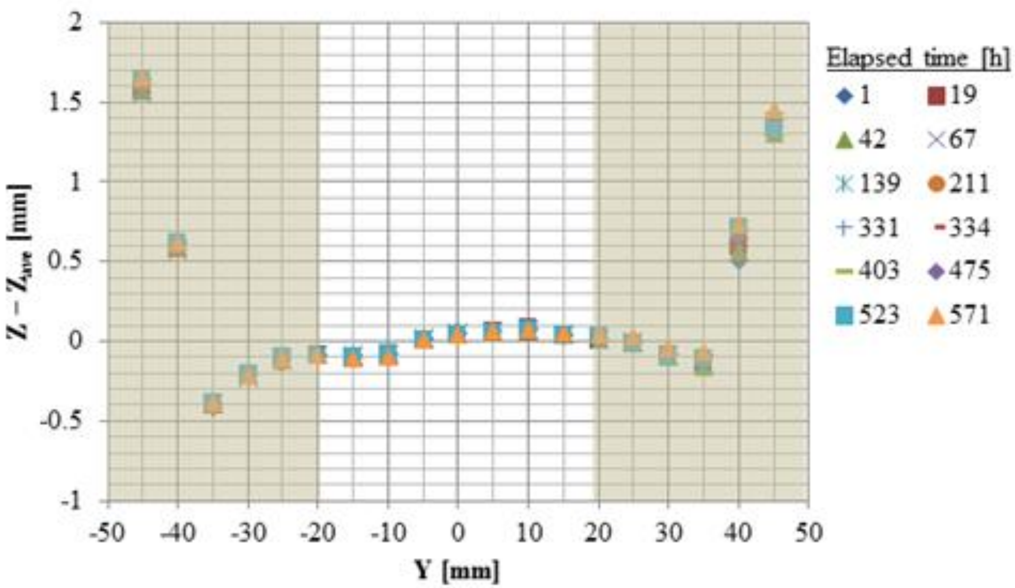


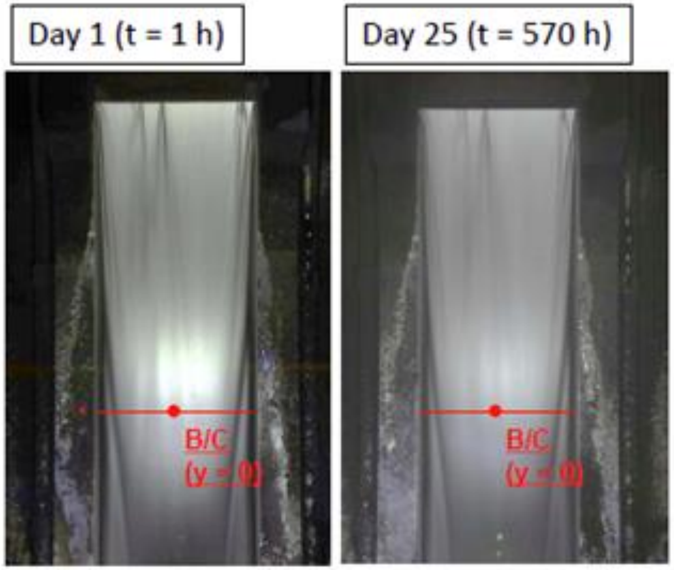
Operated until October 2014

Kondo, H. et al. *Validation of IFMIF liquid Li target for IFMIF/EVEDA Project,* **Fusion Eng. Des. 9697, 117122 (2015)**

2nd concern: Stable flow of lithium at required performance

The result of 25 days continuous operation (24 h/day)





MPT/P5-41

F. Arbeiter et al.,

The Accomplishments of Lithium Target and Test Facility Validation Activities in the IFMIF/EVEDA Phase

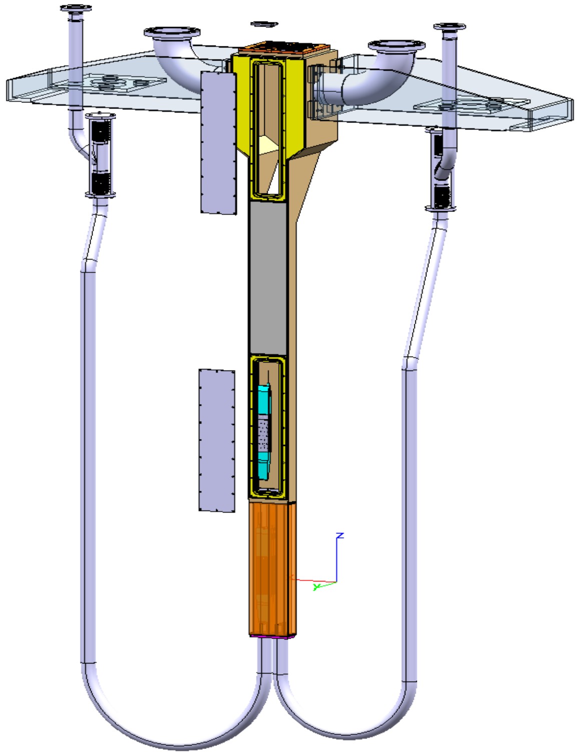
MPT/P5-11

H. Kondo et al.,

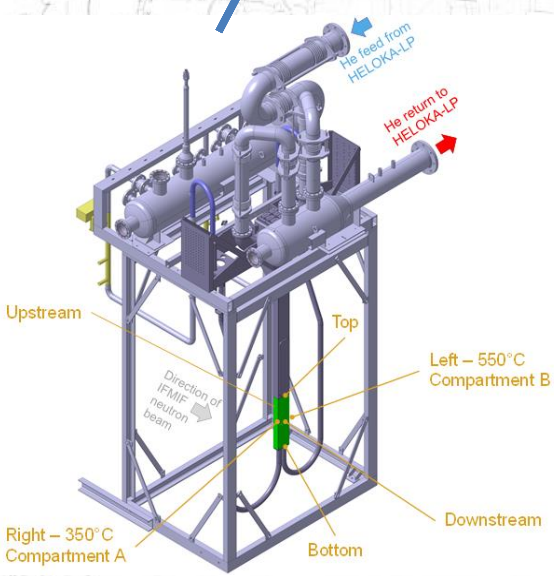
Validation of Liquid Lithium Target Stability for Intense Neutron Source

Long term flow stability demonstrated

3th concern: Irradiated capsules allowing independent cooling



HFTM-Double Compartment



MPT/P5-41
F. Arbeiter et al.,
The Accomplishments of Lithium Target and Test Facility Validation Activities in the IFMIF/EVEDA Phase

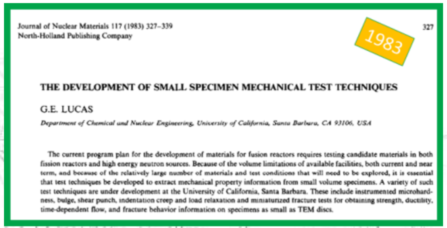
Target T uniformity of specimens demonstrated

4th concern: Small Specimens Test Techniques

Small specimens

are neither exclusive of fusion

nor a new technology


Journal of Nuclear Materials 117 (1983) 327–339
North-Holland Publishing Company
327

1983

THE DEVELOPMENT OF SMALL SPECIMEN MECHANICAL TEST TECHNIQUES

G.E. LUCAS
Department of Chemical and Nuclear Engineering, University of California, Santa Barbara, CA 93106, USA

The current program plan for the development of materials for fusion reactors requires testing candidate materials in both fission reactors and high energy neutron sources. Because of the volume limitations of available facilities, both current and near term, and because of the relatively large number of materials and test conditions that will need to be explored, it is essential that test techniques be developed to extract mechanical property information from small volume specimens. A variety of such test techniques are under development at the University of California, Santa Barbara. These include instrumented microhardness, bulge, shear punch, indentation creep and load relaxation and miniaturized fracture tests for obtaining strength, ductility, time-dependent flow, and fracture behavior information on specimens as small as TEM discs.


ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
journal of nuclear materials

2007

The role of small specimen test technology in fusion materials development

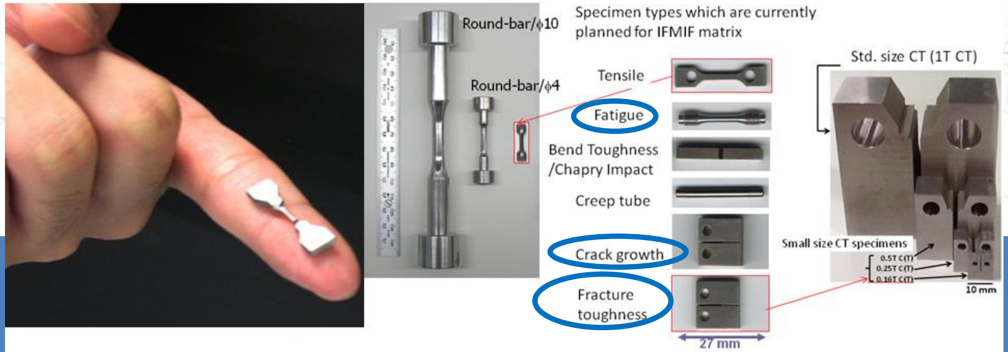
G.E. Lucas, G.R. Odette, H. Matsui, A. Möslang, P. Spätig, J. Rensman, T. Yamamoto

Under EVEDA intense work has been developed on

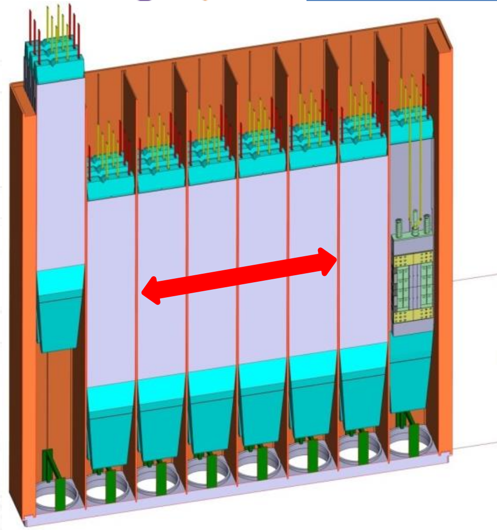
Fatigue

Fracture toughness

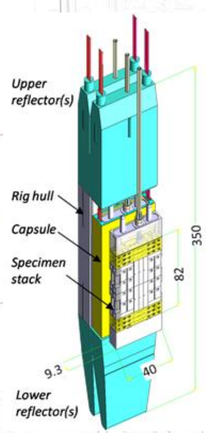
Crack growth rate



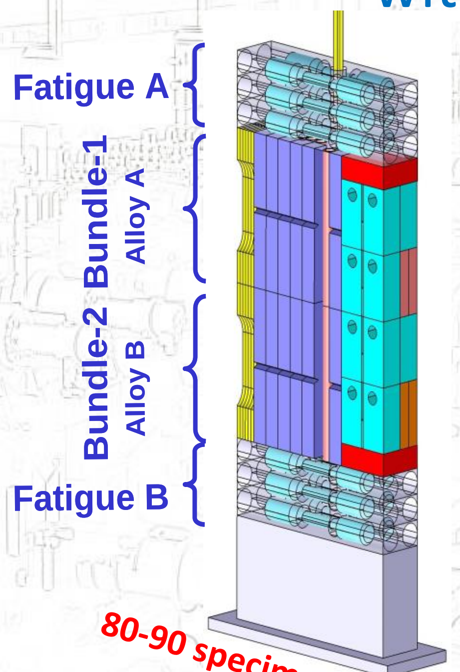
4th concern: Small Specimens Test Techniques



8 compartment
4 central directly irradiated

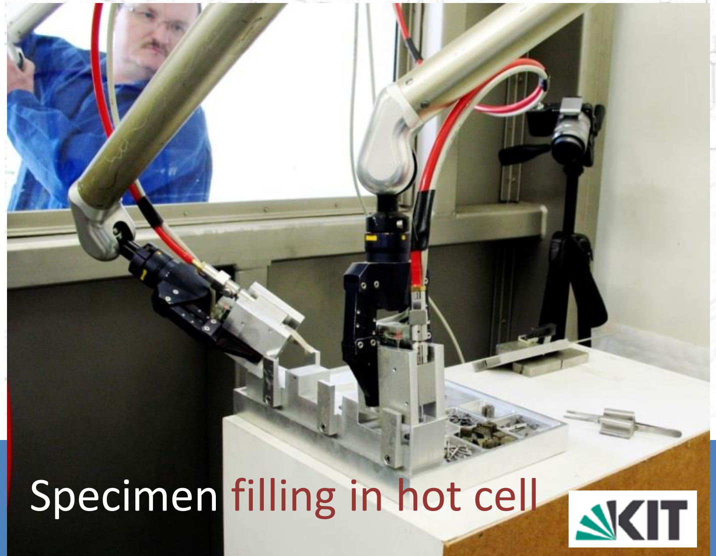


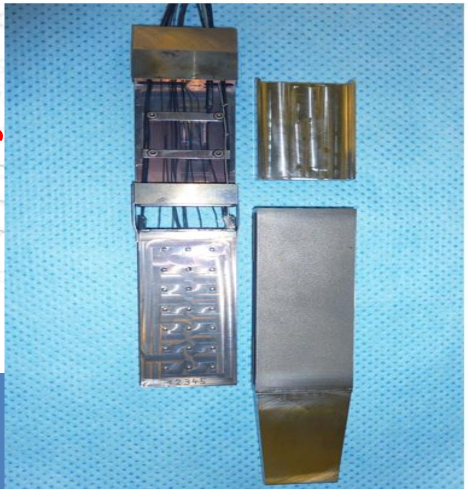
12 capsules within beam footprint
x2 sets of 40-45 spec/capsule
within 3% ΔT/capsule



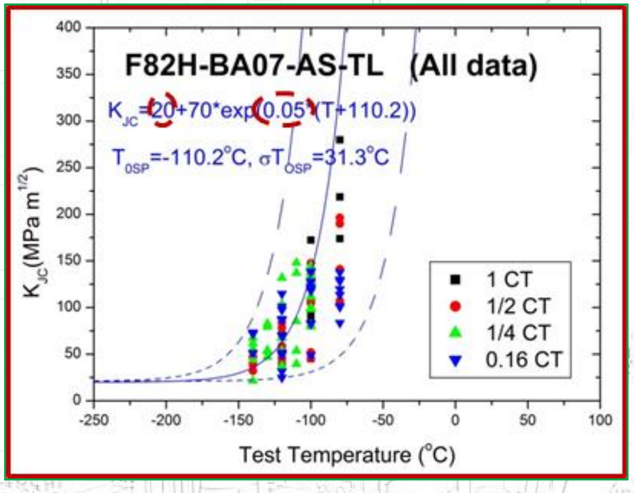
80-90 specimens/capsule

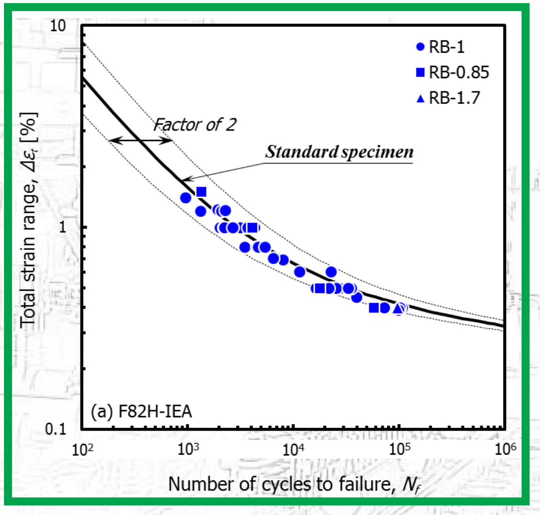
Thermalized with NaK





4th concern: Small Specimens Test Techniques



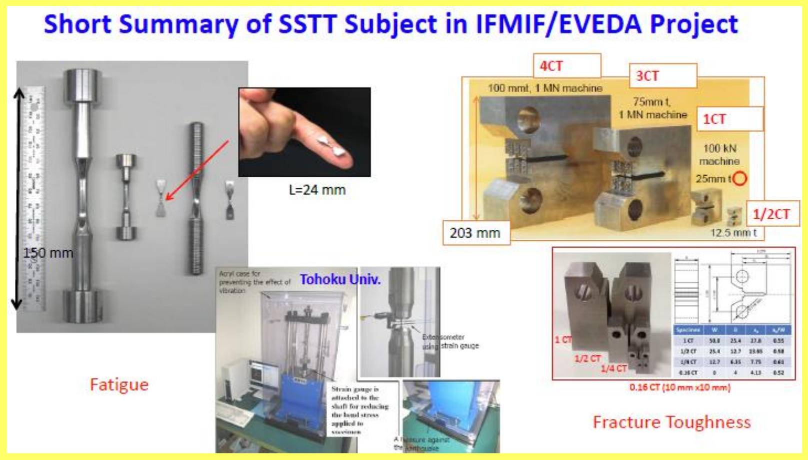


Master Curve for ferritic steels under ASTM E1921 did not work
an adaptation is being studied

Fatigue matches standard specimens

MPT/P5-25

E. Wakai et al., *Small Specimen Test Technology Develop. towards Design of Fusion DEMO Reactors and Future Direction Plan*



IAEA's Coordinated Research Project launched
'Towards standardization of SSTT for Fusion applications'

5th concern: Beam – Li target interaction

Y. Momozaki et al., *Proton beam-on-liquid lithium stripper film experiment*, J. Radioanal Nucl. Chem. (2015)

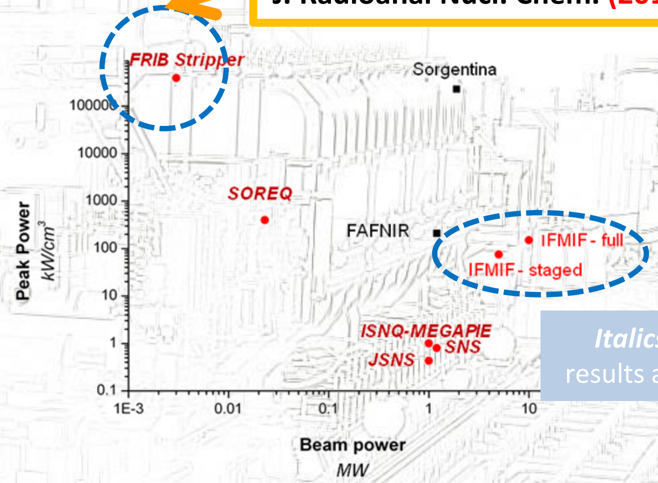
Design of the Li target implements the lessons learnt throughout 30 years of studies

Bragg's peak in Li of 40 MeV at 19 mm
25 mm thick screen +/-1 mm perturbations

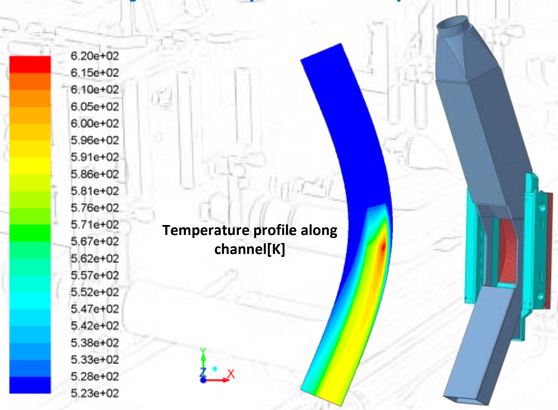
Power density of 1 GW/m^2 (beam footprint maximized)
~x10 lower than FMIT

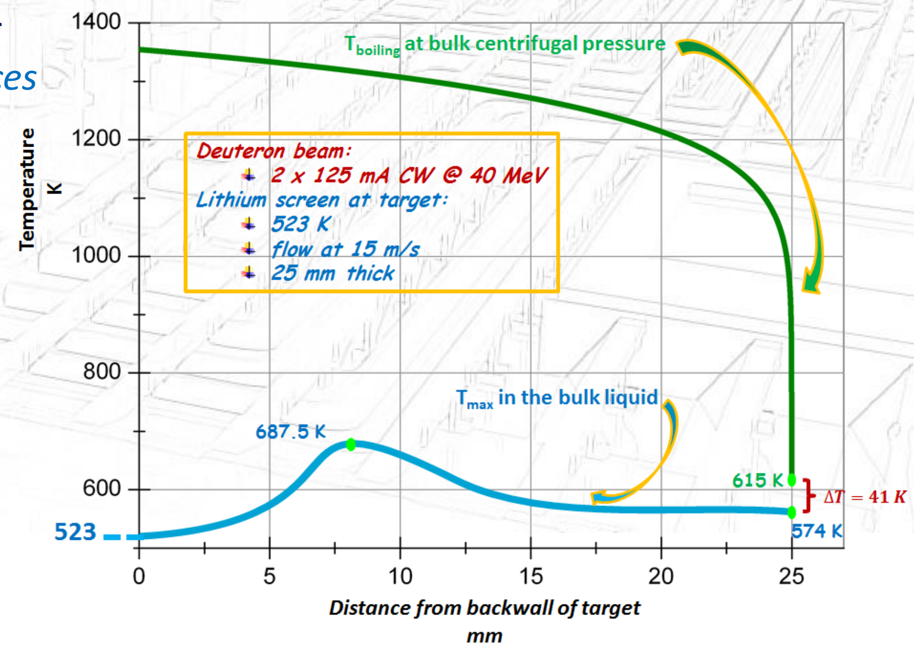
Concave back plate leads to kPa centrifugal pressures
Maximum pressure waves amplitudes of 32 Pa

15 m/s liquid Li speed evacuate the beam power
V_{max} = 0.5 m/s of wave pressure prevents resonances



Italics fonts results achieved





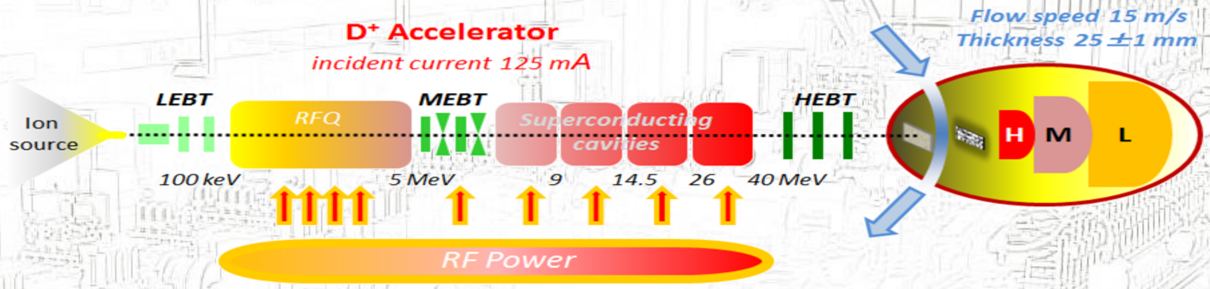
J. Knaster et al., *Assessment of the beam-target interaction of IFMIF: state of the art*, **Fusion Engineering and Design 89 (2014) 1709–1716**

Do we need IFMIF?

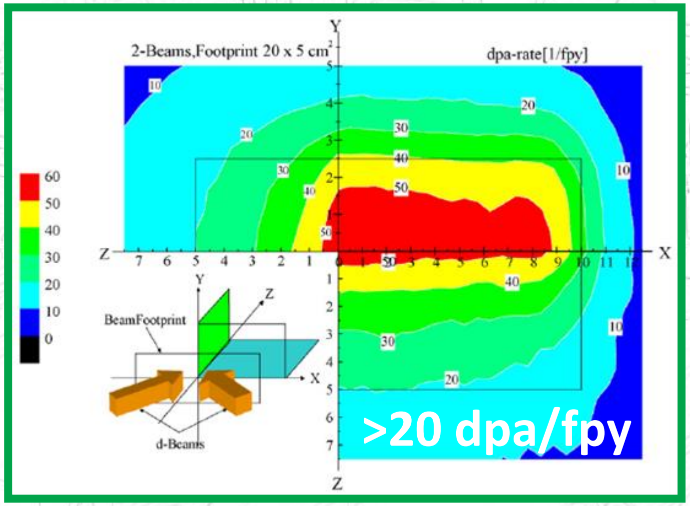
Possibly not

one only accelerator suffices

to cope with present DEMO expected performance



A sensitivity analysis with involved parameters has been carried out



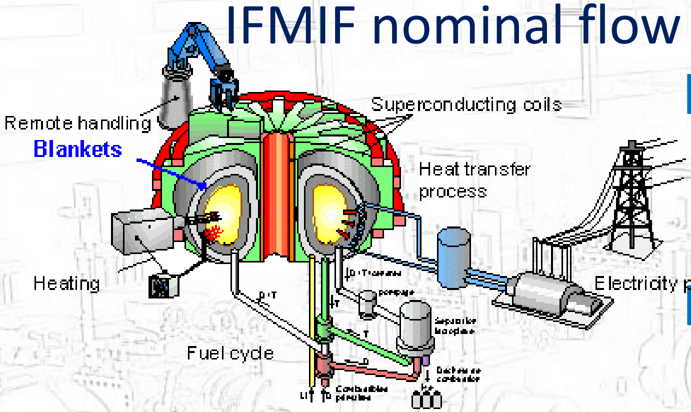
F. Mota et al., *Sensitivity of IFMIF-DONES irradiation characteristics to different design parameters*, **Nuclear Fusion (2016)**

Deuteron energy *MeV*	n spectrum broad peak *MeV*	Bragg peak *mm*	Relative cross section $^{56}Fe(n,\alpha)^{53}Cr$
9	~4	1	2.5 x 10^{-3}
26	~10	7	0.5
40	~15	19	1

Conclusions

The EDA Phase was successfully accomplished on schedule

IFMIF nominal flow operational conditions of liquid lithium have been validated



IFMIF HFTM specs have been validated

LIPAc commissioning is advancing in Rokkasho
125 mA in CW 40 MeV deuteron accelerator
is nowadays at hand of technology

The on-going success of IFMIF/EVEDA
allows us to expect counting next decade
with a Li(d,xn) fusion relevant neutron source
adapted to fusion community needs

for a marginal cost of a fusion reactor

Thanks to the EU-JA IFMIF team (and all people involved in former phases/projects) for their resilient enthusiasm

crucial for the present success of the program

Tohoku University

Osaka University

Nagoya University

Hachinohe Institute of Technology

Kyushu University

Tokyo University

Hachinohe National College of technology

and thanks to you for your attention