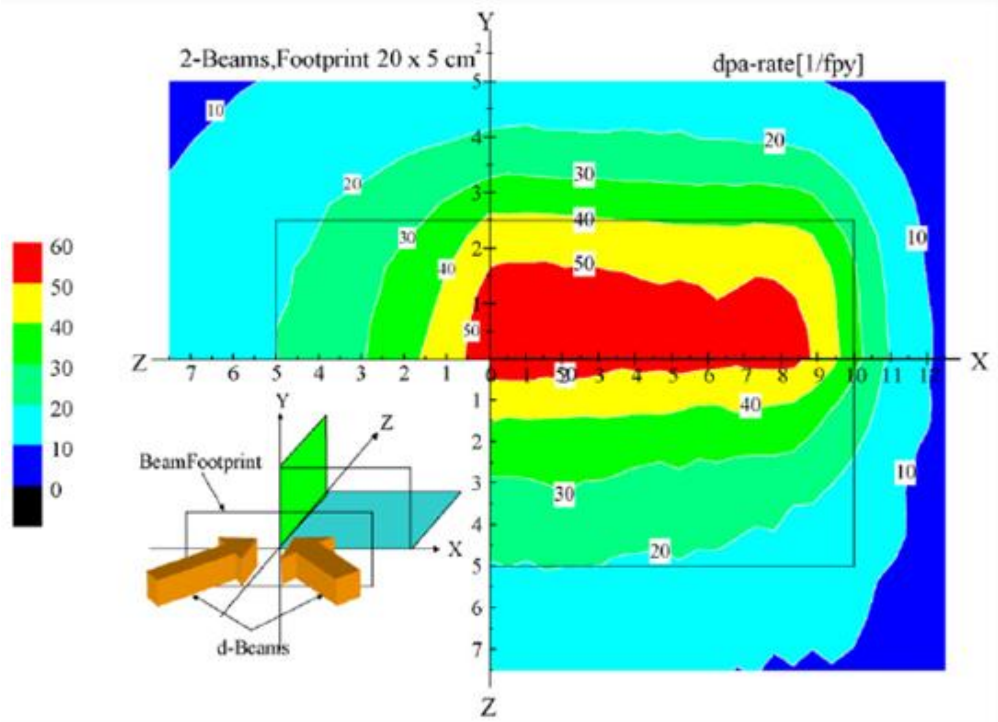
IFMIF

and its 2 x 5 MW superconducting deuteron LINACs

by Juan Knaster

(on behalf of IFMIF family)



Maturity of nuclear fusion

After decades of world research efforts
the construction of Nuclear Fusion Reactors is a reality

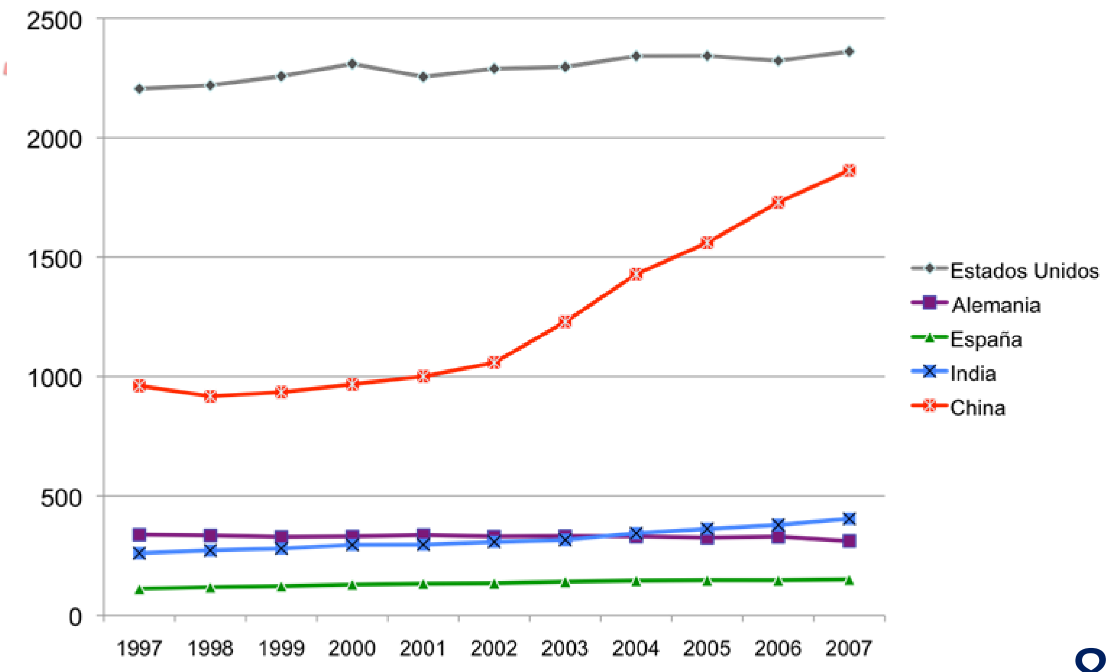
Two methodologies are matured

Inertial Confinement
NIF (US)
Laser Mégajoule (France)

and

Magnetic confinement
ITER (CN, EU, IN, KO, JA, RF, US)

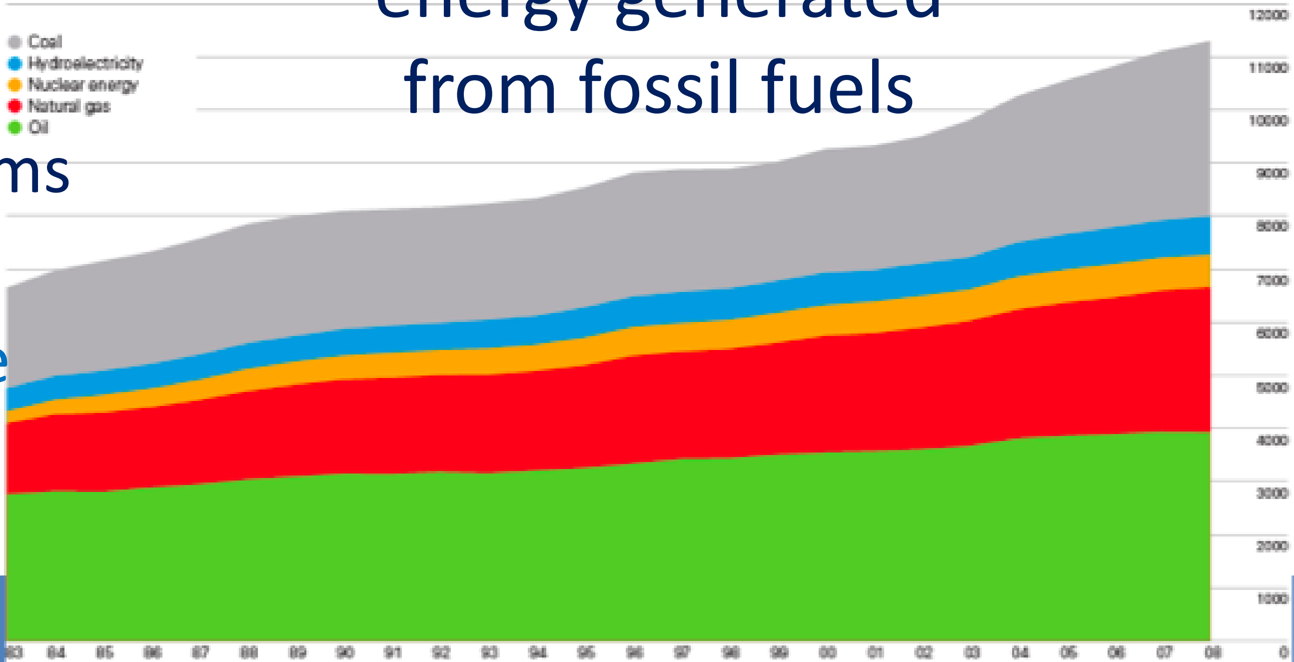
World energy scenario



World Consumption
Million tonnes oil equivalent

In 2 years,
the growth of energy
consumption in China was
greater than total
consumption in Germany

80% of world
energy generated
from fossil fuels

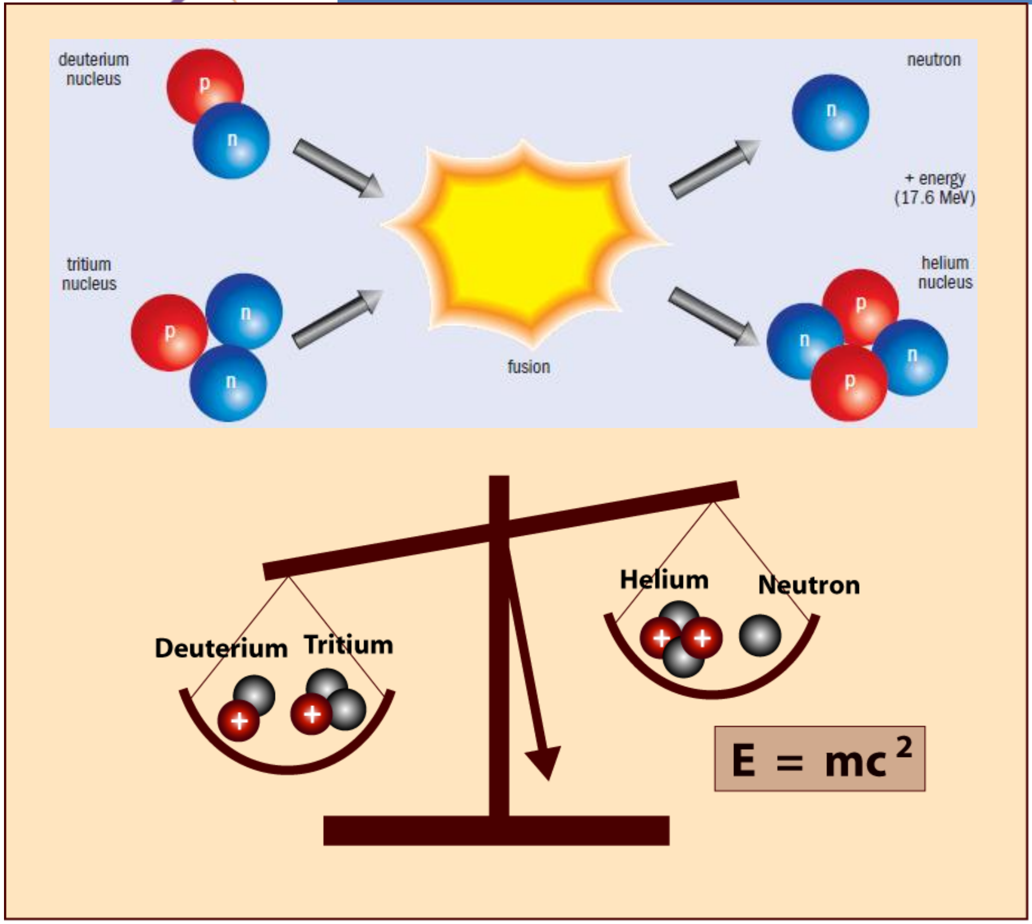


Medium term Problems

Greenhouse effect

Resources are finite

But why fusion?



14.1 MeV

3.5 MeV

Fuel needed
for energy consumption
by a Swiss citizen
for 50 years

Mass loss of ***4 milligram in 1 gram!!***

=

Deuterium

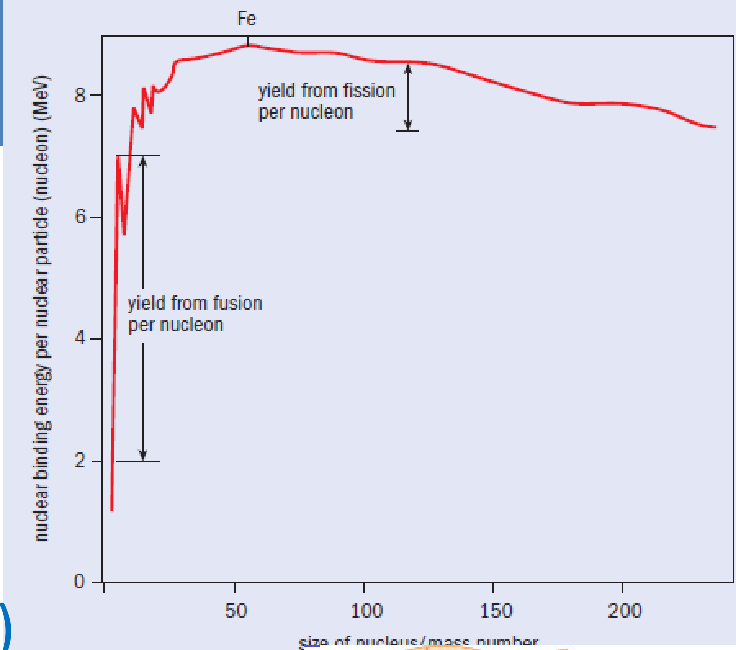
45 liters of water

\+

Lithium

Battery in a laptop

Advantages of fusion



Limitless resources

Lithium and Deuterium

(with an enormous efficiency)

Intrinsically safe

No chain reaction (difficult to maintain…)

Plant in operation contains a few grams of fuel

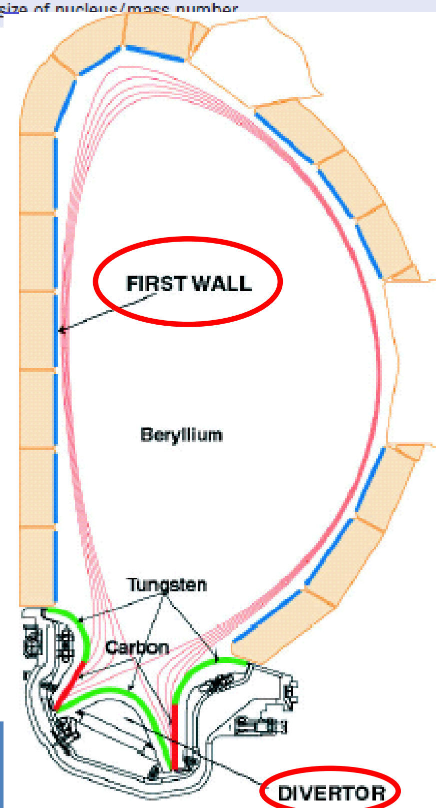
Reaction would extinguish within s

Tritium is produced and burned in a close circuit

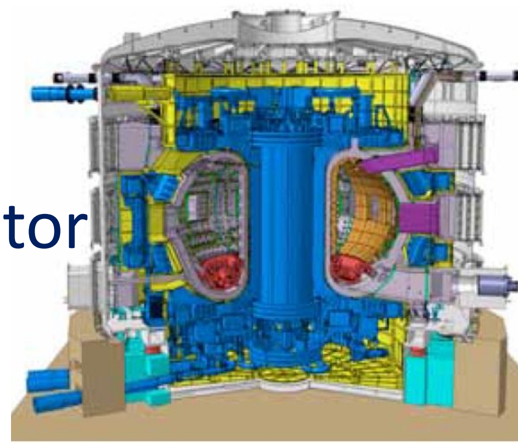
Waste

No long-lived radioactive waste

Recycle of parts from decommissioned plant



World Fusion Programme essential facilities

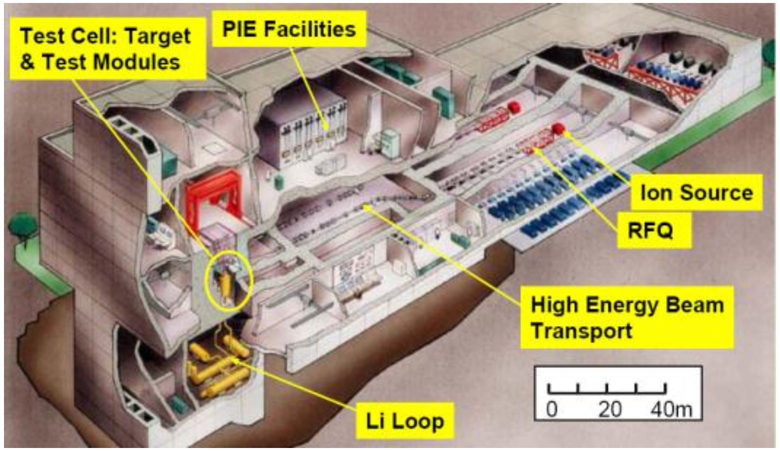


ITER

International Thermonuclear Experimental Reactor

Iter means ***the way*** *in Latin*

IFMIF/EVEDA

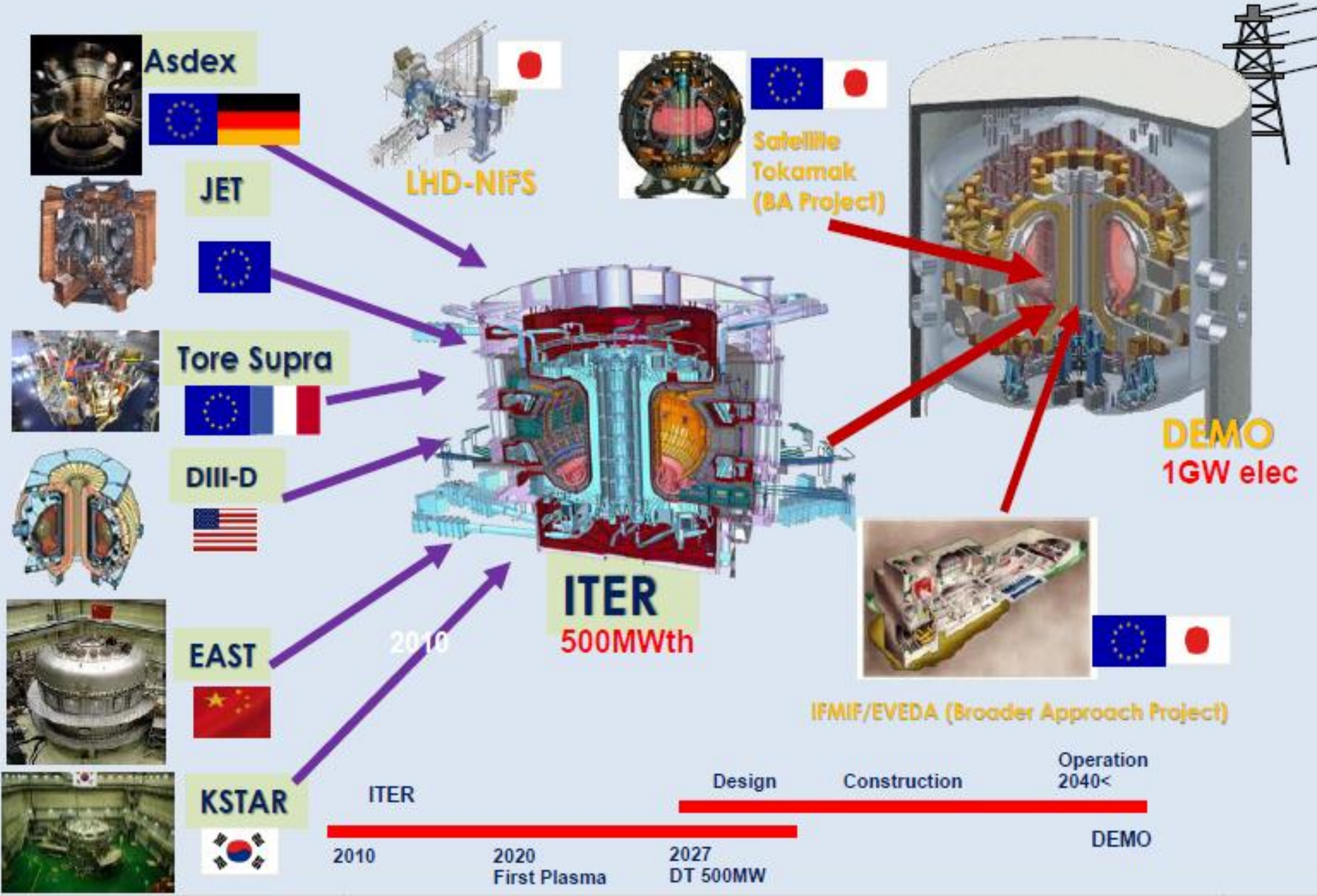


IFMIF

International Fusion Materials Irradiation Facility

EVEDA

Engineering Validation & Engineering Design Activities



Asdex

JET

Tore Supra

DIII-D

EAST

KSTAR

LHD-NIFS

Satellite Tokamak (BA Project)

ITER

500MWth

2010

DEMO

1GW elec

IFMIF/EVEDA (Broader Approach Project)

ITER

2010

2020
First Plasma

2027
DT 500MW

Design

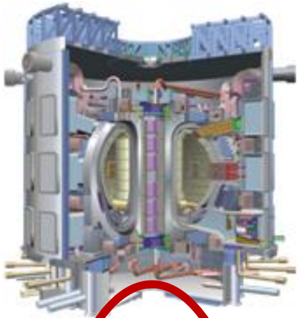
Construction

Operation
2040<

DEMO

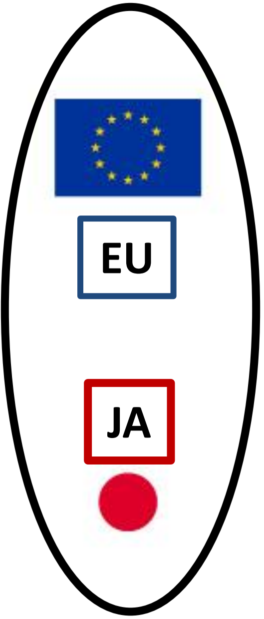
Different organizations/different stakeholders

ITER



7 parties

2 parties

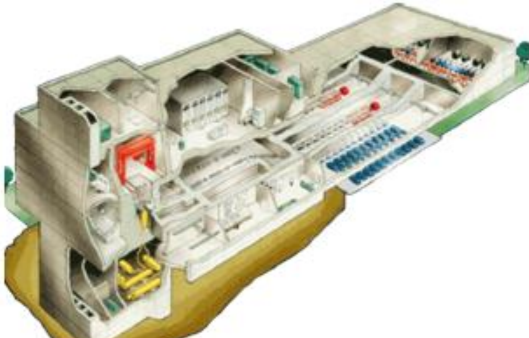


Broader Approach

JT60-SA

IFERC

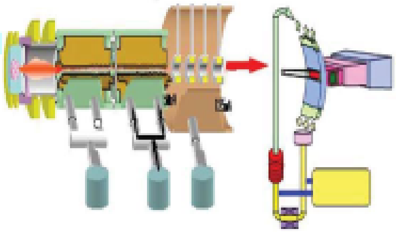
IFMIF-EVEDA



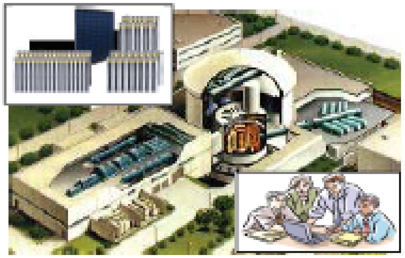
Broader Approach projects

Broader Approach Activities (2007-2017) comprise three Projects

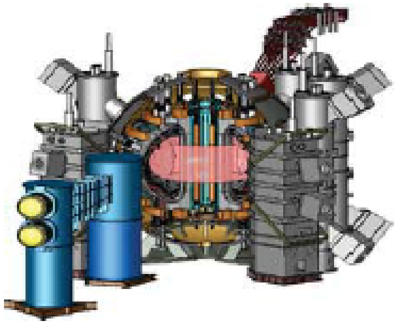
1) Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA)



2) International Fusion Energy Research Centre (IFERC),
   a) DEMO Design and R&D coordination Centre
   b) Computational Simulation Centre
   c) ITER Remote Experimentation Centre



3) Satellite Tokamak Programme
   Participation to upgrade of JT-60 Tokamak to JT-60SA and its exploitation.



Broader Approach projects

Computer Simulation Centre

Super Computer "Helios" started operation January 2012

The LINPAC performance is 1.23 PFlops which is 15th in the world (TOP 500, Nov. 2012).

One of the lighthouse project (Jan.-Mar. 2012) outcomes


Bullx B510
4410 nodes, 70560 cores


Library


Cooling Water System

Gyrokinetic simulations with GENE code for ASDEX-Upgrade and JET discharges can reproduce well those experimental data.

Broader Approach projects

JT-60SA Assembly Starts in Jan. 2013

JT-60 Torus Disassembly Completed => JT-60SA Assembly from Jan. 2013

The first experience of disassembling a radio-activated large fusion device in Japan.

2010 Mar.

2012 Oct.

Cryostat Base delivered from EU: Start Assembly Jan. 2013

Vacuum Vessel

200 deg. (40deg. X 5) completed

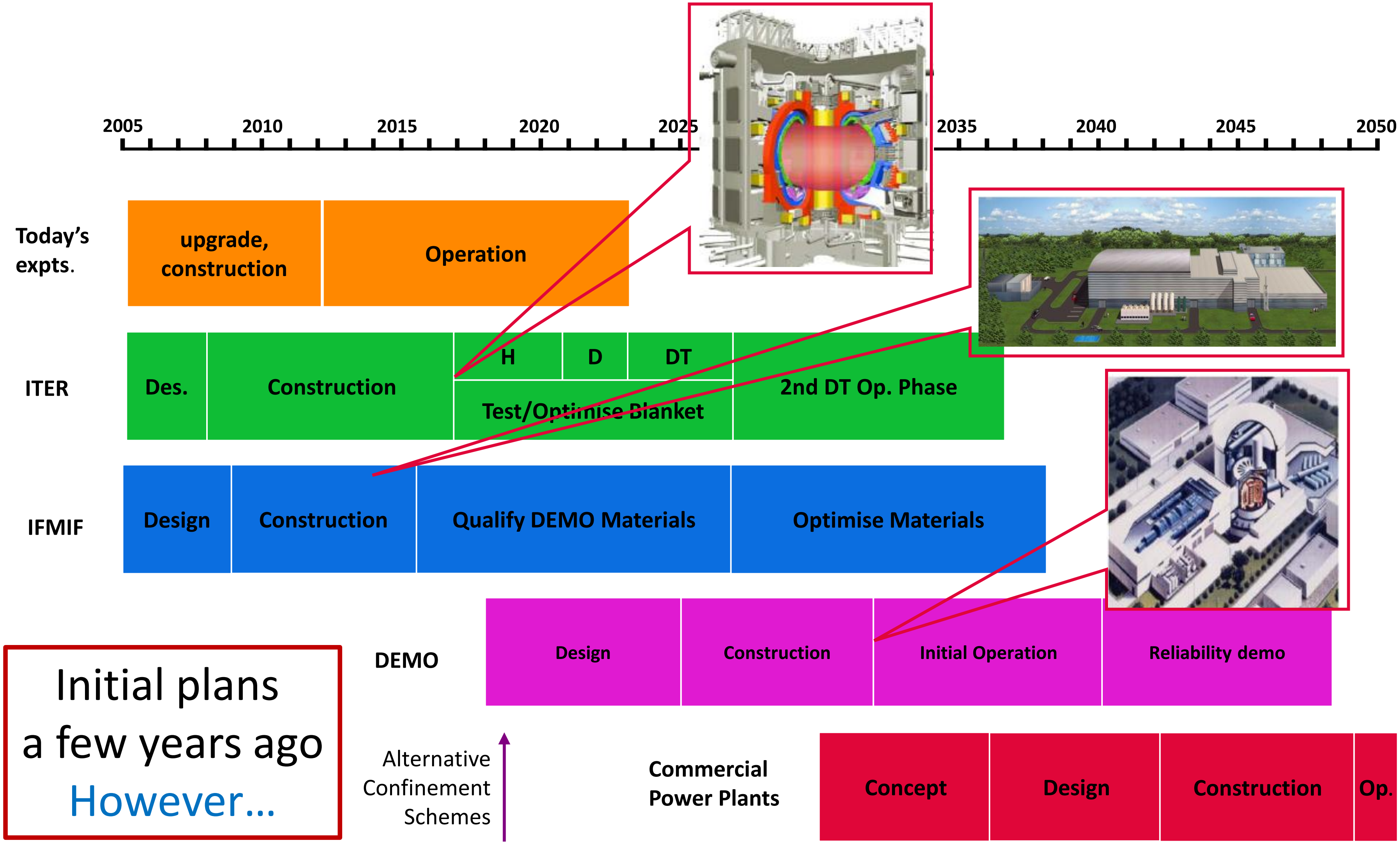
FY2012=> another 40deg.

EF coil

EF4 coil completed

EF5&6 under winding at Naka

Global Fusion programme roadmap (*obsolete*)



Initial plans
a few years ago
However…

Delays being faced, but why…

Expected difficulties faced in settling from scratch a new huge International Organization

Administrative

Suitable recruitment

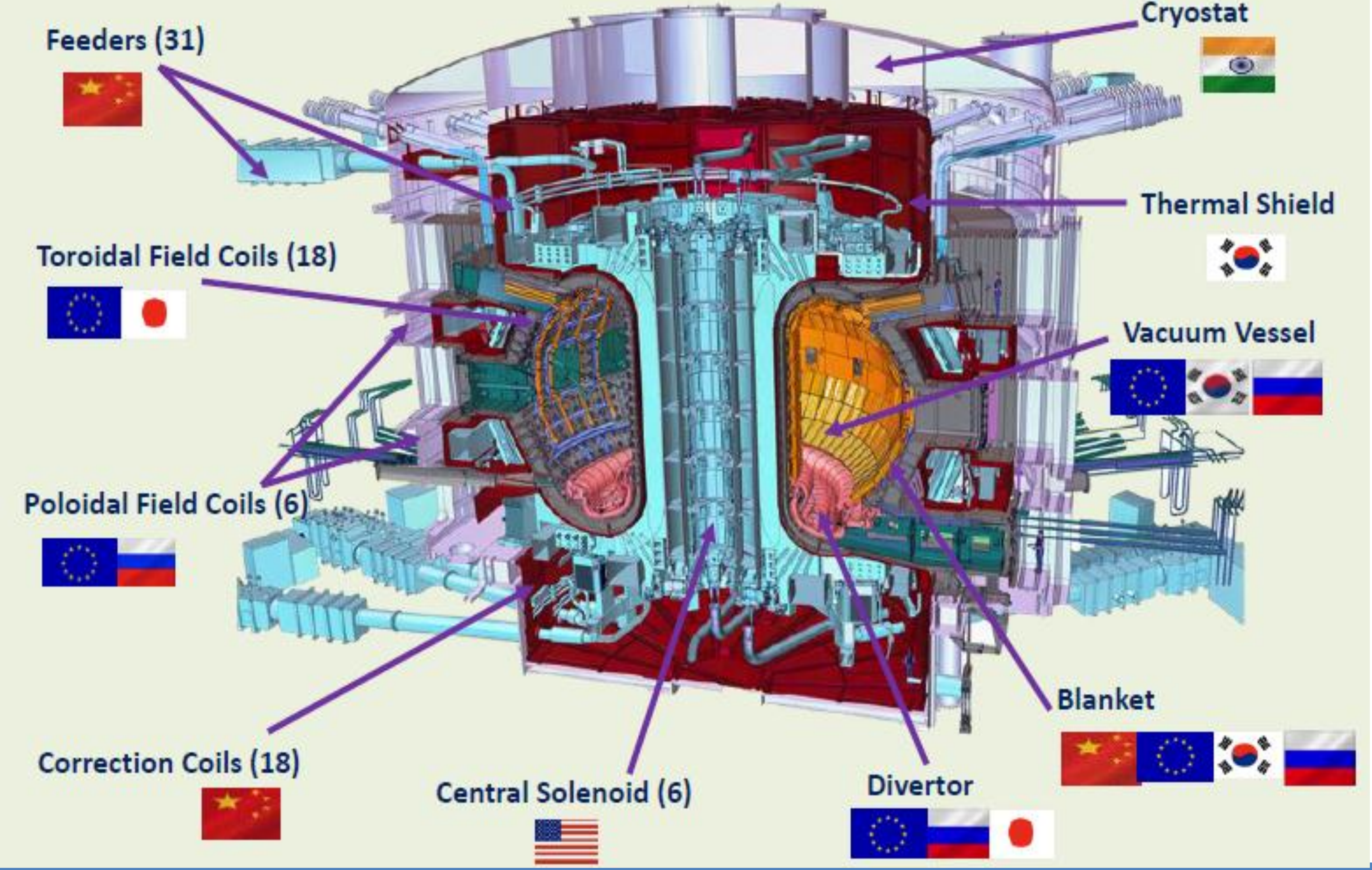
Master the political game

Aligning of interests between stakeholders

Inherent project technical difficulties

All these ITER is facing and overcoming

ITER sharing

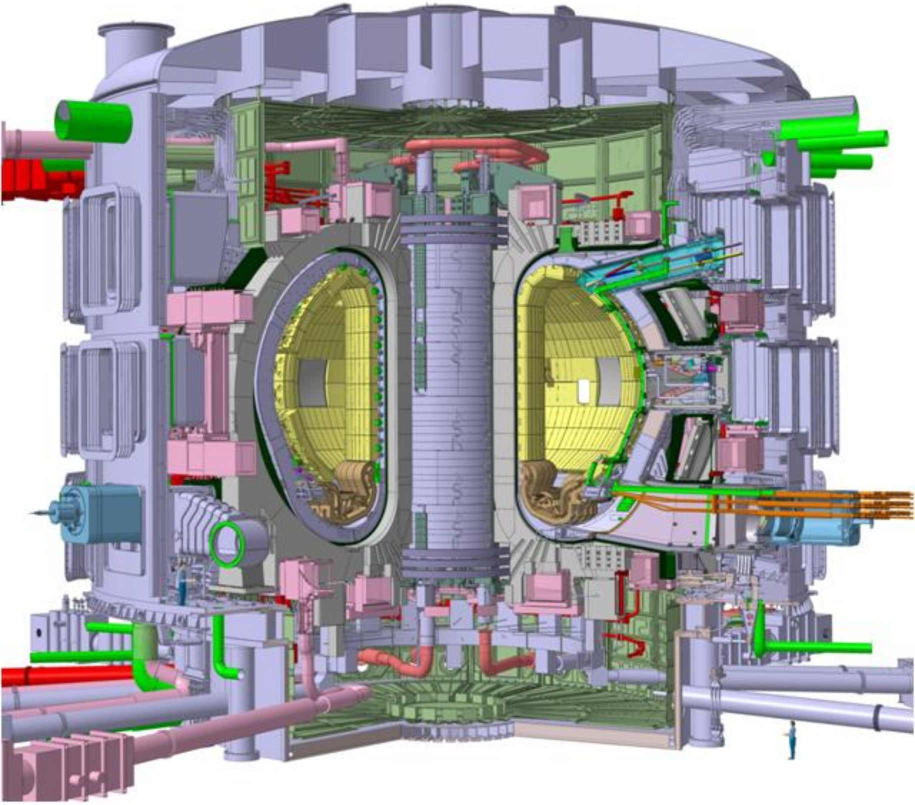


ITER

ITER will produce plasmas at T of 10^8 K

ITER will generate 500 MW of fusion power

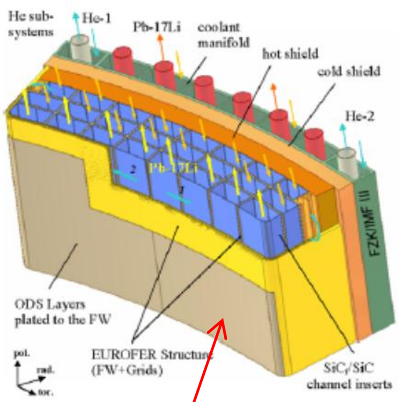
(Q=10)

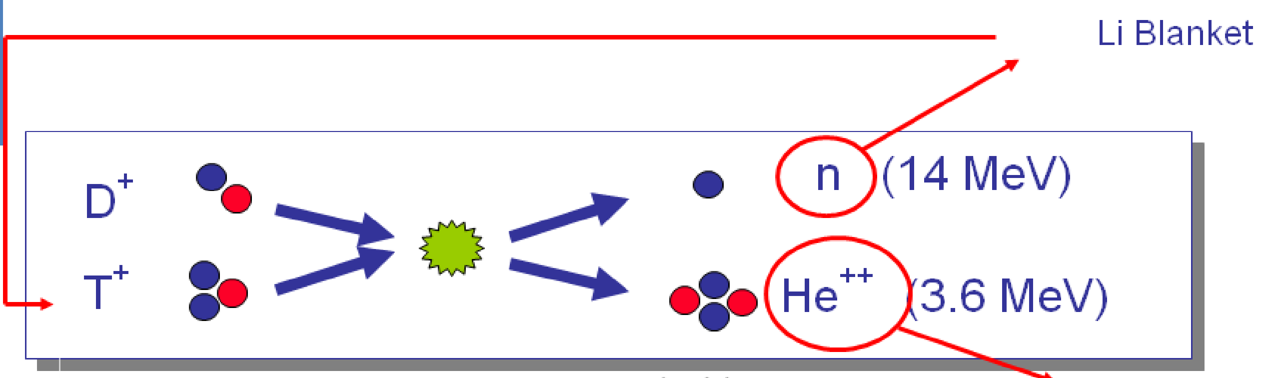


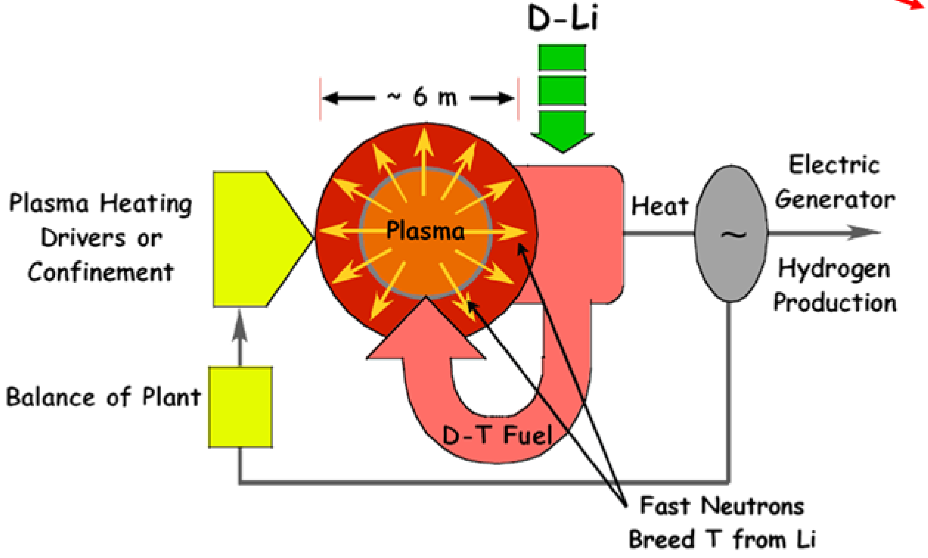
System	Energy GJ	Peak Field	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

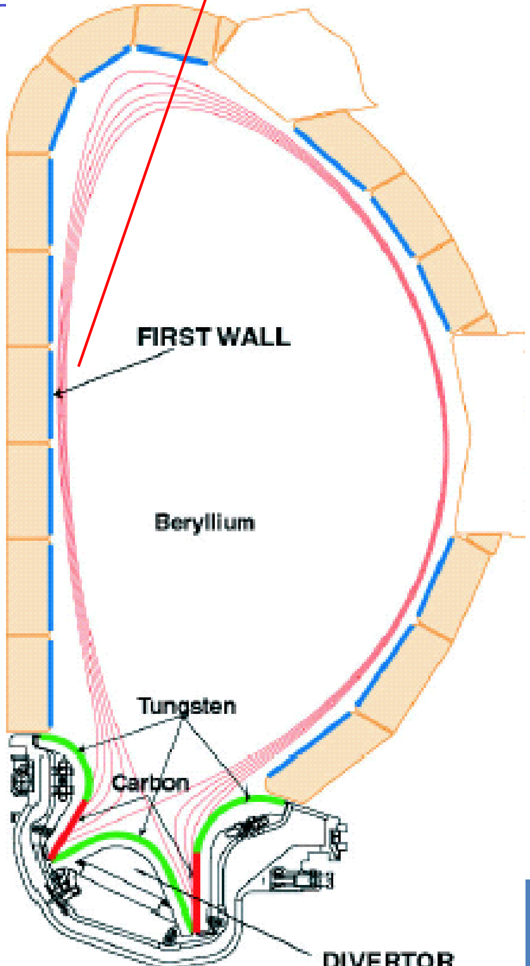
SC Magnet system

18 TF coils
6 CS modules
6 PF coils
18 CC
31 feeders









Power densities in the order of

10 MW/m^2

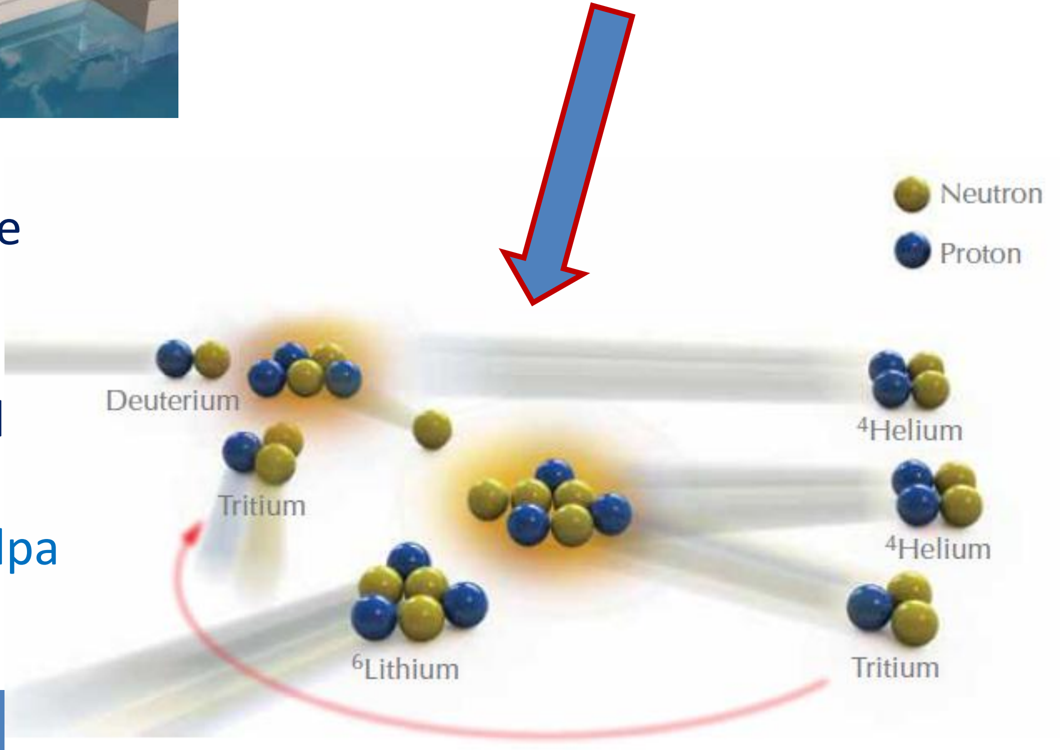
are to be withstood

The first wall
of the reactor vessel shall
absorb neutrons energy
and
breed tritium

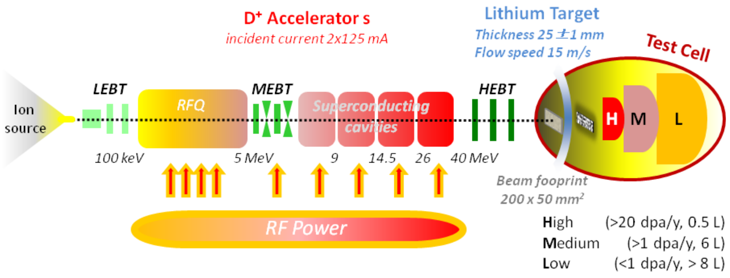
ITER first wall will present
<2 dpa at the end of its operational life

In a Fusion power plant
~150 dpa within 5 years are expected

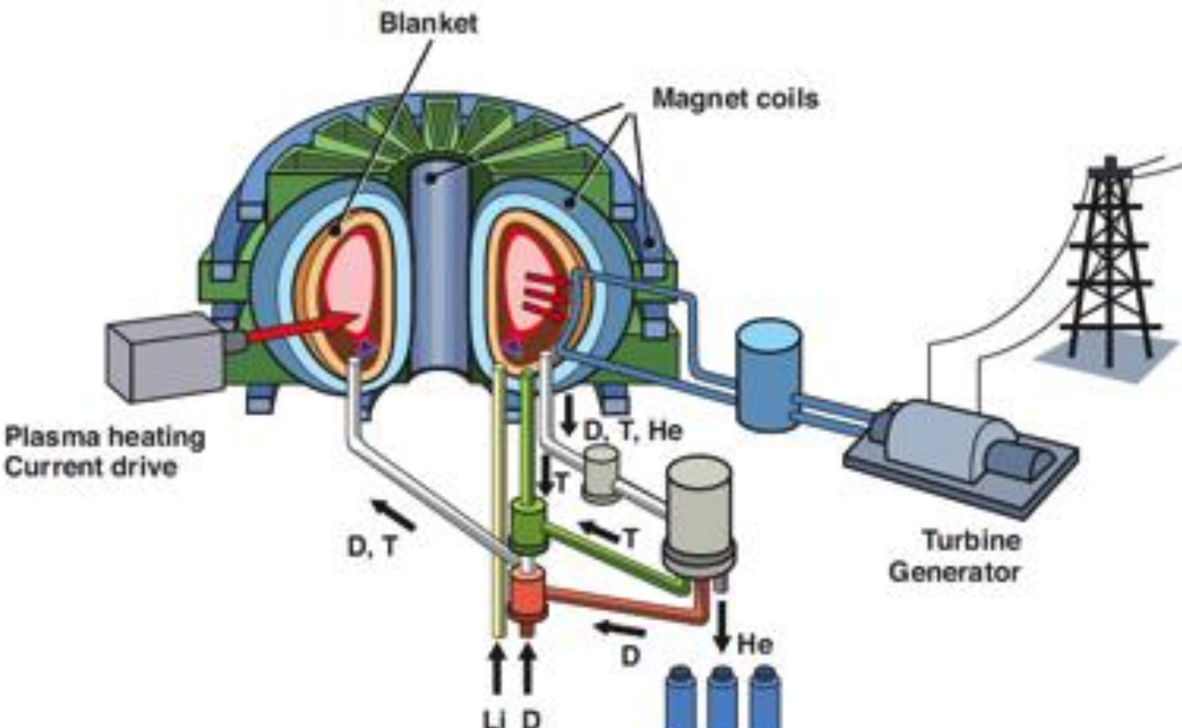
Critical threshold observed beyond 30 dpa
but no relevant data is available



Understanding the degradation of the mechanical properties of the materials critically exposed to 14.1 MeV n flux is a key parameter to allow accomplishment of the design and facility licensing



IFMIF a 14 MeV n source



Materials

RAFM

Reduced Activation Ferritic Martensitic

Eurofer

F82H

High resistance to radiation

High operation T

Activation low and quickly decaying

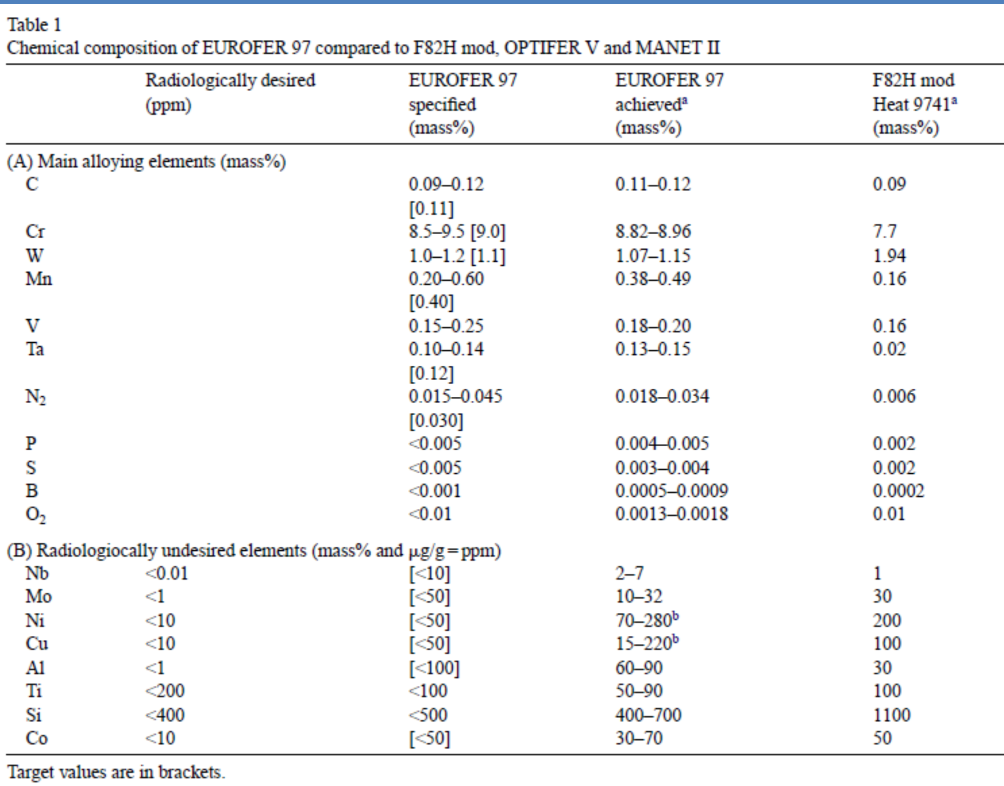


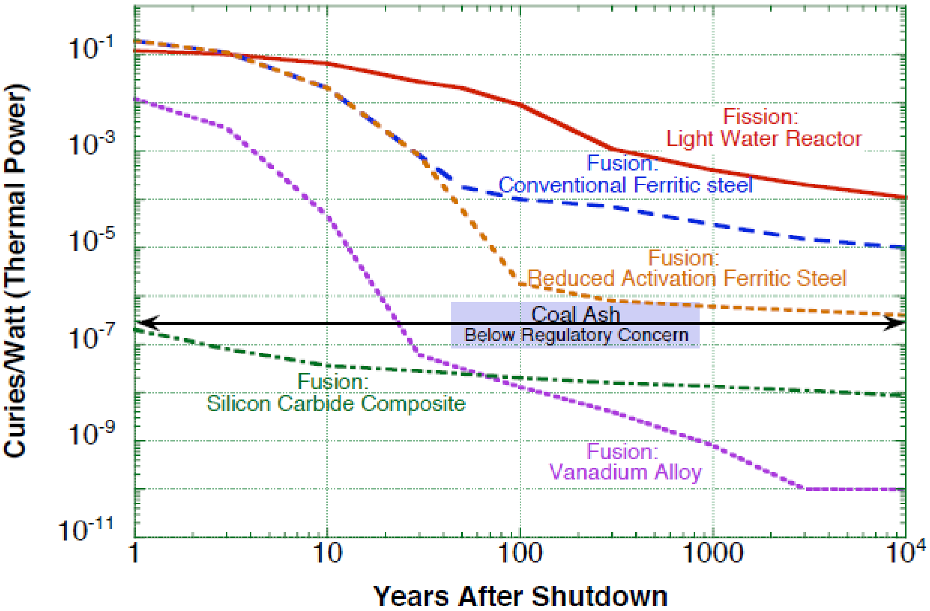
Table 1

Chemical composition of EUROFER 97 compared to F82H mod, OPTIFER V and MANET II

	Radiologically desired (ppm)	EUROFER 97 specified (mass%)	EUROFER 97 achieved[a] (mass%)	F82H mod Heat 9741[a] (mass%)
(A) Main alloying elements (mass%)				
C		0.09–0.12 [0.11]	0.11–0.12	0.09
Cr		8.5–9.5 [9.0]	8.82–8.96	7.7
W		1.0–1.2 [1.1]	1.07–1.15	1.94
Mn		0.20–0.60 [0.40]	0.38–0.49	0.16
V		0.15–0.25	0.18–0.20	0.16
Ta		0.10–0.14 [0.12]	0.13–0.15	0.02
N_2		0.015–0.045 [0.030]	0.018–0.034	0.006
P		<0.005	0.004–0.005	0.002
S		<0.005	0.003–0.004	0.002
B		<0.001	0.0005–0.0009	0.0002
O_2		<0.01	0.0013–0.0018	0.01
(B) Radiologiocally undesired elements (mass% and µg/g = ppm)				
Nb	<0.01	[<10]	2–7	1
Mo	<1	[<50]	10–32	30
Ni	<10	[<50]	70–280[b]	200
Cu	<10	[<50]	15–220[b]	100
Al	<1	[<100]	60–90	30
Ti	<200	<100	50–90	100
Si	<400	<500	400–700	1100
Co	<10	[<50]	30–70	50

Target values are in brackets.

Comparison of Fission and Fusion Radioactivity after Shutdown



Within ~100 years

activation would drop

to hands-on radiological levels

New materials under study

V alloys or SiC

will present lower radiological issues

14 MeV beyond transmutation thresholds

The accumulation of gas in the materials lattice is intimately related with the neutron energy

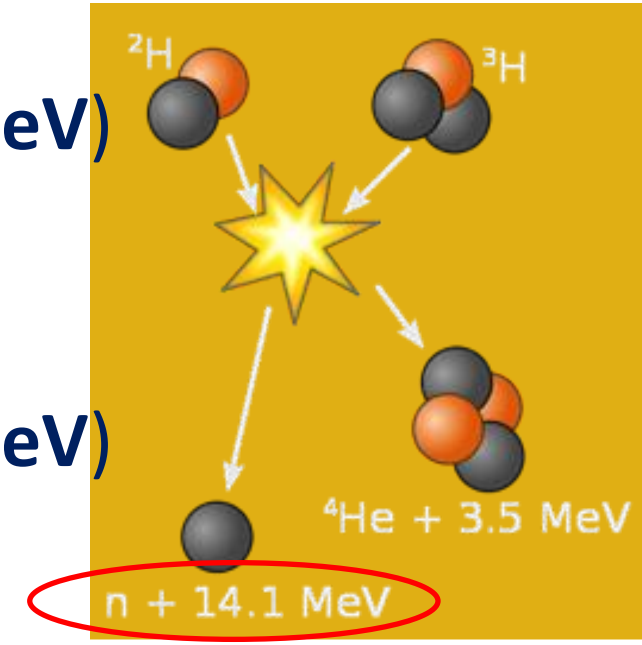
$^{56}Fe(n,\alpha)^{53}Cr$

(incident n threshold at **3.7 MeV**)

and

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

(incident n threshold at **2.9 MeV**)



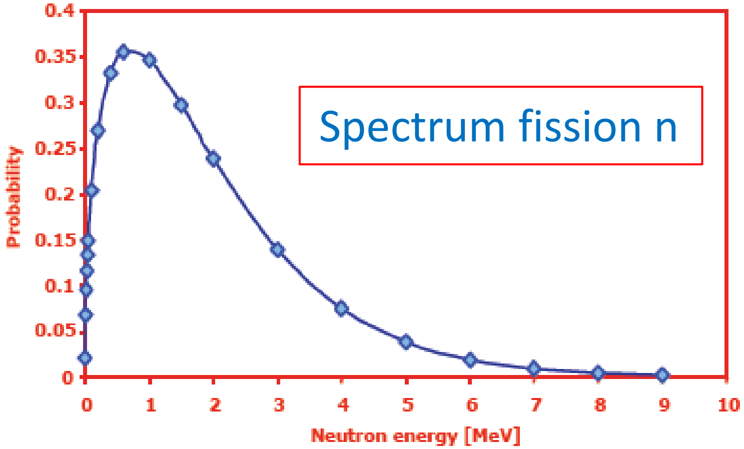
Swelling and embrittlement of materials takes place

Fission and spallation sources no fusion n relevant

Existing neutron sources

do not provide the needed answers

Fission reactors n average energy ~2 MeV



No efficient

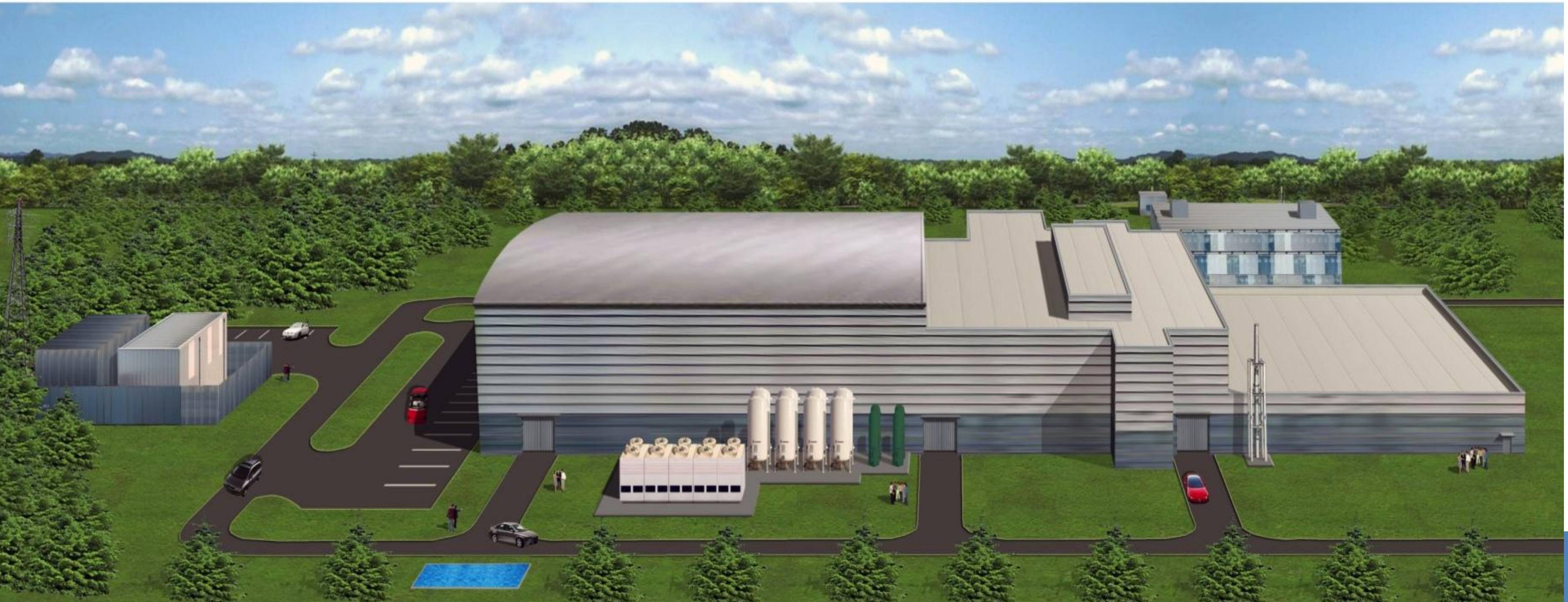
p^+ or α-particle generation

Spallation sources present a wide spectrum with tails in the order of hundreds of MeV

Generation of light isotopes in the order of ppm

Mission of IFMIF

IFMIF is a neutron source tailor-designed to provide
adequate flux
and
suitable energy
to simulate the neutronic conditions in a fusion power plant



Mission of IFMIF

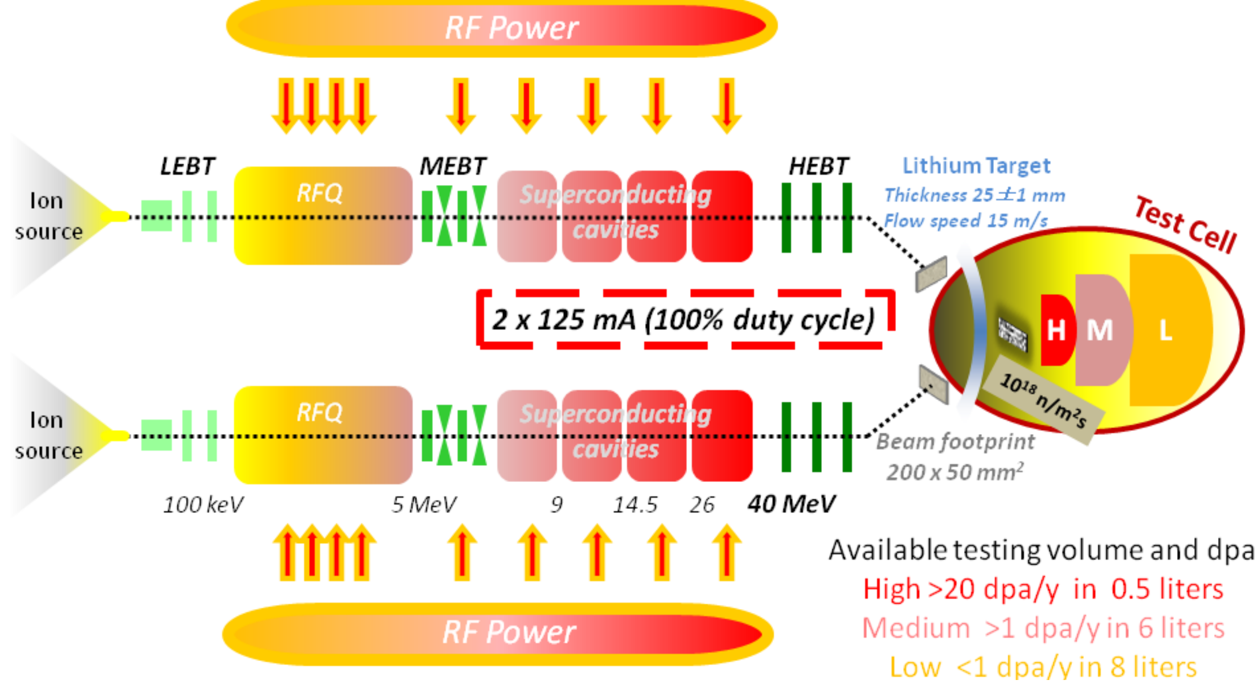
Qualification of candidate materials
for fusion reactors

Generation of engineering data for
design, licensing and safe operation of DEMO

Completion, calibration and validation of databases
(mainly generated from fission reactors research)

Deepening on fundamental understanding of
radiation response of materials hand in hand with
computational material science

IFMIF concept



Available testing volume and dpa

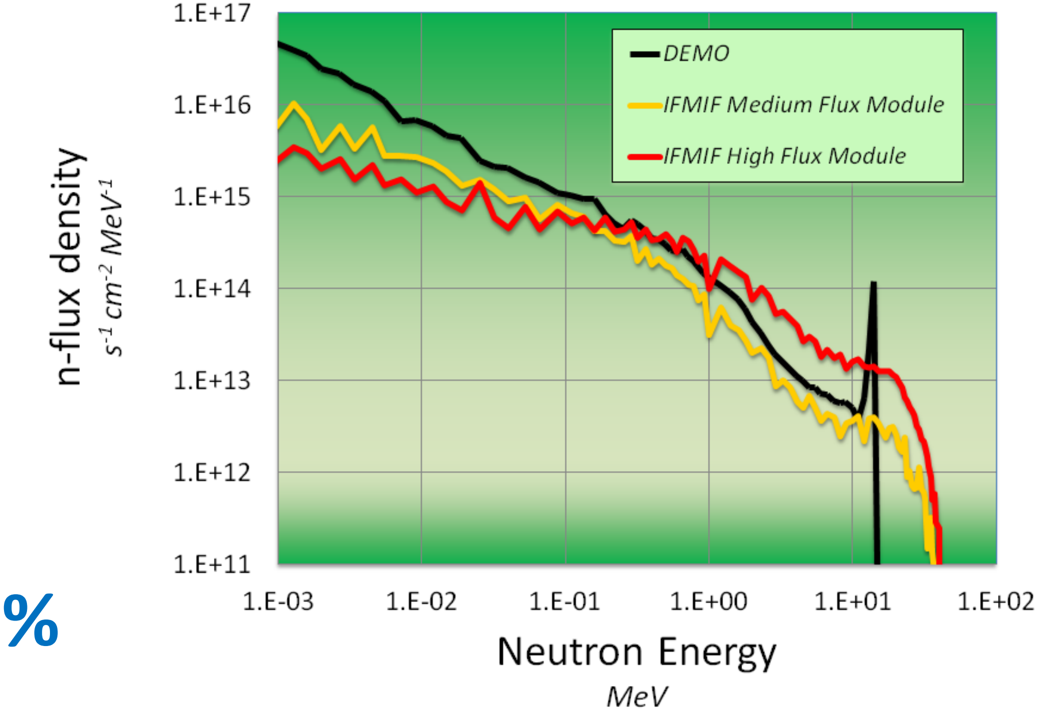
High >20 dpa/y in 0.5 liters

Medium >1 dpa/y in 6 liters

Low <1 dpa/y in 8 liters

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

A flux of 10^{18} n·m^{-2}s^{-1} is stripped with a broad peak at 14 MeV



Availability of facility >80%

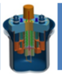
Comparison with other n sources

Neutron flux compared with the one DEMO will present in available and planned neutron sources

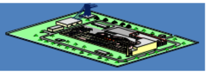
Future Large Scale Materials Irradiation Facilities
Being in advanced design or construction phase

Accelerator driven spallation source
MTS, at Los Alamos

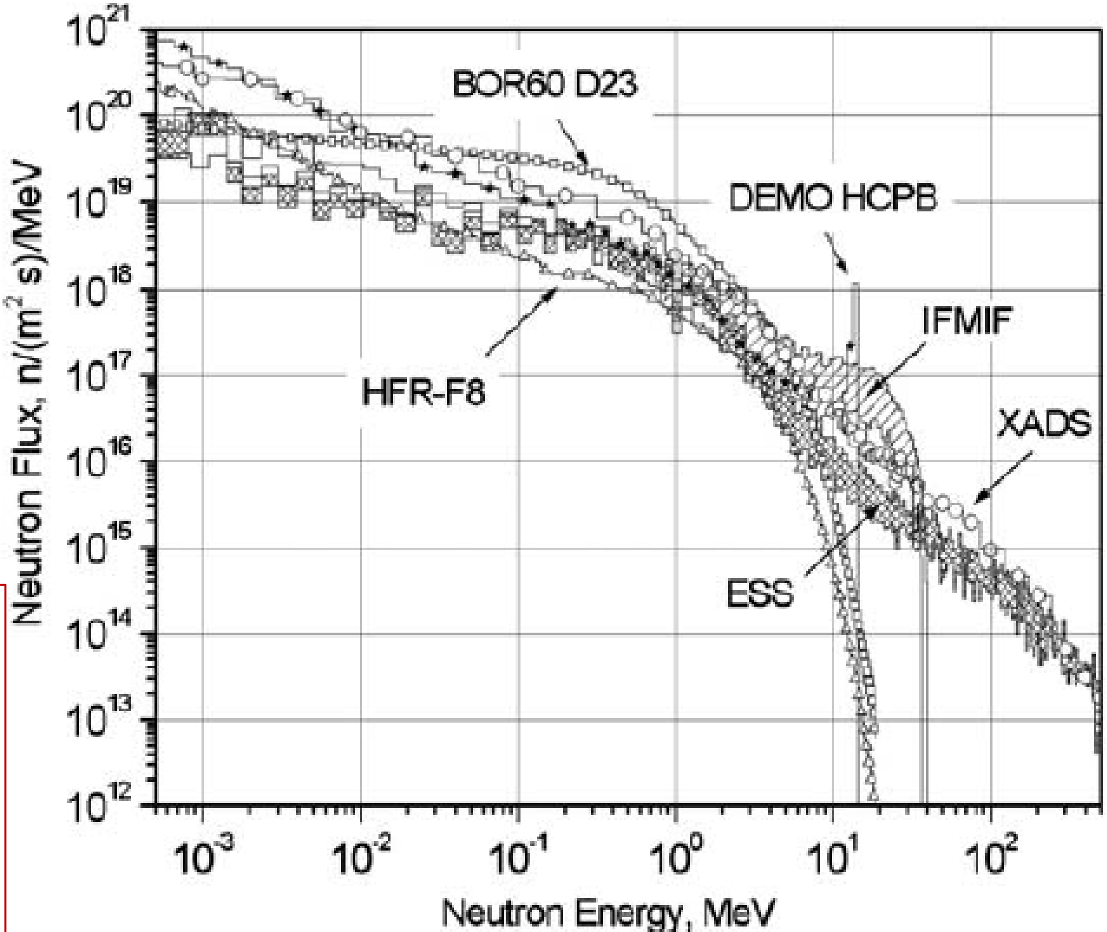
Accelerator driven spallation source
MYRRHA/XT-ADS, at MOL



Accelerator driven D-Li fusion neutrons source
IFMIF, presently bilateral

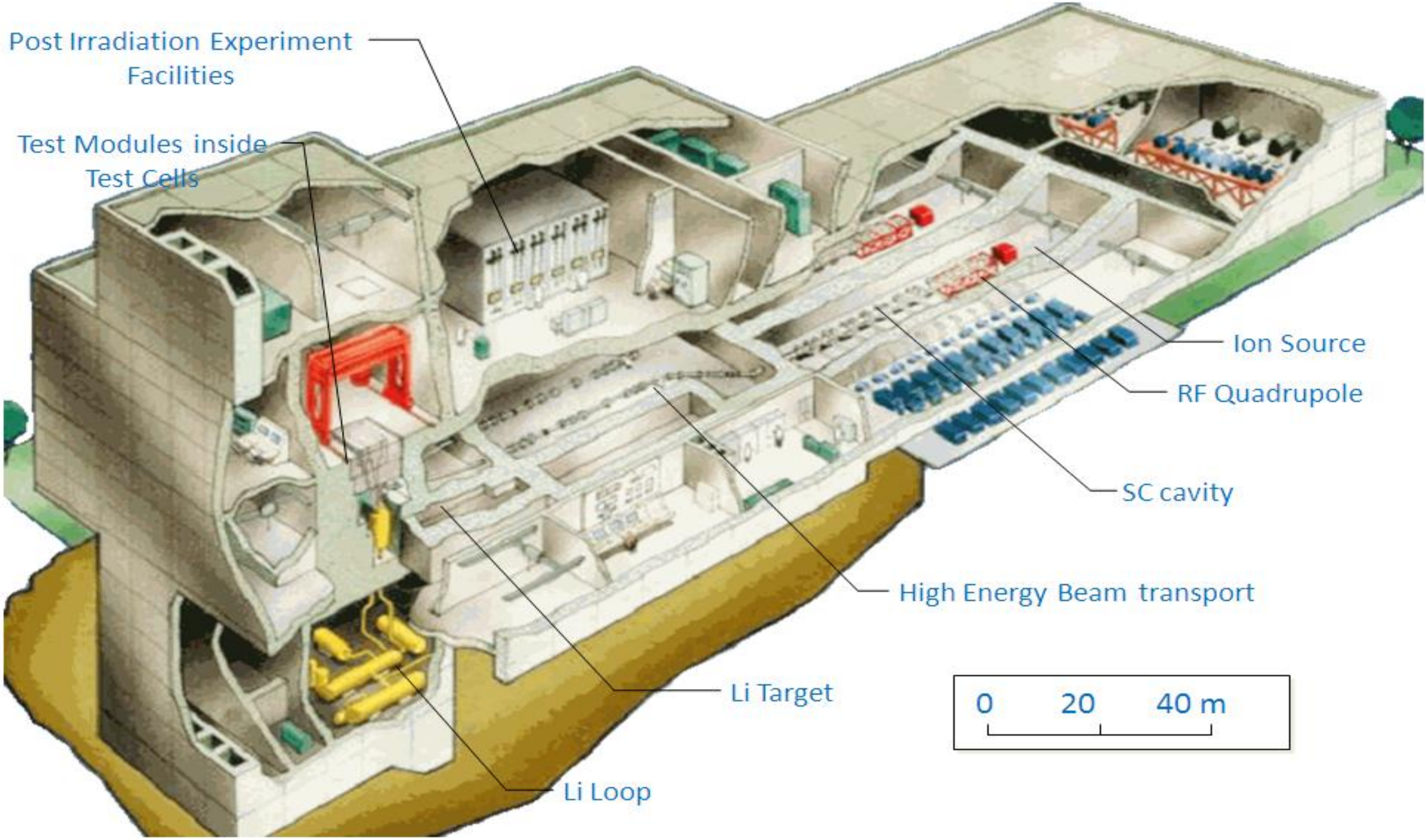


Thermal spectrum reactor
JHR, Cadarache



Vladimirov, P., Moeslang, A., *Comparison of material irradiation conditions for fusion, spallation, stripping, and fission neutron sources*, J. Nucl. Mater. **329-33** (2004) 233

IFMIF concept



IFMIF/EVEDA phase

The validation activities comprises three main facilities

Accelerator facility

Target facility

Test facility

In addition, we are preparing an

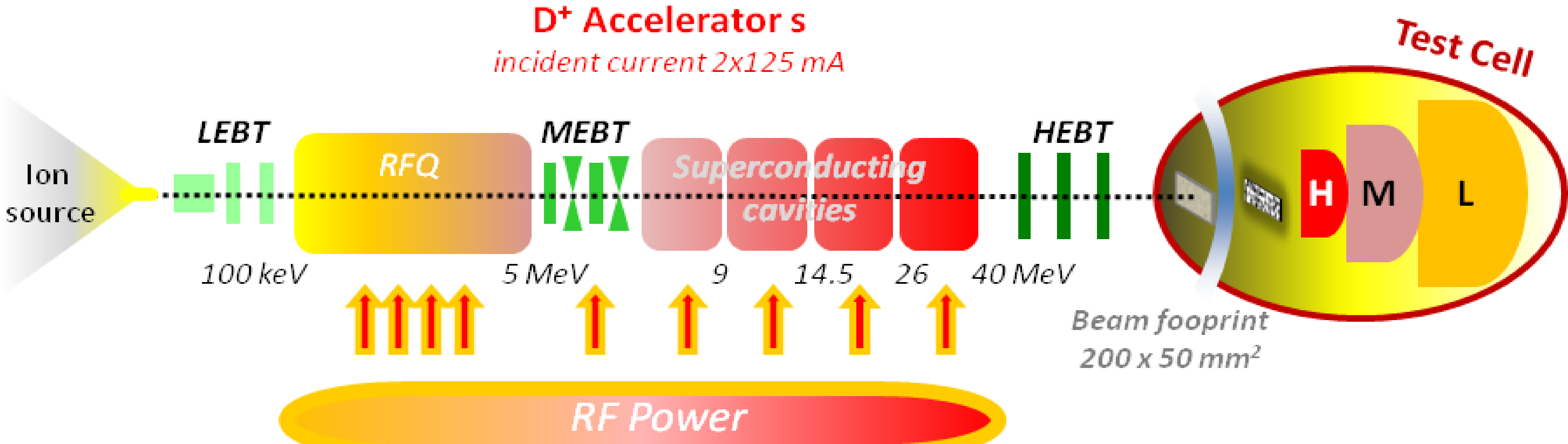
Intermediate IFMIF Engineering Design Report

and the collaboration is very numerous with highest level labs and universities in Europe and Japan

Accelerator facility

2 x 5 MW beams

Individual availability >90%



D$^+$ Accelerator s

incident current 2x125 mA

LIPAc vs IFMIF

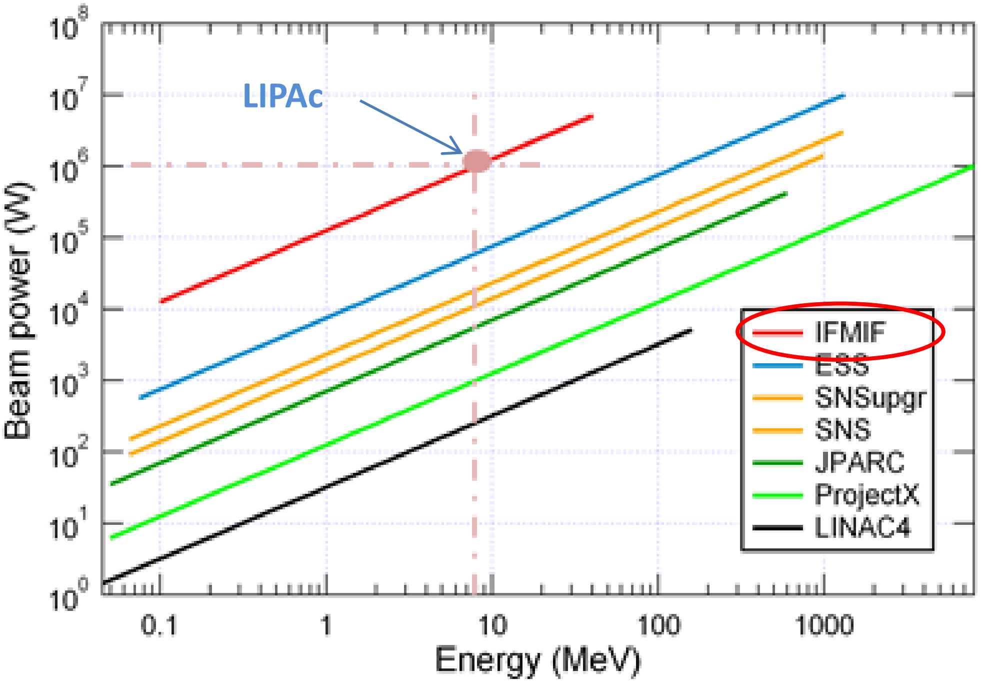
Features of IFMIF vs LIPAc d^+ accelerator

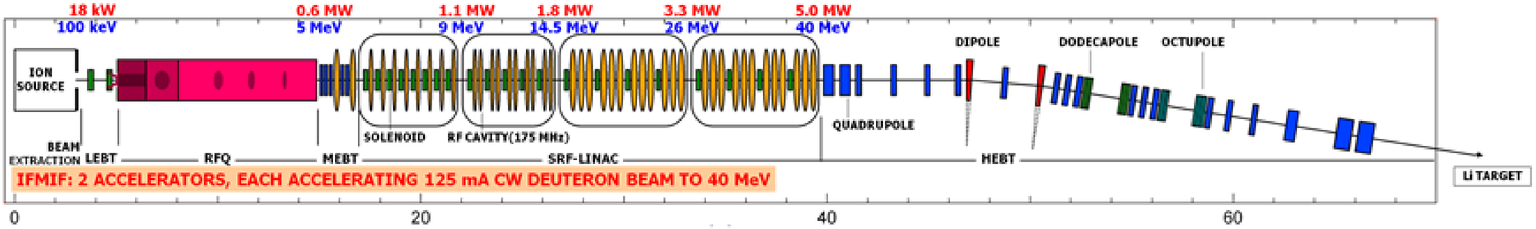
125 mA (100% duty cycle)

5 MW vs 1.125 MW

Space charge issues

Low energy-high power

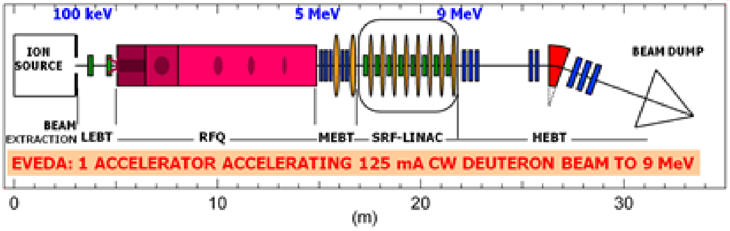




40 MeV

125 mA

5 MW



9 MeV

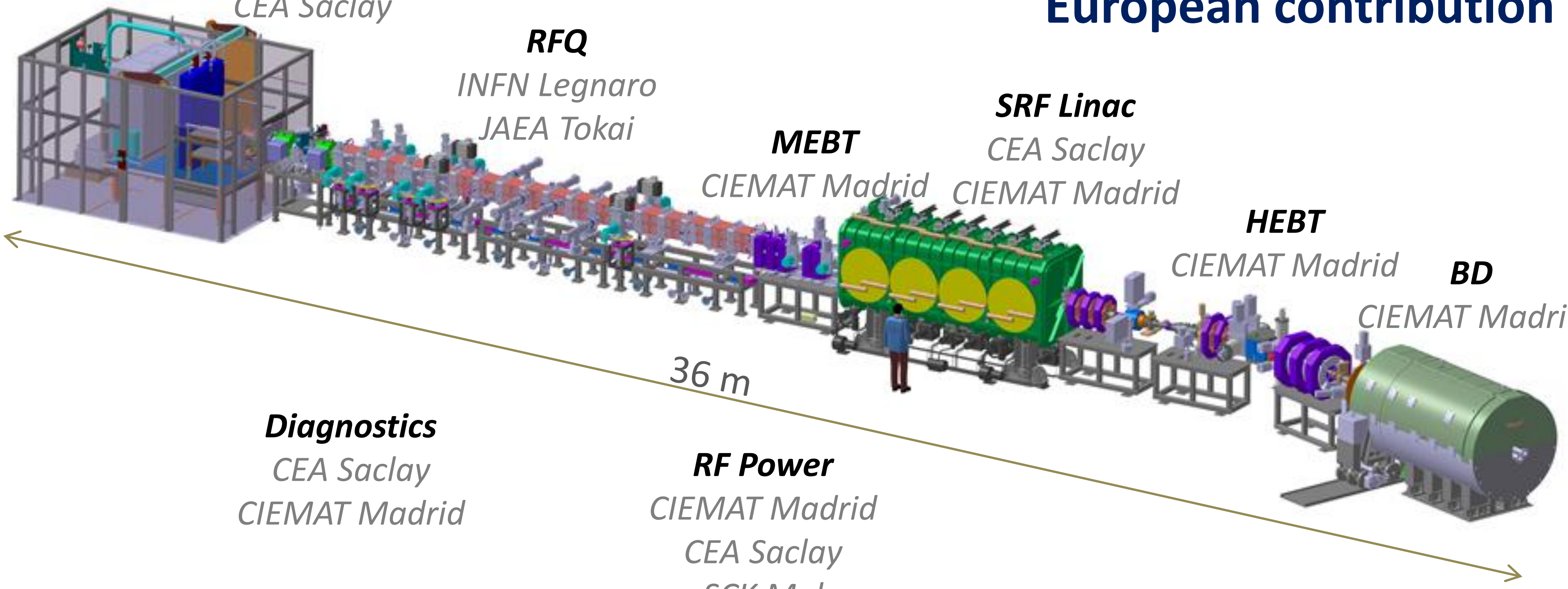
125 mA

1.125 MW

LIPAc contribution

Linear IFMIF Prototype Accelerator

Mainly
European contribution



Injector + LEBT
CEA Saclay

RFQ
INFN Legnaro
JAEA Tokai

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

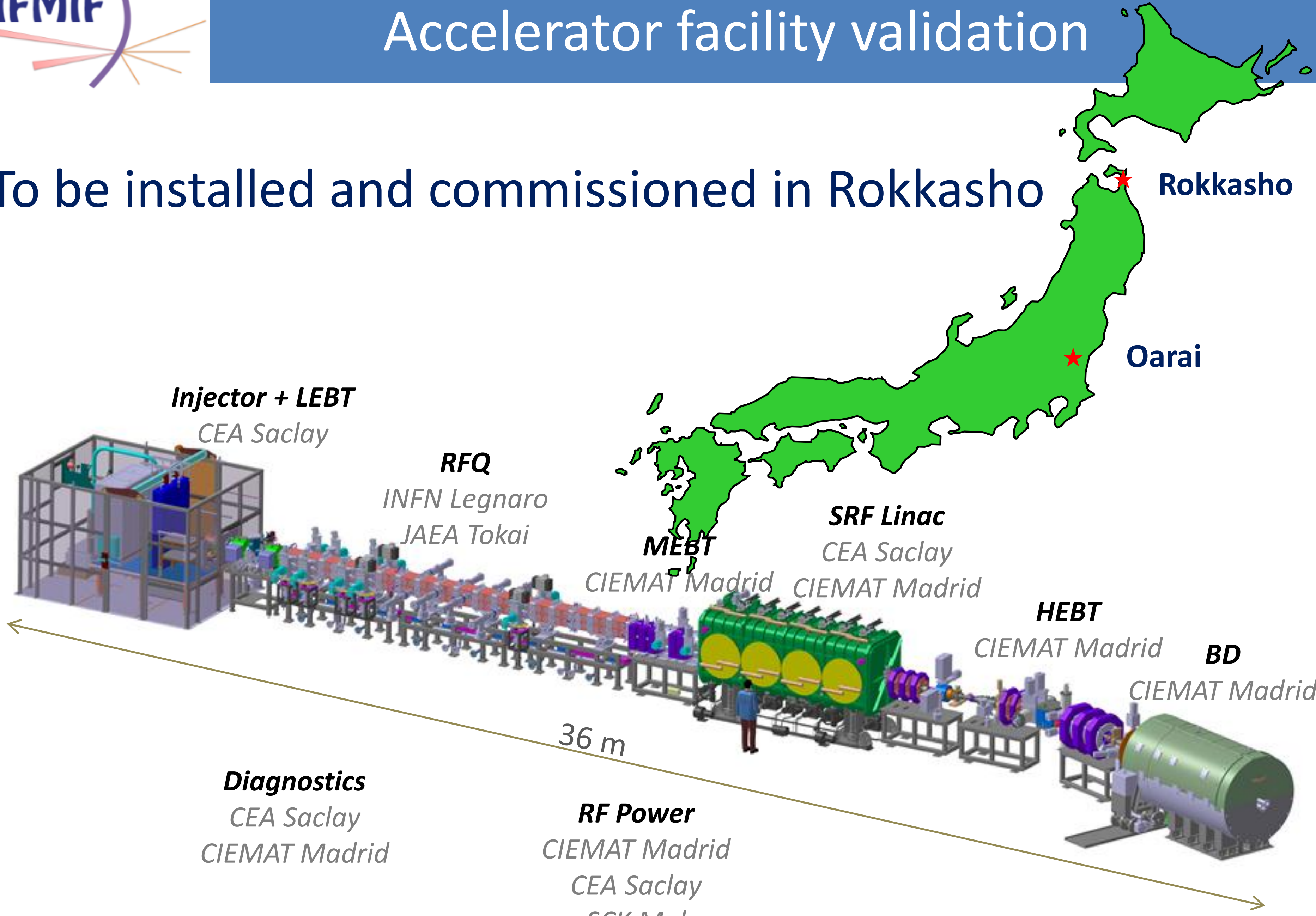
BD
CIEMAT Madrid

Diagnostics
CEA Saclay
CIEMAT Madrid

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Accelerator facility validation

To be installed and commissioned in Rokkasho



Injector + LEBT
CEA Saclay

RFQ
INFN Legnaro
JAEA Tokai

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid

Diagnostics
CEA Saclay
CIEMAT Madrid

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Site is ready

Administration & Research Building

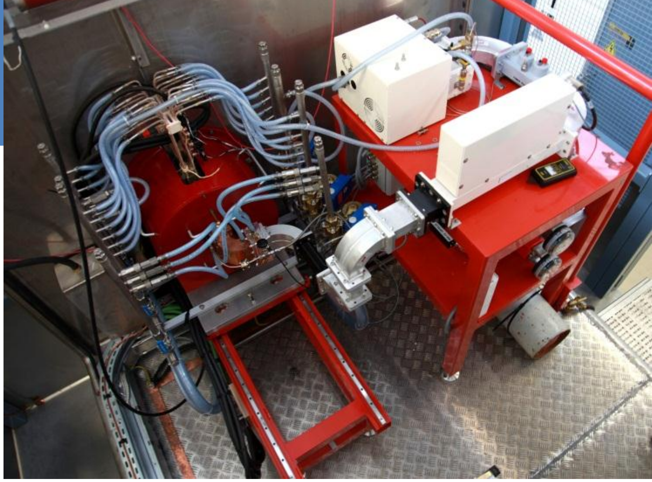
Computer Simulation & Remote Experimentation Building

DEMO R&D Building

IFMIF/EVEDA Accelerator Building

JAEA contribution

Ion source



Continuous Wave ECR (2.5 GHz)

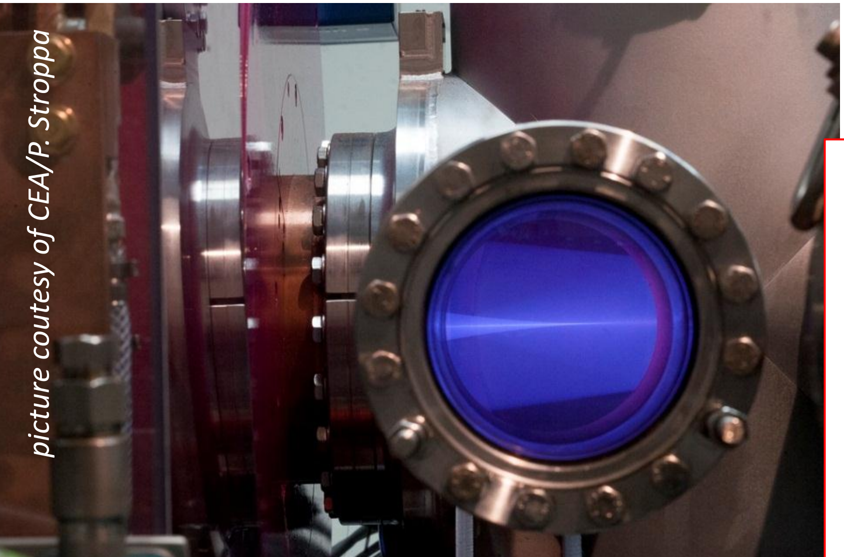
E = 100 keV

I = 140 mA

emittance of 0.25 π mm·mrad

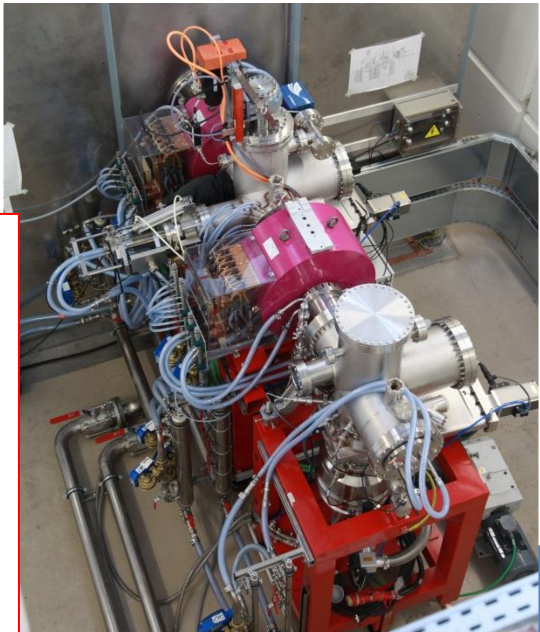
Availability > 95%

Acceptance tests in Saclay successful!!



picture coutesy of CEA/P. Stroppa

R. Gobin et al., *General design of the International Fusion Materials Irradiation Facility deuteron injector: Source and beam line*, Rev. Sci. Inst. 81, 02B301 2010



On its way to Rokkasho

RFQ

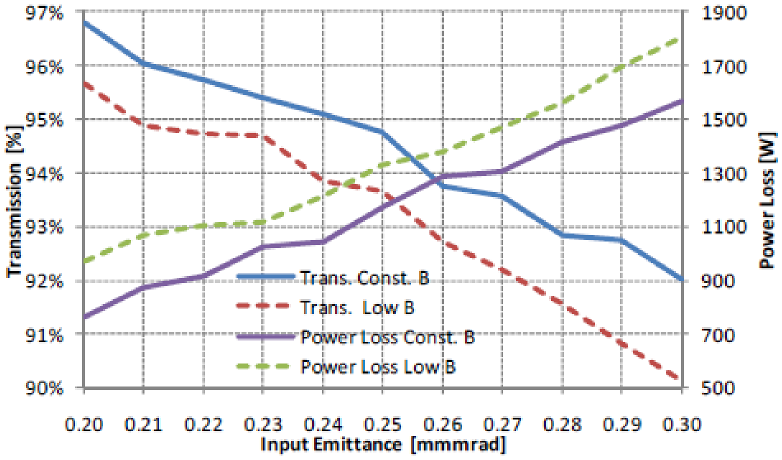
175 MHz

I_{input}= 130 mA

E_{output}= 5 MeV

Up to 10mA beam losses allowed

Max surface field 25.2 MV/m (1.8 Kp)



Tuning feasibility demonstrated in an Al full scale prototype

Brazing technology developed at CERN

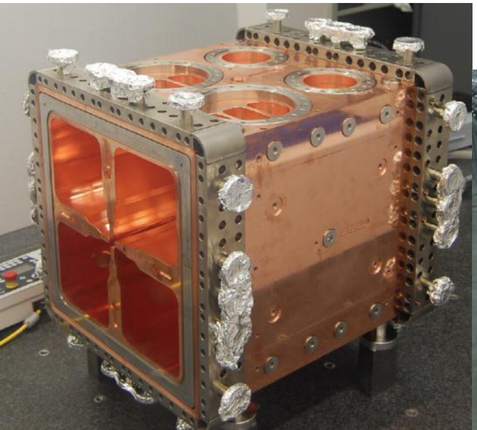
Prototype module leak tight and on tolerances

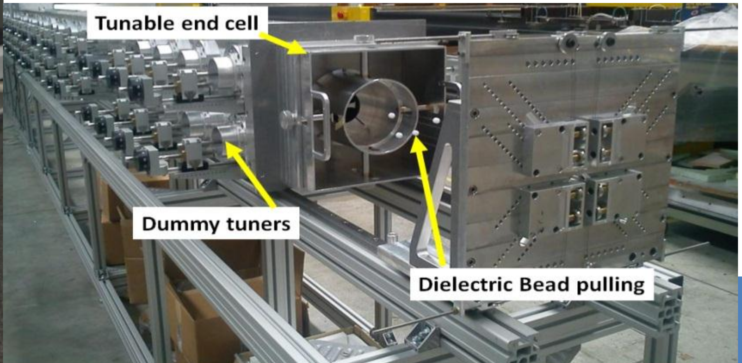
18 modules (9.8 m long RFQ)

Pisent A., et al., *Production and testing of the first modules of the IFMIF-EVEDA RFQ*, Proceedings of IPAC12, New Orleans

M. Comunian, A. Pisent , *The Beam dynamics redesign of IFMIF-EVEDA RFQ for a larger input beam acceptance*, Proc. of IPAC 2011, San Sebastián, Spain

Pepato, A. et al., *Mechanical Design of the IFMIF/EVEDA RFQ*, Proceedings of PAC09, Vancouver





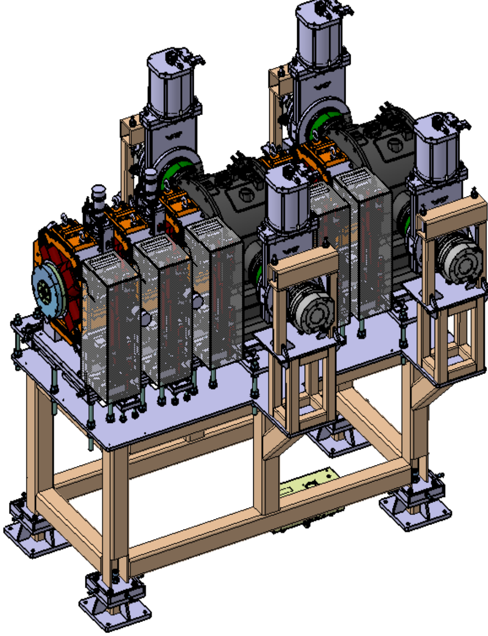
MEBT

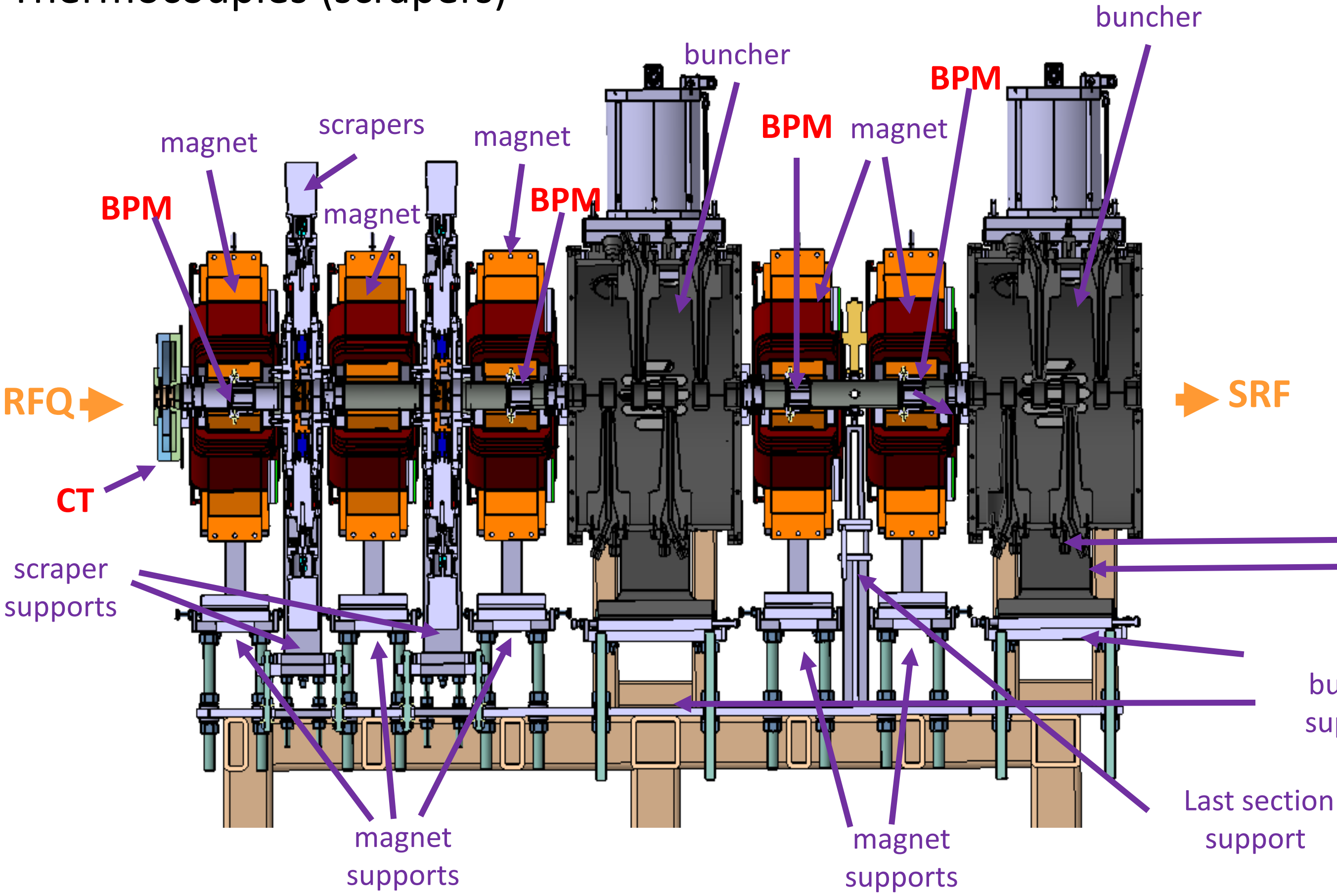
1 ACCT, 1 FCT

4 BPMs (inside magnets)

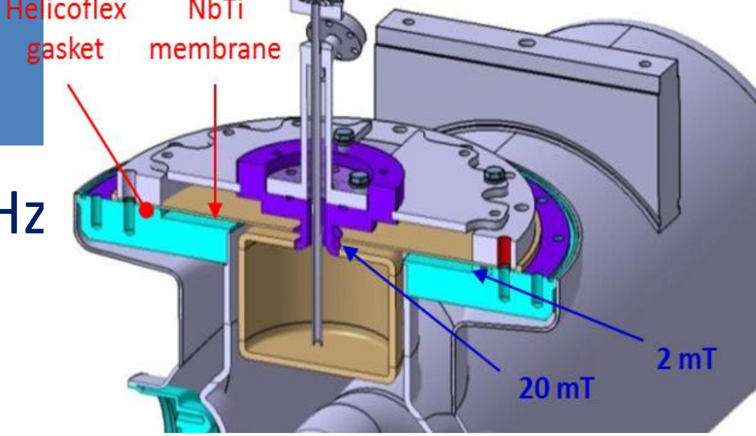
4 BLoMs

4 Thermocouples (scrapers)





Superconducting cavities



Superconducting HWR resonator at 175 MHz

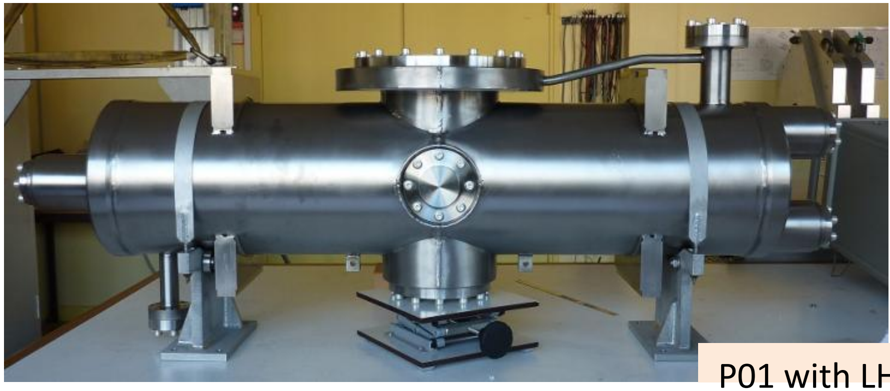
E_{input}= 5 MeV

E_{output}= 9 MeV

Beam loss < 10W

E_{acc}=4.5 MeV/m

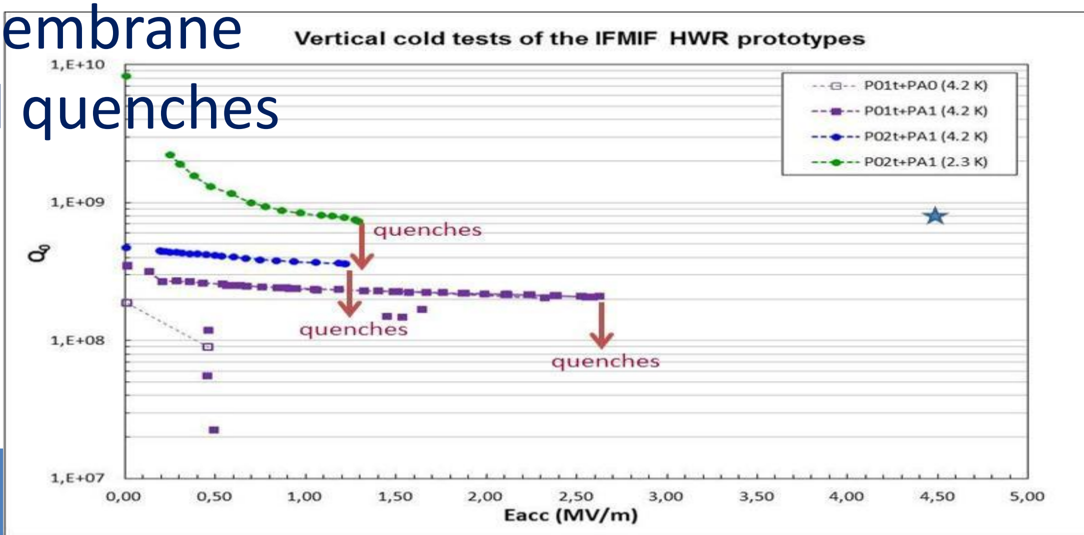
Max transm. RF power = 70 kW

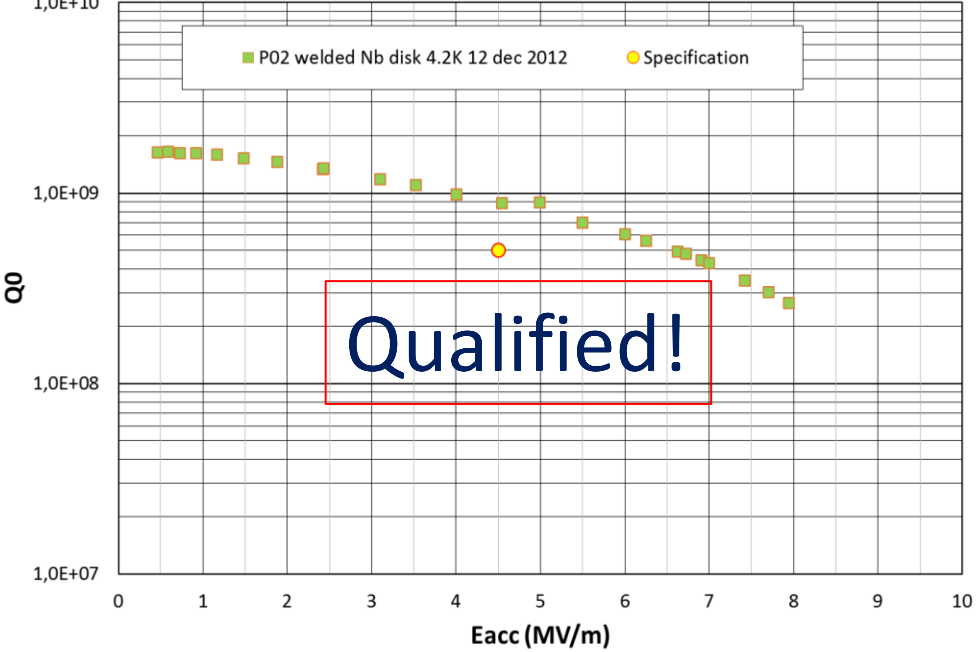


P01 with LH

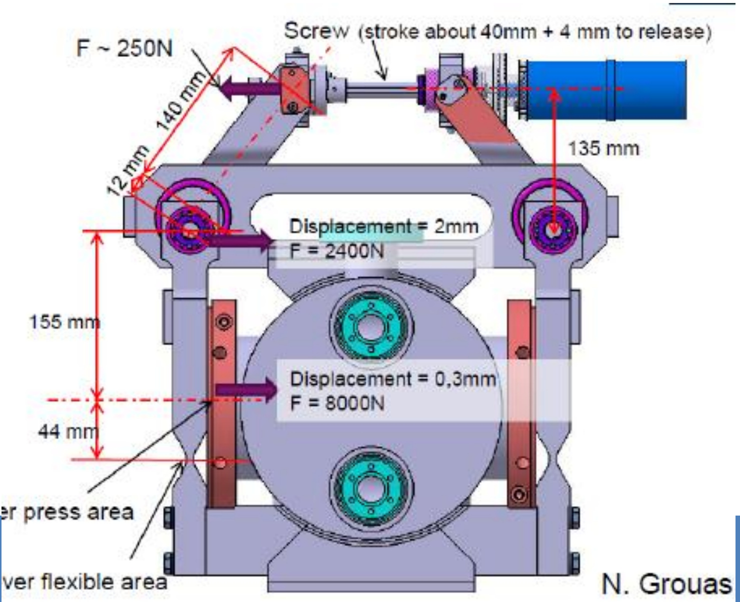
Problems encountered

Plunger tuning system based on NbTi movable membrane caused Qo degradation and quenches at low field



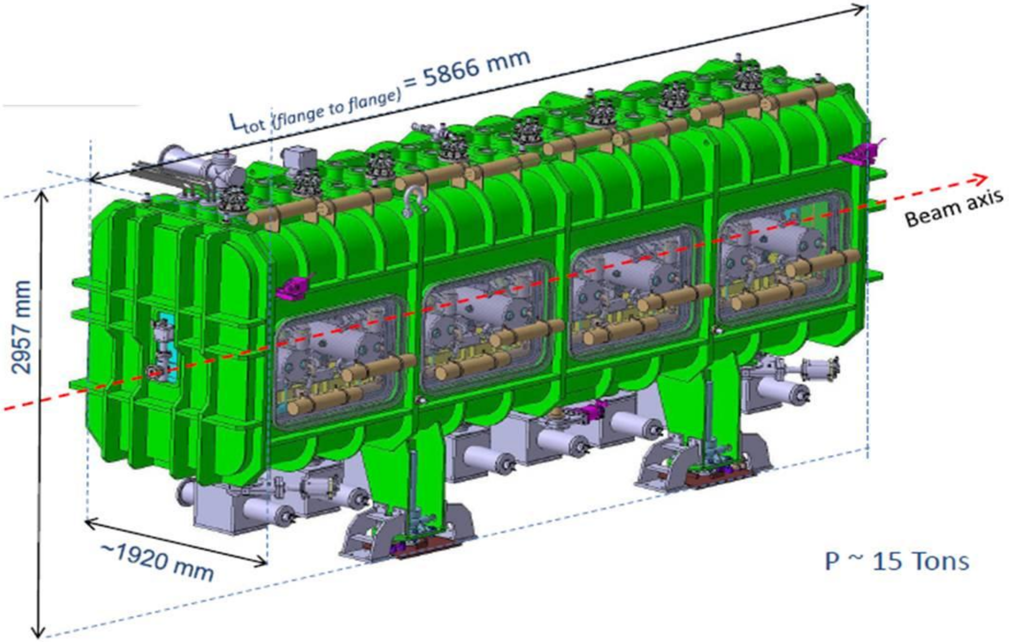


Conventional mechanical tuner following Spiral2 will be adopted



N. Grouas

Integration work is under design

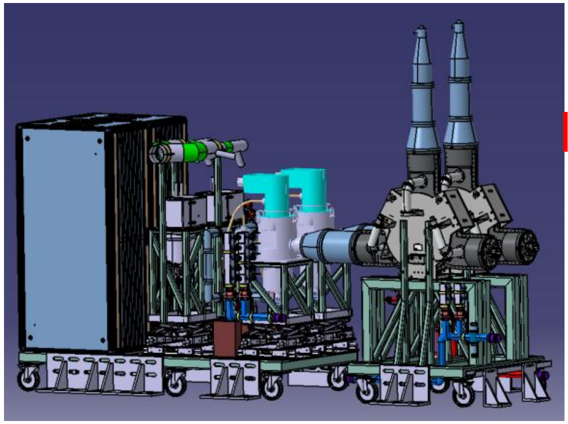


P ~ 15 Tons

RF Power System: Main performances

Parameter	Value
Frequency	175 MHz
Bandwidth	+/- 250 kHz
Phase Stability (Closed loop)	+/- 1º
Amplitude Stability (Closed loop)	+/- 1%
Power Linearity (Closed loop)	1%
Operating Modes	Continuous Wave and Pulsed mode
RF Chains for the RFQ	8 units Up to 200 kW Output Power. Driver and Final Amplifiers based on high power grid tubes technology
RF Chains for the SRF LINAC	8 units Up to 105 kW Output Power Driver and Final Amplifiers based on high power tubes technology
RF Chains for the MEBT	2 units Up to 16 kW Output Power Fully based on Solid State technology

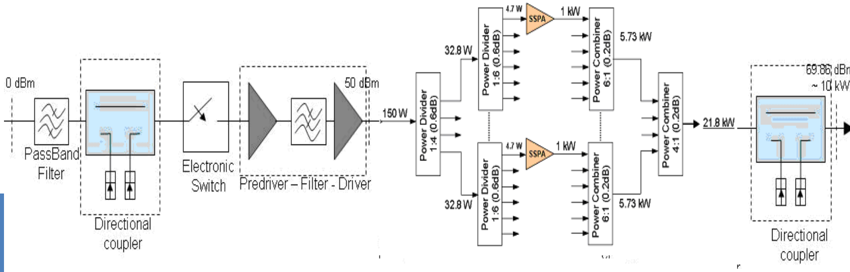
RF Prototype Module
(contains one 200kW RF chain)



One Module contains two RF Chains

200 and 105 kW RF Modules based on high power tubes

16 kW Solid State Power Amplifier



LIPAc Instrumentation

Challenges for beam instrumentation

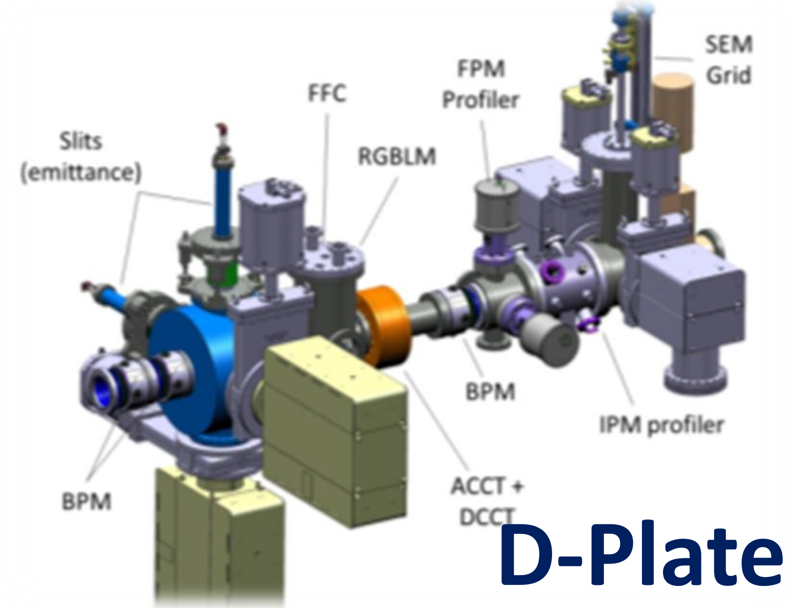
High intensity in CW

Low beam energy

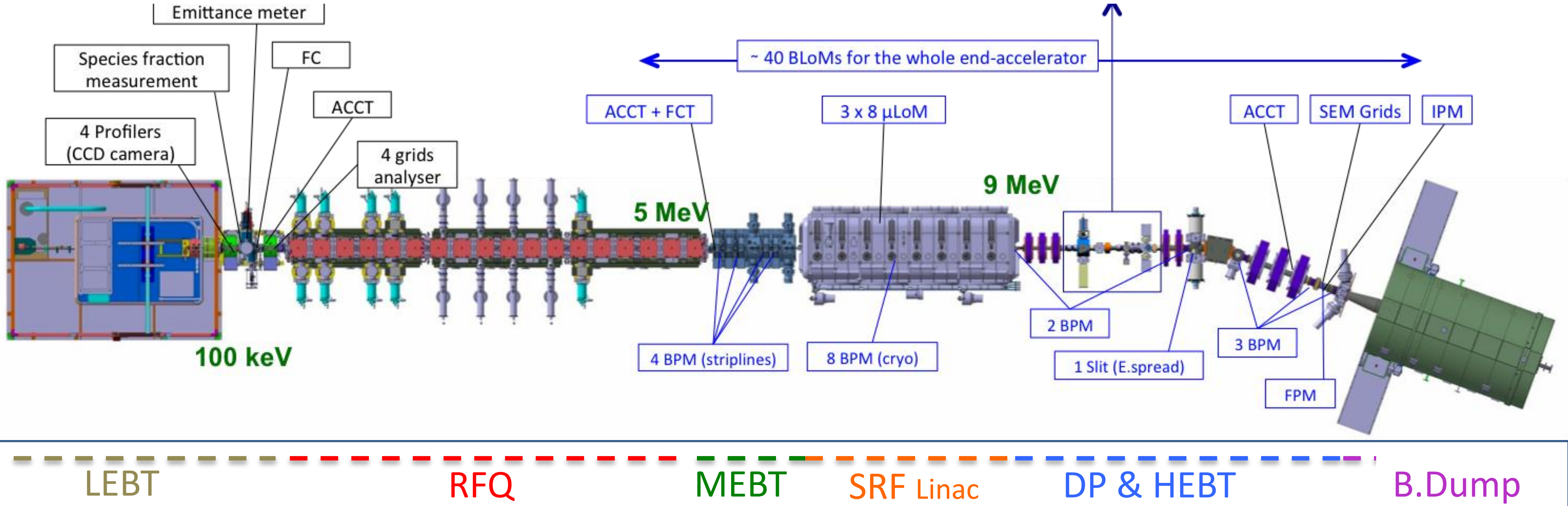
High beam power

High Ionizing radiation

Instrumentation up to the cryomodule valid for IFMIF



D-Plate


Emittance meter

Species fraction measurement

FC

ACCT

4 Profilers (CCD camera)

4 grids analyser

100 keV

5 MeV

~ 40 BLoMs for the whole end-accelerator

ACCT + FCT

3 x 8 μLoM

9 MeV

ACCT

SEM Grids

IPM

4 BPM (striplines)

8 BPM (cryo)

2 BPM

1 Slit (E.spread)

3 BPM

FPM

LEBT

RFQ

MEBT

SRF Linac

DP & HEBT

B.Dump

P.A.P. Nghiem, N. Chauvin, M. Comunian, O. Delferrière, R. Duperrier, A. Mosnier, C. Oliver, D. Uriot , *The IFMIF-EVEDA challenges and their treatment*, Nuclear Instruments and Methods in Physics Research A, 654 (2011) 63-71

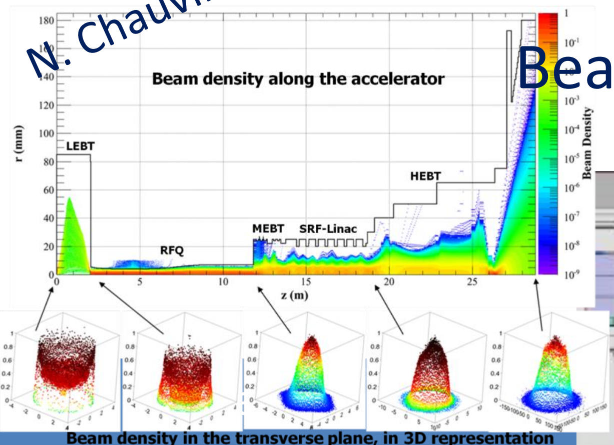
Putting it all together…

LIPAc commissioning will be
a challenging (and fascinating) phase

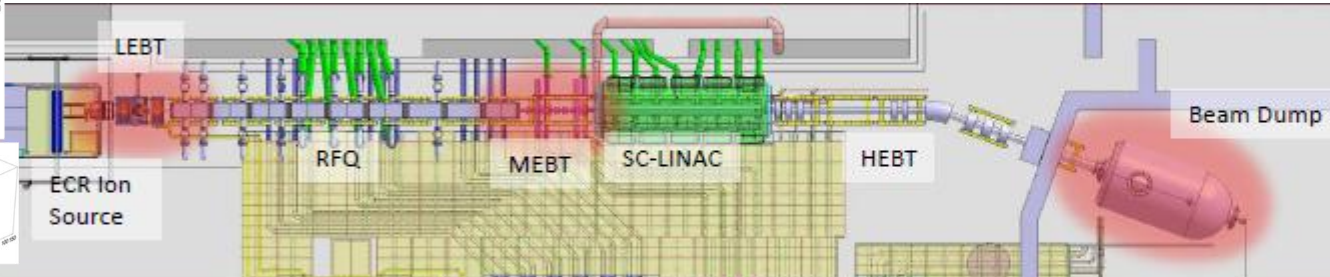
Individual equipment is ‘commissioned’ in labs
and put together in Rokkasho

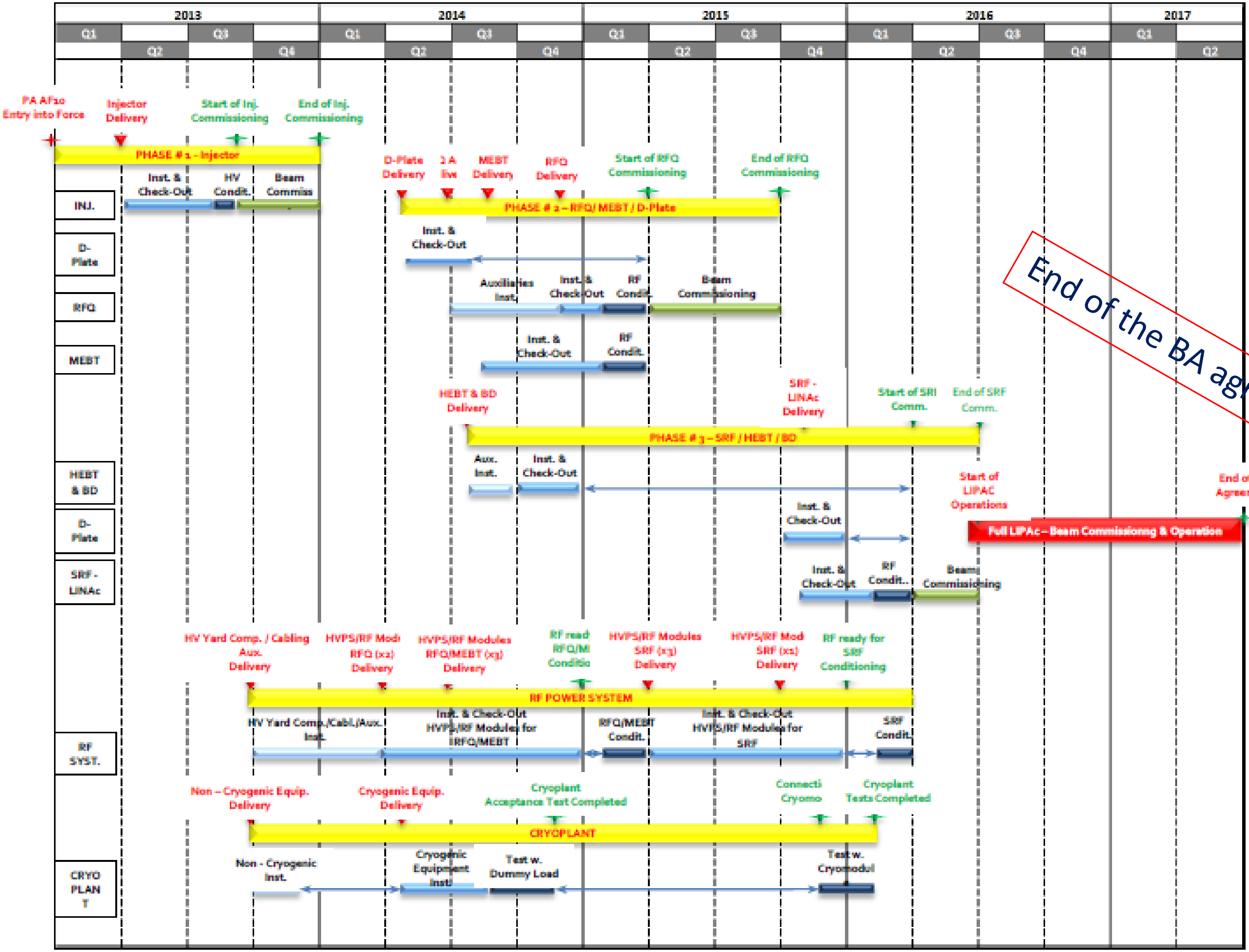
Starting with protons and 0.1% duty cycle

High power, (1.125 MW) high space charge
and nature of particle (deuterons) makes it fun (if I may)


N. Chauvin

Beam physics performed by CEA&CIEMAT&INFN



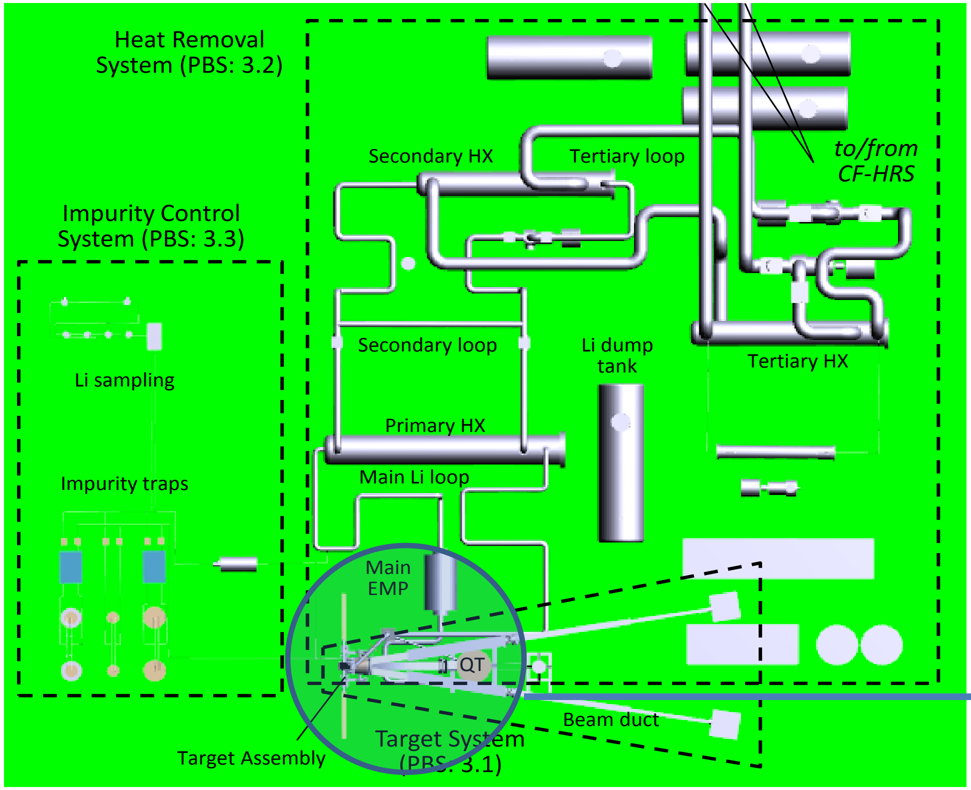


End of the BA agreement

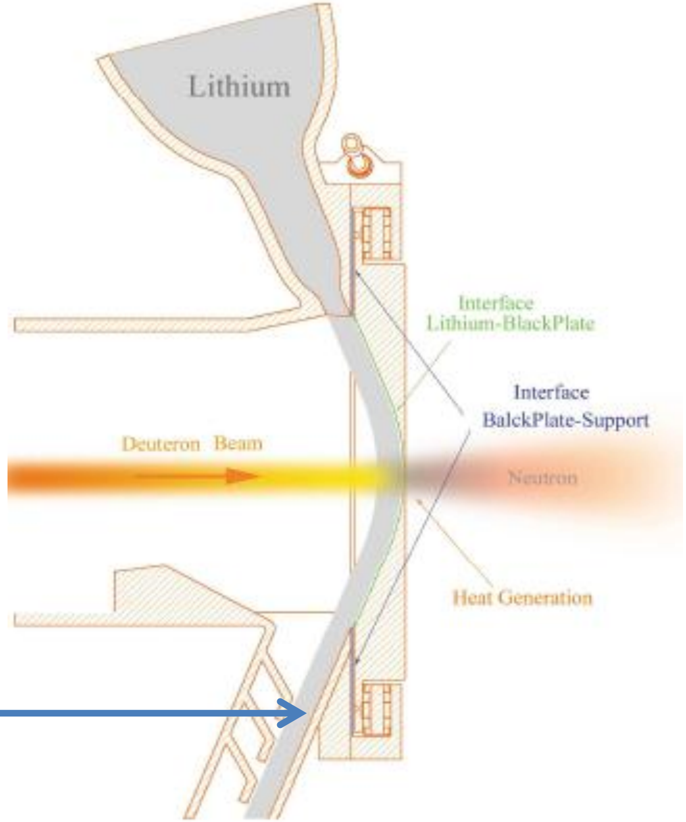
No agreement on what next…

Target Assembly concept

Configuration of the Lithium loop

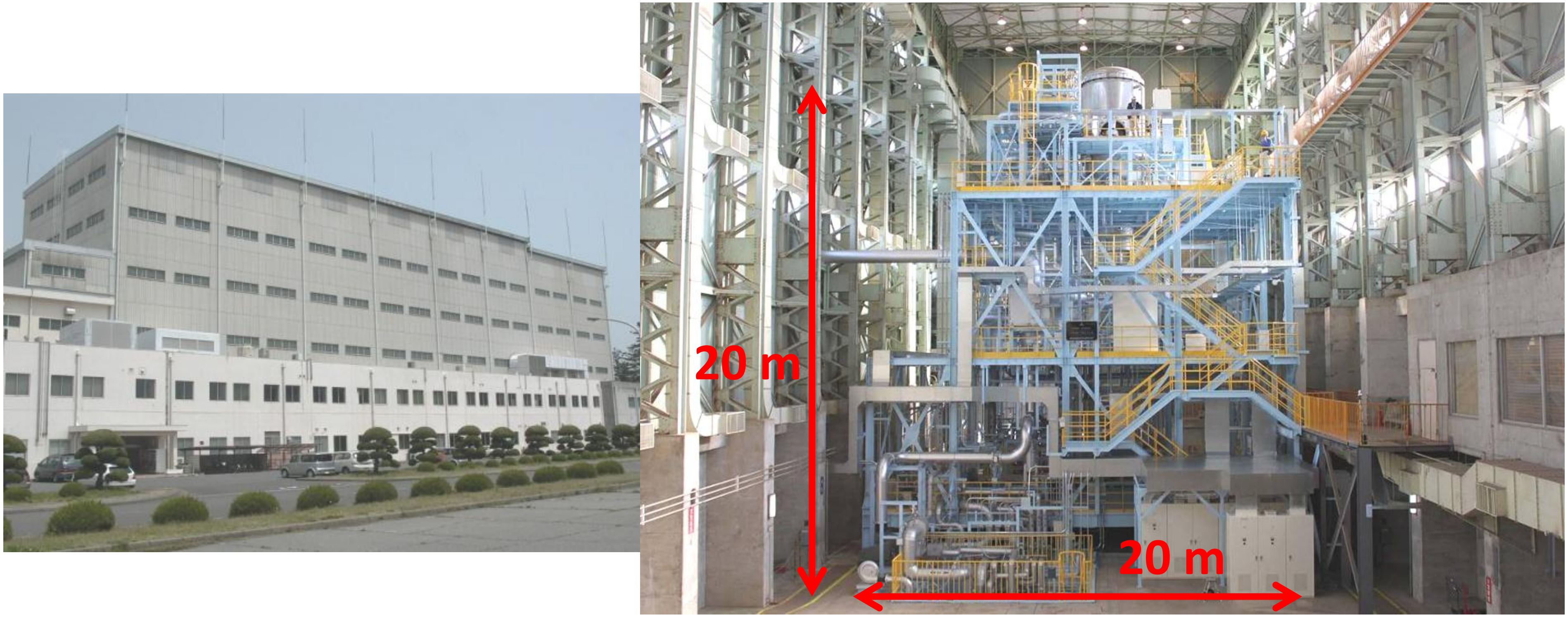


Target assembly concept



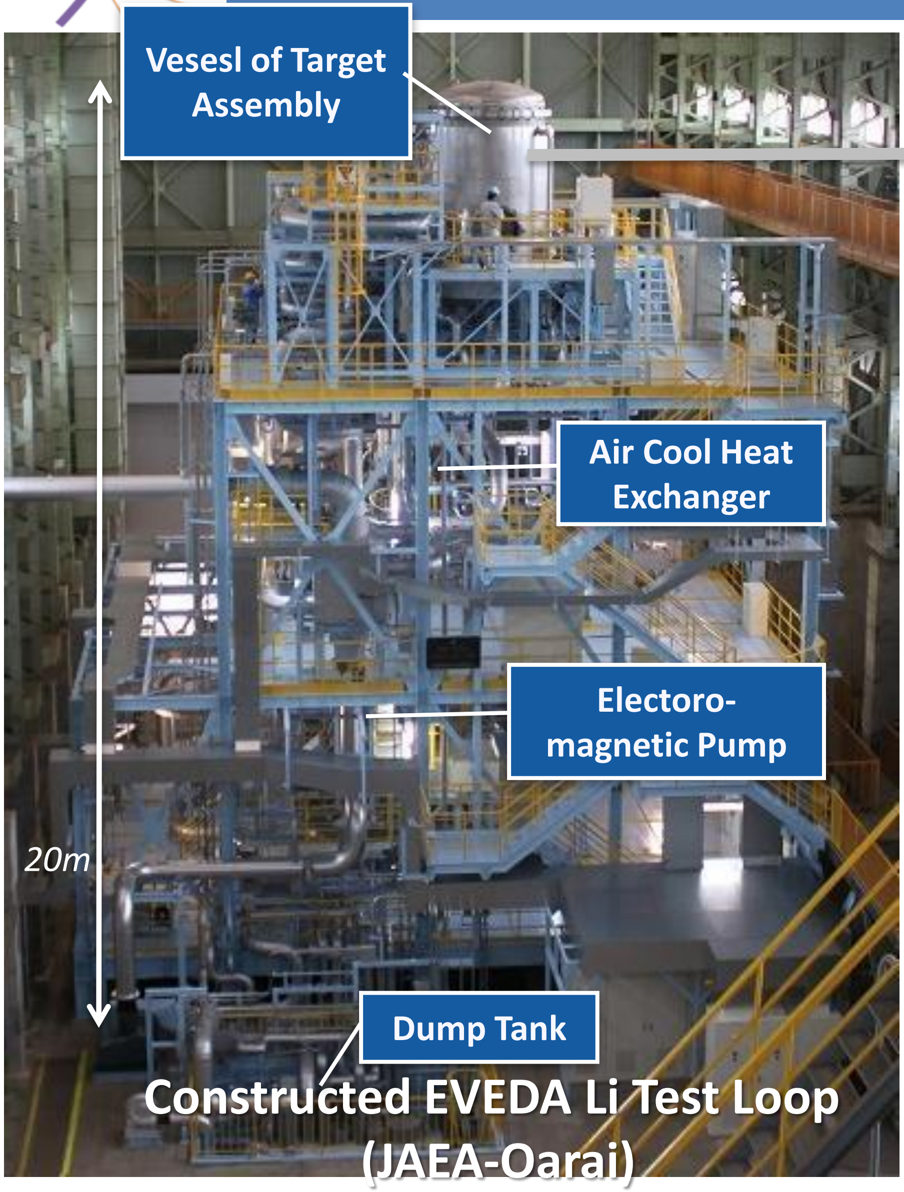
Target facility validation

World largest liquid Li loop constructed by JAEA in Oarai

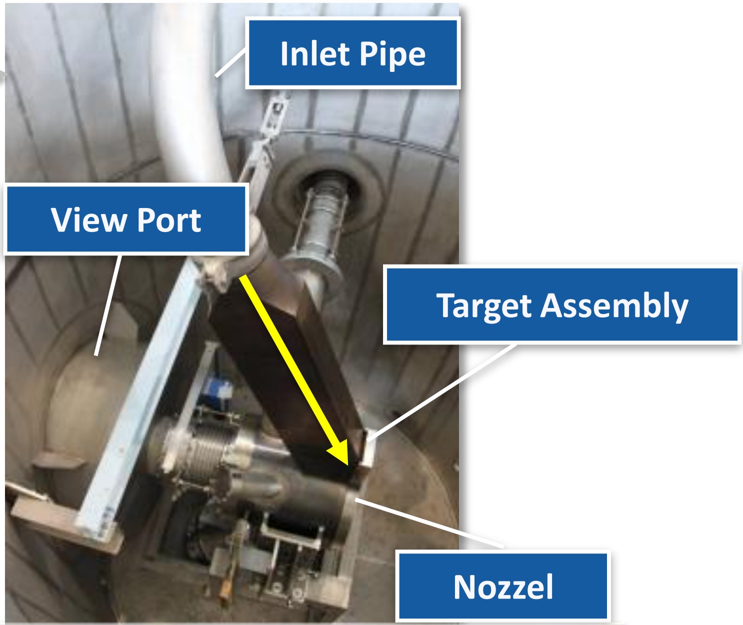


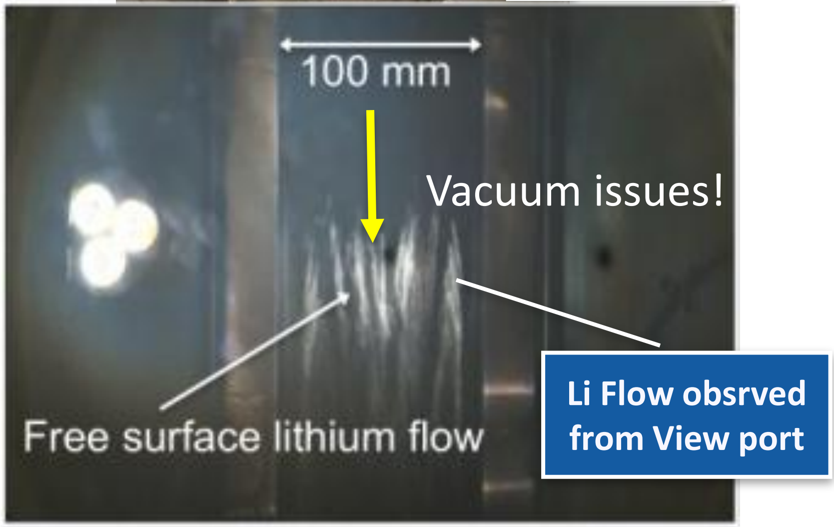
Kondo, H., et al., *Completion of IFMIF/EVEDA lithium test loop construction*, Fus. Eng. Des. **87** (2012) 418

Target facility validation



Constructed EVEDA Li Test Loop (JAEA-Oarai)





Vacuum issues!

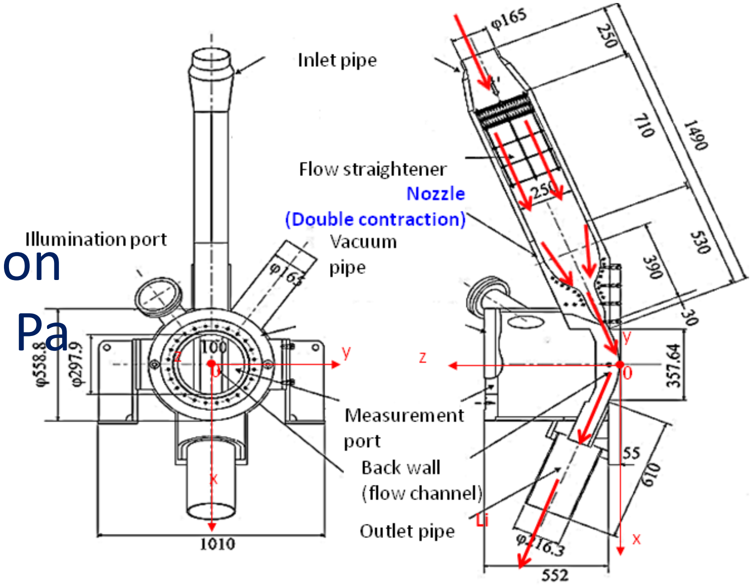
Target facility validation

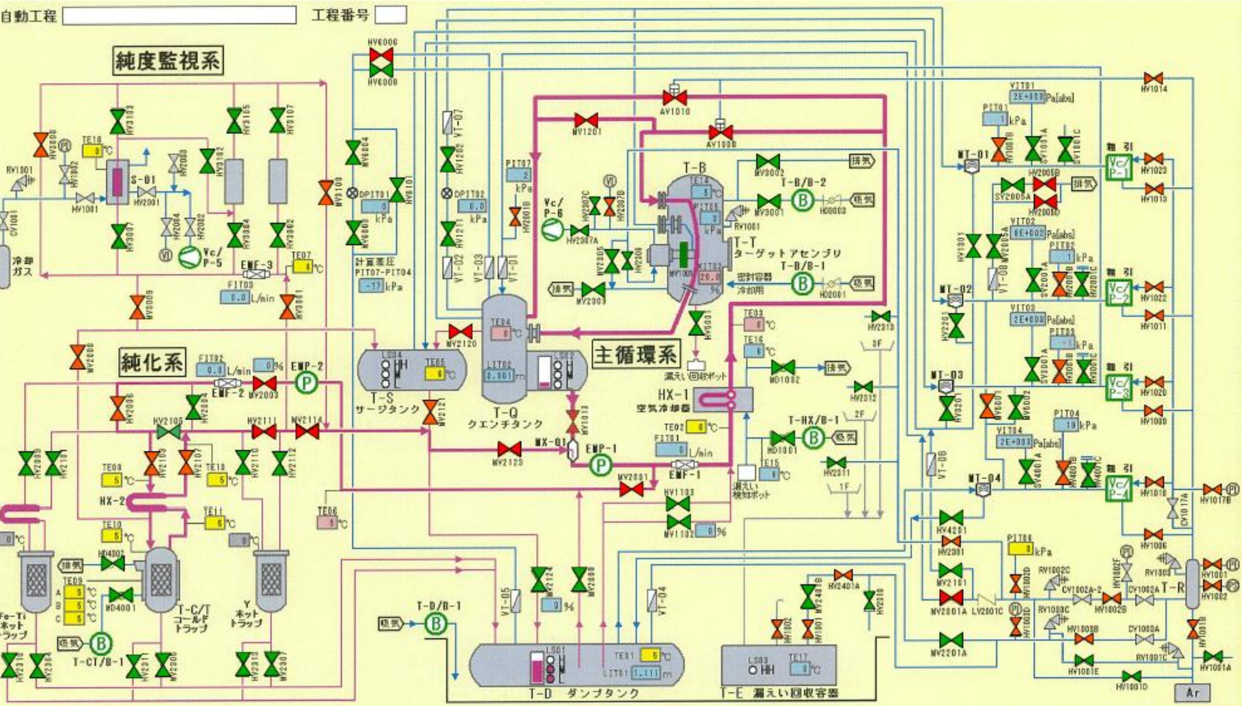
T = 350°C

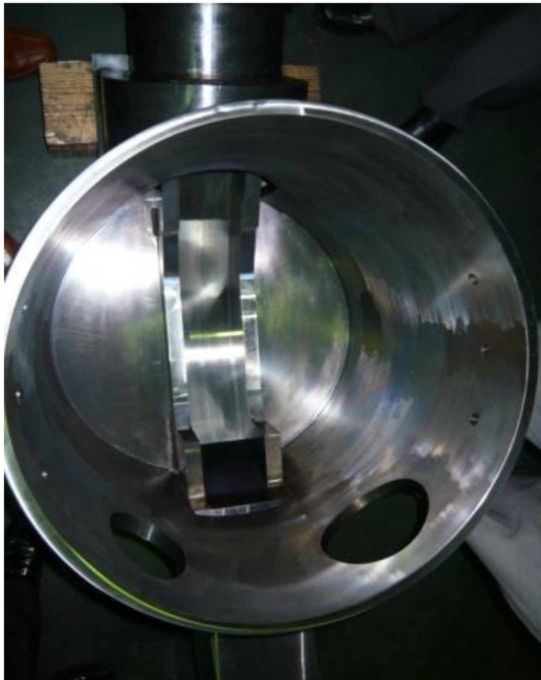
speed: 15 m/s

flow: 2250 l/min vacuum on

Vacuum on beam side: 75 Pa



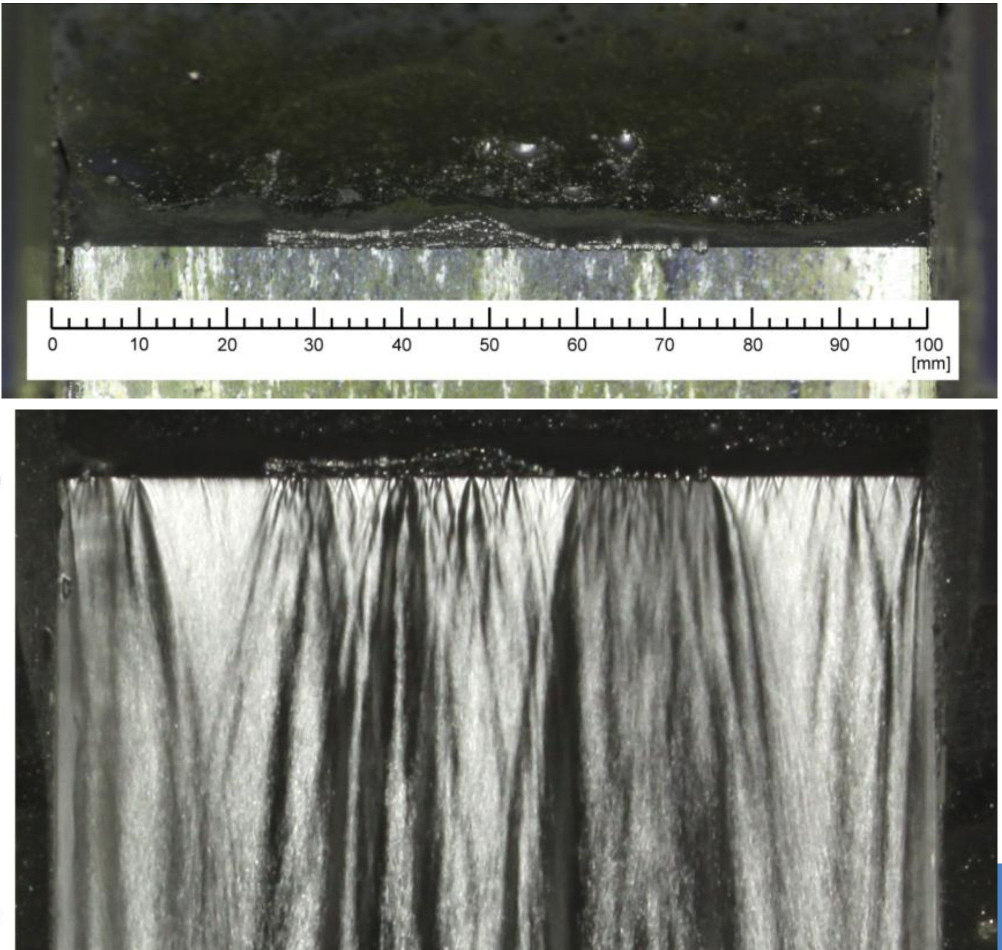




Target facility validation

Droplets in nozzle generate turbulences

Bragg peak of 40 MeV deuterons in liquid Li at ~20 mm



Definition of characteristics of stability of the free surface flow of the Li jet is essential

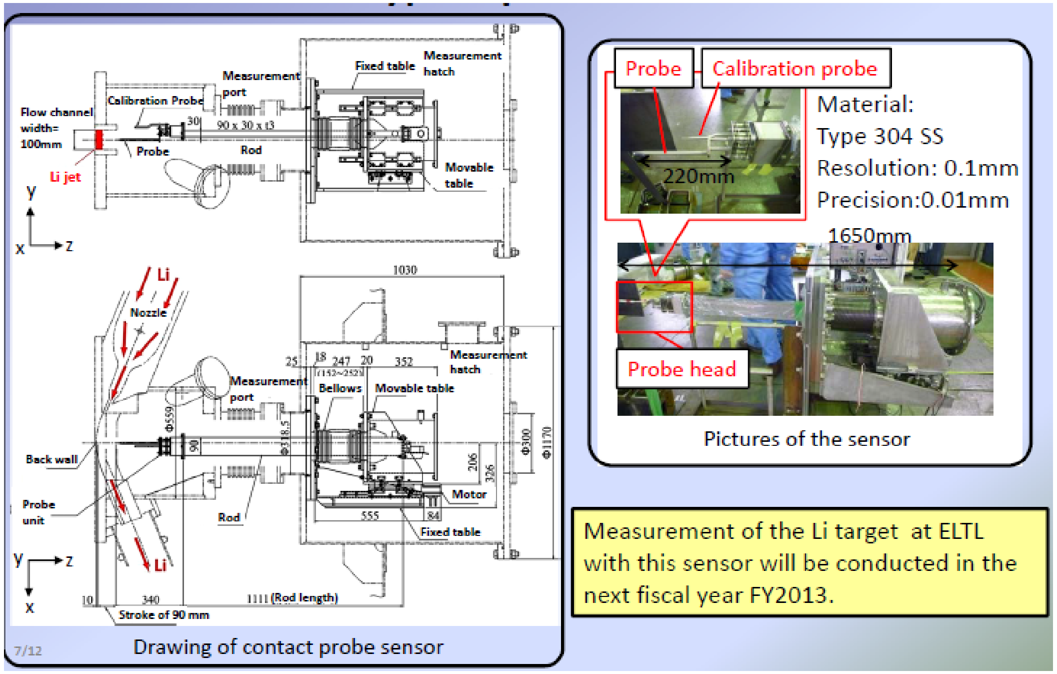
The 25 mm thick jet shall not vary > ± 1 mm

Diagnostics to monitor the flow stability and safely detect deviation beyond the above limits

Target facility validation

Diagnostics of free surface pattern

Contact probe



Material:
Type 304 SS
Resolution: 0.1mm
Precision:0.01mm

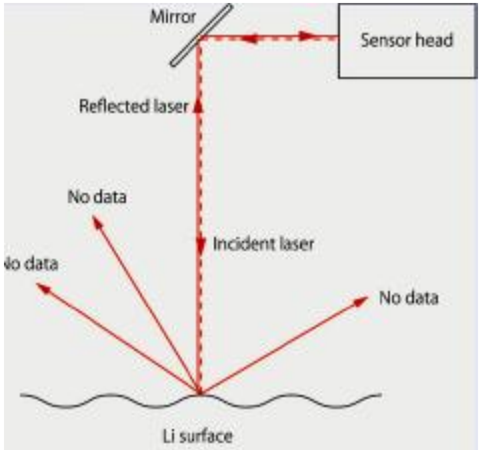
Pictures of the sensor

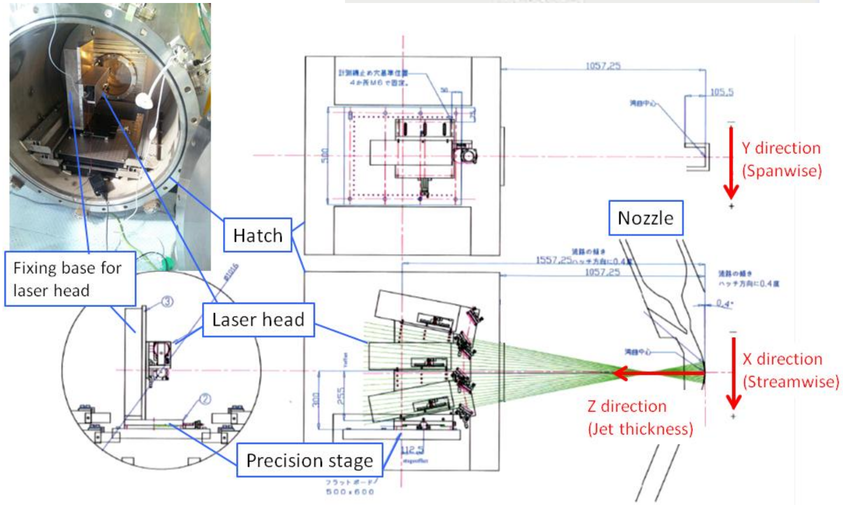
Drawing of contact probe sensor

7/12

Measurement of the Li target at ELTL with this sensor will be conducted in the next fiscal year FY2013.

Optical





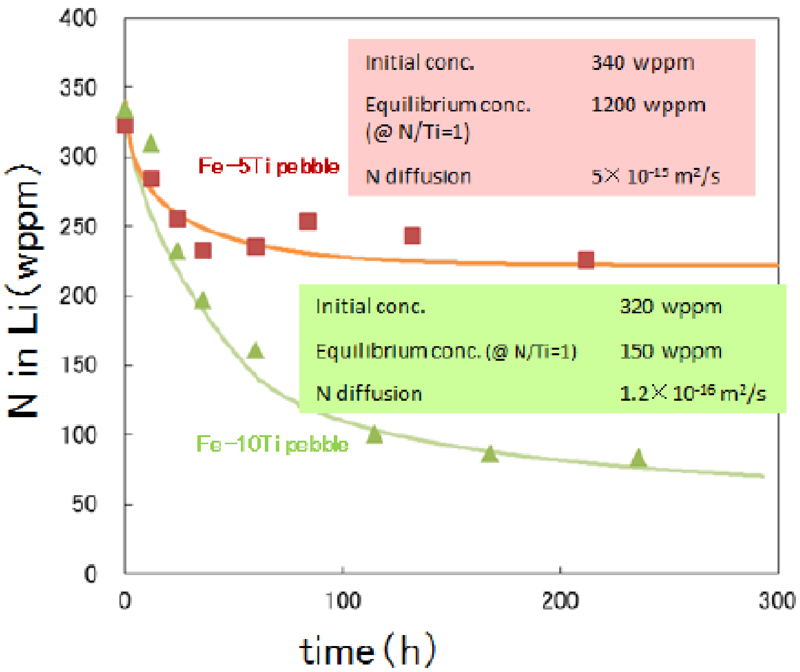
Kanemura. T. et al., *Investigation of free-surface fluctuations of liquid lithium flow for IFMIF lithium target by using an electro-contact probe*, Fus. Eng. Des. 82 (2007) 2550–2557

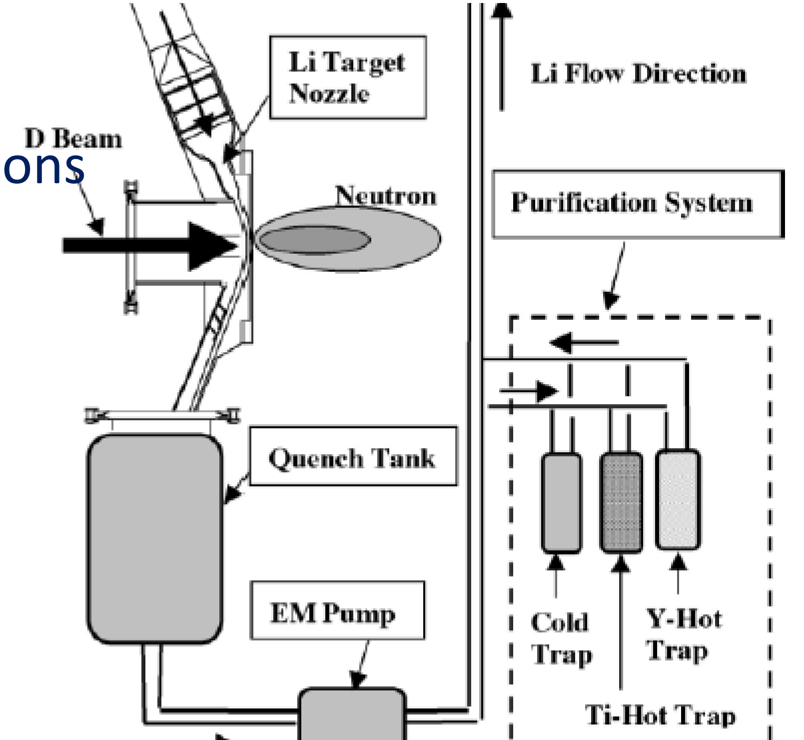
Target facility validation

Purification of Li loop is essential
Formation of N-Li-Cr
that erodes the nozzle
Trapped in Ti
Presence limited to 10 ppm
not achieved

H is present from D
absorbed in flowing Li
Essential to be trapped for safety reasons
Trapped with Y
Presence limited to 1 ppm

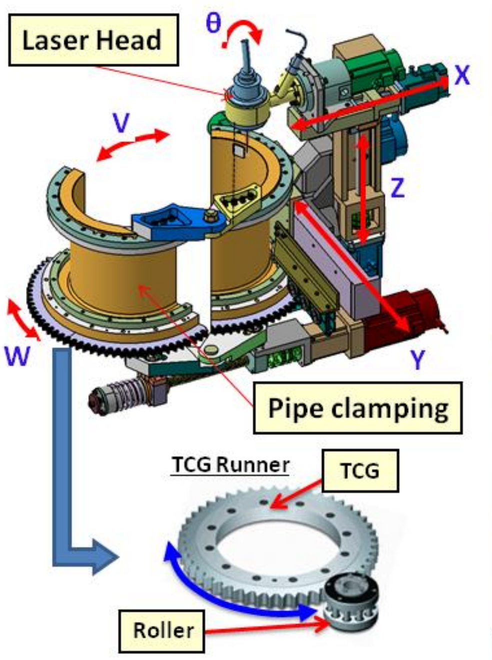
Cold traps of O, C and Be

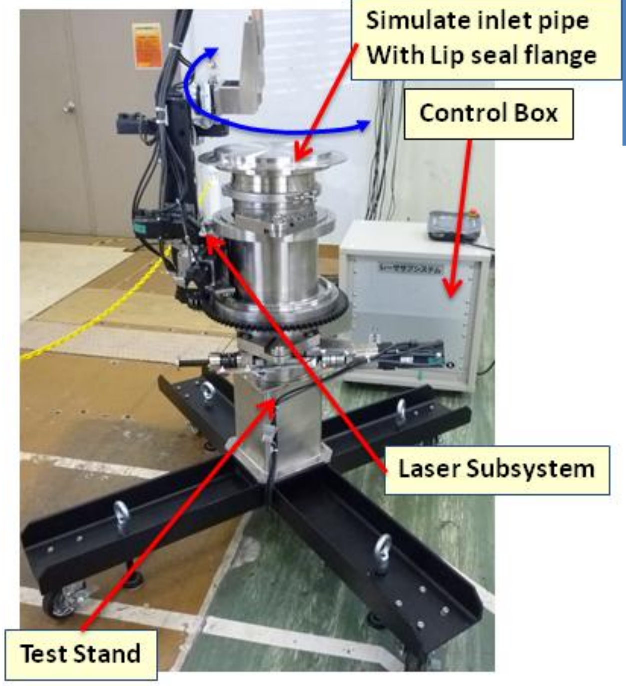


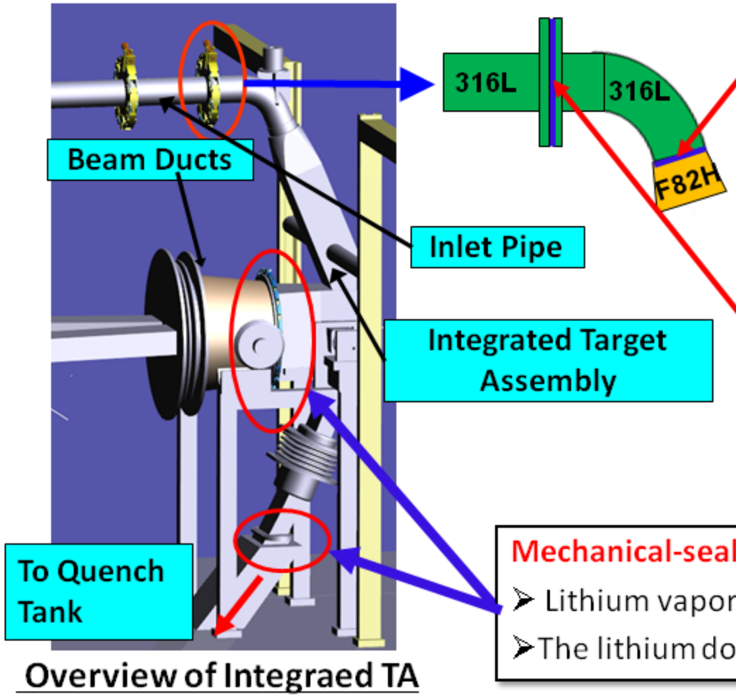


Target facility

Remote handling is being developed by Osaka University







Overview of Integraed TA

Dissimilar welding (off-site)

- Welding by TIG welding or another method at off-site
- Dissimilar materials : 316L/F82H

Lip-seal flange welding & cutting with mechanical clamp (on-site)

- Liquid lithium flow channel
- Welding & cutting by remote handling because of on-site
- Similar materials : 316L
- Connection support by clamping

Mechanical-seal (Quick Disconnecting System)

- Lithium vapor atmosphere
- The lithium doesn't touch direct in the seal part

Target facility validation

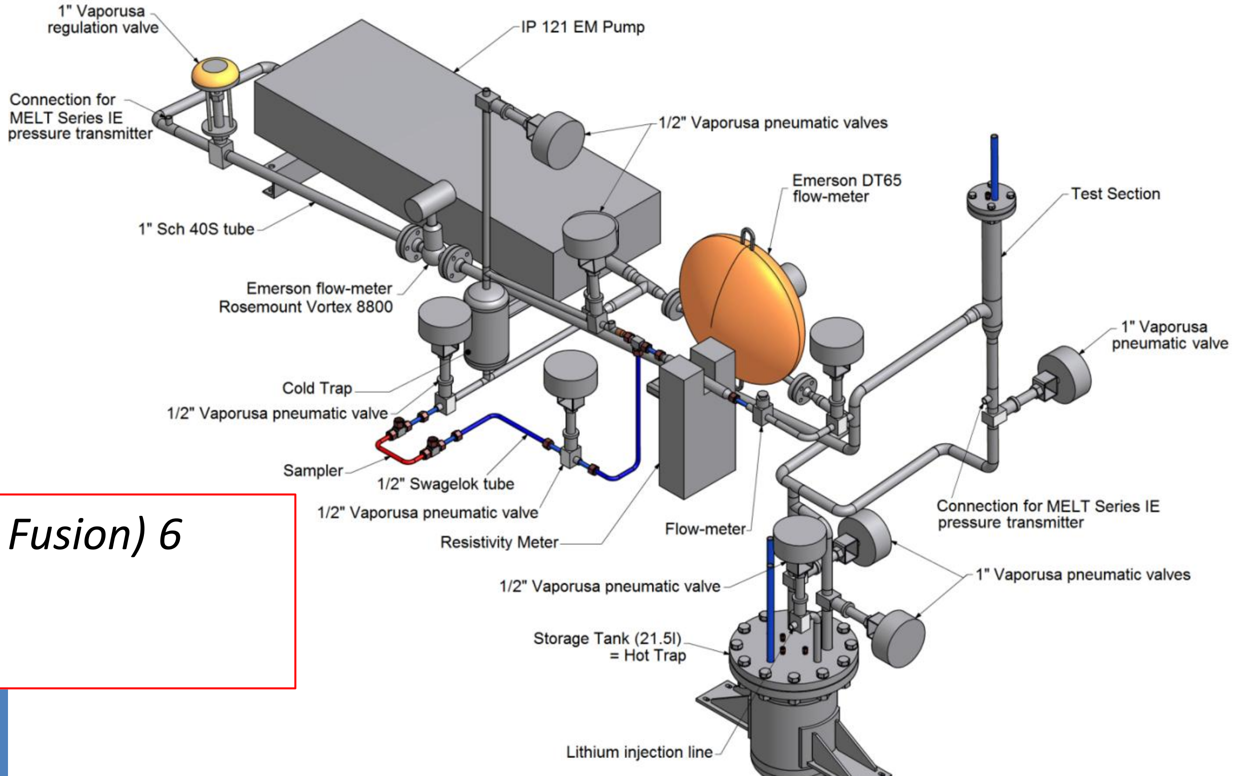
Erosion/corrosion tests performed in ENEA

8000 h tests programmed starting in spring 2013

T=350°C

velocity = 16 m/s,

impurity level, temperature, exposure duration on RAFM target

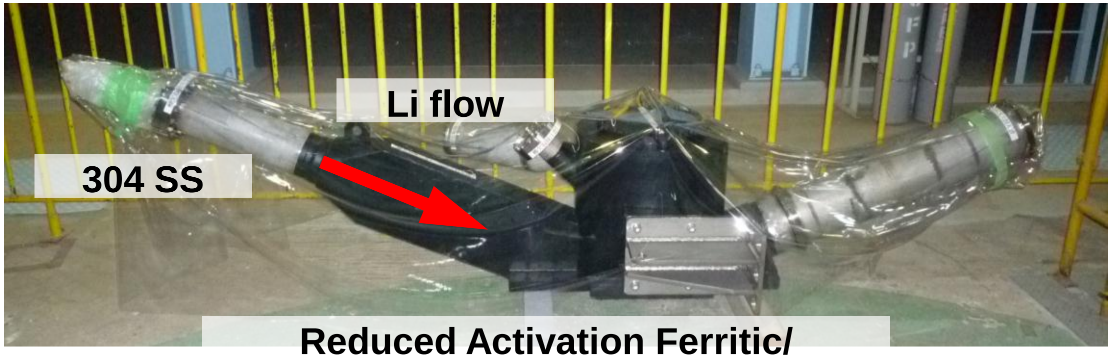


Aiello, A., et al., *Lifus (Lithium for Fusion) 6 loop design and construction*, Proceedings of SOFT 2012, Liege

Target facility validation

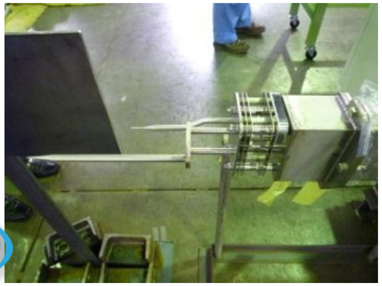
Other hardware under qualification

- Manufacturing and acceptance:
  - F82H target body
  - Nitrogen trap
  - Contact probe
- Procurement of plugging meter



Reduced Activation Ferritic/ Martensitic Steel, F82H, target body

Osaka Univ.



Contact Probe

Resistivity Meter

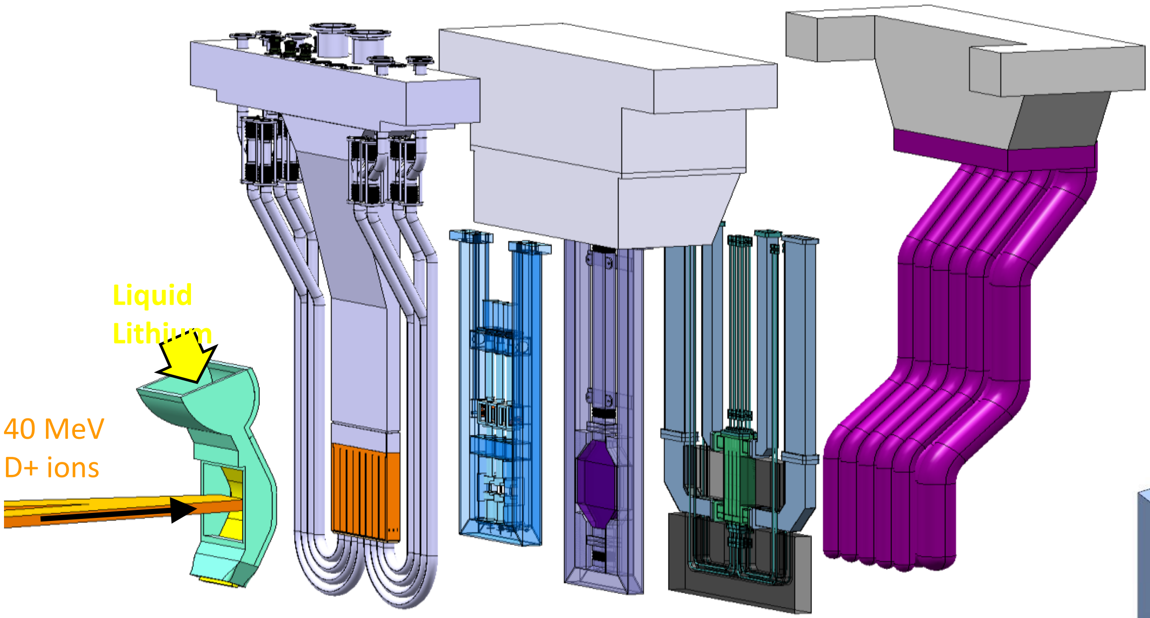
RM was developped by the University of Nottingham&ENEA.
Online monitoring of the N dissolved in Li

Detector Bar for cavitation's vibration

Test facility validation

High >20 dpa/y, 0.5 liters
Medium >1 dpa/y, 6 liters
Low <1 dpa/y, 8 liters

KIT Karlsruhe Institute of Technology
京都大学
JAEA
Ciemat
KIT Karlsruhe Institute of Technology
SCK•CEN



Neutron source	High Flux	Middle Flux Area			Low Flux Area
LT/BP	HFTM	UTM	MOD	TRM	LFTM

Decreasing neutron flux density

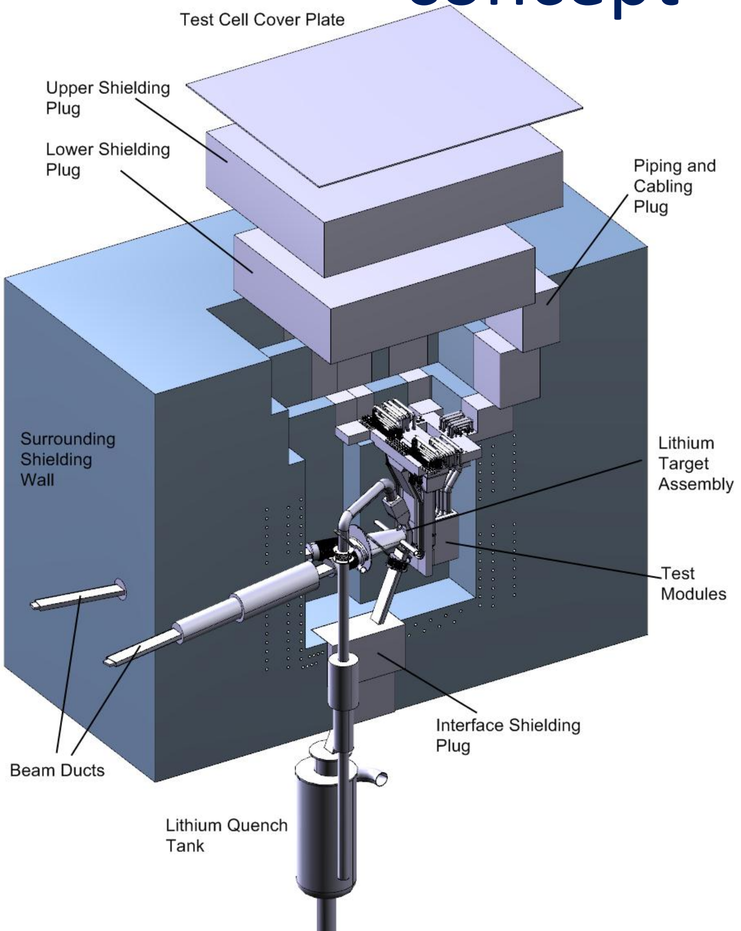
Softening neutron energy spectrum

structural materials (FW, blanket)

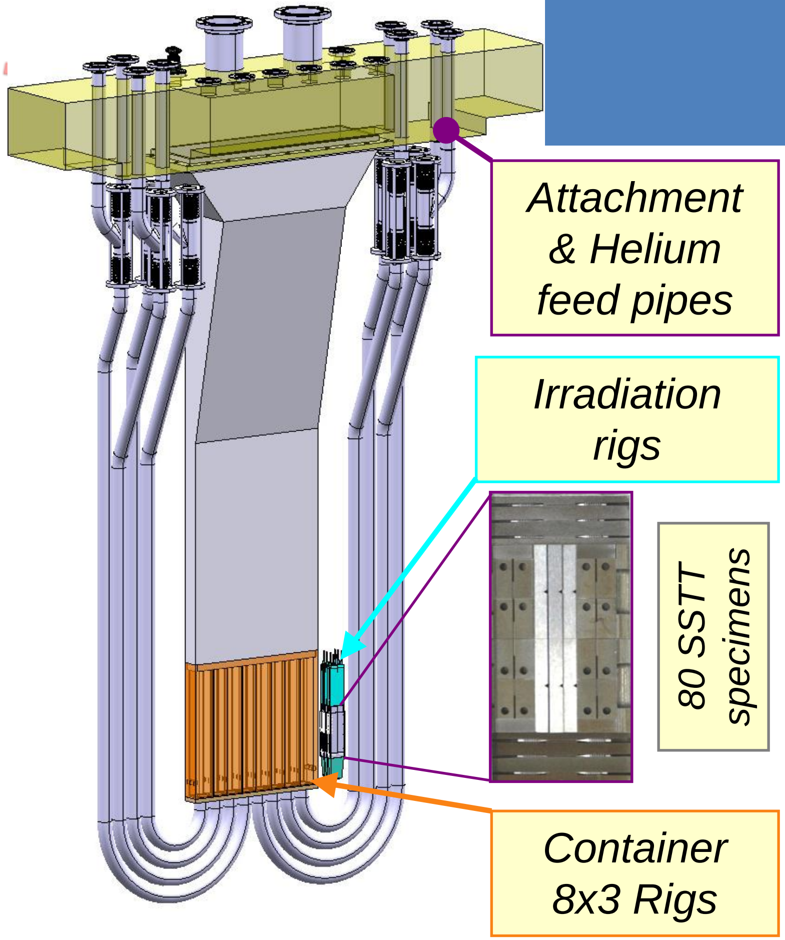
breeder mat. Be, Li-ceramics

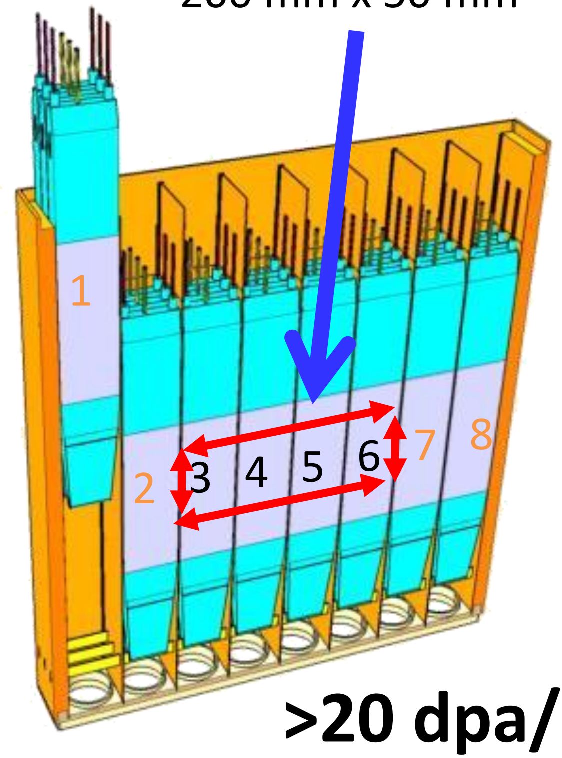
auxillary irradiation spa

Test facility concept



Test facility validation





Beam footprint
200 mm x 50 mm

>20 dpa/y

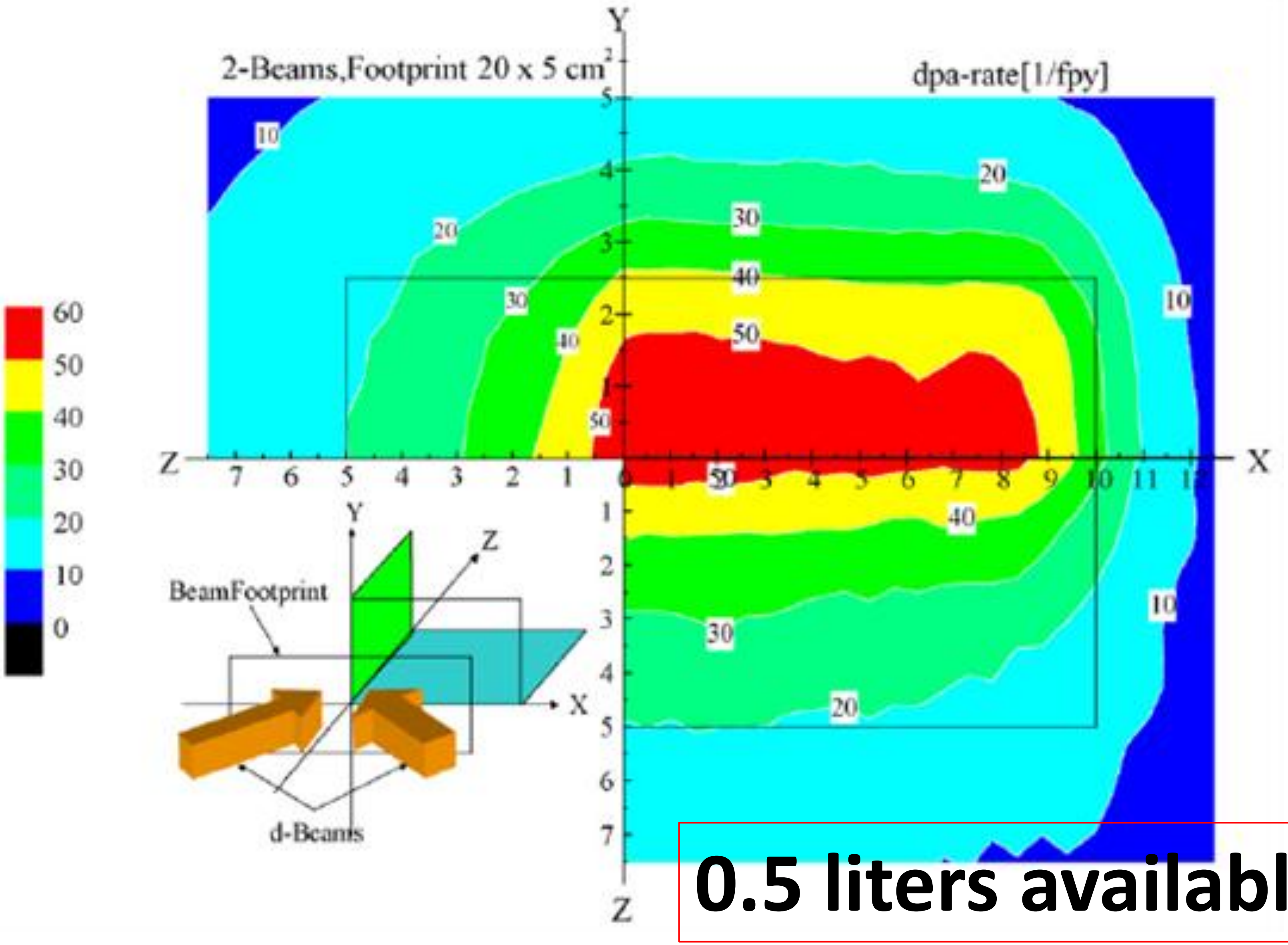
High packing density of material specimens in beam footprint 20 cm x 5 cm

Enable irradiation temperatures
250°C ≤ T_{irr} ≤ 550°C

Arbeiter, A., et al.,
Overview of results of the first phase of validation activities for the IFMIF High Flux Test Module,
Fus. Eng. Des. **87** (2012) 1506.

Minimize temperature spread in specimen stack (within 3%) by NaK filling

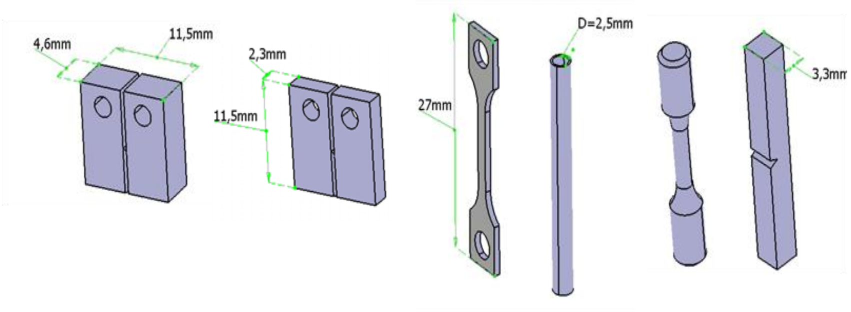
dpa map in HFTM

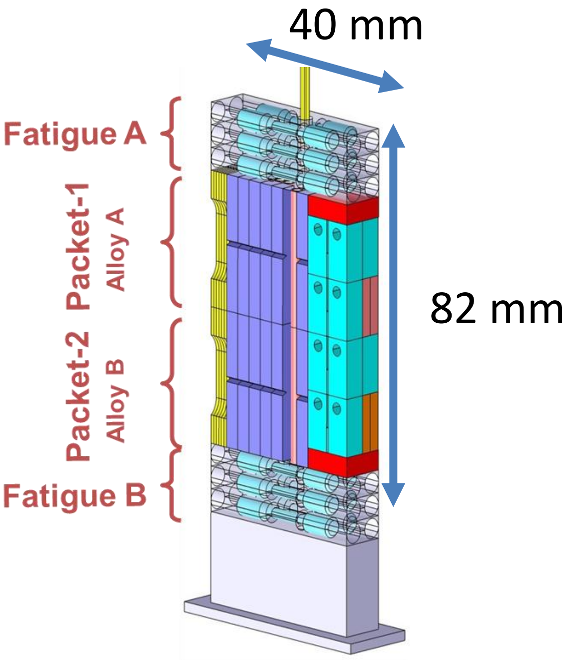


0.5 liters available

Test facility validation

SSTT Specimen: Crack growth, fracture toughness, flat tensile, fatigue, bend/charpy





Property	n of specimen	Volume / Specimen (cm^3)	Specimen package density (%)	Tot. Vol.* occupied in capsule (cm^3)
Microstructure swelling	≥ 5	0.0014	86	0.01
Tensile	12	0.075	76	0.57
Fatigue	6	0.249	51	4.65
Fracture toughness	2	0.560	92	1.83
Crack growth	3	0.280	92	0.61
Bend bar/dynamic fract. toughn.	12	0.291	99	3.53
Creep	8	0.133	79	1,35
Thermocoupl., n/γ-monitors	3 1			

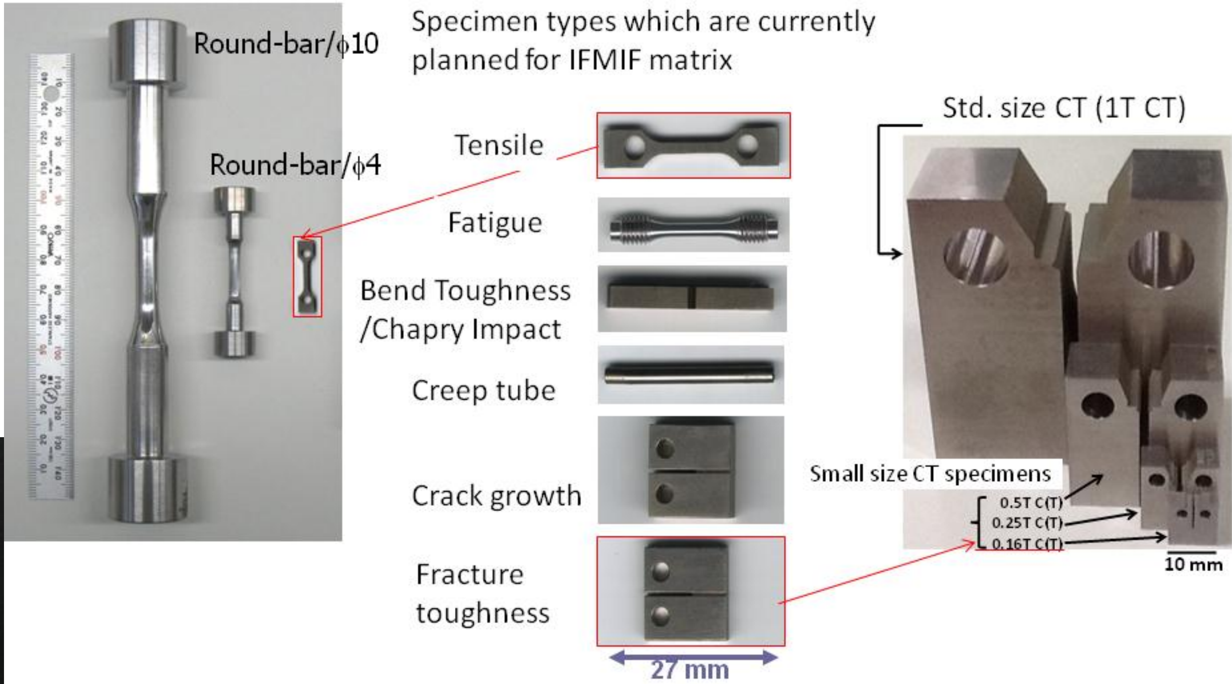
* includes space occupied by NaK

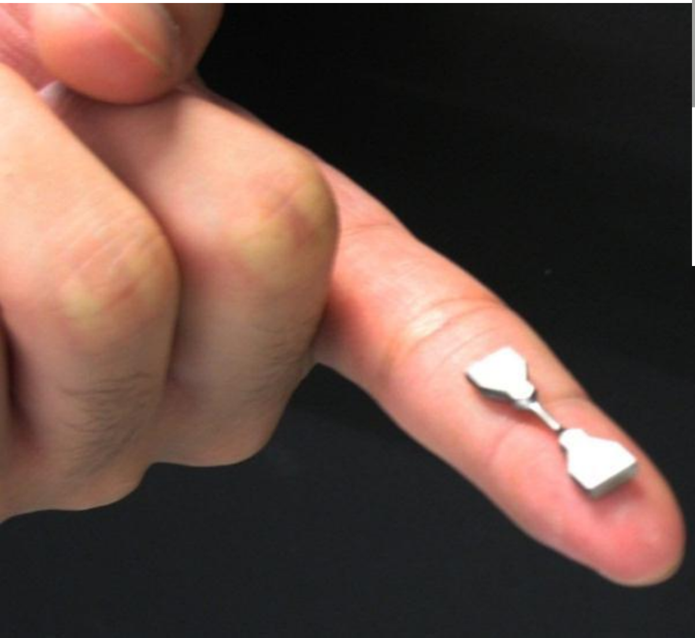
Capability to fit 1032 specimens

Small Specimens Test Technique

Small Specimens technique
is a mature technology developed
for fission reactors materials qualification

G.E. Lucas et al.,
The role of small specimen test technology in fusion materials development,
Journal of Nuclear Materials 367–370 (2007) 1549–1556



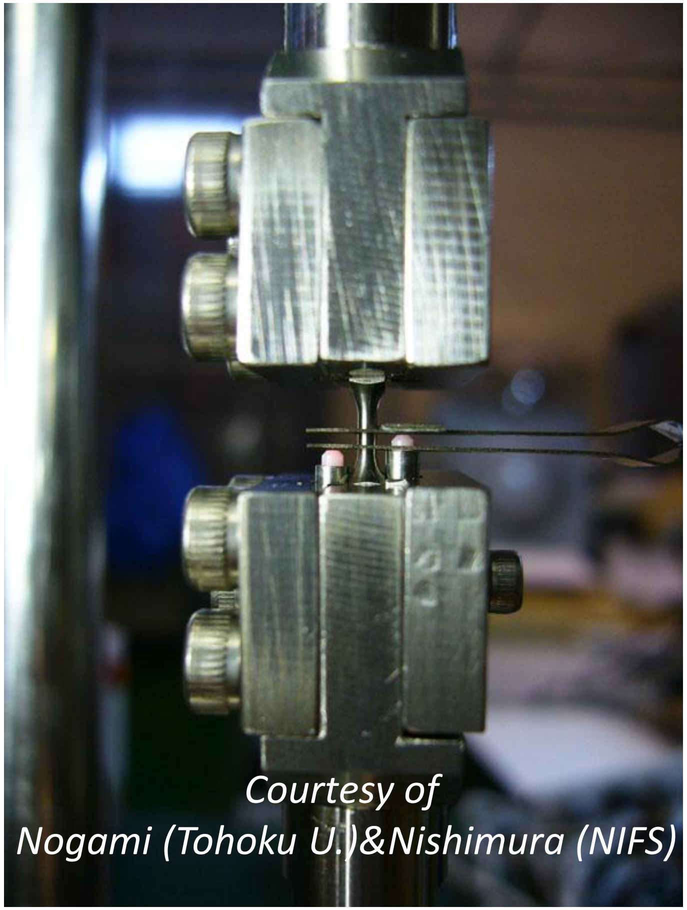


Available results on

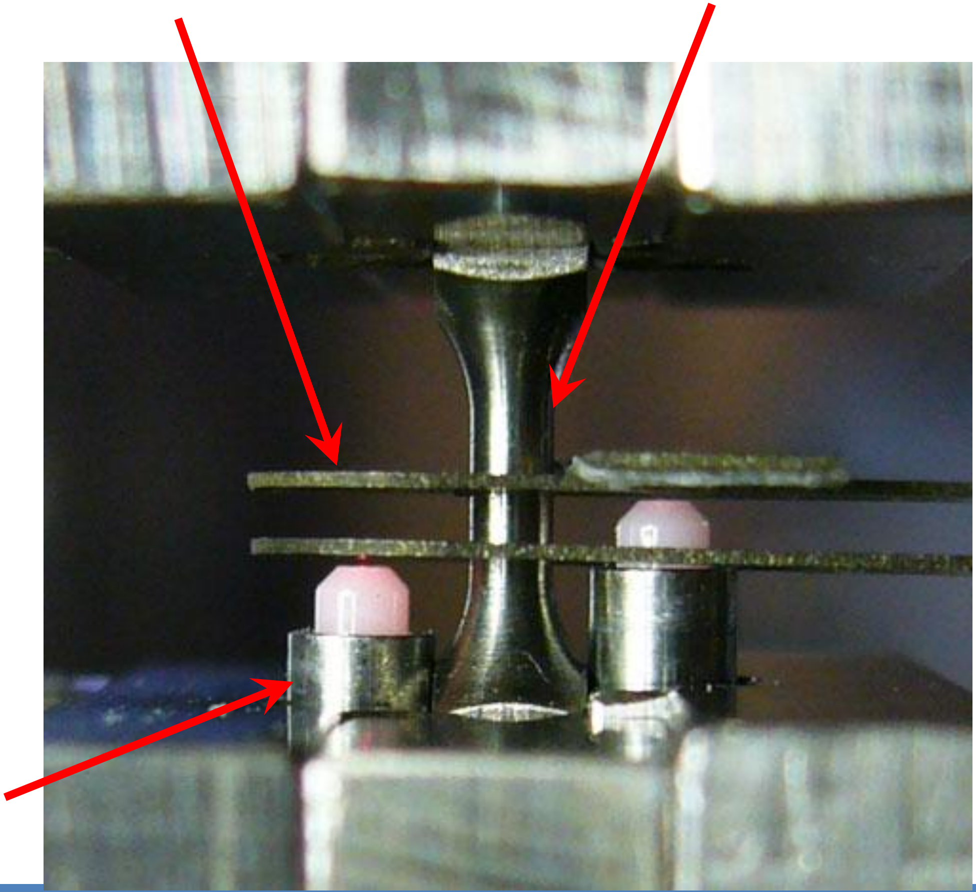
- ***Fatigue***
- ***Fracture toughness***
- ***Crack growth rate***
- ***Creep fatigue behaviour***

Small Specimens Test Technique

Laser extensometer with nanometre accuracy



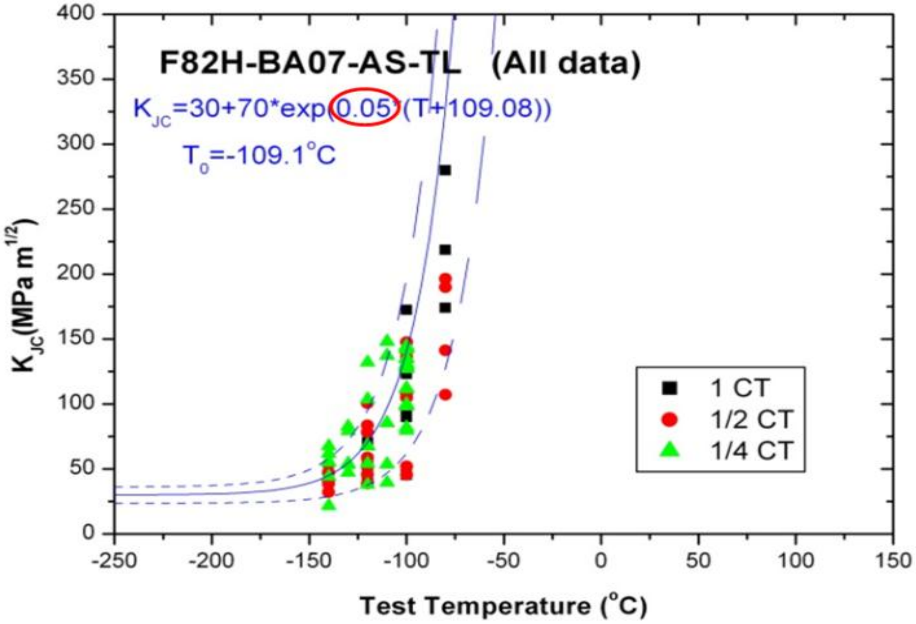
Courtesy of
Nogami (Tohoku U.)&Nishimura (NIFS)



Laser micro head: ϕ1.25 mm

Small Specimens Test Technique

Fracture toughness

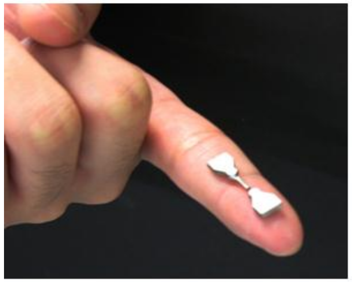


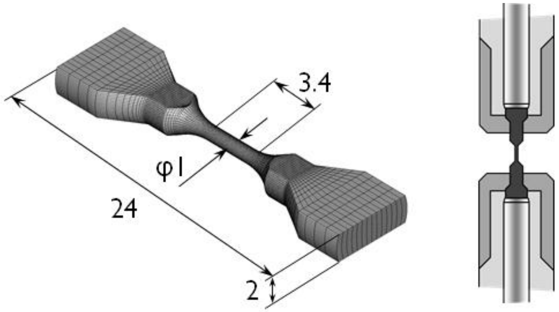
Master curve method (ASTM E1921)

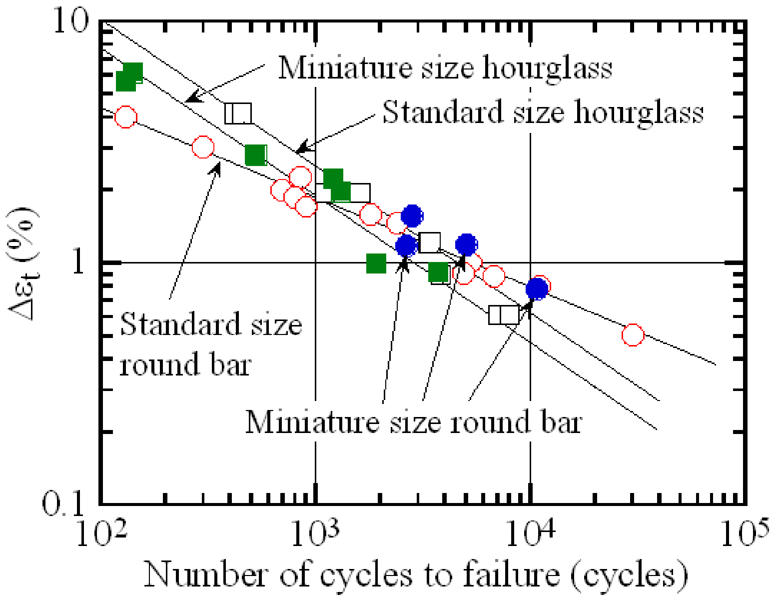
Developed to evaluate irradiation embrittlement for pressure vessel steels used to evaluate shift of DBTT

with limited number of small specimen

Fatigue







Wakai, E., et al., *Development of small specimen test techniques for the IFMIF test cell*, Proceedings of IAEA Fusion Energy Conference 2012, San Diego

Test facility validation

HELOKA loop in KIT

Gas-parameter	HELOKA-LP	HFTM
Massflow	12 – 120g/s	96g/s
Pressure	0.3 – 0.6MPa	0.3MPa
Temperature	20 – 250°C	50°C

The test objectives

verification of the temperature control strategy

assessment of flow induced dynamic loads on the rigs

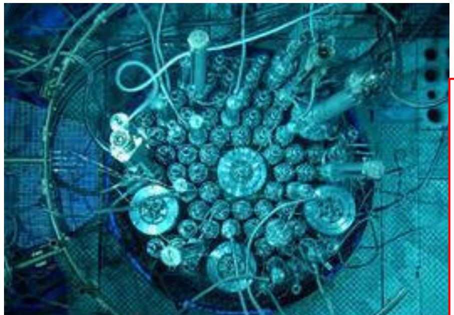
attachment structure and the helium pipes

definition of operational modes

Independent temperature control per capsule
thanks to available heaters to be tested
in an experimental nuclear reactor

Experiments area

Compressor hall



Schlindwein, G., et al., *Start-up phase of the HELOKA-LP low pressure helium test facility for IFMIF irradiation modules*, Fus. Eng. Des. **87** (2012) 737

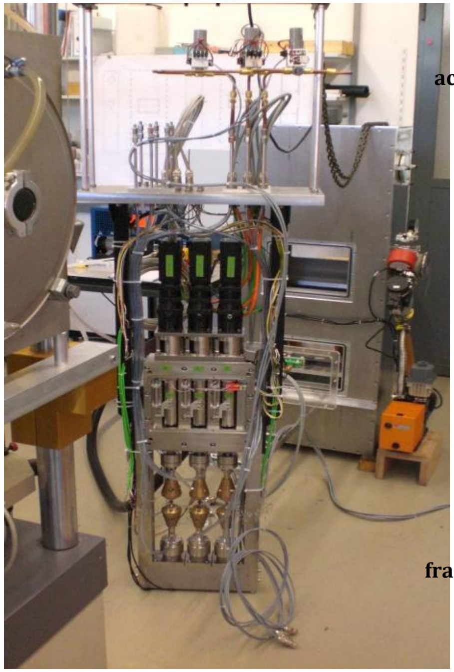
Test facility validation

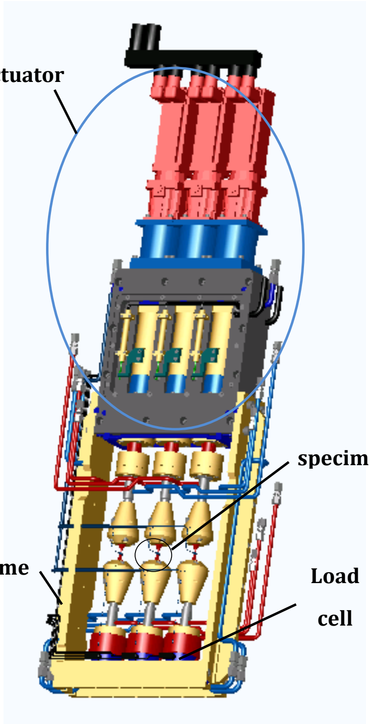
Medium Flux test module

Creep-fatigue tests

The three testing machines
will operate independently
with +/-12.5 kN load
with controlled speed
ranging [1 µm/s, 80 µm/s]

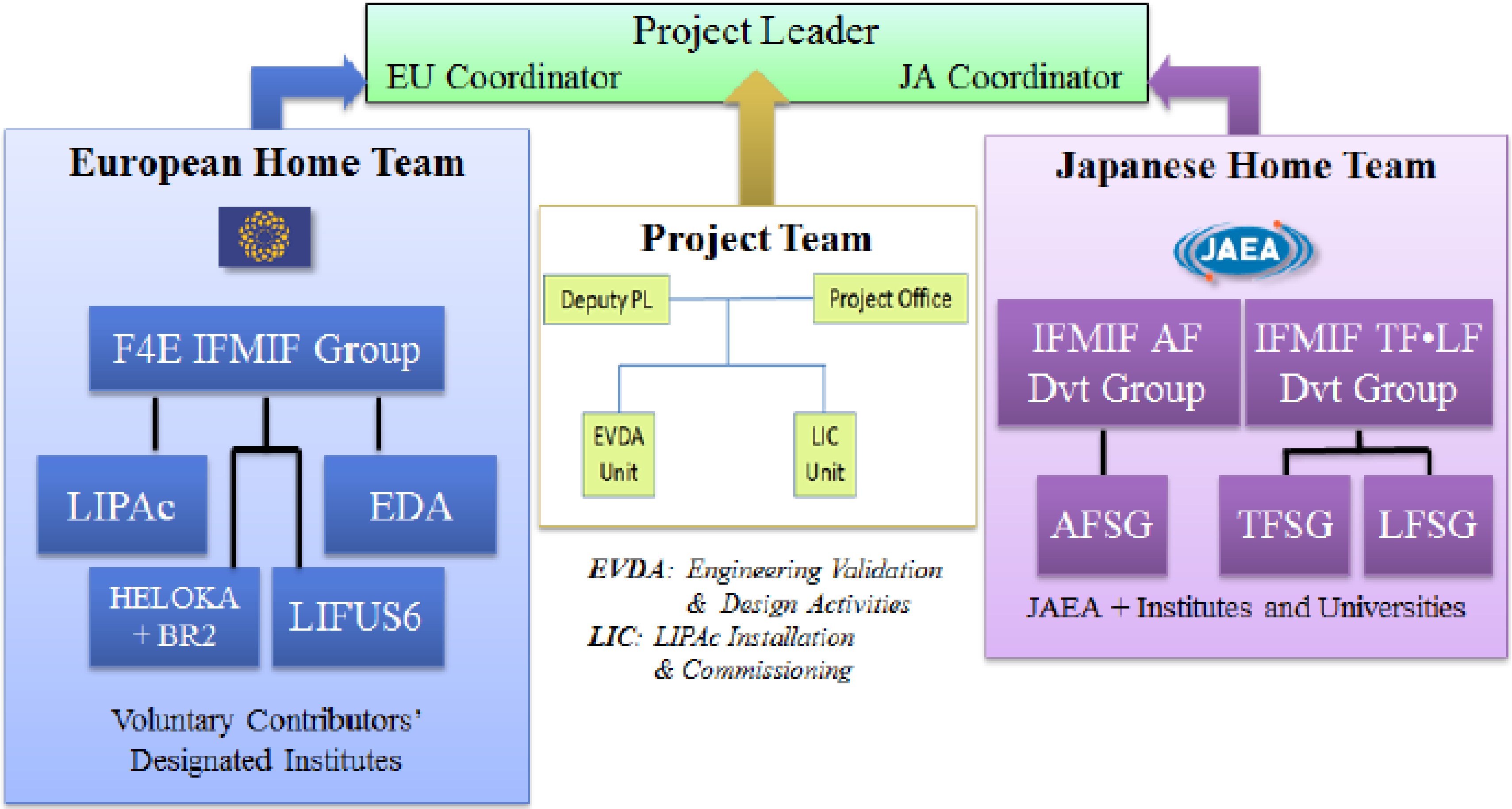
Temperature controlled
through
three different cooling channels





Vladimirov, P., et al.,
Nuclear responses in IFMIF creep-fatigue testing machine,
Fus. Eng. Des. **83** (2008) 1548.

How do we work together?



Project Leader

EU Coordinator

JA Coordinator

European Home Team

F4E IFMIF Group

LIPAc

EDA

HELOKA + BR2

LIFUS6

Voluntary Contributors' Designated Institutes

Project Team

Deputy PL

Project Office

EVDA Unit

LIC Unit

EVDA: Engineering Validation & Design Activities

LIC: LIPAc Installation & Commissioning

Japanese Home Team

IFMIF AF Dvt Group

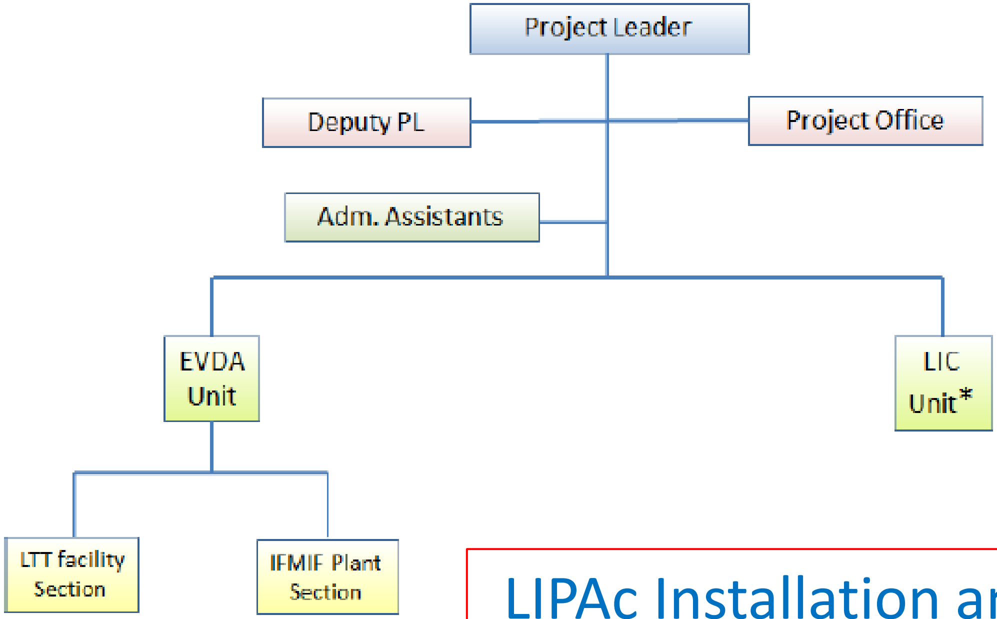
IFMIF TF•LF Dvt Group

AFSG

TFSG

LFSG

JAEA + Institutes and Universities



Project Leader

Deputy PL

Project Office

Adm. Assistants

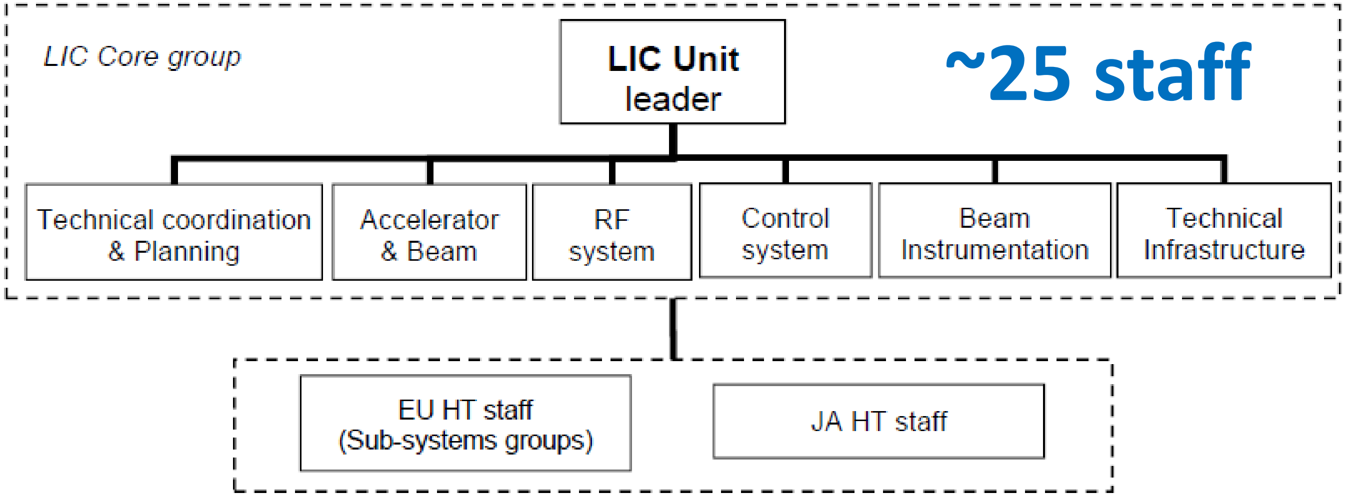
EVDA Unit

LIC Unit*

LTT facility Section

IFMIF Plant Section

LIPAc Installation and Commissioning Unit



LIC Core group

LIC Unit leader

~25 staff

Technical coordination & Planning

Accelerator & Beam

RF system

Control system

Beam Instrumentation

Technical Infrastructure

EU HT staff (Sub-systems groups)

JA HT staff

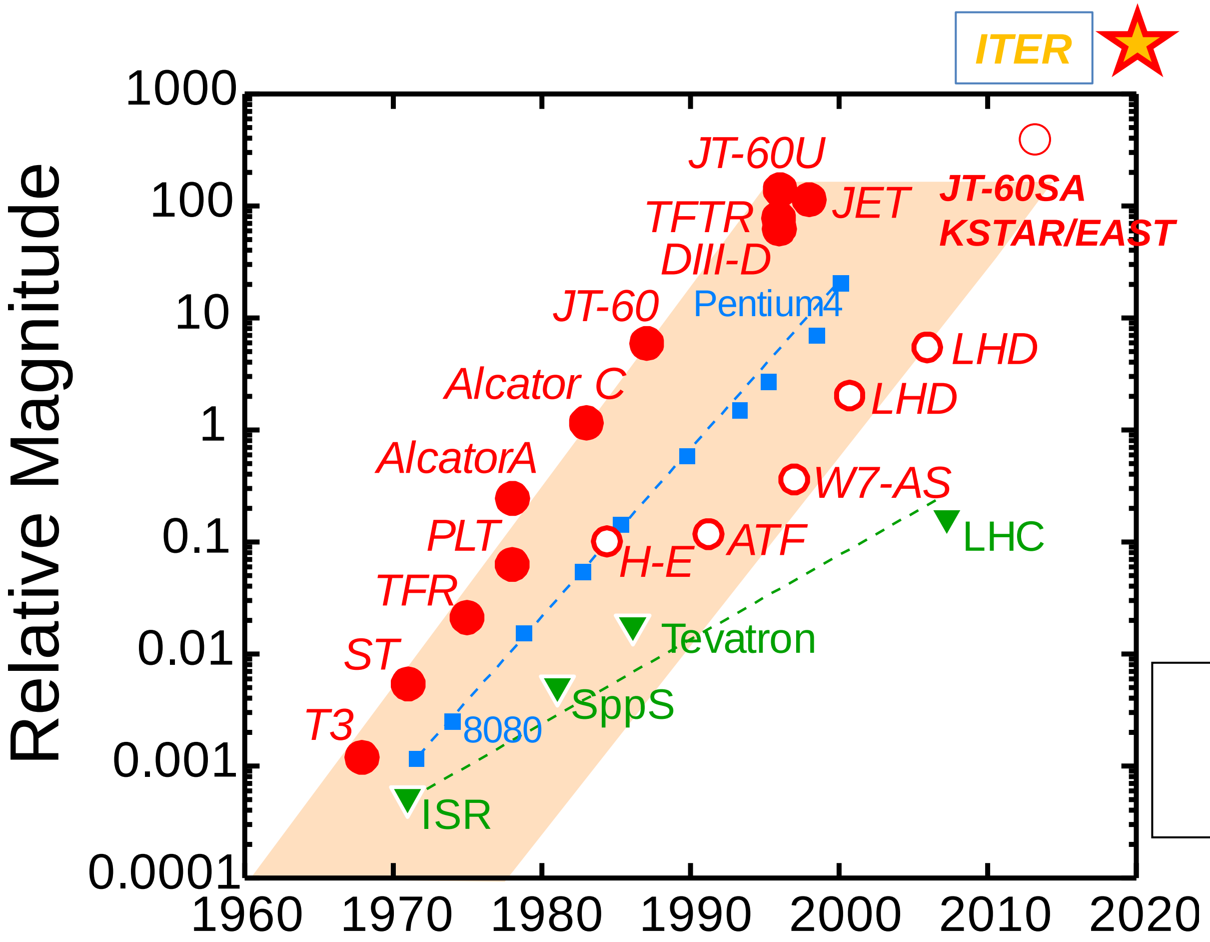
Team under formation

A joke in the fusion community

On 18 April 1967,
Lev Andreevich Artsimovich
said to UK minister of Technology

10 years ago we said it would take us 20 years
to make fusion work
and we still say that it will take 20 years,
so we haven't altered our view in any way…

We are not doing so badly…



Accelerator
Energies doubles
every **3 years**

Microprocessing speed
doubles every **2 years**
(Moore's Law)

Tokamaks
'triple product' doubles
every **18 months**

Lawson criterion
$ntT > 10^{21}$ keVsm^{-3}

Outlook

IFMIF is a unique facility merging
accelerators and fusion communities

Both communities have run in parallel
with common fields
but not joining forces in an optimal way

We have the great luck
to be partaking the efforts of humankind
to tame fire
for the second time in our short history

this time, the fire of the sun…