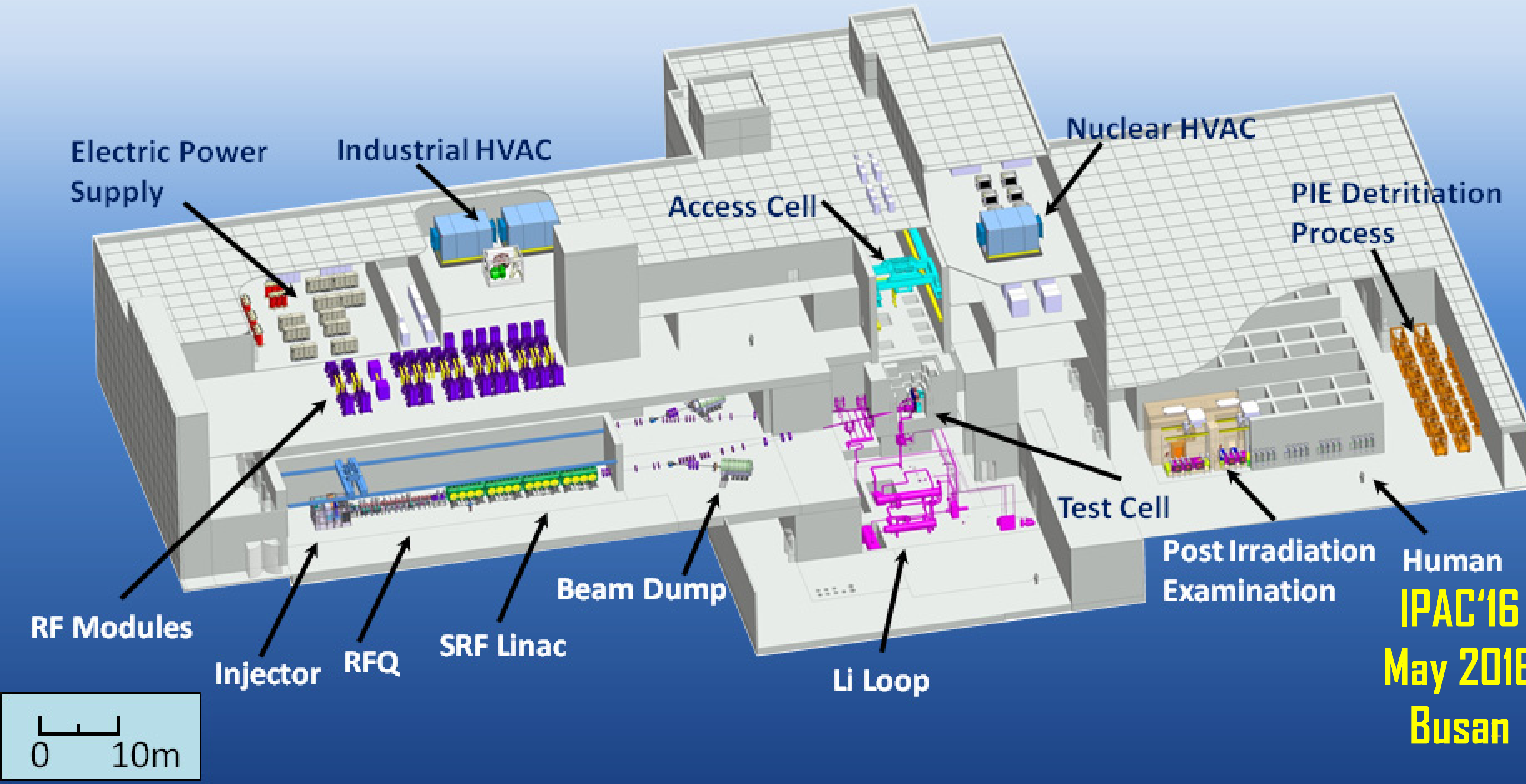
CHALLENGES OF LIPAc
THE HIGH CURRENT PROTOTYPE ACCELERATOR OF IFMIF/EVEDA

J. Knaster & Y. Okumura – IFMIF/EVEDA Project Team

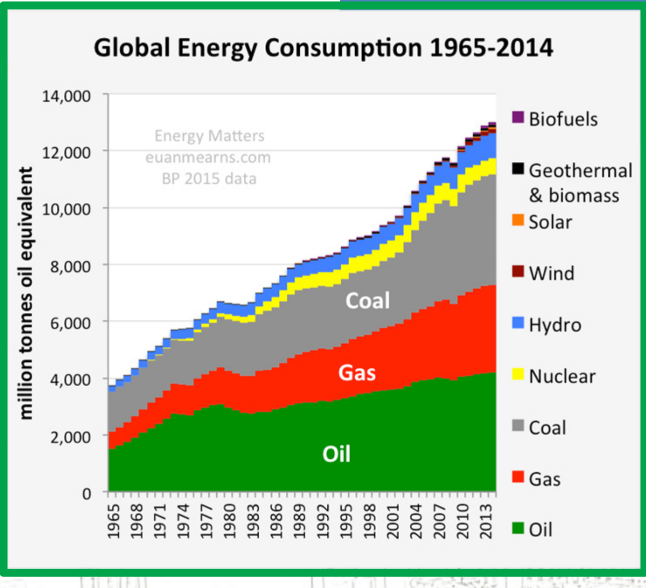
A. Kasugai & M. Sugimoto – QST

P. Cara – F4E

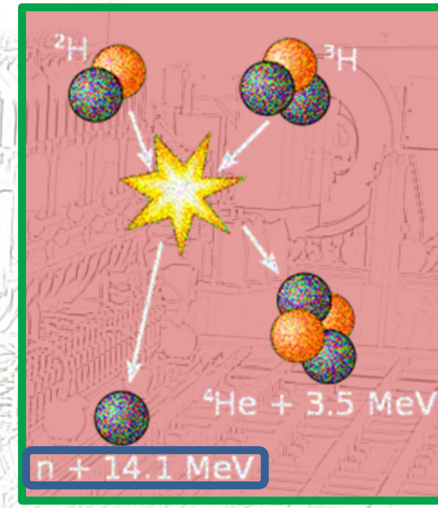


IPAC'16
May 2016
Busan

Fusion potential energy solution

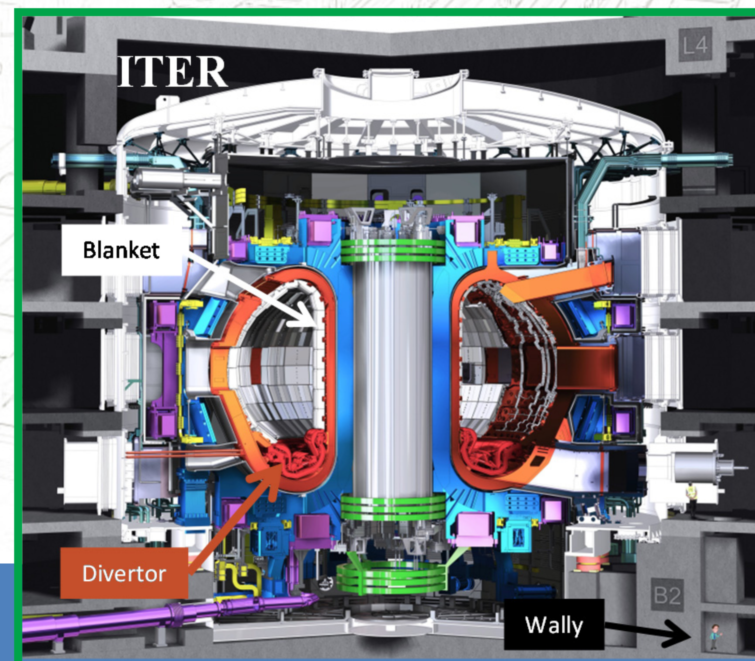


The first wall
of the reactor vessel shall
absorb neutrons energy



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

In a Fusion power plant
~30 dpa per year of operation



Two transmutation reactions become critical

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

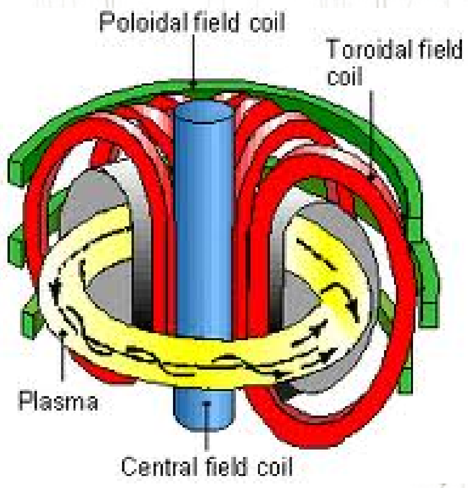
and

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

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

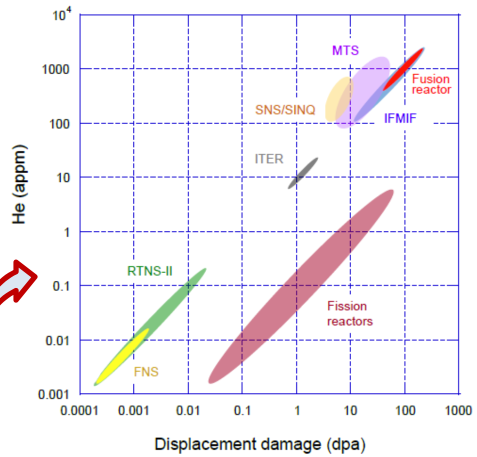


High fluxes (and fluences) 10^{18} n/m^{2}s } **30 dpa/year**

Cyclic stresses Δσ > 100 MPa (Maxwell stresses) } **fracture toughness Crack growth rate**

Thermal loads >10 MW/m^2 (critical in W based divertor) } **W crystallizes if T > 1300 K**

He&H generation ~12 appm He/dpa } **0.3 He/dpa with fission neutrons**

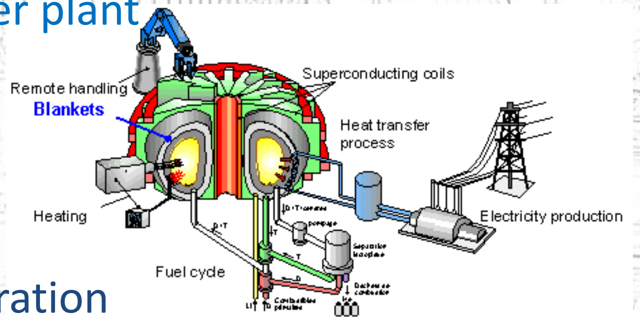


Neither fission reactors (0.3 He/dpa) nor spallation sources (>50 He/dpa) give needed answers

J. Knaster, A. Moeslang, and T. Muroga,
Materials research for fusion,
Nature Phys. 12, 424–434 (2016)

The necessity of a Fusion relevant n source

Understanding the degradation of physical properties
of the materials critically exposed to 14.1 MeV n flux
is a key parameter to allow
accomplishment of the design of a fusion power plant
and
Its licensing



Fluences in ITER will be reduced
ITER's objective is to show stable plasma operation
under DT fusion reactions

But future power plants will have to show
this stable operation for long periods with minimum preventive maintenance interventions

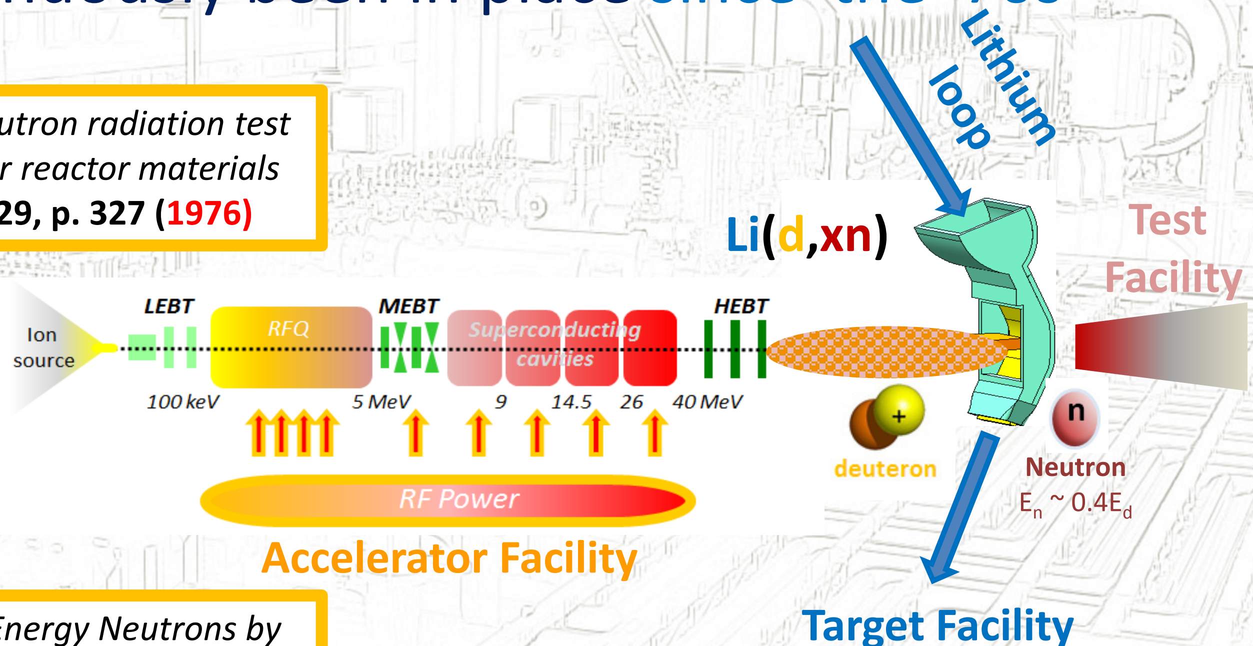
Material scientists need experimental data
given the number of variables
playing a primary role in materials degradation
neutrons spectrum
neutrons fluence
material temperature
thermo-mechanical history
microstructure
mechanical loading
lattice kinetics…

Fusion relevant neutron source is 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, December 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

IFMIF/EVEDA

Signed in February 2007

Entered into force on June 2007

IFMIF

International Fusion Materials Irradiation Facility

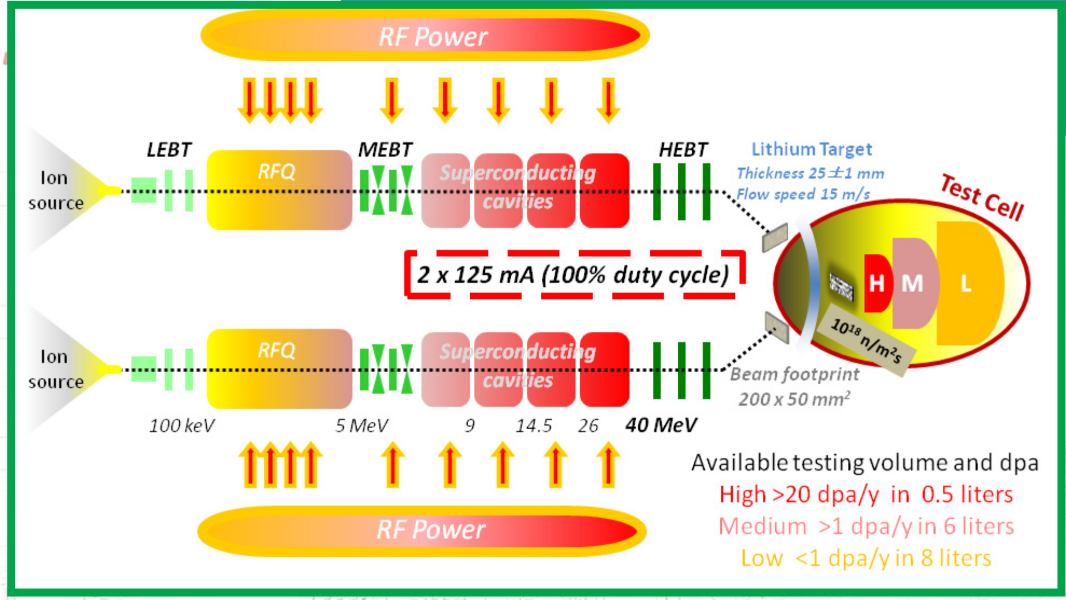
EVEDA

Engineering Validation & Engineering Design Activities

Article 1.1 of Annex A of the **BA Agreement** mandates **IFMIF/EVEDA**

…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

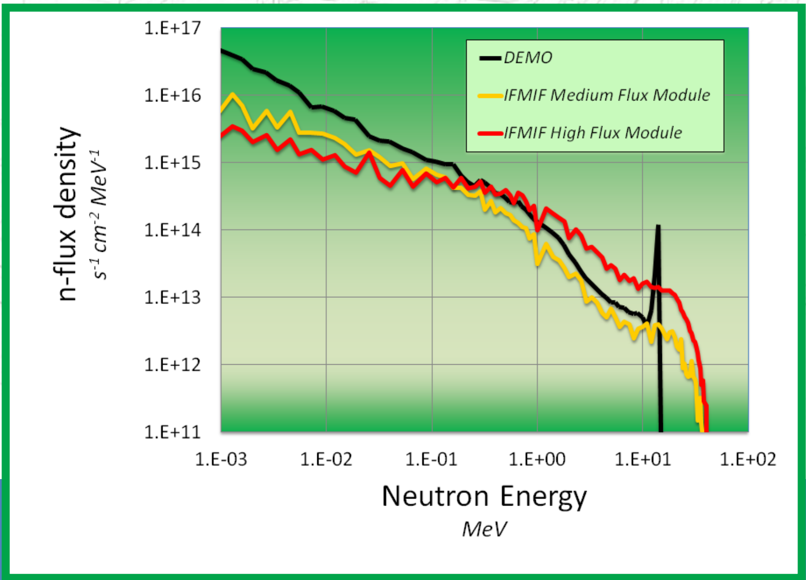
IFMIF concept



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%

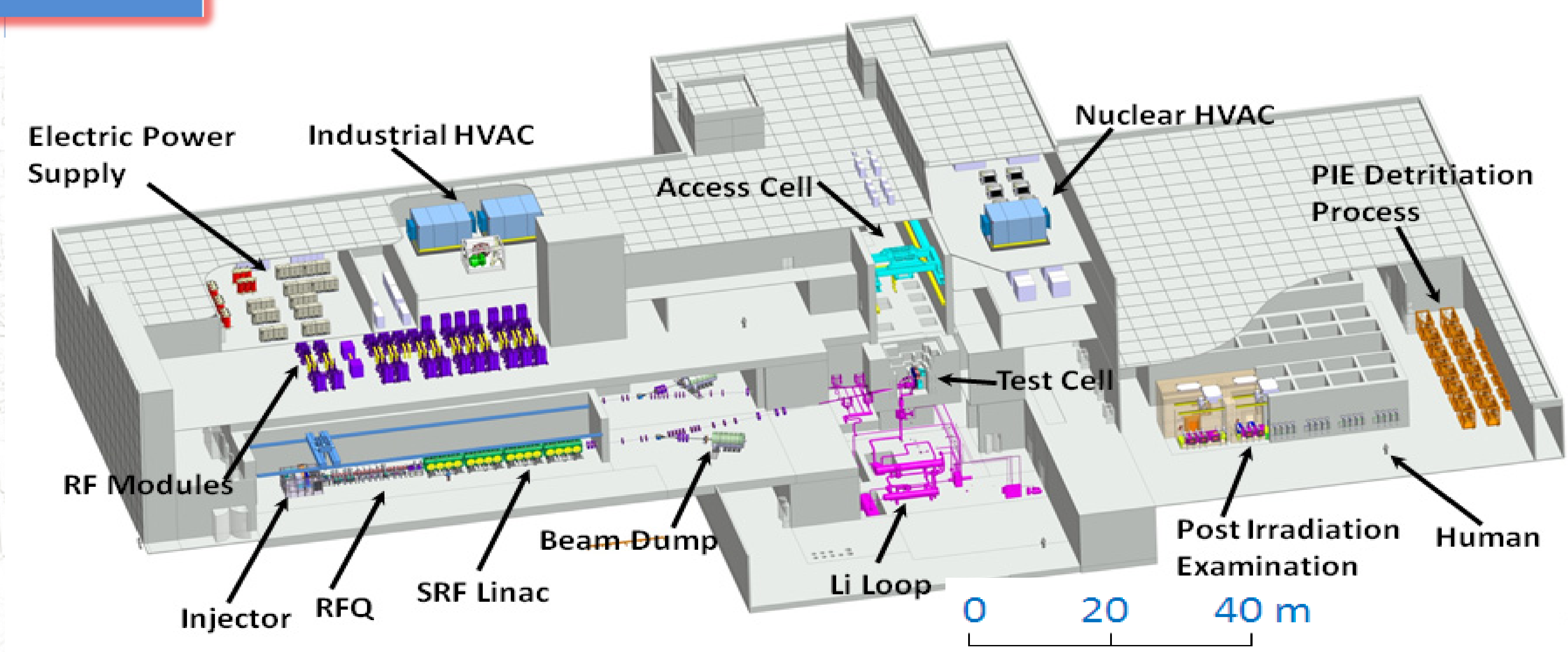


EVEDA = EDA + EVA Phases

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**

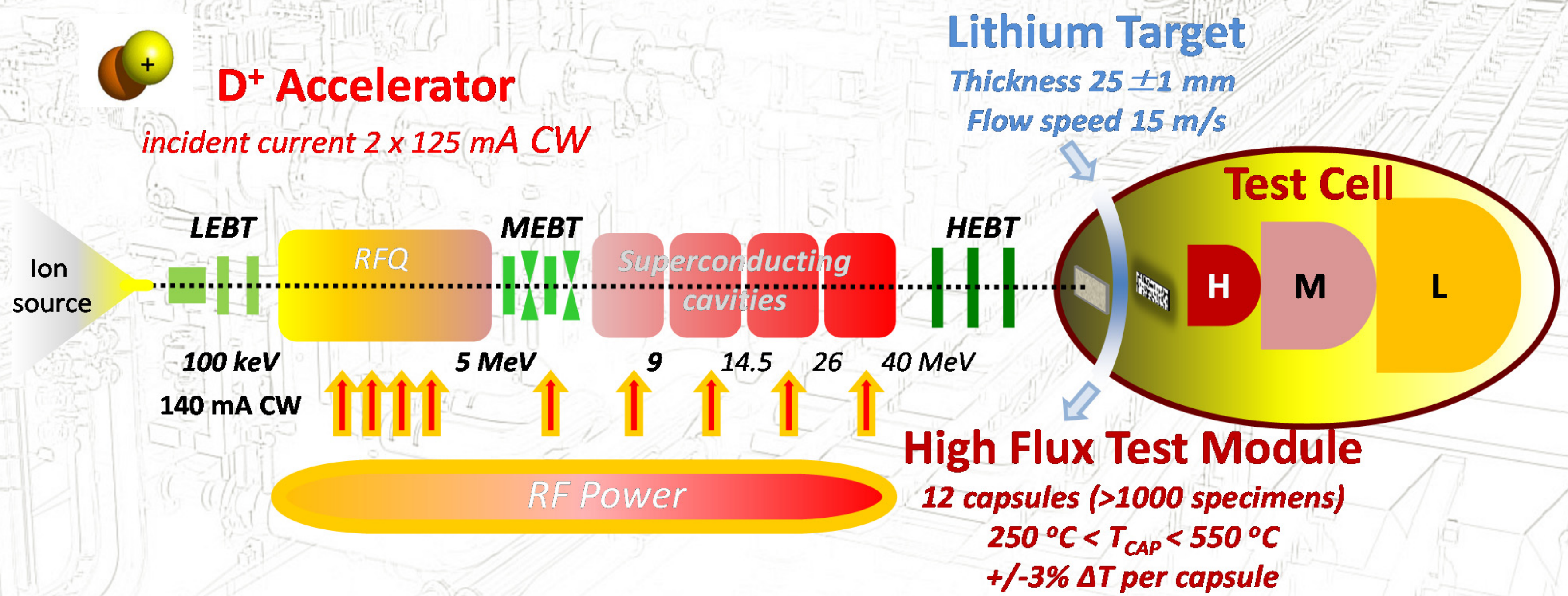


EVEDA = EDA + EVA Phases

Engineering Design Activities – **EDA phase**

Successfully delivered on schedule

Validation Activities – **EVA phase**



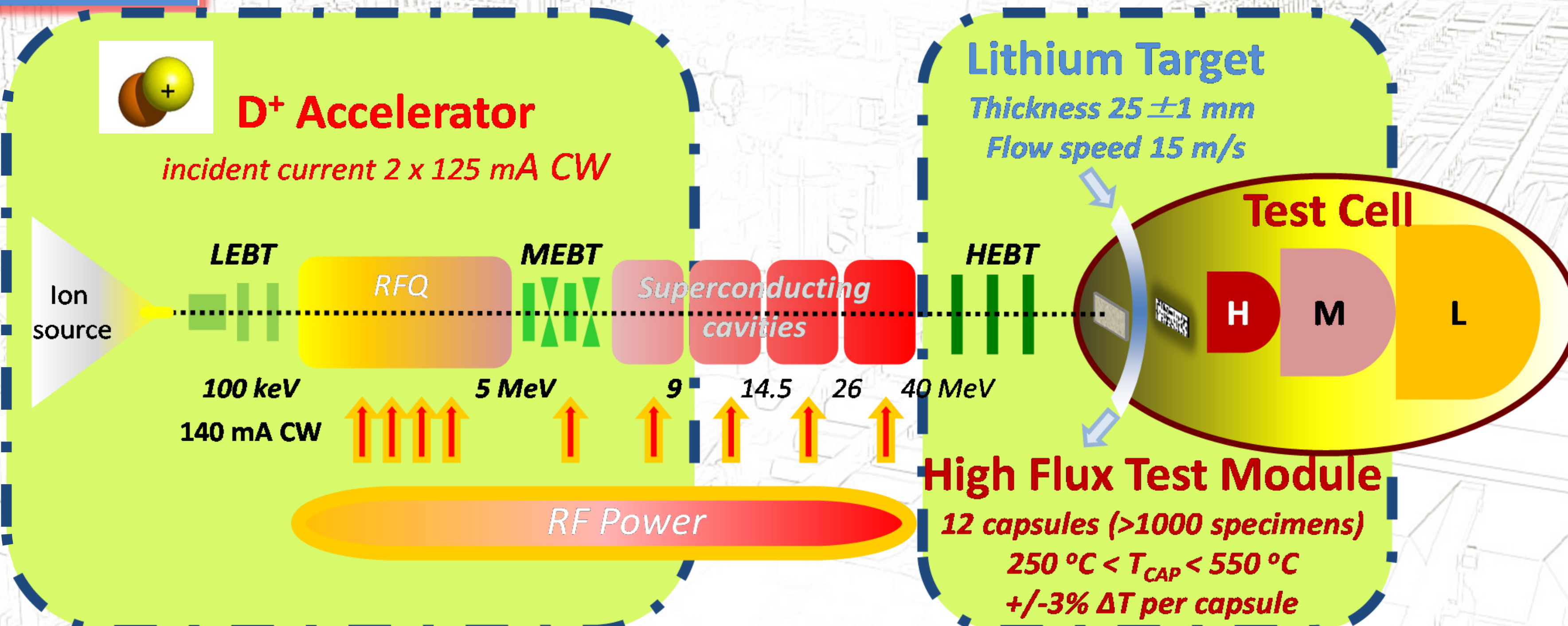
J. Knaster et al., *IFMIF: overview of the validation activities*, **Nuclear Fusion 53 (2013) 116001**

EVEDA = EDA + EVA Phases

Engineering Design Activities – EDA phase

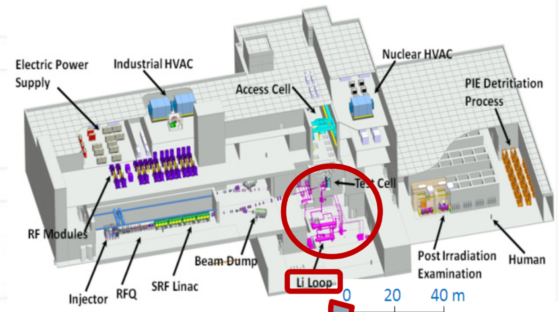
Successfully delivered on schedule

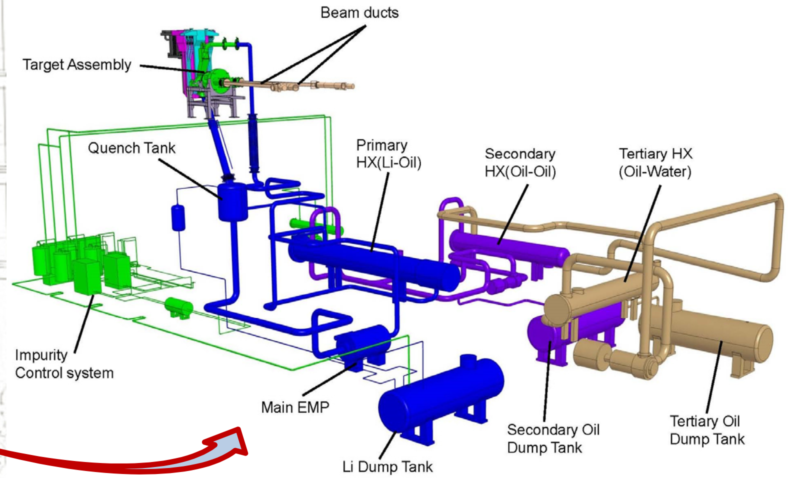
Validation Activities – EVA phase



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

EVA Phase – Target Facility





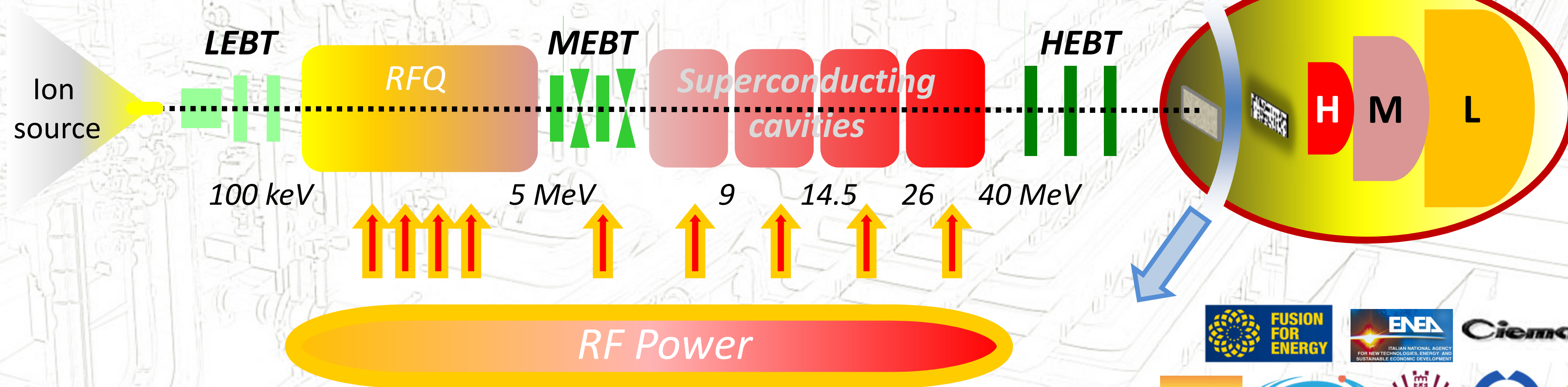
Lithium Target

Thickness 25±1 mm

Flow speed 15 m/s

D$^+$ Accelerator

incident current 125 mA



EVA Phase – Target Facility

LIFUS6 in Brasimone

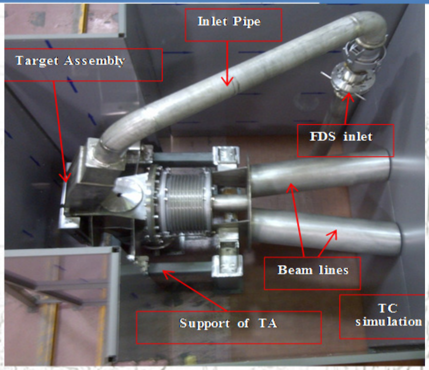
ENEA

Unique experimental data

QST

JAEA

ELTL in Oarai



Bayonet backplate remote handling Brasimone

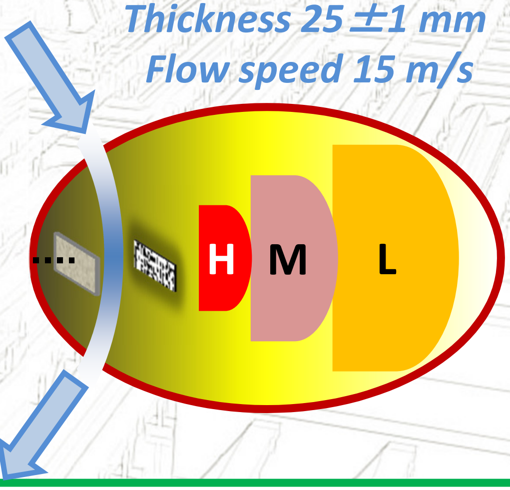
ENEA

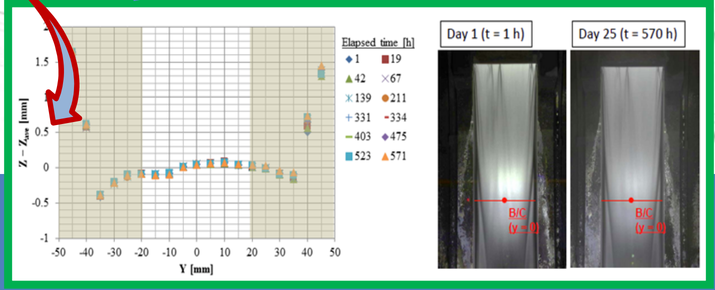
World biggest liquid lithium loop

Lithium Target

Thickness 25 ±1 mm

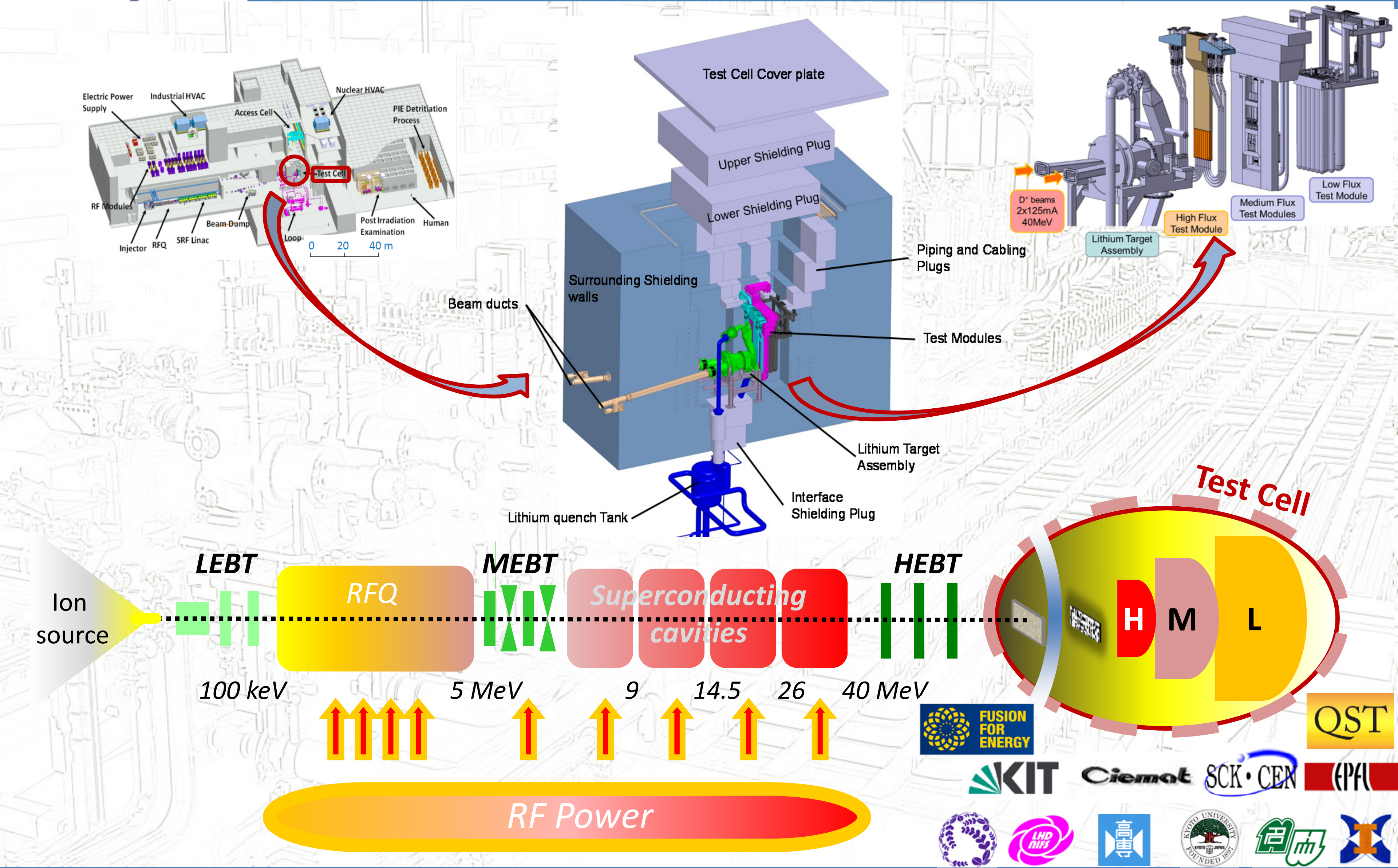
Flow speed 15 m/s



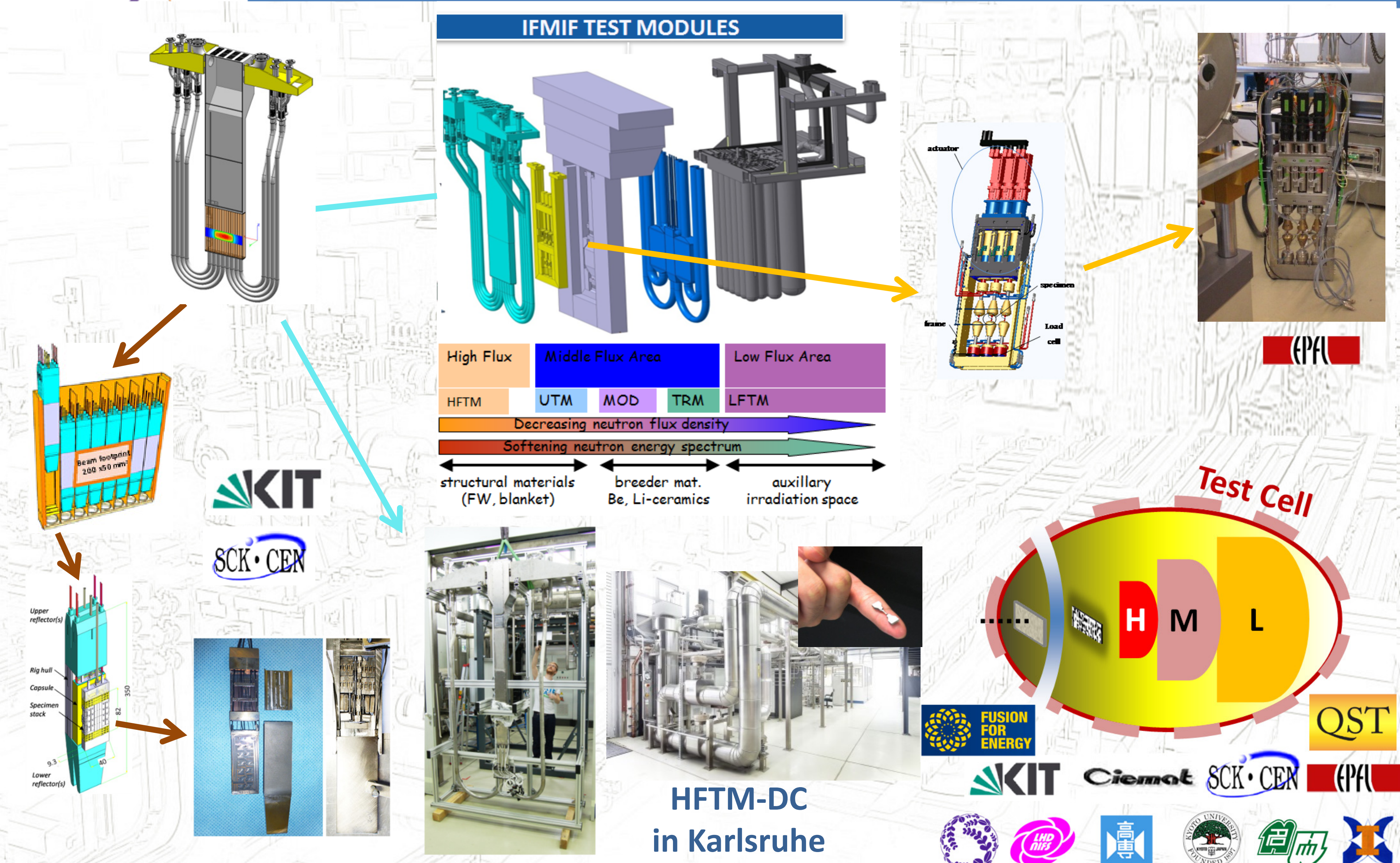


Kondo, H. et al. *Validation of IFMIF liquid Li target for IFMIF/EVEDA project*, **Fusion Eng. Des. 9697, 117122 (2015).**

EVA Phase – Test facility



EVA Phase – Test facility

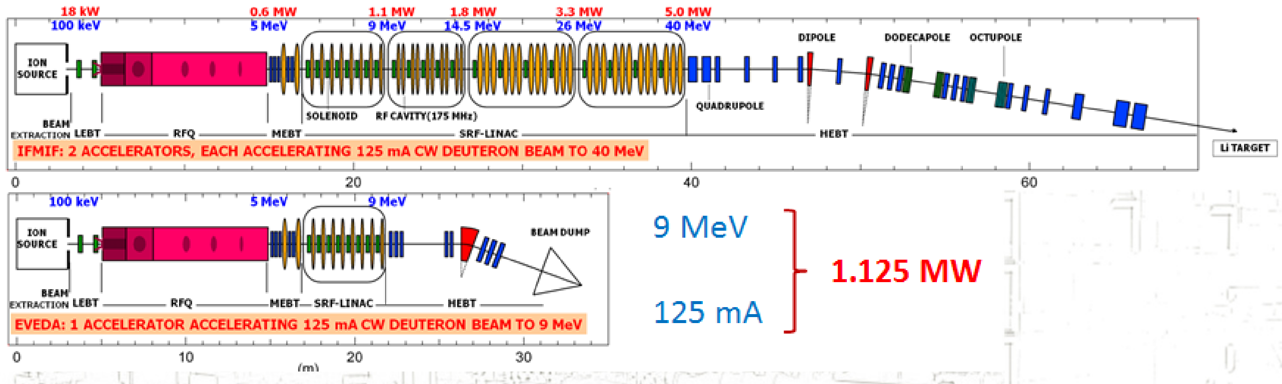


F. Arbeiter et al, *Design description and validation results for the IFMIF High Flux Test Module as outcome of the EVEDA phase,* **Nuclear Materials and Energy (2016)**

EVA Phase – Accelerator facility

IFMIF

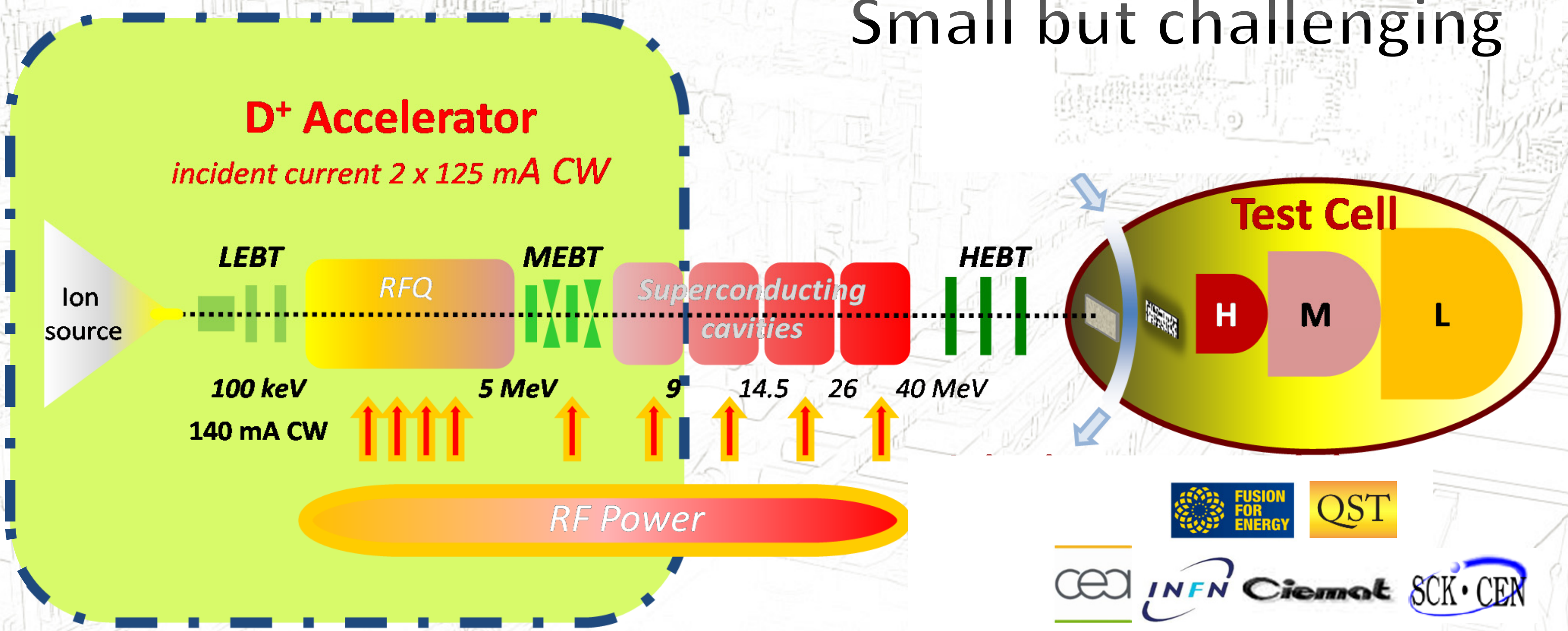
LIPAc



40 MeV
125 mA
5 MW

9 MeV
125 mA
1.125 MW

Small but challenging



LIPAc, the accelerator of records

LIPAc is very ambitious

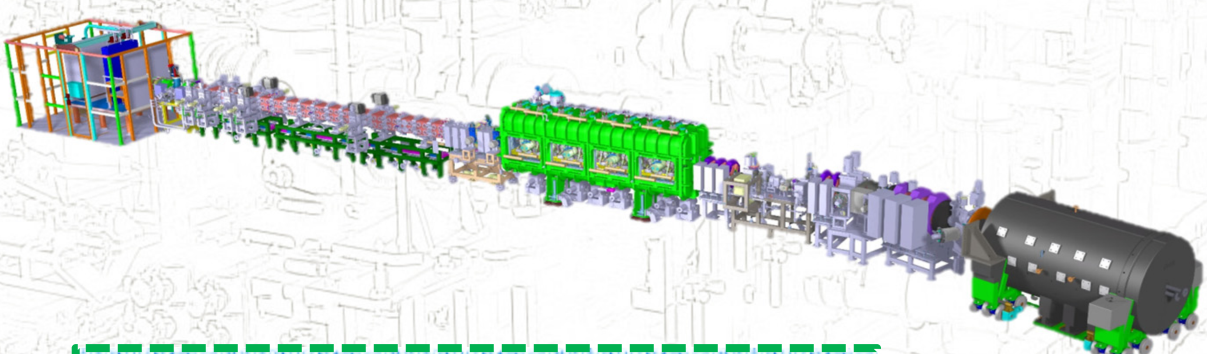
World's highest current linac

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 - MOPOY57

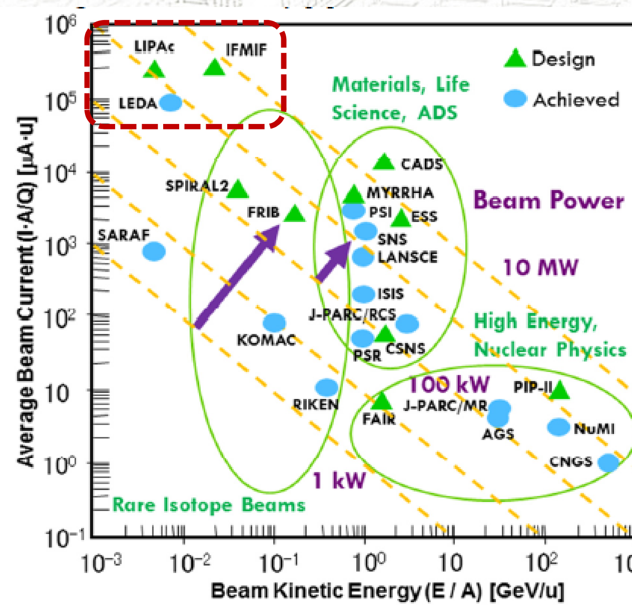


Figure 1: Hadron accelerator power frontier.

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

IFMIF

Equipment designed and constructed in Europe Installed and commissioned in Rokkasho

Injector + LEBT
CEA Saclay

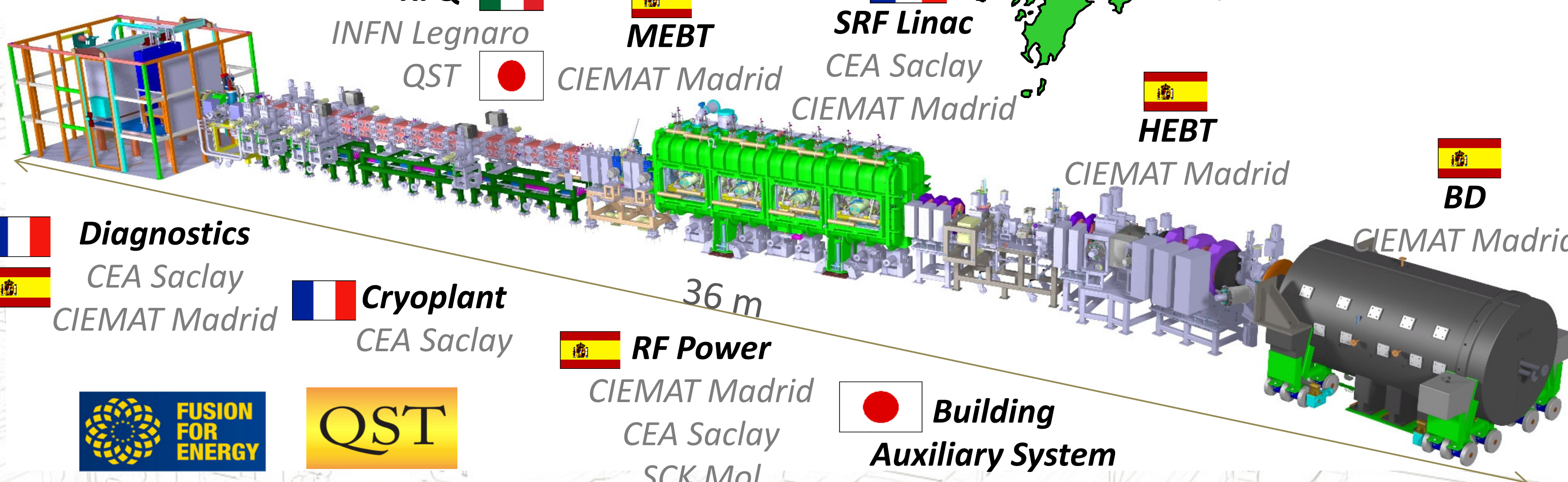
RFQ
INFN Legnaro
QST

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid



Diagnostics
CEA Saclay
CIEMAT Madrid

Cryoplant
CEA Saclay

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Building
Auxiliary System
Control system
Installation
QST

FUSION FOR ENERGY · QST · cea · Ciemat · INFN · SCK•CEN

Are we technologically ready?

I think we are

Fusion materials needs have historically boosted CW linacs research

J. Knaster & Y. Okumura, *Accelerators for fusion materials testing***. Reviews of Accelerator Science and Technology Vol. 8 , (2016) 115-142**

First attempt of constructing
a Li(d,xn) fusion relevant neutron source was in the early 80s

1979

The Fusion Materials Irradiation Test facility
FMIT

E. W. Pottmeyer, *The Fusion Material Irradiation Test facility at Handford***, J. Nucl. Mater. 85–86, 463–465 (1979)**

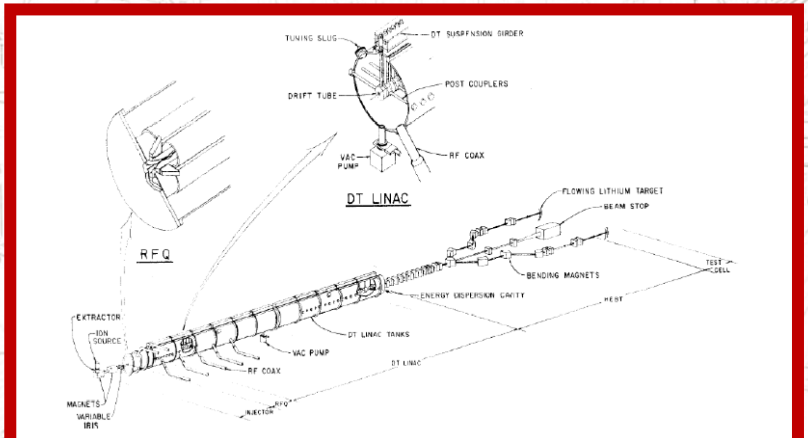


Fig. 7. Layout of the FMIT accelerator.

An accelerator of **100 mA in CW at 35 MeV** was required

A validating prototype was constructed in Los Alamos a **100 mA in CW H_2^+ at 2 MeV** linac that would be upgraded with a 5 MeV DTL in CW

CW operation was achieved briefly
but the RFQ swiftly damaged

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

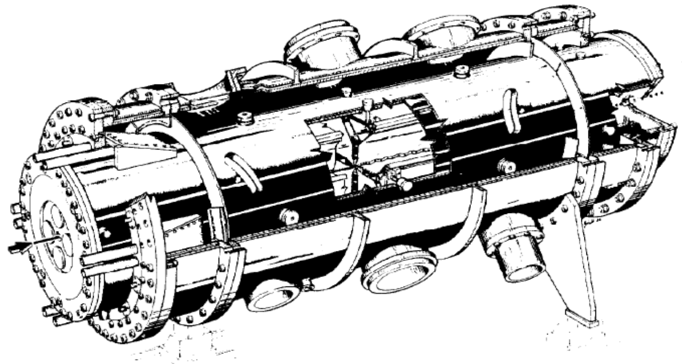


Fig. 1. Initial design of the FMIT RFQ accelerator. The RFQ comprises two coupled, coaxial resonators. The rf power is loop coupled into the outer section, or manifold, which more uniformly distributes the power into the four quadrants of the inner resonator, or core. A 75-keV beam is injected (arrow, left in the figure) and accelerated to 2 MeV.

and the project cancelled in 1985

Beam dynamics understanding was insufficient

H_2^+ was assumed to behave as D^+
Stripping and dissociation of H_2^+
led to unexpected large beam halos

Beam quality injected in RFQ was poor
Cathode based ion sources
110 mA CW at 75 keV
demanded currents >250 mA
space charge induced emittance growth
and bending magnet for ion fraction separation

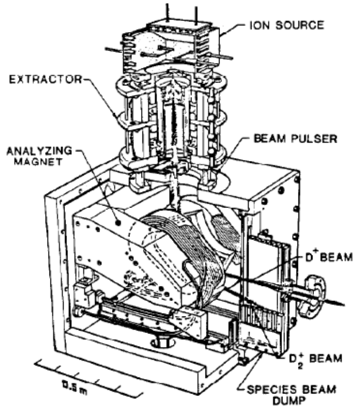


Fig. 1. First stage of the prototype injector.

E.A.. Meyer et al., *Performance optimization of a cusp-field ion source and high perveance extractor,* **IEEE Trans. Nucl. Sci. Vol. NS-28, No. 3, (1981)**

New ideas were proposed by Los Alamos team to continue with a Fusion Materials facility

Two RFQ at 175 MHz funneled into 350 MHz DTL for a 125 mA CW at 35 MeV

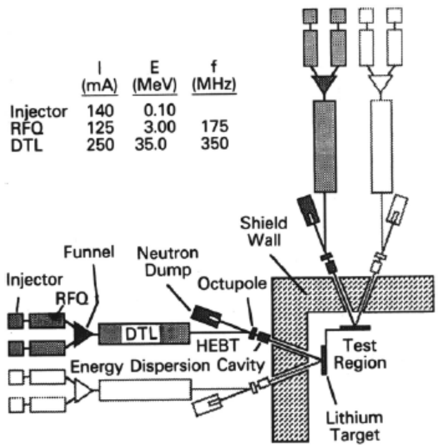


Fig. 9. Layout of a fusion materials test facility proposed in 1990 in collaboration with LANL for the development of the CW deuteron accelerator.

G. L. Varsamis et al., *Conceptual design of a high performance deuterium-lithium neutron source for fusion materials and technology testing*, **Nucl. Sci. Eng. 106, 160–182 (1990)**

ECR ion sources for light hadrons

1991

A technological breakthrough took place in Chalk River labs

Electron-Cyclotron Resonance (ECR) principle
for hydrogen ion sources was developed

Gas fractions of suitable species >90% achievable
Higher availability
No need of bending magnets to discriminate ions

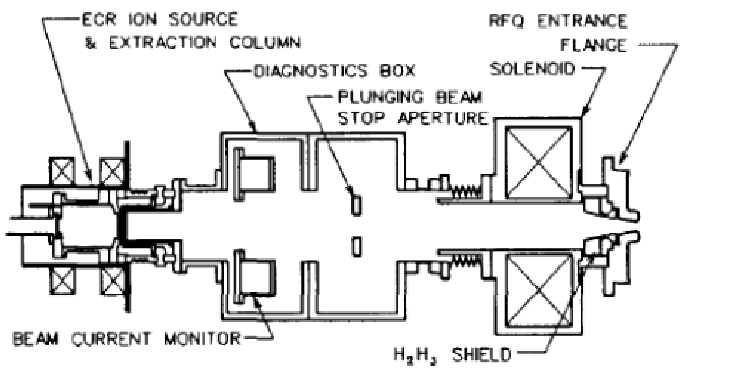


Fig. 8. Layout of ECR for H^+ developed at Chalk River Laboratories for the RFQ1 project.

R. Geller, *Electron cyclotron resonance multiply charged ion sources*, **IEEE Trans. Nucl. Sci. 23, Issue 2 (1976)**

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

LEDA-High current CW operation with an RFQ

1999

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

LEDA

the Low Energy Demonstration Accelerator
the validating prototype of APT
the Accelerator Production of Tritium project
(100 mA deuterons in CW above 1 GeV)
succeeded to operate in CW 100 mA H^+ at 6.7 MeV with 94% transmission for >100 h

Fig. 10. The eight-meter-long RFQ of LEDA in the tuning stand.

The tuning during CW operation was successfully achieved with two independent cooling circuits for the inductive and capacitive part

R. Floersch, *Resonance Control Cooling System for the APT/LEDA RFQ*, **Proceedings of LINAC 1998, Chicago**

LEDA -Beam halo understood!

2002

The beam halo physics were unraveled in LEDA

HEBT and beam dump were shifted ~11 m downstream
room for a 52 quadrupole beam transport line was made

beam-halo of both
matched and unmatched high-current proton beams
was studied

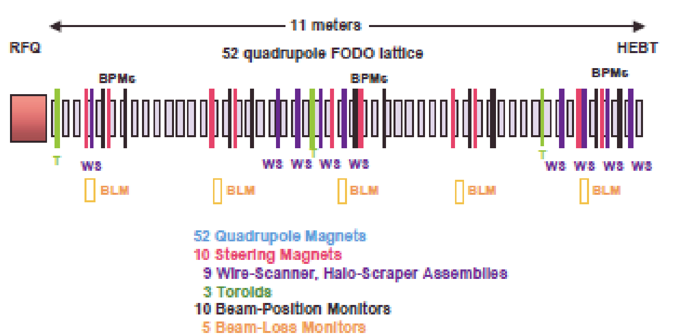


Figure 4. A halo channel photograph taken from the HEBT looking back toward the RFQ. The last four stations of wire-scanner, halo-scrapers (eight units total) are visible on the right.

space-charge forces in mismatched beams are the main source of beam halo in high current proton beams

T.P Wrangler et al.,, *Experimental study of proton beam halo Induced by beam mismatch in LEDA*, **Proceedings of PAC 2001 , Chicago**

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

Beam simulations became more precise

Space charge issues play a relevant role at high currents
being are severe at low-β
they cancel in relativistic regions
Attractive Ampere forces compensate repulsive Coulomb ones

Misalignments of interfacing equipment
play an essential role

No need to play anymore with H_2^+ or H^+ at 100 mA
to validate D^+ nominal requirements
from the generalized perveance expression

$$K = \frac{eI}{2\pi\varepsilon_0 m_0 v^3 \gamma^3}$$

protons at half energy and half intensity behave similar to deuterons at nominal conditions

SC cavities for light hadrons at low-β

LEDA initially planned an upgrade of beam energy
with two sections of CCDTL

the successful development early 2000s of superconducting spoke resonators
for light hadrons and low-β changed the ideas
two superconducting gaps towards 7.3 MeV

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

H. Vernon et al., *Low-energy demonstration accelerator (LEDA) test results and plans*, **Proceedings of PAC 2001, Chicago**

But APT was cancelled, and so were these ideas

In 2004
LEDA was proposed fruitlessly
to the Fusion Materials community
to bridge with IFMIF

D. Post et al., *A potential capability for initial testing of fusion materials based on the LANL Low Energy Demonstration Accelerator (LEDA) facility*, **Proceedings of 11th Int. Conf. Fusion Reactor Materials, Kyoto (2004)**

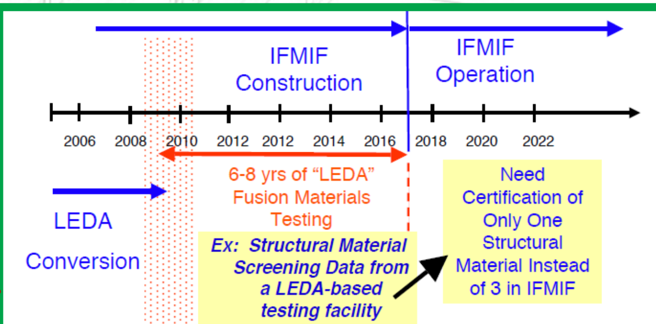


Figure 3. Schedule illustrating use of a LEDA-based fusion materials testing facility to conduct fusion materials tests prior to full testing in IFMIF.

Upon IFMIF/EVEDA approval a DTL was planned for LIPAc

A. Mosnier and U. Ratzinger, *IFMIF accelerators design,* **Fusion Eng. Des. 83 (2008) 1001–1006**

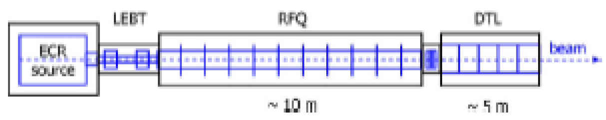


Fig. 12. Schematic layout of the EVEDA prototype accelerator.

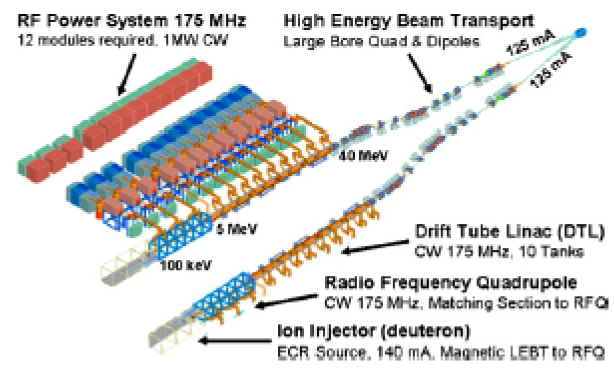


Fig. 1. Sketch of one IFMIF Linac.

Successful development of QWR & HWR last decade Suitable for our operational conditions (β = 0.07)

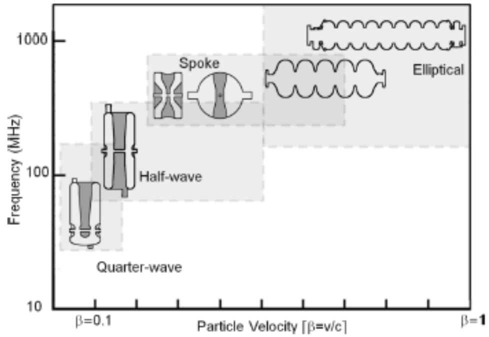


Fig. 1. Practical superconducting cavities spanning the full range of low and intermediate values of beta.

M. Kelly, *Superconducting Radio-Frequency Cavities for Low-Beta Particle Accelerators*, **Reviews of Accelerator Science and Technology Vol. 5 (2012) 185–203**

2010

SARAF operated in CW

176 MHz HWR

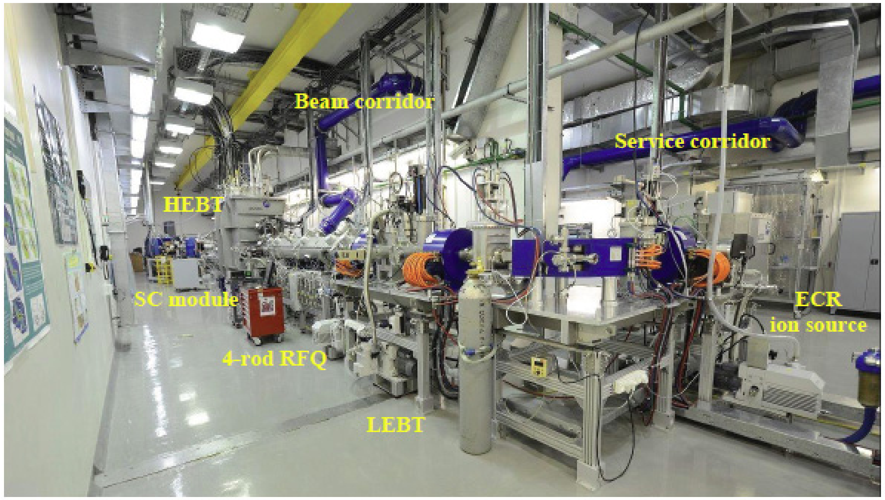


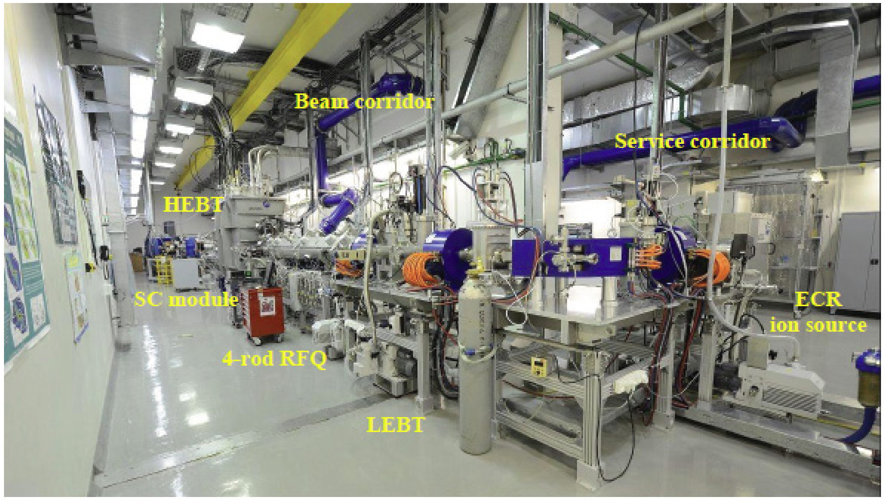
Figure 2: Phase-I 4 MeV protons and 5 MeV deuterons linac in the 4.5 m W, 5 m H and 25 m long beam corridor.

D. Berkovits et al., *Operational experience and Future goals of the SARAF proton/deuteron linac*, **Proceedings of LINAC2012, Tel-Aviv**

2010

SARAF operated in CW

176 MHz HWR



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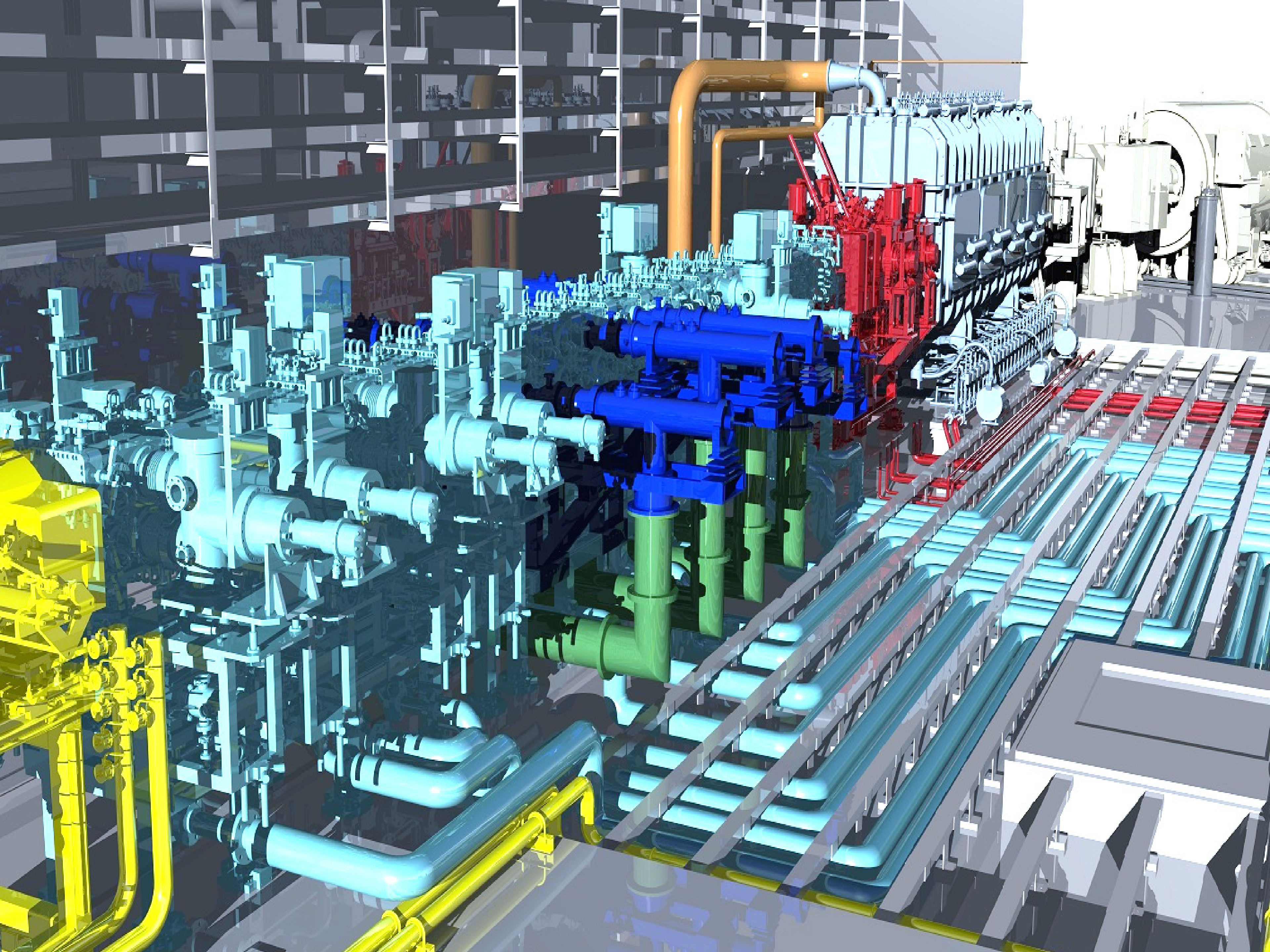
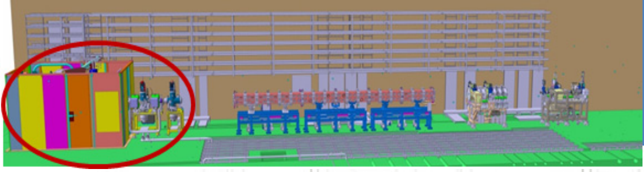
D. Berkovits et al., *Operational experience and Future goals of the SARAF proton/deuteron linac*, **Proceedings of LINAC2012, Tel-Aviv**

but reliably 1 mA protons at 4 MeV

In LIPAc we aim 125 mA CW deuterons at 9 MeV

The challenge is heavy
but we are implementing
best possible technological choices
and available knowhow





ECR H^+/D^+ source + LEBT developed by CEA Saclay

D^+ (95% species fraction)

Ion Source ECR (2.45 GHz) - **CW**

E = 100 keV

I = 140 mA

emittance of 0.25 π mm·mrad

Availability > 95%

Gas fraction >90%

R. Gobin et al., *IFMIF injector acceptance tests at CEA/Saclay: 140 mA/100 keV deuteron beam characterization*, **Rev. Sci. Instr. 85, 02A918 (2014)**

Y. Okumura et al., *Operation and commissioning of IFMIF LIPAc injector,* **, Rev. Sci. Instr.** ***87, 02A739 (2016)***

SILHI, the High Intensity Light Ion Source of 100 mA 95 keV is operating in Saclay since 1996

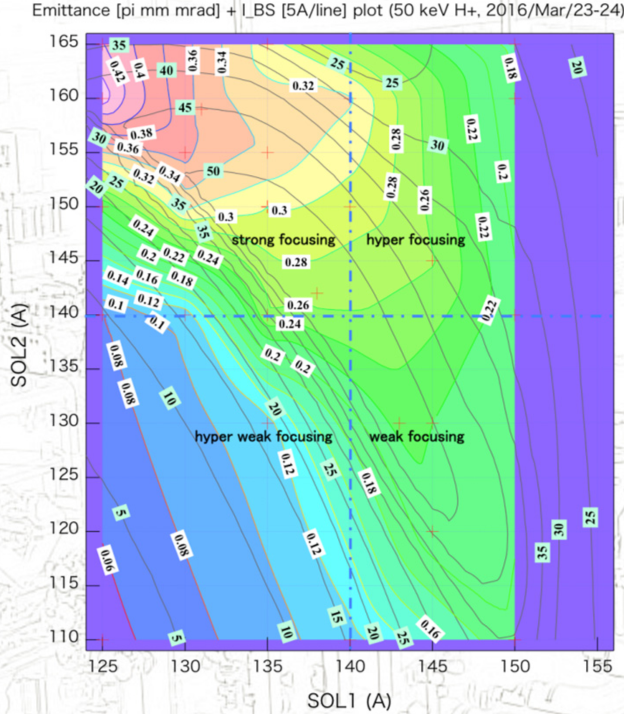
P.Y. Beauvais et al, *First beam of the CEA-Saclay CW high Intensity microwave source,* **PAC 1997, Vancouver**

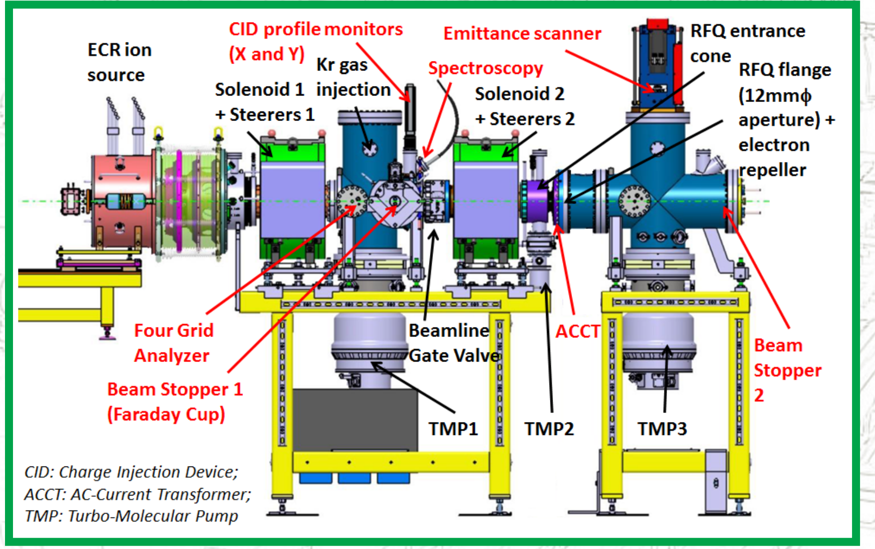
Commissioning is advancing

H^+ at 55 mA and 50 keV in CW

D^+ at 110 mA and 100 keV (10% d.c.)

B. Bolzon et al.
Intermediate commissioning results of the H+/D+ ECR injector of IFMIF/LIPAc
IPAC 2016 - WEPMY033





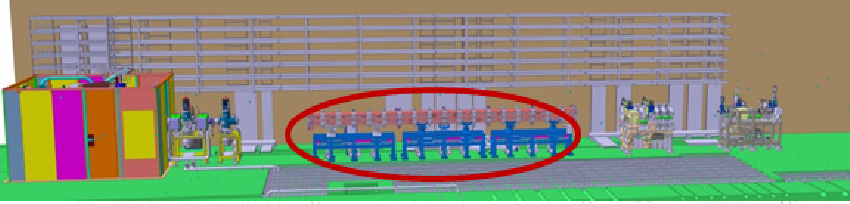
K. Shinto et al., *Space-charge neutralization measurement of high intensity D+ beams for the Linear IFMIF Prototype Accelerator (LIPAc) injector*, **IPAC 2016**

Efforts for further reduction on emittance values

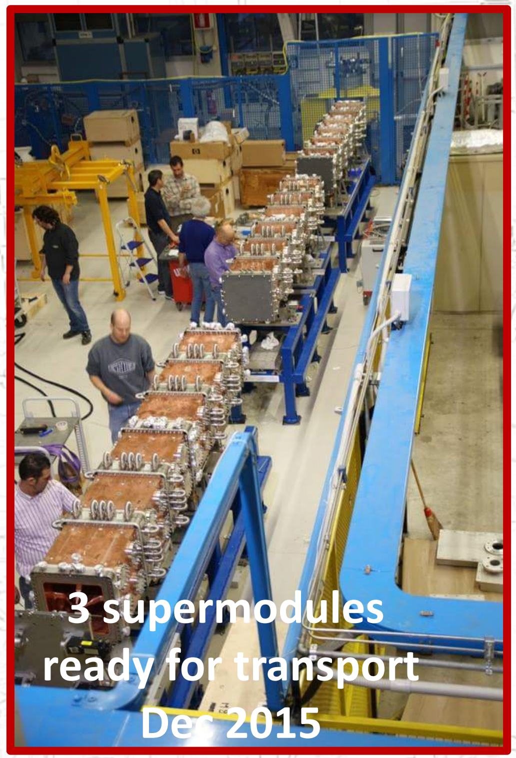
< 0.3 π mm·mrad

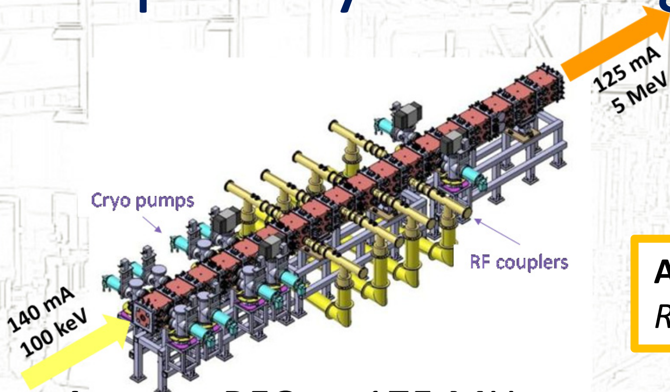
Simulations by INFN Legnaro

now well reproduce the experimental transmission and emittances



RFQ developed by INFN Legnaro





4-vanes RFQ at 175 MHz

E_{output} = 5 MeV

I_{output} = 125 mA in CW

9.7 m long (5.7λ)

Max surface field 25.2 MV/m (1.8 Kp)

A. Pisent et al., *IFMIF/EVEDA RFQ design*, **EPAC 2008**, **Genova**

M. Comunian et al., *Beam dynamics redesign of IFMIF/EVEDA RFQ for a larger input beam acceptance*, **IPAC 2011**, **San Sebastian**

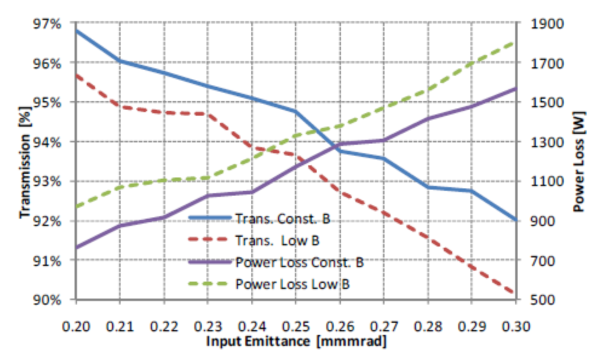


Figure [illegible] Transmission and power loss as function of the input emittance.

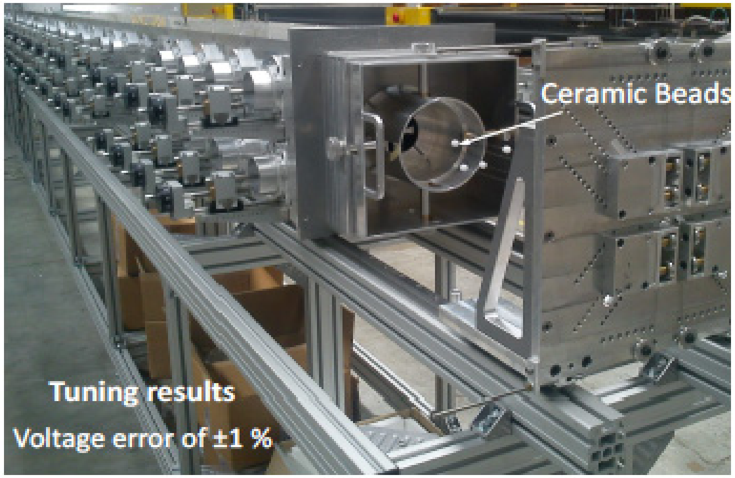


Fig. 11. A 9.7 m aluminum full scale prototype of the RFQ

A. Grenspan et al., *The IFMIF real scale aluminium model: RF measurement and tuning*, **IPAC 2010**, **Kyoto**

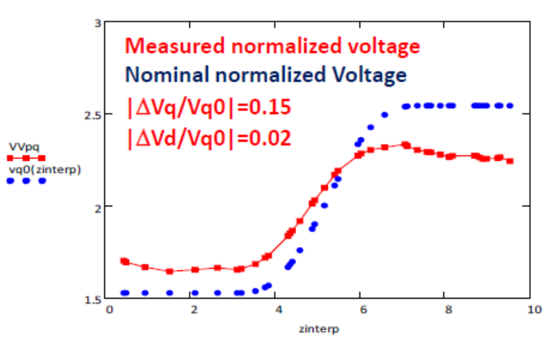
Thanks to A. Palmieri

IFMIF RFQ TUNING PROCEDURE

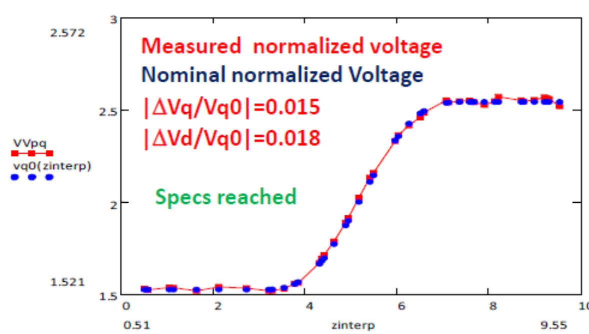
(preliminary)

In the tuning procedure of the IFMIF RFQ, the intra-vane voltage is deducted by magnetic field measurements with metal[...] technique. Initially the measurement is performed with provisional Aluminum tuners and end-cells. In the initial measurement, tuner[s ...] insertion depth, then tuners are adjusted in their insertion depths following the indication of the tuning algorithm, and the end-cell inse[rtion] depths are adjusted as well in order to obtain the proper voltage slope at RFQ ends. The mesurements are iteratively repeated up to the attainment of the f0=175 MHz target frequency and of the Vq voltage specification ±2% variation wrt nominal one Vq0 both for Quadrupolar and Dipolar perturbing terms (i.e **|ΔVq/Vq0|< 0.02** and **|ΔVd/Vq0|< 0.02**). The RFQ length is 9.8 m (5.7 λ)

Initial Measurement f0=174.255 MHz



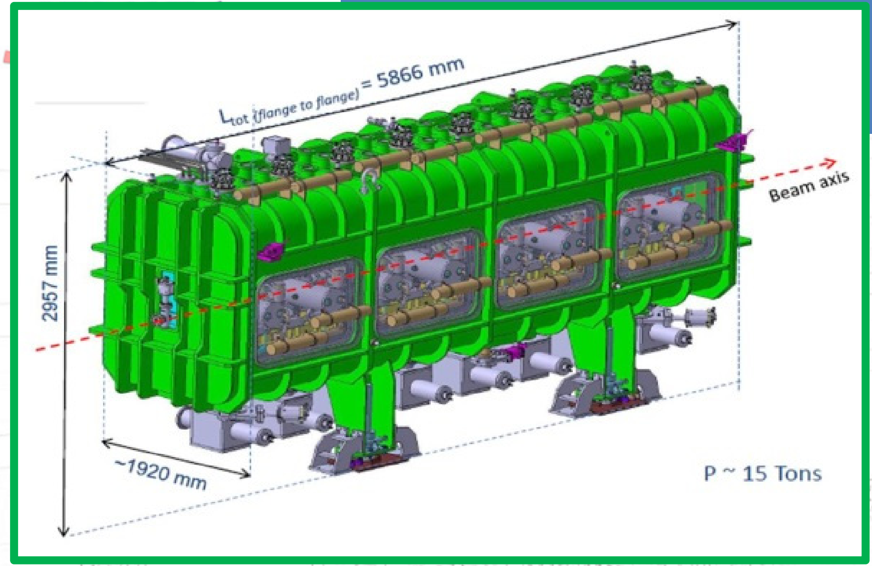
Final Measurement f0=174.994 MHz

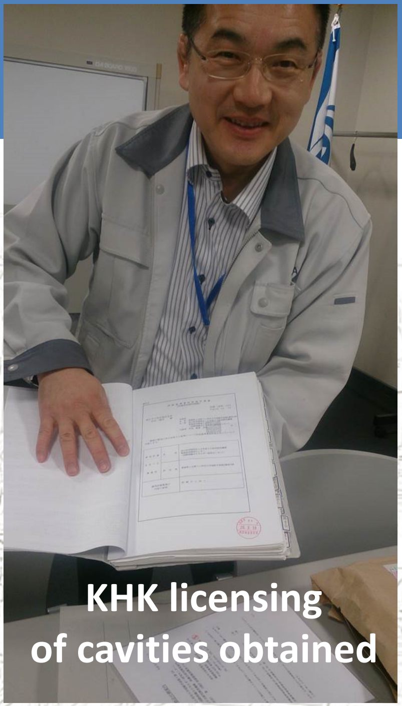


Next steps: replacement of the provisional Al End-cells and tuners with definitive Cu ones (in batches) and confirmation measurements

A. Palmieri et al., *Perturbation analysis on a 4-vane RFQ*, **IPAC 2010**, **Kyoto**

P. Mereu et al., *Mechanical integration of the IFMIF-EVEDA RFQ*, **IPAC 2016 – THPMY025**





SRF Linac

Superconducting HWR (x8) resonators at 175 MHz

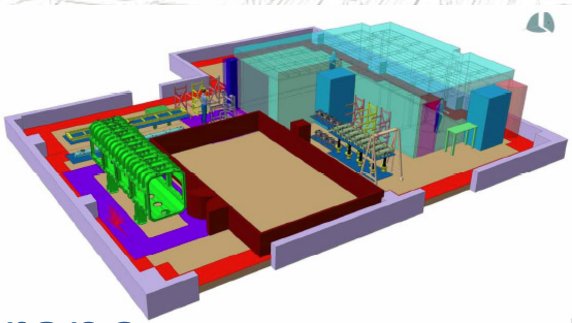
H. Dzitko et al, *Technical and logistical challenges for IFMIF-LIPAC cryomodule construction*, **SRF 2015, Whistler,**

E_{input}= 5 MeV

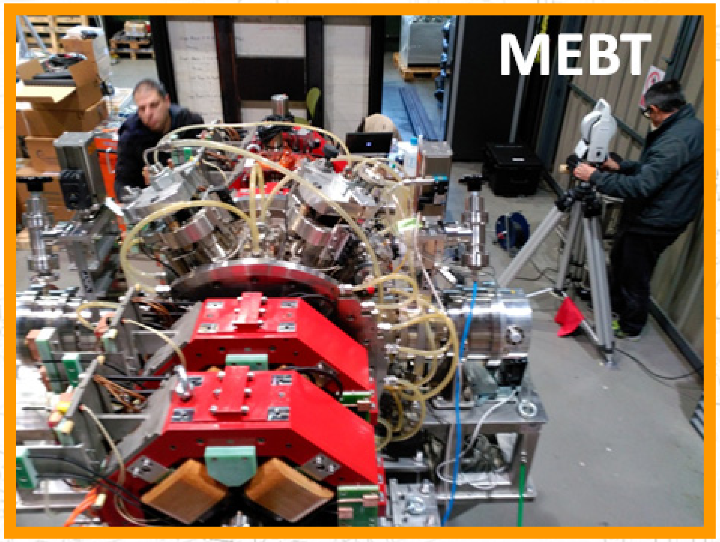
E_{output}= 9 MeV

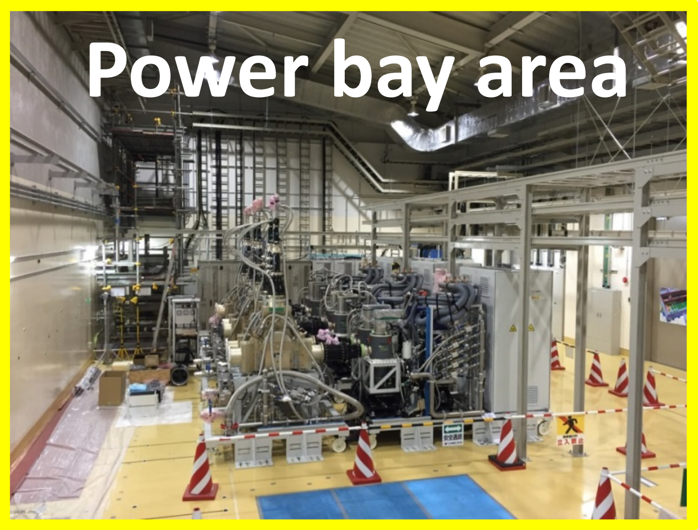
Beam loss < 10W

E_{acc}=4.5 MeV/m



Components under fabrication in Europe will be assembled in Rokkasho during 2017





D. Gex et al.,
Engineering issues of the medium energy beam transport line and srf linac for the LIPAc
IPAC 2016- THYA01

Challenges basically everywhere

Alignment of equipment
uncertainties of 30 μm

F. Scantamburlo et al., *Alignment of LIPAc, the IFMIF prototype high current accelerator: requirements and current status*, **IWAA 2014**

J. Marroncle et al, *IFMIF-LIPAc Diagnostics and its Challenges* , **IBIC 2012**

beam instrumentation
Low energy & High current beam

P.A.P. Nghiem
Advanced Concepts and Methods for Very High Intensity Linacs
IPAC 2016- THYA01

N. Chauvin et al., *Start-to-end beam dynamics simulations for LIPAc, IPAC 2011*

Beam dynamics
Cryogenic μ-loss monitors developed by CEA can allow halo mapping & core-halo matching

RF power
RFQ chains - 8 x 200 kW
SRF Linac - 8 x 105 kW
Bunchers – 2 x 16 kW SSPA

F. Scantamburlo et al.,
Beam Induced Damage Studies of the IFMIF/EVEDA 125mA CW 9 MeV D+ Linear Accelerator
IPAC 2016 - WEPMR044

A. Marqueta et al.,
Machine Protection and Safe Operation of LIPAc Linear Accelerator
IPAC 2016- THPOY035

Tuning of SRF linac in pulsed mode & MPS

Beam dump

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J. Marroncle et al, *IFMIF-LIPAc Diagnostics and its Challenges* **, IBIC 2012**

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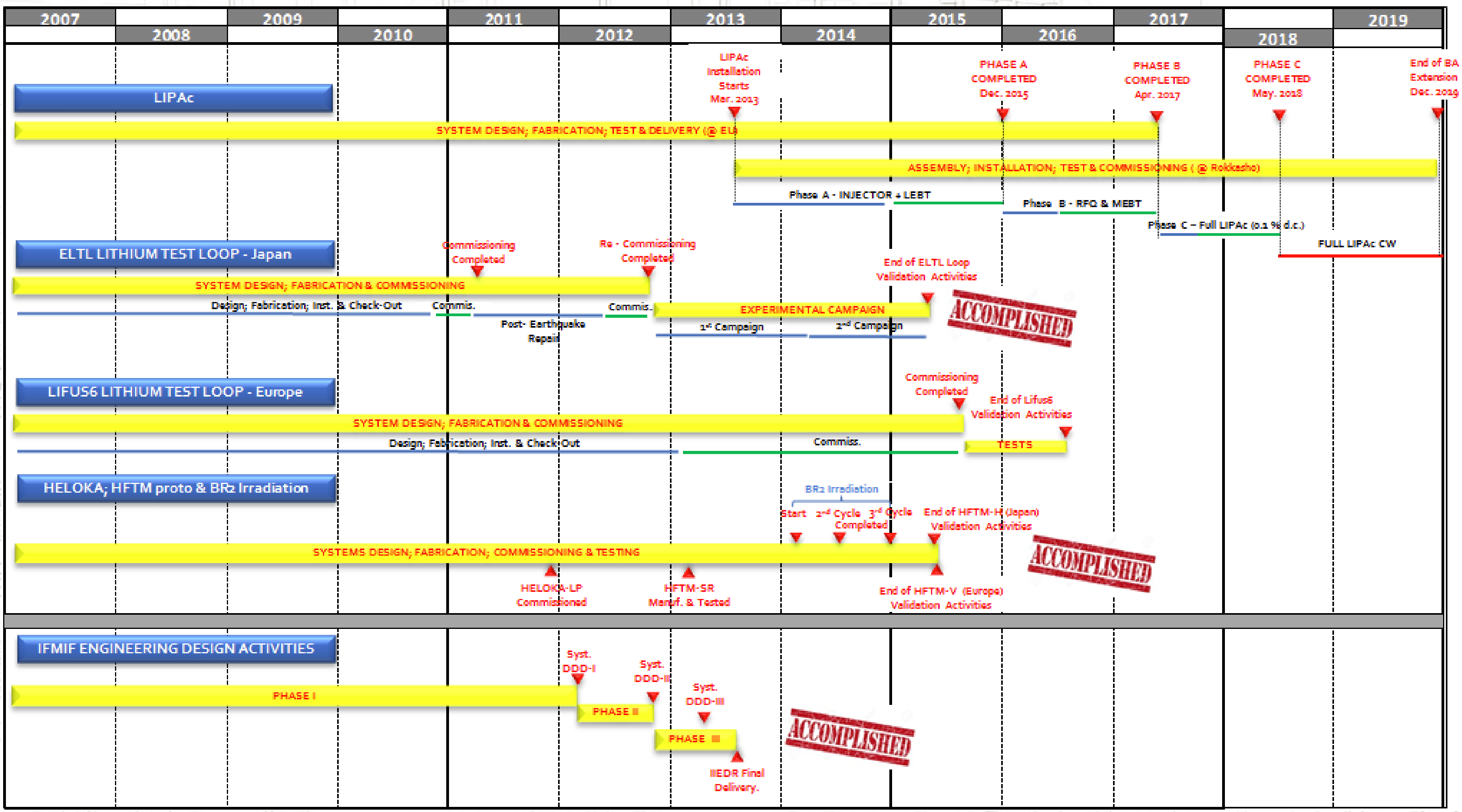
IPAC 2016- THPOY035

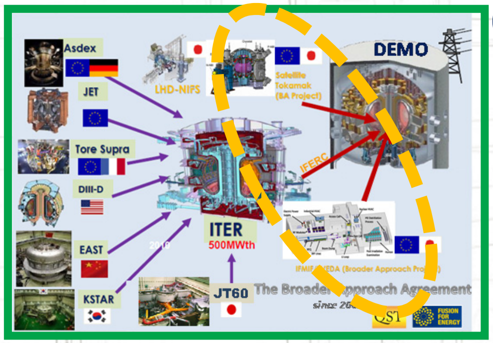
Tuning of SRF linac in pulsed mode & MPS

Beam dump

Limited resources

Our schedule

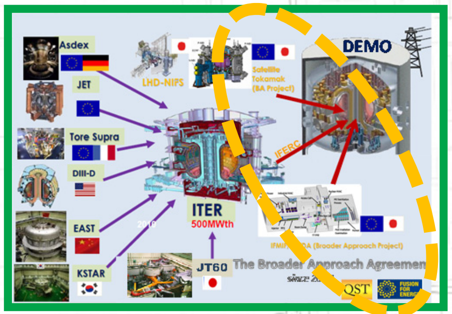




Our technical challenges are enormous

We are an 'in-kind' project
with limited budget
strict ceiling set in the Broader Approach Agreement

Why are we succeeding?



Our technical challenges are enormous

We are an ‘in-kind’ project
with limited budget
strict ceiling set in the Broader Approach Agreement

Why are we succeeding?

We have managed to settle essential aspects
Team spirit
Empathy with the ‘in-kind’ suppliers
(and all possible support)
Trustful and fluent communications at management level

Yes, we can!

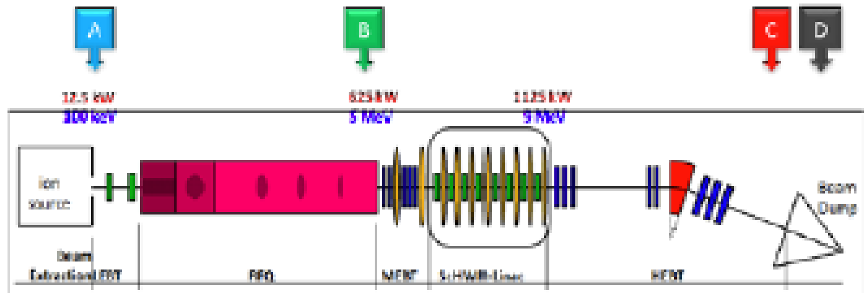


Figure 2: Phases with respect to the different stages

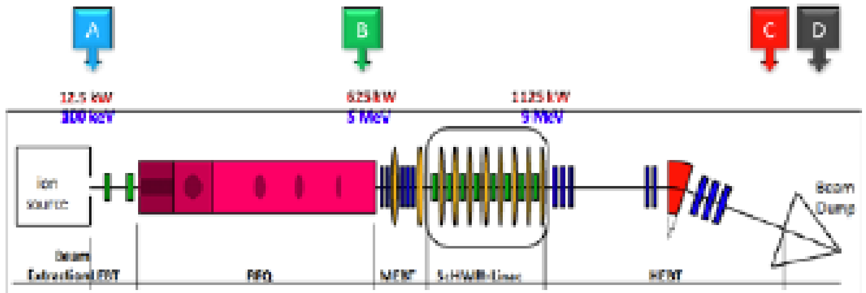
P. Cara et al.
The Linear IFMIF Prototype Accelerator (LIPAc) design development under the European-Japanese collaboration
IPAC 2106 - MOPOY57

1999 LEDA run 100 mA in CW at 6.7 MeV

We hope we can say in the future

Yes, we can!

Phase B commissioning has started



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We hope we can say in the future

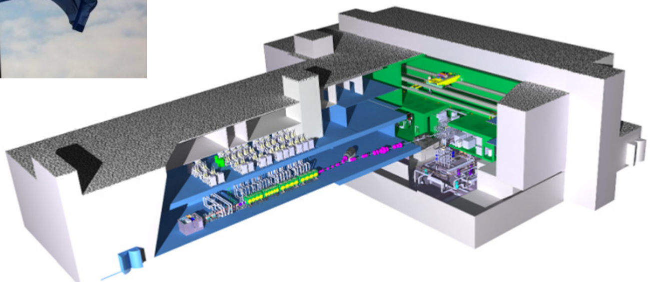
2019

LIPAc run 125 mA D^+ in CW at 9 MeV

A Li(d,xn) yes, but less ambitious

Ideas for a simplified version

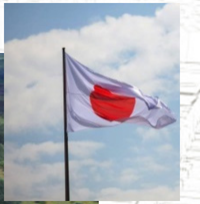
One only accelerator



DONES in Europe

A-FNS in Japan

are maturing



We will have 14 MeV from Li(d,xn) next decade

Decisions are likely to happen in 2016

IBARRA, A., et al., *A stepped Approach from IFMIF/EVEDA toward IFMIF,* **Fus. Sci. Tech. Vol. 66 July/Aug 2014**

HEIDINGER, R. et al., *Technical analysis of an early fusion neutron source based on the enhancement of the IFMIF/EVEDA accelerator prototype,* **Fus. Eng. Des. 89 (2014) 2136–2140**

Thanks to the EU-JA IFMIF family

(and all people involved in former phases/projects)

for their resilient enthusiasm

crucial for the present success of the program

and thanks to you for your attention