LIPAC, THE IFMIF/EVEDA PROTOTYE ACCELERATOR: ALIGNMENT AND ASSEMBLY CURRENT STATUS AND POSSIBLE FUTURE IMPROVEMENTS

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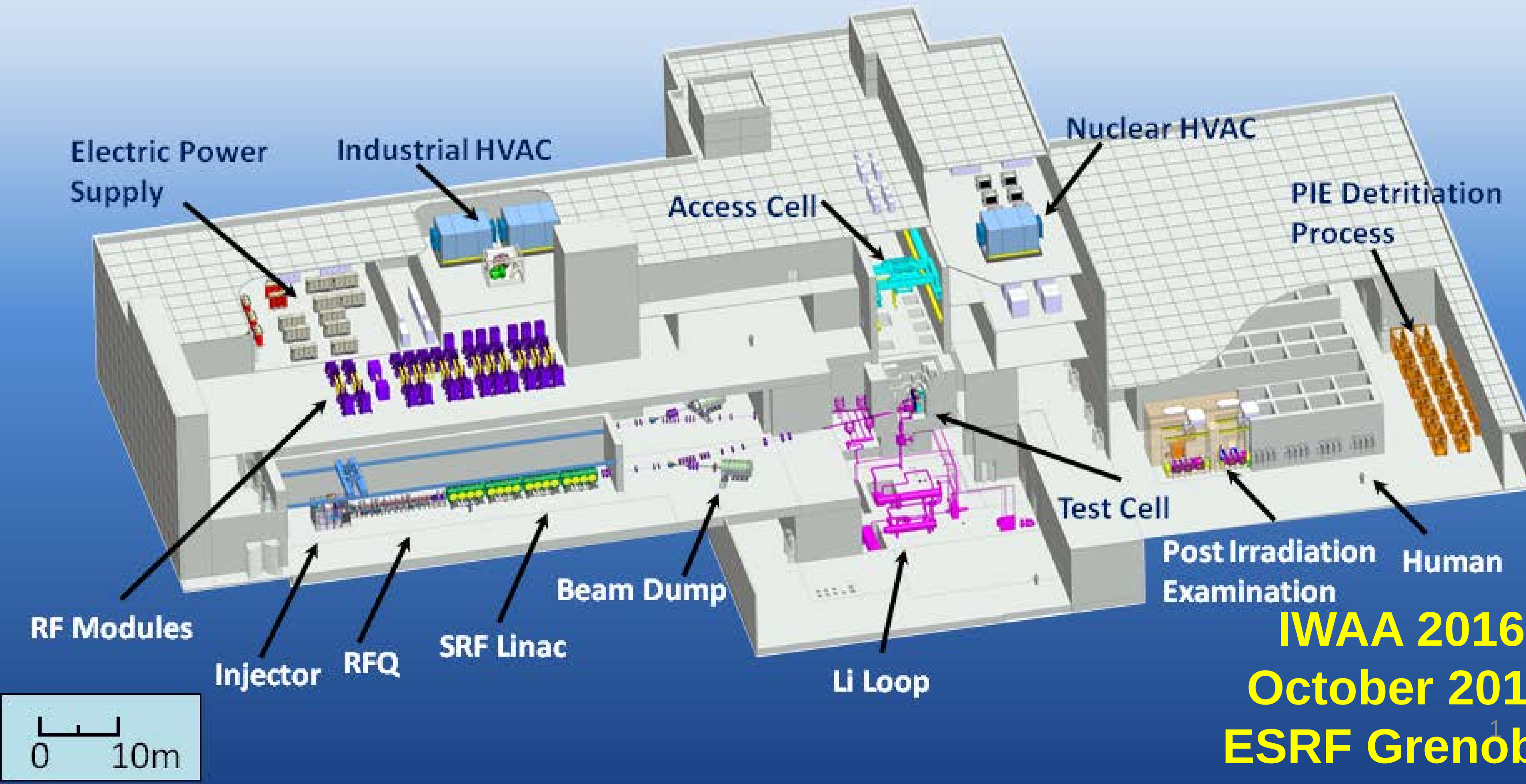
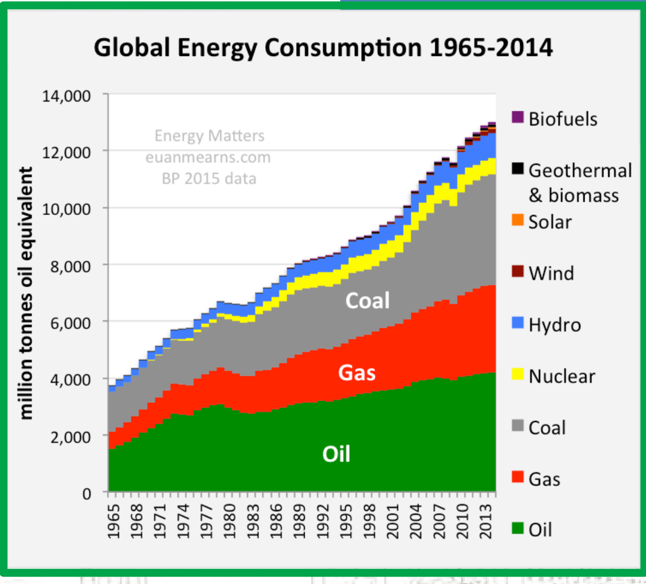
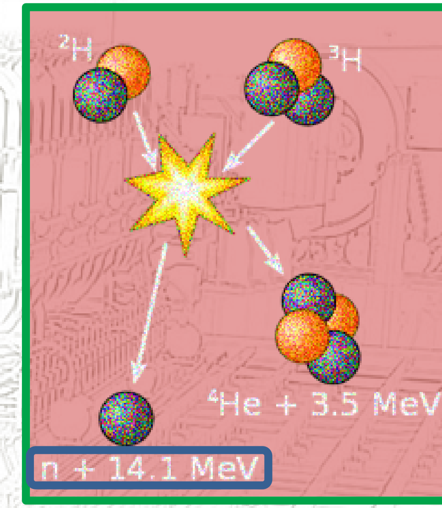


IWAA 2016
October 2016
ESRF Grenoble

Fusion potential energy solution



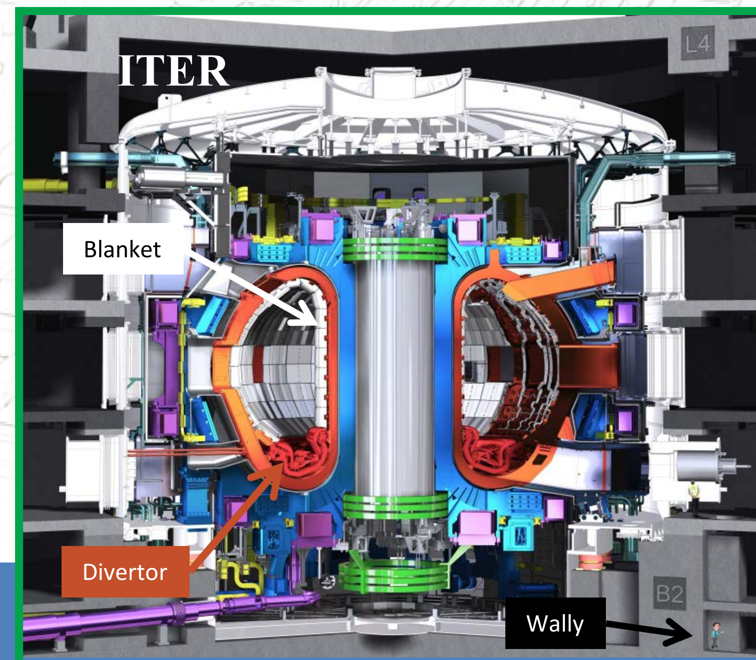
The first wall
of the reactor vessel shall
absorb neutrons energy



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

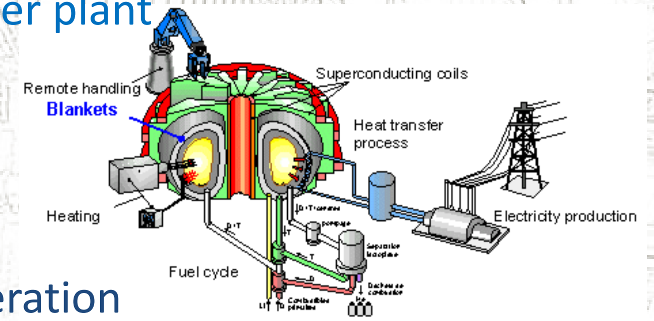
In a Fusion power plant
~30 dpa per year of operation

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**



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…

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

Fusion relevant neutron source is indispensable

IFMIF/EVEDA

Signed in February 2007

Entered into force on June 2007

IFMIF

International Fusion Materials Irradiation Facility

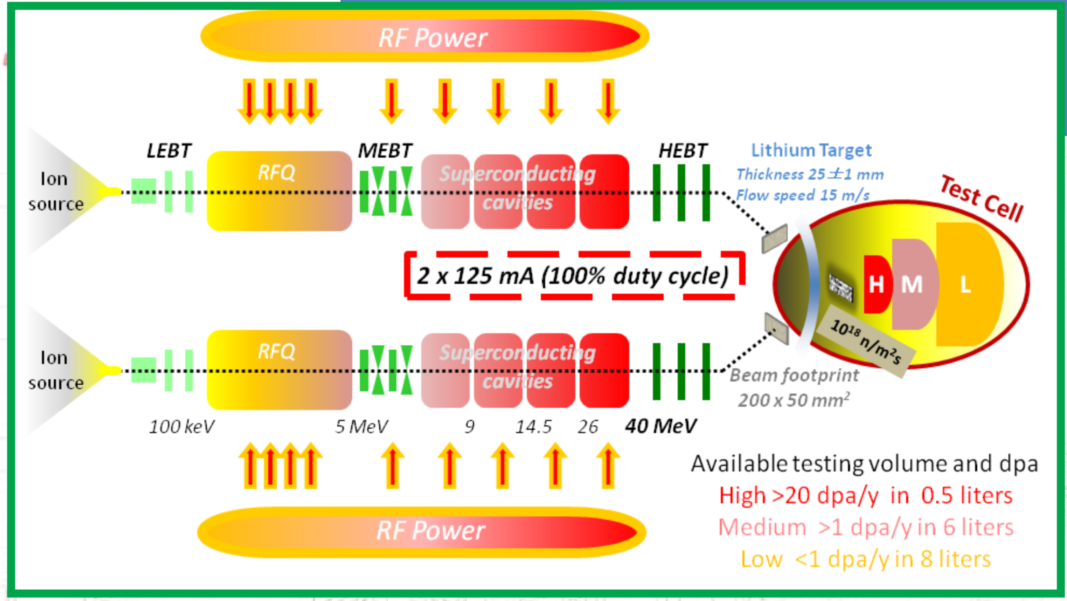
EVEDA

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

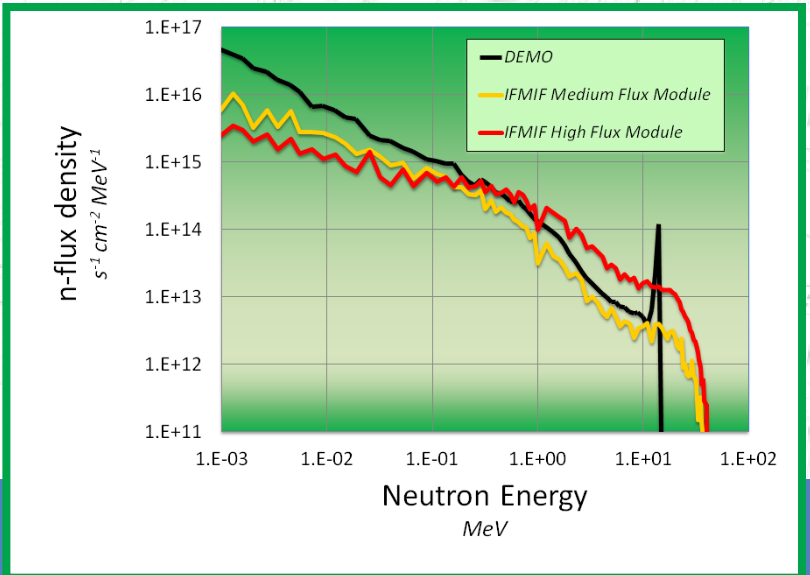
IFMIF concept



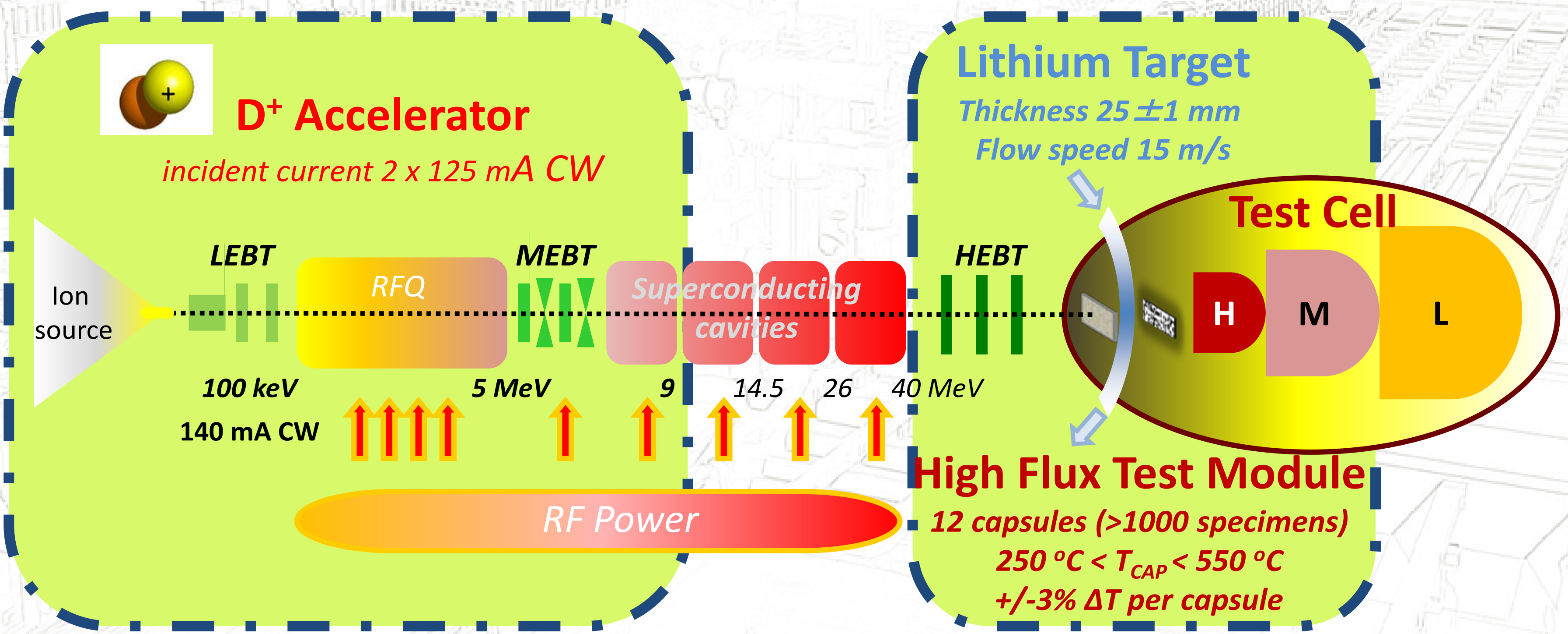
Two concurrent
125 mA CW deuterons beam
at 40 MeV
impact with
a beam footprint of 200 x 50 mm^2
on a liquid Li screen
flowing at 15 m/s

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%



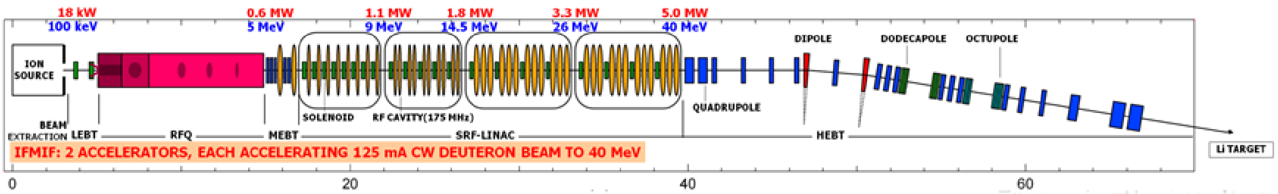
Validation Activities – EVA phase



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

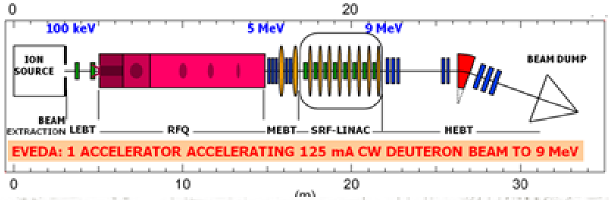
EVA Phase – Accelerator facility

IFMIF



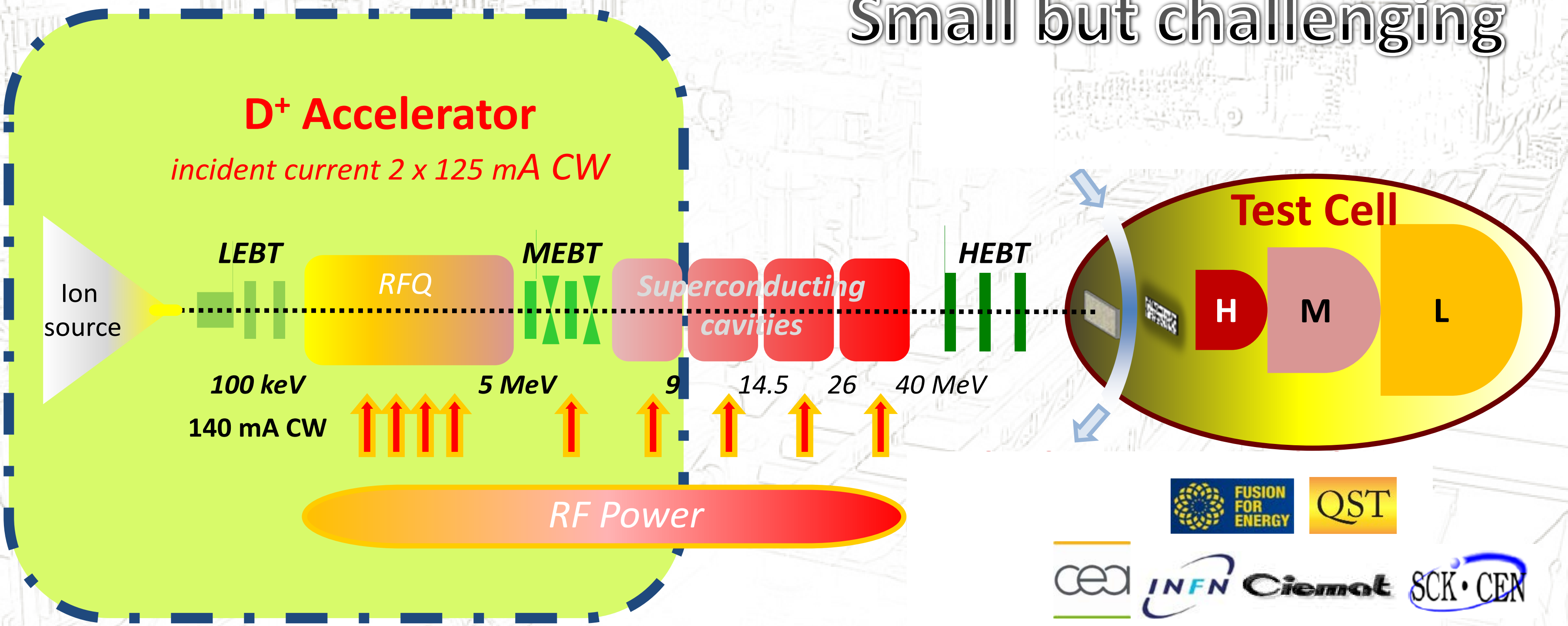
40 MeV
125 mA
5 MW

LIPAc



9 MeV
125 mA
1.125 MW

Small but challenging



LIPAc, the accelerator of records

LIPAc is very ambitious

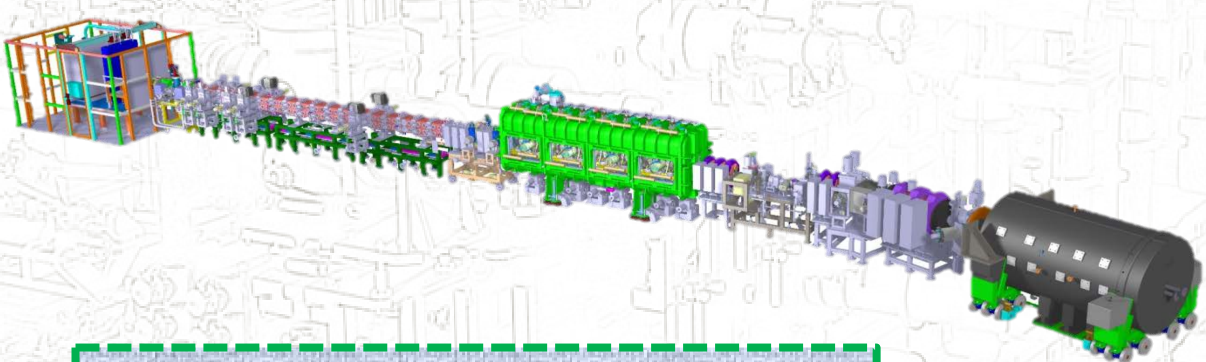
World's highest current linac

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

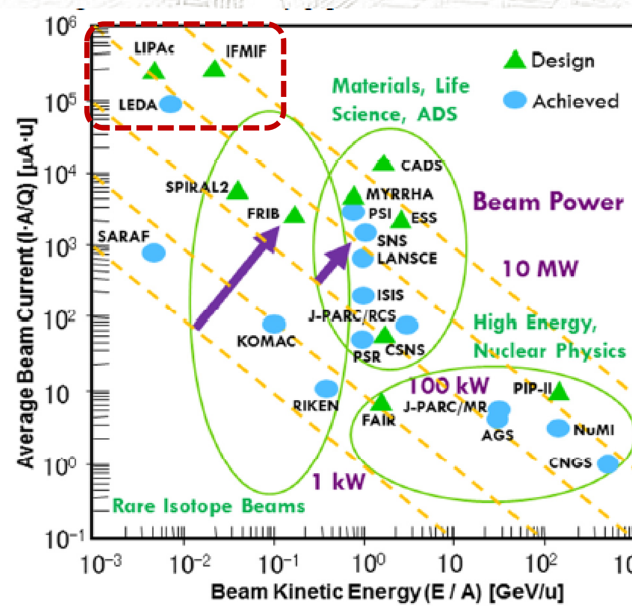


Figure 1: Hadron accelerator power frontier.

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

Equipment designed and constructed in Europe Installed and commissioned in Rokkasho

Injector + LEBT
CEA Saclay

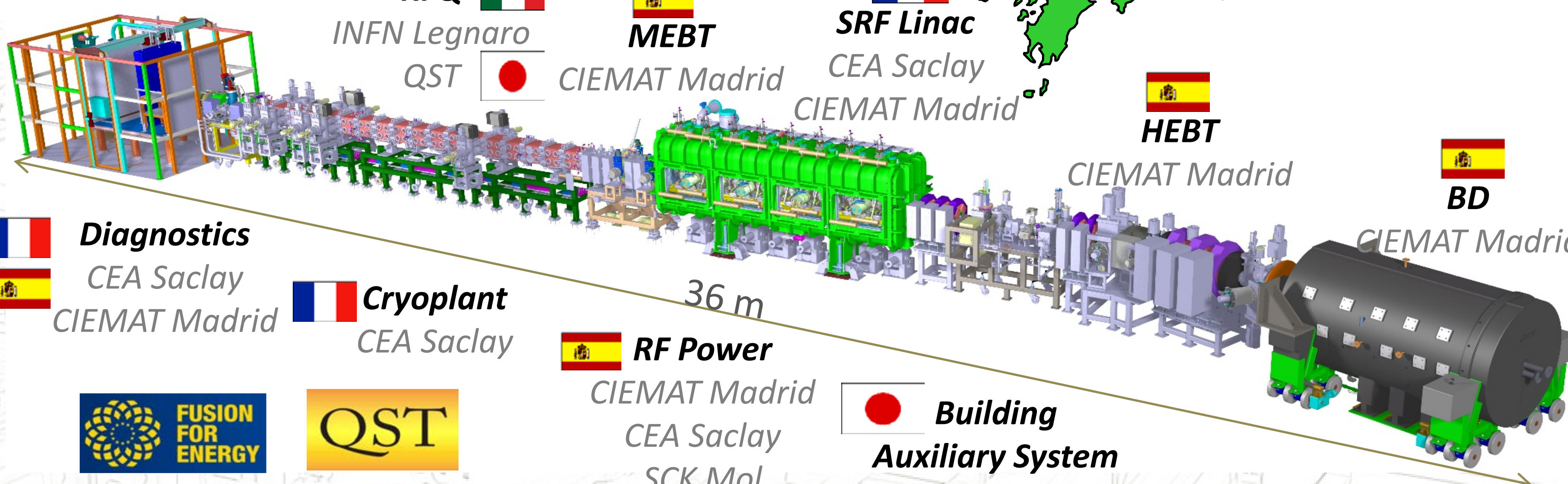
RFQ
INFN Legnaro
QST

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid



Diagnostics
CEA Saclay
CIEMAT Madrid

Cryoplant
CEA Saclay

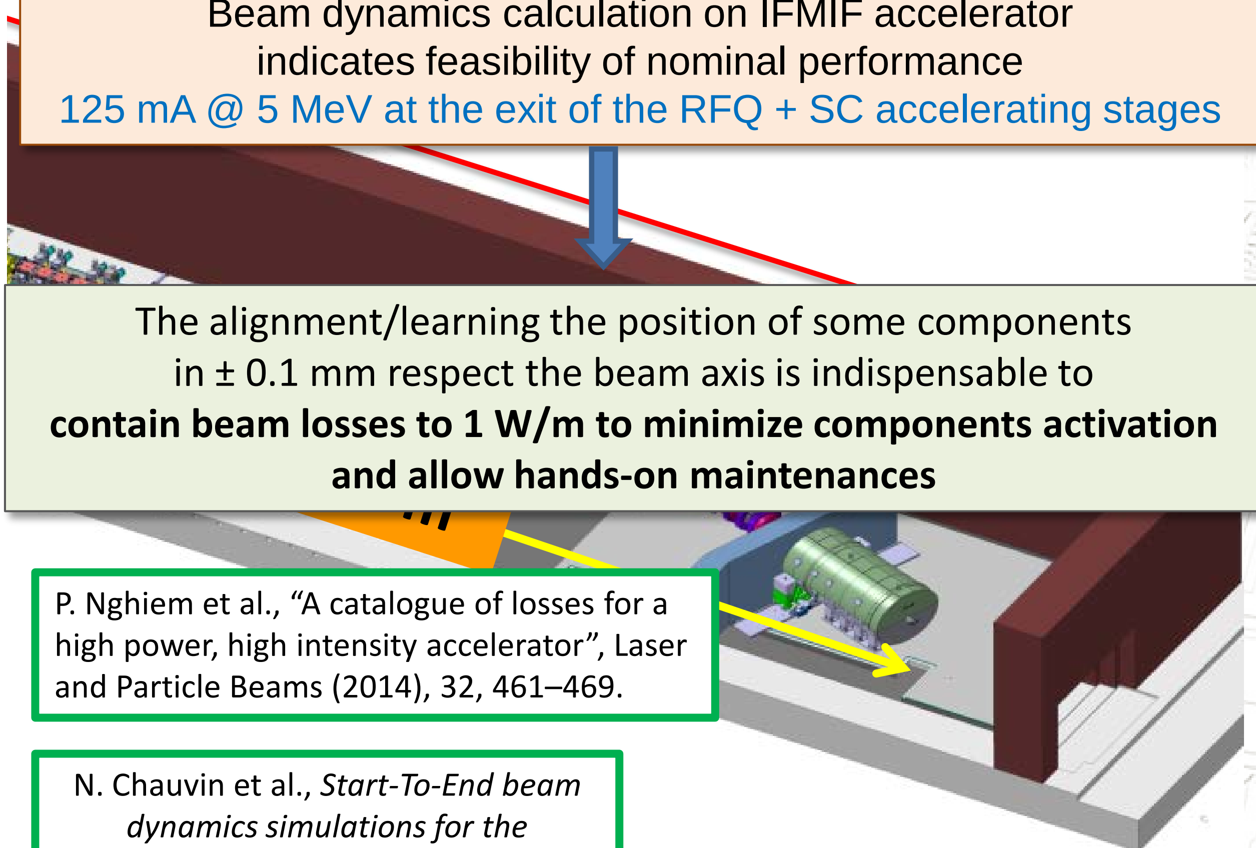
RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Building
Auxiliary System
Control system
Installation
QST

LIPAc alignment requirements, why alignment is important

Table 1: Errors distribution

Error Type	Error range
LEBT	
Solenoids Misalignment [x,y]	±0.2 mm
Solenoids Tilt [φ_x,φ_y]	±3.5 mrad
RFQ	
RFQ Segment Misalignment [x,y]	±0.1 mm
RFQ Voltage (first harmonic shape)	±2 %
RFQ Mean Radius	±20 μm
RFQ Vane Radius	±20 μm
MEBT	
Quadrupoles Misalignment [x,y]	±0.2 mm
Quadrupoles Tilt [φ_x,φ_y]	±10 mrad
Buncher cavities Misalignment [x,y]	±1 mm
Buncher cavities Tilt [φ_x,φ_y]	±30 mrad
BPMs Measurement Accuracy	±0.1 mm
SRF linac	
Resonators Misalignment [x,y]	±2 mm
Resonators Tilt [φ_x,φ_y]	±20 mrad
Resonators Field amplitude	±1 %
Resonators Field phase	±1 deg
Solenoids Misalignment [x,y]	±1 mm
Solenoids Tilt [φ_x,φ_y]	±10 mrad
BPMs Measurement Accuracy	±0.25 mm
HEBT	
Quadrupoles Misalignment [x,y]	±0.2 mm
Quadrupoles Tilt [φ_x,φ_y]	±15 mrad
Quadrupoles Tilt [φ_z]	±3 mrad
Dipole Misalignment [x,y]	±1 mm
Dipole Tilt [φ_x,φ_y,φ_z]	±10 mrad
BPMs Measurement Accuracy	±0.1 mm



LEDA reached 100 mA @ 6.7 MeV at the exit of the RFQ
with protons in CW in 1999:
beam losses mainly due to beam halo

Beam dynamics calculation on IFMIF accelerator
indicates feasibility of nominal performance
125 mA @ 5 MeV at the exit of the RFQ + SC accelerating stages

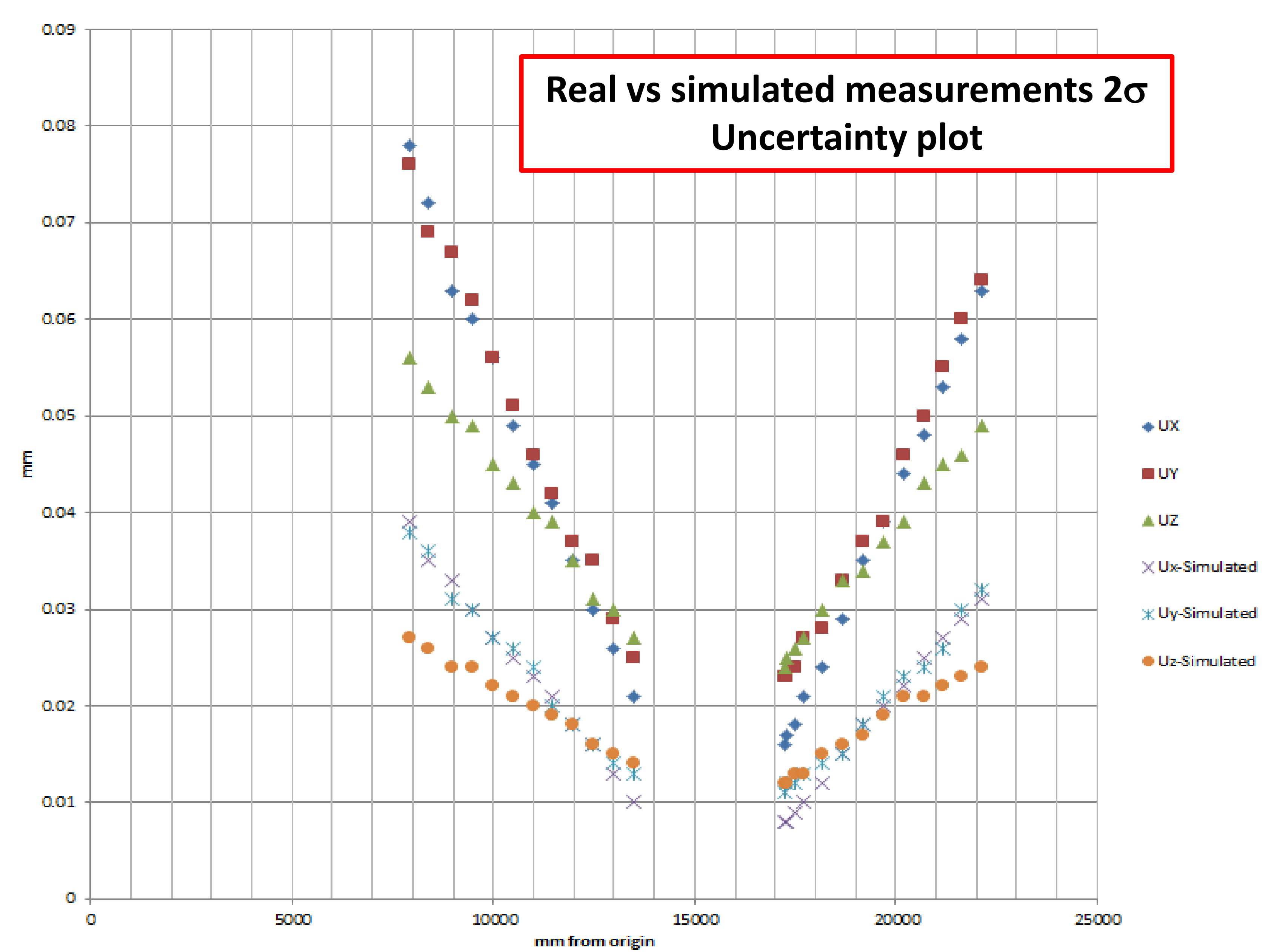
The alignment/learning the position of some components
in ± 0.1 mm respect the beam axis is indispensable to
contain beam losses to 1 W/m to minimize components activation
and allow hands-on maintenances

P. Nghiem et al., "A catalogue of losses for a high power, high intensity accelerator", Laser and Particle Beams (2014), 32, 461–469.

N. Chauvin et al., *Start-To-End beam dynamics simulations for the prototype accelerator of the IFMIF/EVEDA Project*, IPAC 2011

Instrumentation and software

- **LEICA AT401 Laser Tracker:**
  - MPE angle accuracy ±(16μm+5μm/m), MPE distance accuracy: ±10 μm, level accuracy: ± 1 arcsec;
- **Spatial Analyzer Ultimate metrology software:**
  - Experience of F4E Metrology team
  - Capability of estimate the uncertainty of measurements through USMN algorithm
  - Capability of simulations of measurements to optimize measurement process;
  - Verification of instrument performance in the real environment


Real vs simulated measurements 2σ
Uncertainty plot
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
mm
0
5000
10000
15000
20000
25000
mm from origin
UX
UY
UZ
Ux-Simulated
Uy-Simulated
Uz-Simulated

Thermal effects on the metrology network

Rokkasho enjoys hard winters and hot summers.

In the simplest case, for a structure of uniform material, uniform temperature distribution, absence of restraints, a linear model shall be enough accurate to model its thermal expansion

Weekly m … nd walls

Wee … ure

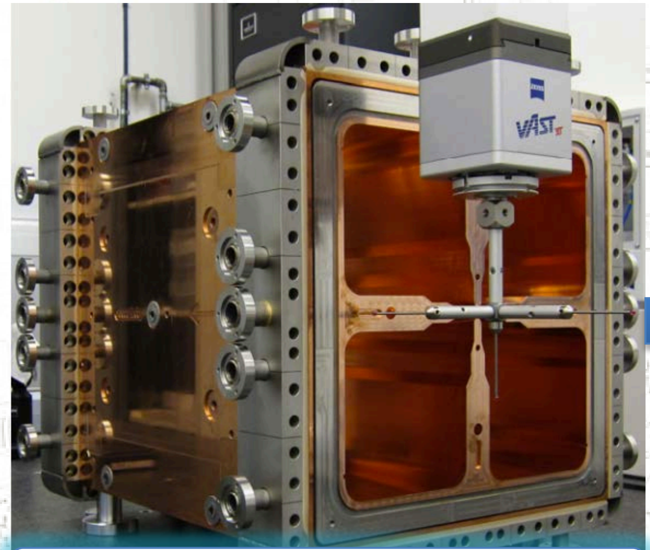
Weekly … walls

Unfortunately we discovered that a linear model to compensate the thermal expansion effect of the vault was not enough accurate to satisfy the uncertainty thresholds for the alignment of the components and FEM analyses may result complicated to be developed.
It resulted to be highly recommendable to re-measure and redefine the coordinates of vault metrology network periodically especially before a precise alignment or survey of the components respect the beam line frame is needed.

Date	FI…									T air [°C]
	USMN…								…m]	
2014.05.02	23562.744	23562.107	-0.637	0.999973		13.2	13	800.001	800.005	14.3
2014.05.08	23562.744	23562.184	-0.56	0.999976	5.1598E-06	13.8	13.5	800.001	800.007	14.8
2014.05.20	23562.744	23562.37	-0.374	0.999984	7.572E-06	14.6	14.7	800.005	800.014	16.5
2014.07.09	23562.744	23562.986	0.242	1.000010	5.91284E-06	19.5	19.7	800.009	800.015	20.8
2014.07.24	23562.744	23563.151	0.407	1.000017	5.90107E-06	20.7	21.3	800.01	800.008	22.2
2014.08.01	23562.744	23563.332	0.588	1.000025	5.99452E-06	21.8	22	800.01	800.015	23.2
2014.09.30	23562.744	23563.595	0.851	1.000036	5.81084E-06	24.0	23.9	800.012	800.01	25.3

IFMIF

RFQ alignment and assembly



CMM fiducialization@ INFN

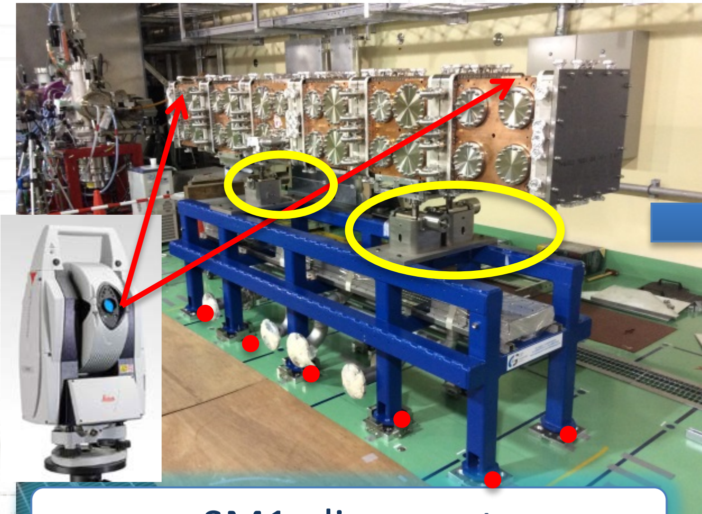
SMs assembly @ INFN LNL

SMs assembly @ INFN LNL

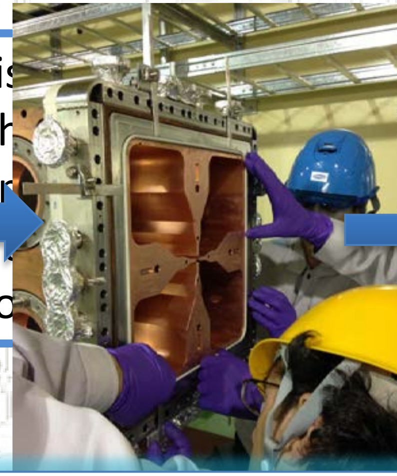
L. Ferrari et al., “IFMIF RFQ Module Characterization via Mechanical and RF Measurements”, Proceedings of LINAC2016, East Lansing, Michigan, USA.

E. Fagotti et al., “Preparation and Installation of IFMIF-EVEDA RFQ at Rokkasho Site”, Proceedings of LINAC2016, East Lansing, Michigan, USA.

RFQ alignment and assembly - 2



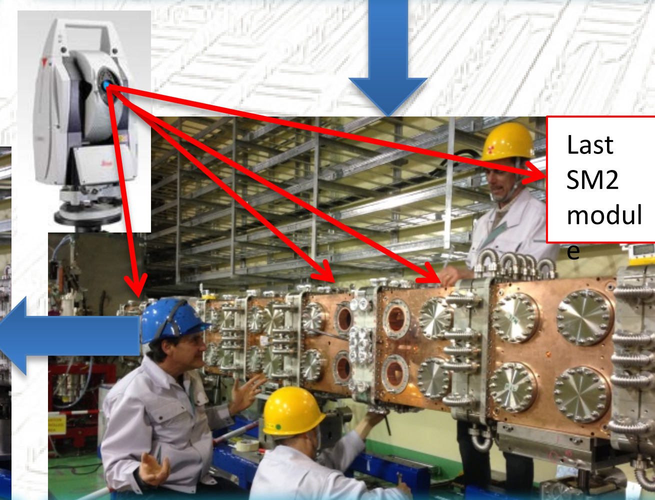
SM1 alignment



SM1-SM2 connection preparation

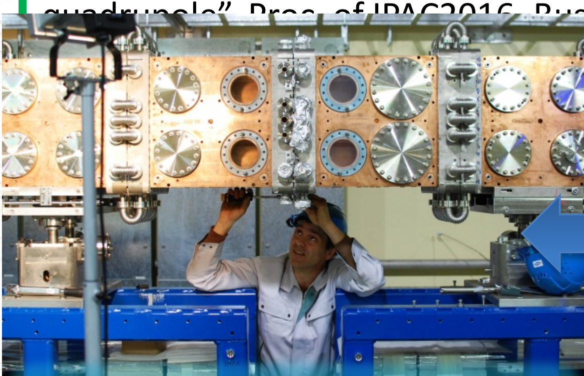
SM2 alignment

P. Mereu et al., “Mechanical integration of the IFMIF-EVEDA radio frequency quadrupole”, Proc. of IPAC2016, Busan



SM1-SM2 connection

SM3 alignment



SM2-SM3 connection

RFQ alignment and assembly – results

The alignment campaingn of the RFQ SMs performed in the temporary position @ IFMIF/EVEDA site showed the feasibility of the assembly.

- The beam axis at the interface of the SMs connection were matched with a precision below 60 μm in transverse direction.
- The beam axis at the entrance and exit of the RFQ were transversally aligned with a precision below 50 μm.
- The 2σ USMN estimated fiducials measurement uncertainty was below 30 μm

MEBT and Dplate alignment

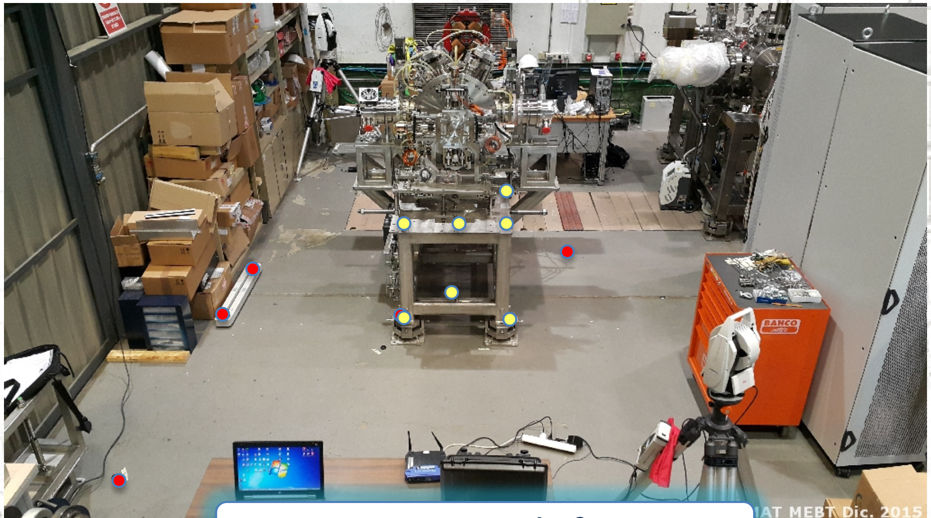
- A fruitful collaboration was established between F4E metrology team, ILIC metrology team and CIEMAT MEBT and DPlate teams to tackle and optimize as much as possible the alignment and assembly aspects (e.g.: determination of number and position of the fiducials, procedures to be followed, etc.). SA simulations were extensively used to support the design of the alignment process.
- In order to prevent potential delays on the installation and commissioning of the accelerator in Rokkasho, alignment and assembly alignment campaigns were orgnized at CIEMAT premises to test the feasibility of the alignment and assembly within the design tolerance requirements
- Before the aligment respect the MEBT and Dplate frame, all the components that needs aligment were charaterized by means of CMM. Magnetic measurements were performed to determine and compensate the magnetic respect mechanical axis deviations.

MEBT alignment – CIEMAT Survey

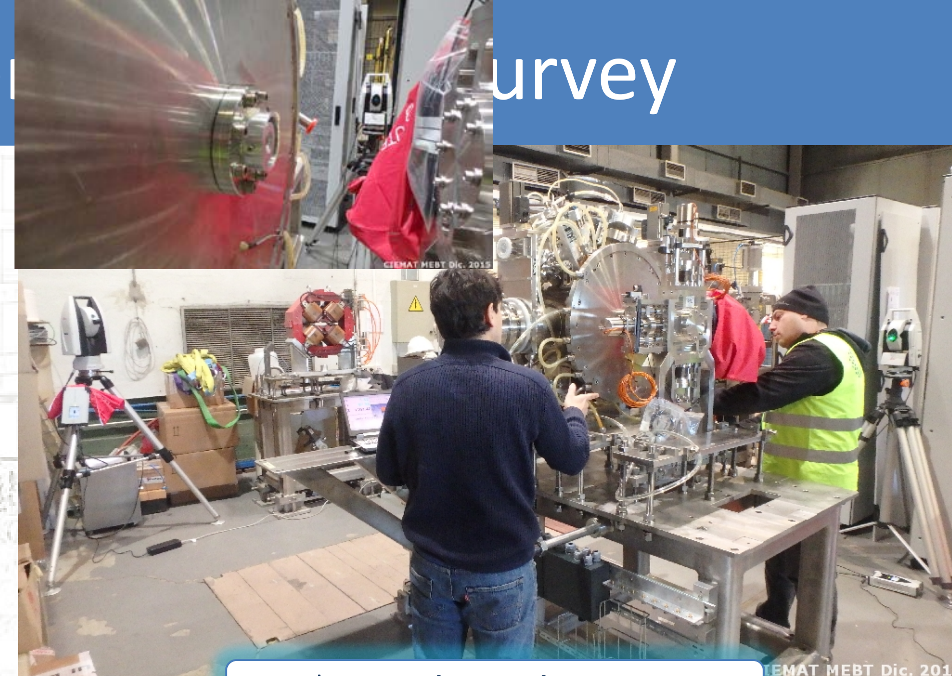
Limited space around the MEBT assembly and visibility of tracking alignment keypoints that would require several changes of tracker station, 2 laser trackers (one Leica AT960 + T-probe and one Leica AT402) were used in parallel

IFMIF

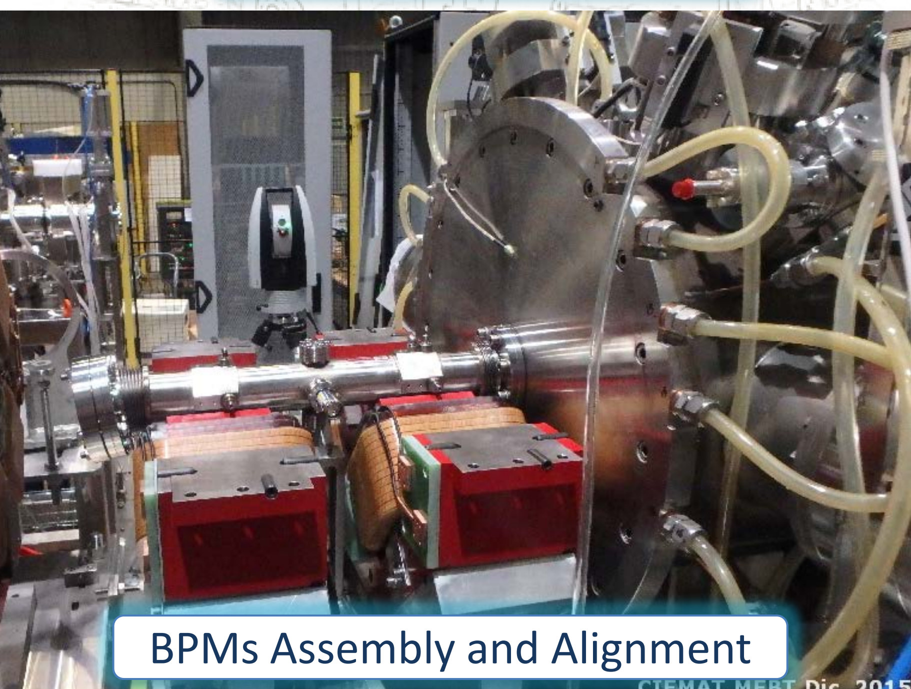
MEBT alignme urvey



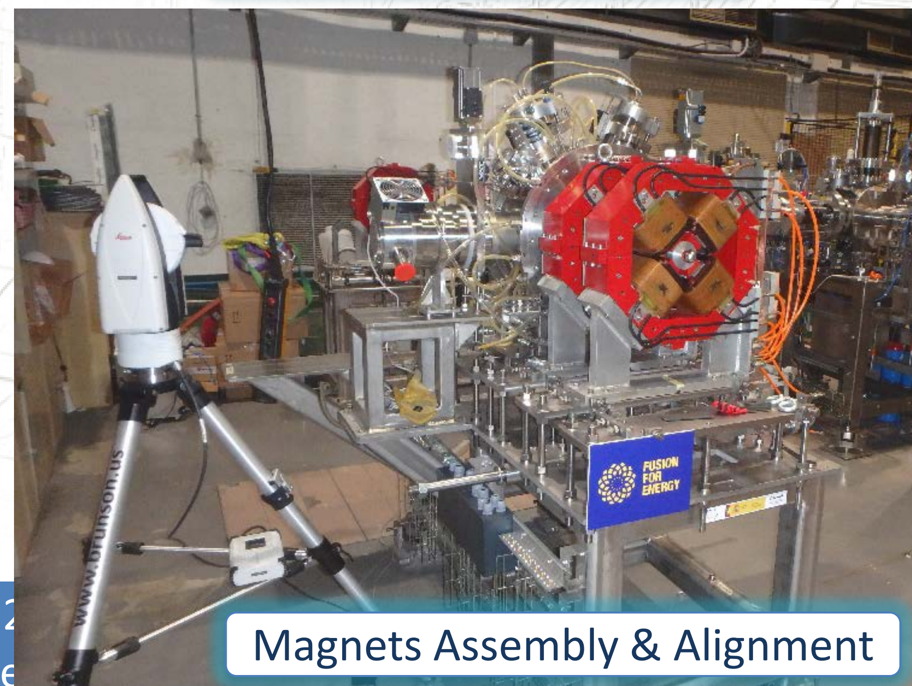
MEBT Frame definition



1st Buncher Alignment

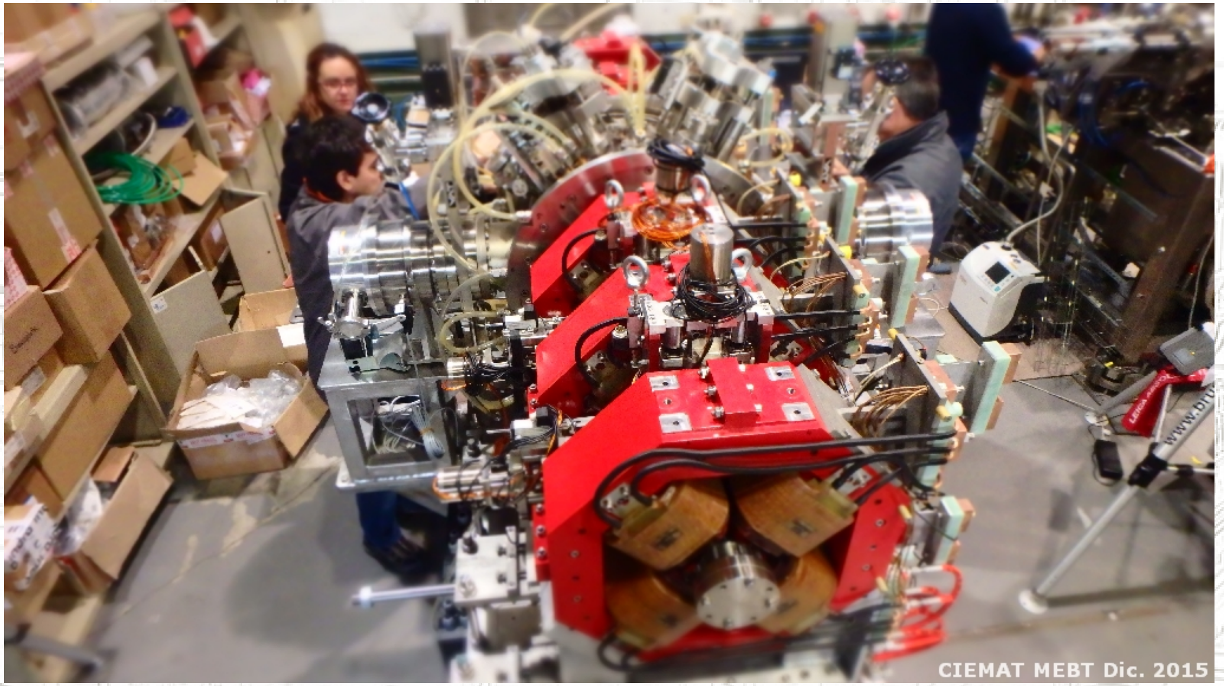


BPMs Assembly and Alignment



Magnets Assembly & Alignment

MEBT alignment – CIEMAT Final Survey



After the assembly and alignment of the components of the MEBT was completed, all the fiducials were surveyed by different station. More than 80 fiducial nests have been surveyed many times realizing a database of more than 500 measurements. For the adopted process and layout, the **2σ uncertainty of each fiducial was below 20 μm** along each transversal and longitudinal directions. The analyses of the data confirmed the feasibility of the alignment of the MEBT components **below ±0.1 mm respect the MEBT beam line frame**, within the required tolerances.

MEBT alignment –Survey and realignment

After shipment to Rokkasho, the MEBT was installed in a temporary position on the beam line in the accelerator vault.

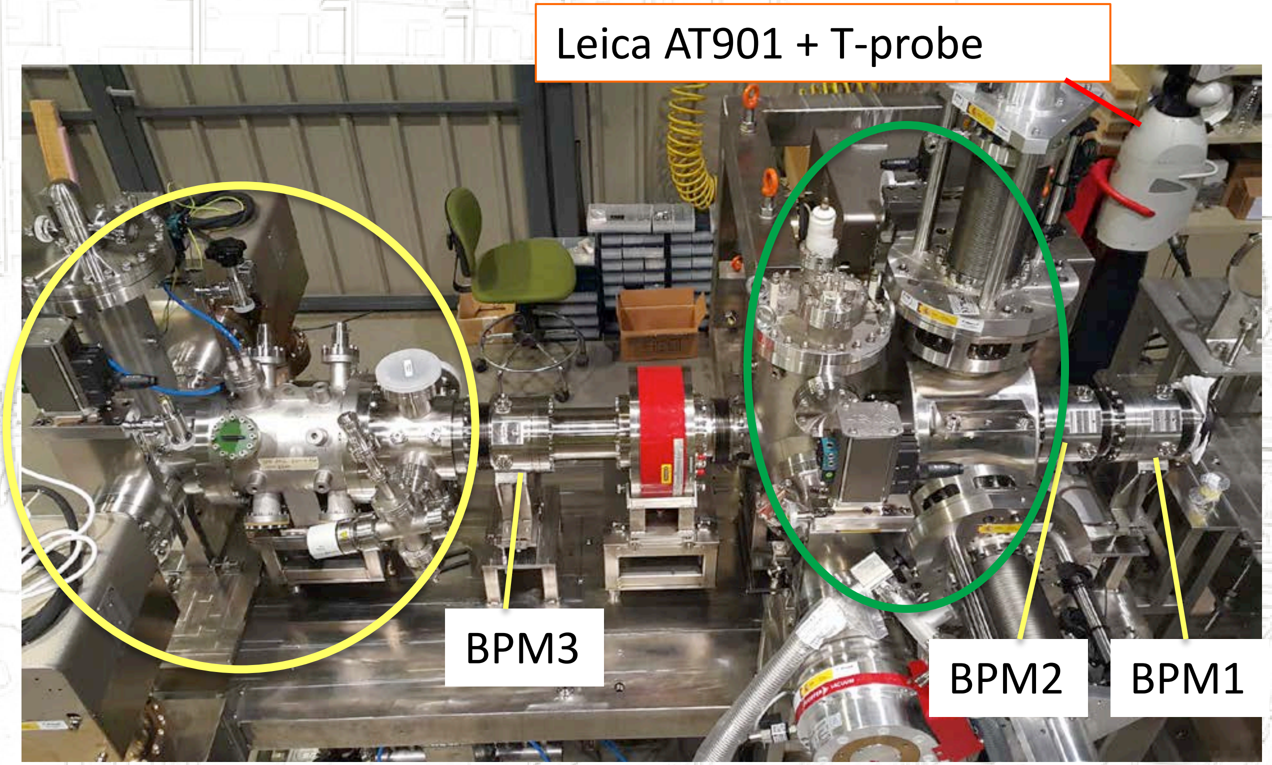
The survey of the fiducials performed last summer showed the magnet center positions were out of alignment tolerances (up to 0.6 mm in horizontal direction)

Due to different hardware availability, one Leica AT401, the process resulted to be quite time consuming (one month and half was spent) and some difficulties were encountered: e.g.: the BPMs would require several iterations from different laser tracker stations. it was decided to mechanically assemble them by means of calibrated gauges and survey their fiducials to determine their center position and tilting respect the MEBT frame.

Dplate Alignment in CIEMAT

As for the MEBT also the Dplate was surveyed at CIEMAT premises before the shipment to Rokkasho with F4E metrology team collaboration.

1) The process started with the definition of the Dplate beam coordinate frame surveying features and nests of the frame
2) The heaviest components were (circled in yellow and green) were firstly aligned
3) Than the BPMs were aligned



4) After the assembly and alignment has been completed, all the nests were surveyed by different laser tracker stations. All the components resulted to be aligned with a precision below 50 μm in transversal direction and the 2σ target uncertainty estimated by USMN resulted to be 20 μm max. along each direction.

Dplate survey in Rokkasho

As RFQ and MEBT, also the Dplate after shipment was installed in a temporary position along the beam line to carry out assembly phases during injector shut down time. A survey of the Dplate fiducials was performed last summer. A realignment campaign is needed and scheduled at beginning of 2017. The BPMs position is out of tolerance and realignment is needed. Some diagnostics may require smaller tolerances according to new calculations performed by beam dynamics group.

Photogrammetry tests

- Needs of periodically check the beam line components alignment
- Although the PG setup of instrumentation and target may be time consuming, it should considerably reduce time required for the survey (minimizing impacts on the commissioning schedule and personnel exposure to ionizing radiations).
- Possibility to share the target nests and easily implement new PG targets.
- PG software is compatible with SA.
- Recent tests performed on a ITER components by ITER metrology team to compare LT and PG, gave same uncertainty results, around 0.02 mm.

Conclusions

- Deformations of the vault induced by thermal effect at the moments can only be treated in the same way as deformations induced by earthquakes/load of components, i.e. a survey and redefinition of the coordinates of the metrology network through USMN is needed
- The alignment campaigns performed at labs and IFMIF/EVEDA vault on the RFQ, MEBT and Dplate demonstrated the feasibility of the alignment of each subsystem within the design tolerances respect the beam line frame. The components are ready for the integration for the phase B commissioning.
- The experience with the realignment of the MEBT with only one AT401 recommends the use of a second laser tracker (e.g.: AT960 + T-probe) to improve the quality and increase the speed of the alignment process.
- The promising results obtained with photogrammetry technique by F4E metrology team gave positive indications on its implementation on the monitoring of the components inside the IFMIF/EVEDA vault.

Thanks a lot for your attention