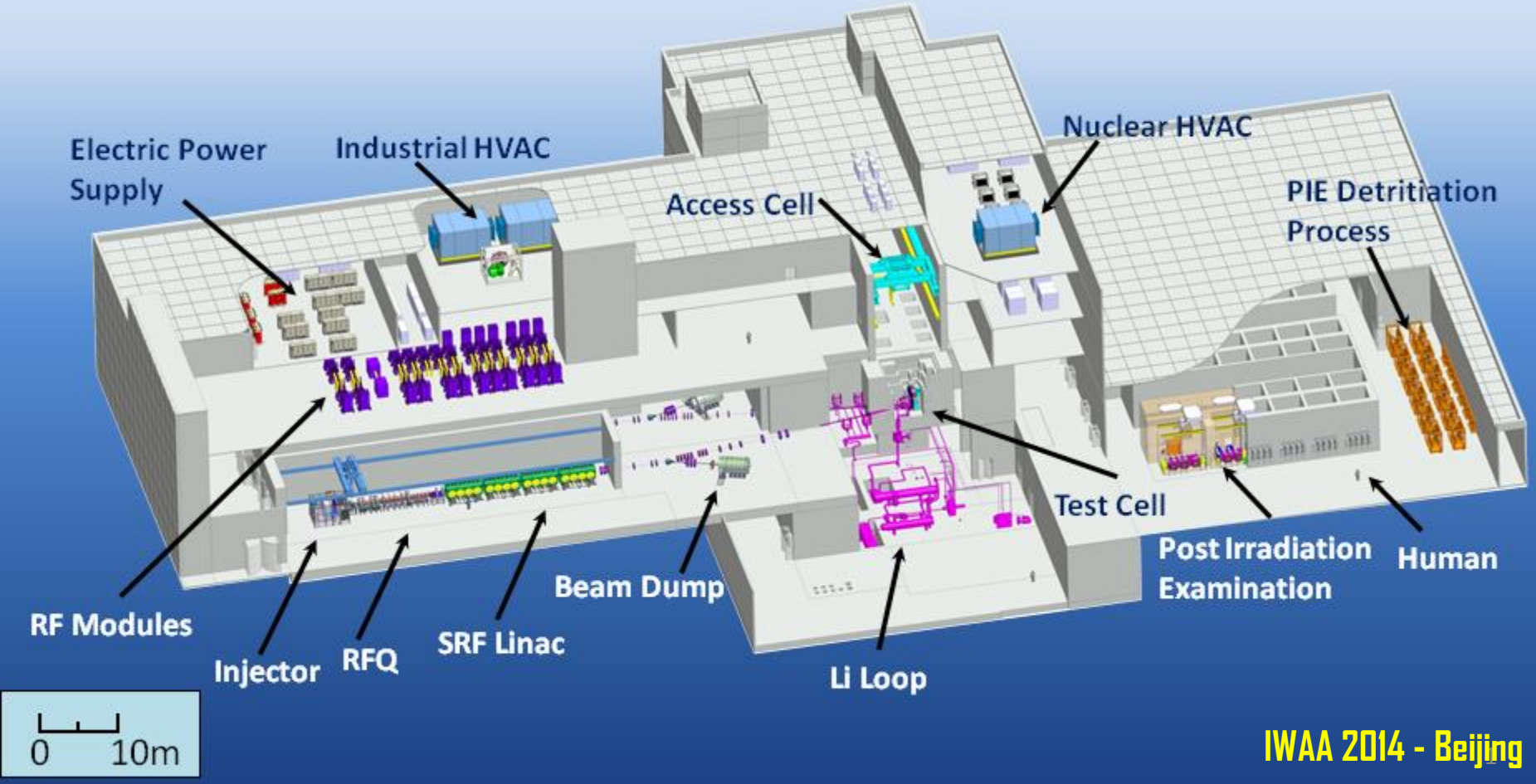
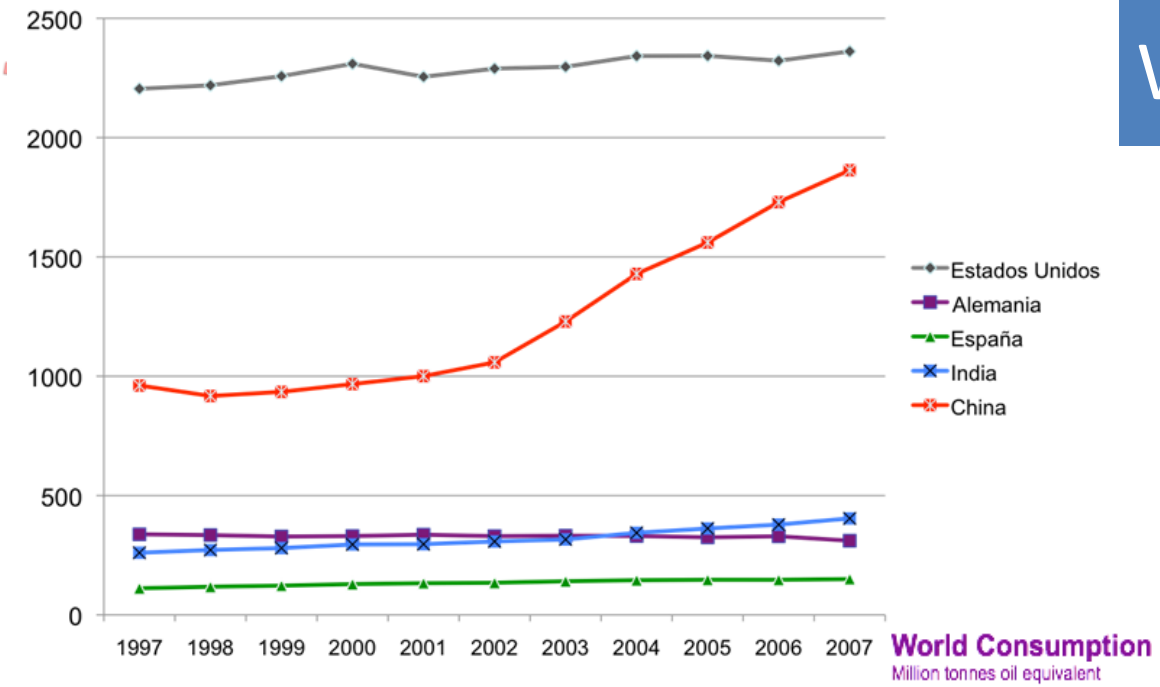
Alignment of LIPAC the Linear IFMIF Prototype Accelerator: requirements and current status

F. Scantamburlo et al.
(IFMIF/EVEDA Project Team)

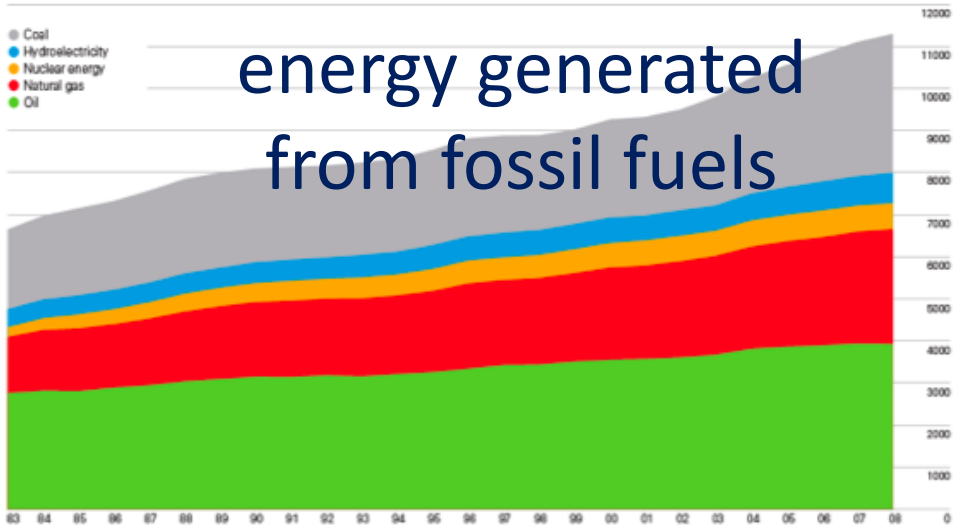


World energy scenario



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



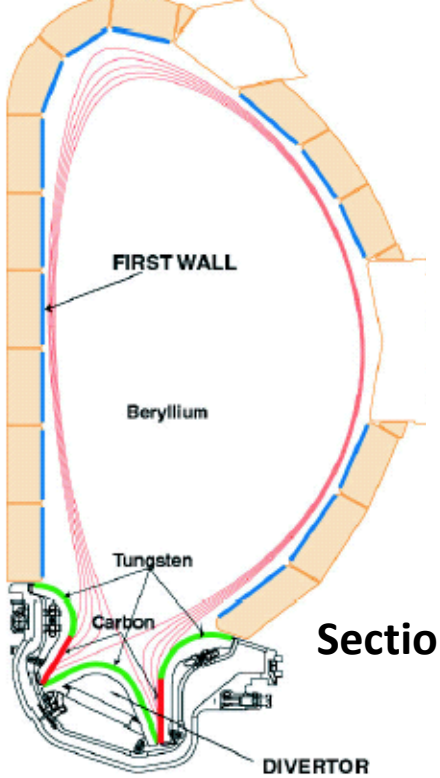
Medium term Problems

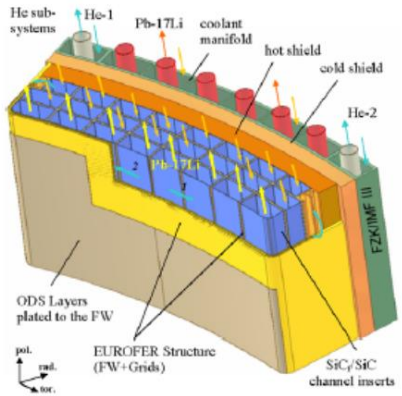
Greenhouse effect

Resources are finite

FUSION ENERGY WILL BECOME A SOLUTION

Neutrons in first wall





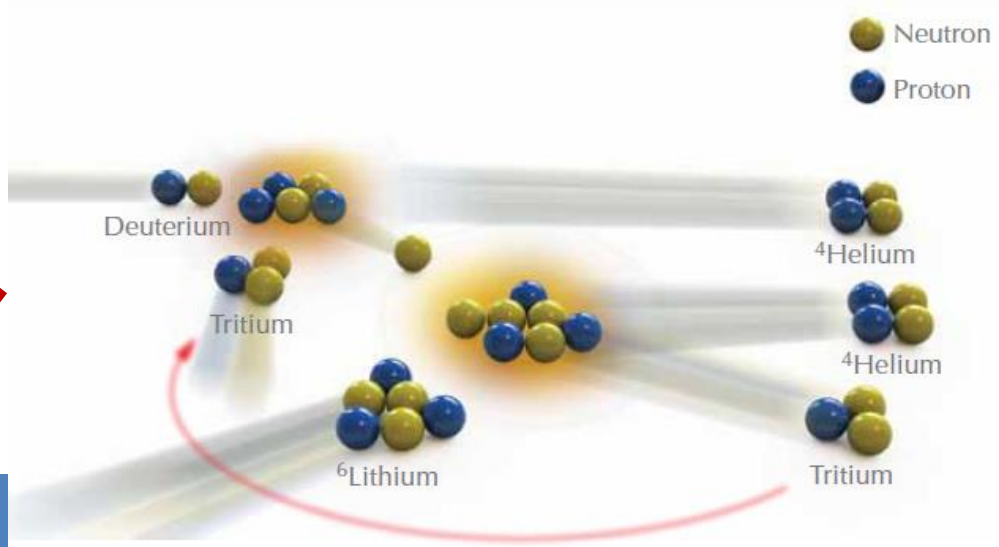
Section of Vacuum Vessel of a Tokamak

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

Transmutation energies threshold
of Fe >3 MeV yield α-particles
He induced embrittlement

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



14 MeV beyond transmutation thresholds

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

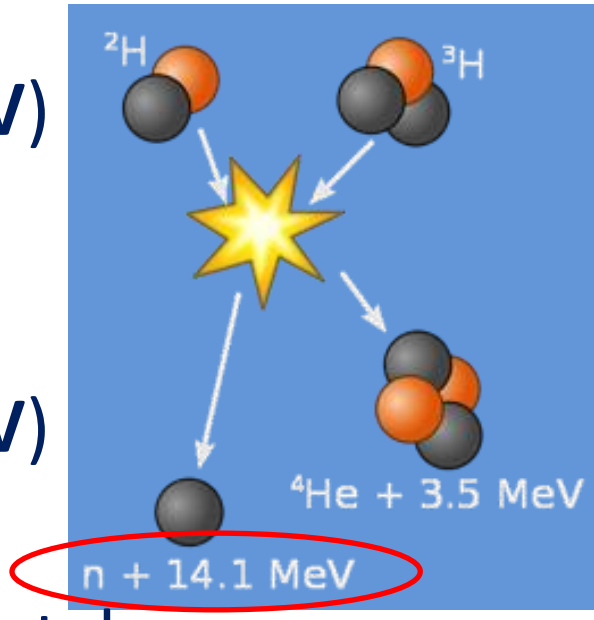
$^{56}Fe(n,\alpha)^{53}Cr$

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

and

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

(incident n threshold at **0.9 MeV**)



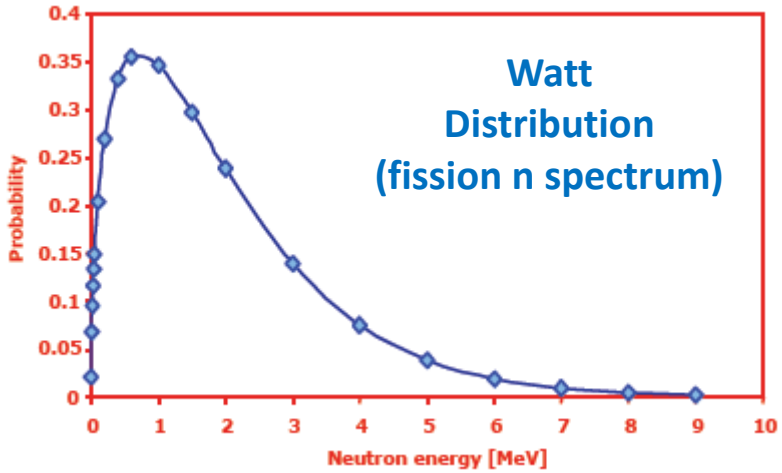
Noble gases are not dissolved in metals

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

Do we need 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 for all machines after ITER to allow

accomplishment of the design

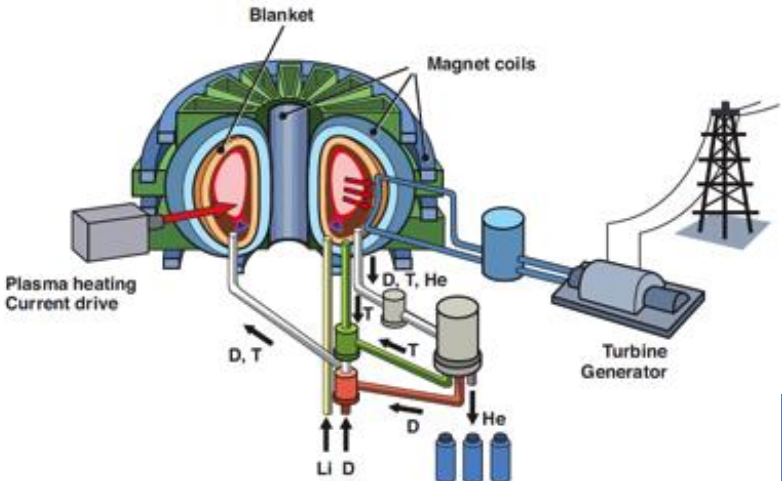
and

facility licensing

Material scientists need experimental data given the number of variables playing a primary role in materials degradation

neutrons flux
neutrons spectrum
neutrons fluence
material temperature,
thermo-mechanical history and microstructure
mechanical loading
lattice kinetics…

In ITER ~3 dpa at its end of life
In a Fusion Power plant ~30 dpa/year



IFMIF/EVEDA

A fruitful Japanese- European International collaboration (Broader Approach Agreement) with 7 countries involved with the respective main research labs in Europe and main universities in Japan

IFMIF

International Fusion Materials Irradiation Facility

EVEDA

Engineering Validation & Engineering Design Activities

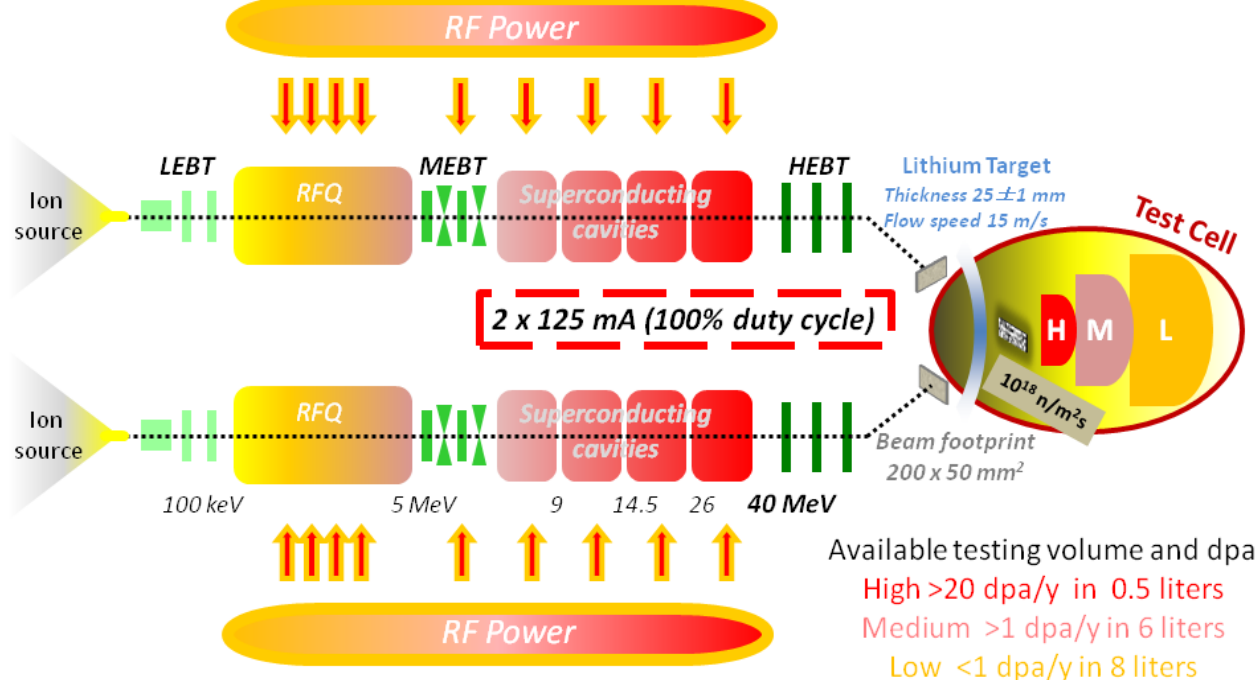
Article 1.1 of Annex A of the BA Agreement
mandates IFMIF/EVEDA

…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

Signed in February 2007

Entered into force on June 2007

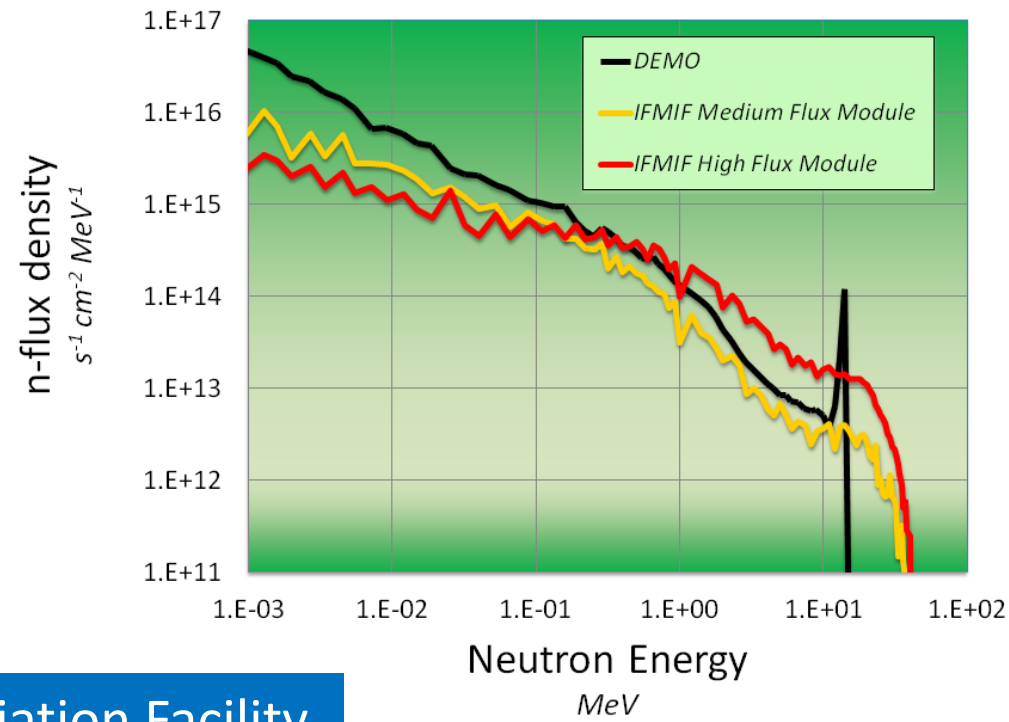
IFMIF concept



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

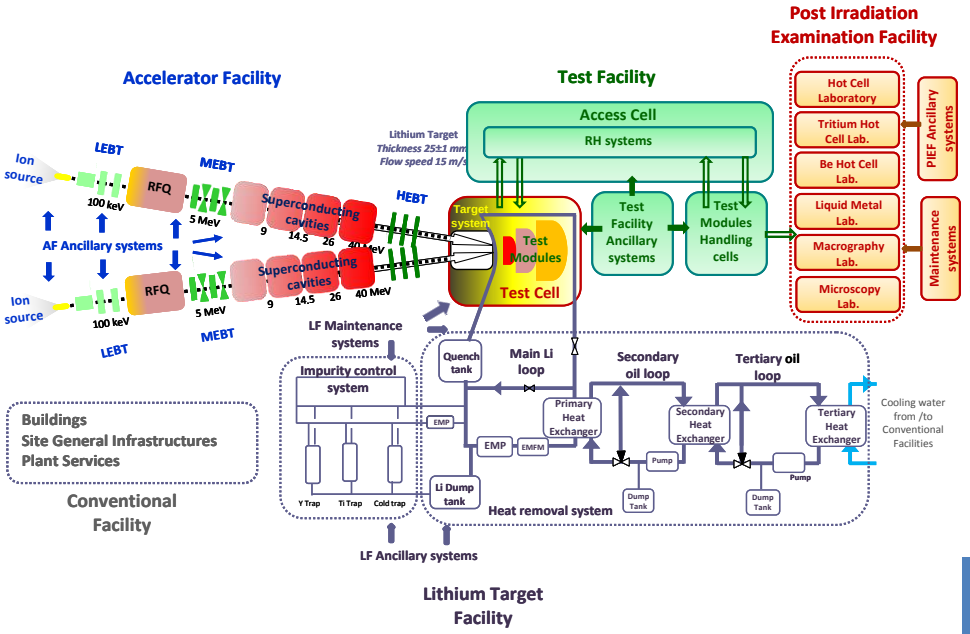


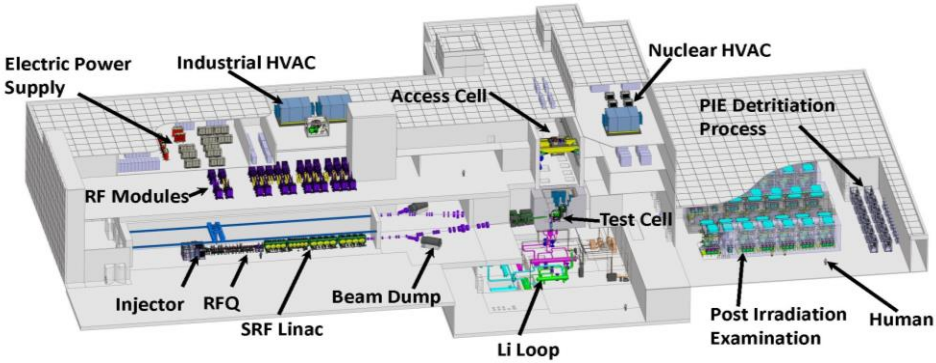
Availability of facility >80%

The Design of IFMIF is broken down in 5 facilities

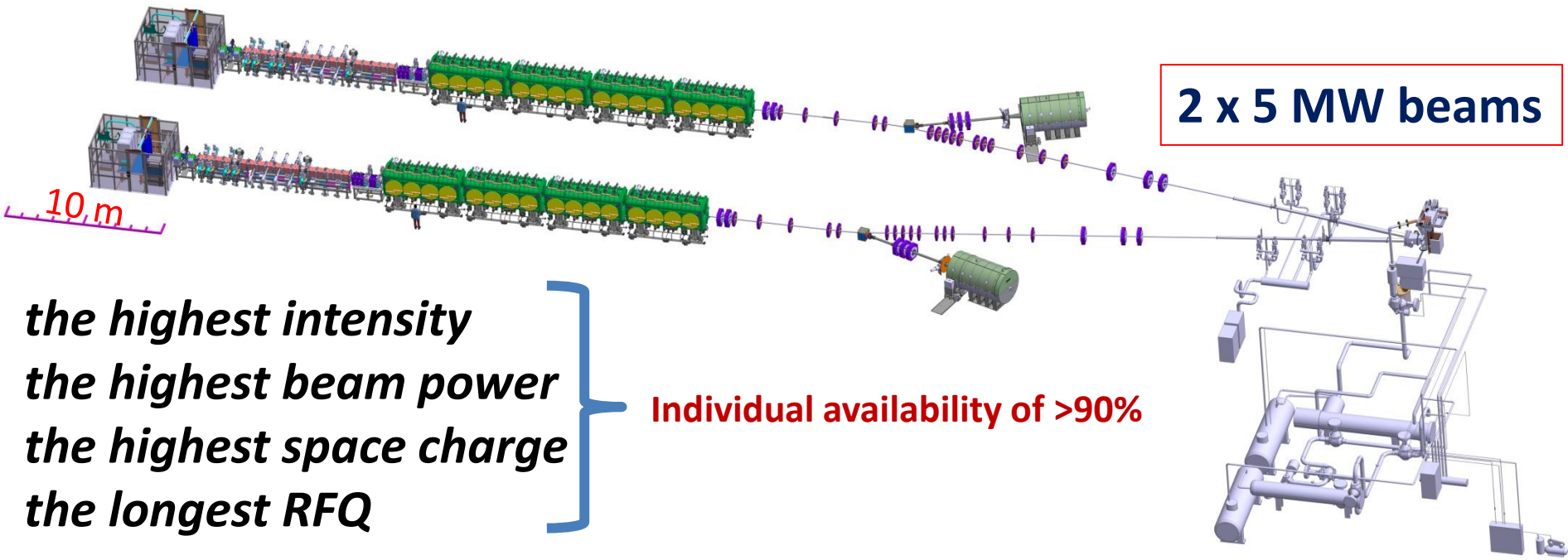
Objective of Validation activities

- Accelerator Facility
- Lithium Target Facility
- Test Facility
- Post-irradiation and Examination Facility
- Conventional Facilities





Accelerator facility of IFMIF



2 x 5 MW beams

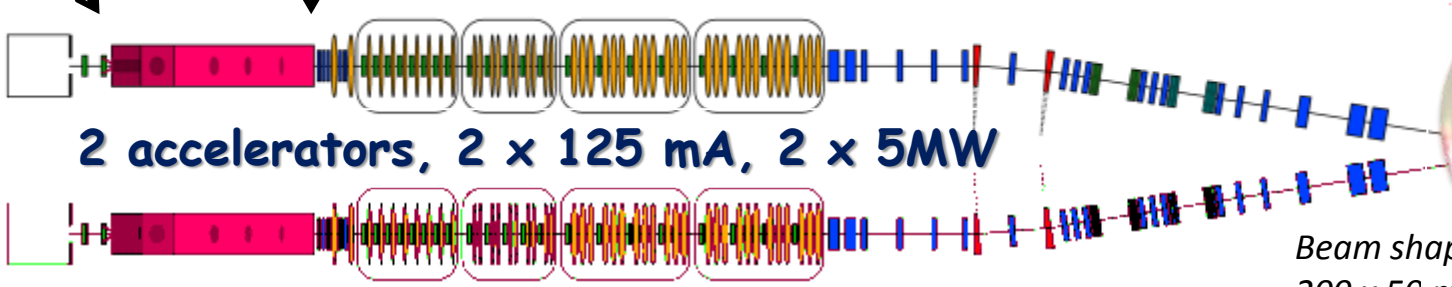
the highest intensity
the highest beam power
the highest space charge
the longest RFQ

Individual availability of >90%

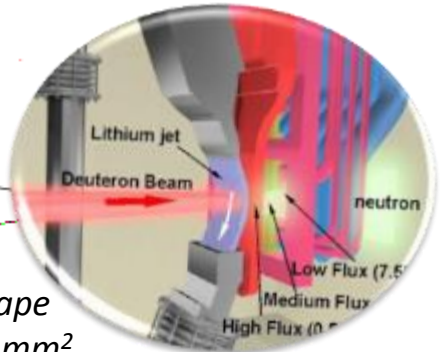
D^+ source
CW 140 mA
100 keV

RFQ
175 MHz
5 MeV

SRF Linac
HWR 175 MHz
40 MeV



2 accelerators, 2 x 125 mA, 2 x 5MW



Beam shape
200 x 50 mm²

Linear IFMIF Prototype Accelerator - LIPAc

Features of IFMIF vs LIPAc

d^+ accelerator

125 mA CW

5 MW vs 1.125 MW

Space charge issues

Low energy/high power

So are LIPAc as IFMIF

within present accelerator technology

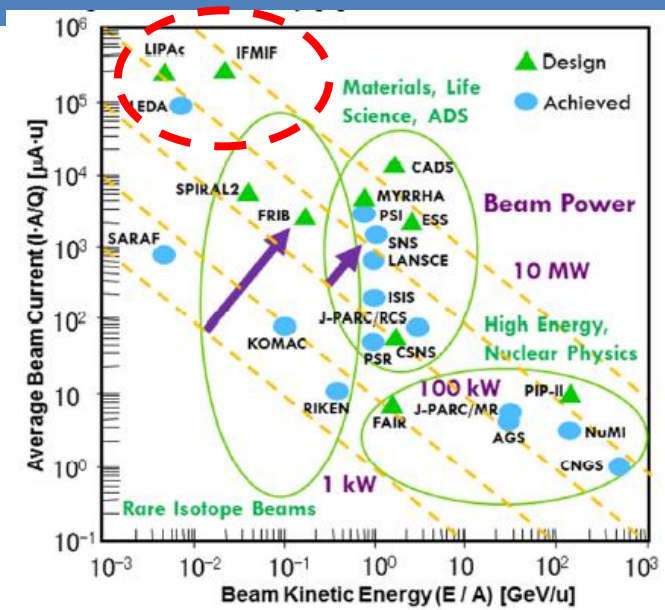
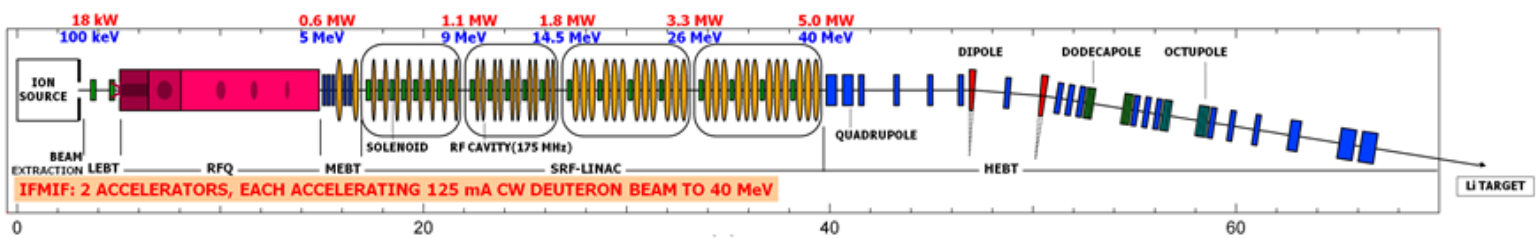


Figure 1: Hadron accelerator power frontier.

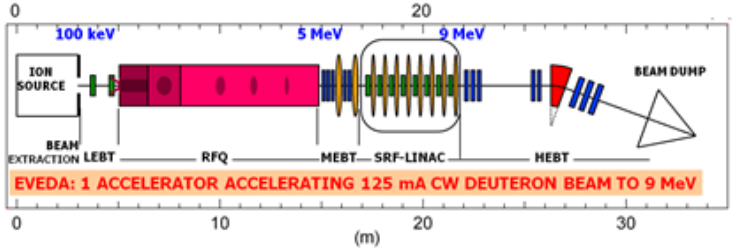
WEI, J. et al., The very high intensity future, IPAC 2014, Dresde, www.jacow.org



40 MeV

125 mA

5 MW



9 MeV

125 mA

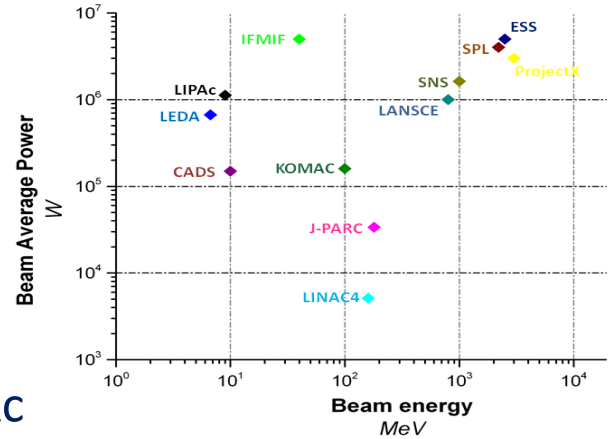
1.125 MW

NGHIEM, P.H.P. et al., *The IFMIF-EVEDA Challenges in Beam Dynamics and their Treatment*, **Nucl. Inst. Meth. 654 (2011) 63–71**

Features of LIPAc

Space charge issues are severe at low β
They cancel in relativistic regions

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



LEDA reached 100 mA CW in 1999
at 6.7 MeV protons at the exit of the RFQ
Many lessons learnt have been implemented in LIPAc

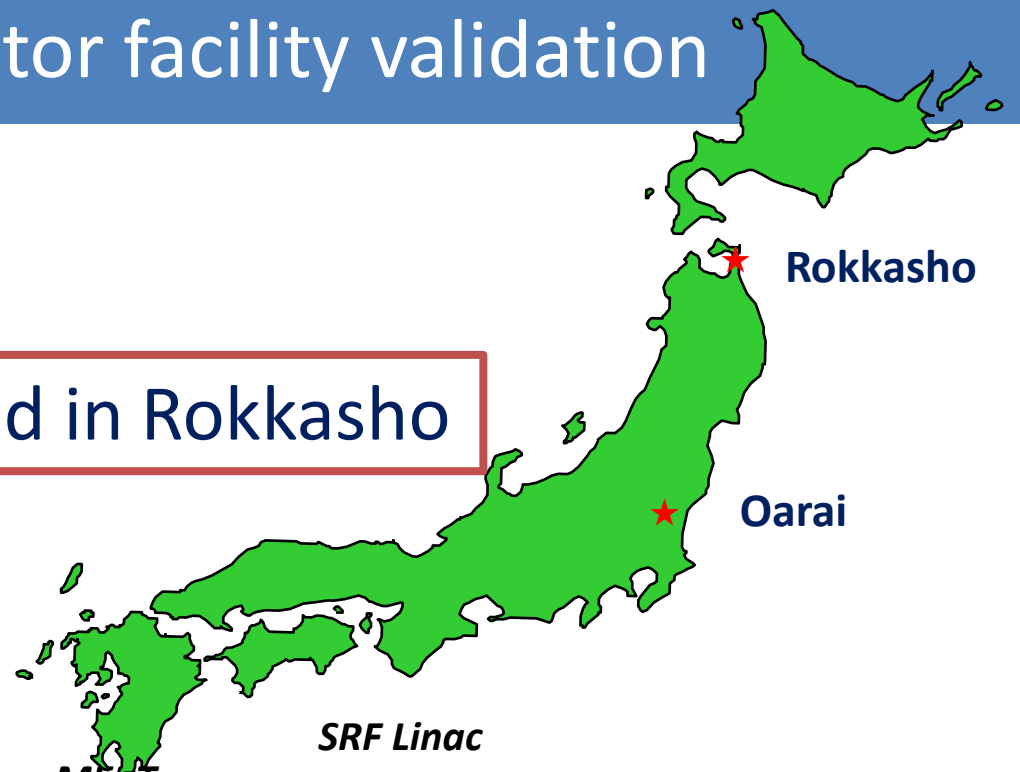
SCANTAMBURLO, F. et al., *LIPAc, the 125 mA/9 MeV CW deuteron IFMIF's prototype accelerator: what lessons have we learnt from LEDA?*, **IPAC2014**

LIPAC&IFMIF target 125 mA
at 5 MeV deuterons at the exit of the RFQ

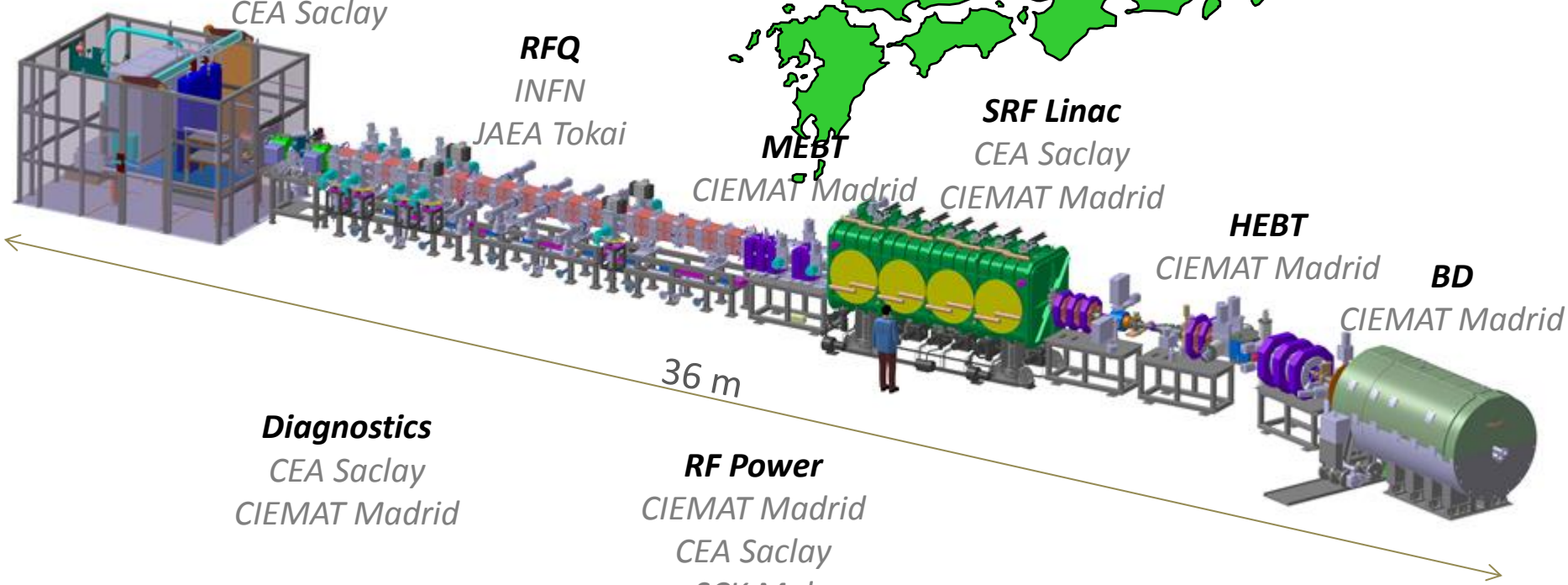
Spoke resonators have been
demonstrated in 2000s to perform for light hadrons at low β

Deuterons present high inelastic cross sections
commissioning would be difficult if done with deuterons
but protons at half energy and half intensity behave
as deuterons at nominal conditions

Accelerator facility validation



Installed and commissioned in Rokkasho



Why accurate alignment in LIPAc 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:

1. **ramp up correctly the current**,
2. **contain beam losses to 1 W/m to allow hands-on maintenances**

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

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

Beam halo physics

Beam halo is known to be a major cause
of beam loss and activation
in high current hadron Linacs

J. Wei, *The very high intensity future*, IPAC 2014

LEDA reached 100 mA at 6.7 MeV with protons
and demonstrated that beam halo is due to resonances between individual particles and beam core oscillations
through optical mismatches in transition regions

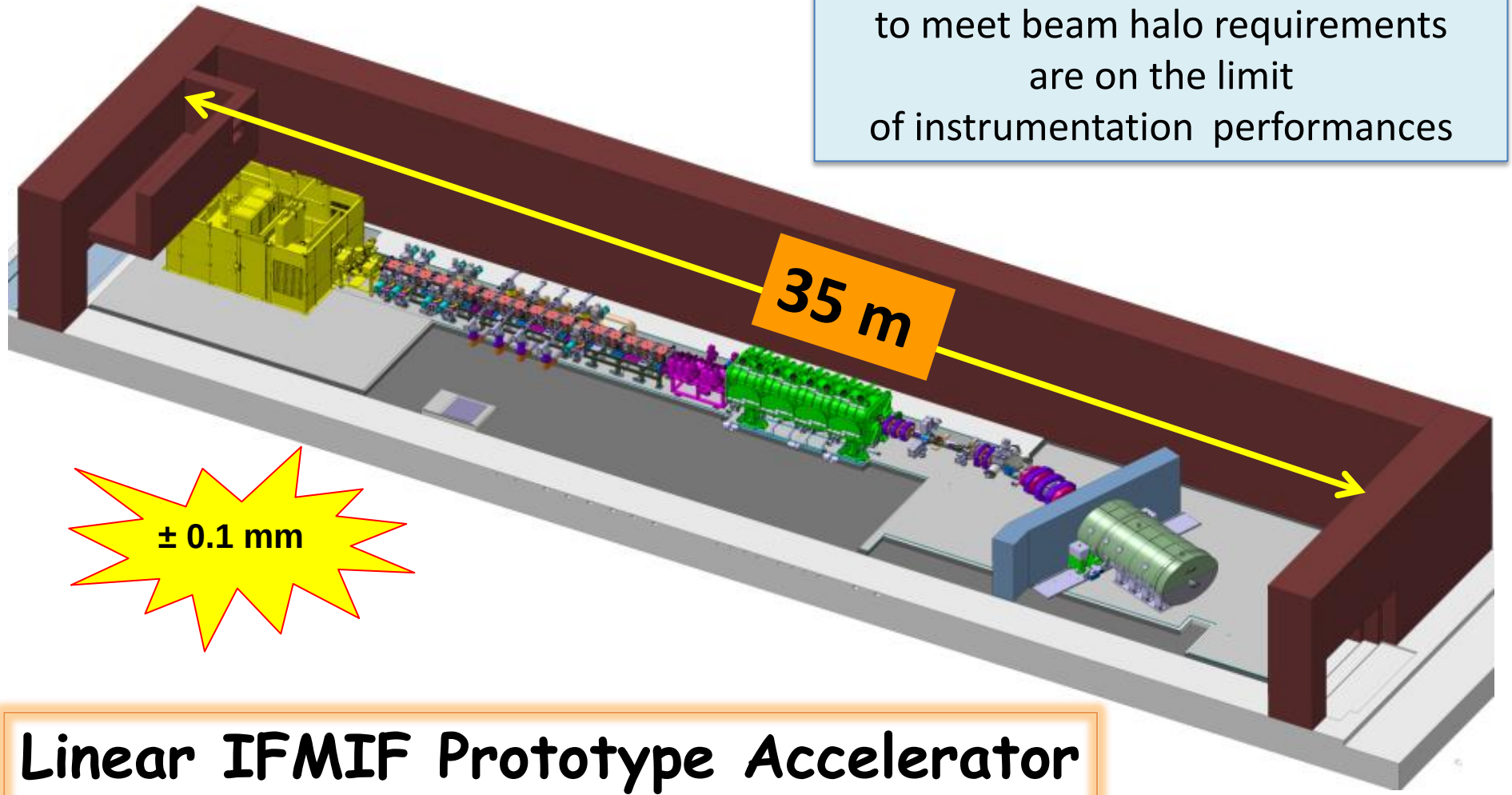
C.K. Allen et al., *Beam Halo Measurements in high current Proton Beams*, Phys. Rev. Lett. 89, 214802

Installation & commissioning key aspects
Precise alignment
Halo-matching approach

P. Nghiem et al., *The IFMIF-EVEDA Challenges in Beam Dynamics and their Treatment*, Nucl. Inst. Meth. 654 (2011) 63–71

LIPAc Alignment requirements

Accuracy assembly requirements
to meet beam halo requirements
are on the limit
of instrumentation performances



Linear IFMIF Prototype Accelerator LIPAc

Instrumentation and software

- **LEICA AT401 Laser Tracker:**
  - One of the most accurate tracker in the market (MPE angle accuracy ±(16μm+5μm/m), MPE distance accuracy: ±10 μm, level accuracy: ± 1 arcsec);
  - Portability
- **Spatial Analyzer Ultimate metrology software:**
  - Experience of F4E ITER 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

Metrology objective

According to ISO and NIST, GUM, the measurements must be accompanied with their uncertainty

To asses device position tolerance range +/- 0.1 mm in the assembly hall

ITER metrology handbook:
Target measuring uncertainty
< 0.02 mm in the assembly hall

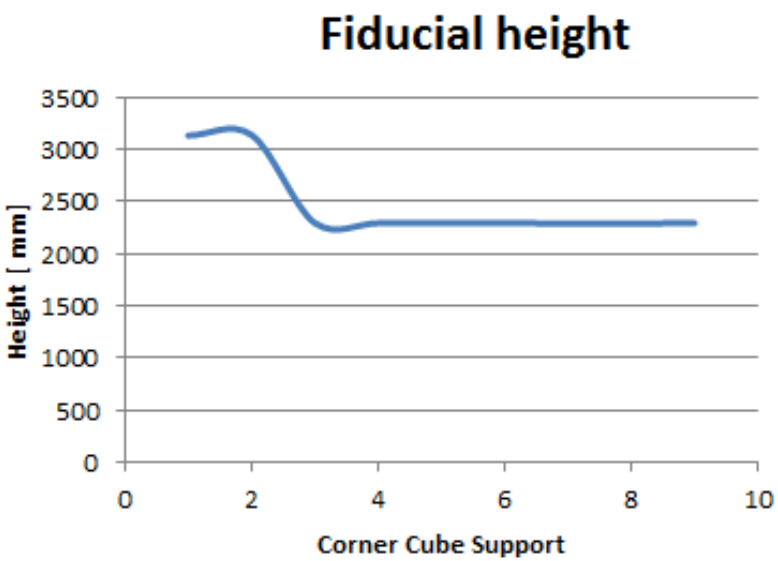
Former original existing Network

Primary base points : Coordinates in the accelerator building

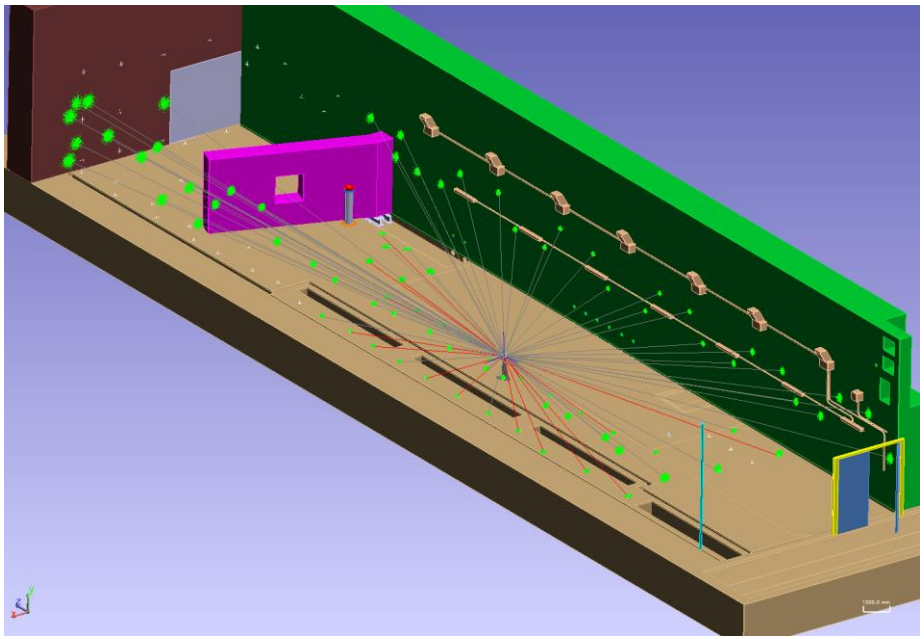
ID	NAME	measured value			Notes
		Z [mm]	X [mm]	Y [mm]	
101	K101	-4884.34	2987.73	3131.45	
102	K102	3407.64	2989.01	3138.56	
103	K103	10464.84	2965.69	3137.37	
104	K104	17968.41	2976.82	3136.35	
105	K105	25093.36	2983.87	3136.11	
106	K106	32449.04	2972.88	2292.50	
151	K151	-4594.26	-4937.61	2291.30	
152	K152	2968.04	-4945.70	2290.42	
153	K153	10373.55	-4951.82	2290.53	
154	K154	18391.95	-4935.15	2288.82	
155	K155	25683.10	-4937.28	2288.04	
156	K156	32212.75	-4938.58	2290.37	
201	D201	-4665.50	4573.69	2594.08	

8 available targets

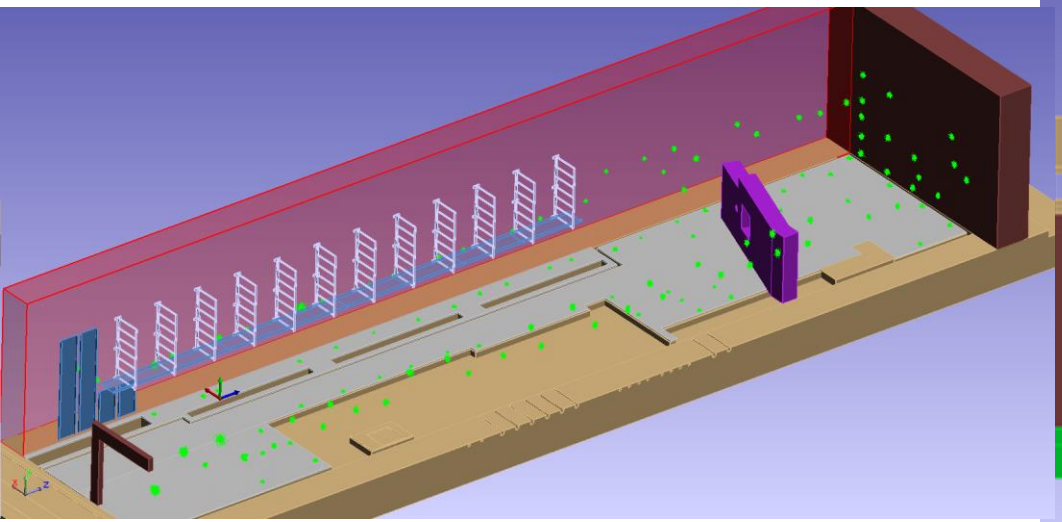
According to Spatial Analyzer Simulation made by F4E
the uncertainty of locating the tracker would be
0.13 mm
which was not compatible
with the tolerance range to be assessed
+/- 0.1 mm

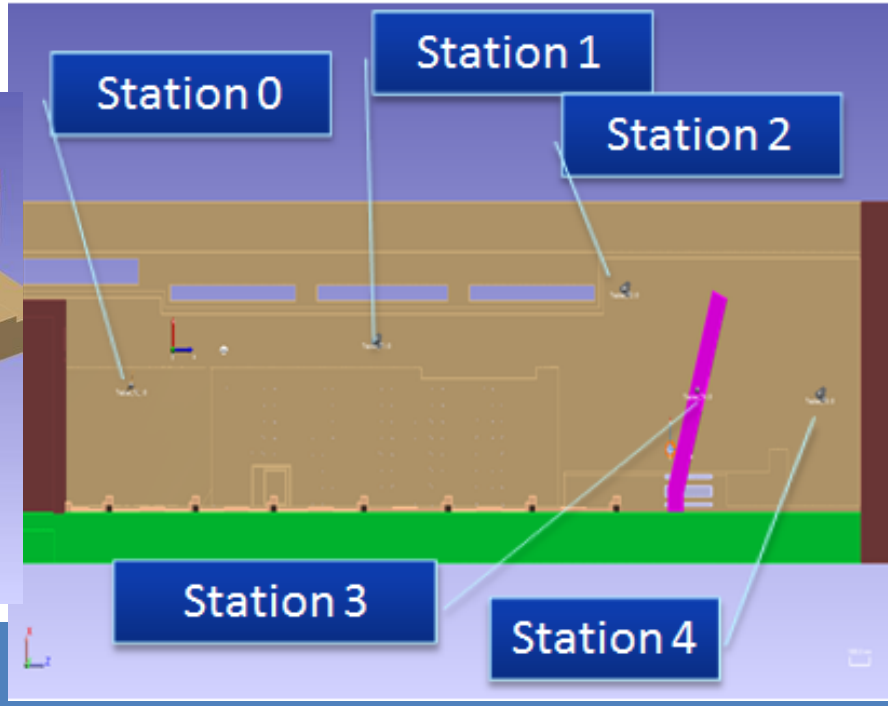


New network design - simulations



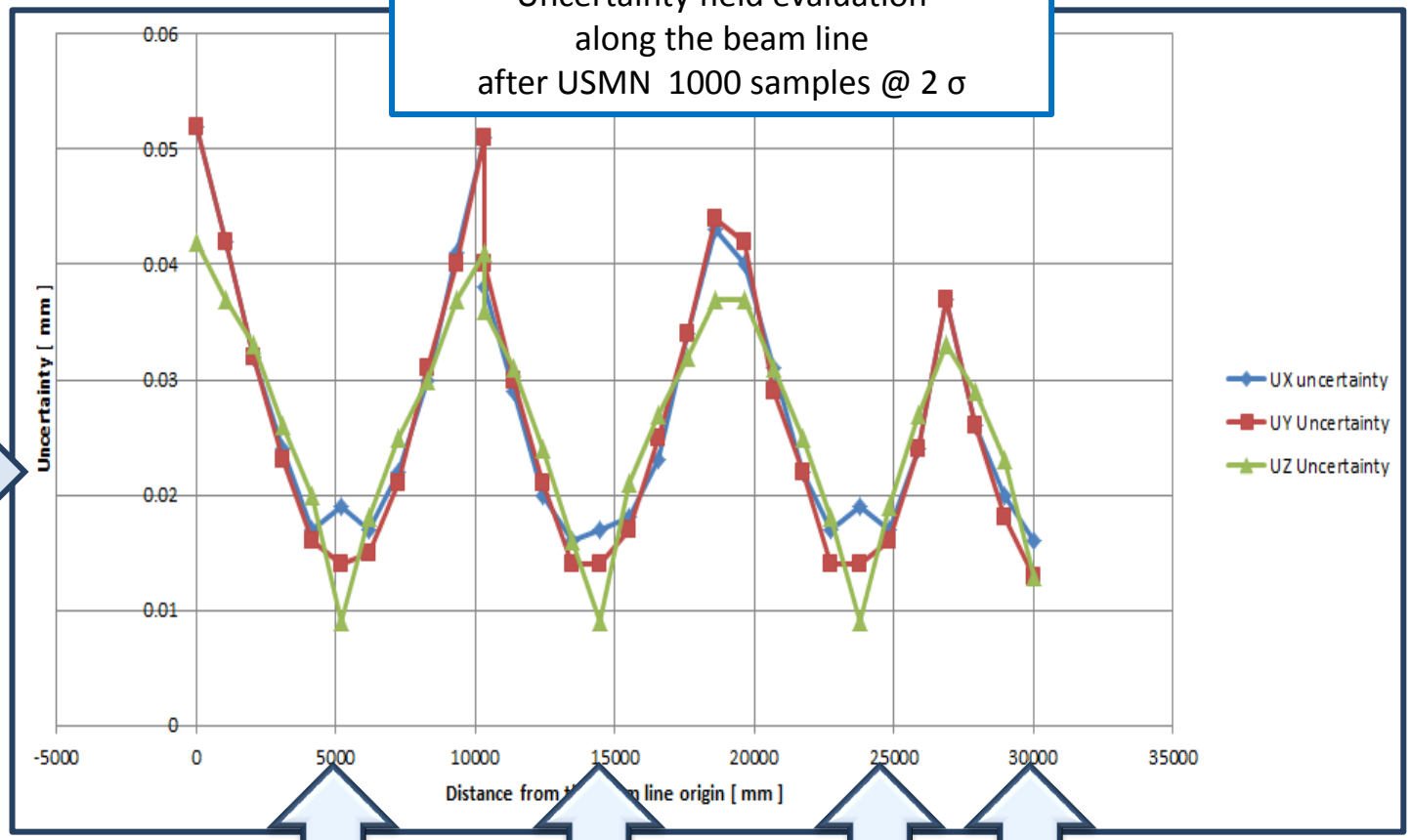
Placement of 120 new fiducials surveyed 5 times by 5 station will limit measurement uncertainties **<0.02 mm** with the laser tracker Leica AT401 suitably located in the accelerator hall during all future alignment tasks





New network design - simulations

Uncertainty field evaluation
along the beam line
after USMN 1000 samples @ 2 σ

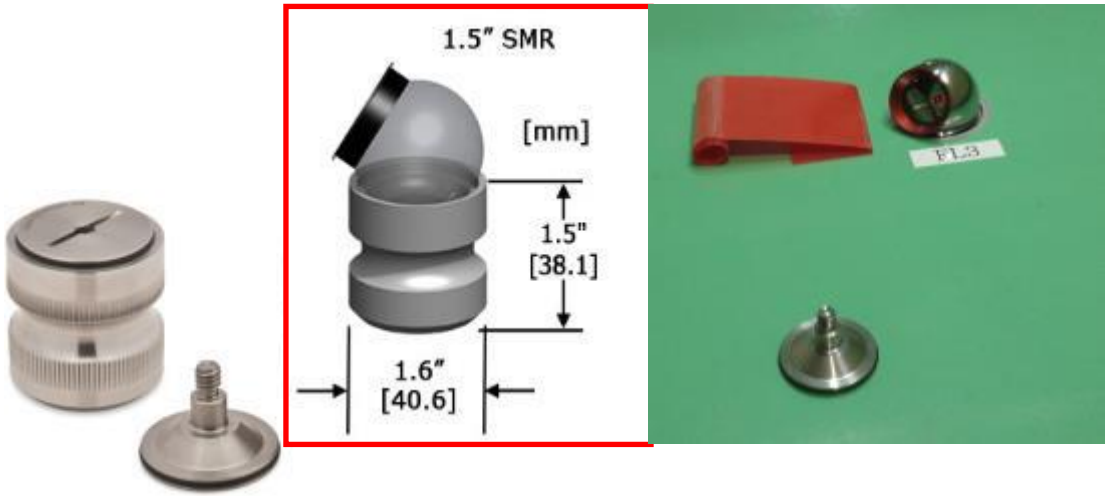


Target uncertainty

Laser Tracker stations

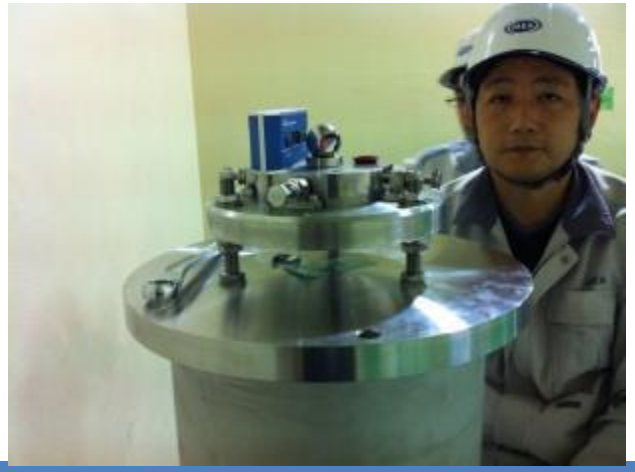
Upgrade of the alignment network - survey

50 Floor nests

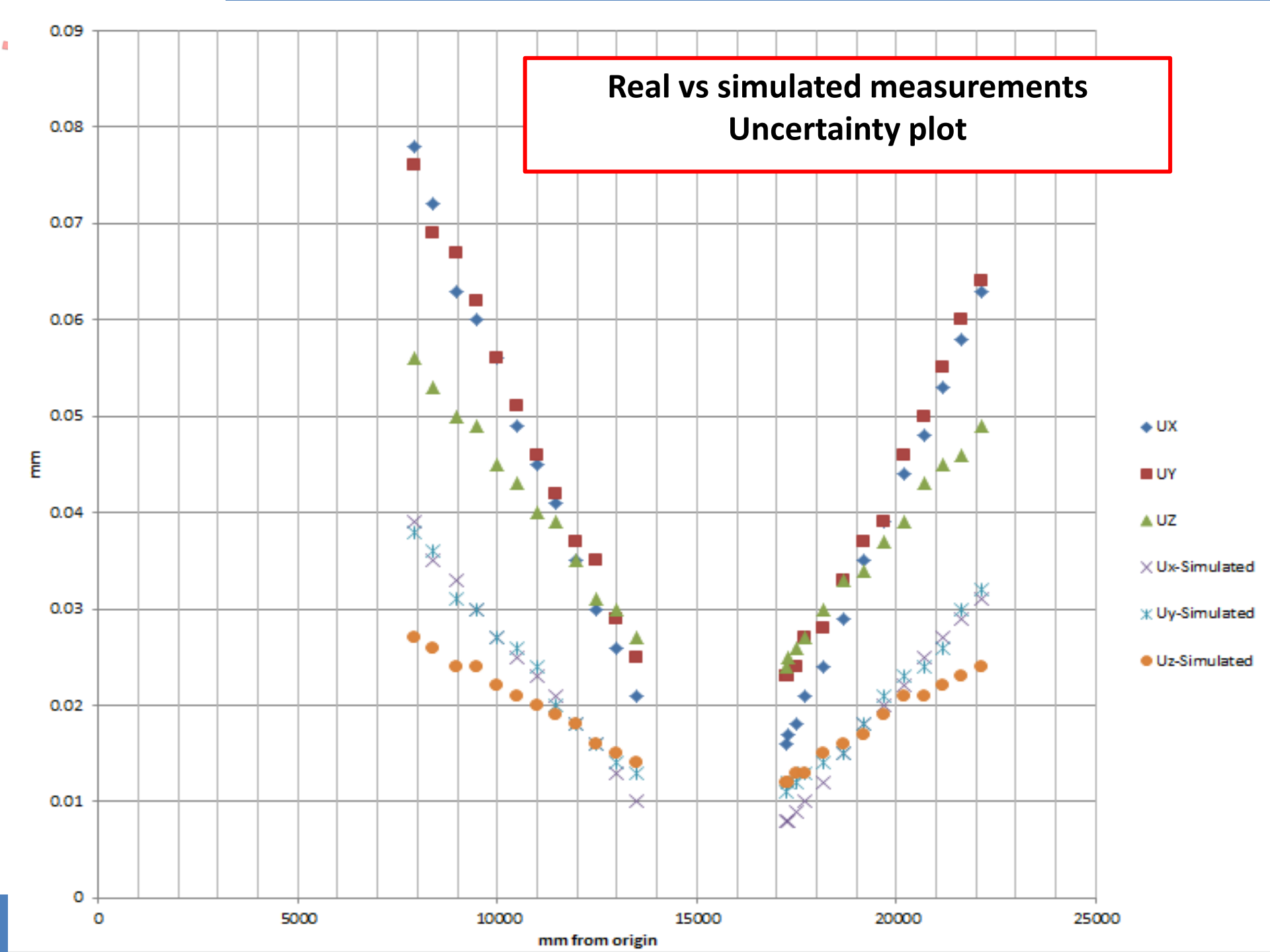


69 Wall supports ad hoc machined

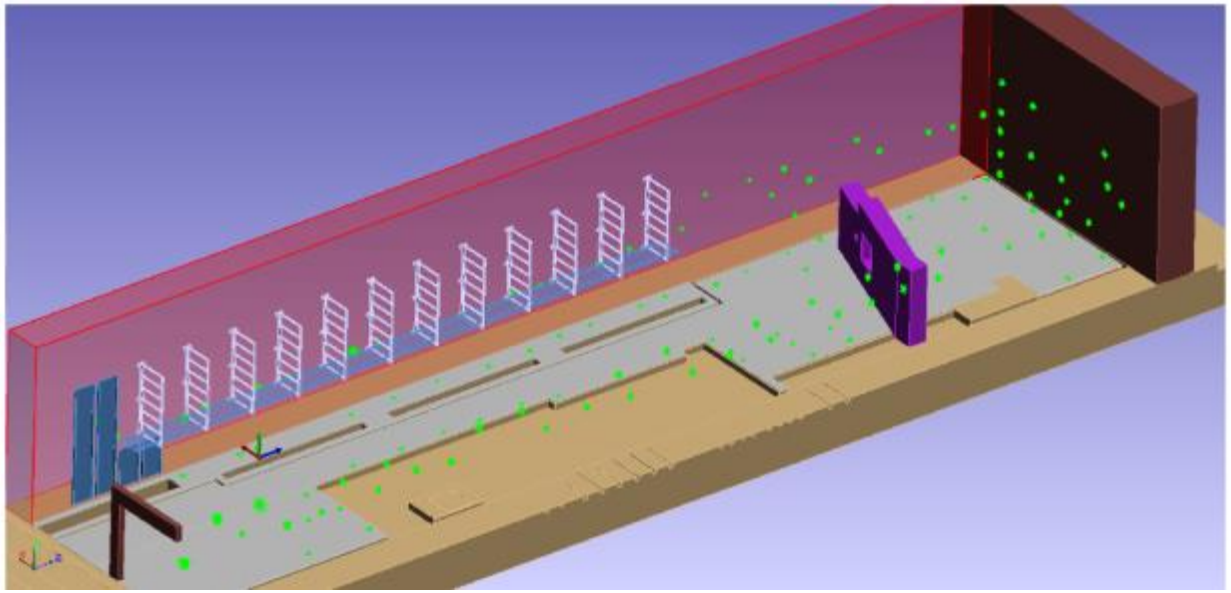
1 datum Pillar with Micro-adjustable screws



Leica AT 401

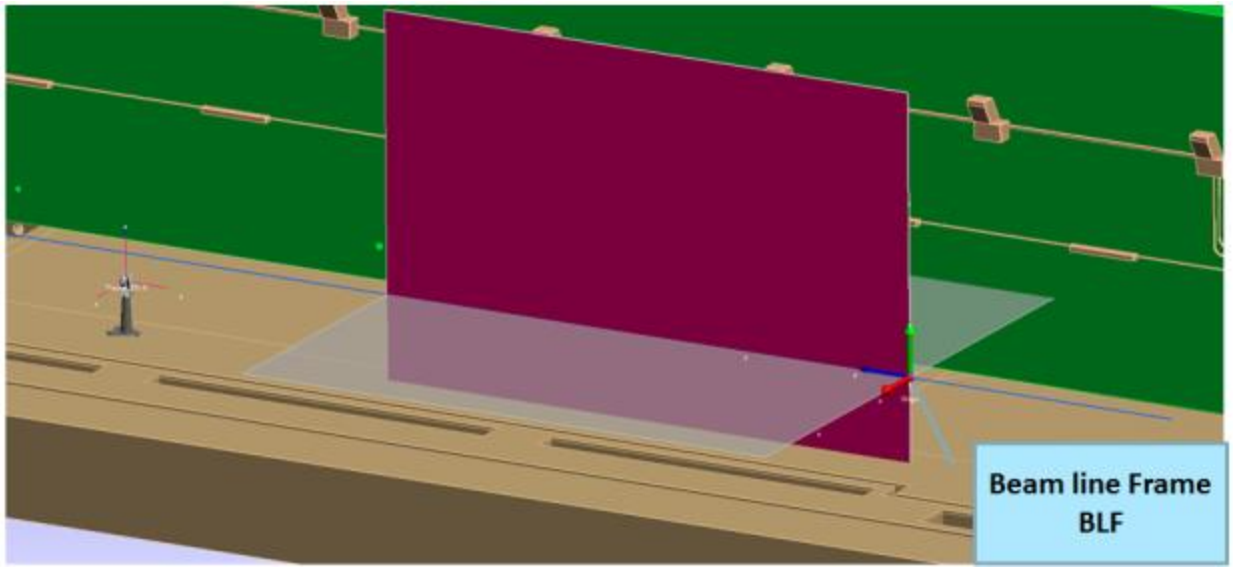

Real vs simulated measurements
Uncertainty plot
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
mm
0
5000
10000
15000
20000
25000
mm from origin
UX
UY
UZ
Ux-Simulated
Uy-Simulated
Uz-Simulated

Beam Line Coordinate Frame (BLF)



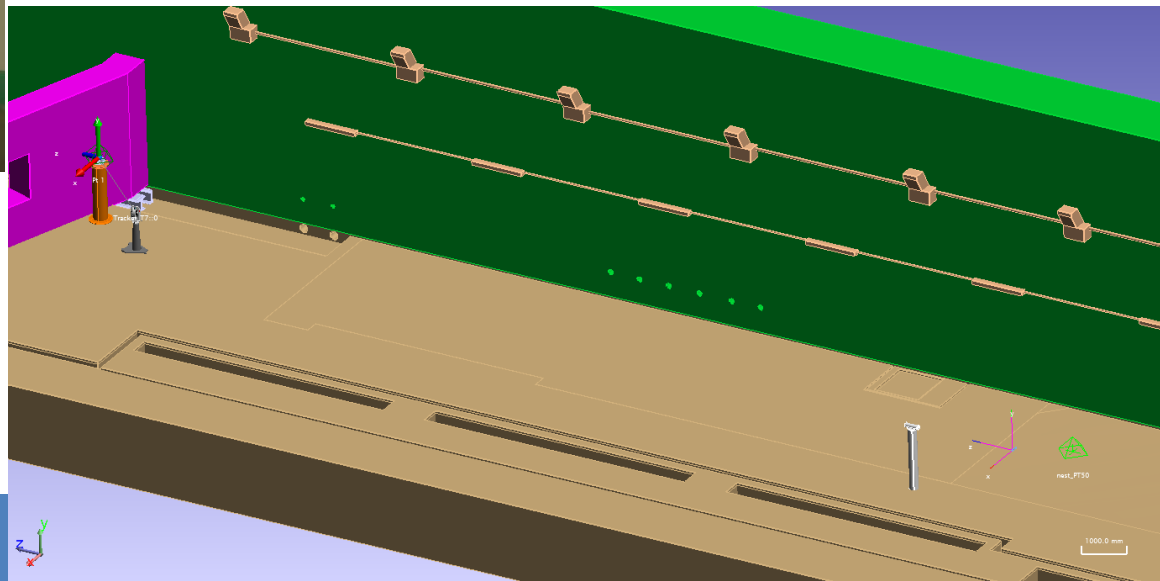
The BLF is intrinsically defined by the coordinate of the 130 network fiducials

Horizontality has been improved using the AT401 levelling capabilities



Global Coordinate Frame (GCF)

Since the beam line frame is not materialized
we retained worth to materialize a coordinate frame
in the accelerator vault to make quick checks
of the impact on the alignment of exceptional events (i.e. an earthquake)
The origin is placed on a particular floor fiducial.
The position of a reference on a pillar has been adjusted
to obtain an axis parallel to the beam line



Effect of thermal expansion of the building

Rokkasho enjoys hard winters and hot summers

we established a simple procedure to study and eventually compensate

the effect of thermal expansion of the building:

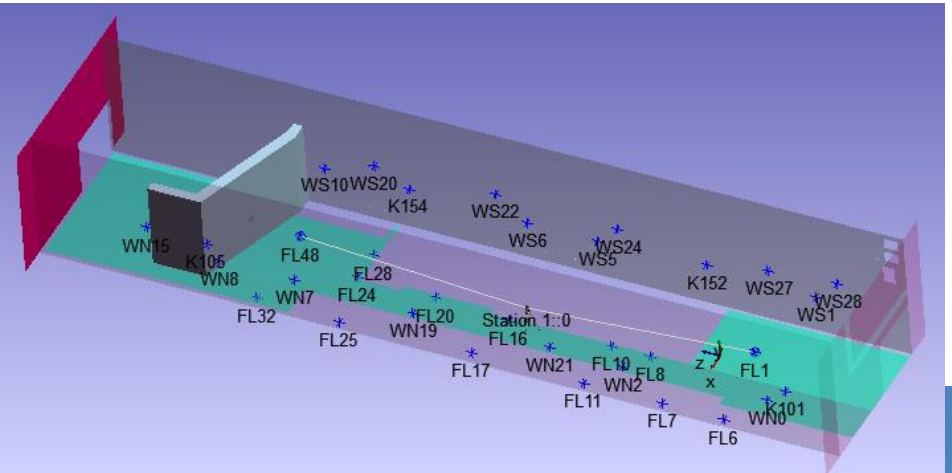
Weekly measurement by LT the distance between two particular points on the floor almost aligned with the beam line

Weekly measurement of the air temperature in the vault and external temperature

Weekly measurement thermometer the temperature of the floor on 30 points evenly spread

Monitoring will continue on a period including at least one winter and one summer

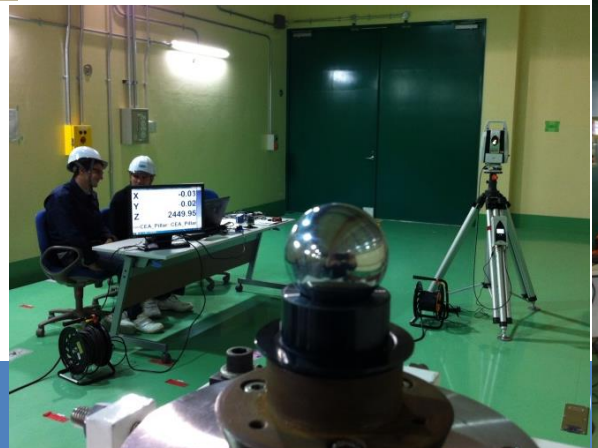
Date	FL1-FL48 Dist [mm]						Scale bar			T air [°C]
	USMN	Measured	Delta [mm]	Scale factro to USMN	alfa [m/°C]	T floor Average [°C]	Temp. [°C]	Nom. Dist. [mm]	Meas. Dist. [mm]	
2014.05.02	23562.744	23562.107	-0.637	0.999973		13.2	13	800.001	800.005	14.3
2014.05.08	23562.744	23562.184	-0.56	0.999976	5.1598E-06	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



Injector alignment

The injector and the LEBT have been successfully assembled and aligned with TH system in May 2014

Differentely from the other components which will be fiducialized in Europe before delivery in Rokkasho the Injector and the LEBT were fiducialized by AT401 after TH alignment.



Injector alignment

With good success!

Max uncertainty

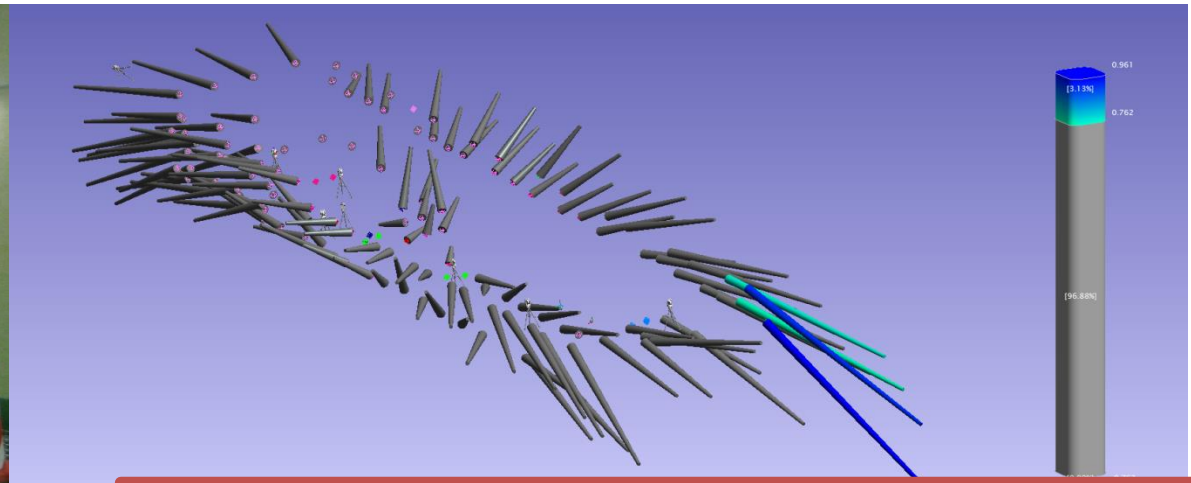
0.04 mm

F: USMN::WORLD)

FL50	-2427.595	-1503.430	304.428	0.015	0.015	0.017	0.027
Frame Dia box 1	-347.070	-379.648	309.027	0.028	0.038	0.032	0.057
Frame Dia box 2	-81.345	-380.735	815.776	0.027	0.036	0.030	0.055
Inj_Src1	-229.882	-117.925	-2212.964	0.027	0.045	0.033	0.062
Inj Src2	-177.007	-187.830	-2146.642	0.029	0.048	0.034	0.066
Inj Src3	-232.312	-113.663	-2034.267	0.024	0.042	0.031	0.058
Inj Src4	-206.530	1.505	-2116.101	0.027	0.044	0.034	0.062
Inj Src5	-141.760	217.923	-2058.784	0.029	0.050	0.040	0.070
Inj_Src6	-15.121	260.072	-2233.545	0.029	0.049	0.038	0.069
Inj Src7	-161.257	120.946	-2303.333	0.030	0.050	0.036	0.069
K101	2987.761	1631.029	-4884.486	0.000	0.000	0.000	0.000
K105	2984.063	1635.880	25093.082	0.000	0.000	0.000	0.000
K106	2973.337	791.959	32448.862	0.000	0.000	0.000	0.000
K152	-4945.820	789.854	2967.298	0.000	0.000	0.000	0.000
K153	-4952.003	789.954	10373.014	0.000	0.000	0.000	0.000
K154	-4935.326	788.243	18391.591	0.000	0.000	0.000	0.000
K155	-4937.165	787.262	25682.759	0.000	0.000	0.000	0.000
K156	-4938.421	789.581	32212.642	0.000	0.000	0.000	0.000
PP	-2427.574	0.047	24586.435	0.000	0.000	0.000	0.000
SB1 1	-3203.779	-1423.502	734.153	0.028	0.031	0.027	0.050
SB1 2	-3724.336	-1424.217	126.663	0.020	0.024	0.021	0.038
SB2 1	-3203.786	-1423.547	734.137	0.038	0.041	0.036	0.067
SB2 2	-3724.346	-1424.246	126.641	0.034	0.040	0.035	0.063
Sol1_1	-211.091	83.624	-1115.449	0.020	0.037	0.030	0.052
Sol1 4	0.121	323.908	-1409.148	0.021	0.039	0.034	0.056
Sol2 1	-225.953	21.296	-575.032	0.019	0.034	0.032	0.051
Sol2 5	1.477	323.397	-481.435	0.020	0.037	0.033	0.053
Sol2 6	1.217	324.090	-241.432	0.021	0.040	0.037	0.059
Vac_Cham1	-191.536	383.045	-941.480	0.019	0.036	0.032	0.052

Redefinition of the network

An update of the network has been performed in August 2014
movements of the building
not related to the thermal expansion
did not allow anymore locating the instrument within the target uncertainty
RMS< 0.025 mm



A deviation of 0.05 mm in transversal (X axis) and vertical (Y axis)
of the beam line has been registered

Conclusions

- SA software with USMN has been a key factor for the definition of the network in the accelerator hall
- Simulation tool demonstrated to be very effective to plan, organize and optimize measurement campaigns
- Thermal expansion study is ongoing
- Efficient alignment actions have been in place and we are ready for the alignment of the components coming in the coming months

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Thank you for your attention