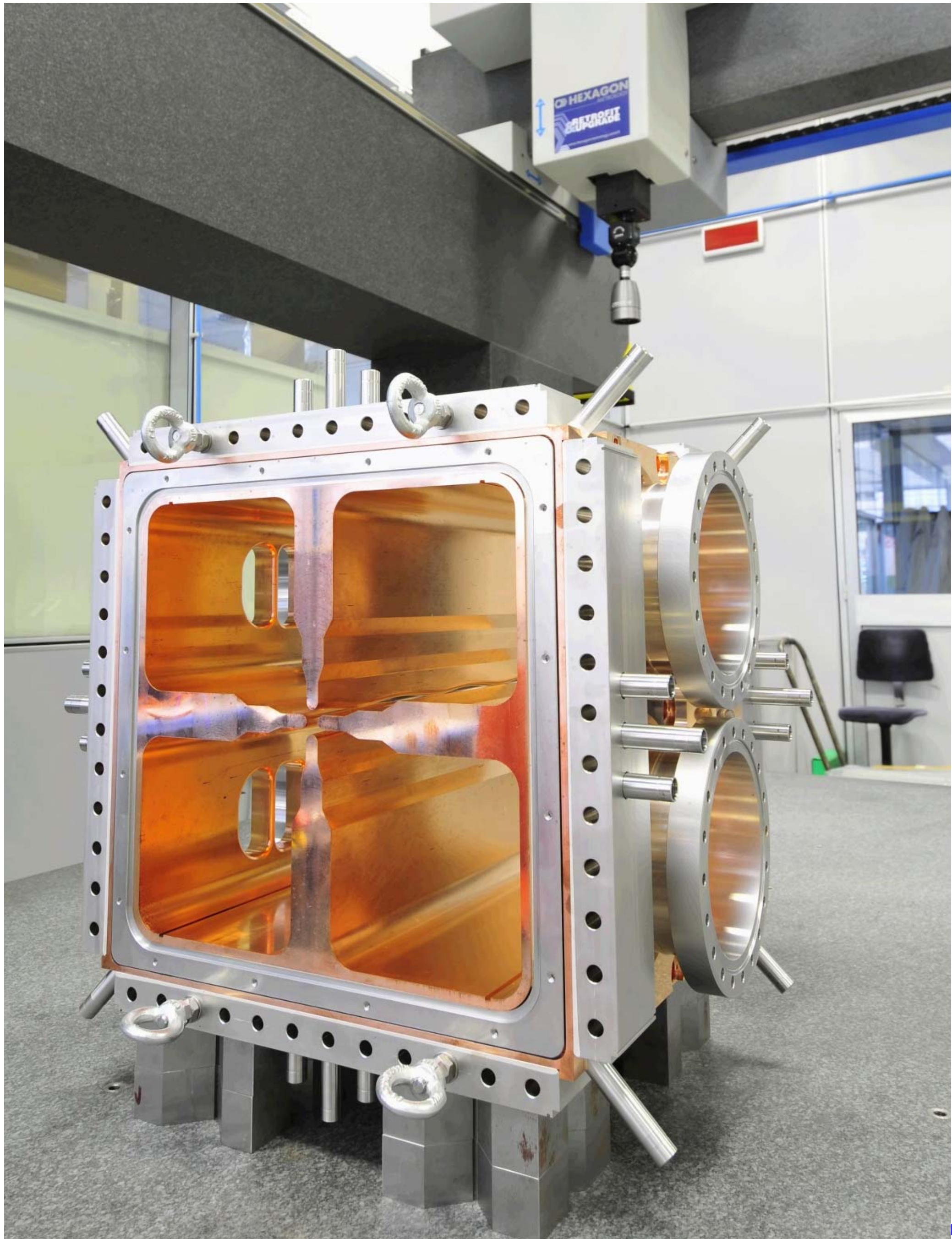
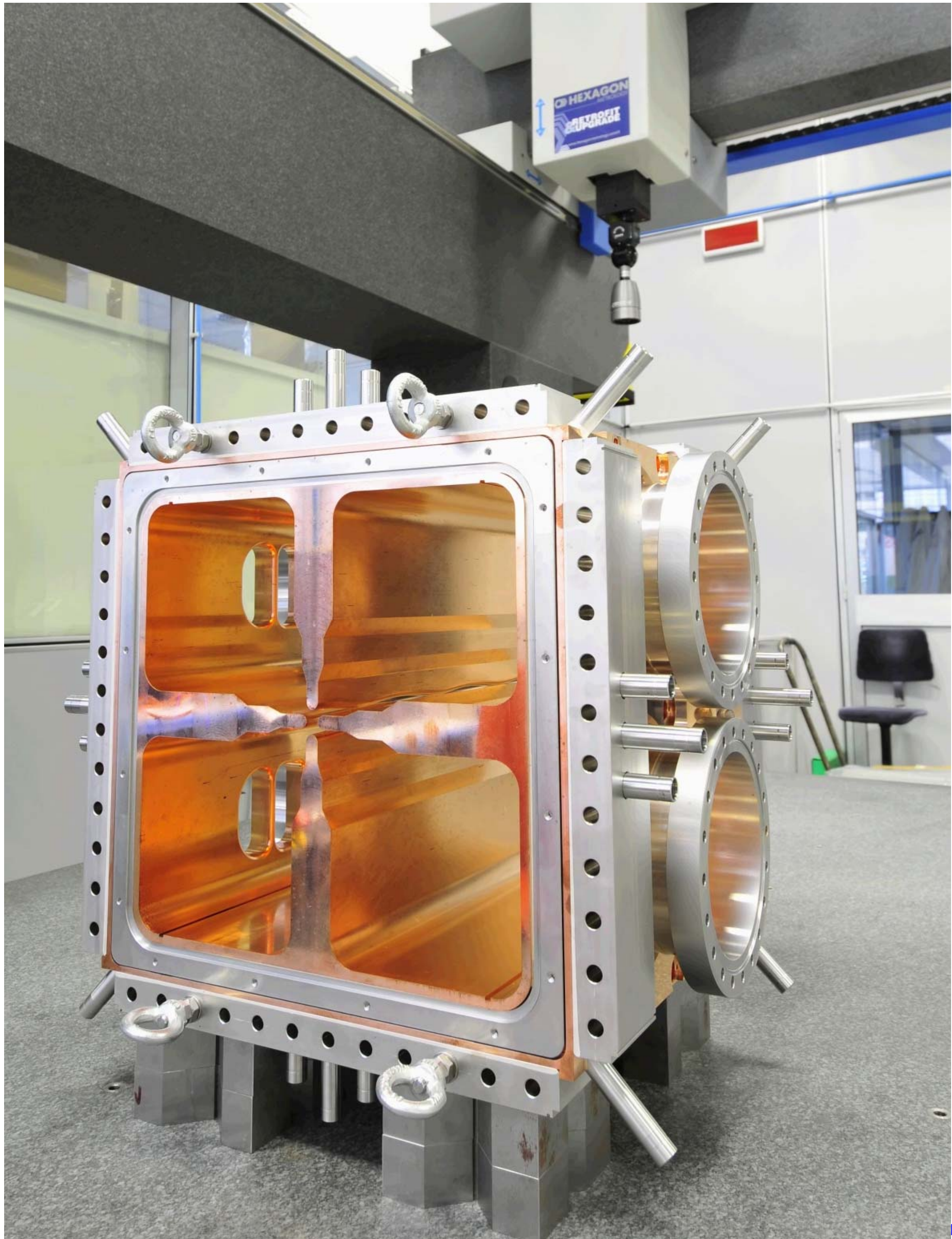


IFMIF: the INFN contribution

International Fusion Materials Irradiation Facility

Andrea Pisent

INFN Laboratori Nazionali di Legnaro

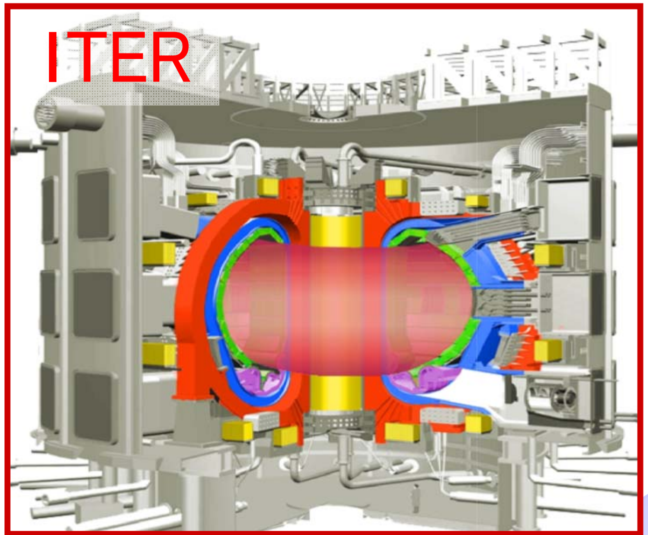


outline

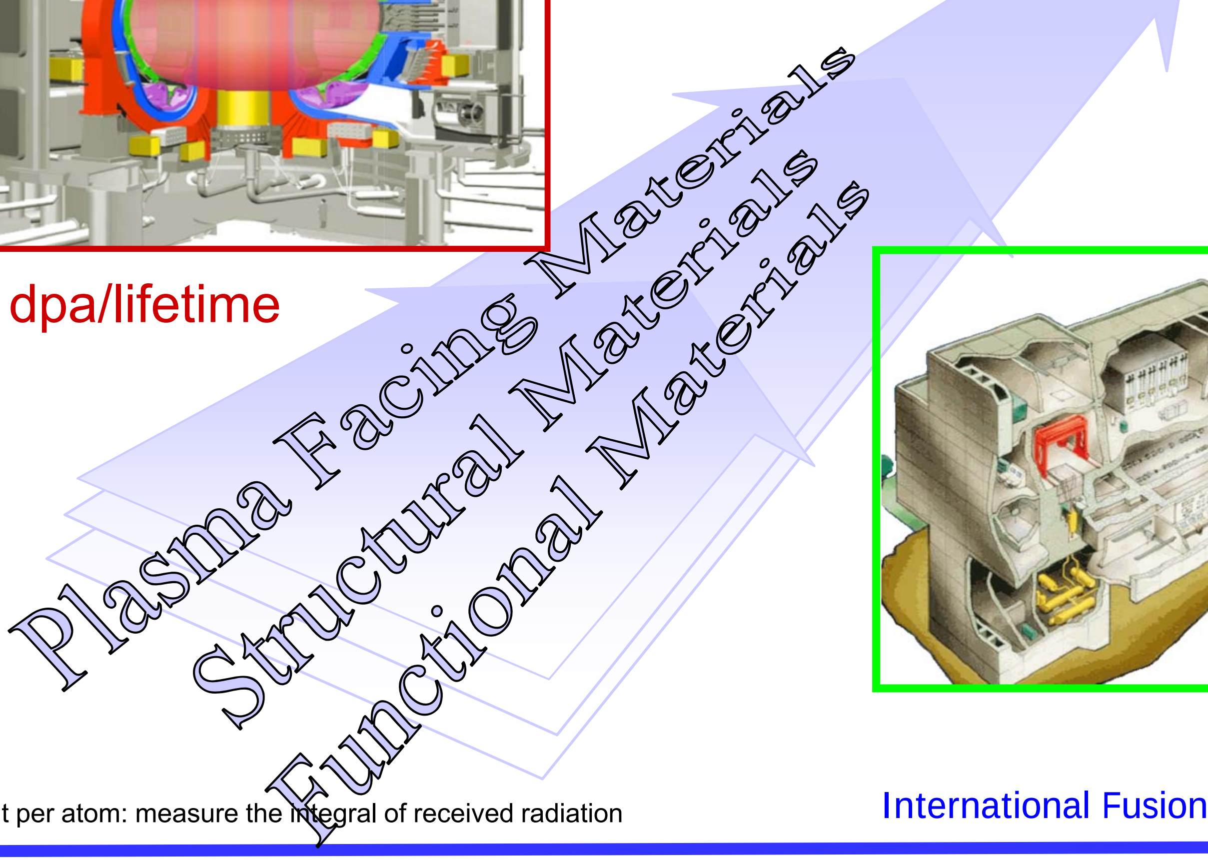
- IFMIF in the contest of Nuclear Fusion Plans
- IFMIF EVEDA project in construction
- INFN contribution with the Radio Frequency Quadrupole
- Beam operation issues for a high intensity machine
- Beam commissioning plans
- Conclusions

International Road Map

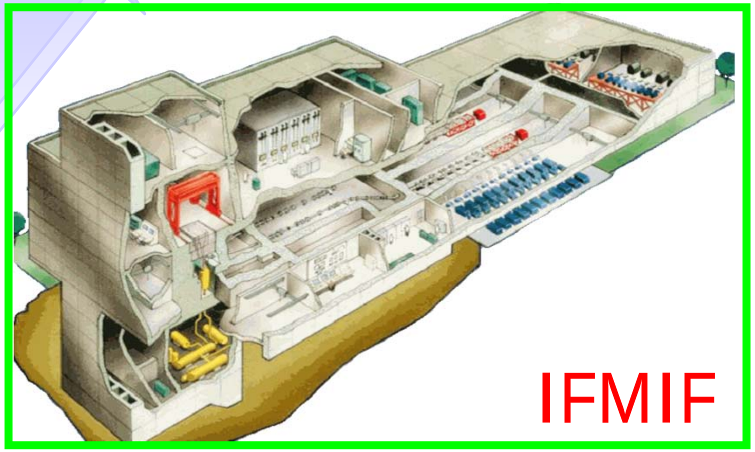
Advanced Materials are at a critical path



1-3 dpa/lifetime



< 150 dpa

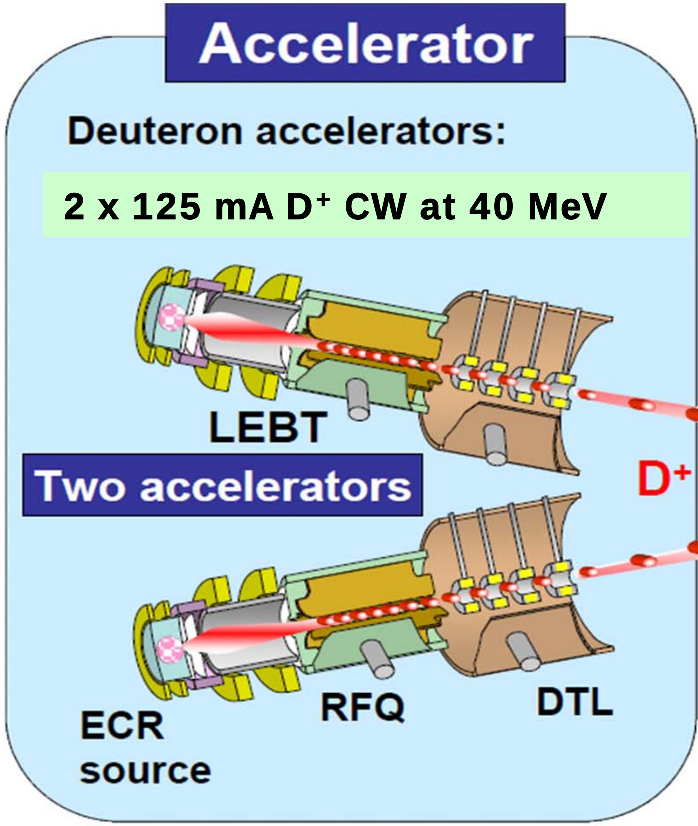


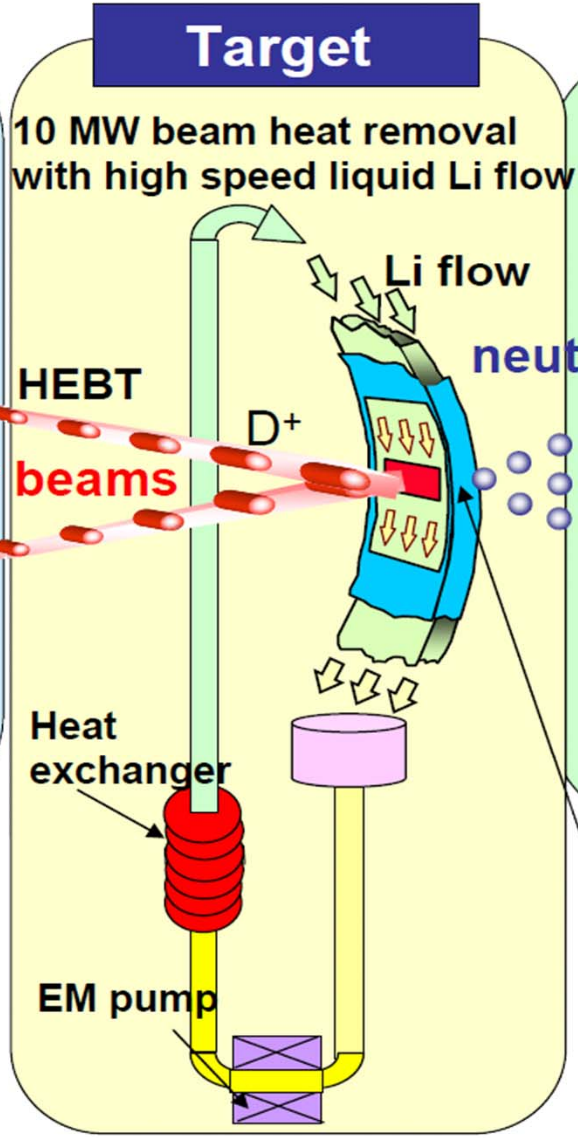
20-40 dpa/year

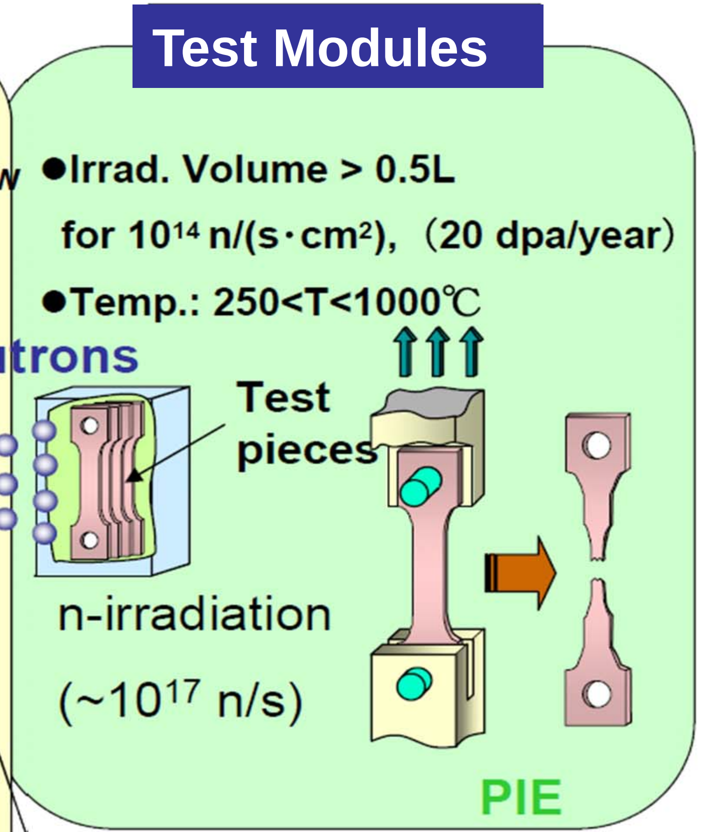
International Fusion Materials Irradiation Facility

Dpa: displacement per atom: measure the integral of received radiation

IFMIF Principles







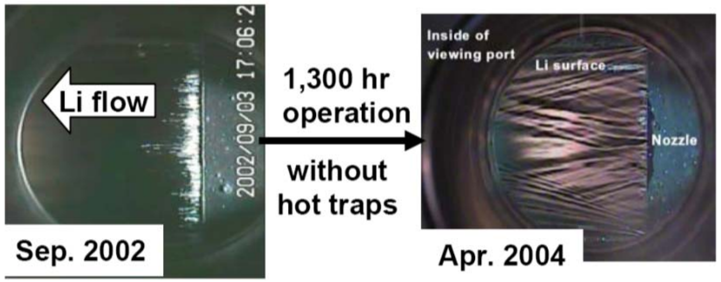
Accelerator based neutron source using the D-Li stripping reaction ⇒ intense neutron flux with the appropriate energy spectrum

Typical reactions:
$^{7}Li(d,2n)^{7}Be$, $^{6}Li(d,n)^{7}Be$, $^{6}Li(n,T)^{4}He$

Beam footprint on Li target
20cm wide x 5cm high
(1 GW/m^2)

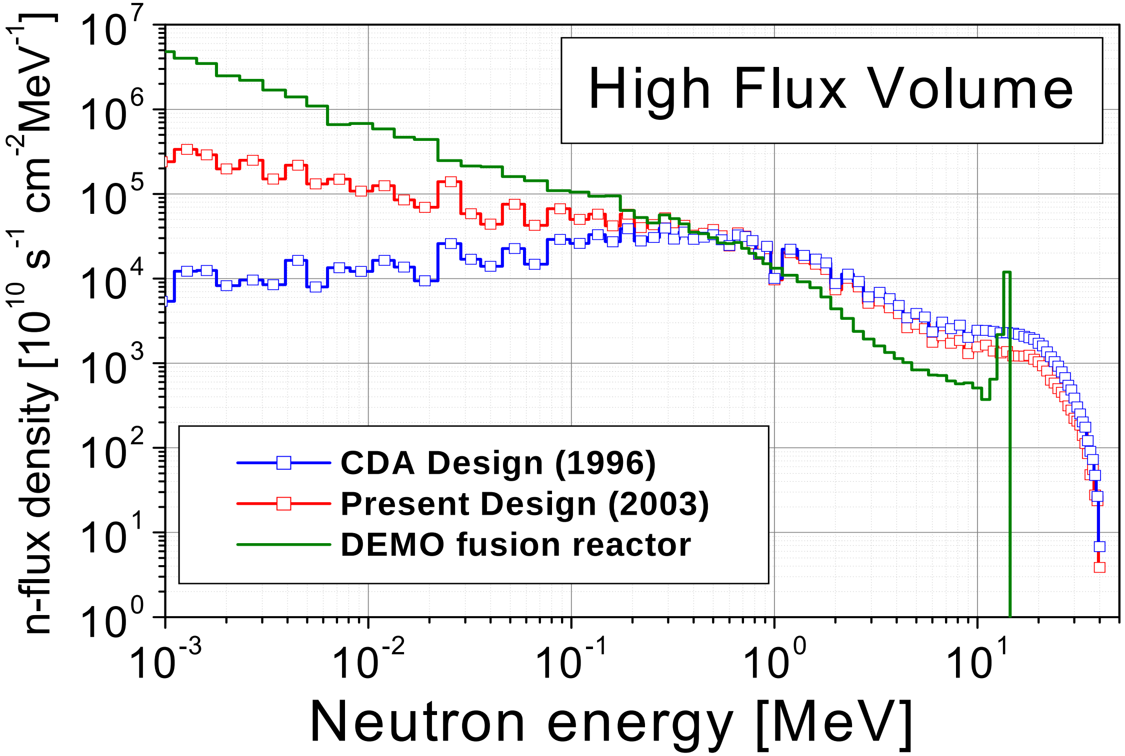
Beam-target choice for neutron production

- **40 MeV deuterons** with Li target **nuclear stripping reaction**



Li free-surfaces at nozzle exit

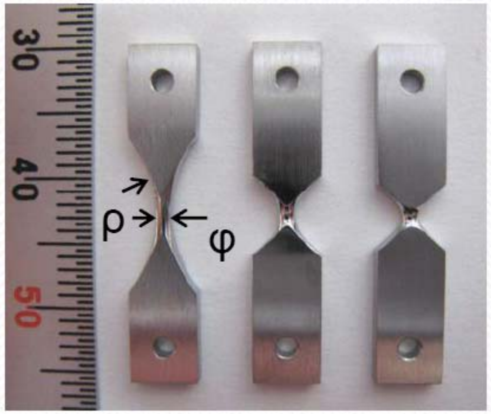
IFMIF-EVEDA tests of LI flux



- 10 MW about 10^{17}n/s and 10^{10} n/s per W or 0.2 n/d
- Vs spallation sources less production but softer spectrum
- Typical reactions ^{7}Li(d,2n)^{7}Be and ^{6}Li(d,n)^{7}Be

Example of after irradiation test of small speciments

Fatigue:

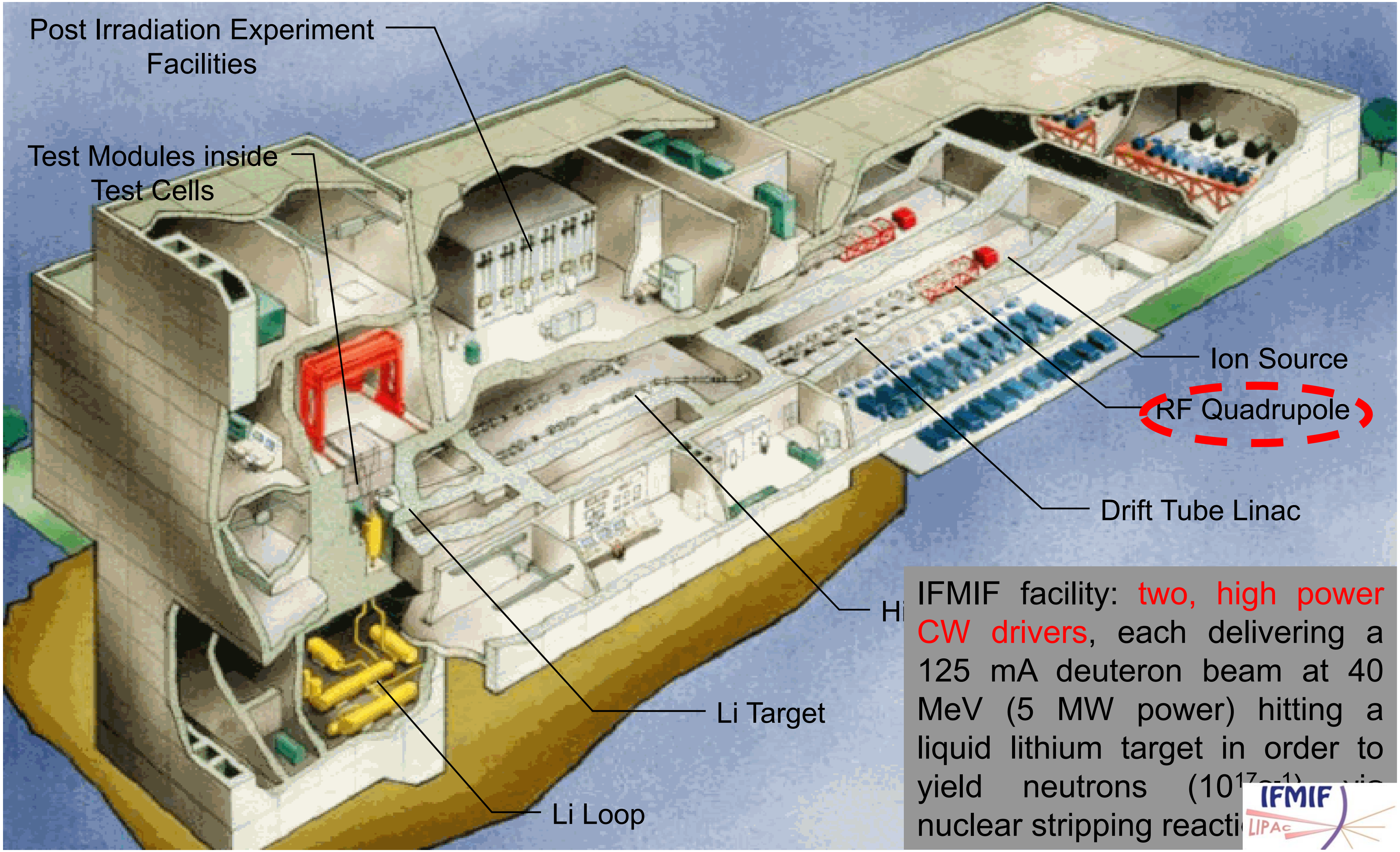


φ[mm]	1.25	1.25	1.25
ρ[mm]	10	2.5	1.25
φ/ρ	0.125	0.500	1.000
K_t	1.03	1.11	1.21

Different shape specimens for fatigue tests

IFMIF "Artist View"

International Fusion Material Irradiation Facility



IFMIF facility: two, high power CW drivers, each delivering a 125 mA deuteron beam at 40 MeV (5 MW power) hitting a liquid lithium target in order to yield neutrons ($10^{17} s^{-1}$) via nuclear stripping reacti

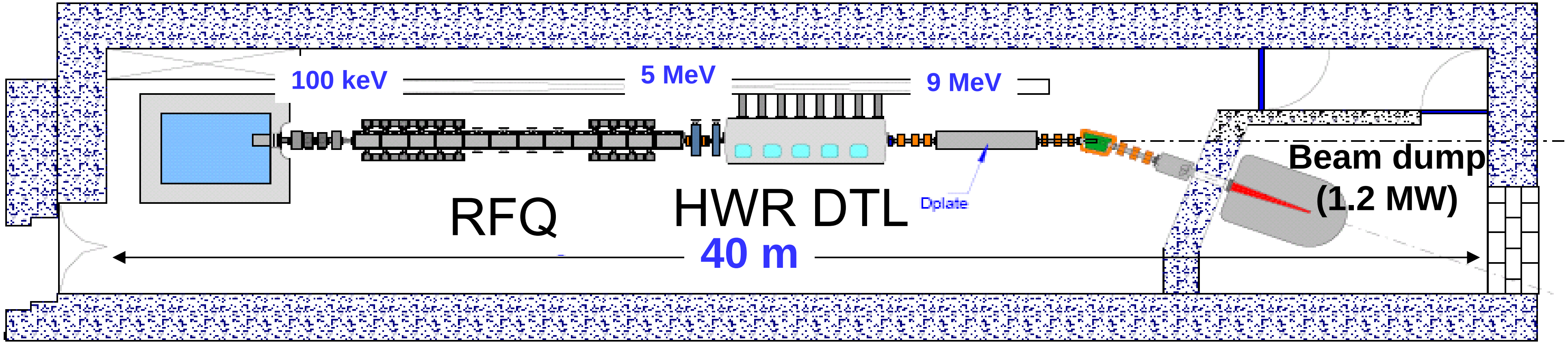
IFMIF EVEDA
(IFMIF Engineering Validation and Design Activities)

- Within the BA (Broader Approach to fusion agreement, 2008) the IFMIF EVEDA activities have been launched with and agreement between Europe (represented by F4E) and Japan (represented by JAEA)

- The **Validation** activities follows three programs (Systems)
  - Prototype Accelerator (LIPAc Linear IFMIF Prototype Accelerator)
  - Prototype of the Lithium target circuit
  - Experimental facility definition
- **Design** activities concern the design of IFMIF facility (preliminary, interim or detailed, is under further definition)

IFMIF EVEDA

- Recently funded within the Broader Approach to Fusion: construction of **a 9 MeV 125 mA cw deuteron accelerator** (to be built in Rokkasho, Japan) based on a high power RFQ followed by a superconducting linac



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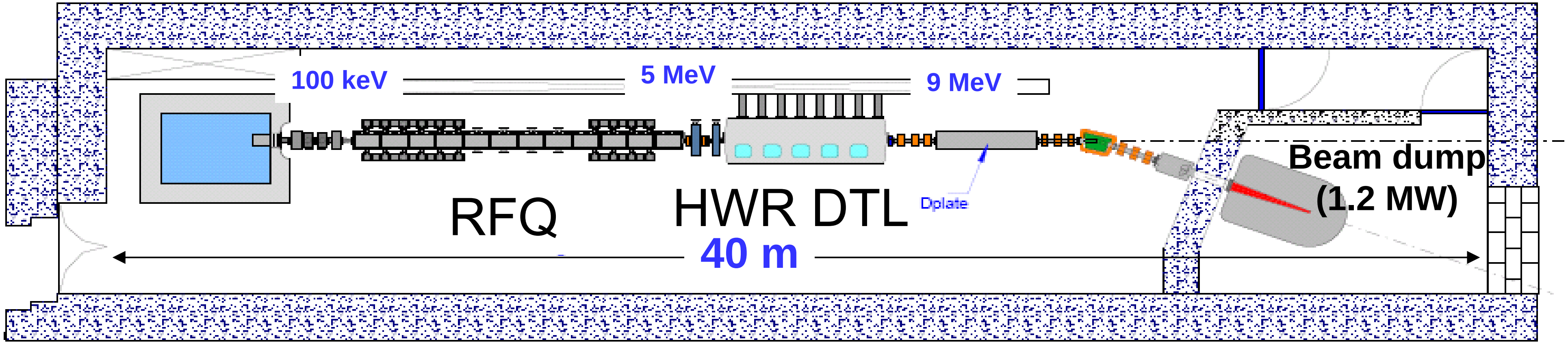

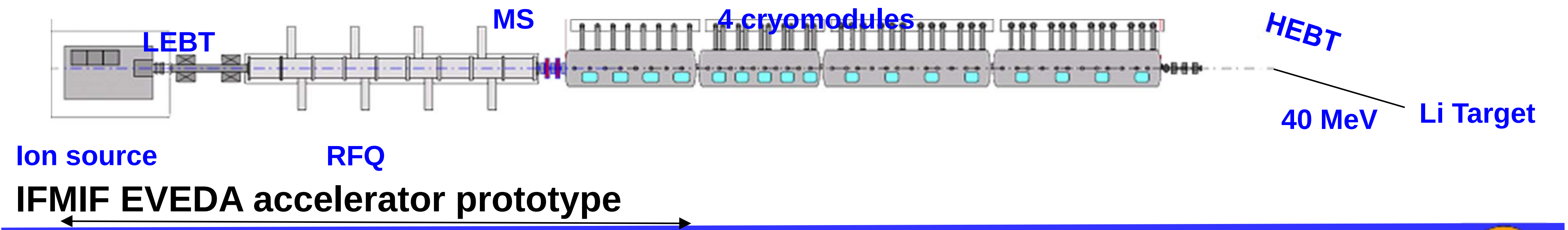

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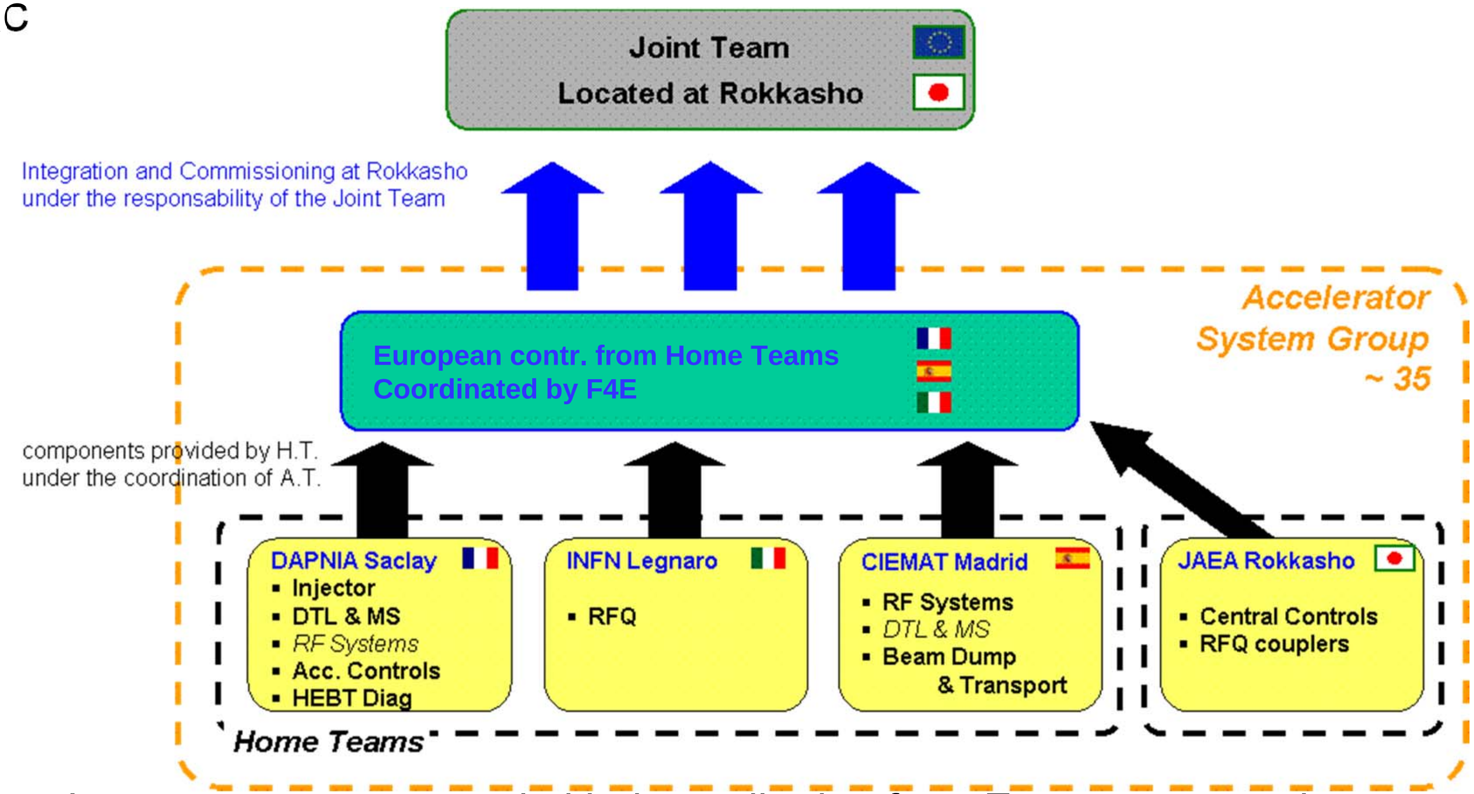


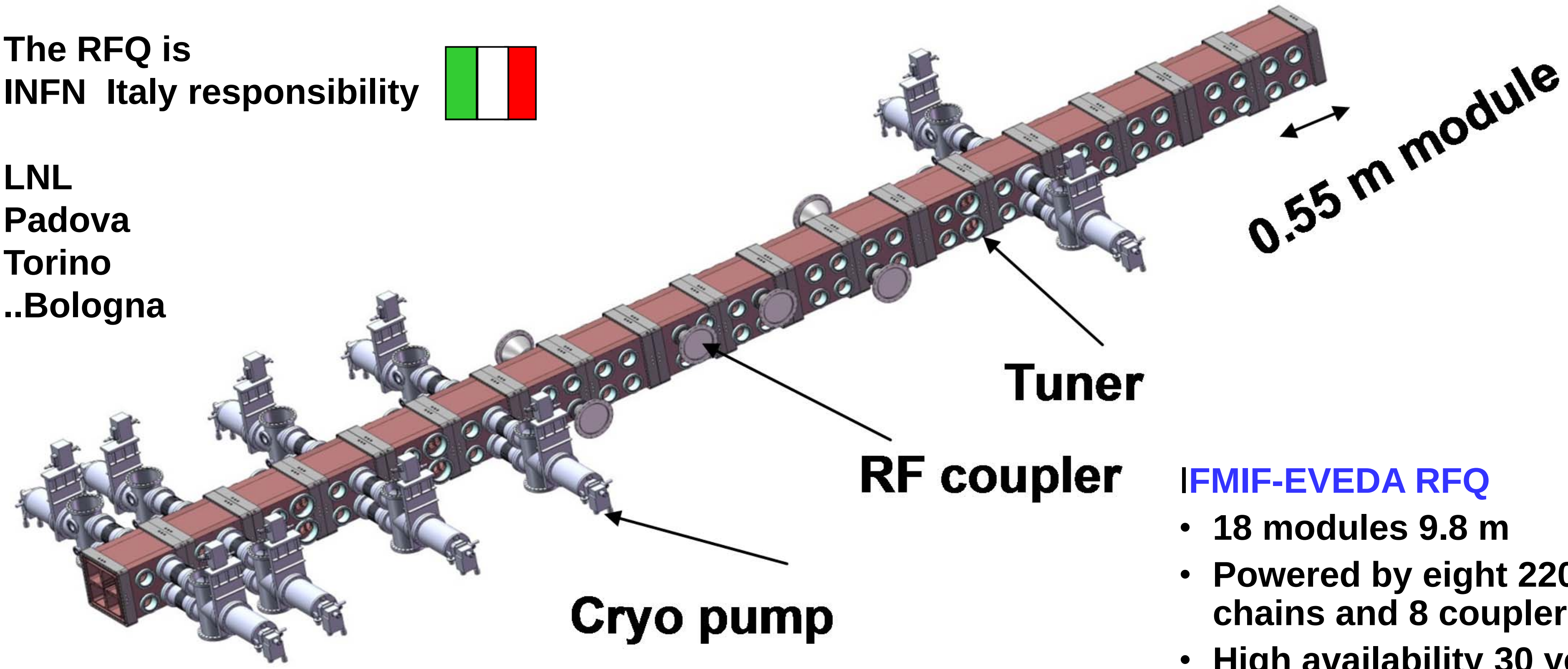
The accelerator components are in kind contribution from European countries

RFQs general parameters

	Name	Lab	ion	energy	vane	beam		RF Cu	Freq.	length		Emax	Power density	
					voltage	current	power	power					ave	max
				MeV/u	kV	mA	kW	kW	MHz	m	lambda	kilpat	W/cm^2	W/cm^2
	IFMIF EVEDA	**LNL**	**d**	**2.5**	**79-132**	**130**	**650**	**585**	**175**	**9.8**	**5.7**	**1.8**	**3.5**	**60**

The RFQ is INFN Italy responsibility

LNL
Padova
Torino
..Bologna



IFMIF-EVEDA RFQ

- **18 modules 9.8 m**
- **Powered by eight 220 kW rf chains and 8 couplers**
- **High availability 30 years operation.**
- **Hands on maintenance**
- **First complete installation in Japan**

RFQ system organization

- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti

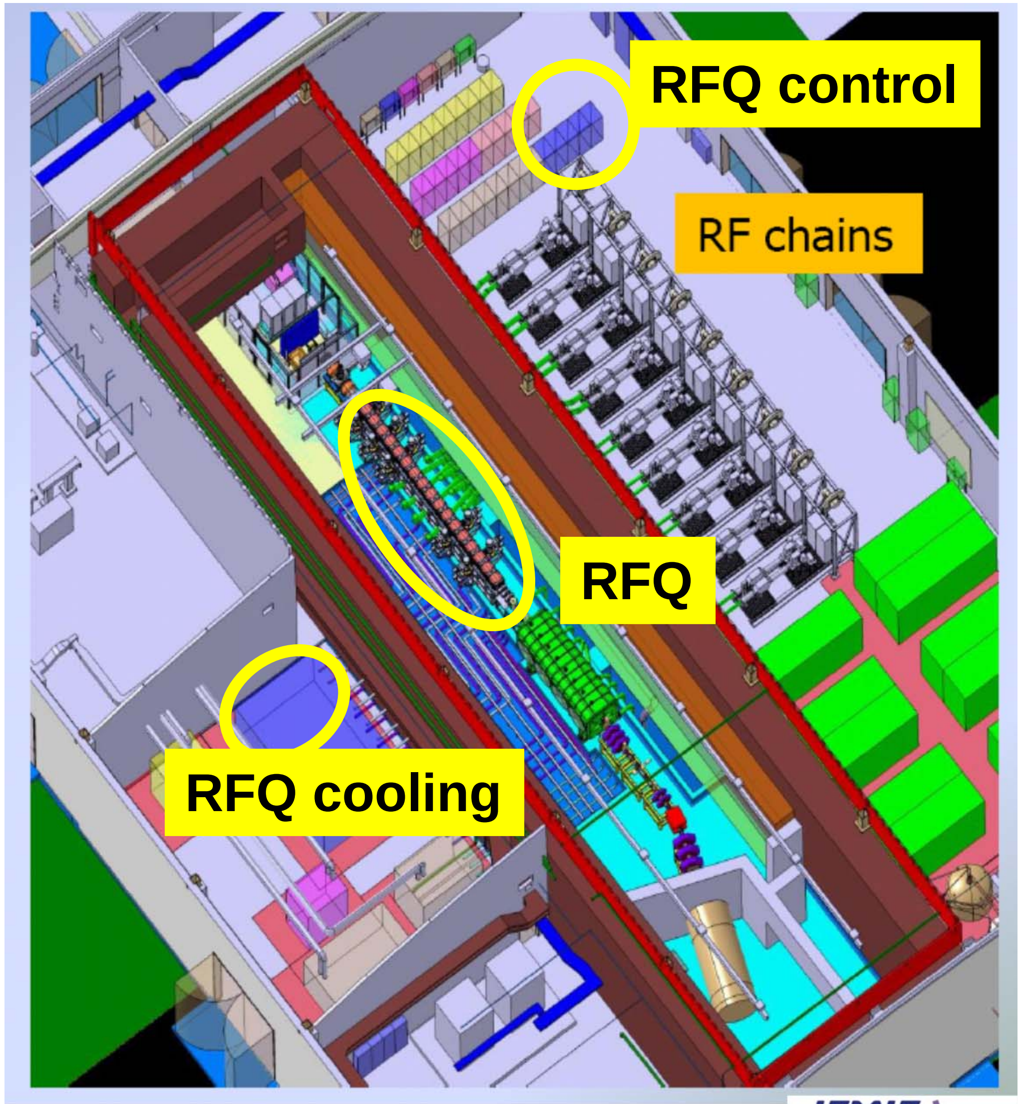
  About 30 persons involved, 20 FTE, 10 dedicated contracts

  The participation of INFN to IFMIF-EVEDA includes
  - RFQ construction
  - Participation to final IFMIF design activity
  - Participation to the man power of the project team in Japan
  - Participation to beam commissioning in Japan

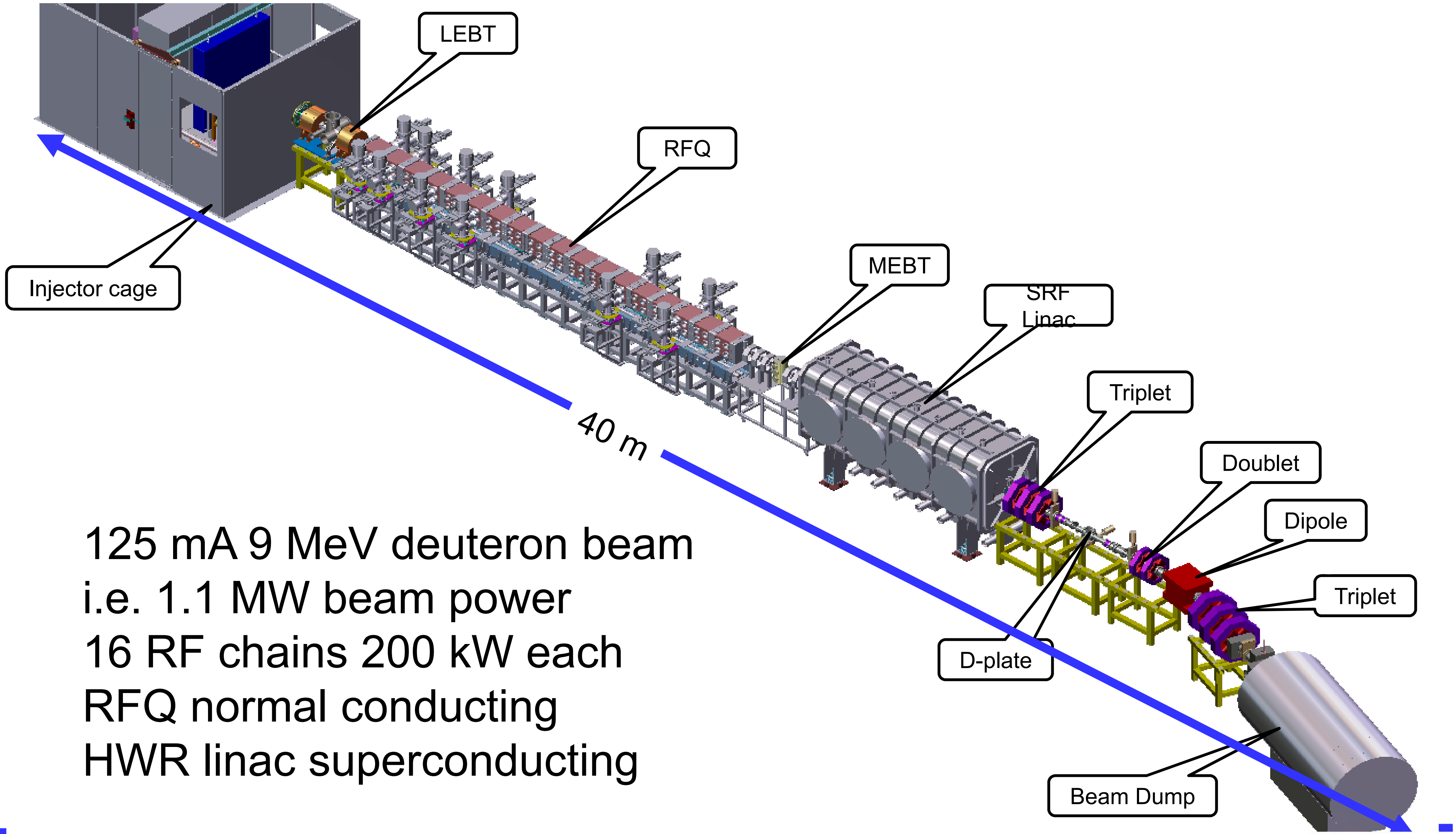
INFN organization

INFN group for RFQ realization

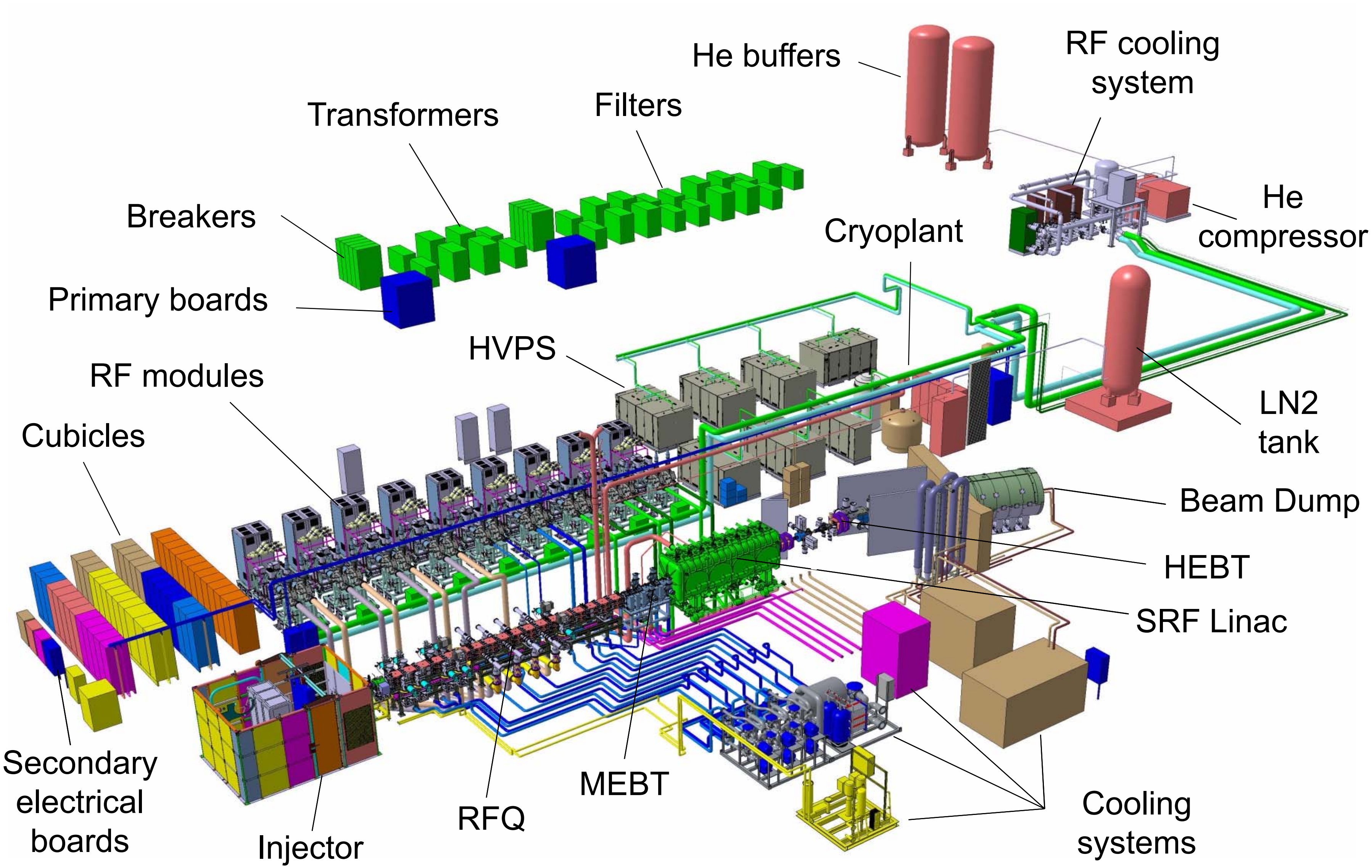
- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti
  - Planning: J. Esposito
- Physical design : M. Comunian
  - Radio frequency: A. Palmieri
  - High power tests: E. Fagotti
  - Computer Controls: M. Giacchini
  - Vacuum system and technological processes C. Roncolato
- Mechanics design and construction A. Pepato
  - Engineering integration P. Mereu
  - Modules alignment D. Dattola
  - Quality assurance: R. Dima
  - Module production follow up M. Benettoni
  - Stainless steel components production A. Margotti
  - Cooling system integration G. Giraudo



Elements of the IFMIF prototype accelerator

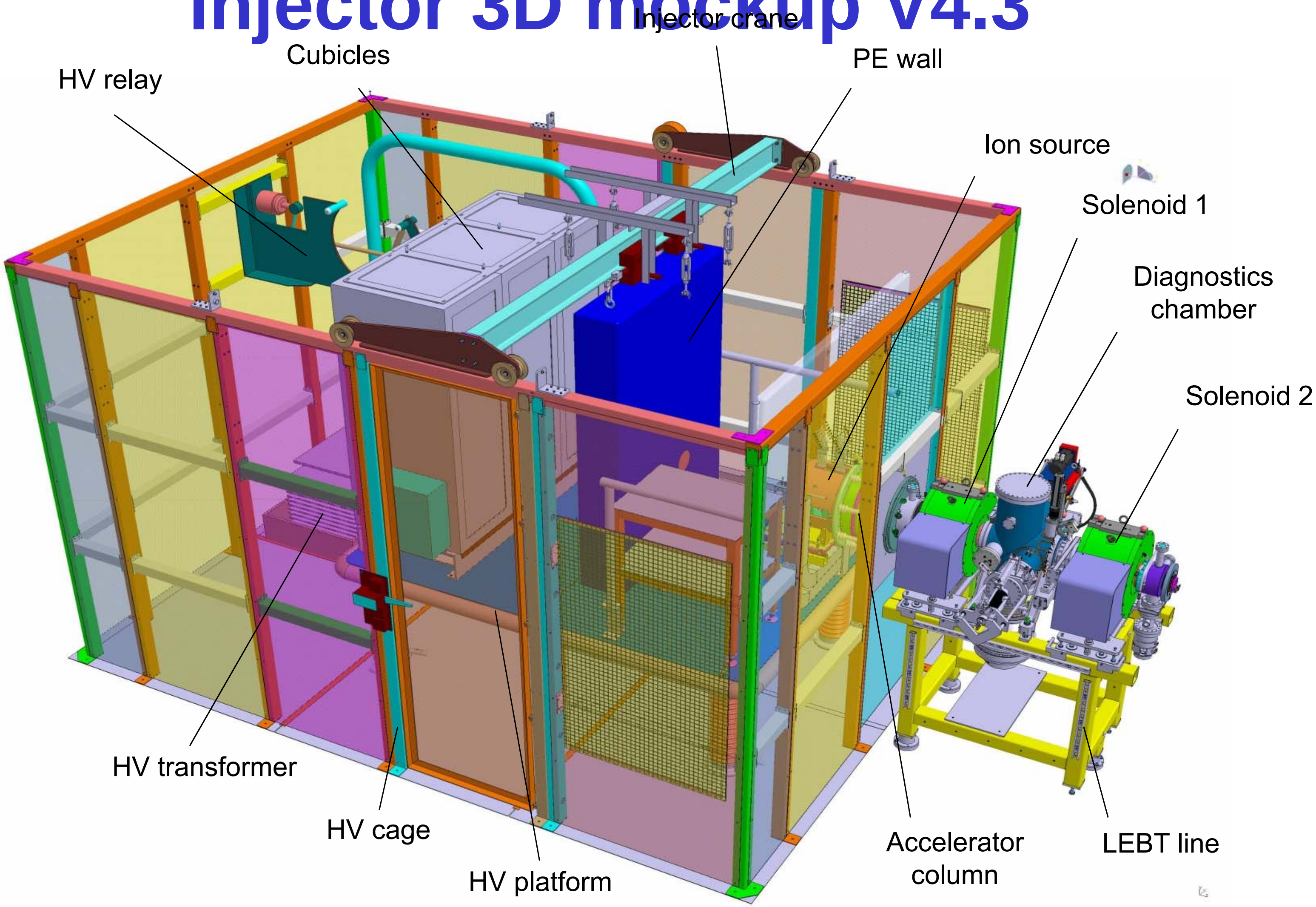


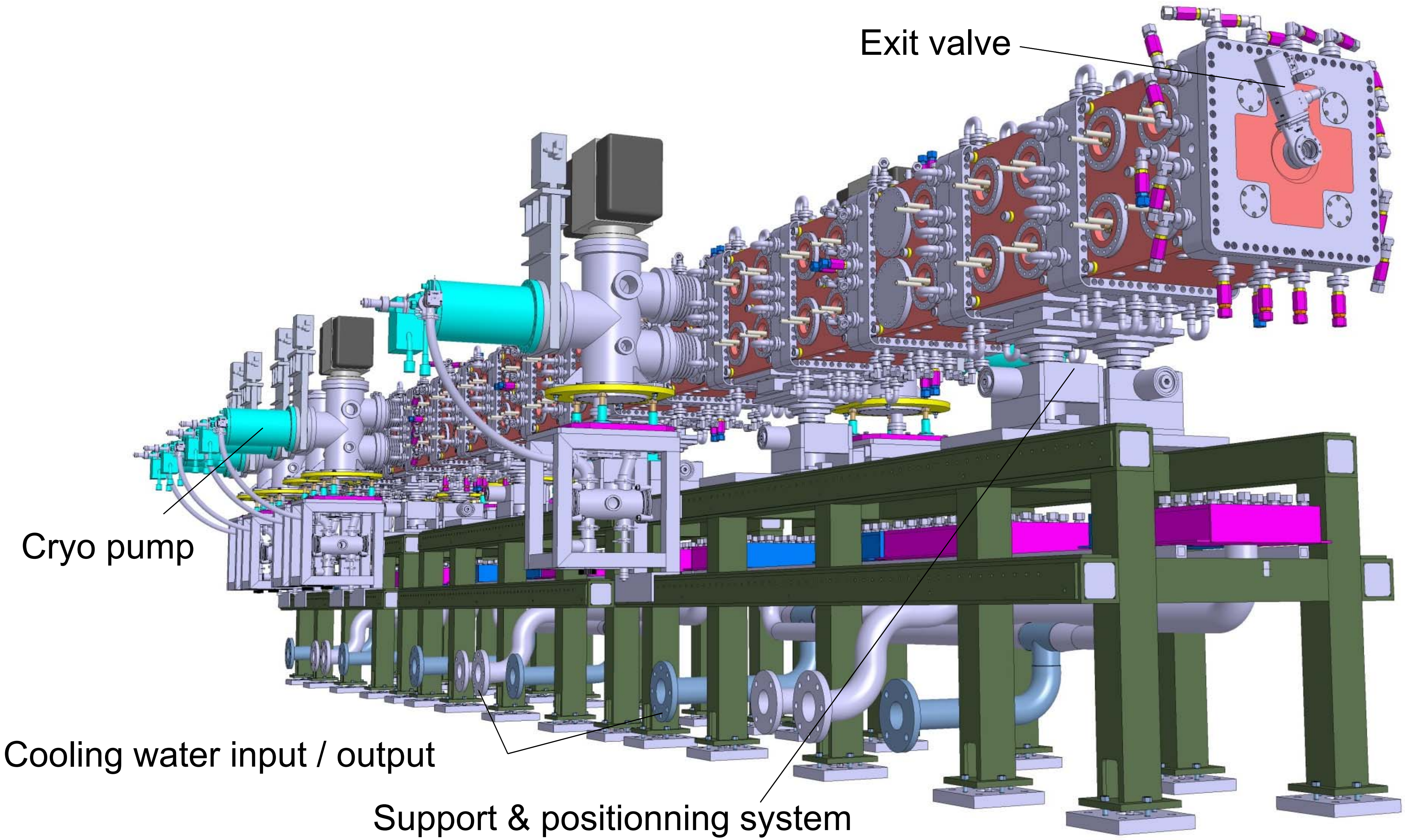
125 mA 9 MeV deuteron beam
i.e. 1.1 MW beam power
16 RF chains 200 kW each
RFQ normal conducting
HWR linac superconducting



Accelerator system 3D Mock-up status D. Gex

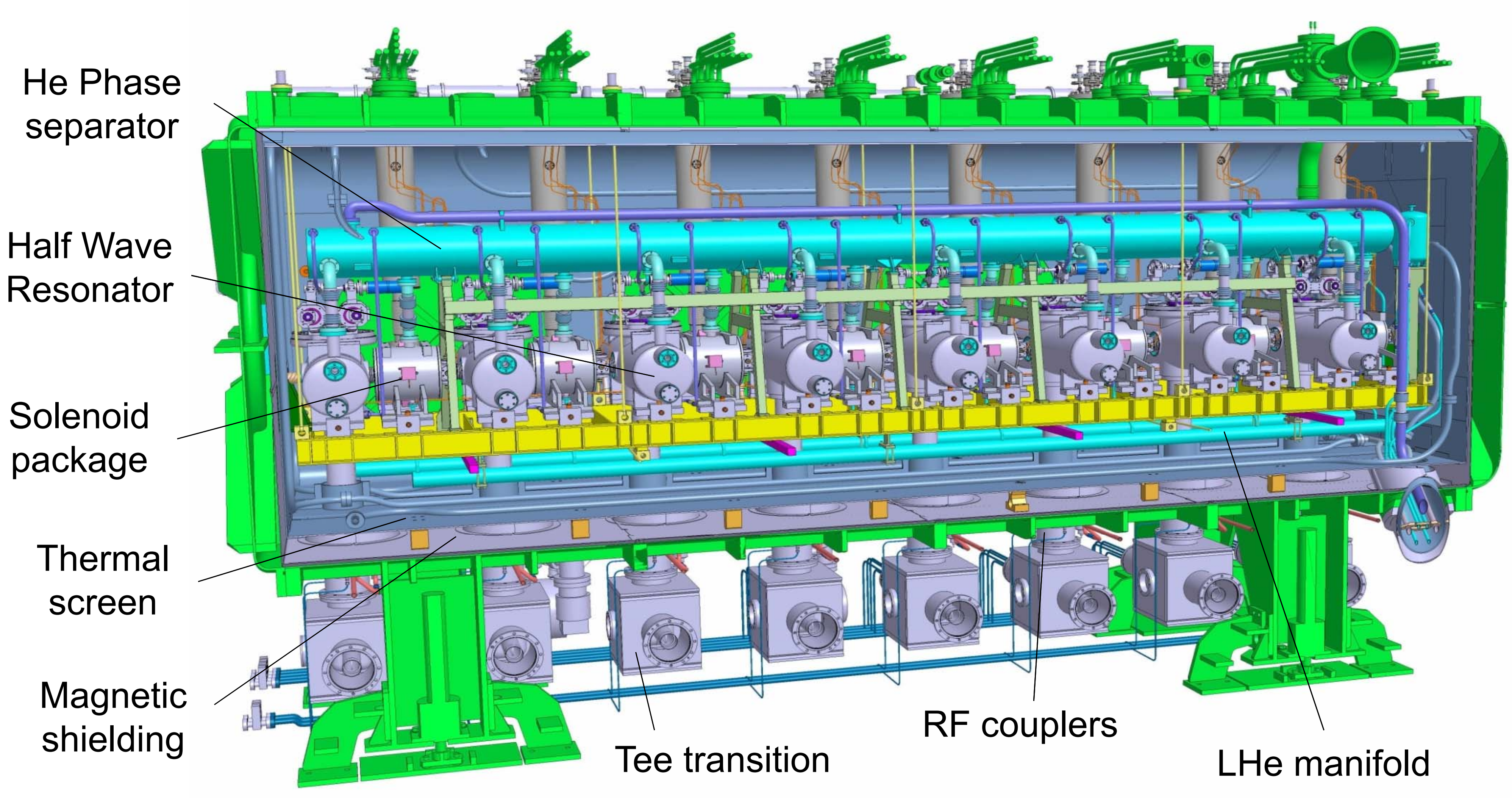
Injector 3D mockup V4.3



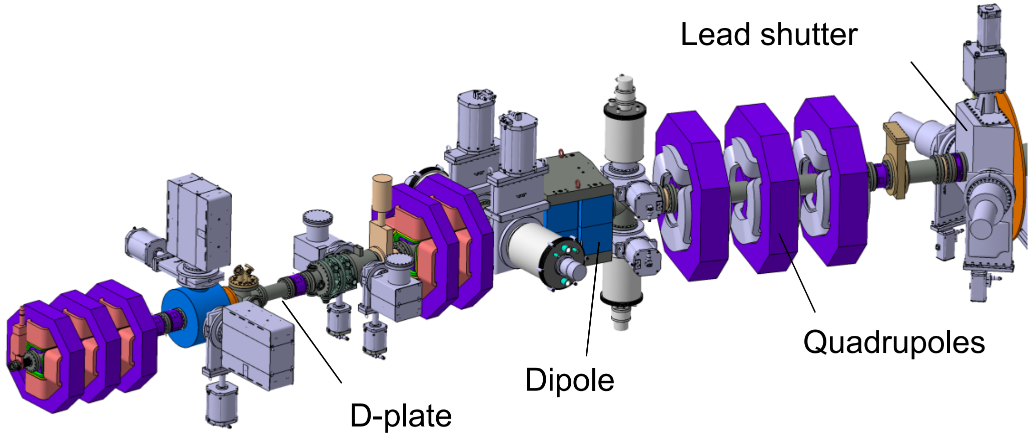


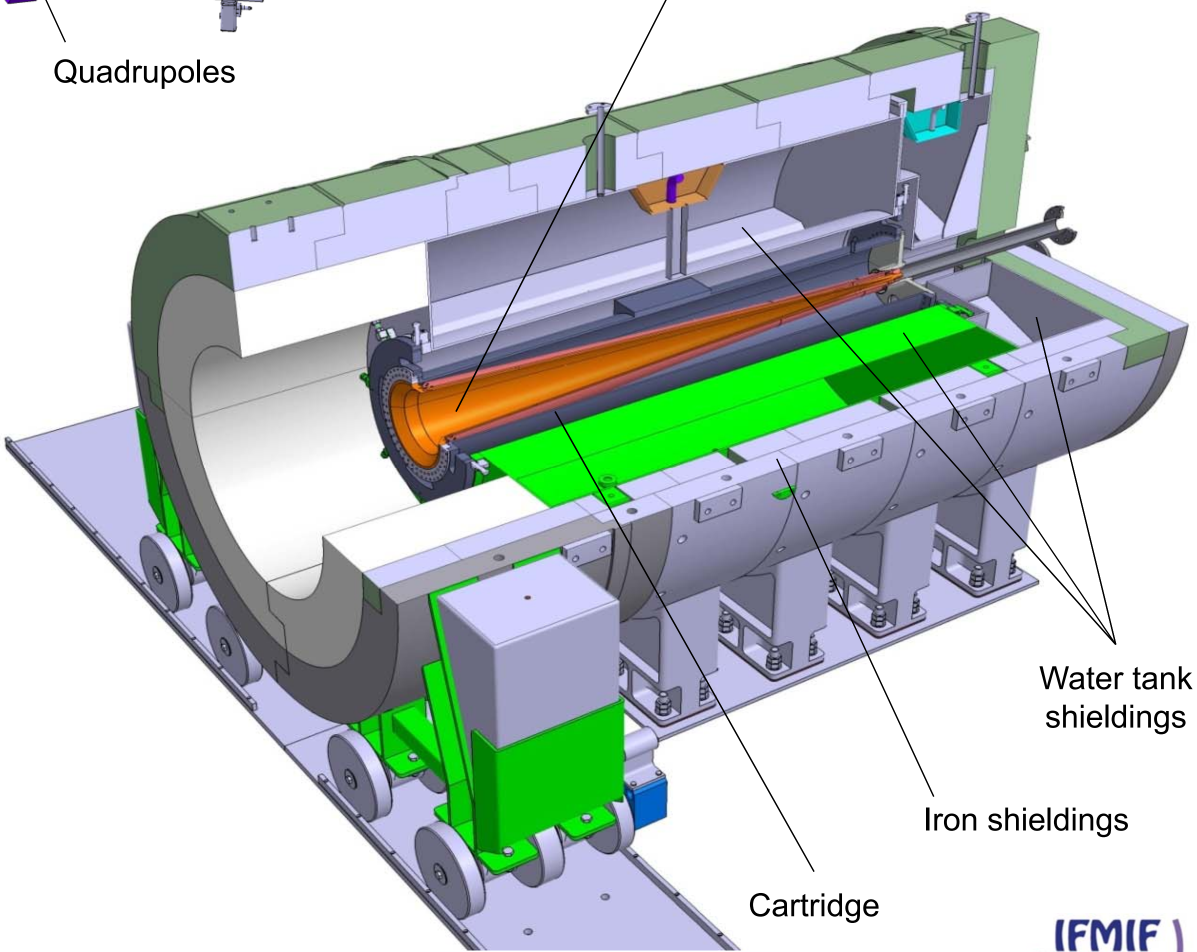
Exit valve
Cryo pump
Cooling water input / output
Support & positionning system

SRF Linac 3D mockup V1.0

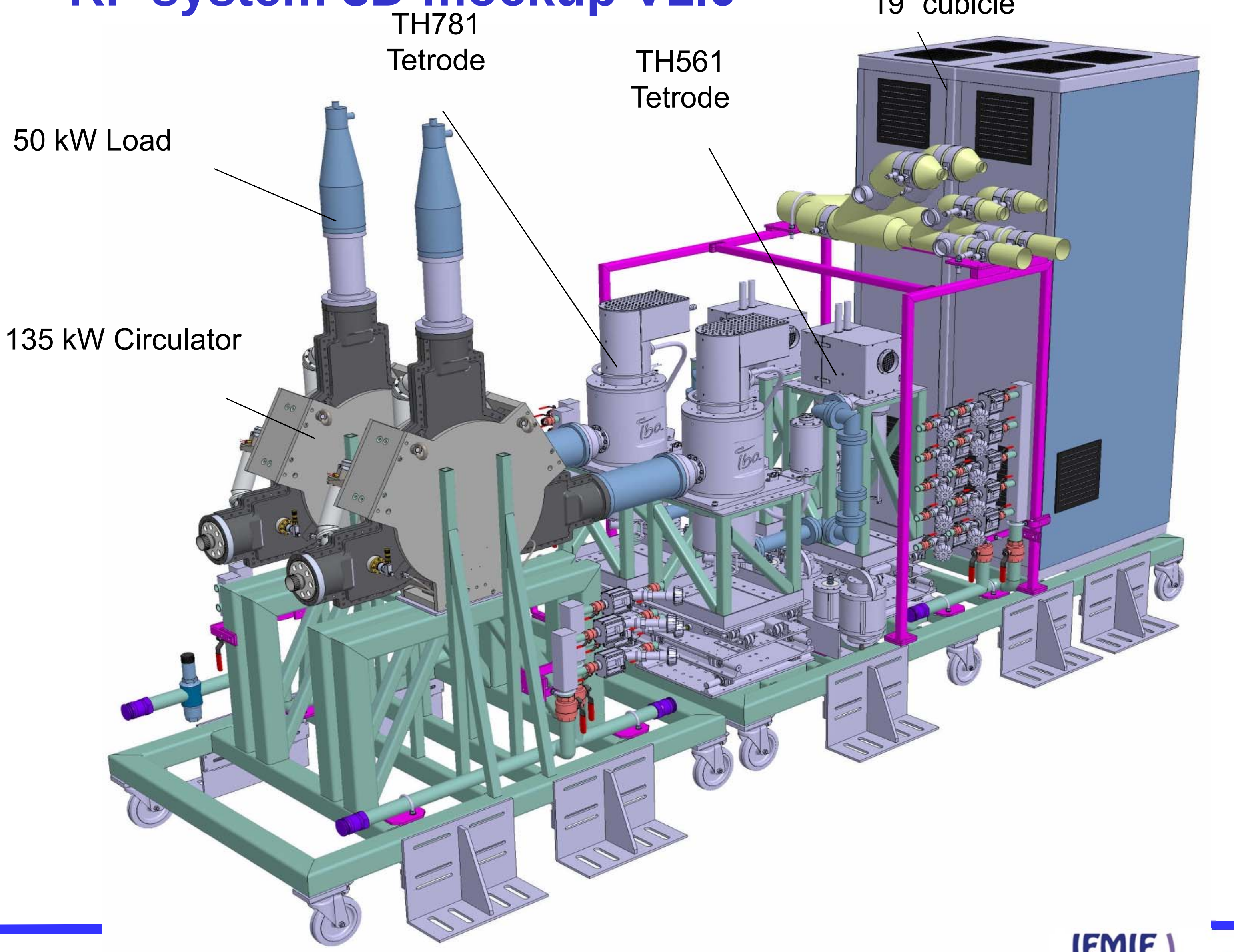


HEBT & BD 3D mockup V8.4



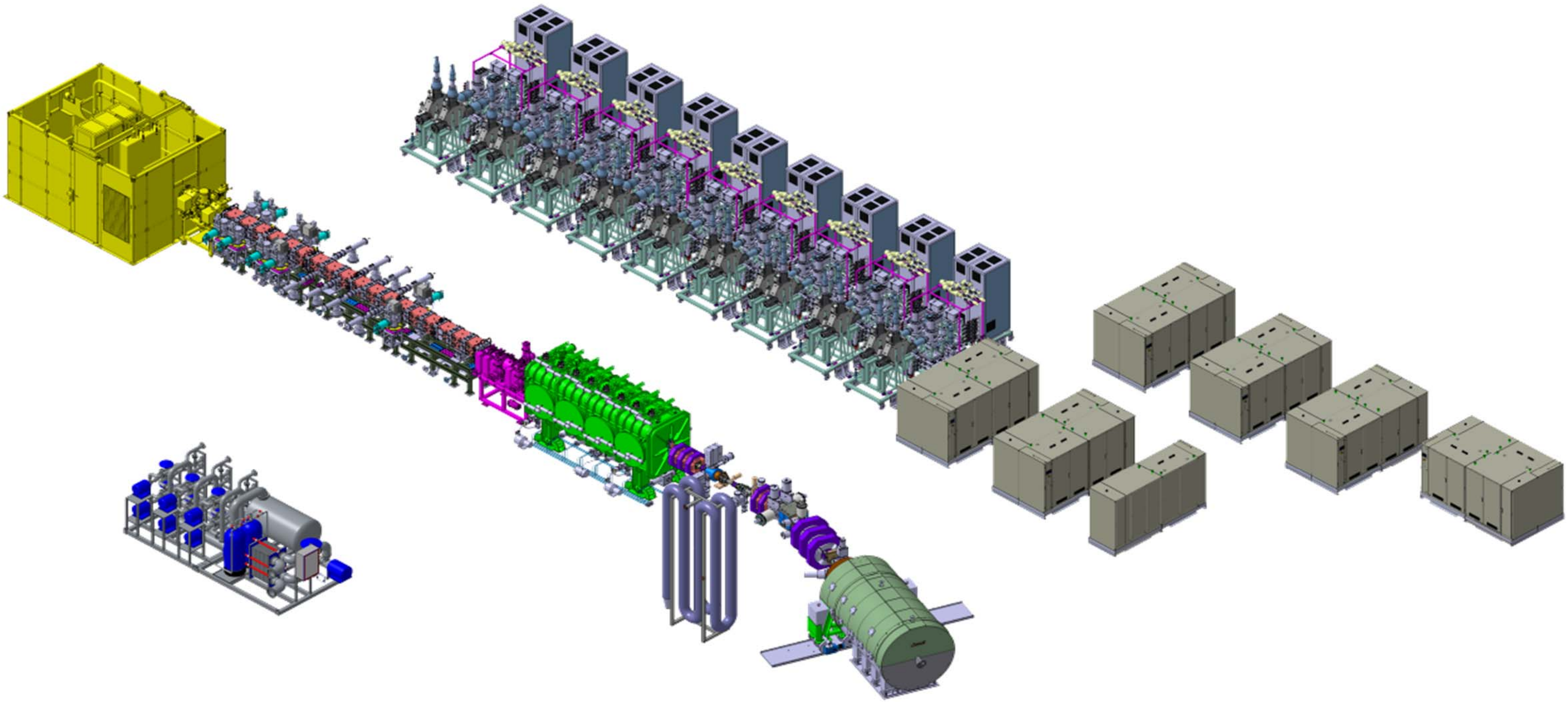


RF system 3D mockup V1.0

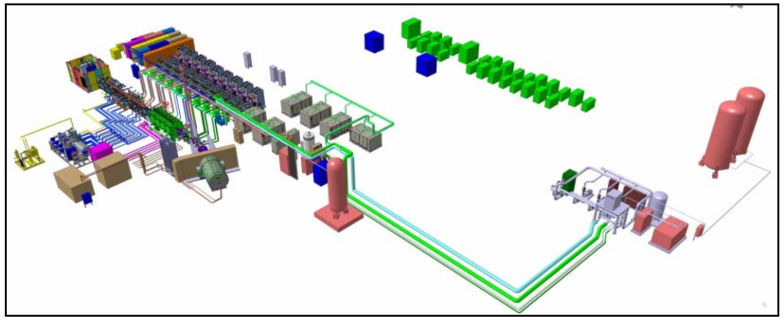


Subsystems mockup

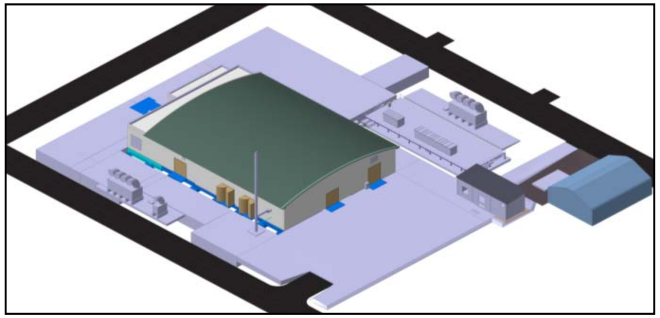
F4E integrates the different mockups sent by all subsystems



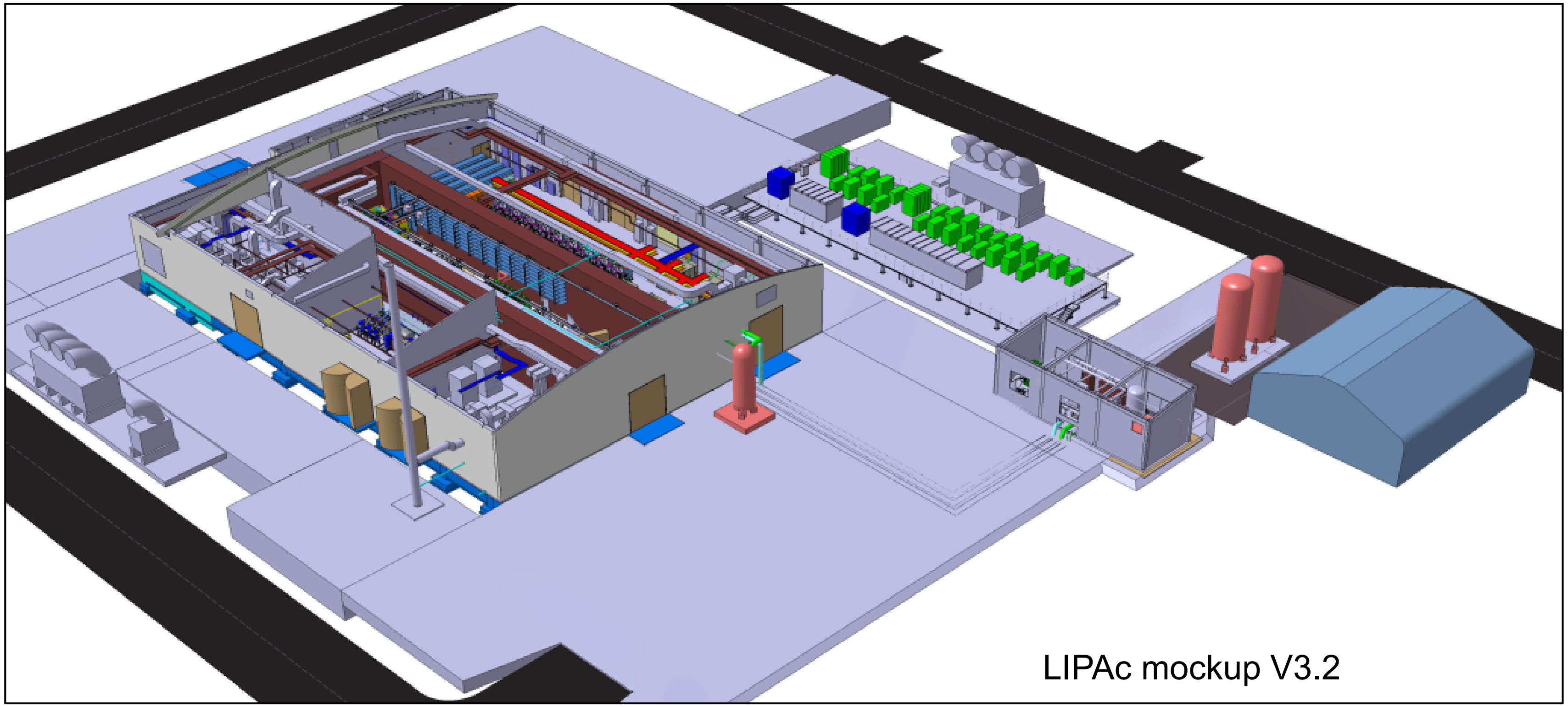
LIPAc mockup V3.2



Accelerator mockup V2.1



Building mockup V1.3



LIPAc mockup V3.2

Integration realized by the Projet Team in Rokkasho

IFMIF/EVEDA
Accelerator building
by JAEA
In Rokkasho (Aomori)

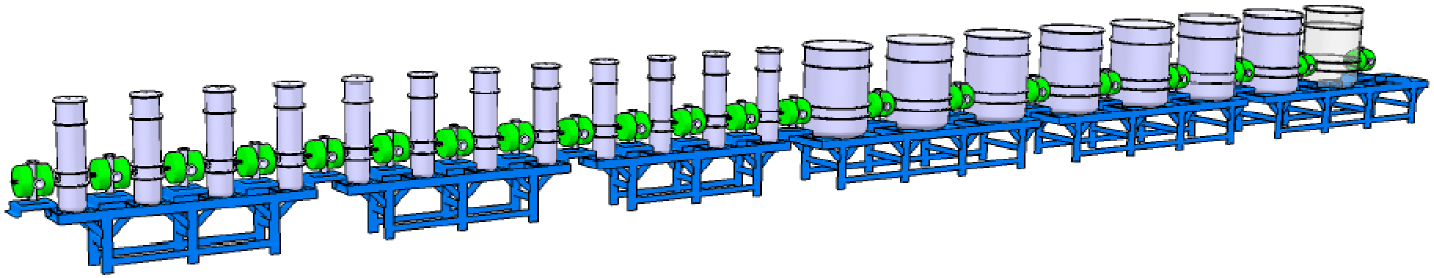
IFMIF EVEDA intensity 125 mA=25*ongoing projects

SARAF at SOREQ (Israel)

SARAF (Israel)
40 MeV
4 mA d and p
176 MHz
Status: beam test up to the first cyomodule

SPIRAL2 at GANIL (France)

SPIRAL2 driver (France)
5 mA d and ions up to A/q=3
40 MeV
80 MHz



Status: in construction

Beam dynamics in IFMIF linac

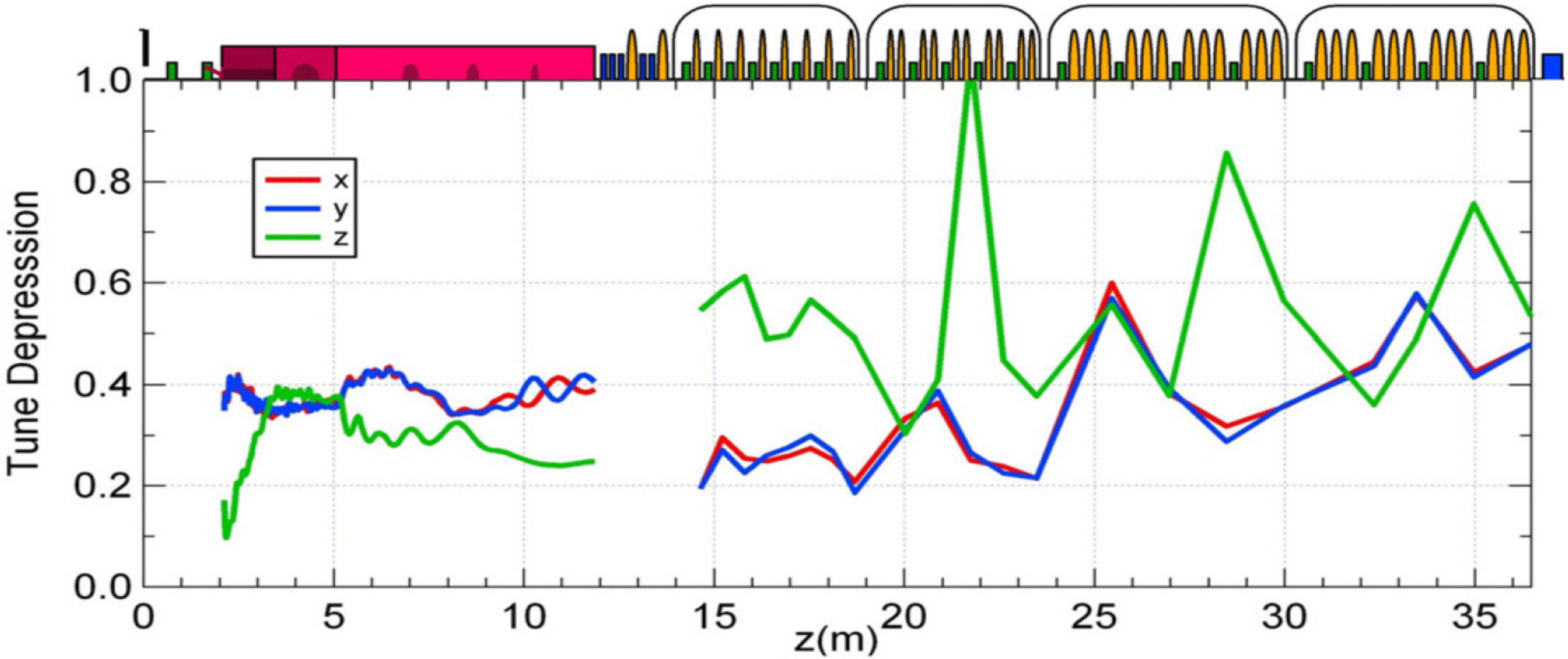


Figure 3: Tune depression in the RFQ and the SRF-Linac

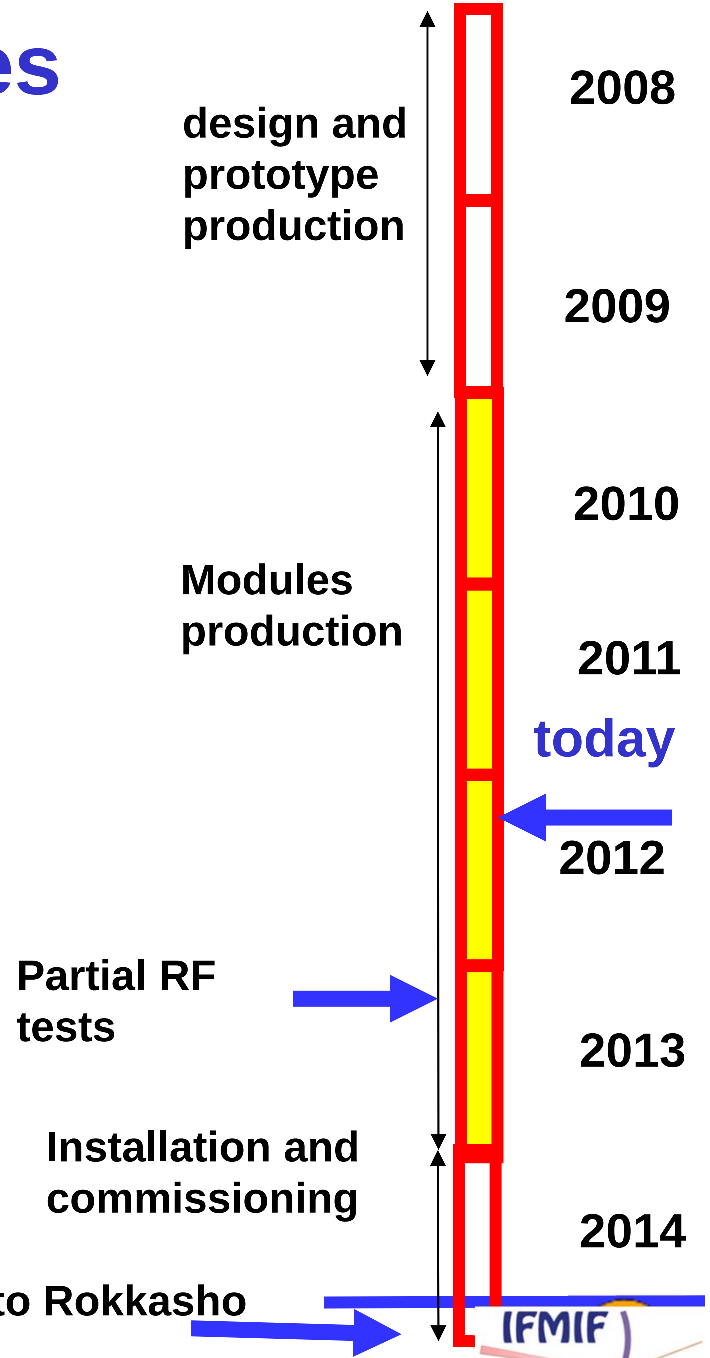
Proceedings of IPAC2011, San Sebastián, Spain MOODB01

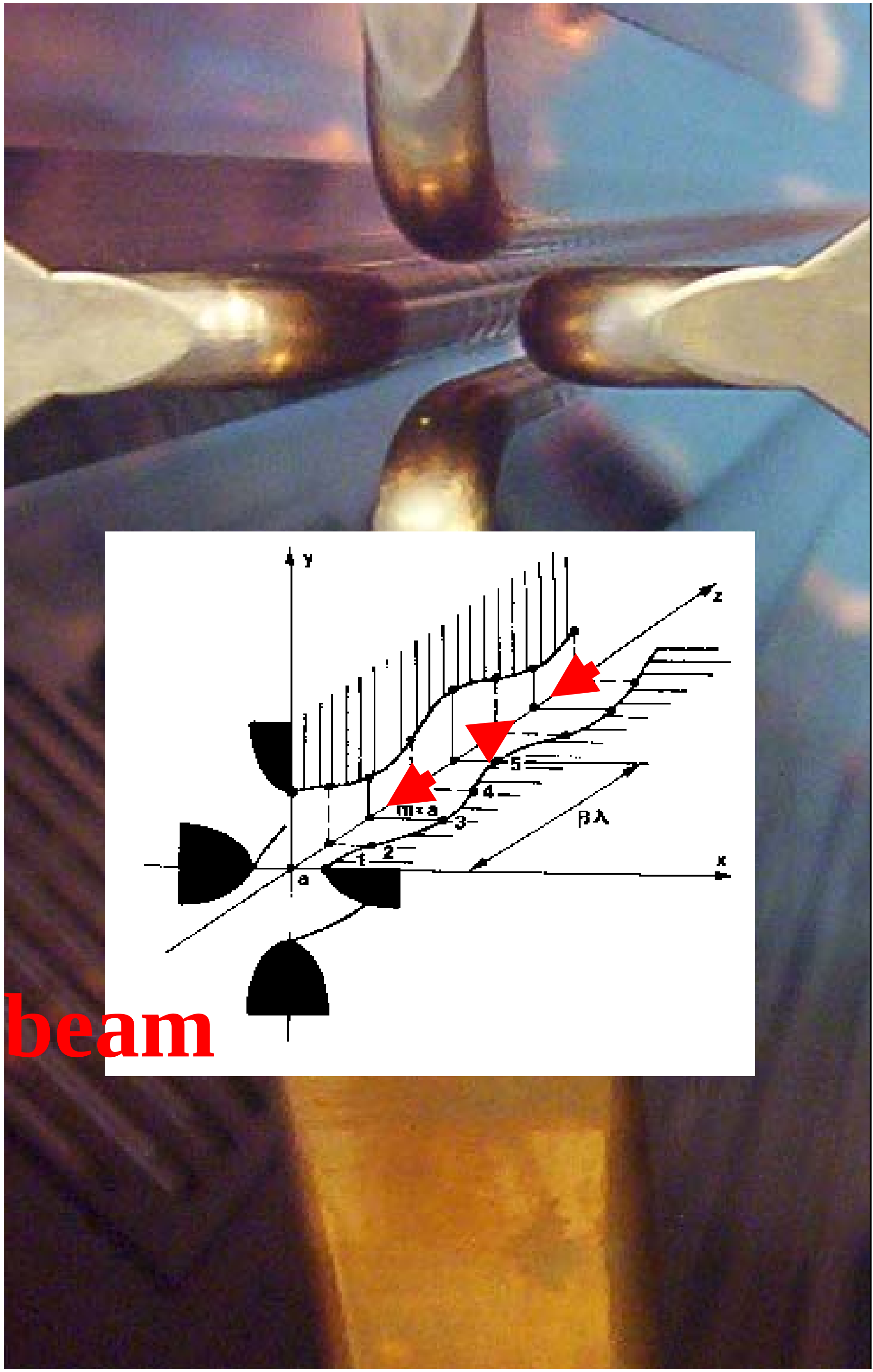
DYNAMICS OF THE IFMIF VERY HIGH-INTENSITY BEAM

P. A. P. Nghiem*, N. Chauvin, O. Delferrière, R. Duperrier, A. Mosnier, W. Simeoni Jr, D. Uriot,
CEA/DSM/IRFU, 91191 Gif-sur-Yvette Cedex, France
M.Comunian, INFN/LNL, Legnaro, Italy, C. Oliver, CIEMAT, Madrid, Spain

IFMIF EVEDA RFQ challenges

- **650 kW beam** should be accelerated with **low beam losses and activation** of the structure so as to allow hands-on maintenance of the structure itself (**Beam losses<10 mA and <0.1 mA between 4 MeV and 5 MeV). (Tolerances of the order of 10-50 um)**
- **600 kW RF dissipated** on copper surface: necessity to keep geometrical tolerances, to manage hot spots and counteract potential instability.
- The RFQ will be the **largest ever built**, so not only the accelerator must be reliable, but also the **production, checking and assembling procedure must be reliable**
  - Fully exploit **INFN internal production capability** (design machining, measurement and *brazing*)
  - Make production accessible for different industrial partners
- At present and **we are in the production of the modules** phase.



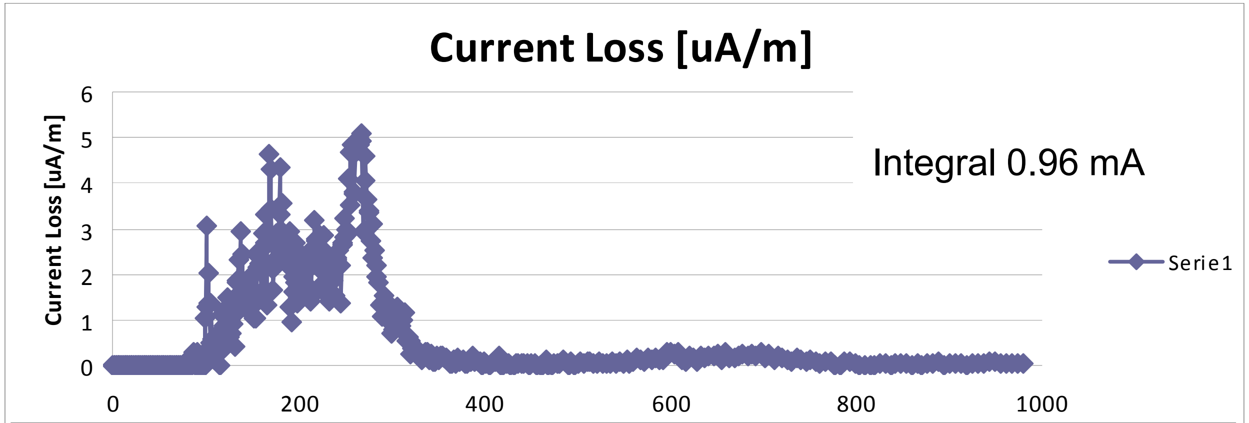


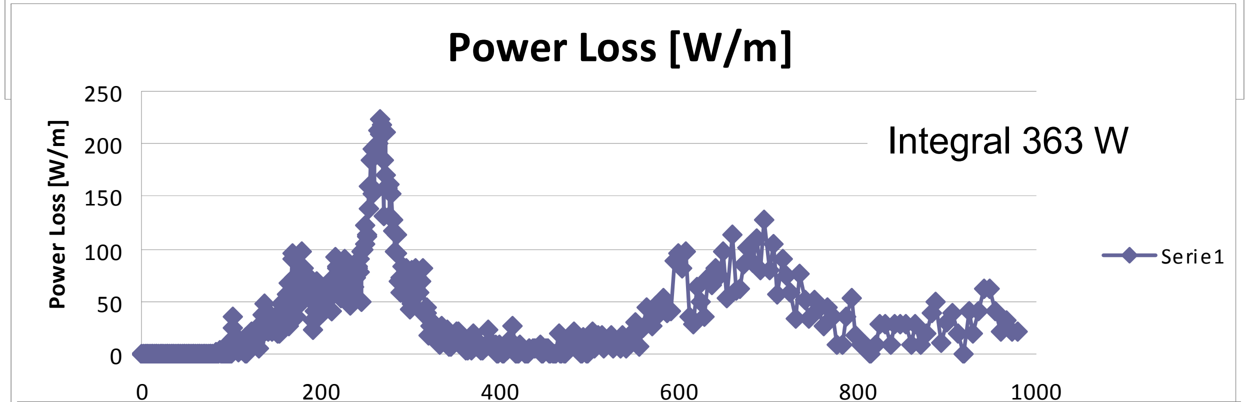
IFMIF RFQ modulation design

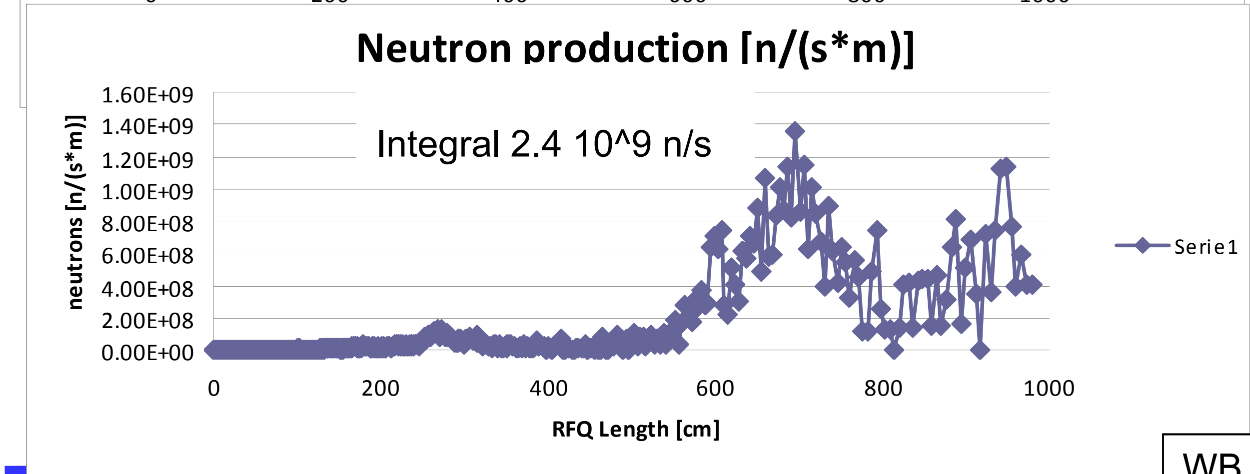
Ions	d	
Energy range	0.1-5	MeV
input-output nom emitt	0.25	mmmrad (rms)
Ouput long emitt.	0.2	MeV deg (rms)
Output current	0.2	
Tansmission	98	% WB distr.
	95	% Gsussian distr.

- The voltage is increased (79-132 kV) following an analytic law
- The focusing in the Gentle Buncher is strong (B=7) so to keep the tune depression above 0.4 for the best control of space charge.
- Main resonances are avoided in the accelerator section
- The focusing in the shaper raises from 4 to 7 to allow an input with smaller divergence.

Beam losses







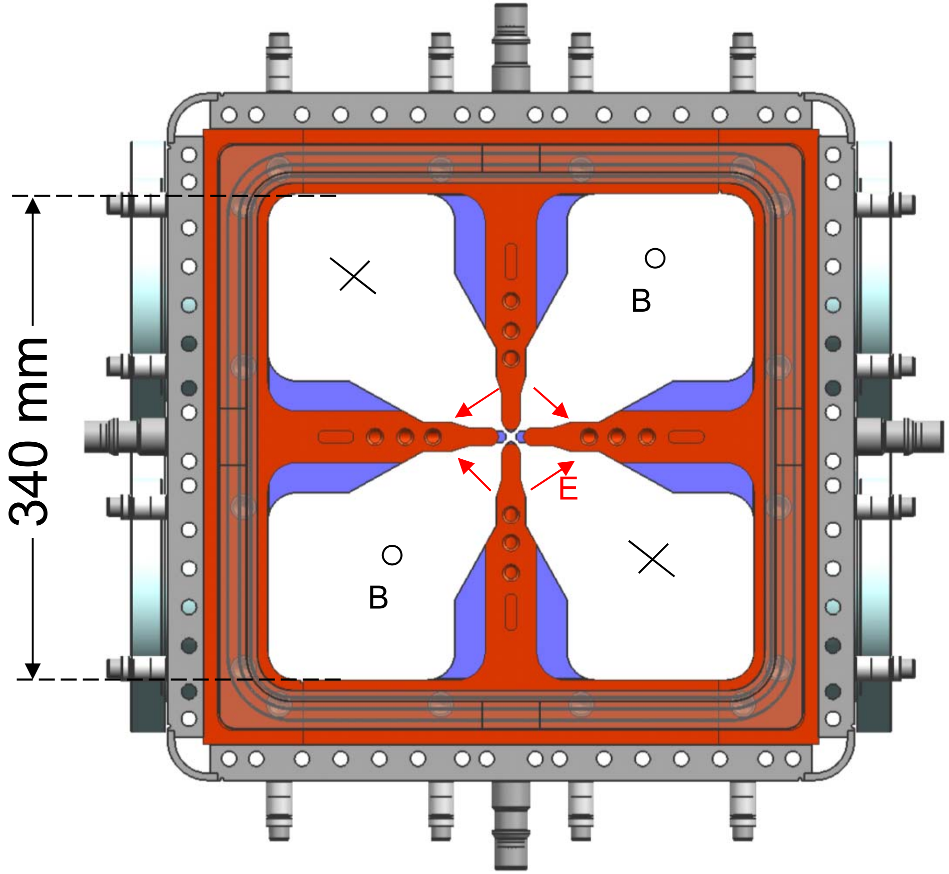
- To achieve Beam losses concentrated in the low energy part is very important since neutron production is proportional to w^2

$$n = 5.15 * 10^{-7} N w^{2.1}$$

WB distribution 0.25 mm mrad rms norm

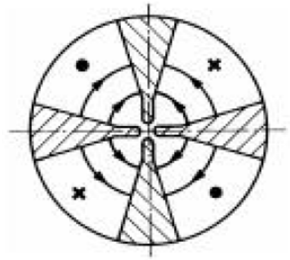
RF cavity design

Cavity cross section

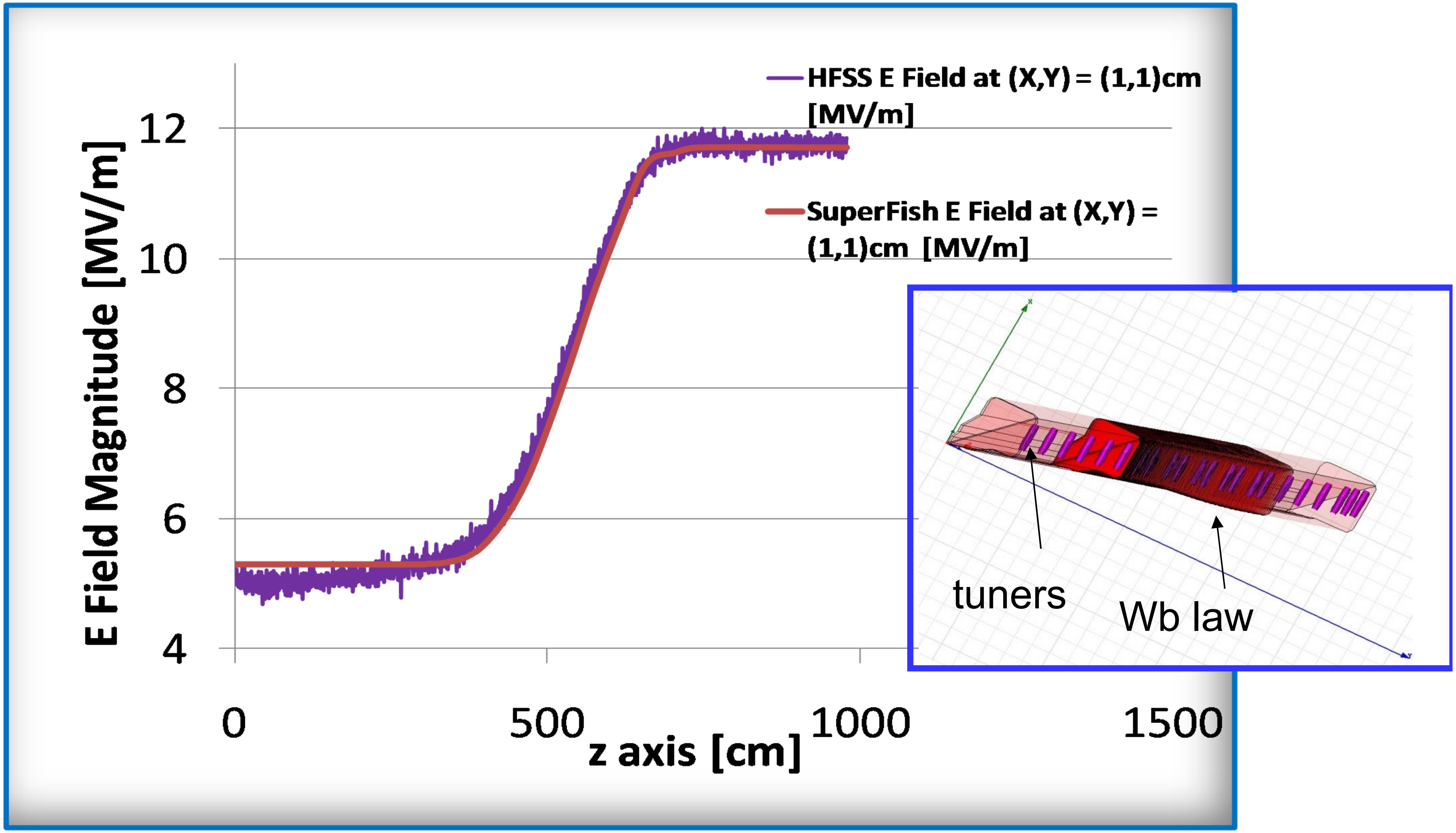


Operating Frequency	175	MHz
Length	9.78	m
Vg (min – max)	79 – 132	kV
R0 (min - max)	0.4135 - 0.7102	cm
Total Stored Energy	6.63	J
Max. RF power to the cavity (beam+SF*1.3*1.21)	1345	kW
Number of slug tuners	96	
Frequency tuning	Water temp.	

$$TE_{21n}$$



3D simulations with HFSS



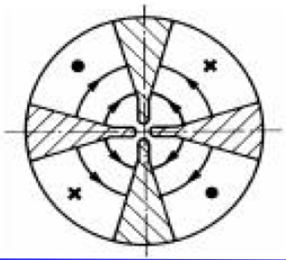
Field Error < 4% in the initial path. F = 174.097 MHz (600000 mesh tetrahedra).

Geometrical tolerances

- The geometrical tolerances for a long RFQ are severe due to the mode contamination from TE21n (spurious quadrupoles) and TE11n (dipole) modes, whose frequencies can be very close to the operating mode.

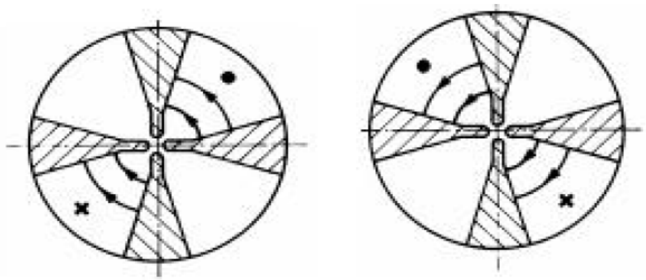
Perturbation to the nominal geometry ⇨ Accelerating mode is not pure

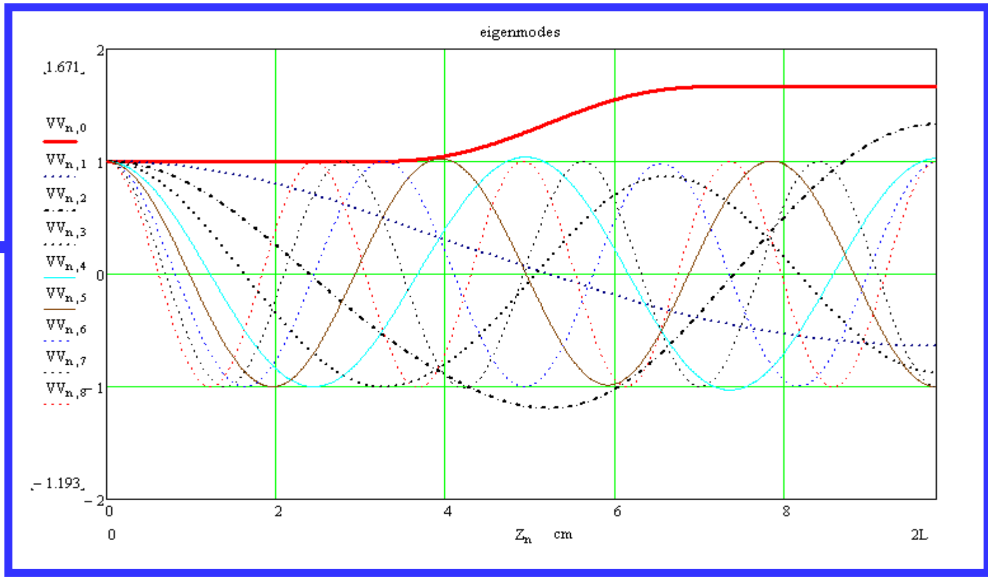
TE_{21n}



TE_{11n}

(dipole modes)





Geometrical tolerances

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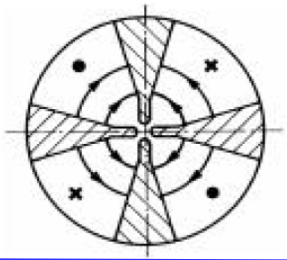
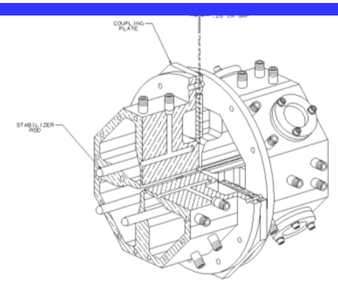
Perturbation to the nominal geometry ⇨ Accelerating mode is not pure

TE_{21n}

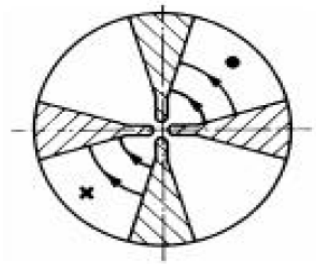


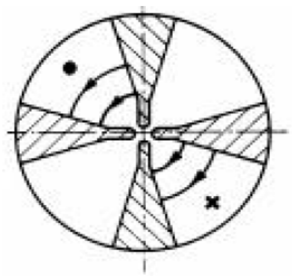
No resonant coupling

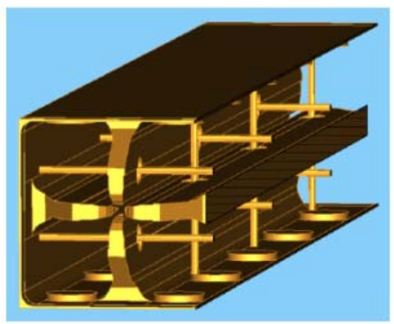


TE_{11n}

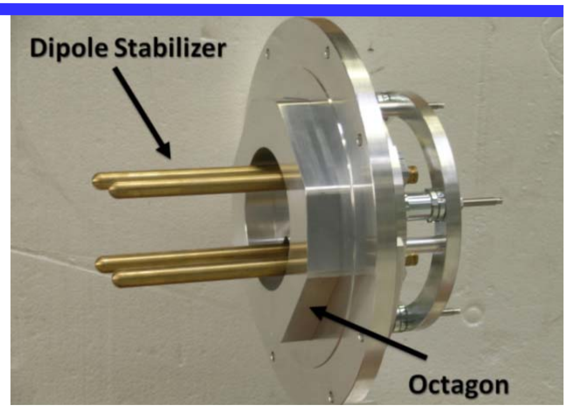
(dipole modes)







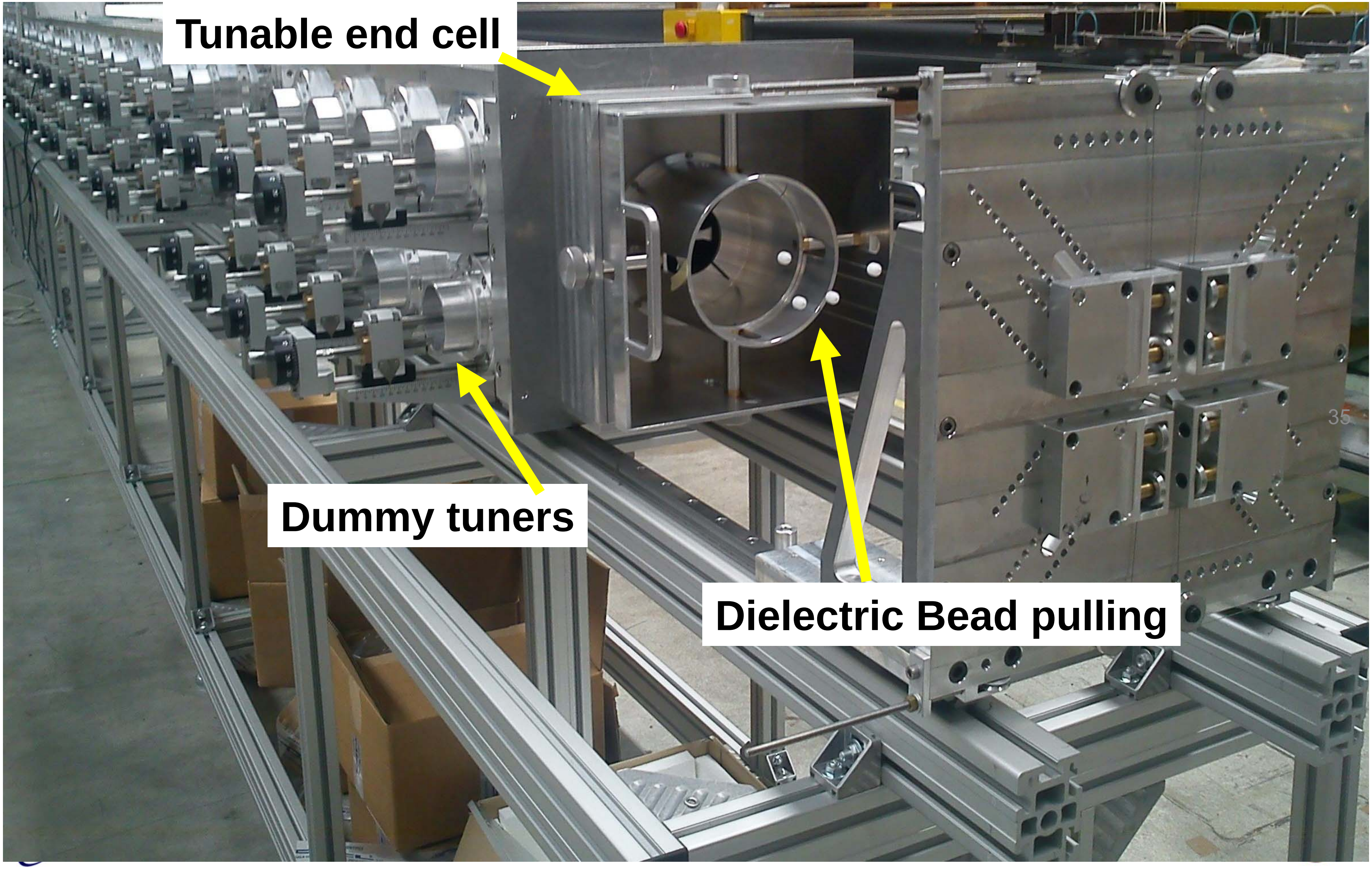
No PILS dipole stabilizers



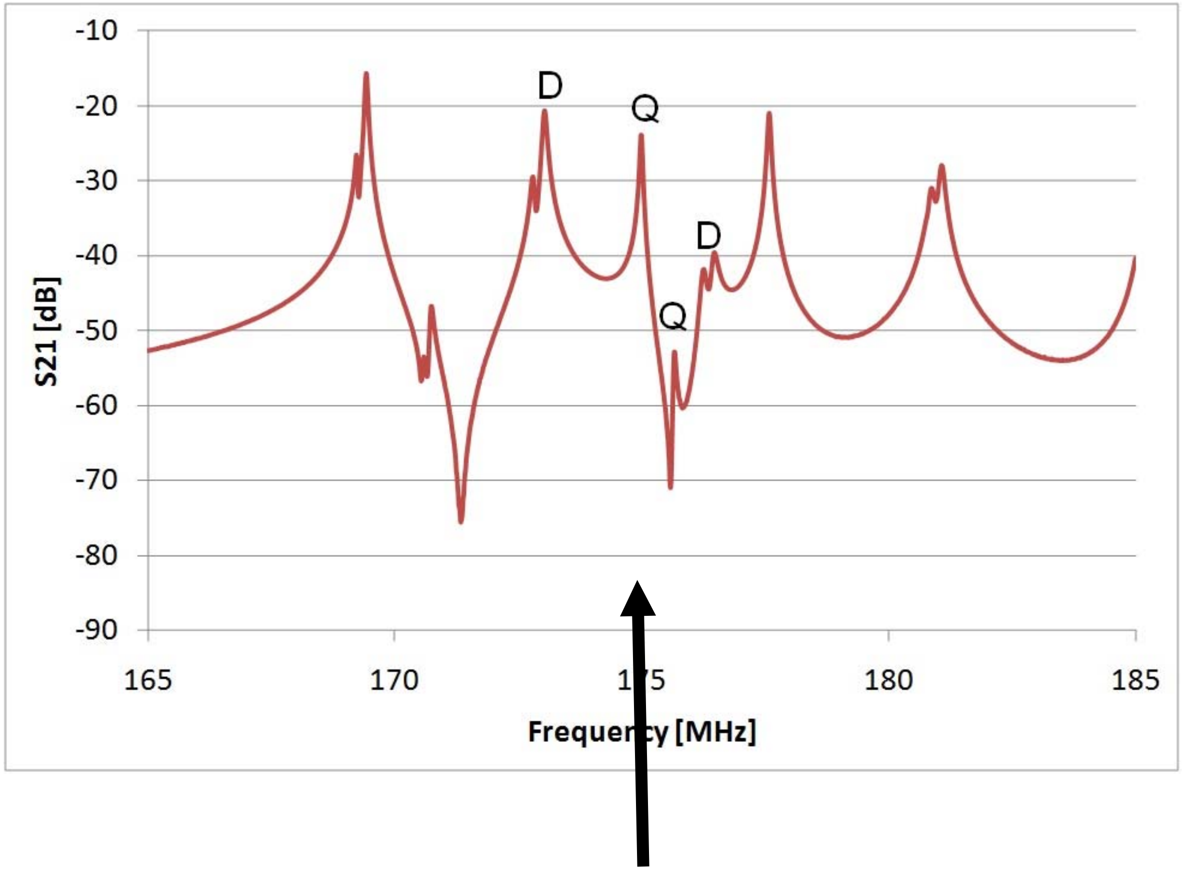
Yes

Dipole rod termination

The aluminum real-scale RFQ model (9.8 meters long)

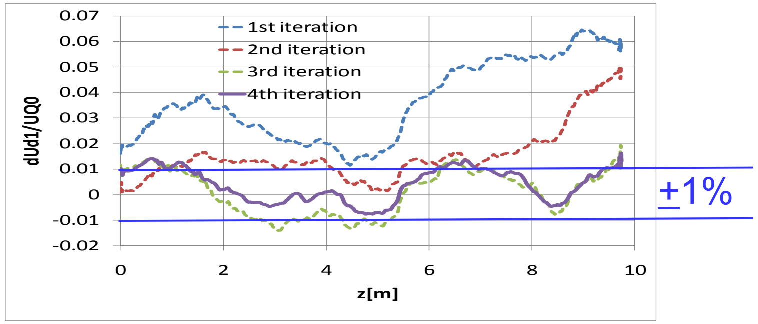


9.8 m model: tuning results

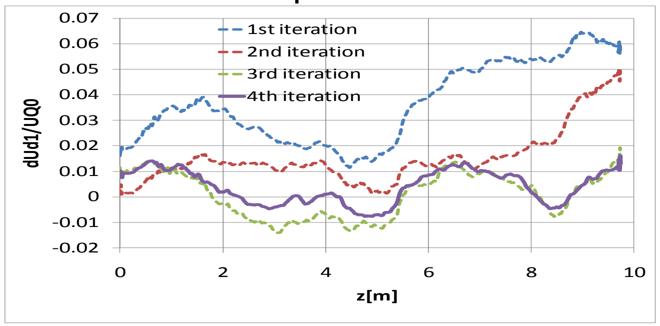


Operating mode; symmetric dipoles

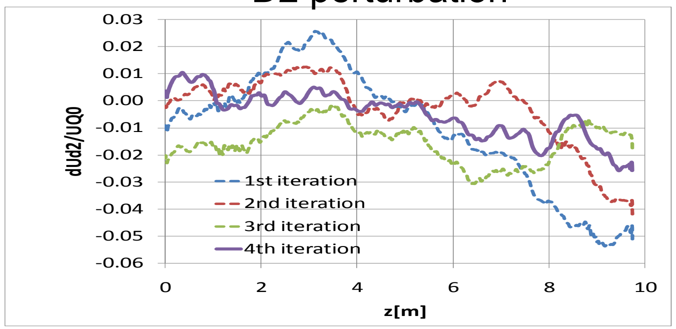
Q perturbation



D1 perturbation



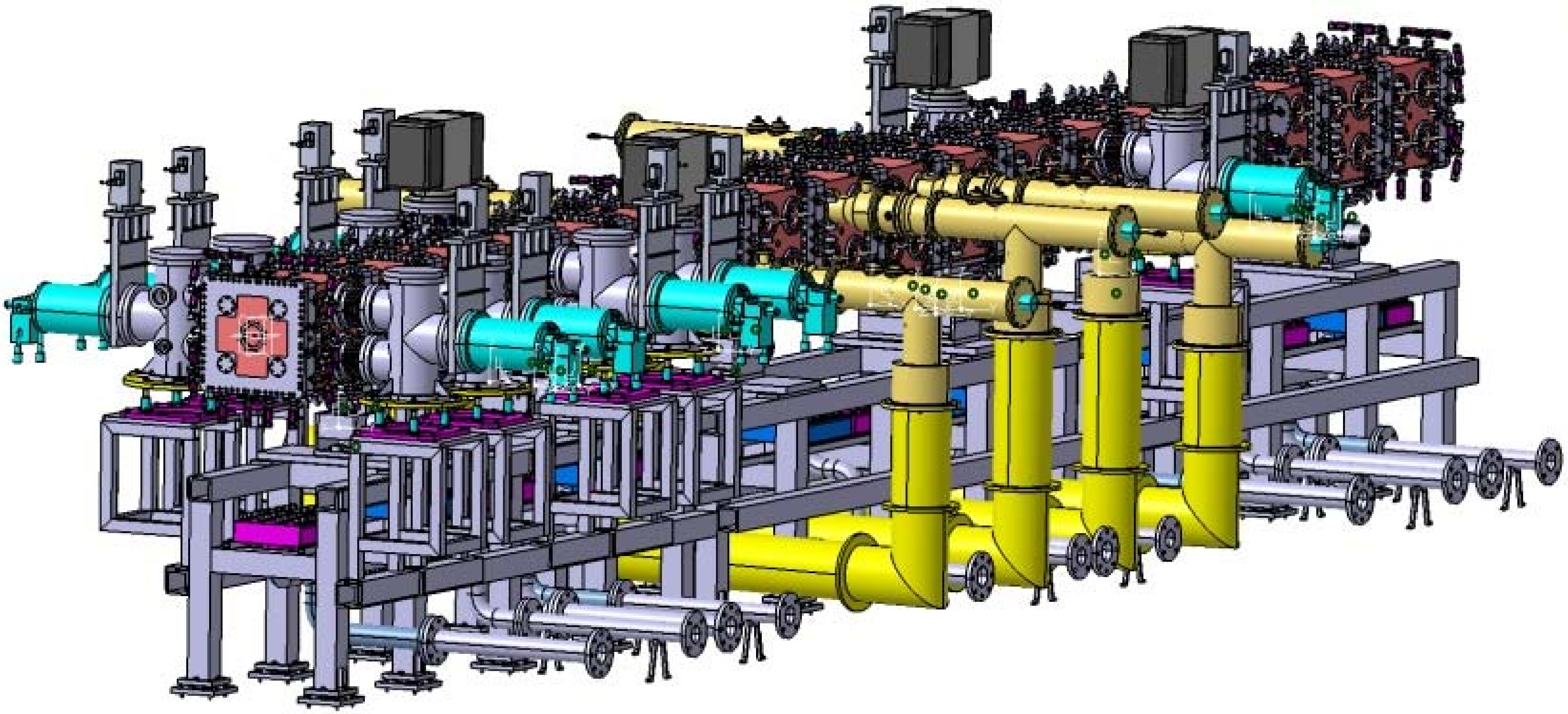
D2 perturbation



After 4 iteration we can achieve a voltage error of +/- 1%

Modules construction

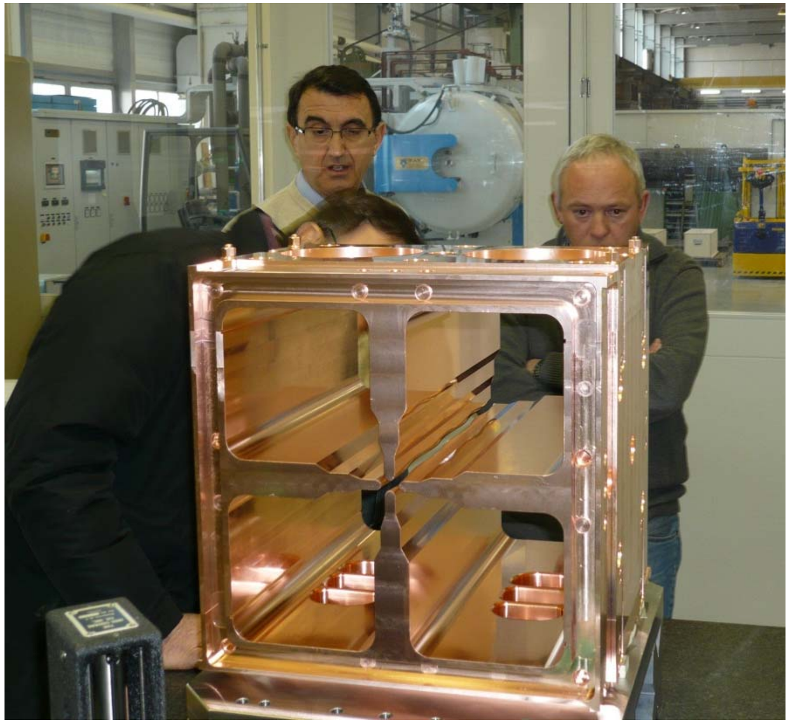
RF cavities built in three supermodules (6 modules each)



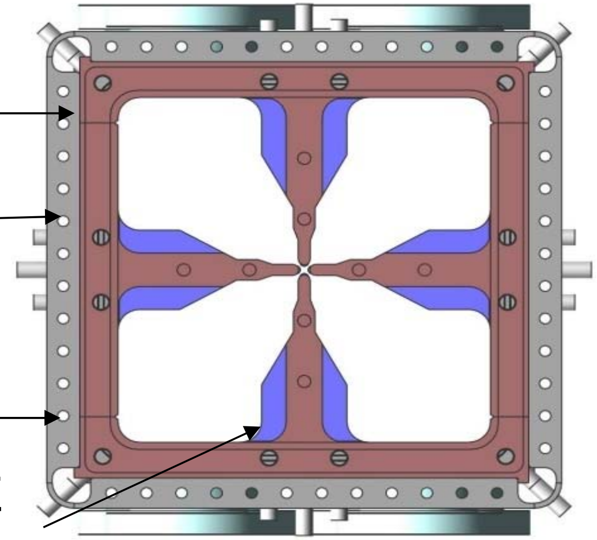
- High energy SM in construction at Cinel, Padua (Italy), Intemediate energy in INFN Padova, Low energy by RI Koln (Germany)

Mechanical design

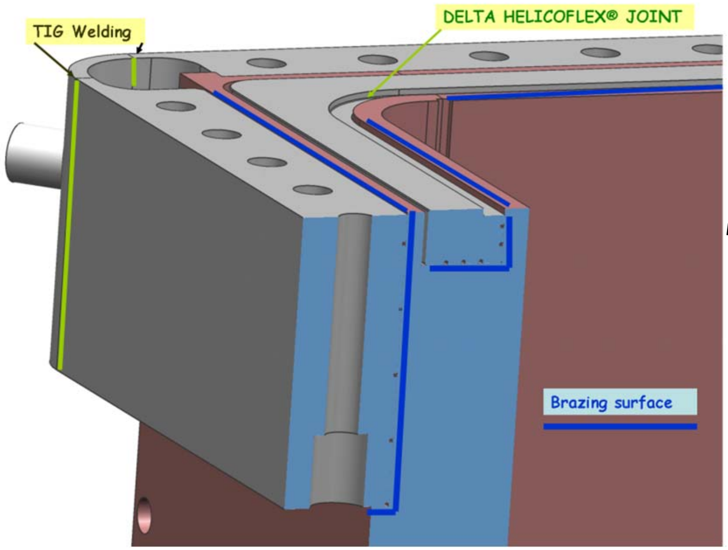
- **Based on vacuum brazing, LNL experience with TRASCO,** CERN experience for RFQ brazing, design compatible with oven at CERN, LNL and in industry (**up to now three modules brazed at CERN, Cinel and LNL respectively**)
- Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass amount (length **550 mm).**
- To minimize the use of Ultra-pure CUC2 and to limit the induced stresses on the raw material, a rough-cut of the shape of the module components from a starting block of about 500x280x570 mm will be performed, by using a EDM (wire electroerosion).
- The accelerator is composed by 18 of these modules.



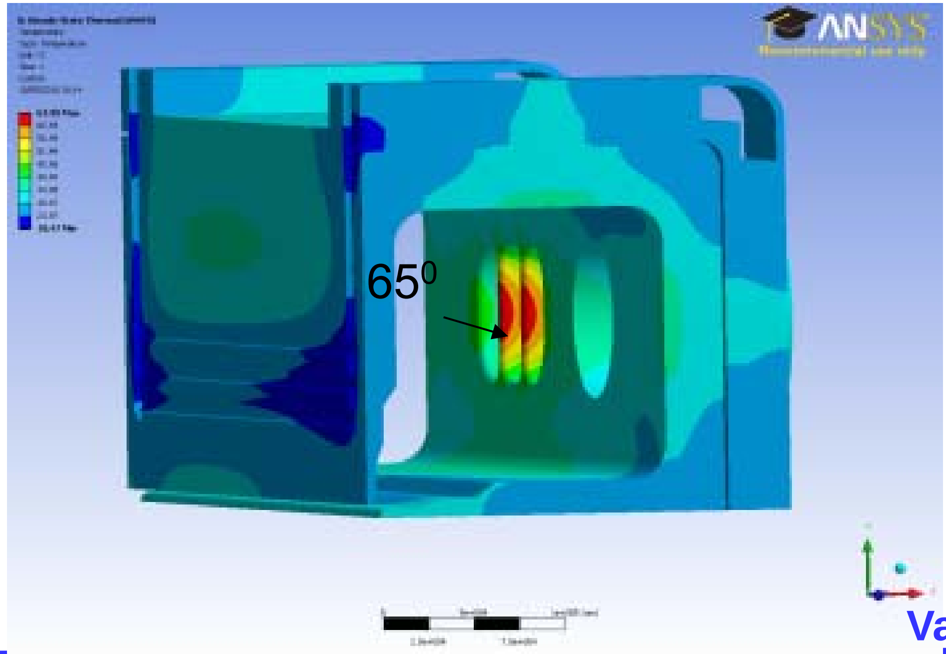
Prototype before brazing at CERN

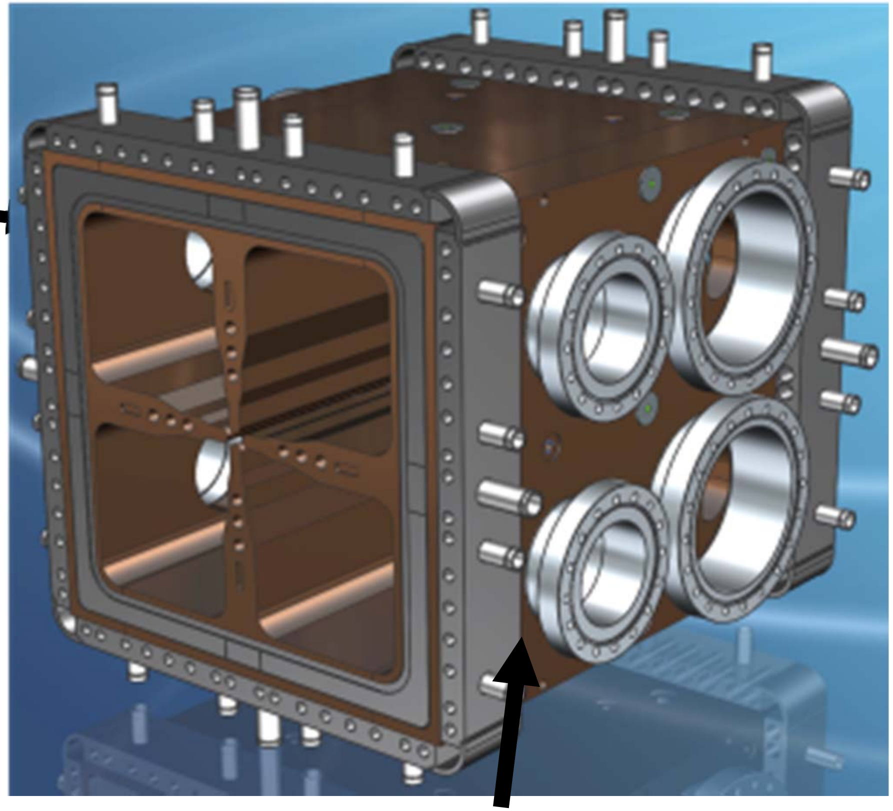


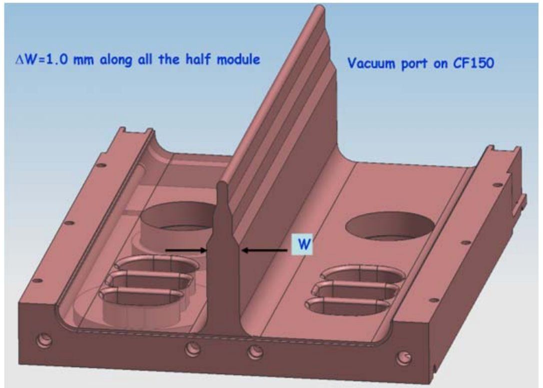
Mechanics details



Head flange



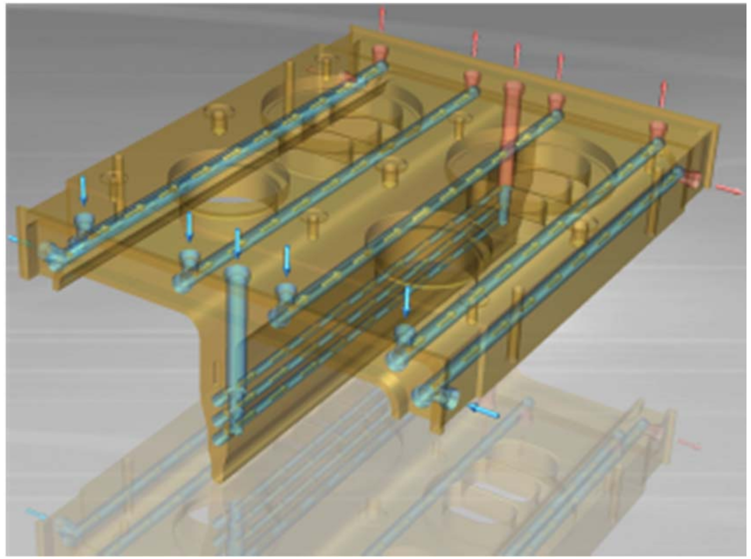


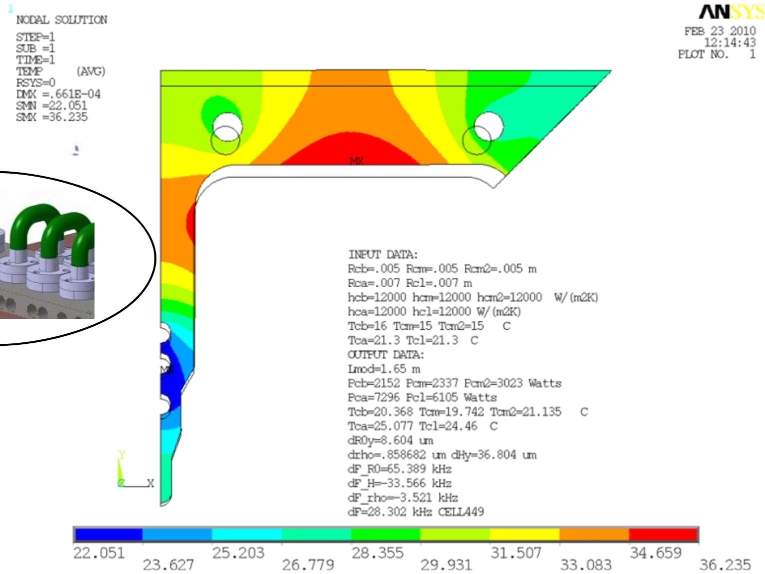


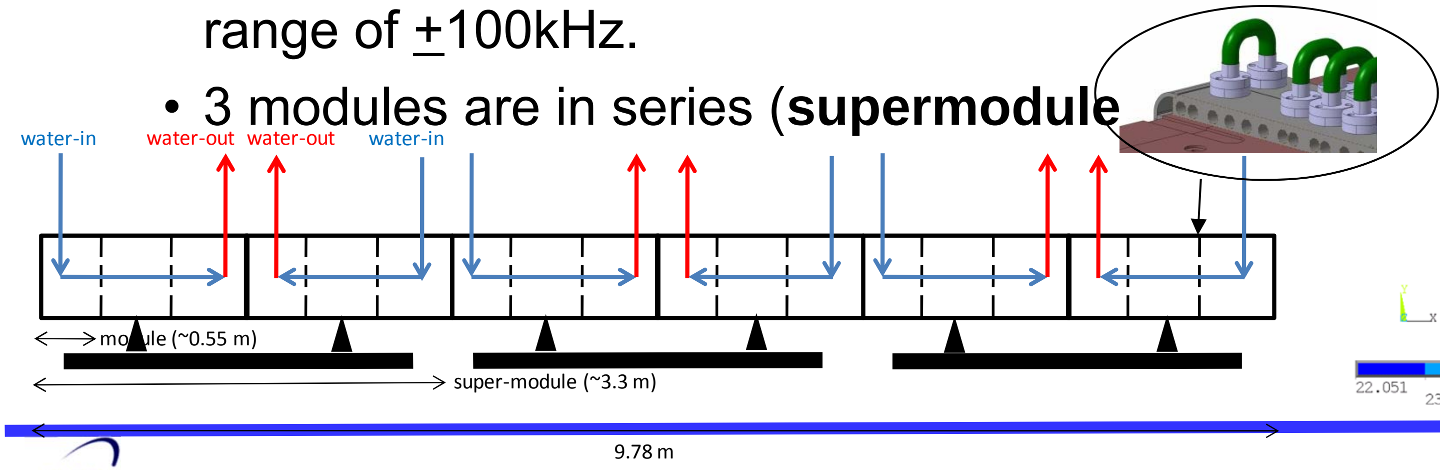
Vacuum grids machined from bulk

Cooling circuit

- About **600 kW RF power** are removed by means of **28 channels** longitudinally drilled along the RFQ modules; the water velocity is approximately 3 m/s,
- **12 channels at fixed low temperature** on the **vanes**
- **16 channels on the cavity wall** with variable temperature for **frequency tuning**
- the temperature of the channels on the vane and on the cavity wall can be separately tuned so to achieve a tuning range of ±100kHz.
- 3 modules are in series (**supermodule**



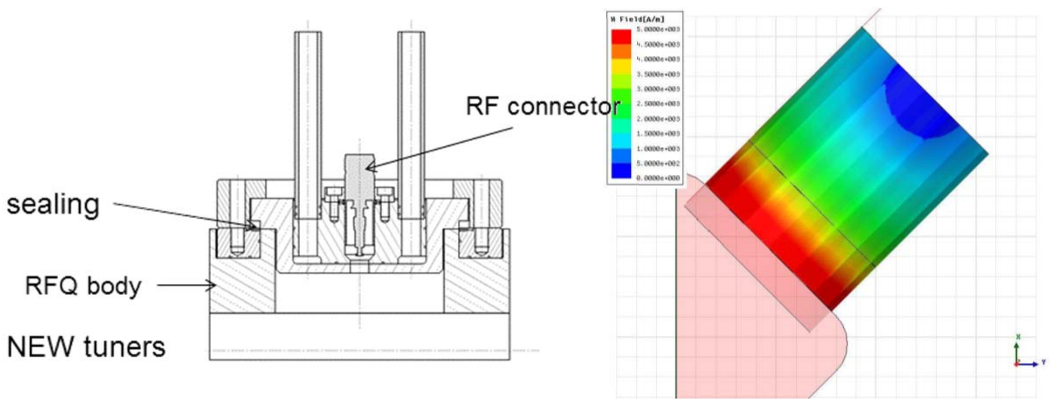




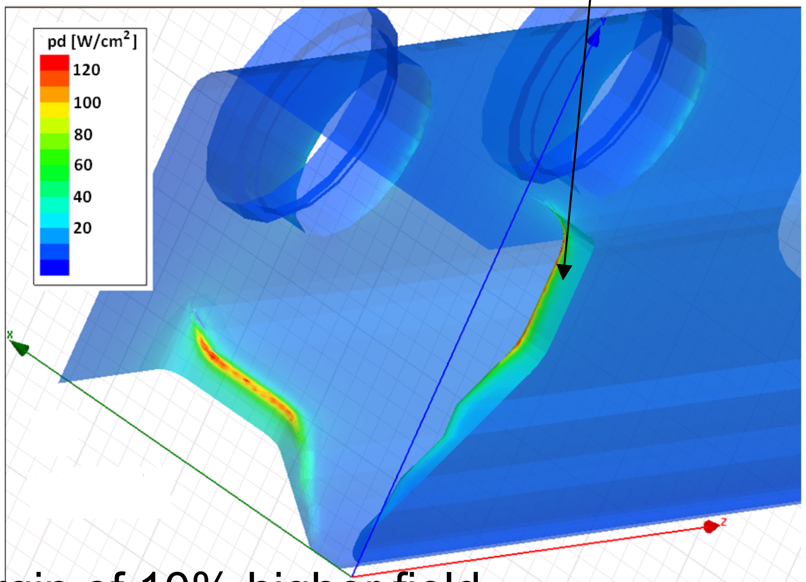
3D details

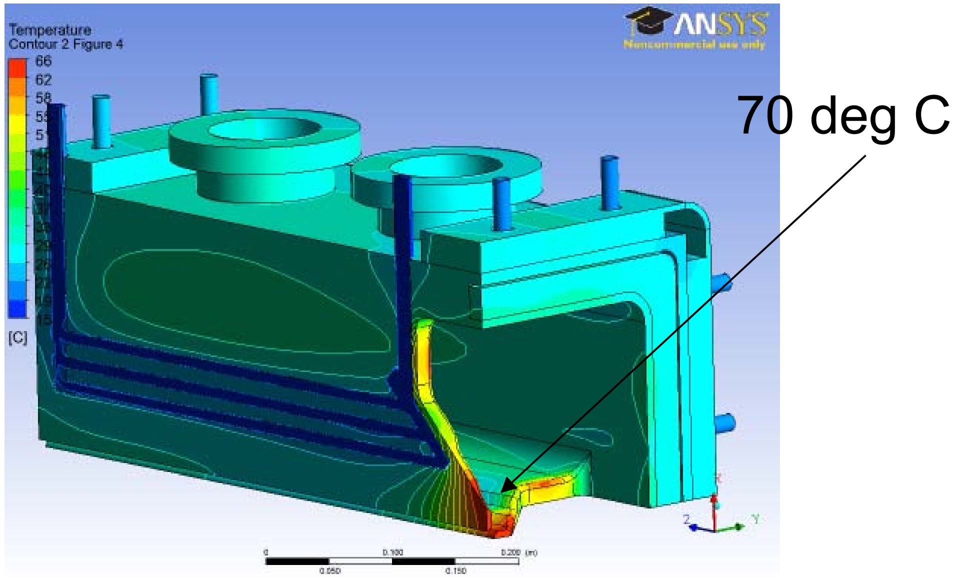
- Dummy tuners, vacuum grids and end cells
- In the end cell the 45° angle of the undercut guarantees the access of the cooling channel as close as possible to the hot spot at the electrode base **(~80 W/cm2*)**, which is the most severe of the entire RFQ
- Deformations of 70 um and field perturbation less than 1%

Slug tuners (CF100)



Tuning range ±1 MHz

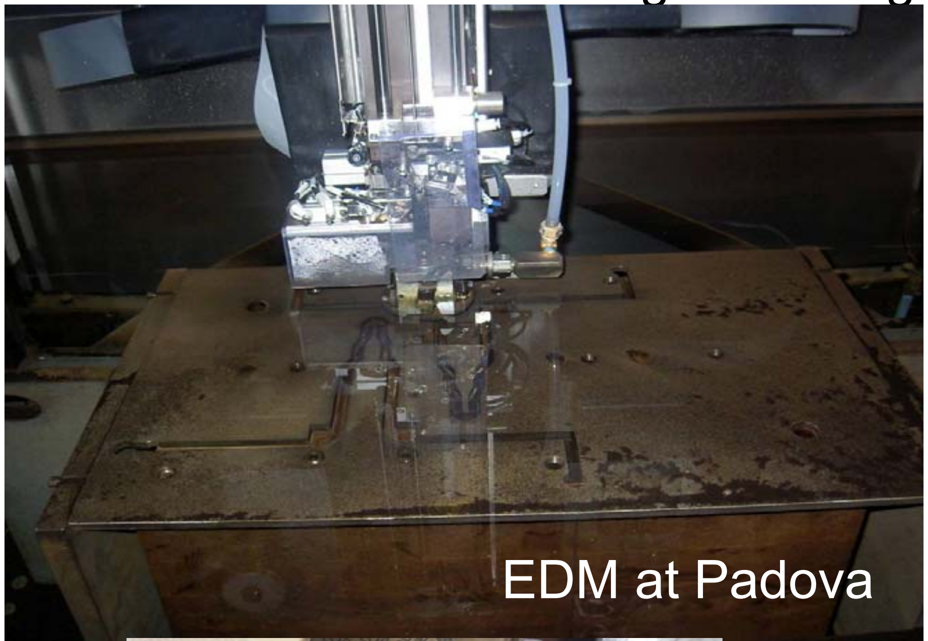




*with margin of 10% higher field

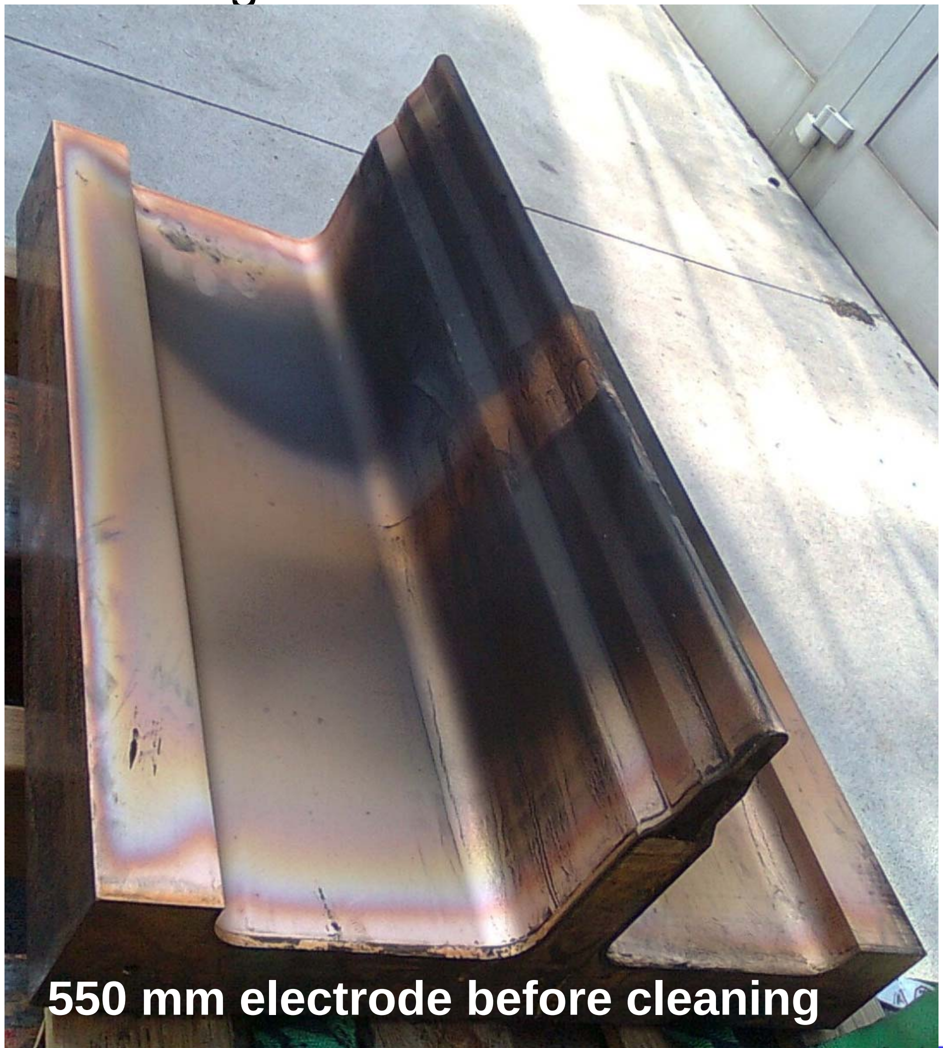
First construction step module n0 16

- Rough machining of block 550 mm long vie EDM for minimal stresses and deformations during annealing and brazing



EDM at Padova

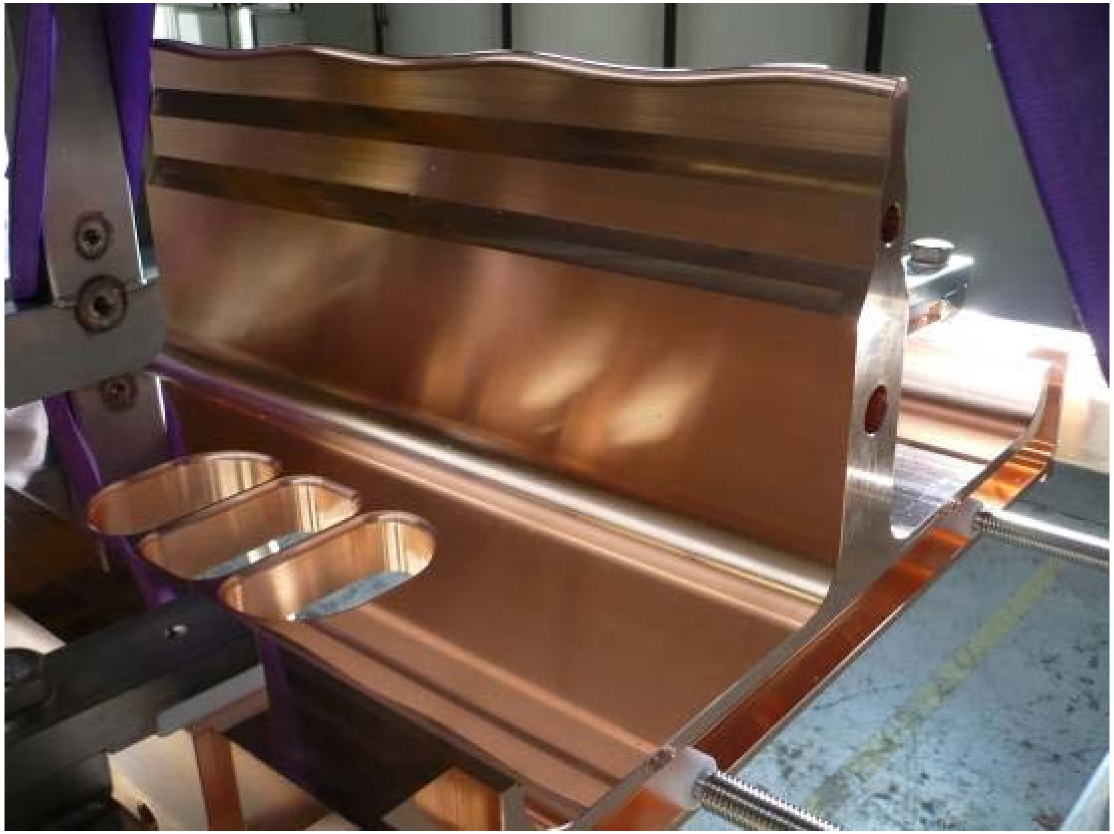
Remaining cupper



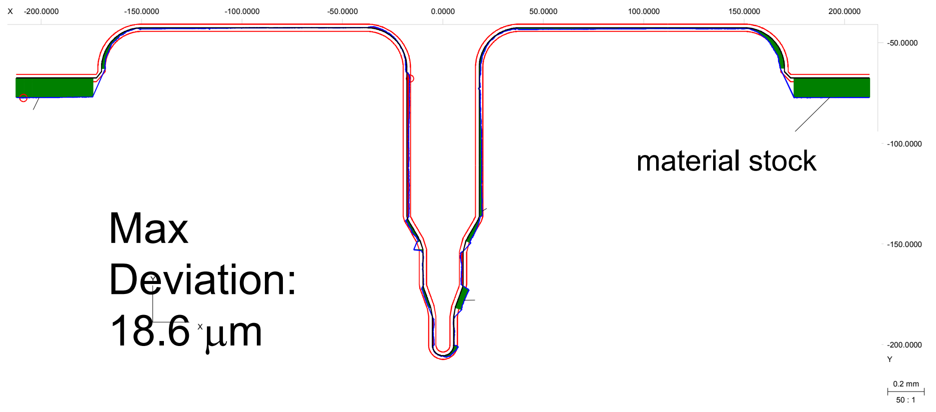
550 mm electrode before cleaning

Finishing

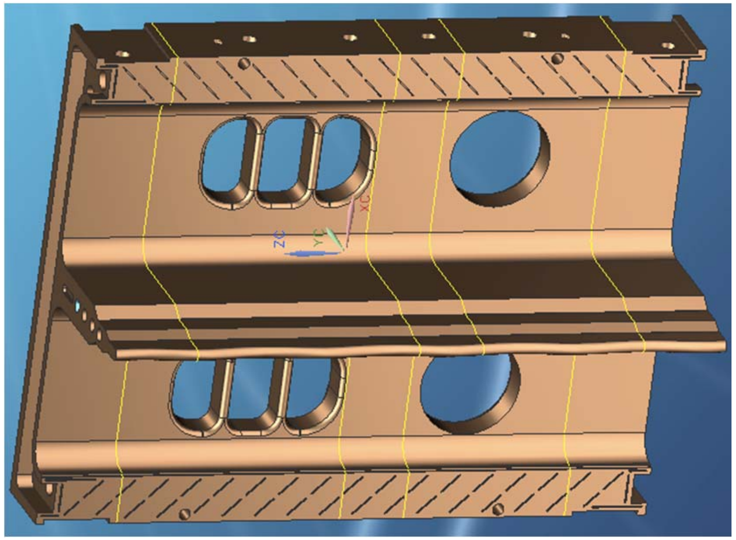
- 0.7 um roughness
- 3d modulation
- 20 um tolerances on vane tip geometry

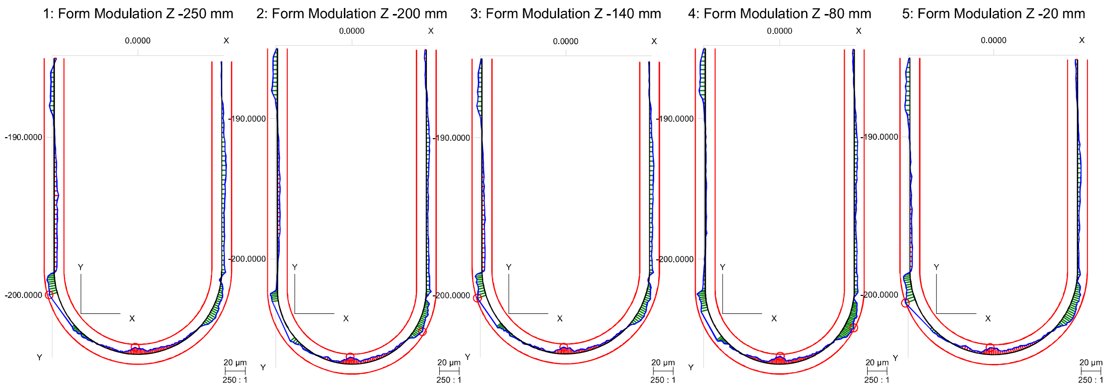


Four electrodes of module #16 electrodes (machined by Cinel) in specs

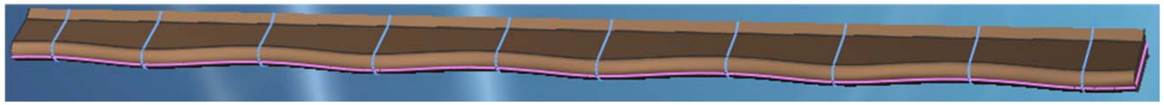


Max Deviation: 18.6 µm

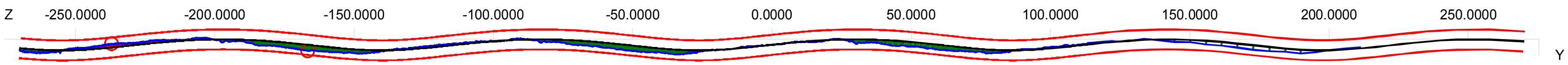




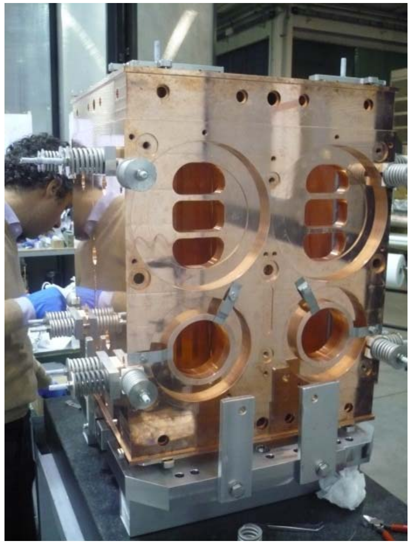
Max Deviation: 10.5 µm

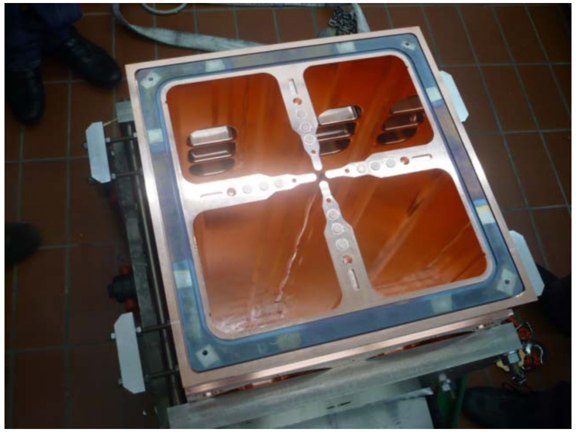


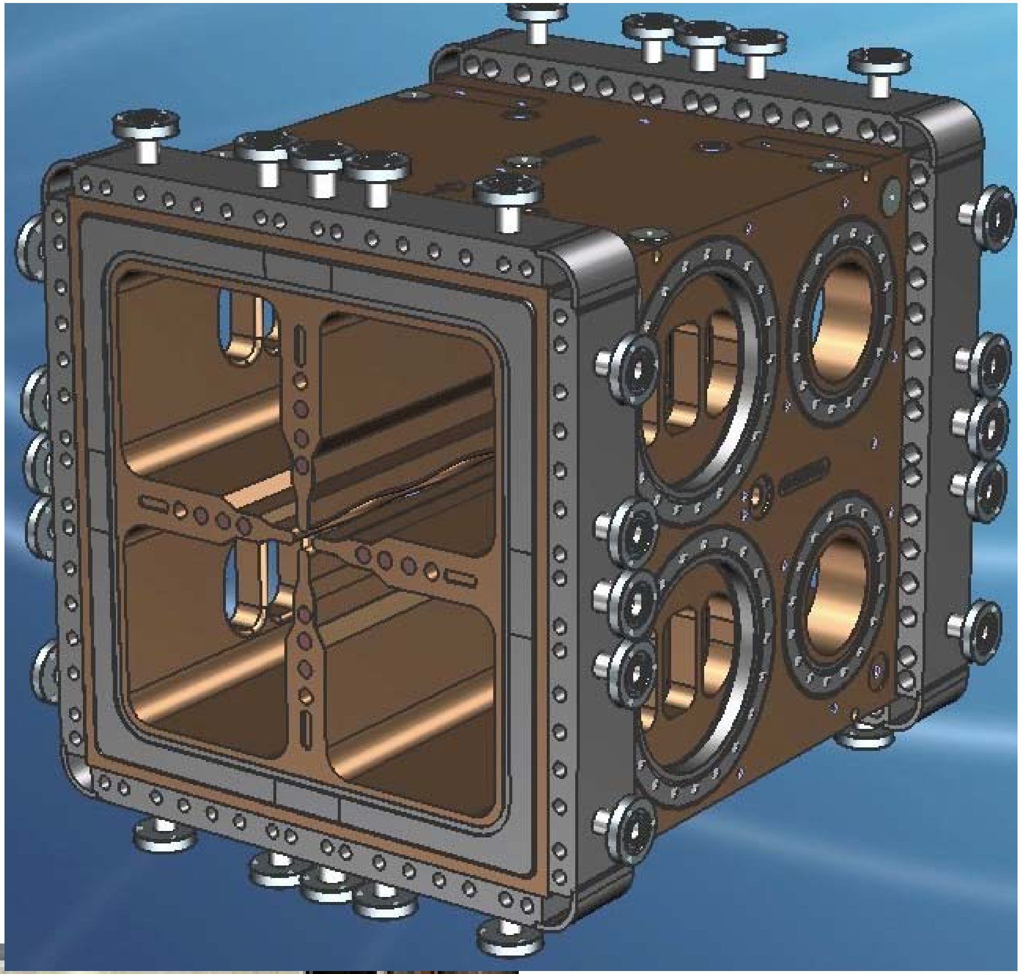
Max Deviation: 6.1 µm

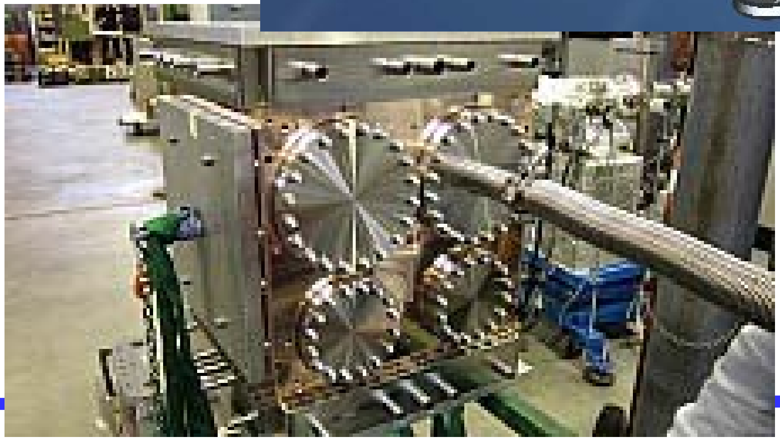


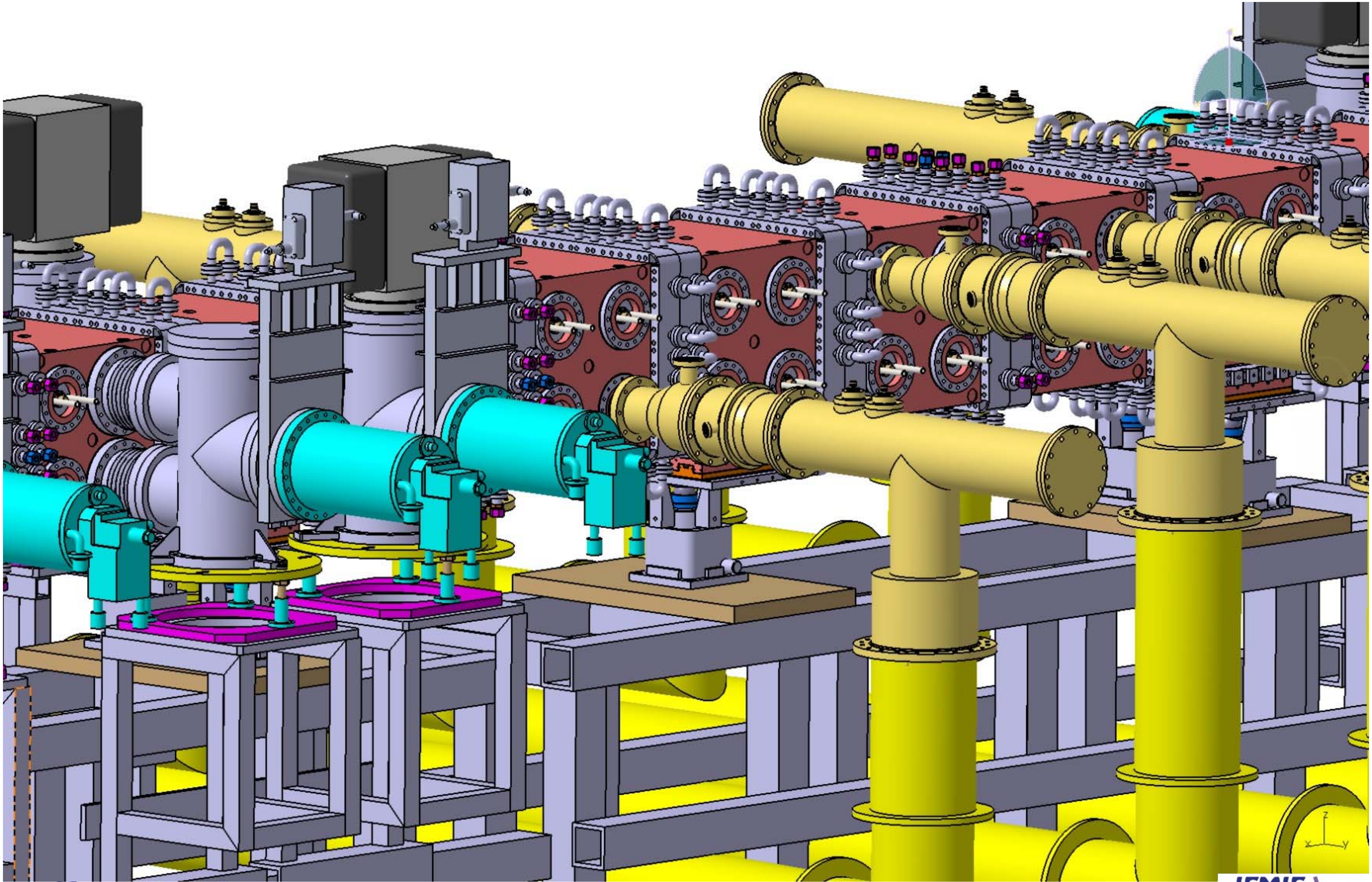
Module 16 construction

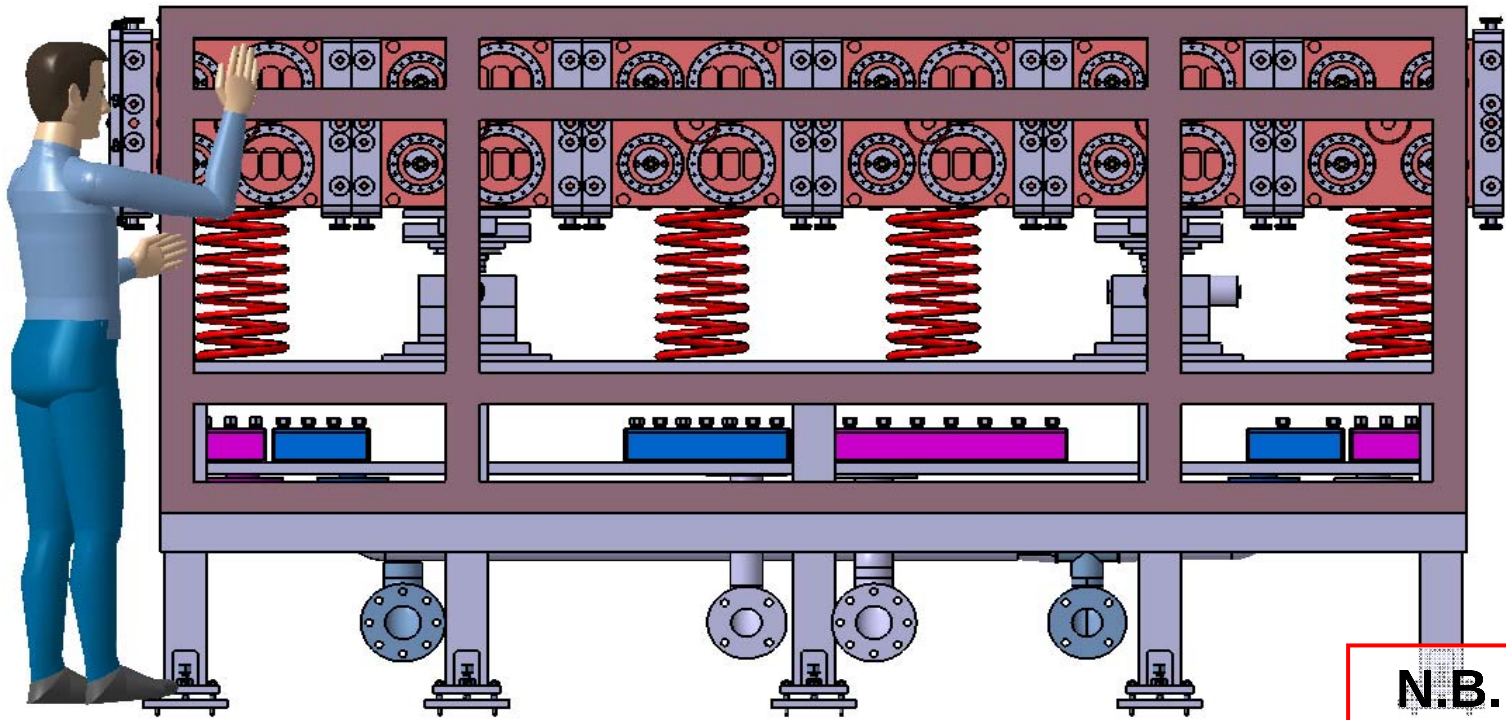


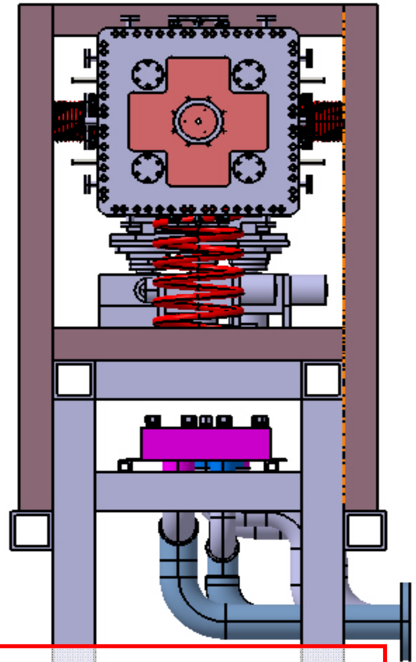












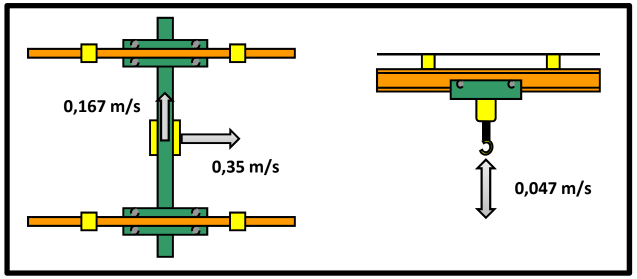
3300x900x1700 mm [LxWxH];

4000 kg;

N.B. Lifting equipment and elastic supports are **conceptual**

Dedicated lifting equipment (under study) to be coupled with the supporting frame;

Update characteristics of the crane in the accelerator vault.



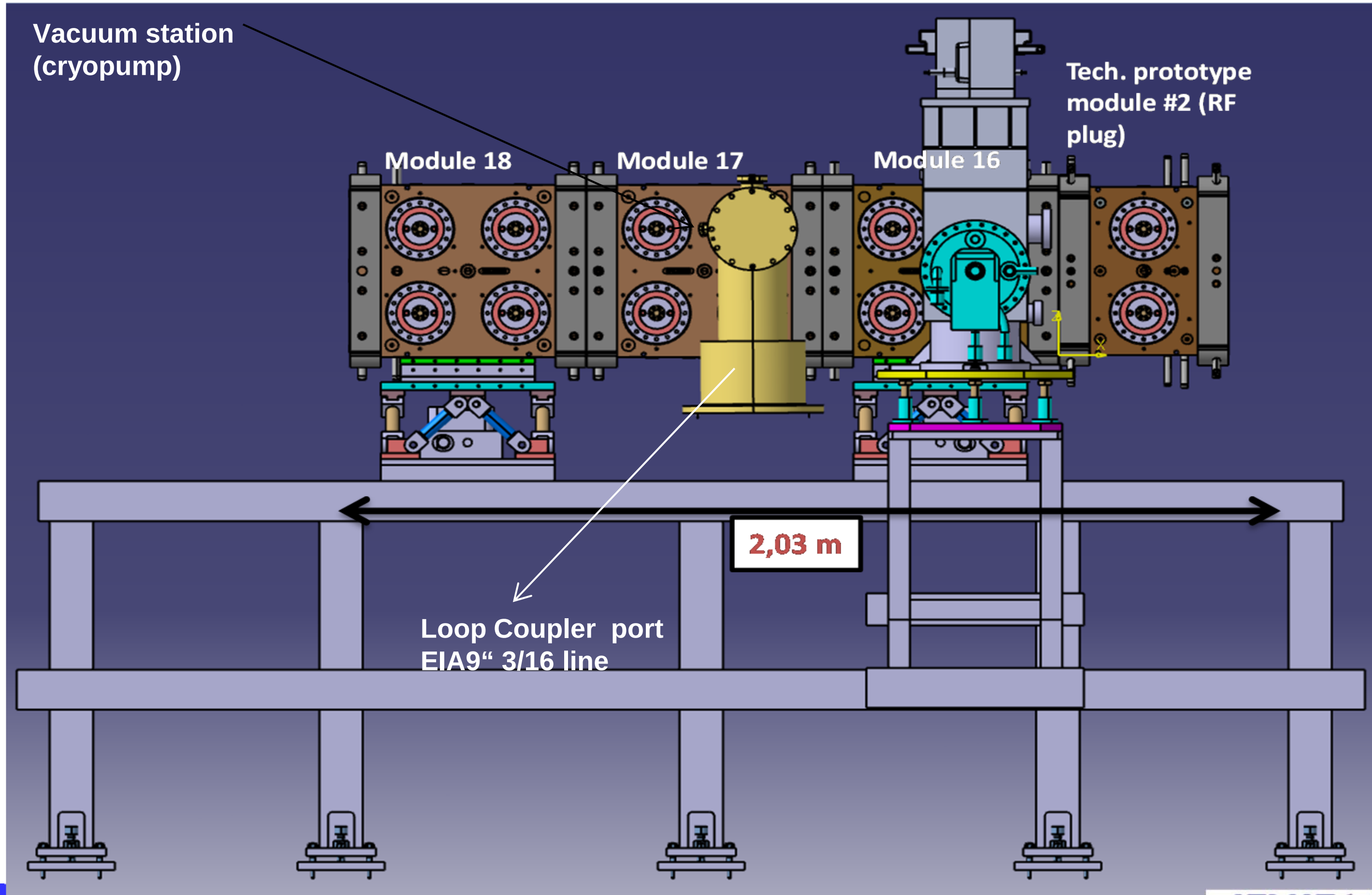
Temporary vertical shock absorbers on the mechanical supporting frame

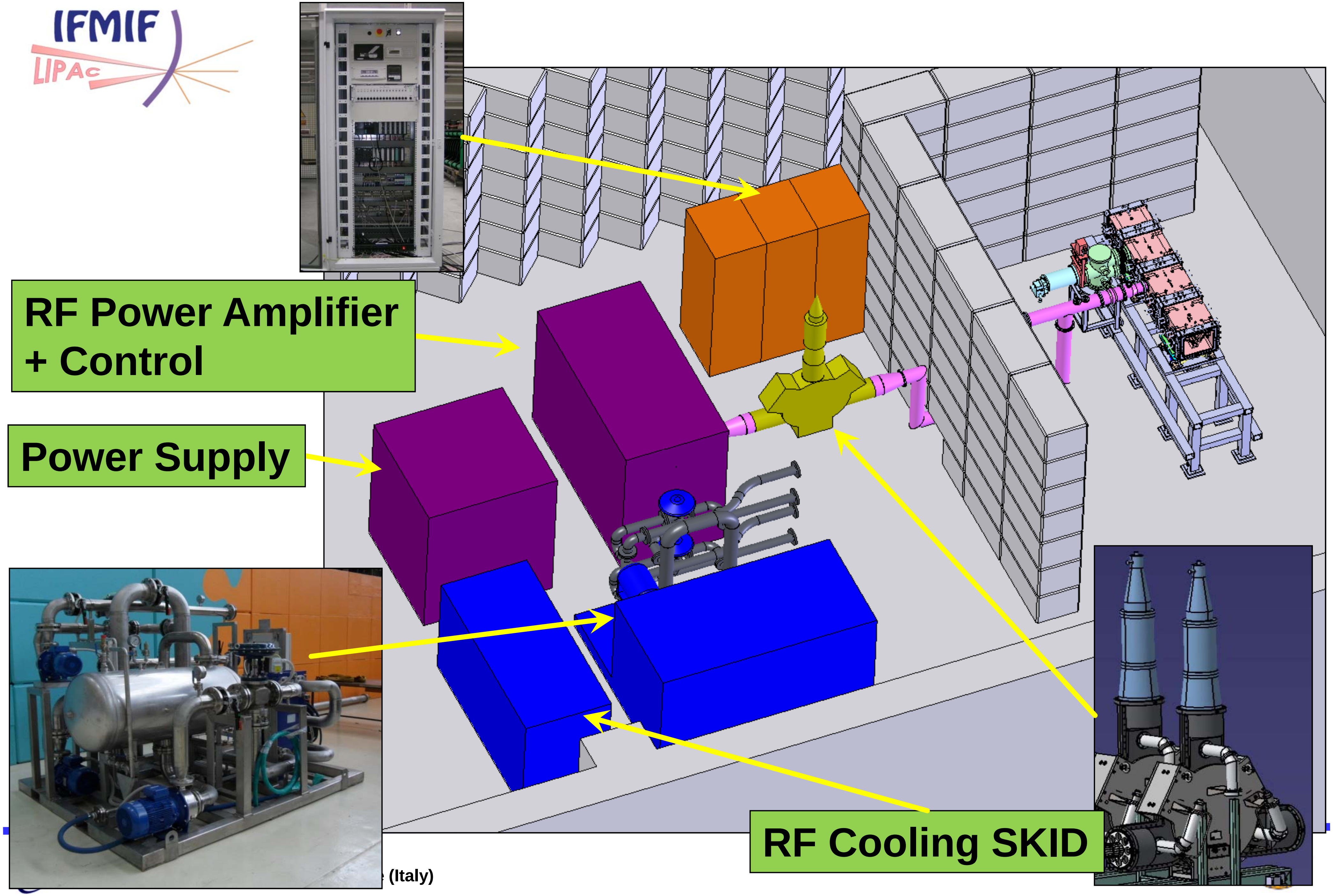
IFMIF HIGH POWERTESTS in LNL (2013)

- Module #16,17 and 18 of the RFQ
- Technological prototype module #2 as RF plug.
- Power coupler by JAEA
- 16 loop-equipped tuners for field sampling

- IFMIF-RFQ test skid
- Vacuum system (test manifolds)
- Control system

f= 175 MHz
L=2.02 m (2/9 of the overall length)
P(L)≈200 kW (V=132 kV, Es=1.8 Kp)
1 loop power coupler



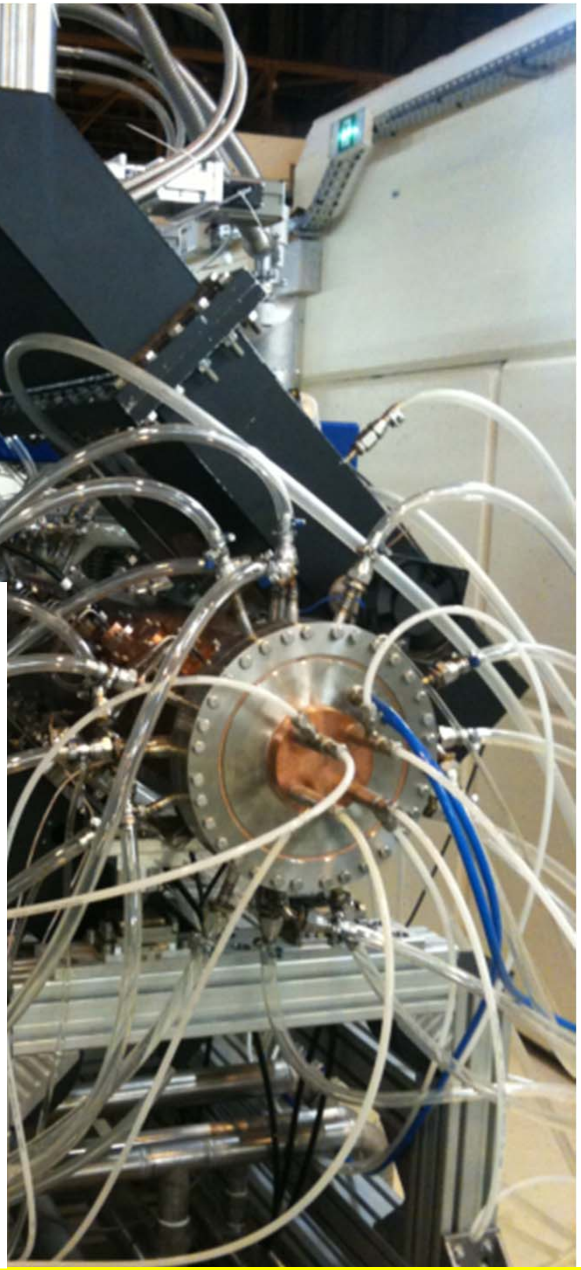

RF Power Amplifier
+ Control
Power Supply
RF Cooling SKID

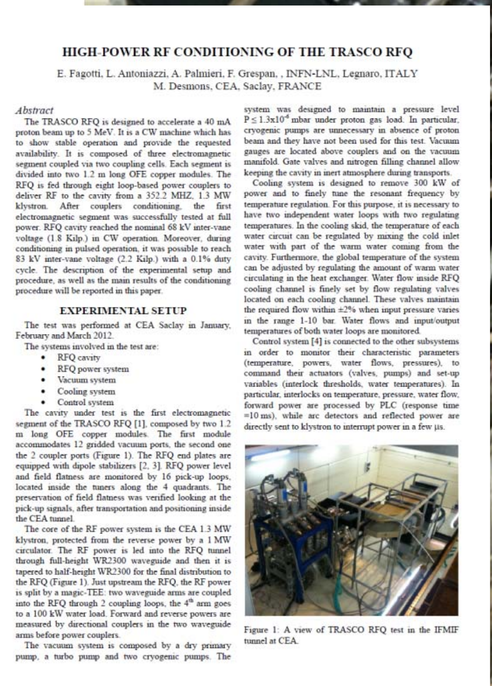
Within IFMIF program the RFQ of TRASCO has been tested at Saclay (CEA)

stable condition cw

nominal field

80kW/m, 1.8 Ekp





HIGH-POWER RF CONDITIONING OF THE TRASCO RFQ

E. Fagotti, L. Antoniazzi, A. Palmieri, F. Grespan, , INFN-LNL, Legnaro, ITALY
M. Desmons, CEA, Saclay, FRANCE

Abstract

The TRASCO RFQ is designed to accelerate a 40 mA proton beam up to 5 MeV. It is a CW machine which has to show stable operation and provide the requested availability. It is composed of three electromagnetic segment coupled via two coupling cells. Each segment is divided into two 1.2 m long OFE copper modules. The RFQ is fed through eight loop-based power couplers to deliver RF to the cavity from a 352.2 MHZ, 1.3 MW klystron. After couplers conditioning, the first electromagnetic segment was successfully tested at full power. RFQ cavity reached the nominal 68 kV inter-vane voltage (1.8 Kilp.) in CW operation. Moreover, during conditioning in pulsed operation, it was possible to reach 83 kV inter-vane voltage (2.2 Kilp.) with a 0.1% duty cycle. The description of the experimental setup and procedure, as well as the main results of the conditioning procedure will be reported in this paper.

EXPERIMENTAL SETUP

The test was performed at CEA Saclay in January, February and March 2012.

The systems involved in the test are:

- RFQ cavity
- RFQ power system
- Vacuum system
- Cooling system
- Control system

The cavity under test is the first electromagnetic segment of the TRASCO RFQ [1], composed by two 1.2 m long OFE copper modules. The first module accommodates 12 gridded vacuum ports, the second one the 2 coupler ports (Figure 1). The RFQ end plates are equipped with dipole stabilizers [2, 3]. RFQ power level and field flatness are monitored by 16 pick-up loops, located inside the tuners along the 4 quadrants. The preservation of field flatness was verified looking at the pick-up signals, after transportation and positioning inside the CEA tunnel.

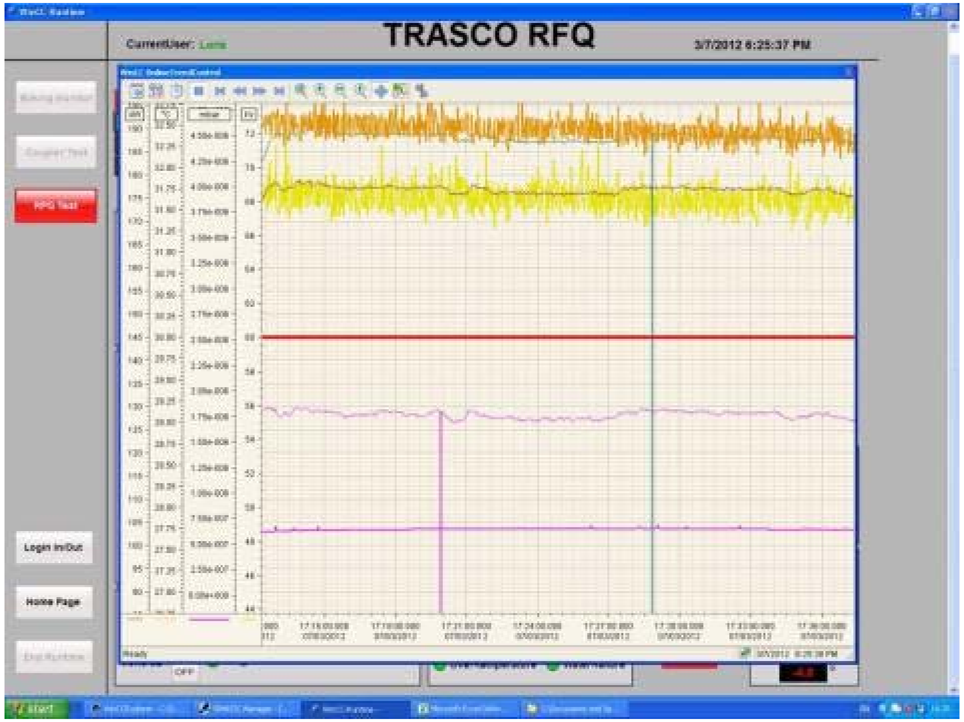
The core of the RF power system is the CEA 1.3 MW klystron, protected from the reverse power by a 1 MW circulator. The RF power is led into the RFQ tunnel through full-height WR2300 waveguide and then it is tapered to half-height WR2300 for the final distribution to the RFQ (Figure 1). Just upstream the RFQ, the RF power is split by a magic-TEE: two waveguide arms are coupled into the RFQ through 2 coupling loops, the 4th arm goes to a 100 kW water load. Forward and reverse powers are measured by directional couplers in the two waveguide arms before power couplers.

The vacuum system is composed by a dry primary pump, a turbo pump and two cryogenic pumps. The system was designed to maintain a pressure level $P \leq 1.3 \times 10^{-6}$ mbar under proton gas load. In particular, cryogenic pumps are unnecessary in absence of proton beam and they have not been used for this test. Vacuum gauges are located above couplers and on the vacuum manifold. Gate valves and nitrogen filling channel allow keeping the cavity in inert atmosphere during transports.

Cooling system is designed to remove 300 kW of power and to finely tune the resonant frequency by temperature regulation. For this purpose, it is necessary to have two independent water loops with two regulating temperatures. In the cooling skid, the temperature of each water circuit can be regulated by mixing the cold inlet water with part of the warm water coming from the cavity. Furthermore, the global temperature of the system can be adjusted by regulating the amount of warm water circulating in the heat exchanger. Water flow inside RFQ cooling channel is finely set by flow regulating valves located on each cooling channel. These valves maintain the required flow within ±2% when input pressure varies in the range 1-10 bar. Water flows and input/output temperatures of both water loops are monitored.

Control system [4] is connected to the other subsystems in order to monitor their characteristic parameters (temperature, powers, water flows, pressures), to command their actuators (valves, pumps) and set-up variables (interlock thresholds, water temperatures). In particular, interlocks on temperature, pressure, water flow, forward power are processed by PLC (response time =10 ms), while arc detectors and reflected power are directly sent to klystron to interrupt power in a few μs.

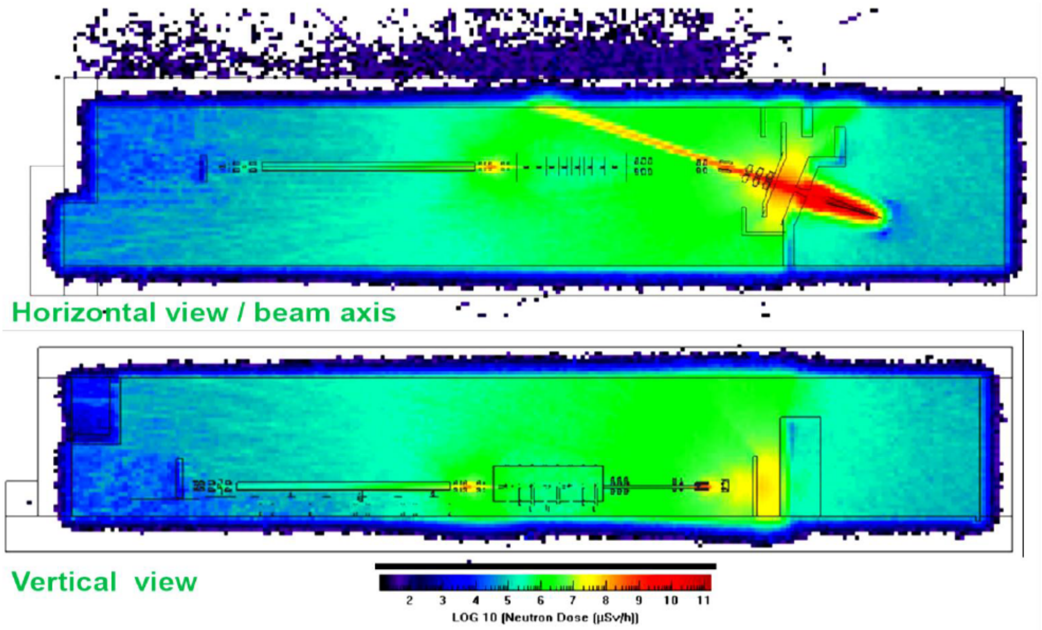
Figure 1: A view of TRASCO RFQ test in the IFMIF tunnel at CEA.

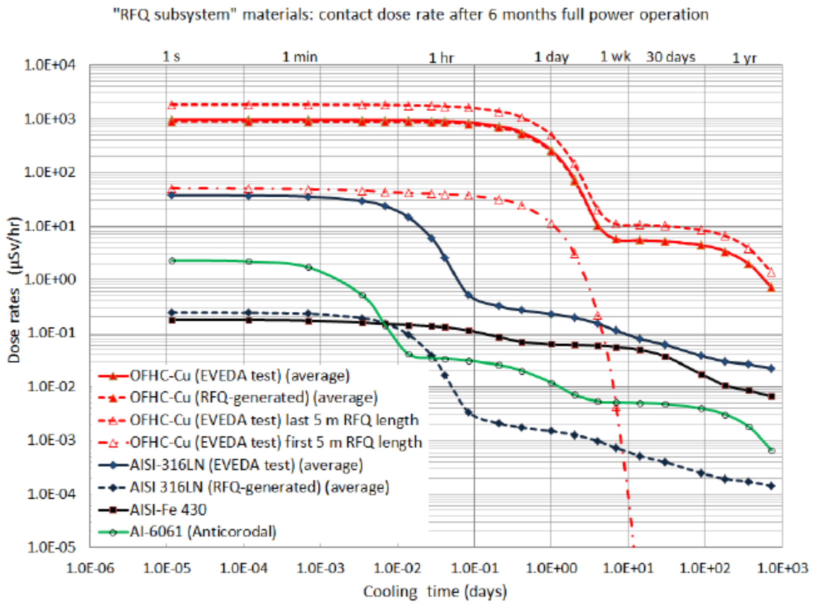


E. Fagotti et al, results published at linac12 conference and this conference

Beam operation aspects

- PPS (personal protection system)
- The beam hall is of course close during operation
- Activation after beam stop has to be evaluated in the various cases (see for example RFQ activation after 6 months operation)





Machine Protection System:

600 kW beam from the RFQ into the cryostat, 1 MW into the beam dump

Purpose of the MPS system:

- Protect the accelerator (beam pipes, cavities, beam dump…) from any damages that could occur, due to the malfunction of a component or due to the mistuning/misalignment of the beam

Inputs:

- **All relevant status/interlock signals from the subsystem LCSs** (vacuum, temperature, cooling, RF, LVPS, valves, slits, BLOMs…)

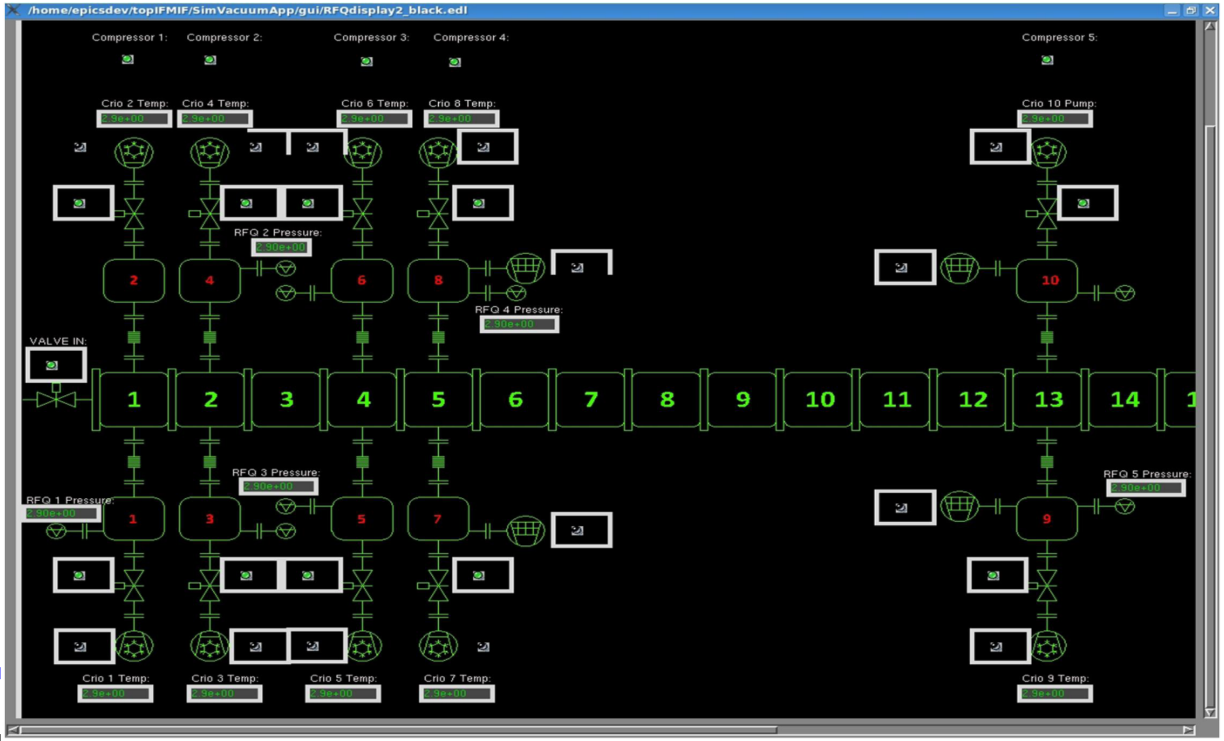
Means of action:

- Stop the beam (pulse reset, fast, slow, CF)
- Close the valves (in line, fast)

Local control system

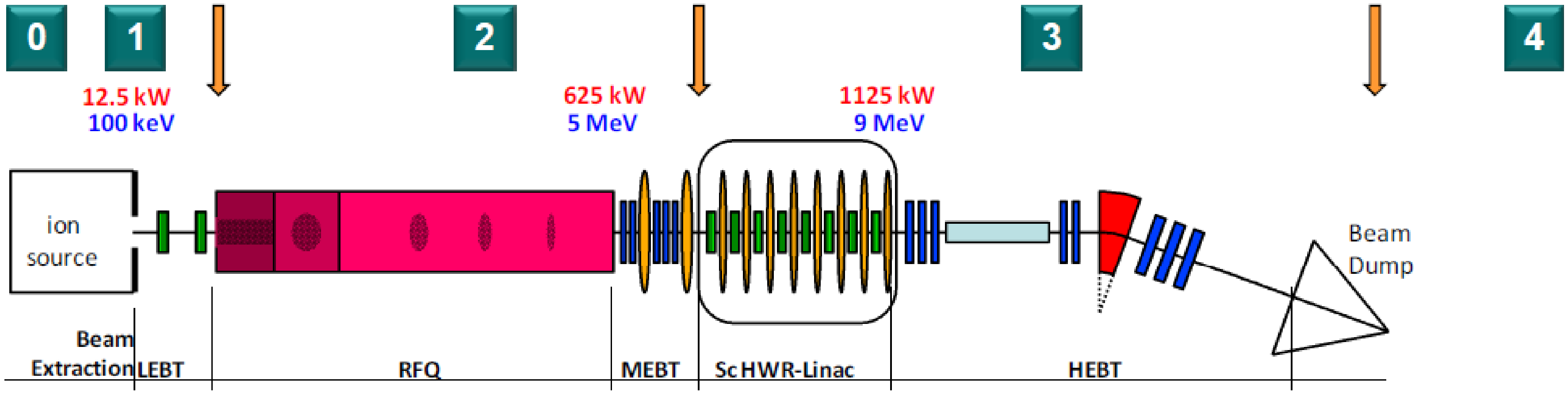
- Based on EPICS and PLC
- Controls Cooling system, Vacuum system, RF signals, interfaces with MPS, PPS and timing
- The group (head by Mauro Giacchini, poster this week)

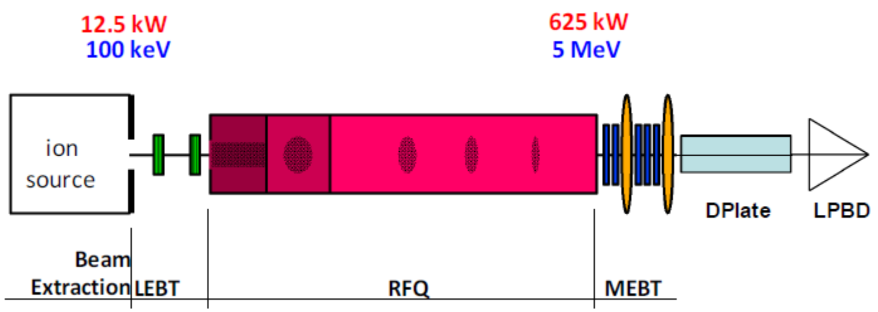
EPICS Vacuum Control System (Simulation)



Beam commissioning phases

Note 2: In stage 2 and 3, the maximum duty cycle in pulsed mode must be determined from activation calculations. Meanwhile, it is arbitrarily fixed to 0.1 % in this document.





The 5 MeV beam is stopped by the LPBD (Low Power Beam Dump)

Conclusions (1/2)

- IFMIF is a high intensity neutron source, based on two high intensity accelerators and a 10 MW liquid lithium target.
- The neutron spectrum is optimized to simulate the spectrum in a fusion reactor (up to 14 MeV)
- Within the Broader Approach agreement (complementary research programs approved together with ITER) the project IFMIF-EVEDA has been launched.
- This program includes a prototype accelerator (1.2 MW) and INFN Italy has the responsibility for the first accelerating structure, the RFQ
- IFMIF EVEDA RFQ is under construction, (12 modules given to industry, 6 modules will be machined at INFN PD and brazed at LNL).
- 4 modules for 200 kW power tests should be ready for the end of 2012

Conclusions (2/2)

- This accelerator development is done in good part within Accelerator division, the same group of people is involved in development an operation of PIAVE-ALPI, and in IFMIF.
- This can create some organization and logistic problem sometimes, but it is at the end a very strong point both for LNL complex operation (young people, up-to-date tools) and for new accelerators development (practical experience in the design).