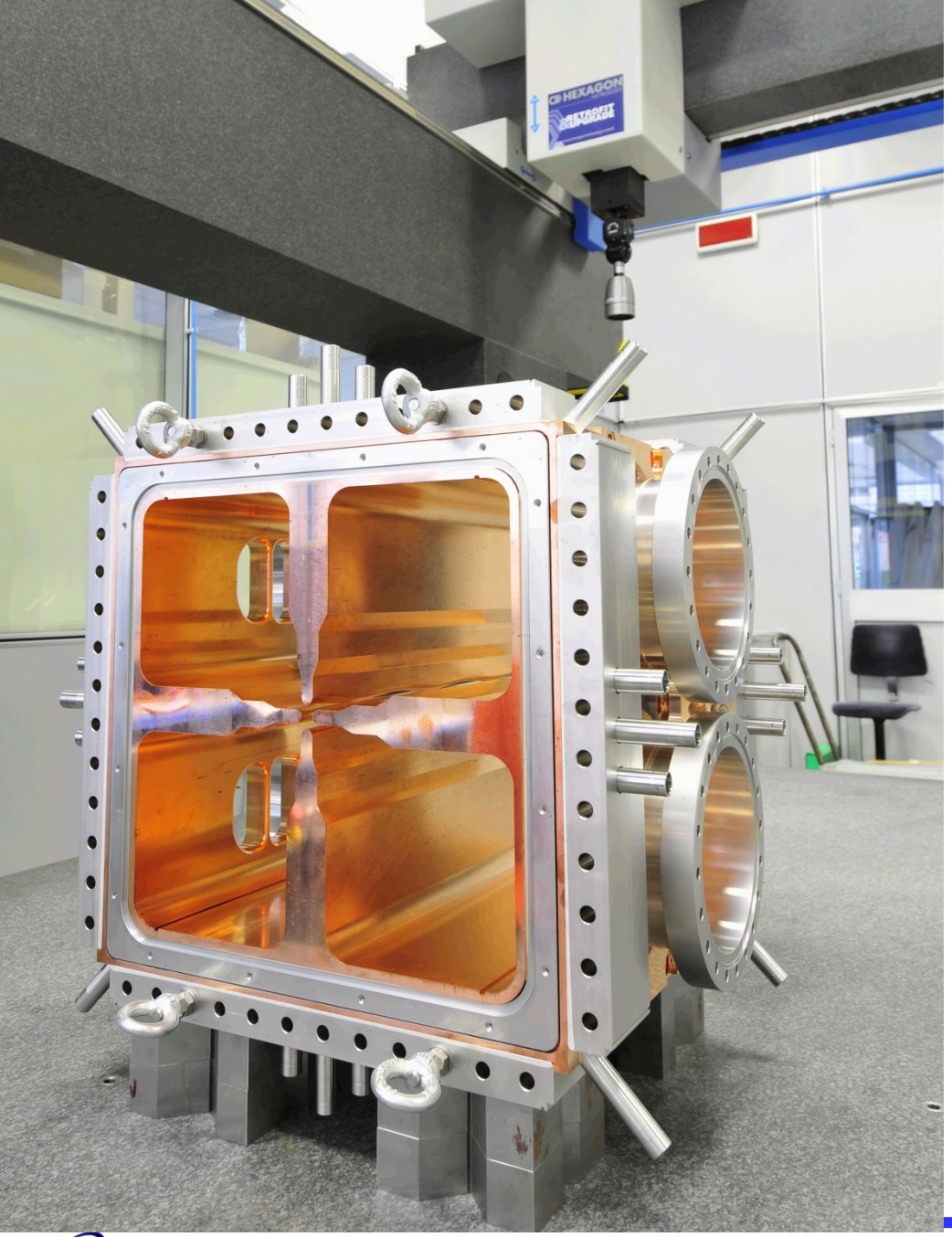


IFMIF: the INFN contribution

International Fusion Materials Irradiation Facility

Andrea Pisent

INFN Laboratori Nazionali di Legnaro

INFN contribution to IFMIF-EVEDA project.

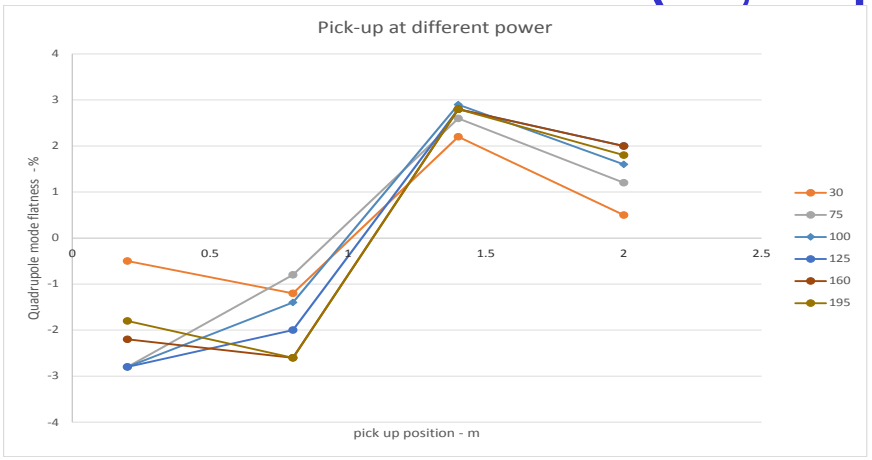
A. Pisent-INFN

On Behalf of the INFN IFMIF-EVEDA collaboration

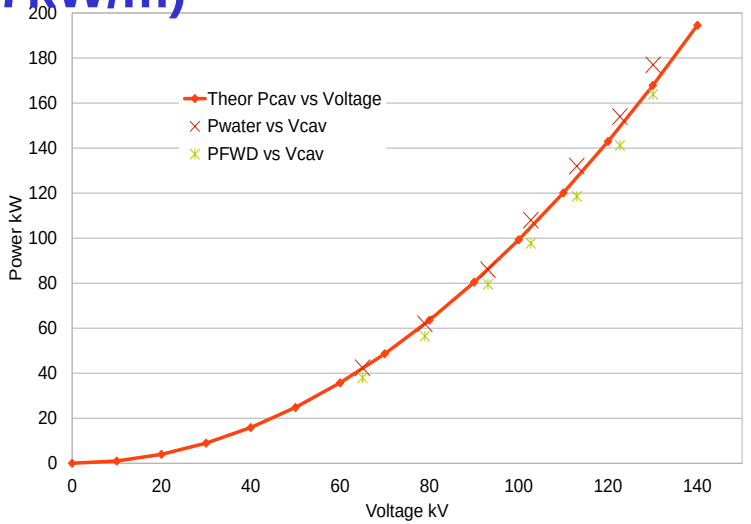
(LNL, Padova, Torino, Bologna)

The RFQ has reached (last week) the nominal field cw

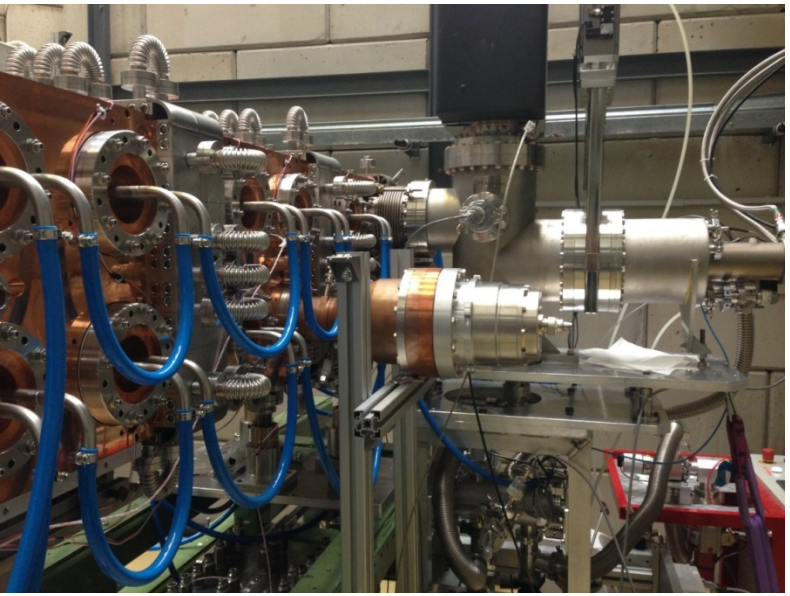
(cw, RF power 87kW/m)

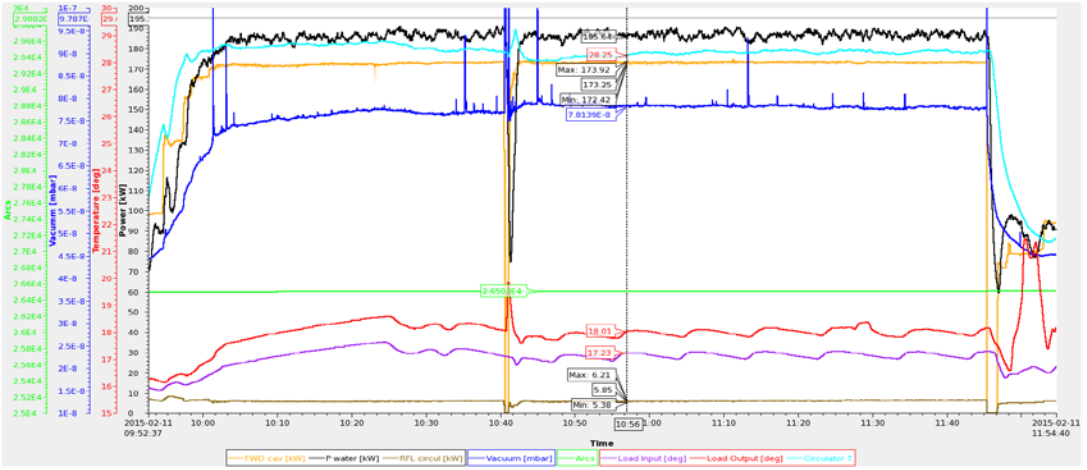


Field configuration (pick up reading) at different RF level



RF conditioning points and theoretical curve calculated for Q_0=12500, i.e. 173 kW vs. 132 kV



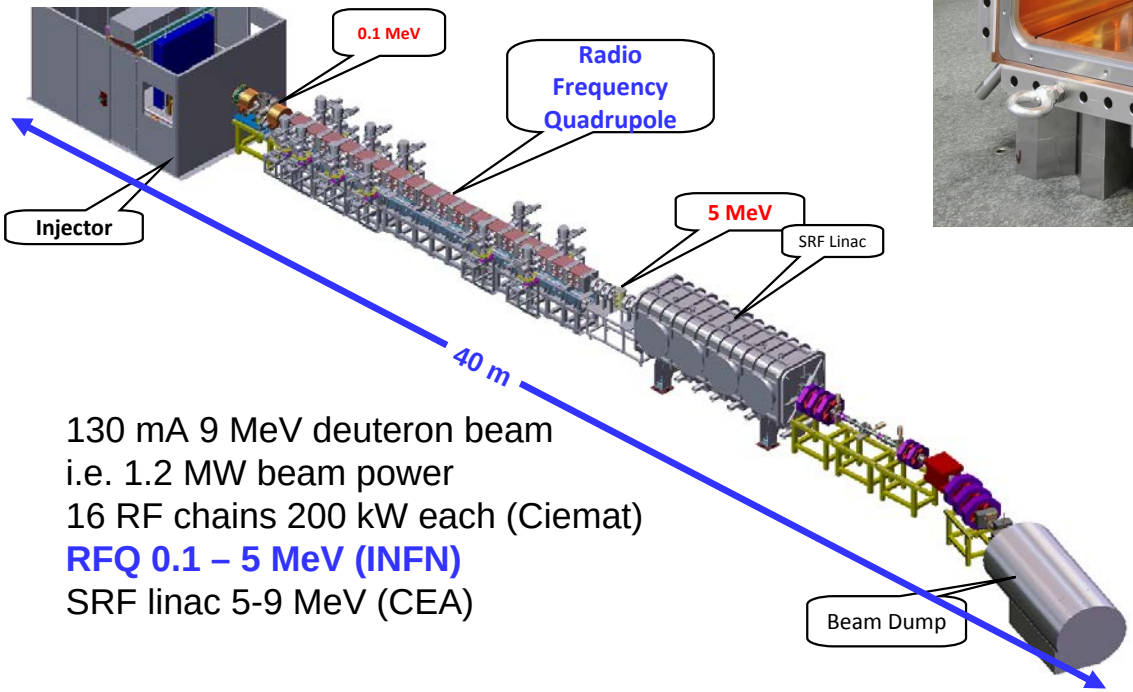


About 2 hrs at nominal power cw (FWD-RF=173kW, P_{water}=190 kW).

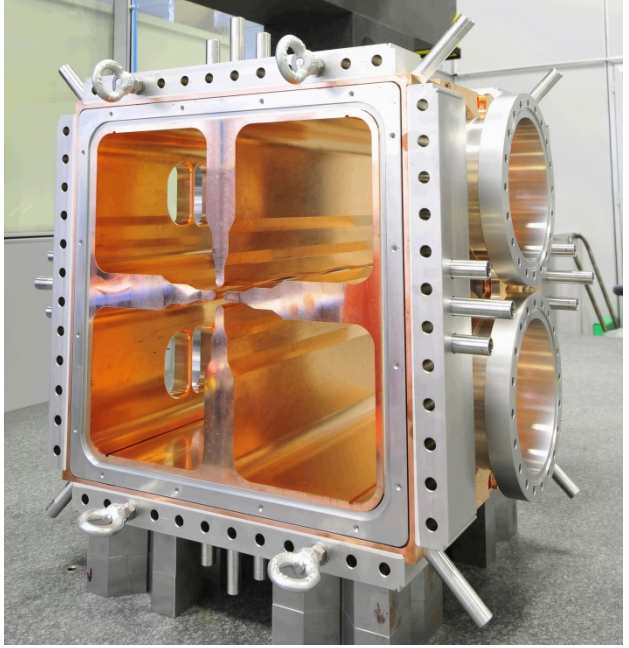
IFMIF

IFMIF prototype accelerator

- Very high intensity, 25 times SPIRAL2 and 250 times SPES cyclotron.



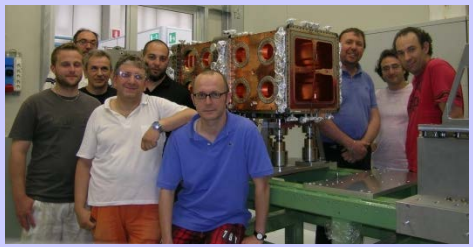
130 mA 9 MeV deuteron beam
i.e. 1.2 MW beam power
16 RF chains 200 kW each (Ciemat)
RFQ 0.1 – 5 MeV (INFN)
SRF linac 5-9 MeV (CEA)



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

2007 start Broader Approach
2008 PDR
2010 DDR and start of production
2014 coupler test
2014 RFQ high power test
2015 RFQ delivery to Rokkasho
2016 beam commissioning

Budget INFN (ext.)
Approx 25 M€

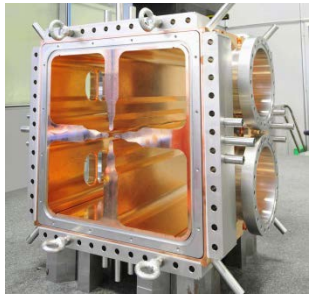


LNL
M. Comunian
E. Fagotti
J. Esposito
F. Grespan
L. Antonazzi
A. Palmieri
M. Giacchini
A. Polato
C. Roncolato
F. Poletto

PD
A. Pepato
M. Benettoni
R. Dima
F. Scantamburlo
L. Ramina
M. Rampazzo
M. Romanato
….off….

TO
P. Mereu
D. Dattola
G.Giraudo
..off..

BO
A.Margotti
M. Guerzoni
..off..



IFMIF EVEDA RFQ system organization

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

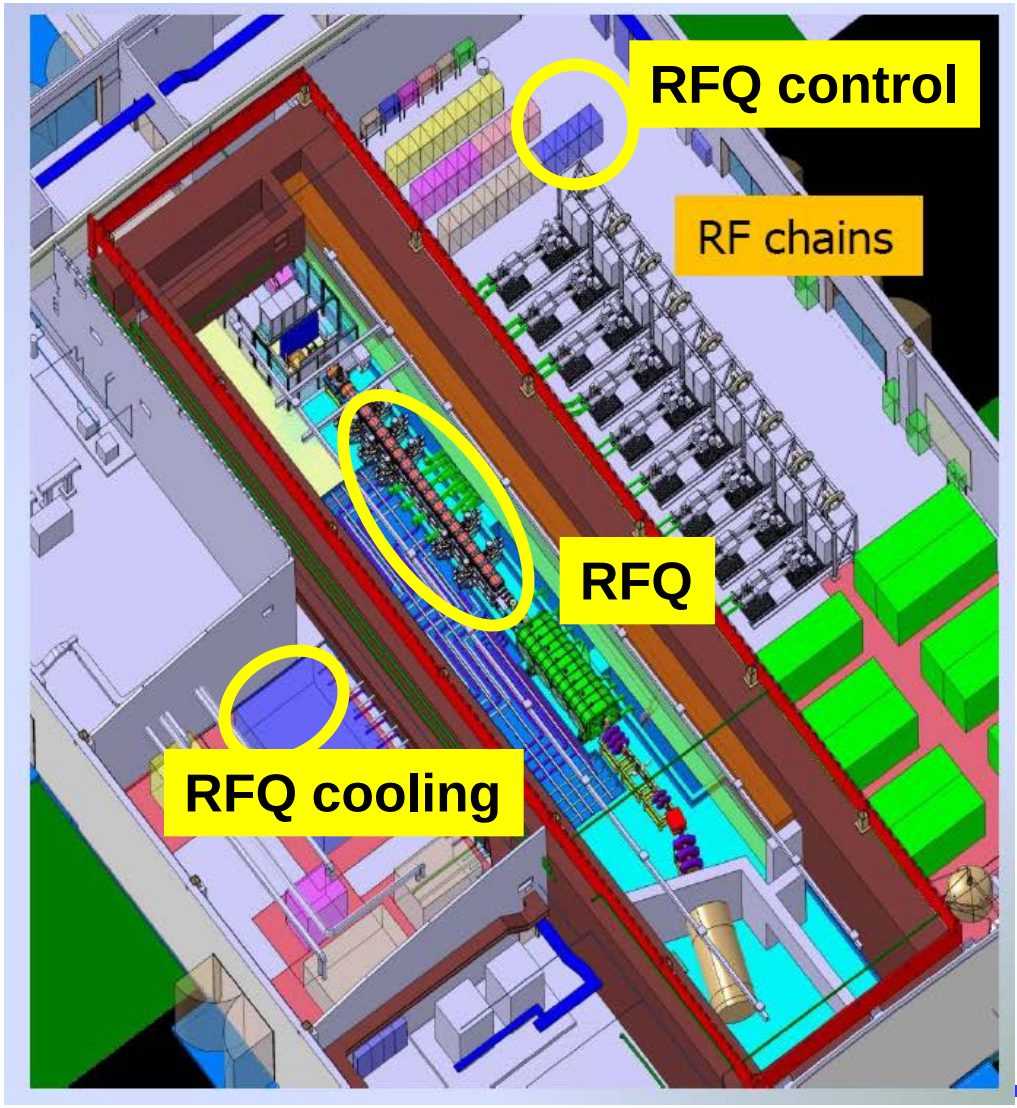
About 30 persons involved, 20 FTE, 10 dedicated contracts

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

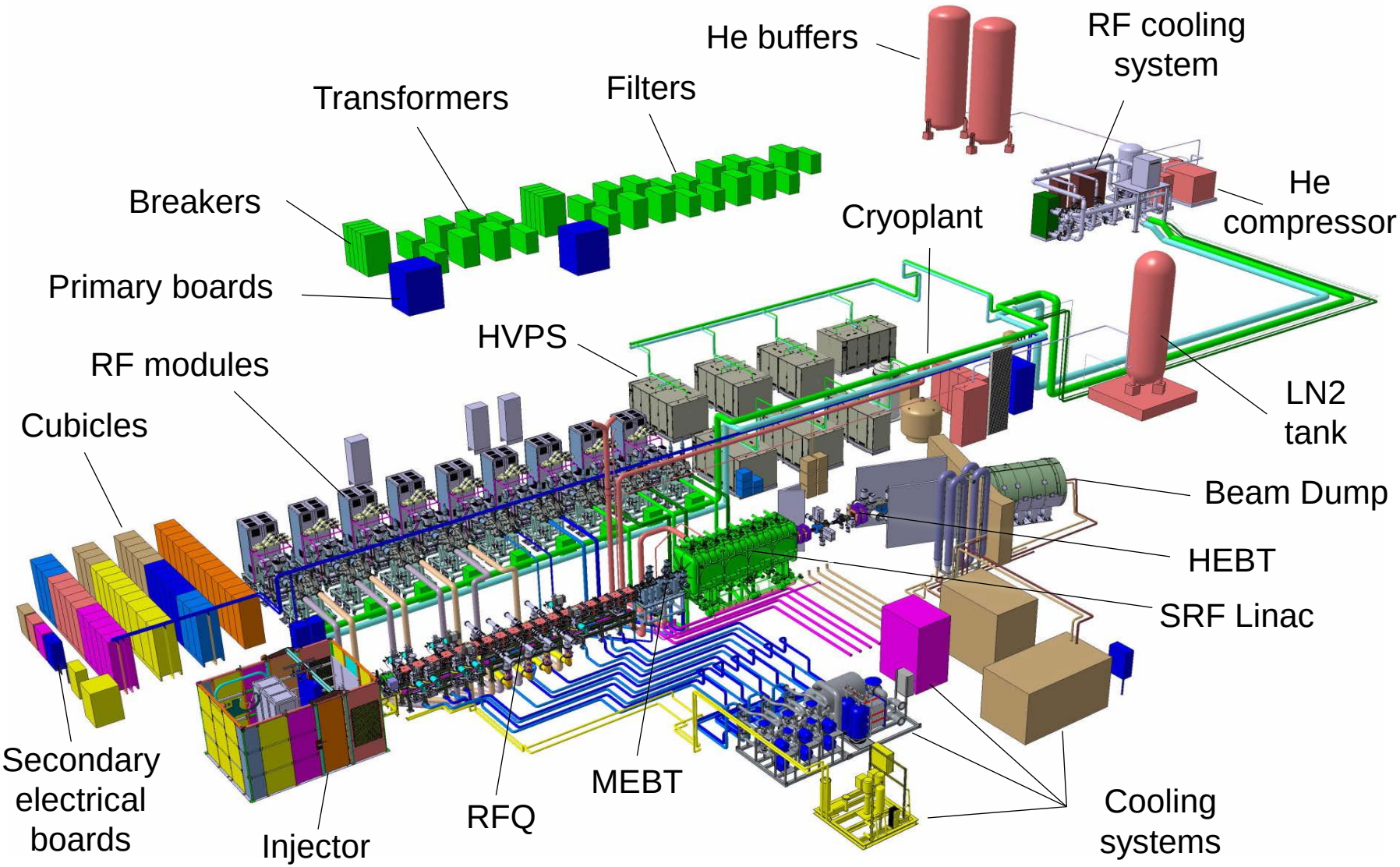
INFN organization

INFN group for RFQ realization

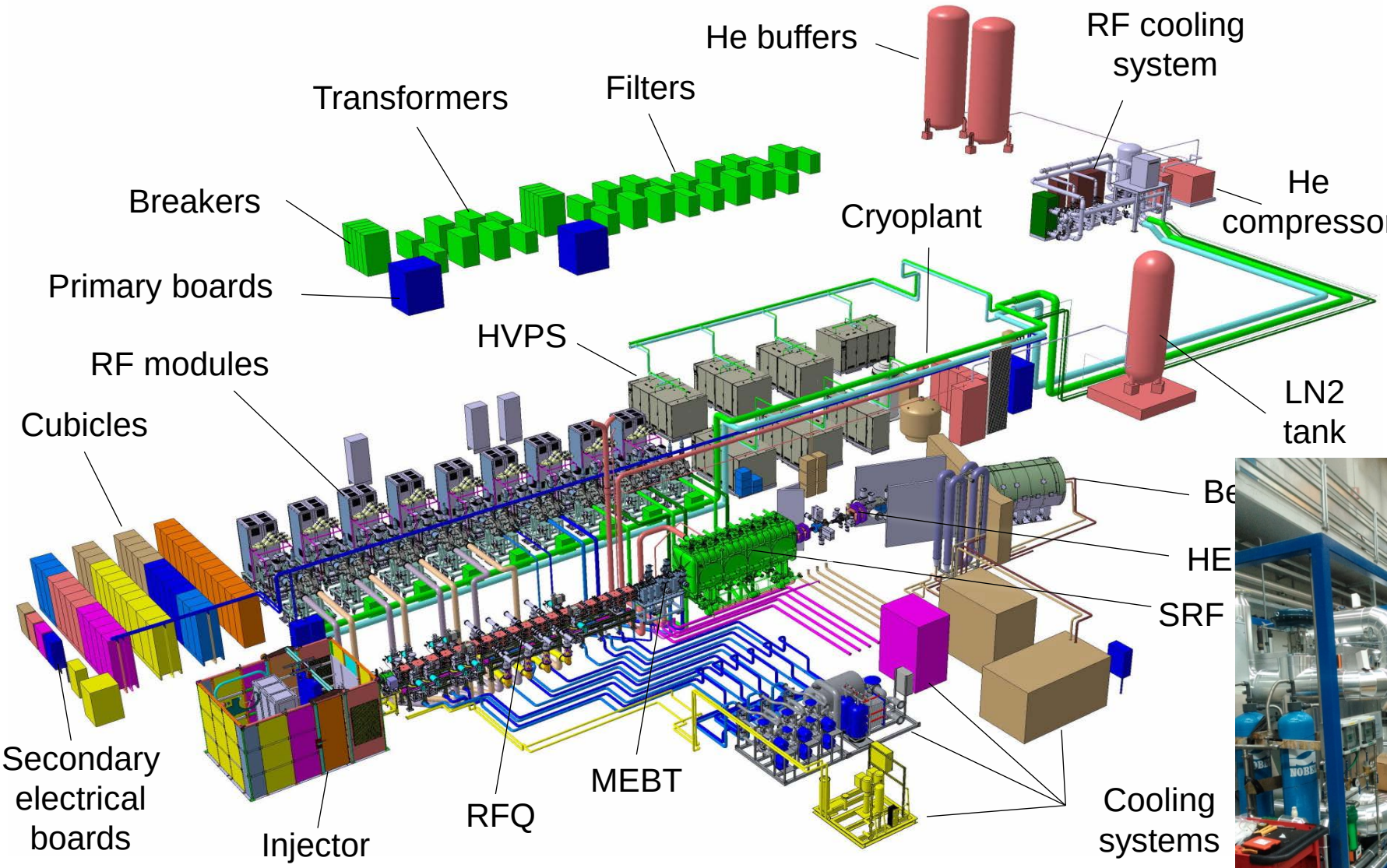
- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti
  - Planning: J. Esposito
- Physical design : M. Comunian
  - Radio frequency: A. Palmieri
  - High power tests: E. Fagotti
  - Computer Controls: M. Giacchini
  - 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



Blu components+RFQ are INFN in-kind contribution

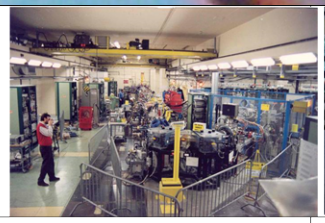
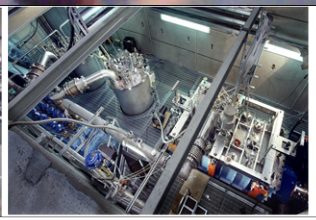


Blu components+RFQ are INFN in-kind contribution

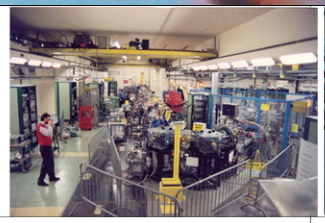
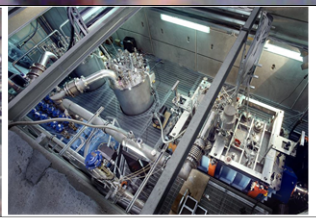


The challenge

RFQ
(Radio Frequency Quadrupole)

Iniettori di cui ho coordinato il beam commissionig			
Dove	CERN-linac3 Iniettore Pb di LHC	LNL-PIAVE Inett. ALPI	CNAO Iniett. Sincrotrone
Quando	1994	2005	2008
Fascio	Pb	A/q<7	C et H (A/q=3)
Corrente(μA)	80	5 cw	170/1000
Trasm. sper.	95%	65%	60%
Trasm. Nom.	95%	65%	90% (30% Heidelberg)
Autore mod.	(Legnaro)	(Legnaro)	(Francoforte)

RFQ
(Radio Frequency Quadrupole)

Iniettori di cui ho coordinato il beam commissionig			
Dove	CERN-linac3 Iniettore Pb di LHC	LNL-PIAVE Inett. ALPI	CNAO Iniett. Sincrotrone
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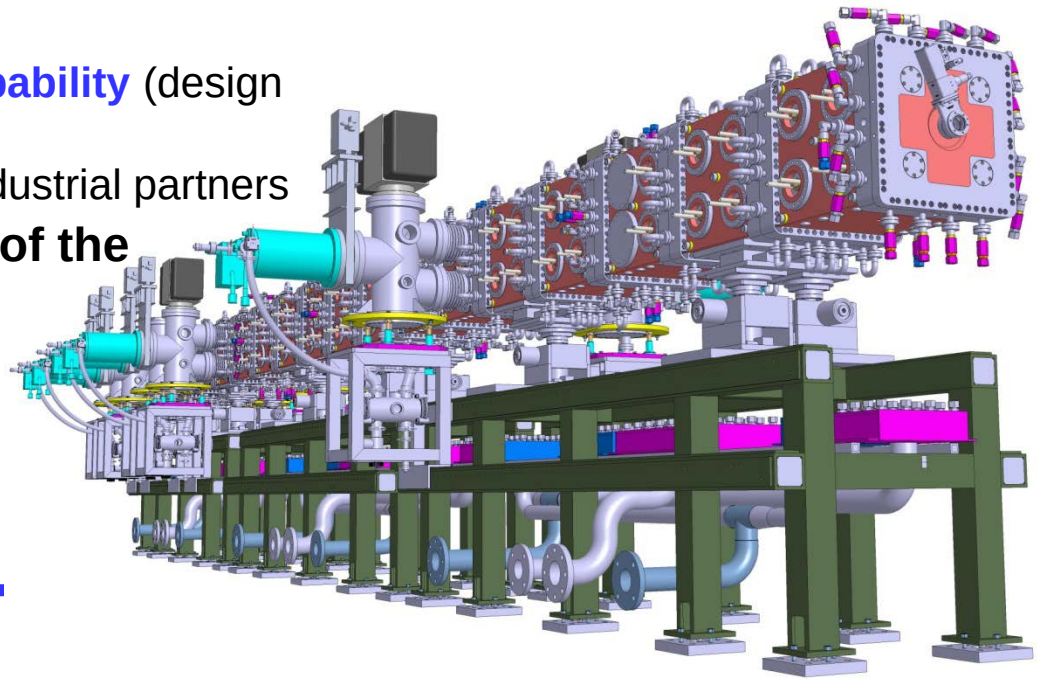
Autore mod.	(Legnaro)	(Legnaro)	(Francoforte)

Low intensity➔high intensity

Beam power **Watt** ➔ **hundreds of kW**

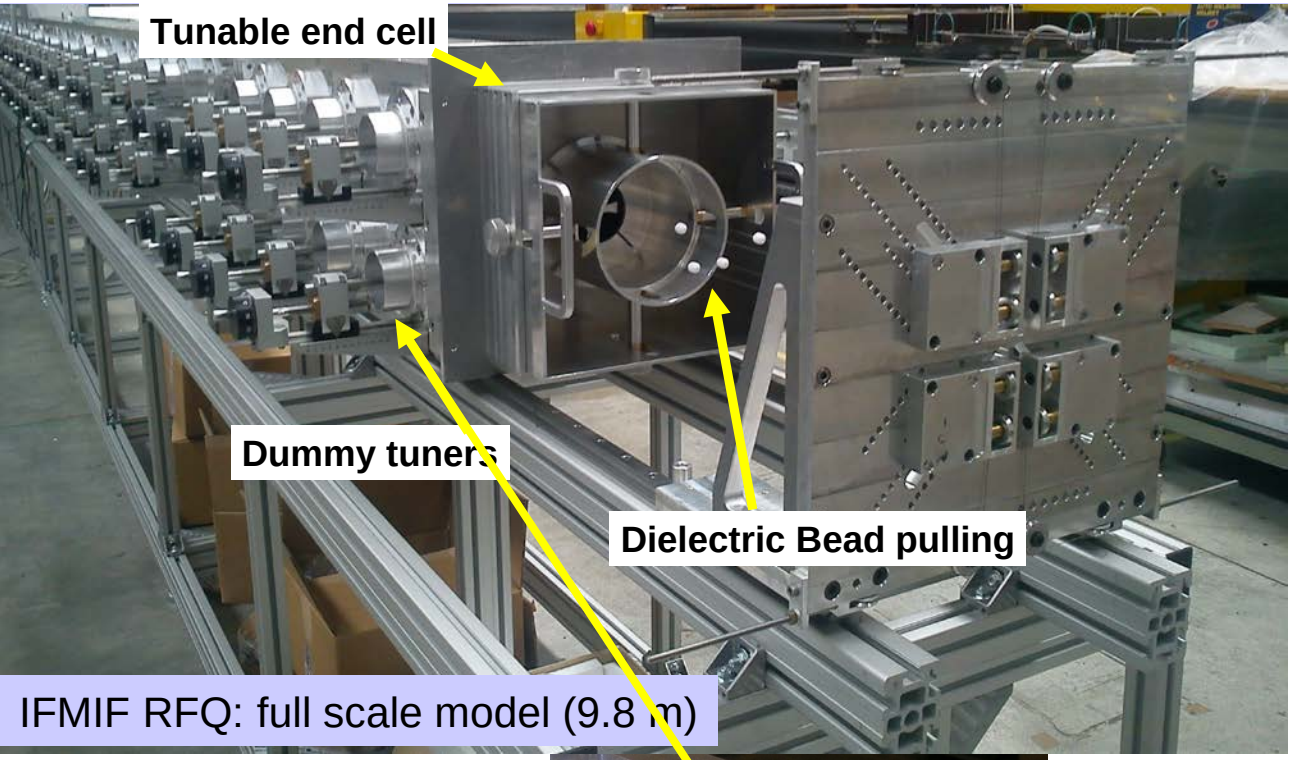
IFMIF EVEDA RFQ challenges

- **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.
- 11/18 have been accepted today

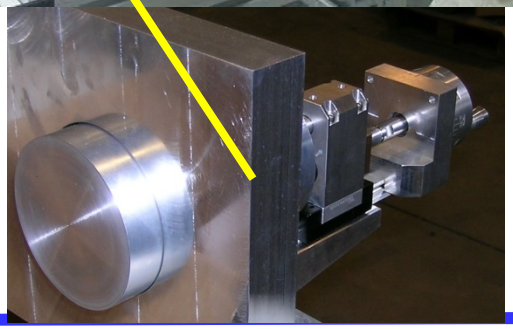


Tuning of a long RFQ

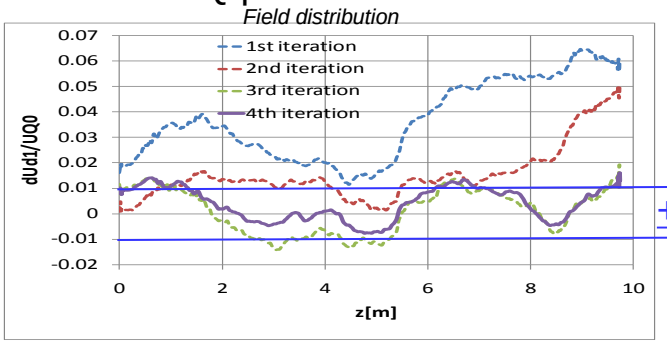
- A long RFQ geometrical implies tolerances proportional to L^{-2} to be corrected by tuners



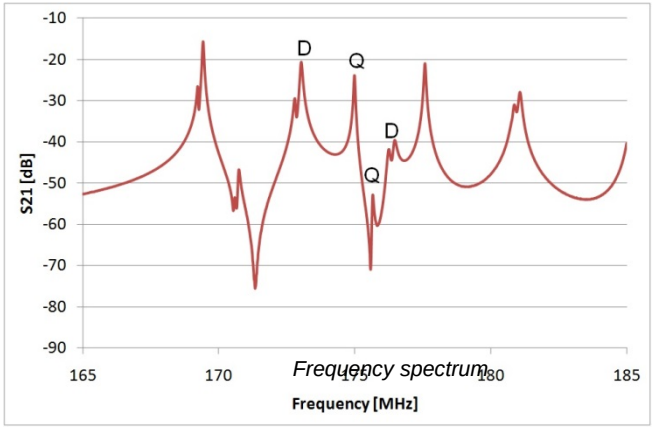
IFMIF RFQ: full scale model (9.8 m)



Q perturbation



Test di tuning sul modello IFMIF RFQ convergenza in 4 iteraz.

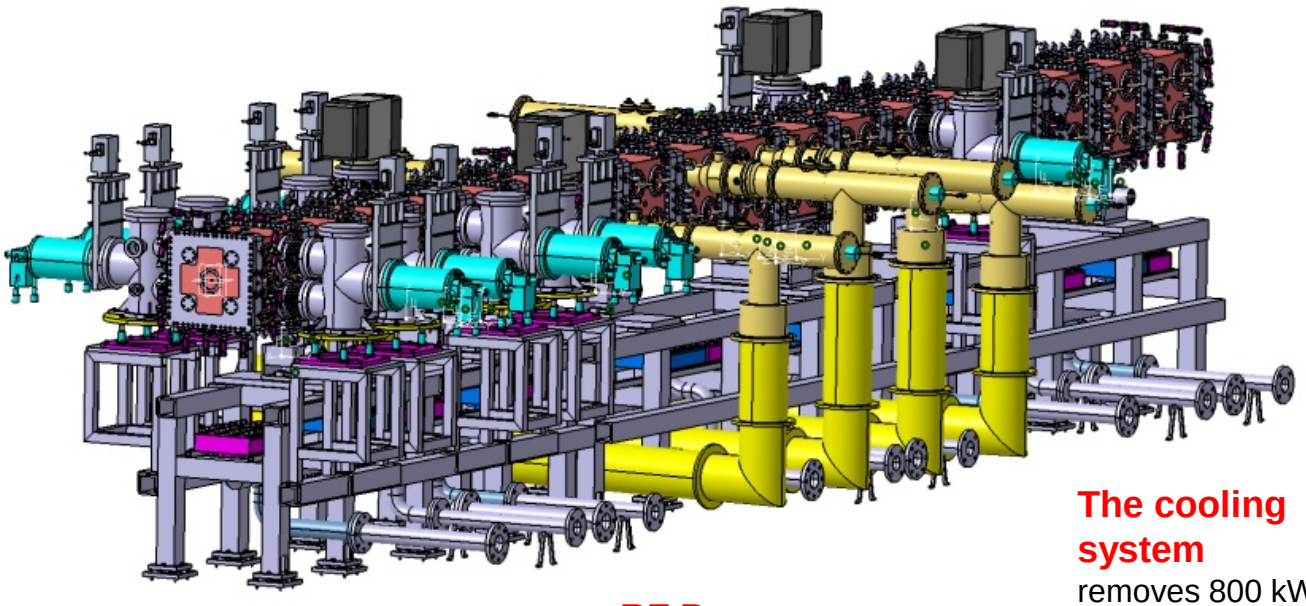


- **±10 μm modulation tolerances**
- **±50 μm tolerance R_0 final (incl brazing) equiv to ±1 MHz.**
- **I 88 "tuners" fissi (±15 mm equiv±1. MHz,) field correction**
- **Active (water temperature, 10 deg approx ±0.1 MHz,))**

RFQ components (and integration)

Components of the RFQ

18 modules
each module approx. 550 mm and 600 kg. Modules assembled and aligned in 3 supermodules (to be separately transported to Japan)



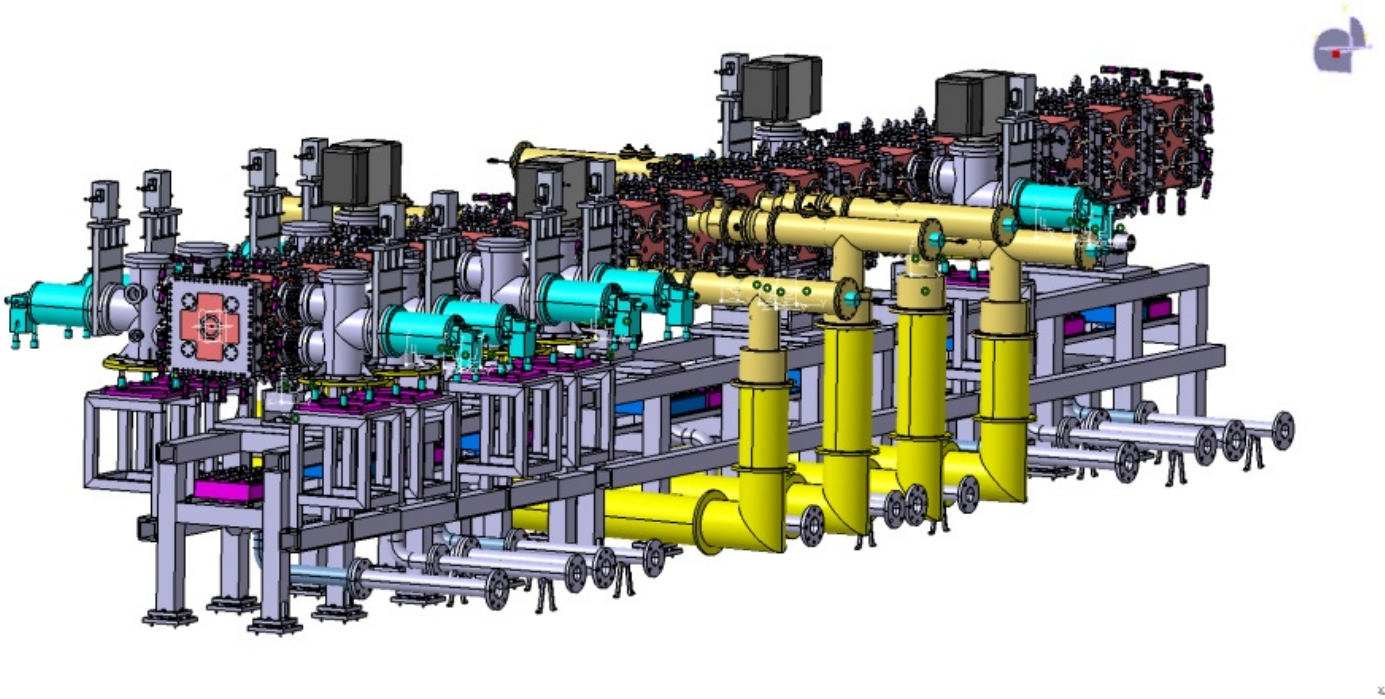
Local Control system
PLC and EPICS, for cooling and vacuum system, temperature and RF probes.

Vacuum system
10 sets, based on cyogenic pumps (in cyan) guarantee 5*10-7 mbar with beam losses gas load

RF Power
8 RF systems and power couplers, 200 kW each. (RF system by Ciemat and couplers by JAEA)

The cooling system
removes 800 kW and assures dynamic tuning

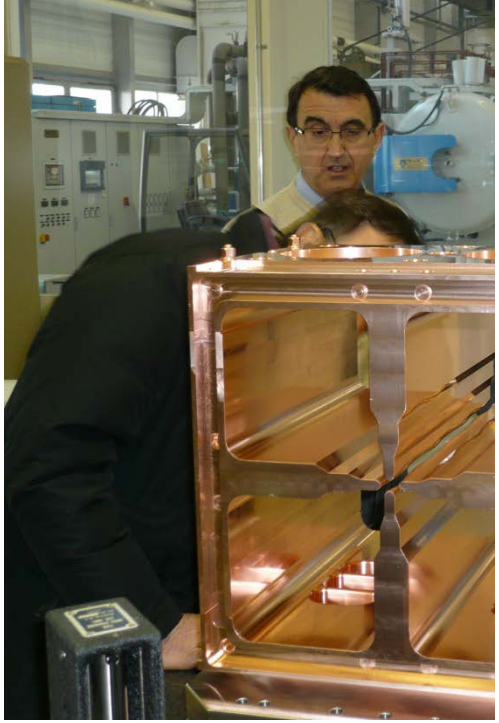
Modules construction

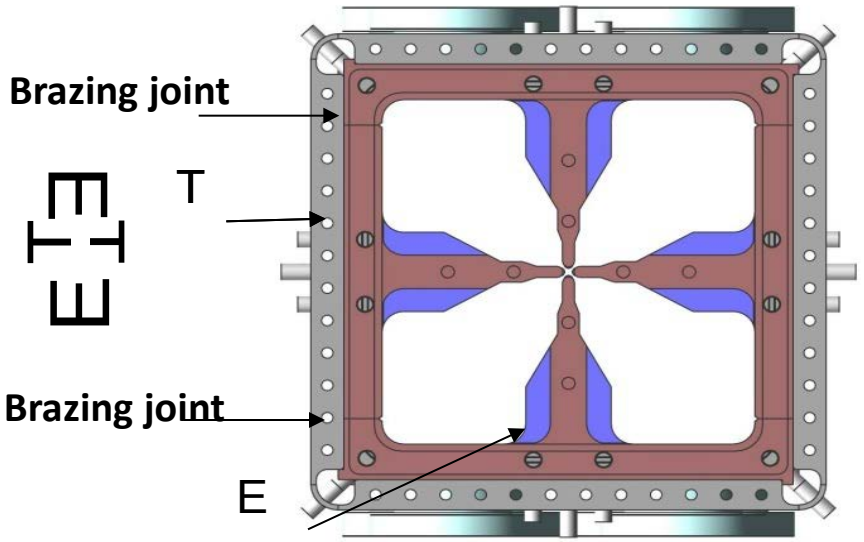


High energy SM in construction at Cinel, Padua (Italy), Intemediate energy in INFN, Low energy by RI Koln (Germany)

Mechanical design

- **Based on vacuum brazing, never used before for such large RFQ cross section (TRASCO was at 352 MHz).** design compatible with oven at LNL and in industry;
- 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 was performed, by using a EDM (wire electro erosion).
- The accelerator is composed by 18 of these modules.





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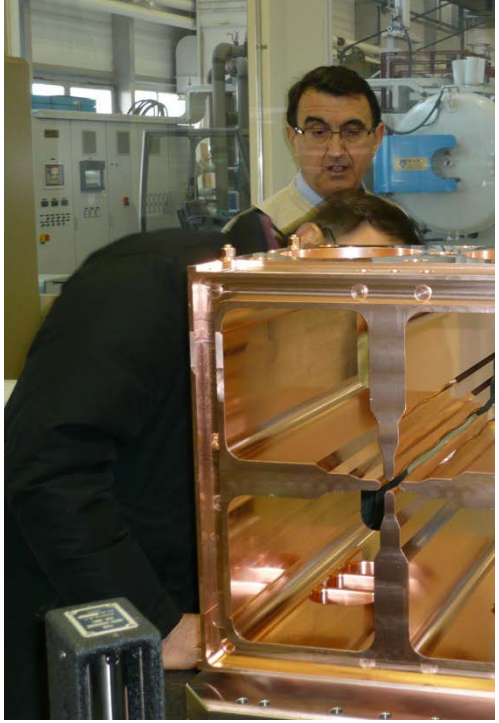
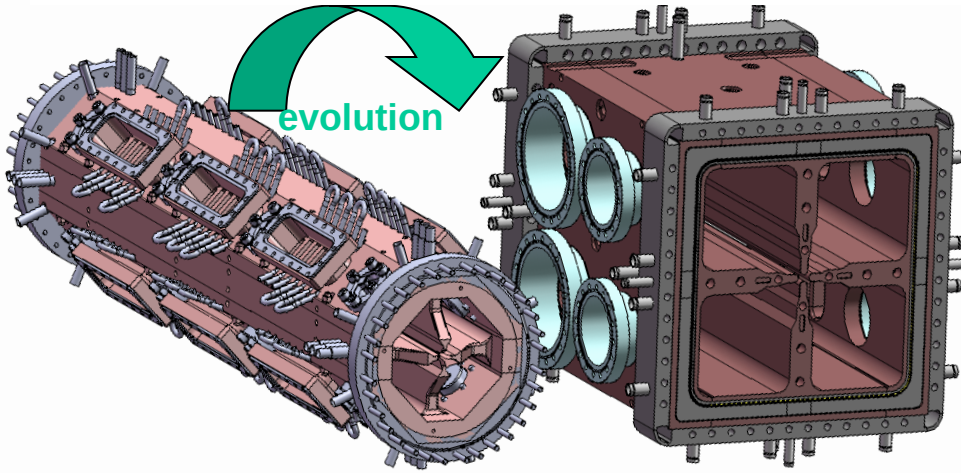
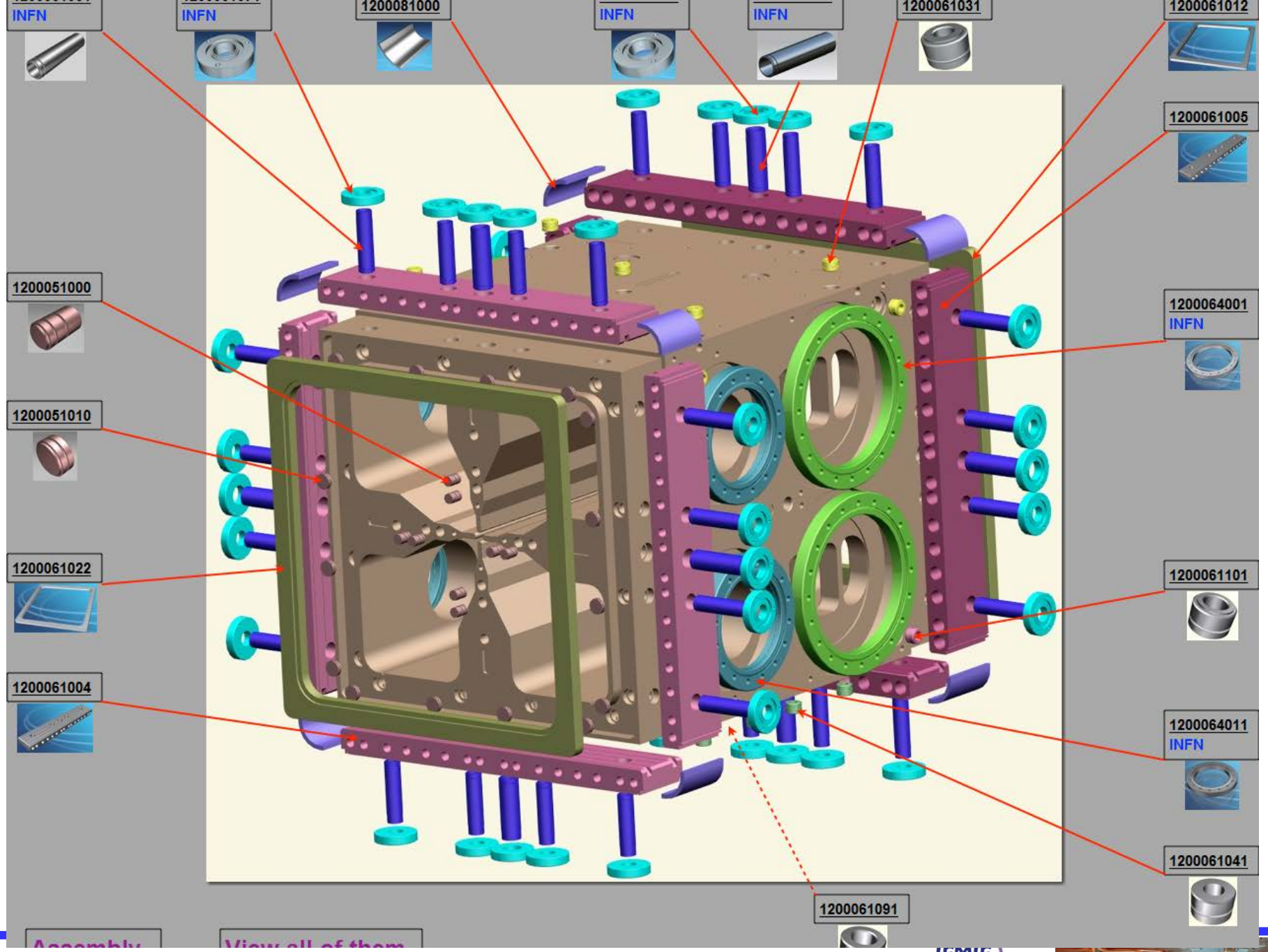




TRASCO and IFMIF module


INFN
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1200061101
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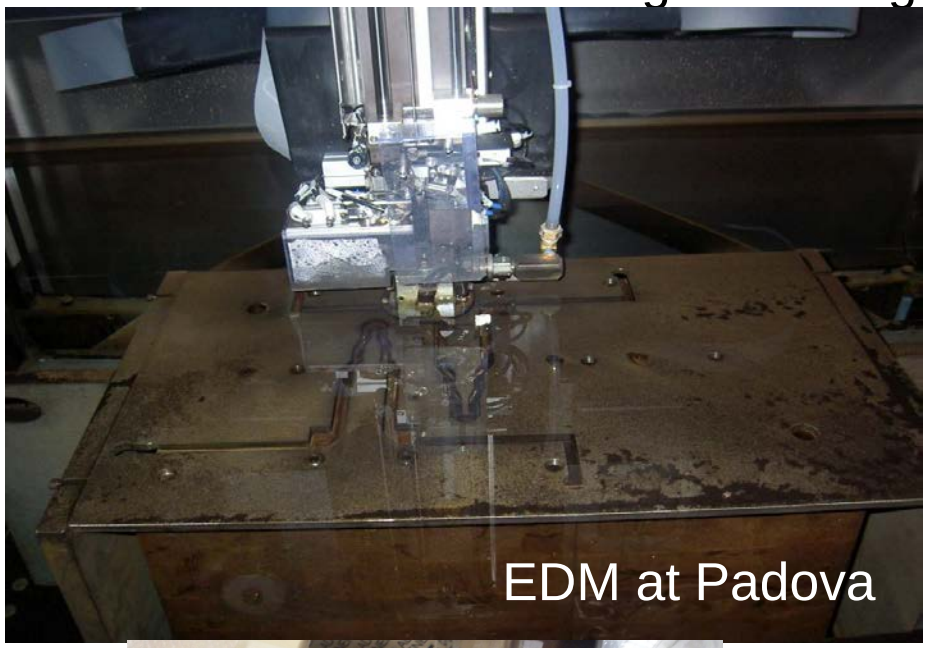
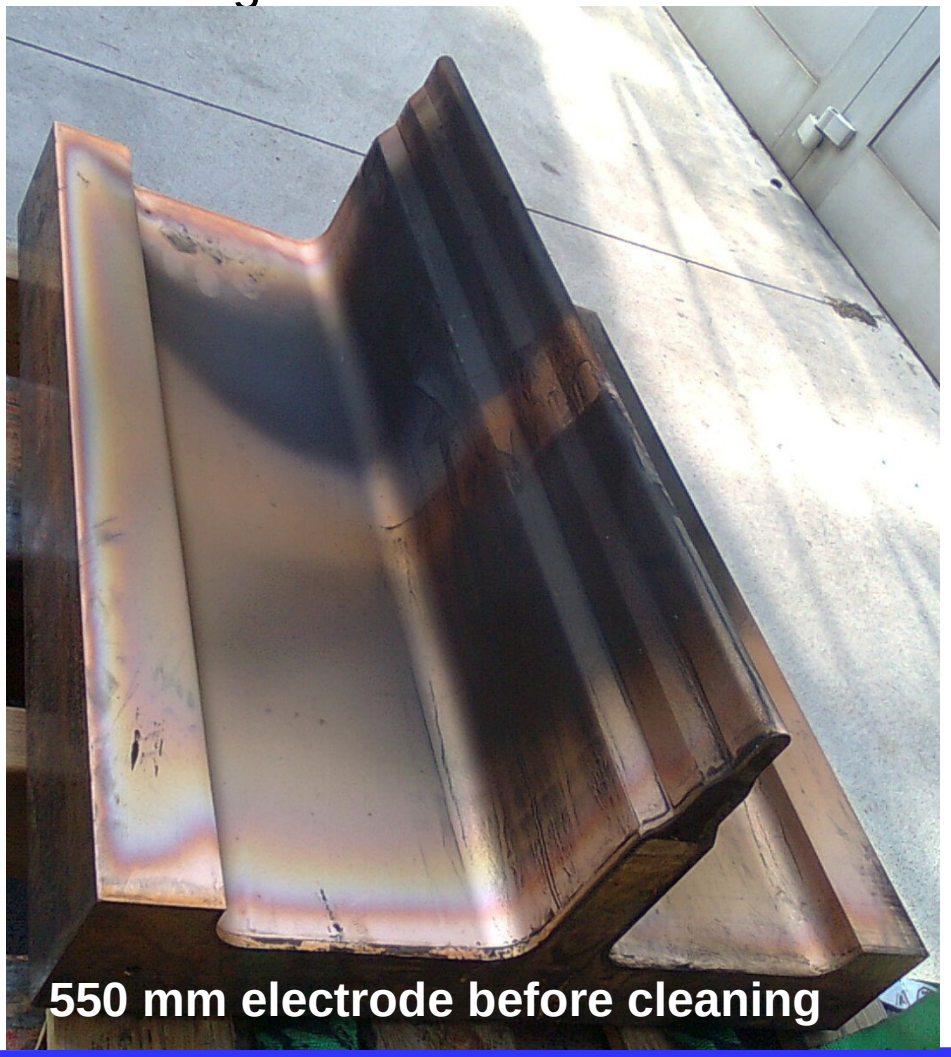
INFN
1200061041
1200061091

First construction step module n0 16

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

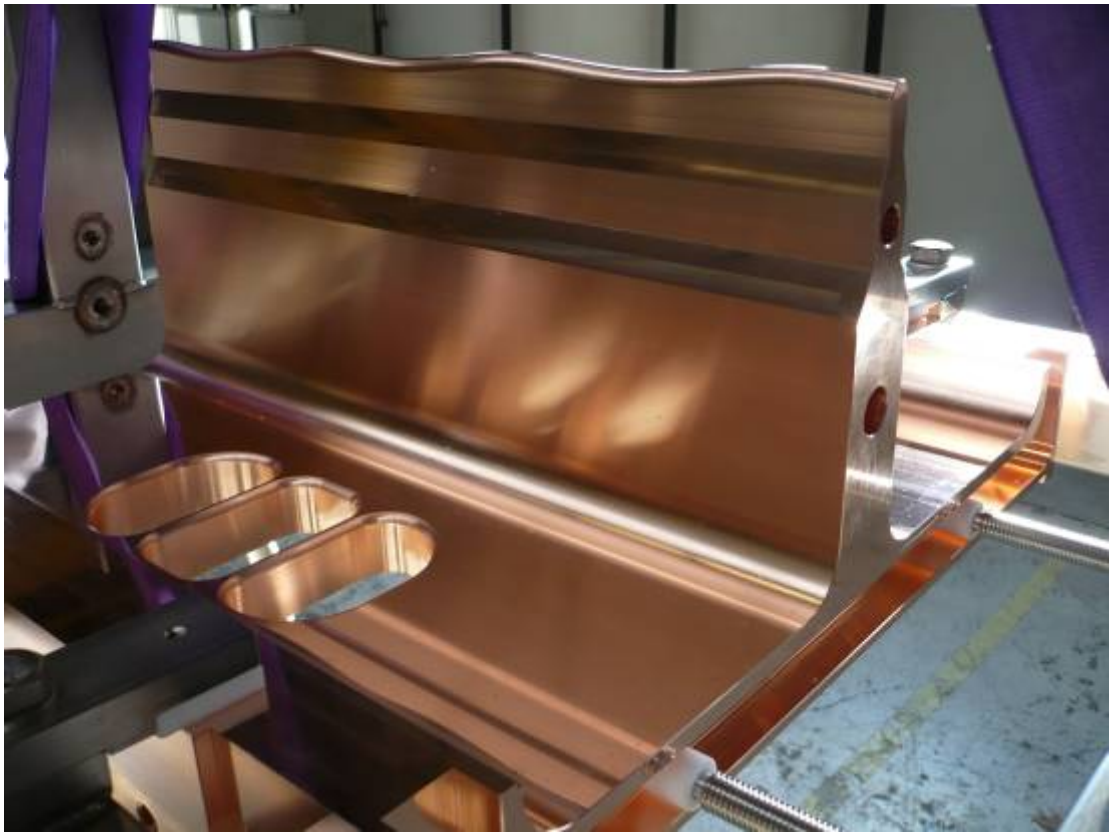

EDM at Padova


550 mm electrode before cleaning

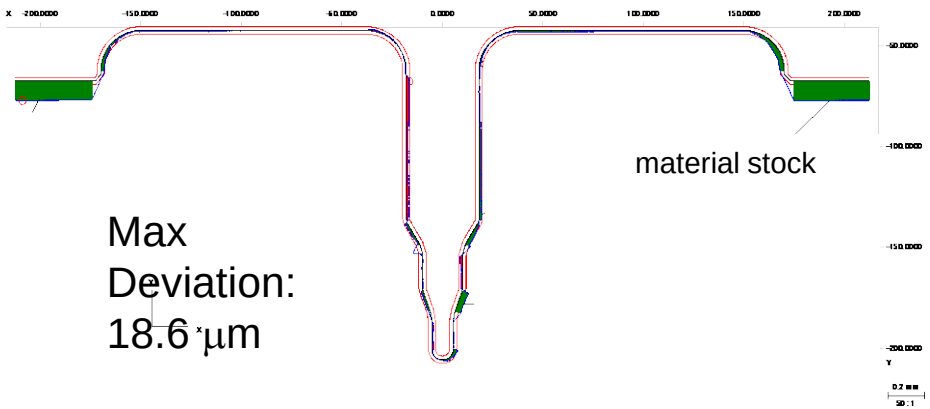

Remaining cupper

Finishing

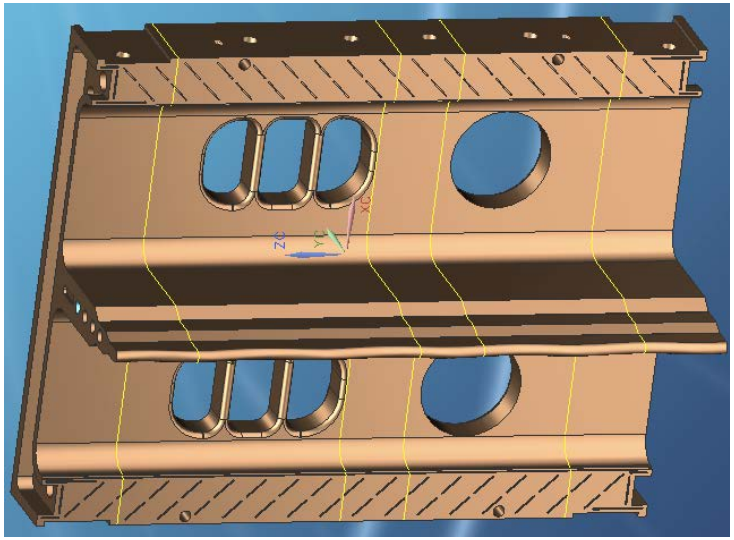
- 0.7 um roughness
- 3d modulation
- 20 um tolerances on vane tip geometry



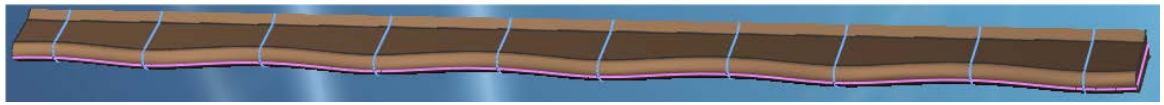
Four electrodes analyzed by CMM (module 16 as an example)



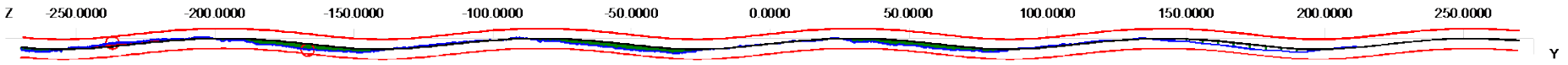
Max Deviation: 18.6 μm



Max Deviation: 10.5 μm

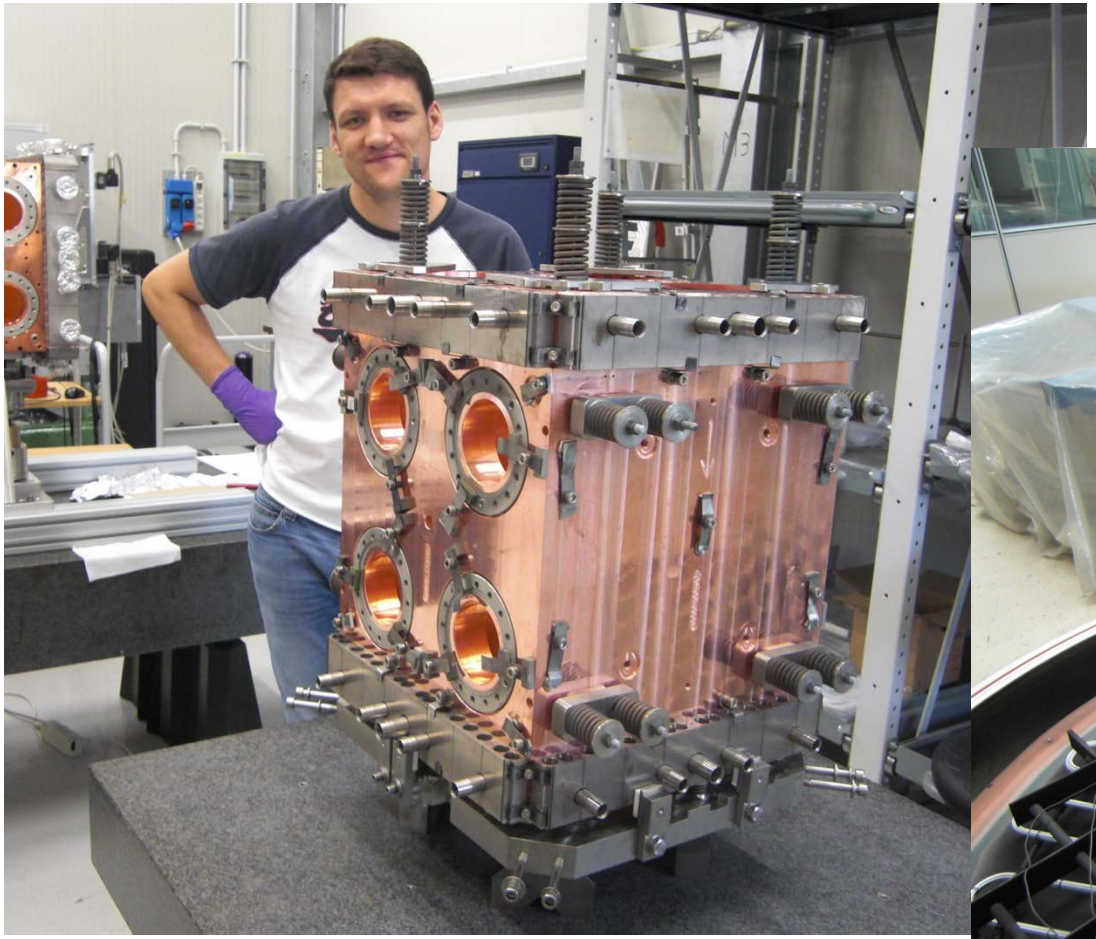


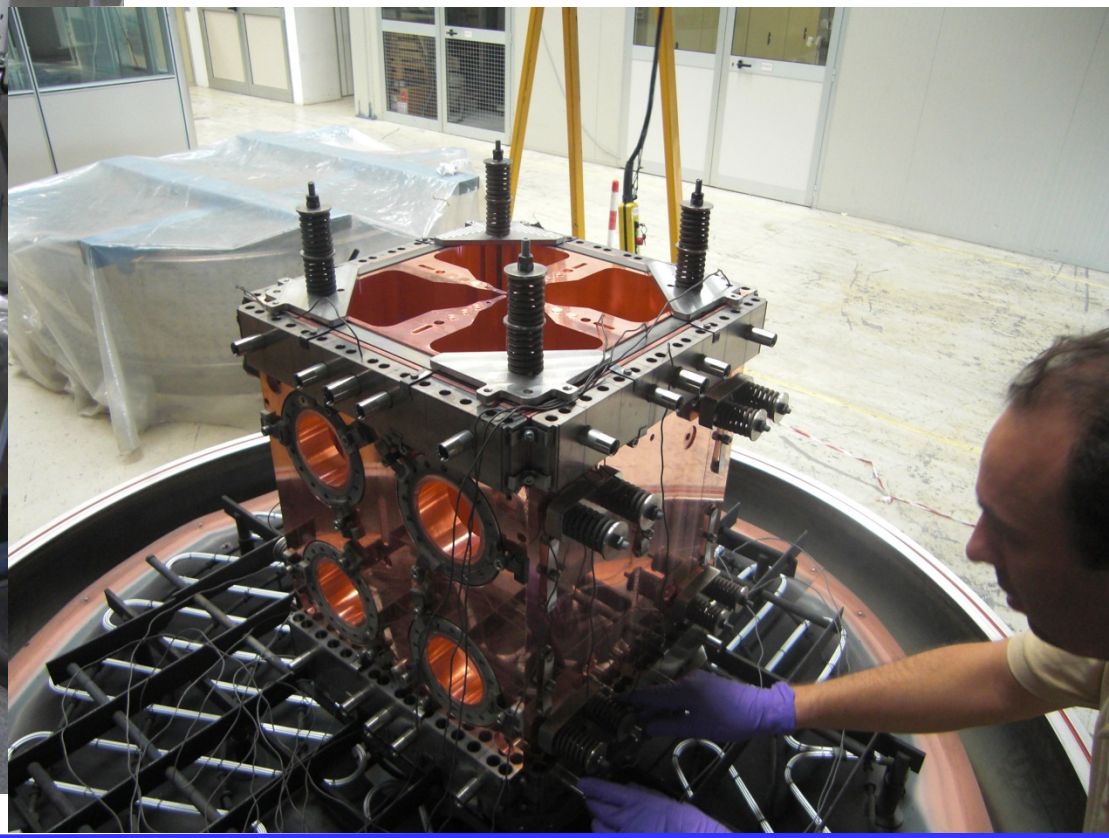
Max Deviation: 6.1 μm



INFN development for Brazing

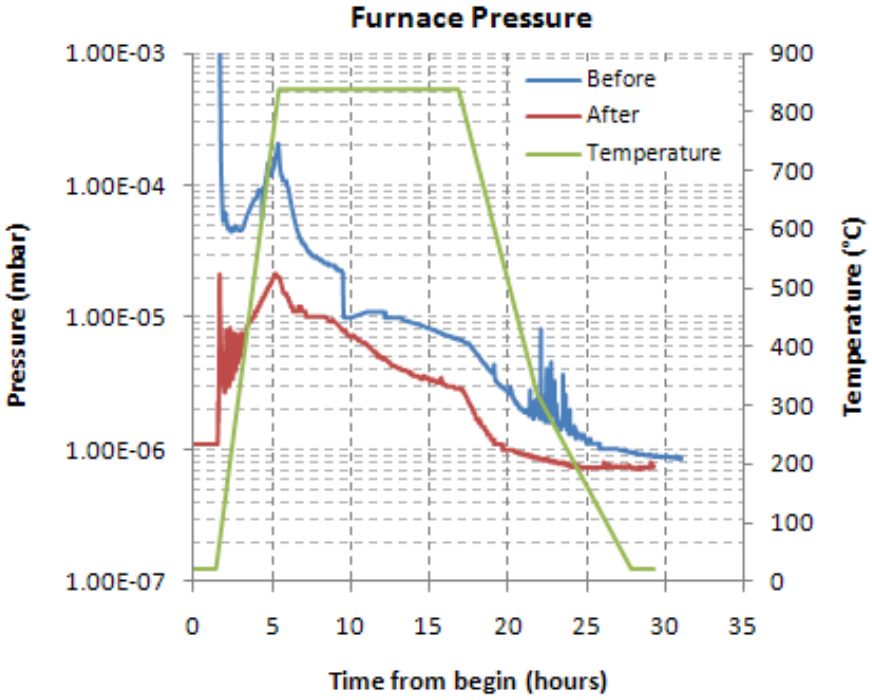
Vacuum oven in INFN LNL

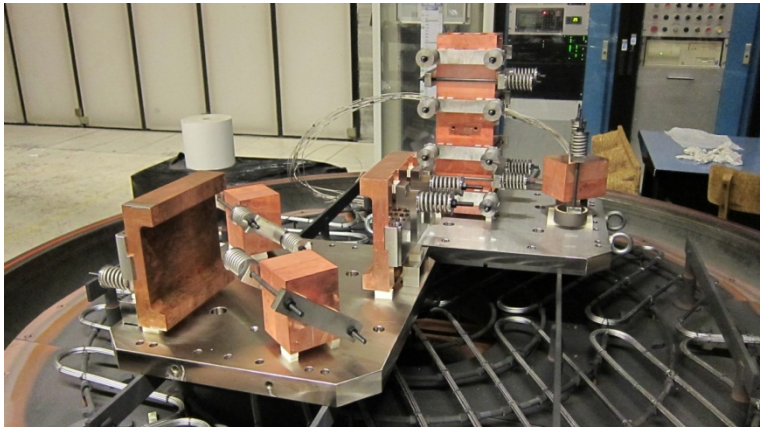


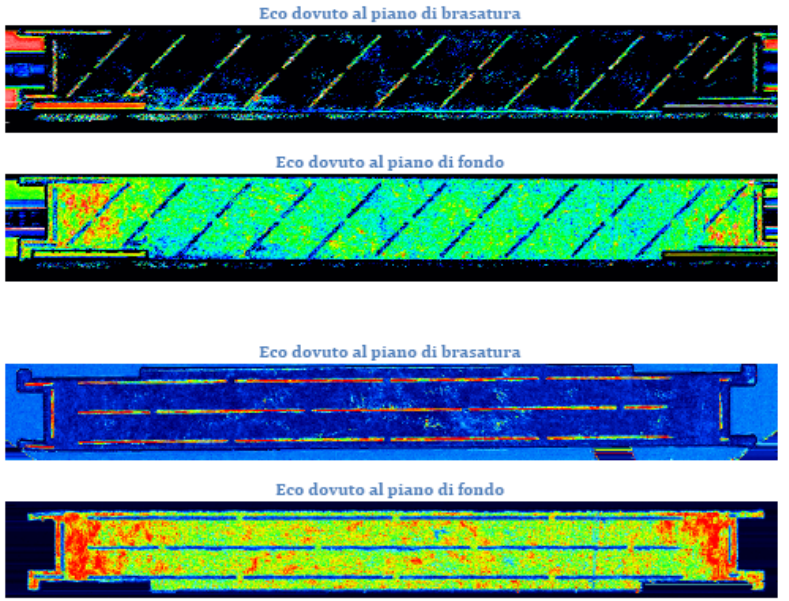


Brazing at LNL (1/2)

- Upgrade of the vacuum system
- Construction of the assembly lab
- Test of brazing geometry with test pieces.
- Ultrasonic check of brazing

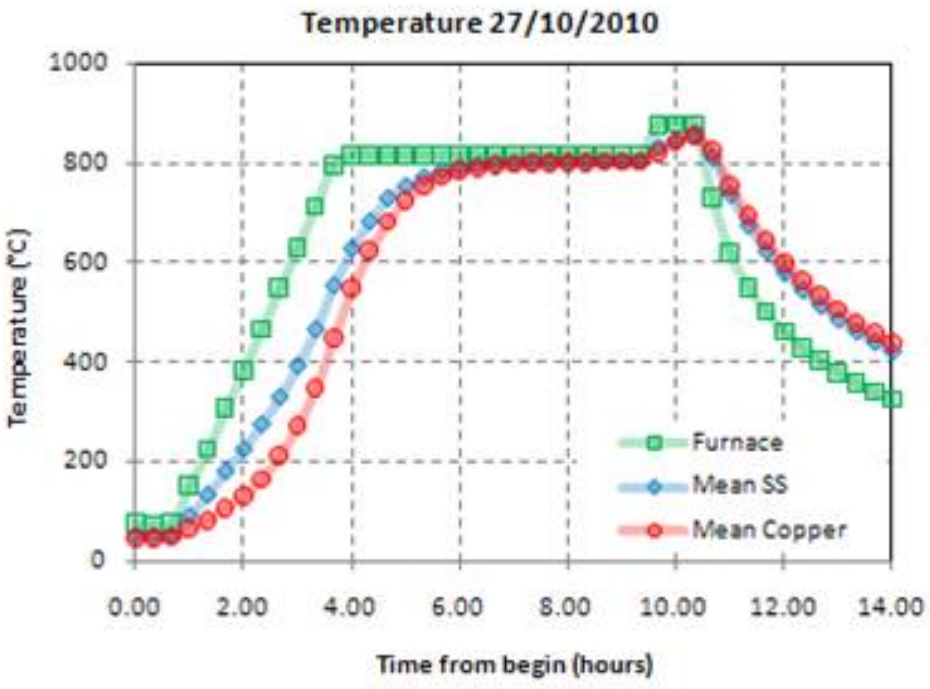


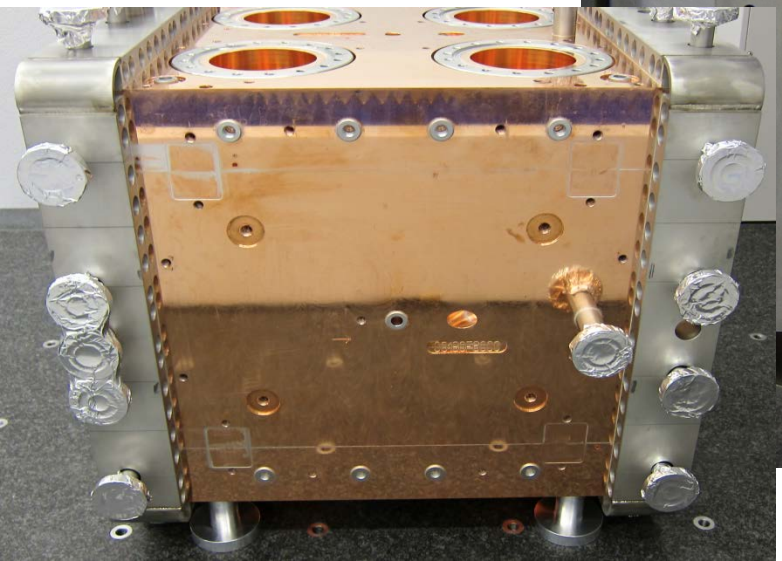




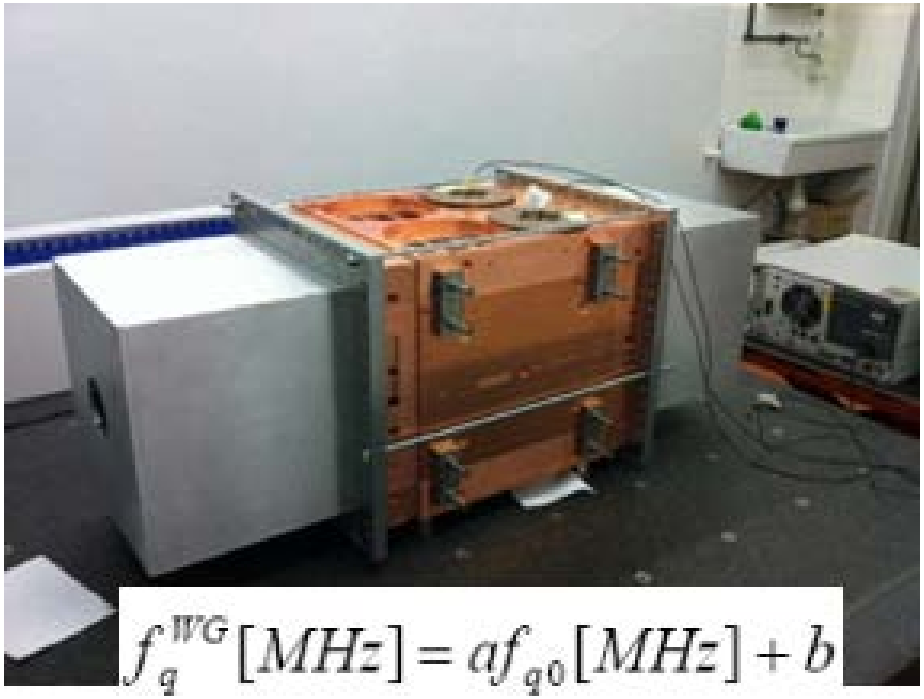
Brazing at LNL (2/2)

- Chemical preparation
- Brazing



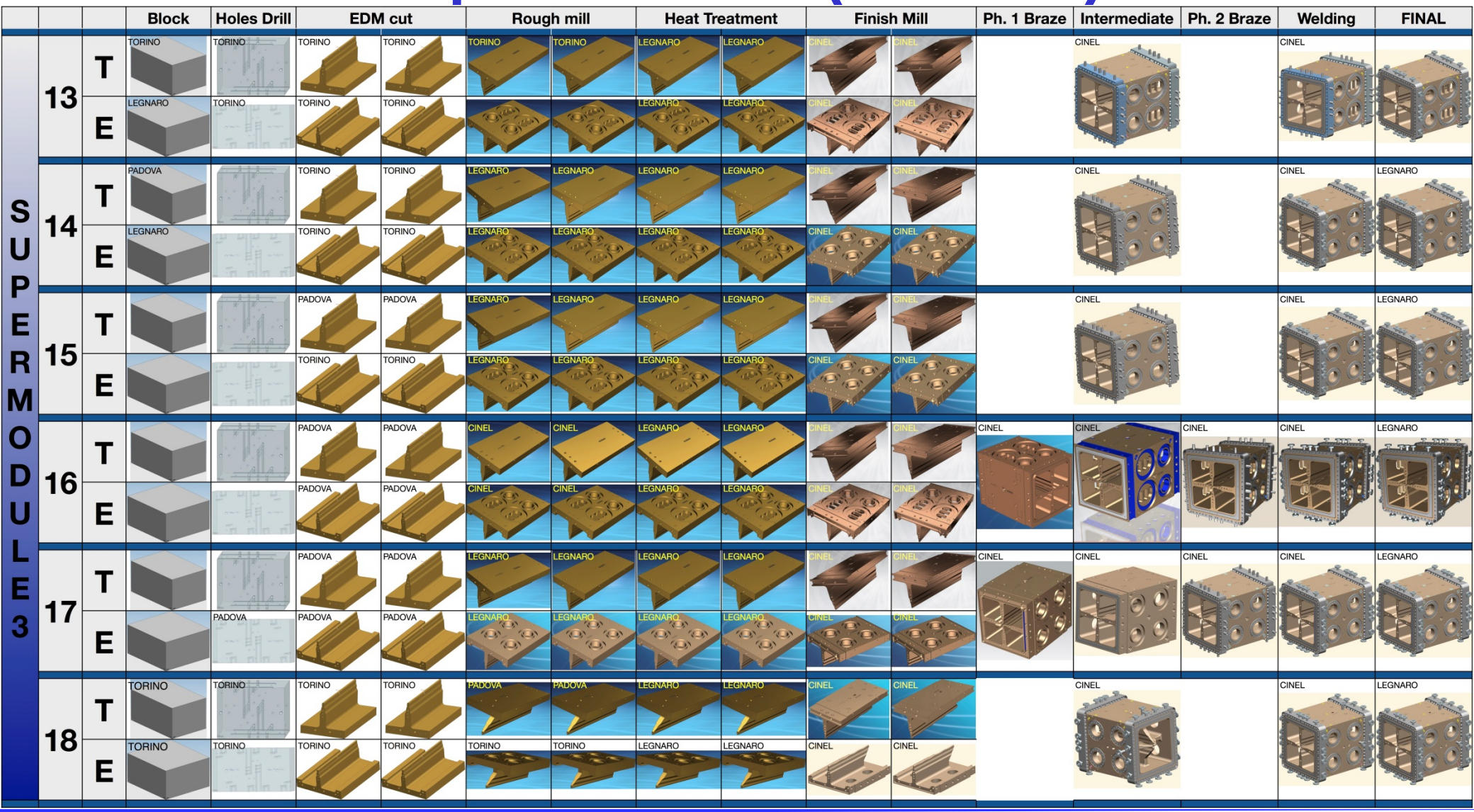


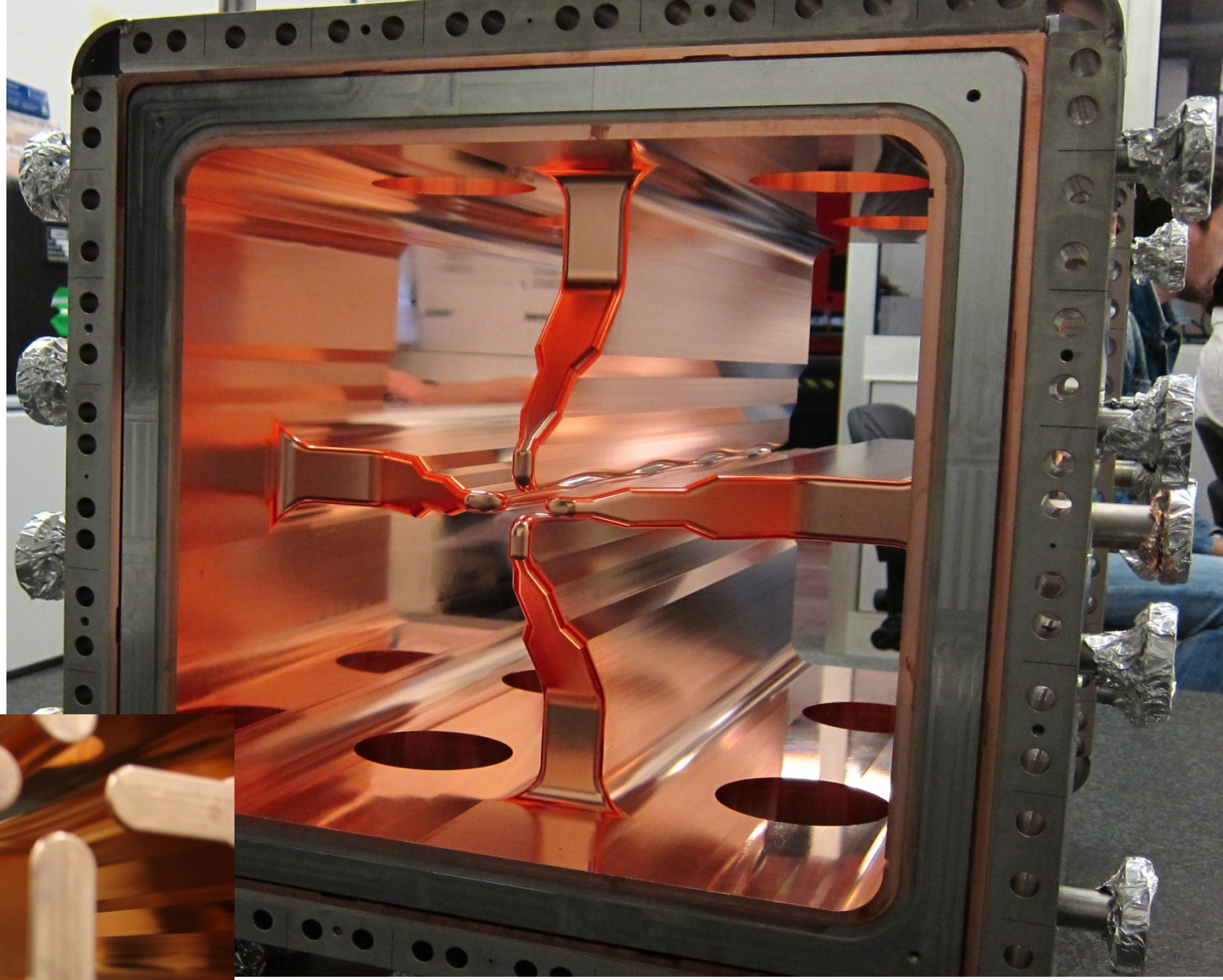
Results of RF measurements before and after brazing



Module	Limit Value	Pre-braze[MHz] fq(WG)	Post-braz[MHz] fq(WG)	Δf MHz/[μm]
M_16	± 50 μm	186.862	186.981	0.119/+17
M_17	± 50 μm	187.015	186.820	0.195/-25
M_15	± 50 μm	187.207	187.359	0.152/+22
M_18	± 50 μm	178.494	178.742	0.248/+35
M_14	± 50 μm	186.935	187,165	0.230/+30
M_13	± 50 μm	187.231		

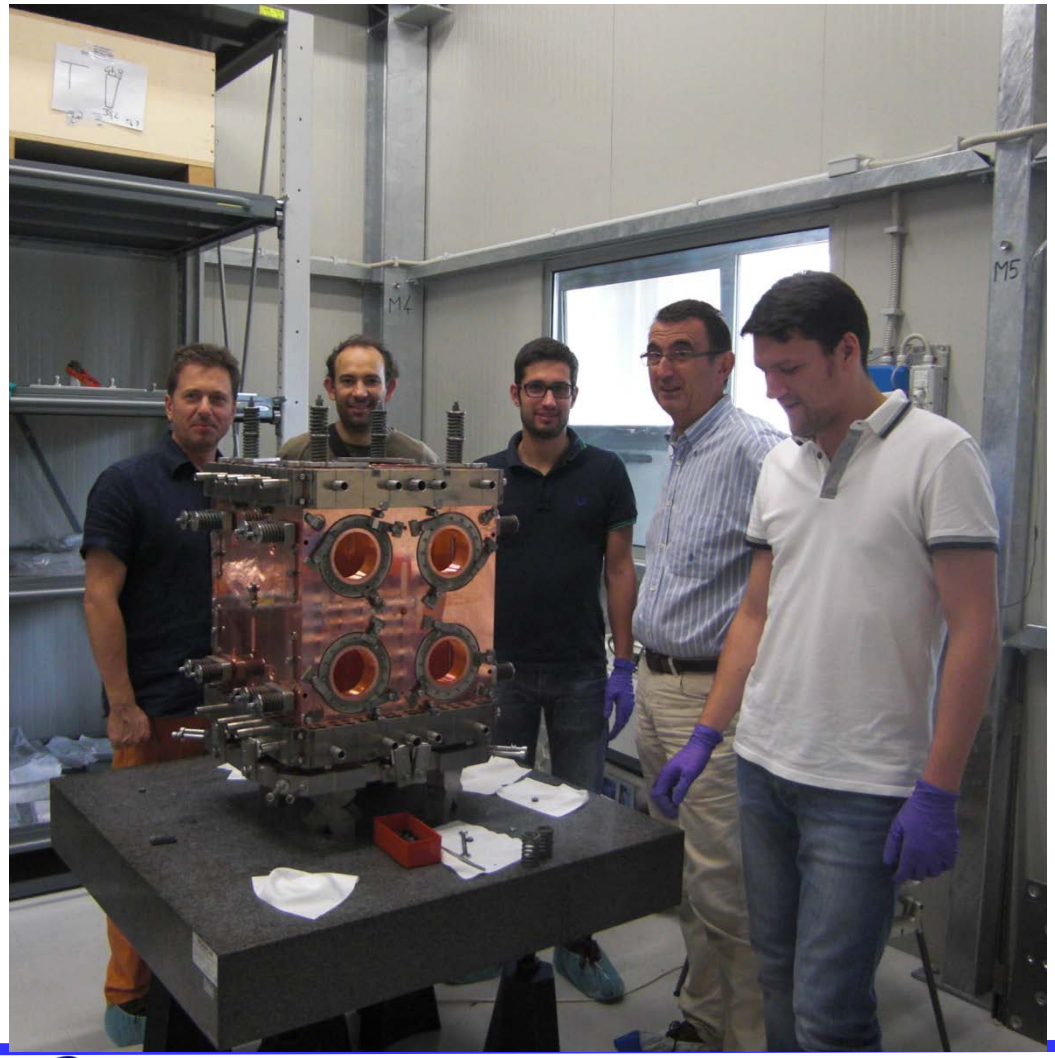
Supermodule 3 (Cinel srl)

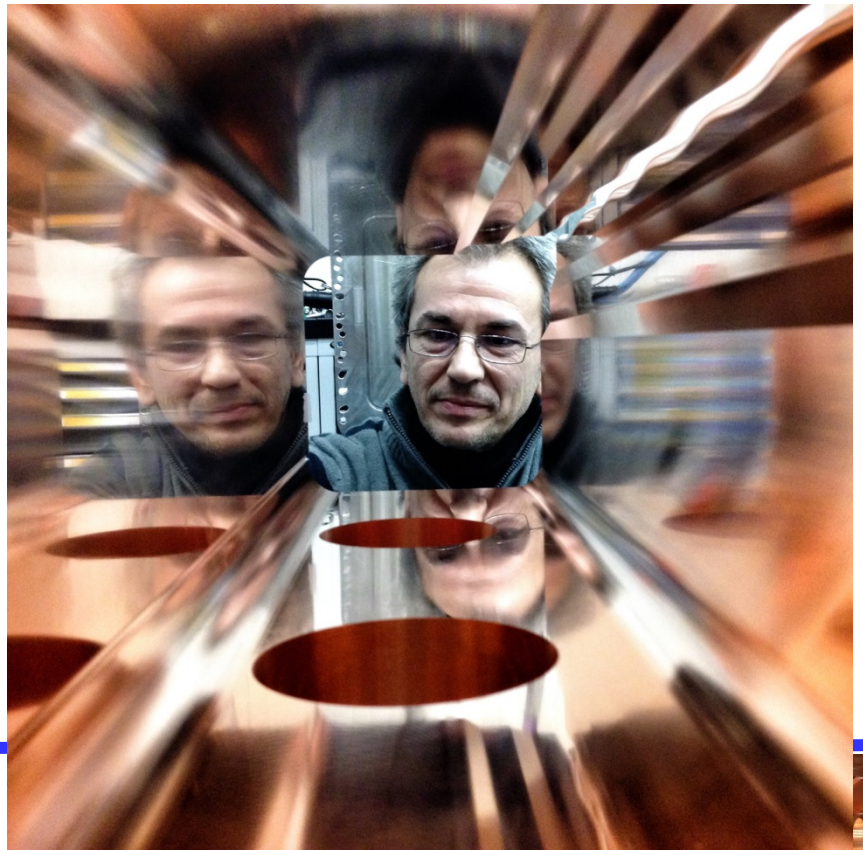




Supermodule 2 (INFN)

INFN production of modules





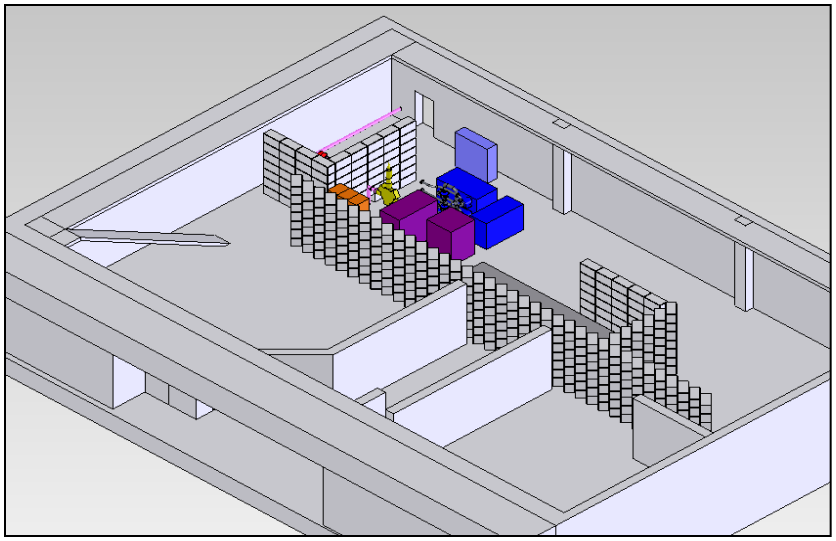
Supermodule 1 (originally RI)

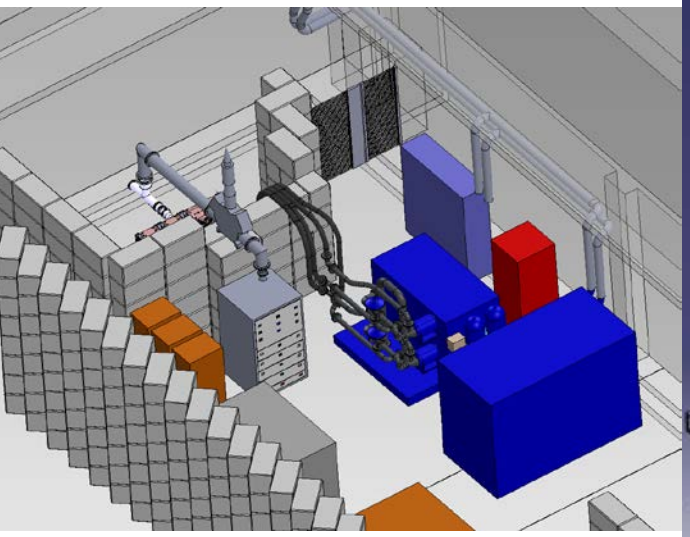
Module production summary

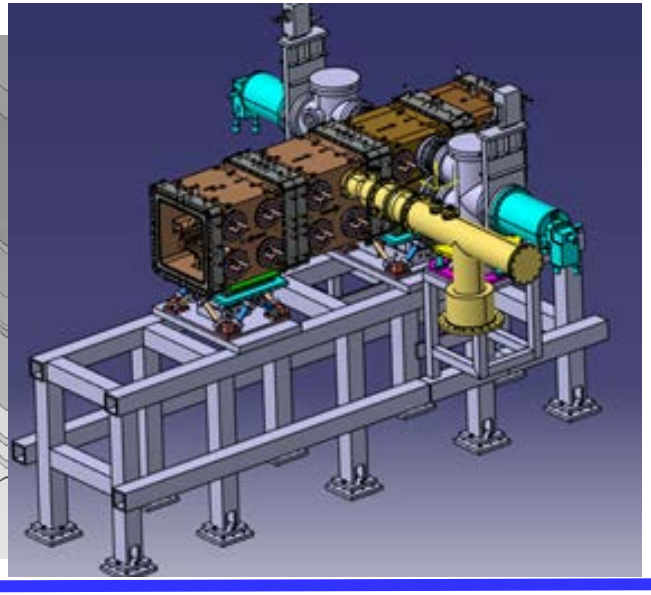
- The Cinel production of the high energy supermodule was concluded last semester,
- the INFN internal production of the intermediate energy supermodule is almost completed (one module remains to be brazed),
- the RI production is being concluded under INFN responsibility; two repairing have already been done.

High power test stand at LNL

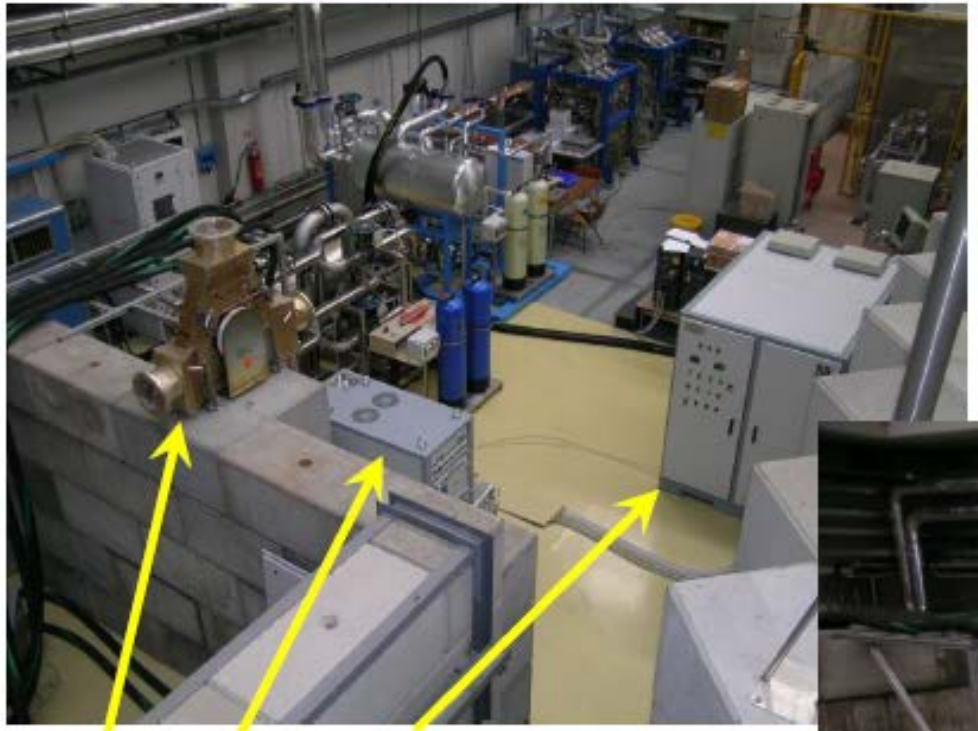
High power test stand a LNL







- A 500 kW test stand able to test 4 RFQ modules, to test at full power density the structure (200 kW RF power)
- The test is necessary to validate the design during the module construction (it was ment to be used at the beginning, now we are at the end of module production)



RF Cooling SKID

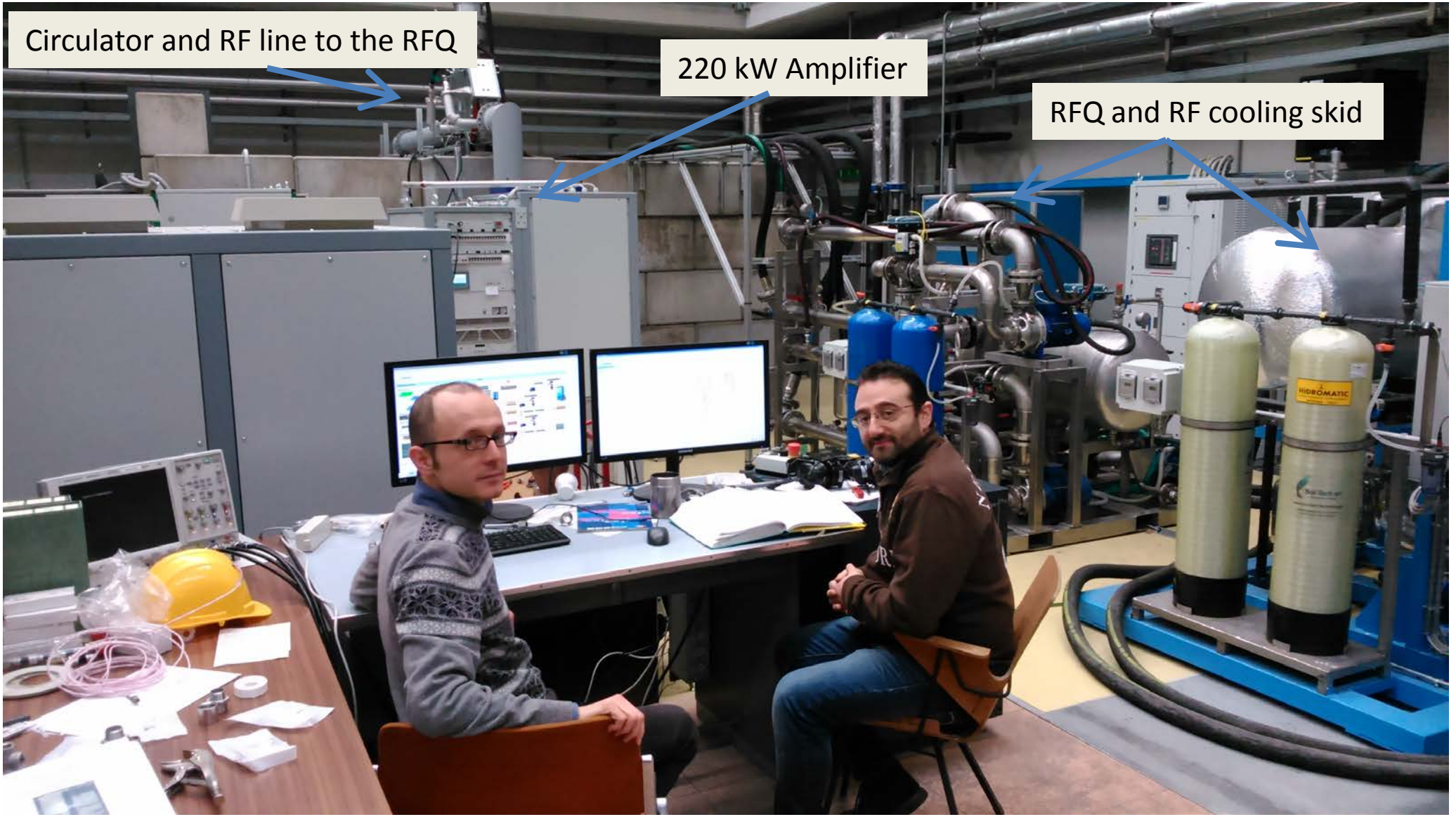
Electrical board

RFQ Cooling SKID

Power Supply

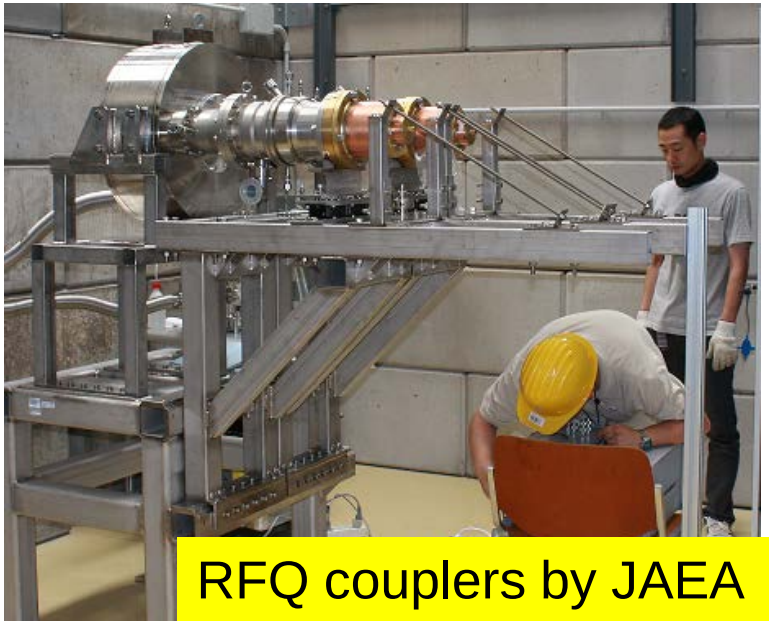
RF Power Amplifier

250 kW Circulator


Circulator and RF line to the RFQ
220 kW Amplifier
RFQ and RF cooling skid

The power couplers: INFN back up solution

- the eight RFQ couplers have to be delivered by JAEA.
- In 2013 two prototypes arrived for testing at LNL, and they were heavily underperforming (25% power losses on RF window).
- As a back up solution INFN and Cinel company have designed, produced and tested in six moths new couplers.
- INFN is participating to a F4E tender (“conto terzi”) for the construction of 9 temporary couplers to be used at Rokkasho.



RFQ couplers by JAEA

Status	Input power (kW)	Duty Cycle (%)
27/05/2014	200	0.02
28/05/2014	200	2.50
29/05/2014	150	100
03/06/2014	200	100

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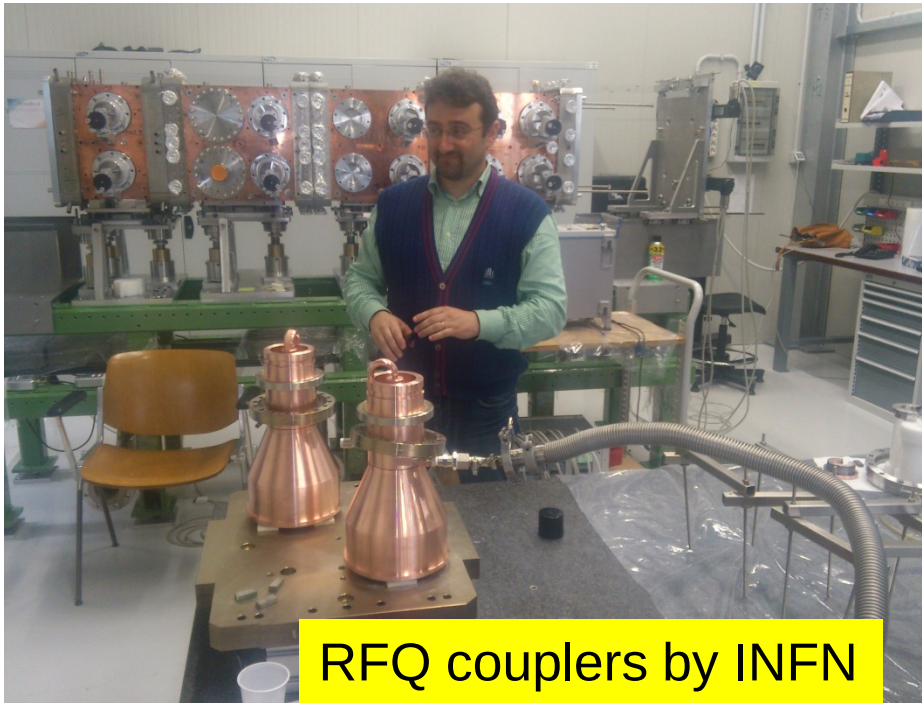
RFQ couplers by INFN

Status	Input power (kW)	Duty Cycle (%)
27/05/2014	200	0.02
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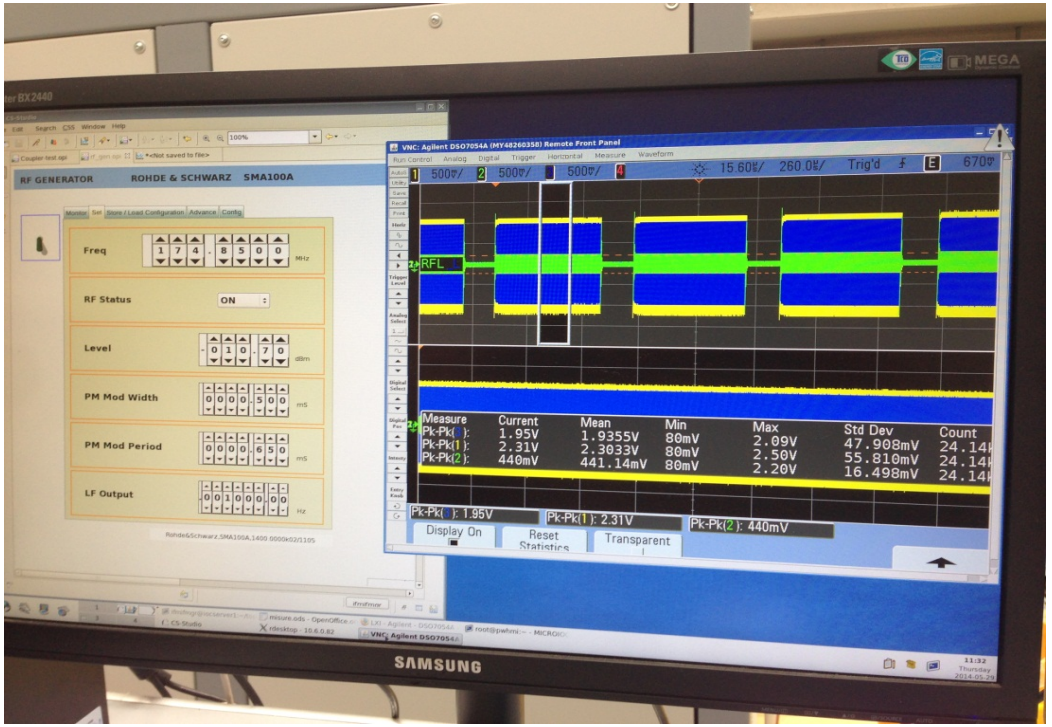
03/06/2014	200	100

High Power Couplers

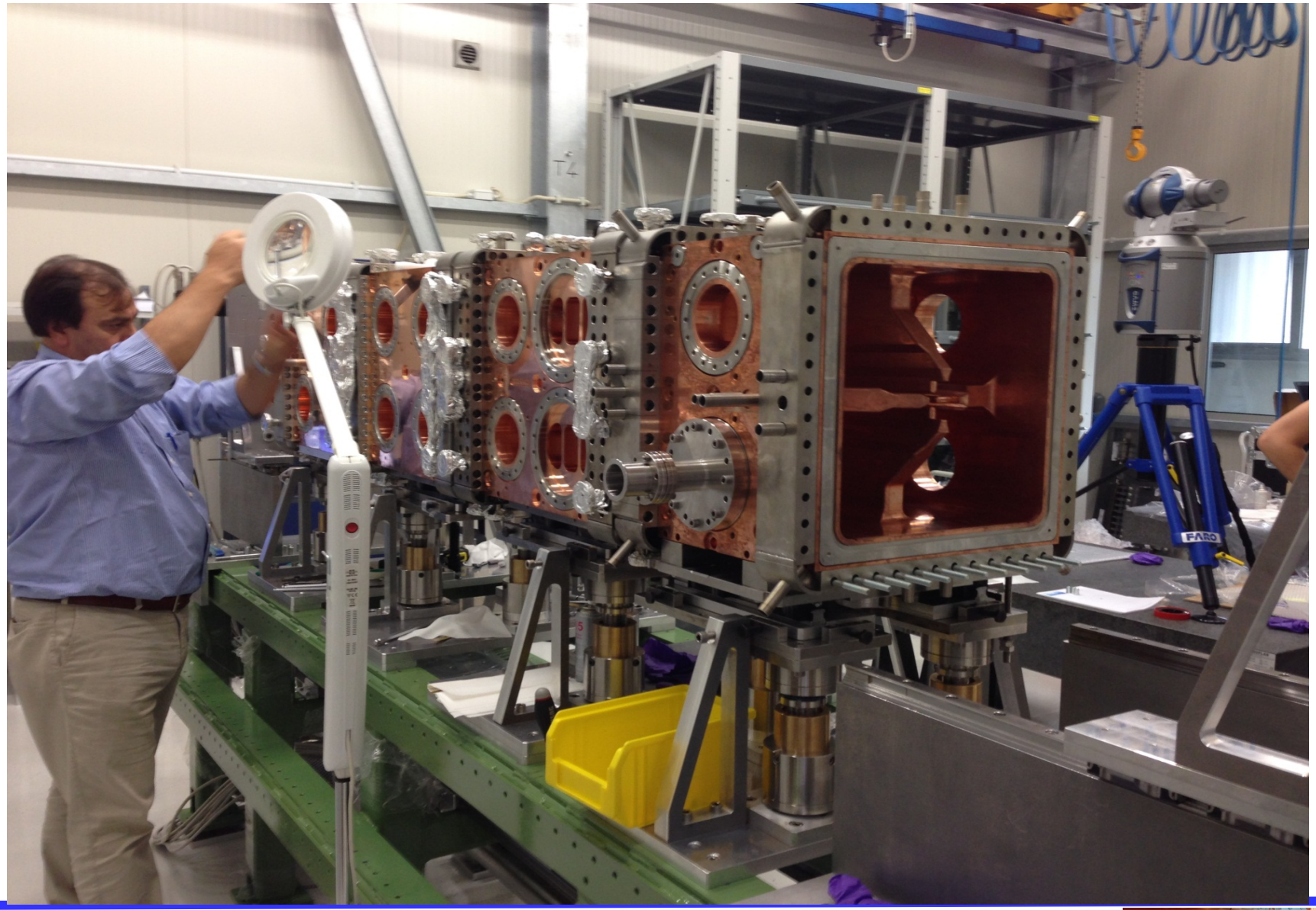
HPC test-stand assembly and measurements

S_{12} = -0.34 dB (7.6% insertion loss) (with dummy couplers)
S_{12} = -0.44 dB (9.7% insertion loss) (with final couplers without joints)

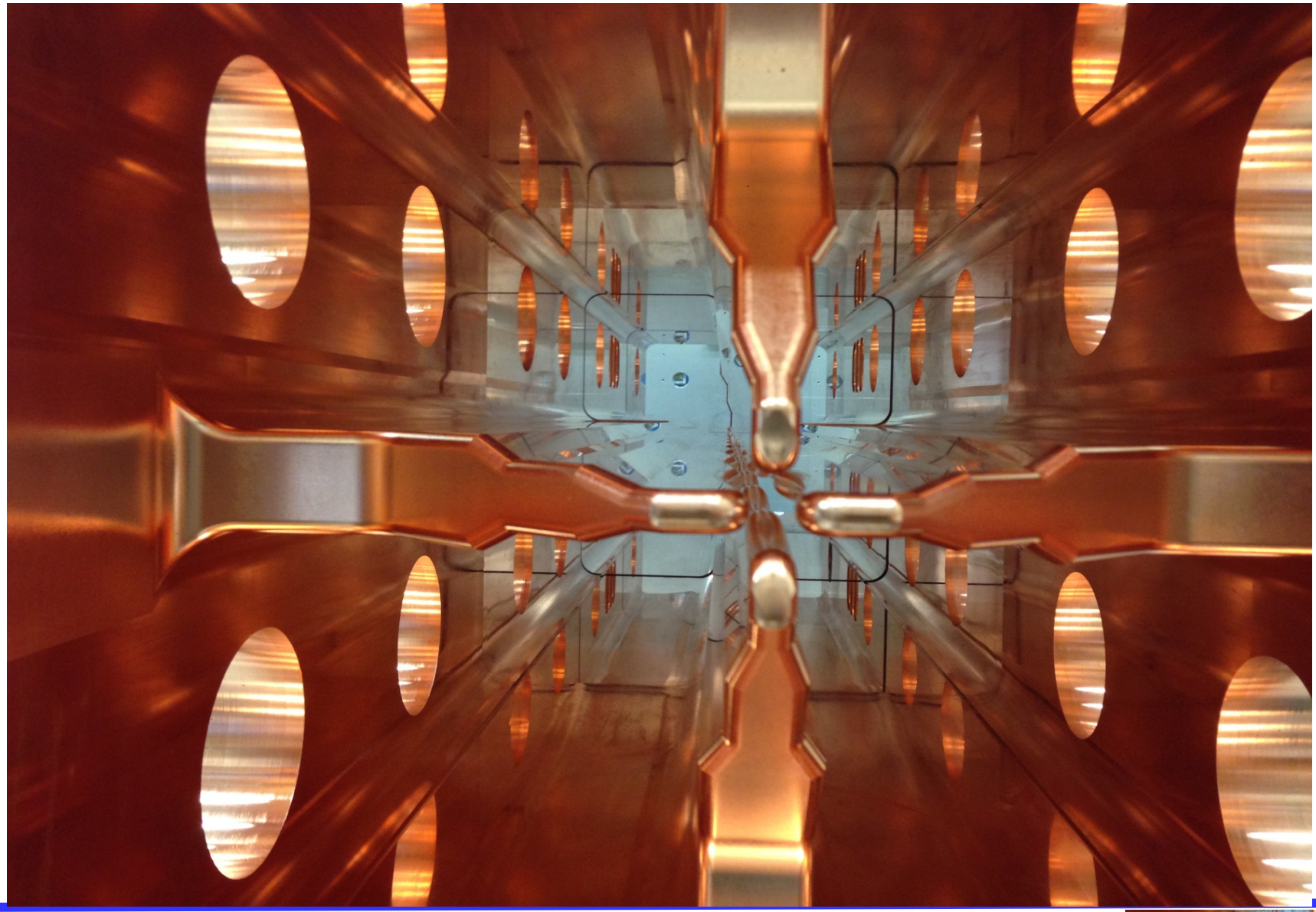
HPC test-stand control system



RFQ alignment (outside view)

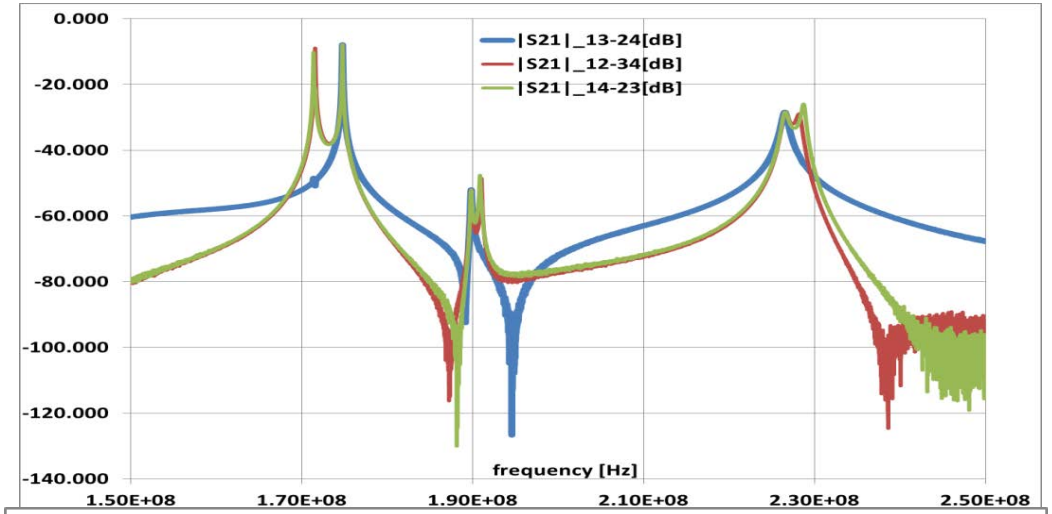


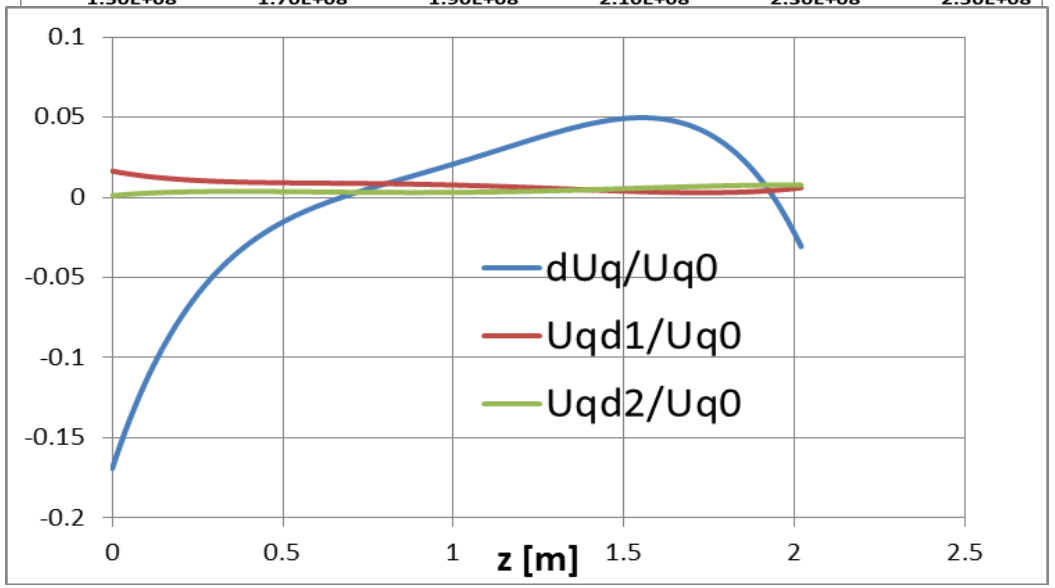
RFQ alignment (inside view)



RFQ Tuning for the High Power Test

1. Tuner flush and end plates @ nominal settings (g=12 mm insertion each): Mode Spectra





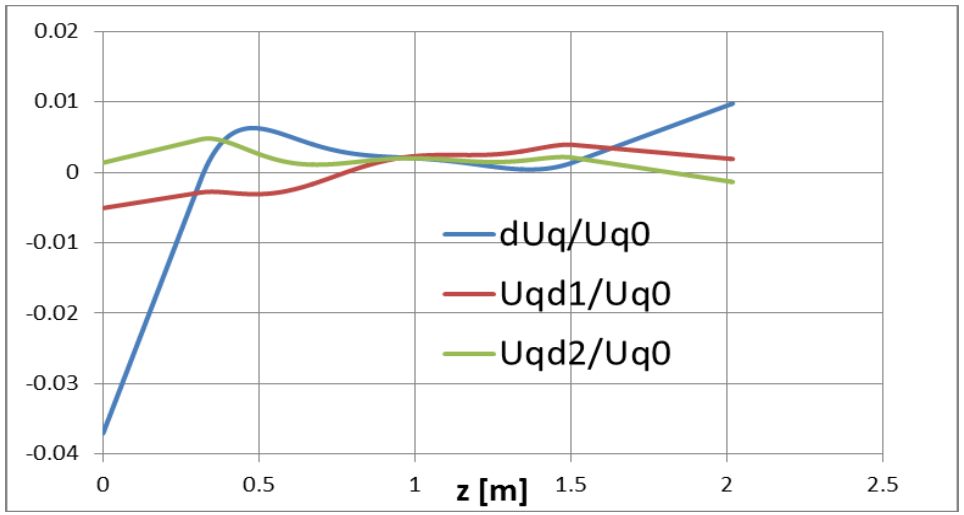
Q modes
fq0=174.77 MHz
fq1=190.79 MHz
fq2=226.52 MHz
Q0 (fq0) = 7040

D modes
fd0=171.38 MHz
(degeneracy= 10 kHz)
fd2=190.86 MHz
(degeneracy= 30 kHz)
fq2=228.68 MHz
(degeneracy= 50 kHz)

Beadpull measurements (metallic bead)
Dipole components are very low:
Strong Q component tilt at LE side
Due to the P2 module frequency mismatch

3. Measurement after 2 tuning steps

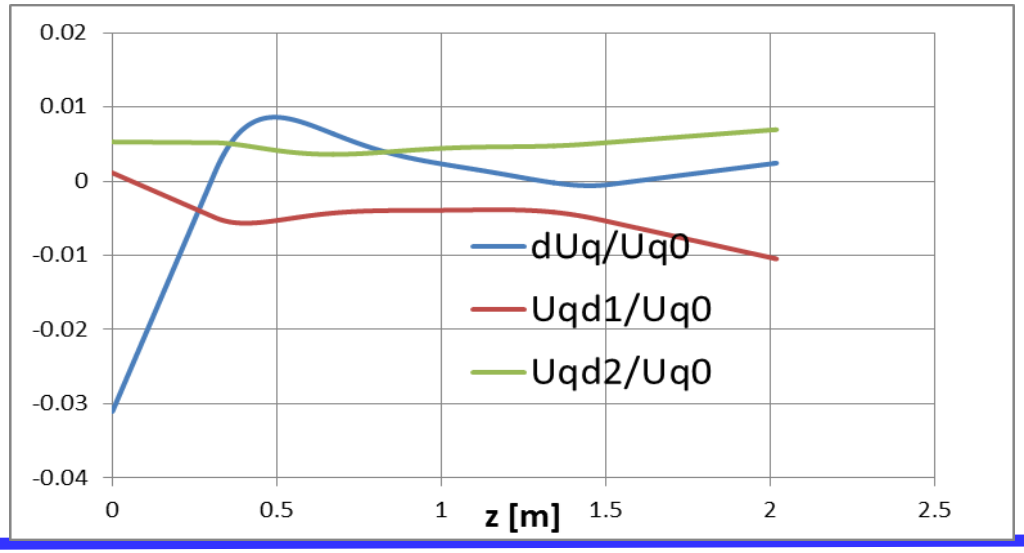
RFQ Tuning for the High Power Test (2)



fq0=175.014 MHz

The attainment of the maximum value of ± 2% voltage perturbation is verified almost everywhere in the RFQ. The zone exceeding this value is related only to the P2 RF plug.

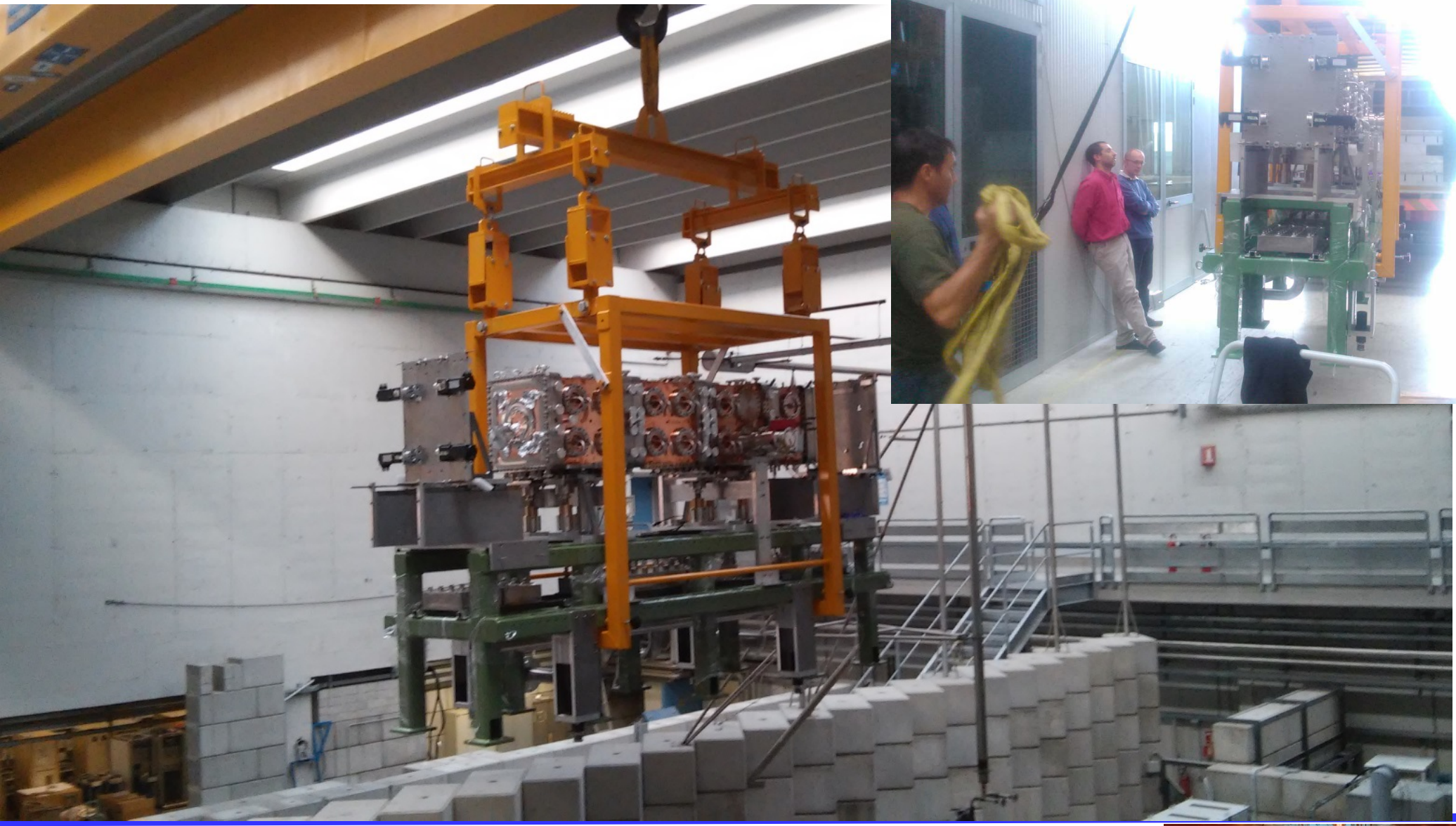
4. Measurement after the insertion of the dummy coupler

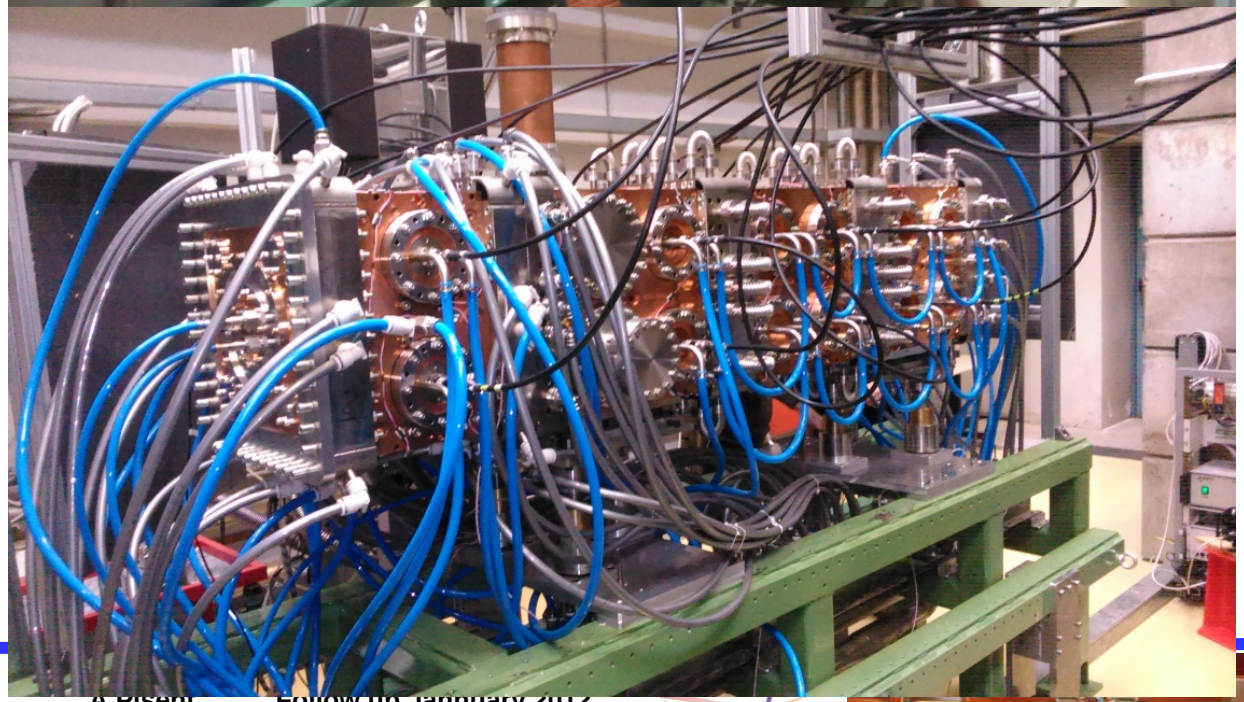


fq0=175.001MHz

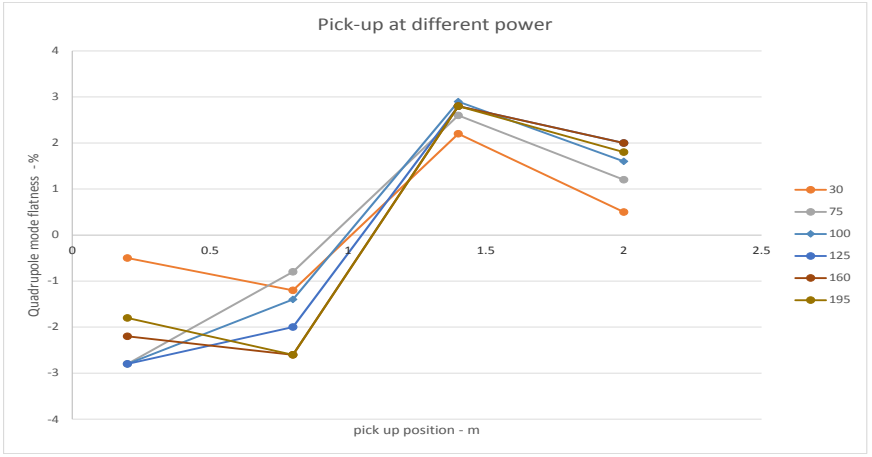
The dummy coupler had only a very slight effect on both fq0 and voltages.

Transportation to the test stand

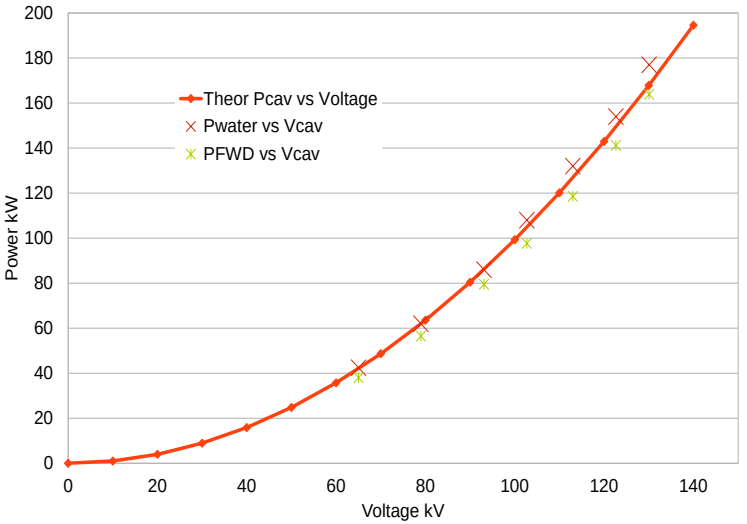




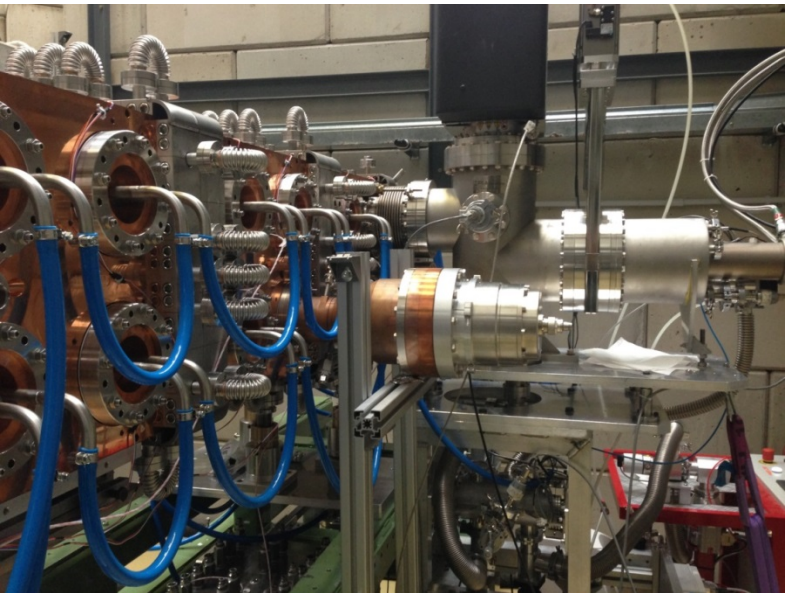
Preliminary Results of high power RF tests

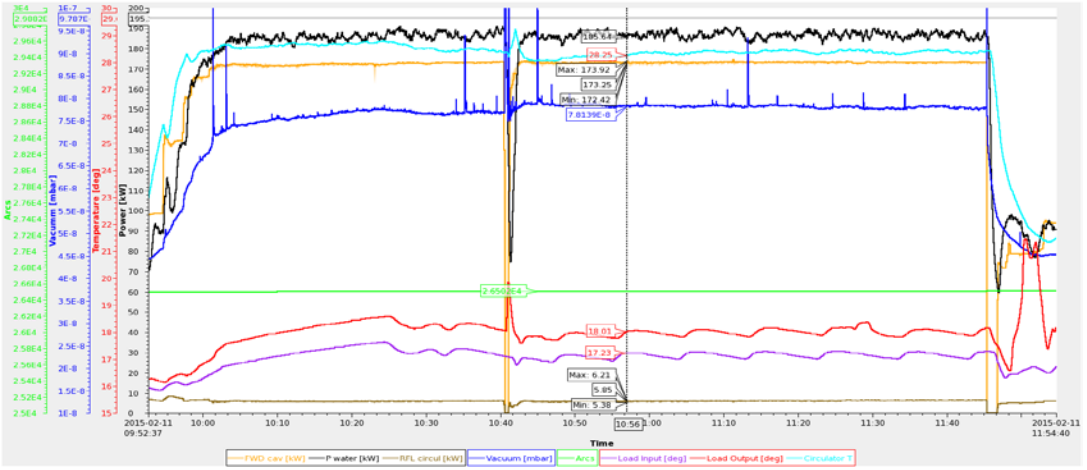


Field configuration (pick up reading) at different RF level



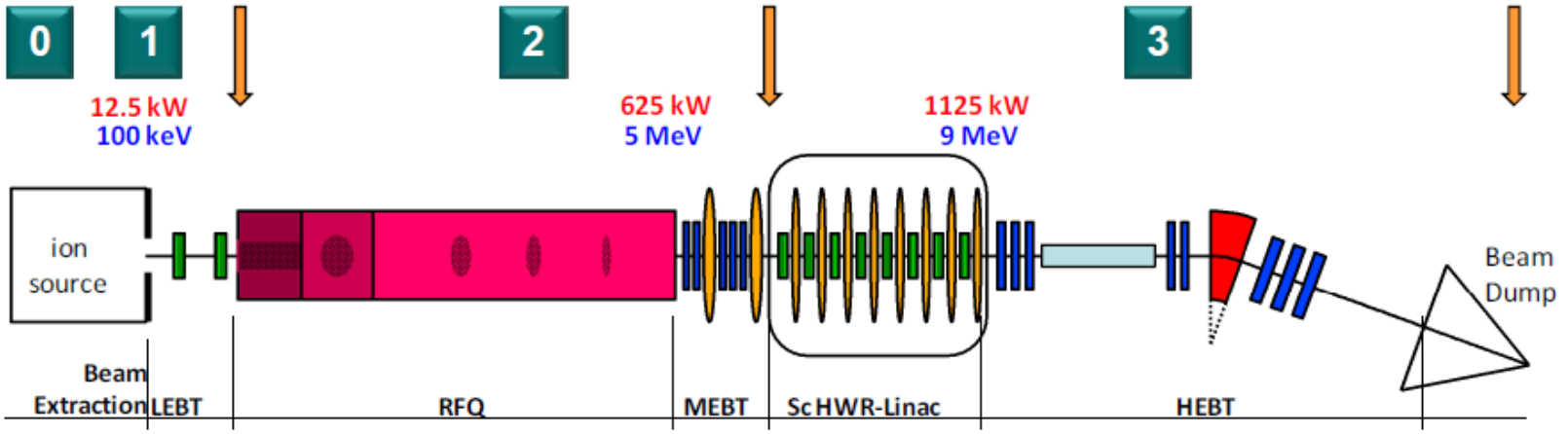
RF conditioning points and theoretical curve calculated for Q_0=12500, i.e. 173 kW vs. 132 kV

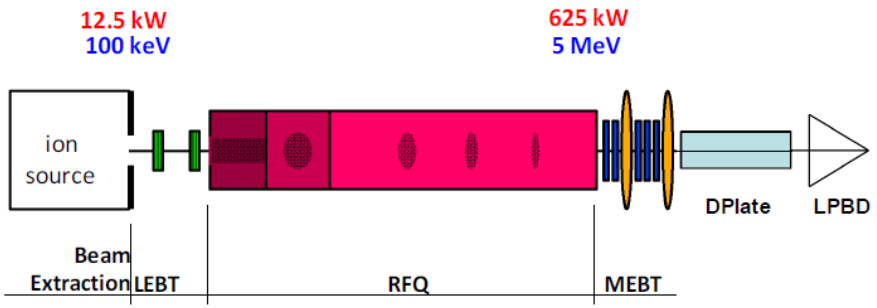


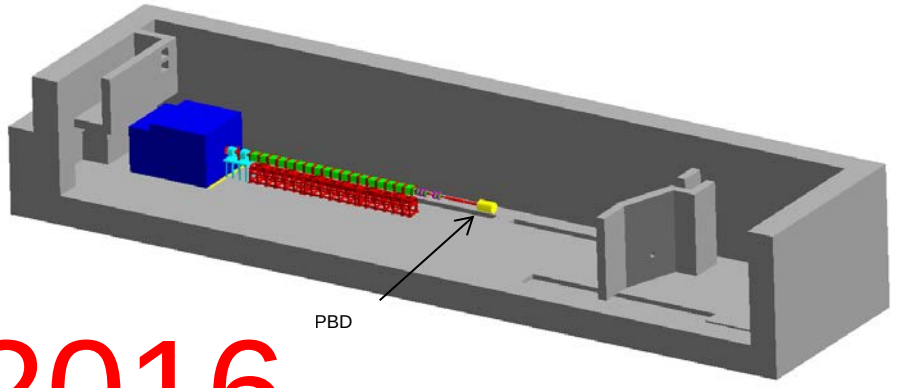


About 2 hrs at nominal power cw (FWD-RF=173kW, P_{water}=190 kW).

Beam commissioning phases



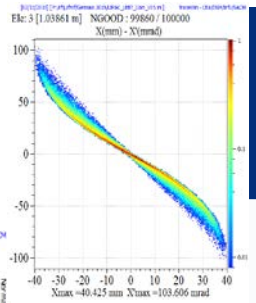


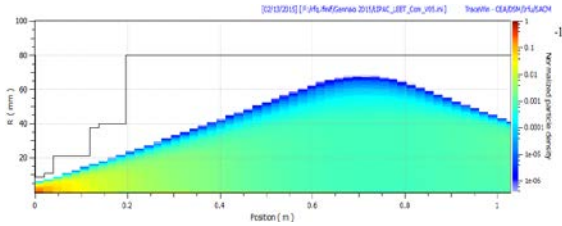


The 5 MeV beam is stopped by the LPBD (Low Power Beam Dump)

2016

First beam in Rokkasho



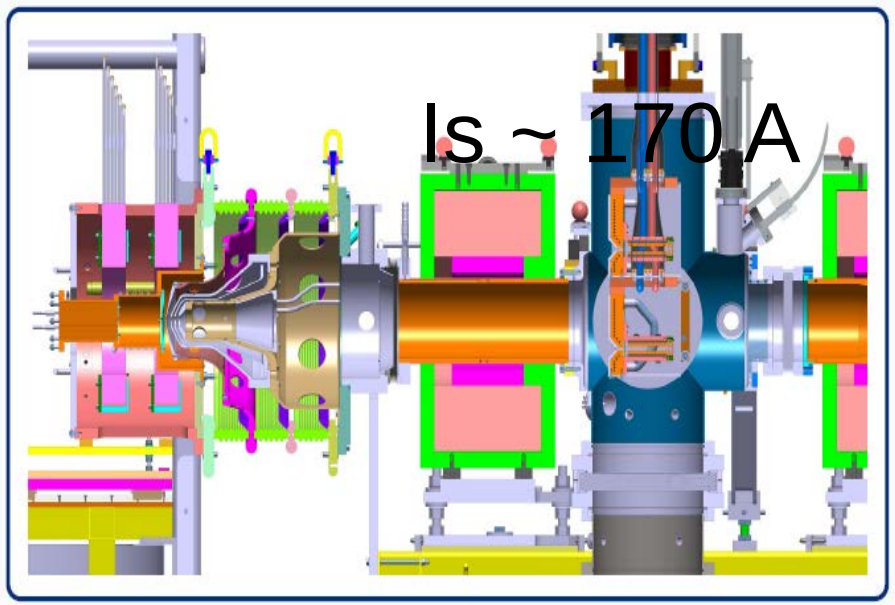


Experiments with electrode ϕ 10 mm

Preliminary emittance value

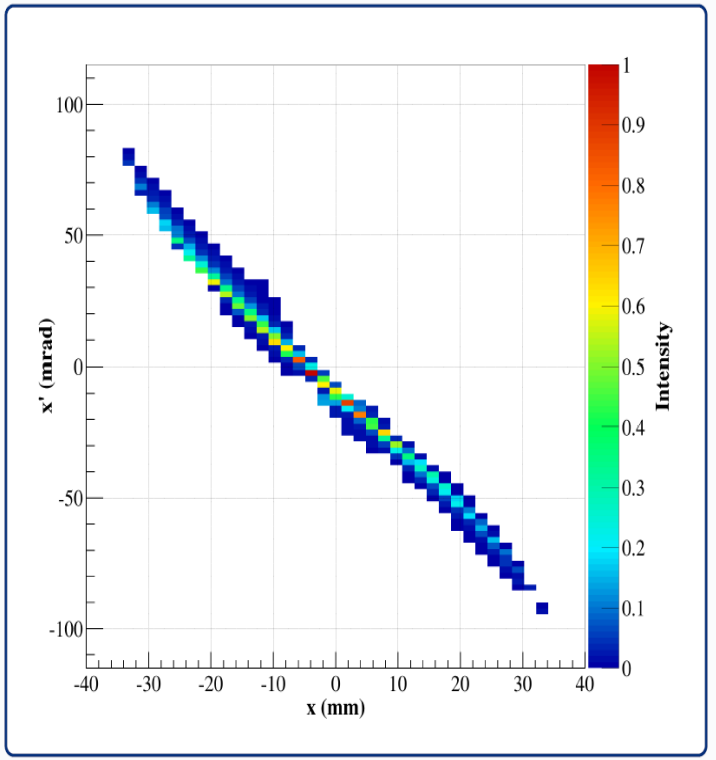
$E = 50\,keV - U_{IE} = 37.5\,kV - I_{Tot} = 74\,mA$

Duty cycle 40% (pulses of 20 ms @ 20 Hz)



Plasma Electrode – EMU

1027 mm

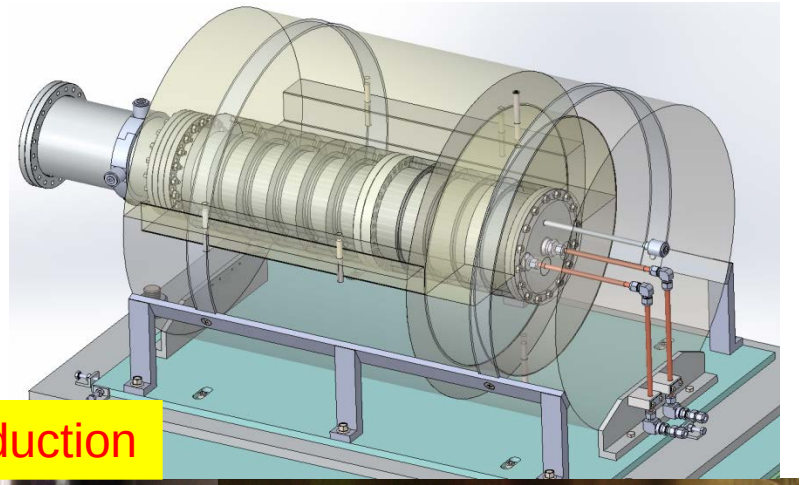


$\varepsilon_{Norm,rms}$ = 0.43 mm.mrad

The nominal is 0.25 mmmrad

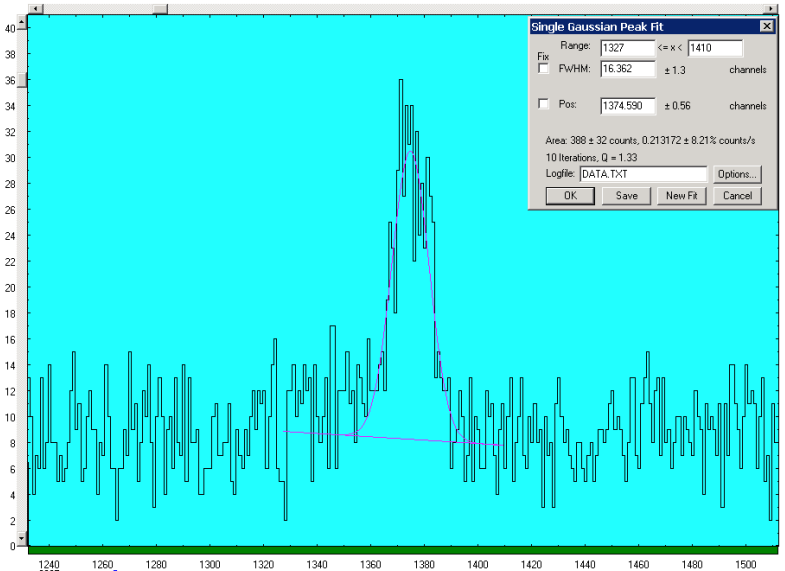
INFN main contributions to beam instrumentation for commissioning

- **Temporary beam dump** for pulsed beam commissioning of the RFQ (125 mA x 5 MV x 10^{-3} ≅ 0.625 kW deuterons) 100 us 10 Hz. Aluminum cone water cooled.



Ready for production

- **Residual Gas Bunch Length Monitor (RGBLM)**

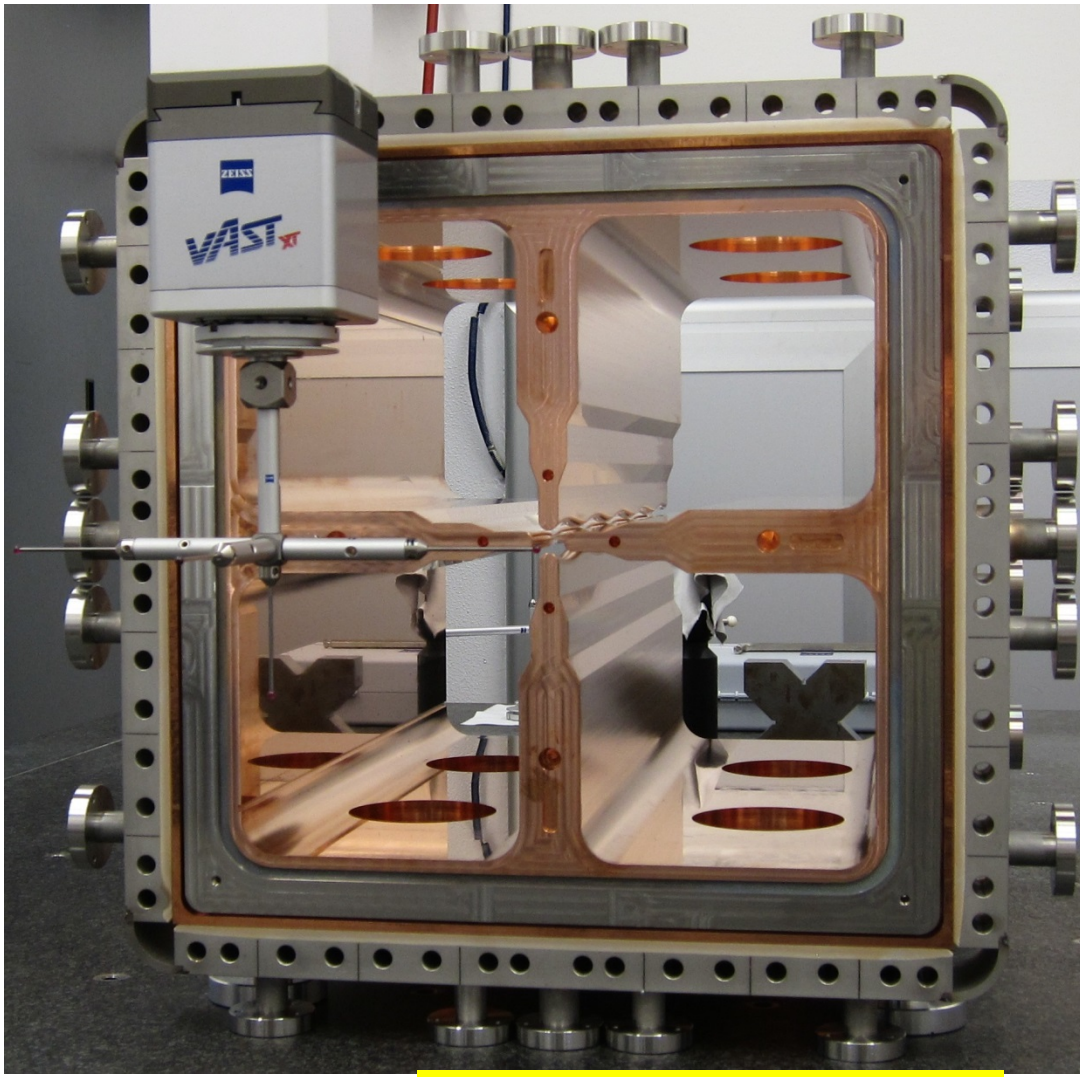


Delivered to Ciemat for integration

PERSPECTIVES

Outcome of INFN participation to IFMIF

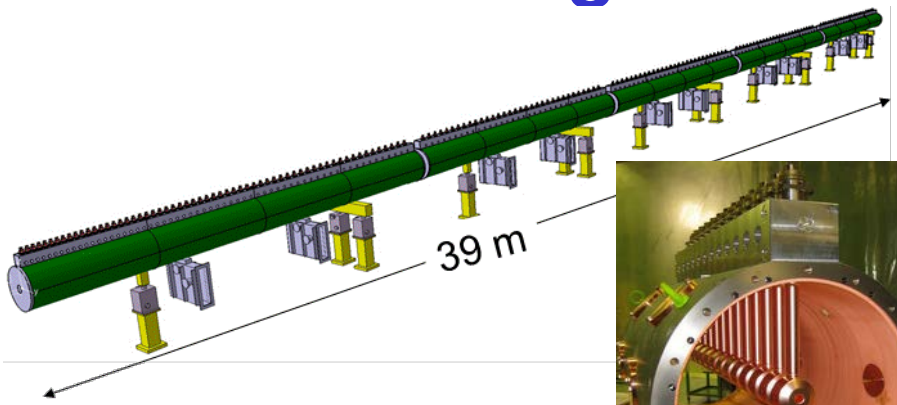
- Industry have been qualified for high intensity linacs (main are Cinel strumenti scientifici for mechanics and DB electronics for RF amplifiers)
- At LNL, Padova, Torino and Bologna many technical infrastructures have improved thanks to the participation to IFMIF-EVEDA
- EDM in PD and TO, CMM at PD, five axis milling machine at PD and TO, laser tracker, mounting lab, high power test stand and oven upgrade at LNL.
- Young people with expertise in mechanics, controls, RF and accelerator Physics have been hired.



CMM machine at Sezione di Padova

Accelerator projects with the same background

- Fusion Material future, 175 MHz cw RFQ in many projects of high intensity (Myrrha, Saraf, Eurisol…..)
- INFN participation to ESS, with the construction of the DTL (previous talk)



DTL: CERN-INFN prototype

Accelerator projects with the same background

- Fusion Material future, 175 MHz cw RFQ in many projects of high intensity (Myrrha, Saraf, Eurisol…..)
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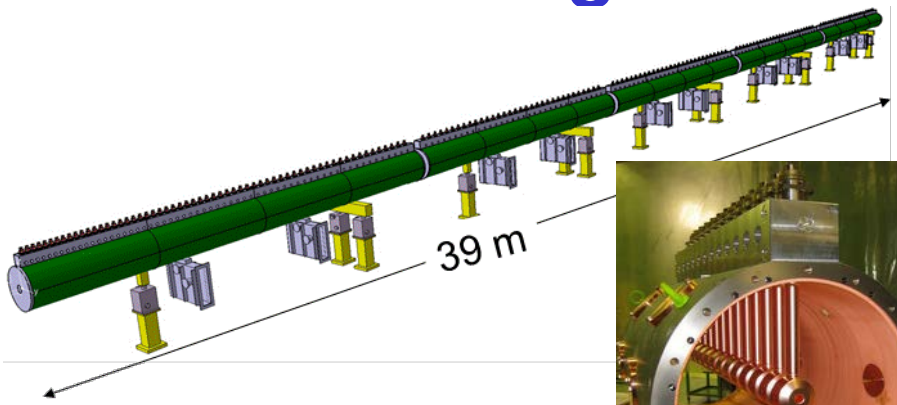
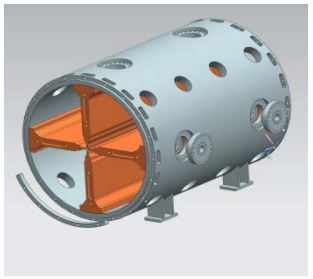
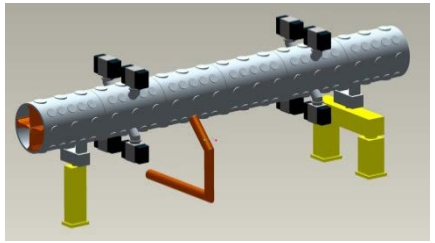
- SPES RFQ, the main accelerating structure to be built is a 7 m long RFQ cw operating at 80 MHz,
- New RFQs (next week meeting with GSI) for a technical collaboration on FAIR proton RFQ.



DTL: CERN-INFN prototype



SPES RFQ Design and Tank material



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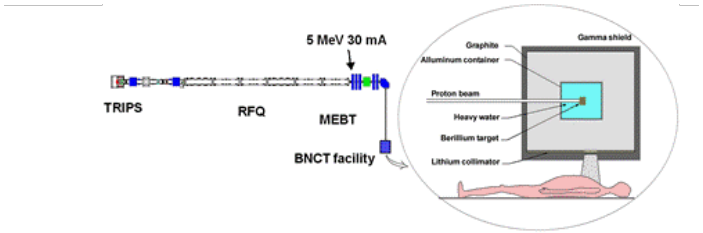
- SPES RFQ, the main accelerating structure to be built is a 7 m long RFQ cw operating at 80 MHz,
- New RFQs (next week meeting with GSI) for a technical collaboration on FAIR proton RFQ.
- MUNES, a compact 10^{14} neutron/s source for BNCT.



TRASCO RFQ

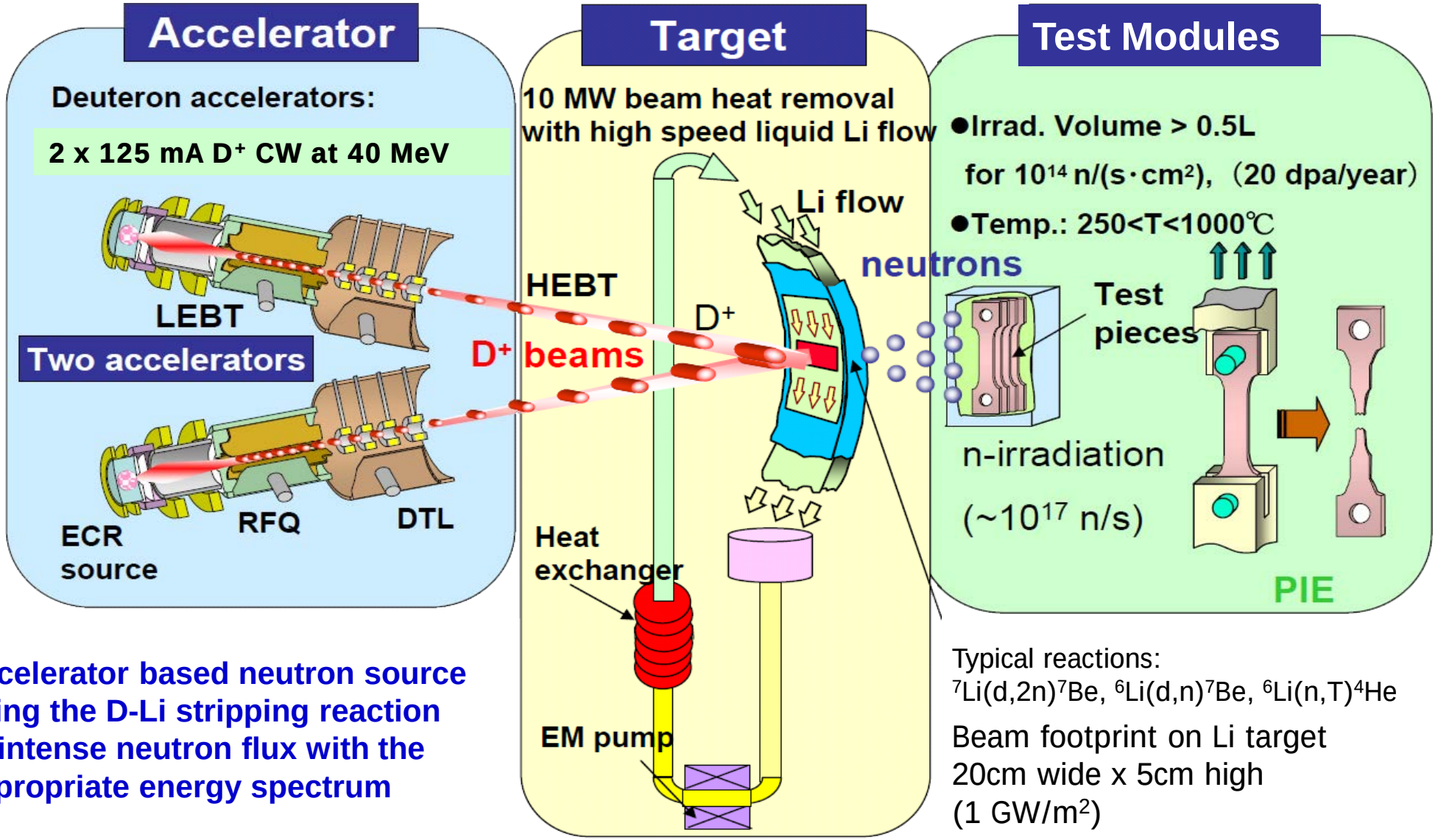
Moderator, low power@CN

Conclusions

- The RFQ construction is very advanced (15/18 modules brazed, some reparations and the final integration missing)
- The RF performances have been achieved in the High power test stand.
- With the beginning of 2016 we should start beam tests in Japan.

Componenti del team INFN RFQ:
A. Pisent (coordinatore, LNL), A. Pepato (responsabile della meccanica, Padova), P. Mereu (responsabile dell'integrazione, Torino), A. Margotti (Bologna), L. Antoniazzi, M. Comunian, D. Dattola, R. Dima, J.Esposito, A. Facco, E. Fagotti, L. Ferrari, M. Giacchini, G. Giraudo, F. Grespan, M. Montis, A. Palmieri, A. Prevedello, L. Ramina ,M. Romanato C. Roncolato, F. Scantamburlo, E. Udup, M. Poggi

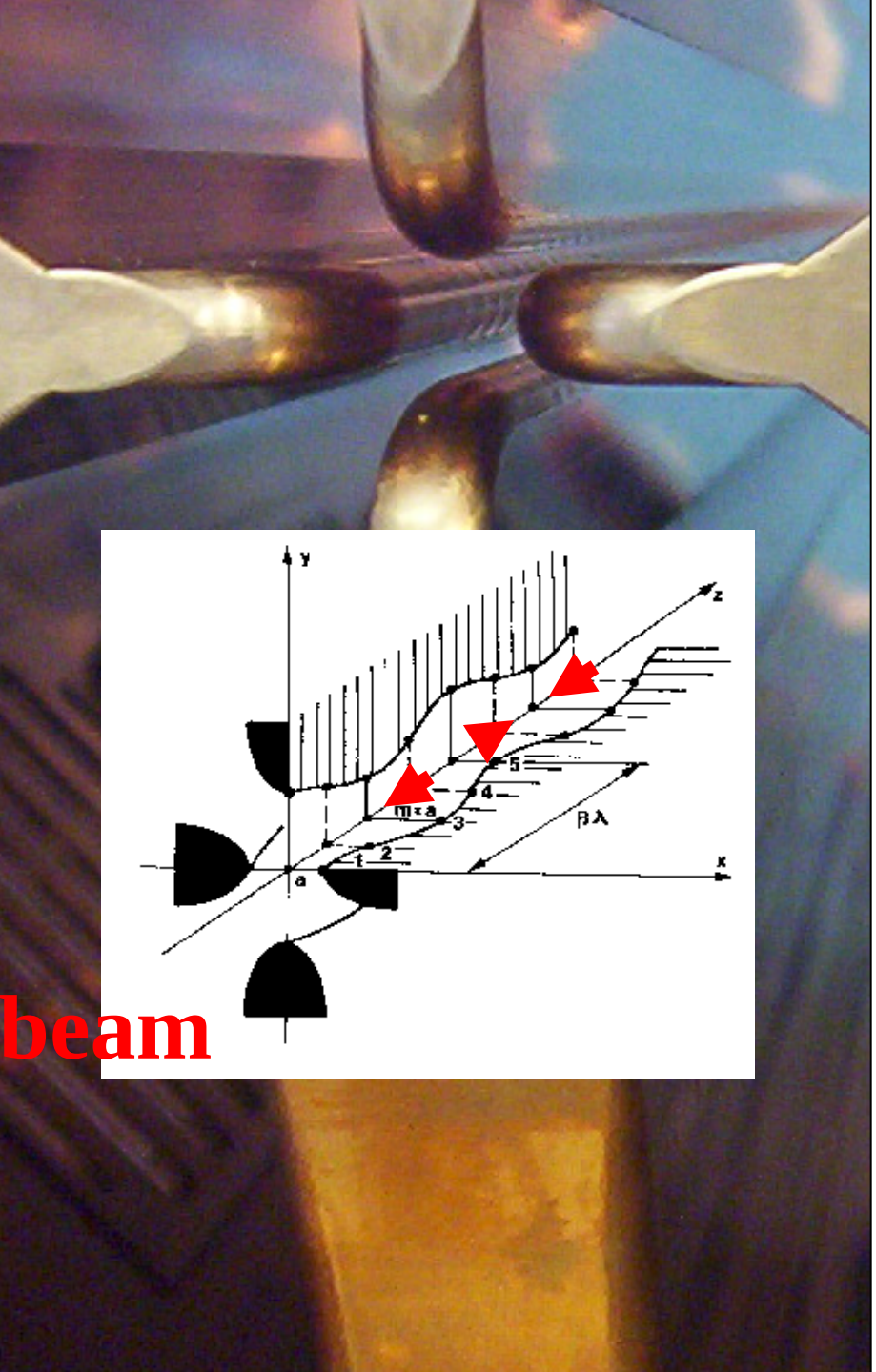
IFMIF Principles



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

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

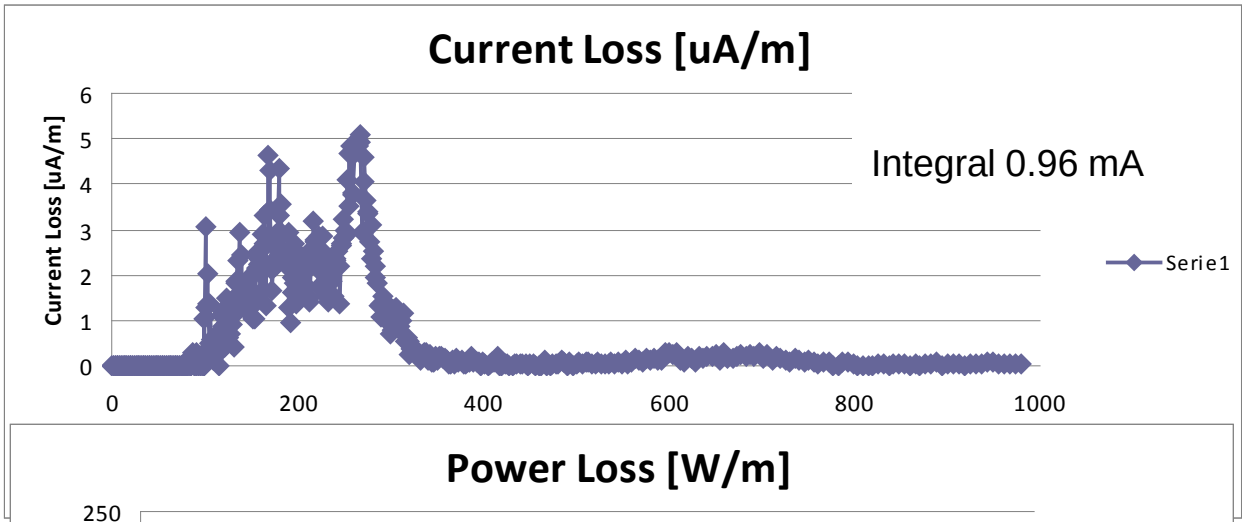
Beam footprint on Li target
20cm wide x 5cm high
(1 GW/m^2)

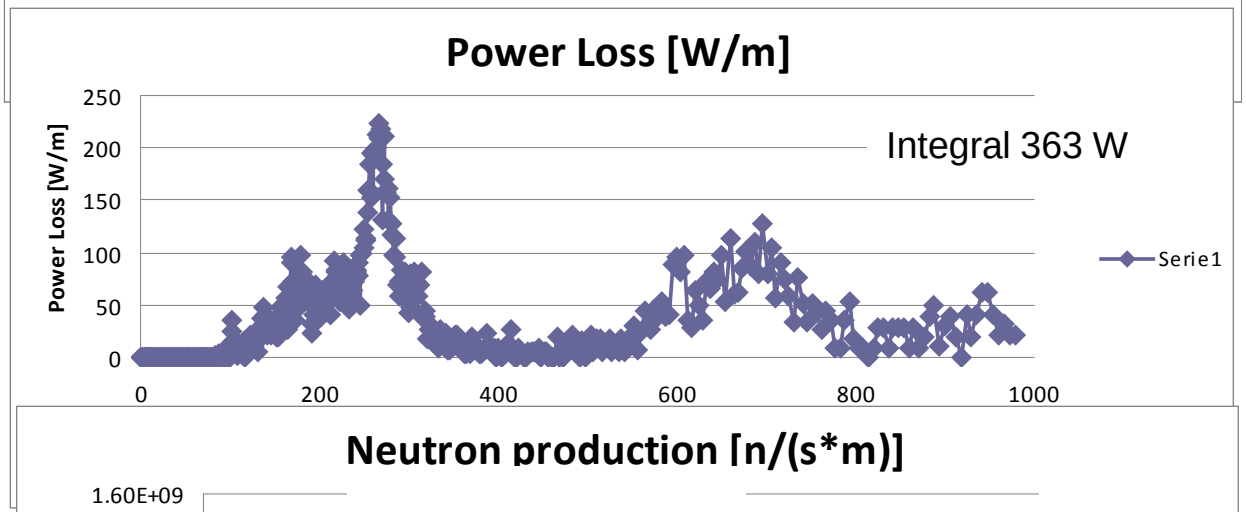


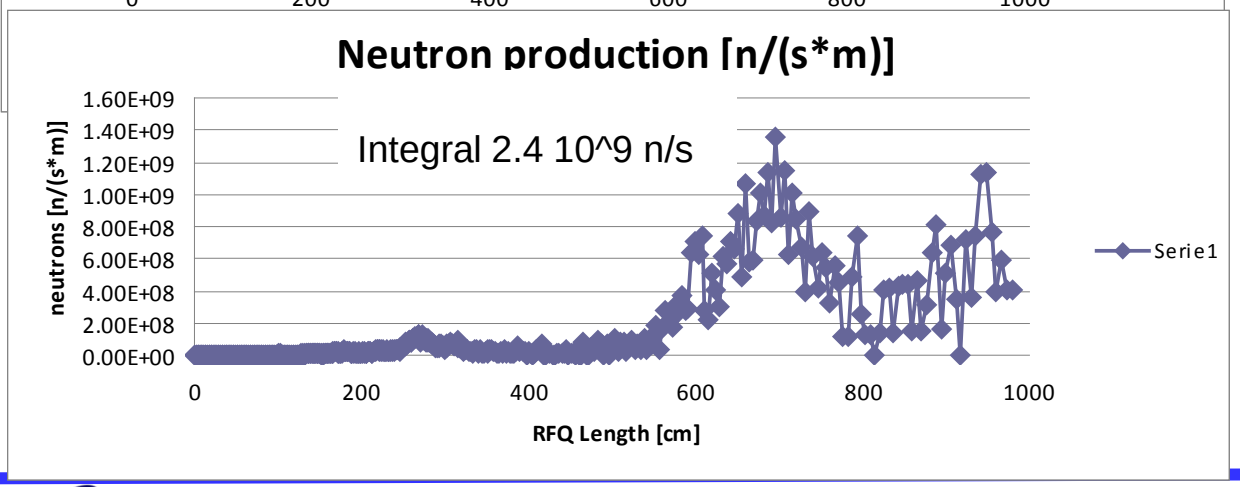
IFMIF RFQ modulation design

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.







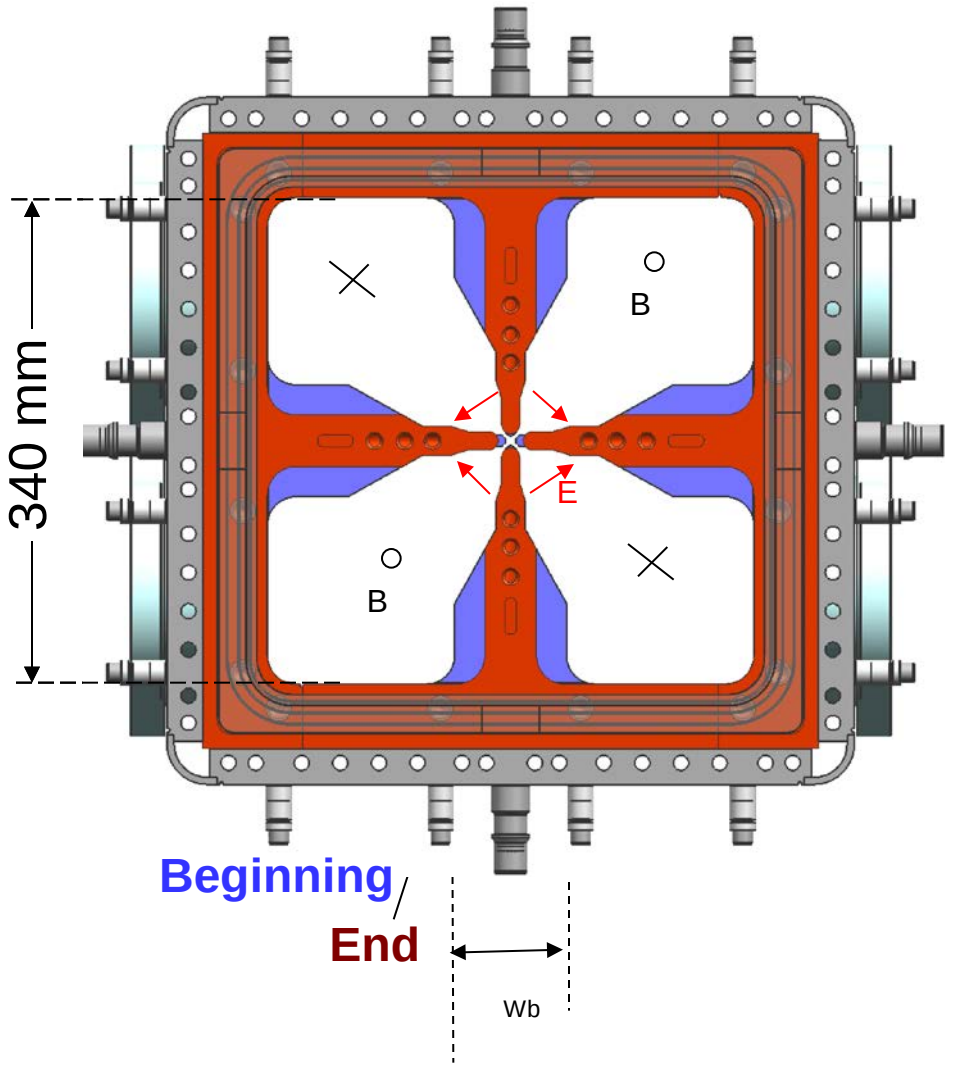
Beam losses

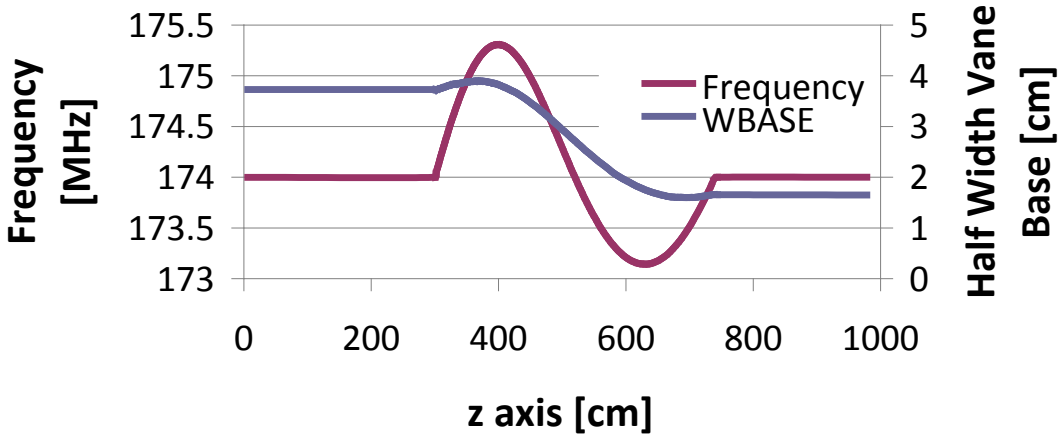
- To achieve Beam losses concentrated in the low energy part is very important since neutron production is proportional to w^2

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

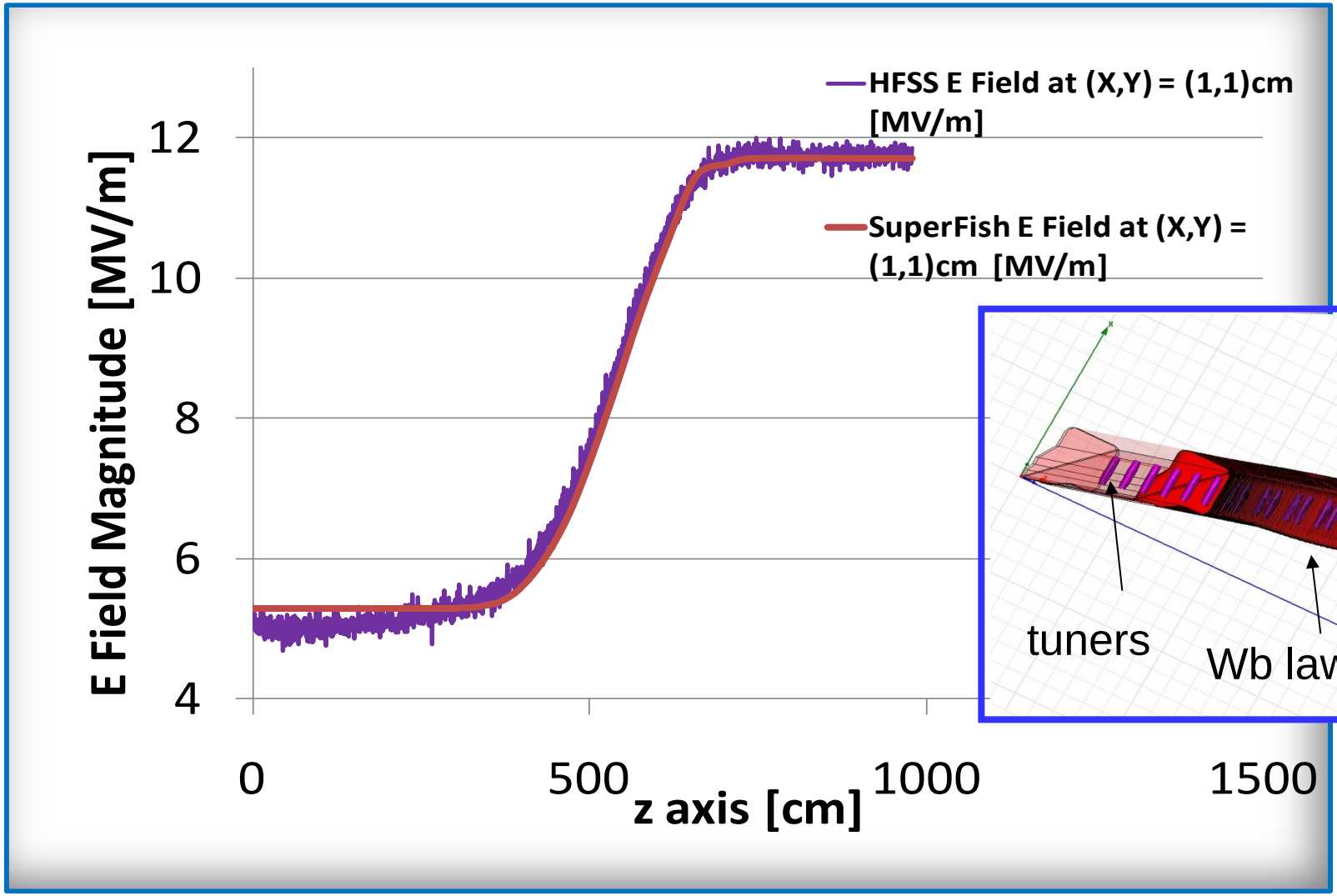
WB distribution 0.25 mm mrad rms norm

Sezione della cavità RFQ





3d simulation of the entire cavity



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