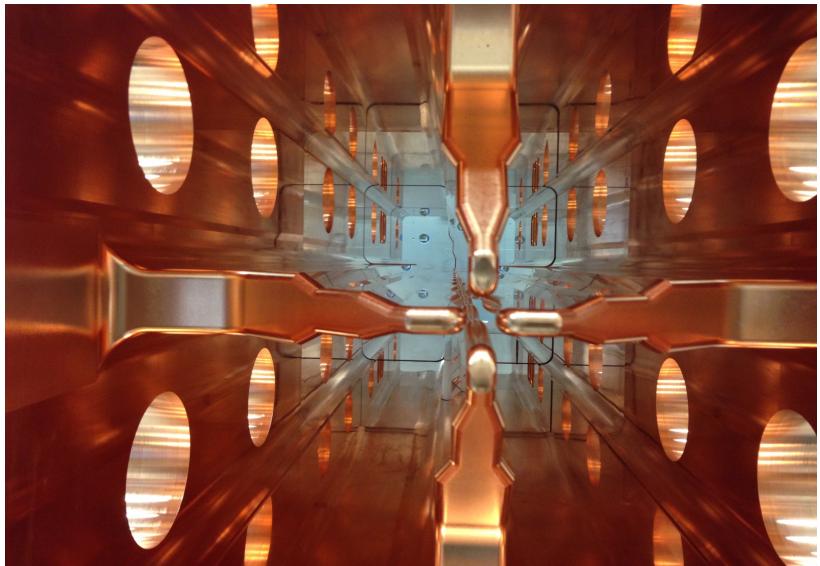


TOWARDS COMMISSIONING OF THE IFMIF RFQ

A. Pisent-INFN

On Behalf of the INFN IFMIF-EVEDA collaboration
(LNL, Padova, Torino, Bologna)

- Outline:
 - Introduction
 - RFQ construction results
 - Cw RF tests in Italy
 - Installation and tuning in Japan

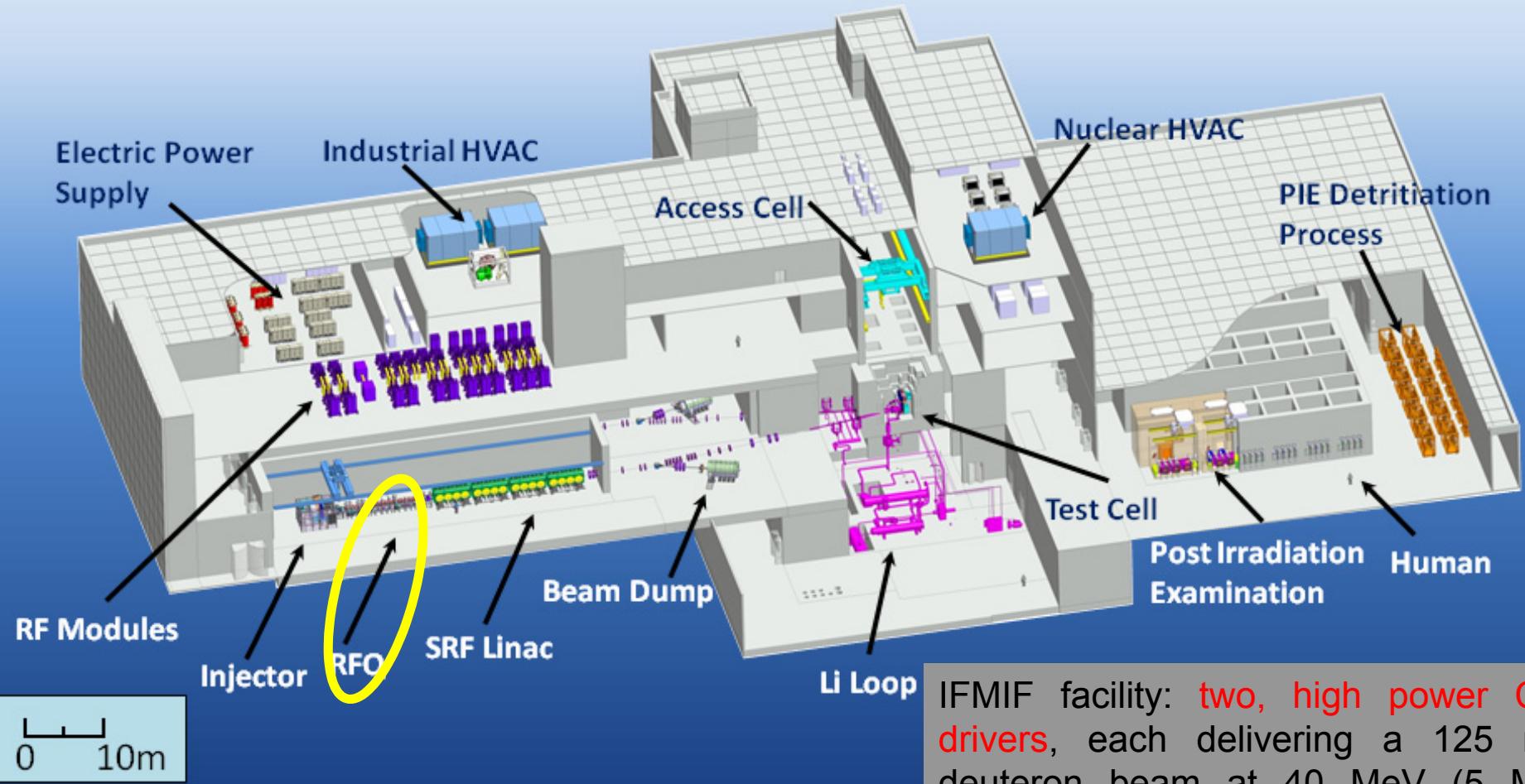


IFMIF-EVEDA RFQ

Input/output Energy	0.1-5	MeV
Duty cycle	cw	
Deuteron beam current	125	mA
Operating Frequency	175	MHz
Length (5.7 λ)	9.78	m
Vg (min – max)	79 – 132	kV
R0 (min - max) $\rho/R0=.75$	0.4135 - 0.7102	cm
Total Stored Energy	6.63	J
Cavity RF power dissipation	550	kW
Power density	90	kW/m
Power density (average-max)	3.5-60	kW/cm ²
Q0/Qsf=0.82	13200	
Shunt impedance ($<V^2>$)L/Pd	201	k Ω –m
Frequency tuning	Water temp.	

IFMIF “Artist View”

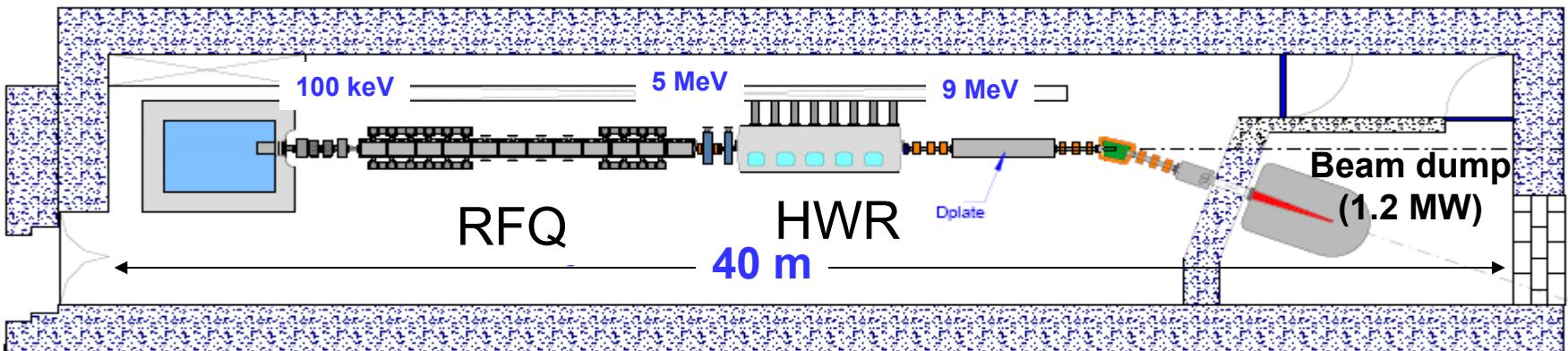
International Fusion Material Irradiation Facility



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 reactions.

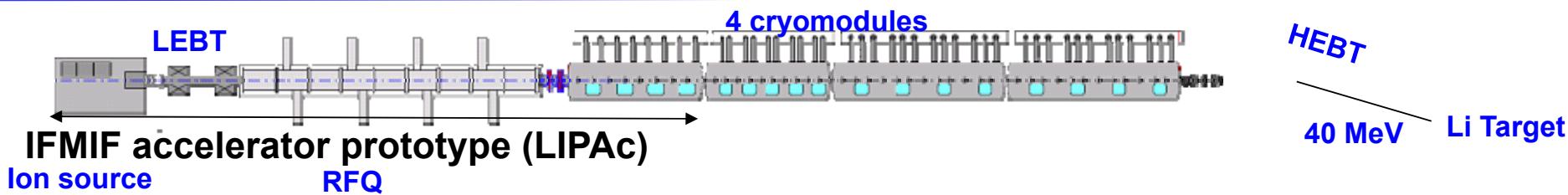
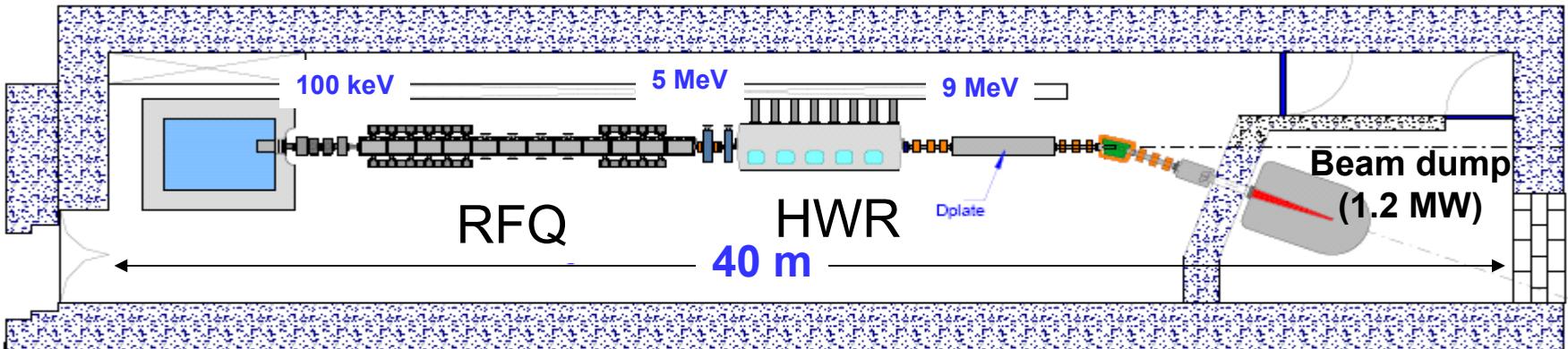
IFMIF EVEDA

- Funded within the Broader Approach to Fusion: construction of a **9 MeV 125 mA cw deuteron accelerator** (LIPAc, Linear IFMIF Prototype Accelerator) to be built in Rokkasho, (Japan), based on a high power RFQ followed by a Half Wave Resonator superconducting



IFMIF EVEDA

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IFMIF/EVEDA

Linear IFMIF Prototype Accelerator

Accelerator components from Europe
Beam tests in Japan



France
Injector + LEBT
CEA Saclay



France
Diagnostics
CEA Saclay
Spain
CIEMAT Madrid
Italy
INFN Legnaro



RFQ
INFN
QST

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid

France
Cryoplant
CEA Saclay

36 m
RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

Building
Auxiliary System
Control system
Installation
QST



Status of LIPAc Phases (Rokkasho site)

Injector under commissioning



MEBT set up



Diagnostics Plate set up



RFQ assembled and tuned

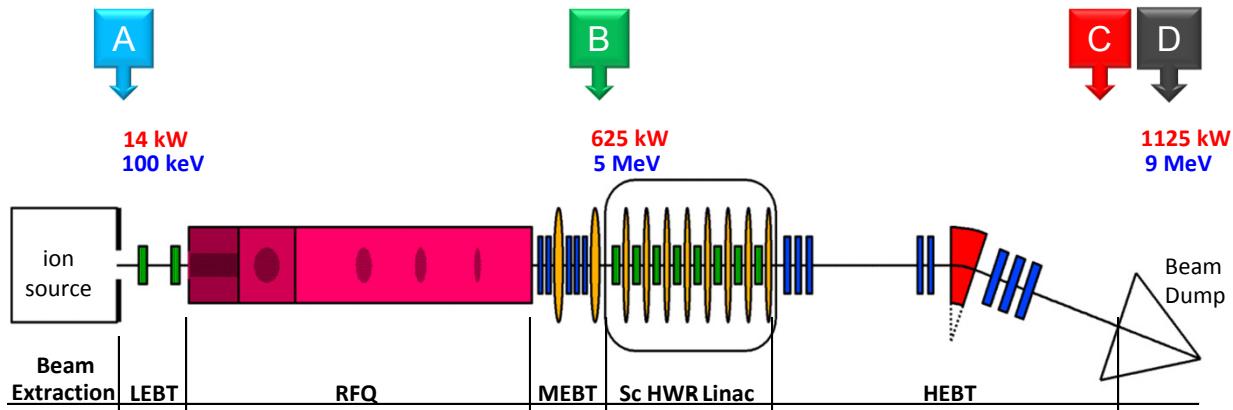
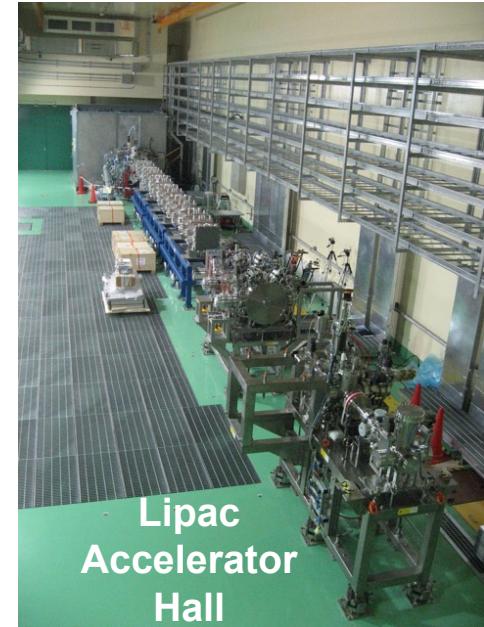


RF power system under completion



LIPAc Commissioning Plan

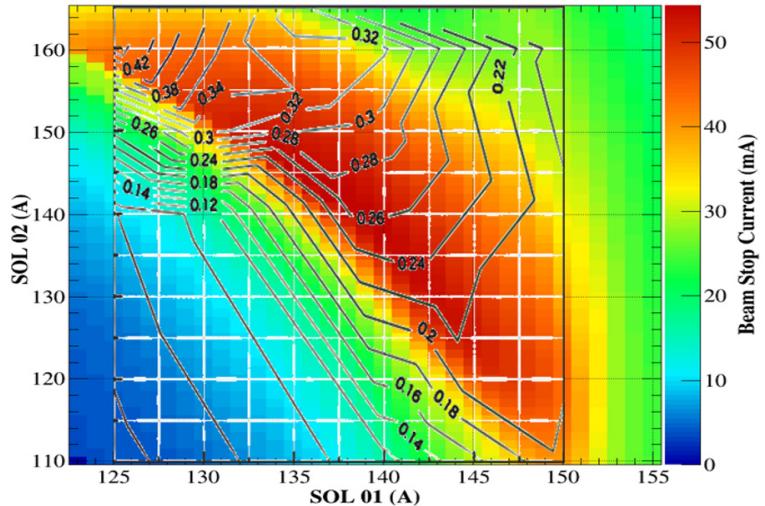
- **Phase A:** 140 mA deuteron current at 100 keV in CW
- **Phase B:** 125 mA deuteron current at 5 MeV at 0.1% duty cycle
- **Phase C:** 9 MeV deuteron current at 9 MeV at 0.1% duty cycle
- **Phase D:** Ramp up the duty cycle up to CW



LEBT Commissioning

Source and LEBT beam preparation for IFMIF-EVEDA RFQ
L.Bellan et al TUPRC005

- At present **commissioning phase A**, is ongoing (extremely important to establish the correct RFQ input condition).
- To **allow the LEBT beam operation**, the RFQ is installed **3.3 m downstream** for assembly and tuning
- In Nov. the RFQ will be installed in final position in view of conditioning and commissioning



Beam stop current scan plot and rms norm. iso-emittance areas (black lines), measured at March work point. It is possible to identify the almost monotonic emittance trend from lower right corner to left upper corner.

INFN: the RFQ system organization

- Contact Person: A. Facco
- 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

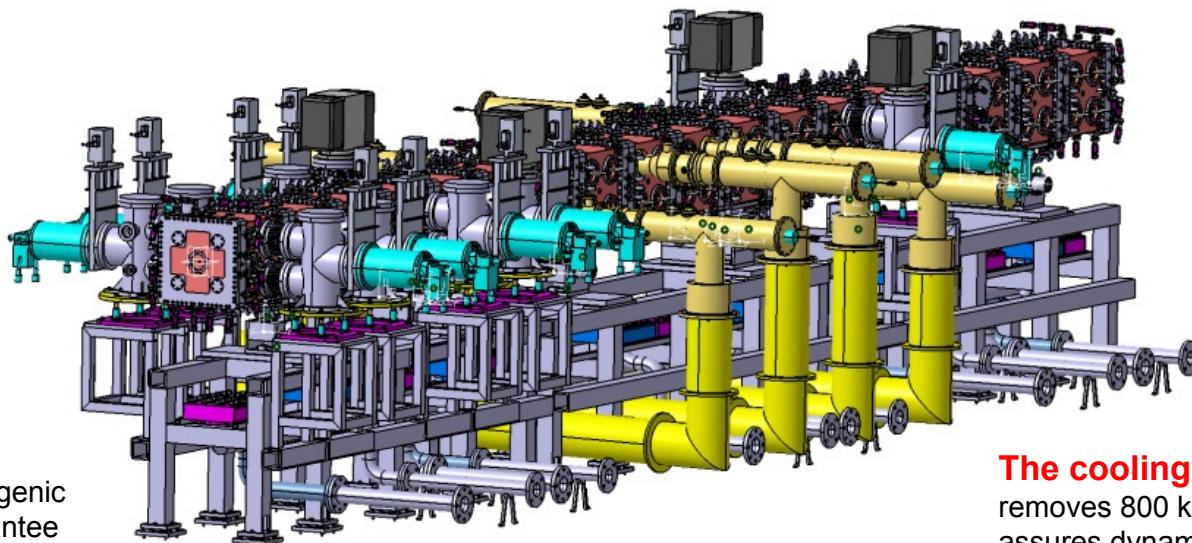


- Responsible A. Pisent
- Module Mechanics design and construction **A. Pepato**
 - Quality assurance: A. Prevedello
 - Module production follow up M. Benettoni
 - Stainless steel components production A. Margotti
- High power tests and RFQ integration: **E. Fagotti**
 - Engineering integration **P. Mereu**
 - Physical design : M. Comunian
 - Radio frequency: A. Palmieri
 - Computer Controls: M. Giacchini
 - Vacuum system and technological processes C. Roncolato
 - Cooling system integration G. Giraudo

Components of the 9.8 m long RFQ

18 modules

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



Vacuum system

10 sets, based on cryogenic pumps (in cyan) guarantee
 5×10^{-7} mbar with beam loss
gas load

RF Power

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

The cooling system

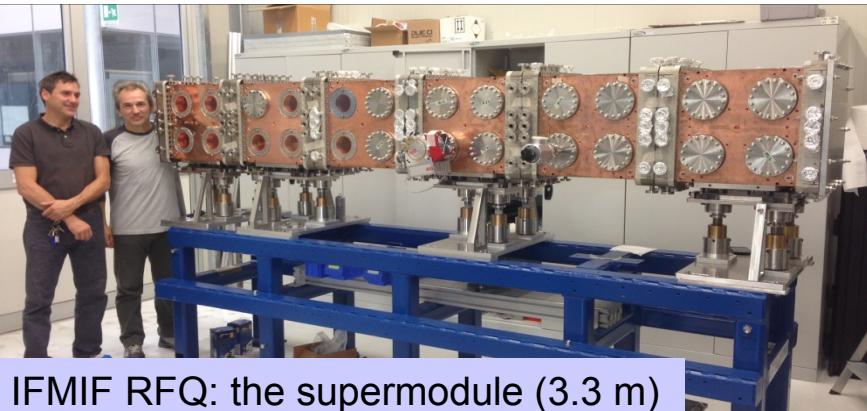
removes 800 kW and
assures dynamic RF
frequency tuning

Local Control system

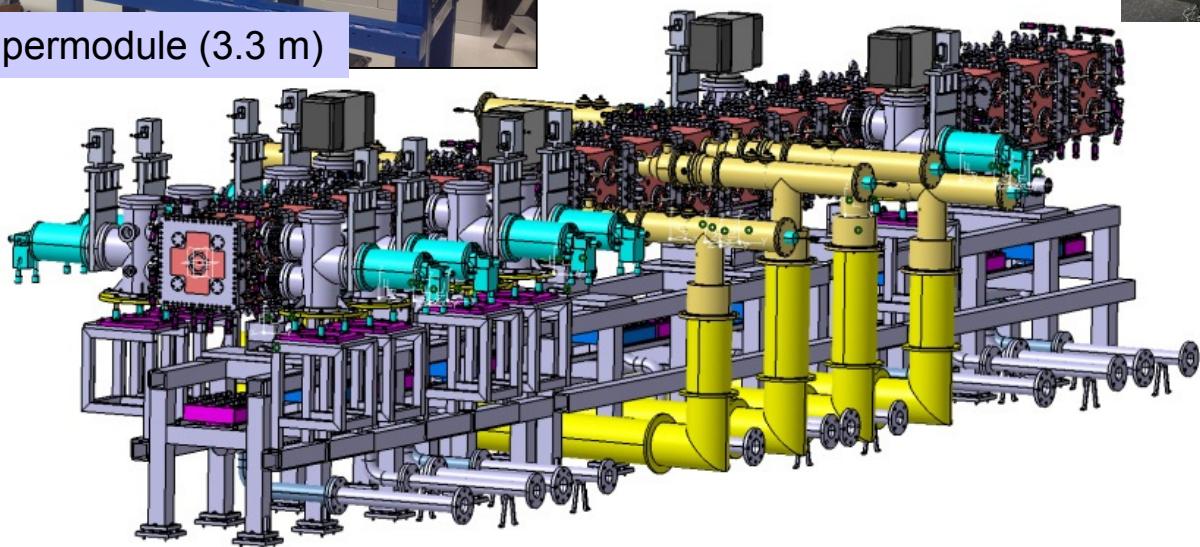
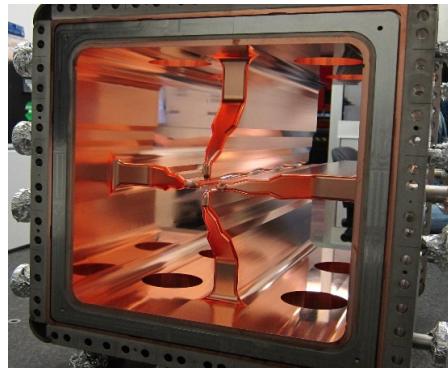
PLC and EPICS, for
cooling and vacuum
systems, temperature
and RF probes.



Modules construction



IFMIF RFQ: the supermodule (3.3 m)



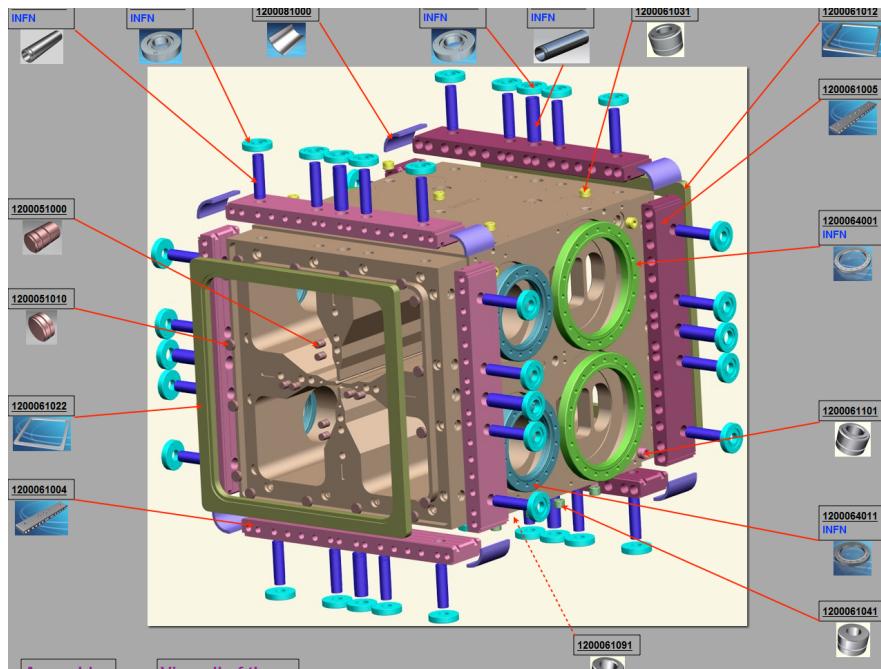
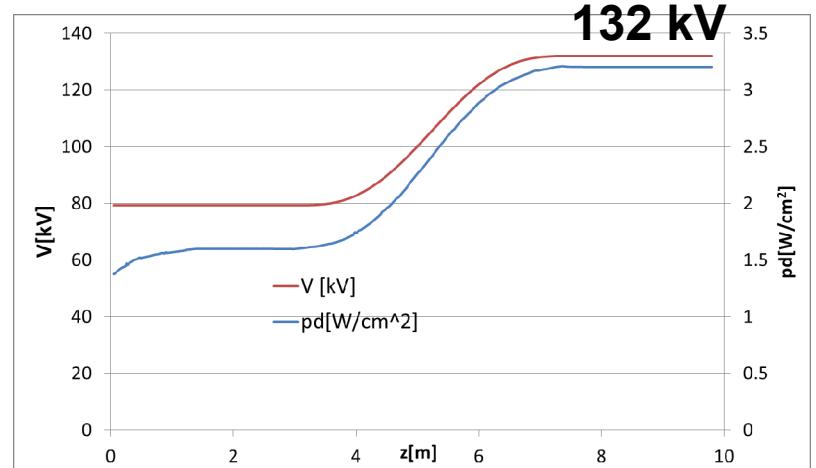
18 modules in three supemodules

- High energy SM built by Cinel, Padua (Italy),
- Intermediate energy built internally by INFN,
- Low energy attributed to RI Kolin (Germany), concluded by INFN



Design choices

- High beam current requires high focussing parameter B, and ramped high voltage
- The **four vane resonator** was the only possible solution for such high intervane voltage
- The **mechanical design** is based on a **brazed structure** and **metal sealing** to guarantee the necessary **high reliability**.
- These two choices determined many aspects of the design (for example 316LN stainless steel for most of the interface points).
- 550 mm long modules to increase the number of possible manufacturer

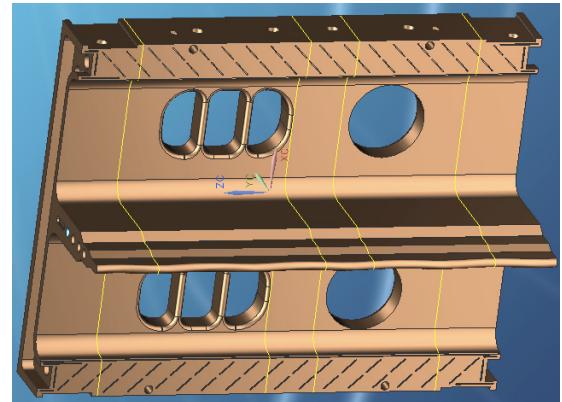


Geometrical tolerances

- The **electrode machining** can be very accurate and for this RFQ it was verified with continuous scanning **CMM** of each of the **72 electrodes** (**20 um max error** in the modulation geometry of each module was achieved).



- The **beam axis accuracy** requires a precise alignment of the quadrupole center module after module (**better than 0.1 mm**).



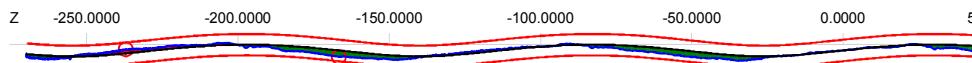
Max Deviation: 10.5 μm

CMM machine at INFN Padova

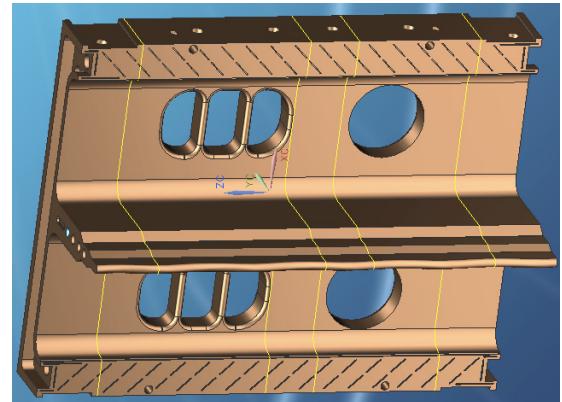


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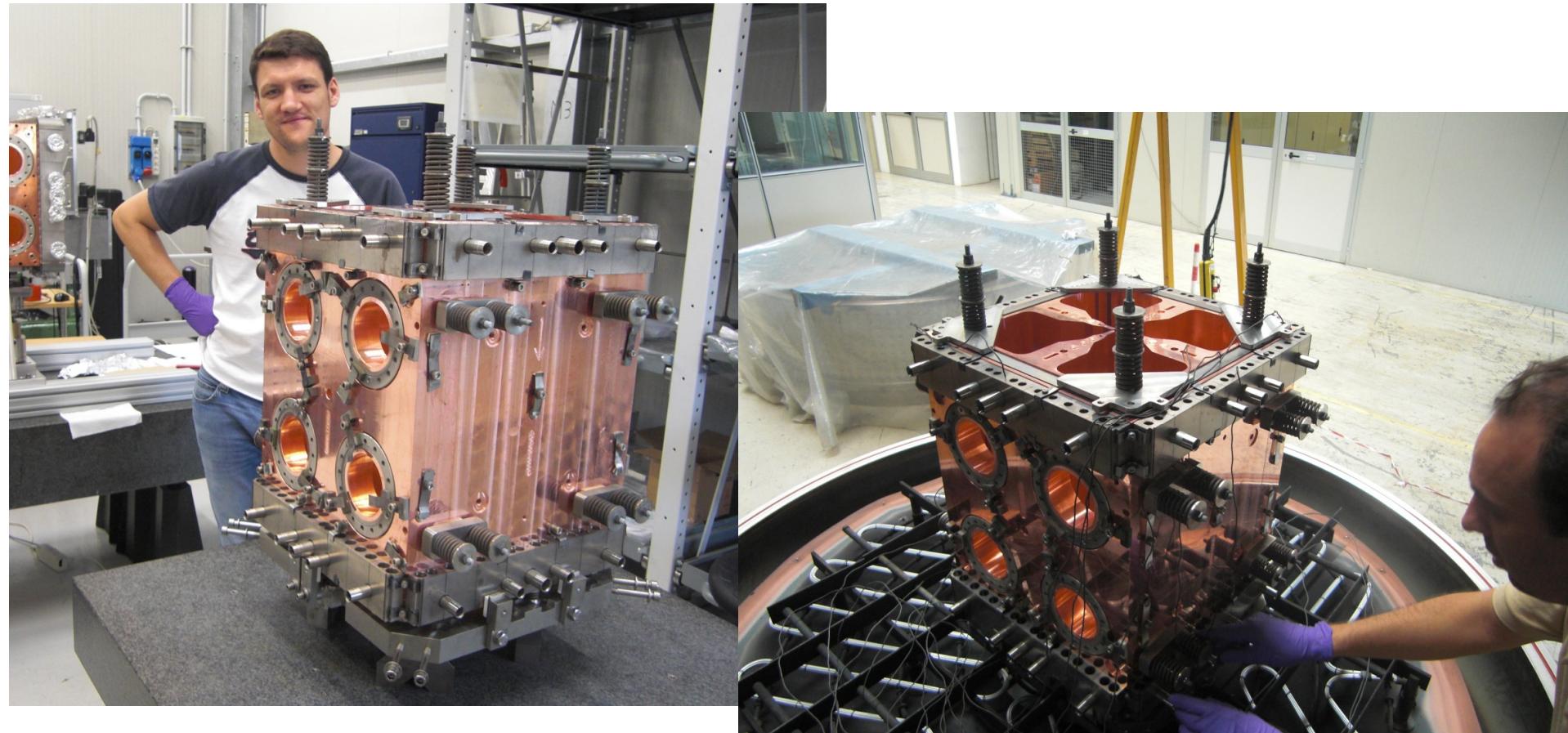
- To keep the frequency within the tuning range and the **voltage law** along the 4.7λ structure requires guarantee electrode displacements below **50-100 μm** (depending on modulation amplitude).



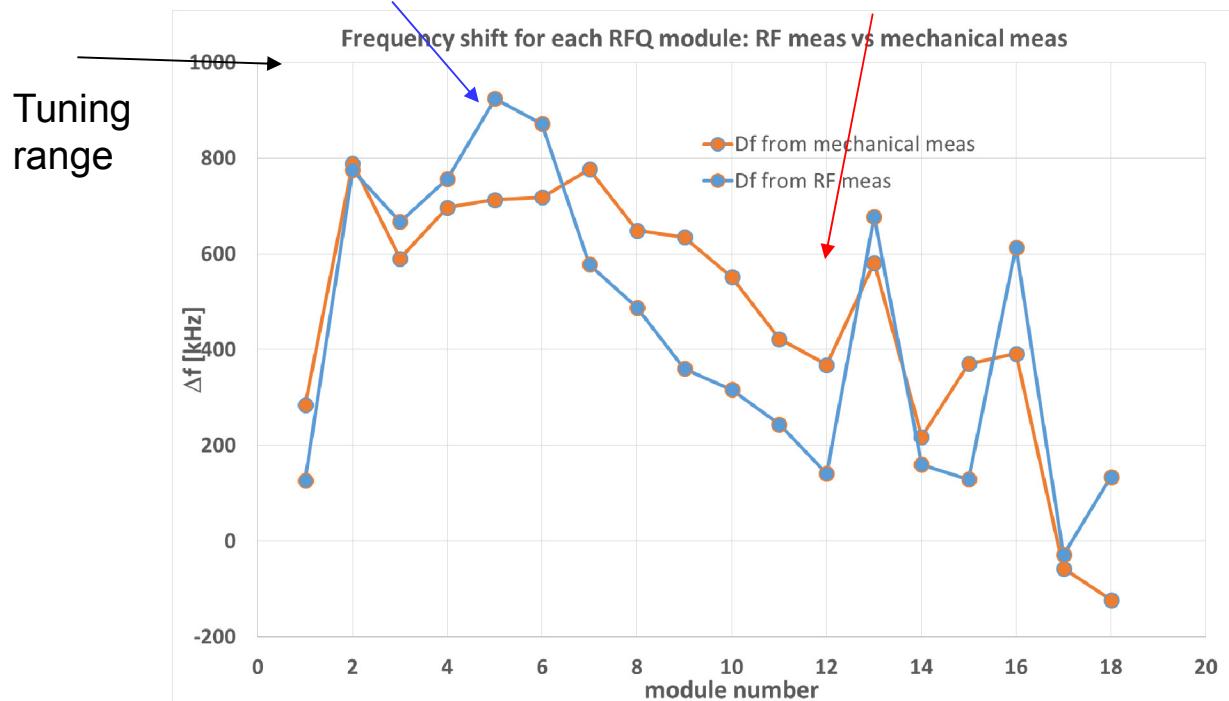
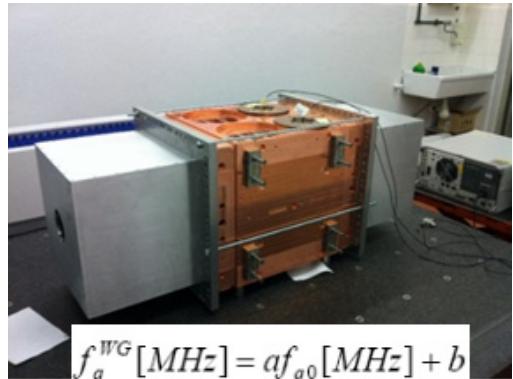
INFN development for Brazing

Large pieces with final tolerances of 50 um in beam region

Vacuum oven in INFN LNL, metrology and precision machining at INFN Padova
Single step brazing procedure was developed and used for most of the modules.

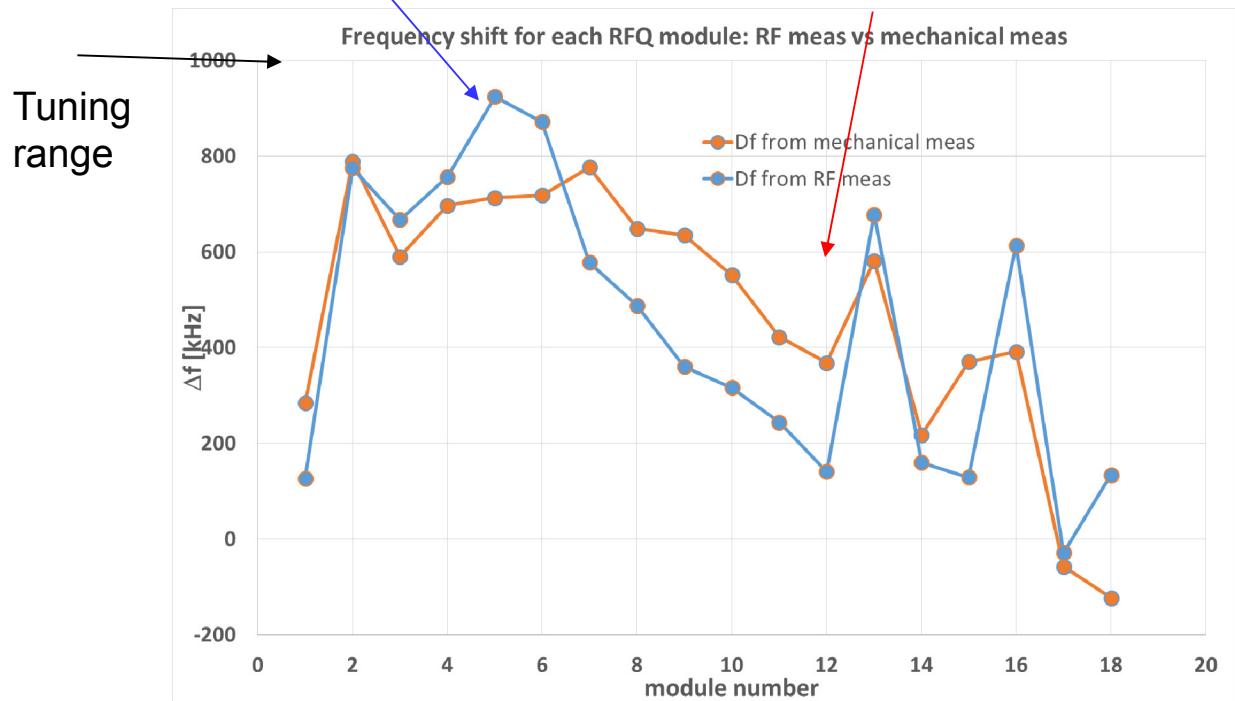
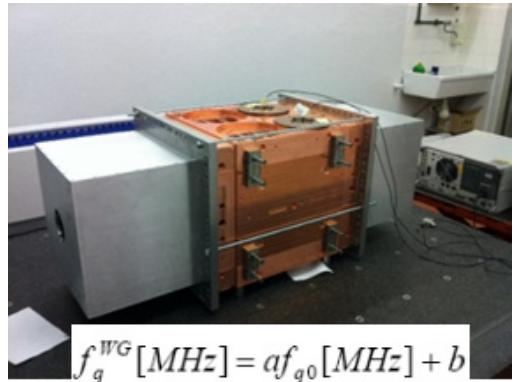


QA of modules: Results of RF measurements before and after brazing



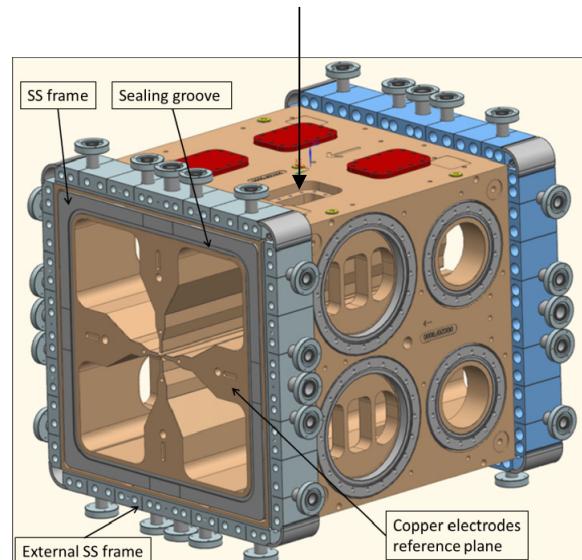
All the measured values are such that $|\Delta R_0| < 100 \mu\text{m}$, with an average value on all the modules of **46 μm for the RF measured data and of $50 \mu\text{m}$ for the mechanical measurement data.**

QA of modules: Results of RF measurements before and after brazing

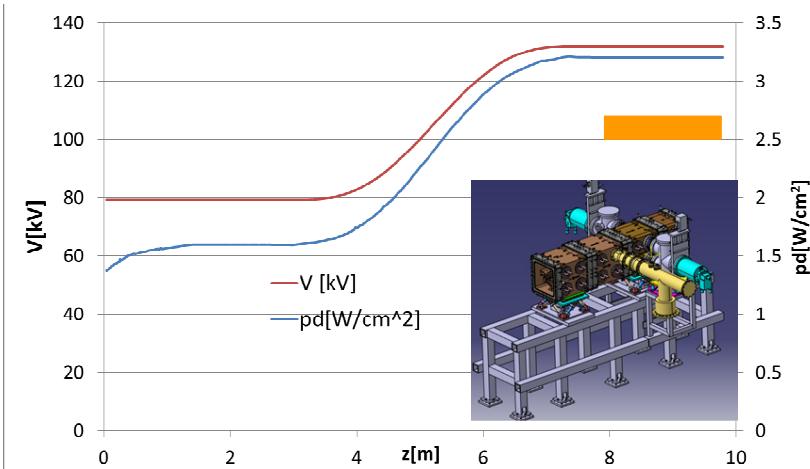


All the measured values are such that $|\Delta R_0| < 100 \mu\text{m}$, with an average value on all the modules of **46 μm for the RF measured data and of $50 \mu\text{m}$ for the mechanical measurement data.**

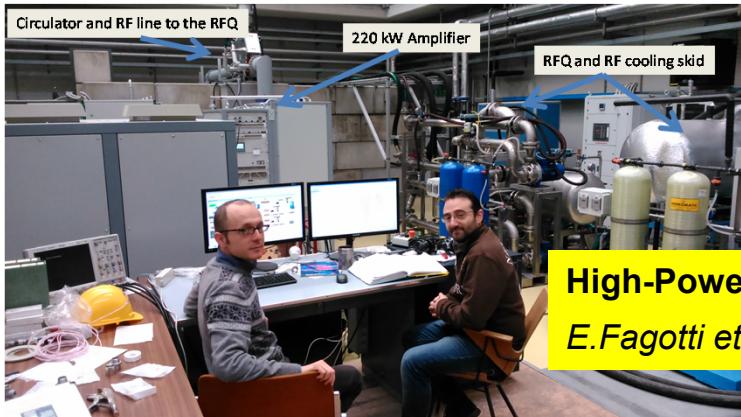
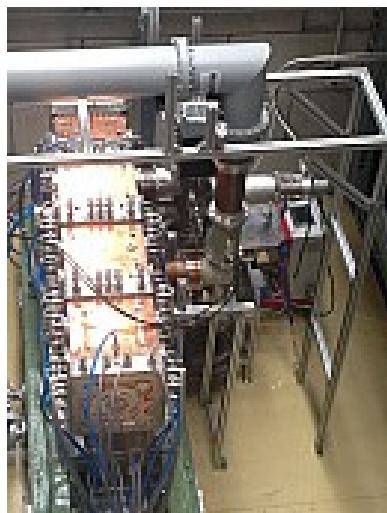
Additional opening for frequency correction



High power tests at Legnaro (1/5 of the structure)



- 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 was necessary to validate the design during the module construction
- **Max field (1.8 Ekp and max power density 90 kW/m) have been demonstrated**

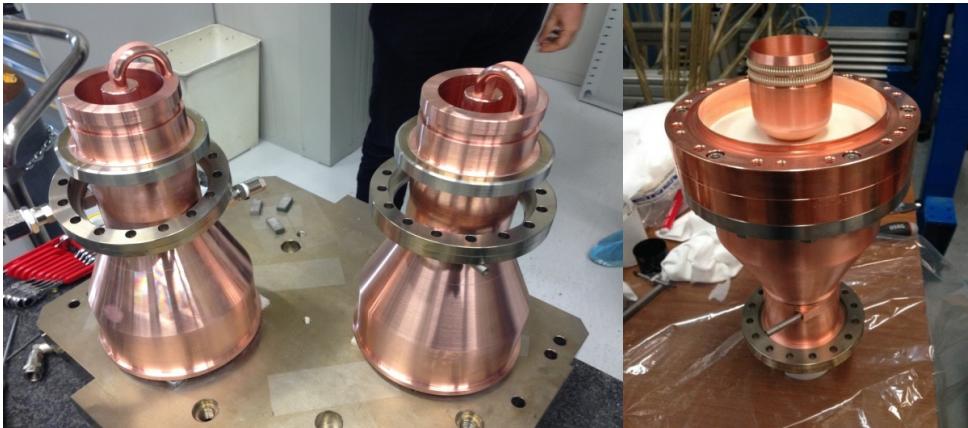


High-Power RF Test of IFMIF-EVEDA RFQ at INFN-LNL
E.Fagotti et al THPLR051

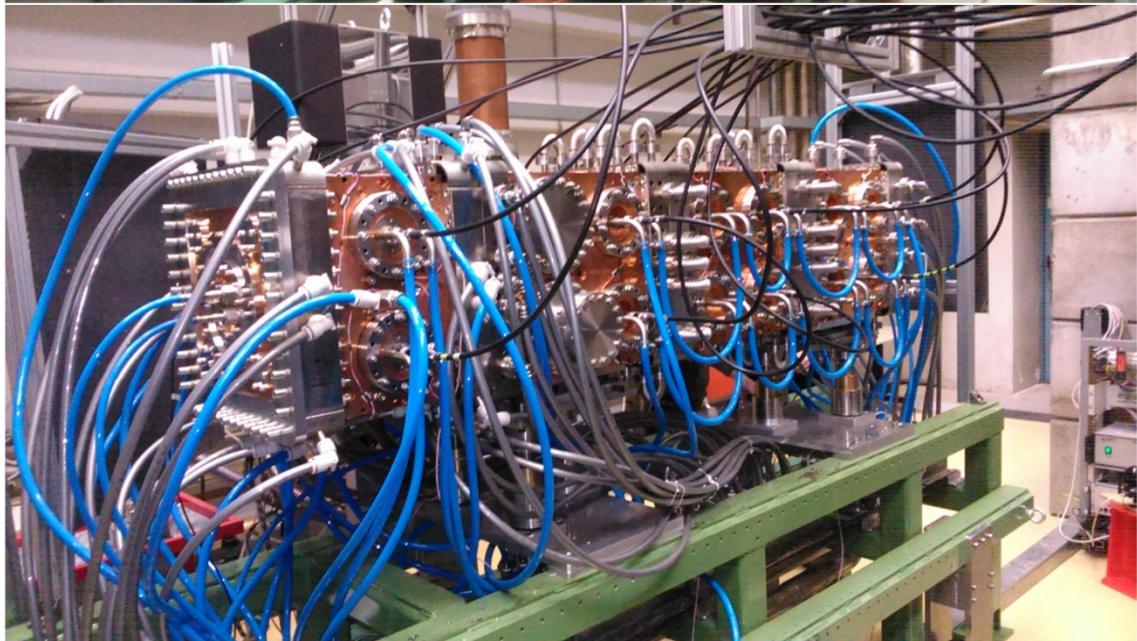
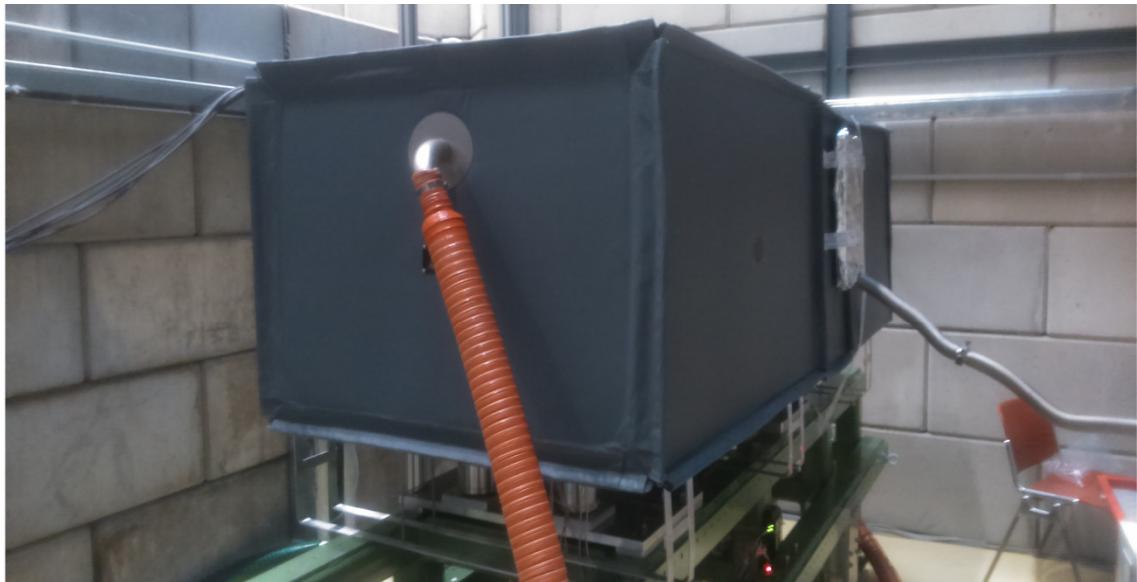
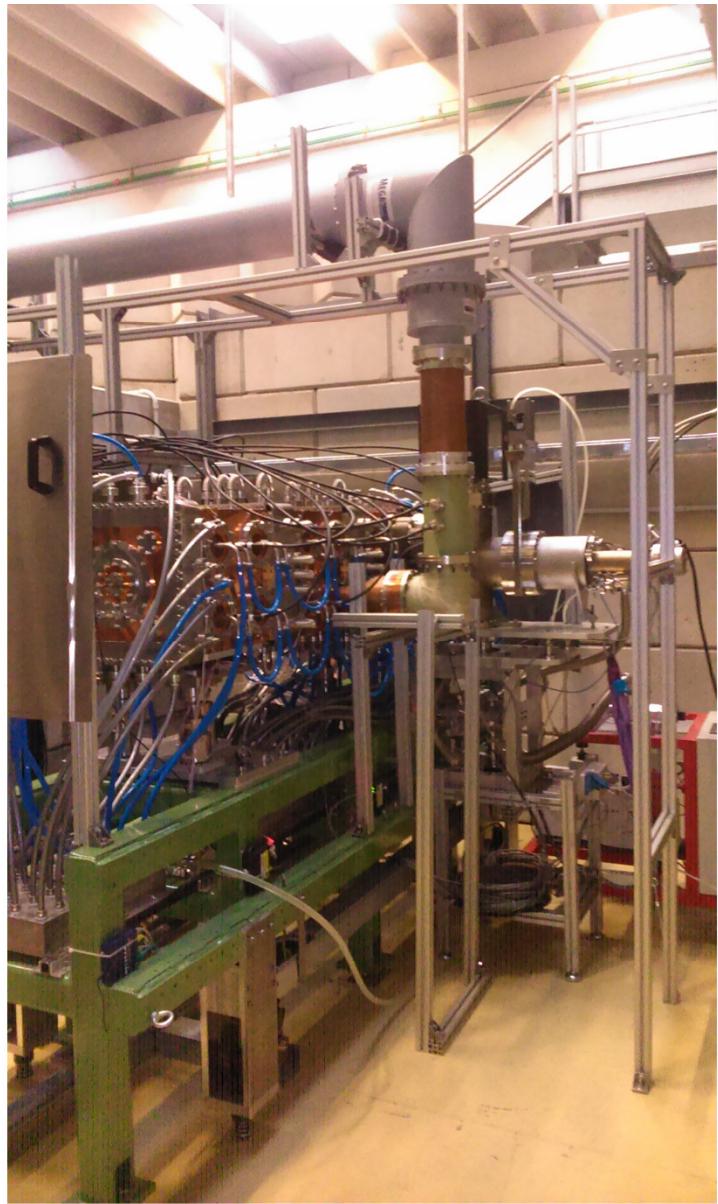


The INFN couplers (200 kW cw)

- Developed by INFN for the power test
- They will be used at Rokkasho for the first RFQ operation.

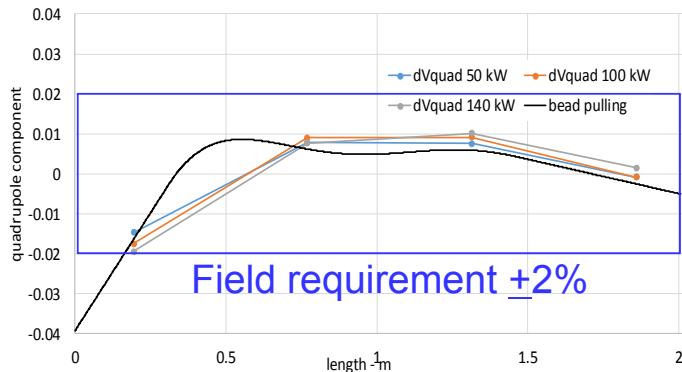


E. Fagotti et al. "The Couplers for the IFMIF-EVEDA RFQ High Power Test Stand at LNL: Design, Construction and Operation" LINAC2014, Geneva (Switzerland) p. 643

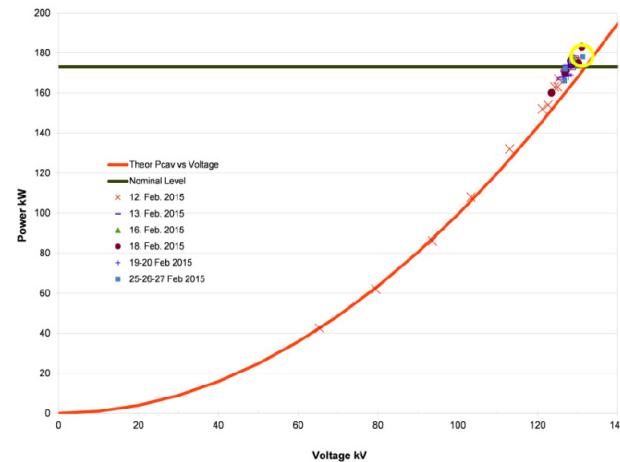


Results: nominal performances demonstrated

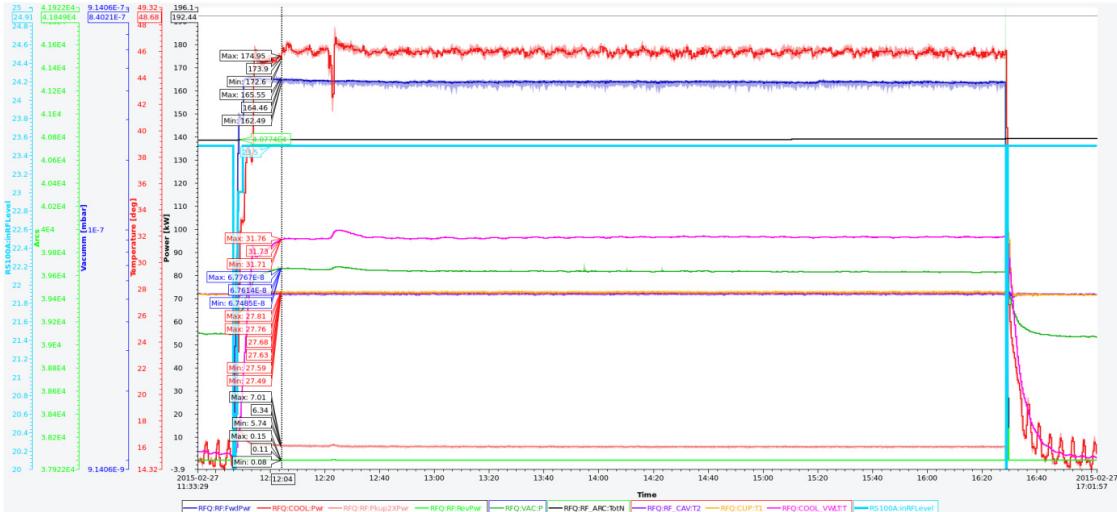
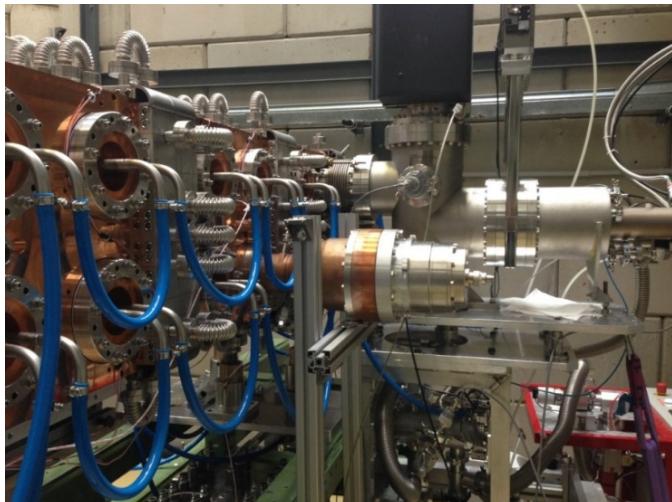
173 kW (90 kW/m)



Field configuration (pick up reading) at different RF level



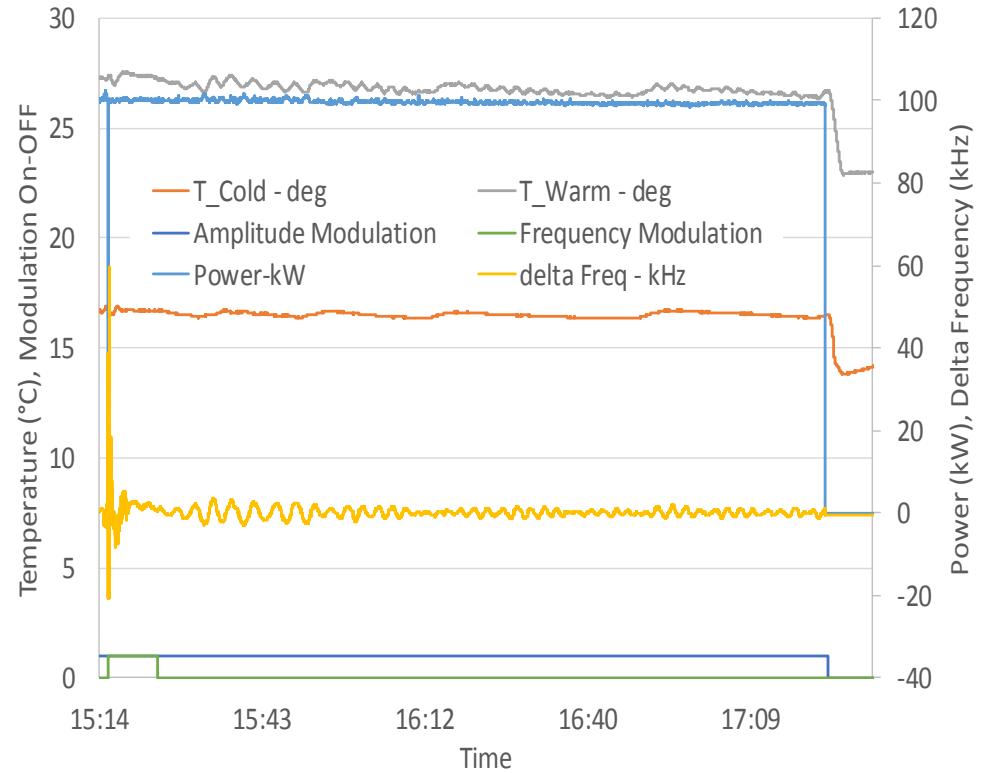
Cavity power (calorimetric measurements) vs. cavity voltage. The yellow circled dot corresponds to the nominal voltage level. $Q_0 = 12500$, i.e. 173 kW vs. 132 kV



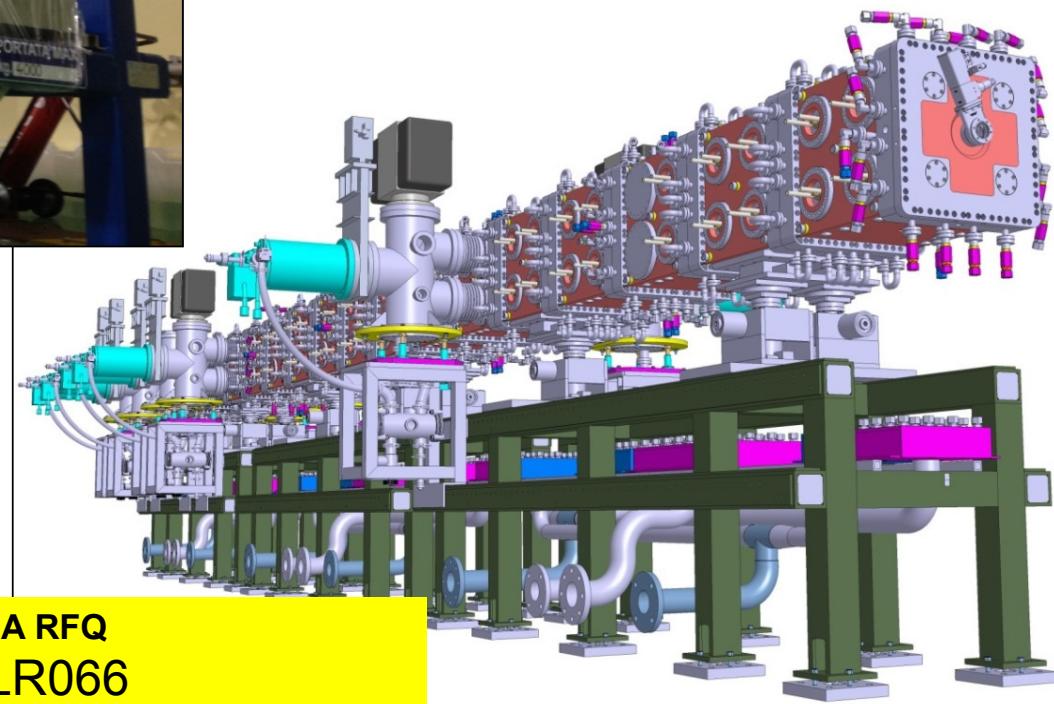
On 27 February '15 the RFQ remained 5 hours at nominal field level. It corresponds to the yellow circle in fig above.

Resonant frequency control demonstrated

- Resonant Frequency Control (RFC) achieved: cavity natural frequency driven cooling water temperature ($16 \text{ kHz}/{}^{\circ}\text{C}$ external channels)
- RFC condition is kept for more than 1.5 hours at 100 kW CW, with frequency oscillation lower than 2 kHz.



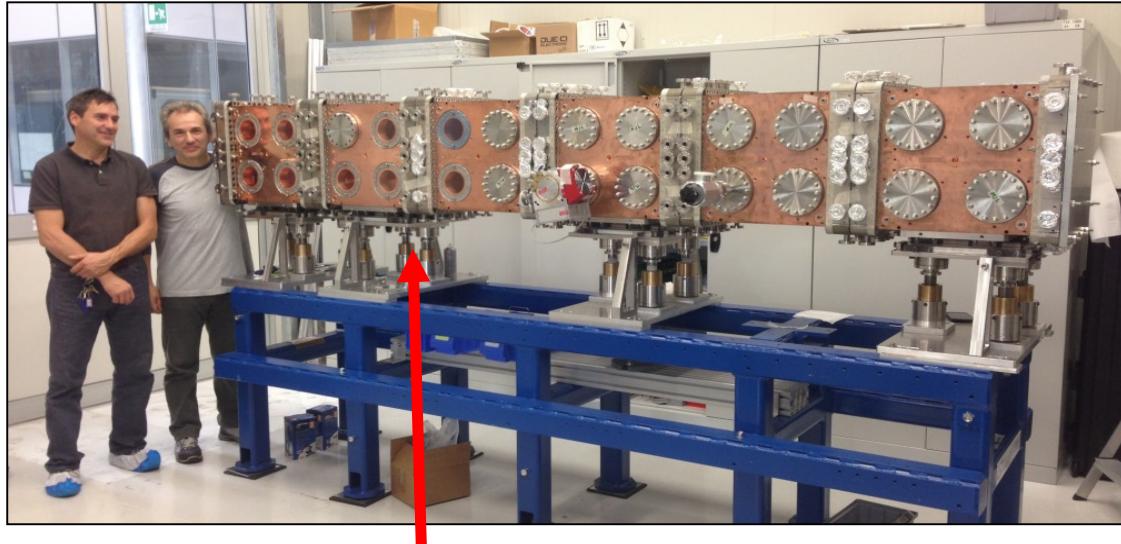
The 9.8 m RFQ assembly



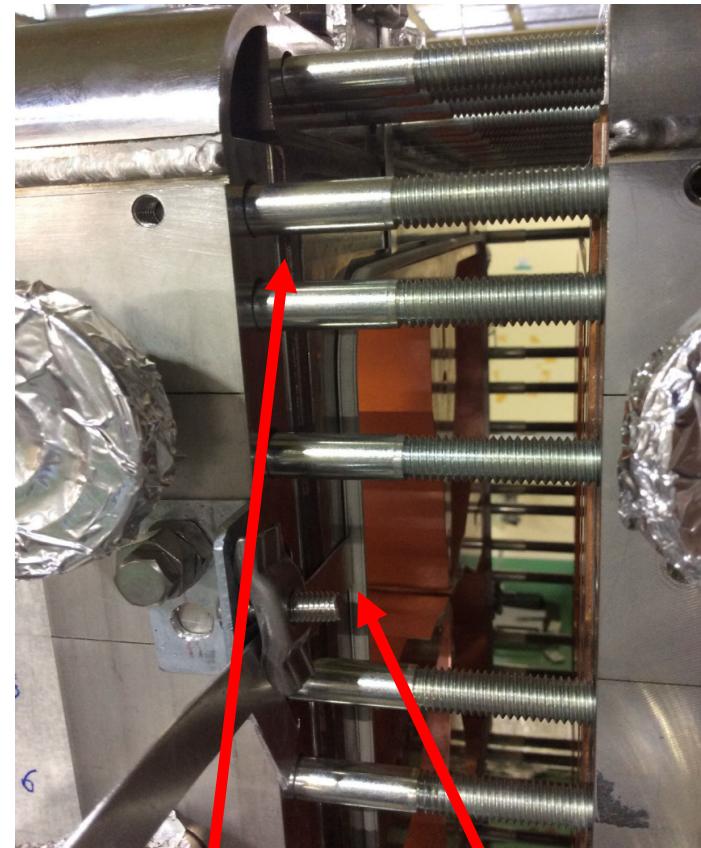
PREPARATION AND INSTALLATION OF IFMIF-EVEDA RFQ
AT ROKKASHO SITE *E.Fagotti et al* THPLR066

SUPERMODULE ASSEMBLY AT LNL

- All alignments determined by FARO Ion Laser Tracker using interferometric option.
- it was possible to reach a module transverse misalignment of 0.03 mm and longitudinal one of 0.04 mm (calibrated spacers).
- End of January 2016 the three supermodules were ready for transportation to Japan

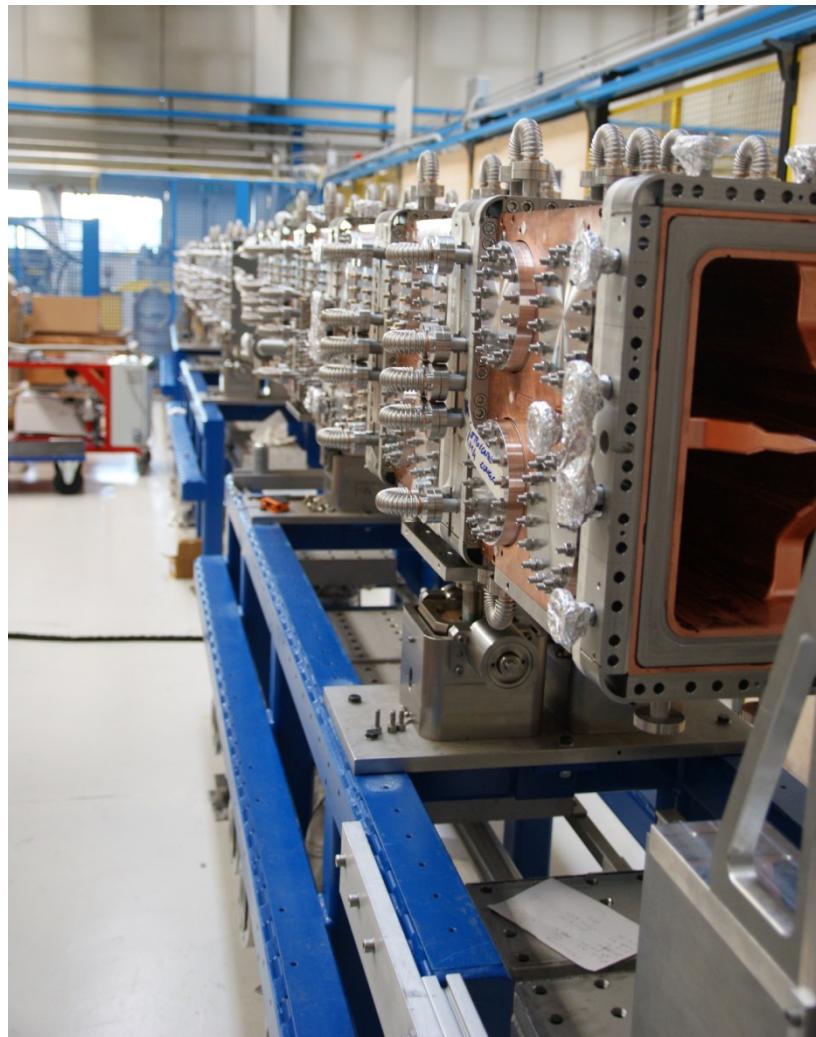


Temporary module support (6 degree of freedom regulation, sliding allowed)

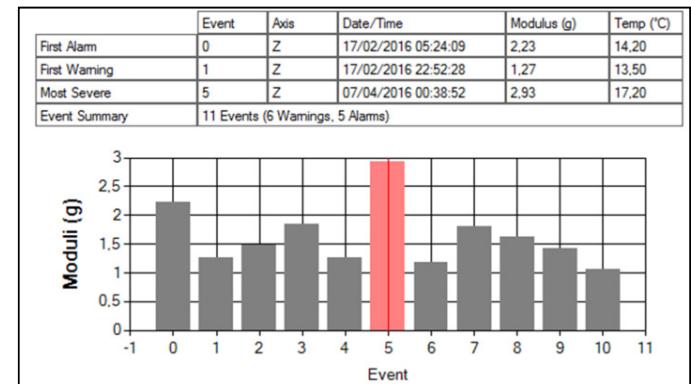
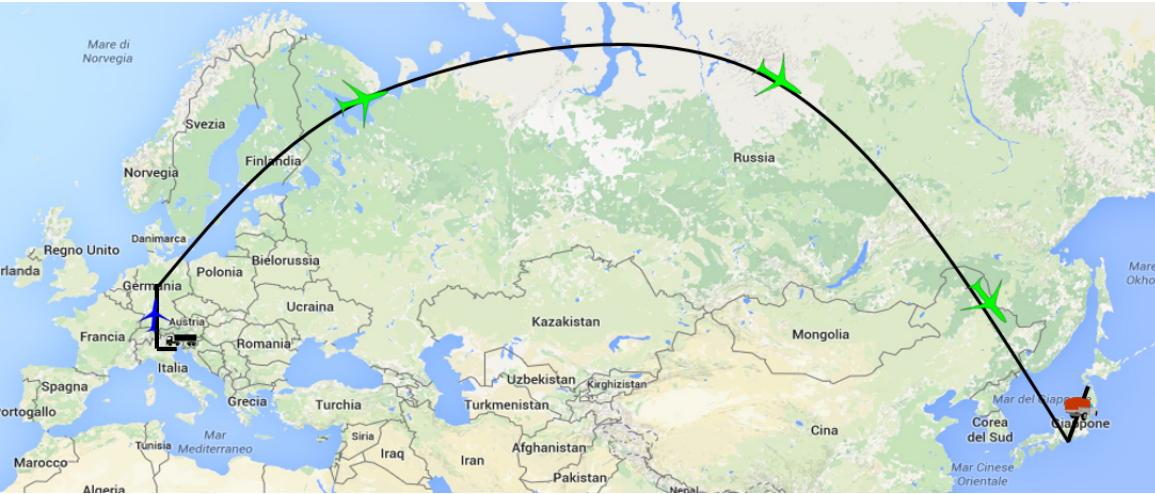


Metallic gasket
Calibrated spacers

Assembled at LNL from 10/2015 to 01/2016



SUPERMODULE SHIPMENT



Data extrapolated from the shock recorder mounted on SM2.



- The three SMs were completely assembled at LNL, filled with nitrogen
- Rubber spacers and wood supports were used between to dump vibrations in the box
- Shock recorders, Shocklog 298, were screwed on the top of each SMs.



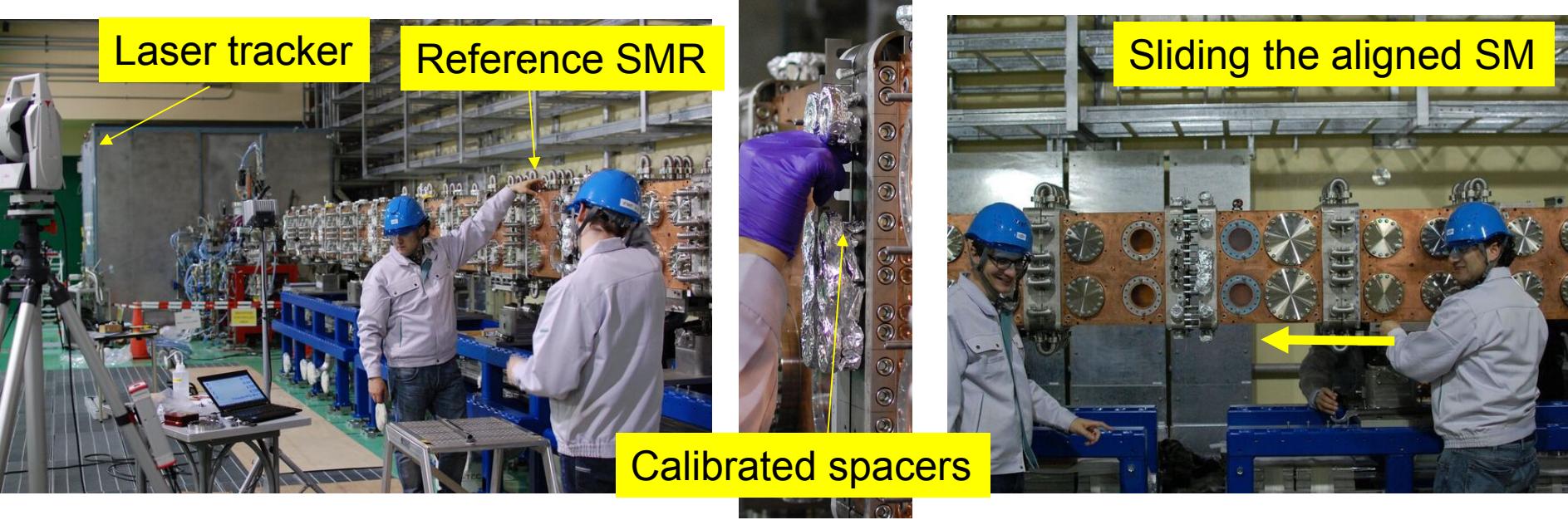
Rokkasho accelerator hall: SM1-SM2-SM3 vacuum leak test



Vacuum leak $< 2 \times 10^{-10}$ mbar-l/s per module



RFQ mechanical installation

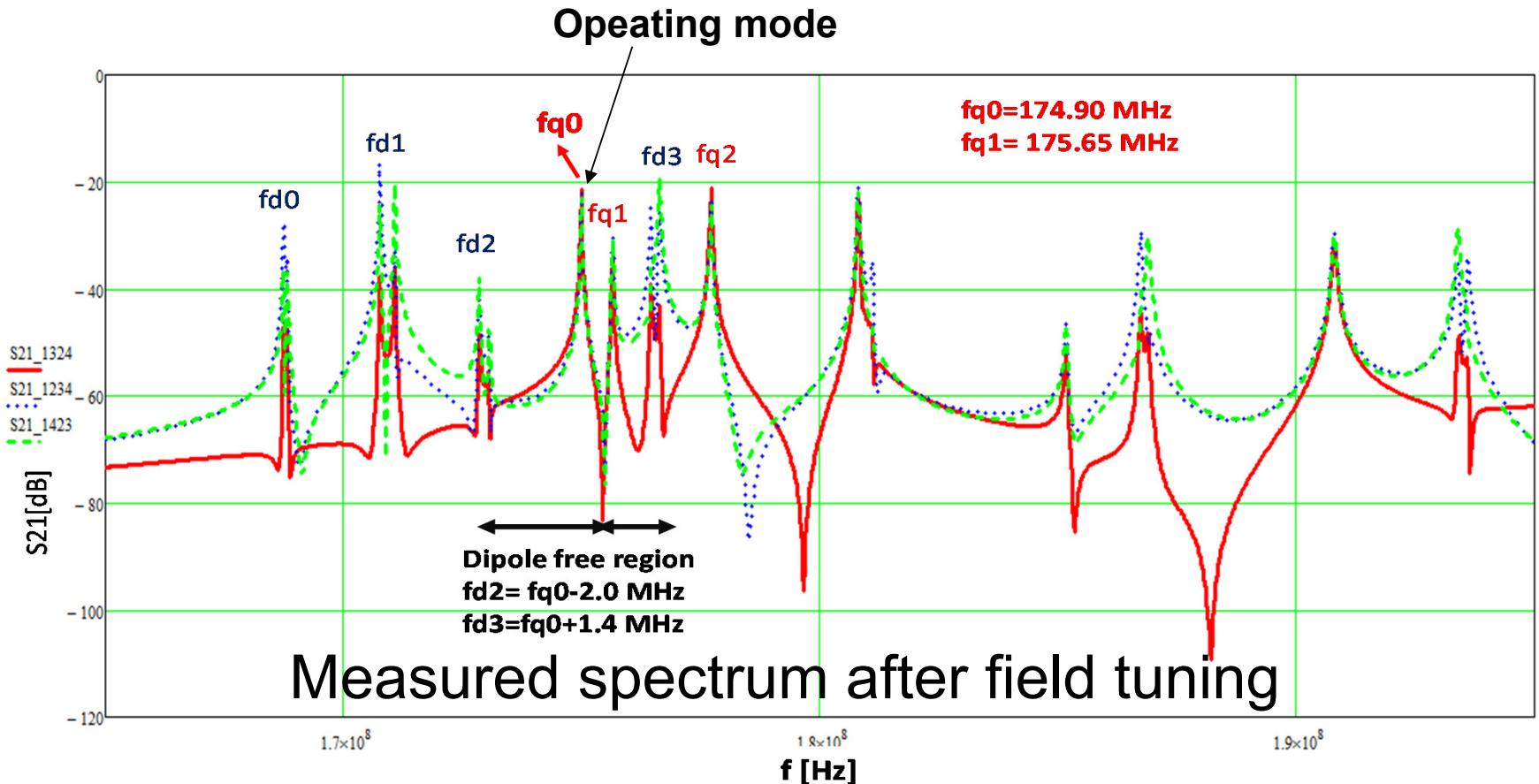


- In particular we achieved 0.03 mm maximum misalignment between SM (± 0.1 mm beam dyn. requ.),
- RFQ axis moves down respect to nominal beam axis up to -0.2 mm at the level of coupling between SM1 and SM2 (acceptable).



A. Pisent – LINAC2016 East Lansing

Tuning of a long RFQ



108 tuners to be set

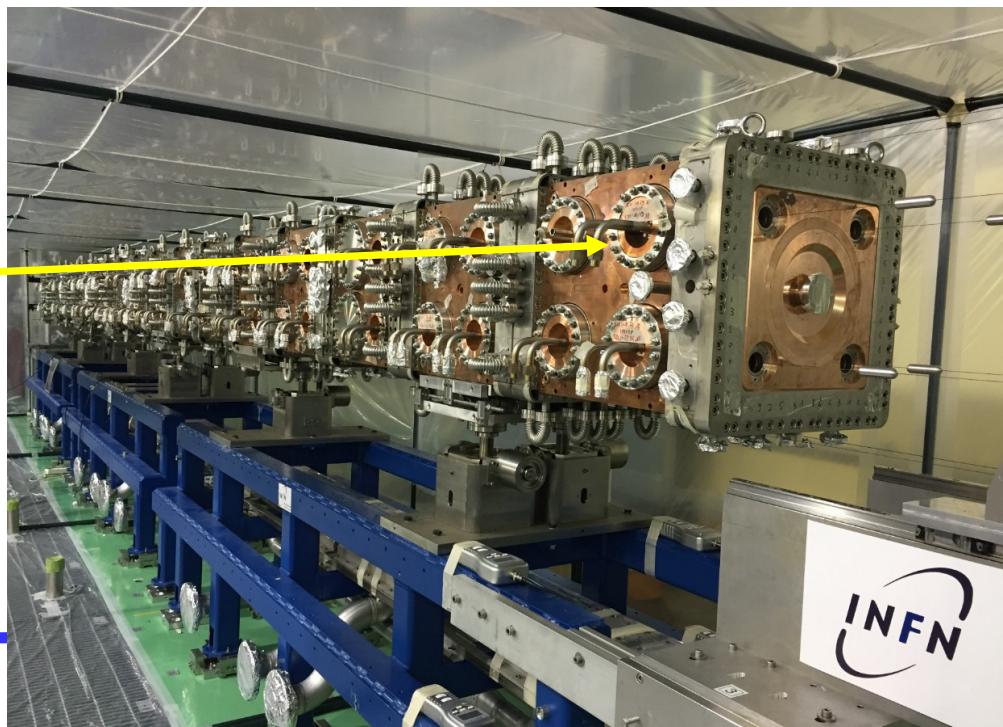
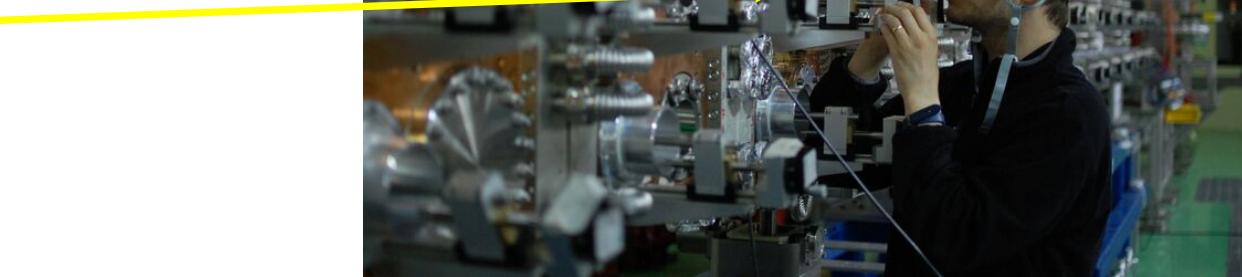
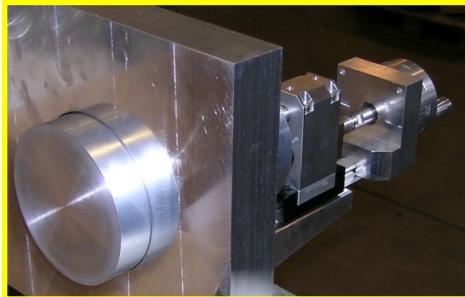
TUNING THE IFMIF 5MEV RFQ ACCELERATOR

A. Palmieri *et al* THPLR049

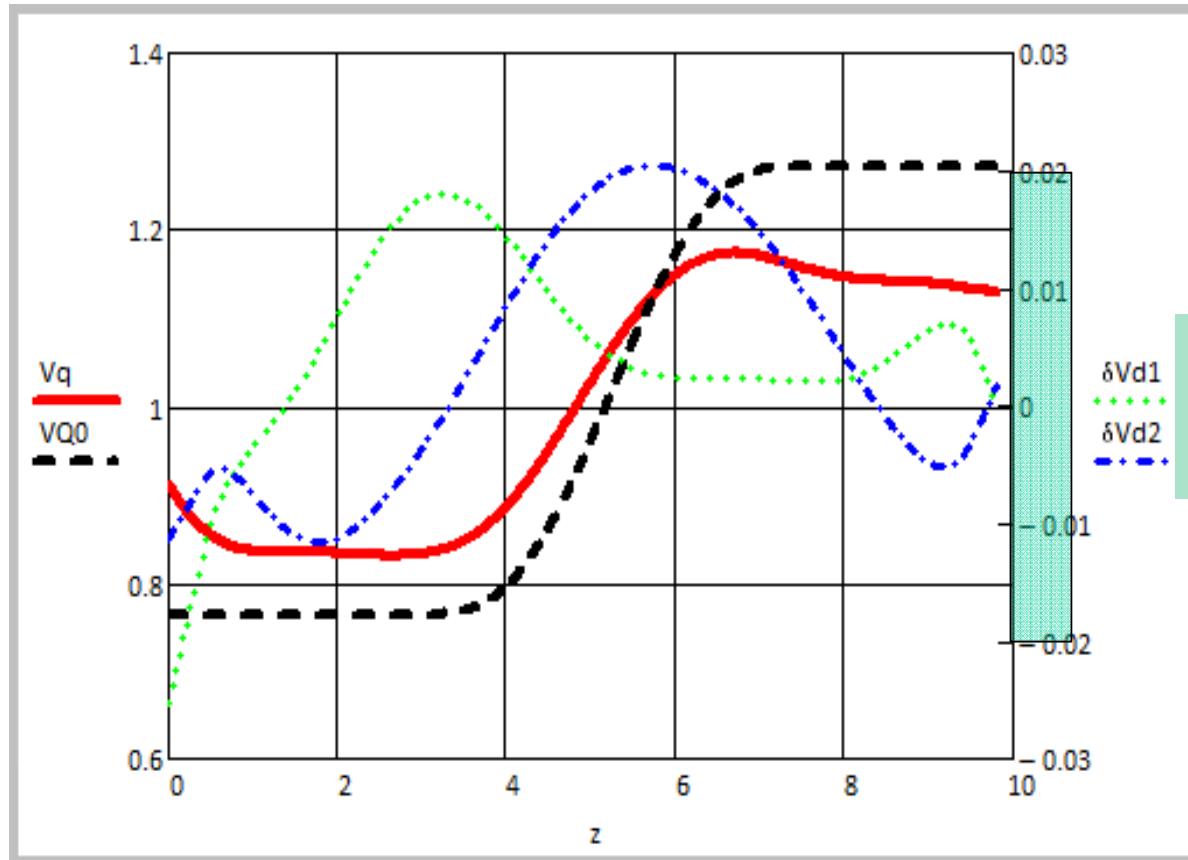
- $\pm 10 \mu\text{m}$ modulation tolerances
- $\pm 60 \mu\text{m}$ tolerance R_0 final (incl brazing) equiv to $\pm 1 \text{ MHz}$.
- 108 dummy tuners ($\pm 15 \text{ mm}$ equiv $\pm 1. \text{ MHz}$,) field correction
- Active (water temperature, 10 deg approx $\pm 0.1 \text{ MHz}$,)



From dummy to final tuners



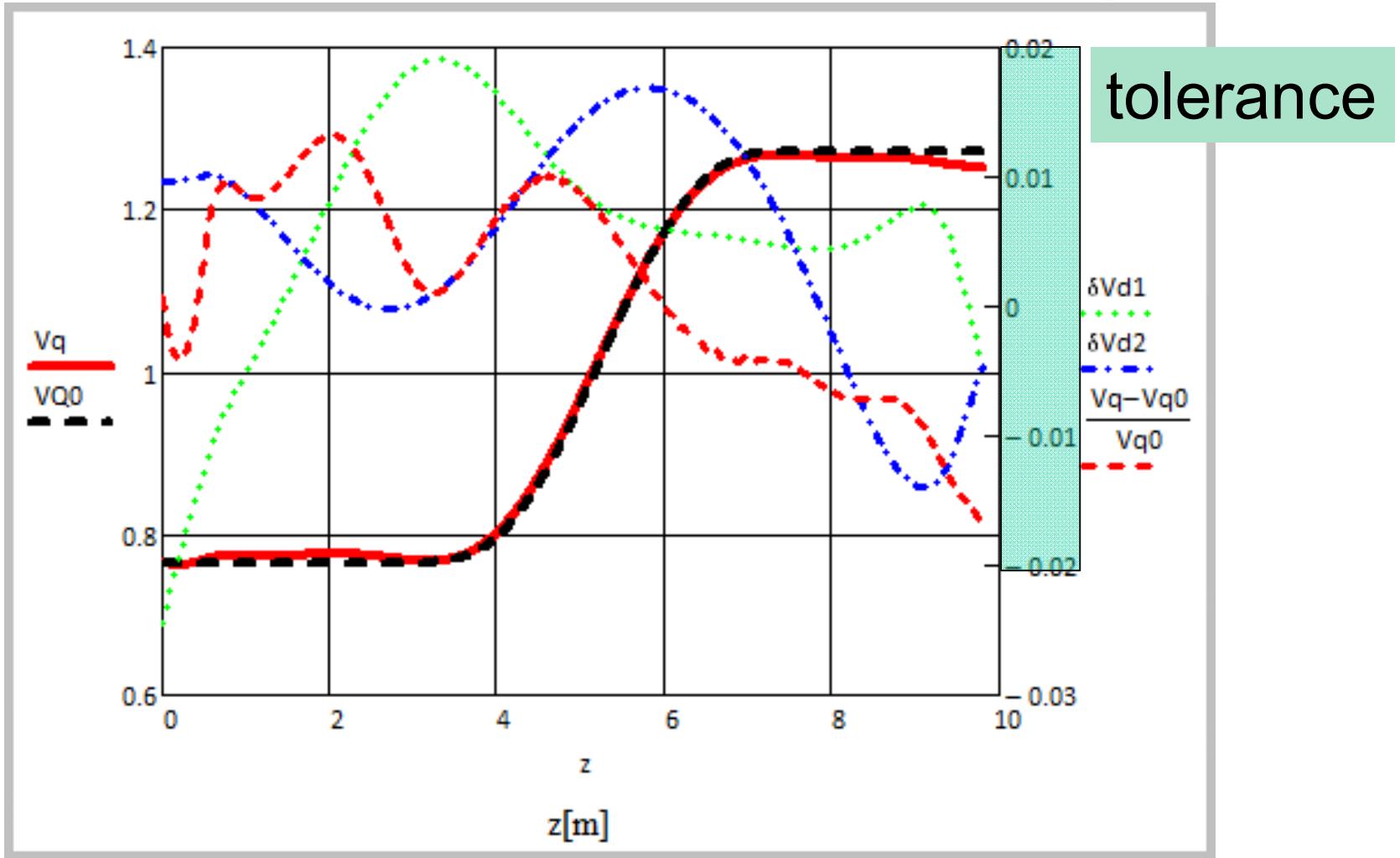
Field distribution before tuning



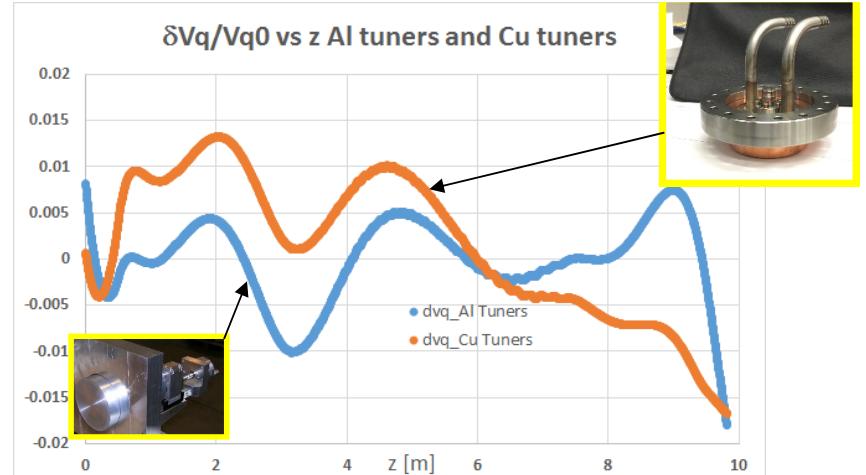
Dipole component
Tolerance

Flush tuners

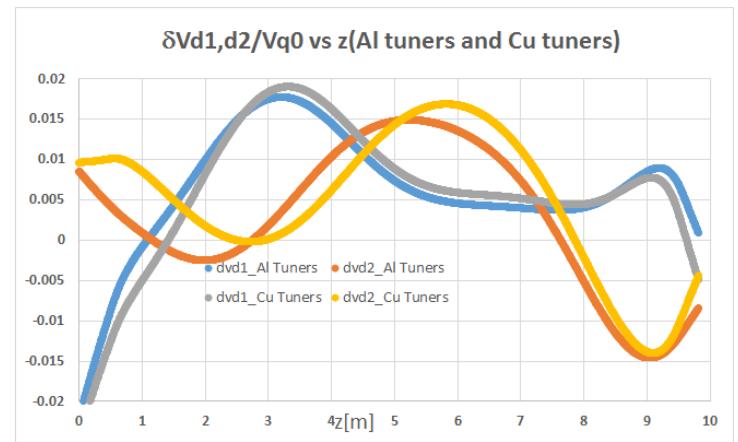
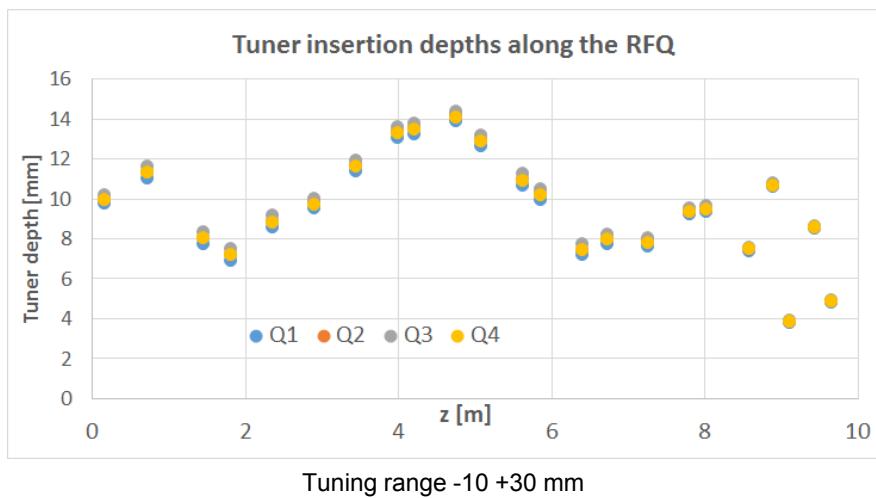
Field distribution after tuning



Quadrupole and dipoles with dummy (Al) and final (Cu) tuners



dV_q/V_{q0} vs z for dummy tuners (Al, blue curve) and final tuners (Cu, red curve)



dV_{qd1}/V_{q0} vs z for dummy tuners (Al, blue curve) and final tuners (Cu, red curve)

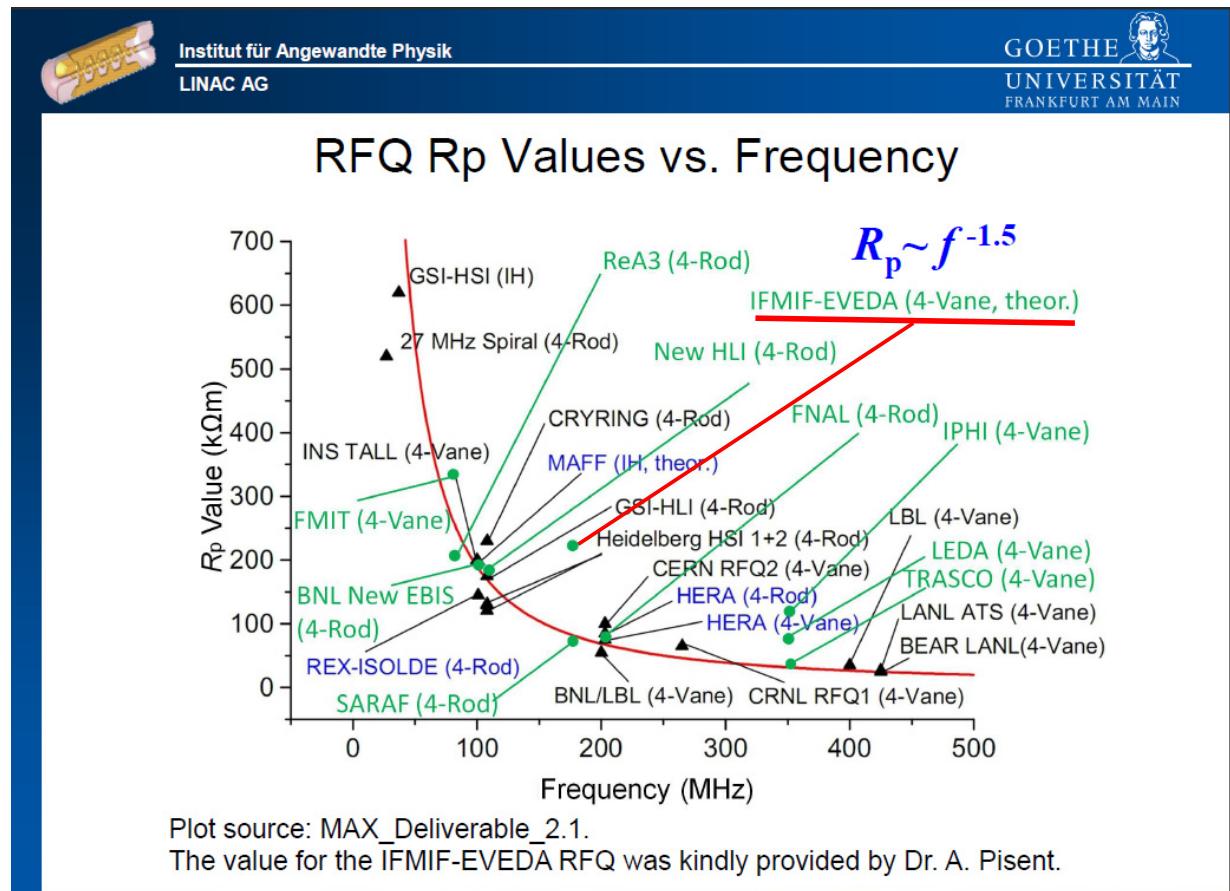
Eigen frequency and shunt impedance achieved

- The final measured frequency was equal to 174.989 MHz, equivalent to **175.014 MHz**, if one takes into account the rescaling to nominal 20° C temperature and the effects of vacuum and beam loading. Such value corresponds to -1° C water temperature regulation for the vessel.
- **$Q_0 = 13'200 \pm 200$**
- (82% of SUPERFISH value), low tuner losses
- **$R_{sh} = 201 \text{ k}\Omega\text{-m}$**



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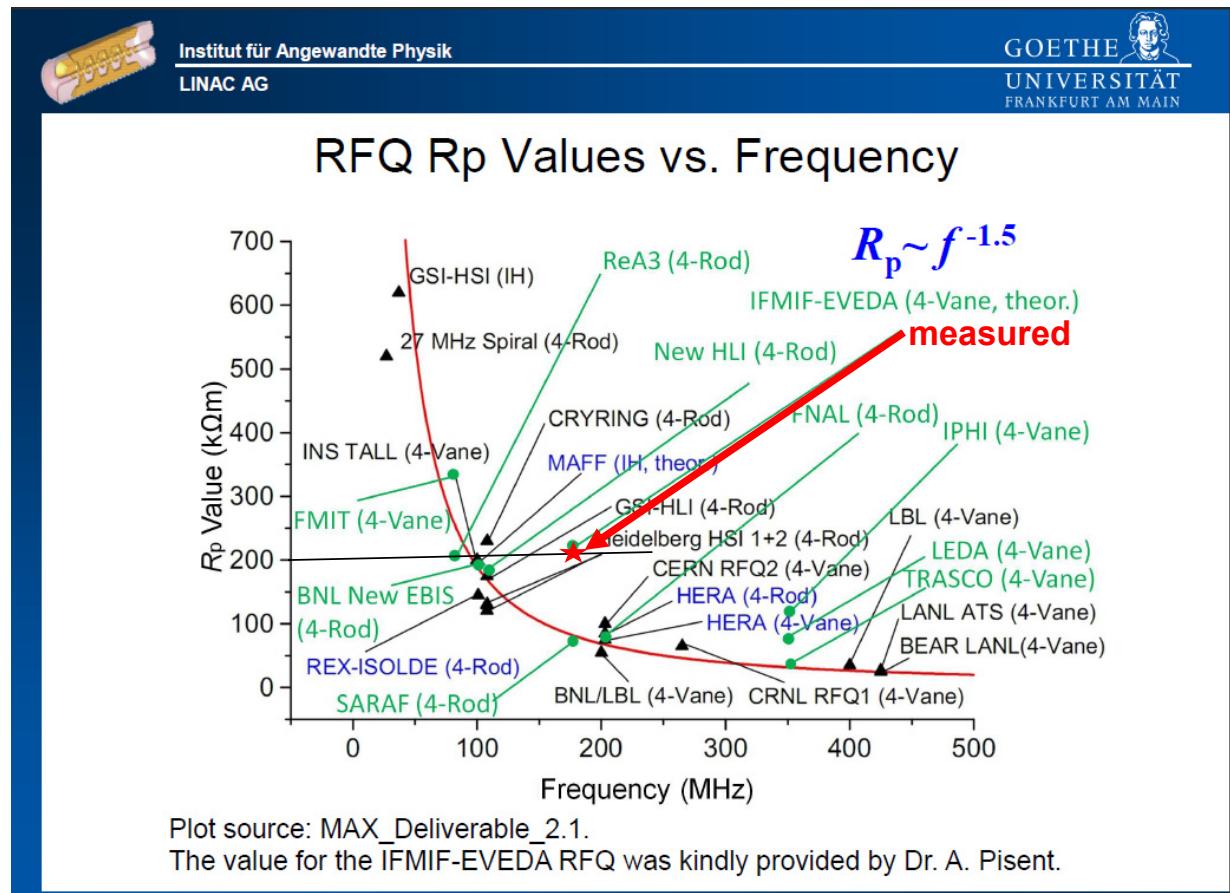


Original transparency by prof. H. Klein



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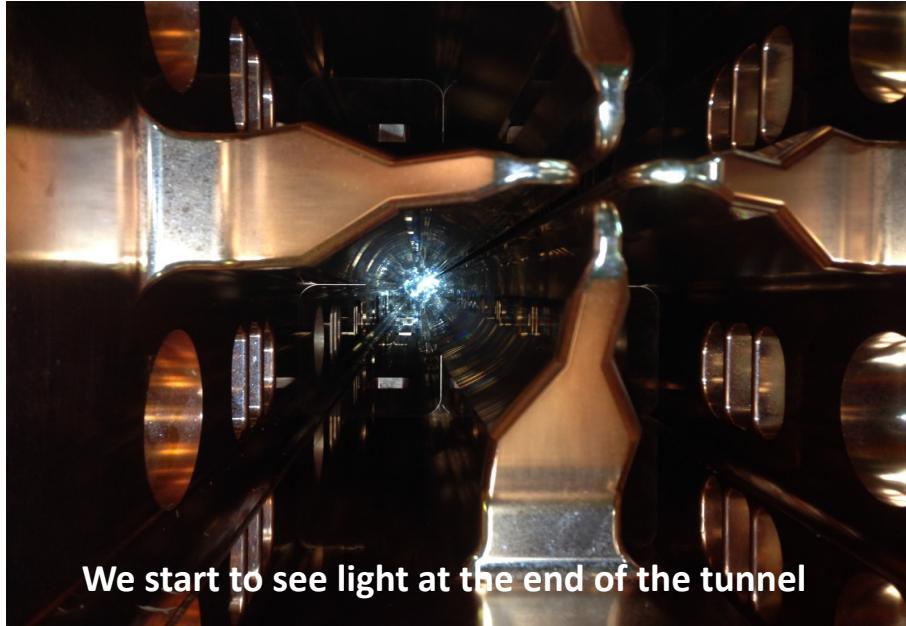


Original transparency by prof. H. Klein



Conclusions

- The RFQ construction is concluded (18/18 module accepted, RF and CMM tests ok).
- The cw RF performances (maximum field, power density, water temperature frequency control loop) have been achieved in the high power test in Italy.
- The air-transportation in three supermodules and the assembly in Japan was successful. The RF field have been tuned to the nominal shape with specified accuracy (2%).
- The excellent shunt impedance of the design has been achieved ($Q=13\ 200$).
- Conditioning and beam commissioning will start March next year.



We start to see light at the end of the tunnel

Components of INFN RFQ team (LNL, Padova, Torino, Bologna):
A. Pisent (coordinator), E. Fagotti (integration and high power tests), A. Pepato (module production), P. Mereu (engineering integration), L. Antoniazzi, D. Agugliaro, A. Baldo, L. Bellan, P. Bottin, A. Conte, M. Comunian, D. Dattola, R. Dima, J. Esposito, L. Ferrari, M. Giacchini, G. Giraudo, F. Grespan, A. Macri, A. Margotti, M. Montis, A. Palmieri, M. Poggi, A. Prevedello, L. Ramina, M. Romanato C. Roncolato

Thanks to our colleagues from QST (ex JAEA), F4E, Project team, CEA and Ciemat for constant support

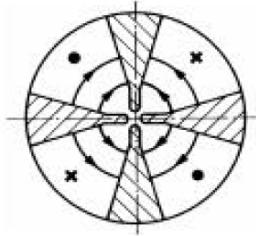
Geometrical tolerances

- The geometrical tolerances for a long RFQ are severe due to the mode contamination from TE_{21n} (spurious quadrupoles) and TE_{11n} (dipole) modes, whose frequencies can be very close to the operating mode.

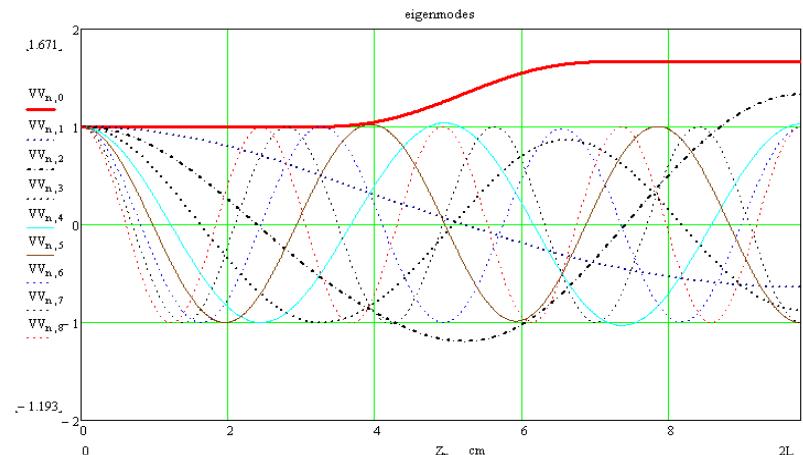
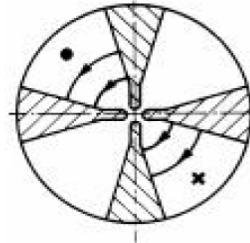
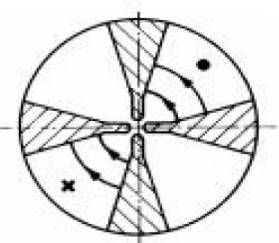
Perturbation to the nominal geometry \Rightarrow Accelerating mode is not pure

$$\left| E_{210}^p \right\rangle = \left| E_{210} \right\rangle + \sum_{n \neq 0} \frac{\langle E_{21n} | P | E_{210} \rangle}{\omega_{21n}^2 - \omega_{210}^2} \left| E_{21n} \right\rangle + \sum_{n=0} \frac{\langle E_{D1n} | P | E_{210} \rangle}{\omega_{D1n}^2 - \omega_{210}^2} \left| E_{D1n} \right\rangle + \sum_{n=0} \frac{\langle E_{D2n} | P | E_{210} \rangle}{\omega_{D2n}^2 - \omega_{210}^2} \left| E_{D2n} \right\rangle$$

TE_{21n}

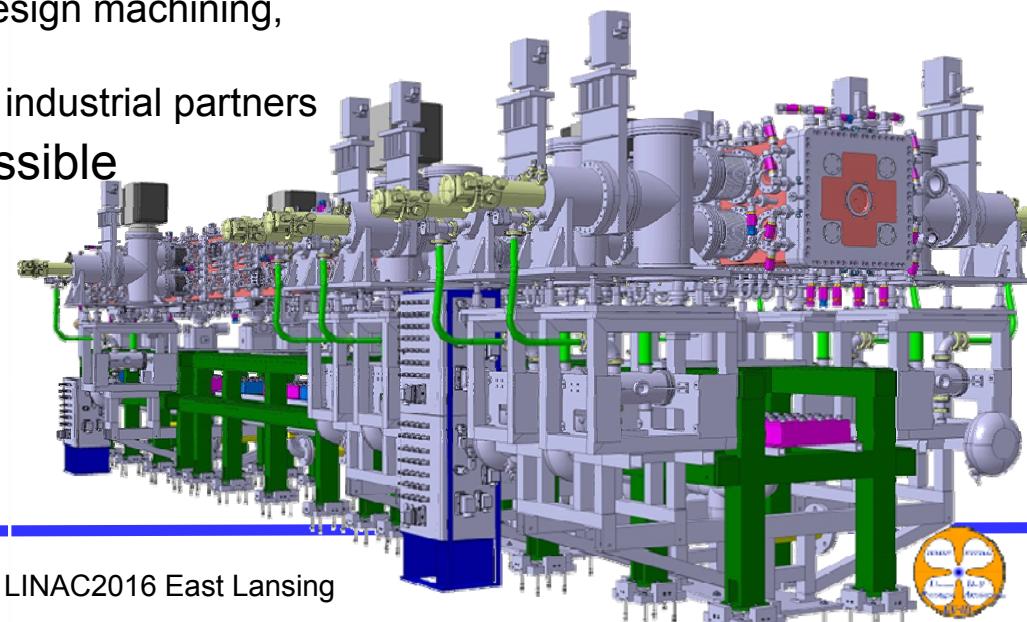


TE_{11n}
(dipole modes)



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 10-100 μm)
- **600 kW RF dissipated** on copper surface: necessity to keep geometrical tolerances, to manage hot spots and counteract potential instability.
- The RFQ is the **largest ever built**, a small production with very severe quality requirements.
 - Fully exploit **INFN internal production capability** for prototypes and part of the production (design machining, measurement and *brazing*)
 - Make production accessible for different industrial partners
- The beam tests are in Japan, all possible preliminary tests have been performed in Italy



A. Pisent – LINAC2016 East Lansing