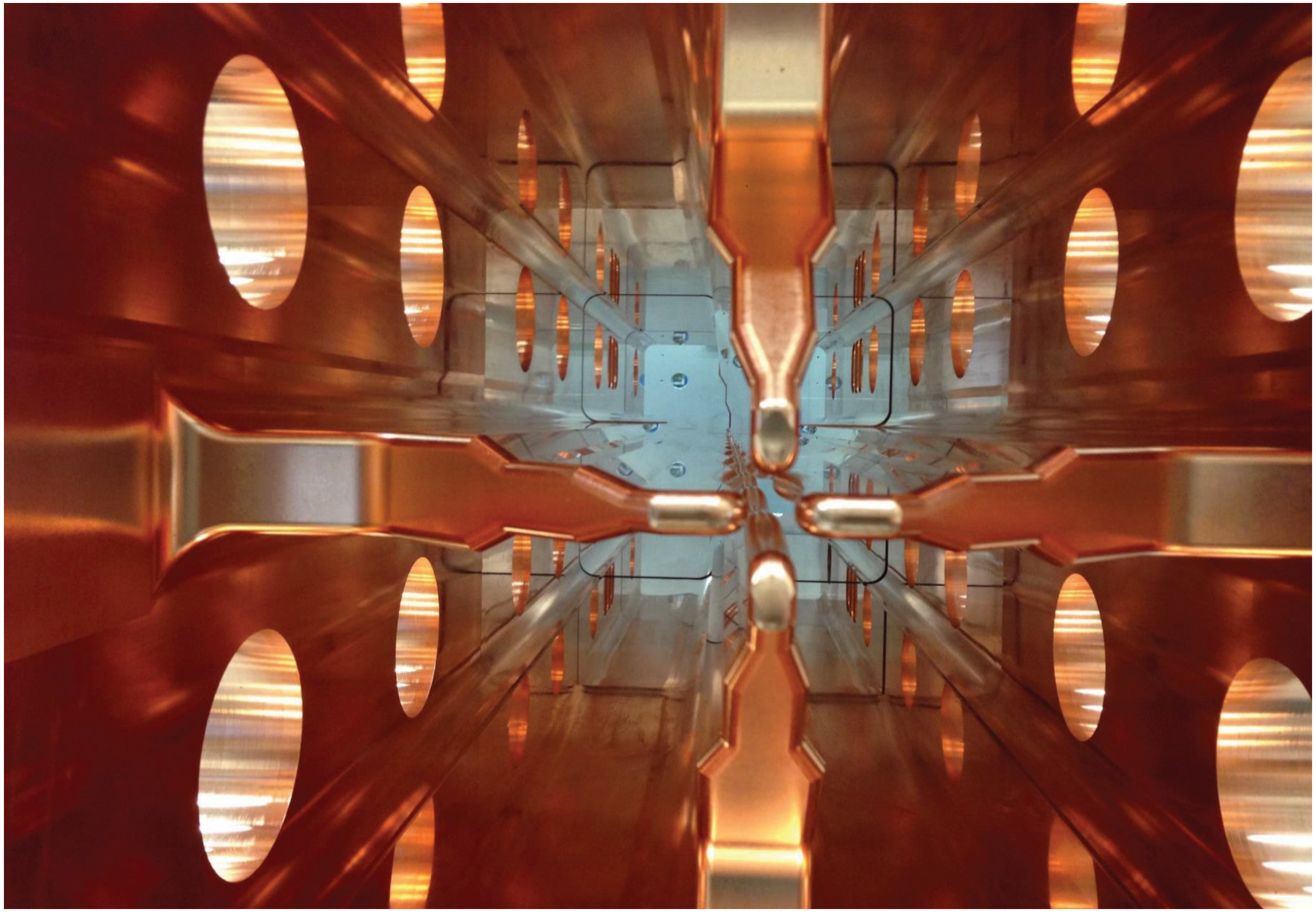
RuPAC 2016 – Tuesday 22th November 2016

Status of IFMIF-EVEDA RFQ

Enrico Fagotti
on behalf of the INFN IFMIF-EVEDA collaboration

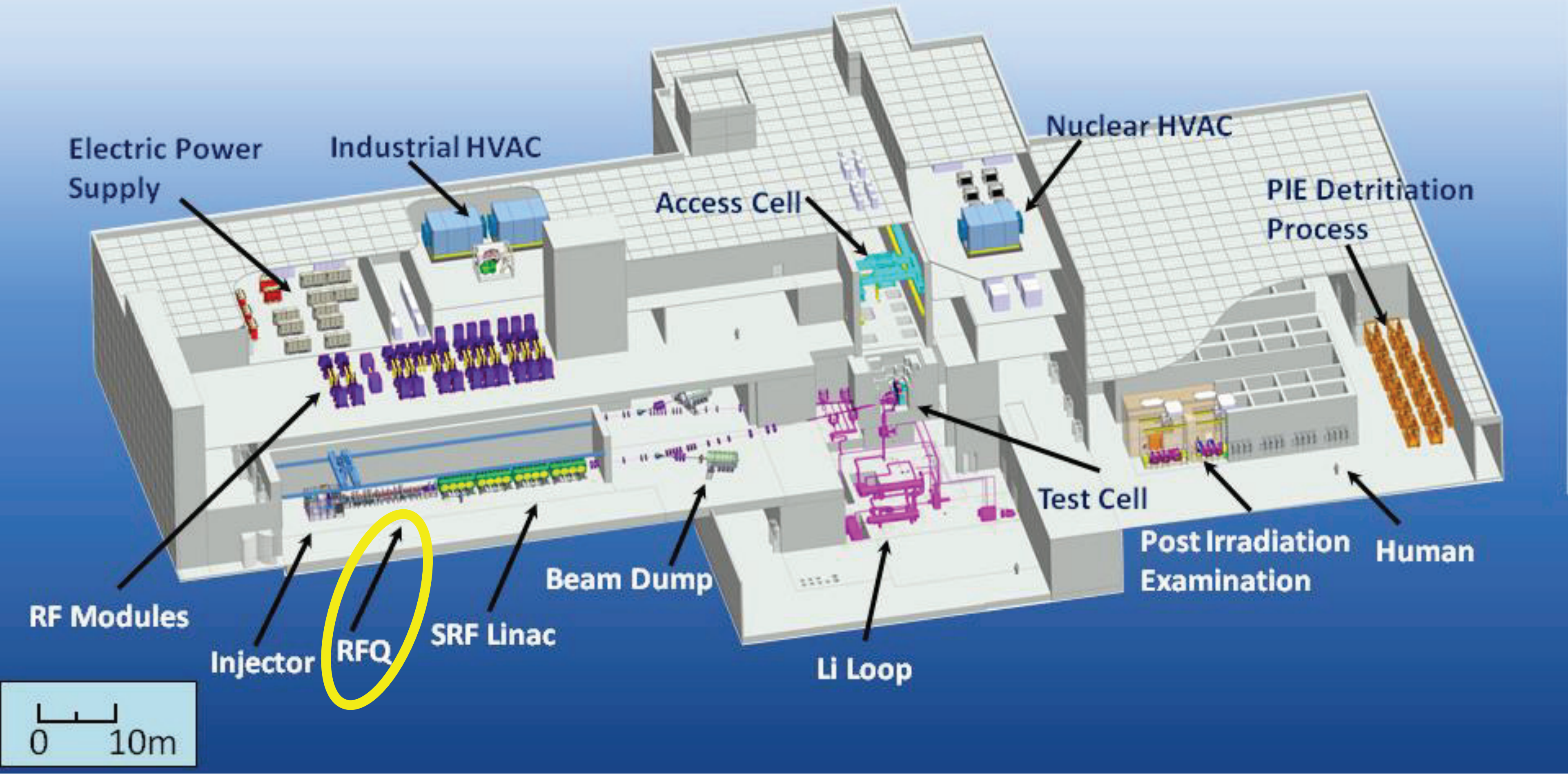


Outline

- Introduction
- RFQ construction results
- CW RF tests in Italy
- Installation and tuning in Japan

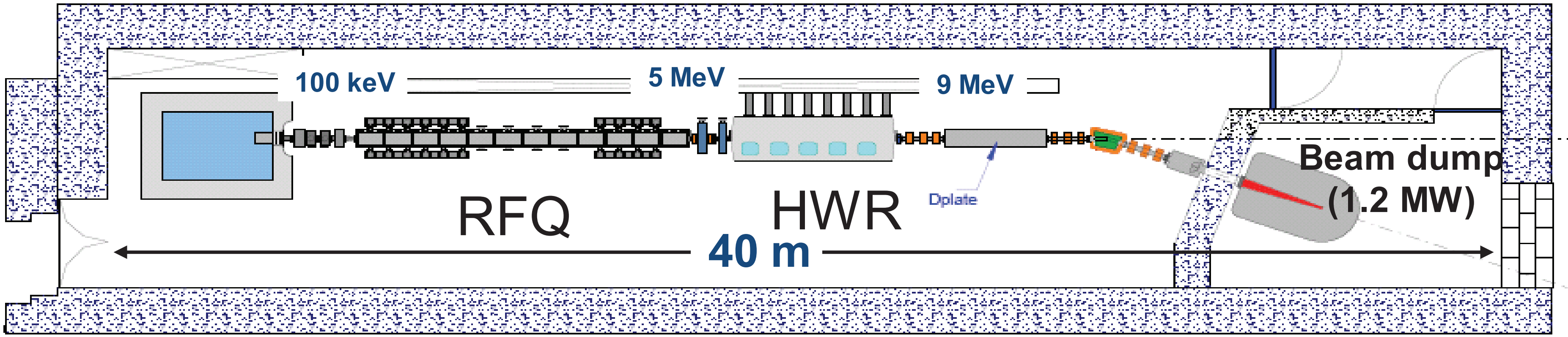
Outline

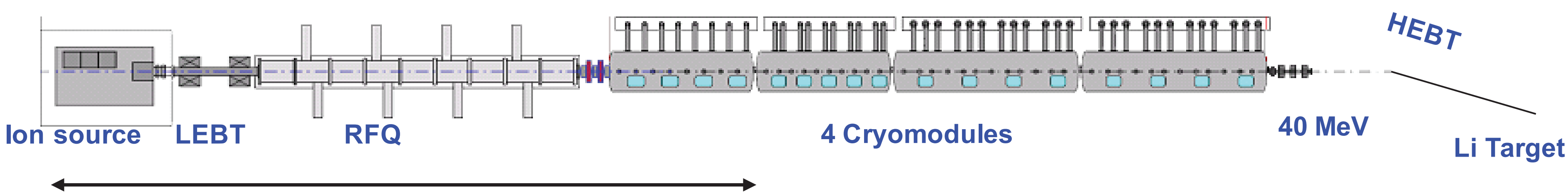
- Introduction
- RFQ construction results
- CW RF tests in Italy
- Installation and tuning in Japan



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.

- 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 linac





IFMIF accelerator prototype (LIPAc)

IFMIF-EVEDA Linear Ifmif Prototype Accelerator

Accelerator components from Europe
Beam tests in Japan

Injector + LEBT
CEA Saclay

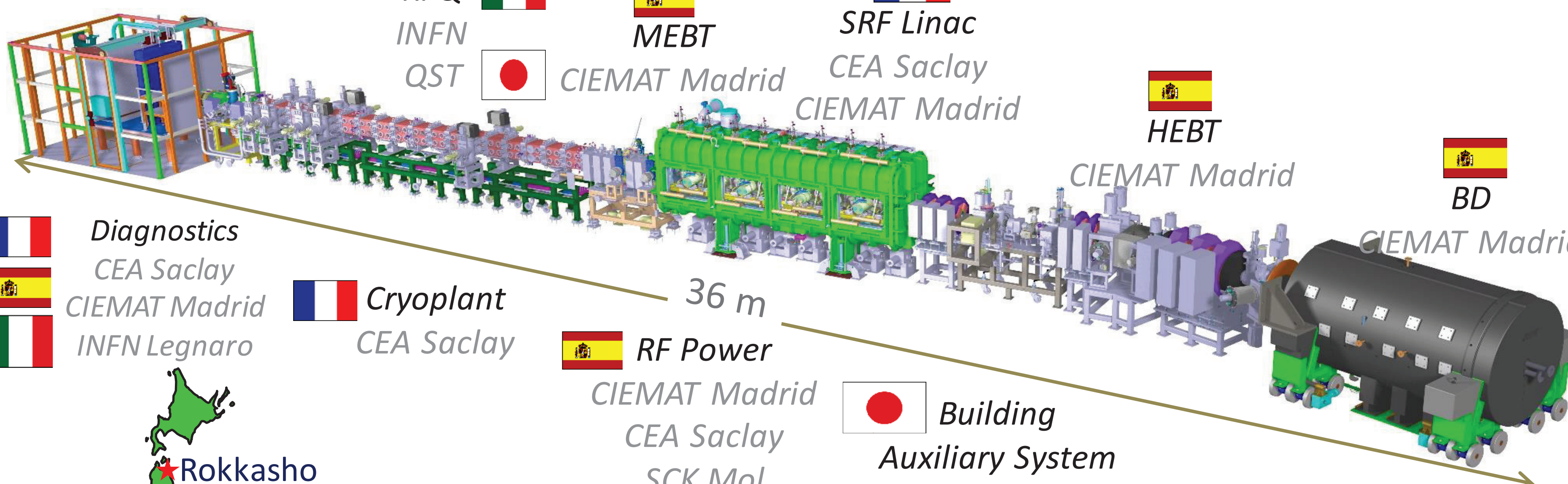
RFQ
INFN
QST

MEBT
CIEMAT Madrid

SRF Linac
CEA Saclay
CIEMAT Madrid

HEBT
CIEMAT Madrid

BD
CIEMAT Madrid



Diagnostics
CEA Saclay
CIEMAT Madrid
INFN Legnaro

Cryoplant
CEA Saclay

RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol

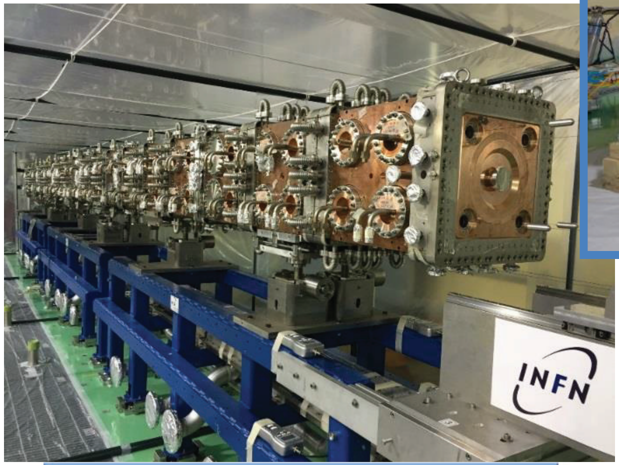
Building
Auxiliary System
Control system
Installation
QST

Status of the LIPAc phases at Rokkasho

Injector under commissioning

MEBT set up

Diagnostics Plate set up



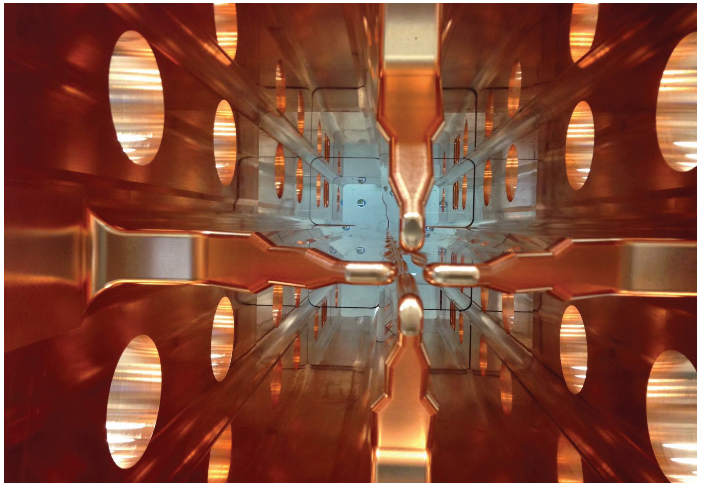
RFQ assembled and tuned

RF power system under completion

Outline

- Introduction
- RFQ construction results
- CW RF tests in Italy
- Installation and tuning in Japan

IFMIF-EVEDA RFQ

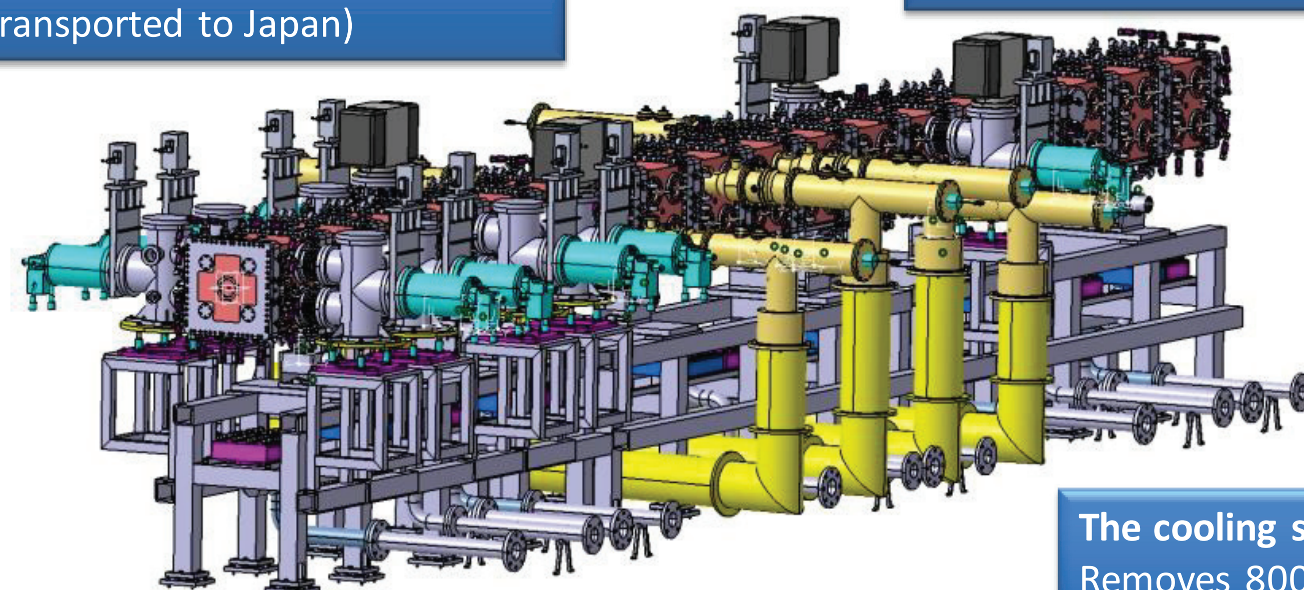


Input/output Energy	0.1 – 5	MeV
Duty cycle	Cw	
Deuteron beam current	125	mA
Operating Frequency	175	MHz
Length (5.7 λ)	9.78	m
Vg (min – max)	79 – 132	kV
R0 (min - max) ρ/R0=.75	0.4135 - 0.7102	cm
Total Stored Energy	6.63	J
Cavity RF power dissipation	550	kW
Power density	86	kW/m
Power density (average-max)	3.5 – 60	kW/cm^2
Q0/Qsf=0.82	13200	
Shunt impedance (<V^2>)L/Pd	201	kΩ –m
Frequency tuning	Water temp.	

RFQ components

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

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

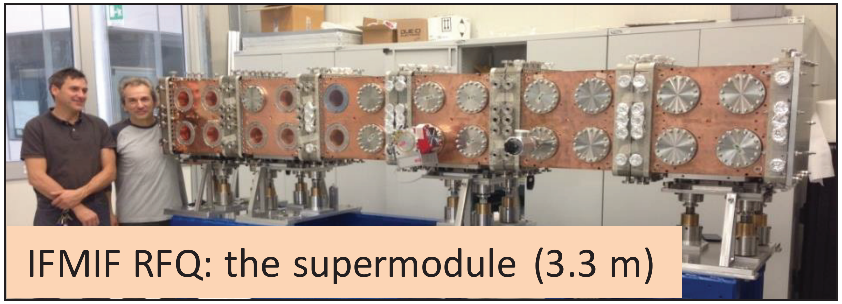


The cooling system
Removes 800 kW and assures
dynamic RF frequency tuning

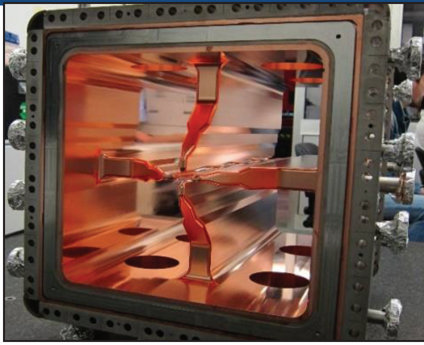
Vacuum system
10 sets, based on cyogenic pumps
(in cyan) guarantee $5*10^{-7}$ mbar
with beam loss gas load

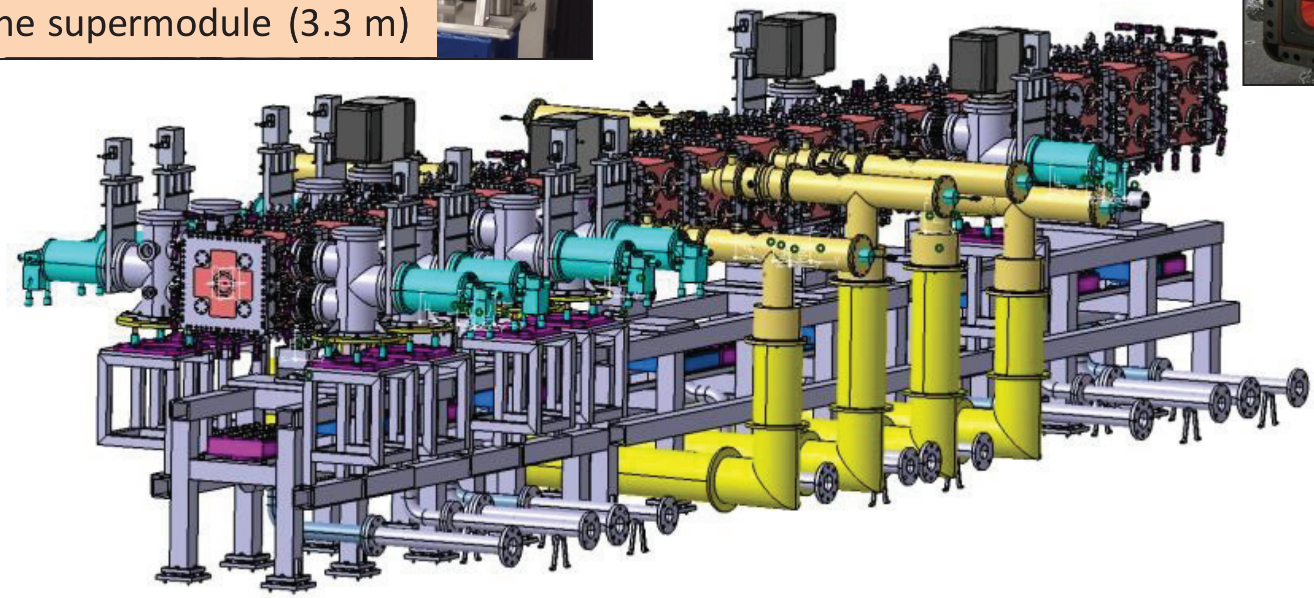
RF Power
8 RF systems and power couplers,
200 kW each. (RF system by Ciemat
and final couplers by JAEA)

Modules construction



IFMIF RFQ: the supermodule (3.3 m)



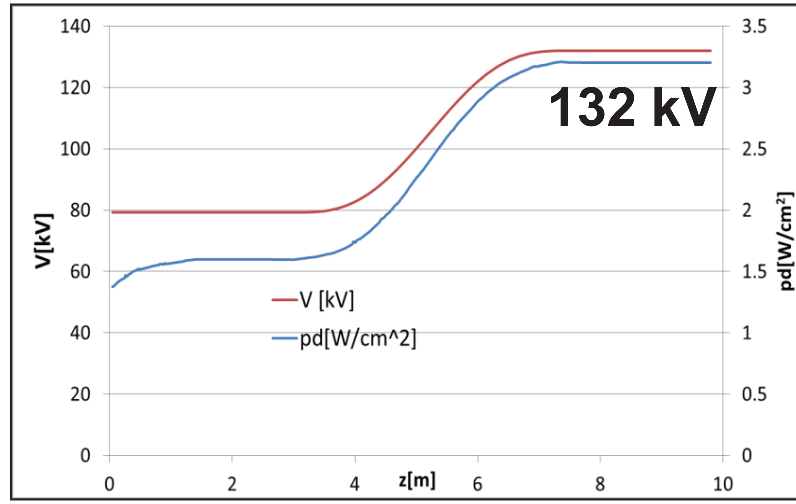


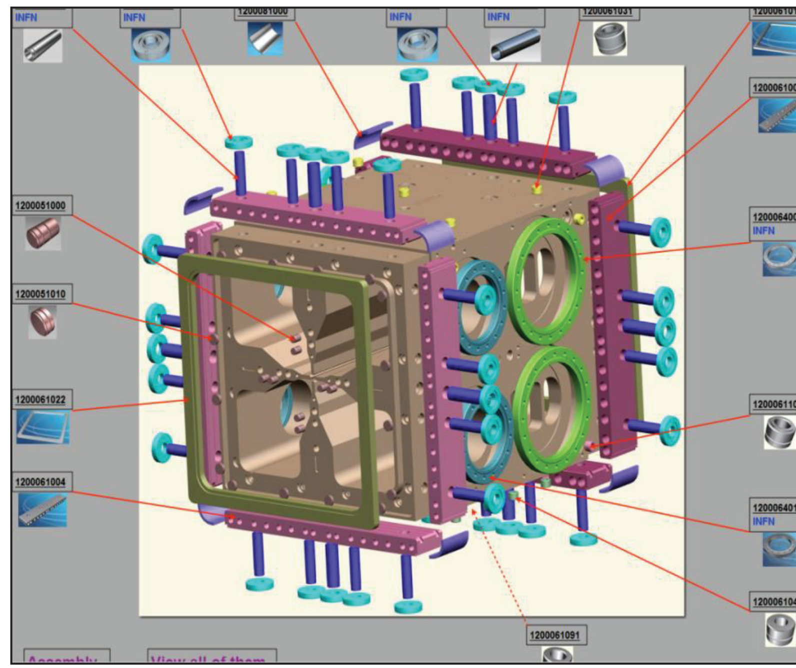
18 modules in three supemodules

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

Design choises

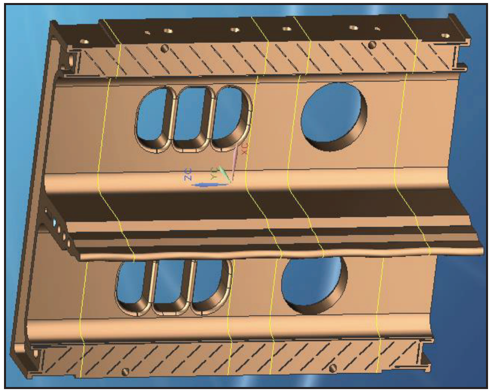
- High beam current requires high focusing parameter B, and ramped high voltage
- The **four vane resonator** was the only possible solution for such high inter-vane voltage
- The **mechanical design** is based on a **brazed structure** and **metal sealing** to guarantee the necessary **high reliability**.
- 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

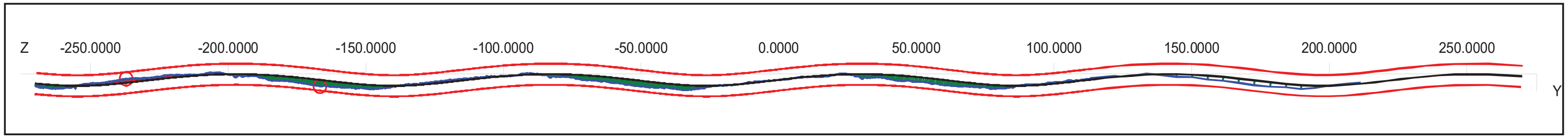




Geometrical tolerances

- The **electrode machining** can be very accurate and for this RFQ it was verified with continuous scanning **CMM of each of the 72 electrodes** (**0.02 mm max error** on each module modulation geometry was achieved).





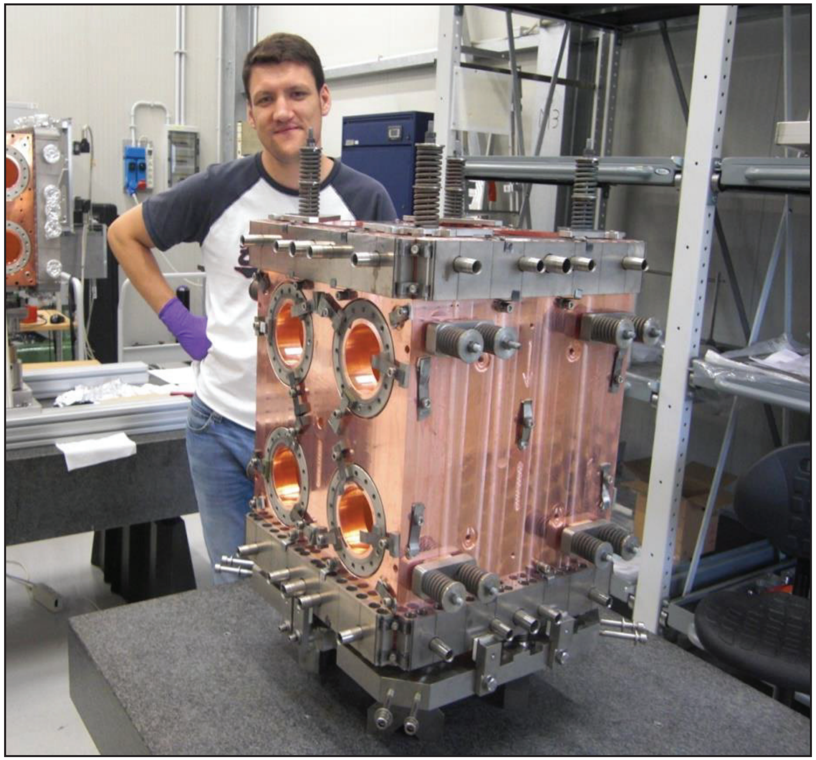
Max Deviat.: 10.5 µm

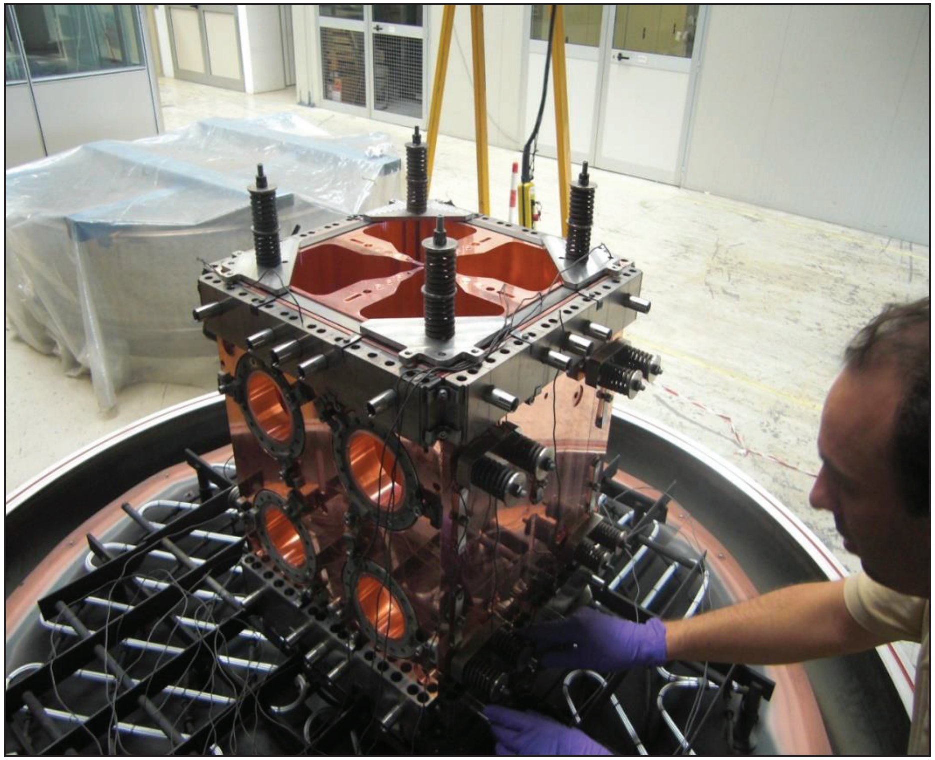
CMM machine at INFN Padova

- The **beam axis accuracy** requires a precise alignment of the quadrupole center module after module (**better than 0.1 mm**).
- To keep the frequency within the tuning range and the **voltage law** along the 5.7 λ structure requires guaranteed electrode displacements below **0.05-0.1 mm** (depending on modulation amplitude).

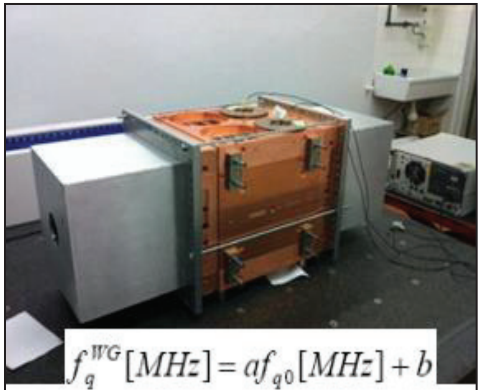
INFN development for Brazing

- Large pieces with final tolerances of 0.05 mm 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.

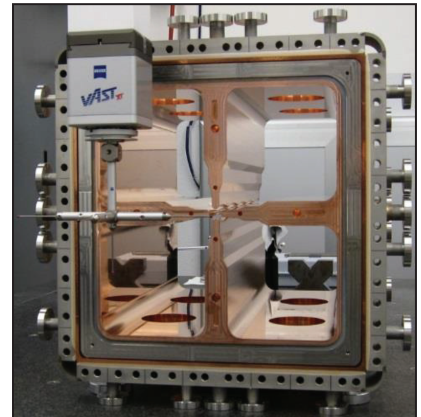




Modules Quality Assurance

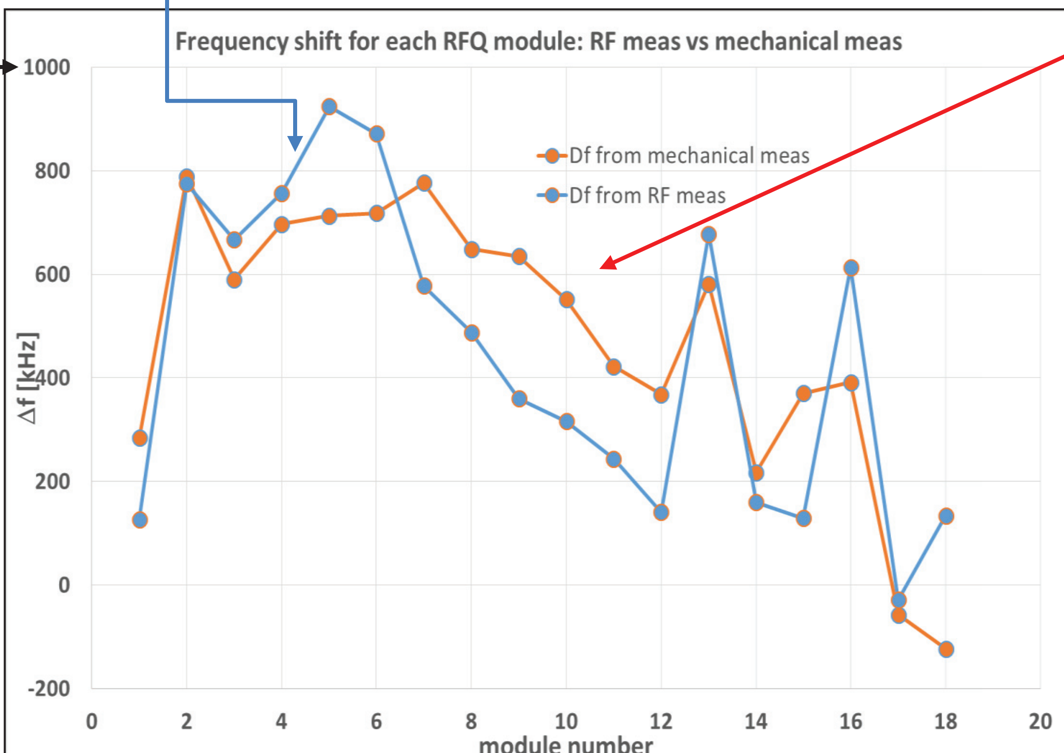


RF measurements before and after brazing



CMM machine at INFN Padova

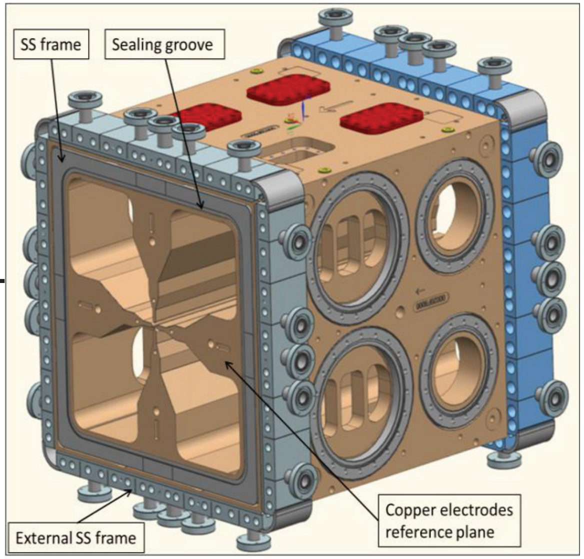
Tuning range



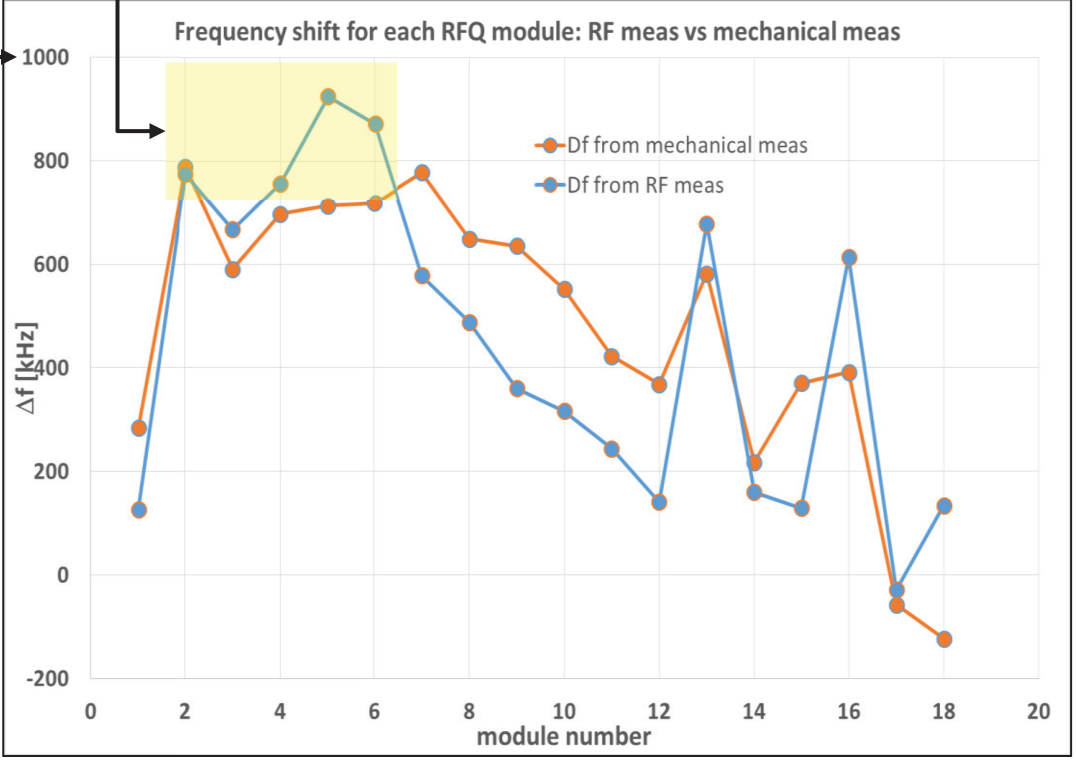
All the measured values are such that $|DR_0| < 0.1$ mm, with an average value on all the modules of **0.046 mm** for the RF measured data and of **0.050 mm** for the mechanical measurement data.

Modules Quality Assurance

Additional opening for frequency correction



Tuning range

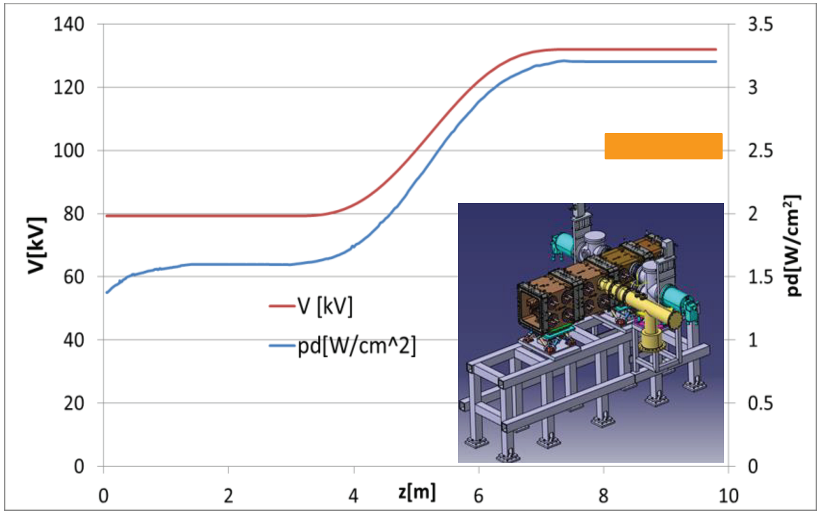


All the measured values are such that **$|DR_0| < 0.1$ mm**, with an average value on all the modules of **0.046 mm** for the RF measured data and of **0.05 mm** for the mechanical measurement data.

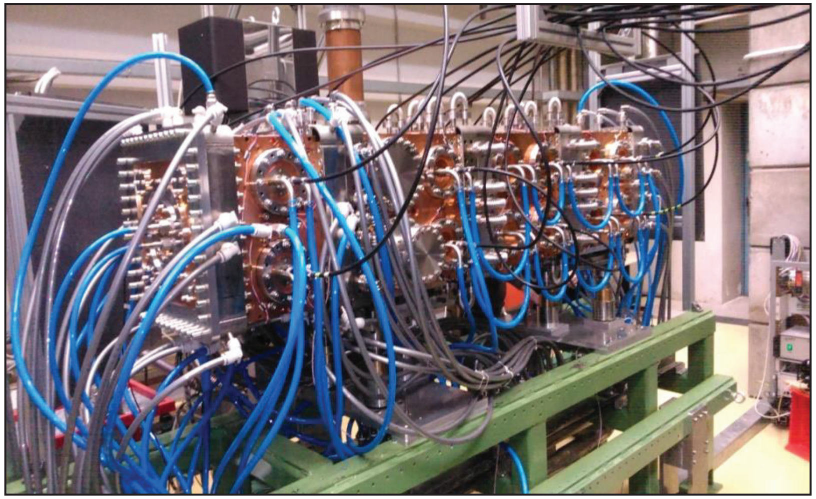
Outline

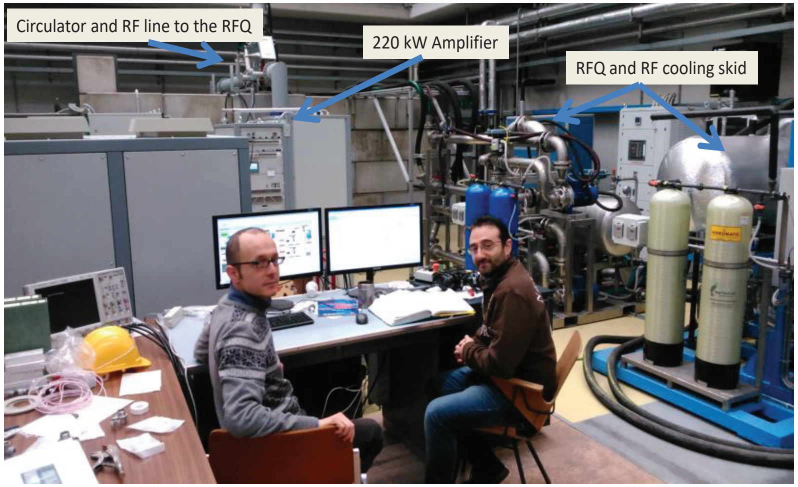
- Introduction
- RFQ construction results
- CW RF tests in Italy
- Installation and tuning in Japan

High power tests at Legnaro



- 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 86 kW/m) have been demonstrated**





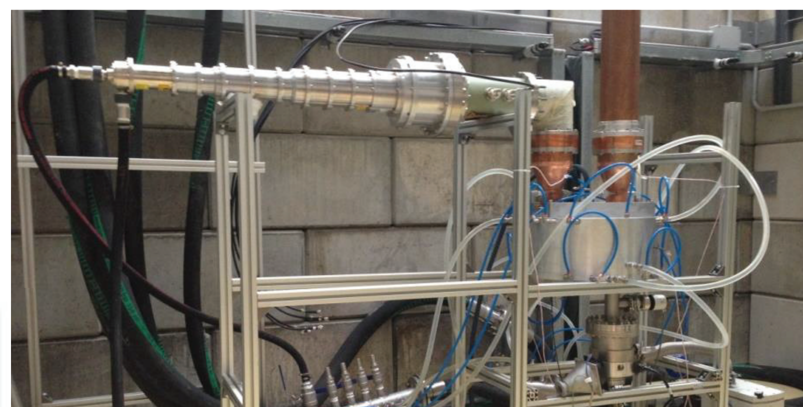
INFN couplers (200 kW cw)

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

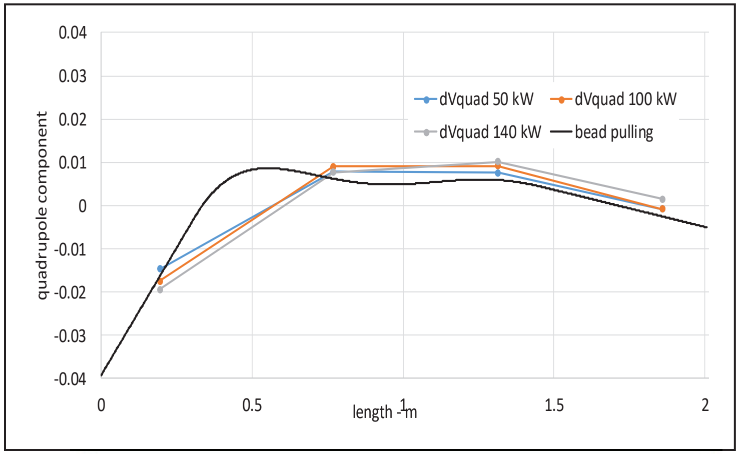

Low power test

Baking

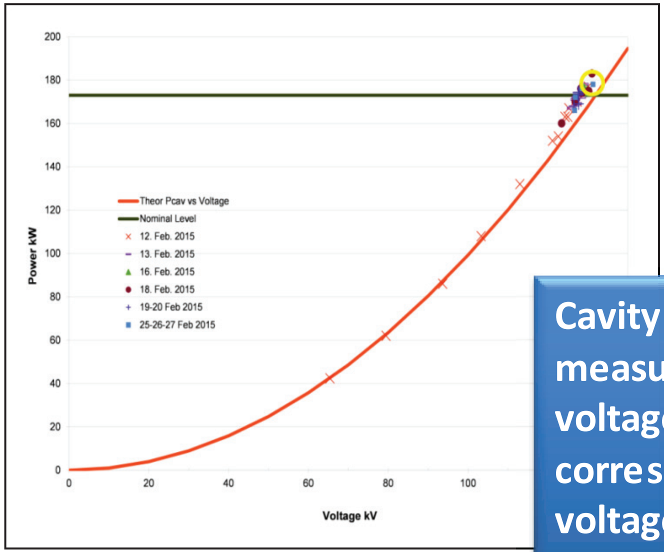
High Power Test



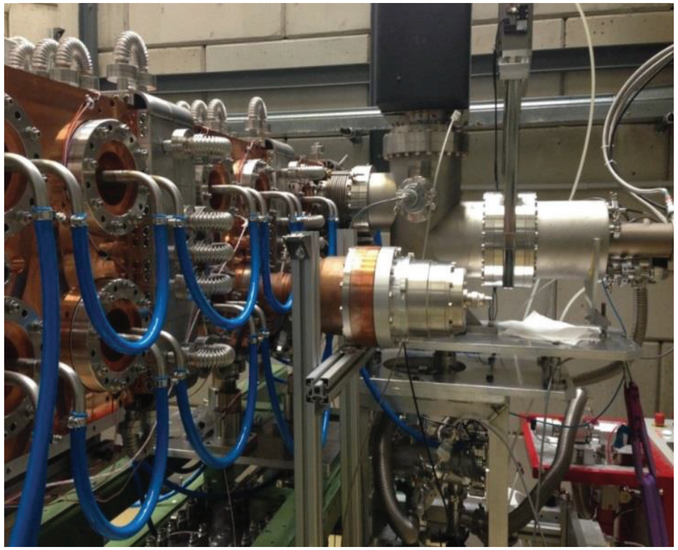
Nominal performances demonstrated

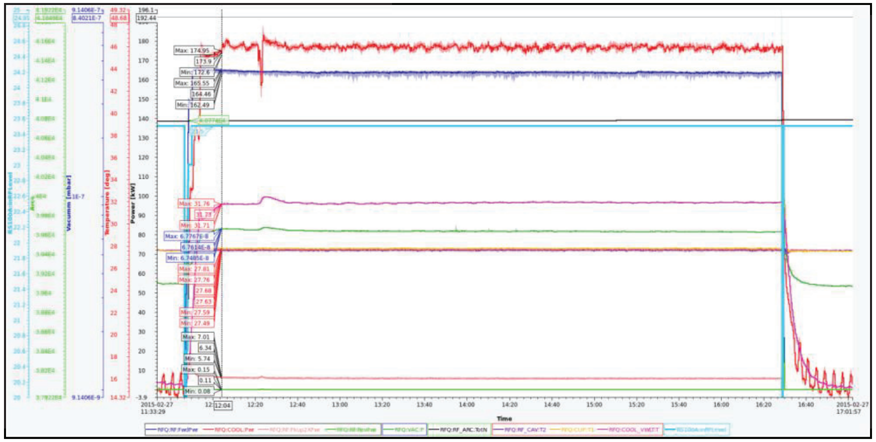


Field configuration (pick up reading) at different RF level



Cavity power (calorimetric measurements) vs. cavity voltage. The yellow circled dot corresponds to the nominal voltage level.Q0=12500, i.e. 173 kW vs. 132 kV

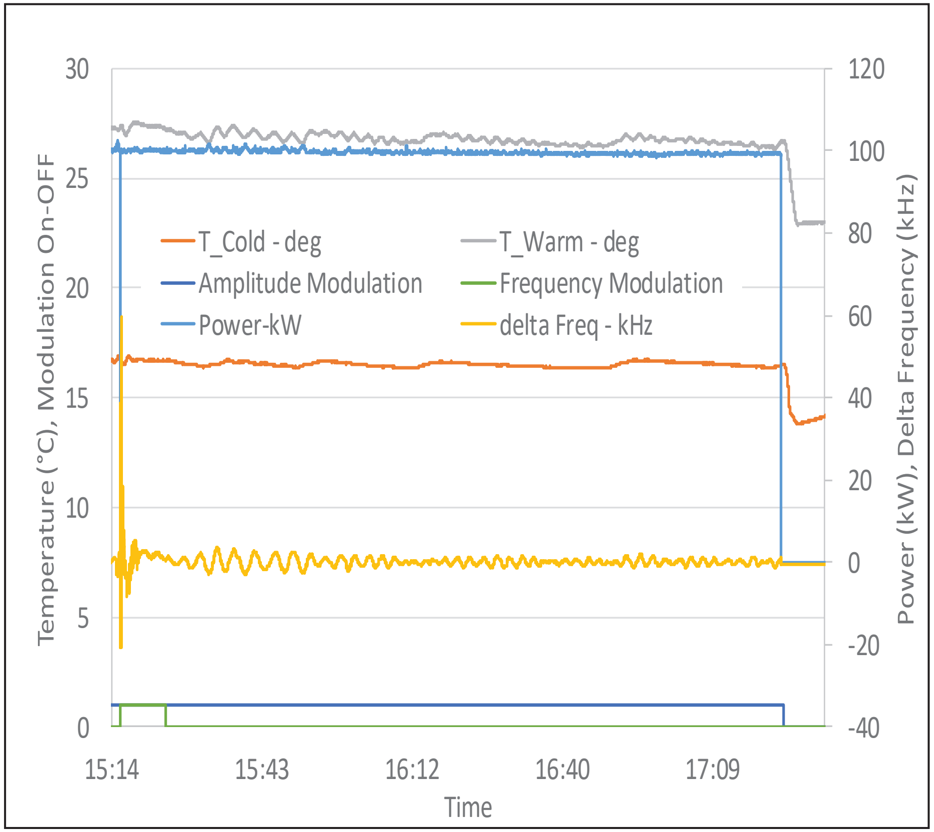




On 27 February '15 RFQ remained 5 hours at nominal field level. It corresponds to the yellow circle in fig above.

Resonant frequency control

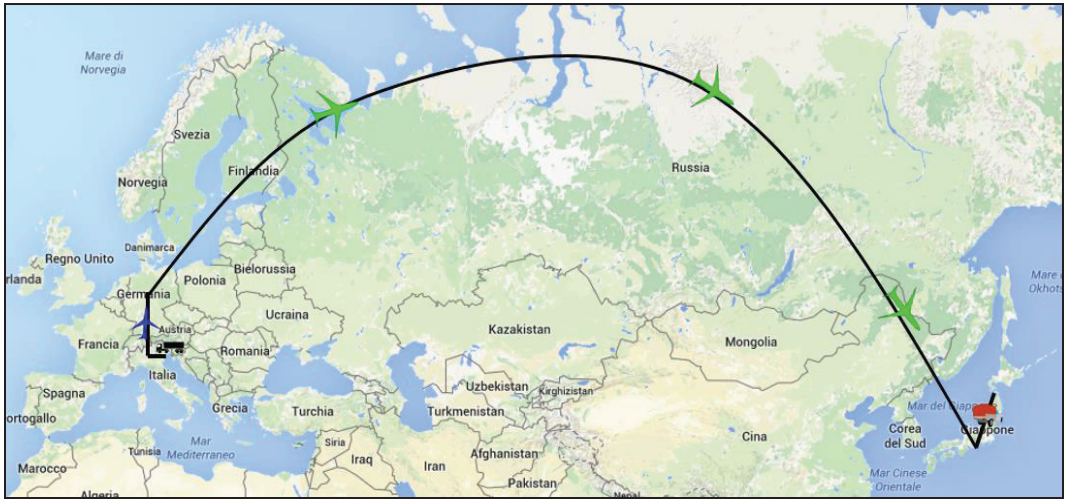
- Resonant Frequency Control (RFC) achieved: cavity frequency driven by coolant temperature (16 kHz/^{0}C external channels)
- RFC was kept active for more than 1.5 hours at 100 kW CW, with frequency oscillation lower than 2 kHz.



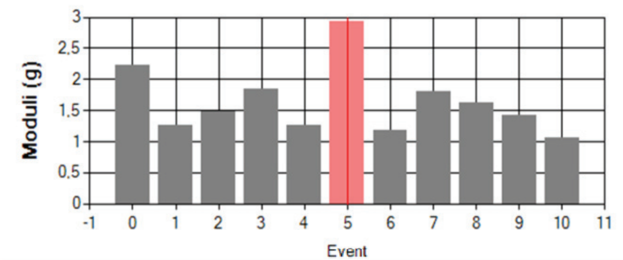
Outline

- Introduction
- RFQ construction results
- CW RF tests in Italy
- Installation and tuning in Japan

RFQ shipment to Rokkasho (Japan)



	Event	Axis	Date/Time	Modulus (g)	Temp (°C)
First Alarm	0	Z	17/02/2016 05:24:09	2,23	14,20
First Warning	1	Z	17/02/2016 22:52:28	1,27	13,50
Most Severe	5	Z	07/04/2016 00:38:52	2,93	17,20
Event Summary	11 Events (6 Warnings, 5 Alarms)				

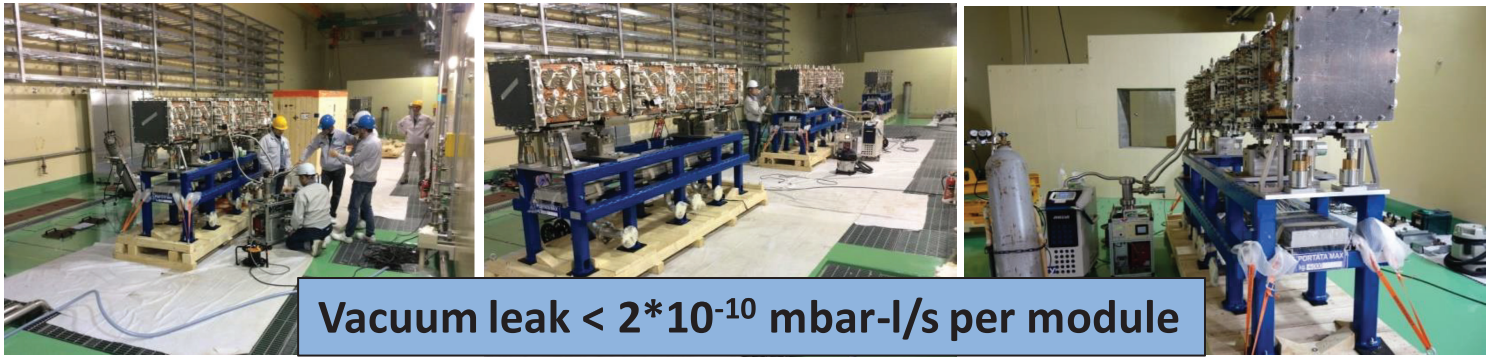


Data extrapolated from the shock recorder mounted on SM2

- The three SMs were completely assembled at LNL, filled with nitrogen
- Rubber spacers and wood supports were used for vibration dumping
- Shock recorders, Shocklog 298, were screwed on the top of each SMs.

RFQ installation in Rokkasho

- RFQ arrived in Rokkasho divided into three SuperModules (SMs).
- Each SM was successfully vacuum tested after arrival.

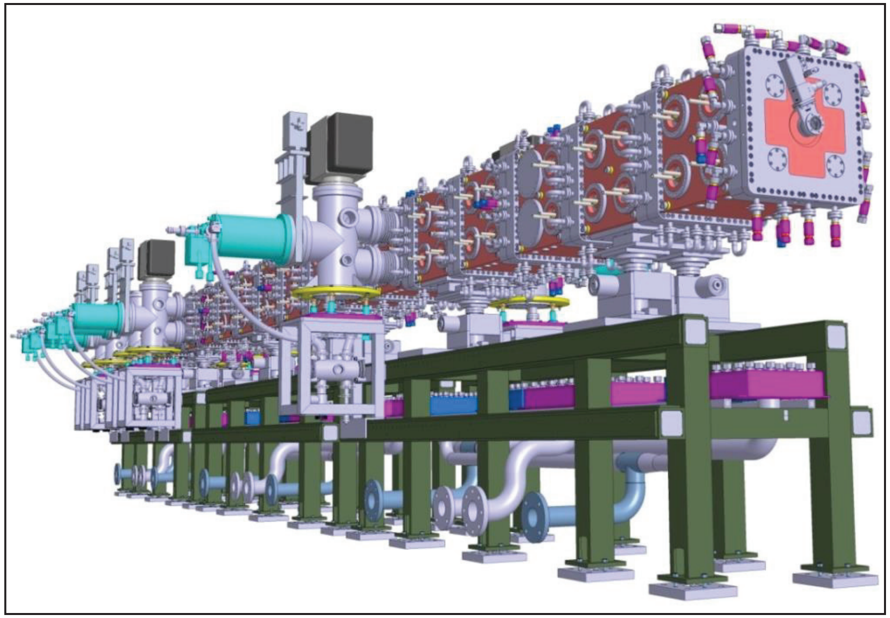


Vacuum leak < $2*10^{-10}$ mbar-l/s per module

- SMs were installed in provisional position, centred on beam axis but moved 3 m away from the LEBT. Final alignment transversal precision was less that 0.05 mm.

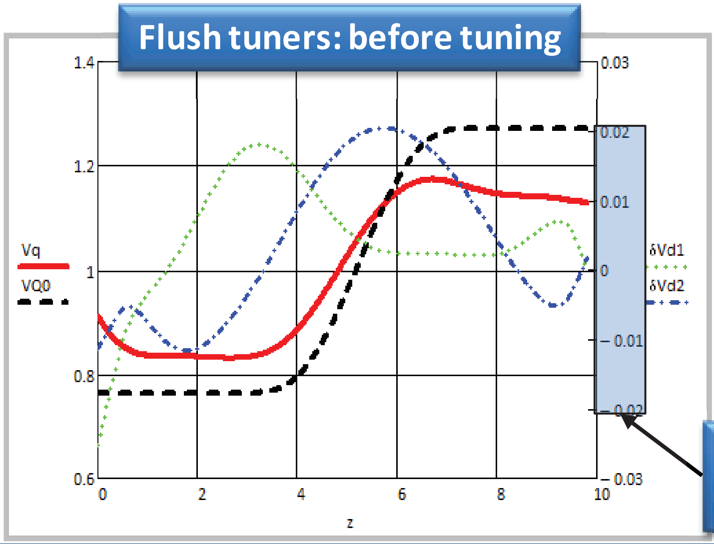
Installation results

- SM1-SM2 vacuum test was successful
- A 0.03 mm maximum misalignment between SMs (±0.1 mm beam dynamics requirements) was obtained
- SM2-SM3 connection revealed a problem related to bad helicoflex sealing

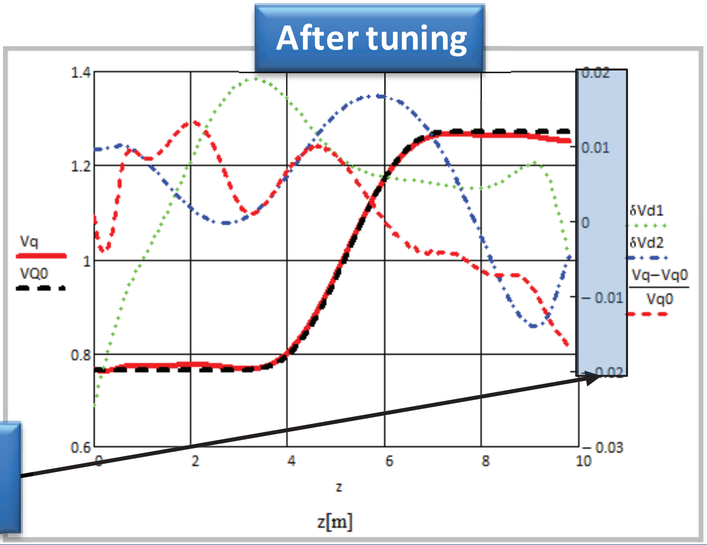


Al component assembly and tuning

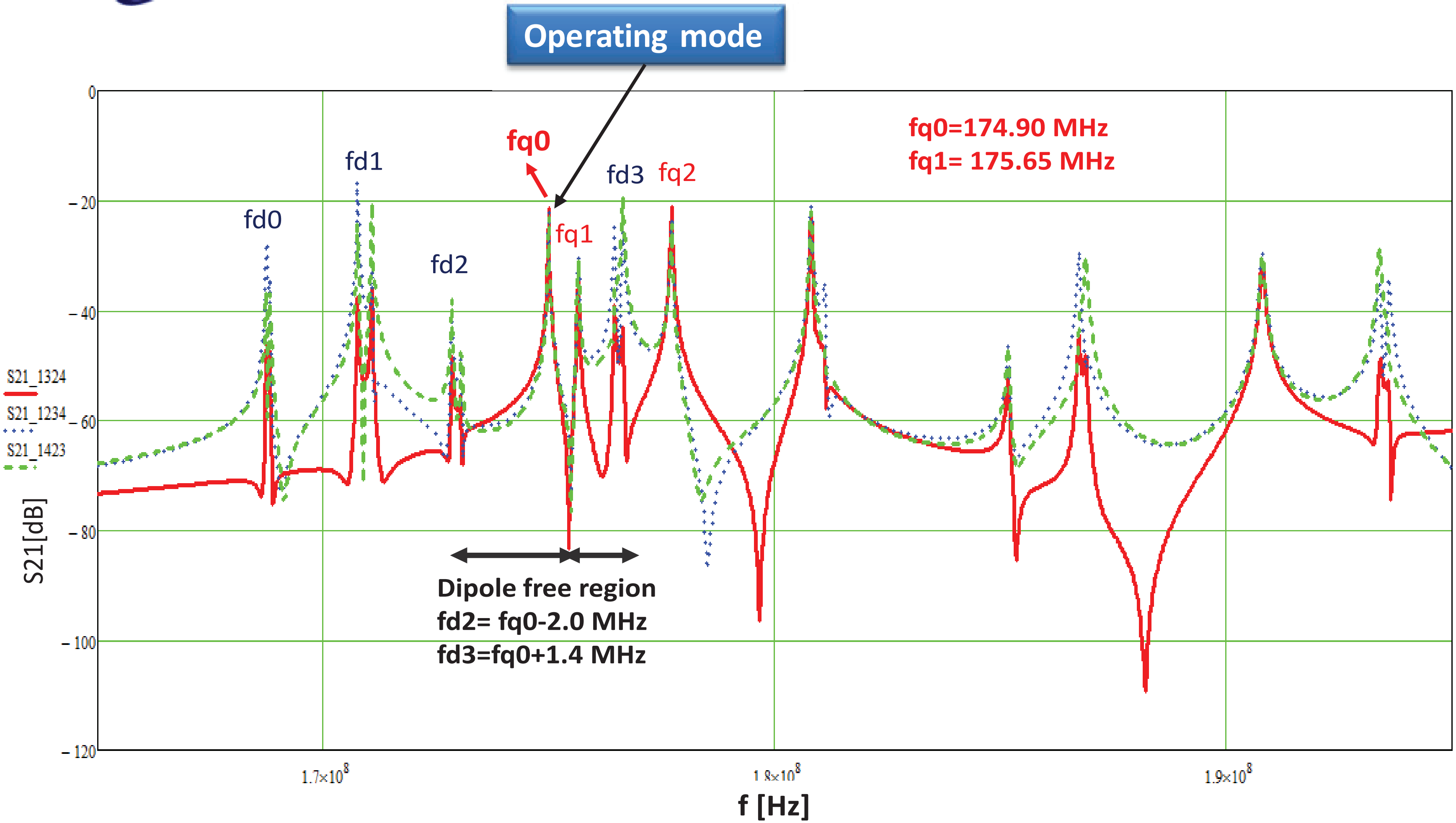
- 108 aluminum tuners and 2 dummy end plates were assembled on the RFQ for tuning purpose.



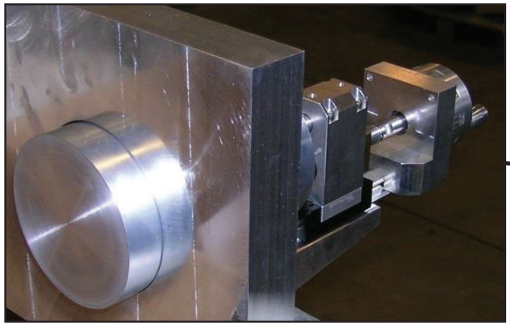
Dipole component tolerances

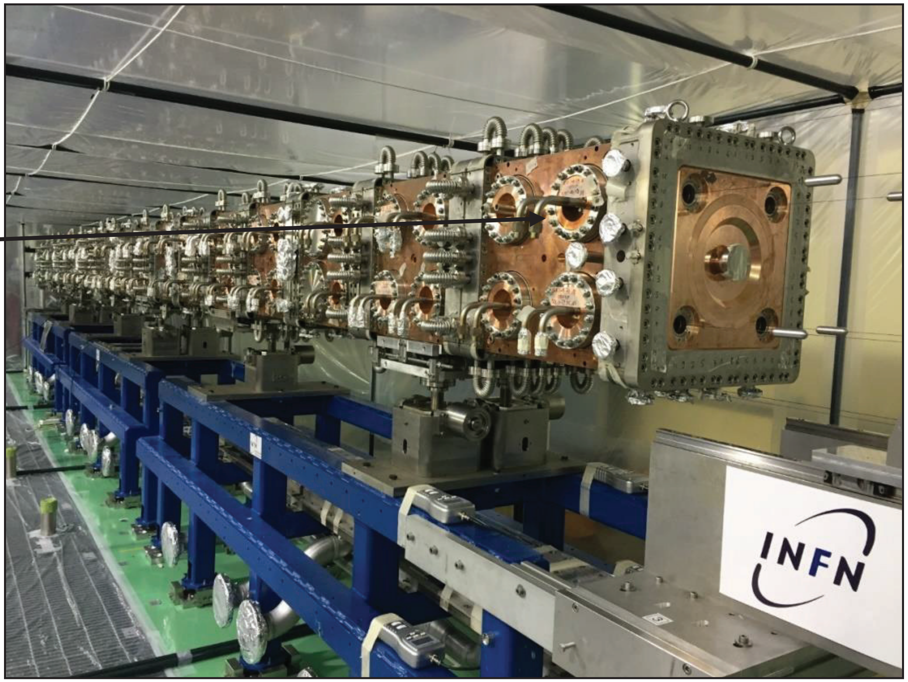


Measured spectrum after field tuning

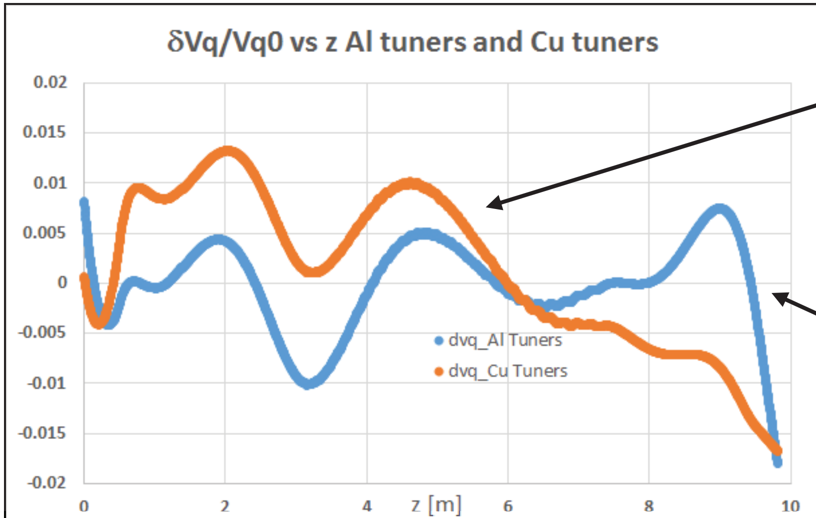


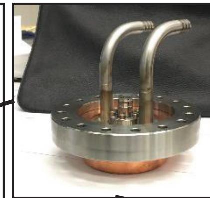
From dummy to final

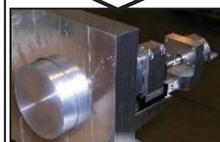


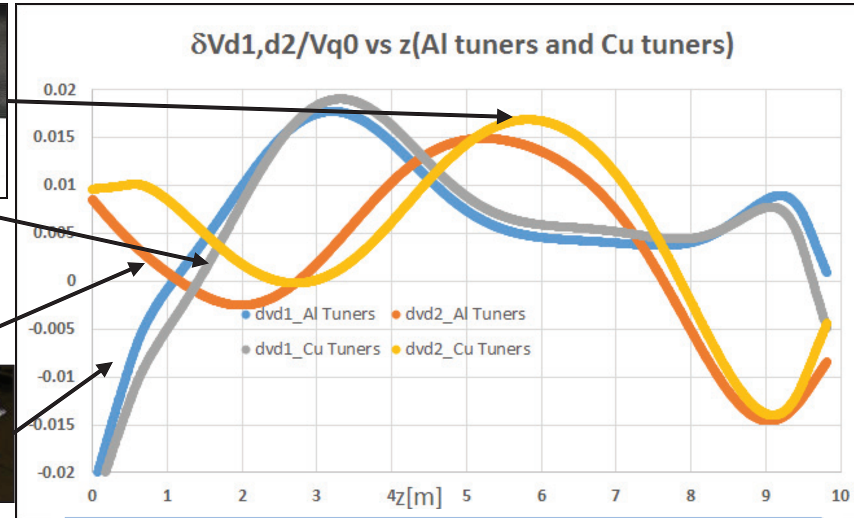


Quad. & Dip. Modes with Al and Cu tuners





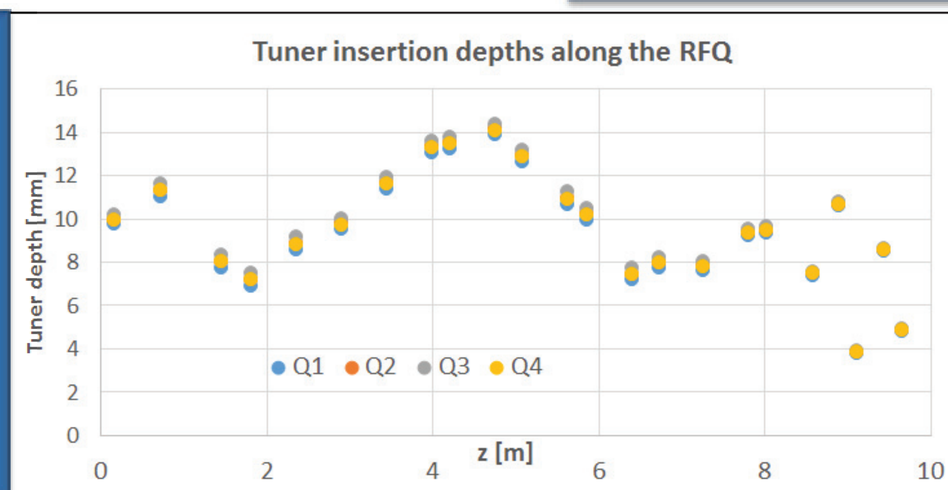




dV_q/V_{q0} vs z for dummy tuners (Al, blue curve) and final tuners (Cu, red curve)

dV_{qd1}/V_{q0} vs z for dummy tuners (Al, blue and dark orange curves) and final tuners (Cu, grey and light orange curves)

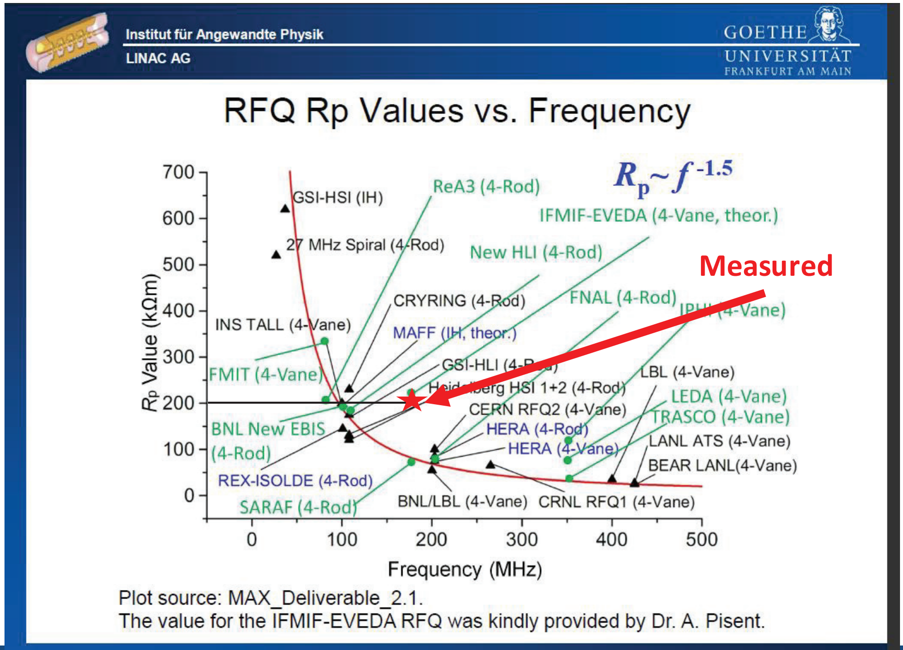
Tuning range -10 +30 mm



Tuning results

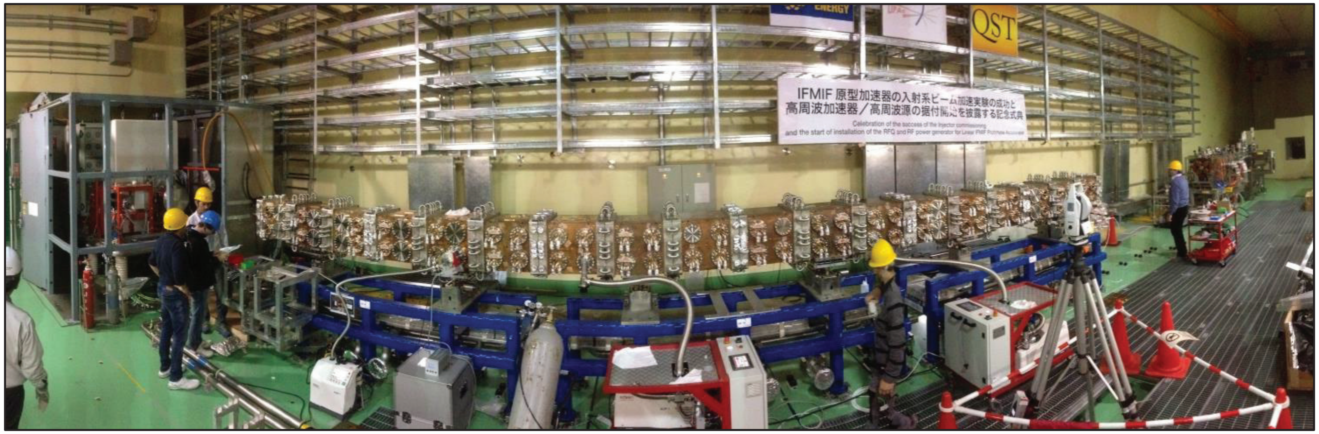
- The final measured frequency was equal to 174.989 MHz, equivalent to 175.014 MHz, if one takes into account the rescaling to nominal 20°C temperature and the effects of vacuum and beam loading (-1°C degree water temperature correction necessary).
- Quality factor was measured $\mathbf{Q_0 = 13200 \pm 200}$ that is 82% of SUPERFISH value (low tuner losses).
- The excellent shunt impedance of the design was achieved:
  - **Rsh=201 kΩ *m**

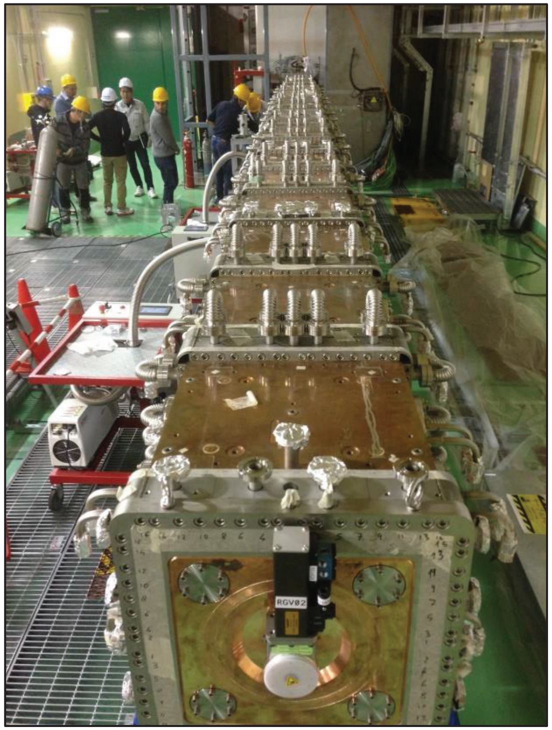
Original transparency by prof. H. Klein



RFQ assembly in the final position

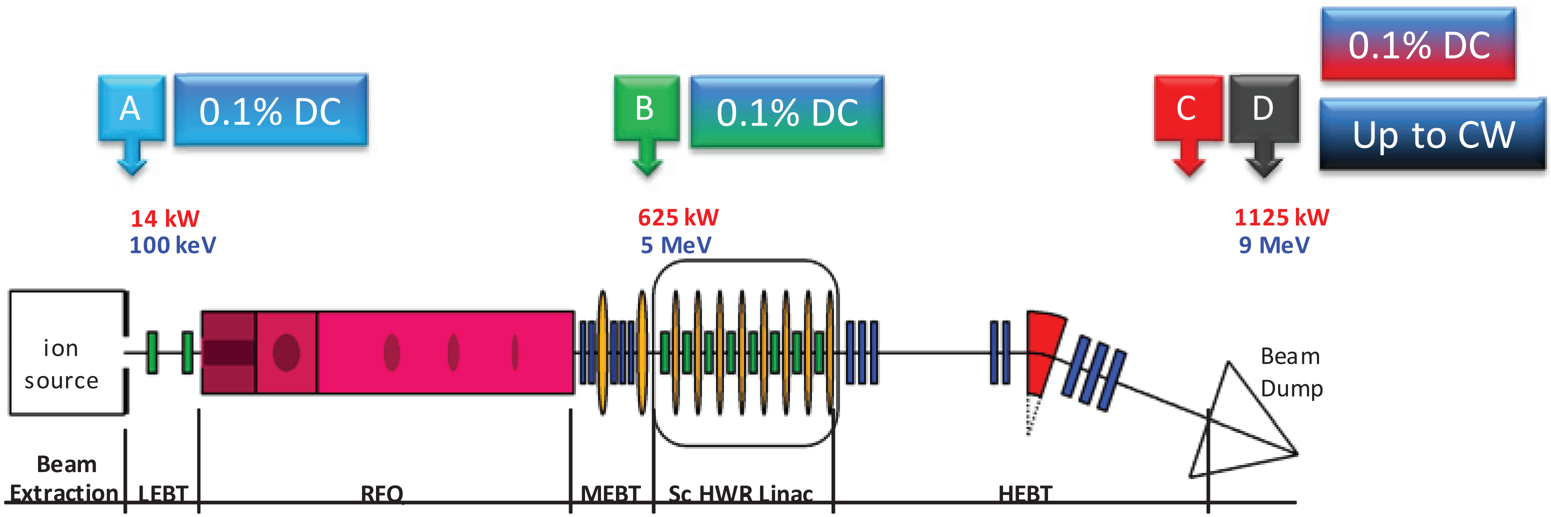
- After helicoflex substitution between SM2 and SM3, and after solving minor vacuum leakages RFQ was repositioned in the final position at the end of the LEBT.
- Final alignment of the entire RFQ guaranteed that each module axis is aligned with the previous and the following modules within ±0.05 mm. Moreover first and last modules are within ±0.03 mm respect to accelerator nominal axis.
- Finally RFQ was vacuum tested and after few hours pumping reached a 9×10^{-11} mbar-l/s leak rate.





Next steps

- Before the end of 2016 control system, vacuum system and power couplers will be installed and RFQ will be baked-out.
- Installation will be completed with cooling system before the end of February 2017.
- Phase B will start on May 2017.



Thank you