# La tecnologia RFQ dalle applicazioni per la fusione alle sorgenti di neutroni (High Power RFQs)

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# HIGH POWER RFQs

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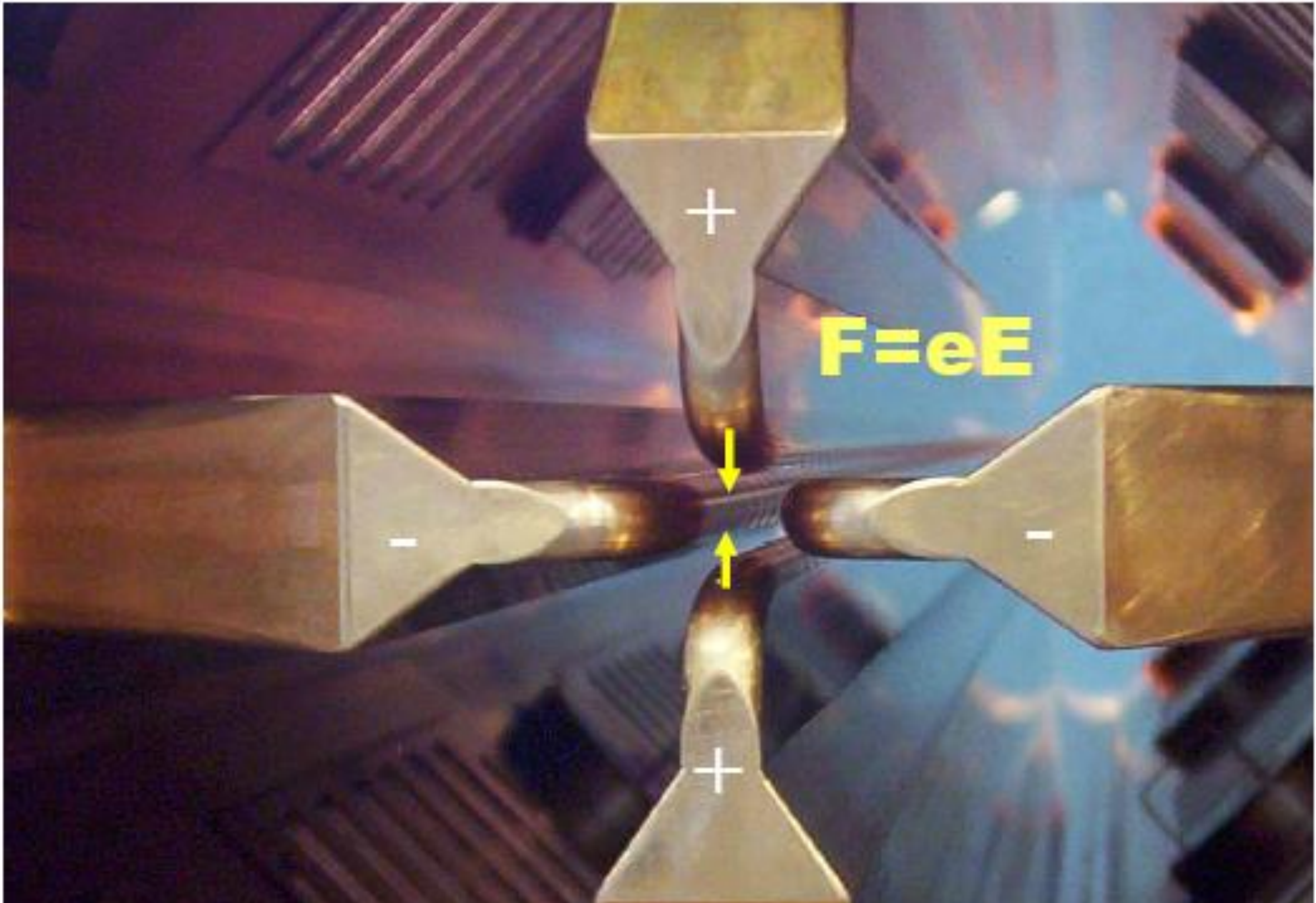
Radio Frequency Quadrupoles (RFQ) are high duty cycle (generally cw) accelerators for light i
beam power in the range 100-700 kW.

- Applications
- State of the art
- IFMIF EVEDA challenges (International Fusion Material Irradiation Facility)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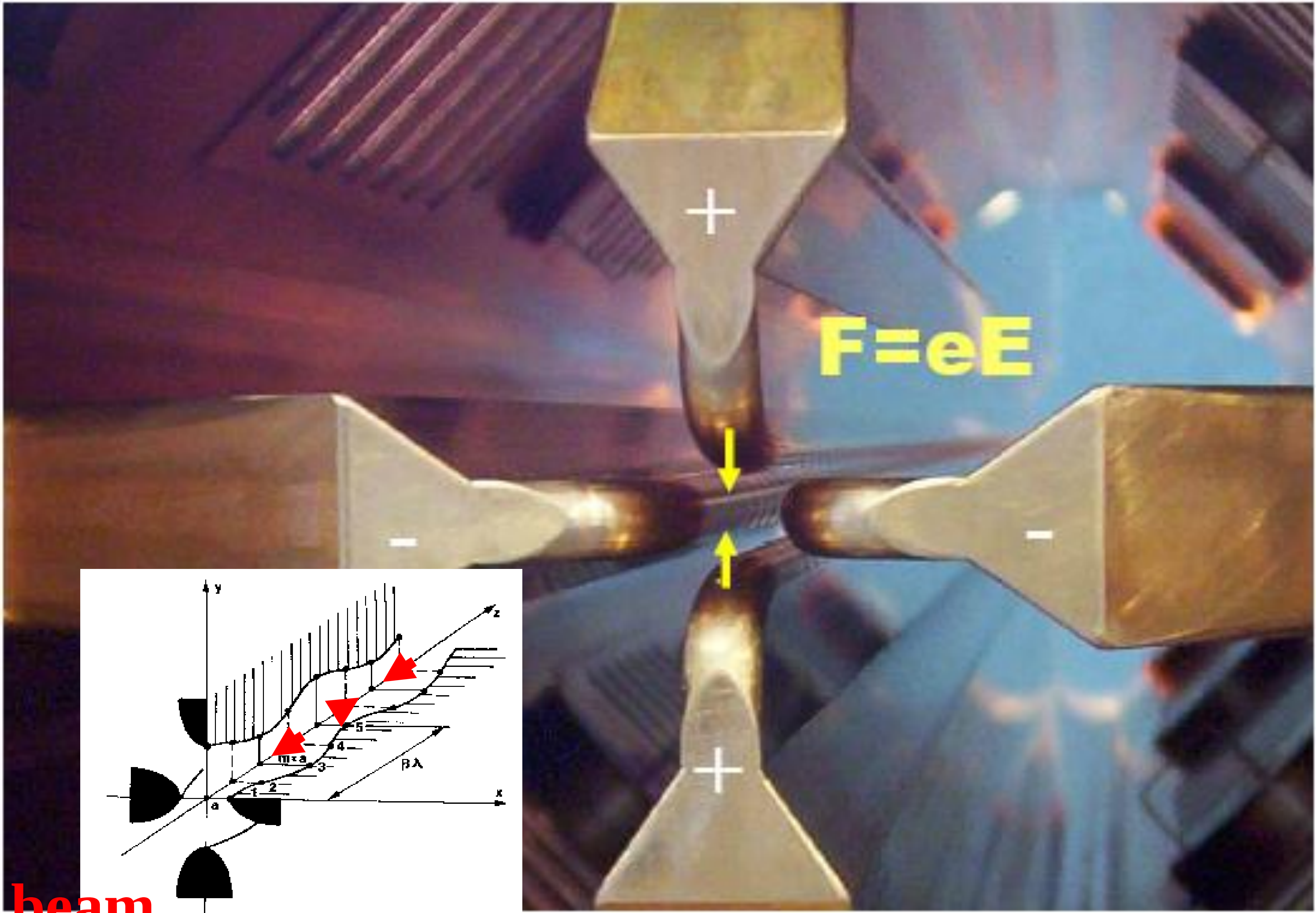
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# Applications of high power RFQs

- Main applications:
  - Injectors of multi MW linacs (protons E>1GeV) for multi MW spallation neutron sources (e.g. **ADS** for nuclear waste transmutation, **radioactive nuclear beams**) or neutrino production
  - Injector for deuteron linac (about 40 MeV) for **Fusion Material Irradiation** tests under large neutron fluxes.
- Lower beam power
  - Stand alone (e.g. 5 MeV 30 mA) application as neutron source for **BNCT (New cancer treatments).**
  - **Intense pulsed neutron source for nuclear waste characterization**
  - **(MUNES Multidisciplinar Neutron Source progetto premiale funded in 2012)**

# Nuclear Waste Characterization

- Part of the management of radiactive waste produced in Italy by industrial research and medical processes is the so called Passive/Active Waste Assay System (PANWAS).
- It uses neutron differential die-away technique to quantify the fissile content ($^{235}$U, $^{239}$Pu etc.)
- Uses a pulsed neutron source (sealed D-T tube, $10^6$ n/pulse in 10 us 100 Hz) and He3 neutron detector.
- With MUNES ($10^9$ n/pulse in 10 us 100 Hz, neutron average energy 1.2 MeV against 14) the sensitivity to Pu contaminiation can be dramatically improved.
- Present sensitivity is to about 1 mg of Pu on a barrel of 400 liters, 1500 kg) 0.1 mg has to be guaranteed for disposal (the limit is  0.1 bq/g , and Pu natural radioactivity is 2 Gbq/g, 10^-10 in mass

WM'06 Conference, February 26-March 2, 2006, Tucson, AZ



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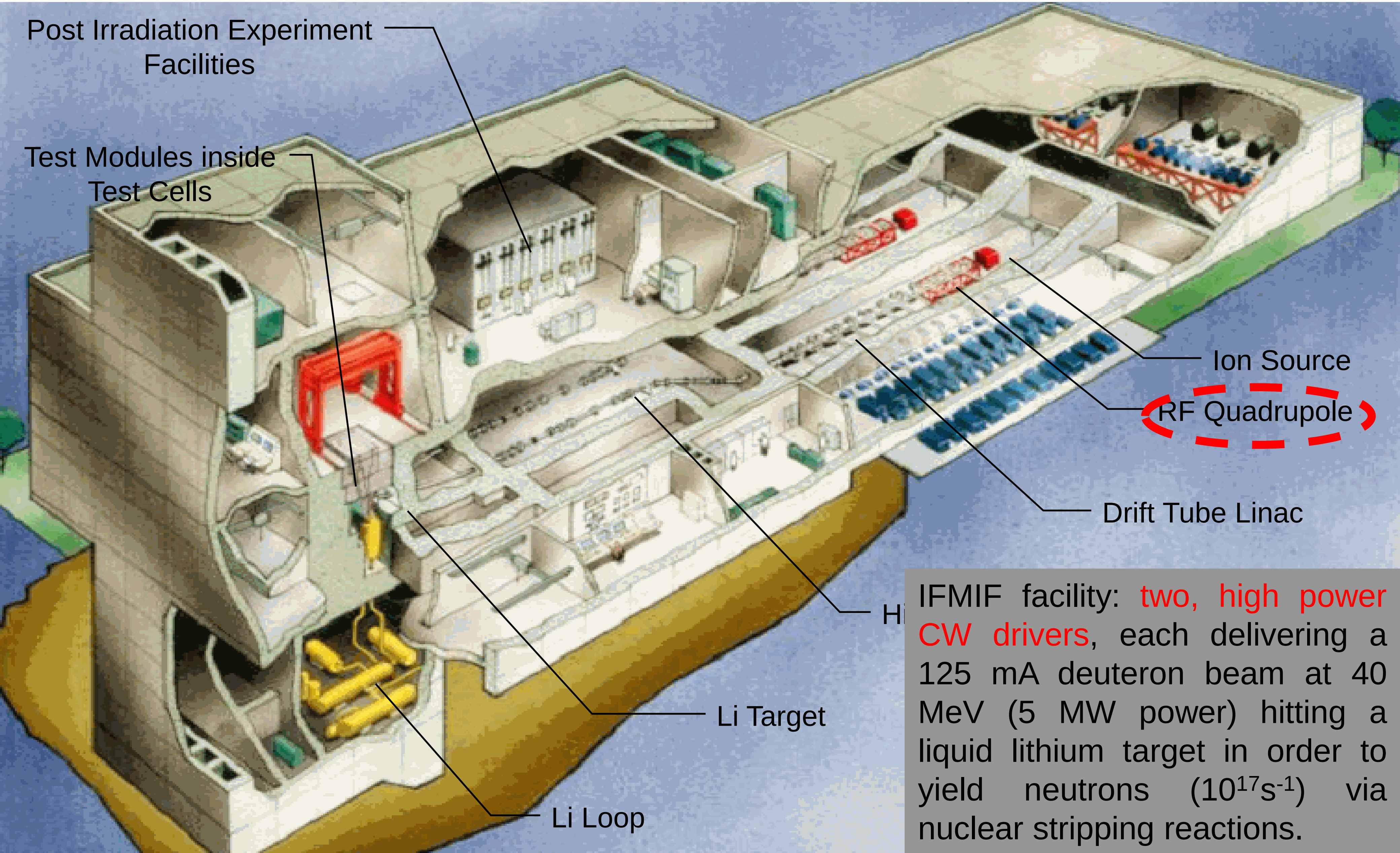
# IFMIF “Artist View”

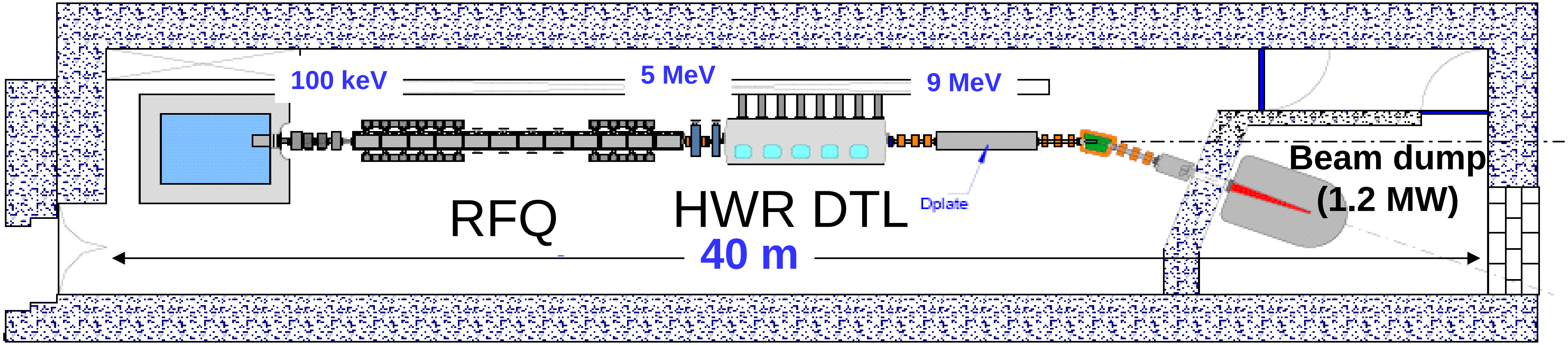
## International Fusion Material Irradiation Facility

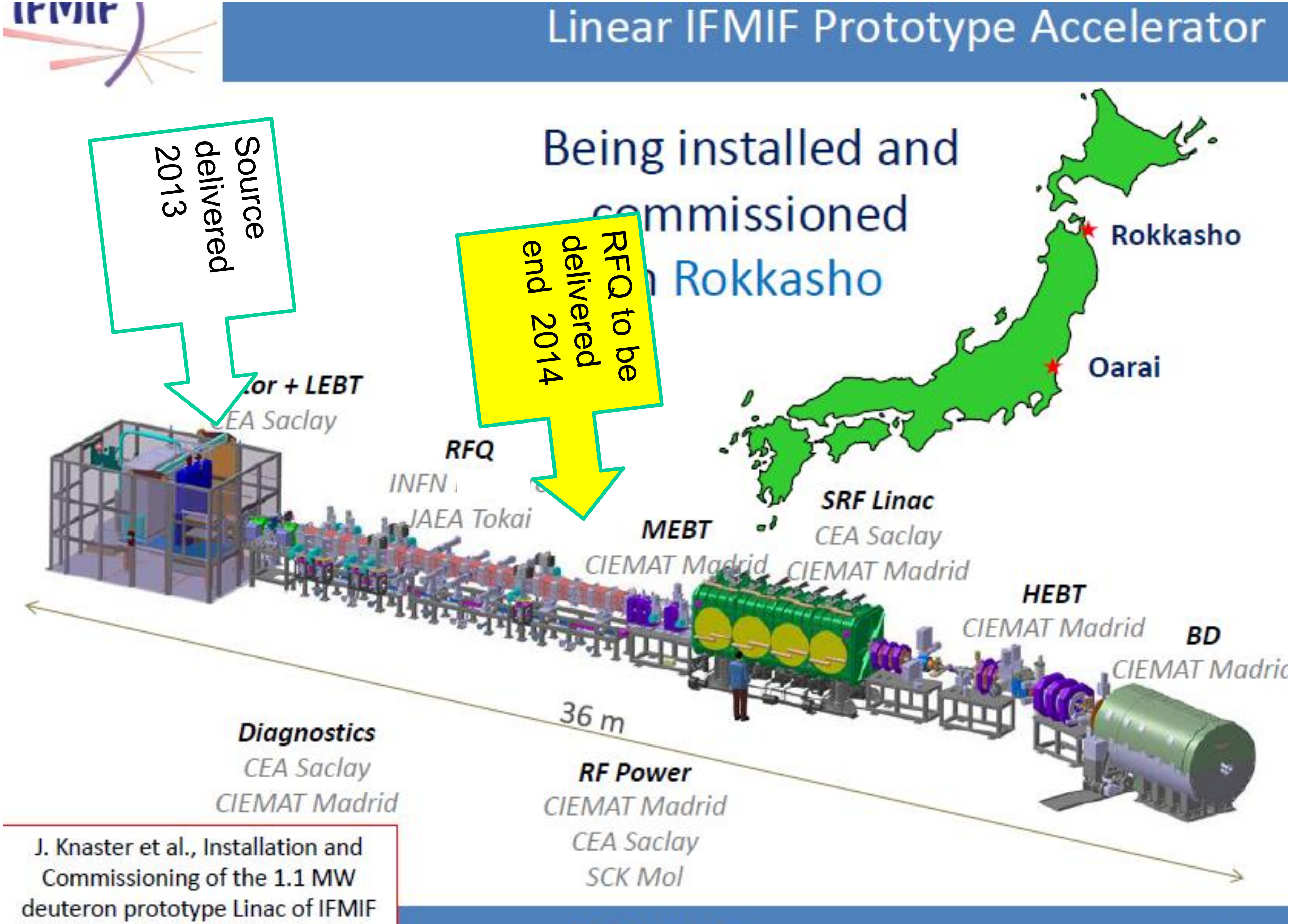



IFMIF facility: two, high power CW drivers, each delivering a 125 mA deuteron beam at 40 MeV (5 MW power) hitting a liquid lithium target in order to yield neutrons ($10^{17}s^{-1}$) via nuclear stripping reactions.

# IFMIF EVEDA

- funded in 2008 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



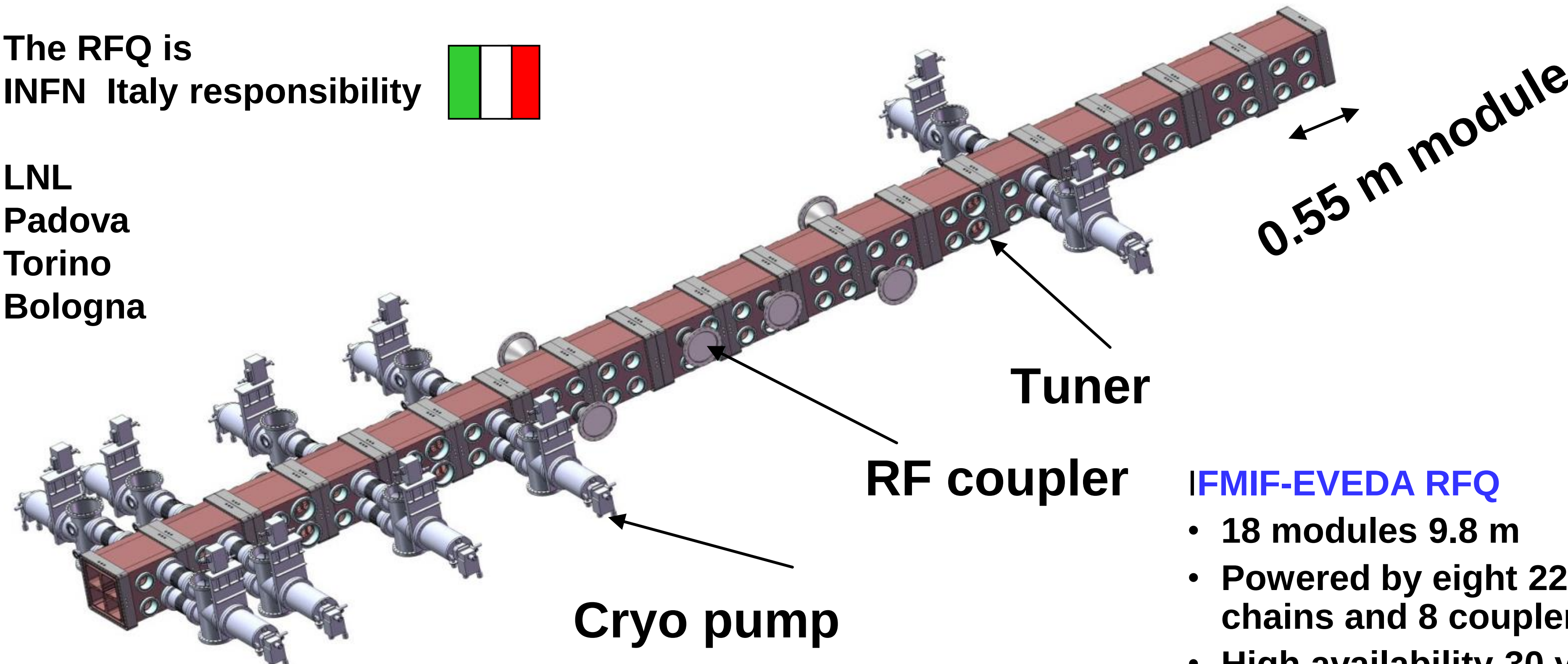
Linear IFMIF Prototype Accelerator
Being installed and commissioned
Rokkasho
Rokkasho
Oarai
Source delivered 2013
RFQ to be delivered end 2014
+ LEBT
CEA Saclay
RFQ
INFN
JAEA Tokai
MEBT
CIEMAT Madrid
SRF Linac
CEA Saclay
CIEMAT Madrid
HEBT
CIEMAT Madrid
BD
36 m
Diagnostics
CEA Saclay
CIEMAT Madrid
RF Power
CIEMAT Madrid
CEA Saclay
SCK Mol
J. Knaster et al., Installation and Commissioning of the 1.1 MW deuteron prototype Linac of IFMIF

# IFMIF-EVEDA: RFQs general parameters

| | Name | Lab | ion | energy | vane voltage | beam current | power | RF Cu power | Freq. | length | | Emax | Power density 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: storia

- L'RFQ è un'invenzione relativamente nuova (anni 70), avvenuta in un mondo recente e antico di Guerra Fredda:
- l'invenzione è di due **scienziati sovietici**, I. M. Kapchinsky and Vladimir Teplyakov, ma il primo prototipo è stato costruito a **Los Alamos**. L'RFQ fu pensato per **l'alta intensità** (fasci di circa 100 mA, potenza di fascio di MW).
- Un RFQ prototipo è stato mandato nello spazio su un razzo (BEAR project).
- per la produzione di grandi flussi di neutroni con applicazioni che vanno dal test dei materiali per i reattori di fusione, trasmutazione scorie radioattive a varie altre applicazioni.

Tepliakov

Primo prototipo a LANL

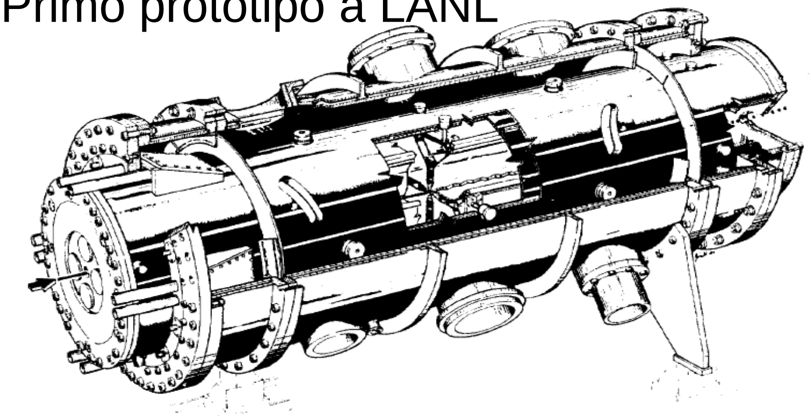
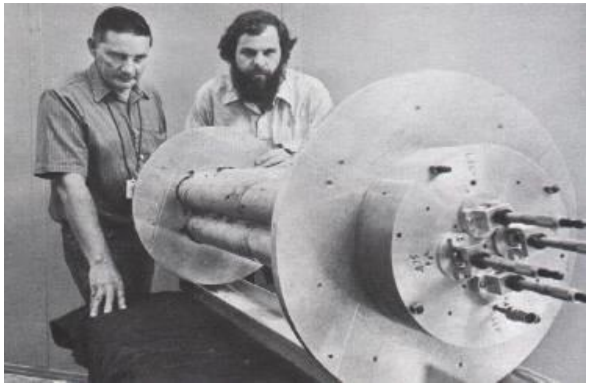


Fig. 1. Initial design of the FMIT RFQ accelerator. The RFQ comprises two coupled, coaxial resonators. The rf power is loop coupled into the outer section. or manifold, which more uniformly distributes the power into the four quadrants of the inner resonator, or core. A 75keV beam is injected (arrow, left in the figure) and accelerated to **2 MeV**.

Arlo Thomas, Jim Potter



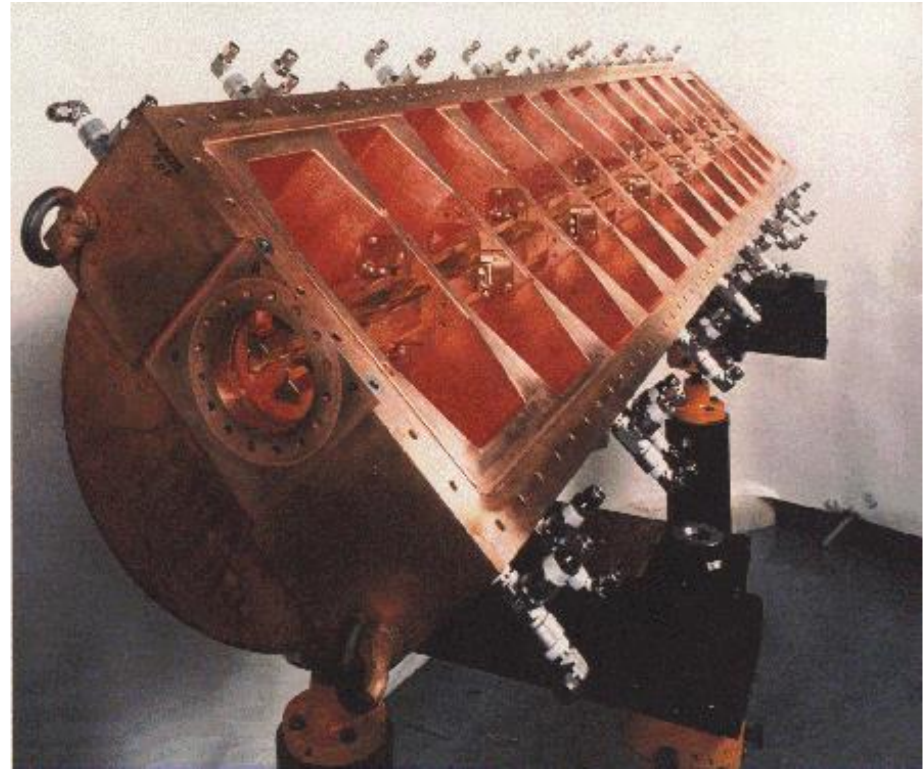
# RFQs general parameters

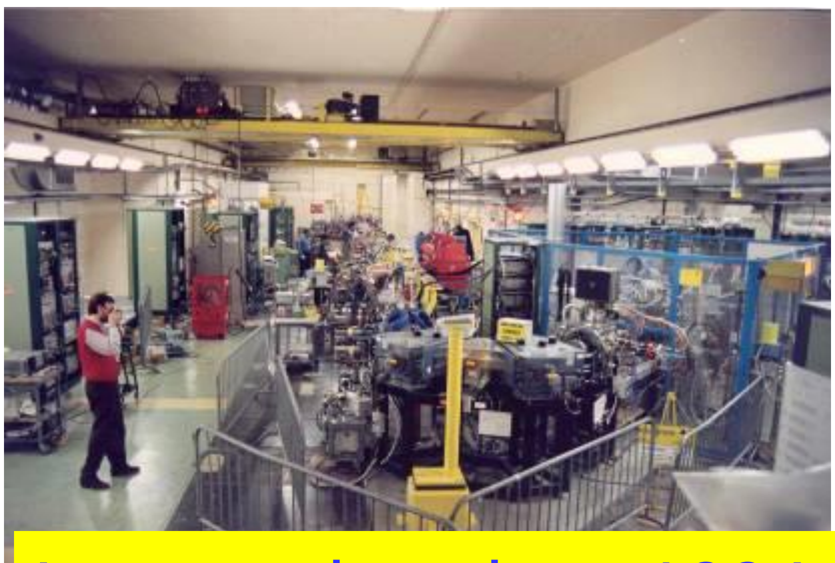
| | Name | Lab | ion | energy | vane voltage | beam current | power | RF Cu power | Freq. | length | | Emax | Power density ave | max | operate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | MeV/u | kV | mA | kW | kW | MHz | m | lambda | kilpat | $W/cm^2$ | $W/cm^2$ | |
| | **IFMIF EVEDA** | **LNL** | **d** | **2.5** | **79-132** | **130** | **650** | **585** | **175** | **9.8** | **5.7** | **1.8** | **3.5** | **30** | **NO** |
| pulsed | CERN linac 2 | CERN | p | 0.75 | 178 | 200 | 150 | 440 | 202 | 1.8 | 1.2 | 2.5 | | | YES |
| | SNS | LBNL | H- | 2.5 | 83 | 70 | 175 | 664 | 402.5 | 3.7 | 5.0 | 1.85 | 1.1 | 10 | YES |
| | CERN linac 3 | LNL | A/q=8.3 | 0.25 | 70 | 0.08 | 0.04 | 300 | 101 | 2.5 | 0.8 | 1.9 | | | YES |

- Since then the experience with CW high power beams from RFQs has been very limited.
- The Radio Frequency Quadrupoles have developed in the following 20 years as the first RF accelerating structure of pused linacs
- This experience (theory, codes, tuning algorithms, engineering tools) is fundamental for the design of a modern high power RFQ,
- Other aspects are specific of the high power application and require dedicated R&D.
- Few examples can be mentioned, chosen in a vast and mature field

# CERN lead ion RFQ (Pb injector of LHC)

- Realized by INFN LNL
- A/q=208/25
- 100 uA Pb beam
- Energy range 2.5-250 keV/u
- Transmission 93% with large multipole correction ($kR_0$=3.3, m=1.1)
- Built in Italy at De Pretto and Cinel





- The linac was built by an international collaboration (INFN-GANIL-GSI-CERN).
- INFN LNL delivered in time and in specs the LEBT the MEBT and the RFQ (except the RF, done by GSI)

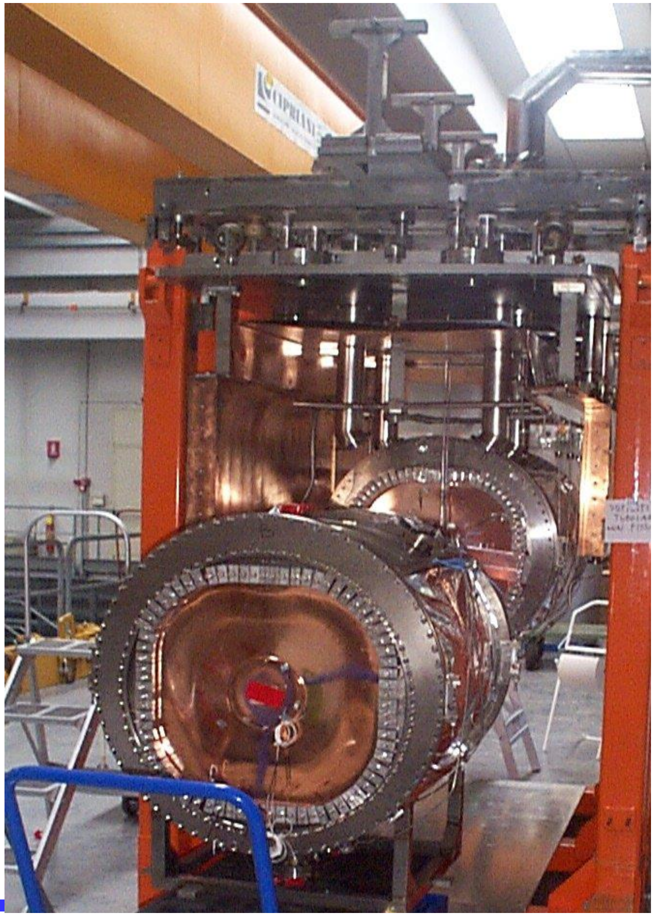
In operation since 1994

# RFQs general parameters (PIAVE RFQ)

| | Name | Lab | ion | energy | vane voltage | beam current | power | RF Cu power | Freq. | length | | Emax | Power density | | operated |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | 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** | **30** | **NO** |
| pulsed | CERN linac 2 | CERN | p | 0.75 | 178 | 200 | 150 | 440 | 202 | 1.8 | 1.2 | 2.5 | | | YES |
| | TRASCO | LNL | p | 5 | 68 | 30 | 150 | 847 | 352 | 7.3 | 8.6 | 1.8 | 6.6 | 90 | *NO* |
| lp | PIAVE | LNL | A/q=7.3 | 0.58 | 280 | 0 | 0 | 8e-3 (SC) | 80 | 2.1 | 0.5 | 2.1 | - | - | *YES* |

The only superconducting RFQ operting in the world

Successfully in cw operation since 2006 at INFN
A/q=8.5 (used up to 7)
5 uA cw current
Energy range 37-585 keV/u
Large modulation factor (m up to 3) and intervane voltage (up to 280kV)
Transmission 60% with external bunching
Operational since 2006
Built in Italy at INFN (Nb electrodes machining) and Zanon.



In operation since 2004

# RFQs general parameters

| | Name | Lab | ion | energy | vane voltage | beam current | power | RF Cu power | Freq. | length | | Emax | Power density ave | max | operate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | MeV/u | kV | mA | kW | kW | MHz | m | lambda | kilpat | W/cm$^2$ | W/cm$^2$ | |
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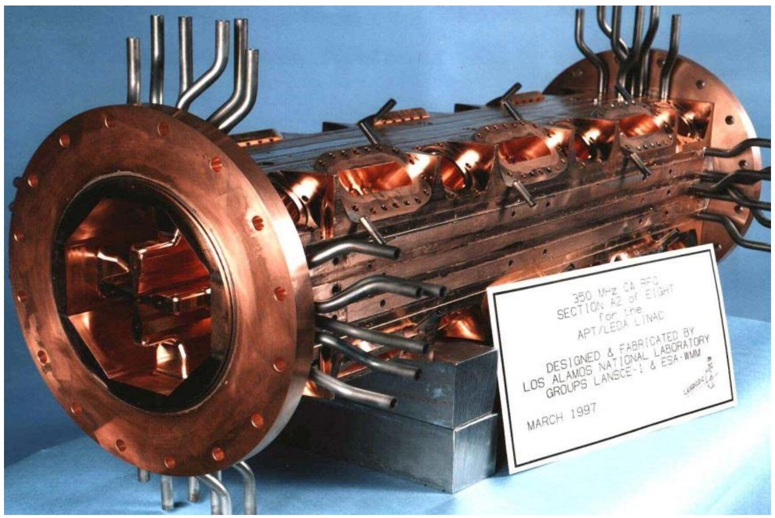
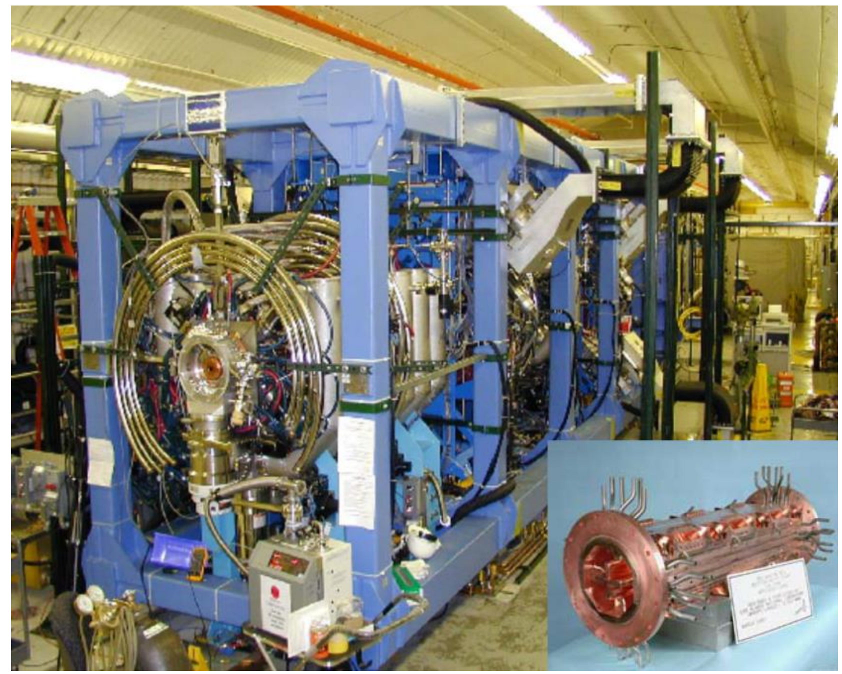
| pulsed | CERN linac 2 | CERN | p | 0.75 | 178 | 200 | 150 | 440 | 202 | 1.8 | 1.2 | 2.5 | | | YES |
| | SNS | LBNL | H- | 2.5 | 83 | 70 | 175 | 664 | 402.5 | 3.7 | 5.0 | 1.85 | 1.1 | 10 | YES |
| | CERN linac 3 | LNL | A/q=8.3 | 0.25 | 70 | 0.08 | 0.04 | 300 | 101 | 2.5 | 0.8 | 1.9 | | | YES |
| CW | LEDA | LANL | p | 6.7 | 67-117 | 100 | 670 | 1450 | 350 | 8 | 9.3 | 1.8 | 11.4 | 65 | YES |

# LEDA

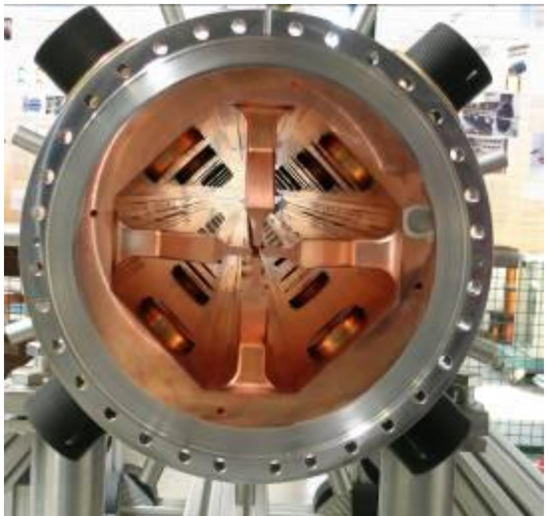



Technology established.
Beam performances reached
About 110 hrs of operating above 90 mA cw



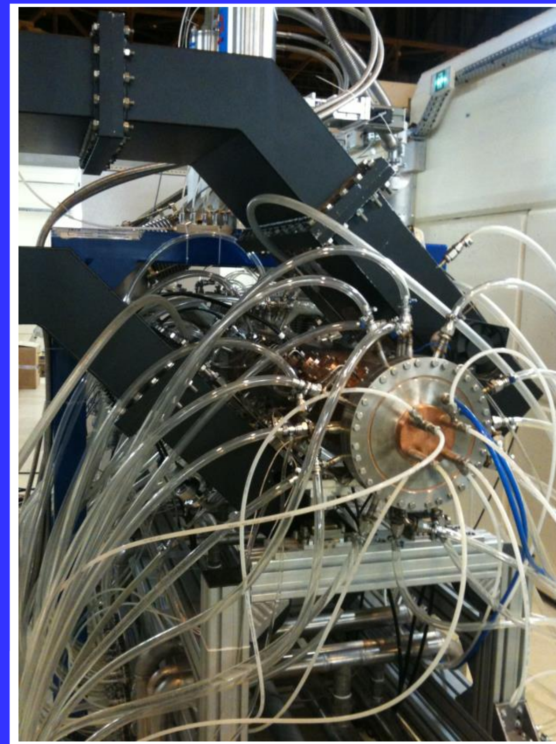
# TRASCO RFQ (developed for ADS studies)

| | Name | Lab | ion | energy | vane voltage | beam current | power | RF Cu power | Freq. | length | | Emax | Power density ave | max | operate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 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** | **NO** |
| CW | LEDA | LANL | p | 6.7 | 67-117 | 100 | 670 | 1450 | 350 | 8 | 9.3 | 1.8 | 11.4 | 65 | *YES* |
| | FMIT | LANL | d | 2 | 185 | 100 | 193 | 407 | 80 | 4 | 1.0 | 1 | 0.4 | | *YES* |
| high p | IPHI | CEA | p | 3 | 87-123 | 100 | 300 | 750 | 352 | 6 | 7.0 | 1.7 | 15 | 120 | *NO* |
| | TRASCO | LNL | p | 5 | 68 | 30 | 150 | 847 | 352 | 7.3 | 8.6 | 1.8 | 6.6 | 90 | *NO* |



TRASCO@LegnaroINFN

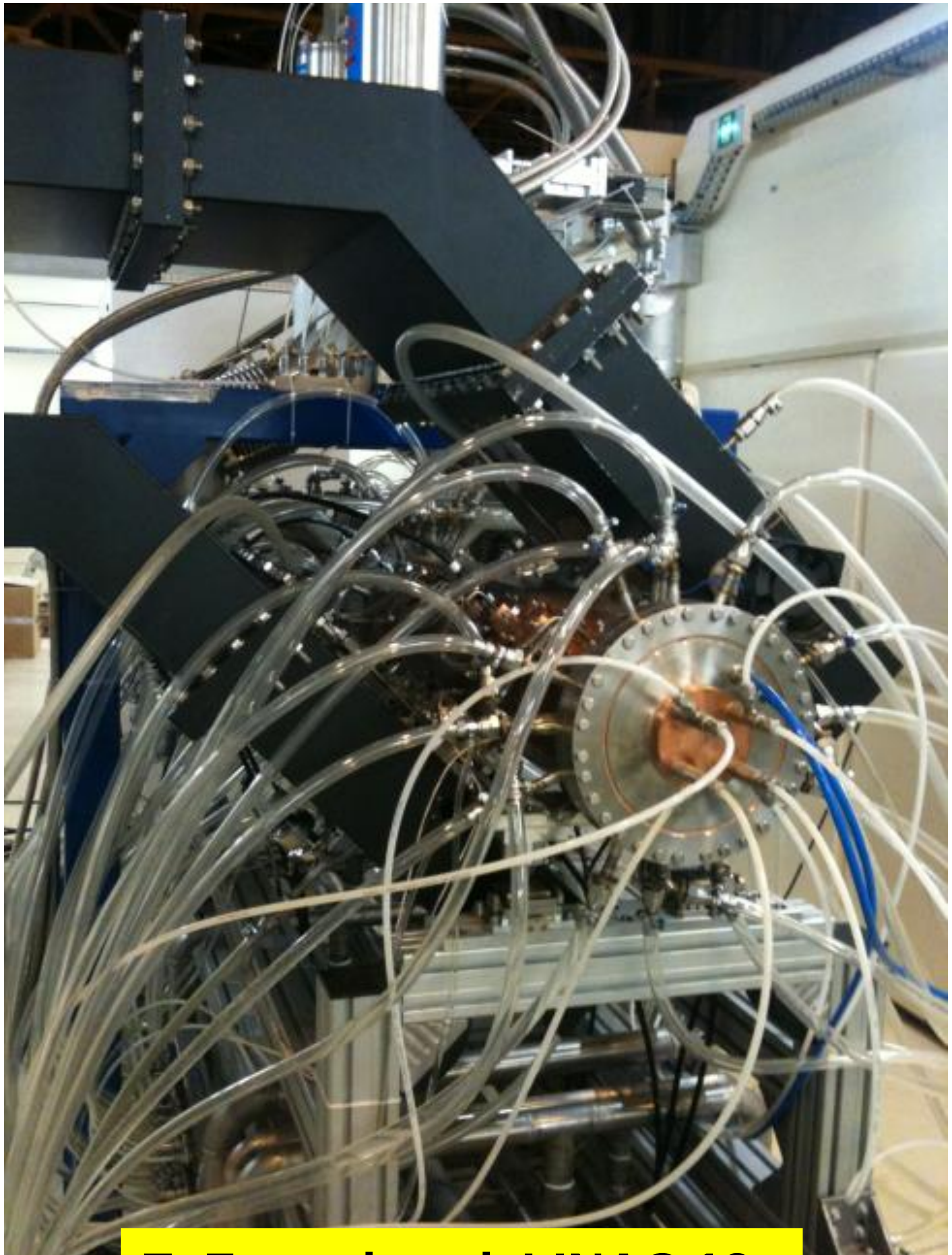
TRASCO RF tests @Saclay.CEA

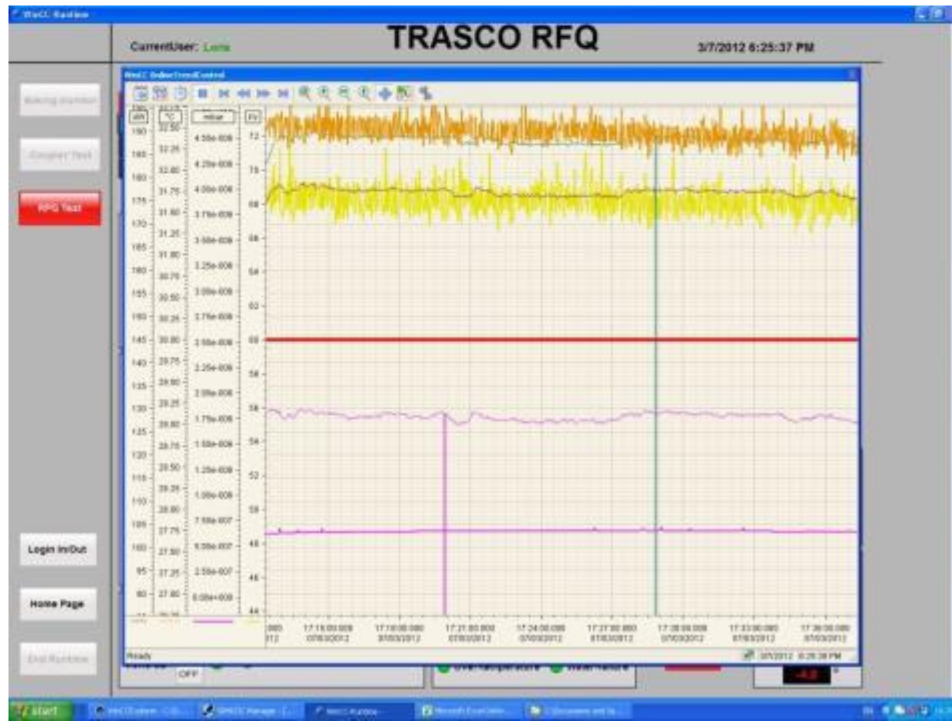


Tested up to 2 Ekp, 80 kW/m
100% duty cycle

# RFQ of TRASCO stable condition cw

## nominal field
## 80kW/m, 1.8 Ekp

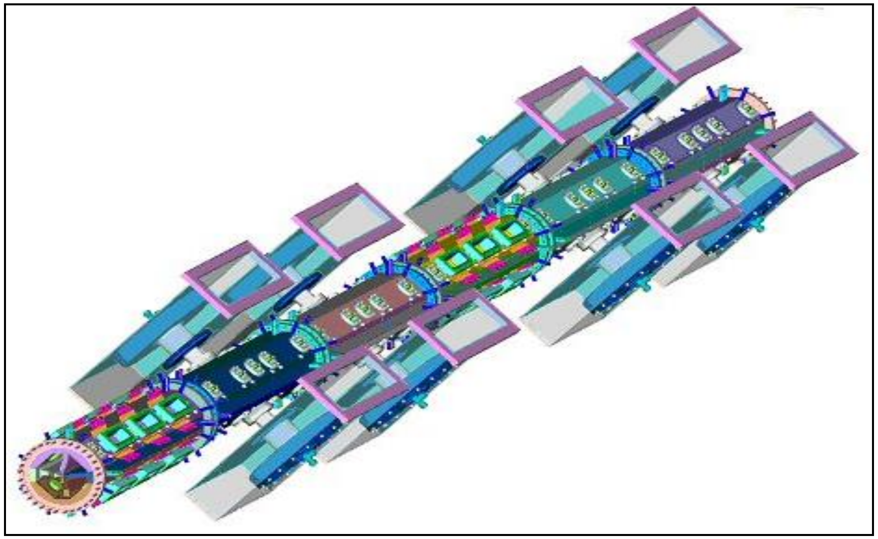





E. Fagotti et al, LINAC 12

# With MUNES new applications need new technologies

Eight independent 125 kW amplifiers (one per RF coupler) are coming (5 amplifiers available in 2015, tender concluded last week). Each amplifier needs 3 racks as in the following scheme (including power supply)

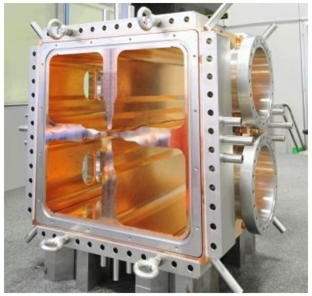


*Advantages respect to a klystron*

- *Lower operating costs (cost and duration of components)*
- *Availability e reliability (no stop operation in case of components failure)*
- *Absence of high voltages very important for the operation in a hospital*

# IFMIF RFQ project

# IFMIF EVEDA RFQ system organization



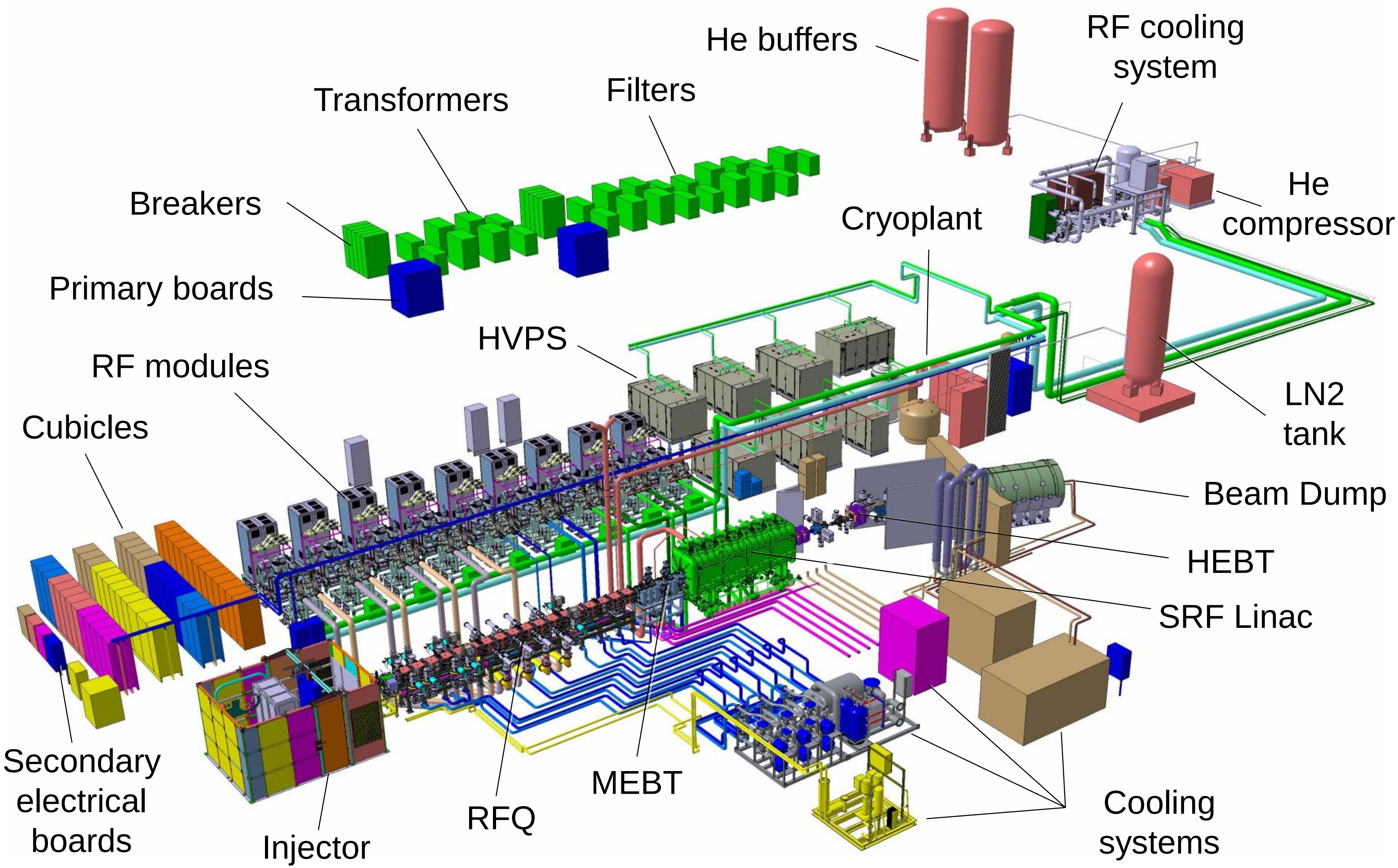
- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti

**About** 30 **persons involved,** 20 **FTE,** 10 **dedicated contracts, dedicated funds from MIUR of about 25M€**

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

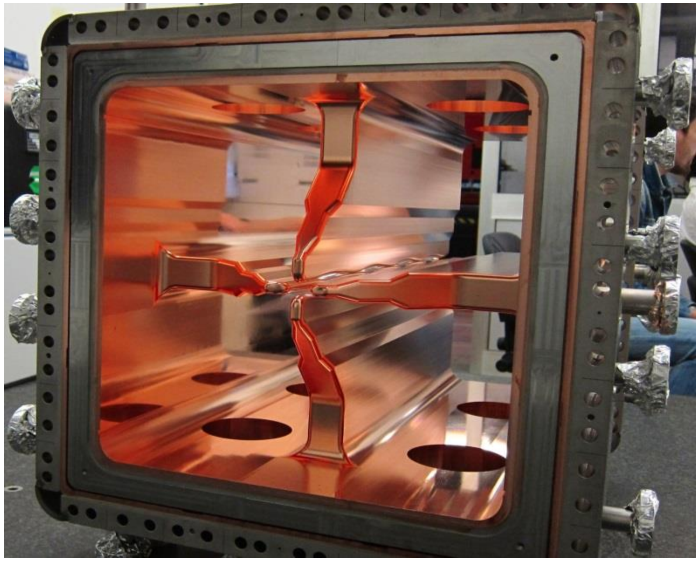

INFN organization

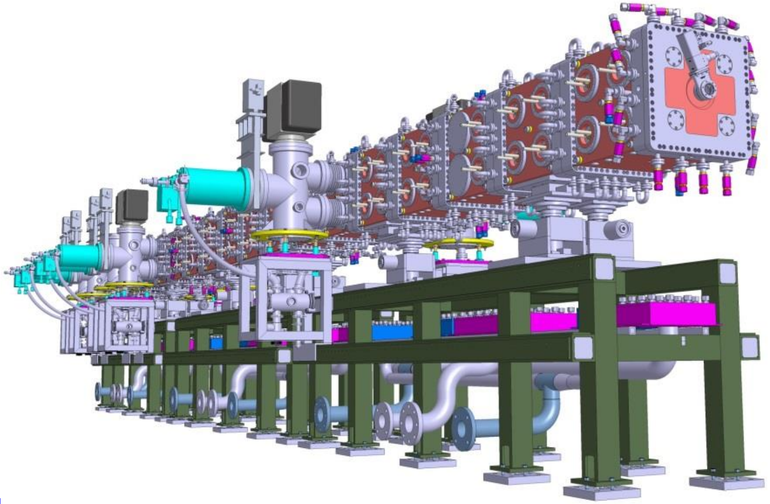



Accelerator system 3D Mock-up status D. Gex

# 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
  - High energy SM in construction at Cinel, Padua (Italy), Intemediate energy in INFN Padova, Low energy by RI Koln (Germany)
- At present and **we are in the production of the modules** phase and ready for for partial test at full power





# Modules construction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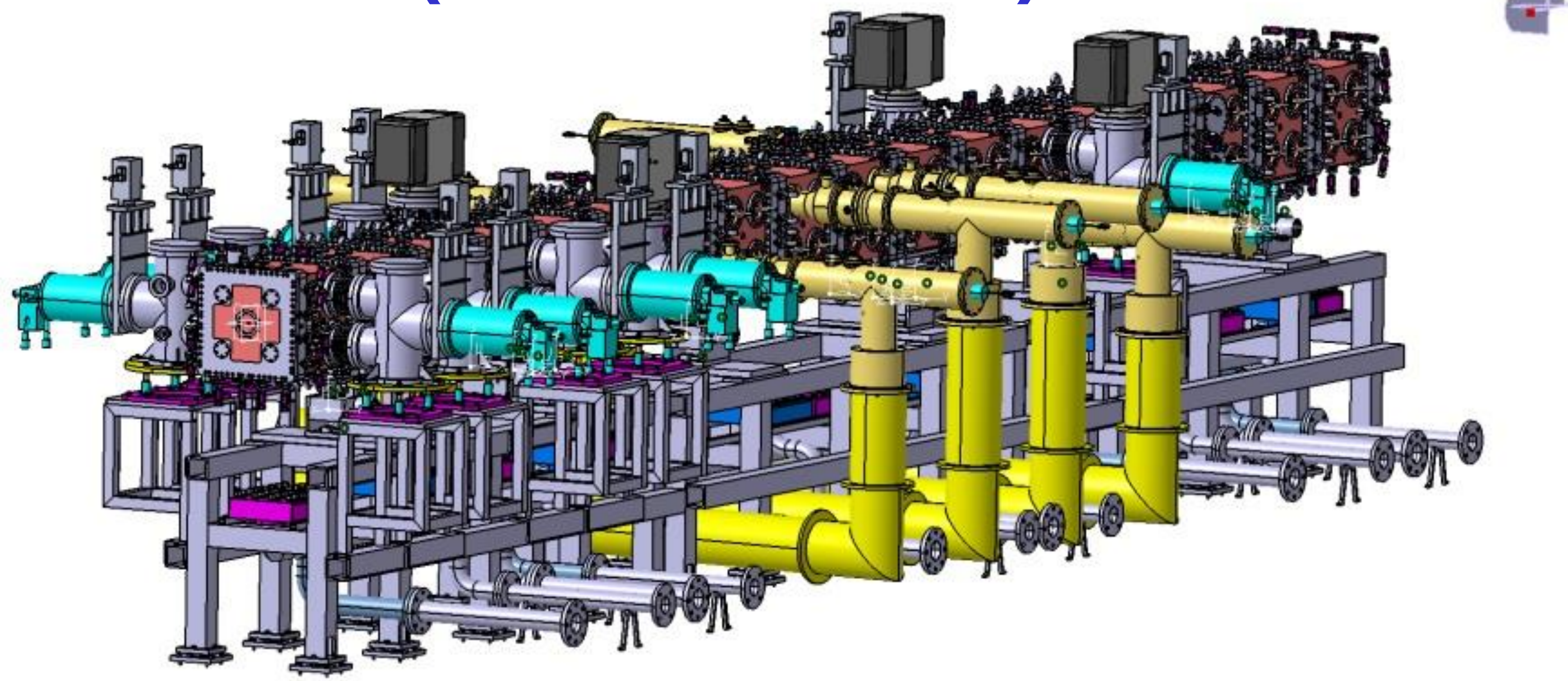
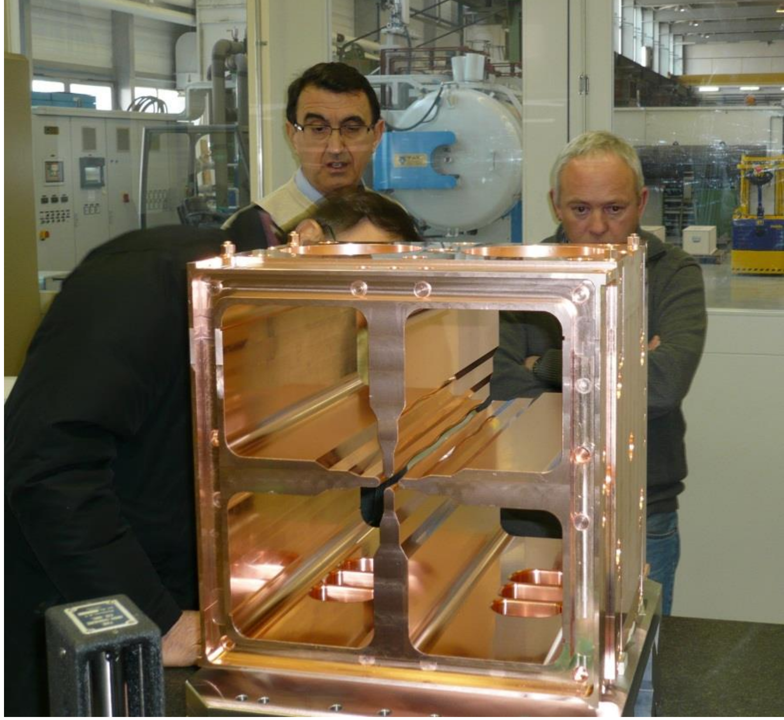
# RF cavities built in three supermodules (6 modules each)



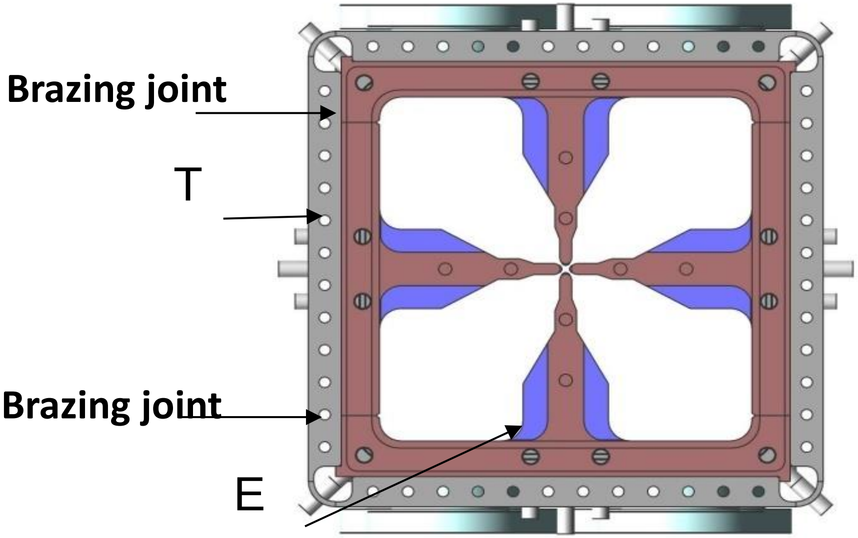
- High energy SM in construction at Cinel, Padua (Italy), Intemediate energy in INFN Padova, Low energy by RI Koln (Germany)

# Mechanical design

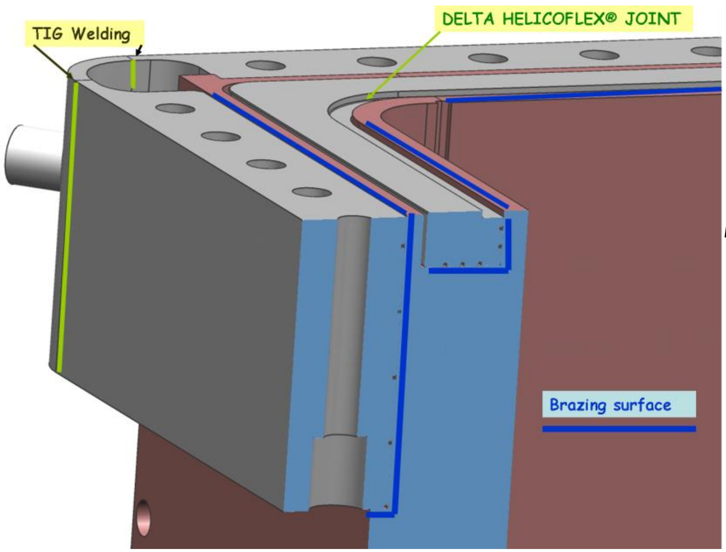
- **Based on vacuum brazing, LNL mechanical experience with TRASCO,** CERN experience for RFQ brazing, design compatible with oven at CERN, LNL and in industry;
- Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass 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 will be performed, by using a EDM (wire electroerosion).
- The accelerator is composed by 18 of these modules.



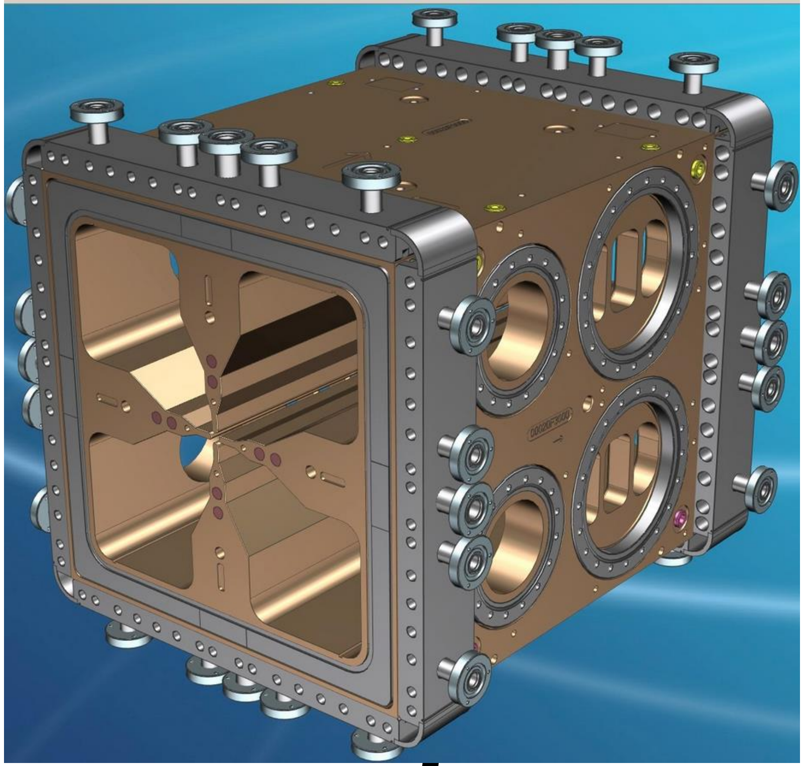
**Prototype before brazing at CERN**

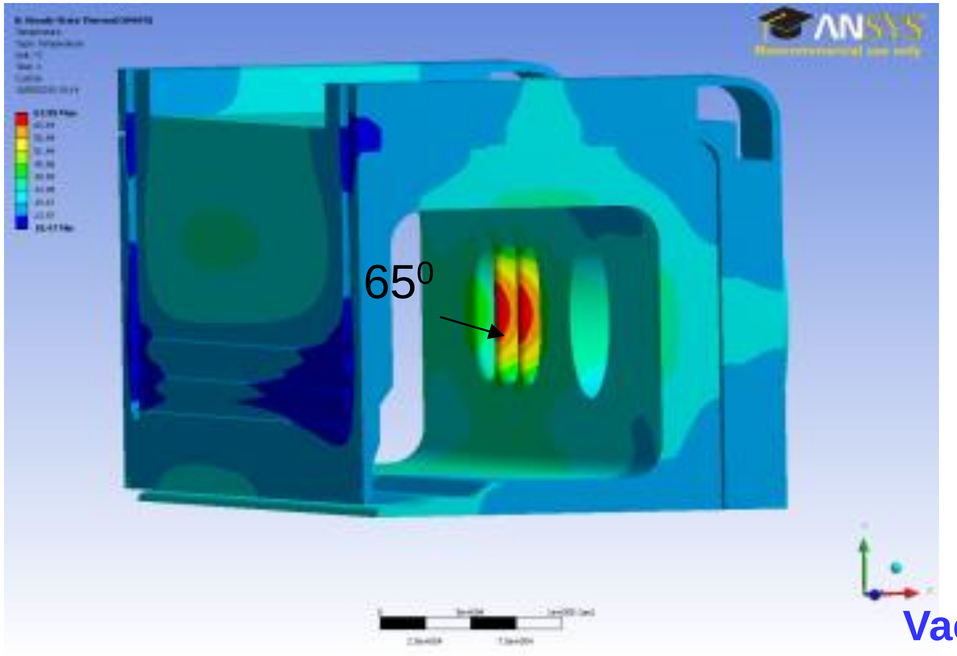


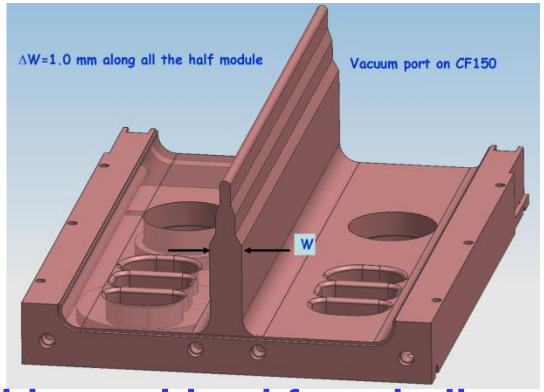
# Mechanics details




## Head flange



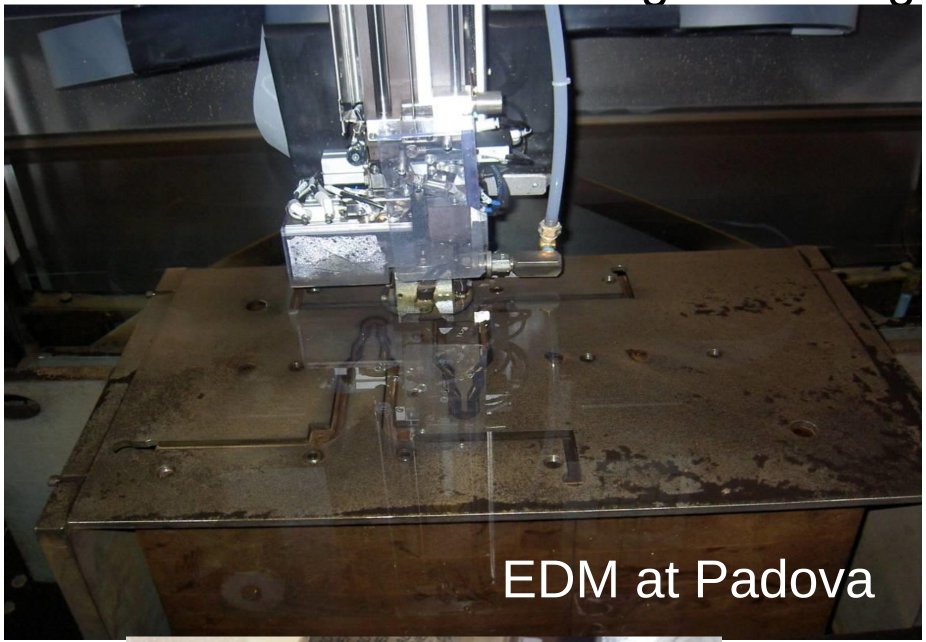



## Vacuum grids machined from bulk

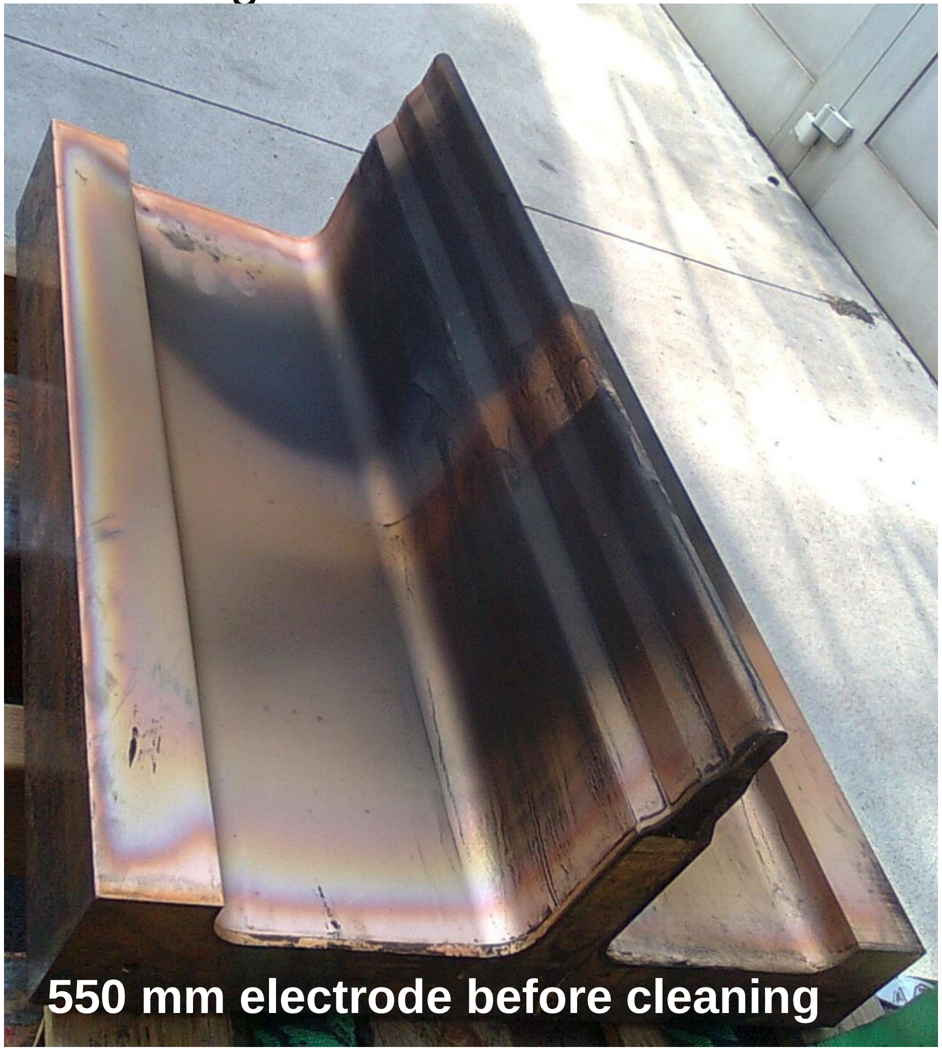
# First construction step module n0 16

- 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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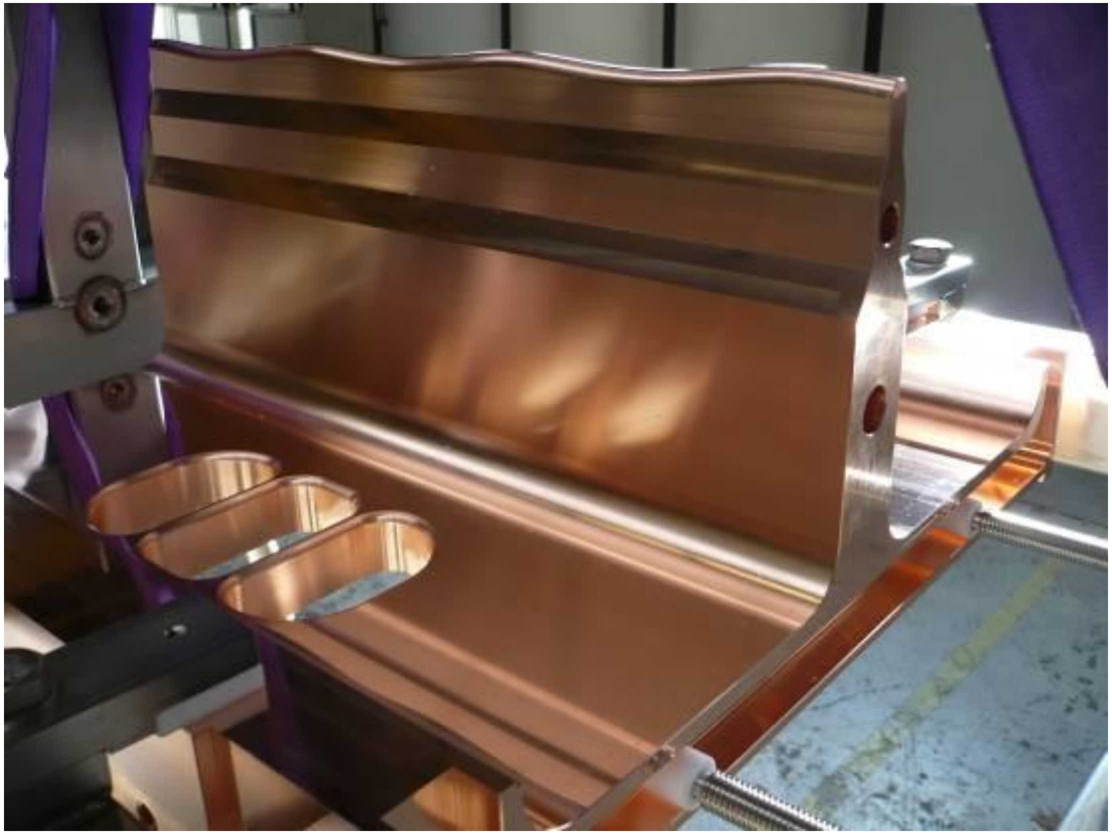
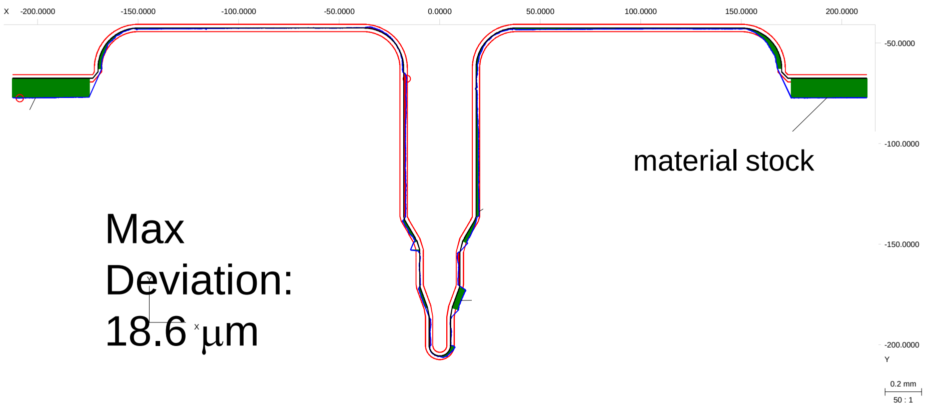
# Finishing

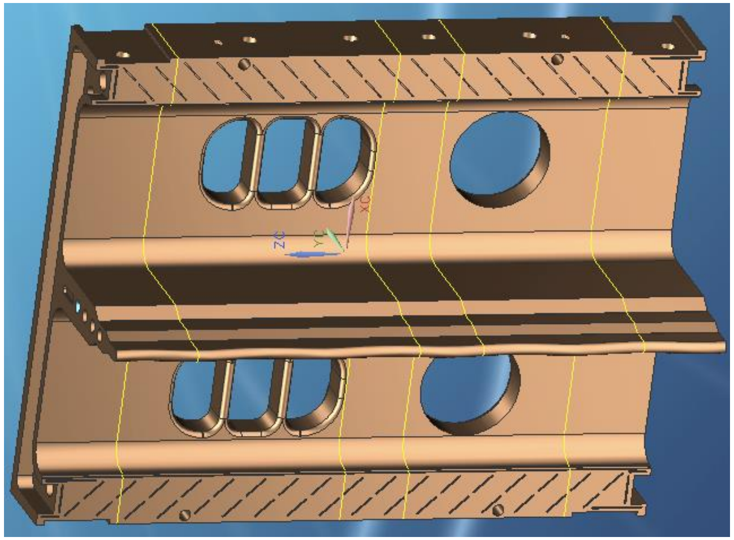
- 0.7 um roughness
- 3d modulation
- 20 um tolerances on vane tip geometry

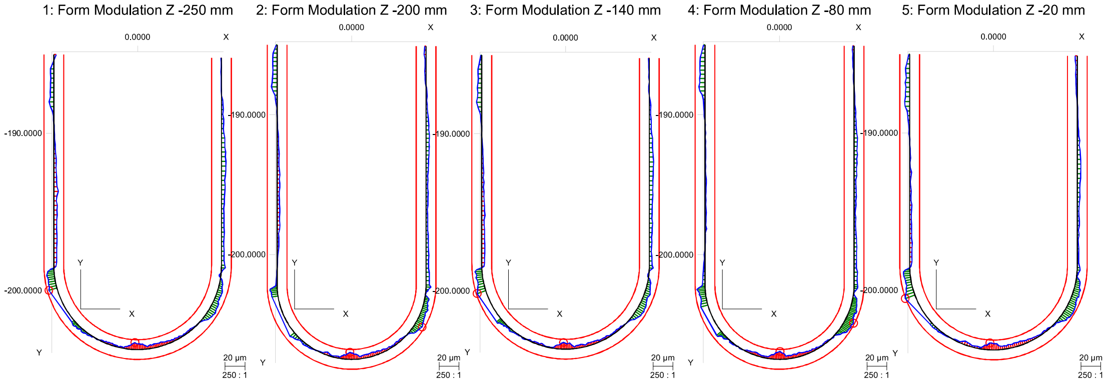


# Four electrodes of module #16 electrodes (machined by Cinel) in specs

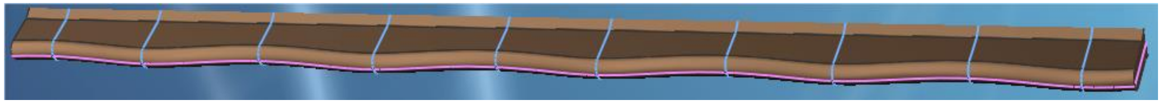



Max Deviation: 18.6 μm

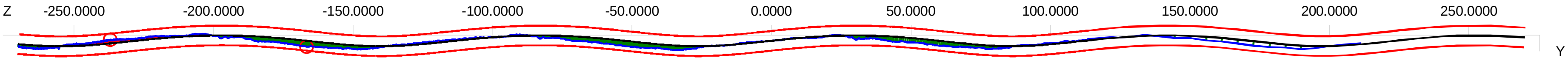





Max Deviation: 10.5 μm



Max Deviation: 6.1 μm



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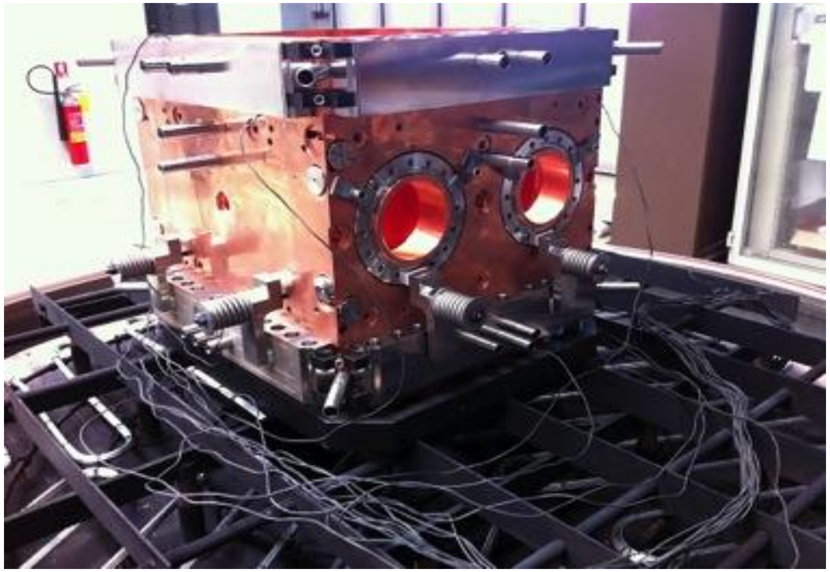
# INFN development for Brazing

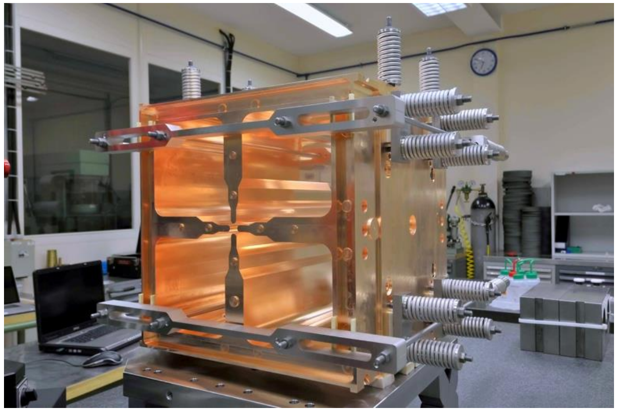
Necessary for the large production (18 modules could not be done at CERN).

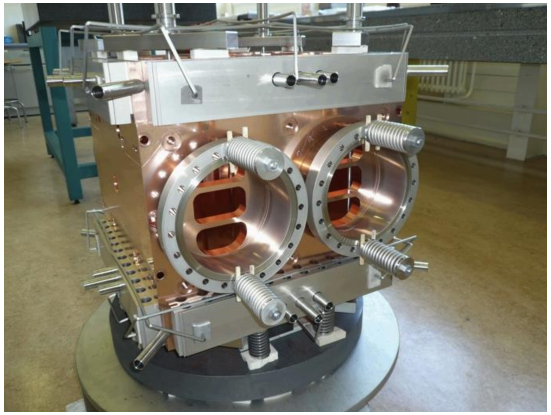
Vacuum oven in INFN LNL



# Report: Technological prototype results (Brazed at CERN 2010)

Two phases brazing procedure: 1st horizontal, 2nd vertical





| | | |
|---|---|---|
| mean $\Delta R0$ | [μm] | 66.83 |
| $\partial f/\partial R0$ | [kHz/ μm] | 7.60 |
| $\Delta f$ (calc) | [kHz] | 507.87 |
| $\Delta f$ (exp) | [kHz] | 510.00 |

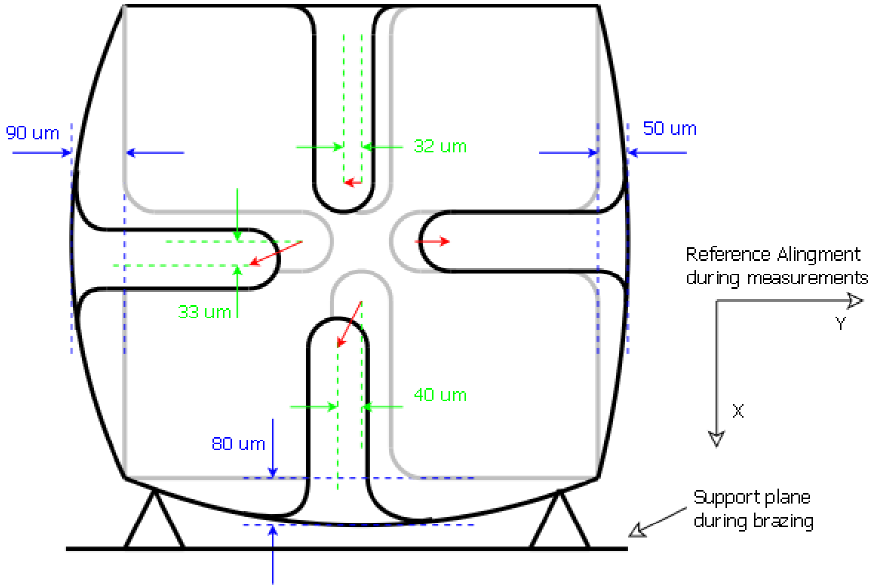
**LEAK TEST PASSED**

The test did not show any variation of the helium sensor from the background level that was 5 x $10^{-10}$ mbar-lt/s.

**DIMENSIONAL TEST**

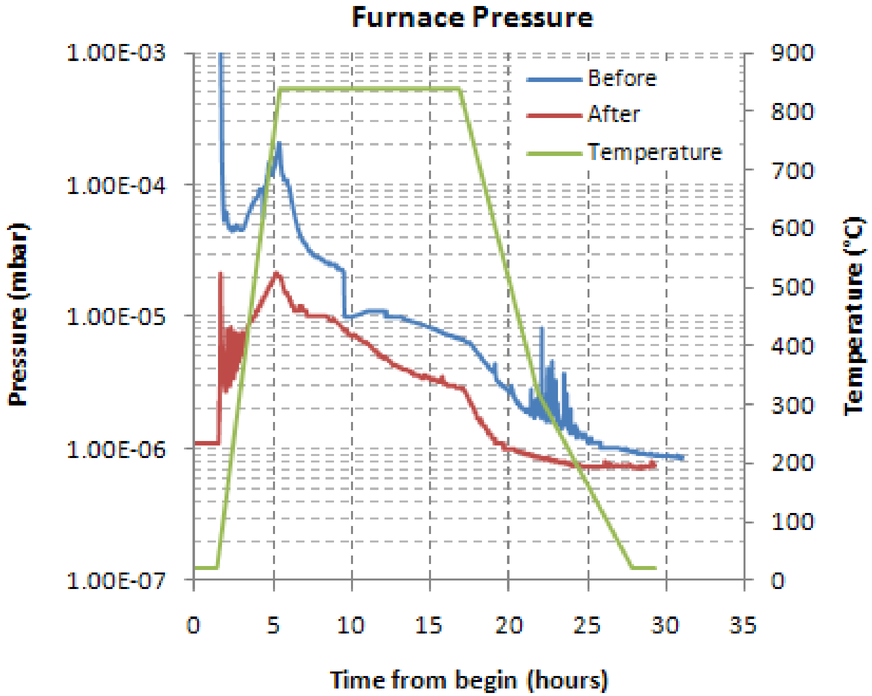
The displacement corresponds to a beam axis with coordinates (-36 um, -20 um), to a maximum displacement respect to bam axis of 88 um (for the electrode at right in the figure) and to an average displacement of 56 um (for the four vane tips).

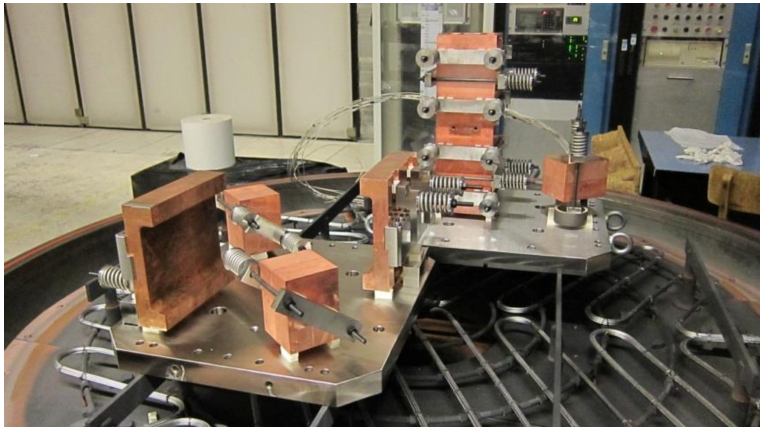
Effect of *Horizontal* Brazing

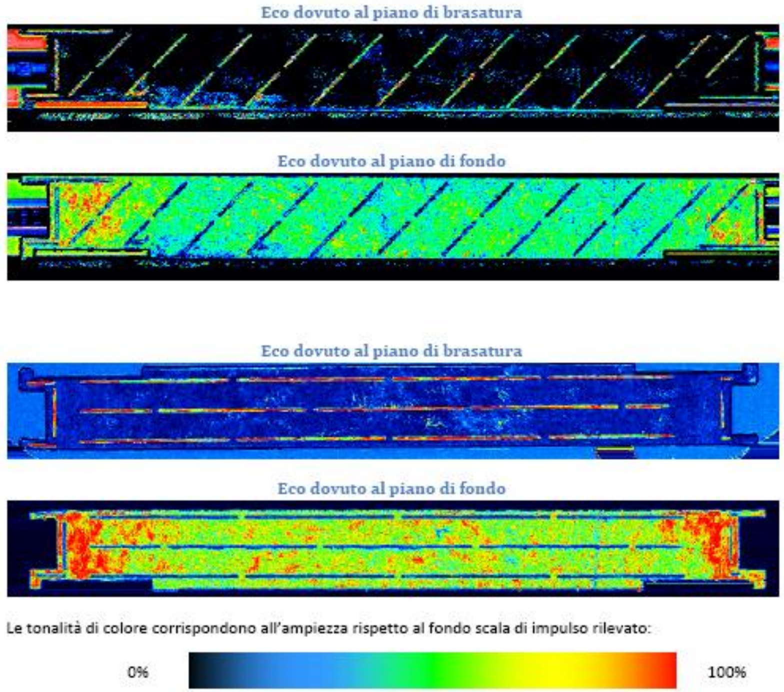


# Brazing at LNL (1/2)

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

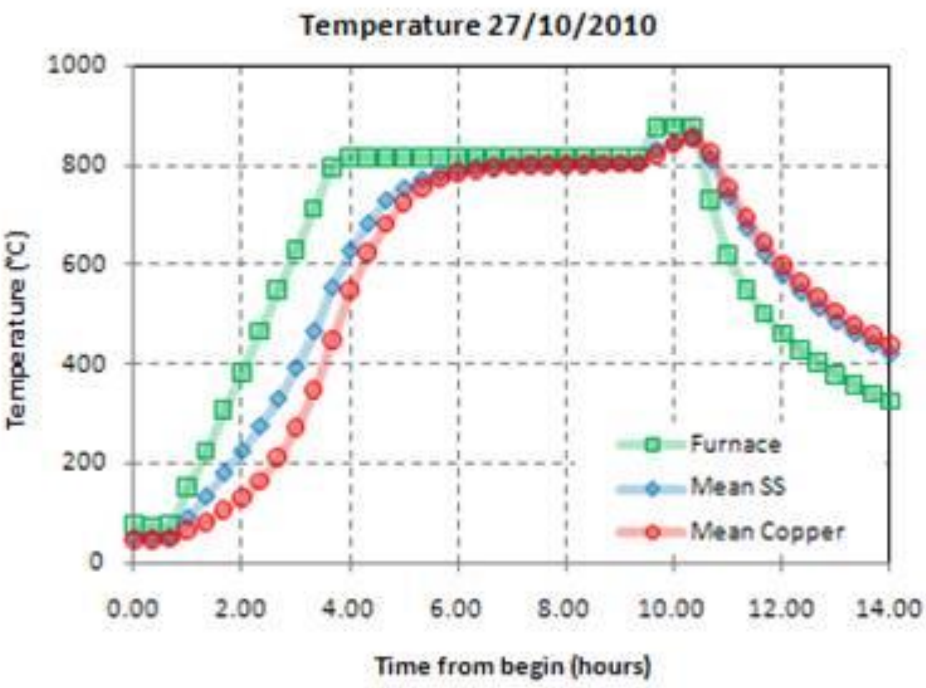


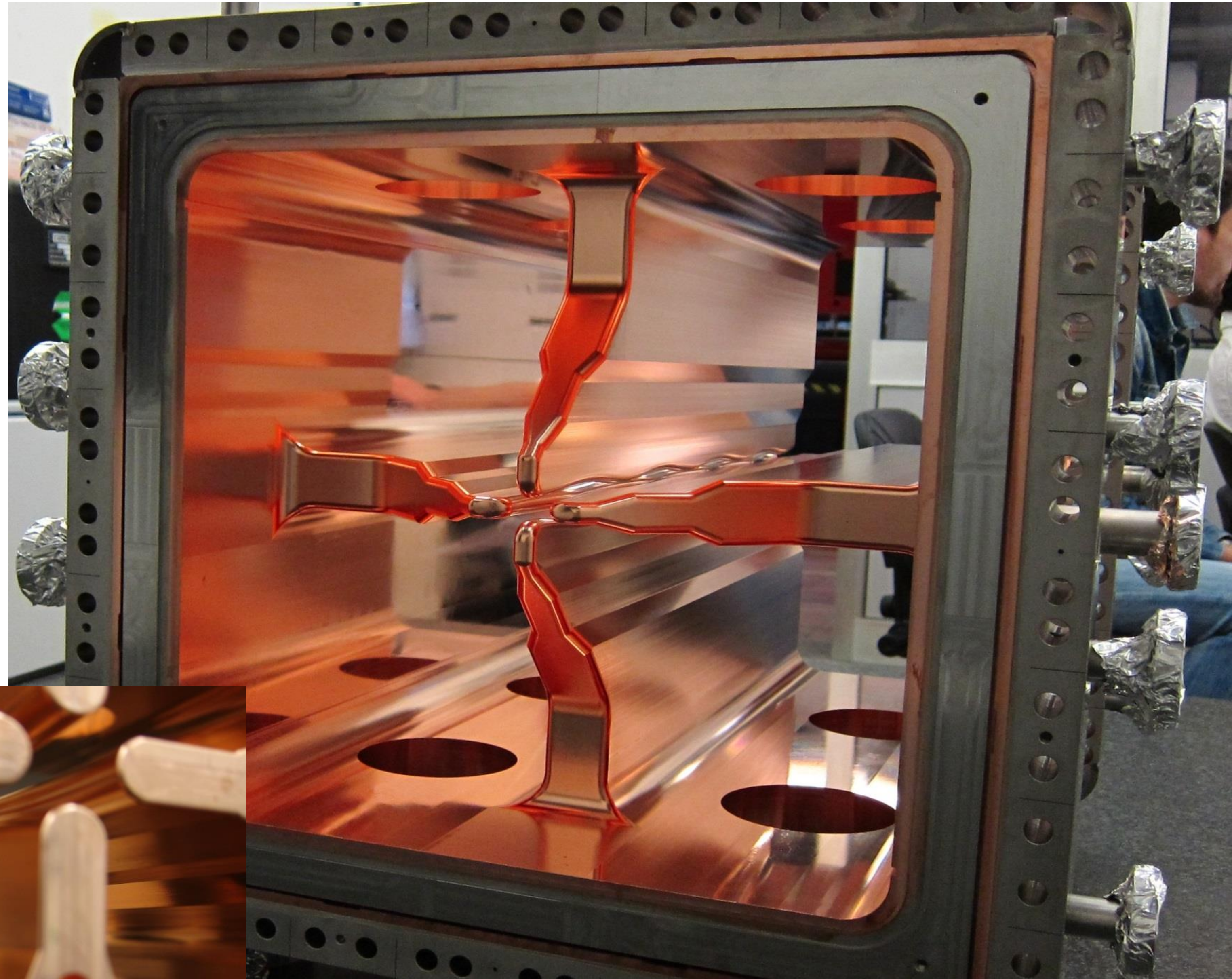


# Brazing at LNL (2/2)

- Chemical preparation
- Brazing




# Module 18 by Cinel (single brazing, perfect!)



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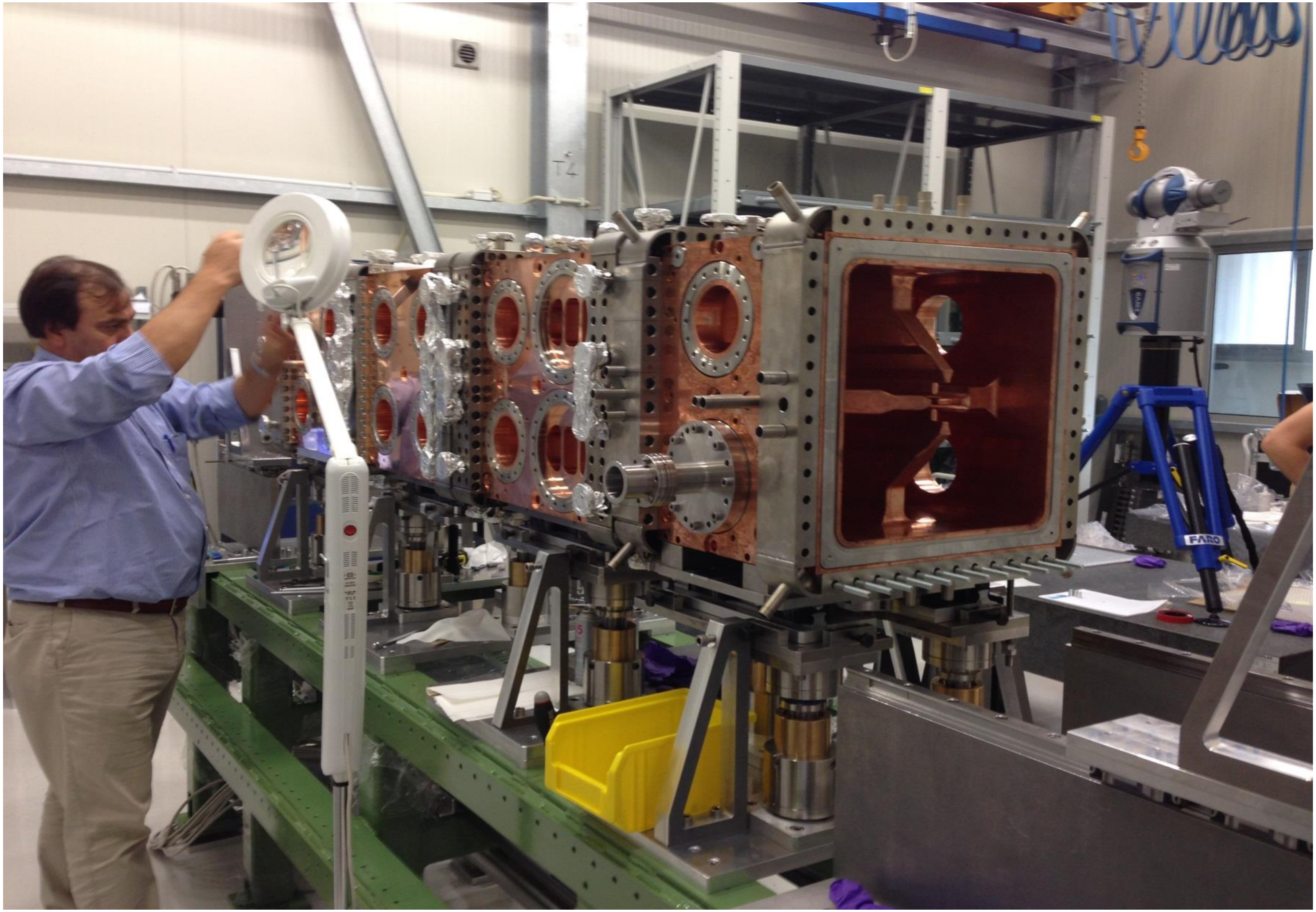
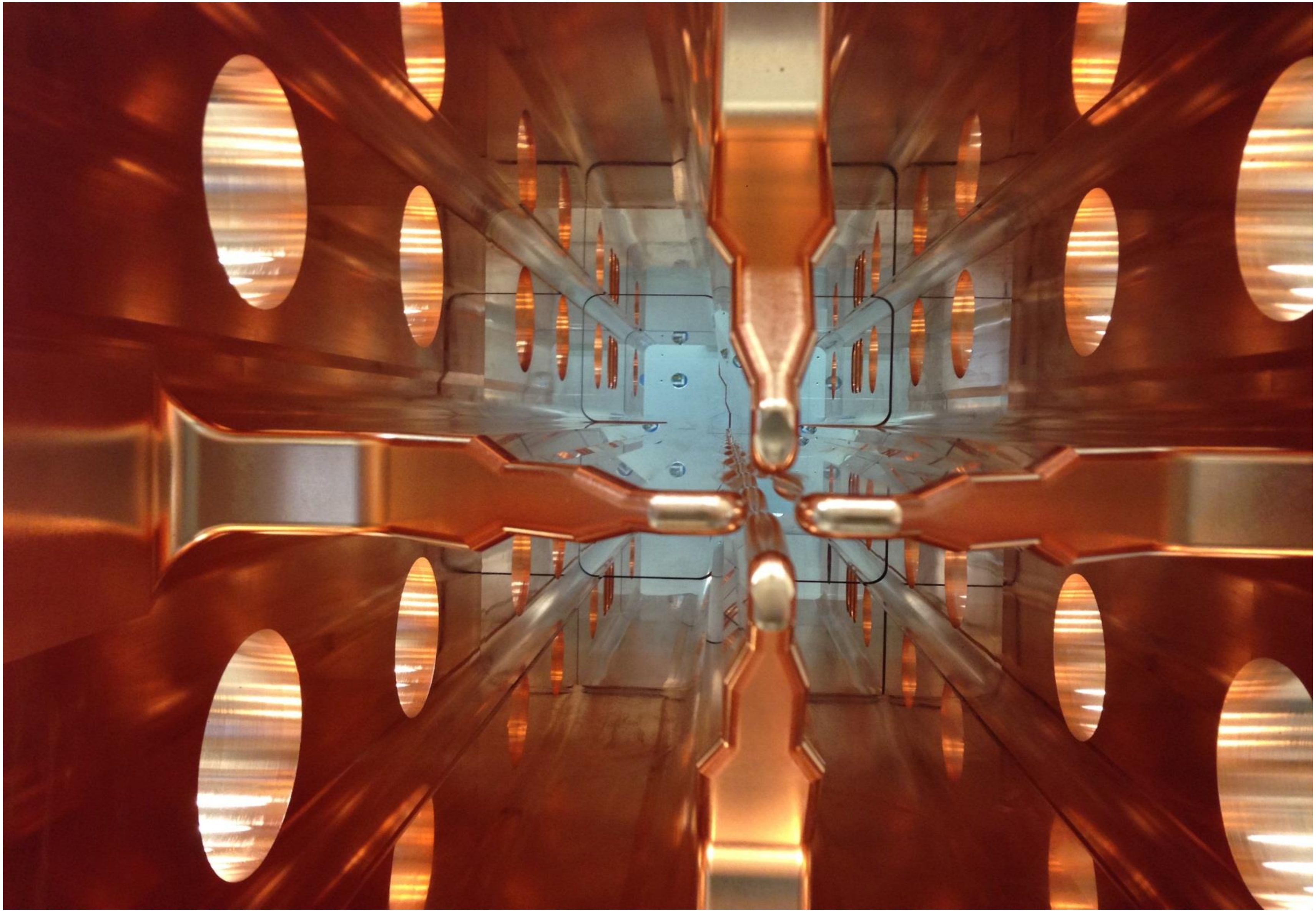
# RFQ alignment (outside view)



# RFQ alignment (inside view)

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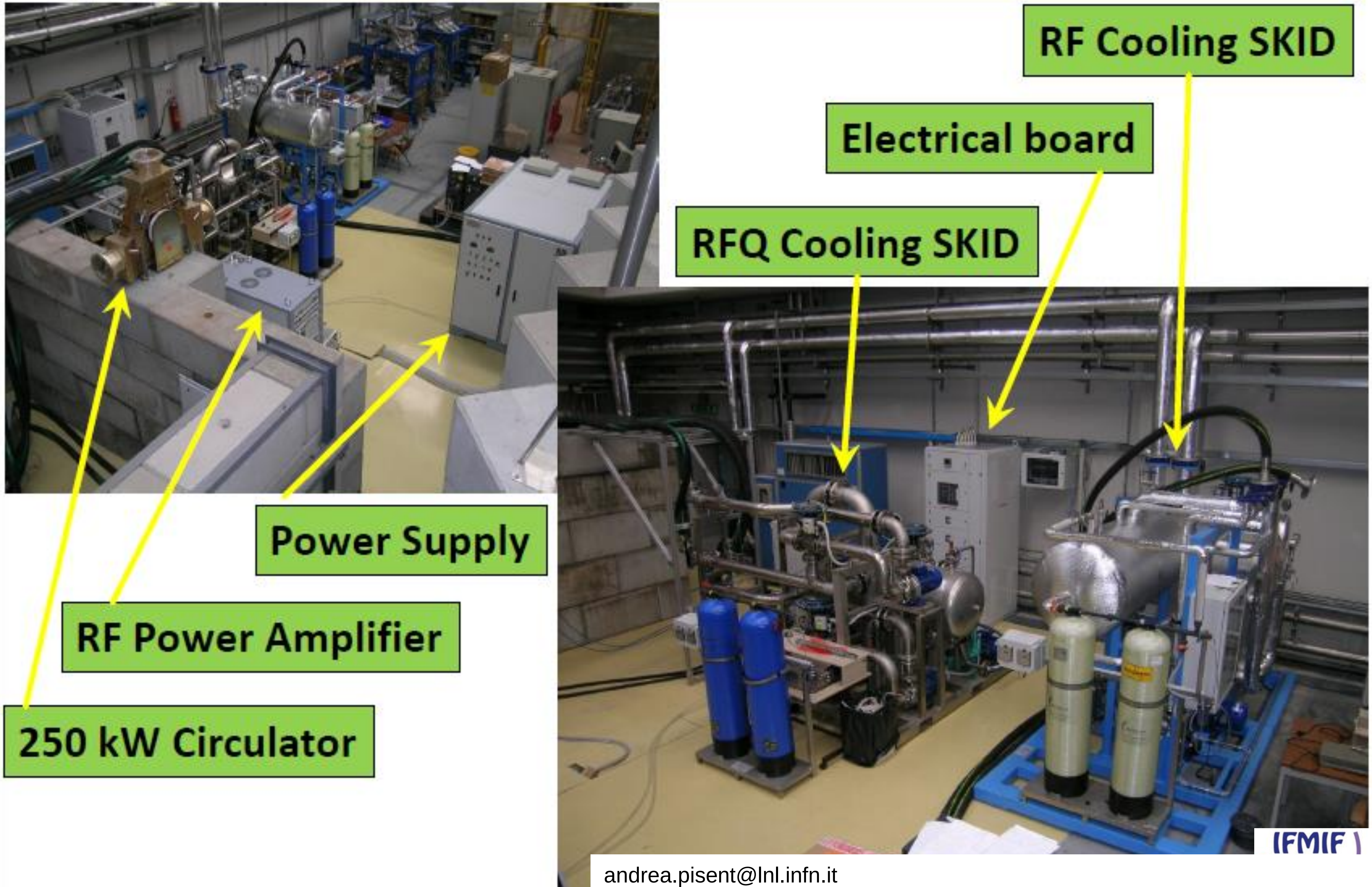
# High power test stand in Legnaro (220 kW cw)



# Status of module production

- High energy supermodule (Cinel): complete except brazing of M13 completed March 14
- Low energy supermodule (INFN):  M2 brazed, the others machined in parallel, completion June 14
- Intermediate energy supermodule (RI); M12 assembled will be brazed next week, the others machined sequentially, completion November 14
- RFQ delivery to Rokkasho end 2014
- 2015 we shall be in Japan for beam commissioning.