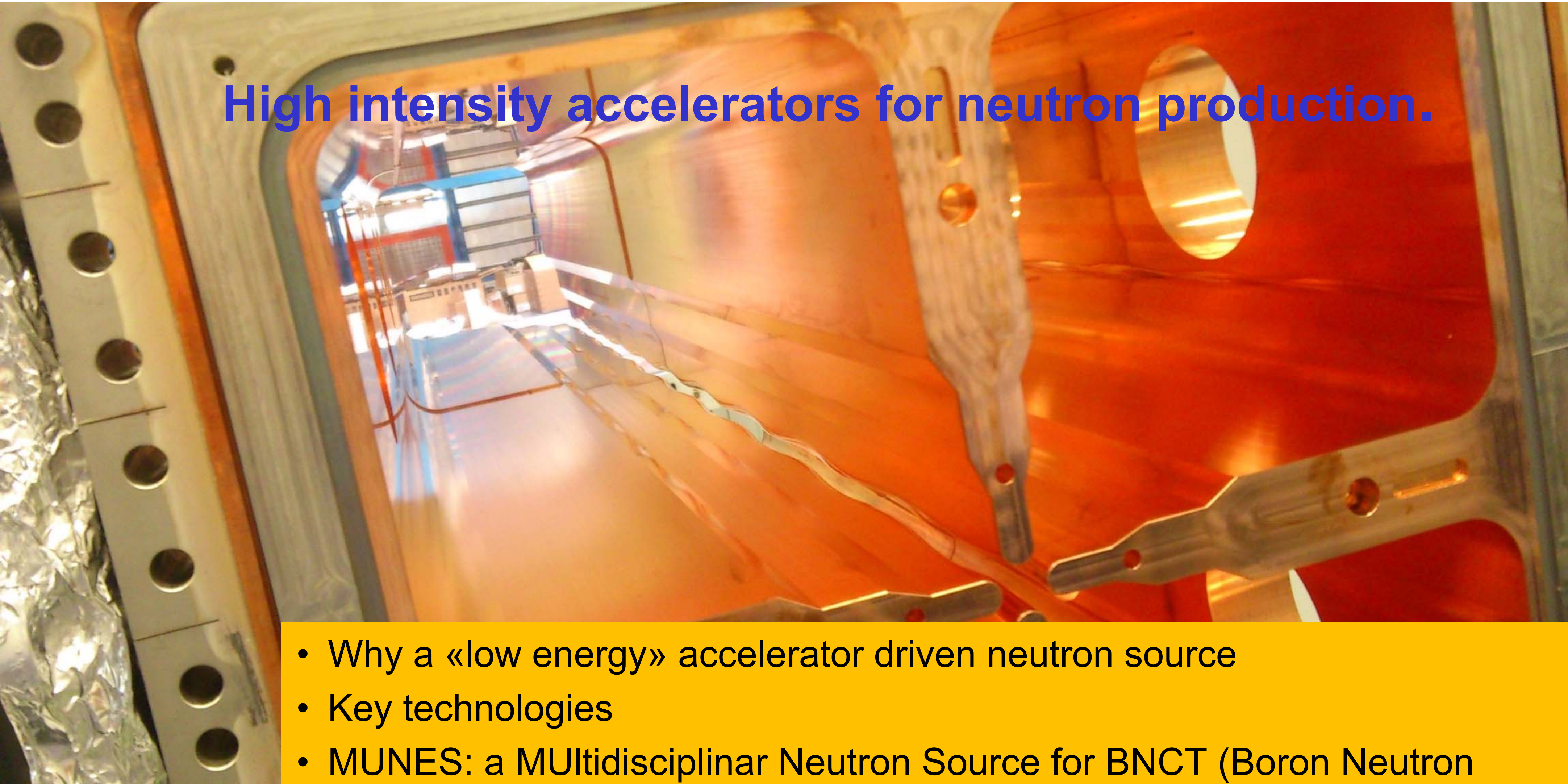
High intensity accelerators for neutron production.

A. Pisent- INFN Laboratori Nazionali di Legnaro

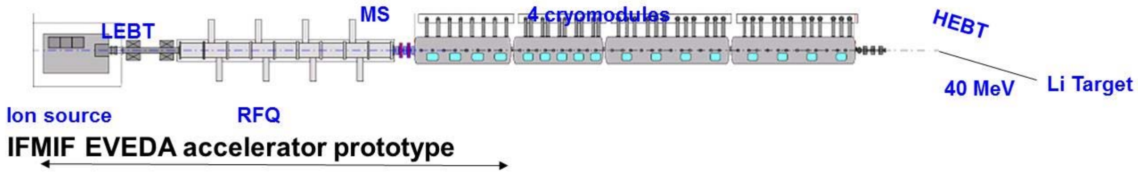
High intensity accelerators for neutron production.



- Why a «low energy» accelerator driven neutron source
- Key technologies
- MUNES: a MUltidisciplinar Neutron Source for BNCT (Boron Neutron Capture Therapy) and Nuclear Waste characterization in Italy. Applications
  - Advanced cancer treatments (BNCT)
  - Nuclear waste characterization (classification of nuclear waste barrels for disposal, determination of very low quantity of Pu)
- IFMIF, the international facility for the irradiation of fusion materials

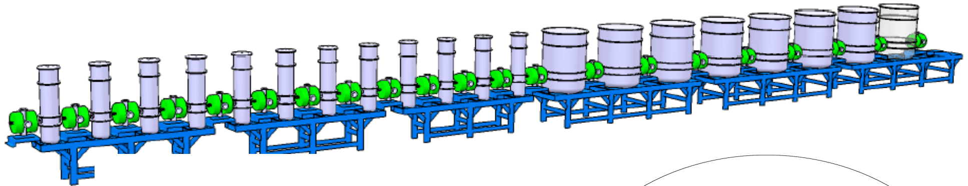
Examples of high intensity linacs

IFMIF EVEDA (EU-JA) 9 MeV
130 mA d. 175 MHz
IFMIF 2*130 mA at 40 MeV

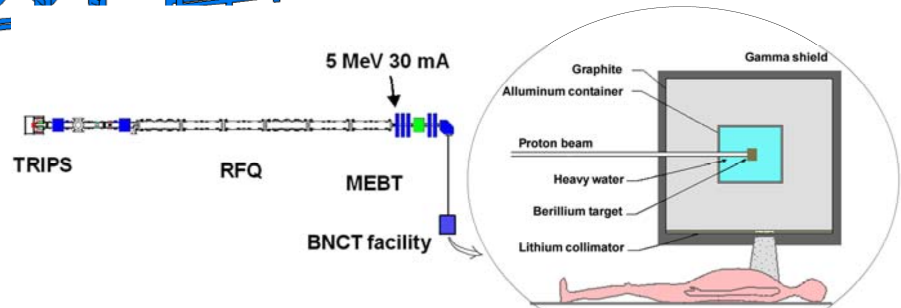


SARAF (Israel) 40 MeV
4 mA d and p. 176 MHz

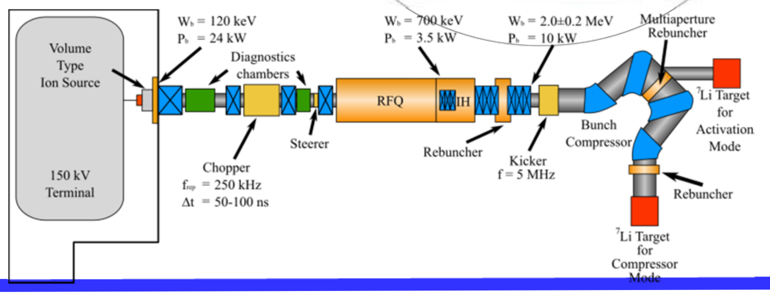
SPIRAL2 driver (France)
5 mA d and ions up to A/q=3
40 MeV 80 MHz



MUNES (LNL) 5 MeV
30 mA p 352.2 MHz

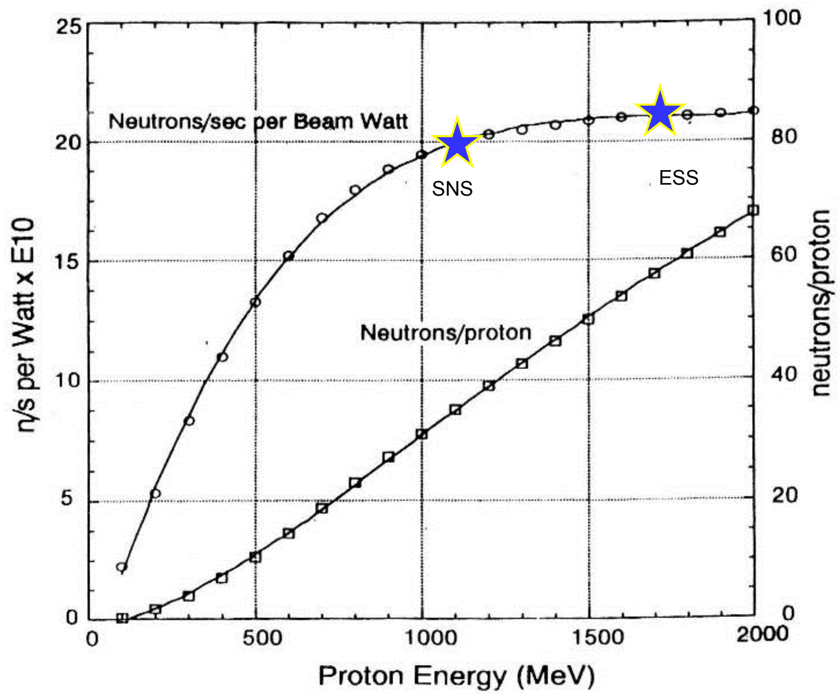


FRANZ (Germany)
p 175 MHz



Neutron sources

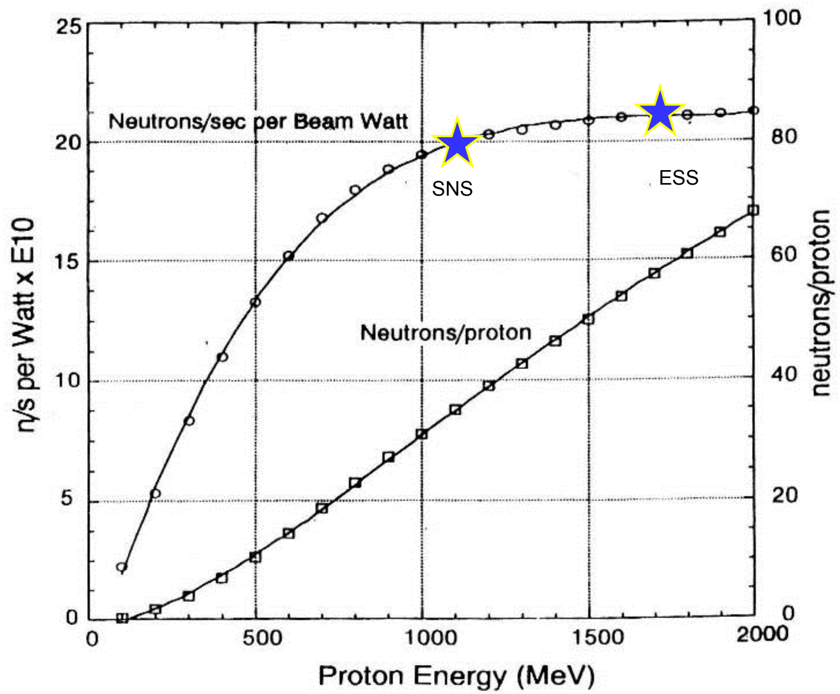
- Most used neutron sources are
  - Research reactors (critical reactors with a large external flux)
  - Spallation sources (p accelerators above 600 MeV)



Spallation production
(W solid target)

Neutron sources

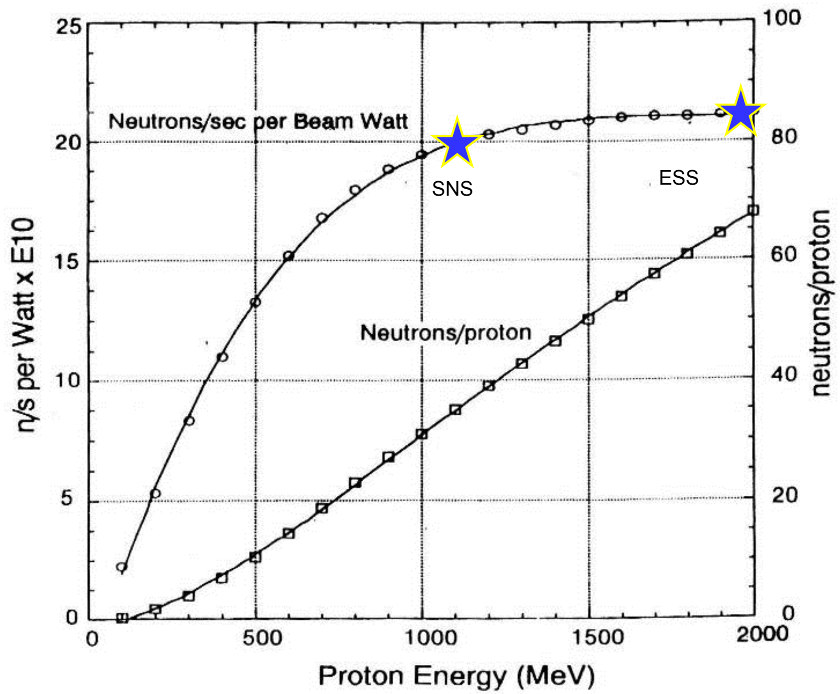
- Most used neutron sources are
  - Research reactors (critical reactors with a large external flux)
    - Energy to be dissipated (in the core) about 200 MeV per neutron produced
  - Spallation sources (p accelerators above 600 MeV)
    - Energy to be dissipated (in the production target) About 30 MeV per neutron produced



Spallation production
(W solid target)

Neutron sources

- Most used neutron sources are
  - Research reactors (critical reactors with a large external flux)
    - Energy to be dissipated (in the core) about 200 MeV per neutron produced
  - Spallation sources (p accelerators above 600 MeV)
    - Energy to be dissipated (in the production target) About 30 MeV per neutron produced
  - Low energy accelerator sources (d linac 40 MeV, p linacs 3-5 MeV)
    - Energy to be dissipated (in the production target) About 600 MeV per neutron produced for d at 40 MeV and 9 GeV per neutron produced for 5 MeV p on beryllium

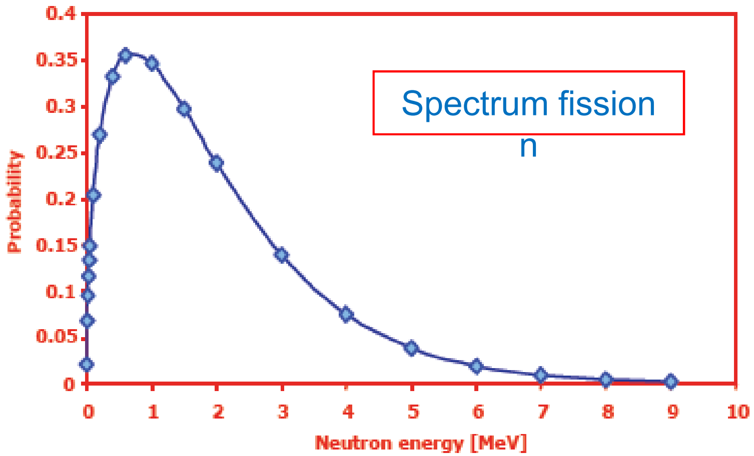


Spallation production (W solid target)

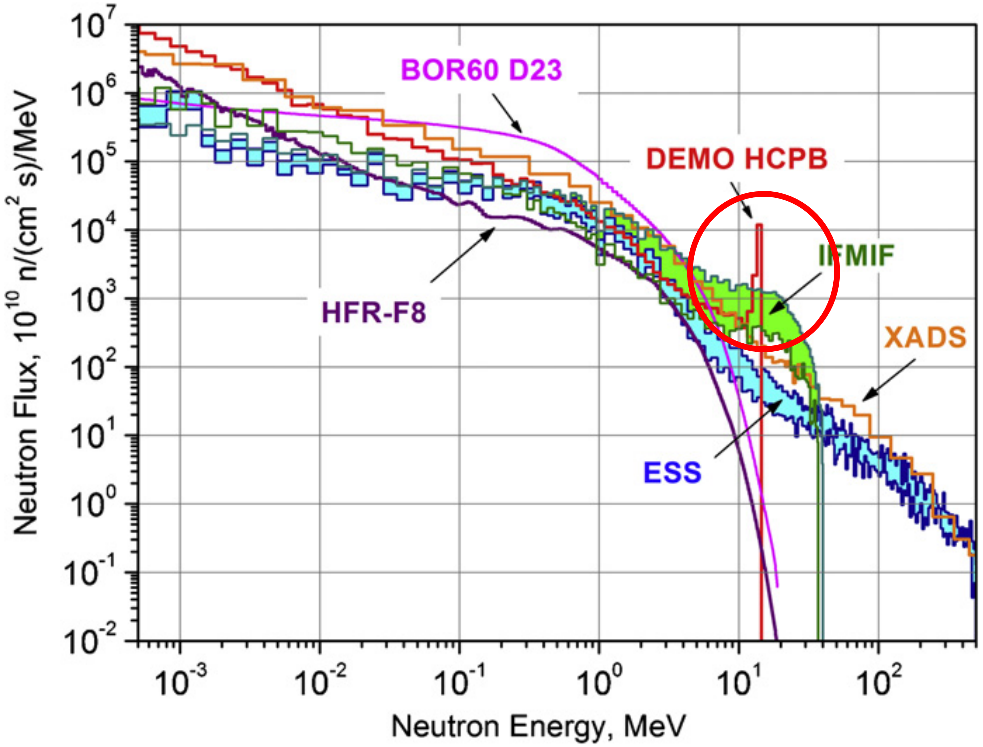
A specific source is needed to simulate DEMO

- The accumulation of gas in the materials lattice is intimately related with the neutron energy
- $^{54}Fe(n,\alpha)^{51}Cr$
- (incident n threshold at **2.9 MeV**)
- and
- $^{54}Fe(n, p)^{54}Mn$
- (incident n threshold at **0.9 MeV**)

- Swelling and embrittlement of materials takes place



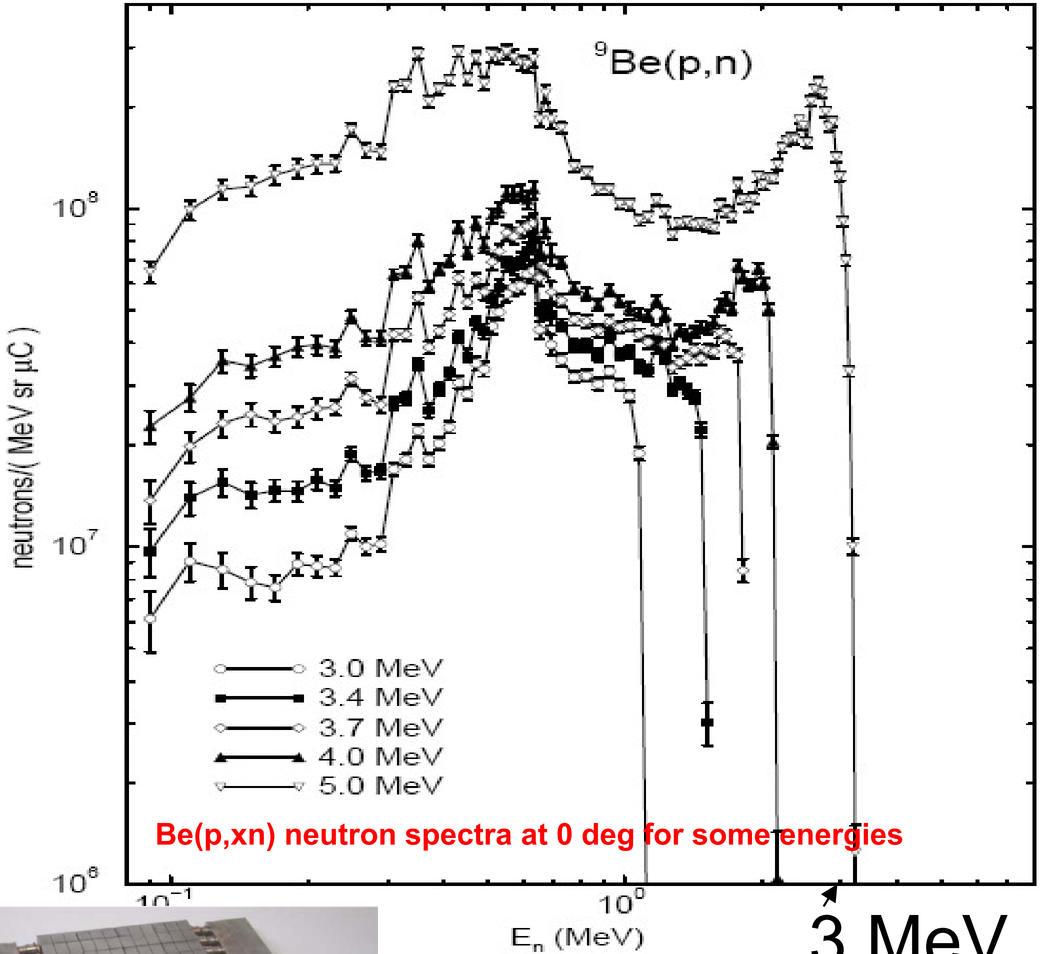
Neutron flux compared with DEMO's in available and planned neutron sources



Steven J. Zinkle, A. Moeslang, *Evaluation of irradiation facility options for fusion materials research and development*, Nuclear Engineering & Design, pre-printed (2013)

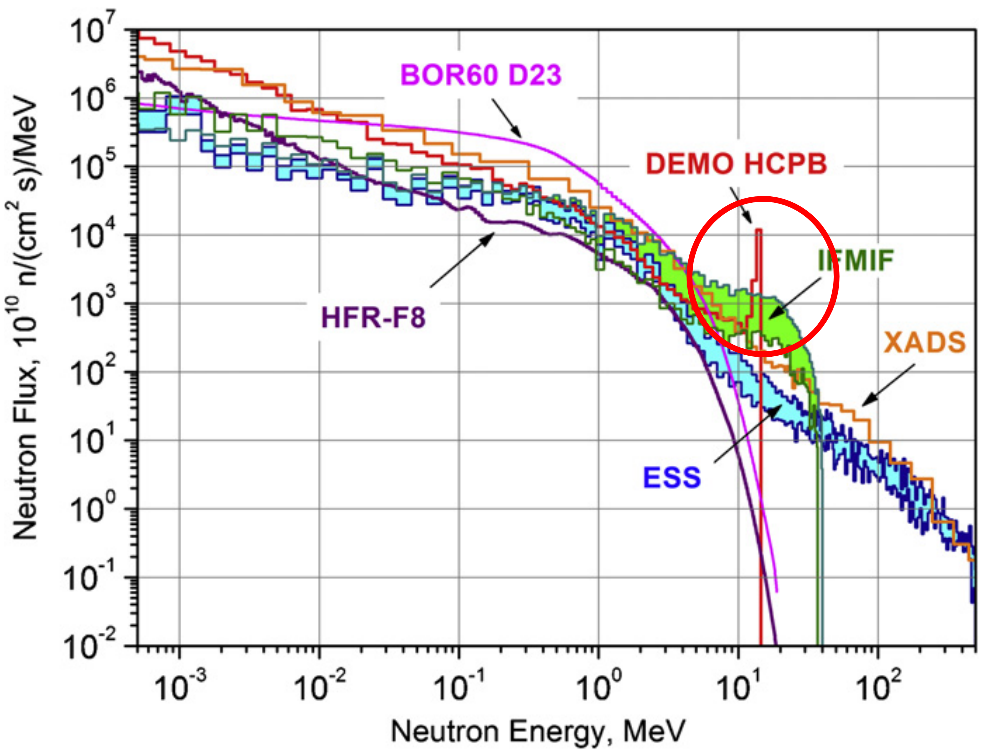
A specific source is needed for BNCT

- For Boron Neutron Capture Therapy is necessary to avoid high energy tails (non specific damage to tissues)

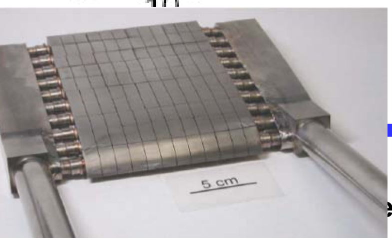


3 MeV

Neutron flux compared with DEMO's in available and planned neutron sources



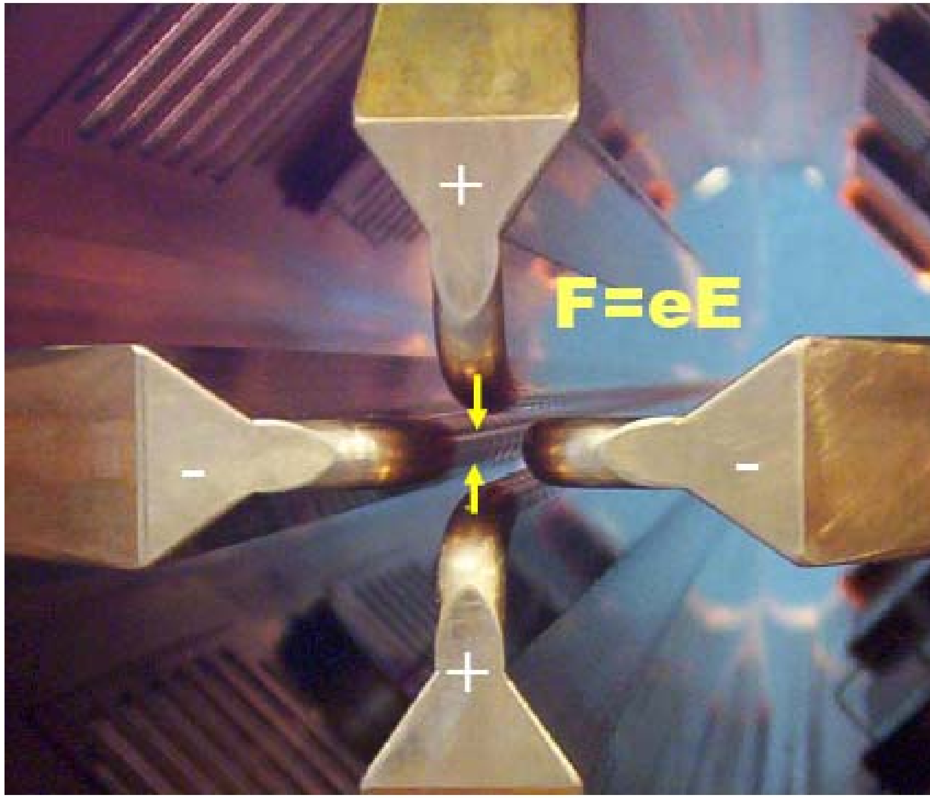
Steven J. Zinkle, A. Moeslang, *Evaluation of irradiation facility options for fusion materials research and development*, Nuclear Engineering & Design, pre-printed (2013)

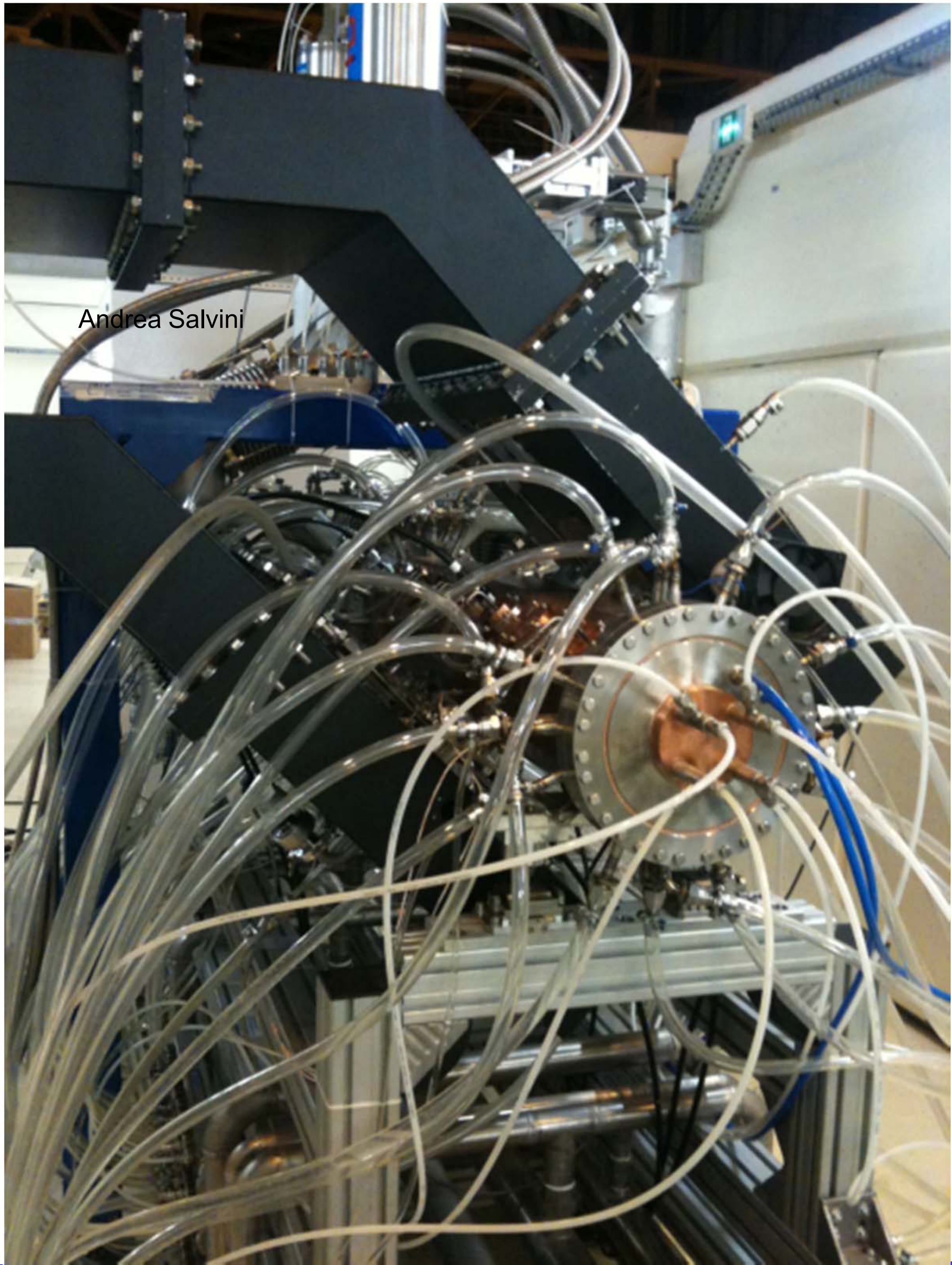


5 MeV protons with Be target
MUNES

Key technologies for a cw p or d linac (5-40 MeV)
(well developed in INFN)

- ECR sources (high intensity, high reliability continuous beam)
- RFQ acceleration with high transmission (about 90%) of a continuous beam and preparation of time structure for RF acceleration.
- Superconducting cavities for cw linac operation (HWR or QWR derived from heavy ion linacs like ALPI)
- Solid state RF amplifiers for reliable cw operation (10-150 kW)
- High power targets (solid beryllium or carbon, liquid lithium). SPES BNCT and SPIRAL2 prototypes
- Dosimetry to characterize the neutron field





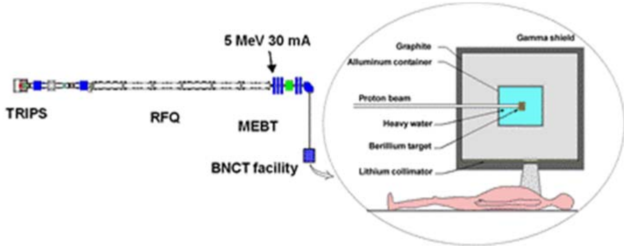
MUNES

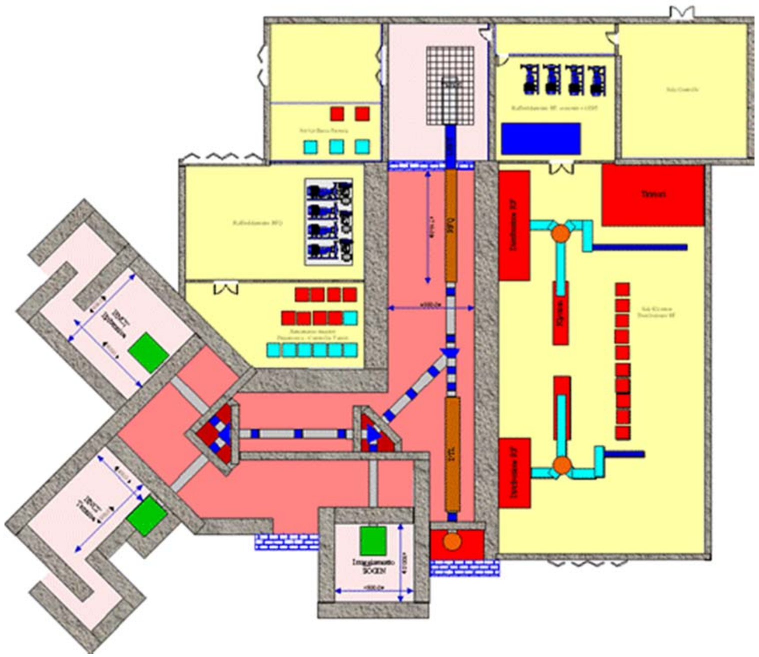
MUltidisciplinar Neutron Source

A. Pisent, P. Colautti, E. Fagotti

- First ideas with **SPES-BNCT**, based on TRASCO RFQ, almost abandoned with the choice of the cyclotron for SPES project at LNL.
- In **2011** trilateral agreement **INFN, University of Pavia and SOGIN** (pubblic company for nuclear sites decommissioning) for the study of a neutron source based on INFN **high intensity linear accelerato**r to be installed in Pavia.
- **2012** MUNES Granted as «progetto premiale» by Italian Ministery for research (5 M€, previous INFN investments in TRASCO RFQ and BNCT for about 10 M€)

Main parameters of the system source-n production target-moderator





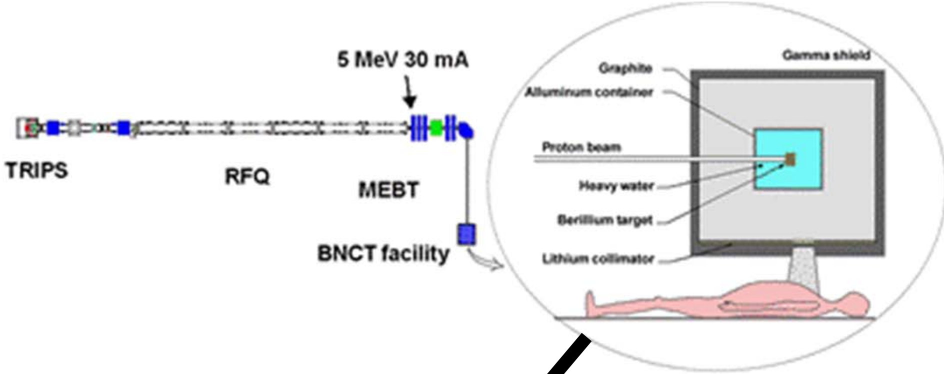
Ion source	TRIPS	Proton energy 80 keV, 50 mA intensity
Accelerator type	RFQ	Radio Frequency Quadrupole
Final energy	5 MeV	
Accelerated beam current	30 mA	
Duty cycle	CW	Continous wave
Neutron converter	Berillio	Water cooled 150 kW
Neutron source intensity	~10^{14} s^{-1}	On the entire solid angle, Ave. neutron energy 1.2MeV
RF power	1.3 MW	
Electrical power	5 MVA	

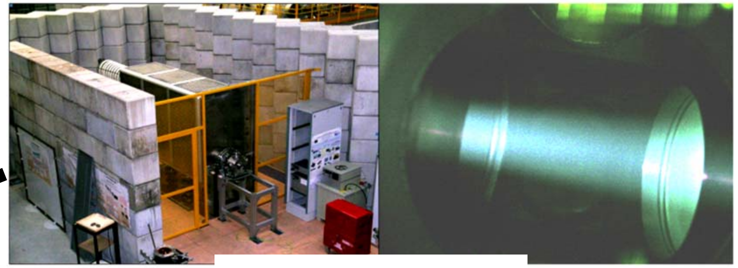
Nuclear Waste Characterization

- 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

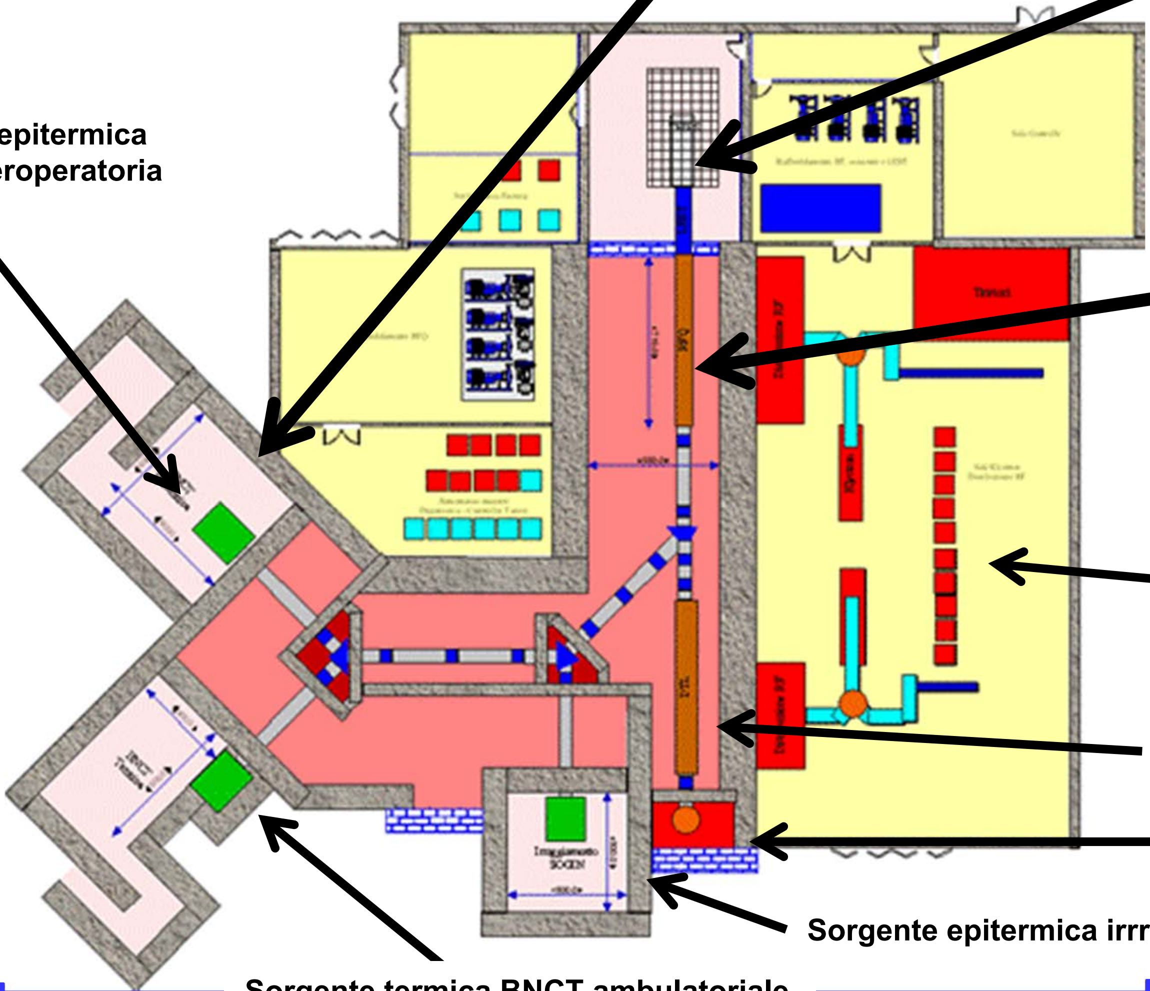
Lay-out of the facility





ECR source TRIPS

Radio Frequency Quadrupole



43 m

Sorgente epitermica BNCT interoperatoria

Sala RF

Spazio per DTL produzione tecnezio

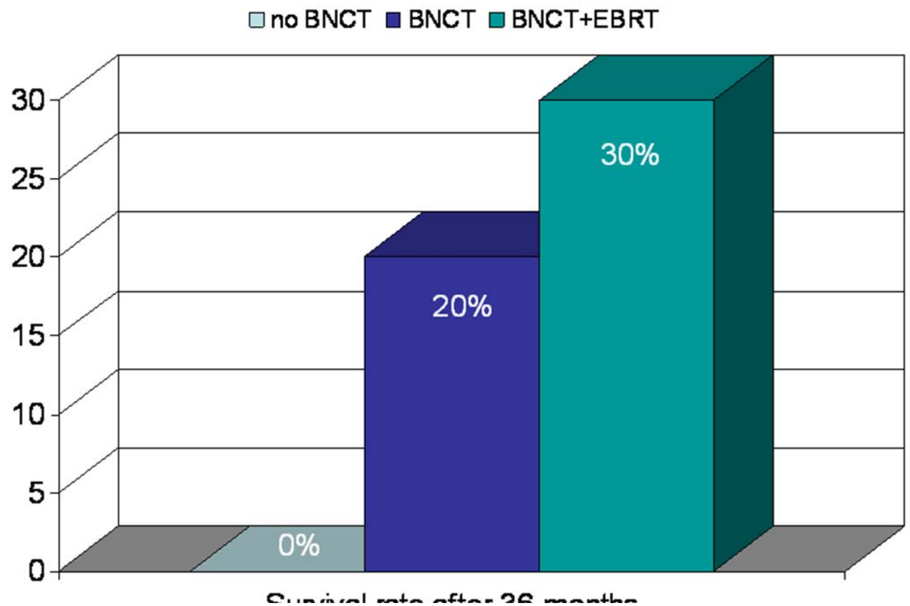
Irraggiamento per produzione radioisotopi

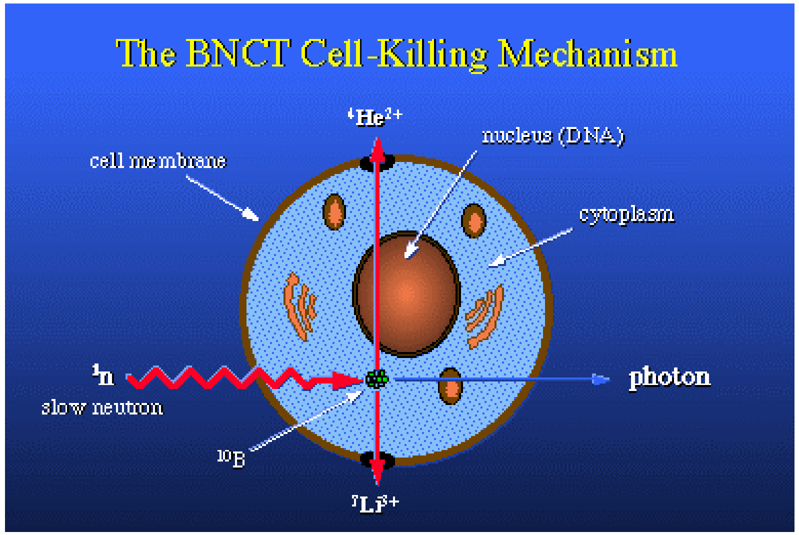
Sorgente epitermica irrraggiamento scorie

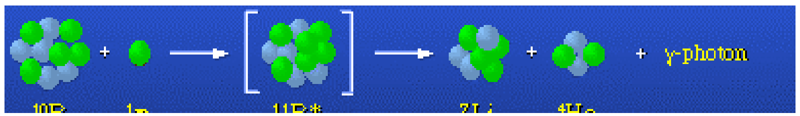
Sorgente termica BNCT ambulatoriale

The Boron Neutron Capture Therapy

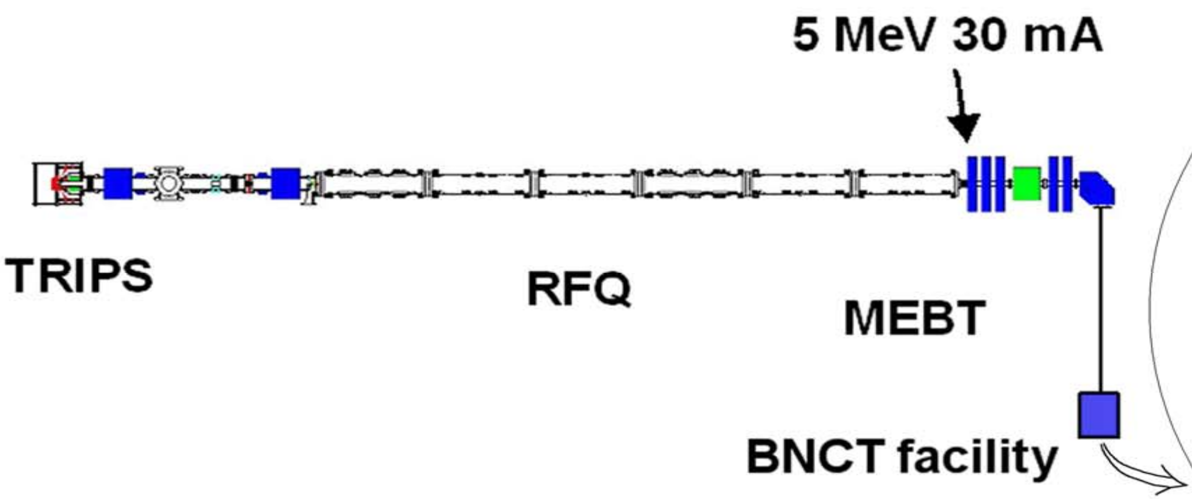
- From 1994, at least 227 patients with **glioblastoma multiforme**, a form of brain cancer associated with a poor prognosis, underwent BNCT, in many cases with the association of chemotherapy ; the inclusion of BNCT in the therapeutic scheme was able to determine a rate of increase in overall survival after 30 months from the diagnosis.
- In patients with **cutaneous melanoma**, more than 50 patients underwent BNCT with proven effects, especially in case of relapse in brain or other distant organs.
- Many other type of cancer have been treated by BNCT for example liver metastases from colon cancer (Pavia, Italy)
- In general with BNCT **improvement of quality of life**
- Under investigations new applications such **as breast and lung tumour**. (Padova and Pavia)

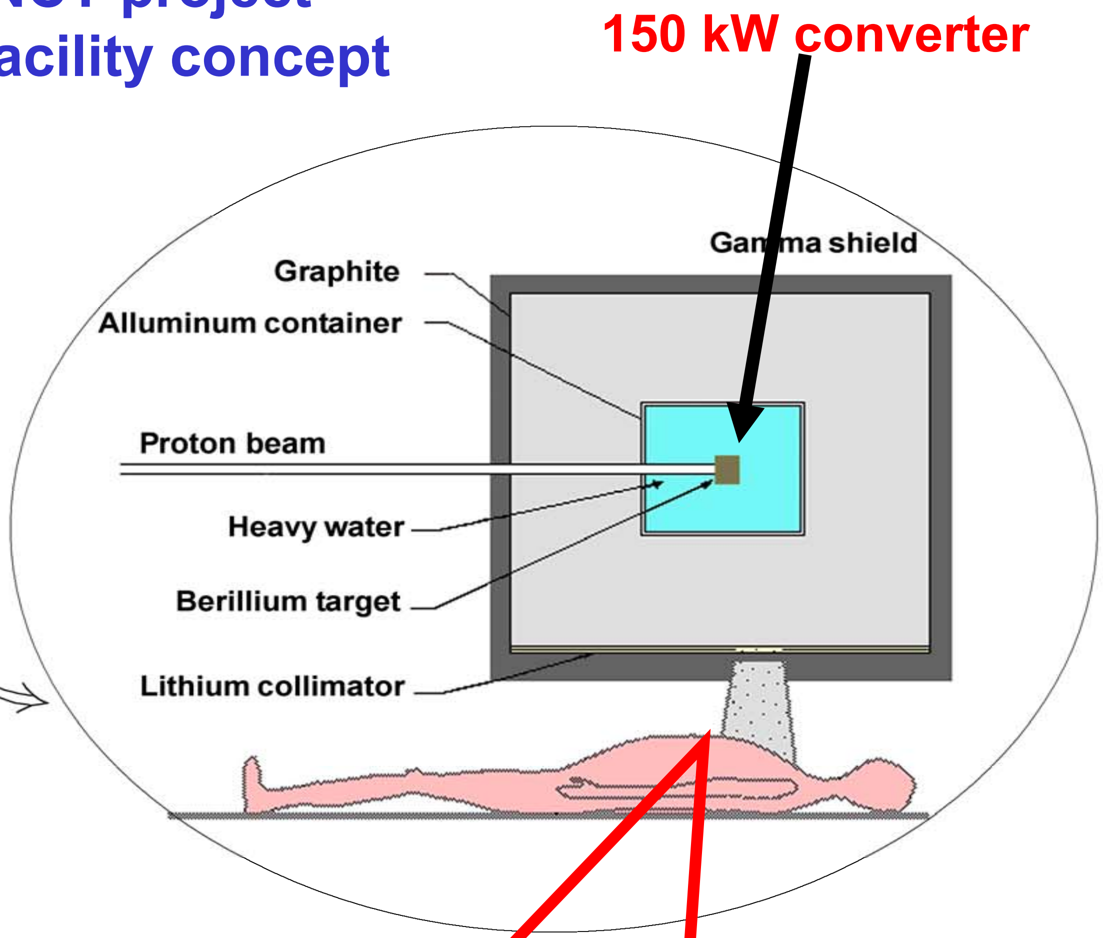






The SPES-BNCT project
the irradiation facility concept





neutron beam requirements

$\phi_{n\ th}$ (≤ 0.4 eV) $\geq 10^9$ [cm^{-2} s^{-1}]

$\phi_{n\ th} / \phi_{n\ total} \geq 0.9$

$D_{n\ epi+fast} / \phi_{n\ th} \leq 2 \cdot 10^{-13}$[Gy cm^{-2}]

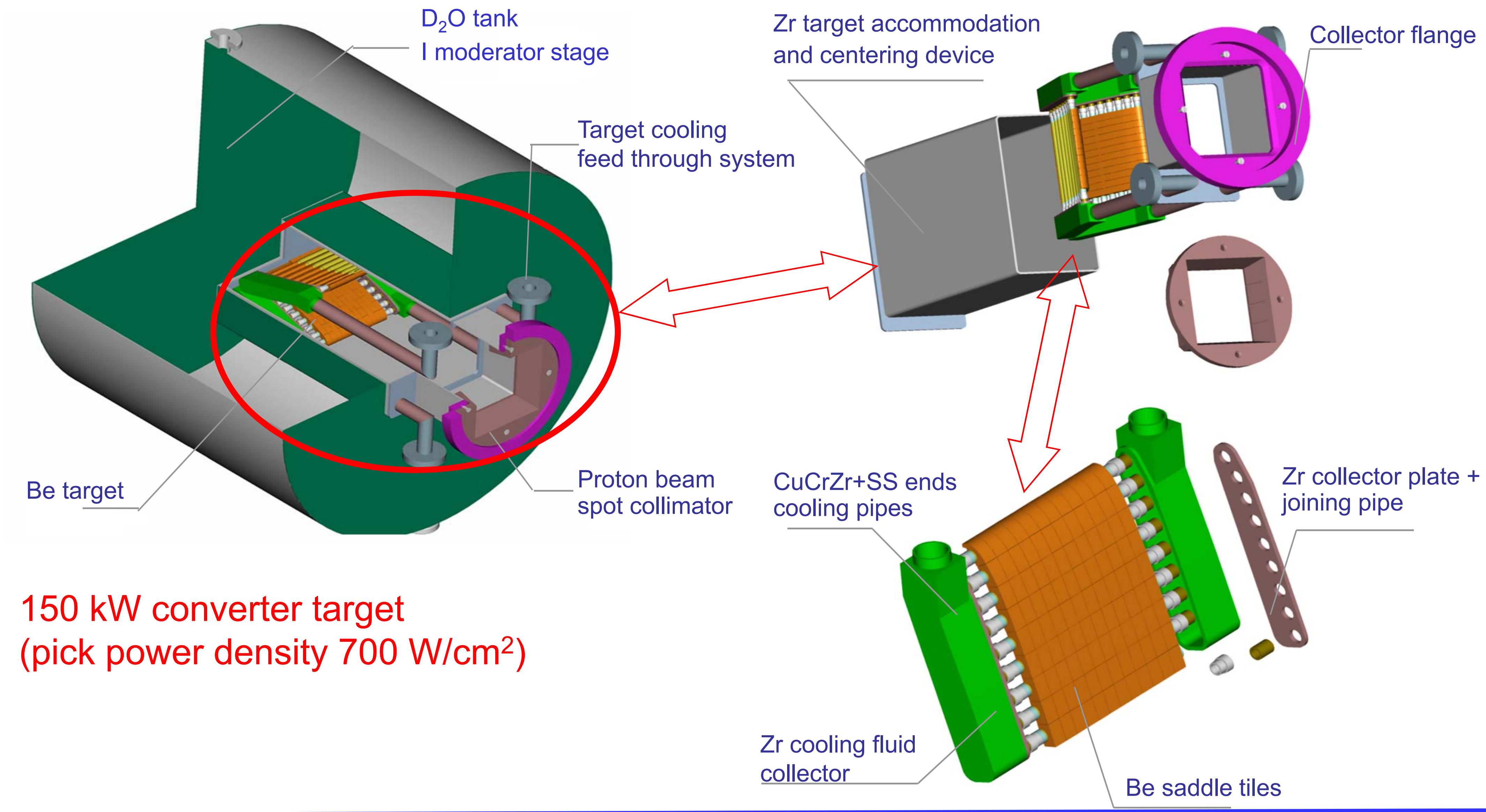
$D_\gamma / \phi_{n\ th} \leq 2 \cdot 10^{-13}$[Gy cm^{-2}]

accelerator specifications

- ✓ beam particle: proton
- ✓ beam energy: 5 MeV
- ✓ beam current: 30 mA
- ✓ beam power: 150 kW

The LNL-BNCT project

Efremov Step II neutron converter prototype design

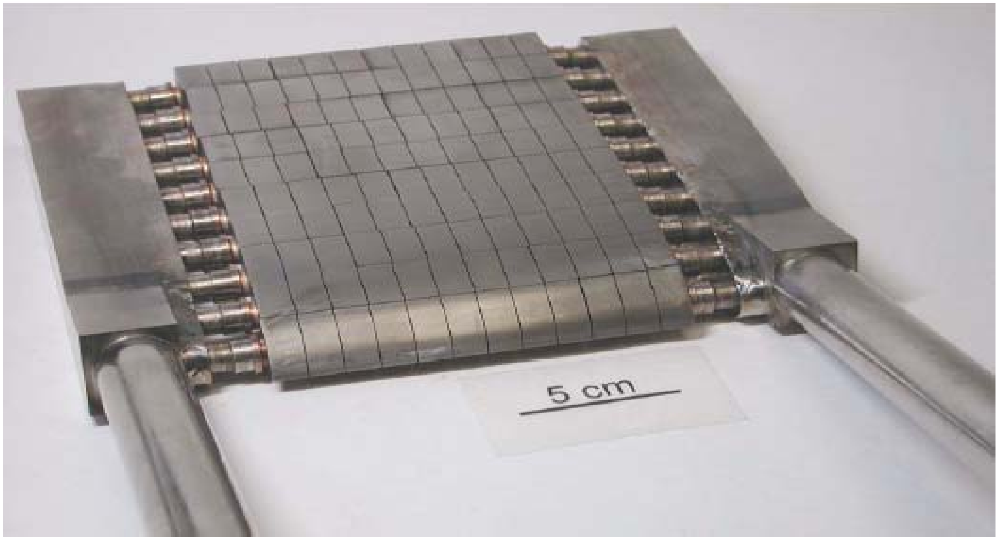


150 kW converter target
(pick power density 700 W/cm^2)

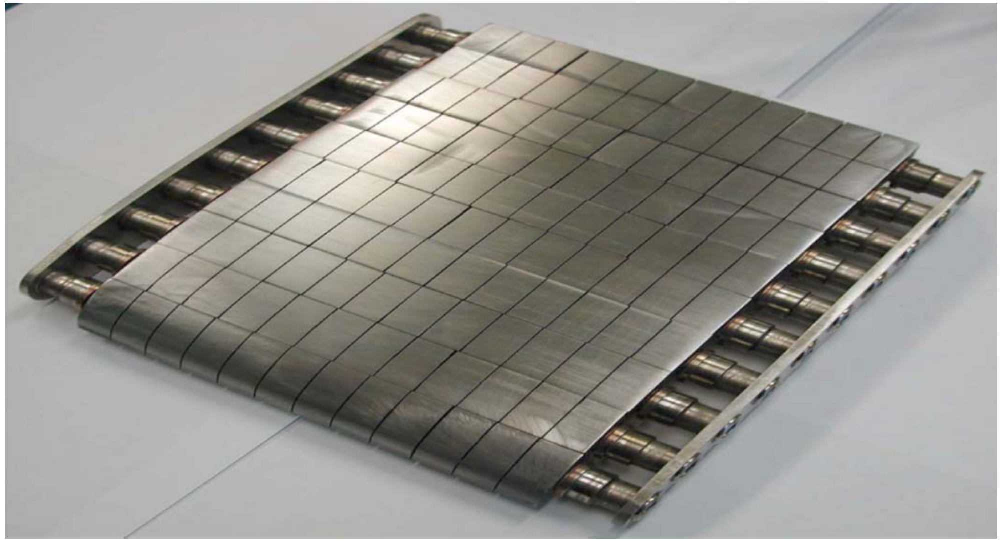
The LNL-BNCT project

neutron converter prototype assembling and first full beam power test

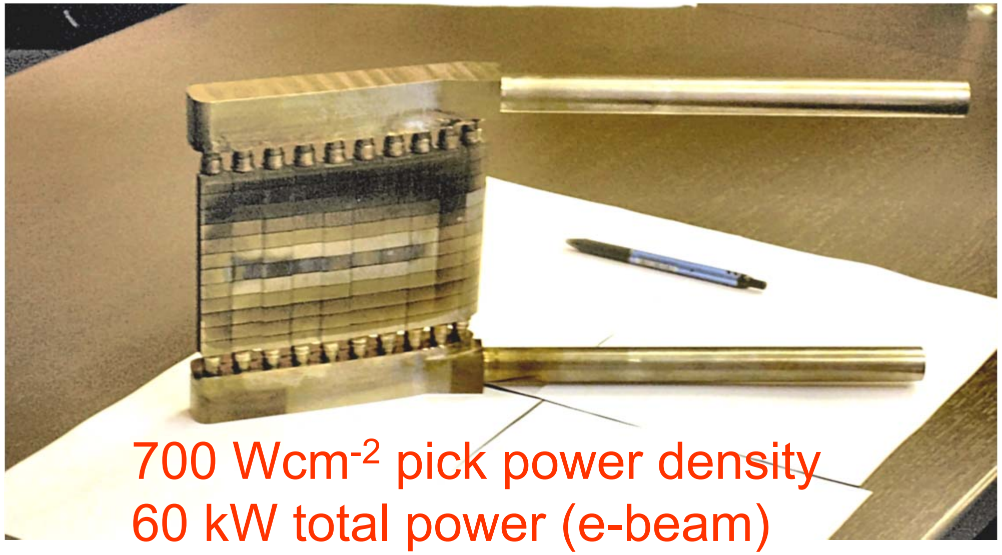
1. Be tile brazed cooling pipes



3. Final target assembling



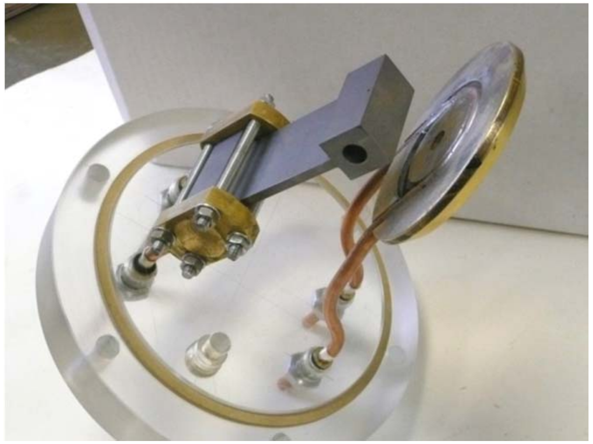
2. collector plates welding & EDM manufacturing process



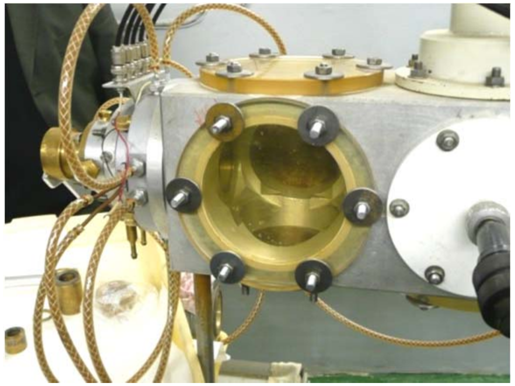
4. Visual inspections after e-beam full power test

Test of target damage by protons

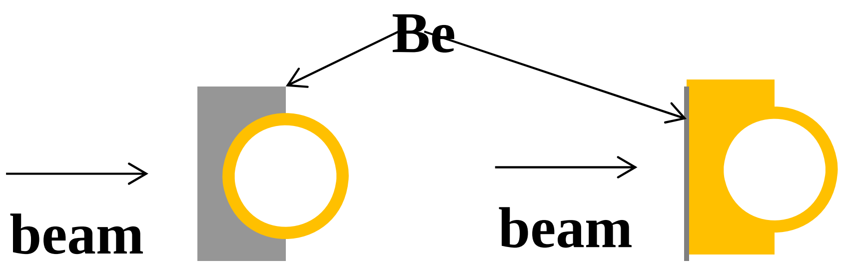
- **Assesment of target duration** (Be has high melting point 1278 degC and high heat conductivity, but gas permeability if extremely low (9 order lower than average materils). H bubbles can be trapped in bulk beryllium and cause fractures (swelling problem).
- Proton radiation damage effects on Be surface were planned in 2008, measurements at the State Polytechnic Institute (SPbSPU), St. Petersburg (Russia) (interrupted for funds problem, contract now under preparation)
- New target design to be tested based on a very thin Be foil brazed on Cu alloy tube

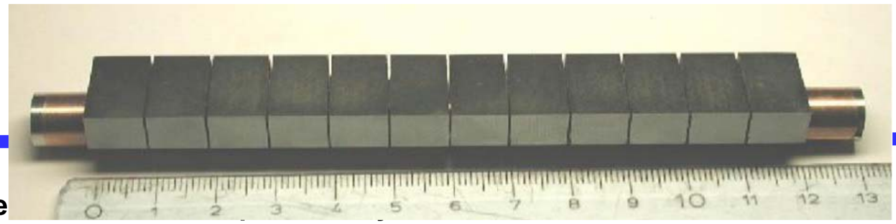


Be element equipped with collimator to simulate the proper proton hitting angle on target surface with same power density

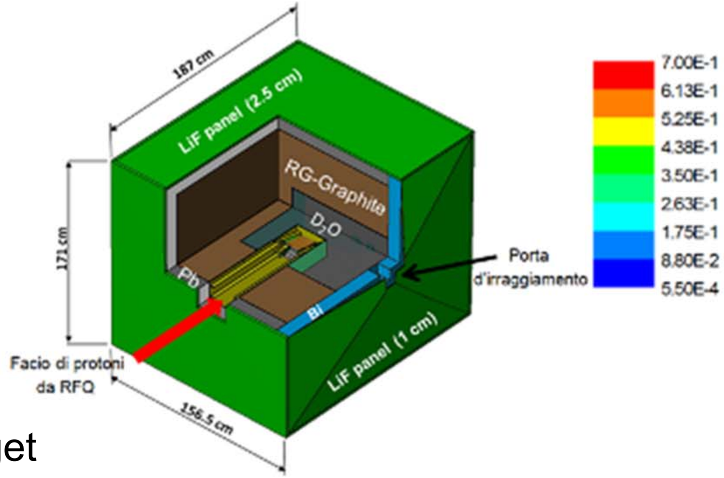


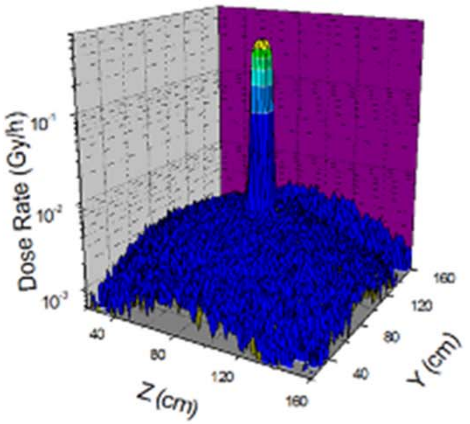
Test camera at the Cyclotron facility
proton beam Ep=5 MeV, I= 20 μA





Thermal moderator design (by J. Esposito)



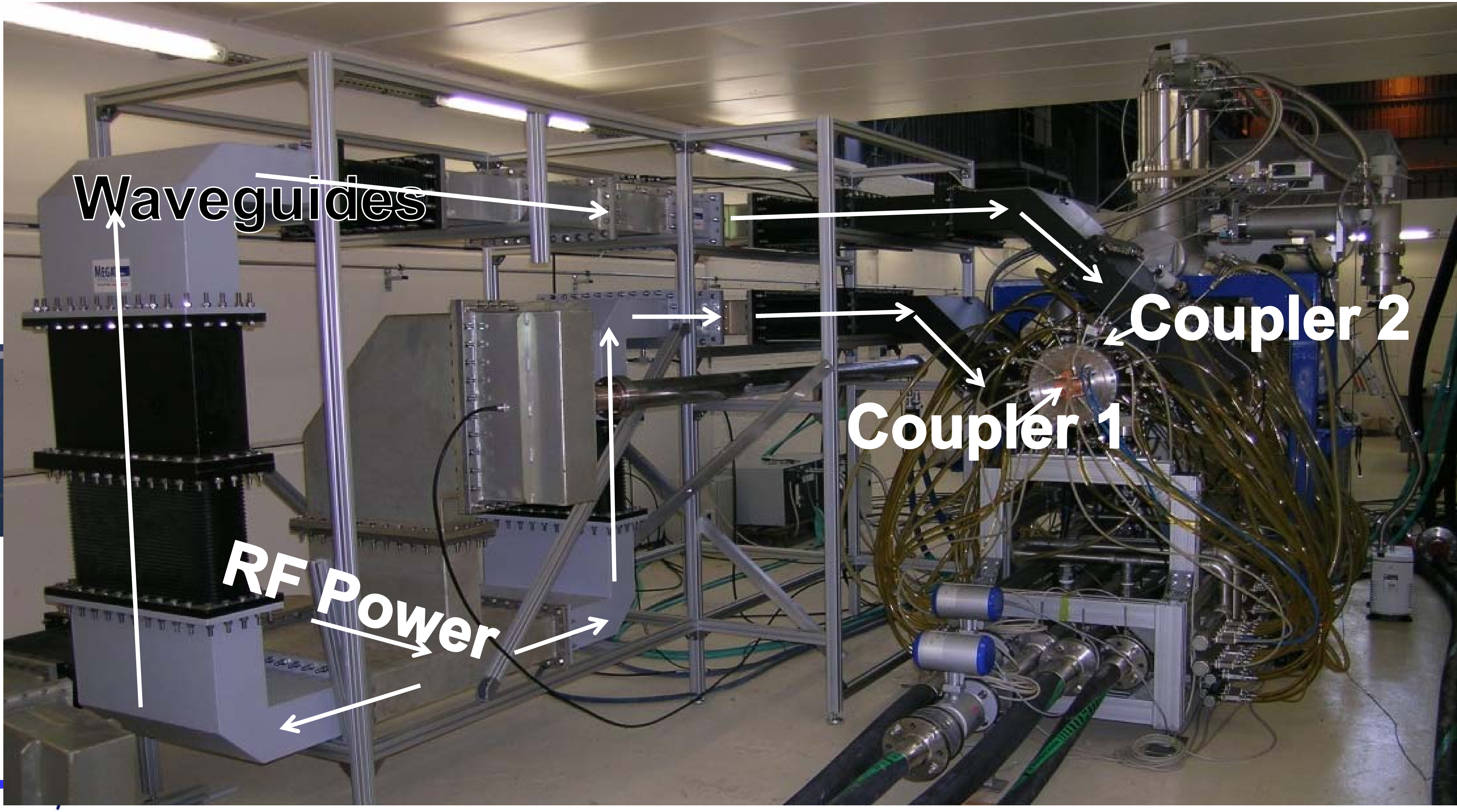


30 mA 5 MeV into target

	Φ_{th} (E≤ 0.5 eV) ($cm^{-2}s^{-1}$)	Φ_{th} / Φ_{total}	K_{nth} ($Gy \cdot h^{-1}$)	$K_{n\ epi\text{-}fast}$ ($Gy \cdot h^{-1}$)	K_{γ} ($Gy \cdot h^{-1}$)	$K_{\gamma} / K_{n\ tot}$	$K_{n\ (E>10\ eV)} / \Phi_{th}$ ($Gy \cdot cm^2$)	K_{γ} / Φ_{th} ($Gy \cdot cm^2$)
IAEA ref. parameters	**> 1E+09**	**> 0.90**					**≤ 2E-13**	**≤ 2E-13**
RG-Graphite reflector	**2.84E+09**	**0.995**	1.70	0.023	1.24	0.72	**2.27E-15**	**1.23E-13**

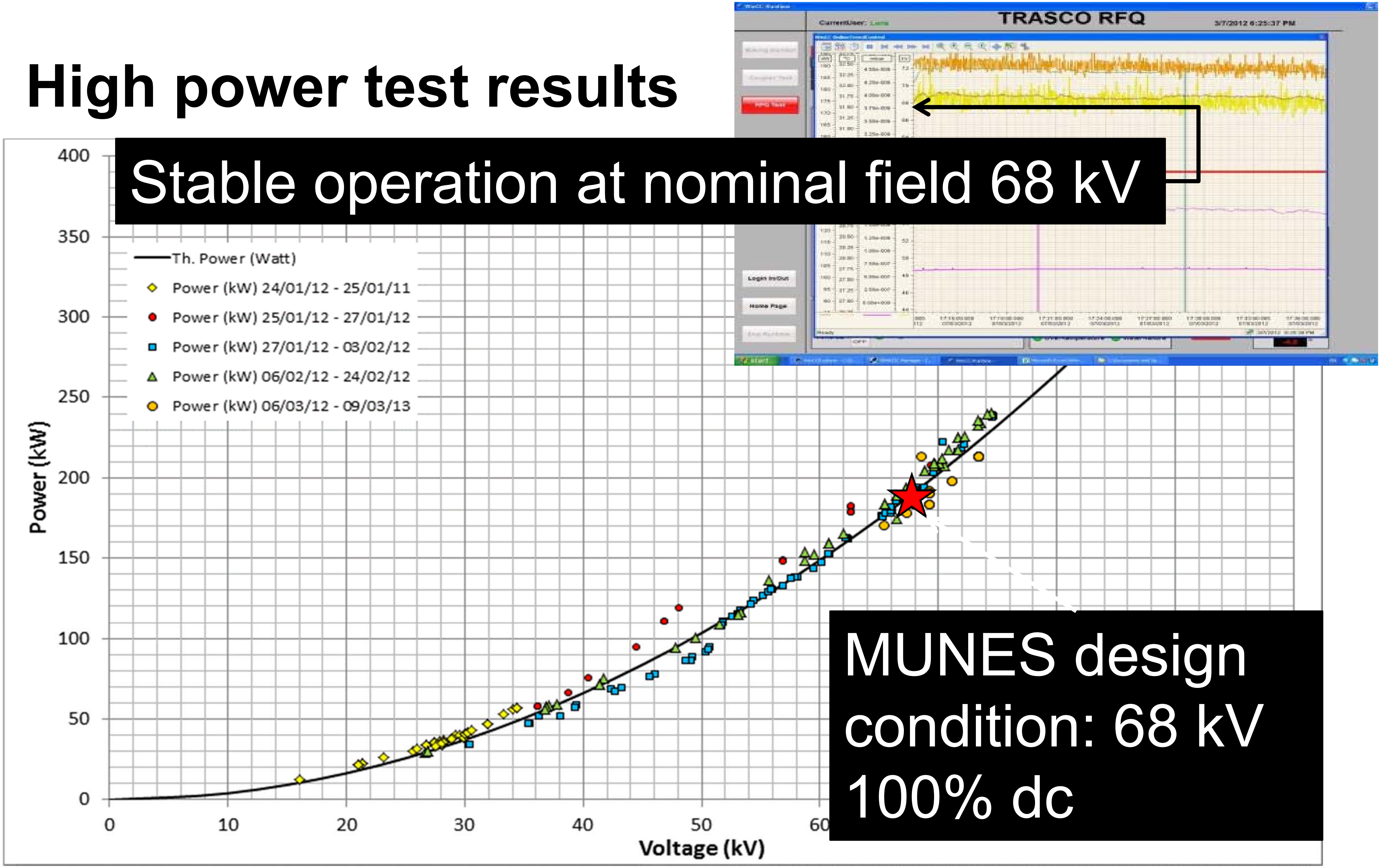
The second moderator will be for epithermal (0.5<E_n <10 keV) neutrons, needed for deep tumours is being designed by INFN Pavia.

The Accelerator Has Successfully Passed the RF Power Test



High power test results

Stable operation at nominal field 68 kV

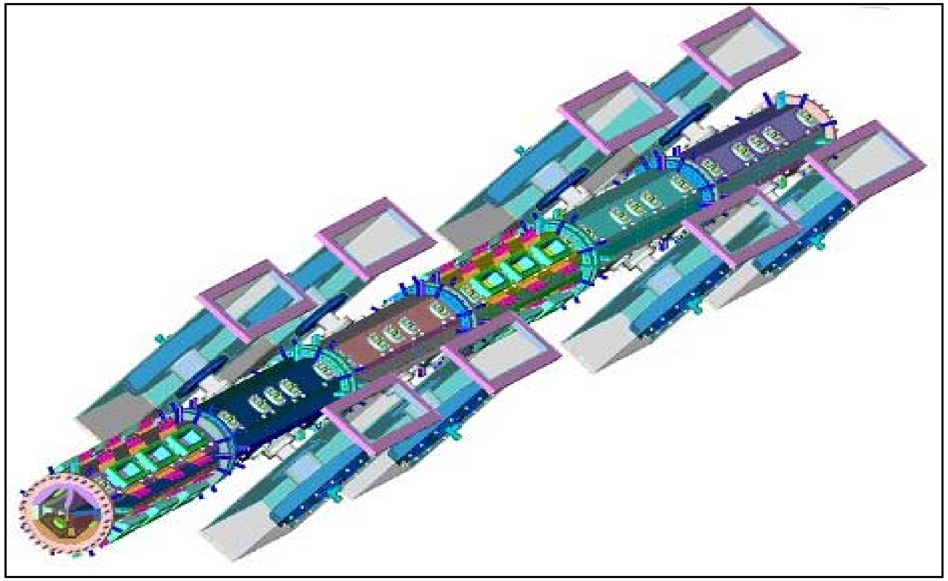


MUNES design condition: 68 kV 100% dc

With MUNES new applications need new technologies

Eight independent 125 kW amplifiers (one per RF coupler) are coming (5 ordered amplifiers, delivery in 2015).

Each amplifier needs 3 racks as in the following scheme (including power supply)

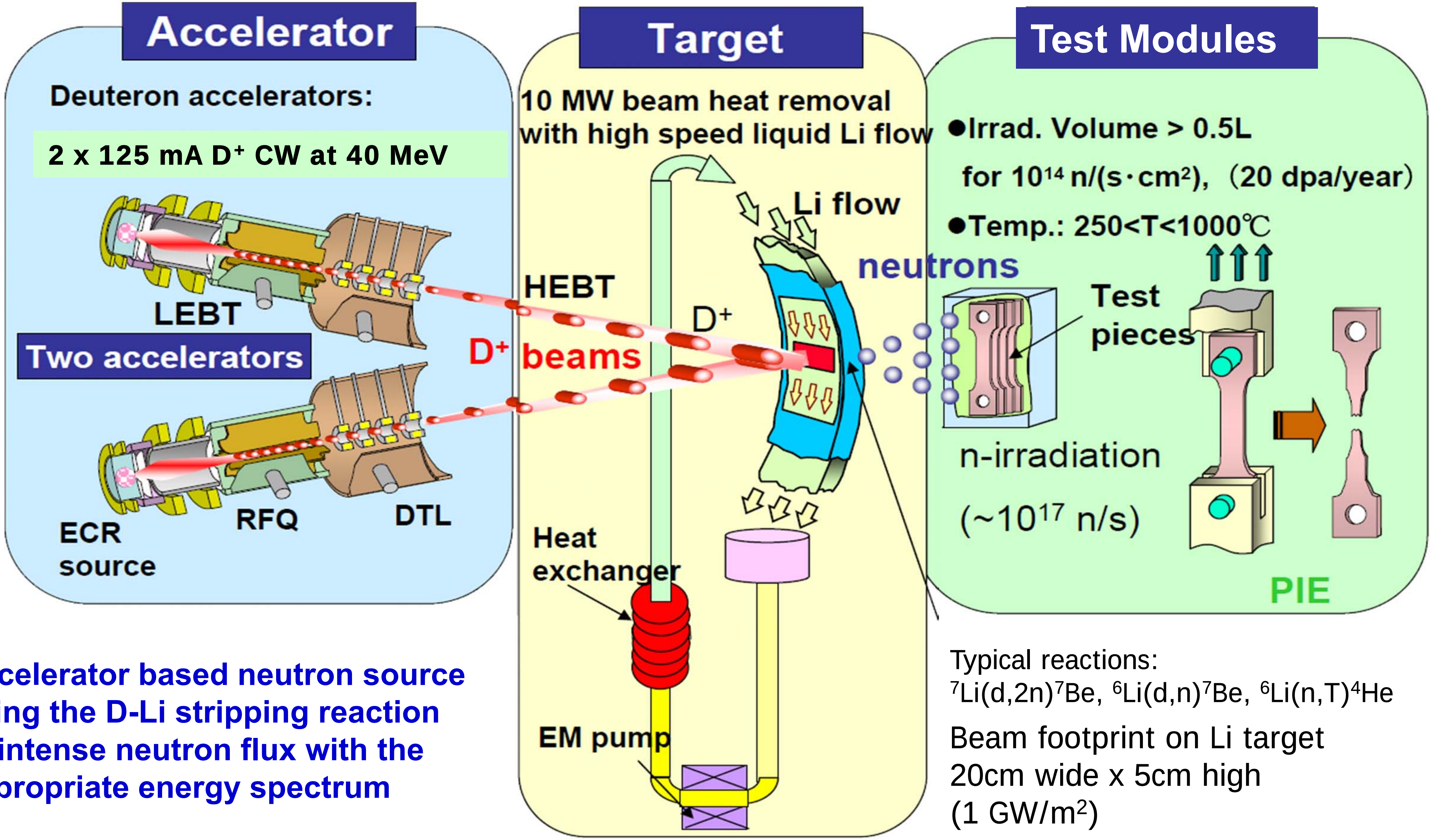


Advantages respect to a klystron

- *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 International Fusion Material Irradiation Facility

IFMIF Principles



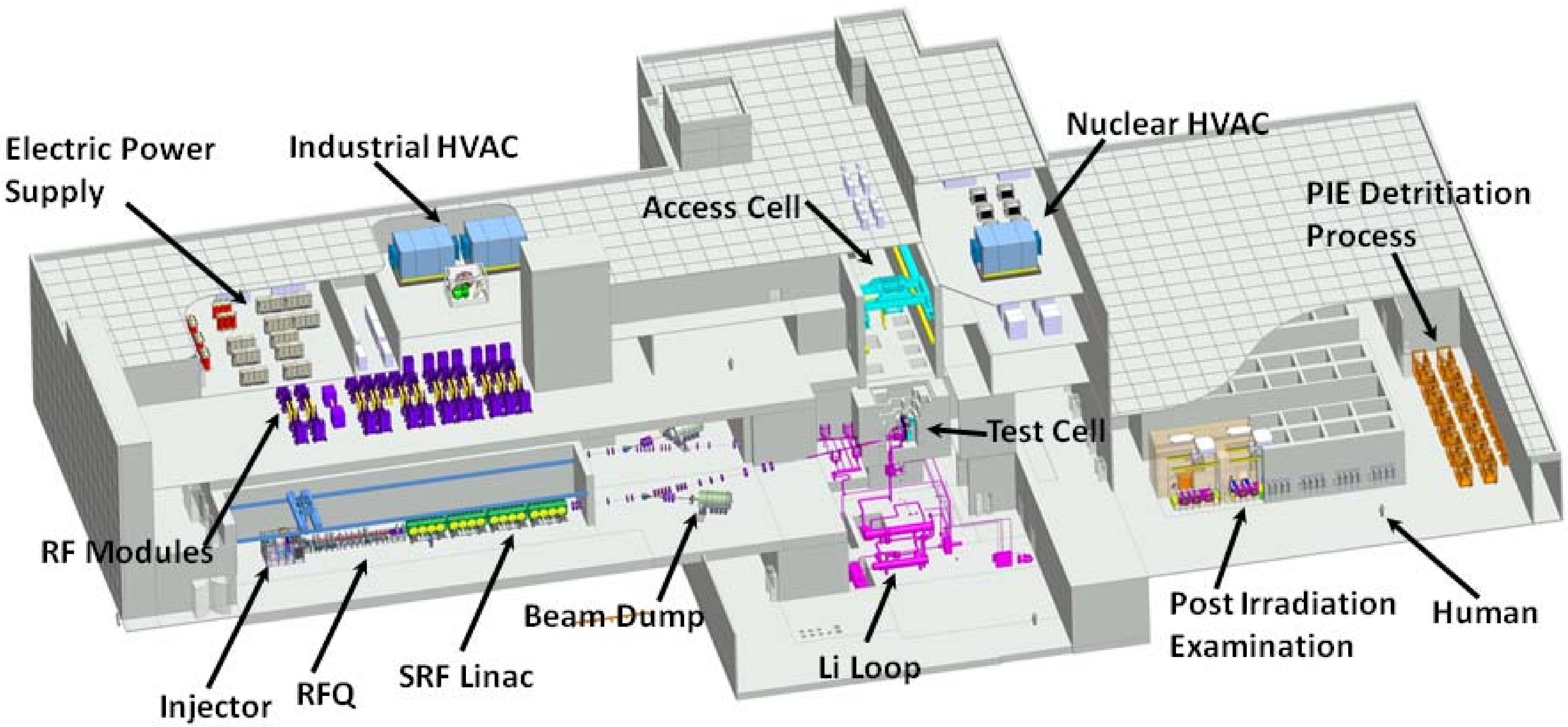
Accelerator based neutron source using the D-Li stripping reaction ⇒ intense neutron flux with the appropriate energy spectrum

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

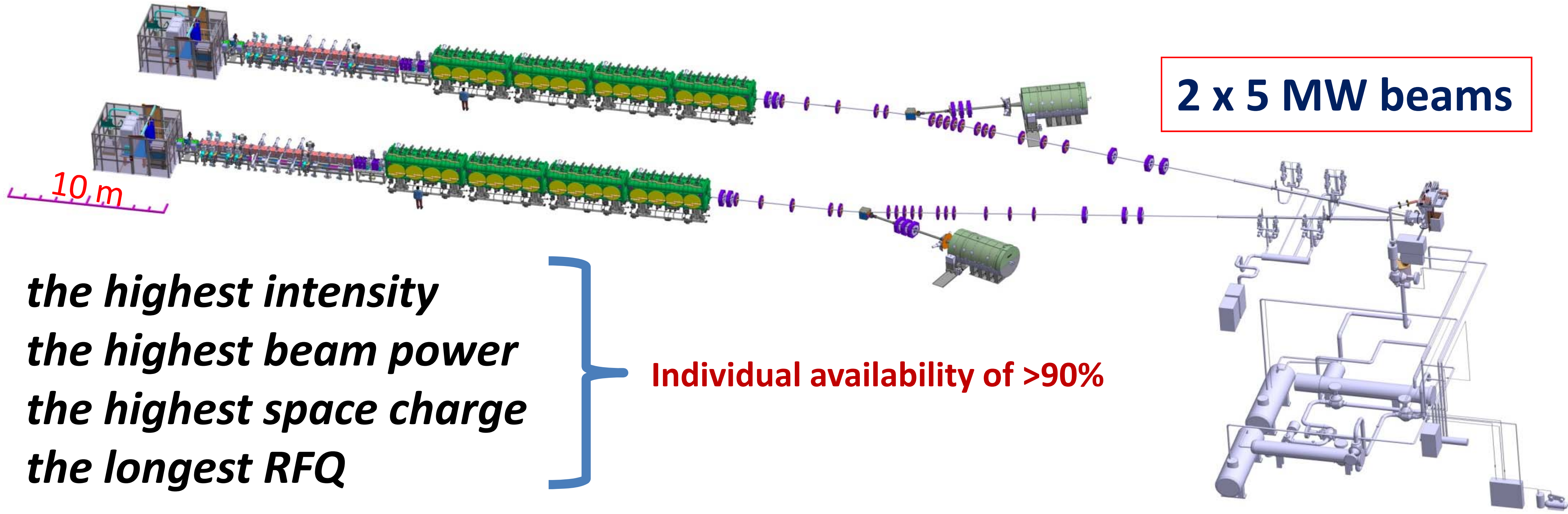
Beam footprint on Li target
20cm wide x 5cm high
(1 GW/m^2)

Facility design

(to be concluded this summer '13 with a new cost estimate by an independent Engineering private company)



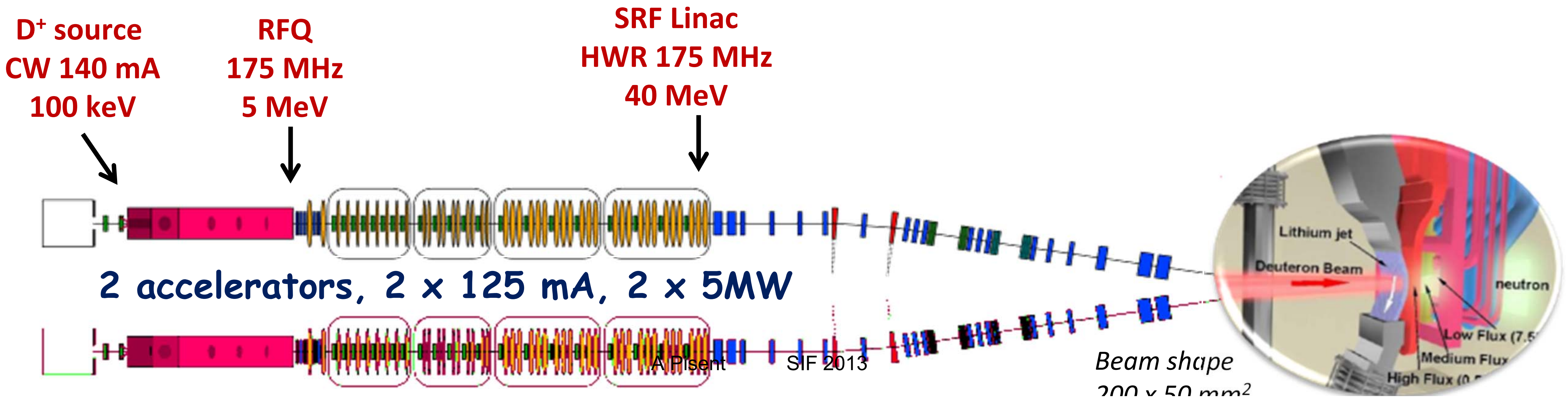
Accelerator facility of IFMIF



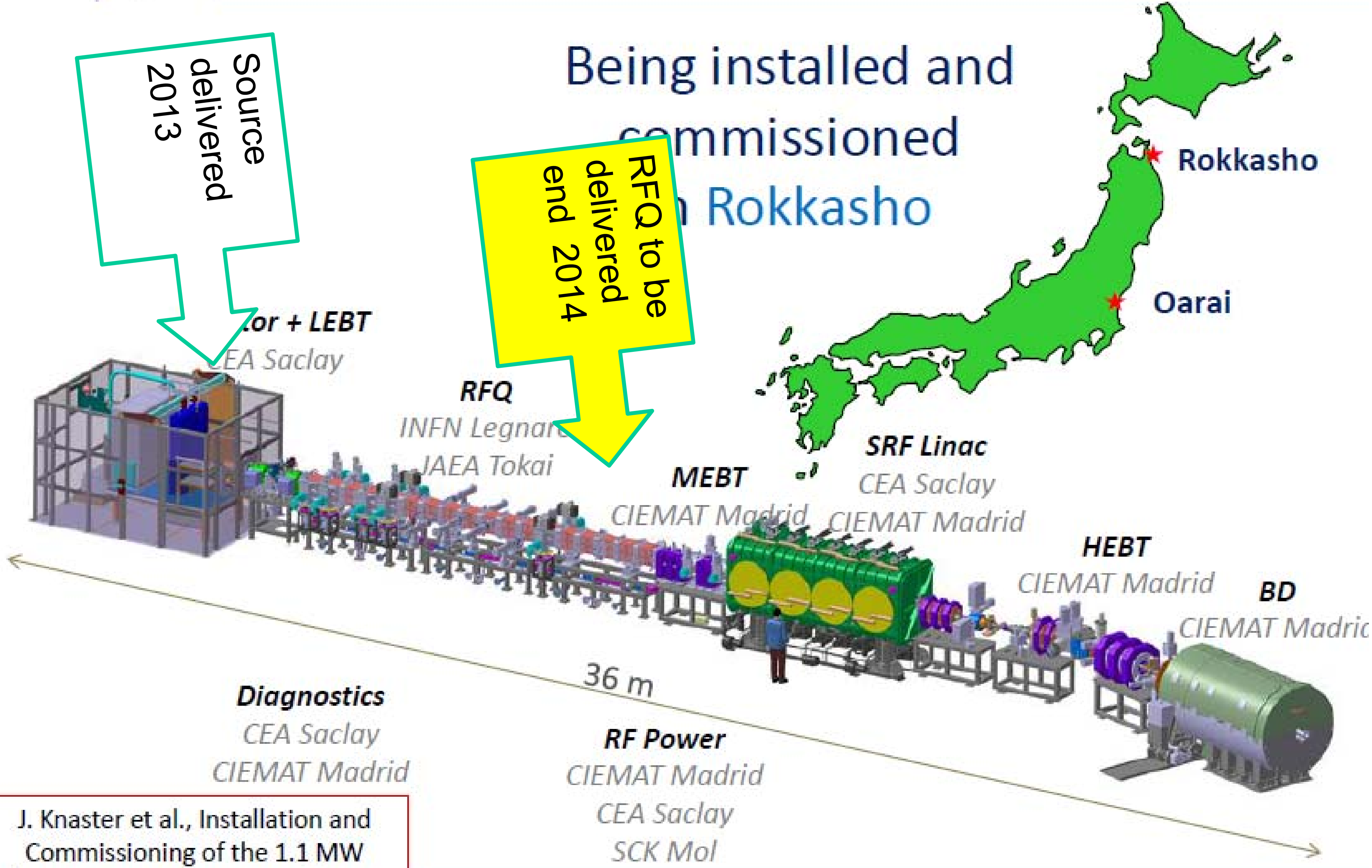
2 x 5 MW beams

the highest intensity
the highest beam power
the highest space charge
the longest RFQ

Individual availability of >90%



Linear IFMIF Prototype Accelerator



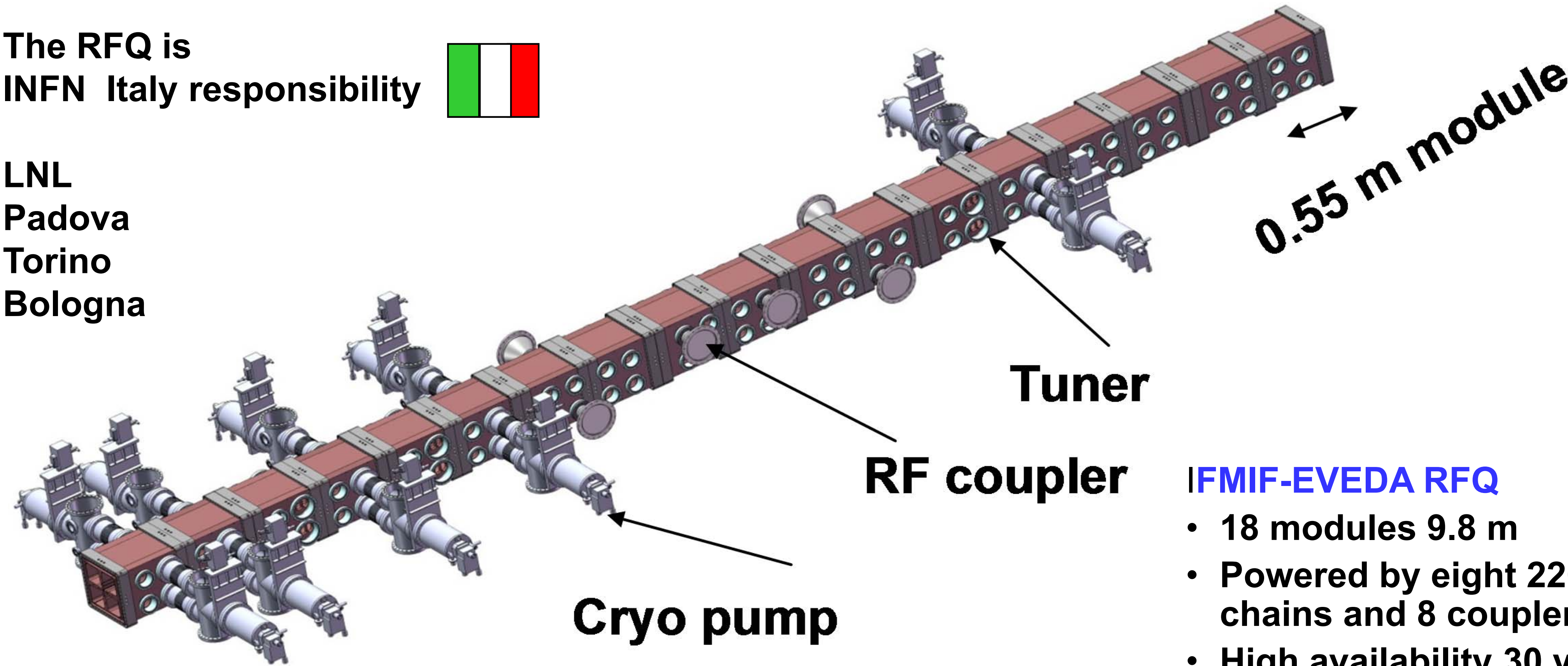
J. Knaster et al., Installation and Commissioning of the 1.1 MW deuteron prototype Linac of IFMIF IPAC 2013 Shanghai

IFMIF-EVEDA: RFQs general parameters

	Name	Lab	ion	energy	vane voltage	beam current	power	RF Cu power	Freq.	length		Emax	Power density ave	Power density 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**

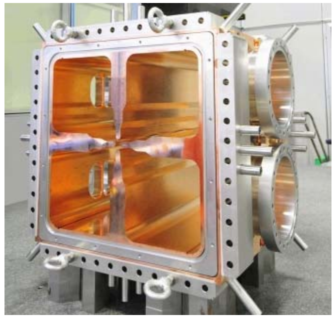
The RFQ is
INFN Italy responsibility

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**



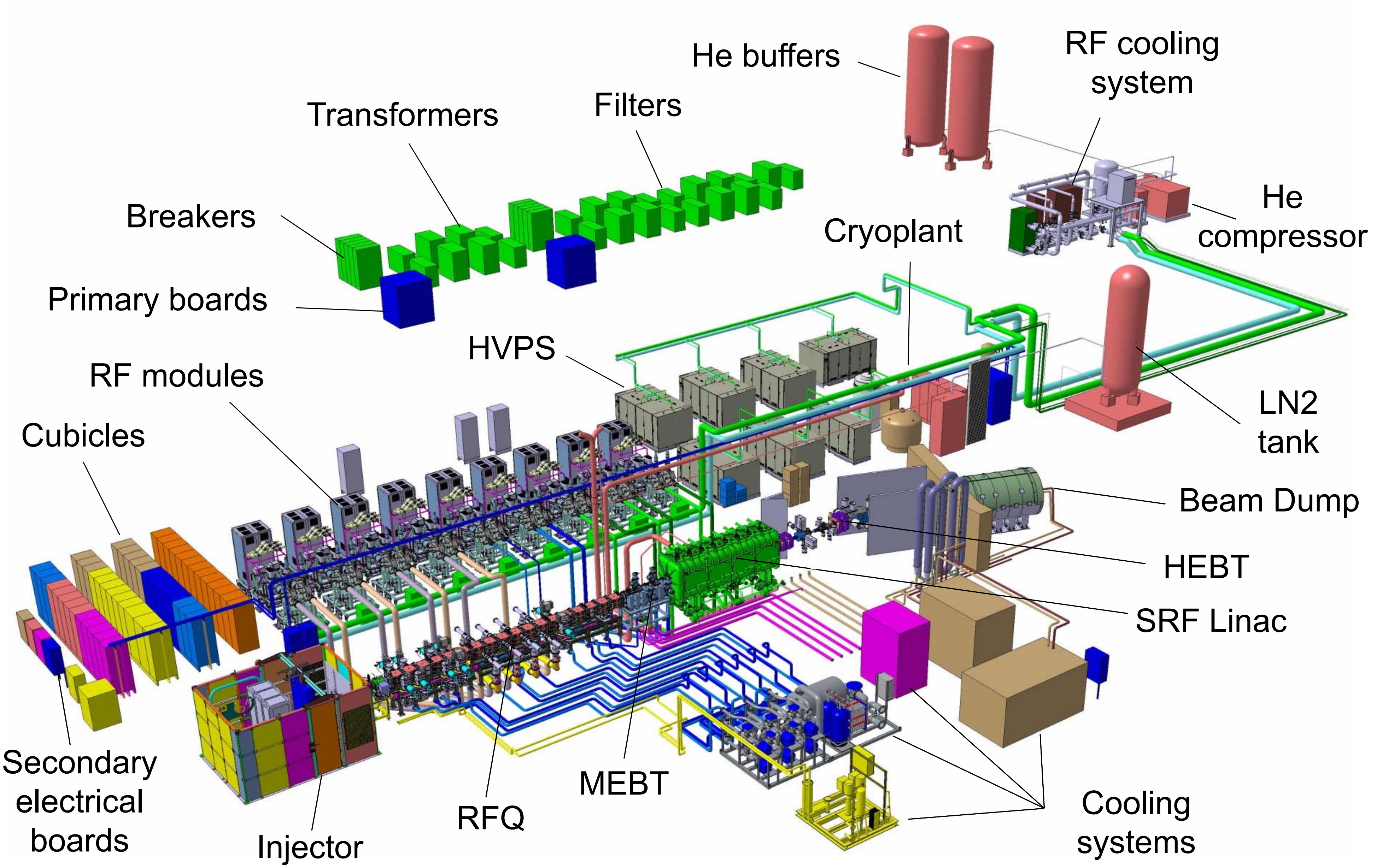
IFMIF EVEDA RFQ system organization

- 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€

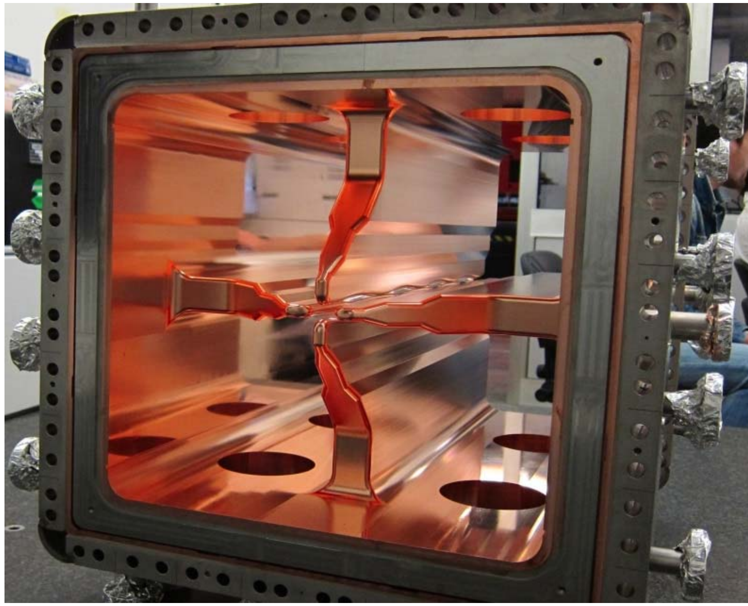
The participation of INFN to IFMIF-EVEDA includes
- RFQ construction
- Participation to final IFMIF design activity
- Participation to the man power of the project team in Japan
- Participation to beam commissioning in Japan

INFN organization

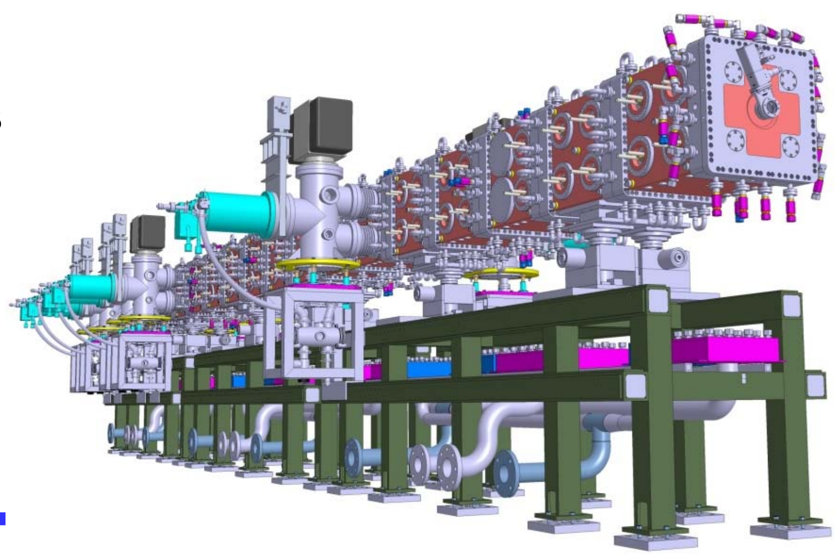


Accelerator system 3D Mock-up status D. Gex

IFMIF EVEDA RFQ challenges

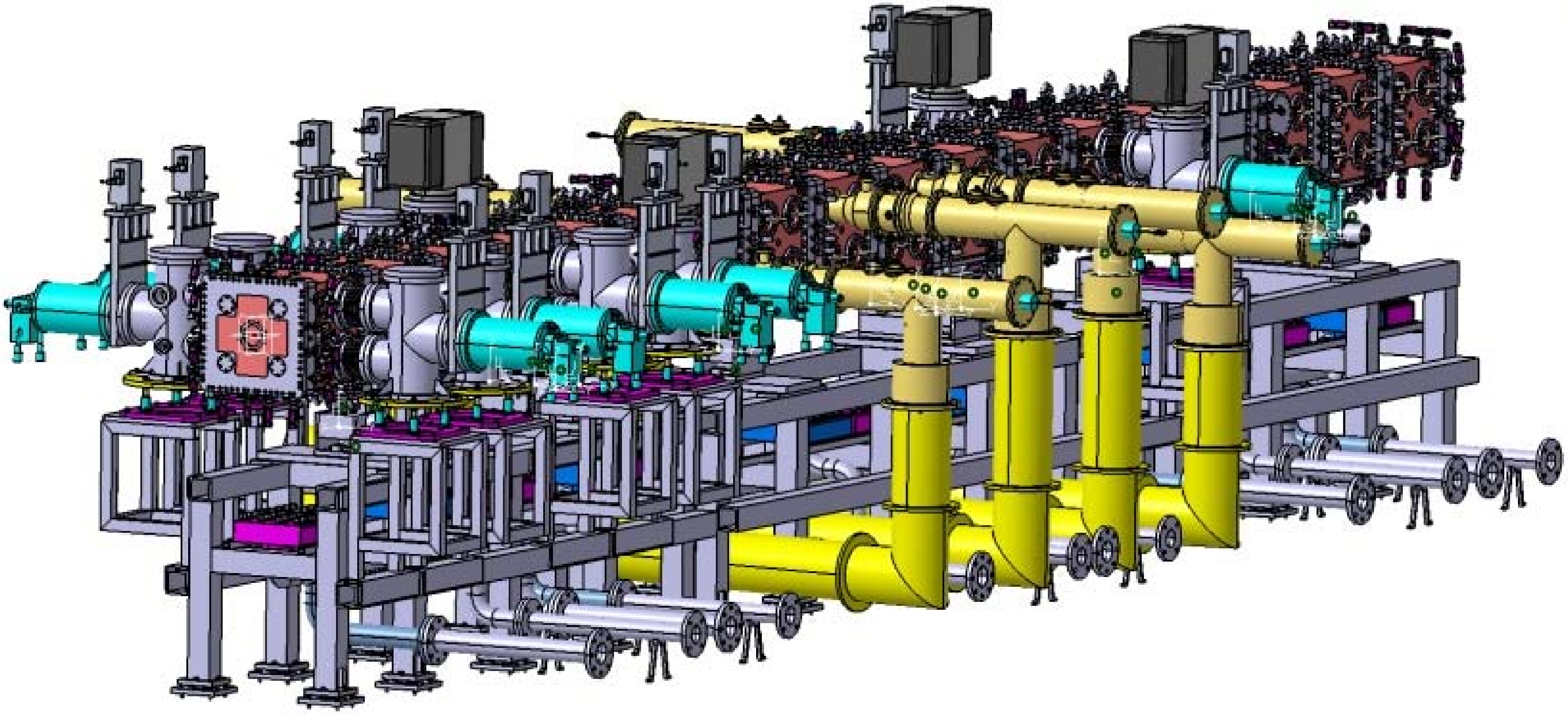


- **650 kW beam** should be accelerated with **low beam losses and activation** of the structure so as to allow hands-on maintenance of the structure itself (**Beam losses<10 mA and <0.1 mA between 4 MeV and 5 MeV). (Tolerances of the order of 10-50 um)**
- **600 kW RF dissipated** on copper surface: 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

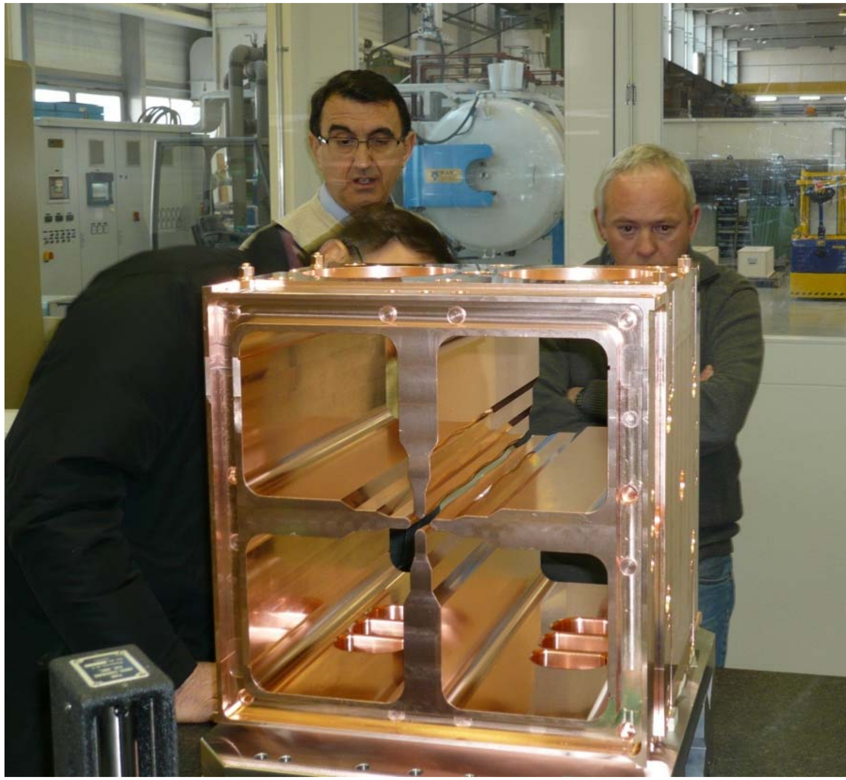
RF cavities built in three supermodules (6 modules each)



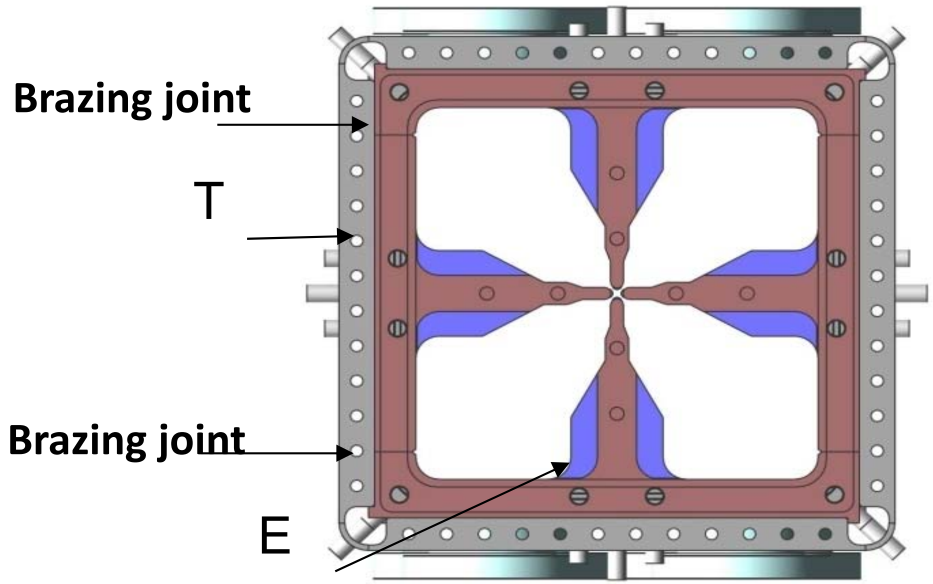
- High energy SM in construction at Cinel, Padua (Italy), Intemediate energy in INFN Padova, Low energy by RI Koln (Germany)

Mechanical design

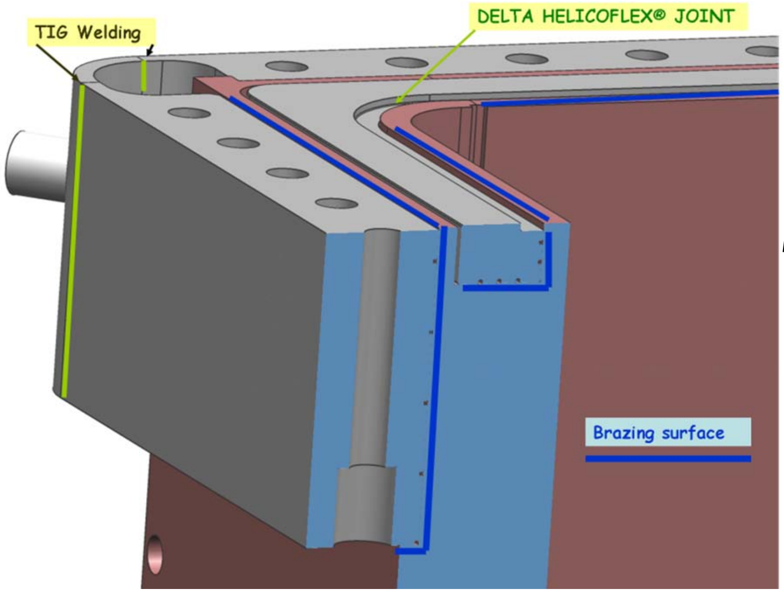
- **Based on vacuum brazing, LNL mechanical experience with TRASCO,** CERN experience for RFQ brazing, design compatible with oven at CERN, LNL and in industry;
- Due to the relatively large transverse dimensions of the RFQ, the procurement of the CUC2 raw material blocks is limited by the total mass 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.



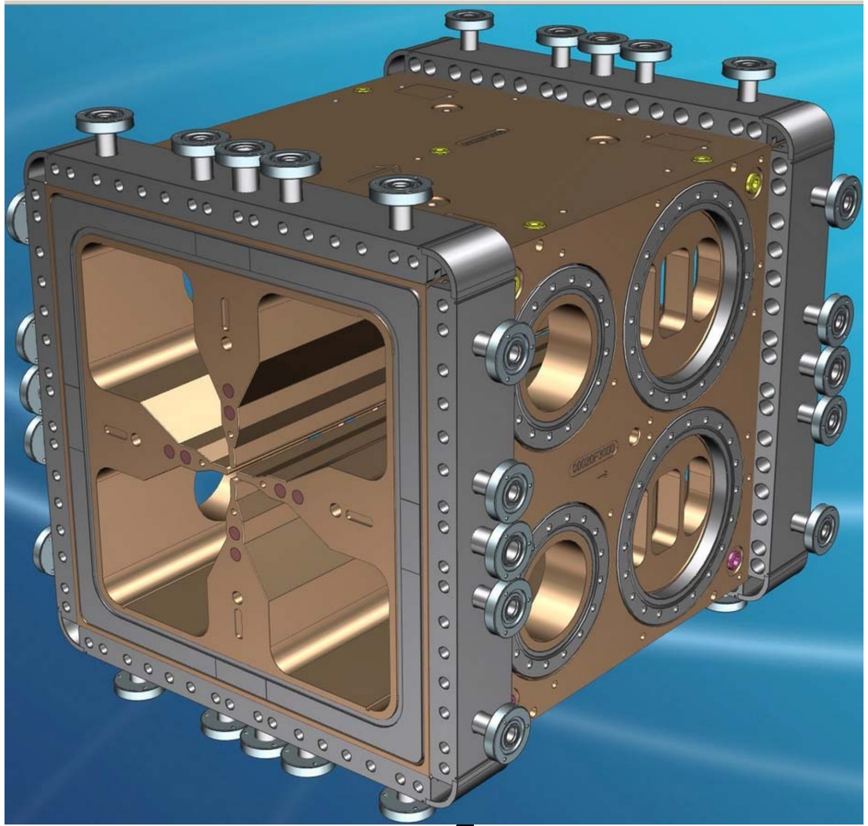
Prototype before brazing at CERN

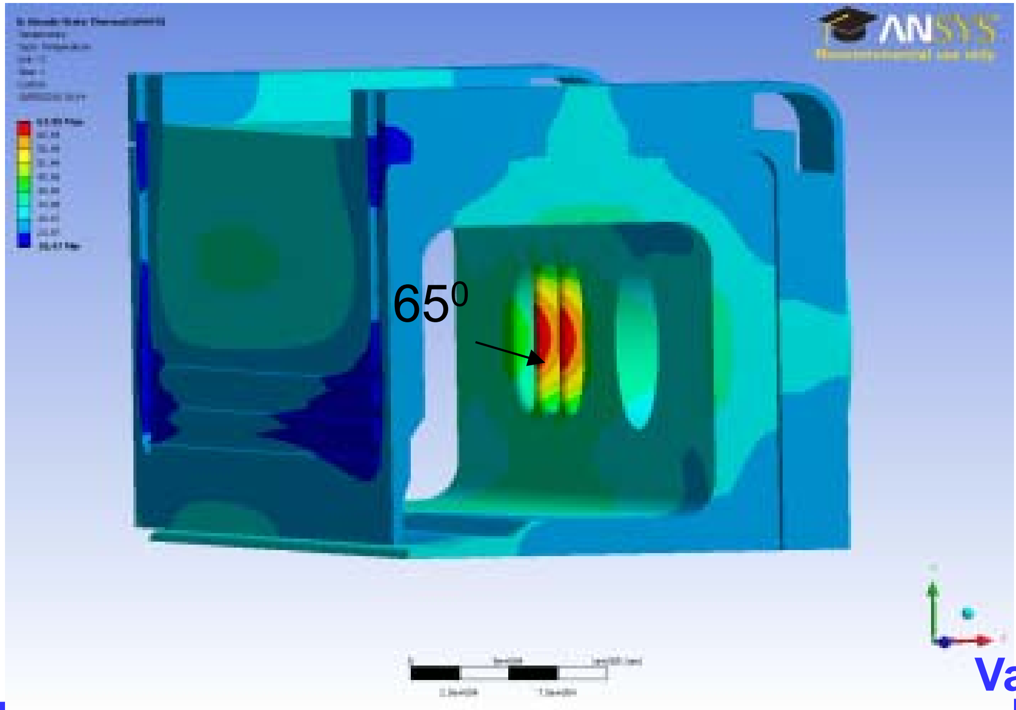


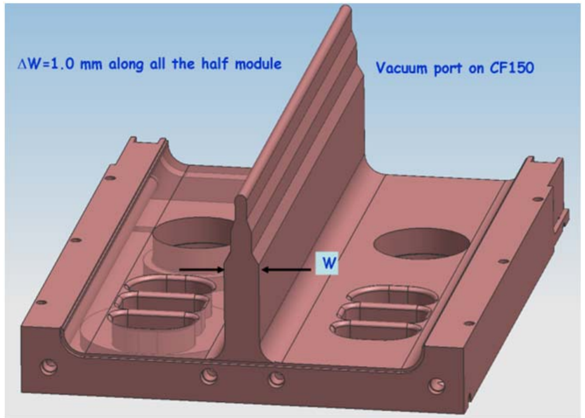
Mechanics details



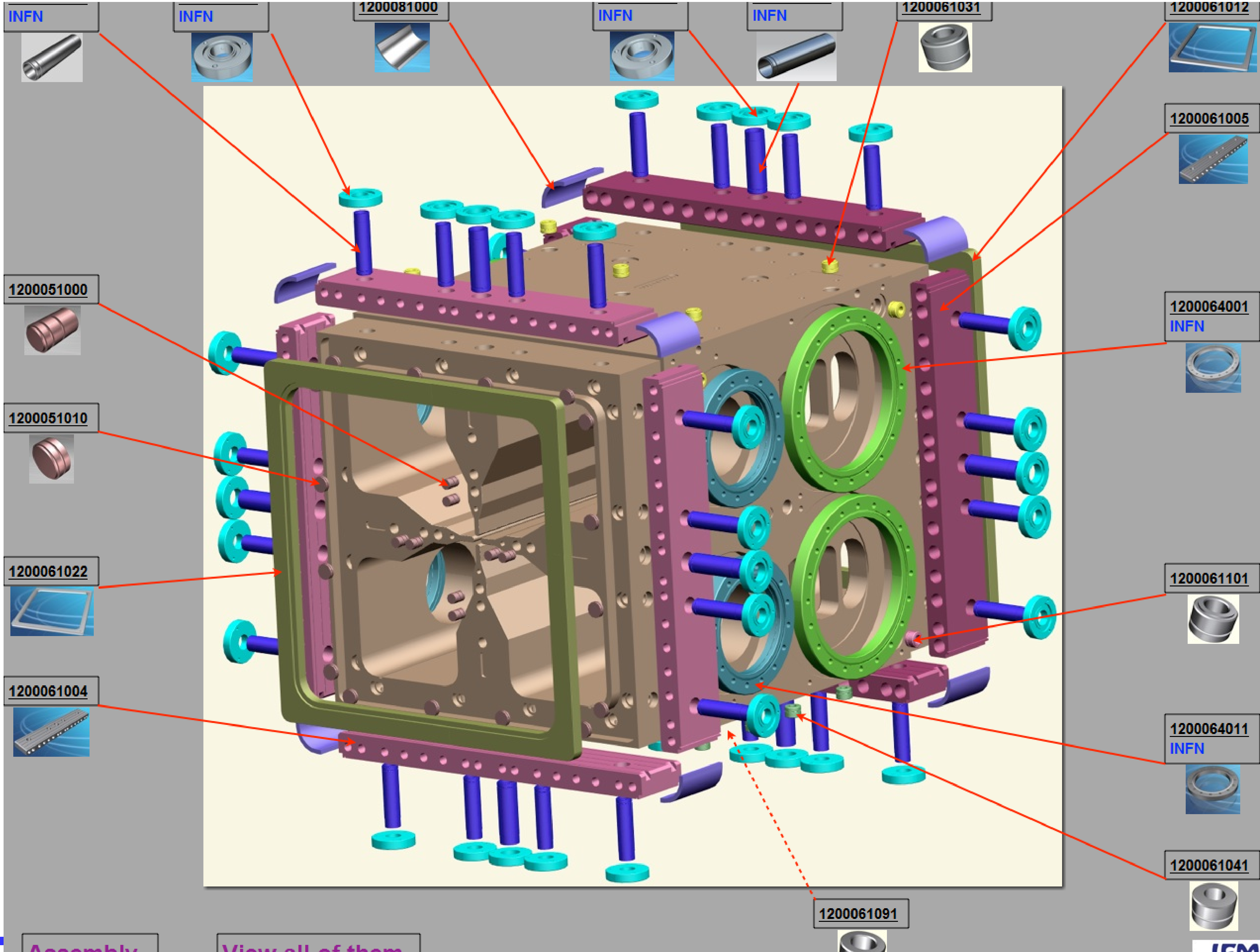
Head flange







Vacuum grids machined from bulk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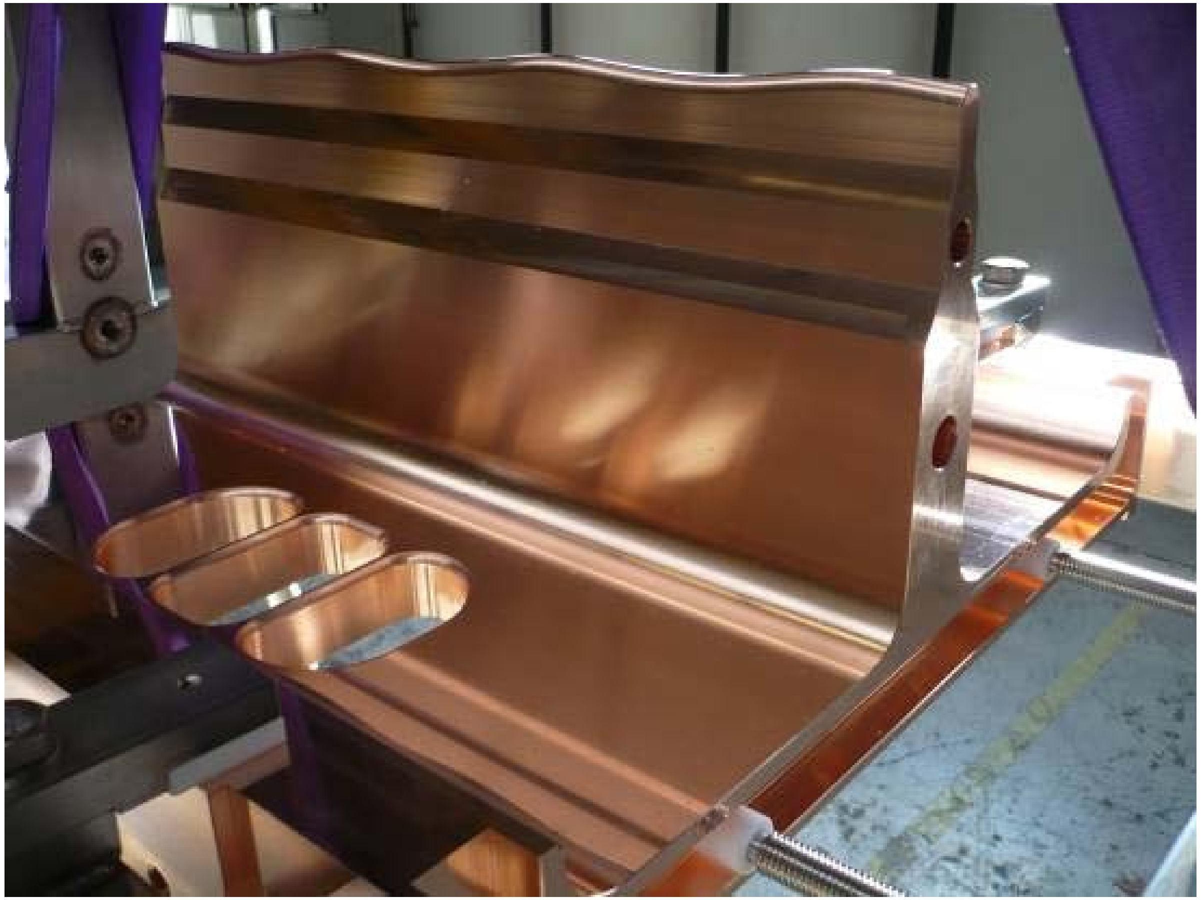
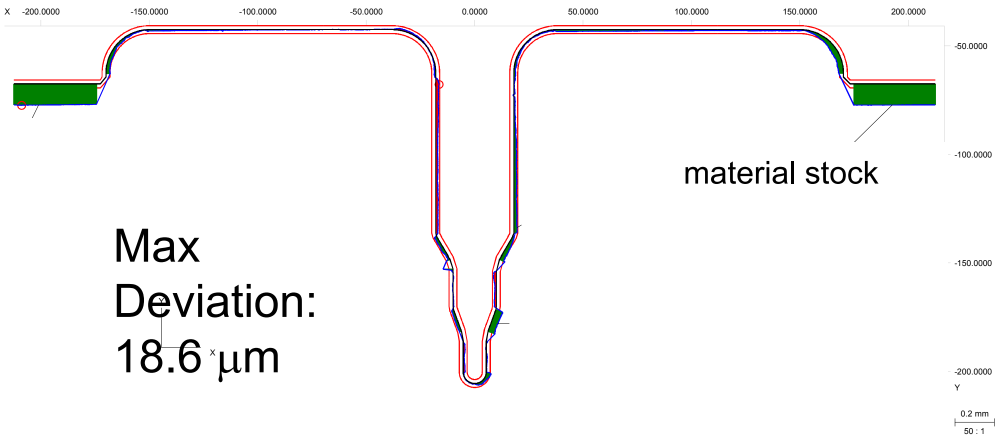
Finishing

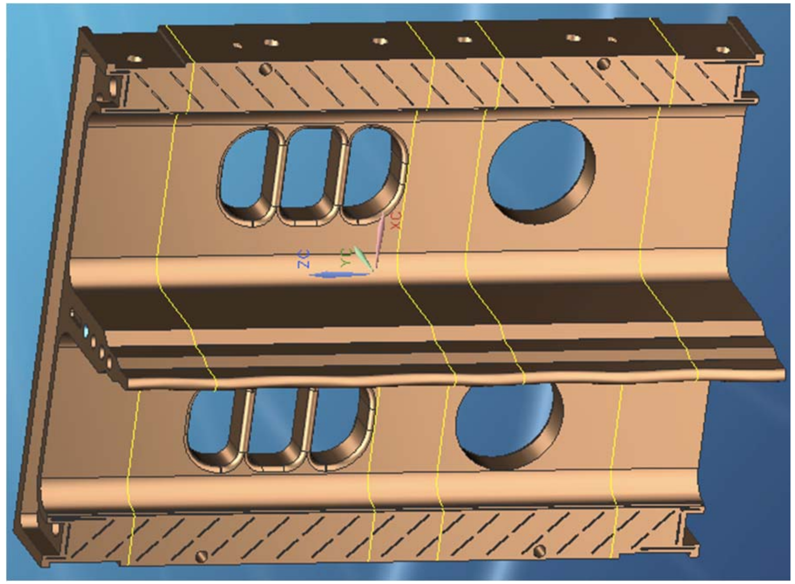
- 0.7 um roughness
- 3d modulation
- 20 um tolerances on vane tip geometry

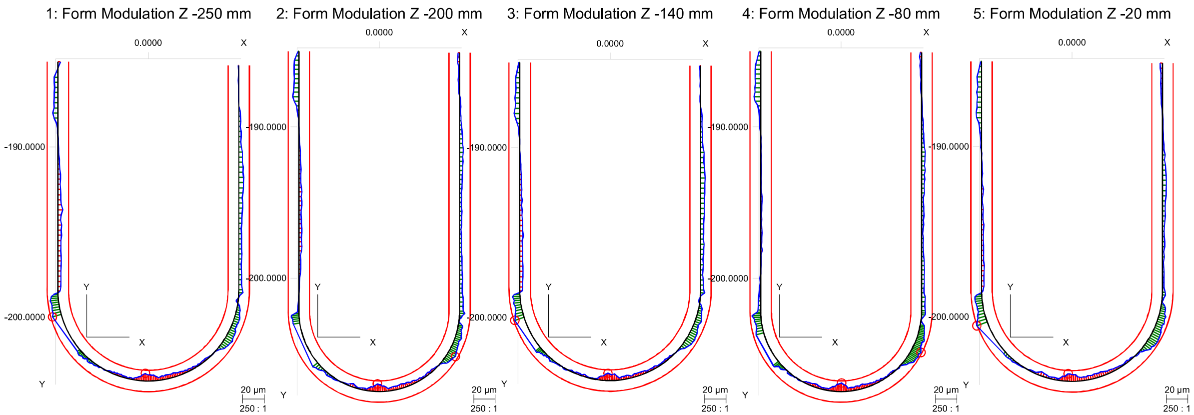


Four electrodes of module #16 electrodes (machined by Cinel) in specs

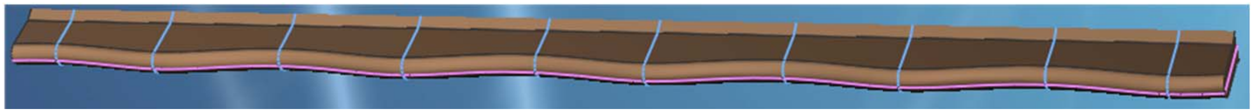


Max Deviation: 18.6 μm

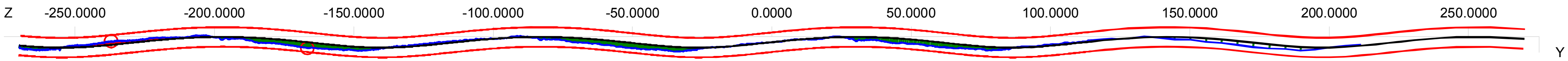




Max Deviation: 10.5 μm



Max Deviation: 6.1 μm



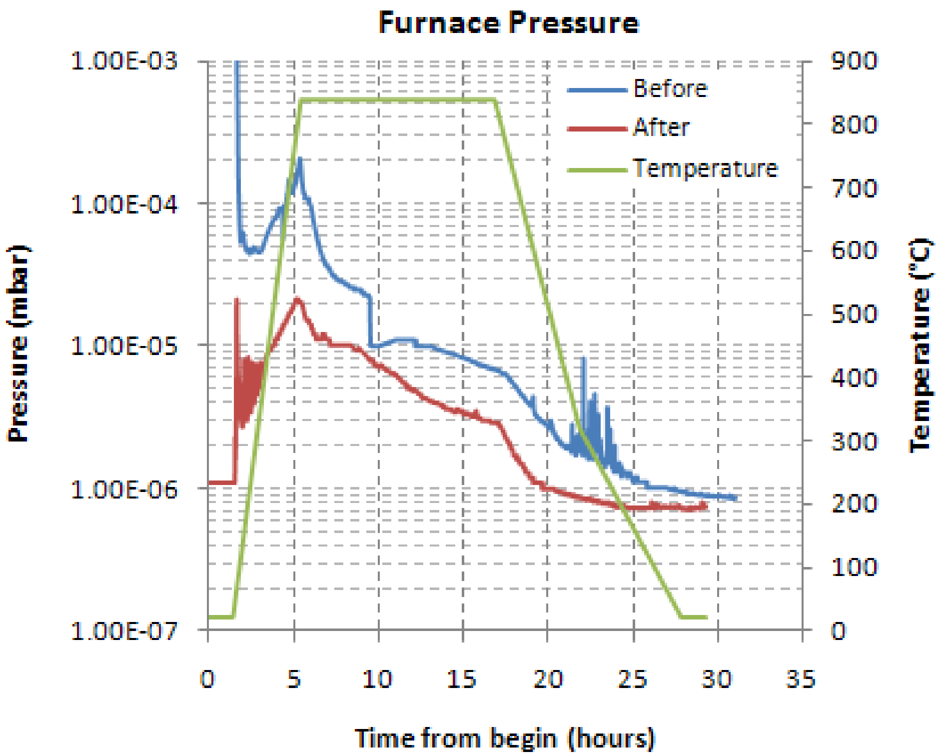
INFN development for Brazing

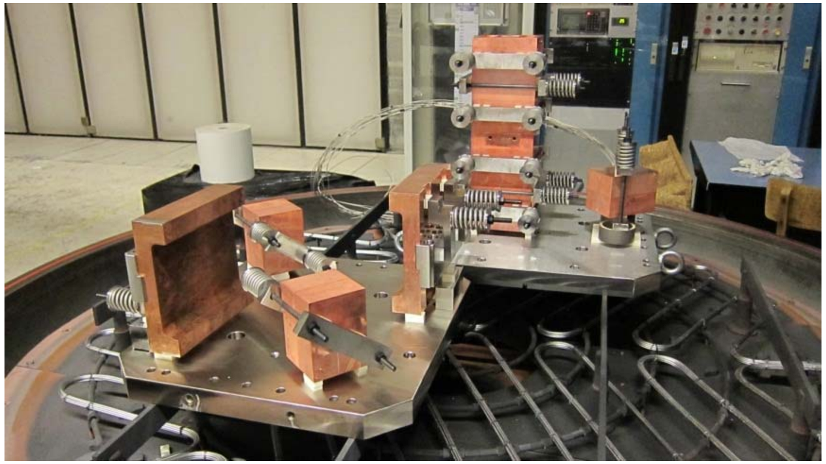
Necessary for the large production (18 modules could not be done at CERN).

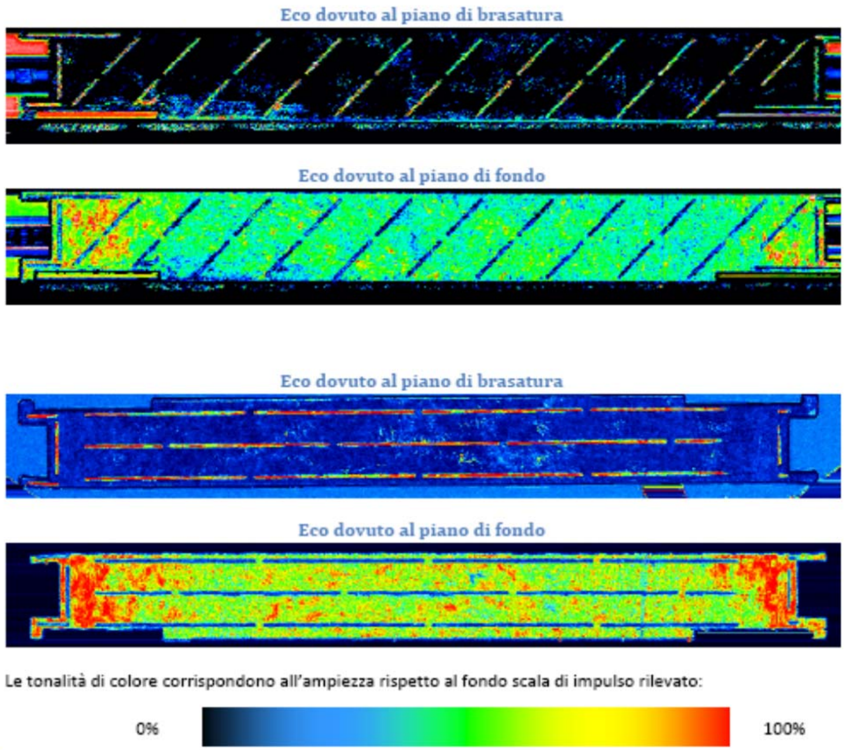
Vacuum oven in INFN LNL

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







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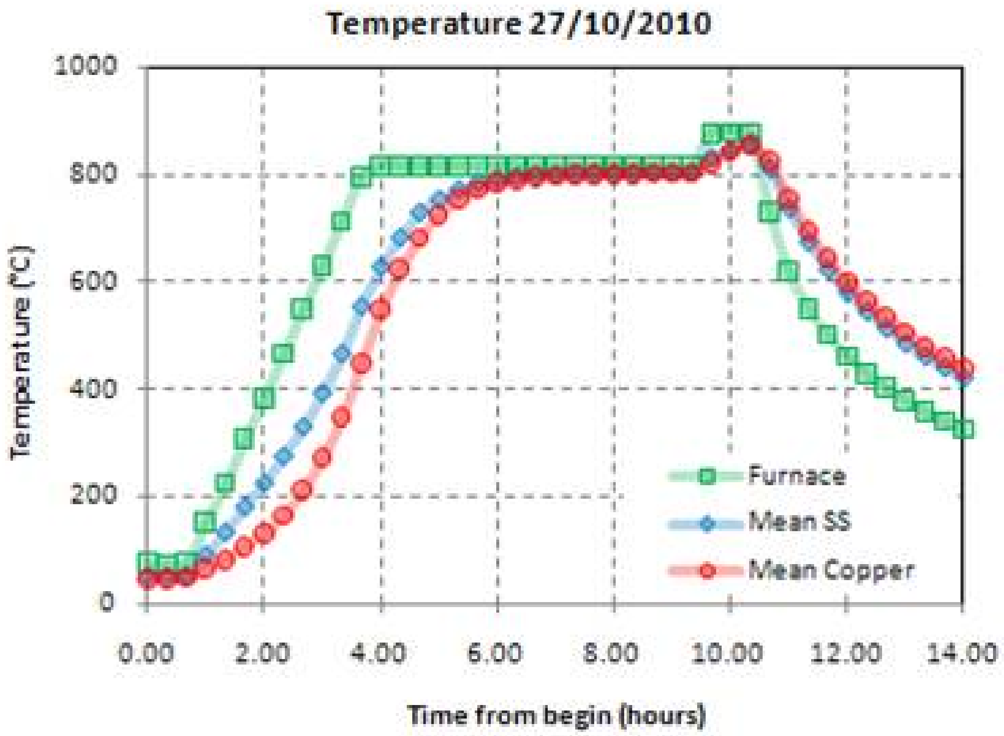
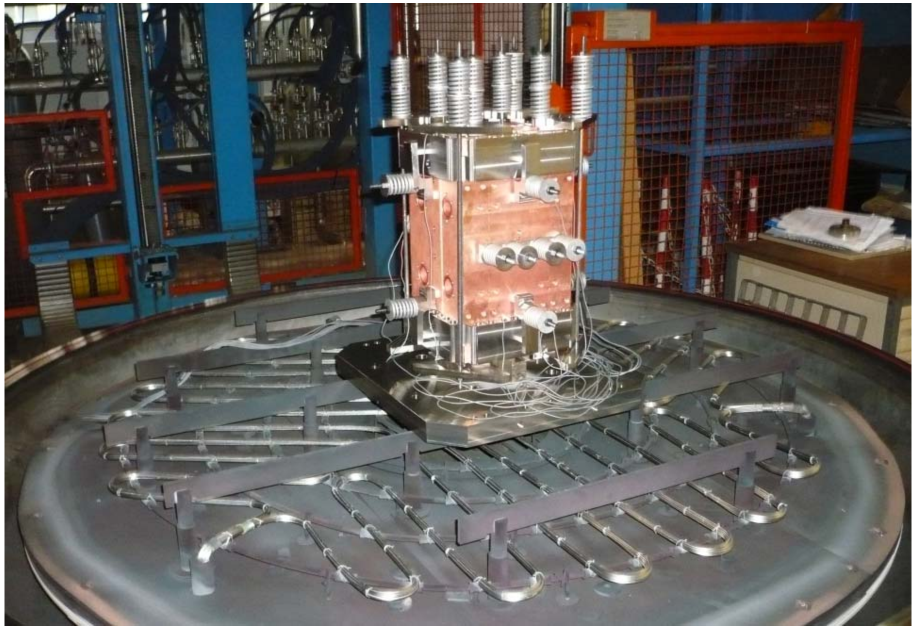
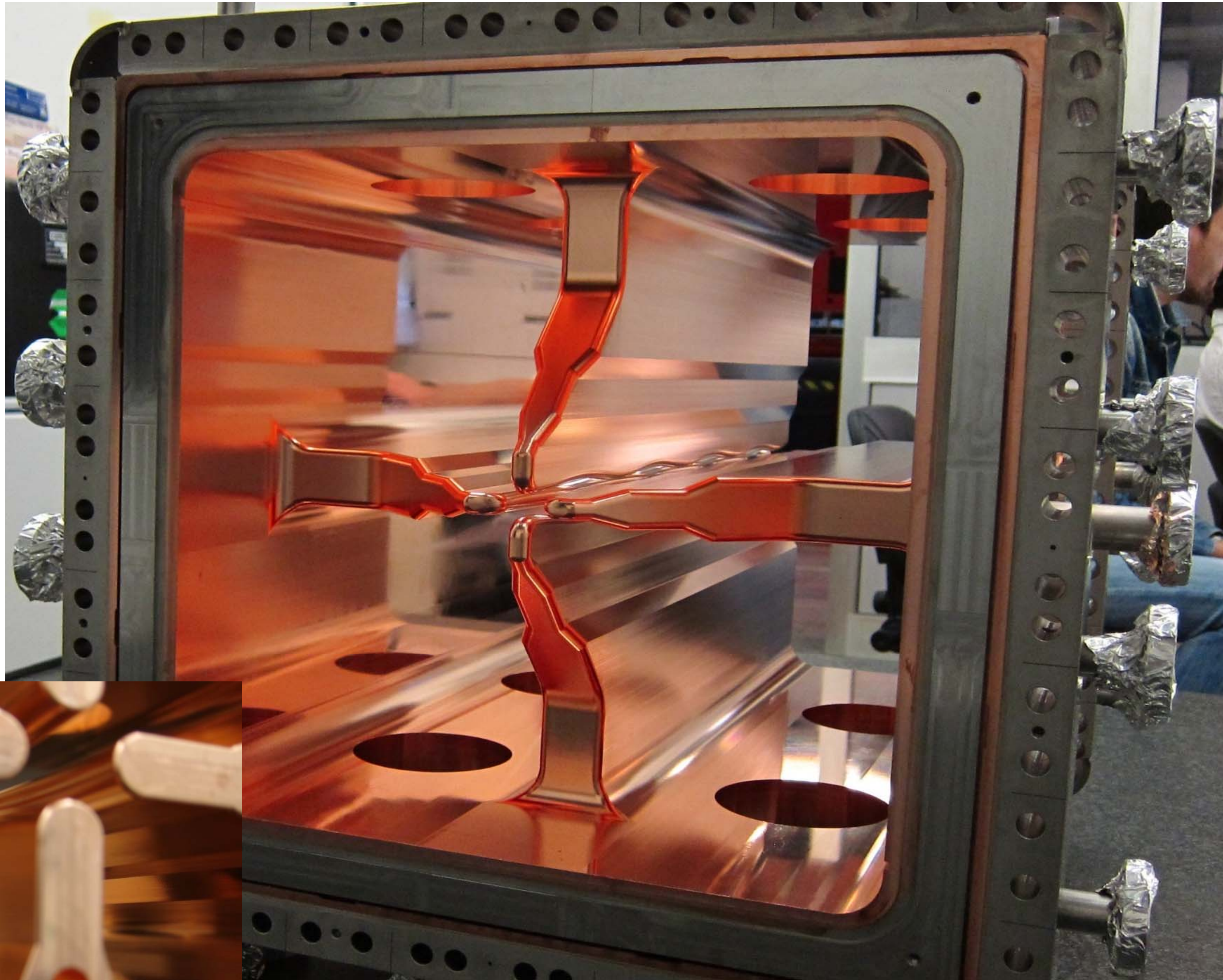
Brazing at LNL (2/2)

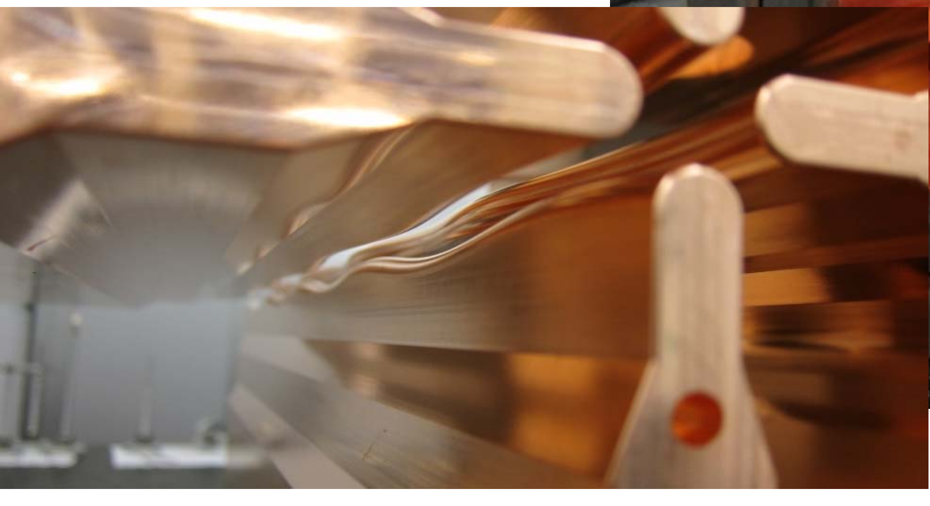
- Chemical preparation
- Brazing





Module 18 by Cinel (single brazing, perfectly within tolerances)





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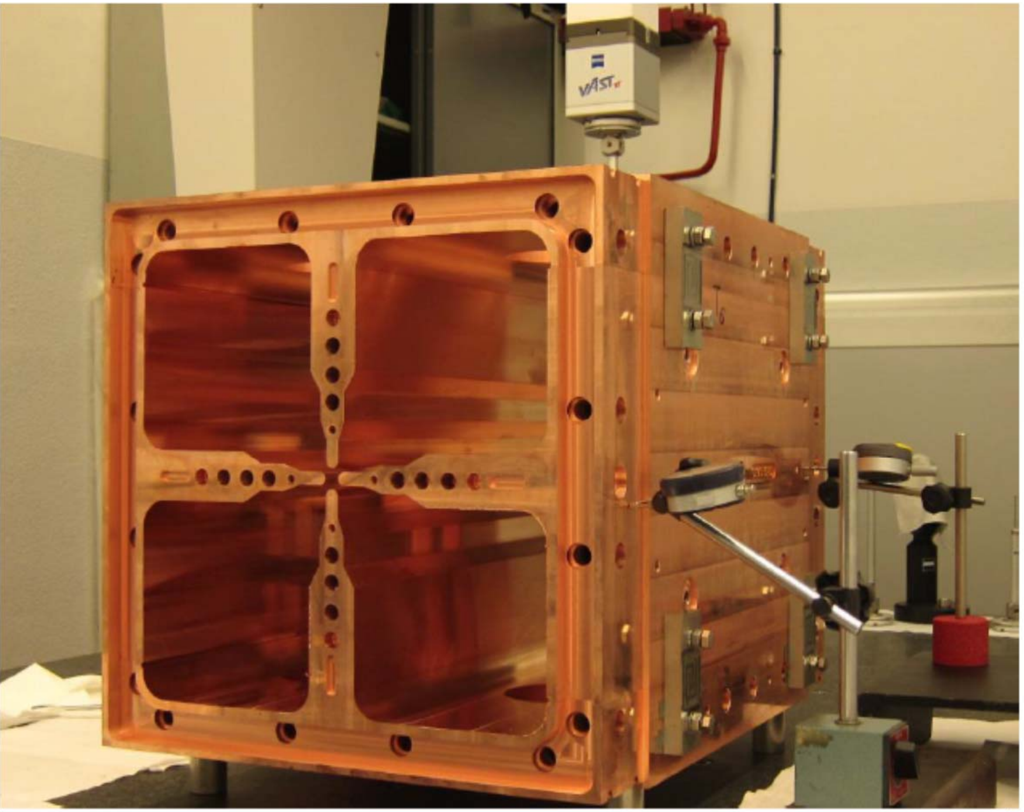
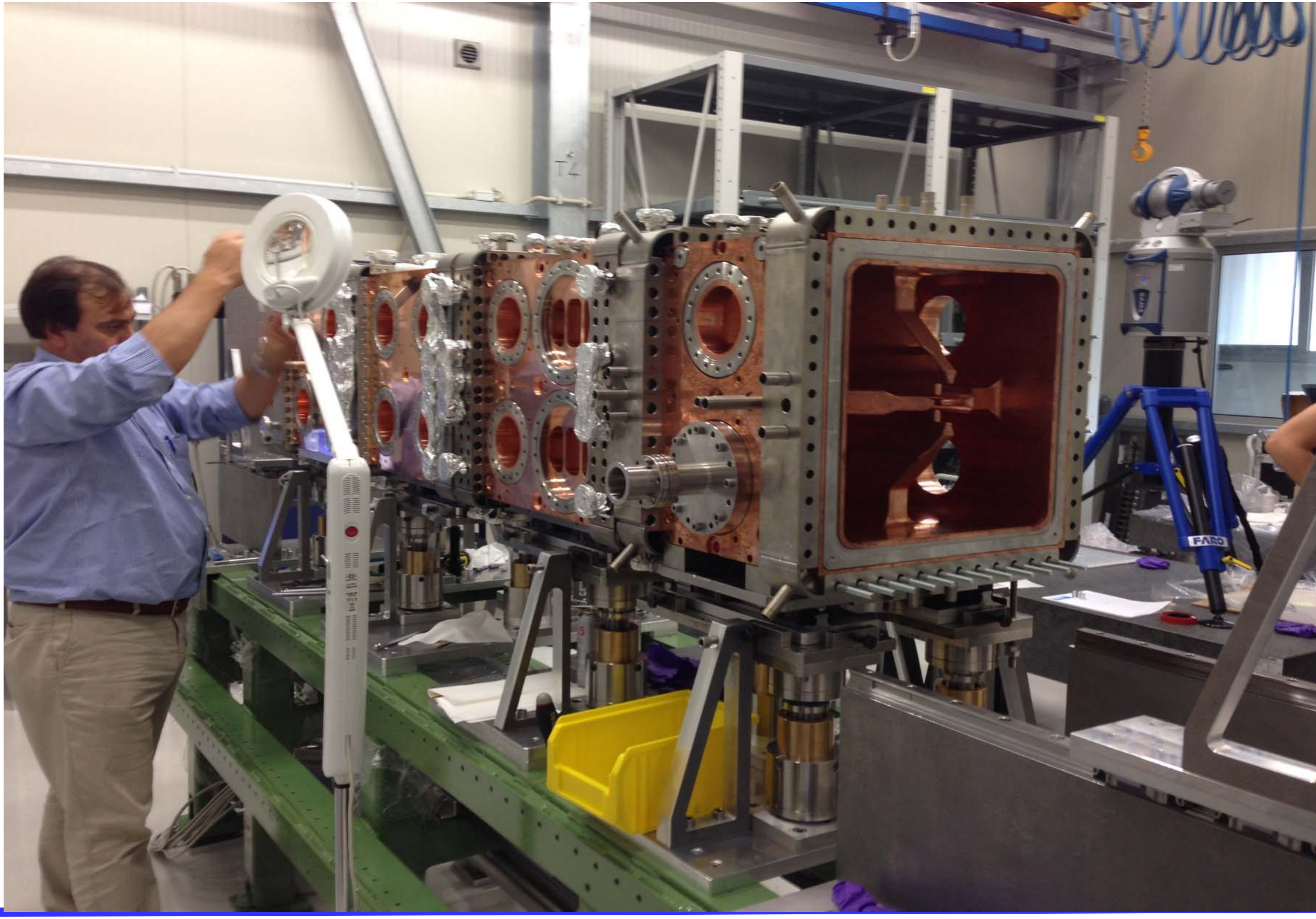
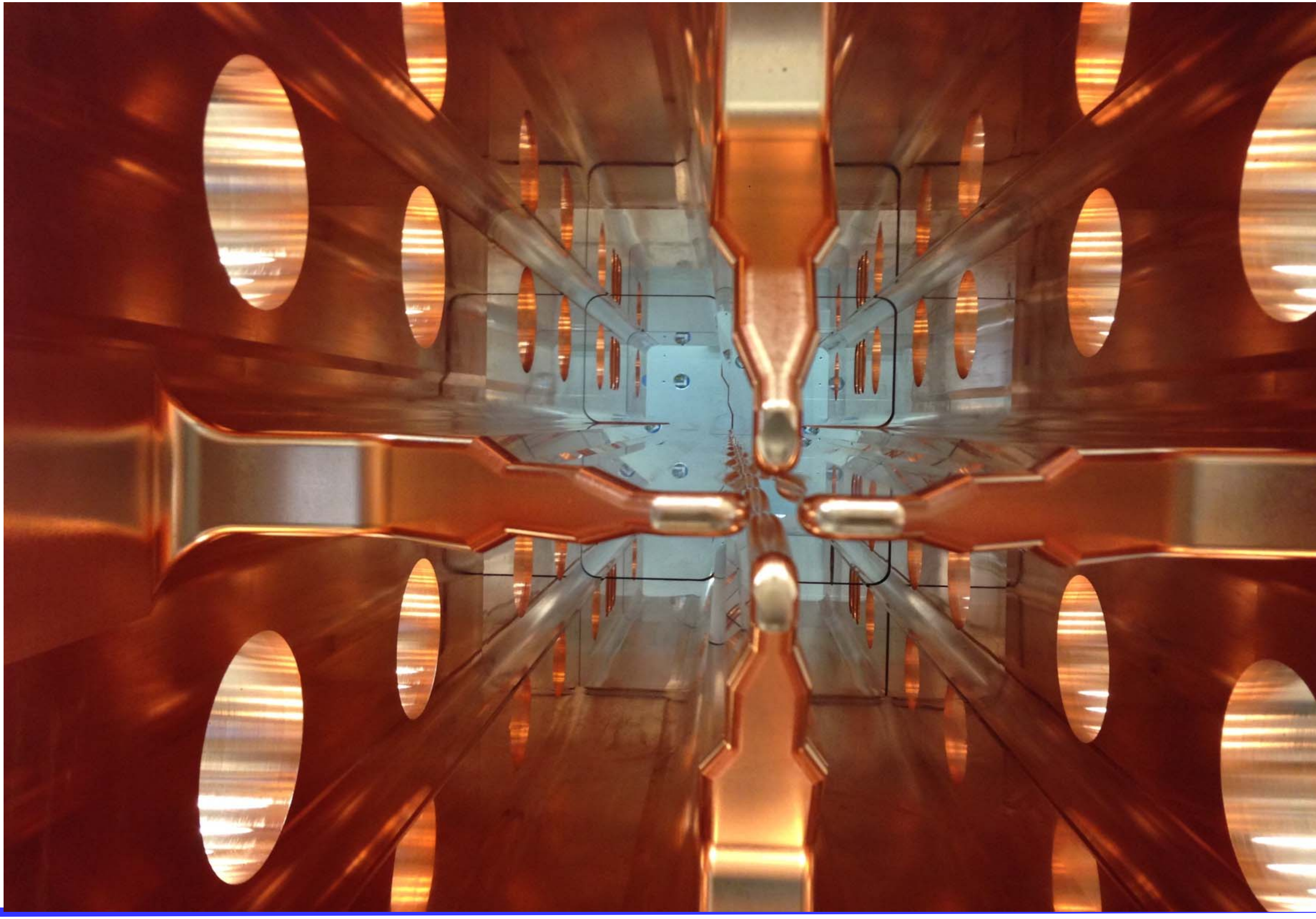


The M_12 during the alignment before RF test and the common planes milling @Metrological Lab INFN PD.

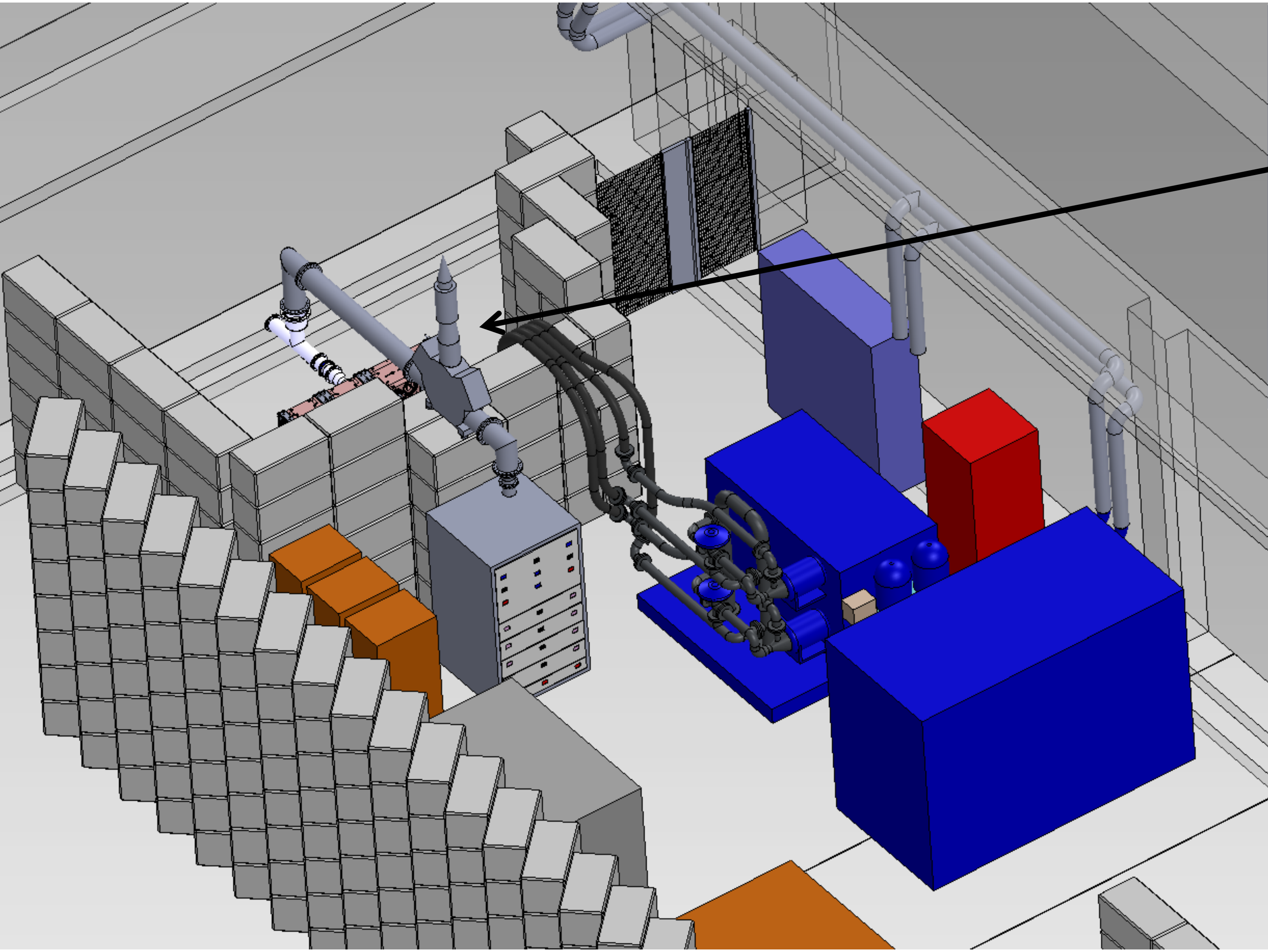
RFQ alignment (outside view)

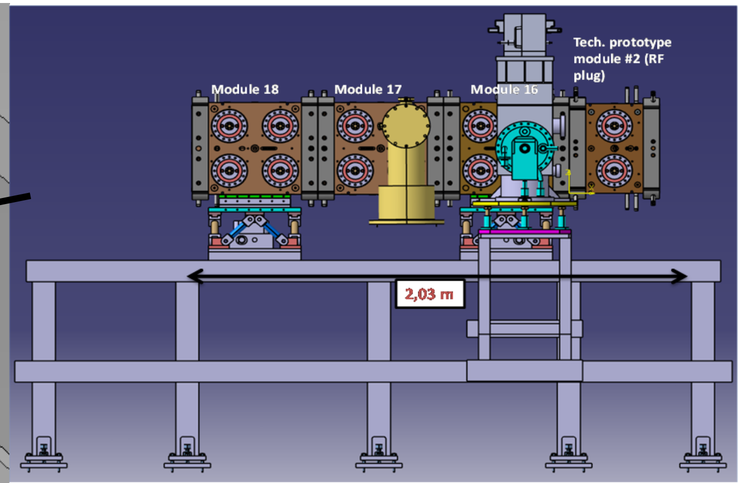


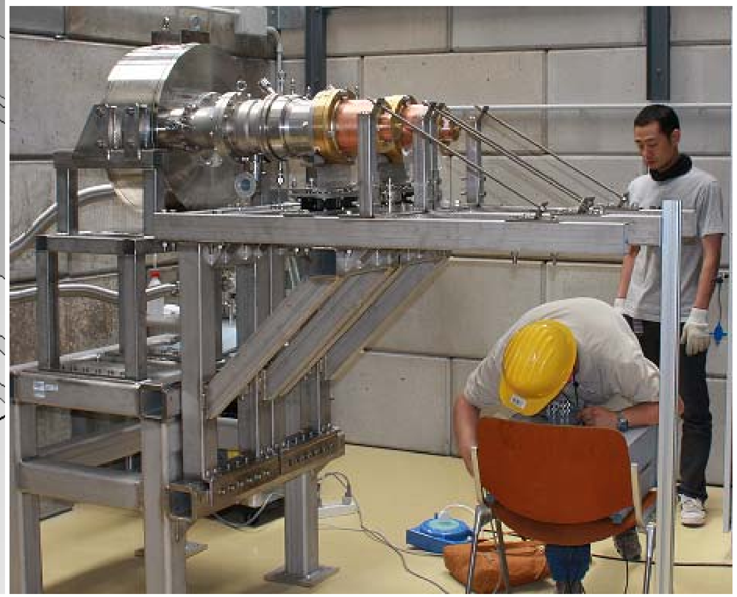
RFQ alignment (inside view)



RF power TESTs at LNL
(partial structure 220 kW 175 MHz)



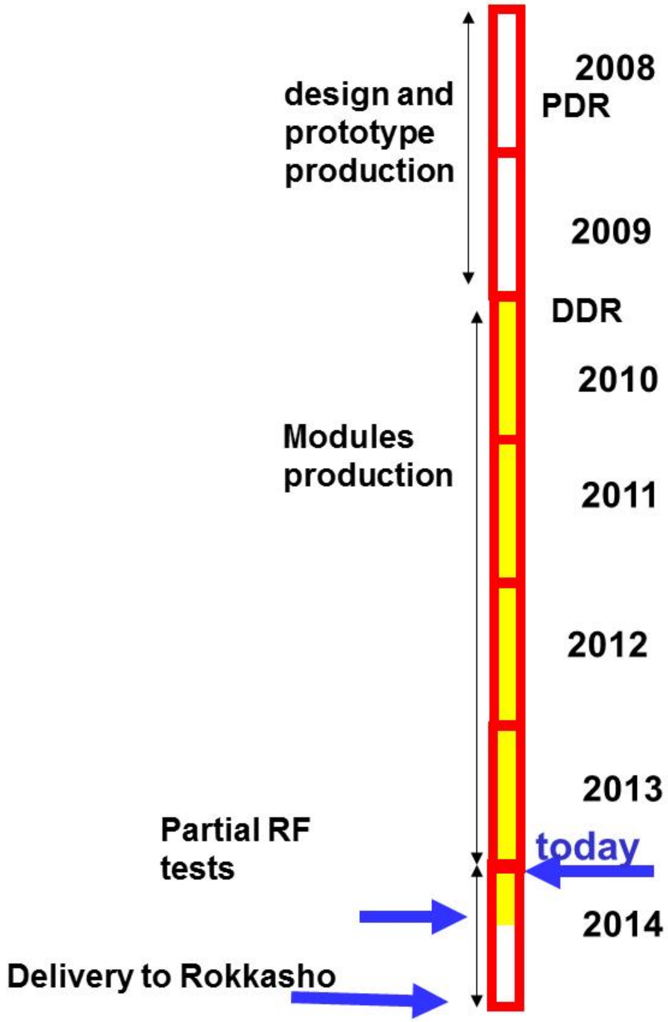




RFQ module and RF couplers ready for high power tests

Status of module production

- High energy supermodule (Cinel): complete except brazing of M13 that needs reparation.
- 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.



Conclusions

- IFMIF is a high intensity neutron source, based on two high intensity accelerators and a 10 MW liquid lithium target.
  - IFMIF EVEDA RFQ is under construction, (12 modules given to industry, 6 modules will be machined at INFN PD and brazed at LNL).
  - Partial high power tests in Legnaro in the next months, delivery n Rokkasho end 2014
- MUNES is a small size accelerator based neutron source, designed for BNCT and nuclear waste classification,
  - The source is very intense (10^{14} neutrons/s) and relatively compact (suitable to be installed in a Hospital or in a nuclear disposal enviroment).
  - It is based on a high performance proton RFQ and a high power be target, so the main challanges are to obtain the best reliability for those technologies.
  - The specific choices like the kind of target (Be solid, water cooled) and kind of RF system (solid state) are done in this direction.

- Thanks to many collegues that have contributed to the preparation of this talk, in particular J. Knaster (IFMIF project leader), A. Pepato, E. Fagotti, M. Comunian, P. Colautti, Laura Evangelista (IOV)