High power low energy accelerators for neutron production: MUNES and IFMIF-EVEDA case

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On behalf of MUNES and IFMIF collaboration

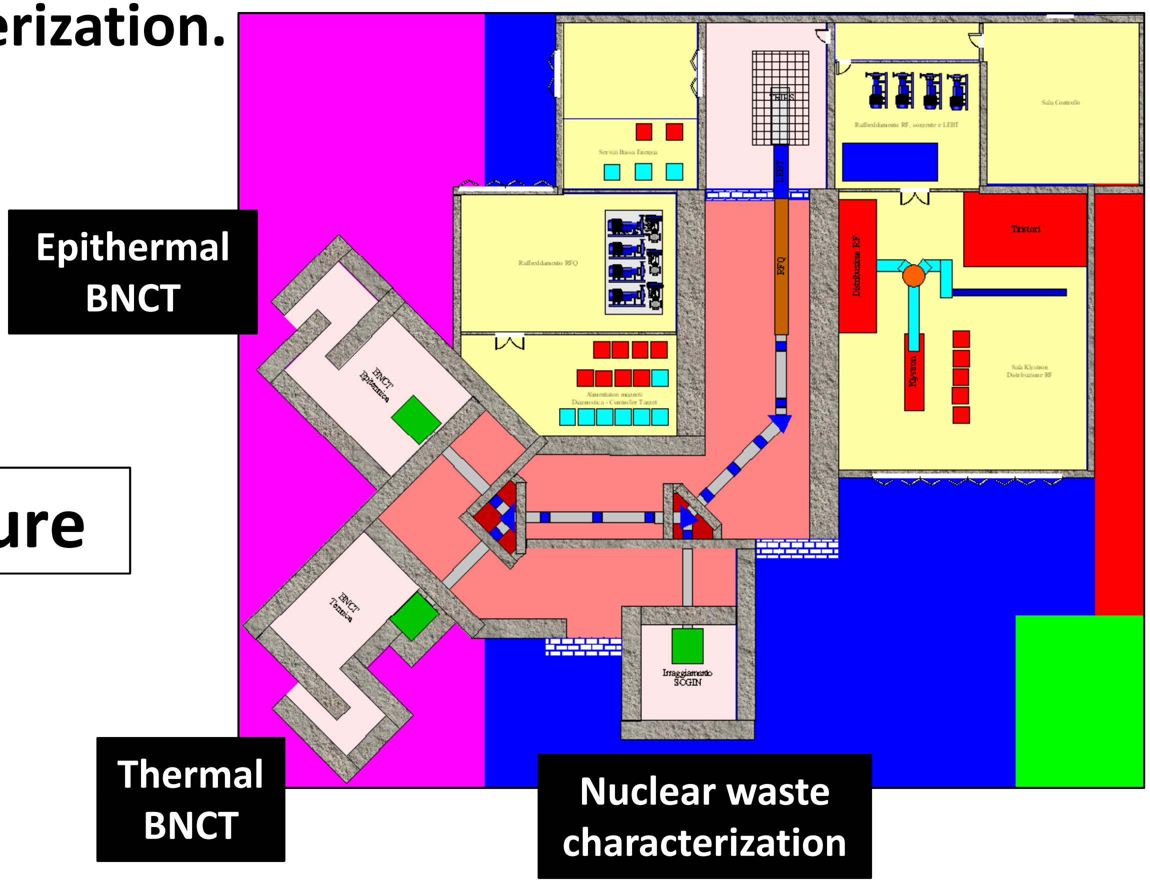
Outline

- **MUNES**
  - **Project overview**
  - **BNCT application**
  - **Nuclear wastes characterization**
  - **High intensity accelerator status**
  - **Target status and future perspectives**
  - **Conclusion**
- ***IFMIF-EVEDA***
  - ***Accelerator status***

MUNES main Goal

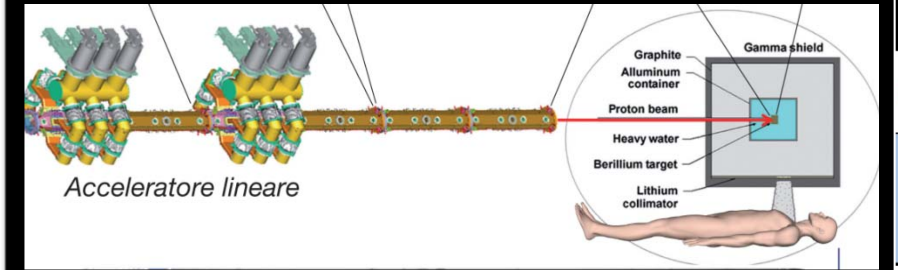
MUNES is a three year project, the goal of which is the realization of a thermal and an epithermal neutron source for BNCT and for radioactive waste characterization.

Research Infrastructure



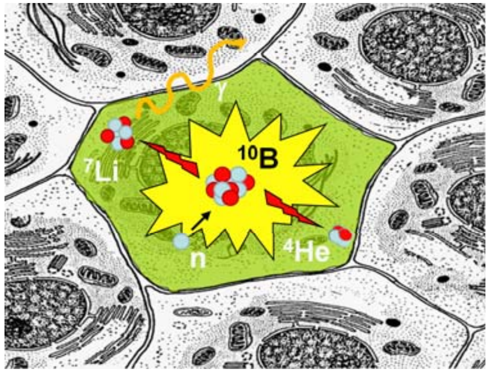
Main parameters

Accelerator type: LINAC
Proton current: up to 50 mA
Proton energy: 5 MeV
Time structure: up to CW
Beam power: up to 250 kW
Neutron converter: Be
Operative power density on Be target: 700 Watt/cm^2
Neutron source intensity: 10^{14} s^{-1}
Main application: BNCT



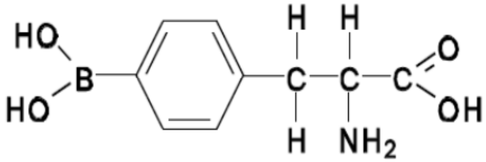
	Φ_{th} (E≤ 0.5 eV) ($cm^{-2}s^{-1}$)	Φ_{th} / Φ_{total}	$K_{n\,(E>0.5\,eV)}$ / Φ_{th} (Gy·cm^2)	K_γ / Φ_{th} (Gy·cm^2)
LNL neutron source	4.3E+09	0.96	0.33E-13	0.92E-13
IAEA recommendations for BNCT	> 1.0E+09	> 0.90	≤ 2.0E-13	≤ 2.0E-13

Boron Neutron Capture Therapy (BNCT)

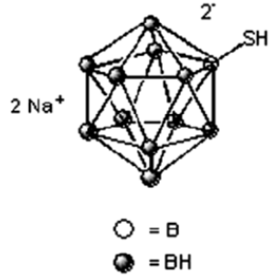


Boron Neutron Capture Therapy (BNCT) is an experimental binary radiotherapy which exploits the neutron capture reaction $^{10}B(n,\alpha)^{7}Li$ induced by thermal neutrons (<E> = 25 meV).
The α-particle and ^{7}Li recoiling nucleus are high LET and short range (< mean cell diameter ≈ 10 μm) particles able to deposit their energy entirely inside the ^{10}B loaded cell.

BPA



BSH

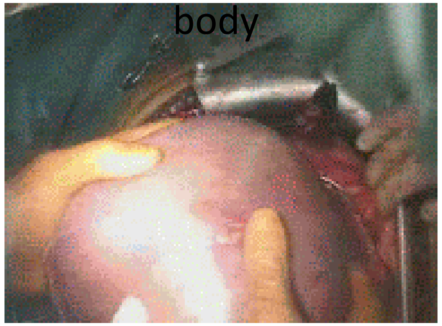


In this way the selectivity of BCNT depends on ^{10}B distribution and not on the irradiation field. This feature makes BNCT a valid option against the diffused tumors
Another crucial aspect for the good outcome of the treatment in the availability of ^{10}B carriers able to realize a selective delivery. The clinically approved molecules are BSH and BPA. Nowaday, the major challenge in BNCT research is the development of more dedicated carriers.

BNCT at Pavia: the TAOrMINA method

The therapeutic concept is based on the irradiation of the isolated, previously ^{10}BPA-infused organ in a neutron field where neutrons coming from all directions can irradiate the whole liver

After BPA infusion the liver is removed from the patient body



It is washed and put into 2 teflon bags

and then put into a teflon container

and irradiated into the reactor

Two terminal patients affected with colon adenocarcinoma liver metastases were treated in Pavia with the TAOrMINA method between 2001 and 2003.
In both cases, about 10 days after treatment the CT scanning evidenced the liver in normal condition while the adenocarcinoma metastases appeared in a necrotic state.

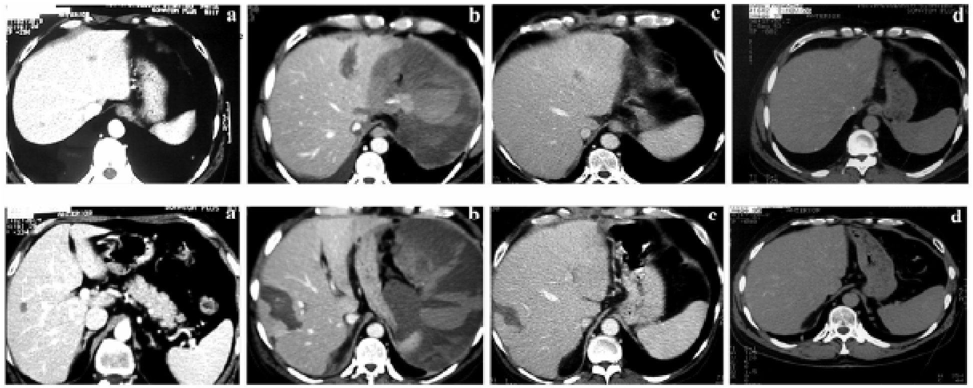


Figure 6. Sequence of CT images of the liver on a cranial (above) and a caudal (below) level in the first patient subjected to BNCT. Evolution at different times of the metastases towards necrosis with final substitution by normal hepatic tissue. (a): pre-operatively; (b): at 7 days, (c): at 6 months; (d): at 12 months after the procedure.

Nuclear waste characterization

- Part of the management of radiactive waste produced in Italy by industrial research and medical processes is analyzed by 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

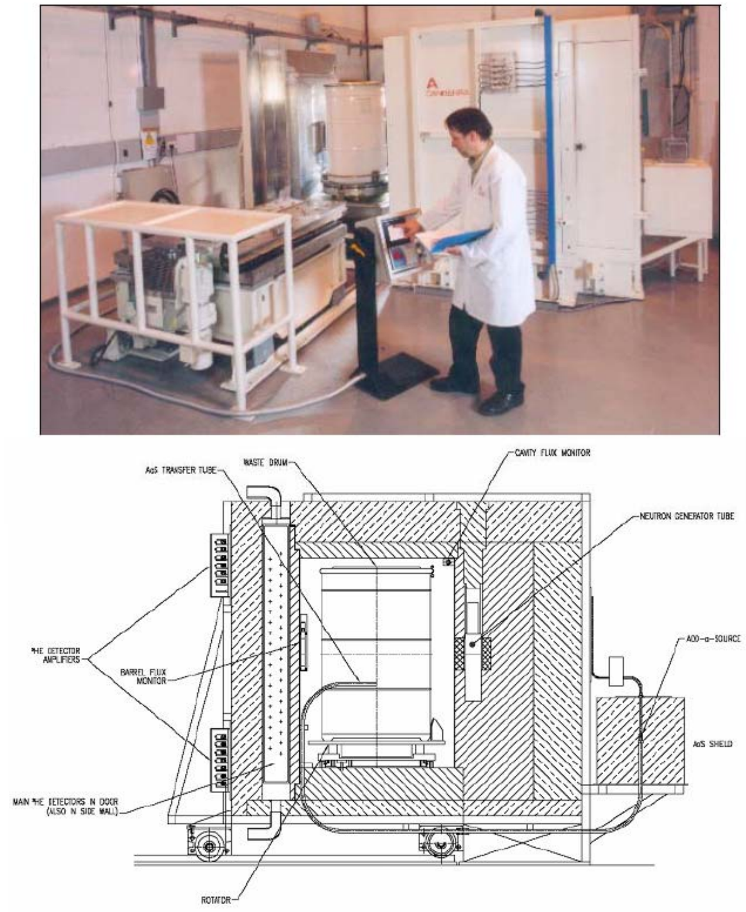


Fig. 1. Photograph and cut-away side view of the PANWAS System

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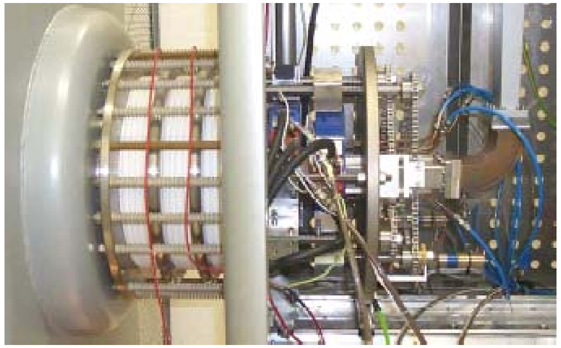
High Intensity Accelerator Status

Proton Source

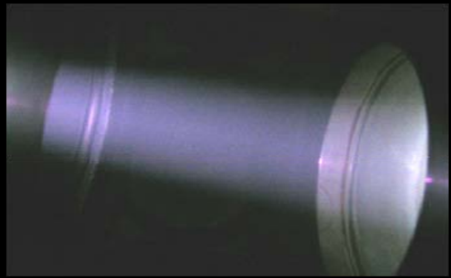


PS developed at LNS (2000)

PS optimized at LNL with magnetic shielding (2007)

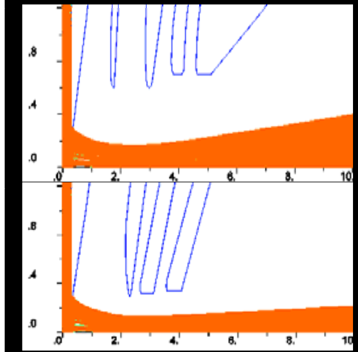
STATUS

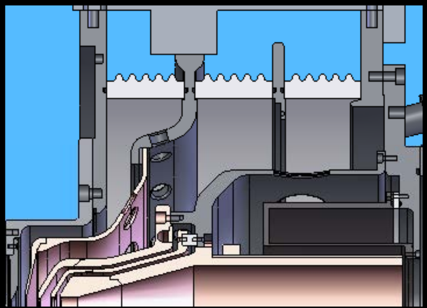
$I_p \approx 45$ mA
E = 80 KeV
$\varepsilon_{n,rms} < 0.1$ mm-mrad
$\varphi_b(z = 200 \text{ mm}) = 34$ mm
Beam time structure: CW

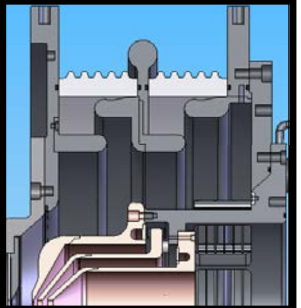


NEAR FUTURE

$\varphi_b(z = 200 \text{ mm}) = 10$ mm
[New extractor design] [LNL]

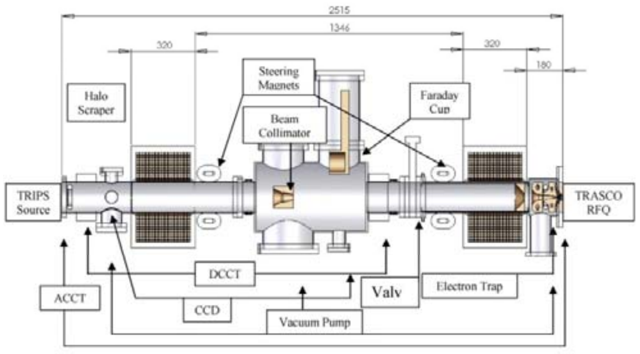




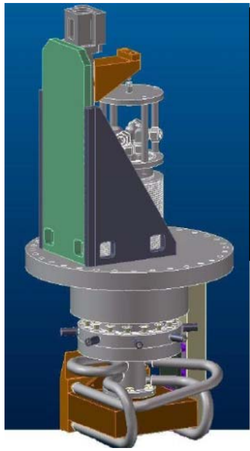


Beam time structure: CW & pulsed

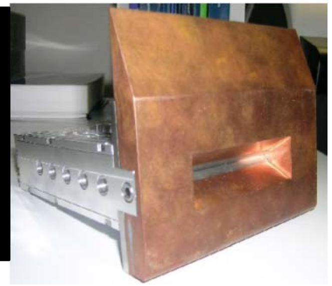
Low Energy Beam Transport

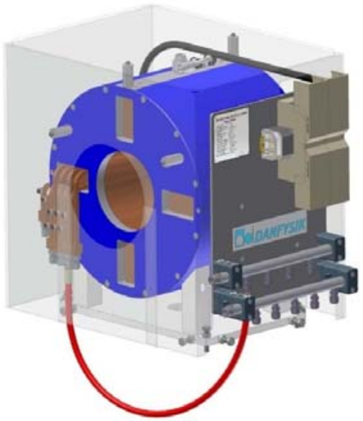


LEBT developed at LNL



Fast Emittance Scanner (FES): high resolution q-q' rms emittance in less than 2 seconds

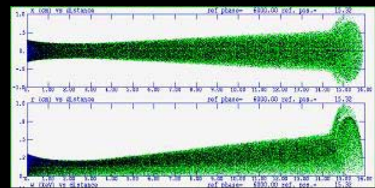




Solenoids developed at LNL

STATUS

LEBT ready for assembly with solenoids, pumping system, non interceptive profile and current diagnostics, interceptive profiler and termination FC.



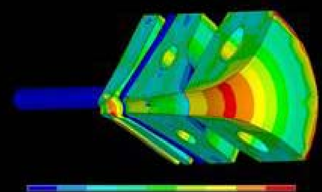
NEAR FUTURE

Neutralized transport optimization

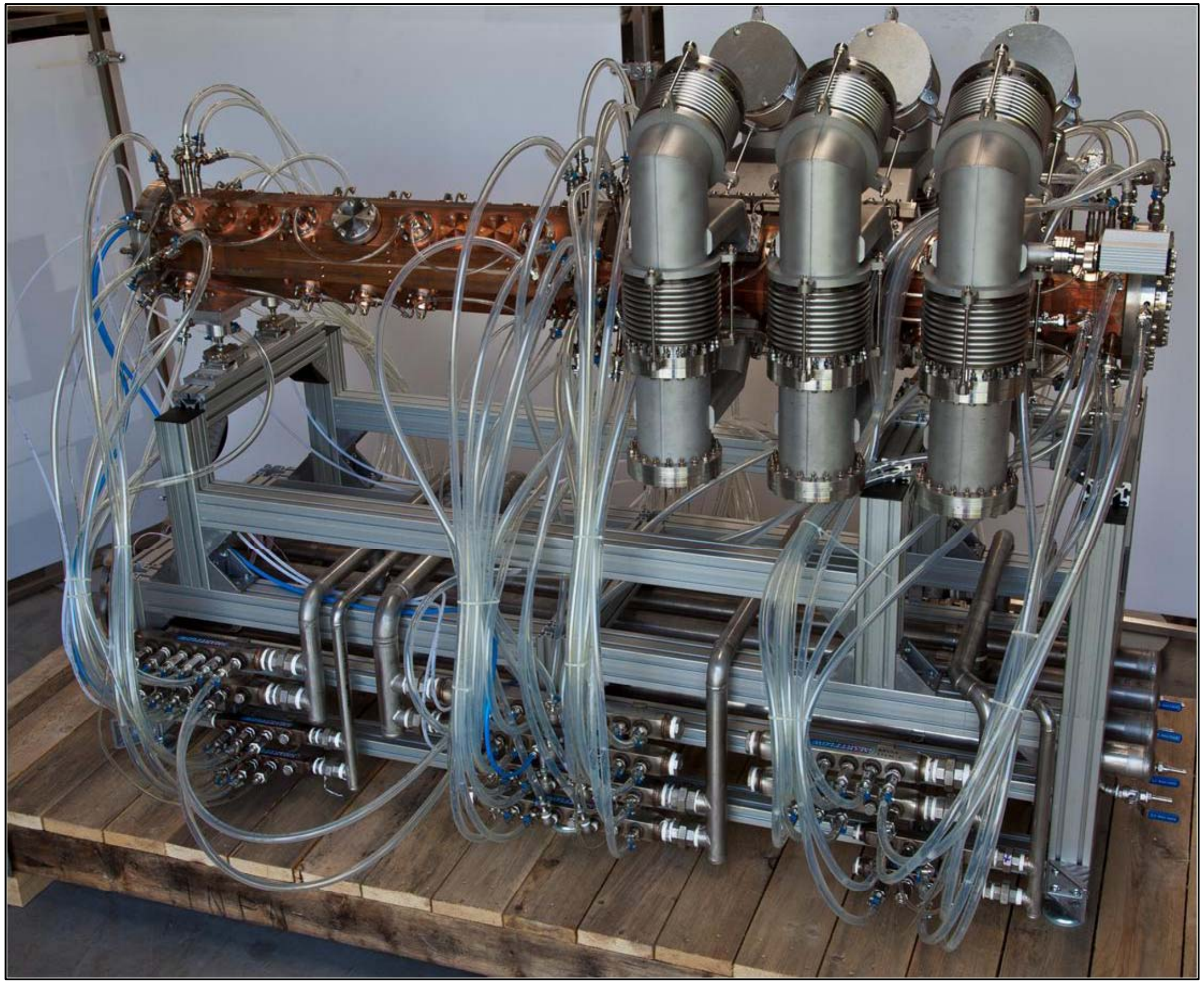
FGA development

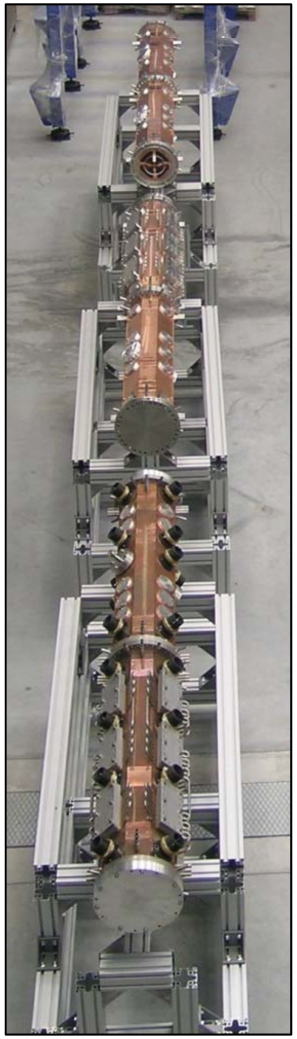
LEBT control system upgrade

e-trap construction

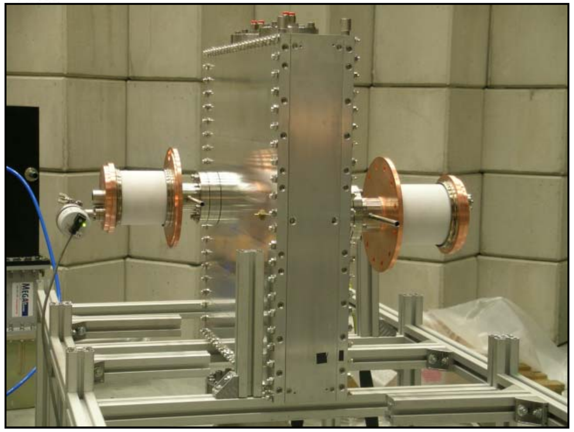


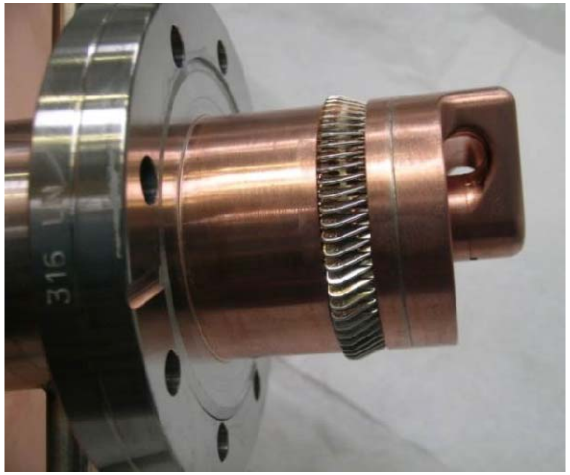
RFQ: Fabrication Complete



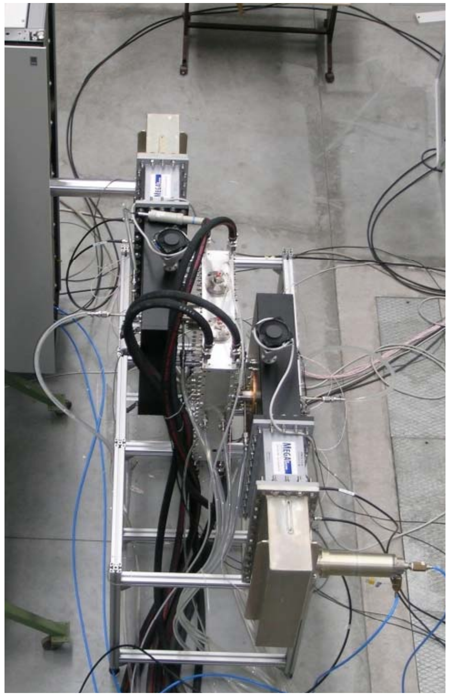


RFQ: RF coupler high power test



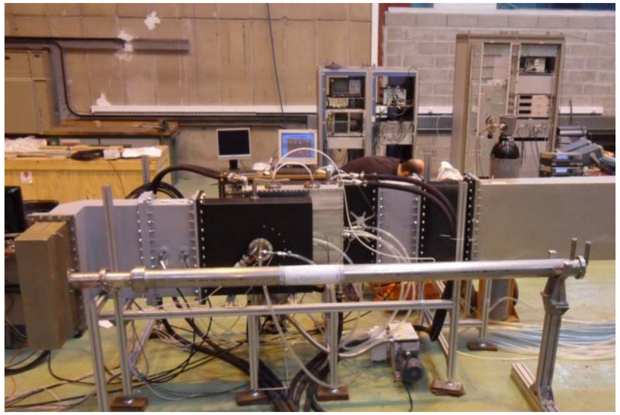


March 2011
10 kW couplers test



LNL

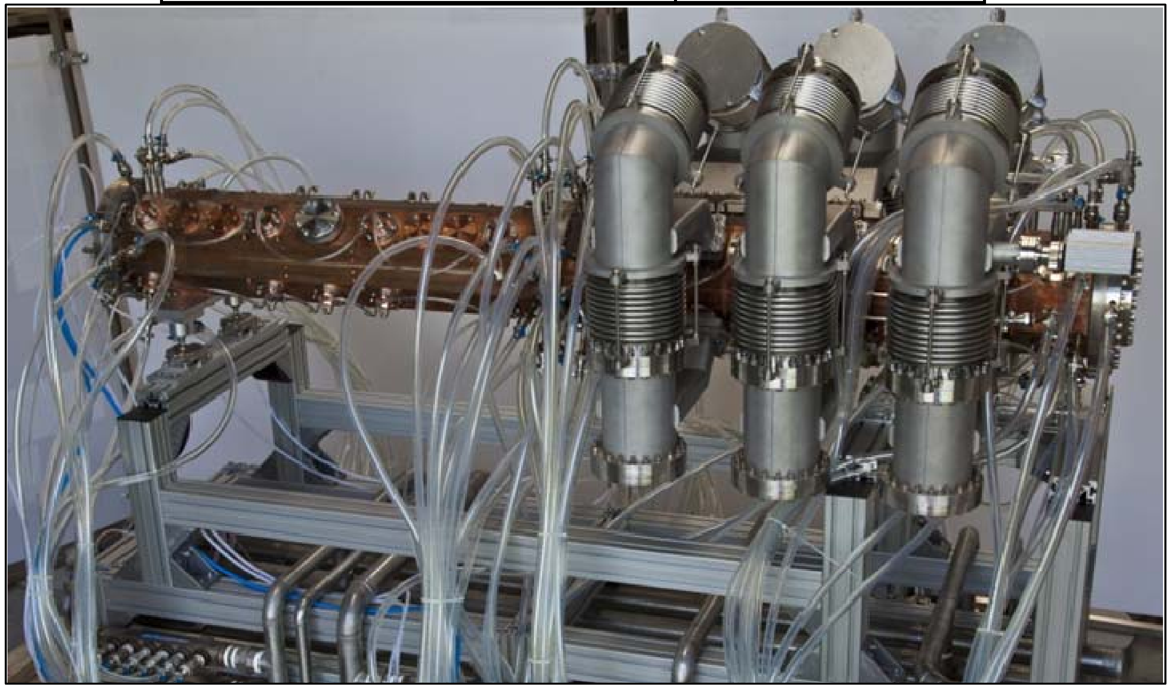
June 2011
150 kW couplers test



CEA Saclay

RFQ: First Segment High Power Test

First segment parameters	
Frequency	352.2 MHz
Inter-vane Voltage	68 kV (1.8 Kilp.)
Q_0 Expected(SF/1.3)	7600
RF Power diss. (exp.)	215 kW
Freq. detuning (full power)	-132 kHz
Field flatness	±1%



RF Test Stand at CEA

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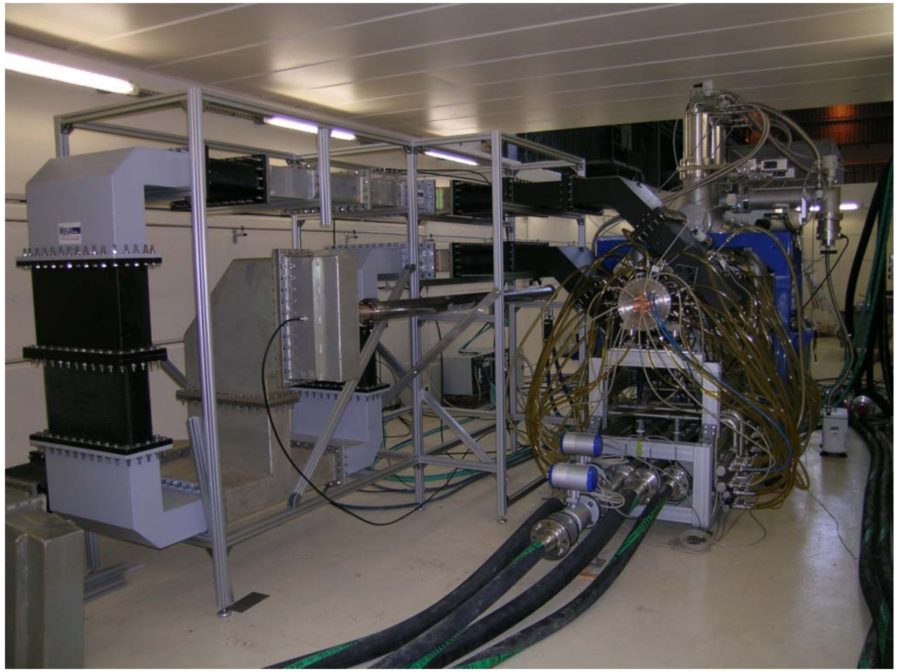
di Fisica Nucleare





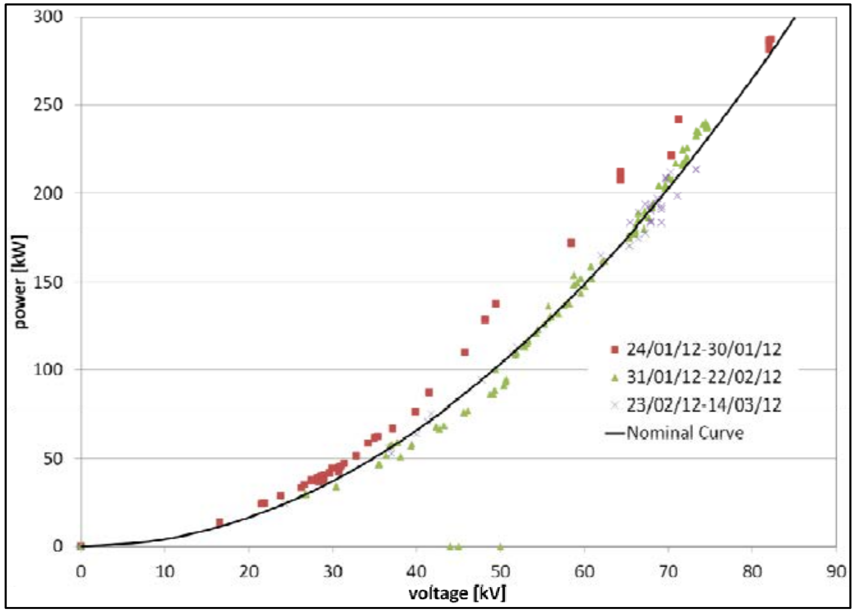

Collaboration agreement between INFN and CEA for TRASCO high power test in CEA Saclay



Results

Measured Parameters		Comments
Inter-vane Voltage	68 kV CW (1.8 Kilp.)	82 kV (2.2 Kilp.) with 0.4 ms 1.1Hz time structure
Q_0	8460	no degradation with RF joint opening
RF Power diss.	192 kW	80 kW/m
Freq. detuning (full power)	-238 kHz	thermal elongation of the noses near end plates
Field flatnes	±2%	same reason

Peak cavity power, obtained as function of the cavity voltage.



High Power Test Conclusions

- Nominal voltage achieved in steady state CW operation.
- 120 % of the nominal voltage achieved in pulsed mode (0.1% DC).
- Power balance requires 900 kW for accelerating 40 mA proton beam up to 5 MeV with 10 % of margin on cavity voltage.

New RF sources

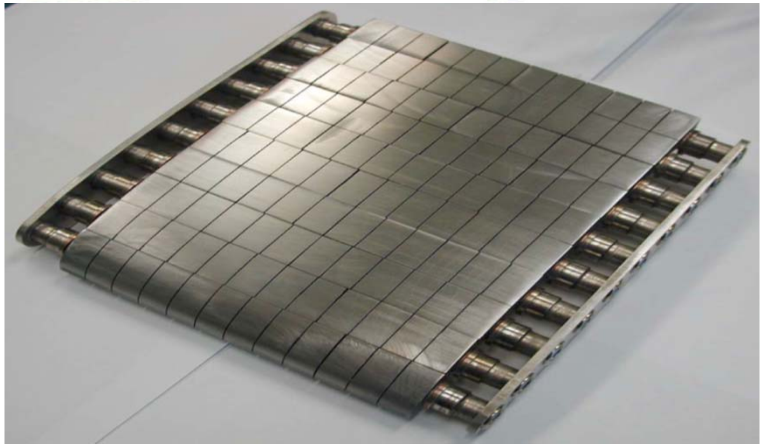
- High power solid state technology is matured to be implemented for hundreds kilowatts power sources
- Eight independent 125 kW SS amplifiers (one per RF coupler) will be used as power source for RFQ (first 125 kW RF module ready April 2016)

Advantage respect to high voltage power supply + CW klystron

- Lower capital and operating costs (cost and duration of components)
  - 2.5 M€ power supply + 0.5 M€ klystron VS 2,3 M€ SS power system
- Availability and reliability (no stop operation in case of components failure)
- Absence of high voltages (very important for in-hospital operation)

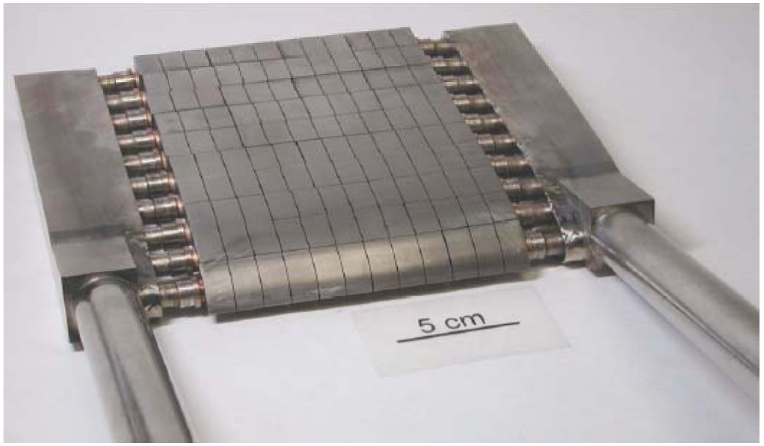
The Beryllium converter

1. Be-tile brazed cooling pipes with Zr adapters



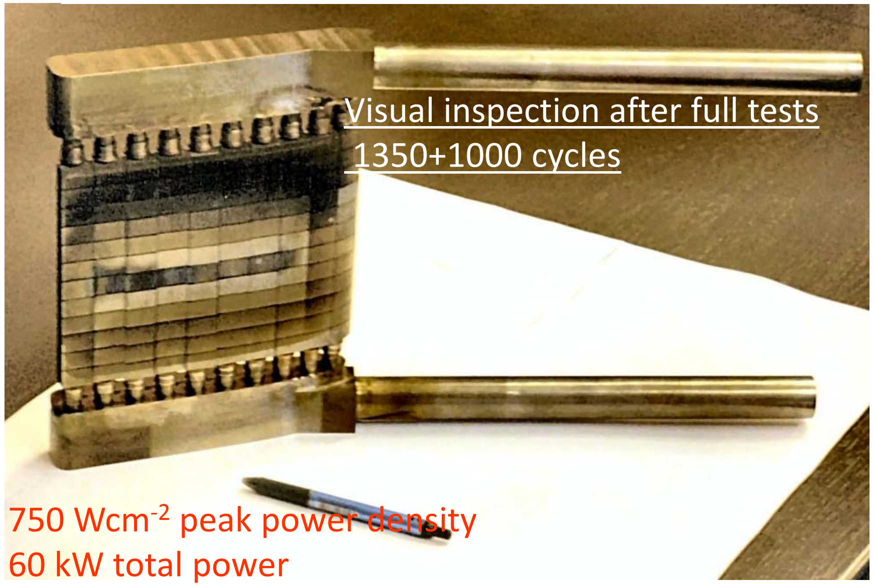
3. collector plates welding & EDM manufacturing process

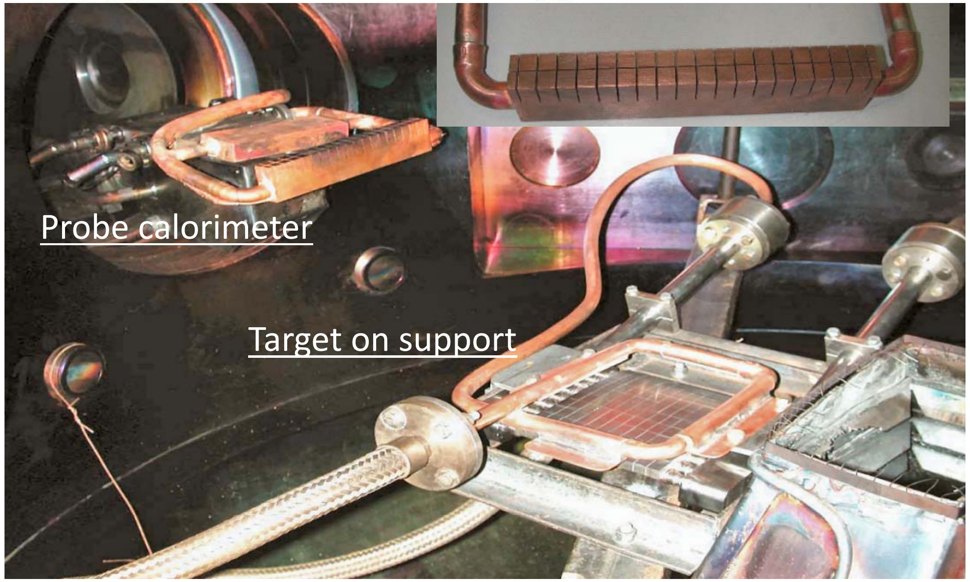
2. Zr cooling system manifold & collector plates

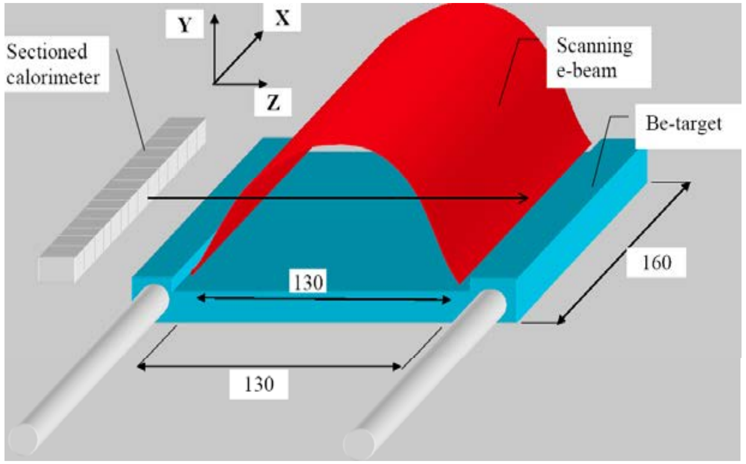


4. Half target: final assembling ready for e-beam test

Neutronconverter prototype: first e-beam full power test



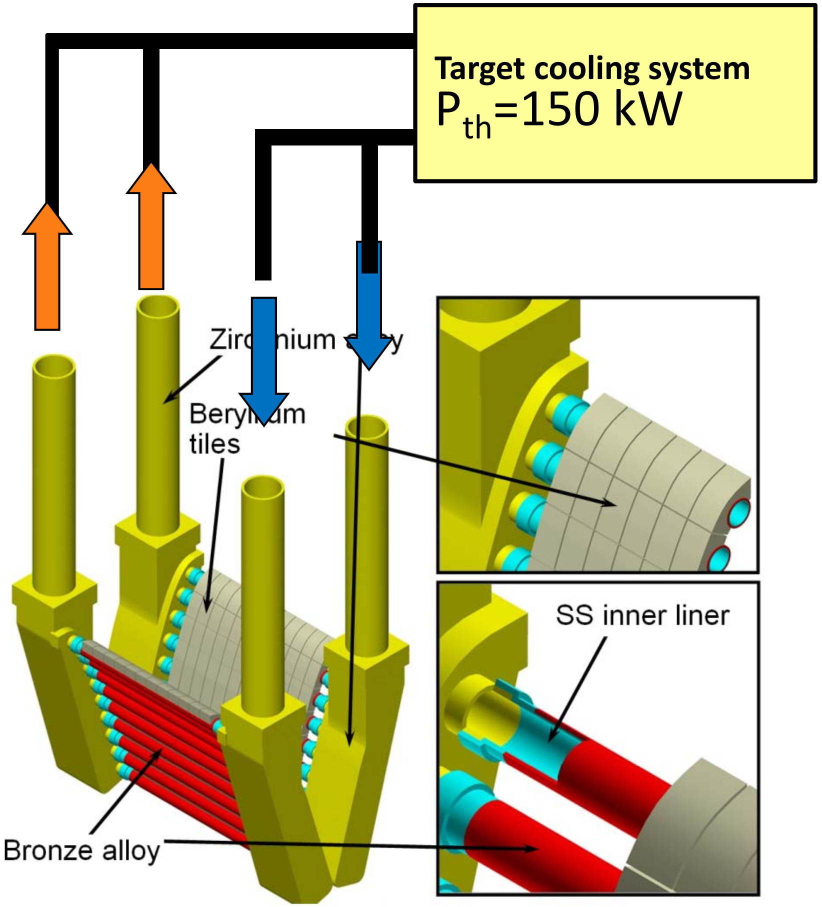




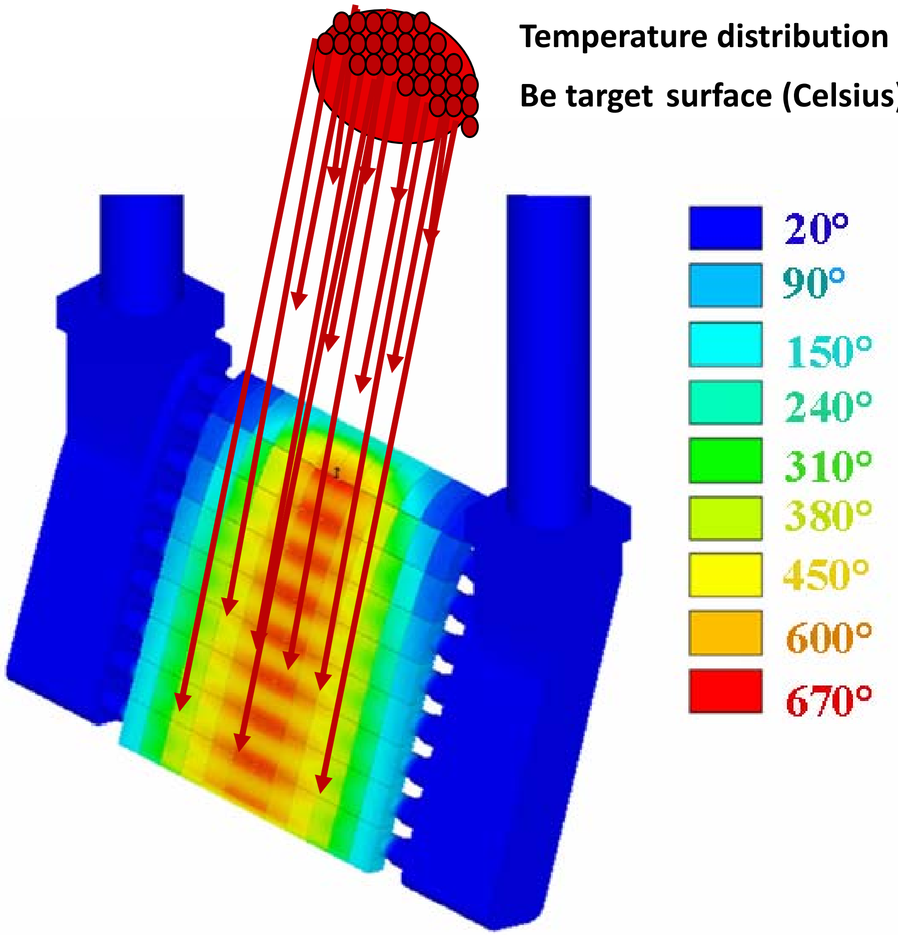
- **Planned testing condition (half-target): Tsefey facility**

• E-beam	E=20 keV, I=3.0 A; P=60 kW
• Beam power distribution	close to parabolic shape;
• Peak power density in loading area	0.75 kW/cm^2
• Number of cycles	1350 +1000, 15 s-on and 15 s-off;
• Target position	horizontal;
• Cooling system mechanical fixing	as in the converter design;
• Cooling parameters	Pinlet =0.3 - 0.5 MPa,
•	w=3.0 l/s, Tinlet=20 oC
• Diagnostics	surface temperature (IR camera)

Target cooling system and surface temperature control

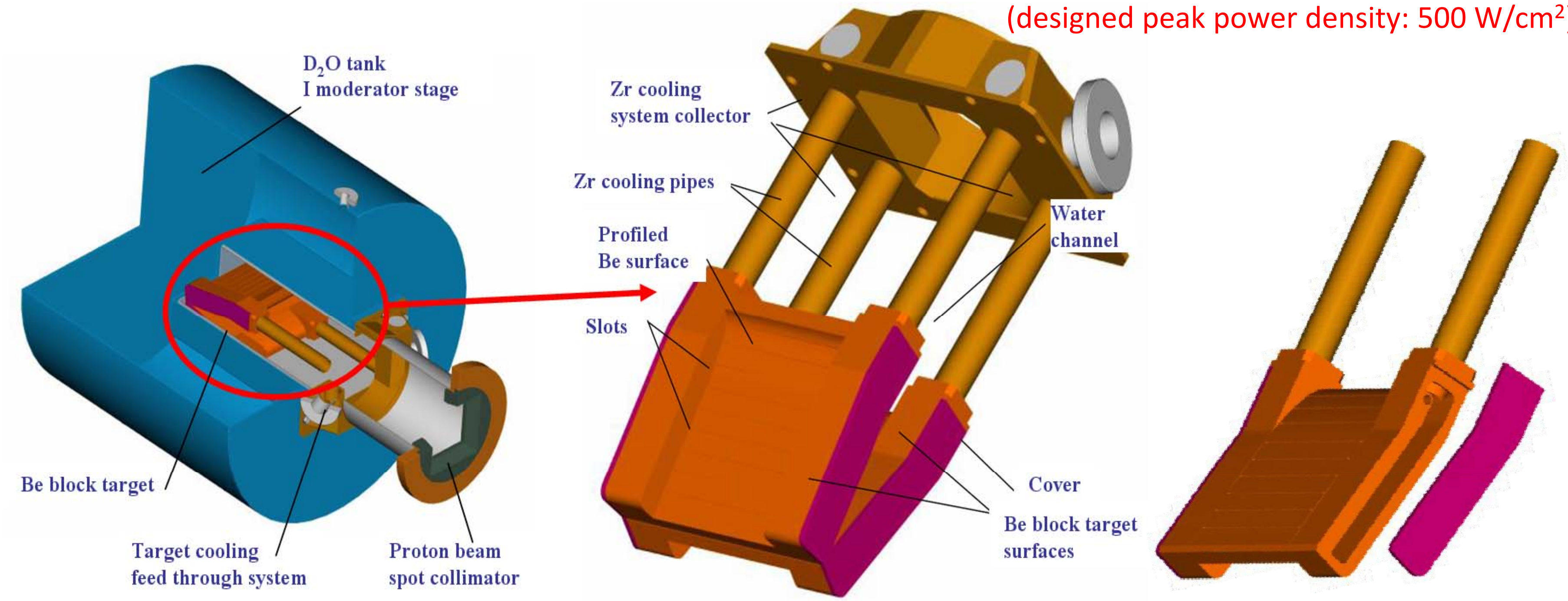


Temperature distribution on Be target surface (Celsius)



Bulk Be neutron converter concept

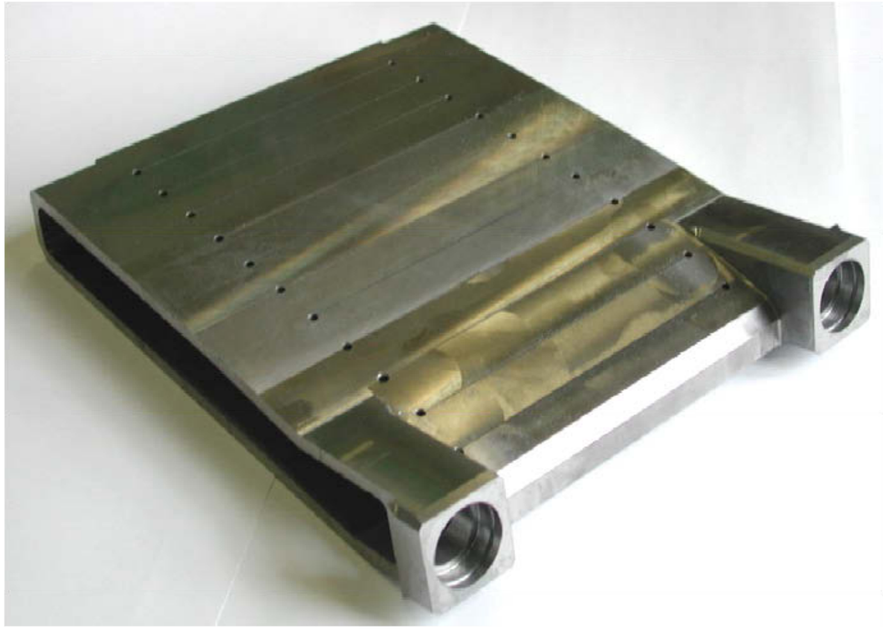
150 kW target converter
(designed peak power density: 500 W/cm²)



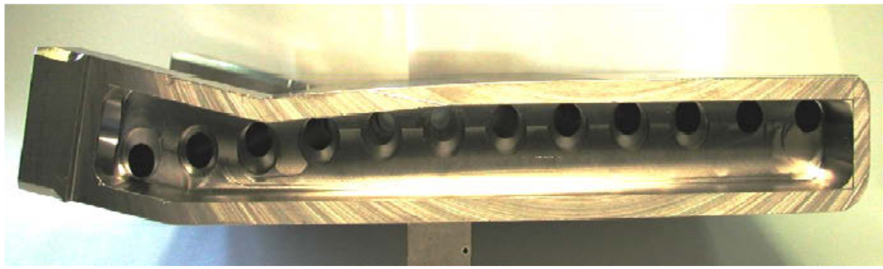
Main advantages & technological challenges

- better neutron moderating power: neutron beam port performance improvement
- lower prompt gamma yield from neutron converter (contamination from structural materials)
- Assessment of HHF limit for Be target reliability made from a solid Be block

Bulk Be converter prototype manufacturing



1. Target shaping from solid Be block machining

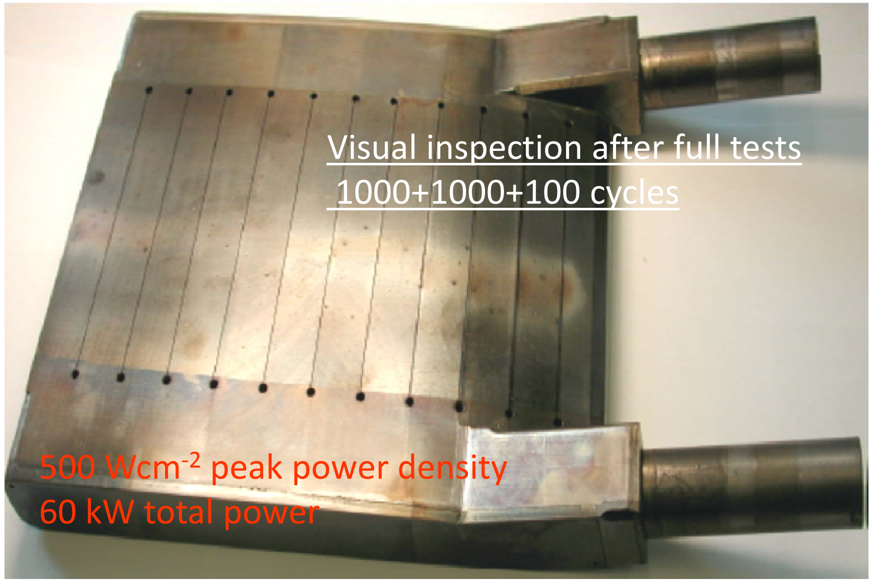


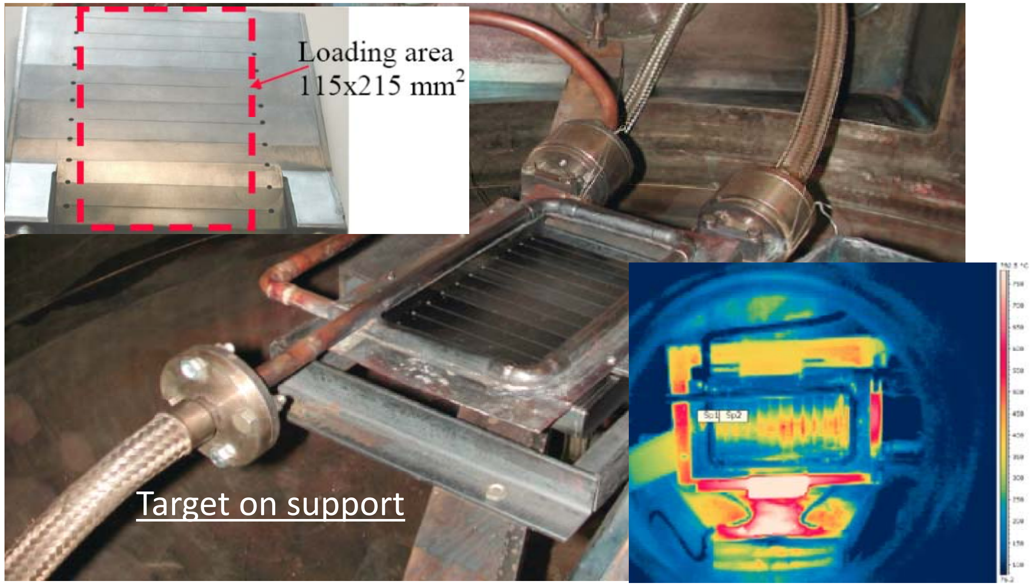
2. Drilling to create cooling water channels inside Be-block

3. EDM cutting of slots between contiguous cooling channels

4. Half target after cover plates + joining pipes brazing

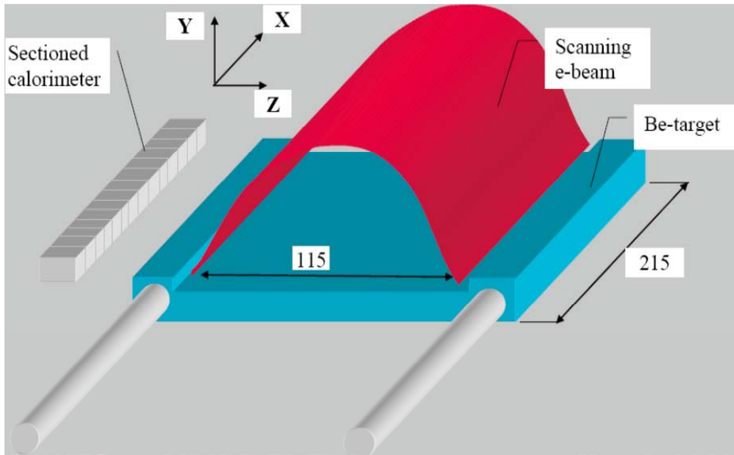
Bulk Be converter prototype: first e-beam full power test





Planned testing condition (half-target): Tsefey facility

- E-beam: P=60 - 40 - 47 kW
- Beam power distribution: close to parabolic shape;
- Peak power density in loading area: 0.5 – 0.6 – 0.7 kW/cm^2
- Number of cycles: 1000 +1000 +100   12 s-on 12 s-off;
- Target position: horizontal;
- Cooling system mechanical fixing: as in the converter design;
- Cooling parameters: P_{inlet}=0.3 - 0.5 MPa,
- w=3.0 l/s, T_{inlet}=20 ^{o}C
- Diagnostics: surface temperature (IR camera)



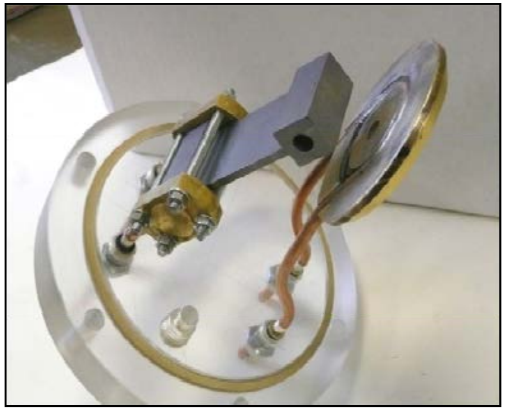
Beryllium target test result summary

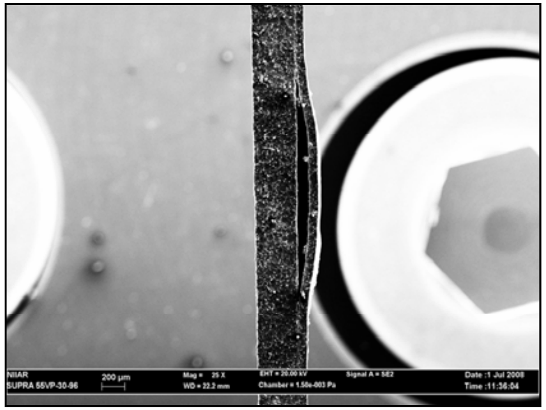
Test type	Test performed	Main test results	Test passed
Thermal-mechanical	Number of cycles: 2350 ~ 10 times higher than requested (200)	• No any visible damage • No cracks observed at metallographic analyses • Reliability better than expected	YES
Radiation damage: neutron	Proper neutron fluence levels (10^{18}-10^{20} cm^{-2})	• Material hardening level half than expected • Mechanical properties not compromised even at higher dose levels (~0.1 dpa) • He bubbles generation observed at higher dose levels only (~0.08 dpa) • Lifetime estimation: 3100 hrs (doubled) with respect to design parameters (1600 hrs) =1yr	YES
Radiation damage: proton	Proton radiation damage preliminary tests (E=5 MeV, I=20μA)	Blistering problem	NO

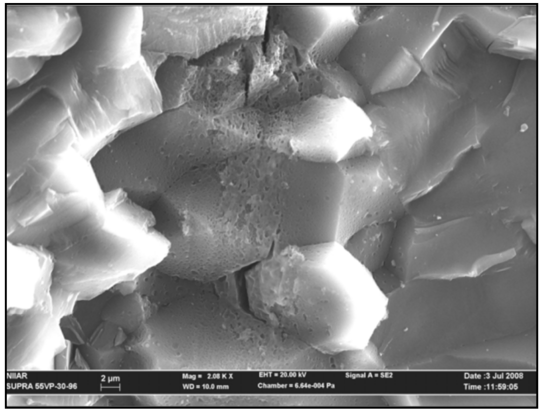
Blistering problem

Proton radiation damage preliminary tests (E=5 MeV, I=20μA)

Evidence of swelling problem caused by low hydrogen diffusion in Be

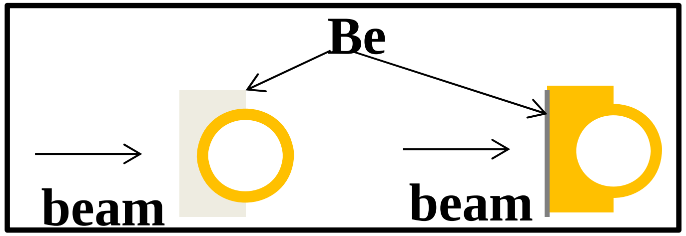






New target concept

Test of new thin Be target concept to mitigate and hopefully suppress swelling problem.



Characterization of a new heavy water-graphite moderator simulated, assembled and installed on +15° CN beamline for neutron spectrum moderation.

Test at CN accelerator

INFN Istituto Nazionale di Fisica Nucleare

Target type:	Thin Be foil (60 µm), brazed on a copper substrate. Target is water cooled and assembled in such a way to reduce activation after irradiation.
Target inclination:	67,85° inclination respect to beam direction.
Beam diameter on target:	1,1 mm.
Process description:	5 MeV proton beam interacts with Be foil producing neutrons. Protons reach Be boundary with 2 MeV residual energy and stop in the transition region between brazing alloy and copper.
Neutron source intensity:	10^{10} s^{-1} with 3 µA proton beam.

Moderator constituents:	- graphite	4014	kg
	- heavy water	88,5	kg
	- PTFE	53	kg
	- bismuth	24	kg

Neutron flux characterization with Bonner spheres and Si-detectors.

Test at CN accelerator

Poster N.02 for more details

- Protons pass through the nominal interface between Be and Cu with 2 MeV residual energy. With this energy, beam is stopped at 9 μm maximum from the Be surface. Considering to have about 20-30 μm brazing region penetrating into Be and into Cu, beam is stopped exactly in the brazing region.
- There is a high risk that beryllium concentration at this level is high enough to have hydrogen accumulation, that is swelling phenomena can appear with high probability.

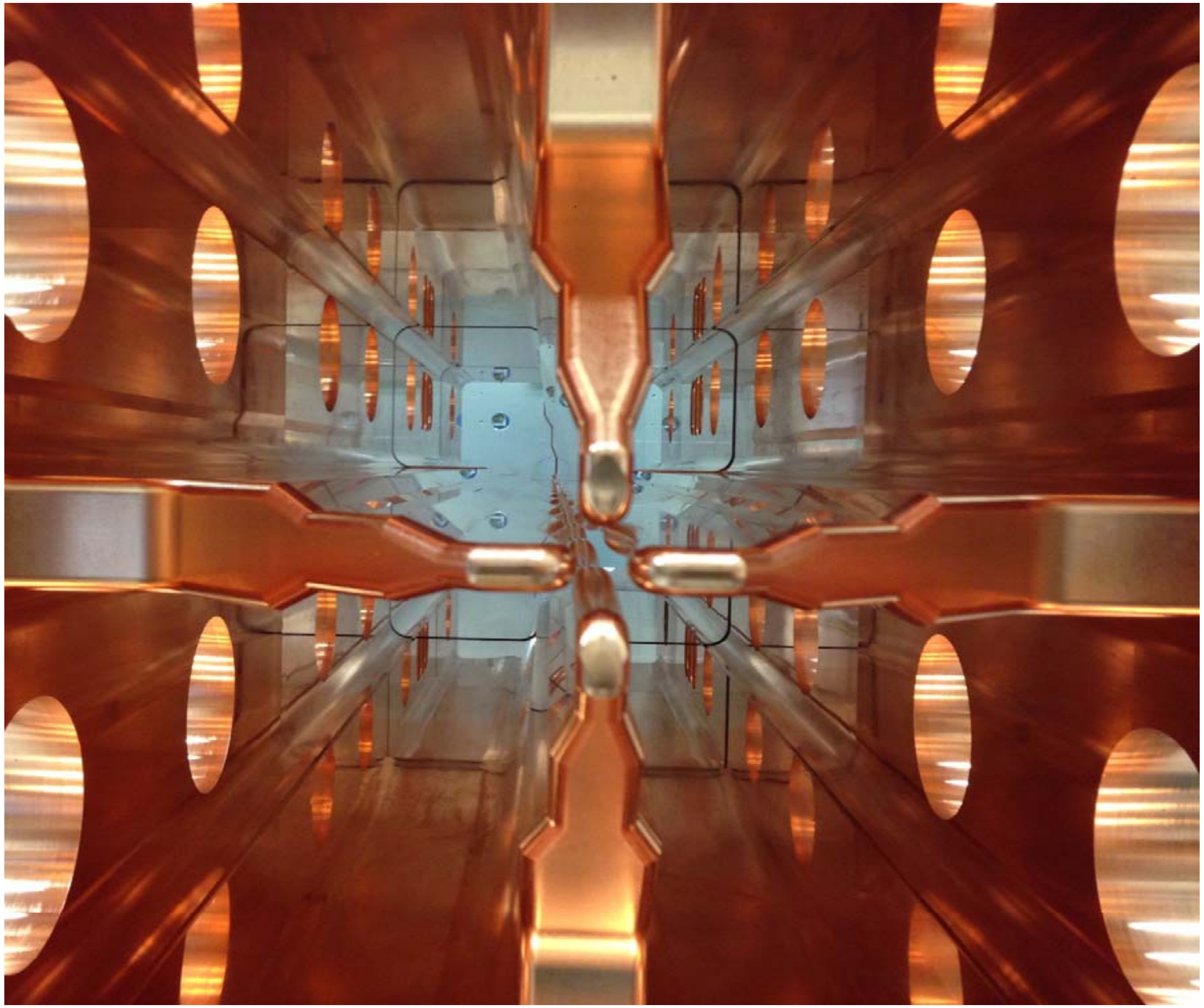
Results & Next Step

- Neutron source with thermal flux as high as $1{,}2\times10^{6}$ n/(s-cm^2) (>90% respect to total neutron flux).
- Swelling appeared after 43 h irradiation time at 700 Watt/cm^2 power density.
- Next step: target perpendicular to beam direction (hydrogen production inside copper) but lower (50%) neutron flux.

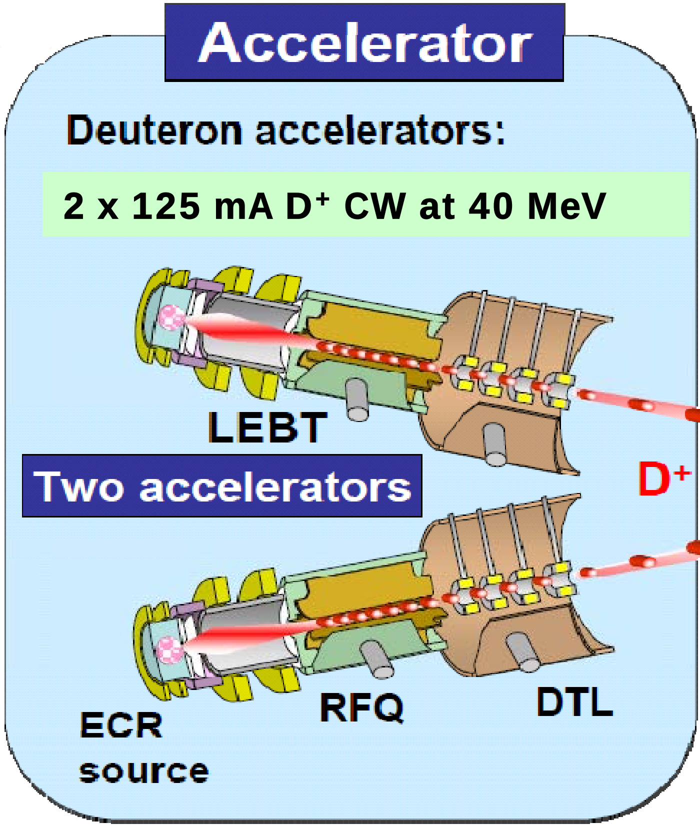
Conclusions and future perspectives

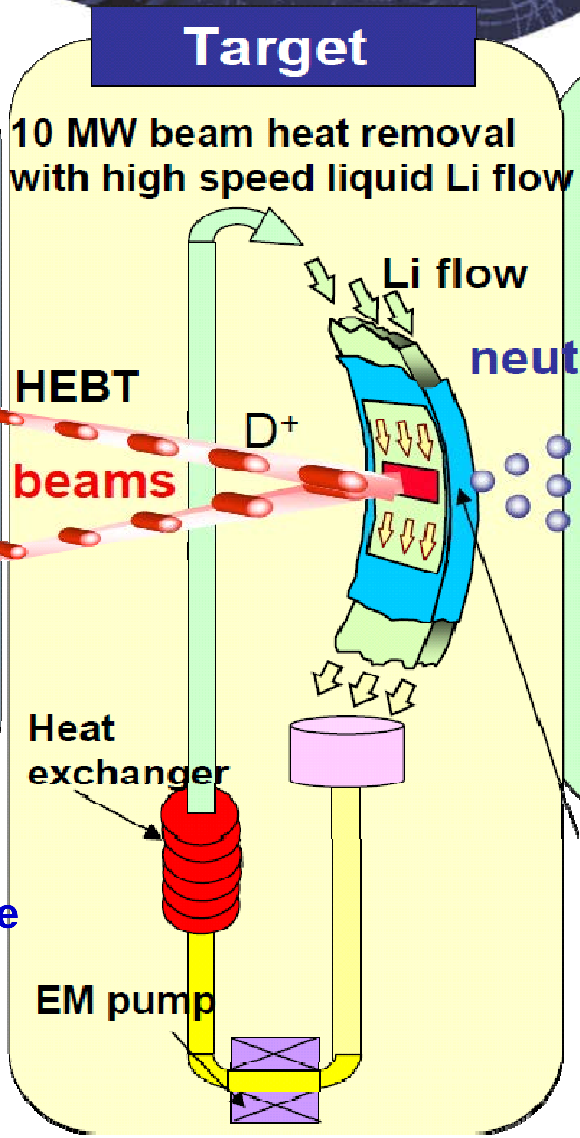
- High technology part of the accelerator was developed.
- RFQ cavity reached outstanding performances during high power test.
- Neutron converter successfully passed thermal-mechanical and radiation damage tests but failed proton test.
- New thin target concept is under test at CN facility at LNL.
- Tender for MUNES accelerator building is on the launching pad.

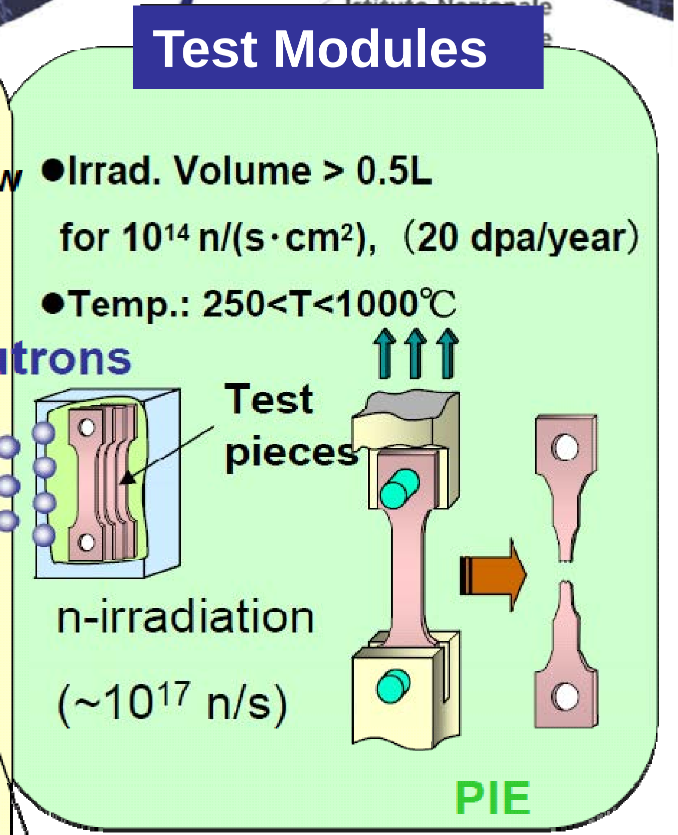
IFMIF-EVEDA: accelerator status



IFMIF Principles







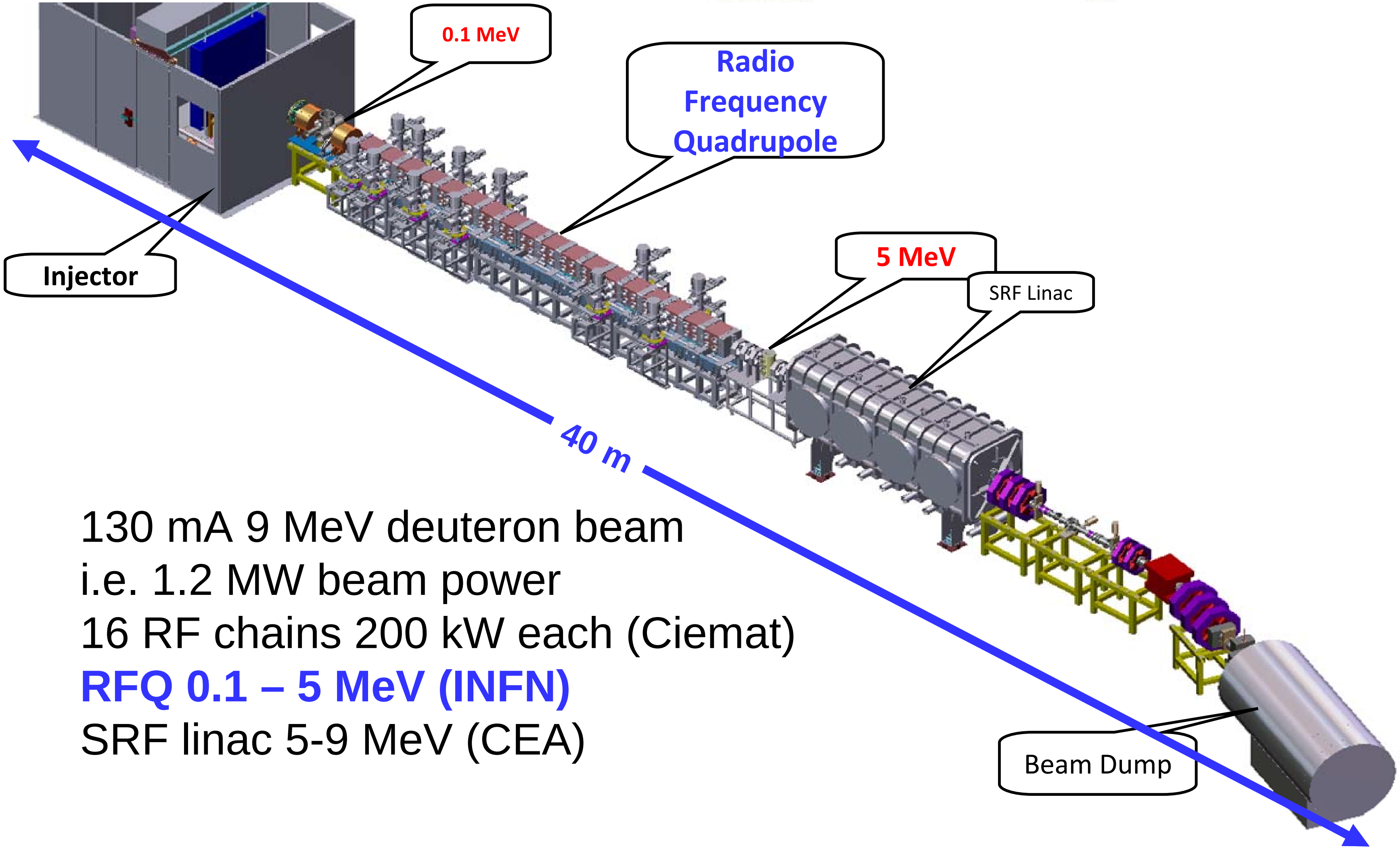
Accelerator based neutron source using the D-Li stripping reaction
⇒ intense neutron flux with the appropriate energy spectrum

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

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

IFMIF-EVEDA: main parameters

INFN Istituto Nazionale di Fisica Nucleare



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

IFMIF EVEDA: RFQ system organization

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

About 30 persons involved, 20 FTE, 10 dedicated contracts

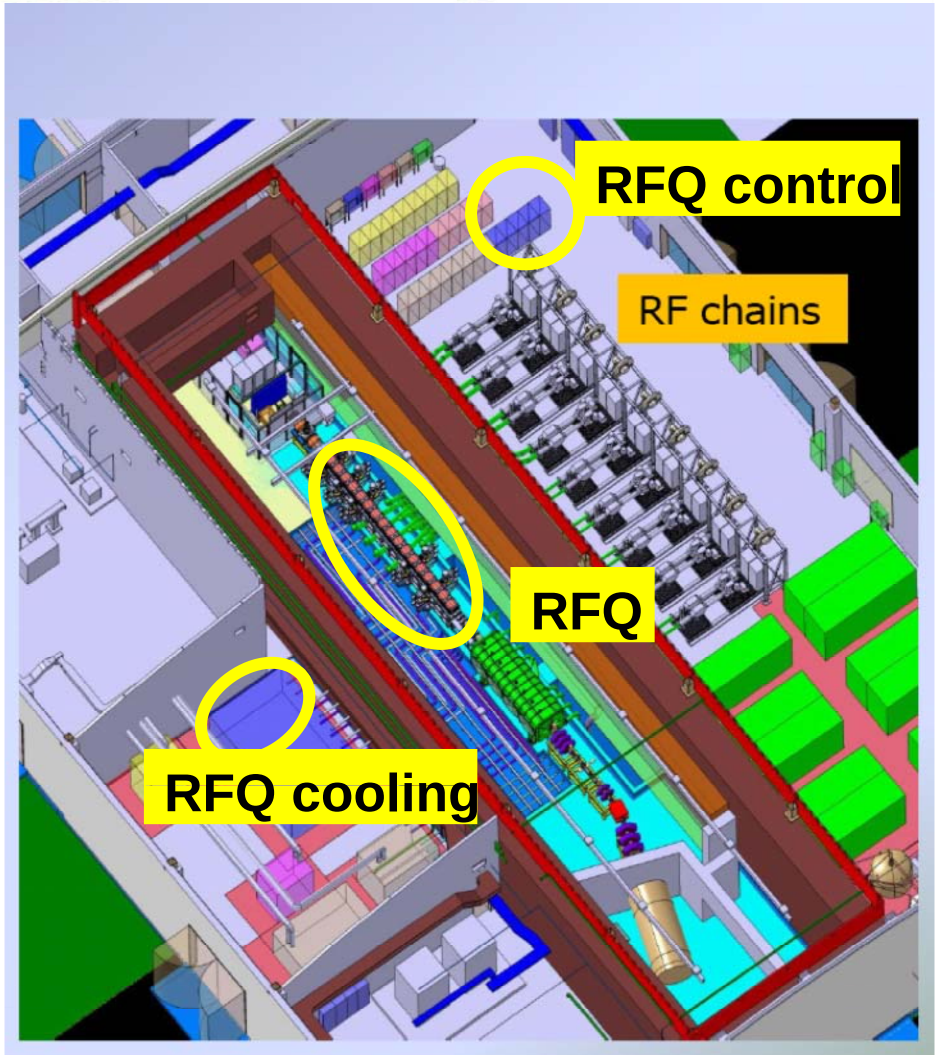
The participation of INFN to IFMIF-EVEDA includes

- RFQ construction
- Participation to final IFMIF design activity
- Participation to the man power of the project team in Japan
- Participation to beam commissioning in Japan

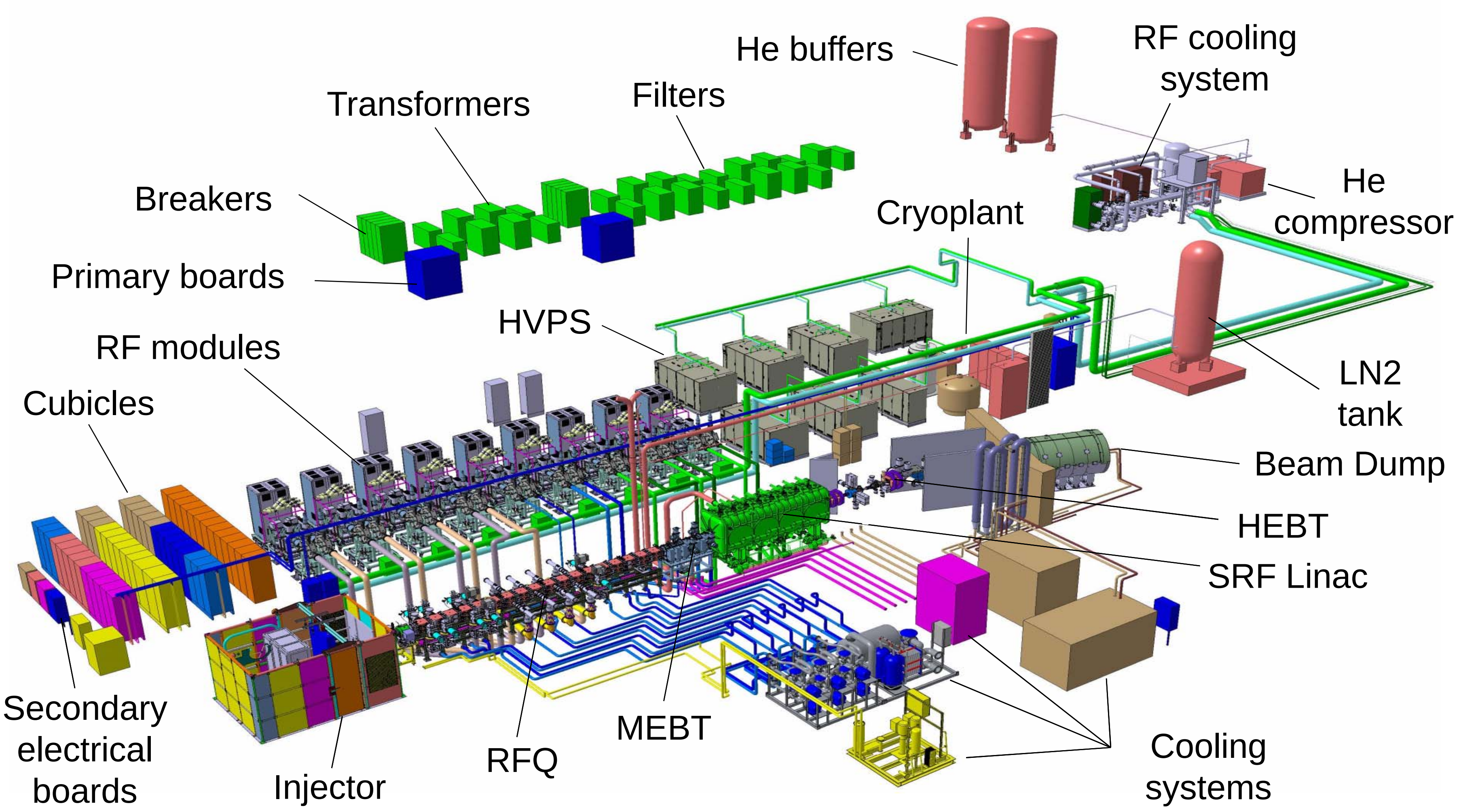
INFN organization

IFMIF EVEDA: RFQ system organization

- Responsible A. Pisent
  - Responsible for Padova: A. Pepato
  - Responsible for Torino: P. Mereu
  - Responsible for Bologna: A. Margotti
  - Planning: J. Esposito
  - System Integration at Rokkasho: E. Fagotti
- Physical design : M. Comunian
  - Radio frequency: A. Palmieri
  - High power tests : E. Fagotti
  - Computer Controls: M. Giacchini
  - Vacuum system and techn. processes C. Roncolato
- Mechanics design and construction A. Pepato
  - Engineering integration P. Mereu
  - Quality assurance: R. Dima
  - Module production follow up M. Benettoni
  - Stainless steel components production A. Margotti
  - Cooling system integration G. Giraudo

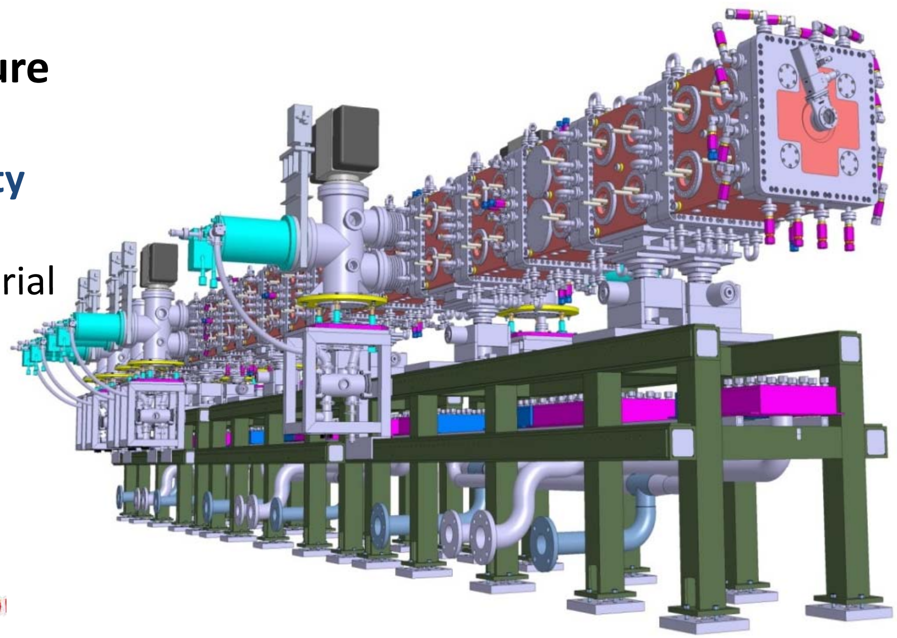


IFMIF-EVEDA: installation at Rokkasho



IFMIF-EVEDA: RFQ CHALLENGE

- **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
- Last month **RFQ shipped to Rokkasho**.
- Next month will start cavity installation.



RFQ JUST BEFORE SHIPMENT TO JAPAN

IFMIF-EVEDA: next future

- Ion source optimization will continue up to next summer.
- RFQ installation will start next month and it is foreseen to be concluded in November 2016.
- RFQ high power conditioning will start on February 2017.
- First beam from RFQ foreseen before Summer 2017.


Thank you