MUNES project: status and perspectives of an RFQ based neutron facility in Italy

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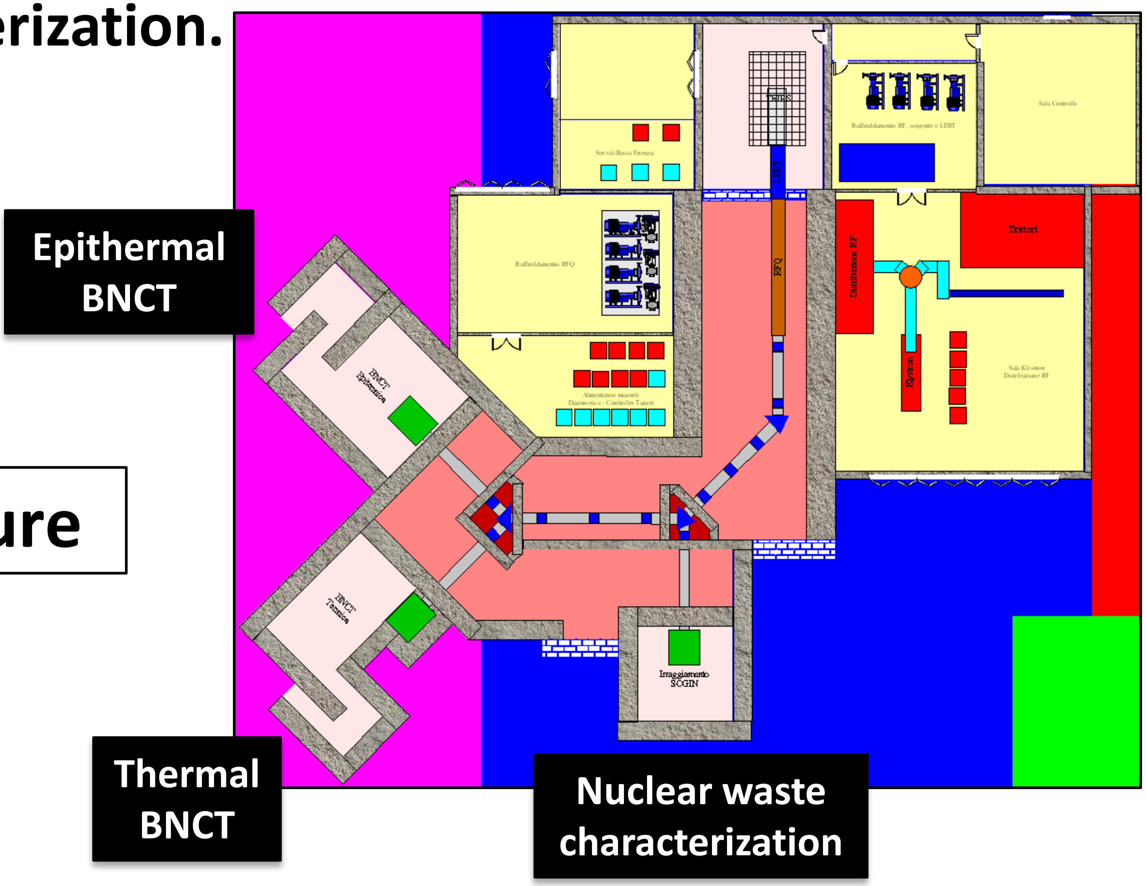
On behalf of MUNES collaboration

Outline

- **Project overview**
- **BNCT application**
- **High intensity accelerator status**
  - ***Proton source***
  - ***Low energy beam transport***
  - ***RFQ***
  - ***Beryllium target and neutron beam shaping assembly***
  - ***RFQ high power test***
- **Conclusions**

Main Goal

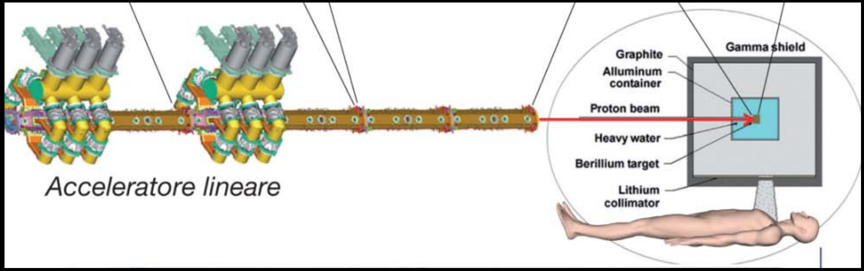
MUNES is a three year project, the goal of which is the realization of a thermal and an epithermal neutron source for BNCT and for radioactive waste characterization.



Research Infrastructure

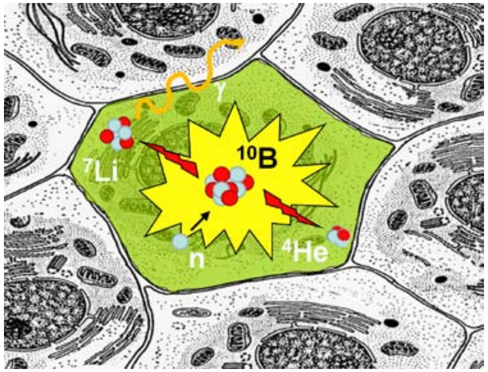
Main parameters

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



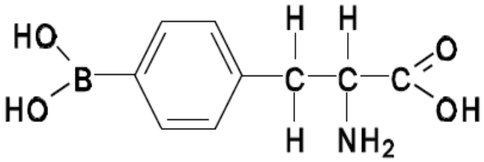
	Φ_{th} (E≤ 0.5 eV) (cm^{-2}s^{-1})	Φ_{th} / Φ_{total}	$K_{n\,(E>0.5\,eV)}$ / Φ_{th} (Gy·cm^2)	K_γ / Φ_{th} (Gy·cm^2)
LNL neutron source	4.3E+09	0.96	0.33E-13	0.92E-13
IAEA recommendations for BNCT	> 1.0E+09	> 0.90	≤ 2.0E-13	≤ 2.0E-13

Boron Neutron Capture Therapy (BNCT)

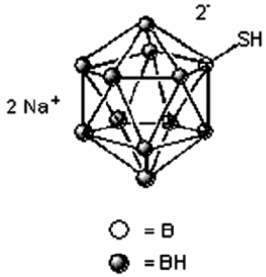


Boron Neutron Capture Therapy (BNCT) is an experimental binary radiotherapy which exploits the neutron capture reaction $^{10}B(n,\alpha)^{7}Li$ induced by thermal neutrons (<E> = 25 meV).
The α-particle and ^{7}Li recoiling nucleus are high LET and short range (< mean cell diameter ≈ 10 μm) particles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

BPA



BSH

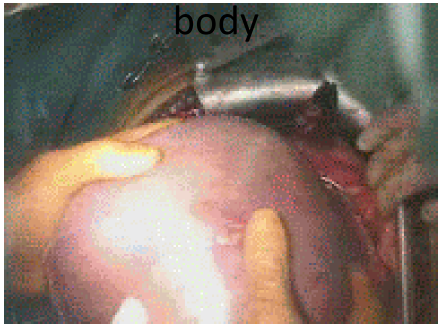


In this way the selectivity of BCNT depends on ^{10}B distribution and not on the irradiation field. This feature makes BNCT a valid option against the diffused tumors
Another crucial aspect for the good outcome of the treatment in the availability of ^{10}B carriers able to realize a selective delivery.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

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.

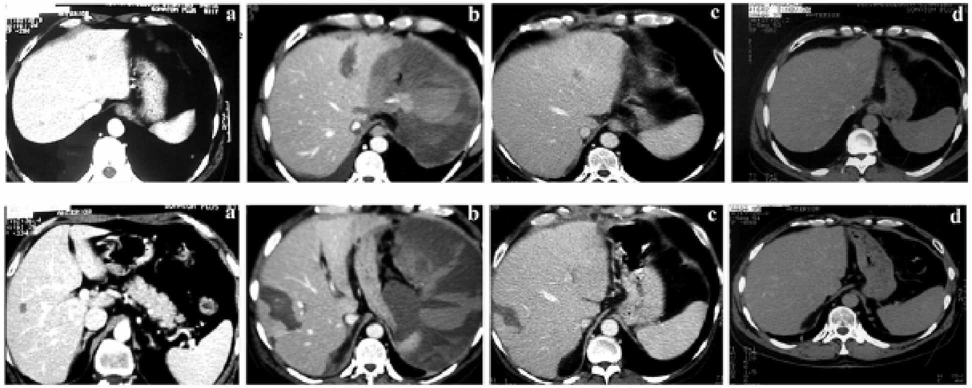
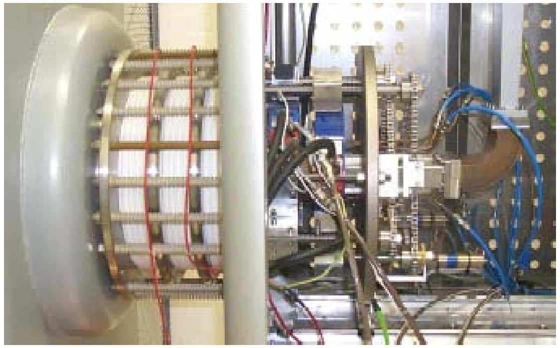


Figure 6. Sequence of CT images of the liver on a cranial (above) and a caudal (below) level in the first patient subjected to BNCT. Evolution at different times of the metastases towards necrosis with final substitution by normal hepatic tissue. (a): pre-operatively; (b): at 7 days, (c): at 6 months;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

High Intensity Accelerator Status

Proton Source

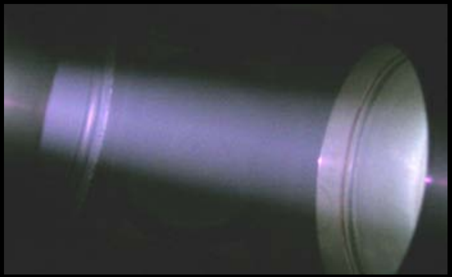


PS developed at LNS (2000)

PS optimized at LNL with magnetic shielding (2007)

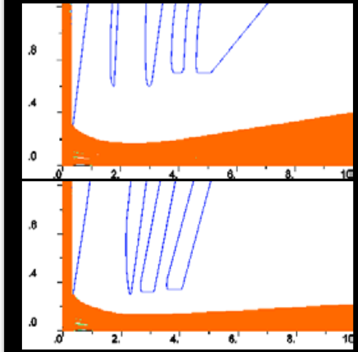
STATUS

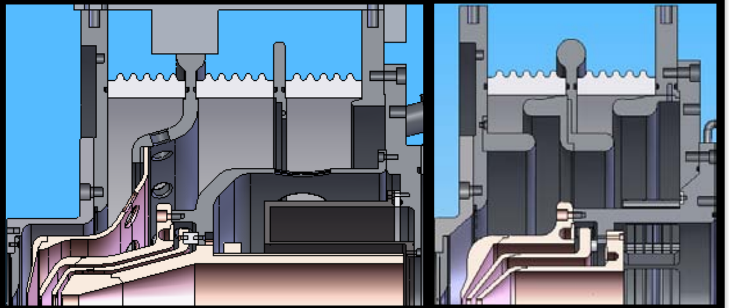
$I_p \approx 45$ mA
E = 80 KeV
$\varepsilon_{n,rms} < 0.1$ mm-mrad
$\varphi_b(z = 200\text{ mm}) = 34$ mm
Beam time structure: CW



NEAR FUTURE

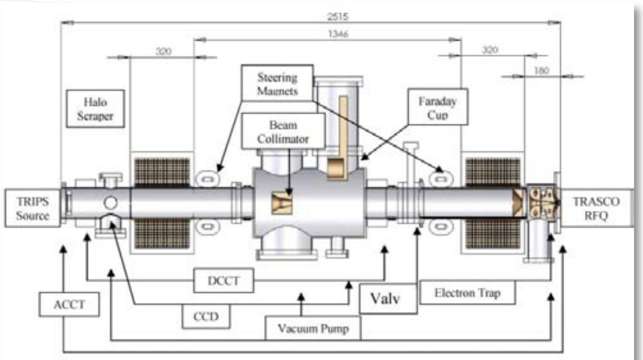
$\varphi_b(z = 200\text{ mm}) = 10$ mm
[New extractor design] [LNL]





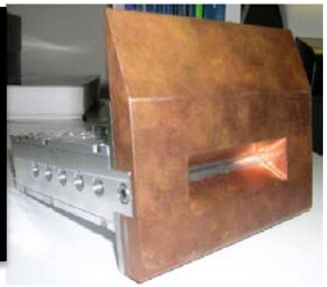
Beam time structure: CW & pulsed
[Magnetron pulser] [LNL & DEE/UPV]

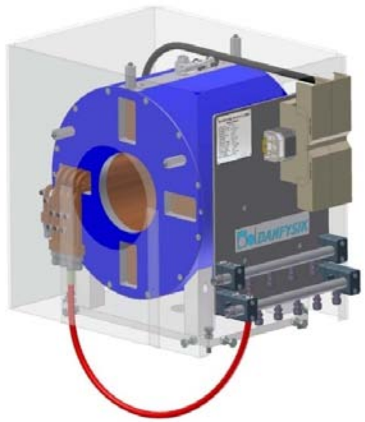
Low Energy Beam Transport



LEBT developed at LNL

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

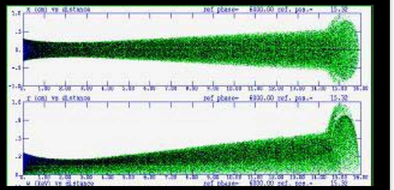




Solenoids developed at LNL

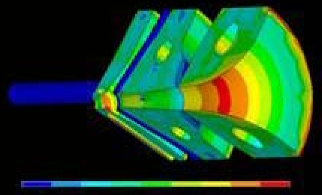
STATUS

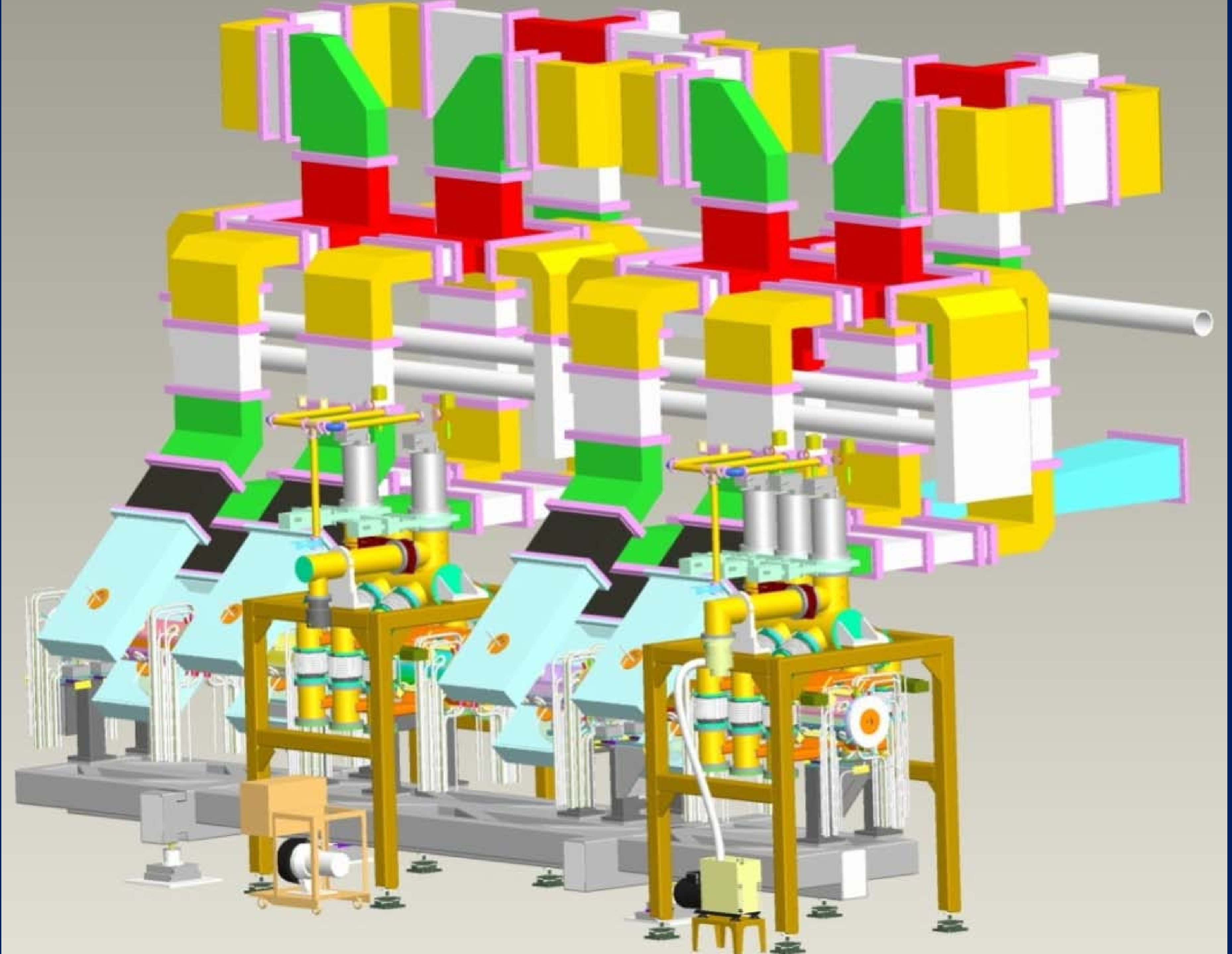
LEBT ready for assembly with solenoids, pumping system, non interceptive profile and current diagnostics, interceptive profiler and termination FC.



NEAR FUTURE

Neutralized transport optimization
FGA development
LEBT control system upgrade
e-trap construction





RFQ: Fabrication History…

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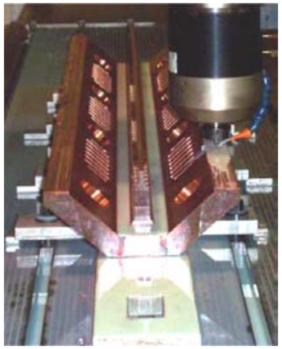
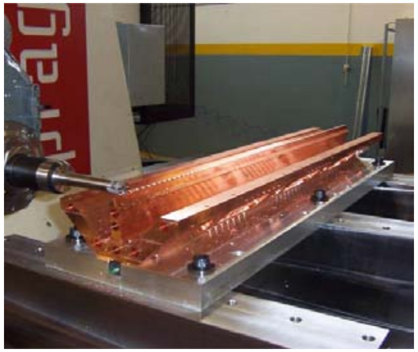
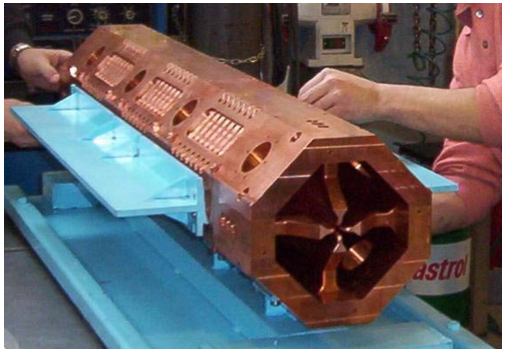
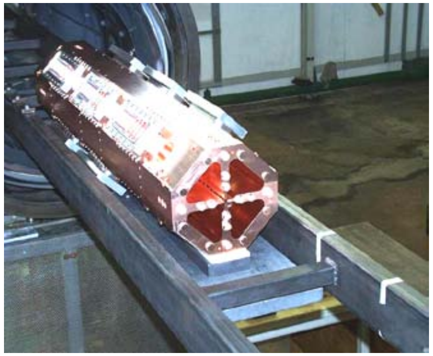
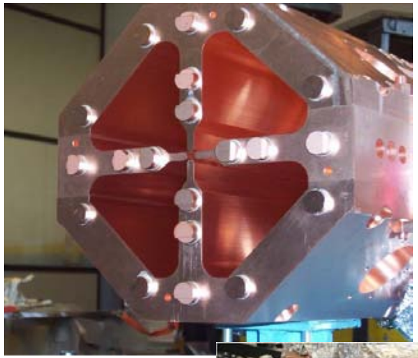
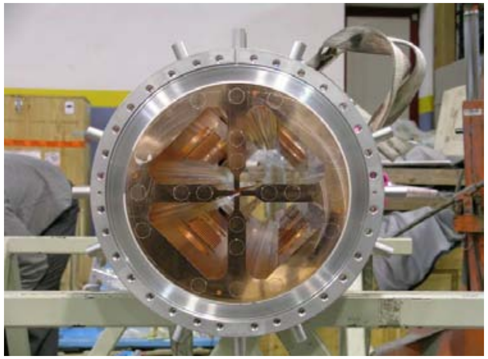
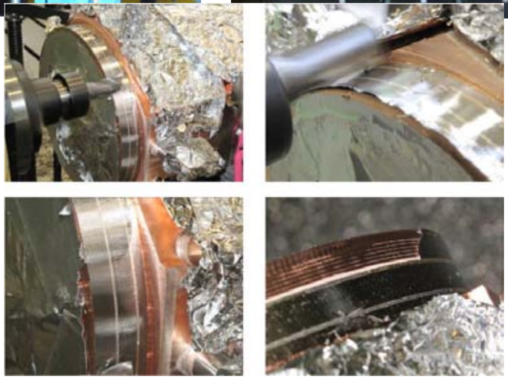
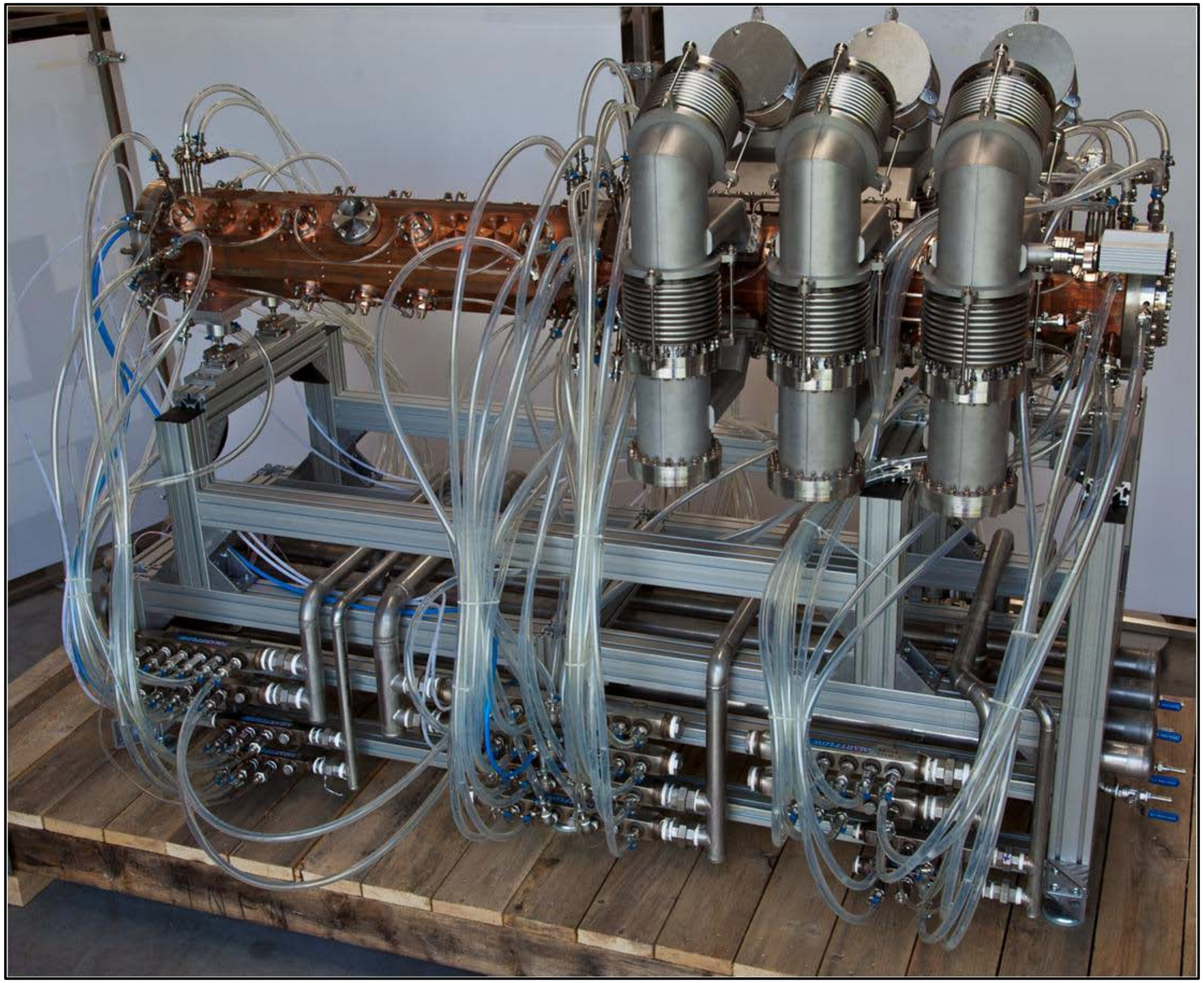



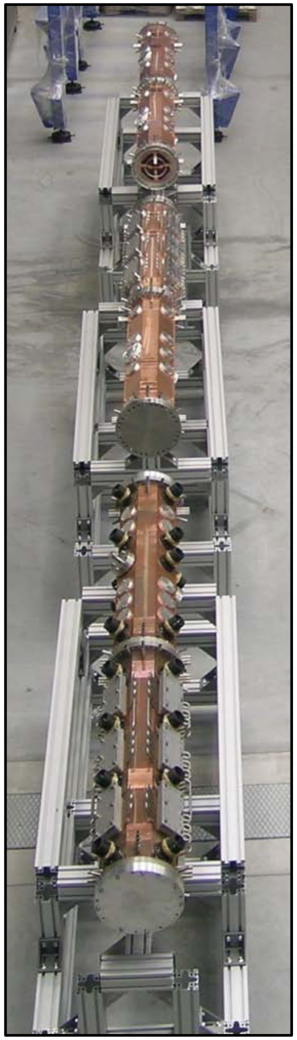





… and some troubles

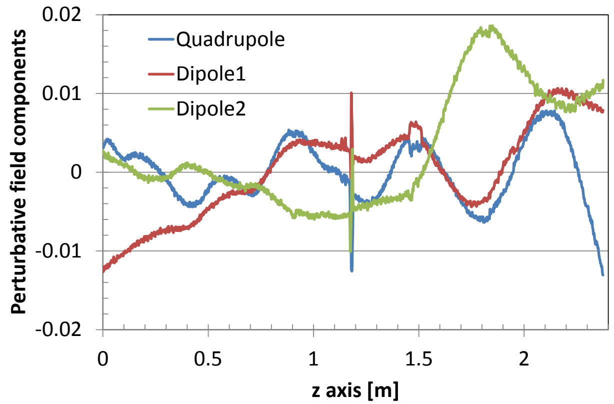


RFQ: Fabrication Complete



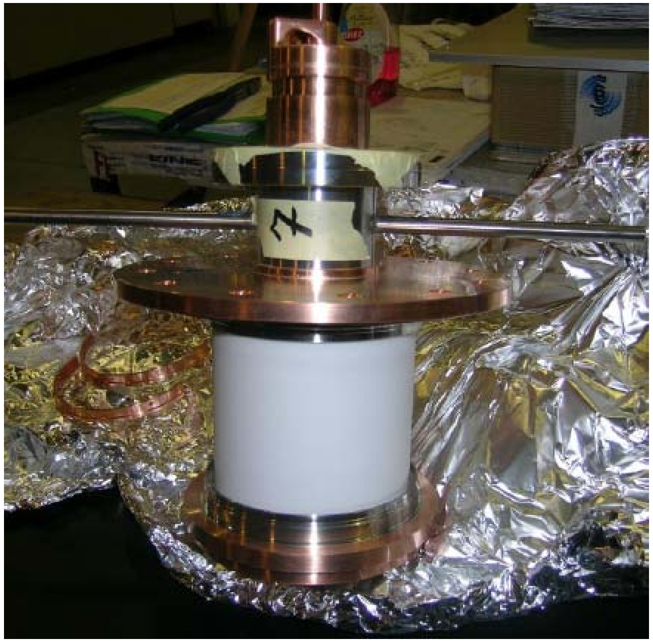


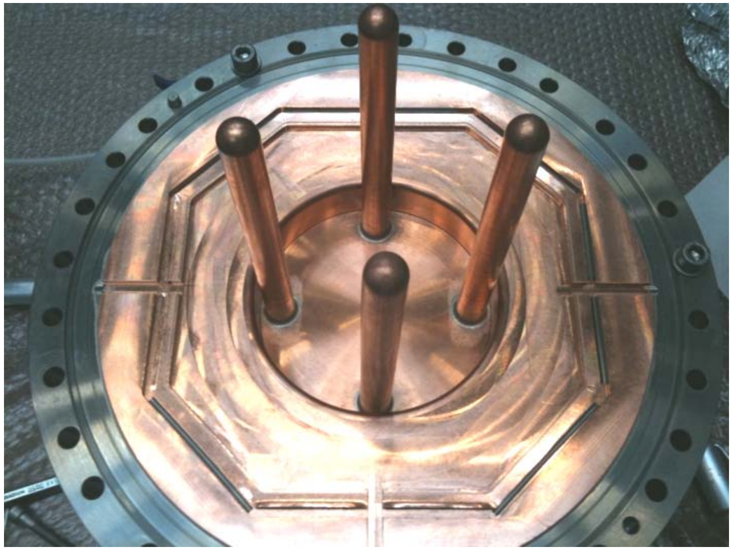
RFQ: tuning



2010. Low power RF measurements.

- Field and frequency tuning with aluminum couplers
- Copper Tuners and Copper End Plates with RF contacts
- Q_0=8100 (SF 9900)
- Final High Power Coupler design (3D HFSS simulations) and Coupler Production

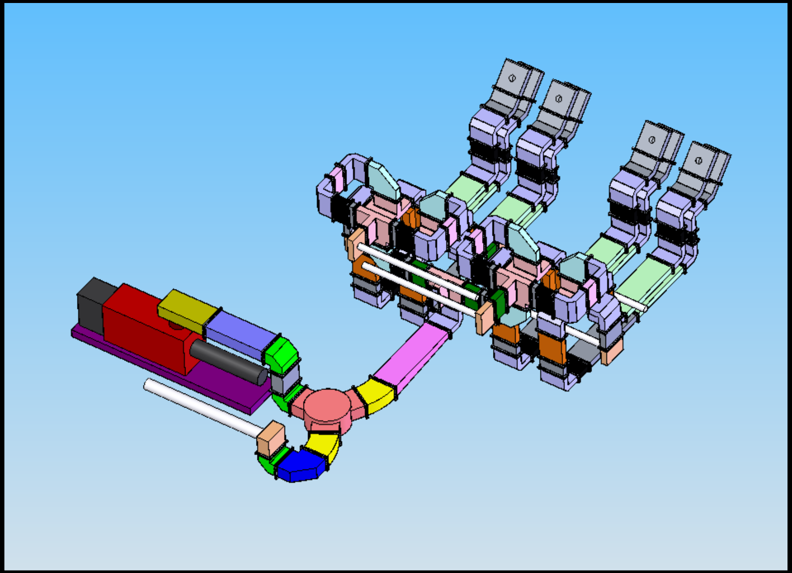


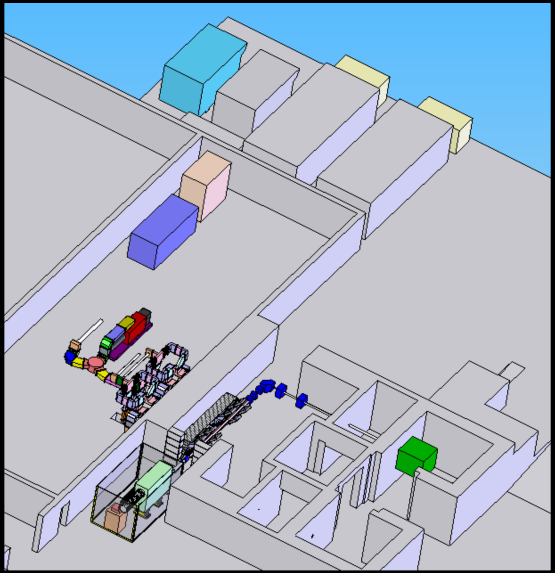


RFQ: ancillaries

2010/2011. All Ancillaries for High Power Test ready and tested

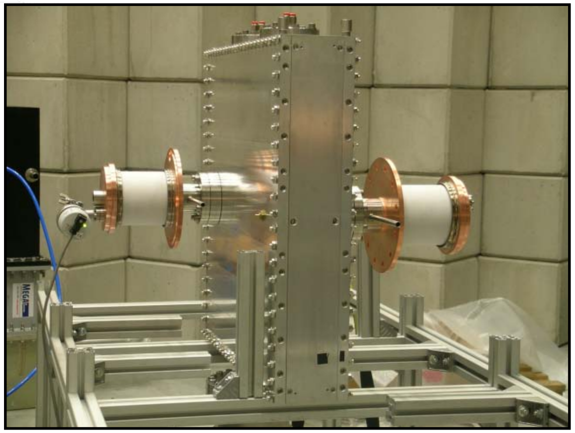
- High technology part (RFQ cavity, RF distribution, local cooling/tuning system, local control system) was developed

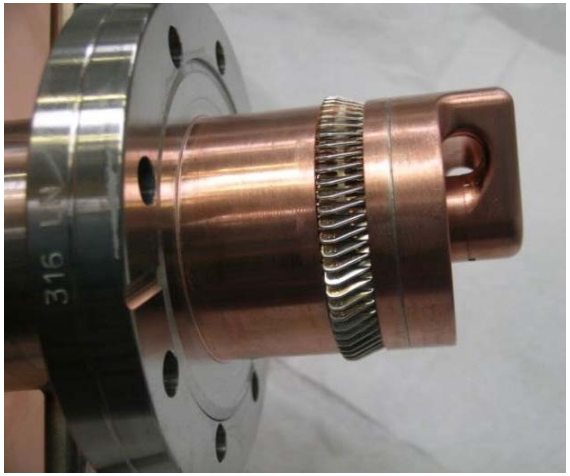




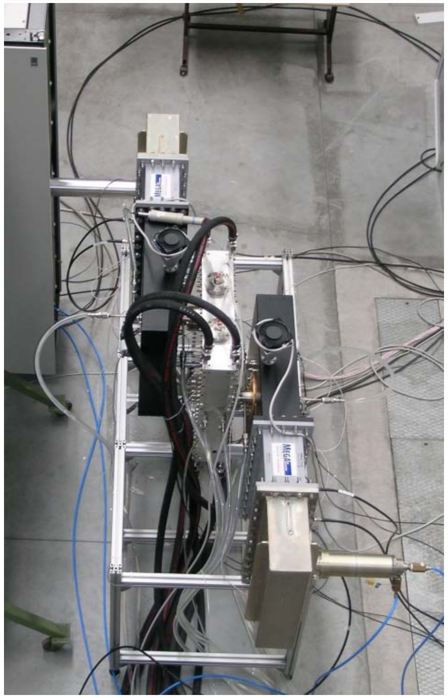
- Conventional installation (Klystron and conventional power supplies, secondary cooling system, building) is required.
- According to an agreement between INFN and CEA, couplers and RFQ are under high power test at Saclay.

RFQ: RF coupler high power test



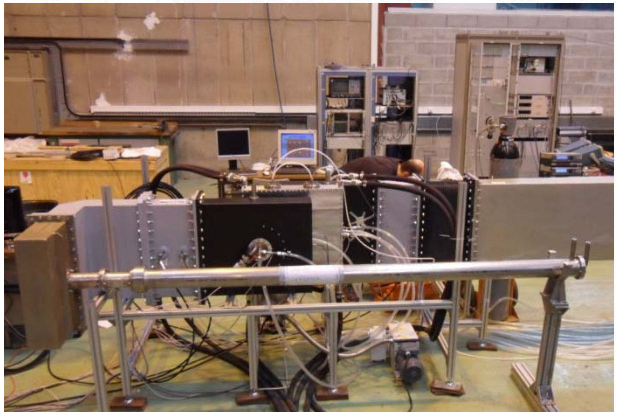


March 2011
10 kW couplers test



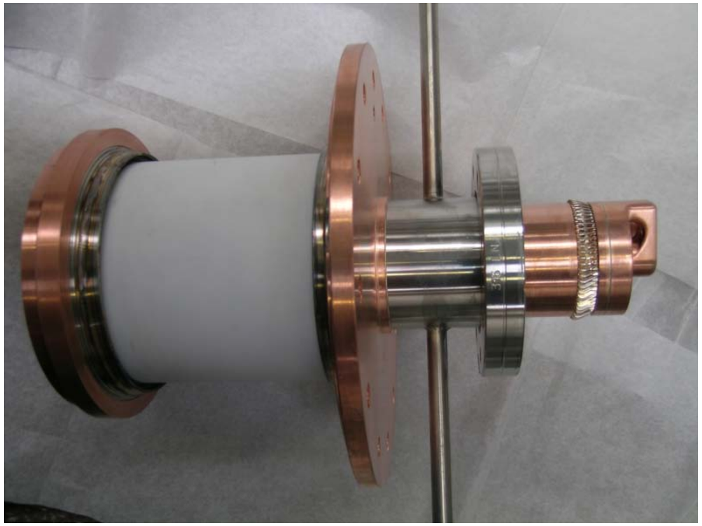
LNL

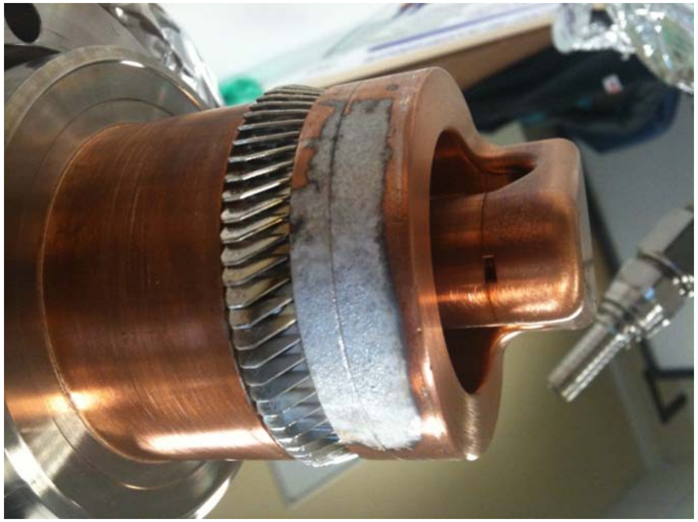
June 2011
150 kW couplers test

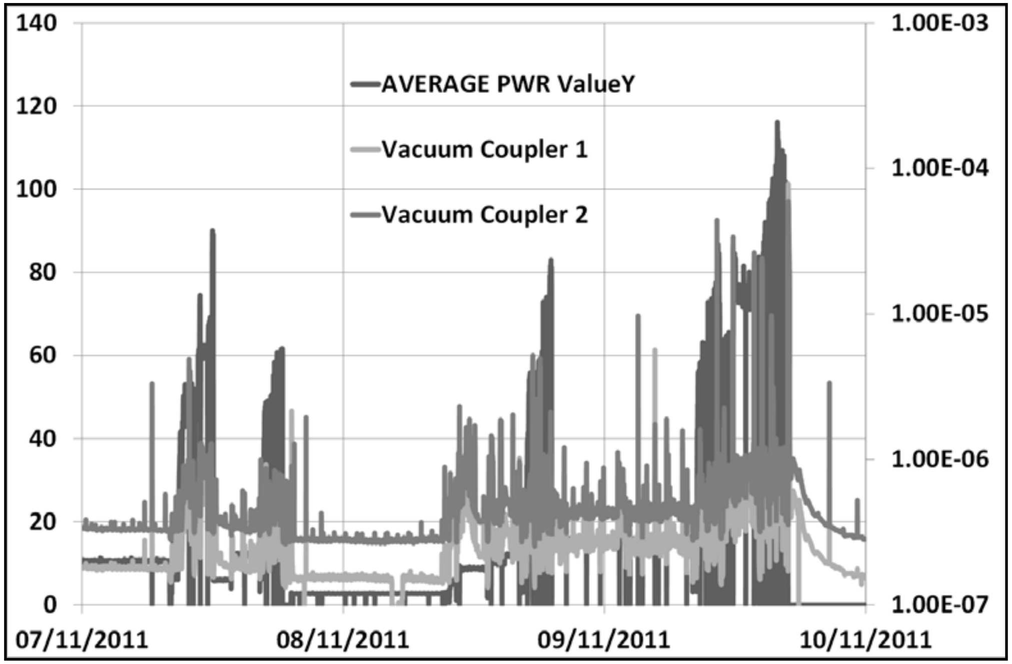


CEA Saclay

RFQ: RF coupler high power test

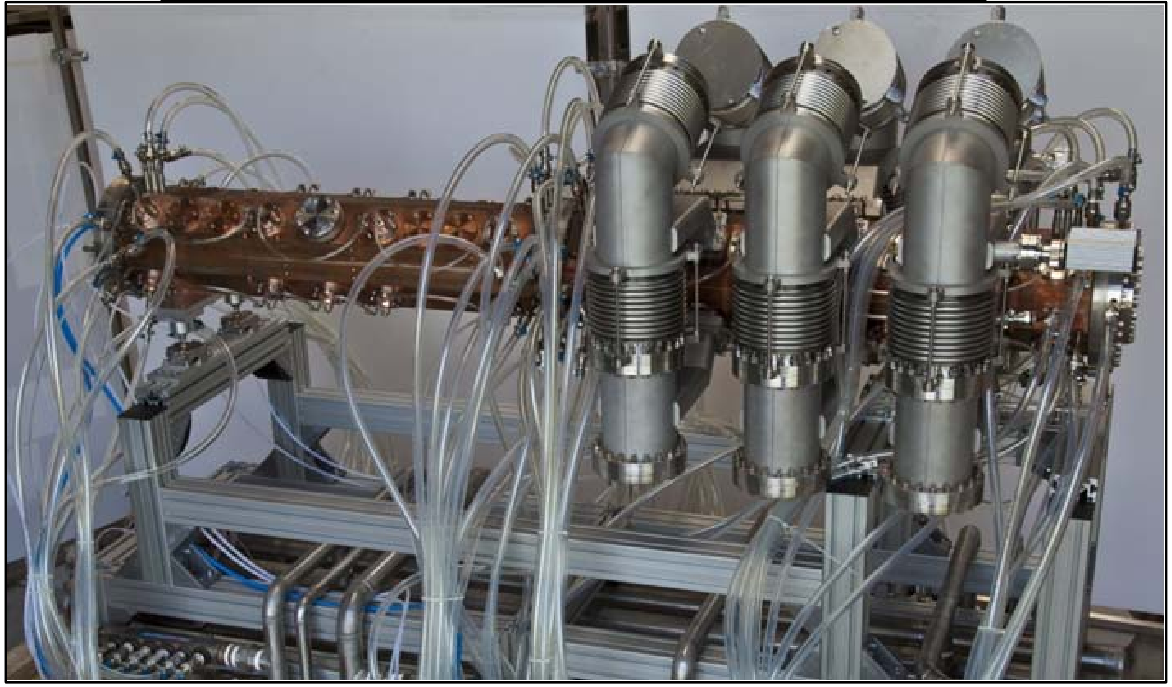




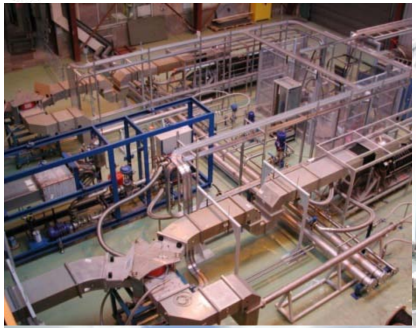


RFQ: First Segment High Power Test

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%

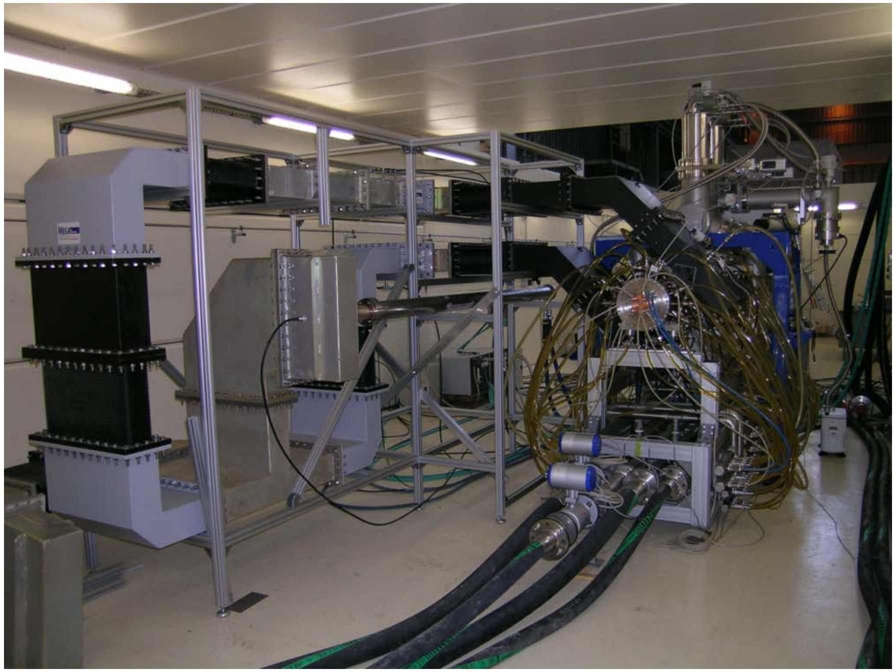


RF Test Stand at CEA





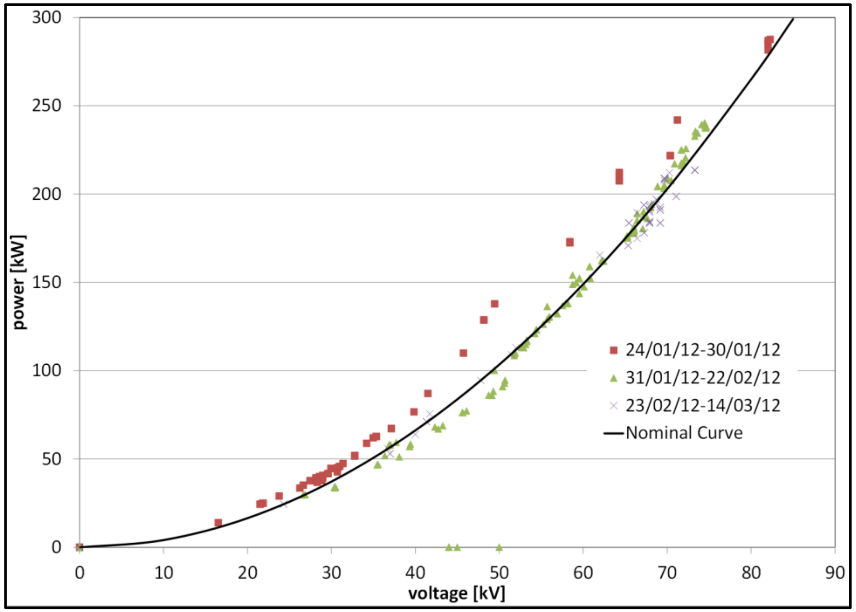

Collaboration agreement between INFN and CEA for TRASCO high power test in CEA Saclay



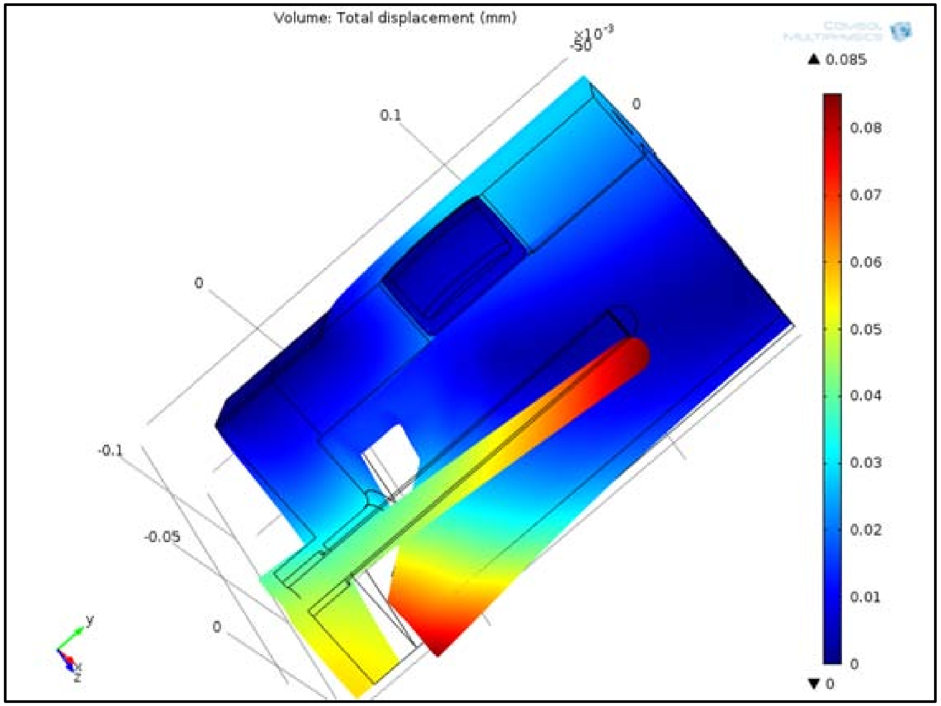
Results

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

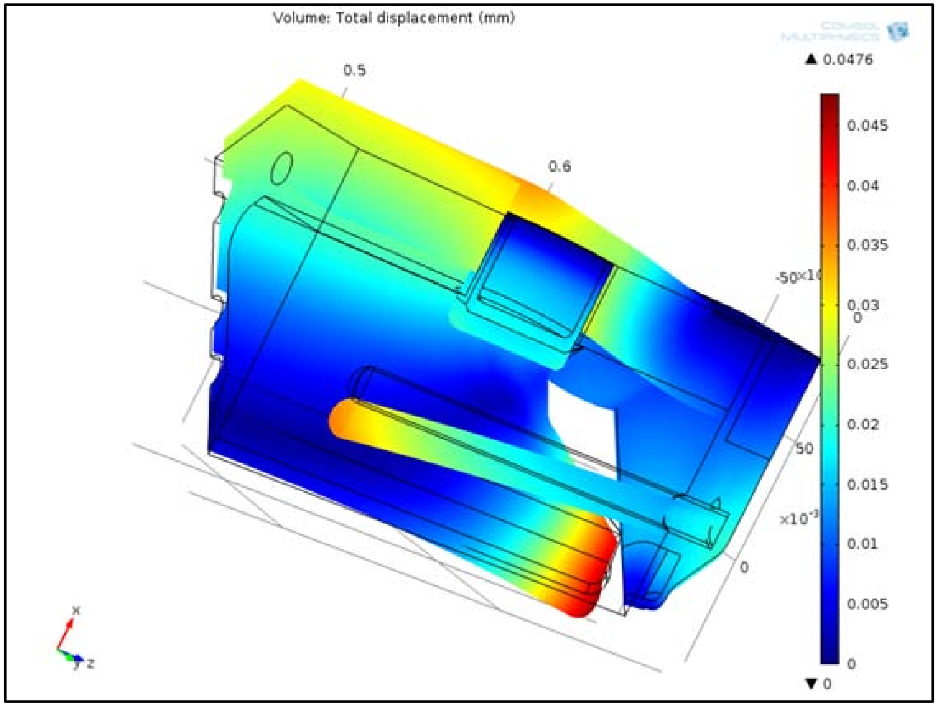
Peak cavity power, obtained as function of the cavity voltage.



Thermal elongation of the noses



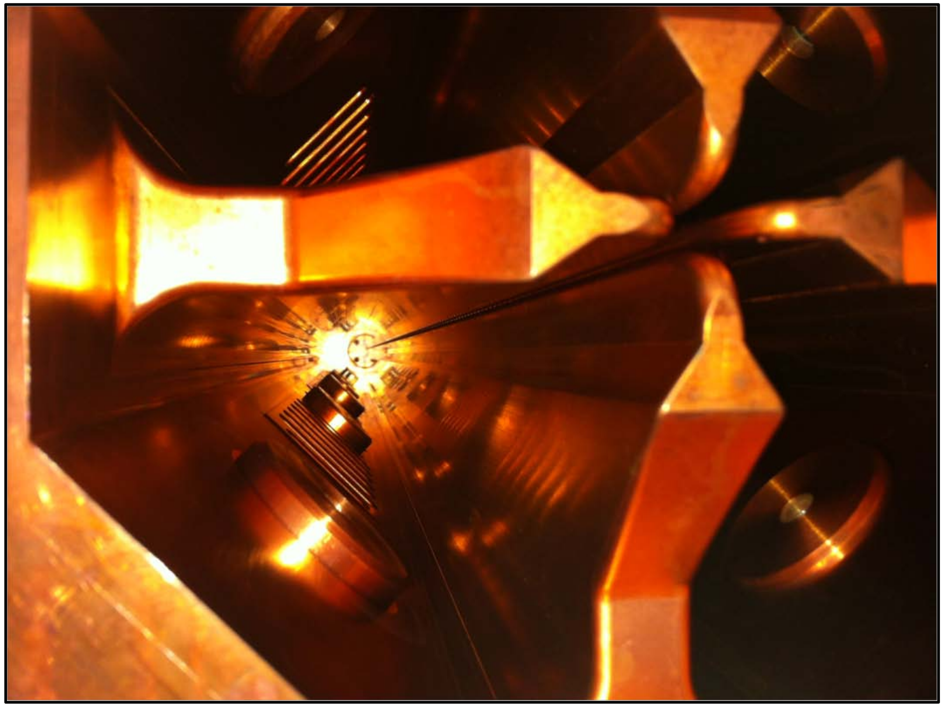
High Energy End Cell

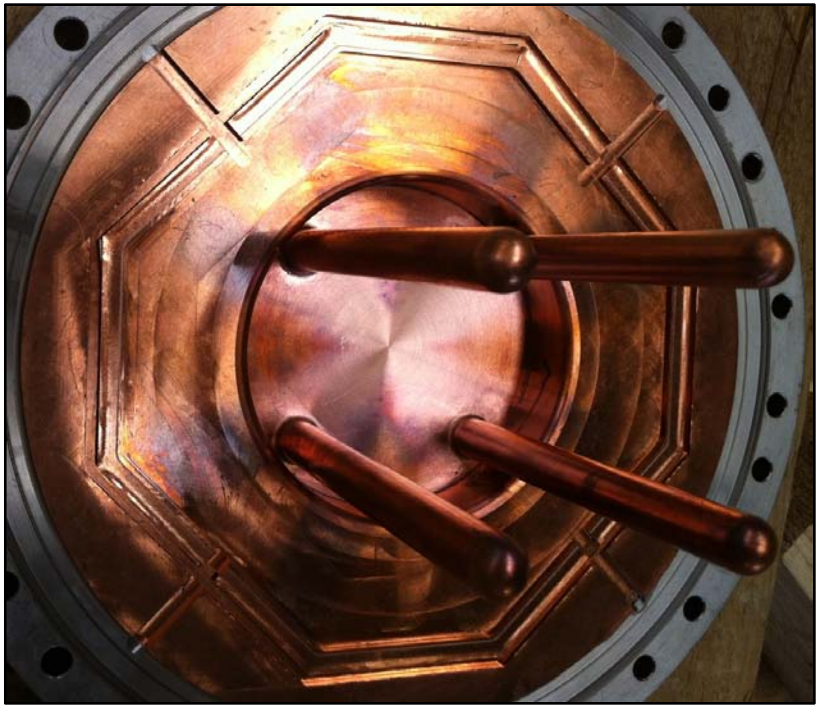


Low Energy End Cell

Results

Inspection of internal surface and termination plates after high power test





Traces of discharge on vane tips high energy part (low field region) and on high energy termination plate

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.
- Noses region has strong impact on frequency detuning and field flatness. Final tuning must take into account these effects.

The Beryllium converter

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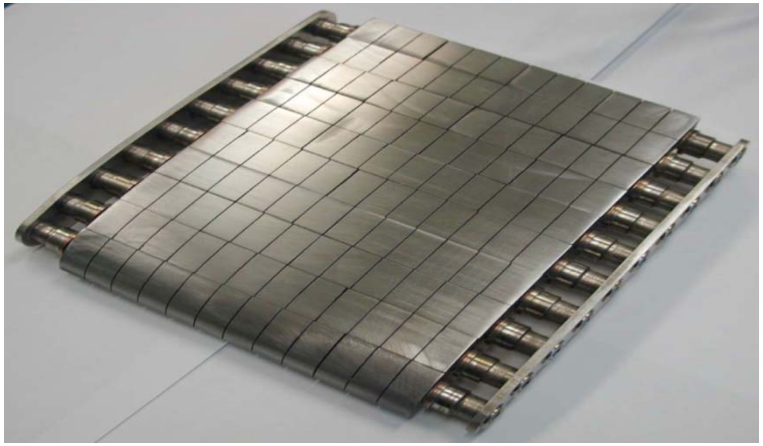
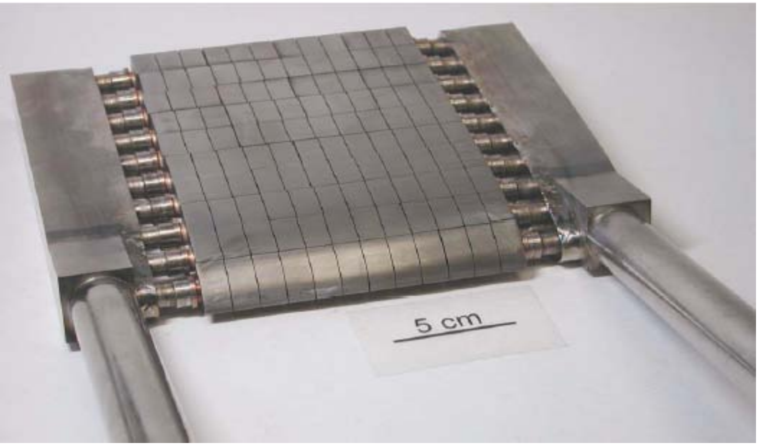
1. Be-tile brazed cooling pipes with Zr adapters



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

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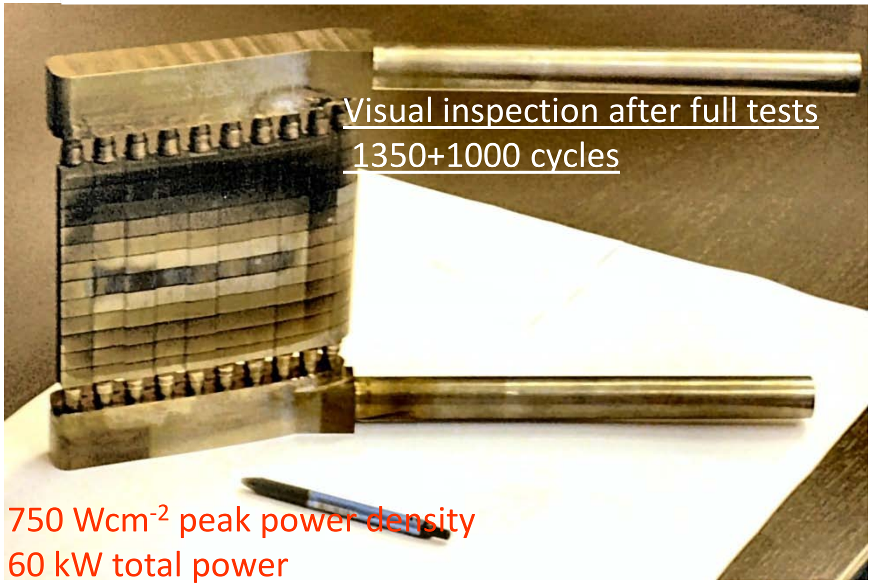
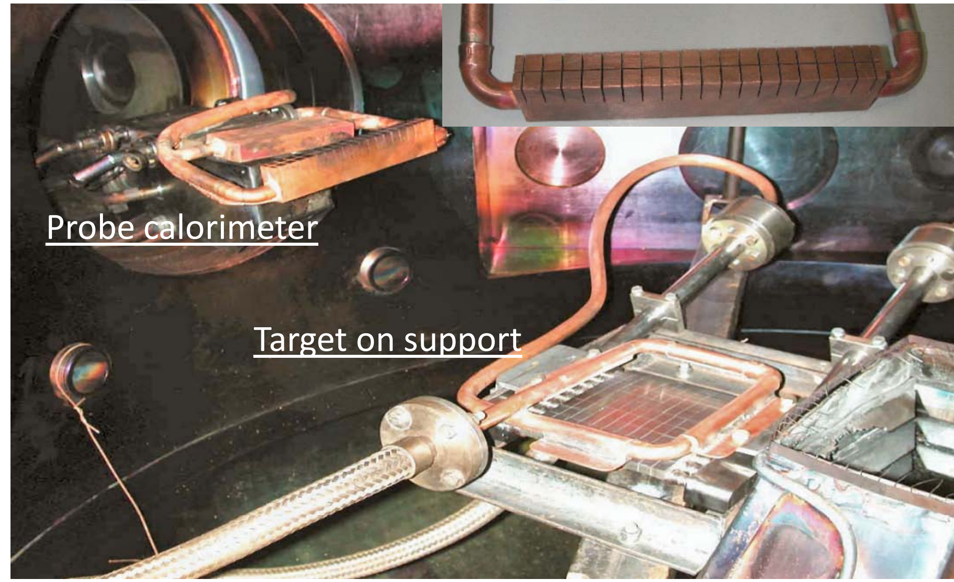
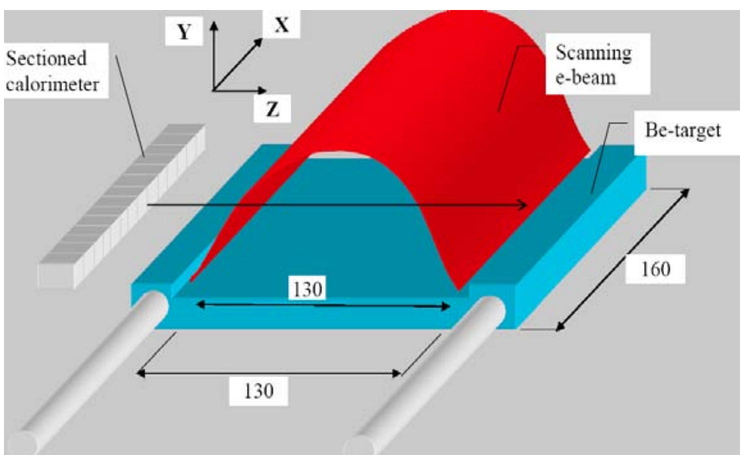


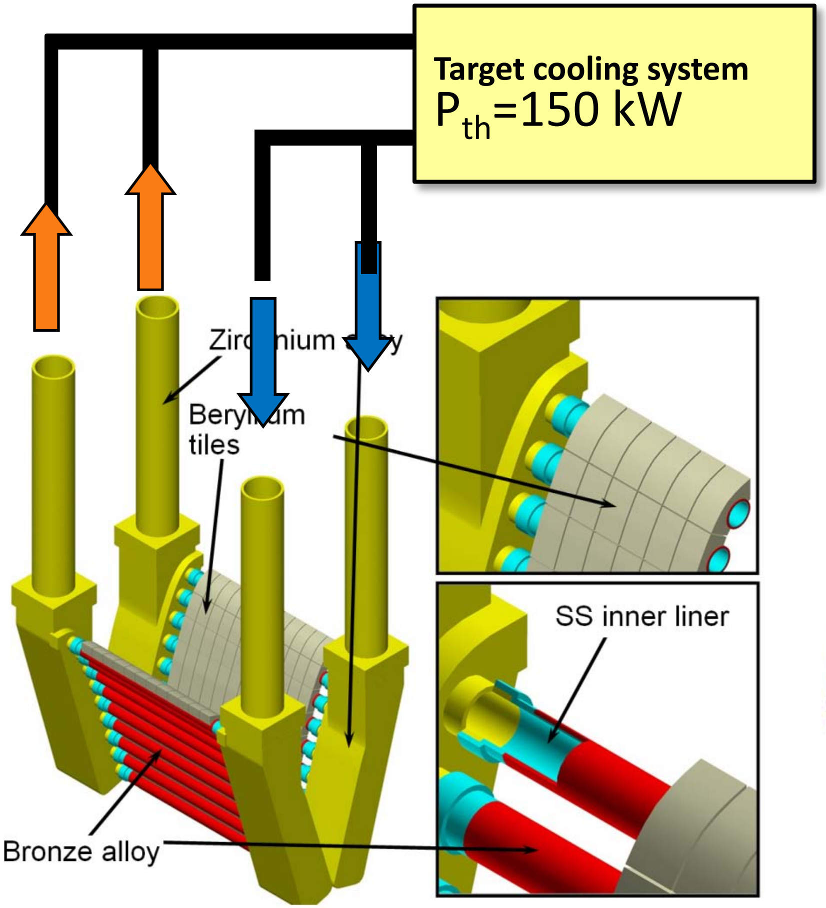




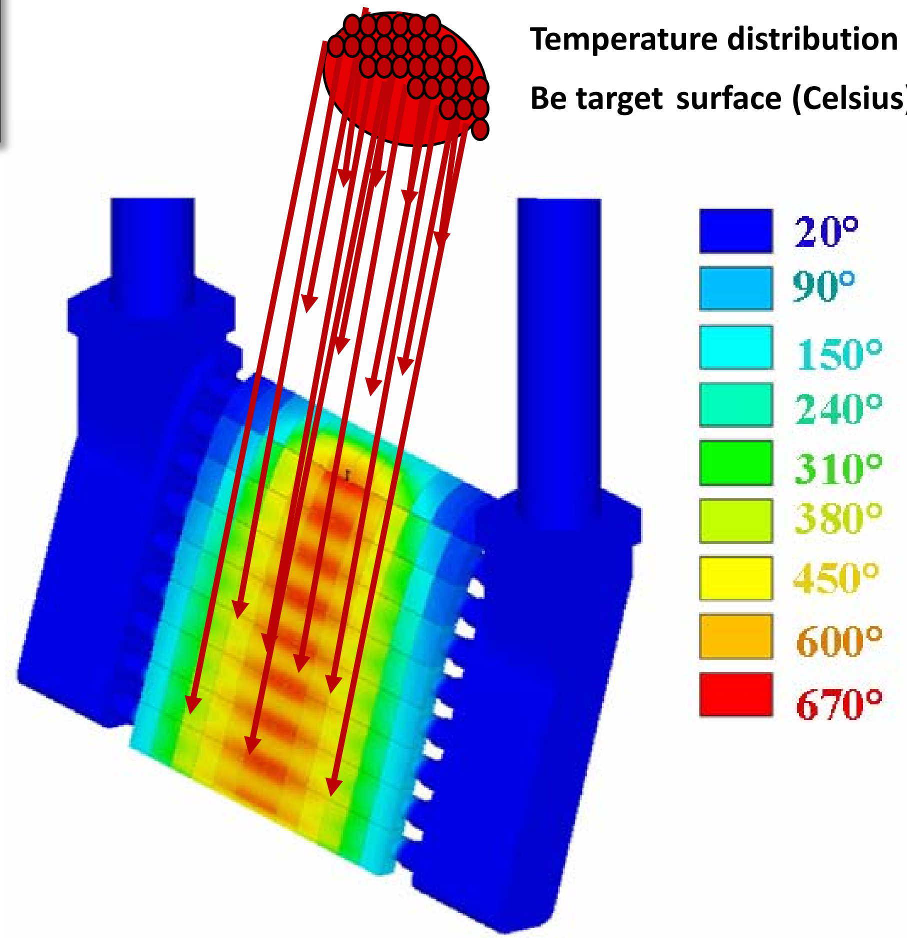
- **Planned testing condition (half-target): Tsefey facility**

- 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

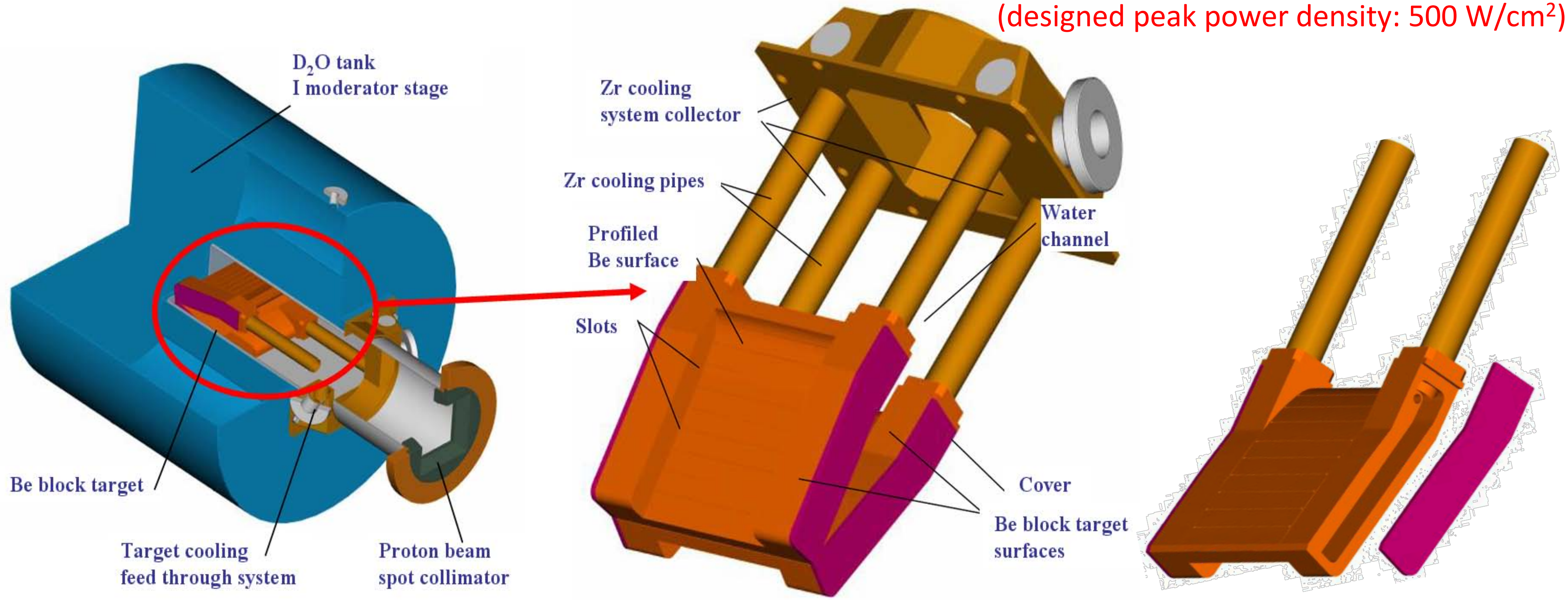


Temperature distribution on Be target surface (Celsius)



Bulk Be neutron converter concept

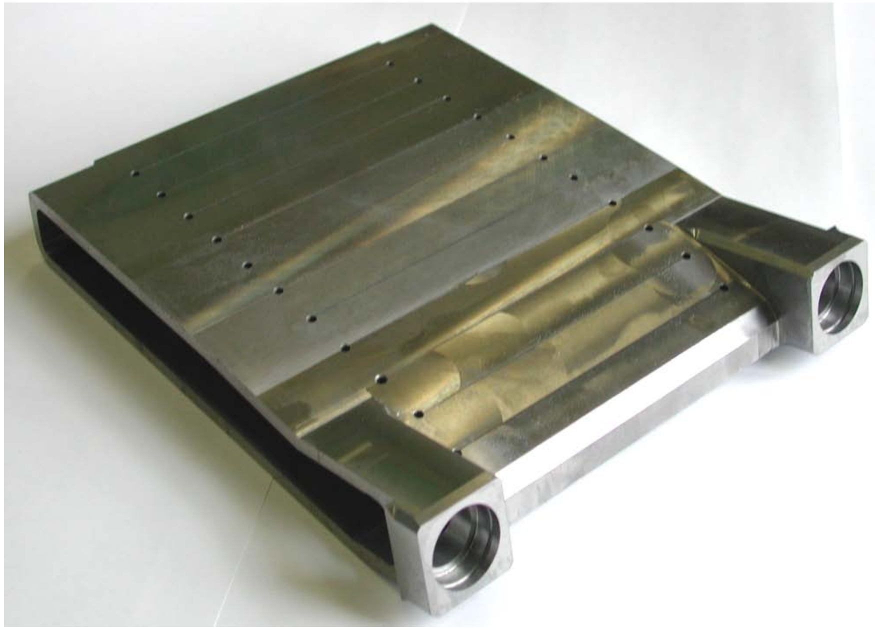
150 kW target converter
(designed peak power density: 500 W/cm^2)



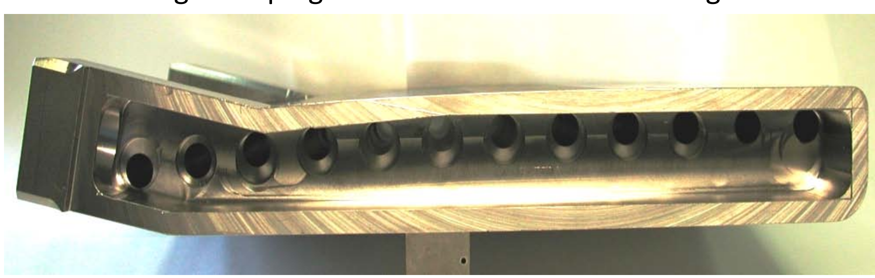
<u>Main advantages & technological challenges</u>

- 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

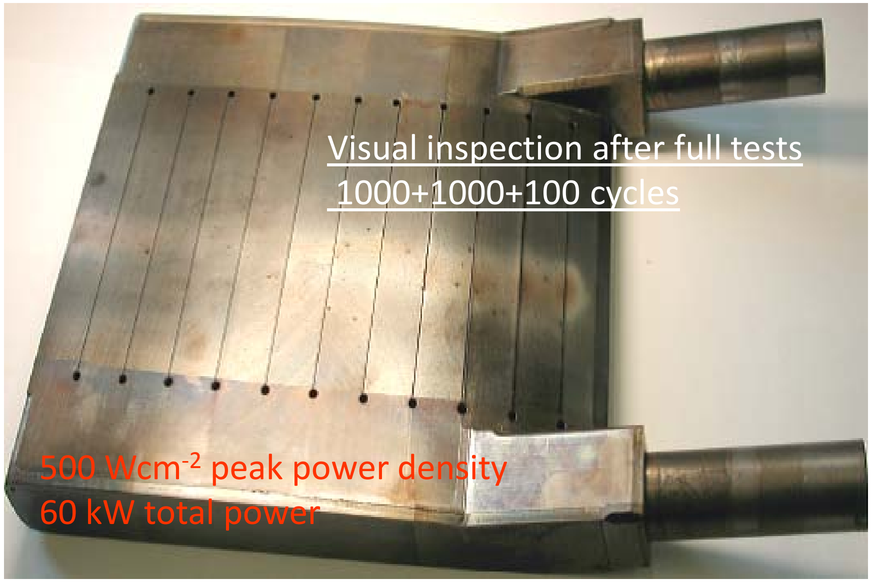


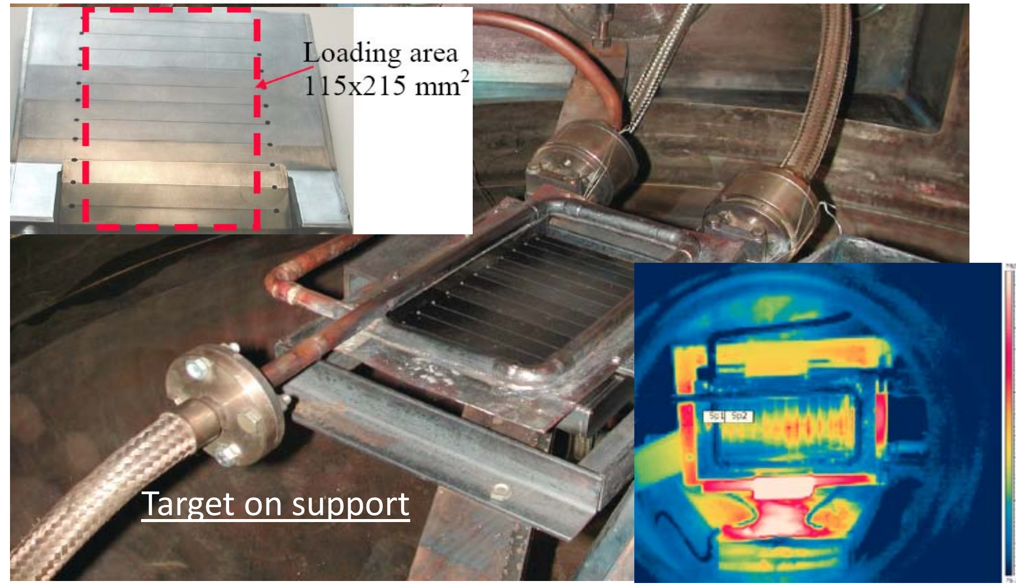
2. Drilling to create cooling water channels inside Be-block

3. EDM cutting of slots between contiguous cooling channels

4. Half target after cover plates + joining pipes brazing

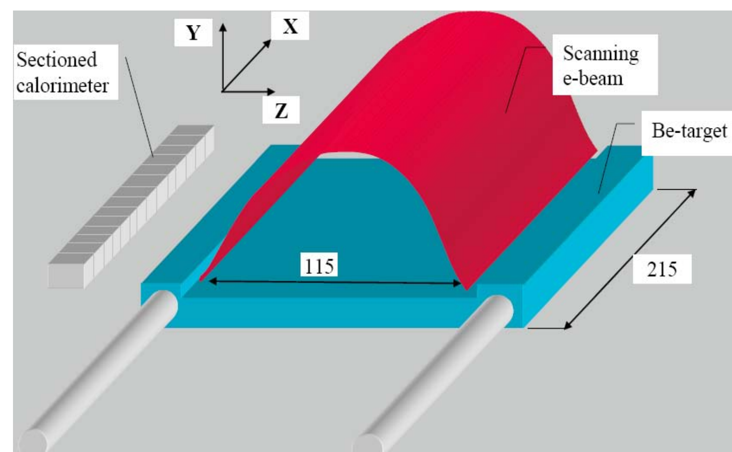
Bulk Be converter prototype: first e-beam full power test





Planned testing condition (half-target): Tsefey facility

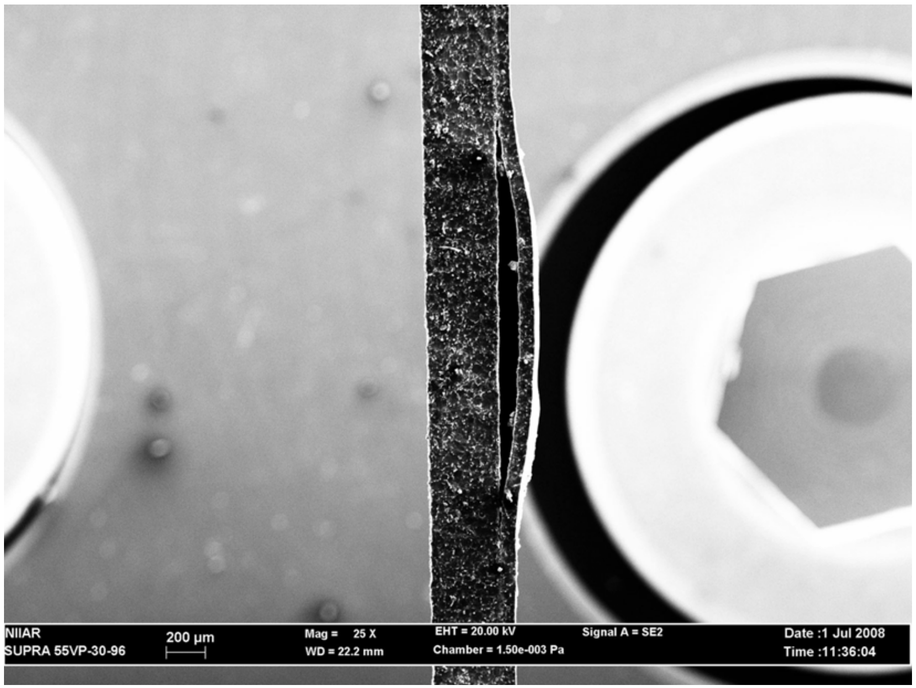
-	E-beam	P=60 - 40 - 47 kW
-	Beam power distribution	close to parabolic shape;
-	Peak power density in loading area	0.5 – 0.6 – 0.7 kW/cm^2
-	Number of cycles	1000 +1000 +100 12 s-on 12 s-off;
-	Target position	horizontal;
-	Cooling system mechanical fixing	as in the converter design;
-	Cooling parameters	P_{inlet}=0.3 - 0.5 MPa,
-		w=3.0 l/s, T_{inlet}=20 ^oC
-	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	Preparation of experimental set-up	In progress	

Blistering problem



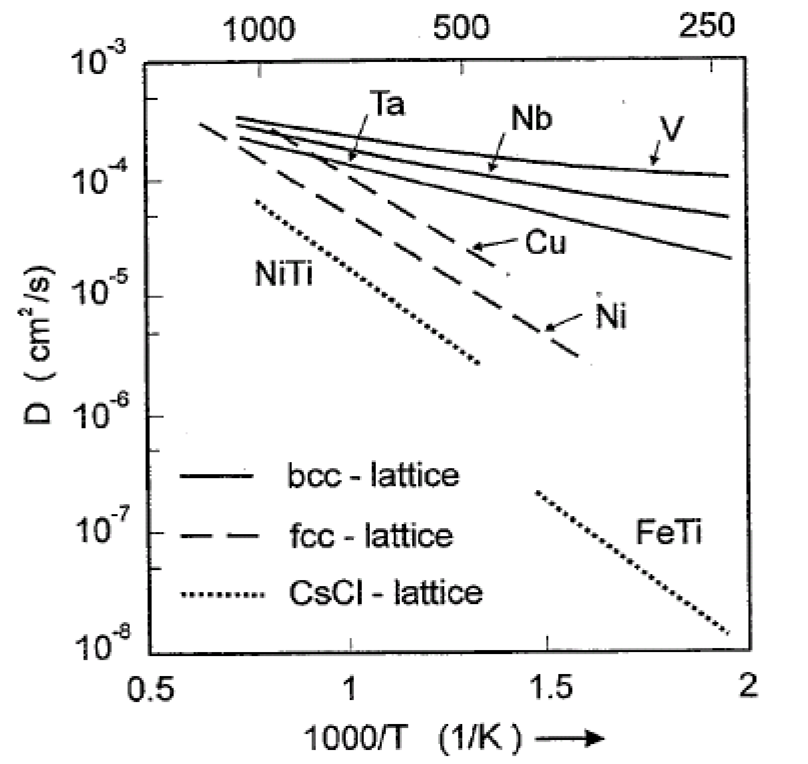
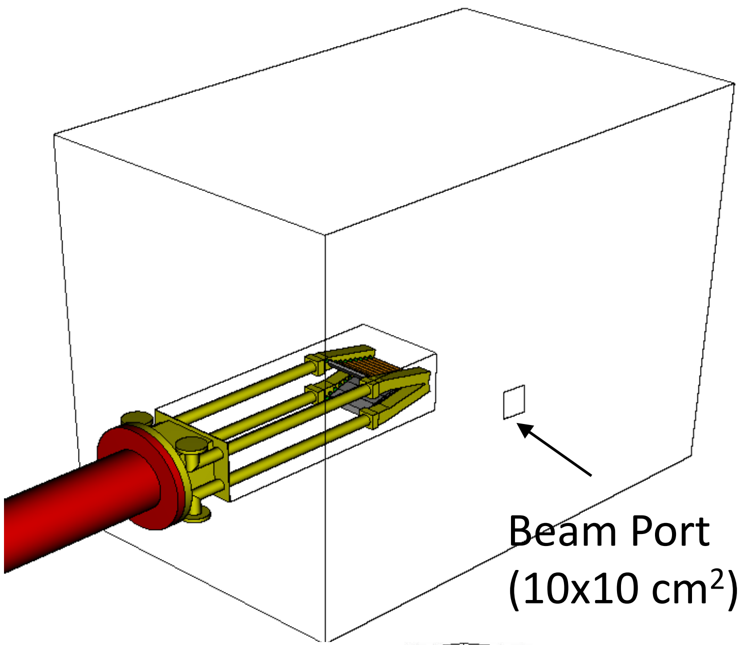
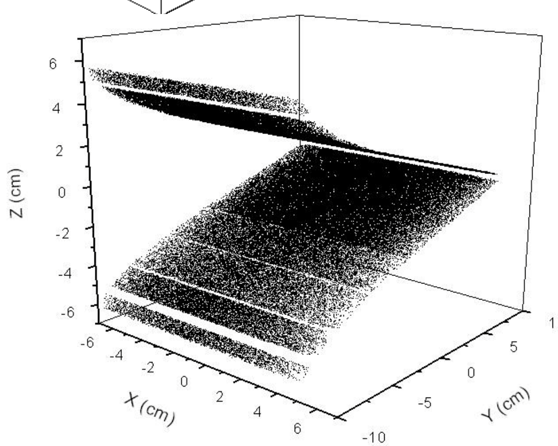


Fig. 8. Arrhenius plot of the diffusion coefficient *D* of hydrogen in metals with bcc, fcc and CsCl structures (according to [18]). The upper abscissa shows the temperature in °C. The data are valid for low hydrogen concentrations.

Diffusion coefficient of hydrogen in Beryllium is order 10^{-9} cm^2/s

The Beam Shaping Assembly modeling





In-air beam port quality design requirements

$\phi_{n\ th}$ ($\leq$ 0.5 eV) $\geq 10^{9}$ [cm^{-2} s^{-1}]

$\phi_{n\ th} / \phi_{n\ total} \geq 0.90$

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

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

Current Status of BNCT. *IAEA-TECDOC-1223, IAEA. May 2001*

Be(p,xn) neutron yielding and spectra at E = 5 MeV

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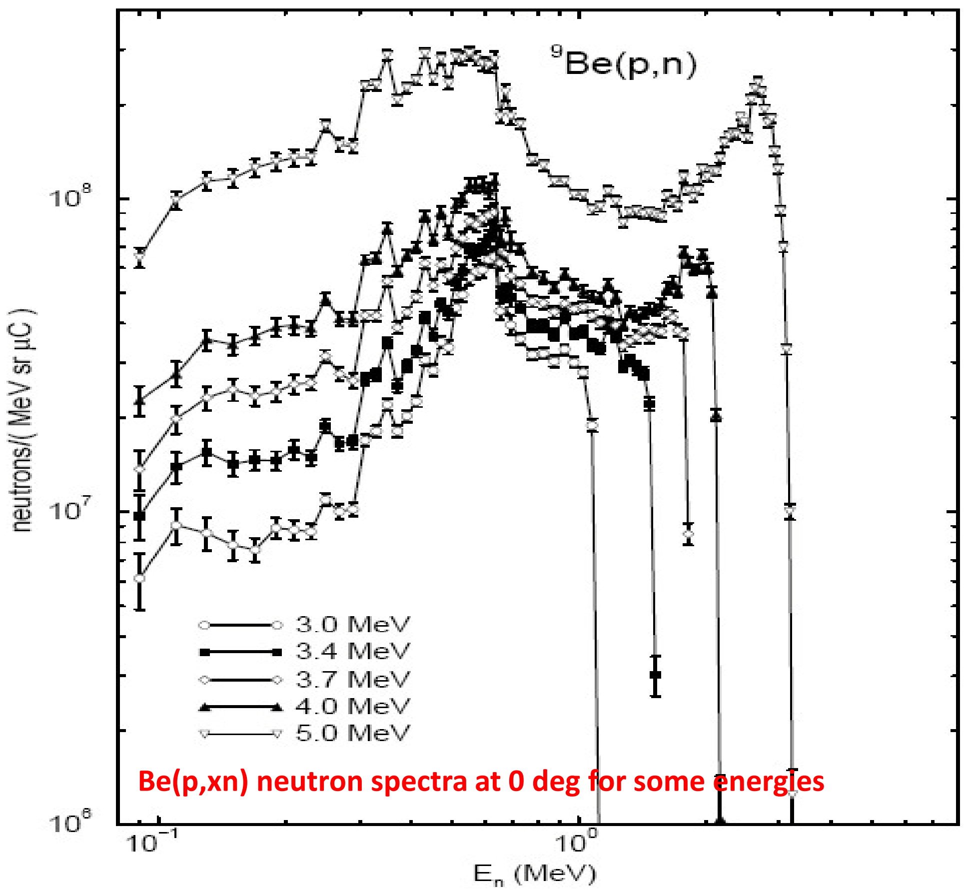
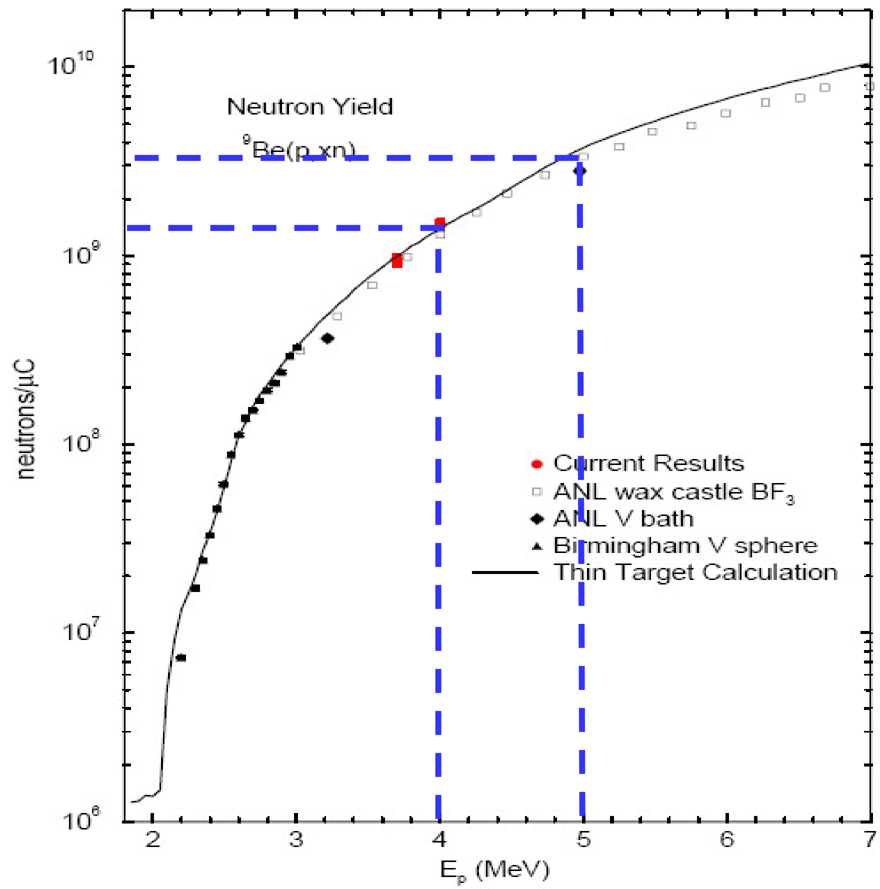
The only one experimental measurements available so far ……TOF technique, MIT (2000)

Howard, et.al., *Measurement of the thick-target 9Be(p,n) Neutron Energy Spectra,* ***Nuc. Sci. Eng., 138, 145-160, (2001)***





Total neutron yield measured at Ep= 4 MeV: **Yn $1.05\cdot10^{12}$ $s^{-1}mA^{-1}$**

Neutron source gain factor expected at Ep= 5 MeV ≅ 2.8 → Yn ~$2.9\cdot10^{12}$ $s^{-1}mA^{-1}$

Ep=5 MeV Be(p,xn) thick target neutron spectra measurements at the 7 MeV Van de Graff accelerator at LNL

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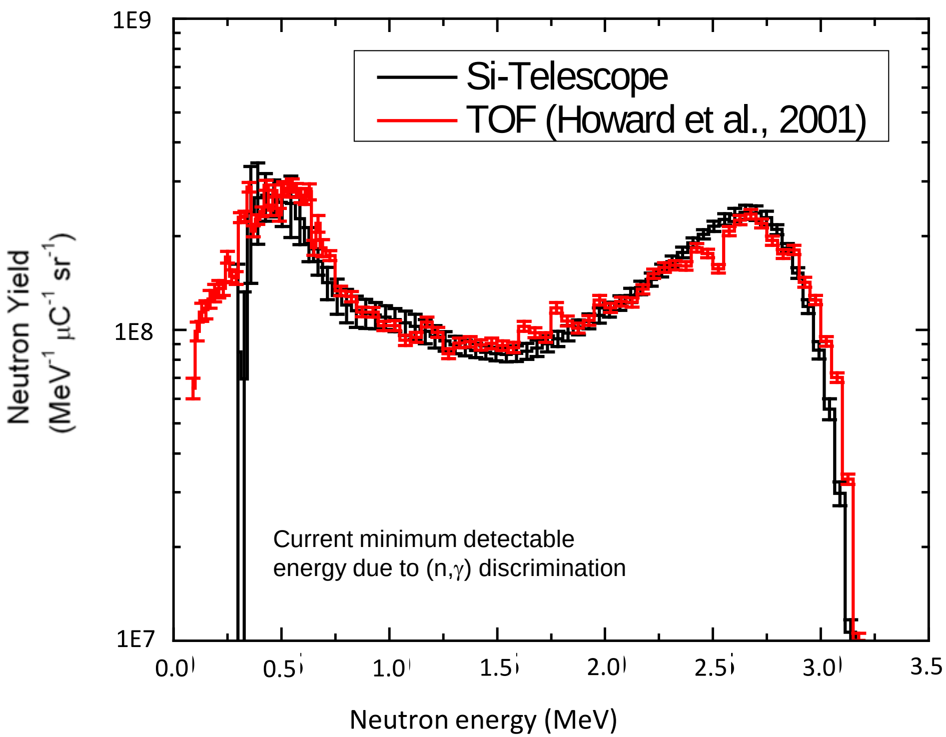
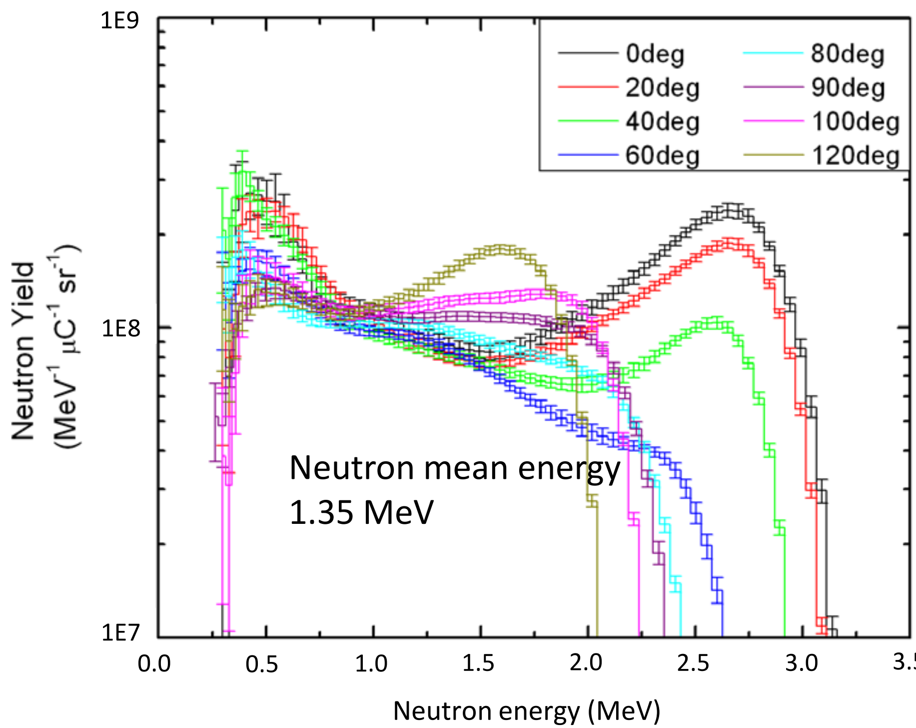
Be(p,xn) neutron spectra comparison with at 0 deg



Be(p,xn) all measured neutron spectra

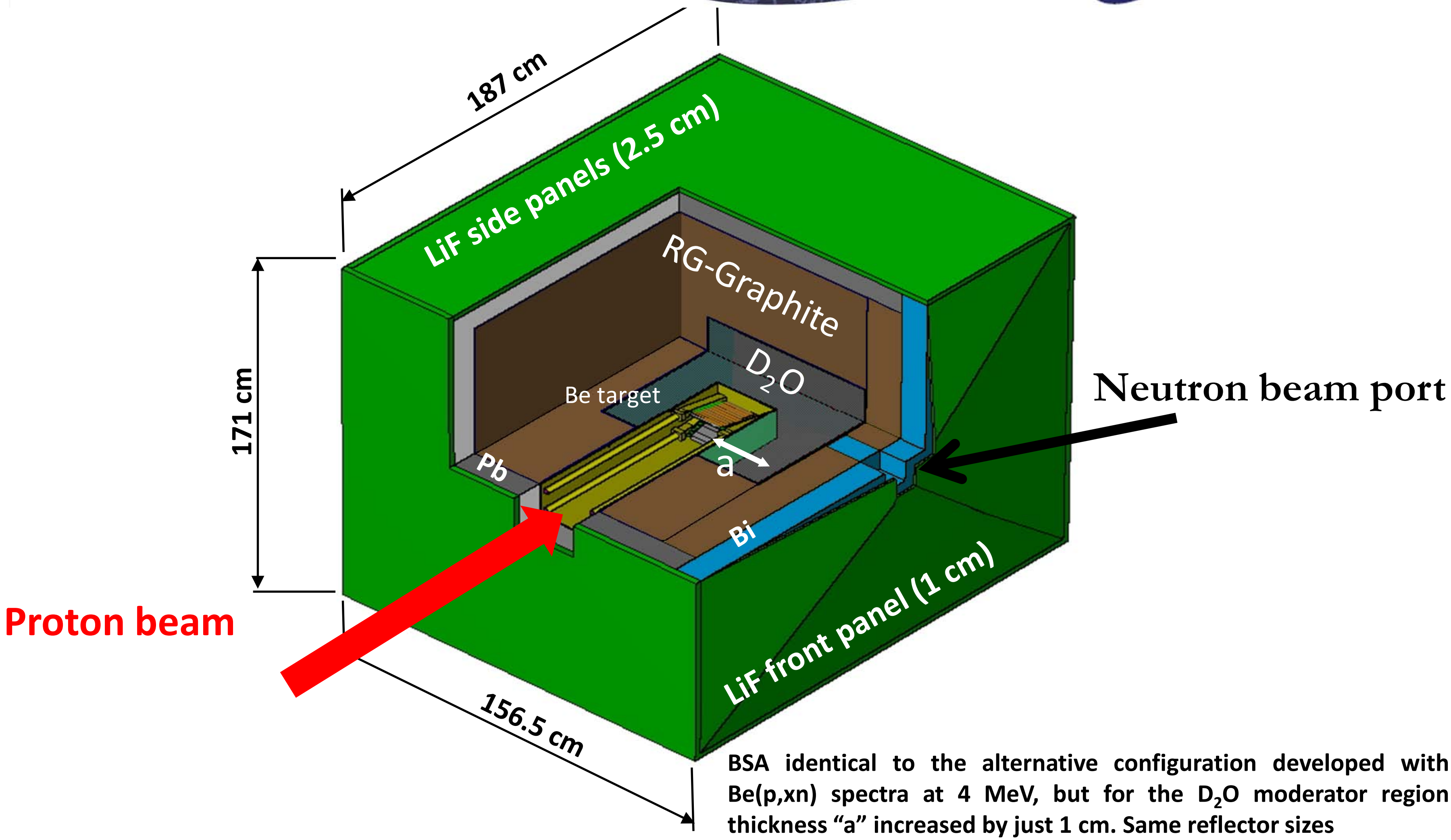


POLIMI - Silicon Telescope

Be(p,xn) Ep= 5 MeV total neutron Yield measured $Y_{n\,(4\pi)} = 3.05\cdot10^{12}\ s^{-1}mA^{-1}$

Neutron source level expected with TRASCO RFQ + Be target → Sn ~$1.05\cdot10^{14}\ s^{-1}$

The Beam Shaping Assembly solution



BSA identical to the alternative configuration developed with Be(p,xn) spectra at 4 MeV, but for the D_2O moderator region thickness "a" increased by just 1 cm. Same reflector sizes

MCNPX calculation results

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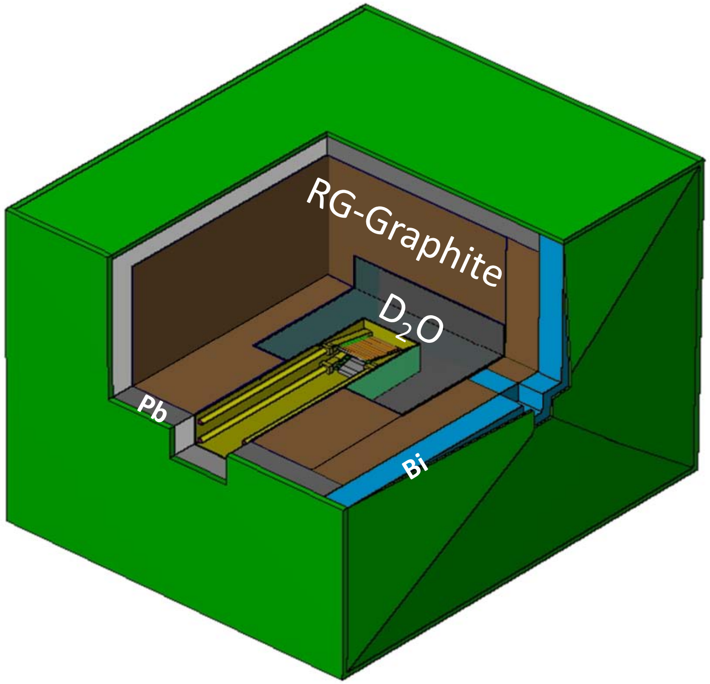

Neutron Fluence-to-kerma conversion factors from ICRU-63

Gamma Fluence-to-kerma conversion factors from ICRU-46

Total measured neutron yield ~$3.05 \cdot 10^{12}\ s^{-1} \cdot mA^{-1}$

Agosteo et al., 2010. Proc. of ICNCT-14, Argentina (2010)

	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} ($Gy \cdot h^{-1}$)	$K_{\gamma} / K_{n\ tot}$	$K_{n\ (E>0.5\ eV)} / \Phi_{th}$ ($Gy \cdot cm^2$)	K_{γ} / Φ_{th} ($Gy \cdot cm^2$)
IAEA TECDOC-1223 ref. parameters	**> 1.0E+09**	**> 0.90**					**≤ 2.0E-13**	**≤ 2.0E-13**
MCNPX results	**4.30E+09**	**0.96**	2.53	0.51	1.42	0.46	**0.33E-13**	**0.92E-13**

Neutron & gamma dose beam port wall mapping

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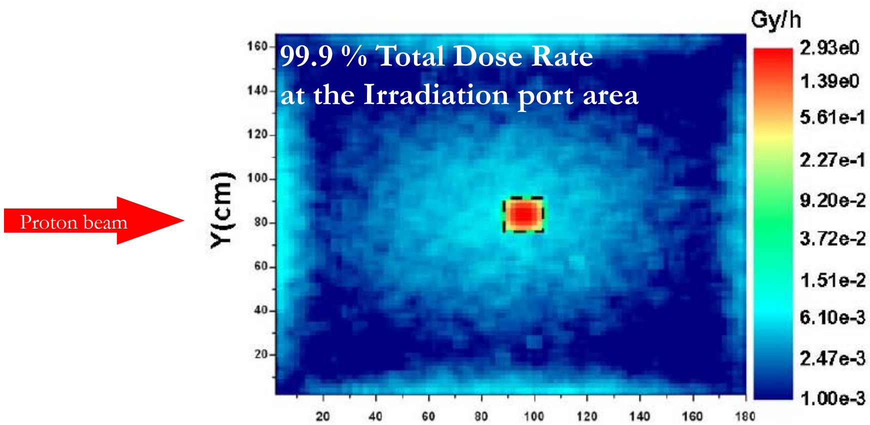
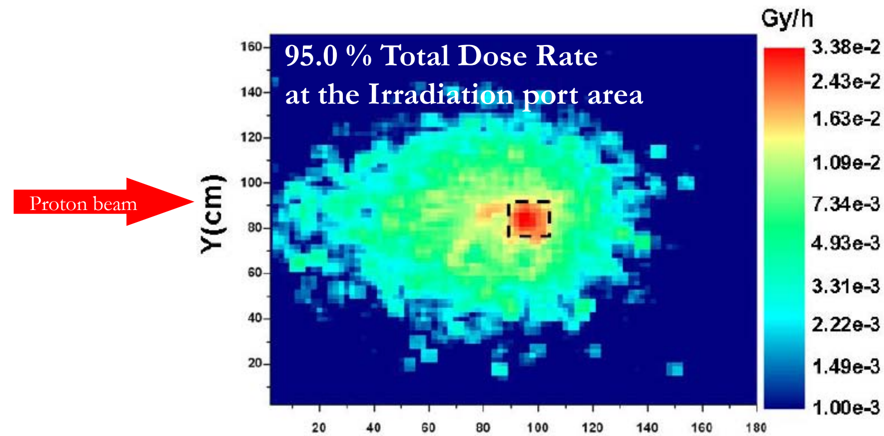
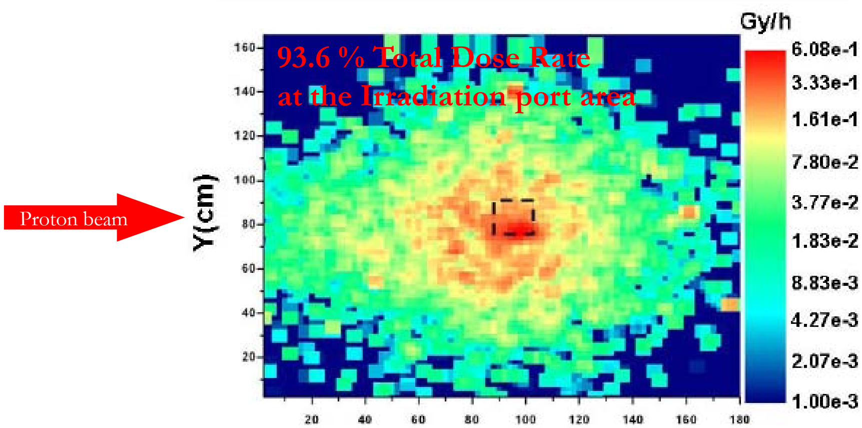


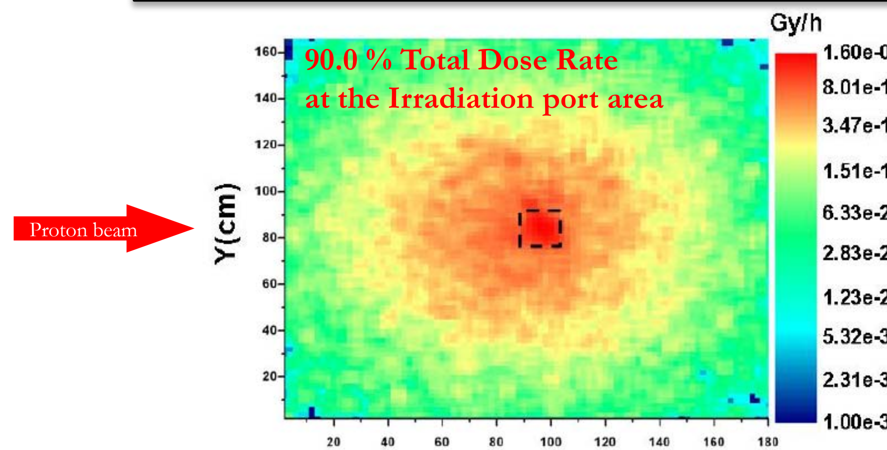
Thermal neutrons (E≤ 0.5 eV)



Epithermal neutrons (0.5 eV≤E≤10 keV)



Fast neutrons (E>10 keV)



Prompt gammas

Conclusions

- 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.
- Proton irradiation test is needed. Blistering phenomena must be mitigated to extend target life-time.
- In the next three year, accelerator, transfer lines, targets, neutron moderators with ancillary technological plant will be completed. At the end 2015 neutron source will be commissioned at low duty cycle (high peak, low average) inside a shed with light shielding.