Thin Beryllium target for ^{9}Be(d,n)-driven BNCT

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ABNP2014, April 14-15, Legnaro, Italy.

Outline

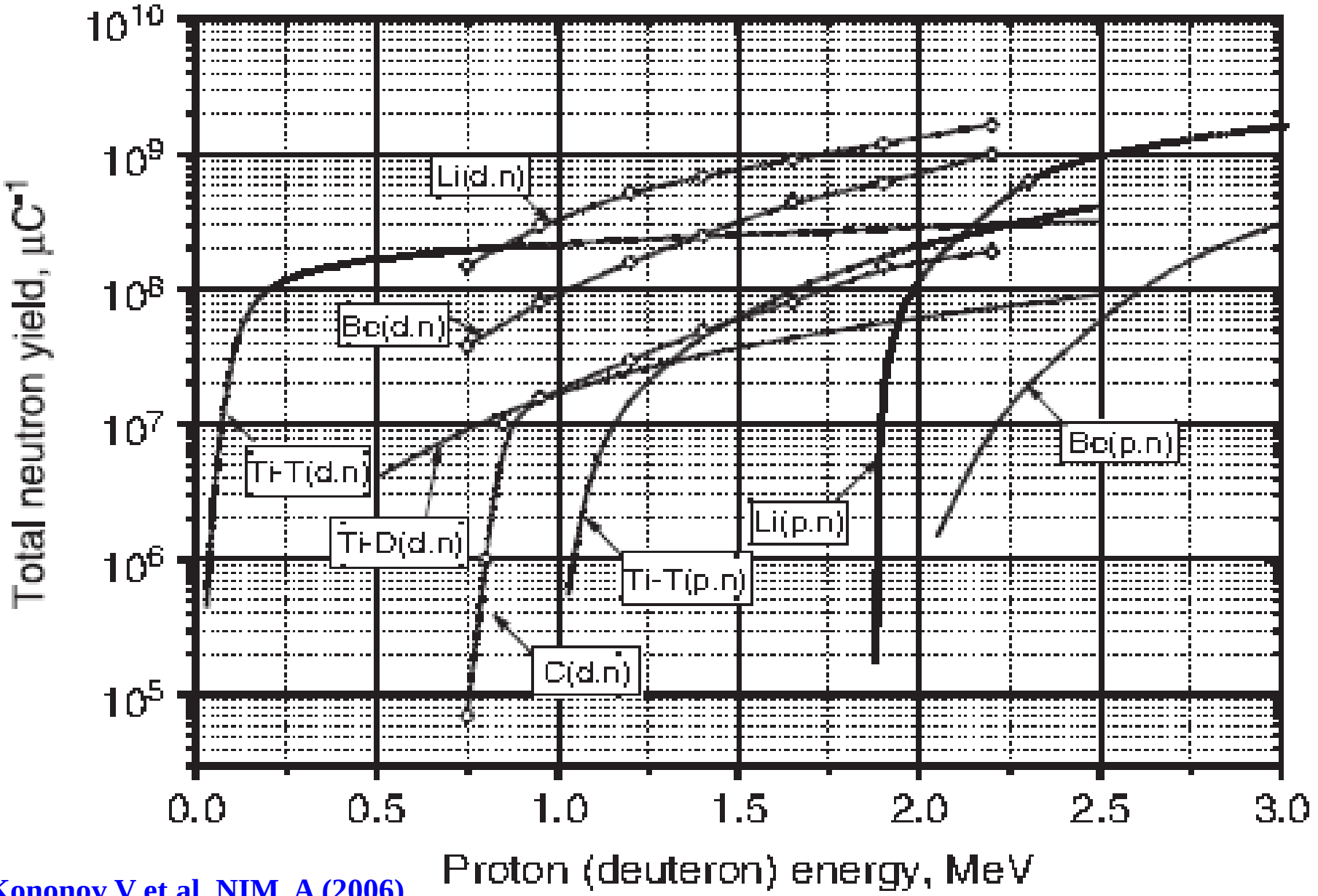
- **Possible nuclear reactions.**
- **The ^{9}Be(d,n)^{10}B reaction and thin targets.**
- **Program in Argentina: Development of a Tandem-Electro-Static-Quadrupole (TESQ) accelerator-based facility.**
- **Conclusions/remarks**

In-hospital AB-BNCT

Quest for "best" solutions. Criteria for widest possible dissemination:

- **Safety**
- **Simplicity**
- **Lowest possible cost**

Neutron producing reactions



Kononov V et al. NIM. A (2006)

Nuclear reactions & material properties

Reaction	E_{thres} (MeV)	Radioactive products	Melting T (^oC)	Therm cond (W/m-K)
$^7Li(p,n)^7Be$	1.88	Yes	180	84.7
$^9Be(p,n)^9B$	2.06	No[a]	1287	190
$^9Be(d,n)^{10}B$	0 (exoergic)	No	1287	190
$^9Be(d,n)^{10}B^*$	1[b]	No	1287	190

[a]Very short lived activity with no gamma emission.
[b]Population of excited states at ≈ 5.1 MeV in ^{10}B. The reaction for population of these states has an effective threshold of ≈1 MeV.

Reminder: Coulomb barriers of protons on common structural materials, Fe and Cu ≈ 5 MeV. Activation threshold for neutrons ≈ 6 MeV.

Neutron sources based on the $^{9}Be(d,n)^{10}B$ reaction

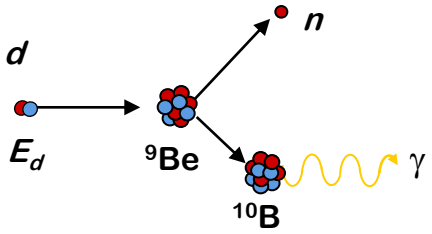
Computational assessment of deep-seated tumor treatment capability of the $^{9}Be(d,n)^{10}B$ reaction for accelerator-based Boron Neutron Capture Therapy (AB-BNCT), Phys. Med. (EJMP) 30-2 (2014)133-146 (March 2014)

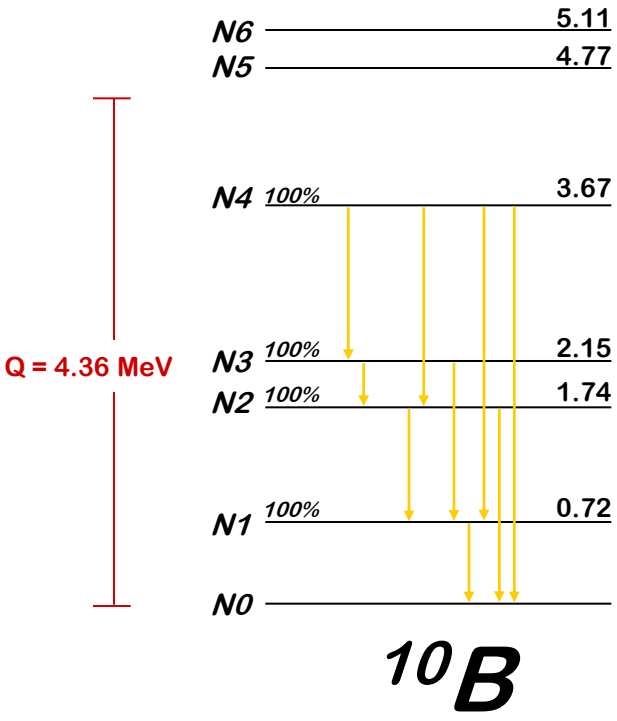
M.E. Capoulat, D.M. Minsky, and A.J.Kreiner

PhD Thesis M. E. Capoulat, March 2014.

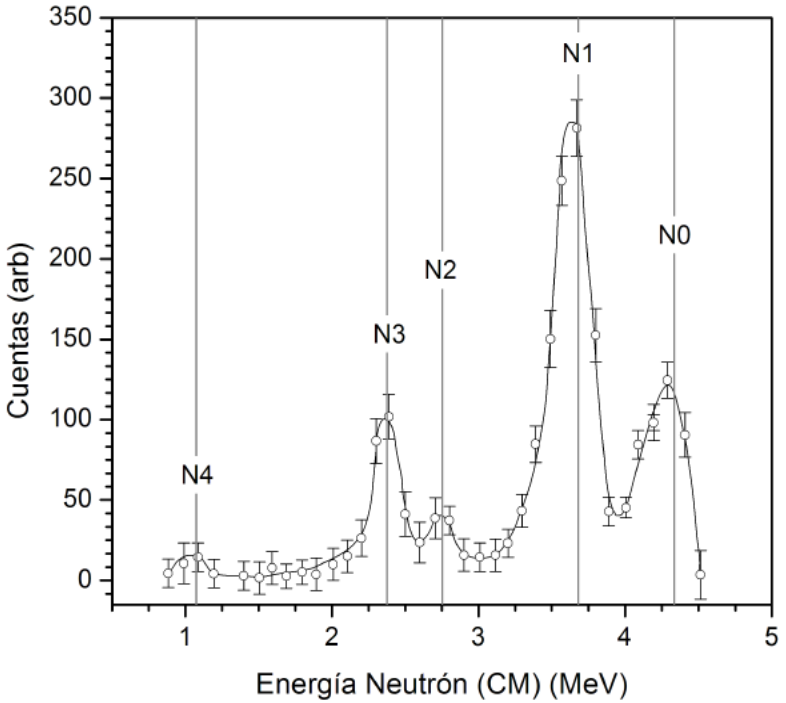
$^{9}Be(d,n)^{10}B$: population of ^{10}B

Q = 4.36 MeV



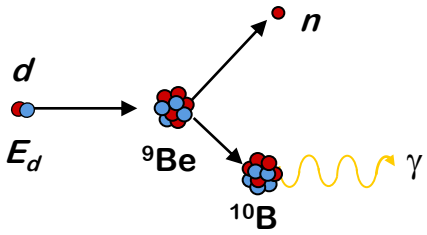


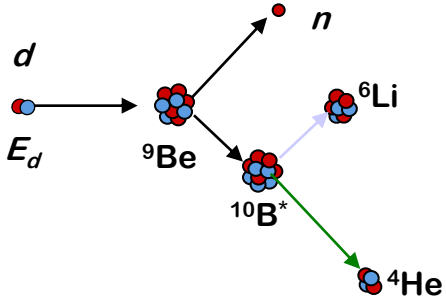
Deuterons of 500 keV

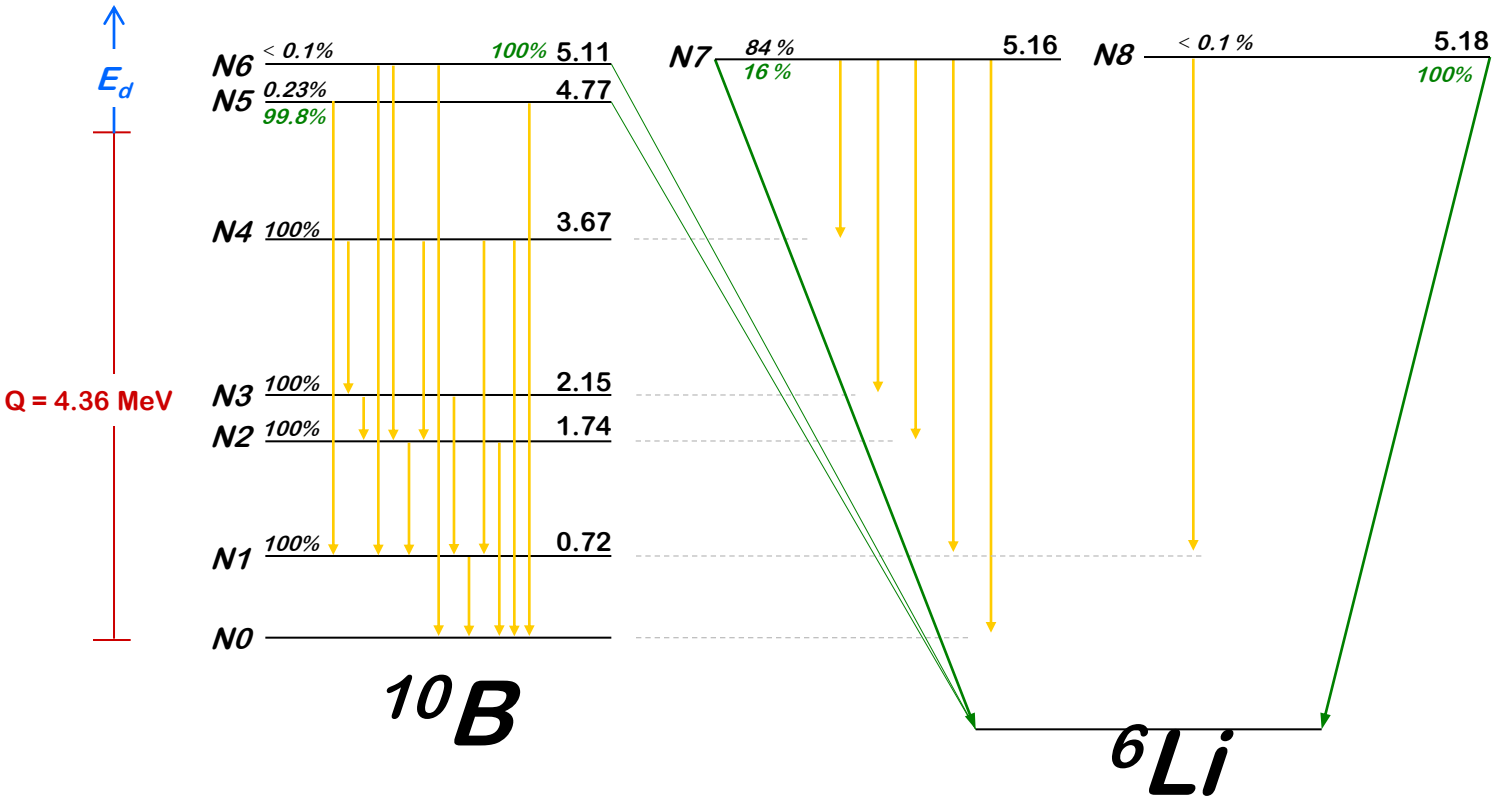


$^{9}Be(d,n)^{10}B$: population of ^{10}B

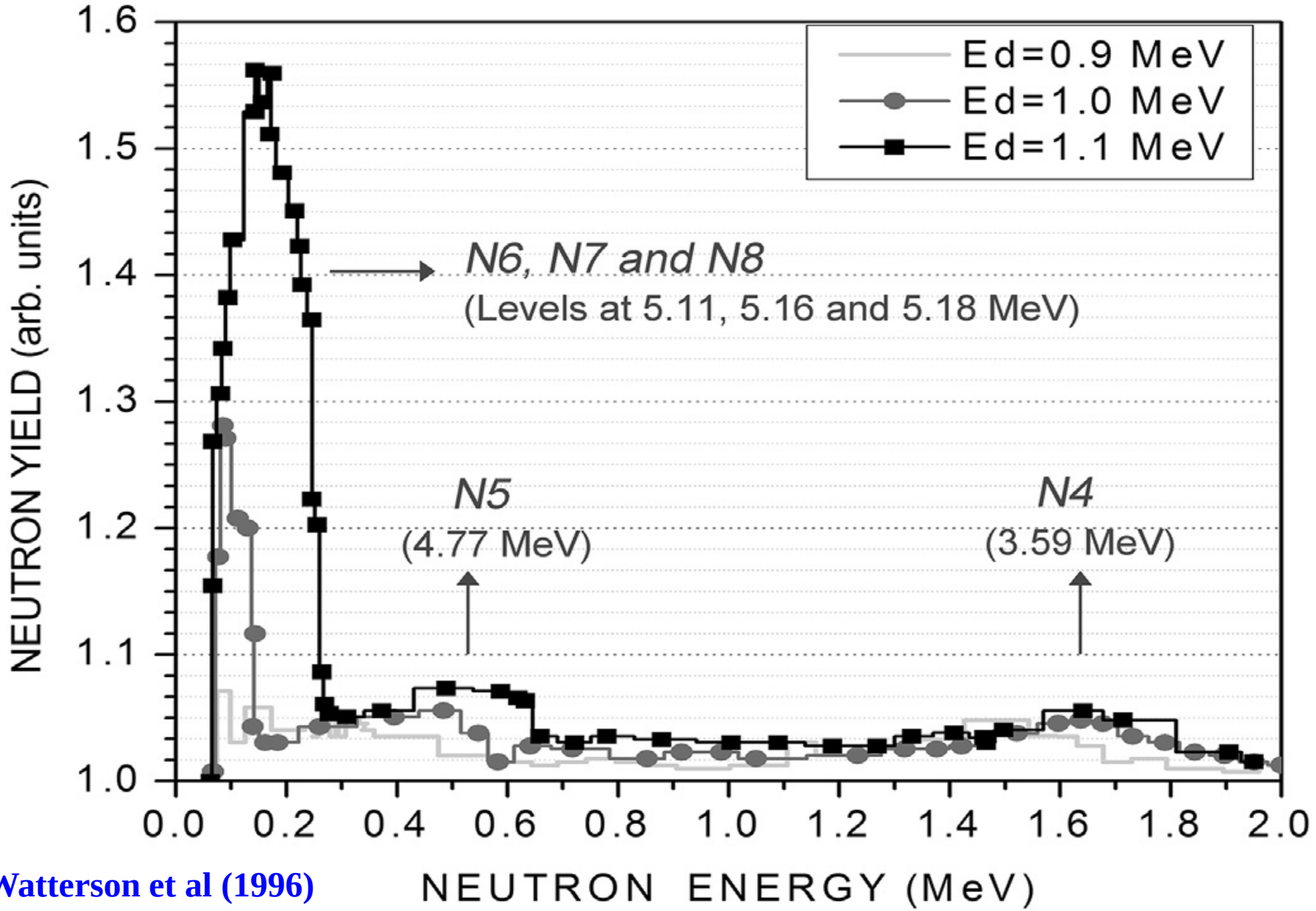
Q = 4.36 MeV







Neutron spectrum of ^{9}Be(d,n)



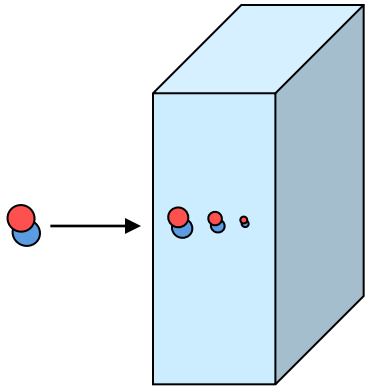
Watterson et al (1996)

The $^{9}Be(d,n)^{10}B$ reaction

1

Thick target

Deuterons loose <u>all</u> its energy in the target

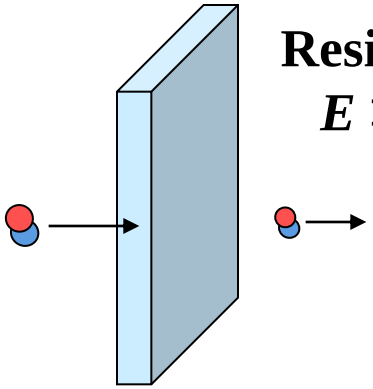


Many reactions take place at an energy less than 1 MeV.

2

Thin target

Deuterons loose only <u>part</u> of its energy in the target



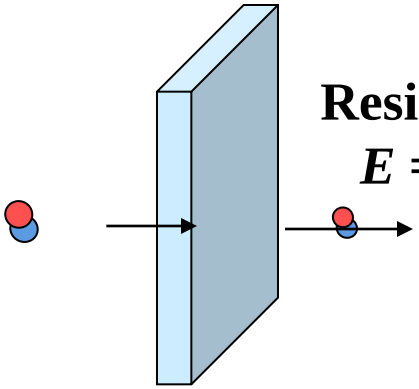
All reactions take place at an energy larger than 1 MeV

→ A thin target allows us to eliminate a significant part of the more energetic neutrons

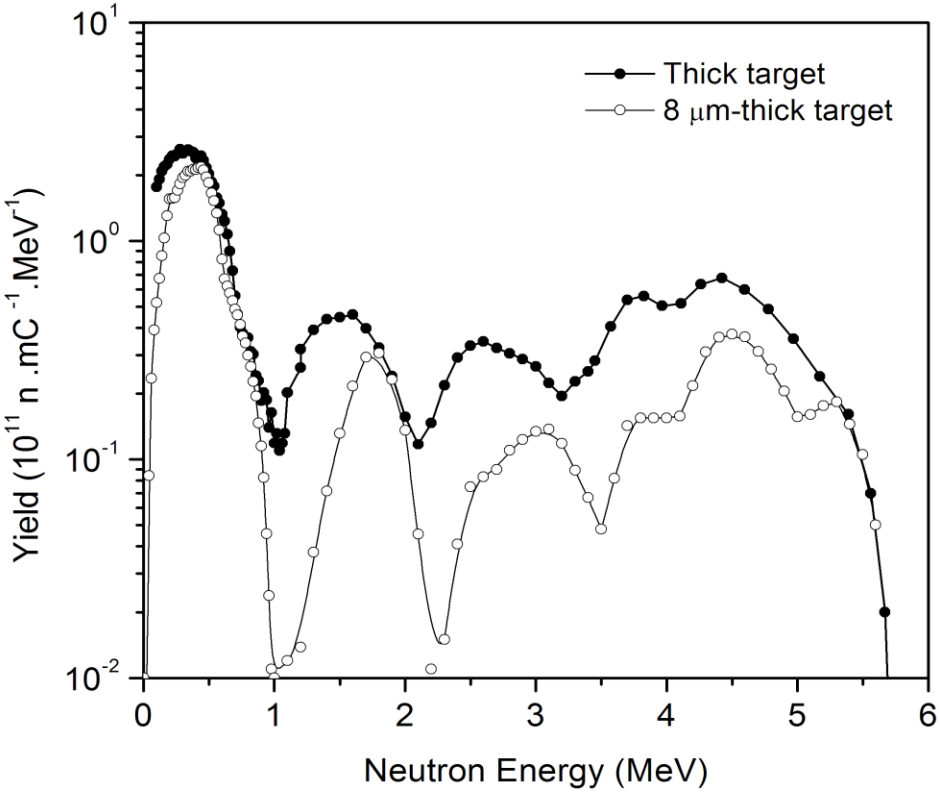
Thin target $^{9}Be(d,n)^{10}B$

Deuterons of 1.45 MeV

Thickness of Be: 8 microns



Residual Energy
E =1.05 MeV

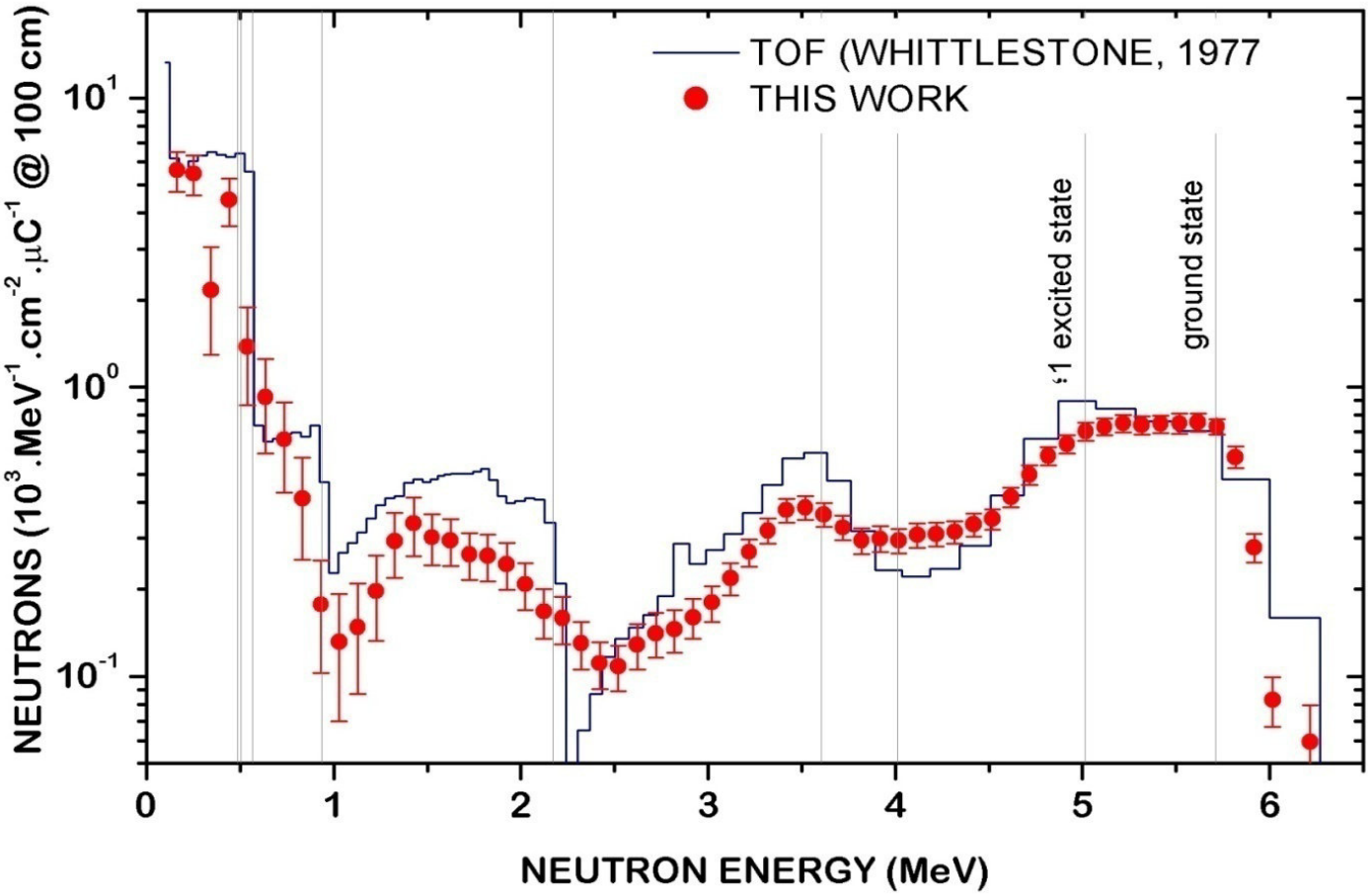


→ **A thin target eliminates many of the more energetic neutrons**

All reactions ***which would occur at E_d <1 MeV are eliminated***

Measurement of the Double Differential Cross Section of the $^{9}Be(d,n)^{10}B$ Reaction in the low Energy Regime

M. E. Capoulat, D.M. Minsky, A.J. Kreiner, M.V. Introini, M. Lorenzoli, A. Pola, S. Agosteo



Thick target neutron spectrum for Ed = 1.45 MeV

Thin targets

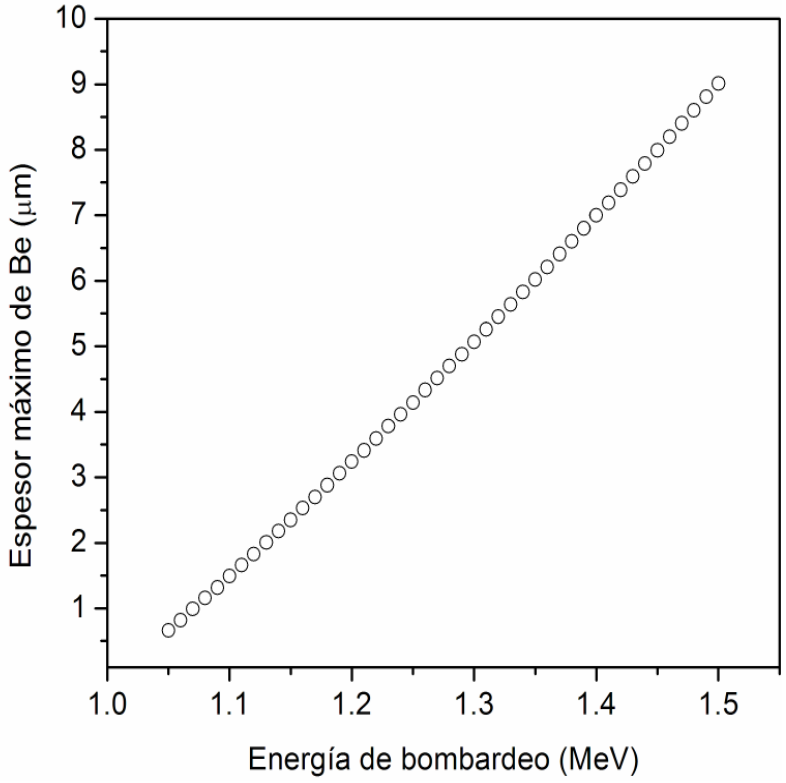
Goal : ***Minimize the contribution of high energy neutrons in the primary neutron spectrum***

Bombarding energies and thicknesses of interest:

- **Energies** → $1 < E_d < 1.5$ **MeV**
- **Thicknesses** → $x < x_{max}$

For the energy and thickness ranges of interest the neutron spectrum is divided in two regions:

- **neutrons with $E_n > 1$ MeV → associated to N0-N4**
- **neutrons with $E_n < 1$ MeV → associated to N5-N8**



Maximum Be thickness (x_{max}) for each E_d

Thin targets

Objective

Minimize the contribution of primary high energy neutrons

$$R = \frac{Y_{<1\mathrm{MeV}}}{Y_{>1\mathrm{MeV}}}$$

Bombarding energies and thicknesses of interest :

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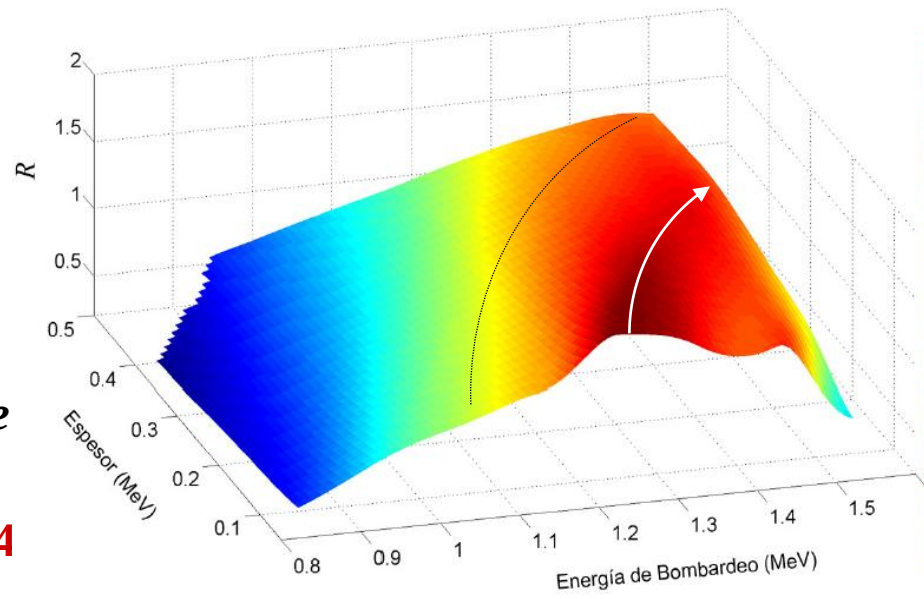


Relative neutron production of E_n <1 MeV

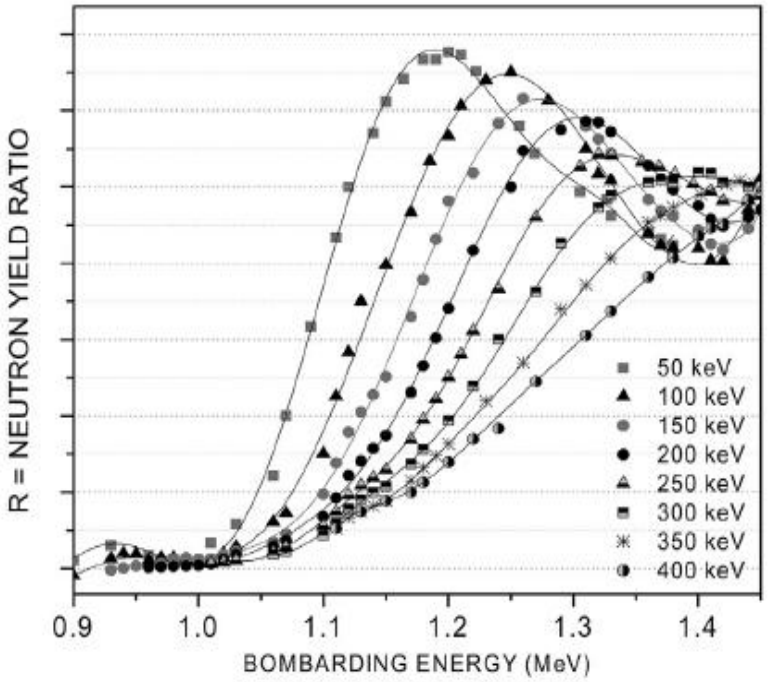
Thin target

Objective: ***Minimize the contribution of high energy neutrons to the primary neutron spectrum***

$$R = \frac{Y_{<1\mathrm{MeV}}}{Y_{>1\mathrm{MeV}}}$$

Selected configurations

	Thickness (μm)	E_d (MeV)	R	Production ($n.mC^{-1}$)
#1	0.2	1.20	1.63	$4.6\ 10^{09}$
#2	0.9	1.24	1.62	$2.4\ 10^{10}$
#3	1.8	1.27	1.60	$4.3\ 10^{10}$
#4	2.8	1.32	1.56	$6.1\ 10^{10}$
#5	3.7	1.35	1.53	$8.2\ 10^{10}$
#6	5.6	1.42	1.48	$1.2\ 10^{11}$
#7	6.5	1.44	1.44	$1.4\ 10^{11}$
#8	7.4	1.45	1.41	$1.6\ 10^{11}$



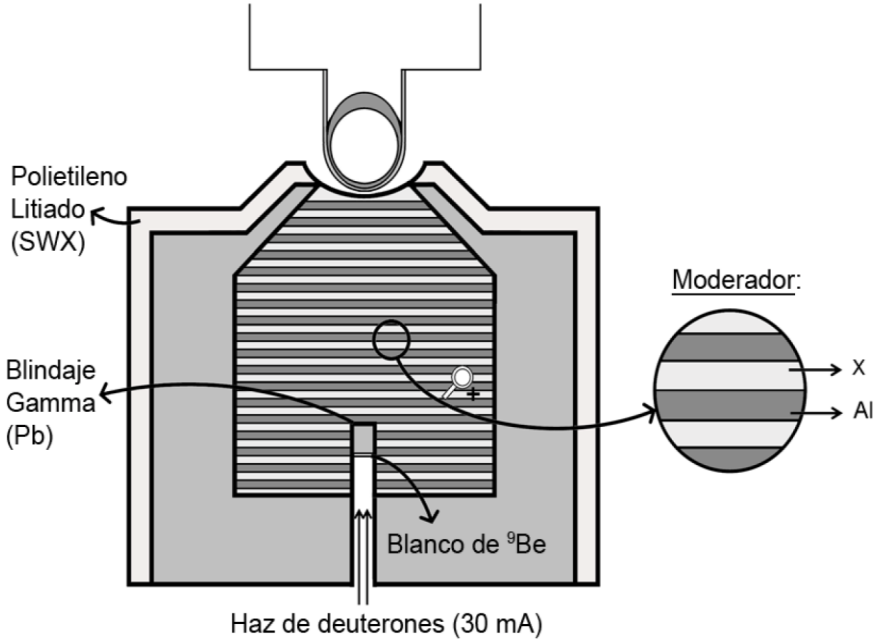
Relative neutron production with E_n <1 MeV

Deep seated tumor treatment

Beam Shaping Assembly

Objectives

Obtain an epithermal beam.
Maximize the neutron flux in the patient direction.
Provide shielding.



Beam Shaping Assembly

Moderator materials

- **Aluminium, fluorated compounds, Fluental ®**

Thermal neutron filtering

- **Materials enriched in ^{6}Li, ^{10}B**

Shielding for fast neutrons

- **Hidrogen, lithiated polyethylene**

Neutron Reflector

- **Pb**

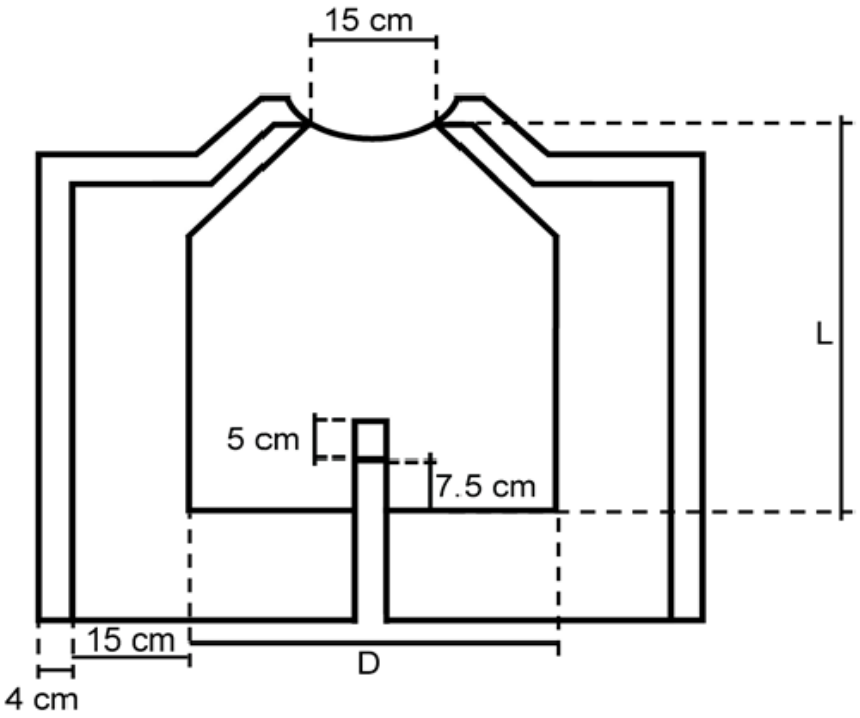
Gamma shielding

- **High Z materials, Pb**

Beam shaping

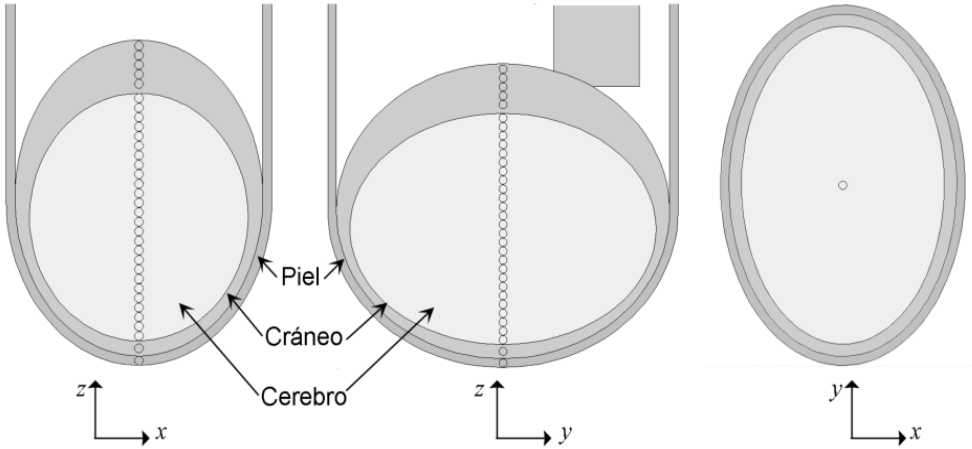
Optimization

The section (D) and length (L) of the moderator were optimized using the MCNP code



Optimization criteria:

- **Maximize tumor dose**
- **Treatment time: ≤ *60 minutos***
- **Skin dose: ≤ *16.7 Gy-Eq***
- **Healthy brain dose: ≤ *11.0 Gy-Eq***

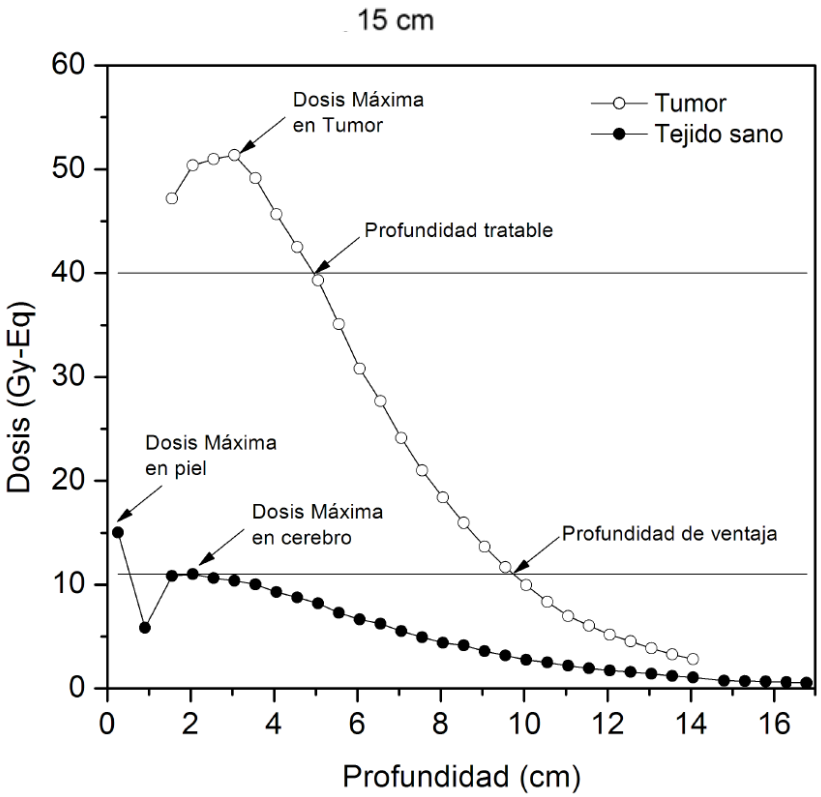


Snyder phantom

Beam shaping

Optimization

Section (D) and length(L) of moderator were optimized for each configuration #1-#8 using the MCNP code



Optimization Criteria:

- **Maximize tumor dose**
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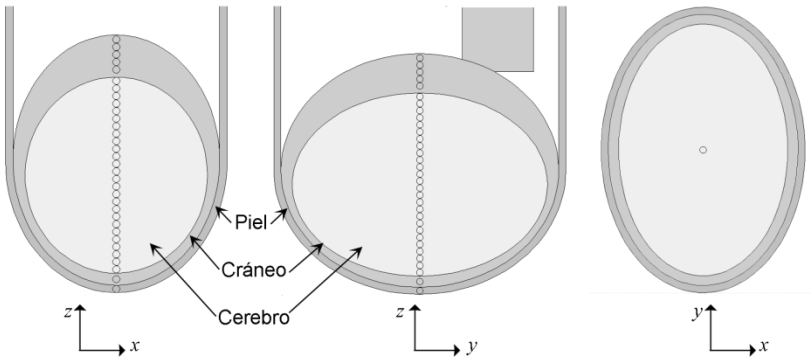
- **Healthy brain dose:** $\leq$ ***11.0 Gy-Eq***



Depth dose profile in Snyder phantom.

Beam shaping

Results of BSA optimization for each target configuration.

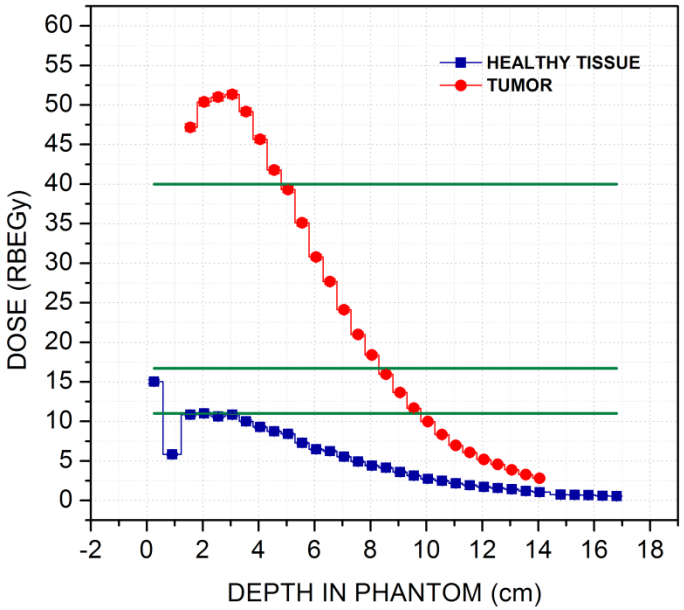
	Maximum dose			*Treatable Range*	*Time*
	Tumor (Gy-Eq)	*Healthy brain (Gy-Eq)*	*Skin (Gy-Eq)*	*(cm)*	*(min.)*
#1	**16.9**	**10.7**	**16.7**	**-**	**58**
#2	**28.6**	**10.8**	**15.5**	**-**	**60**
#3	**35.6**	**11.0**	**15.7**	**-**	**59**
#4	**40.4**	**11.0**	**15.2**	**-**	**58**
#5	**42.9**	**11.0**	**14.9**	**2.3-2.8**	**60**
#6	**47.3**	**11.0**	**15.2**	**1.7-3.8**	**57**
#7	**50.0**	**11.0**	**15.2**	**1.5-4.8**	**58**
#8	**50.9**	**10.9**	**15.0**	**1.5-4.8**	**60**

Best Case: 8 µm Be target

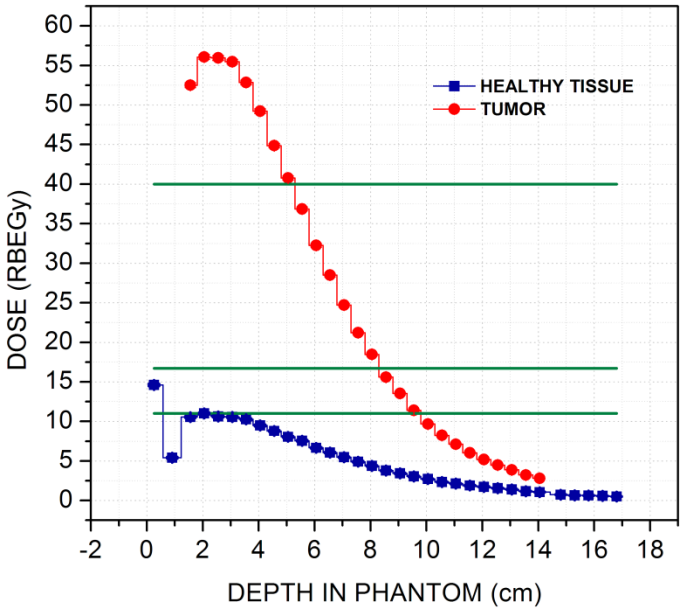
- **The best dose performance was shown by Source #8 (deuterons of 1.4 MeV on an 8 micron thick Be target)**

	Length [cm]	Cross-Section [cm^2]	Max. Dose to Tumor [RBEGy]	MDT Position [cm]	Advantage Depth [cm]	Treatable Depth [cm]	Max. Skin Dose [RBEGy]	Max. Healthy Brain Dose [RBEGy]	Treatment Time [min.]
SINGLE FRACTION	55	40x40	51.3	2.72	9.79	1.55-4.82	15.0	10.9	60
TWO FRACTIONS	66.3	40x40	56.8	2.62	9.76	1.55-5.13	14.7	11.0	120

Single irradiation treatment



Two irradiation treatment

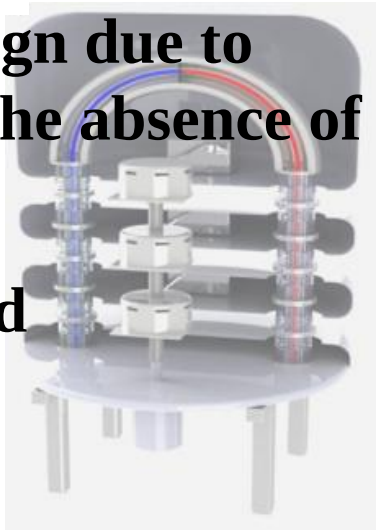


M.E. Capoulat et al. EJMP 2014 "Neutron sources based on the ^{9}Be(d,n)^{10}B reaction"

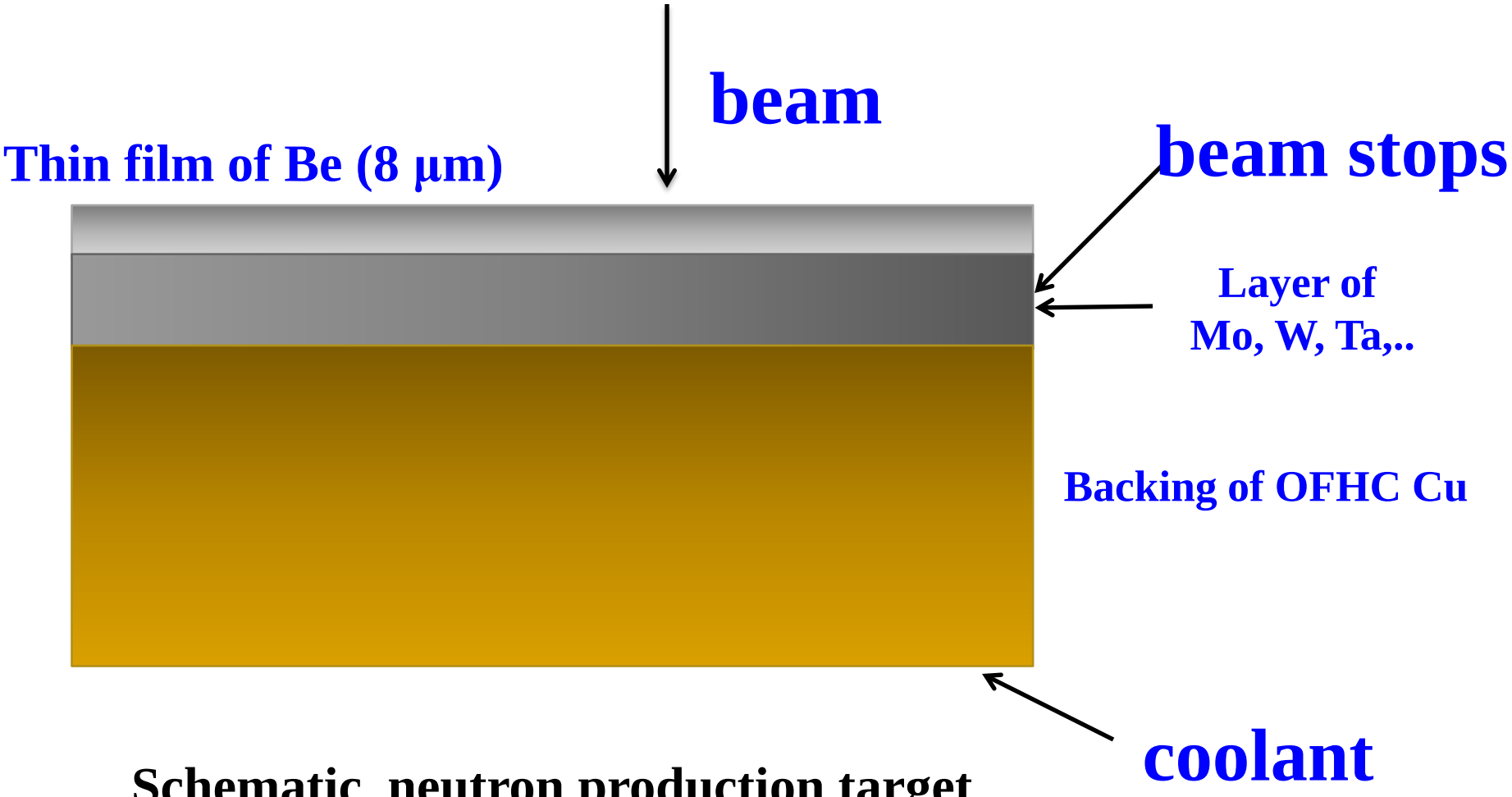
Conclusions

- **$^{9}Be(d,n)^{10}B$ @ 1.45 MeV was established as a useful neutron source for deep-seated BNCT.**
- **Utilization of thin targets *(~8 microns)* (*Also usable as a source of thermal neutrons with thick target and D_2O moderation).***
- **It is possible to obtain dose distributions comparable to other neutron sources. Both reactor and accelerator based.**
- **This option has several important technological advantages.**
- **$^{9}Be(d,n)^{10}B$ allows a simplification of the target design due to much better thermomechanical properties of Be and the absence of residual radioactivity.**
- **Smaller accelerator (700 kV Tandem) or single ended**

1.4 MV.



Neutron Production Target

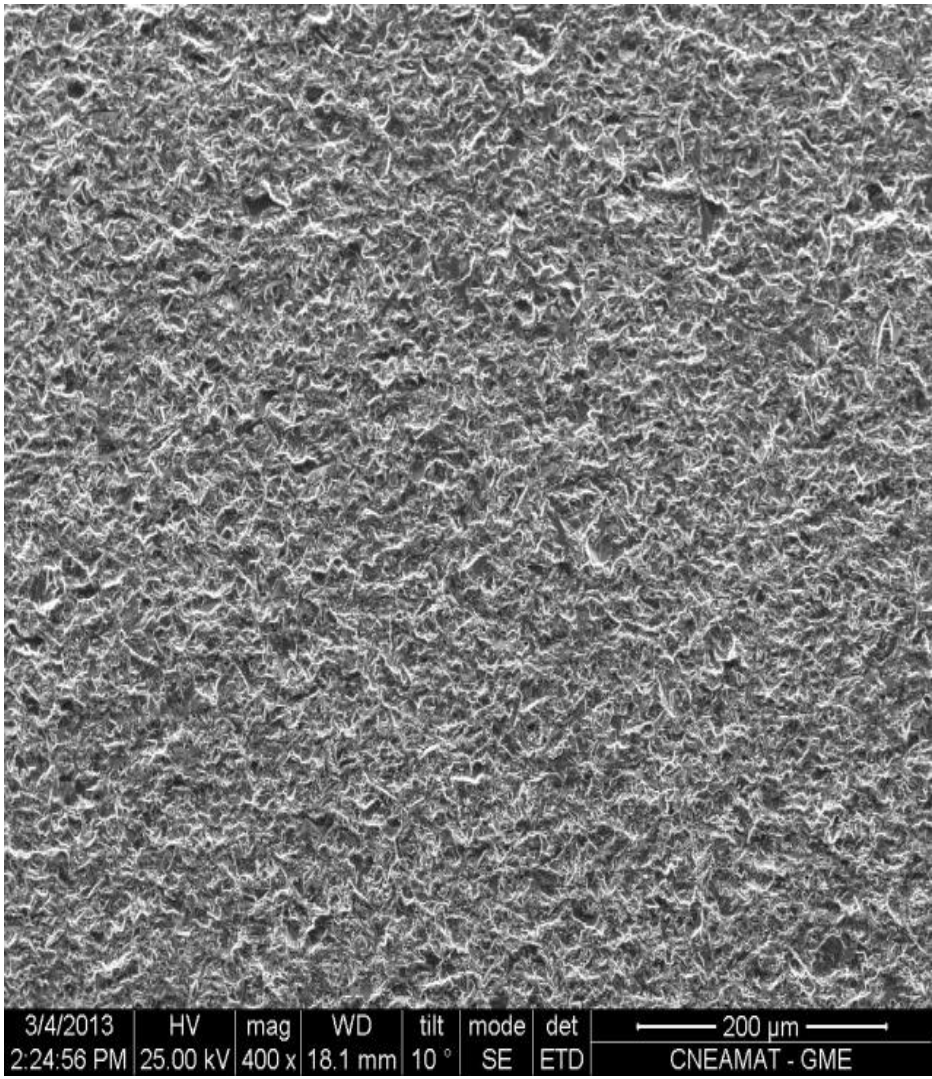


Schematic neutron production target

Beryllium deposits

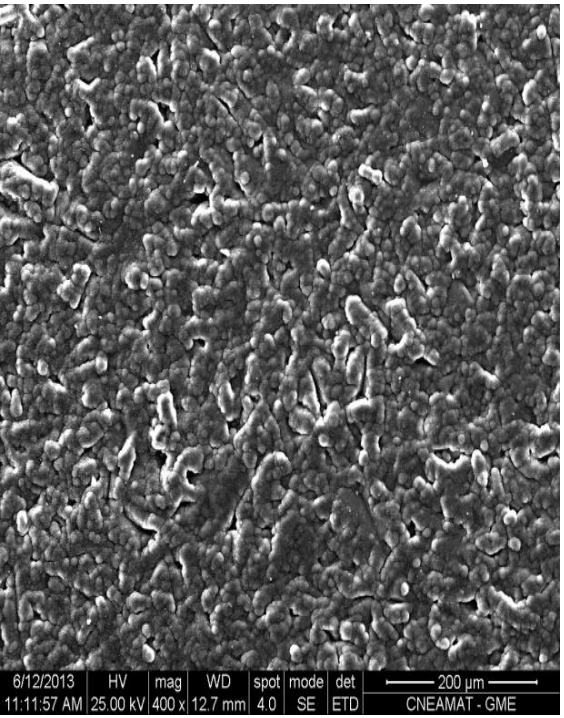
Adhesion: To obtain a good adhesion Be is evaporated on a substrate which has been blasted with alumina and quartz microspheres to have a rough surface.

To enhance adhesion: a 0.5 μm deposit of Ag on the substrate before evaporating the Be.

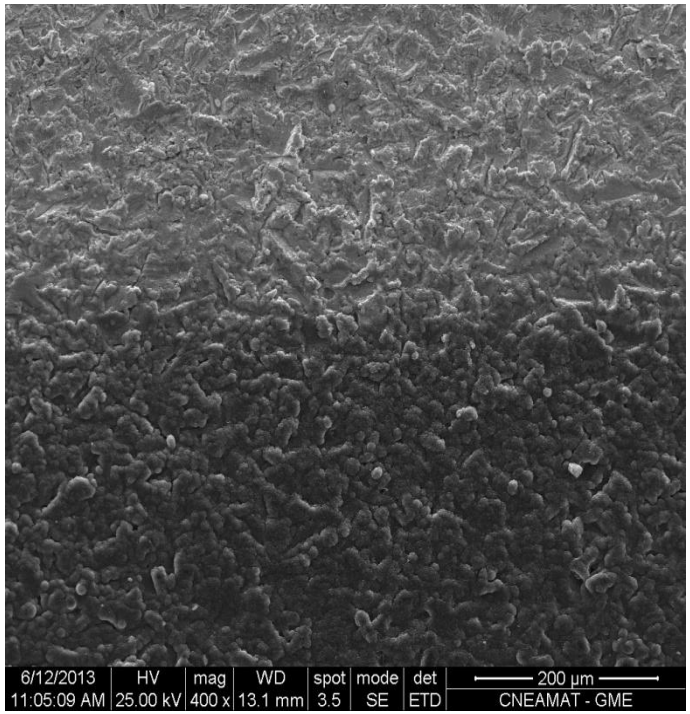


Target

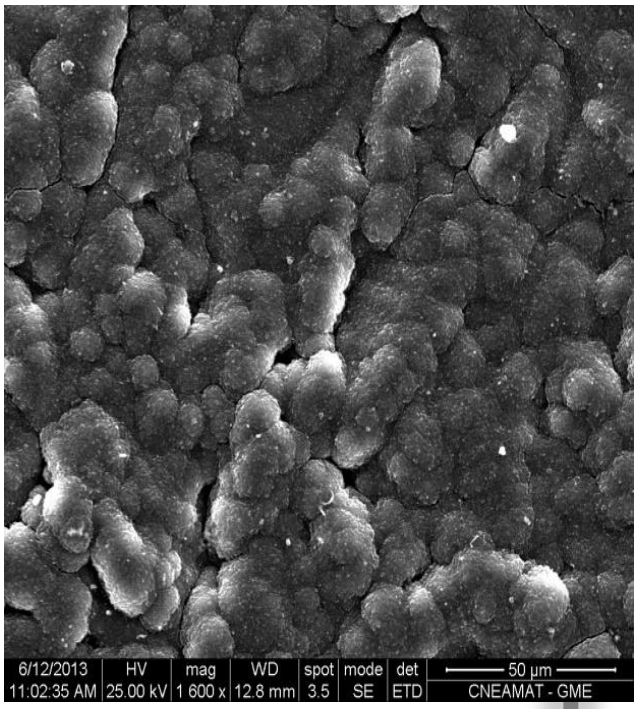
First images of Be deposits on different substrates.



Substrate: Tungsten
Thickness: 10 µm



Substrate: Molibdenum
Midlayer: 0.5 µm Ag
Thickness: 10 µm

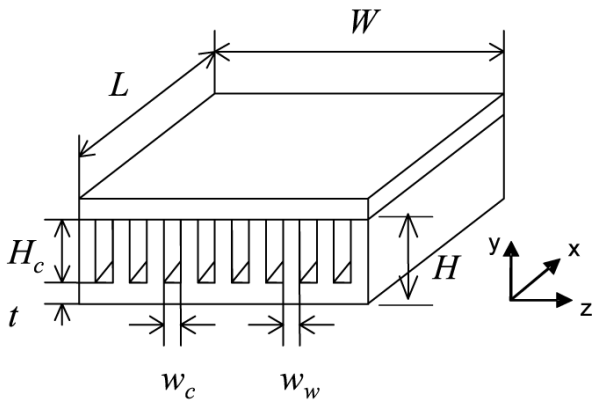


Substrate: Molibdenum
Midlayer: 0.5 µm Ag
Thickness: 10 µm

Backing (Heat dissipation)

Microchannels

- **Channels: 0.5 mm wide and 2 mm high**

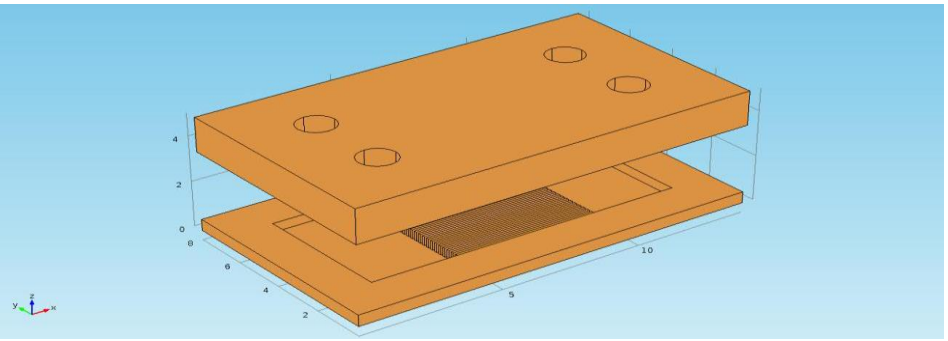


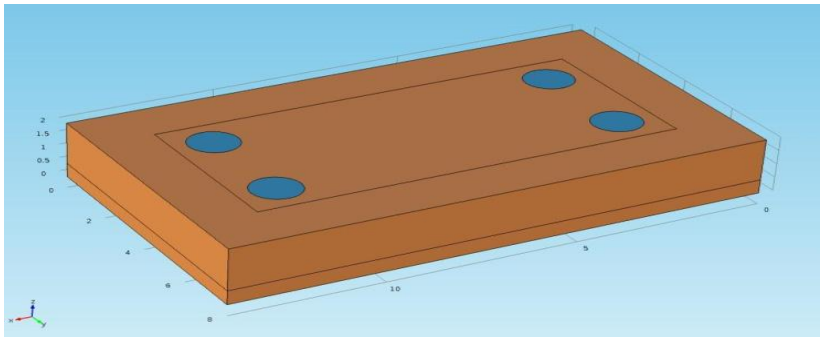
- **High pressure water circulates through the microchannels.**

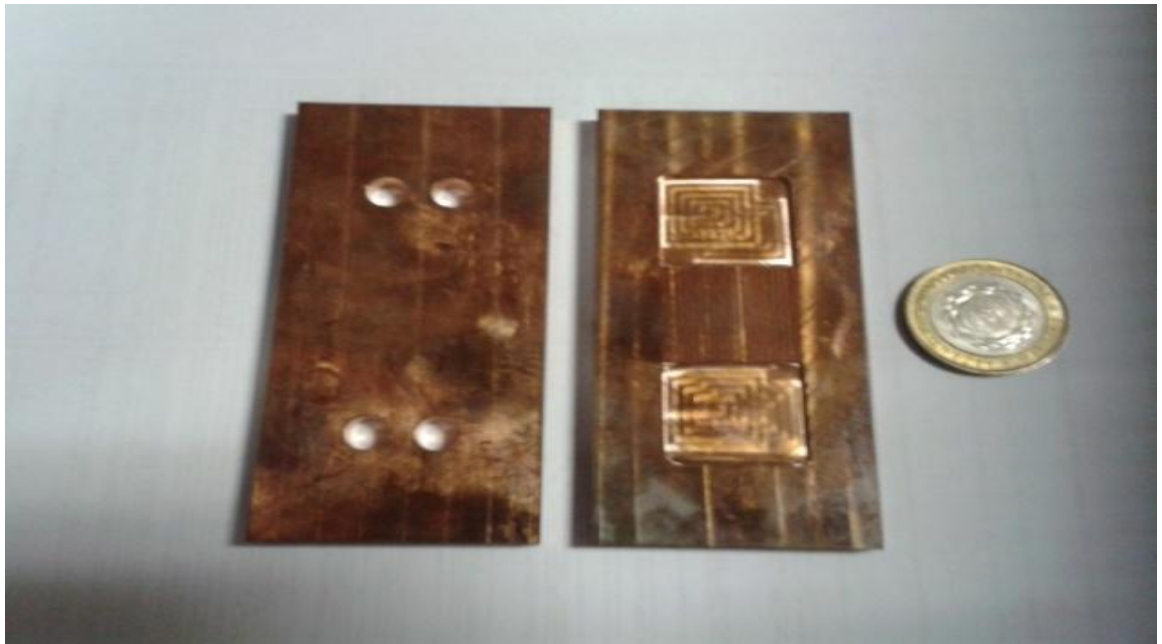
Target backing

Finite element simulations

- **Proposed prototype:**







Machined prototype:

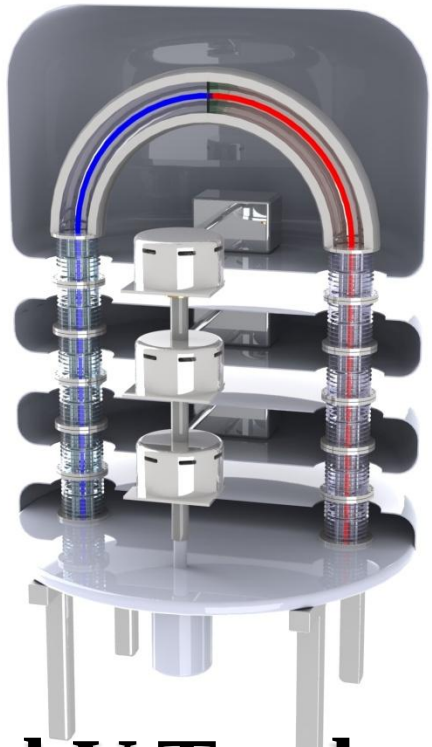
Development of a Tandem-Electrostatic - Quadrupole Accelerator (TESQ) Facility for BNCT and other Accelerator types

"A Tandem-ESQ for Accelerator-Based Boron Neutron Capture Therapy", Kreiner, A. J. et al, NIM B261 (2007) 751-754.

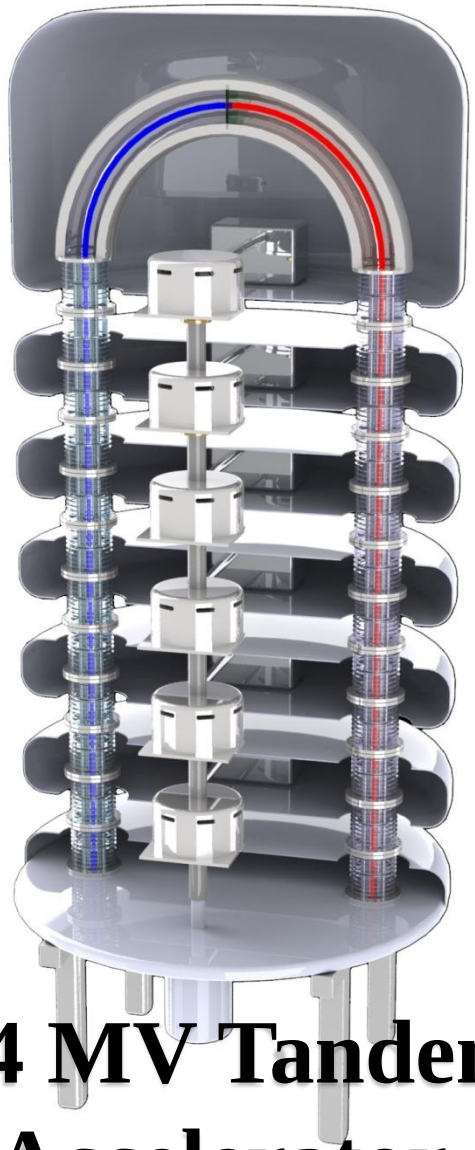
Appl. Rad. & Isotopes: 67 (2009)S266-S269 ; 69(12) (2011) 1672–1675; (2013) apradiso.2013.11.064i.

Different accelerators under development

200 kV Accelerator



700 kV Tandem Accelerator



1.4 MV Tandem Accelerator or single ended

200 kV accel mounted with Faraday cage

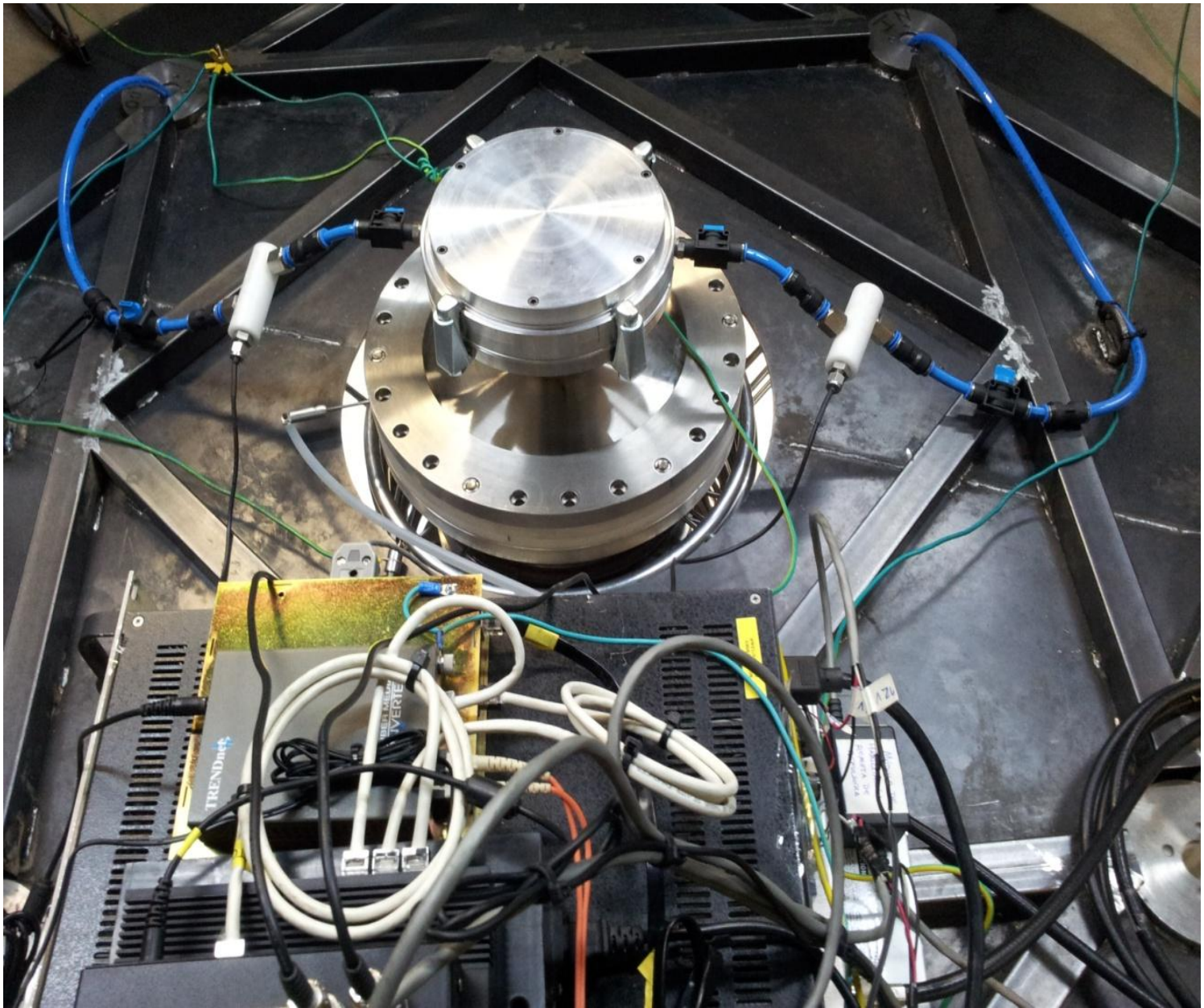
Mounting the tubes

Accelerator tubes in place and tested

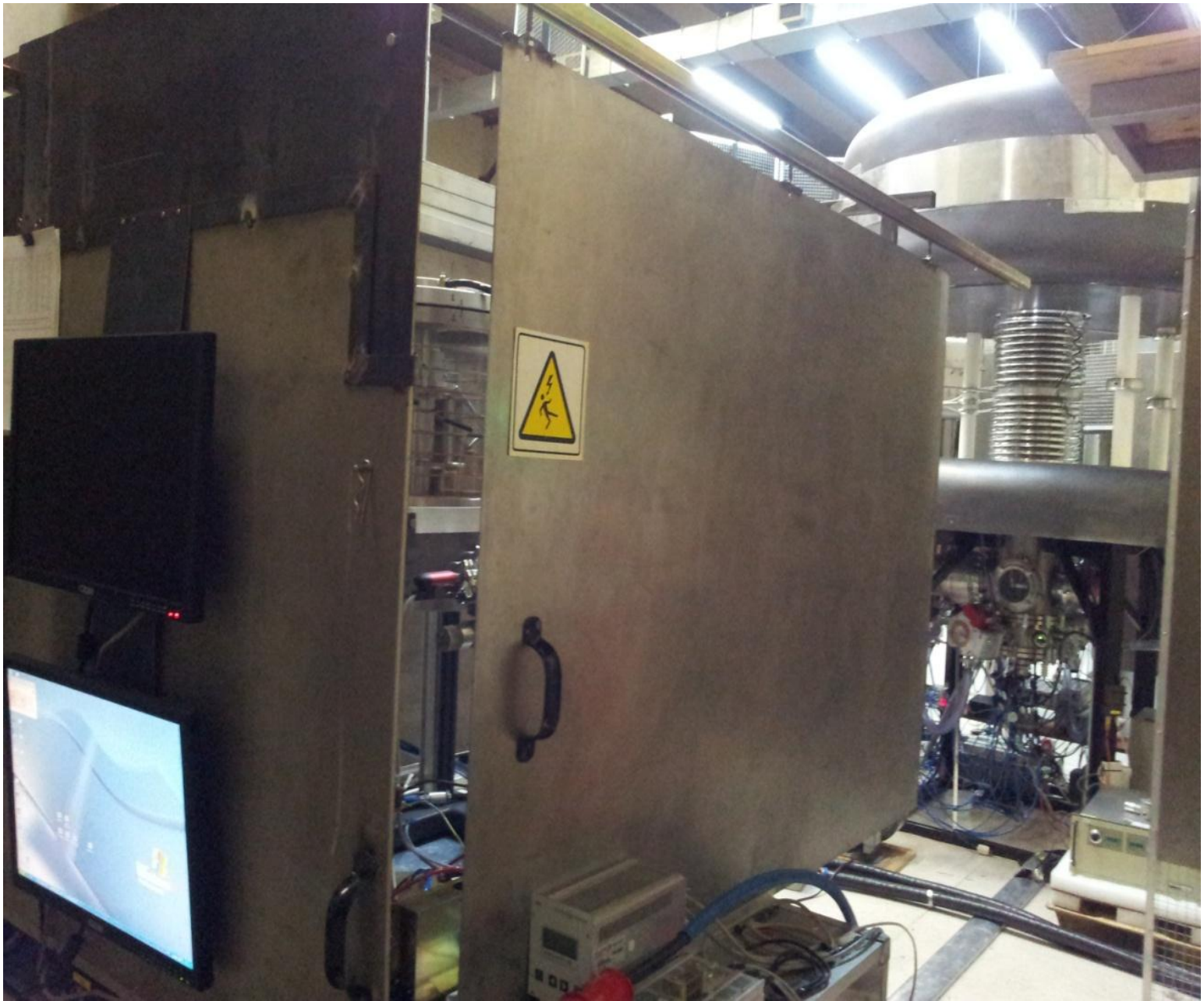
Accelerator with all systems mounted (HV, cooling, vacuum, control)

Accelerator column with tubes under vacuum

Neutron production target (cooled)



Control system, test stand & accelerator



Control and monitoring system

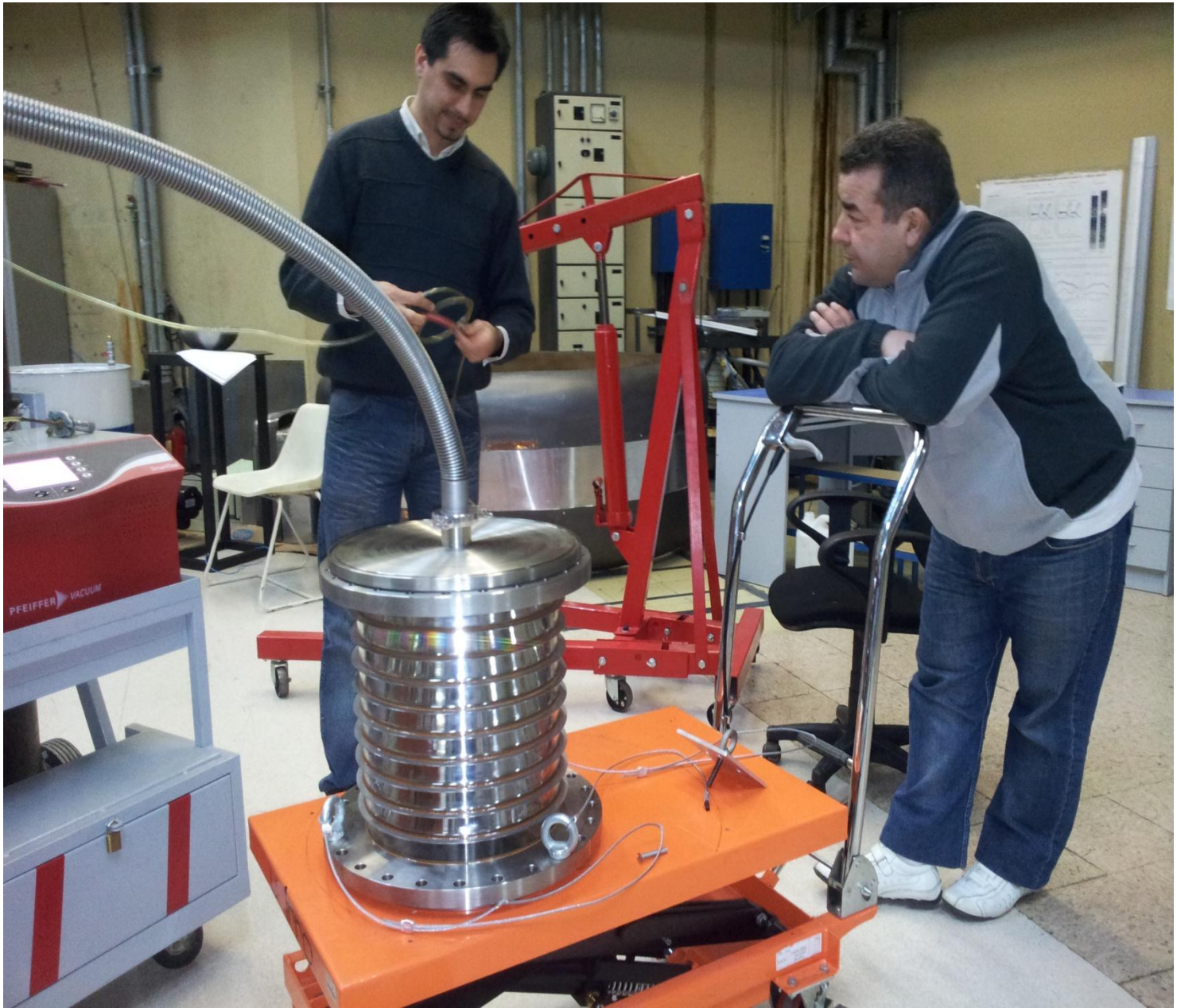
Mechanical structure of 700 kV Tandem ESQ

Generator ready to be installed

Installed generator being tested

Accelerator tubes

Accelerator tube leak test



100 kV tubes, assembled and tested

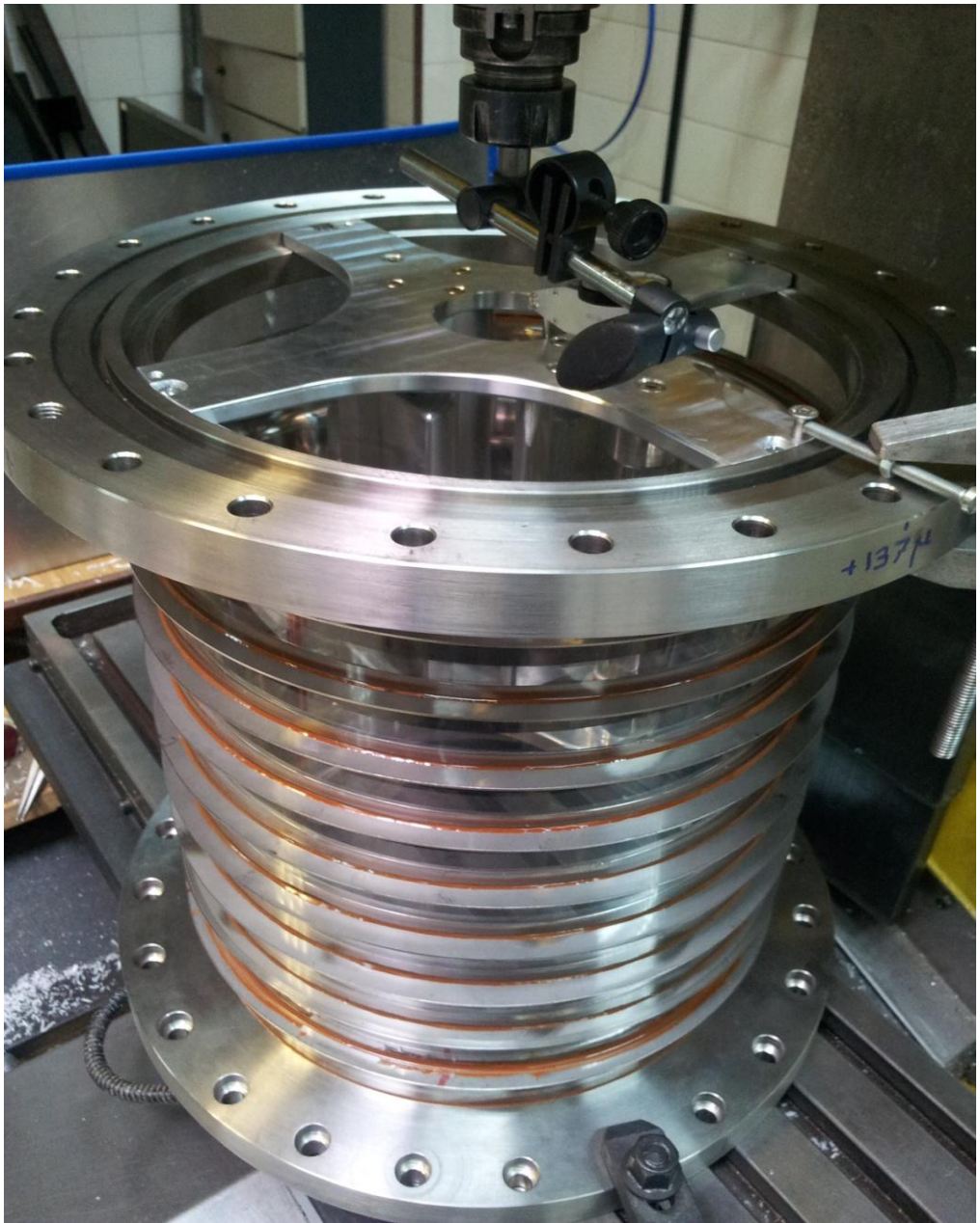
Before assembling the quads

Quads assembled

Quadrupoles installed inside tube

Tube with quads on milling machine

Centering of quadrupoles inside tube



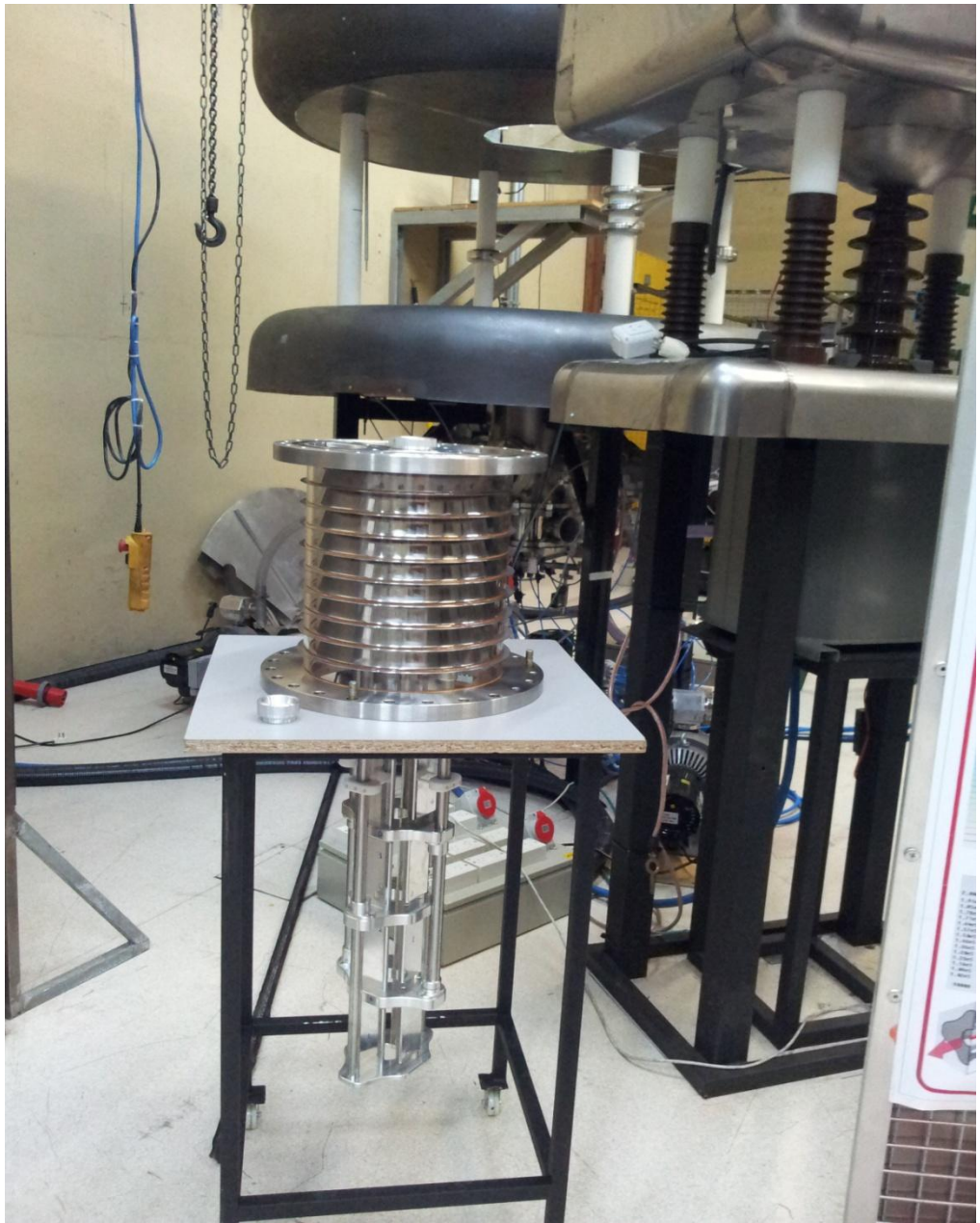
Centering of quads inside tube

Assembling the matching section (MS)

Assembling and centering the MS

Matching section being assembled

Tube with MS next to accelerator



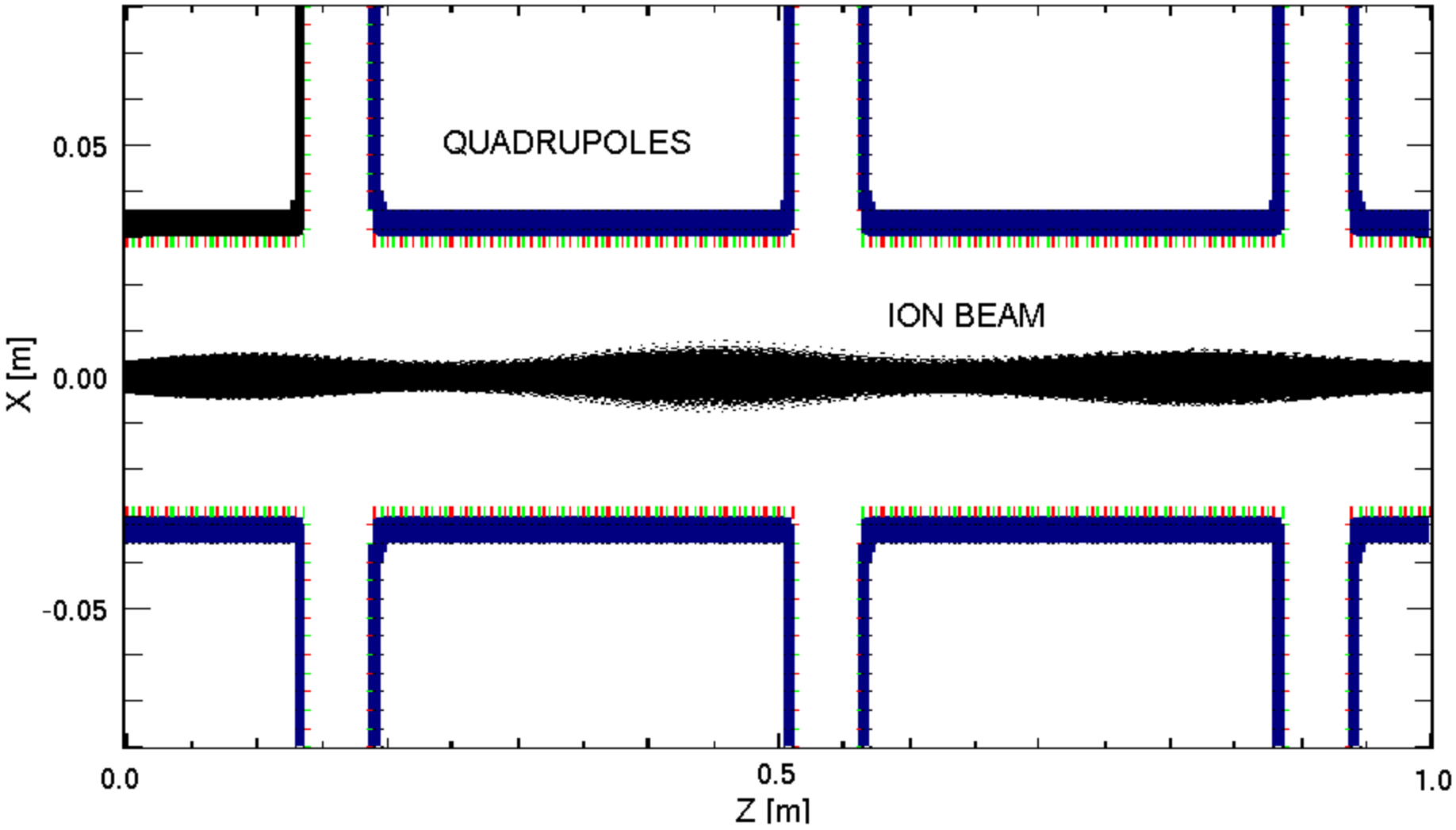
Watching into accel tube with quads

Watching along the tube axis

Lifting MS and tube into accelerator

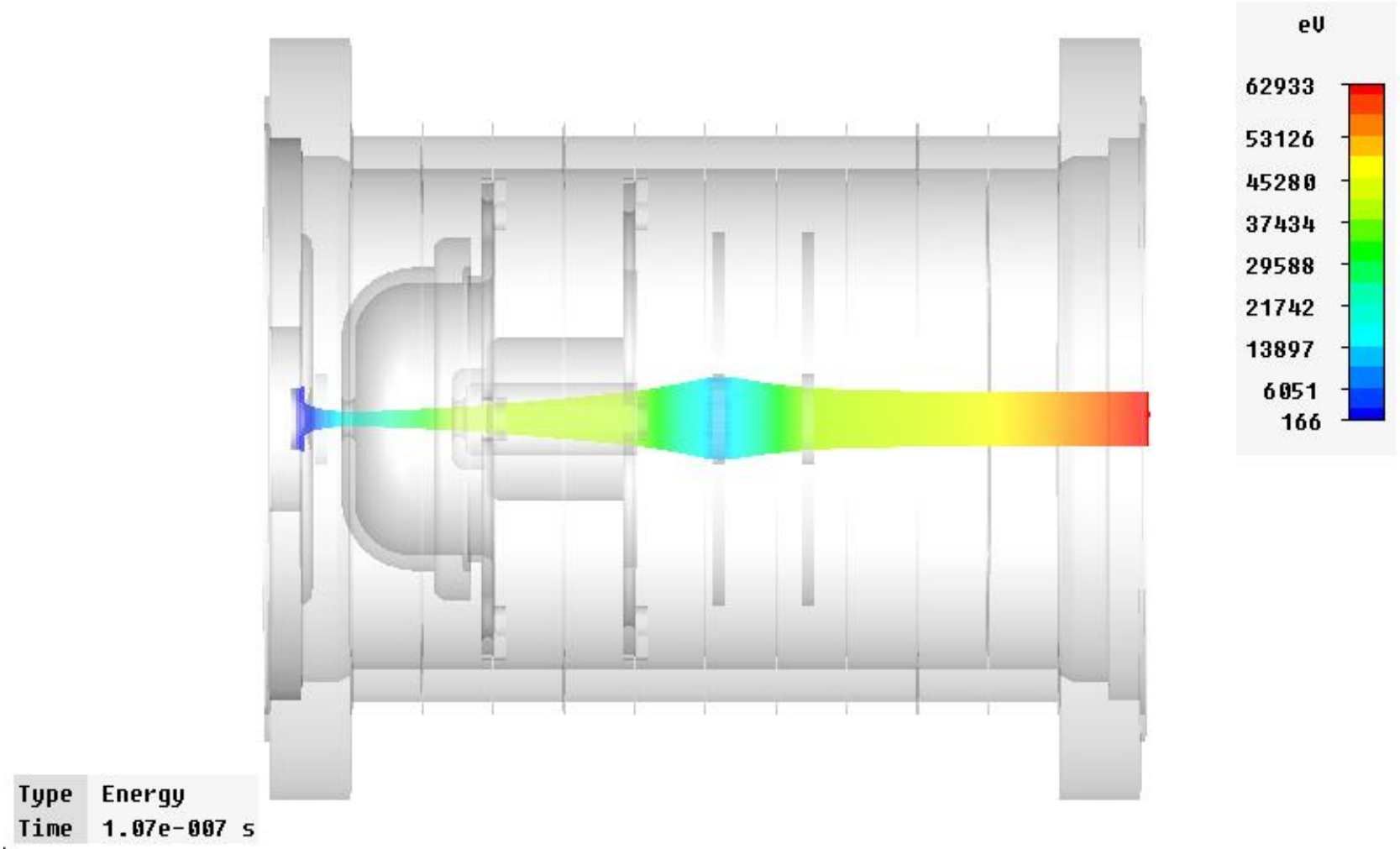
Ion Optics (high intensity beam transport, space charge effects)

Proton beam transport (30 mA)

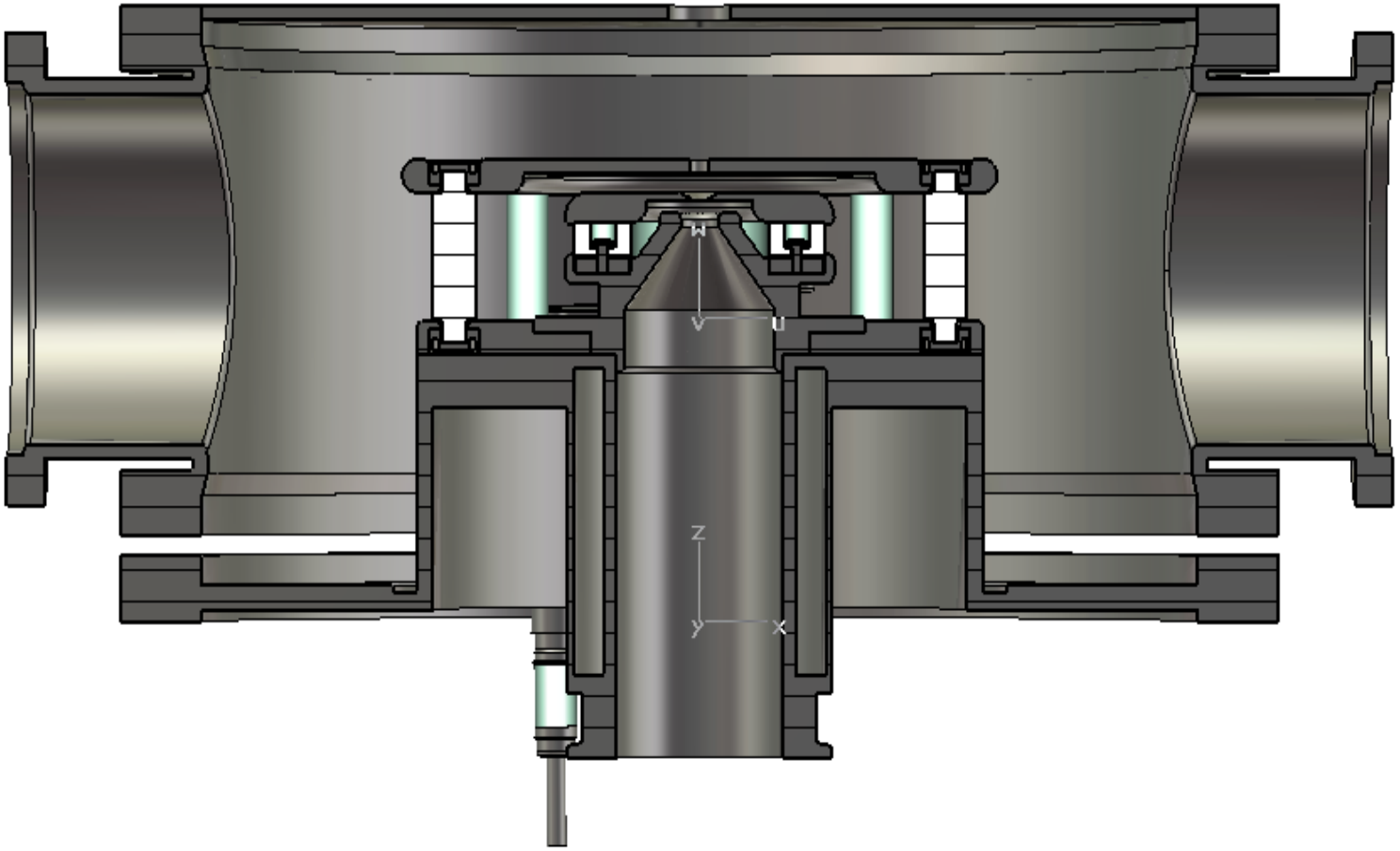


Ion sources and injector: Volumen plasma filament driven.

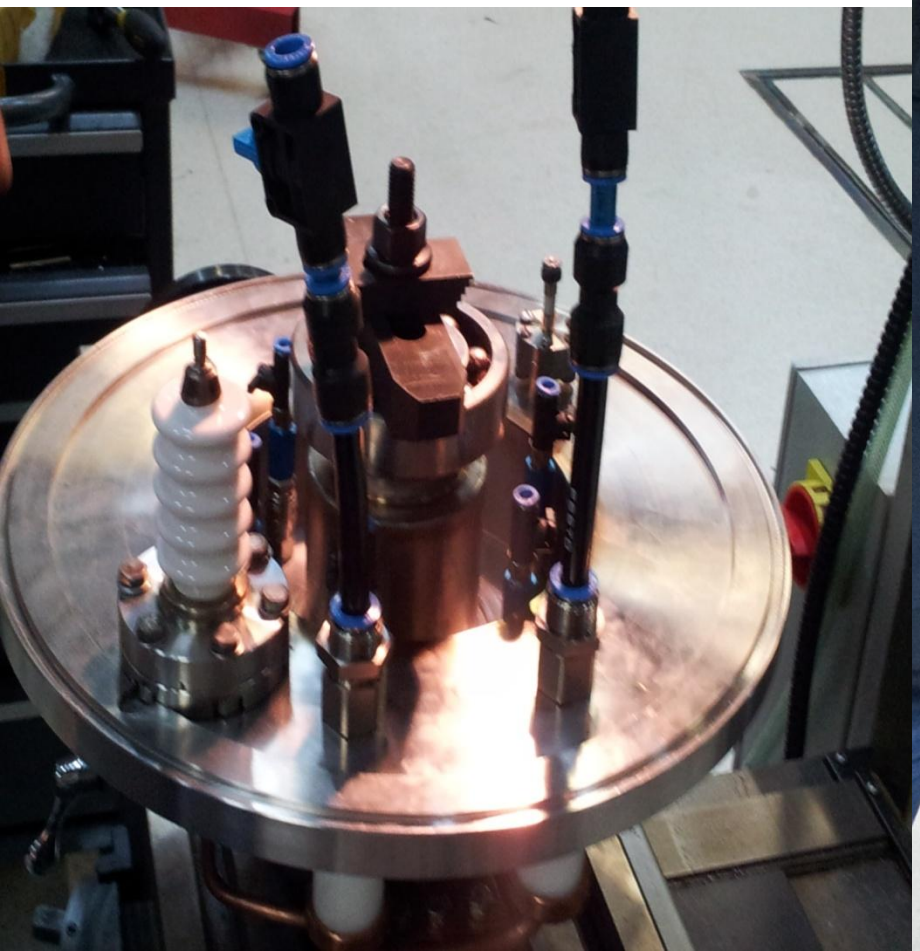
Simulations of extraction and pre-acceleration region



Latest design of ion source and extraction.

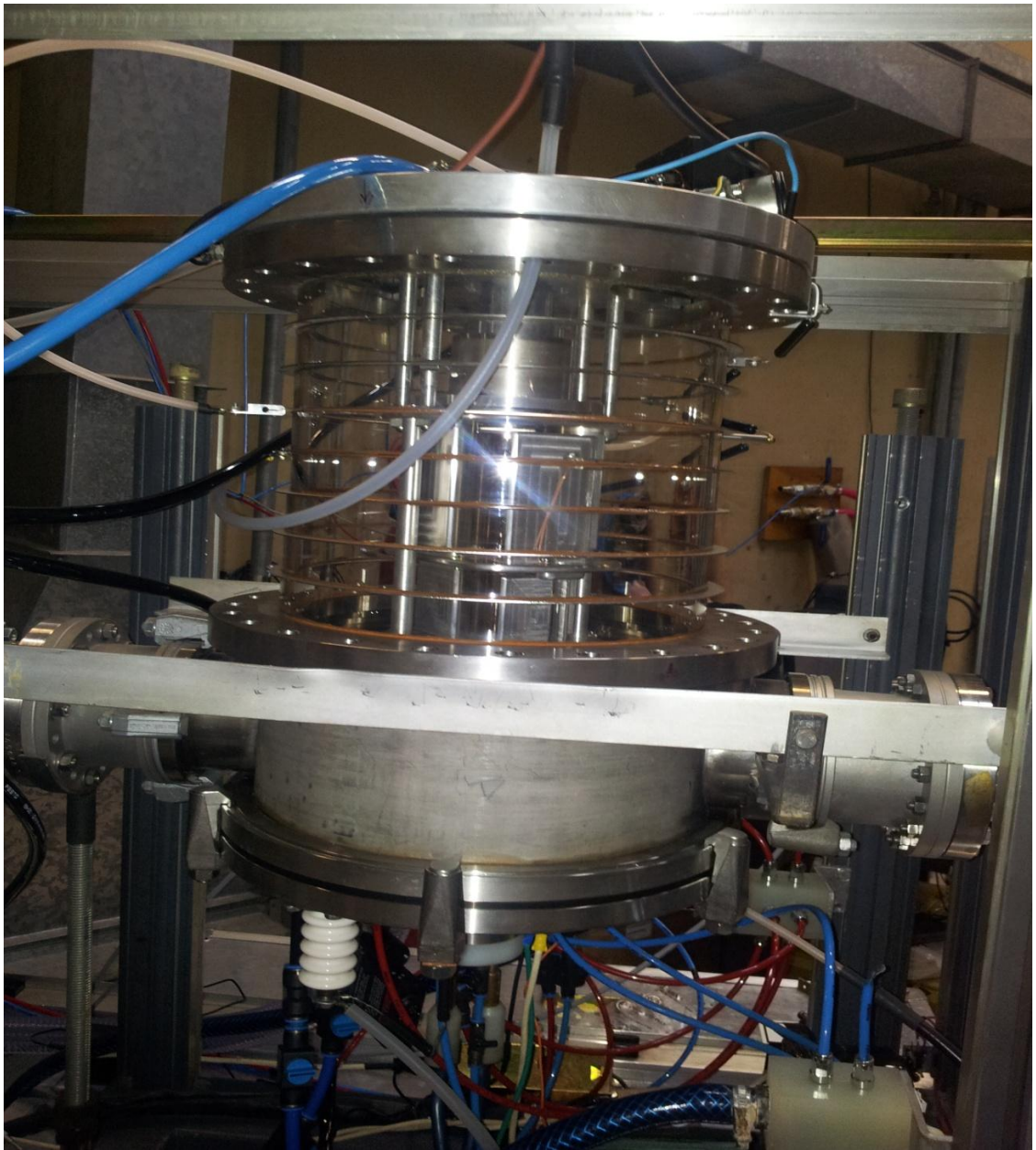


New Ion Source being built

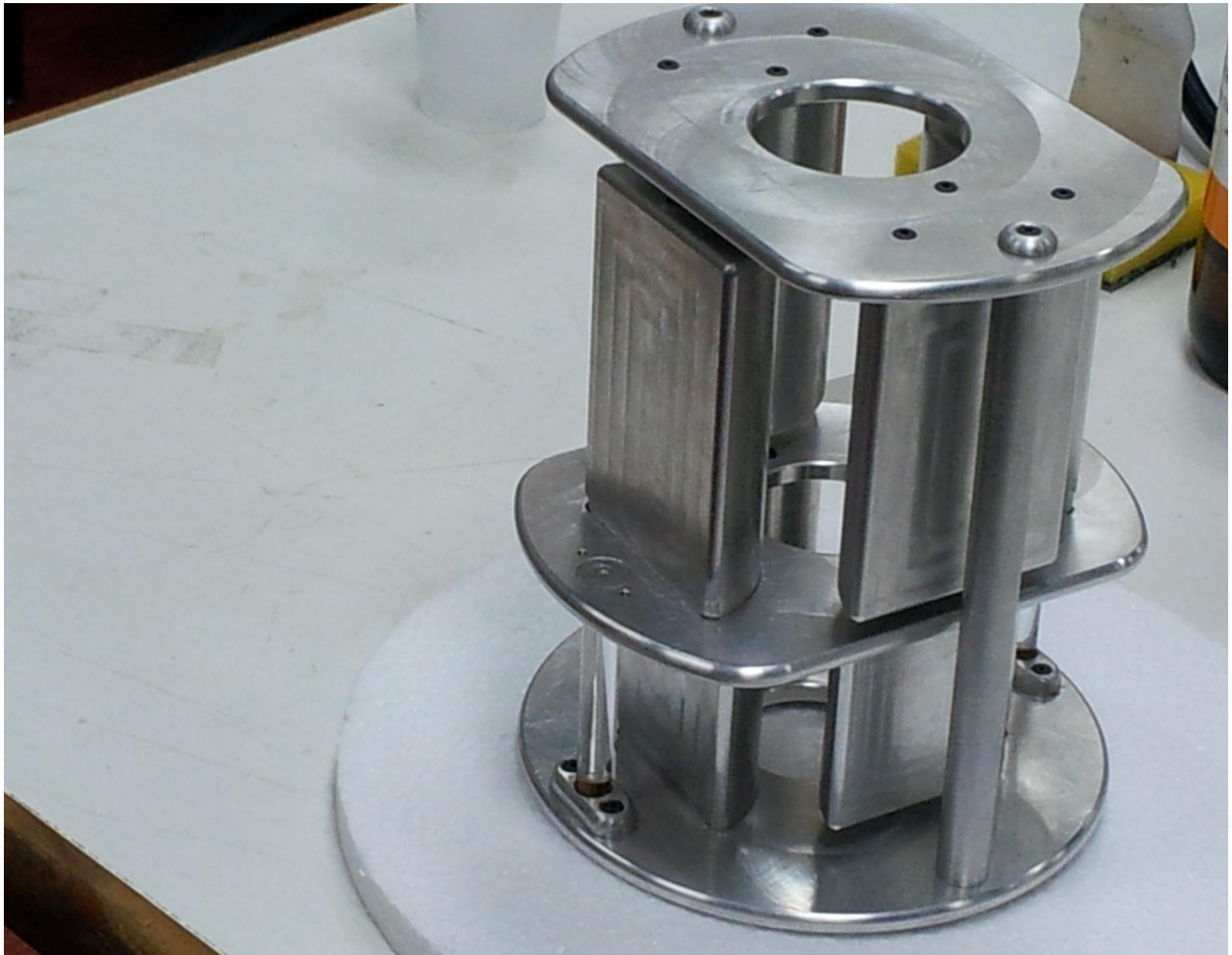


New high power ion source: ready

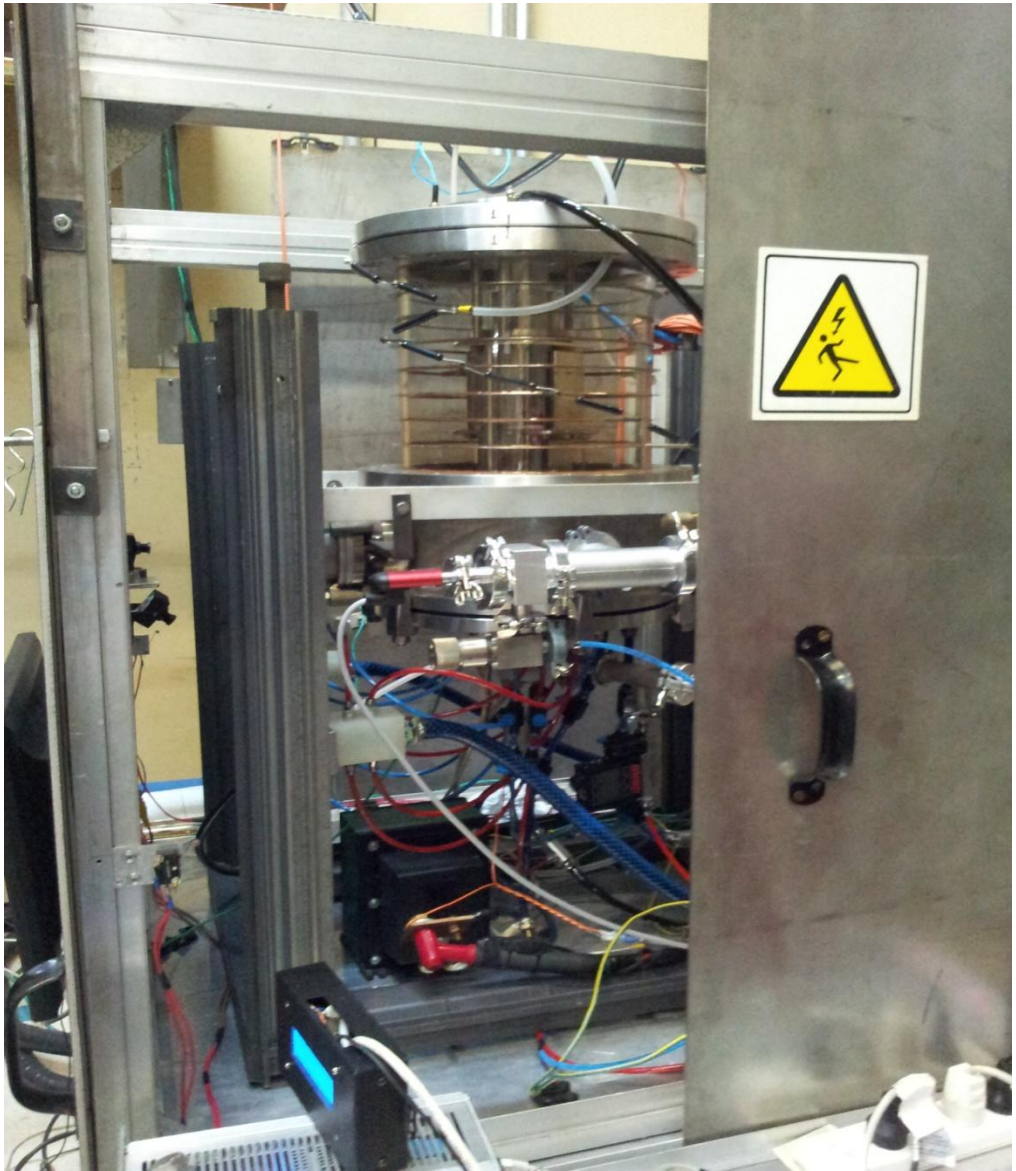
Ion source test stand (40 kV)



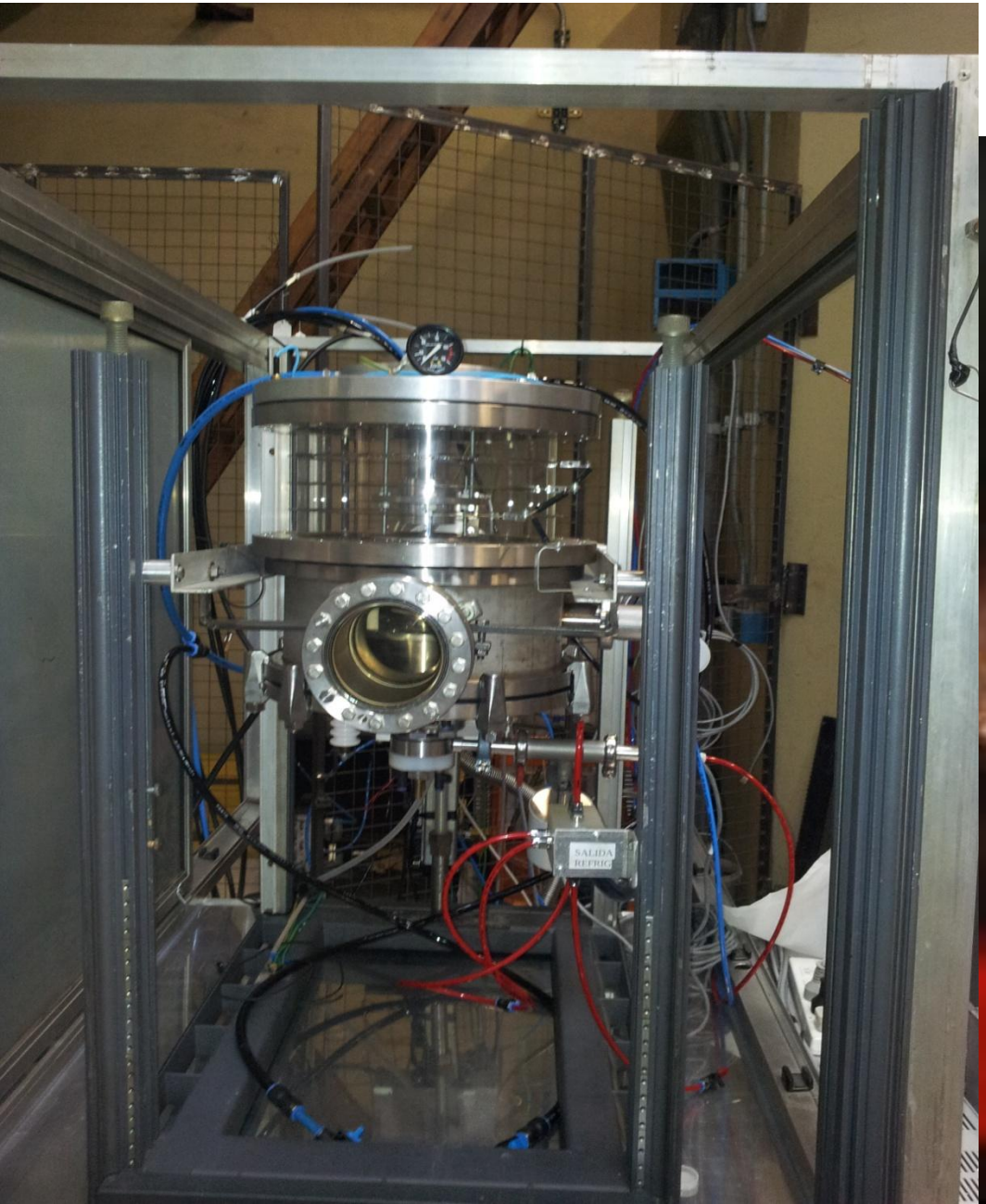
Quad doublet ready (0.01 mm precision)



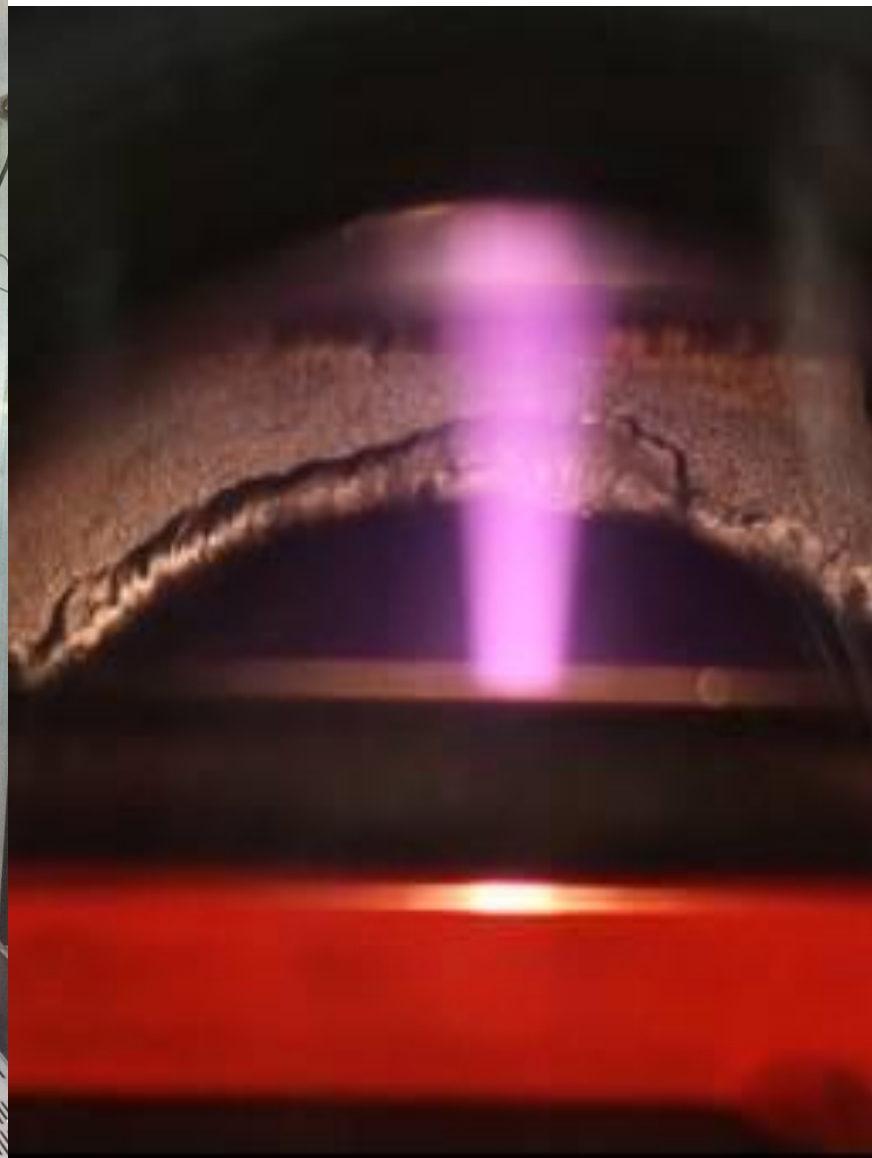
Ion source test stand with quadrupole doublet- 40 kV



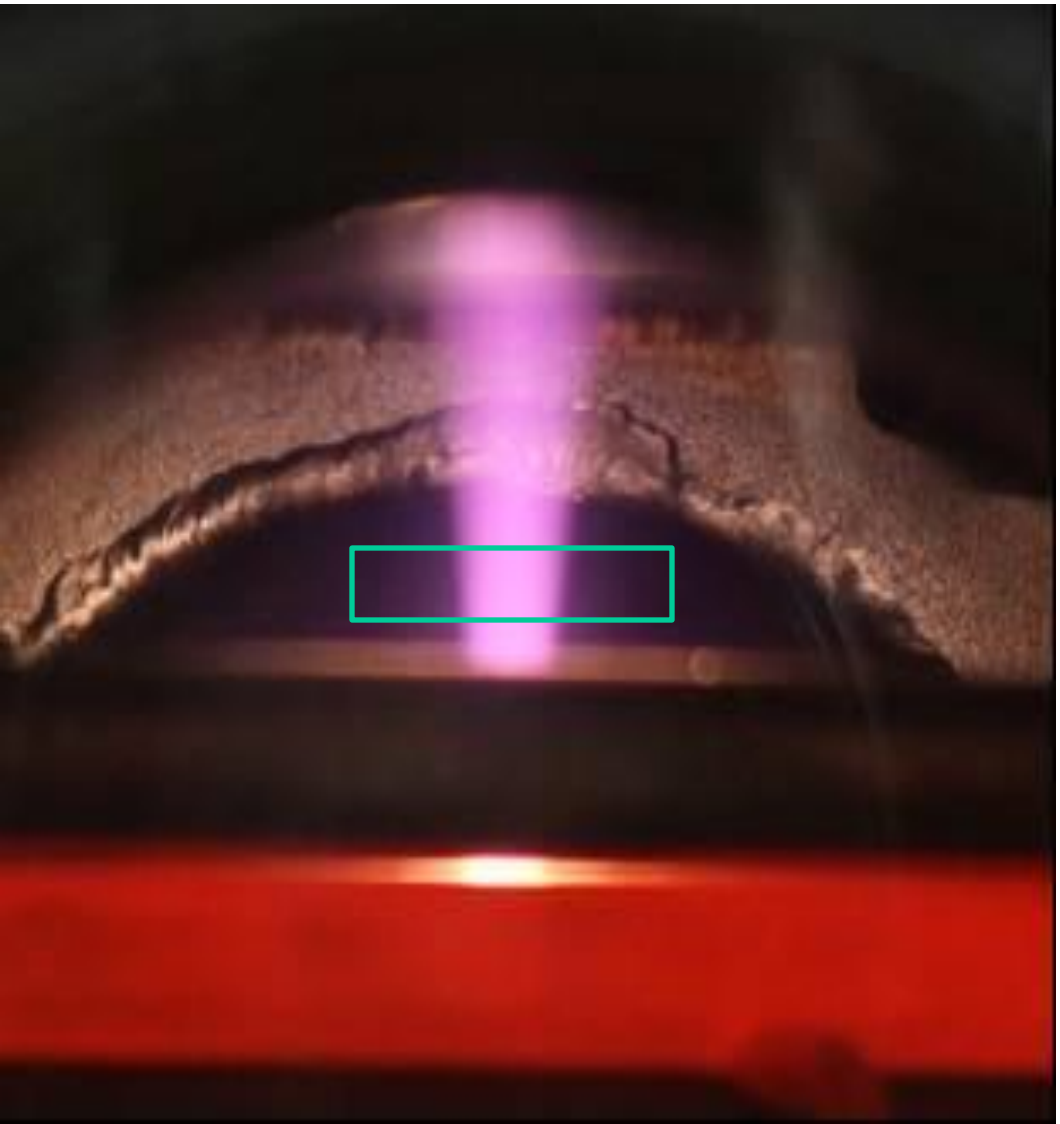
New test stand for ion sources

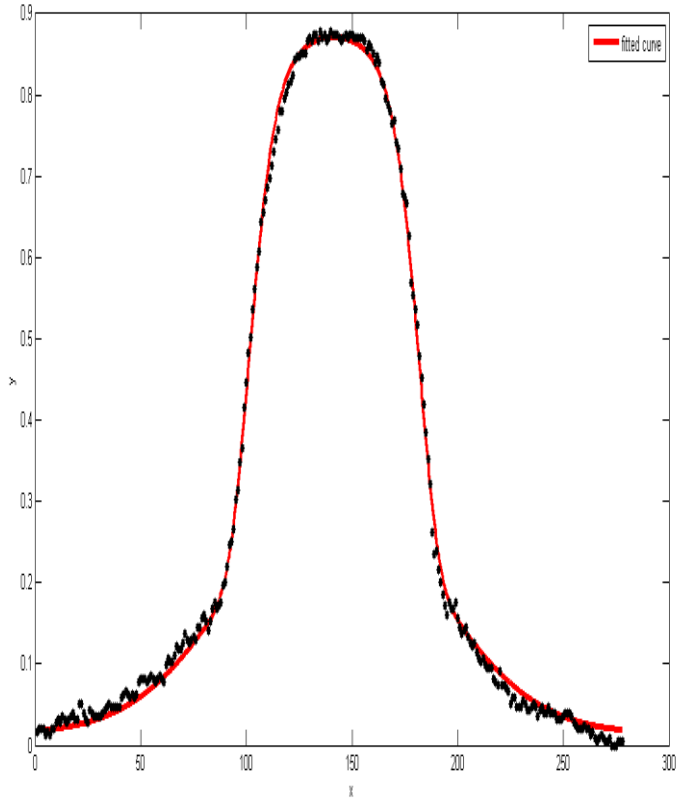


30 mA prot beam

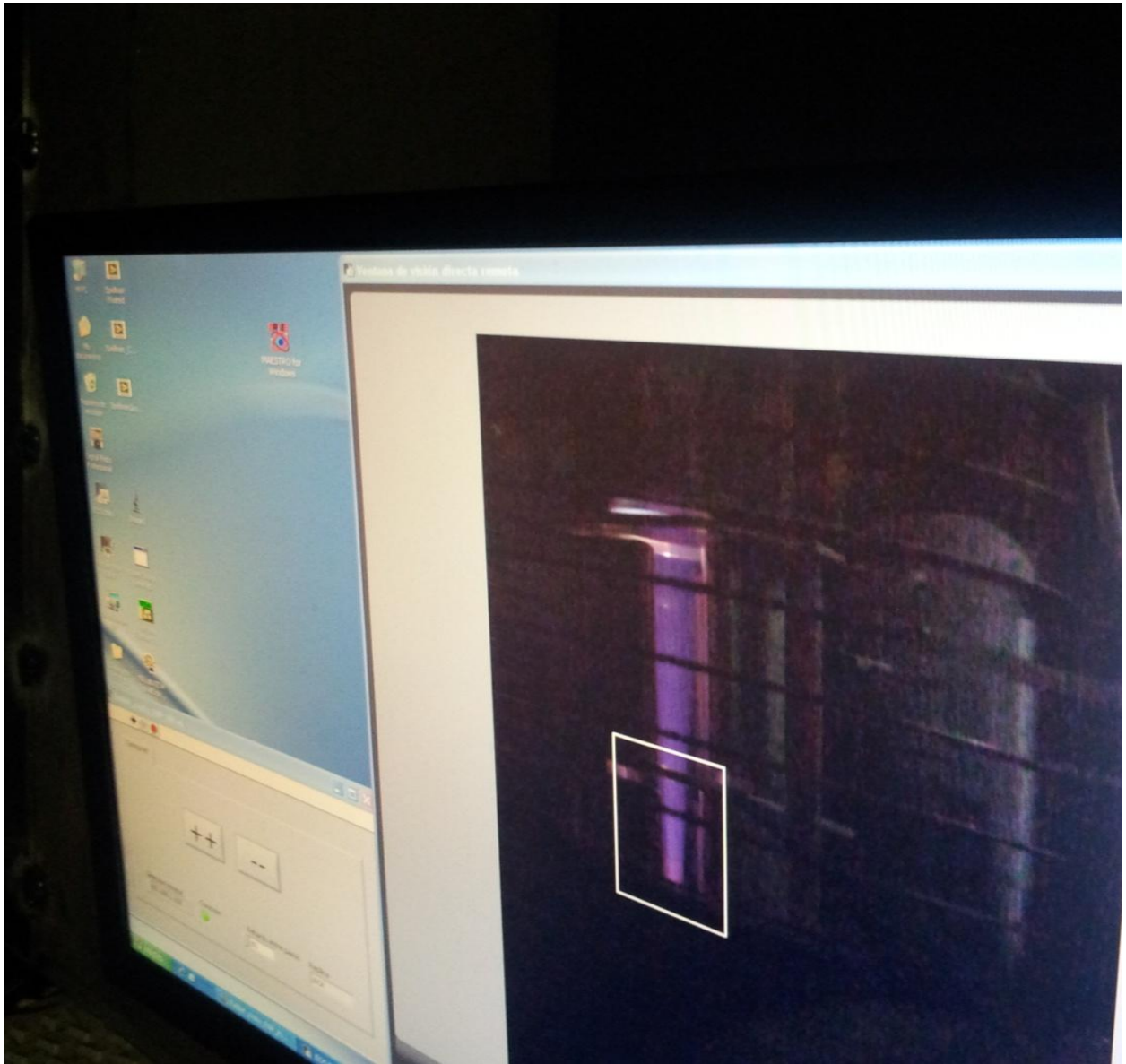


Beam shape analysis through induced fluorescence in residual gas



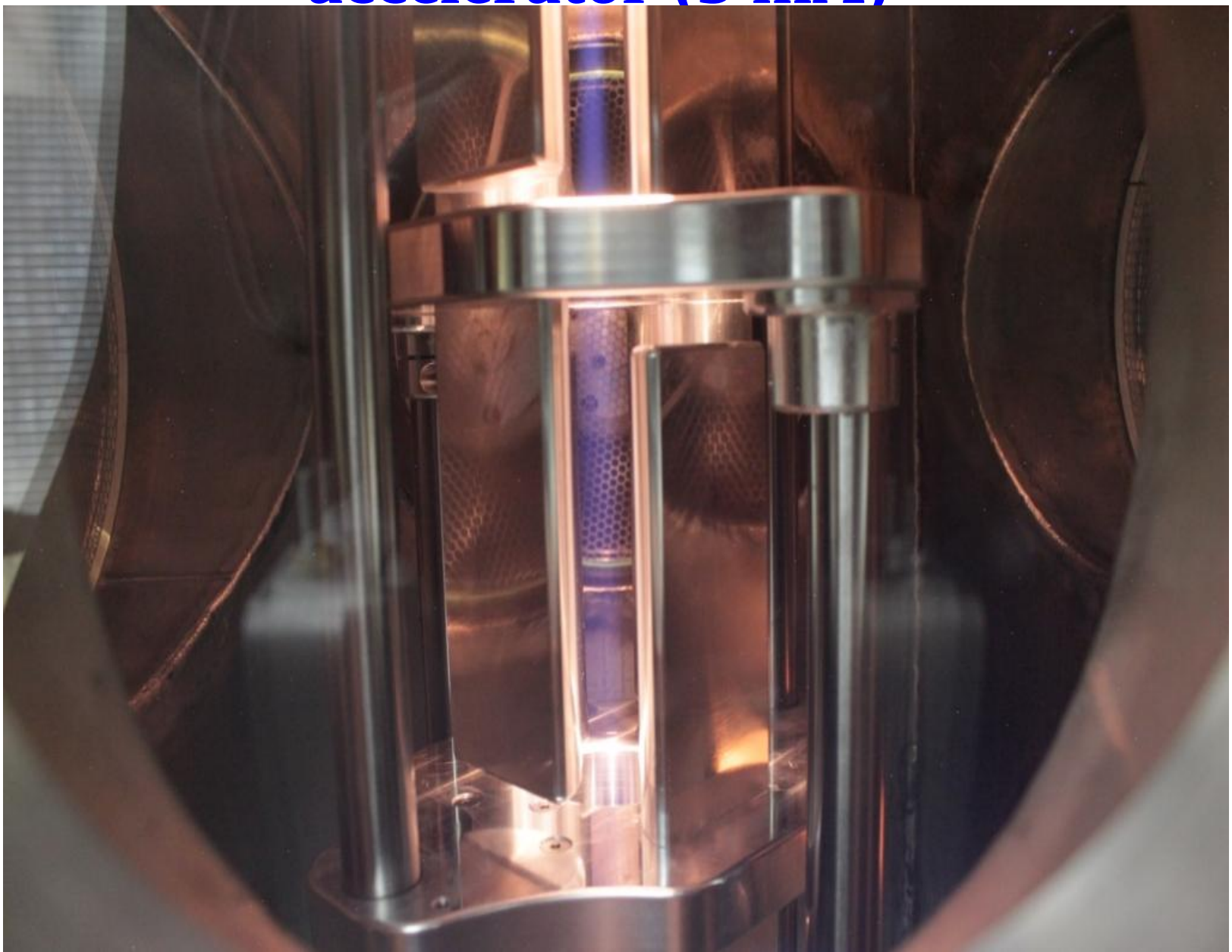


30 mA beam propagating thru a quadrupole doublet in test stand (40 kV)

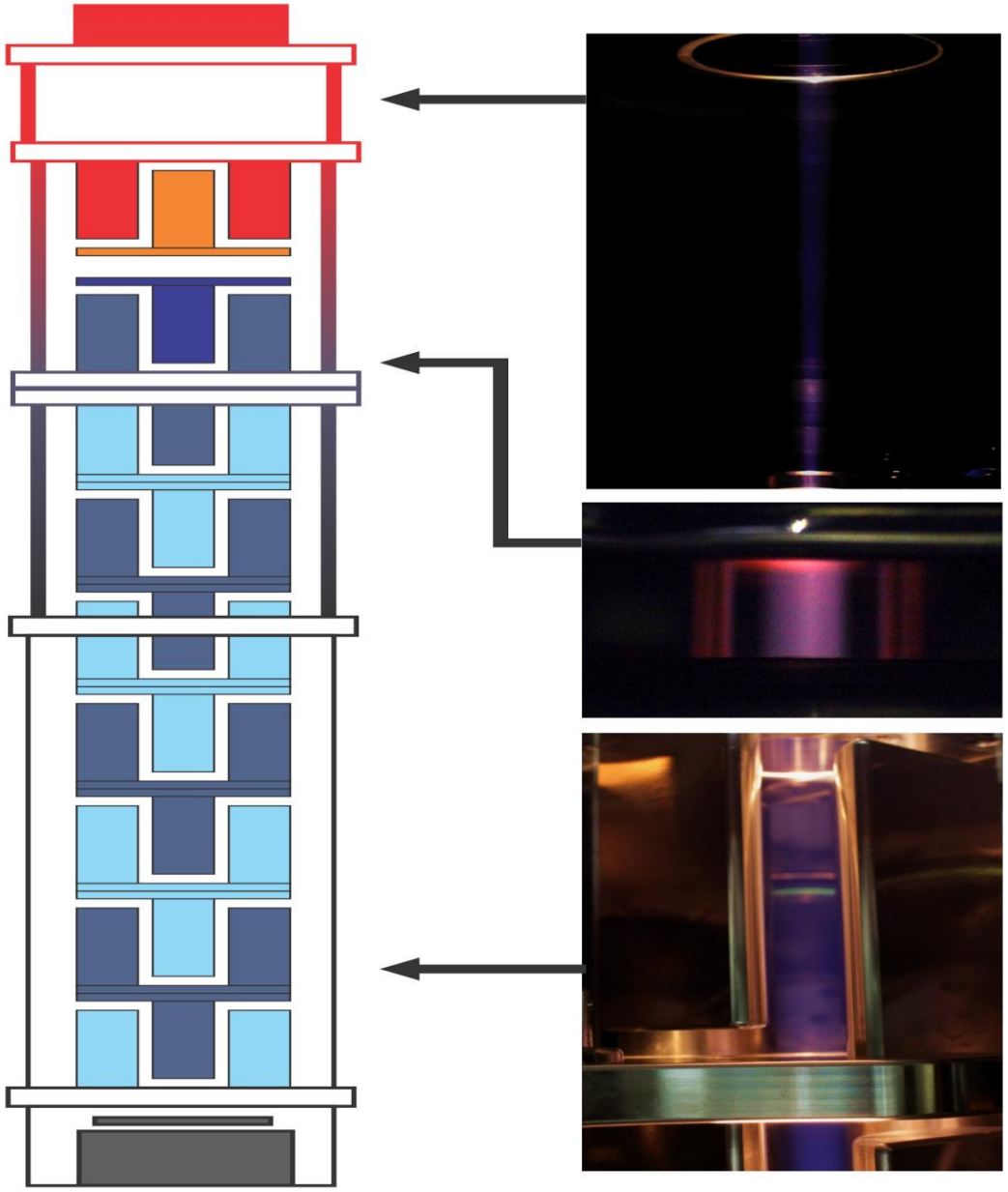


30 mA being transported to FC

First beam propagating through the 200 kV accelerator (3 mA)



Beam images along the tube



CONCLUSIONS/REMARKS

- **The era of in-hospital neutron sources is starting.**

- **Worldwide effort: a variety of different accelerators and nuclear reactions are being tested. So merits, demerits and costs may be compared.**

- **The feasibility of $^{9}Be(d,n)^{10}B$ @ 1.4 MeV as an epithermal/thermal neutron source was demonstrated.**

- **0.2 MV accel almost ready. In-air folded 0.7 MV Tandem ESQ (TESQ) is being built. Other options (single ended 1.4 MV and 1.4 MV Tandem) are also being pursued.**