



Development of Accelerator Technology for BNCT in Argentina

(Neutron sources for BNCT treatment facilities)

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***IAEA, Technical Meeting on Advances in BNCT
July 27-30, Vienna, Austria and the rest of the world.***



Tecdod1223

- **2.6. Accelerators**

An accelerator would be a useful NCT neutron source in a hospital for several reasons.

First, accelerators are much more acceptable to the public than reactors. Second, it generally involves fewer complications with respect to licensing, accountability and disposal of nuclear fuel. It can also be switched on and off.

However, it must be recognized that the technology is not yet proven.

The radiofrequency quadrupole (RFQ) accelerator is considered as the most promising method. The RFQ can be used to generate a high current of protons with an energy slightly higher than the threshold (1.88 MeV) for the ${}^7\text{Li} (p,n) {}^7\text{Be}$ reaction.

The resulting neutrons generally require less moderation than those from a reactor.

Outline

- **Low-energy Accelerator Based-BNCT programs worldwide. Some comparisons.**
- **Program in Argentina: Development of an Electro-Static-Quadrupole (ESQ) Accelerator-Based treatment facility.**
- **Conclusions/remarks.**



In-hospital AB-BNCT

Quest for “**best**” solutions and criteria for widest possible dissemination:

- Safety (e.g., lowest activation of facility, no potentially hazardous materials).
- Simplicity-Reliability (smallest number of ancillary systems, e.g. no SF6).
- Lowest possible cost (smallest accelerator and simplest possible technologies).

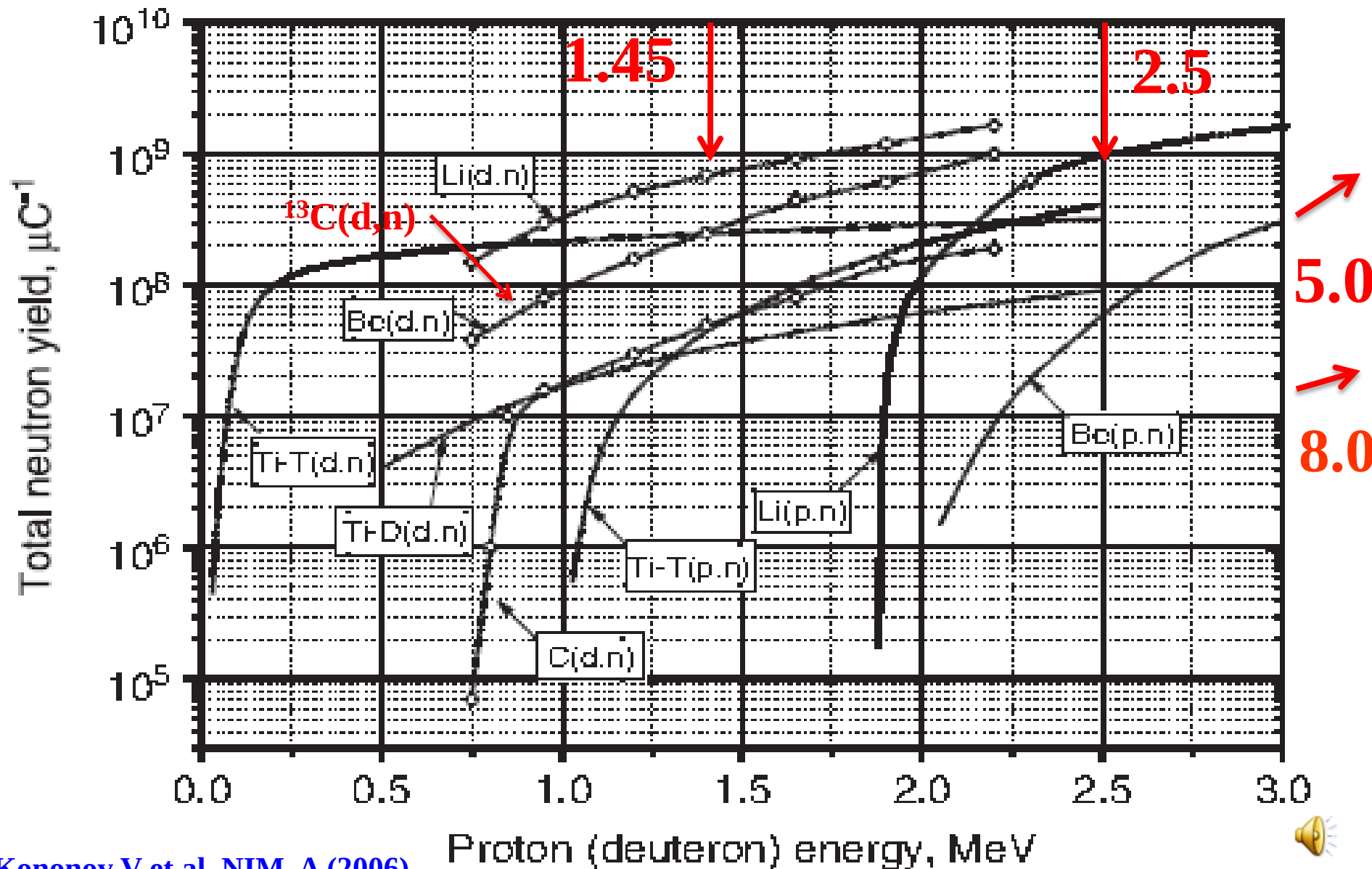


Active low-energy AB-BNCT programs worldwide

1. Japan: Tsukuba, Nat. Cancer Center-Tokyo, Nagoya, Okinawa,..
2. Russia: Budker Institute Nuclear Physics, Novosibirsk.
3. Finland: Helsinki University Central Hosp.-NTI, Helsinki.
4. Argentina: CNEA, Buenos Aires.
5. Israel: SARAF, Soreq.
6. Italy: INFN-CNAO, Legnaro & Pavia.
7. China: Xiamen Humanity Hospital. Xiamen. TAE Life Sciences.
8. Korea: **KIRAMS-CNEA-Collaboration.** +LINAC-based (10 MeV, commissioning phase)
9. UK : Birmingham.



Neutron producing reactions



Nuclear reactions & material properties

Reaction	E_{thres} (MeV)	Radioactive products	Melting T (°C)	Therm cond (W/m-K)
${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$	1.88	Yes	180	84.7
${}^9\text{Be}(\text{p},\text{n}){}^9\text{B}$	2.06	No ^a	1287	201
${}^9\text{Be}(\text{d},\text{n}){}^{10}\text{B}$	0 (exoergic)	No	1287	201
${}^9\text{Be}(\text{d},\text{n}){}^{10}\text{B}^*$	$\approx 1.0^{\text{b}}$	No	1287	201
${}^{13}\text{C}(\text{d},\text{n}){}^{14}\text{N}$	0	No	3550	230

^aVery short lived activity with no gamma emission.

^b Strong population of an excited state at ≈ 5.1 MeV in ${}^{10}\text{B}$. The reaction for population of this 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.



Accelerators/facilities for BNCT worldwide

Location	Machine /Facility Status/Final power	Target & reaction	Beam energy (MeV) % Neutron yield at $0^\circ <$ 1 (MeV)	Int. goal Actual (mA)
Budker Institut, Novosibirsk Russia	Vacuum insulated Tandem. Developed. 23 kW.	Solid $^7\text{Li(p,n)}$	2.0 - 2.3 100%< 1 MeV	10 9
Tsukuba Japan	RFQ-DTL. Under development. 80 kW	thick 0.5mm Be(p,n)	8 21% < 1MeV	10 (> 5) 2
HUCH-NTI Helsinki Finland	Single-ended. DC. Commissioning. 78 kW.	Solid $^7\text{Li(p,n)}$	2.6 100%< 1 MeV	+30 +30
CNEA Buenos Aires Argentina	Single-ended ESQ. Under development & construction. 43.5 kW	$^9\text{Be(d,n)}$ thin $^{13}\text{C(d,n)}$ thick	1.45 $69\pm 3\% < 1 \text{ MeV}$ $70\% < 1 \text{ MeV}$	30 7
NCCenter- CICS Tokyo, Japan	RFQ. Clinical Trial. 50 kW.	Solid $^7\text{Li(p,n)}$	2.5 100% < 1 MeV	20 12
Nagoya Univ. Japan	Dynamitron. DC. Commissioning. 42 kW.	Solid $^7\text{Li(p,n)}$	2.8 95% < 1 MeV	15 4
Soreq Israel	RFQ-DTL. Under development. 50 kW	Liquid (jet) $^7\text{Li(p,n)}$	2.5 100%< 1 MeV	20 2
INFN-CNAO Legnaro-Pavia Italy	RFQ-DTL. Under development.100 kW.	Be(p,n)	5 34% <1 MeV	20-30 ?
Xiamen Humanity Hosp. China	Vacuum insulated Tandem. 25 kW.	Solid $^7\text{Li(p,n)}$	2.5 100%< 1 MeV	10 ?



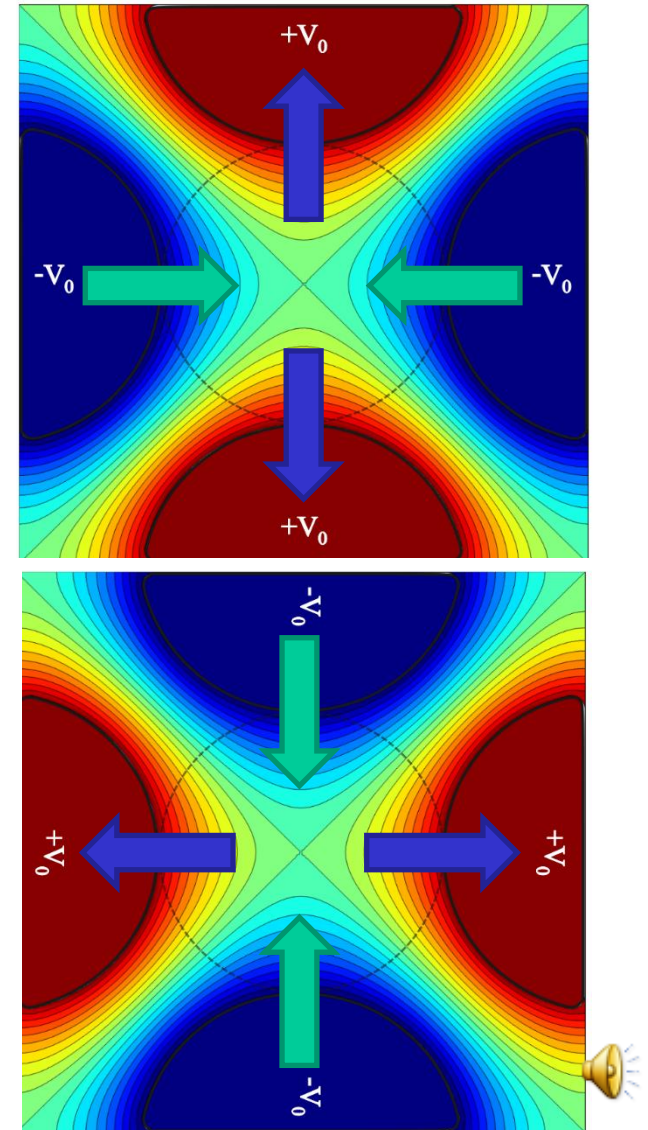
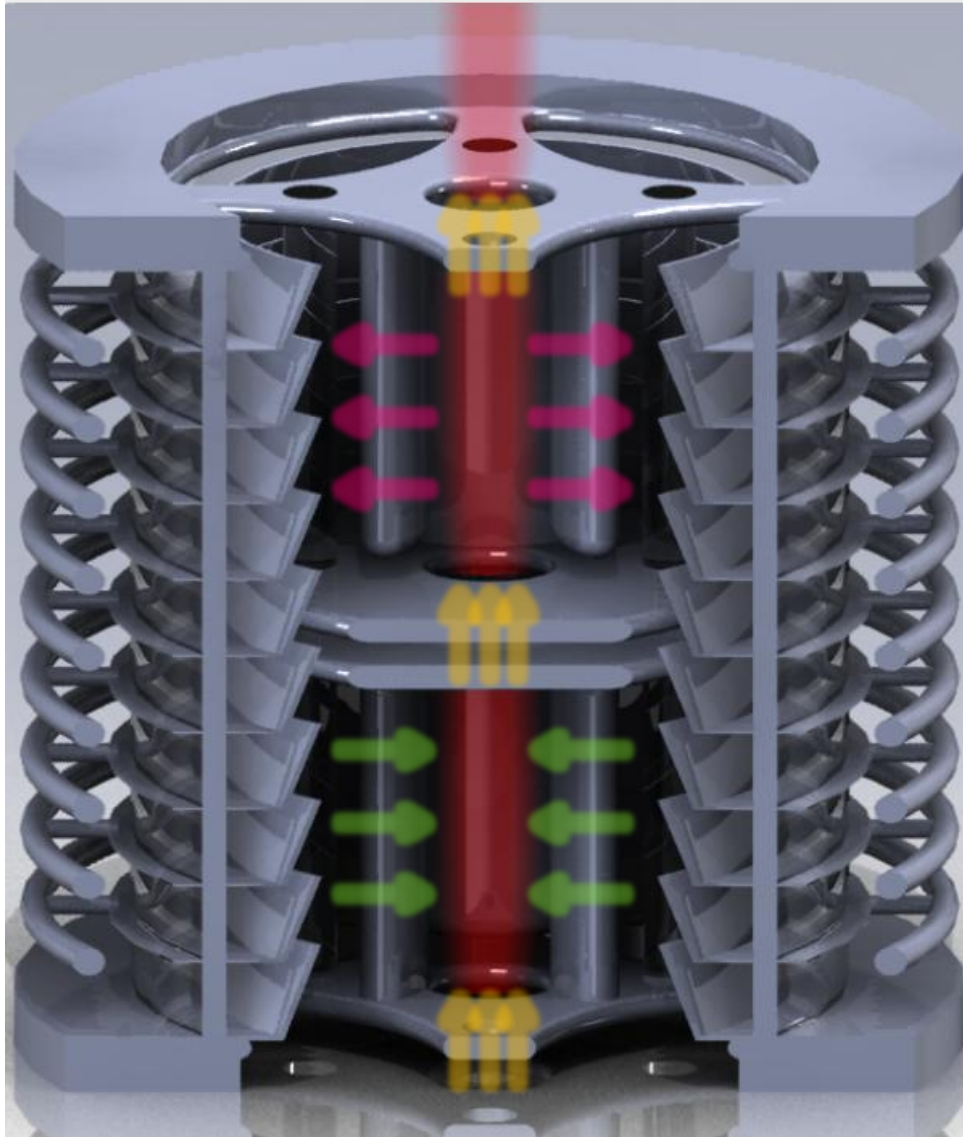
Two technologies

- **1. Electrostatic (ES):**
Vacuum insulated Tandem,
Electrostatic Quadrupole,
Single-ended DC,
Dynamitron
- **2. Radiofrequency (RF)**



Quadrupole focusing ESQ (Argentina)

Compensation of beam divergence by a strong transverse field



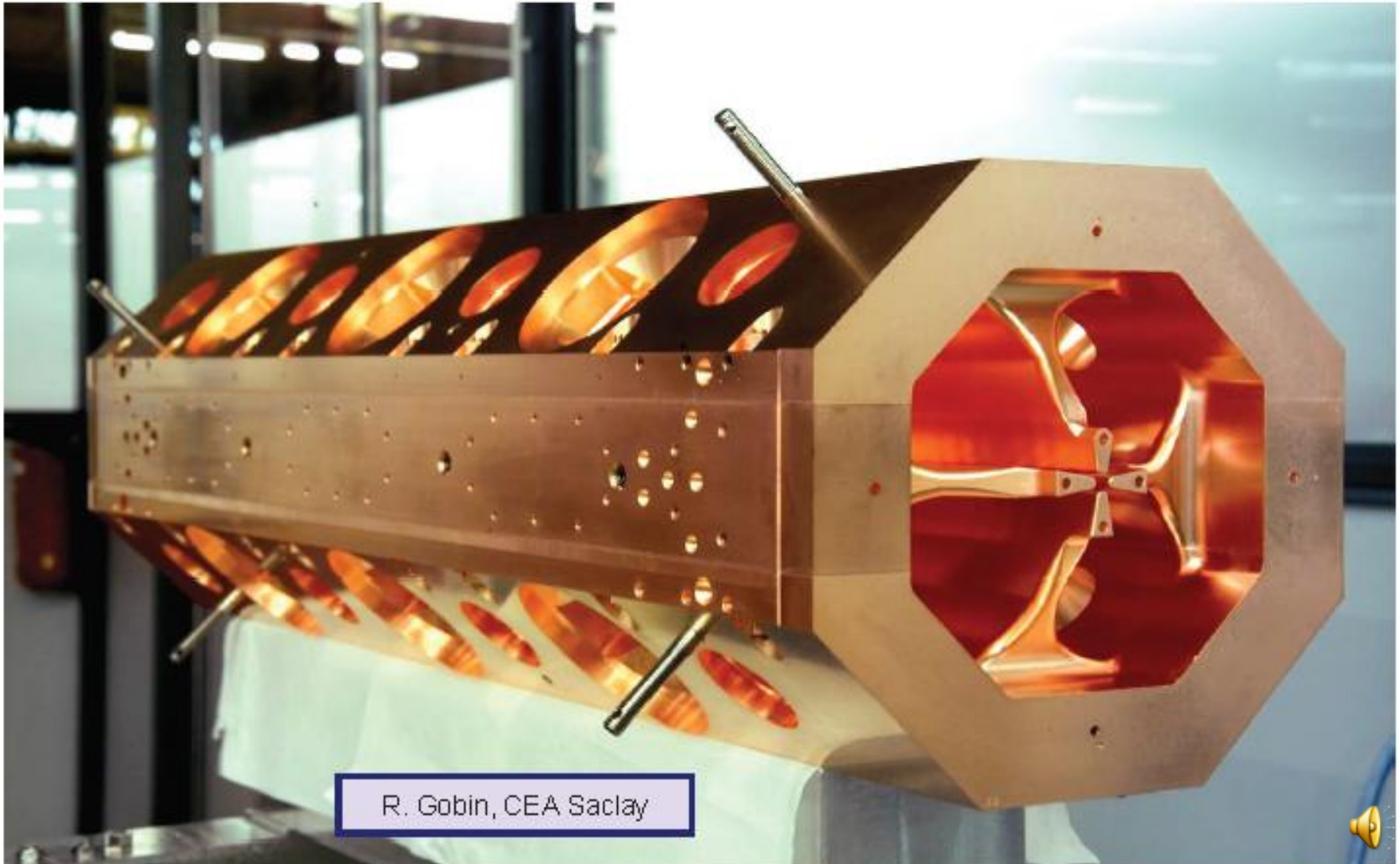
Two technologies

- **1. Electrostatic (ES)**
- **2. Radiofrequency (RF):**
RF Quadrupole (RFQ),
Drift Tube LINAC (DTL)



RFQ- Radiofrequency Quadrupole

RFQ Herstellung



R. Gobin, CEA Saclay



Tsukuba University (Ibaraki)

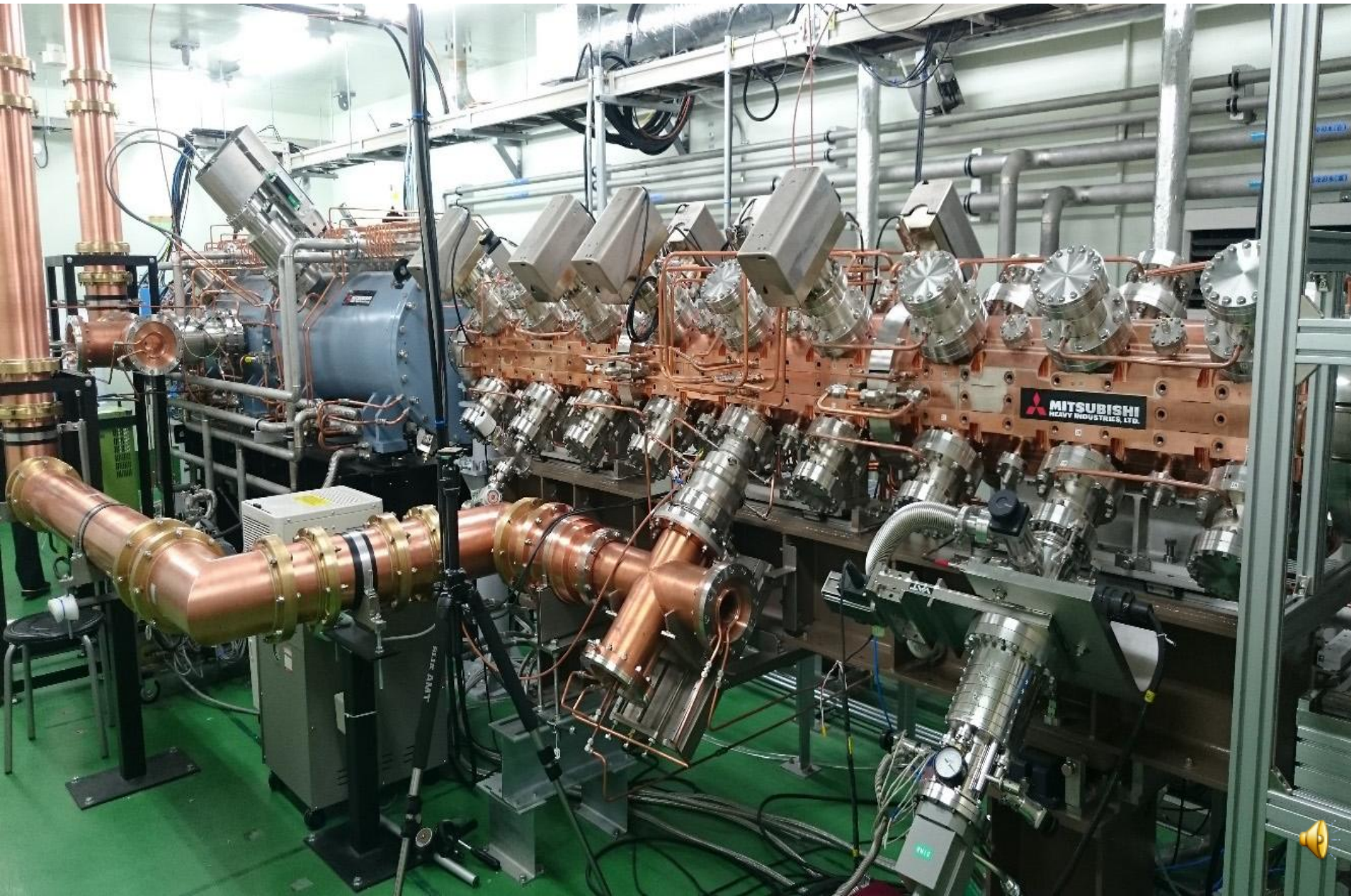
- RFQ + DTL
- 8 MeV proton beam; 10 mA (goal), actual (few mA).
- Be target. ${}^9\text{Be}(p,n){}^9\text{B}$ reaction
- 6.1 MeV max. neutron energy. $\langle E_n \rangle \approx 1.7 \text{ MeV}$.

National Cancer Center (Tokyo)

- RFQ
- 2.5 protons; 20 mA
- Solid ${}^7\text{Li}(p,n)$
- Clinical trial



Ibaraki prefecture RFQ + DTL



Argentina project



A comprehensive study of deuteron induced reactions: $^9\text{Be}(\text{d},\text{n})^{10}\text{B}$ and $^{13}\text{C}(\text{d},\text{n})^{14}\text{N}$ -based neutron sources for deep tumor treatment.

Computational assessment of deep-seated tumor treatment capability of the $^9\text{Be}(\text{d},\text{n})^{10}\text{B}$ reaction for AB-BNCT, Physica Medica (Europ. Journal Med. Phys.), 30 (2014) 133-146.

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

A $^{13}\text{C}(\text{d},\text{n})$ -based epithermal neutron source for BNCT, Phys. Med. 33(2017)106-113. M.E. Capoulat & A.J.Kreiner

Neutron spectrometry of the $\text{Be}(\text{d}(1.45\text{MeV}),\text{n})$ reaction for AB-BNCT, NIM B445(2019)57, Capoulat et al.



Beam Shaping Assembly (BSA)

Design

- ✓ Epithermalizes, filters & collimates the primary neutron beam
- ✓ Maximizes the neutron flux in the direction of the patient
- ✓ Shields radiation in the lateral directions

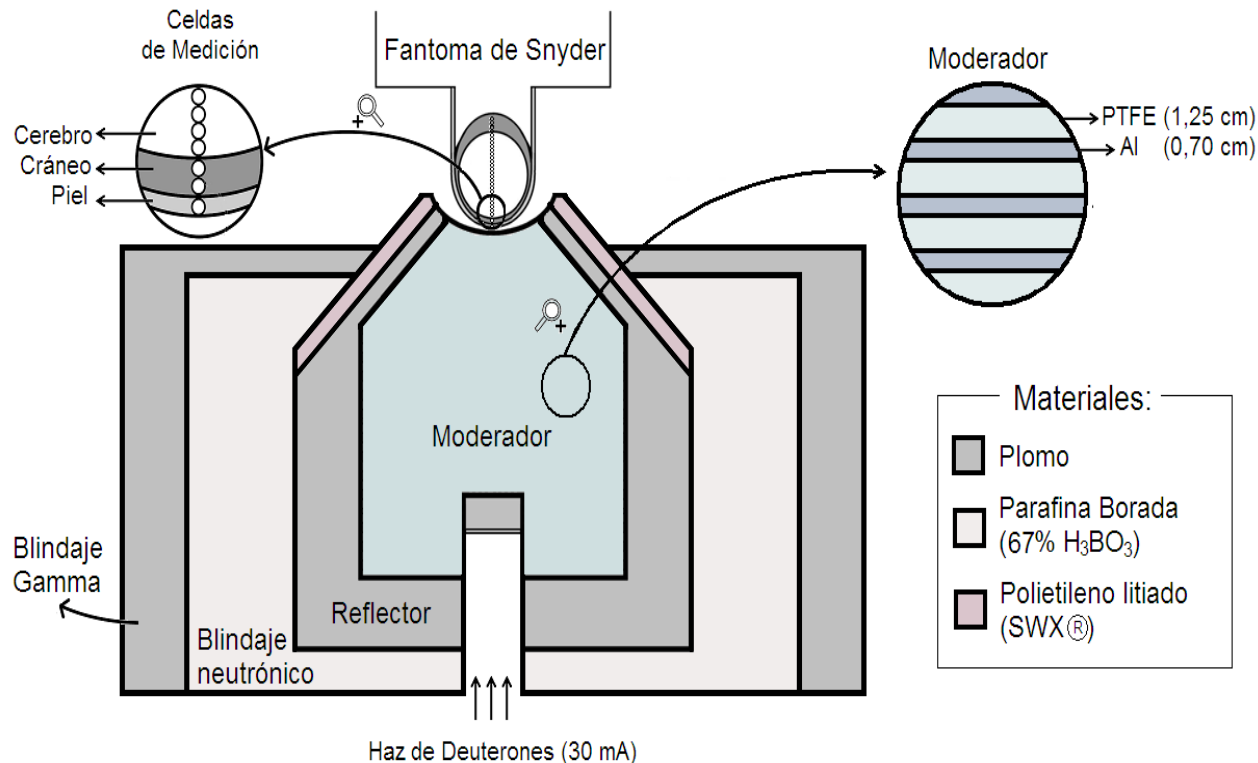
Epithermalization:
Al, fluorinated compounds,
Fluental ®, PTFE

Filtering of thermal neutrons
Boronated/ lithiated materials,
 ^6Li , ^{10}B

Neutron reflector:
Lead, graphite

Neutron shielding:
Hydrogenous materials,
polyethylene, boronated
paraffin

Gamma shielding
High Z materials, Lead.

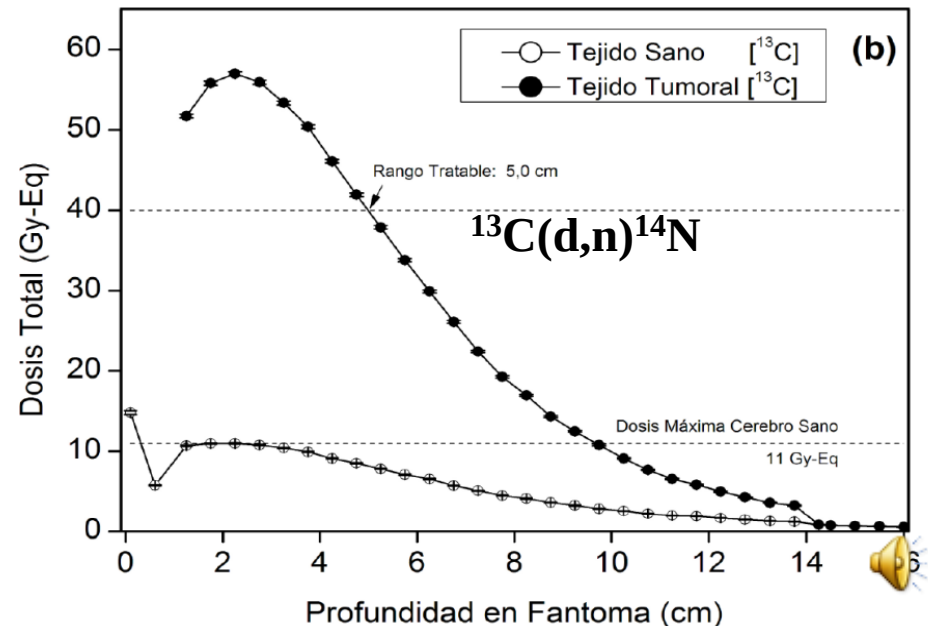
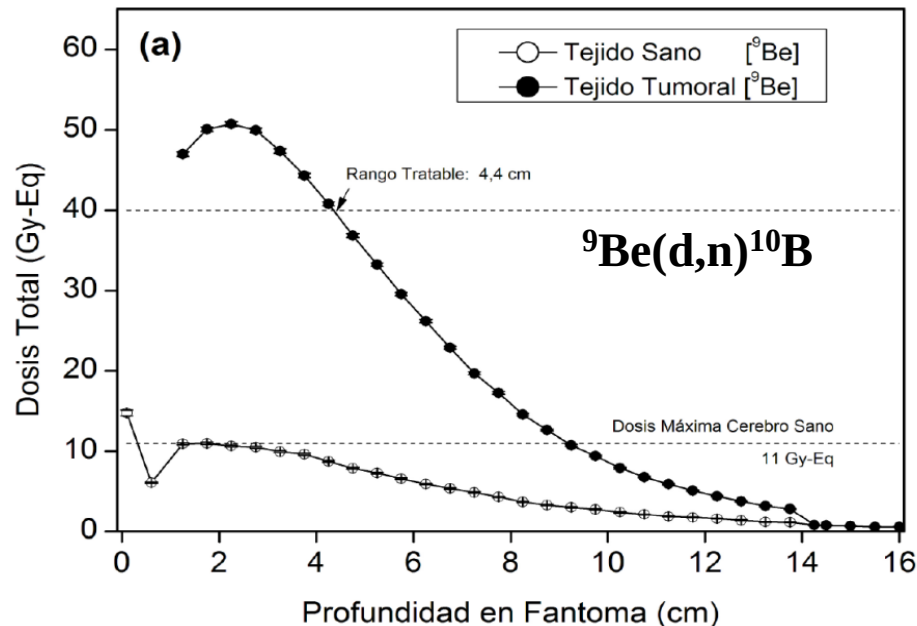


Optimal configurations: $^{13}\text{C}(\text{d},\text{n})^{14}\text{N}$ & $^9\text{Be}(\text{d},\text{n})^{10}\text{B}$ (see Phys. Med. 30(2014)133 & 33(2017)106 for details)

Reaction	Treatment Time	Maximum dose [Gy-Eq]			Treatable depth [cm]
		Tumor	Skin	Healthy brain	
$^{13}\text{C}(\text{d},\text{n})^{14}\text{N}$	2:20 h	57.7	11.9	11.0	5.40
$^{13}\text{C}(\text{d},\text{n})^{14}\text{N}$	1 h (non opt)	50.0	15.7	11.0	4.61
$^9\text{Be}(\text{d},\text{n})^{10}\text{B}$	2:30 h	50.9	11.2	11.0	4.80
$^7\text{Li}(\text{p},\text{n})^7\text{Be}$ *	1 h	56.7	12.4	11.0	5.40

* Protons 2.3 MeV, 100% $E_n < 1$ MeV, more than doubles the neutron production of $^{13}\text{C}(\text{d},\text{n})$ and $^9\text{Be}(\text{d},\text{n})$., all currents: 30mA

✓ Dose profiles:



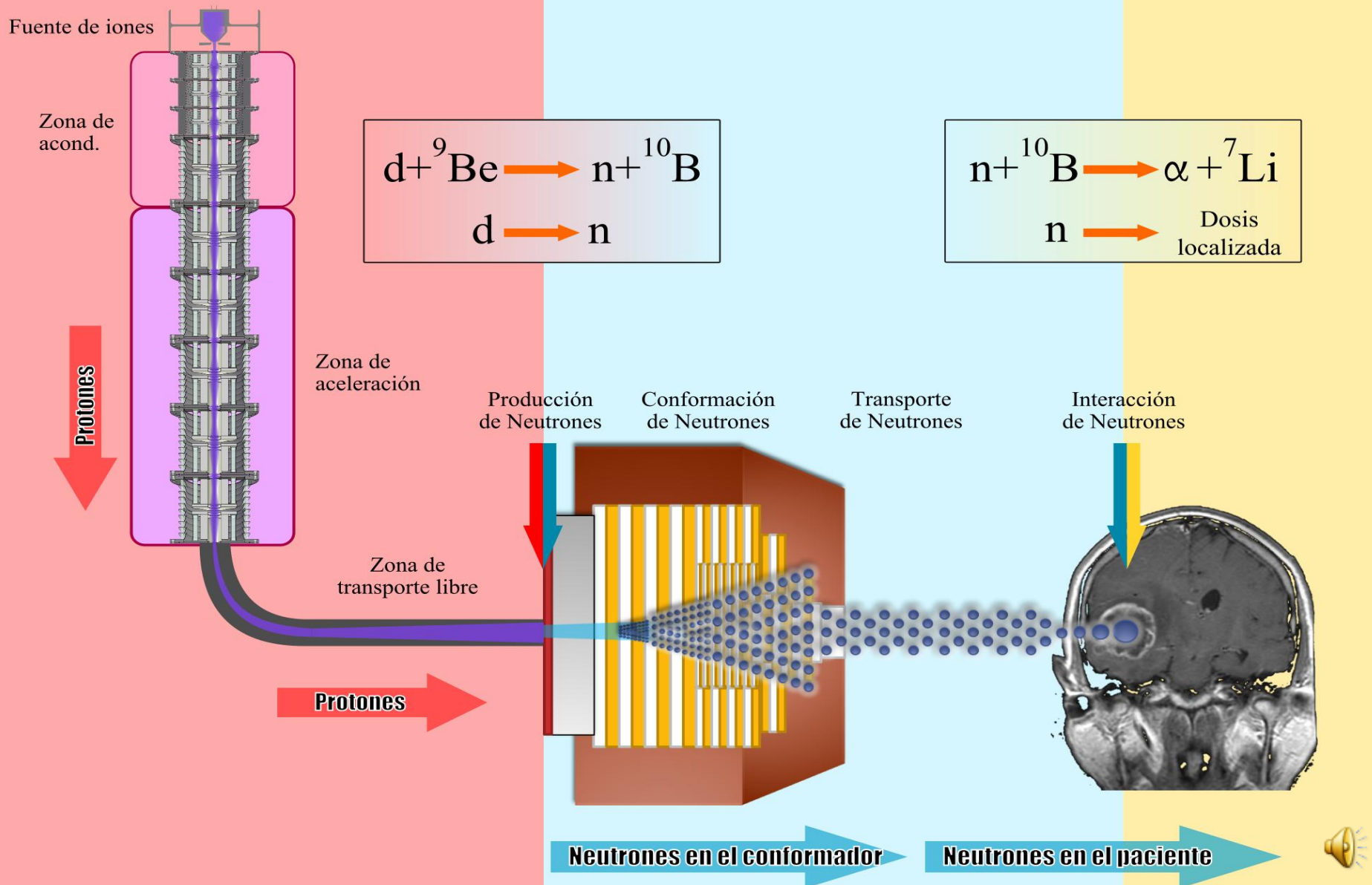
Additional comments to previous slide

- **It is our understanding that the parameters described in the previous slide (like the doses to tumor, healthy tissue, other organs at risk and similar quantities) are the relevant quantities to judge if a given AB-BNCT facility is capable to deliver an acceptable treatment. If these parameters satisfy the requirements of a given protocol we would then say that the facility is apt.**

Development of ESQ at CNEA, Argentina



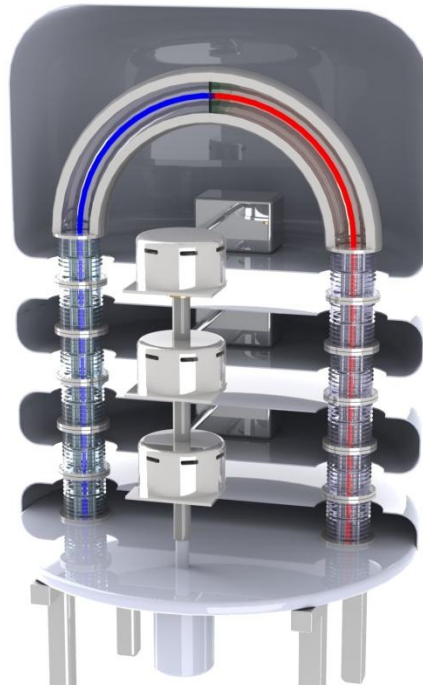
Layout of facility



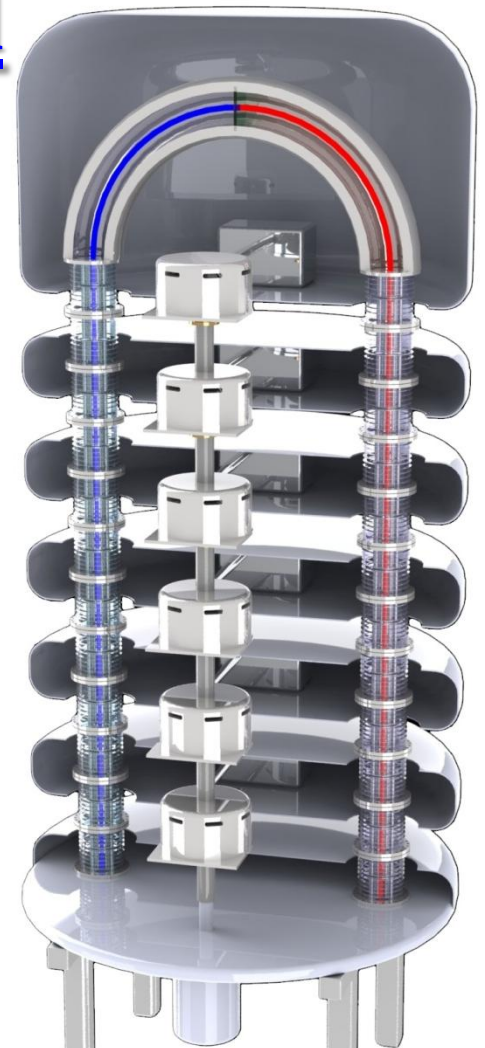
Different accelerators developed or under development



**240 kV ESQ
Accelerator**



**720 kV single ended
ESQ & Tandem
Accelerator**



**1.44 MV ESQ
Accelerator** 🔊

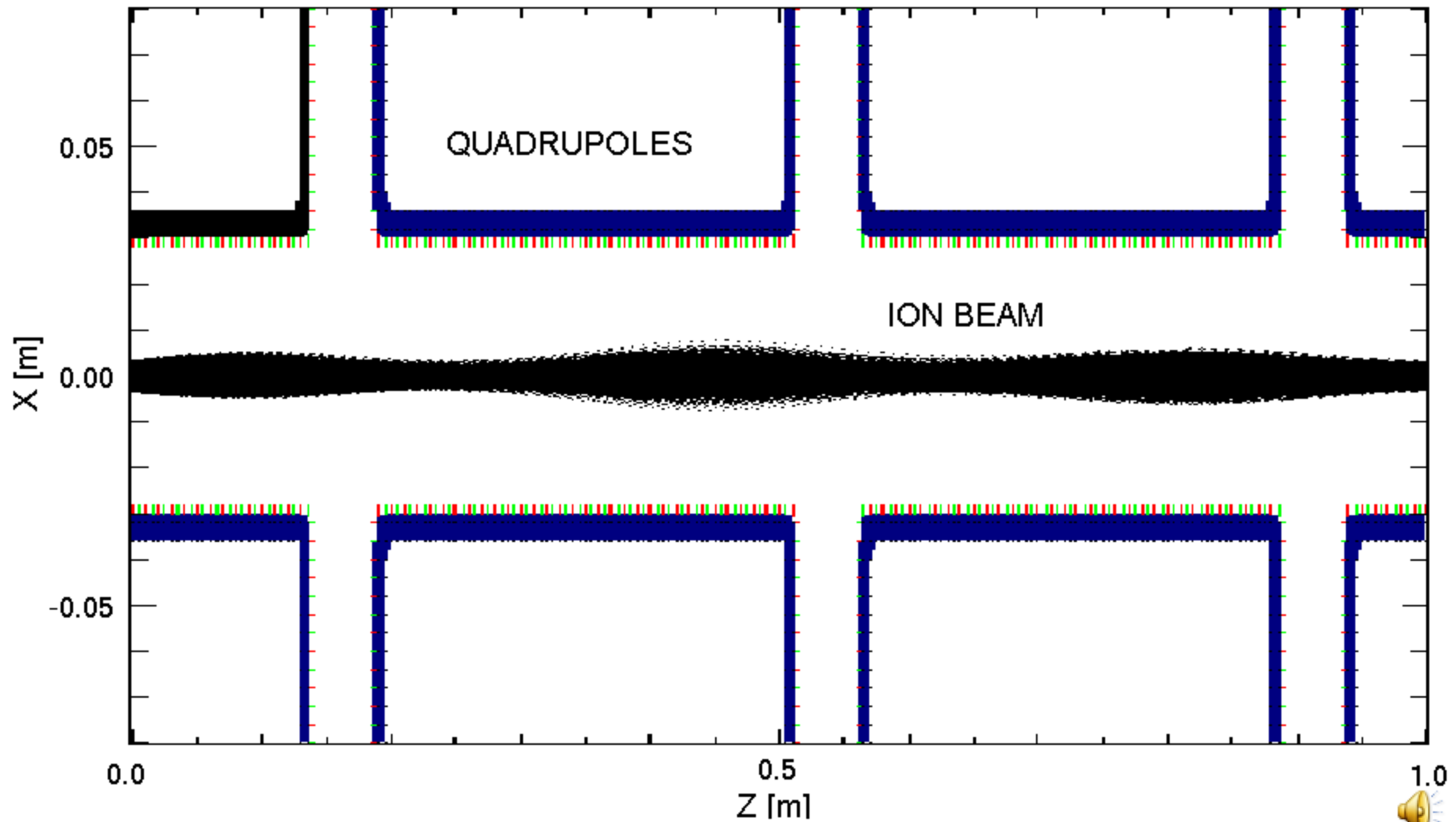
Accelerator with all systems mounted (HV, cooling, vacuum, control)



**Ion Optics (high intensity selfconsistent
beam transport taking into account
space charge effects):**



Proton beam transport (30 mA)



Accelerator tubes with quadrupoles for high currents & strong tranverse fields



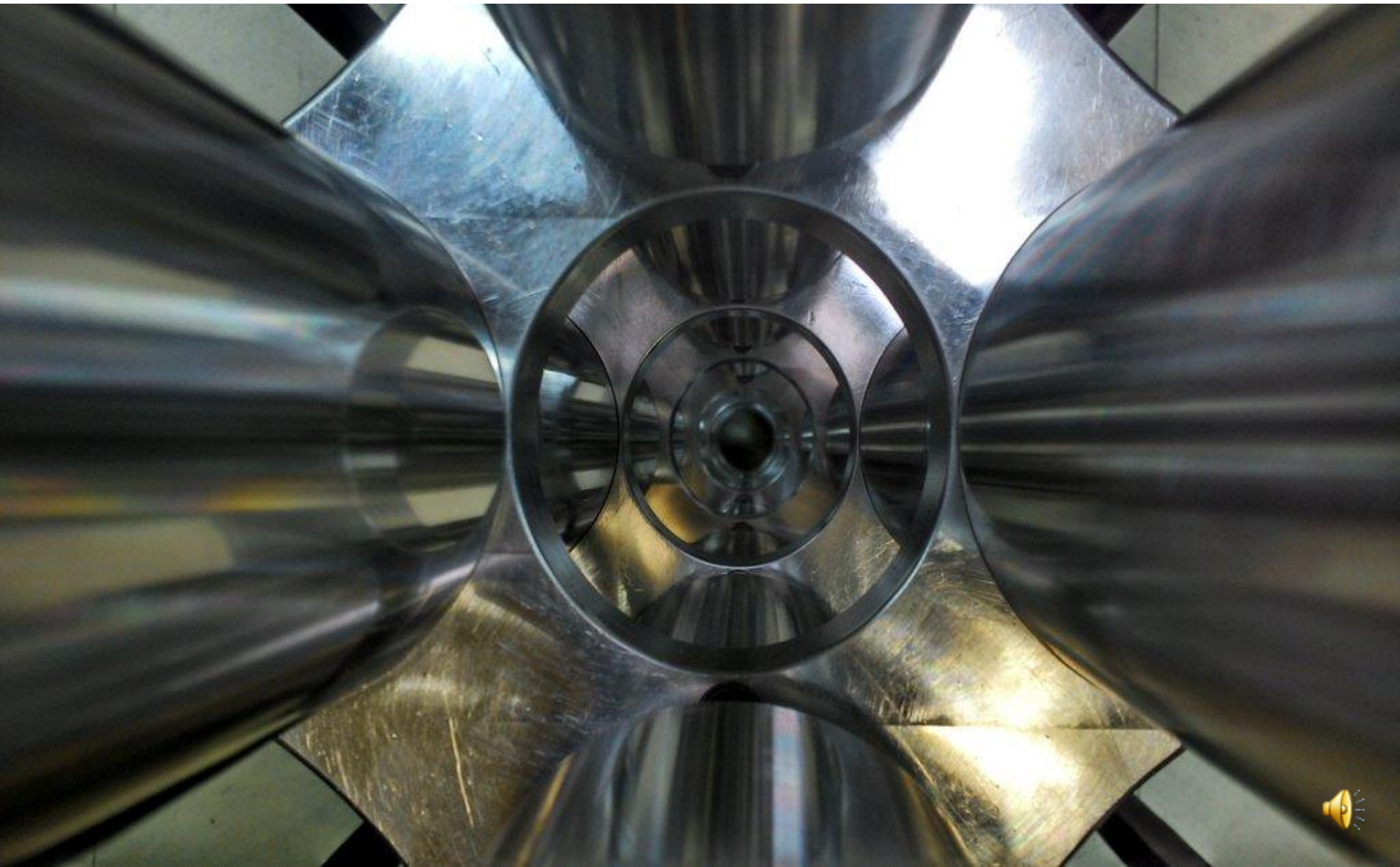
120 kV tubes, assembled and tested



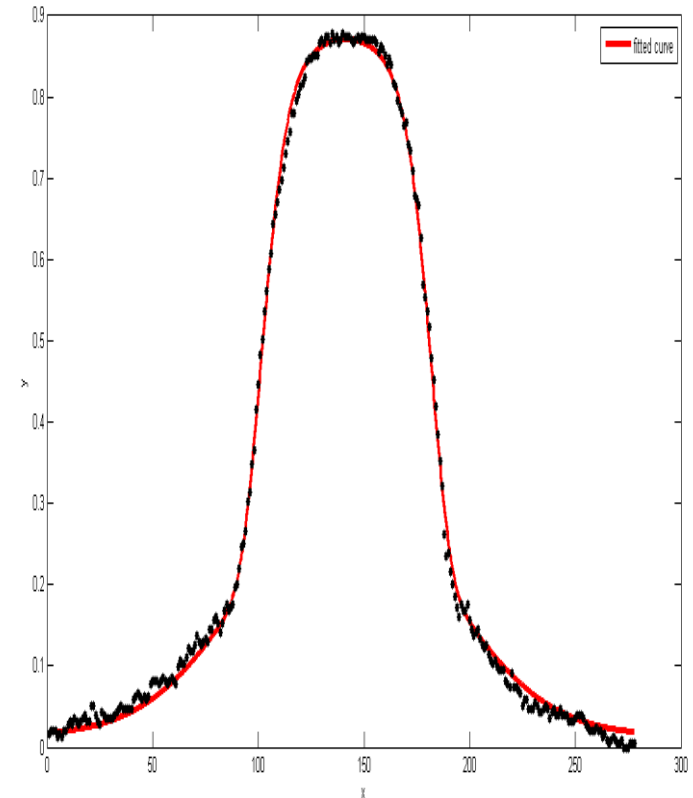
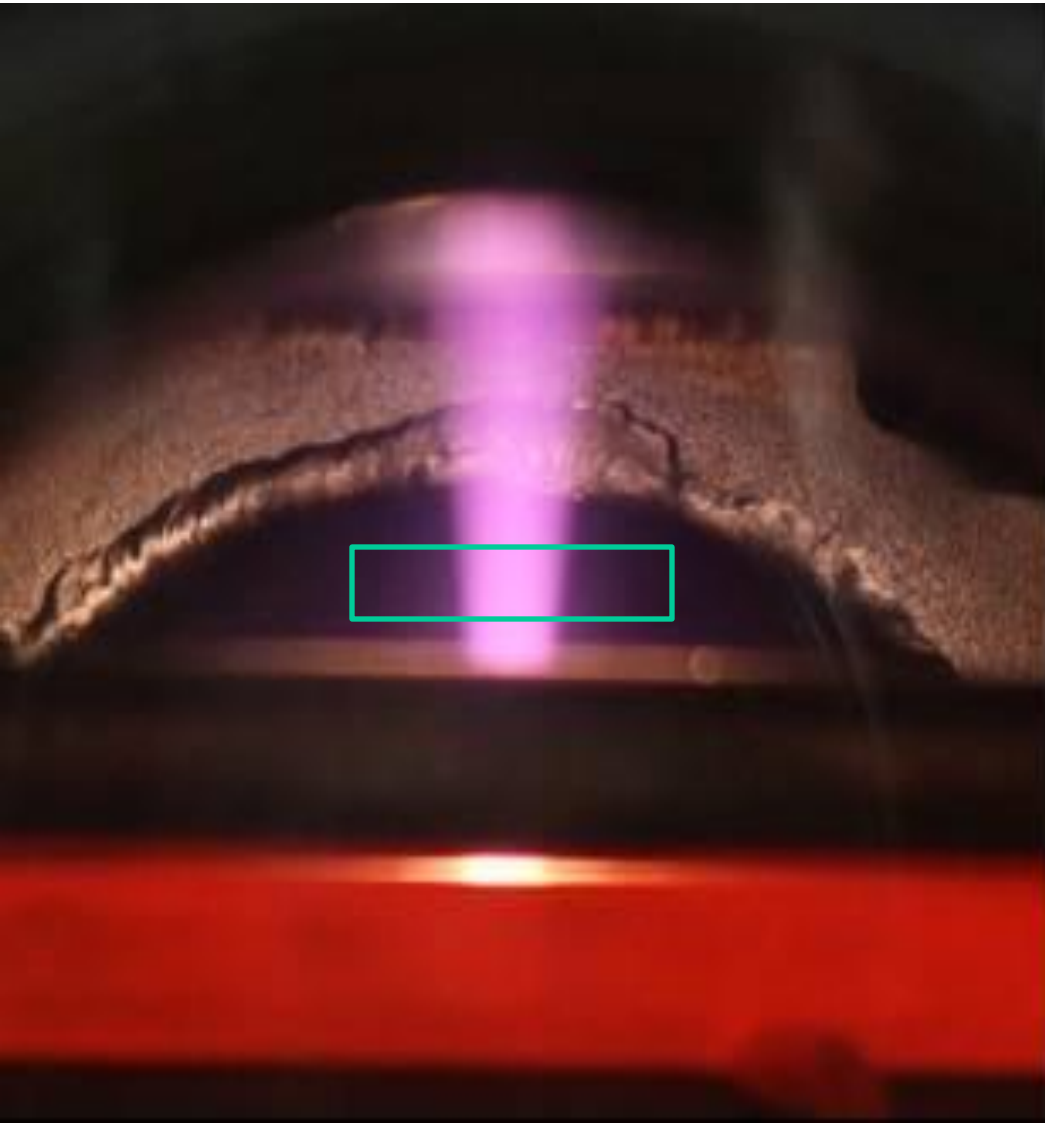
Centering the quads inside tube



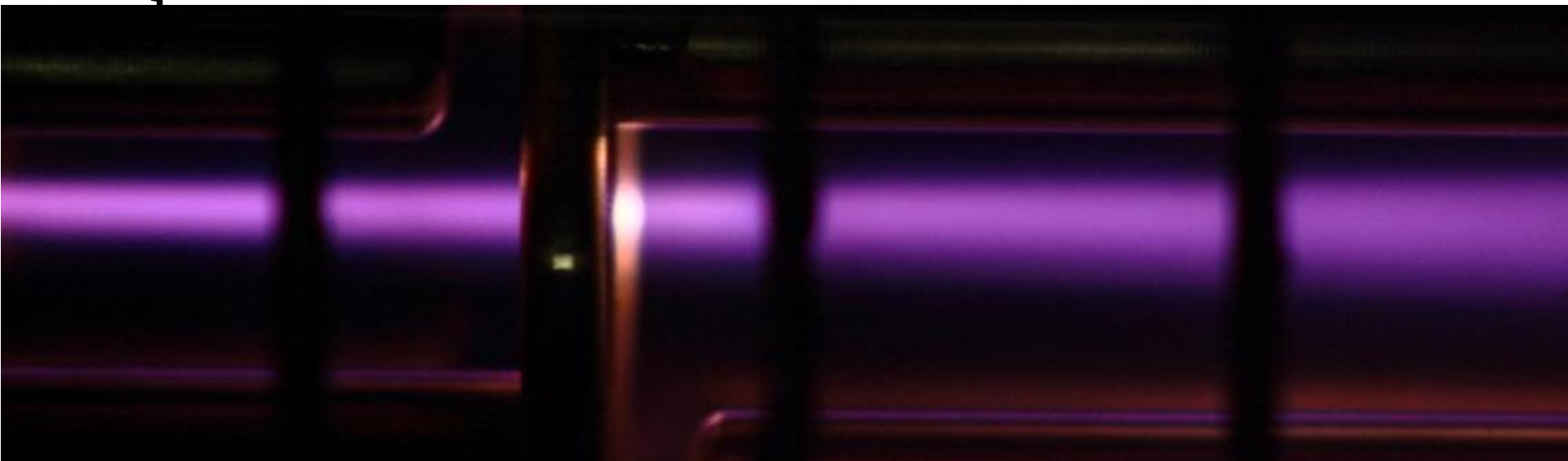
Watching along the tube axis



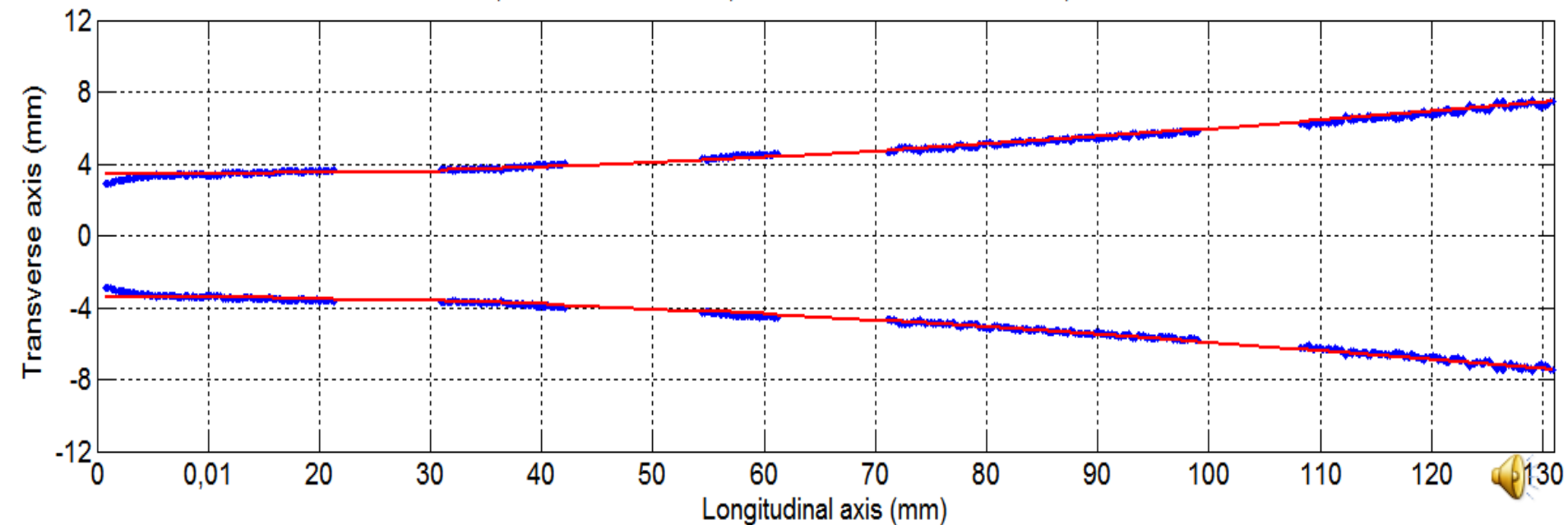
Beam shape analysis through induced fluorescence in residual gas



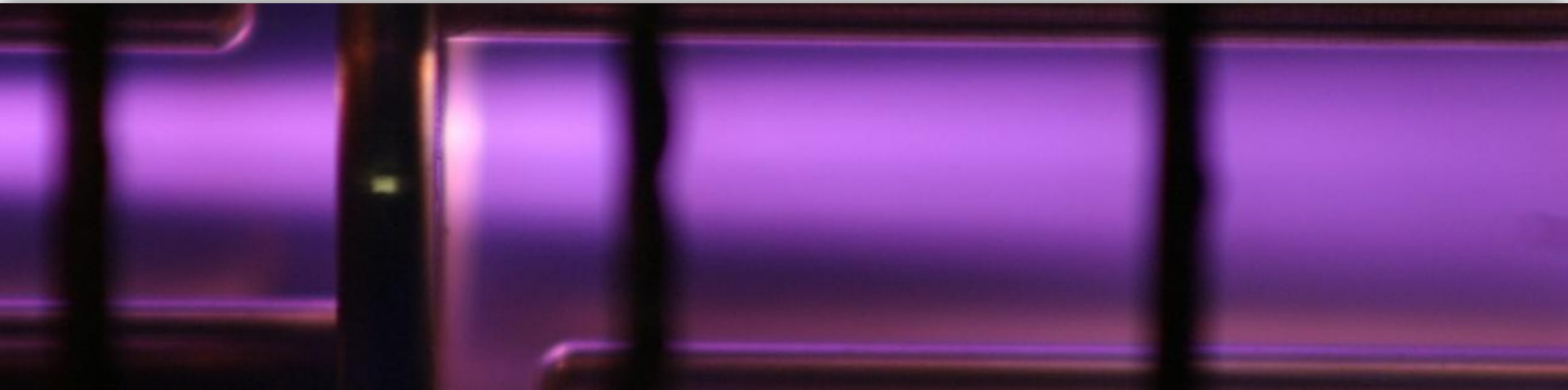
9.5 mA, Radius=3.5 mm; Emittance_N=0.38 π mm mrad



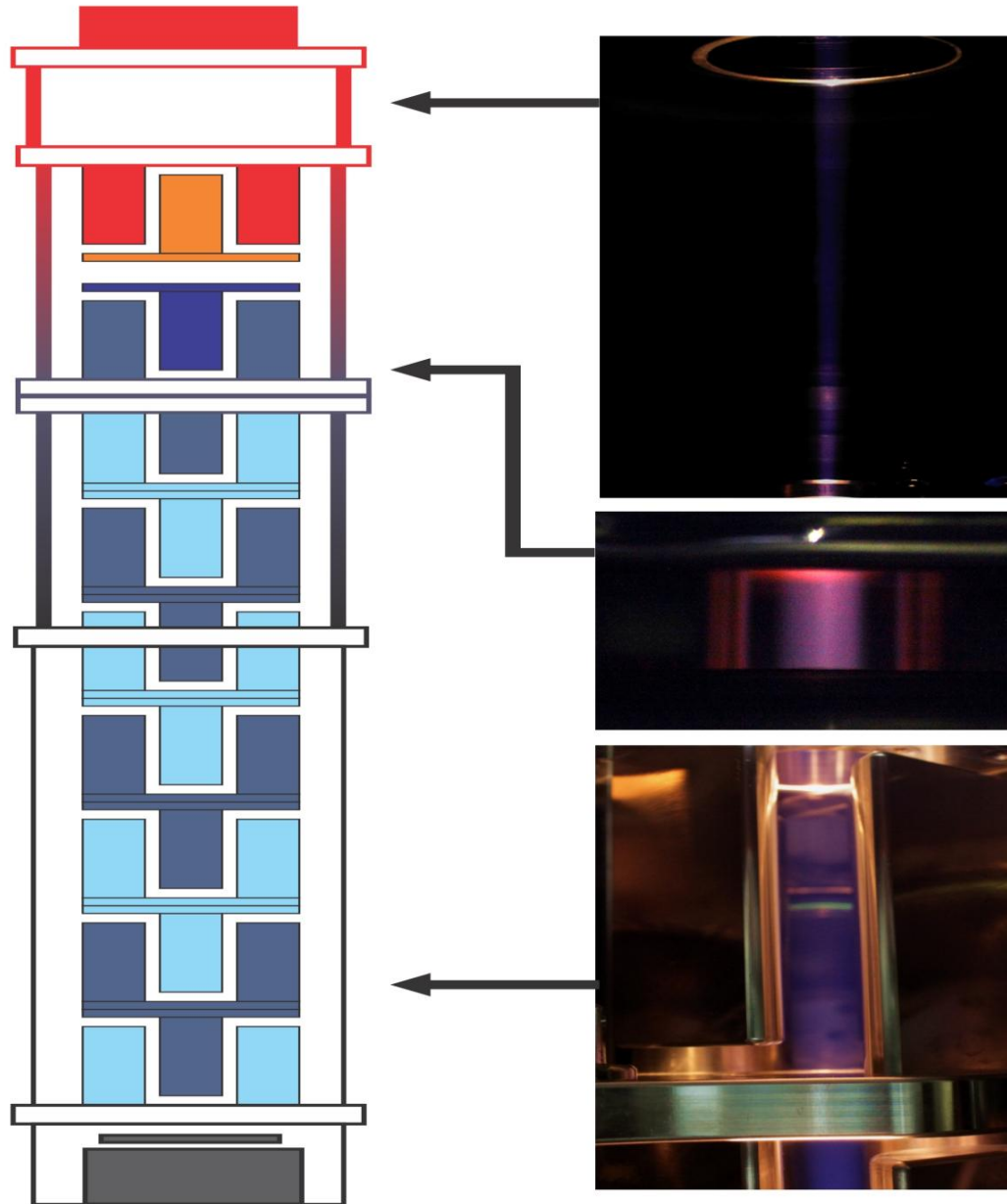
$x = 3.46\text{mm}$; $x' = -0.004094$; $\text{Emit.nor} = 1.2 \times 10^{-6} \text{ rad}$; Current = 9.5 mA



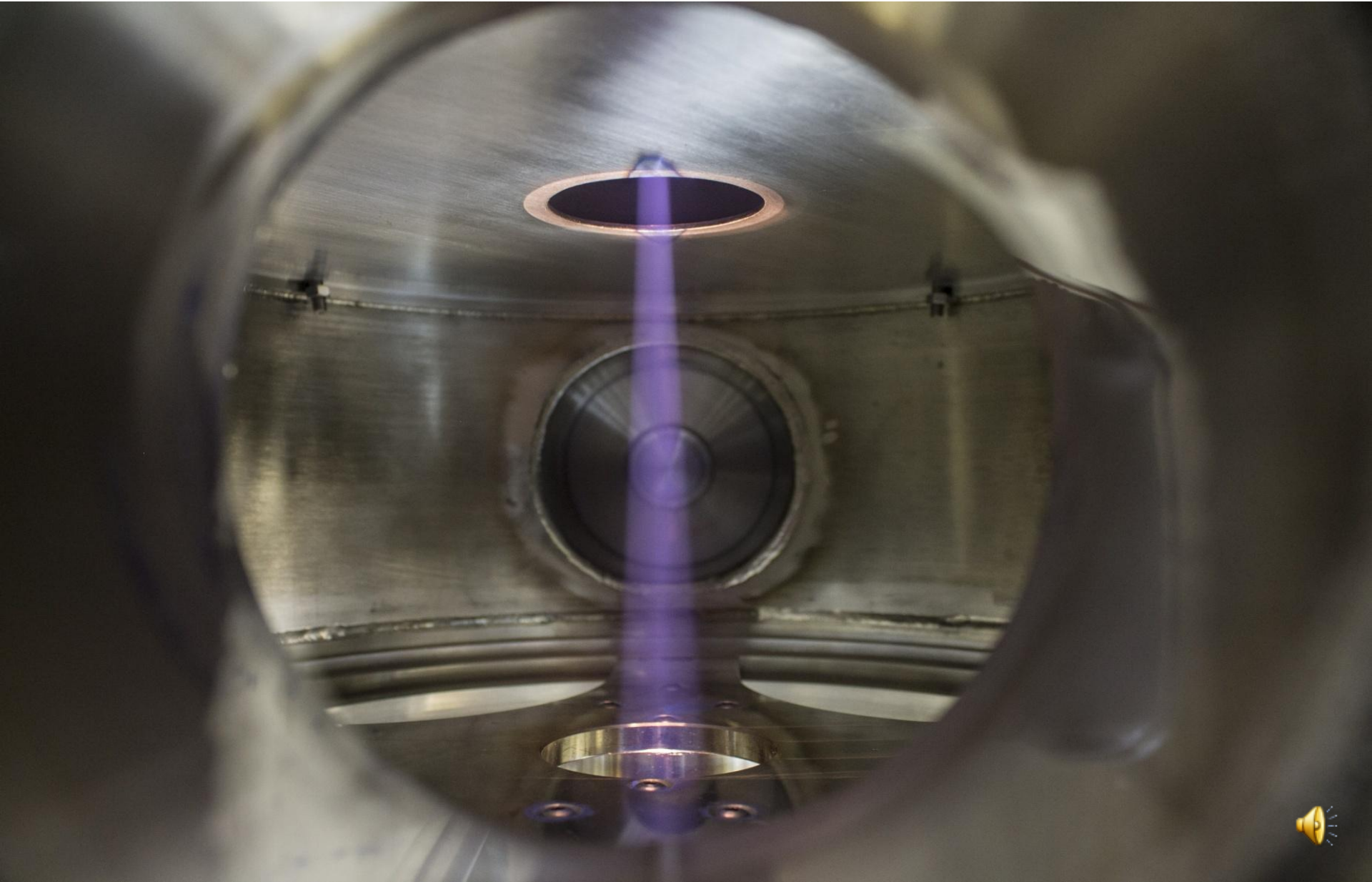
20.3 mA, Radius=6.3 mm; Emittan_N= 1.36 π mm mrad



Beam images along the accel. column



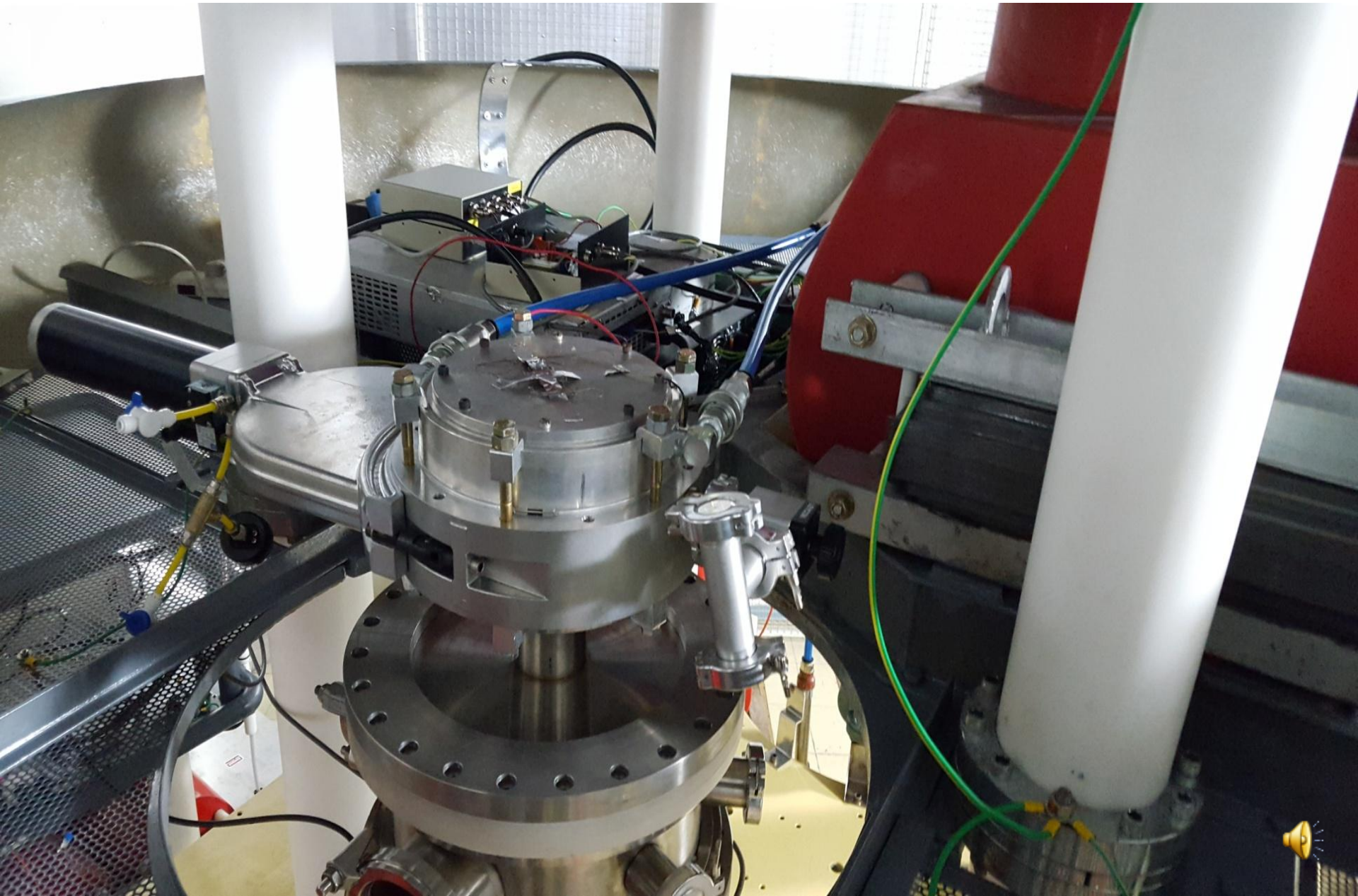
10 mA, view of beam into upper chamber,
going into FC



0.72 MV machine completed



Cooled high power target



Conceptual design of Neutron Production Target

TARGET

✓ Device to generate neutrons through an appropriate nuclear reaction.

BNCT

C

Be

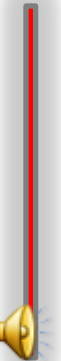
High
intensity
d beam



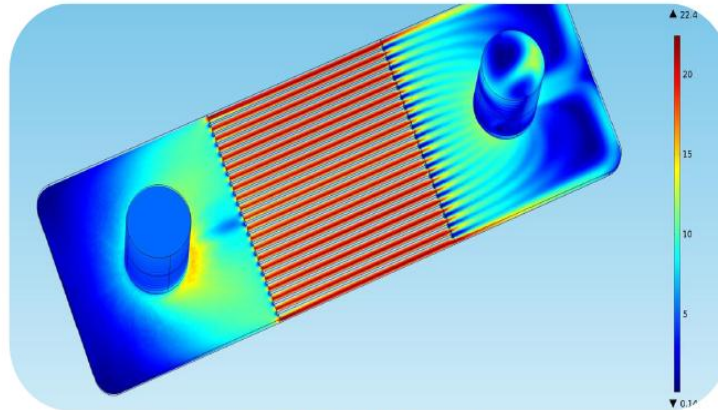
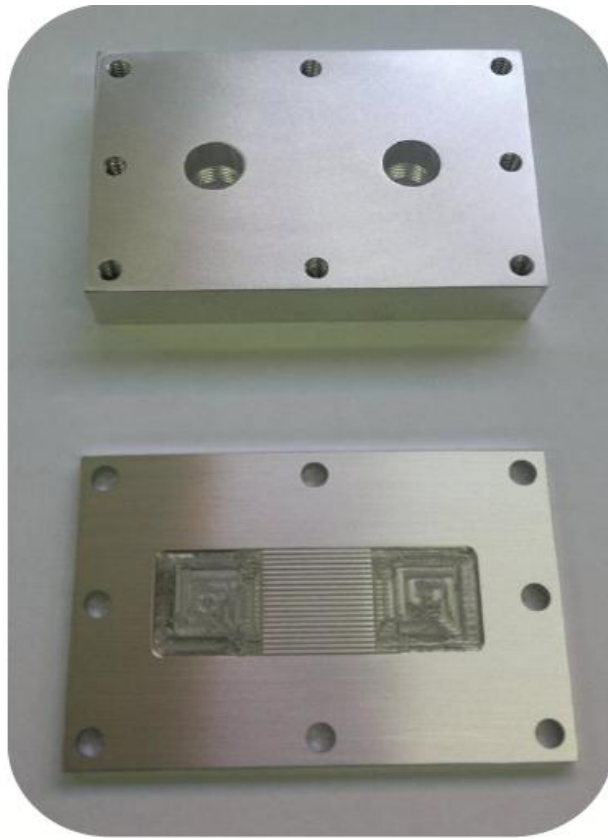
Cooling system

Cooling

✓ Has to carry away all the heat deposited by beam.

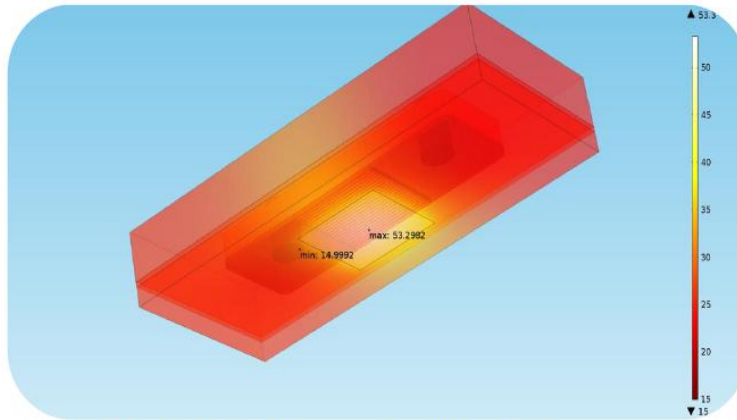


Cooling system for neutron production targets: microchannels



Simulación de la velocidad del fluido en el prototipo.

Fluid dynamics simulations



Simulación de la temperatura del prototipo.

Temperature simulations

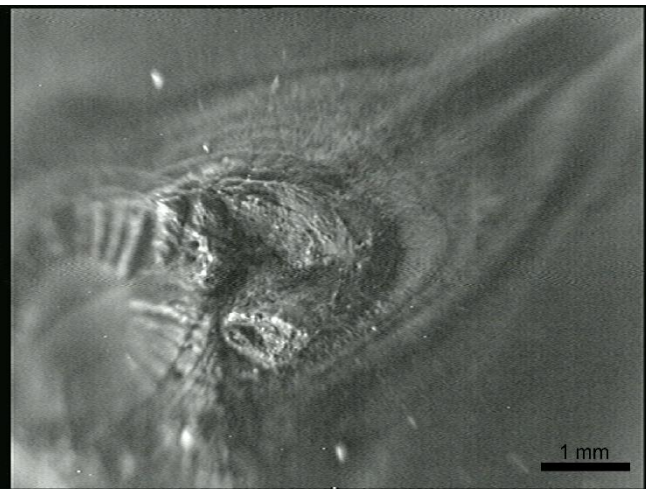
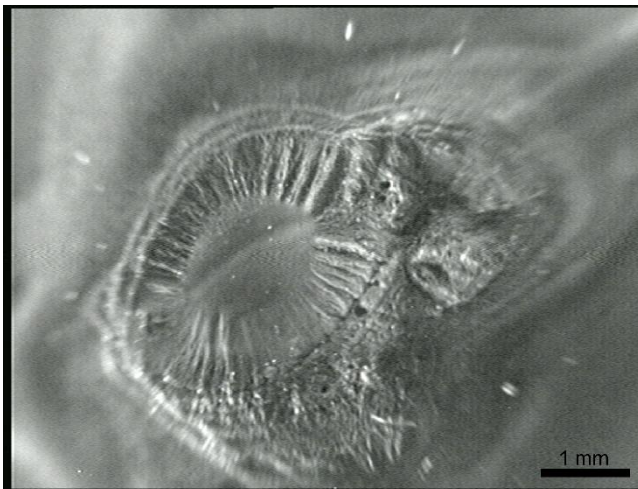
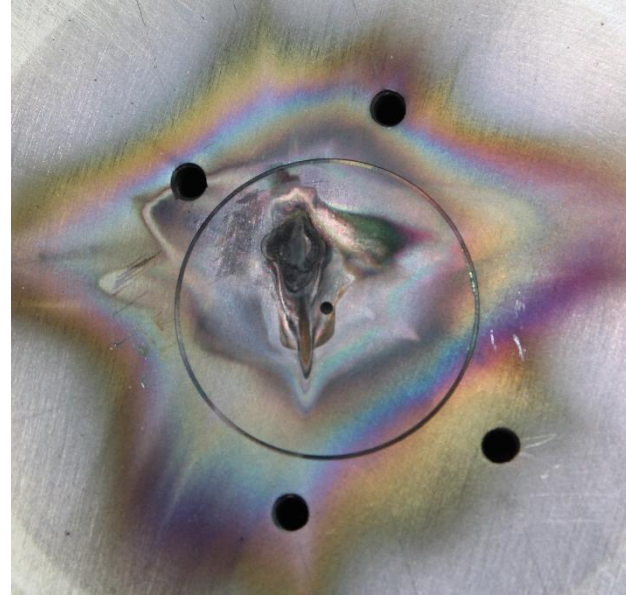
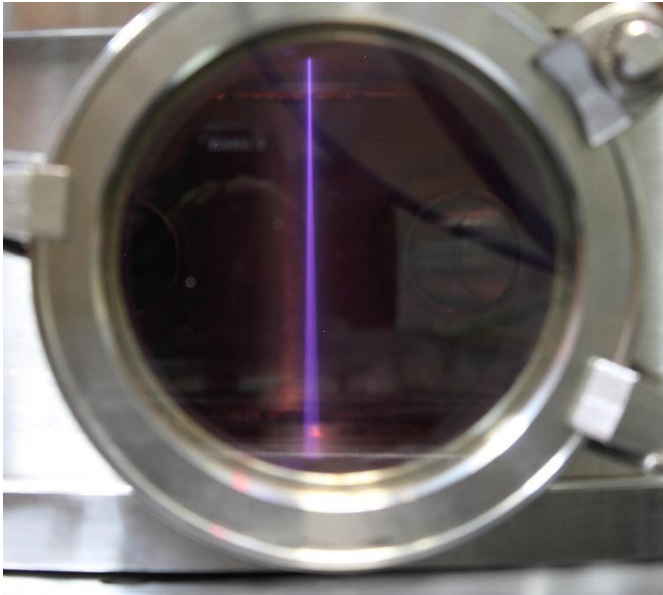


**Experimental
validation of
simulations**

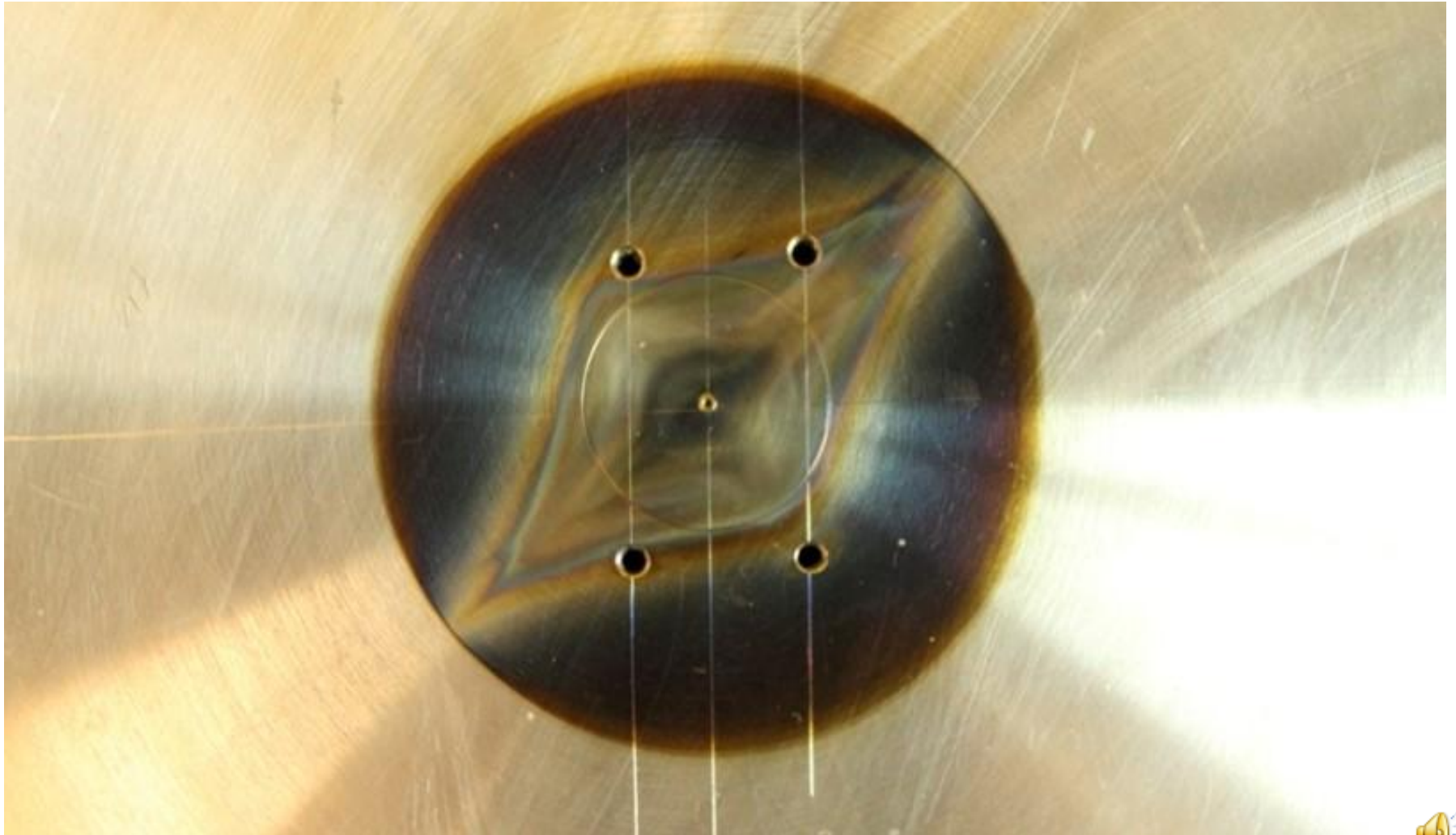


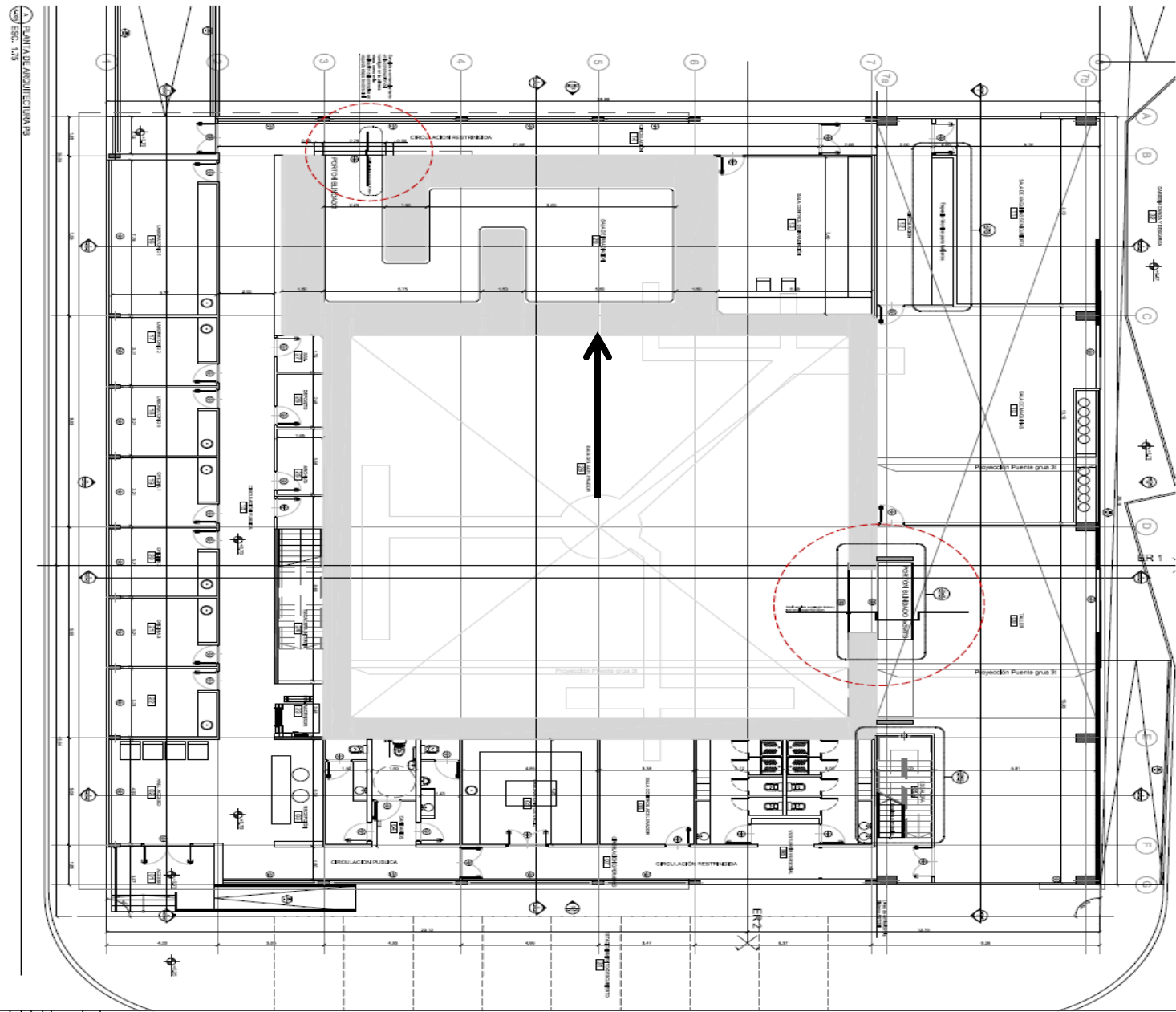
Study of limits in power density

High power density beams $\sim 650 \text{ W/cm}^2$ Radius $\sim 0.4 \text{ mm}$



Irradiated Aluminum microchannel target (small chann., up to 1 kW/cm^2)





Stand December 2019: Accelerator development lab and future BNCT treatment Centre.



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CONCLUSIONS/REMARKS

- The era of in-hospital neutron sources has started. Worldwide effort: a variety of different accelerators and nuclear reactions are being evaluated. So relative merits and costs may be compared. As good as best reactor. The electrostatic solution seems to us the most appropriate one due to simplicity and cost.
- The suitability of ${}^9\text{Be}(\text{d},\text{n}){}^{10}\text{B}$ and ${}^{13}\text{C}(\text{d},\text{n}){}^{14}\text{N}$ @ 1.45 MeV as epithermal/thermal neutron sources has been demonstrated. Target technology is well advanced.
- 0.24 MV ESQ accelerator ready. In-air single-ended 0.72 MV ESQ is almost ready. Single ended 1.45 MV machine is also being constructed. 