Accelerator-based neutron sources and the Buenos Aires project.

M. Baldo[1], J. Bergueiro[1], M.E. Capoulat[1,2,3], D. Cartelli[1,2,3], J. Padulo[1], J.C. Suárez Sandín[1], M. Igarzabal[1], M.F. del Grosso[1,3], L. Gagetti[1,2,3], A.A. Valda[1,2], N. Canepa[1], N. Real[1], D.M. Minsky[1,2,3], G. Conti[1], J. Erhardt[1], H.R. Somacal[1,2], A. Bertolo[1], D. Sosa Selaya [1], M. Gun[1], M.E. Debray[1,2], **A. J. Kreiner [1,2,3]**

[1]Subgerencia de Tecnología y Aplicaciones de Aceleradores, "Fisica", GAIyANN, CNEA. [2]Escuela de Ciencia y Tecnología, UNSAM. [3]CONICET.

CUIA Favaloro, Buenos Aires, 05/05/2018

Outline

- **Context, economic significance and applications.**

- **Medical applications: proton and carbon therapy & Boron Neutron Capture Therapy (BNCT).**

- **Development of accelerator technology.**

- **Conclusions/Final comments.**

Context & significance

- **More than 30000 accelerators installed in the last 60 years.**
- **Production: 1000 accelerators for 2000 MU$S/year.**
- **A conservative estimate: the value of products that contain parts & materials treated with accelerators exceed 500 thousand millon U$S/year (order of Argentine GNP).**
- **The main application is ion implantation to produce semiconductors & integrated circuits. Commercial value: 250 billon U$S/year**

Applications of Accelerators

1. **Medicine**: **Protontherapy, Hadrontherapy, BNCT**, **Radioisotope production**: Imaging, Therapy.
2. **Materials**: Caracterization & Modification of Properties: **Ion Implantation** , Rad damage, Microanalysis, Micromachining.
3. **Environment, Archeometry, Cultural heritage**: High sensitivity analysis techniques: PIXE, PIGE, RBS, AMS.
4. **Detection of special nuclear materials (U, Pu), drugs, explosives & oil logging: Active interrogation with** neutrons & γ's.
5. **Incineration/transmutation of radiactive waste (future).**
6. **Energy production (future).**
7. **Studies on matter structure: Subnuclear, nuclear, atomic, molecular, solid state....**

Medical Applications

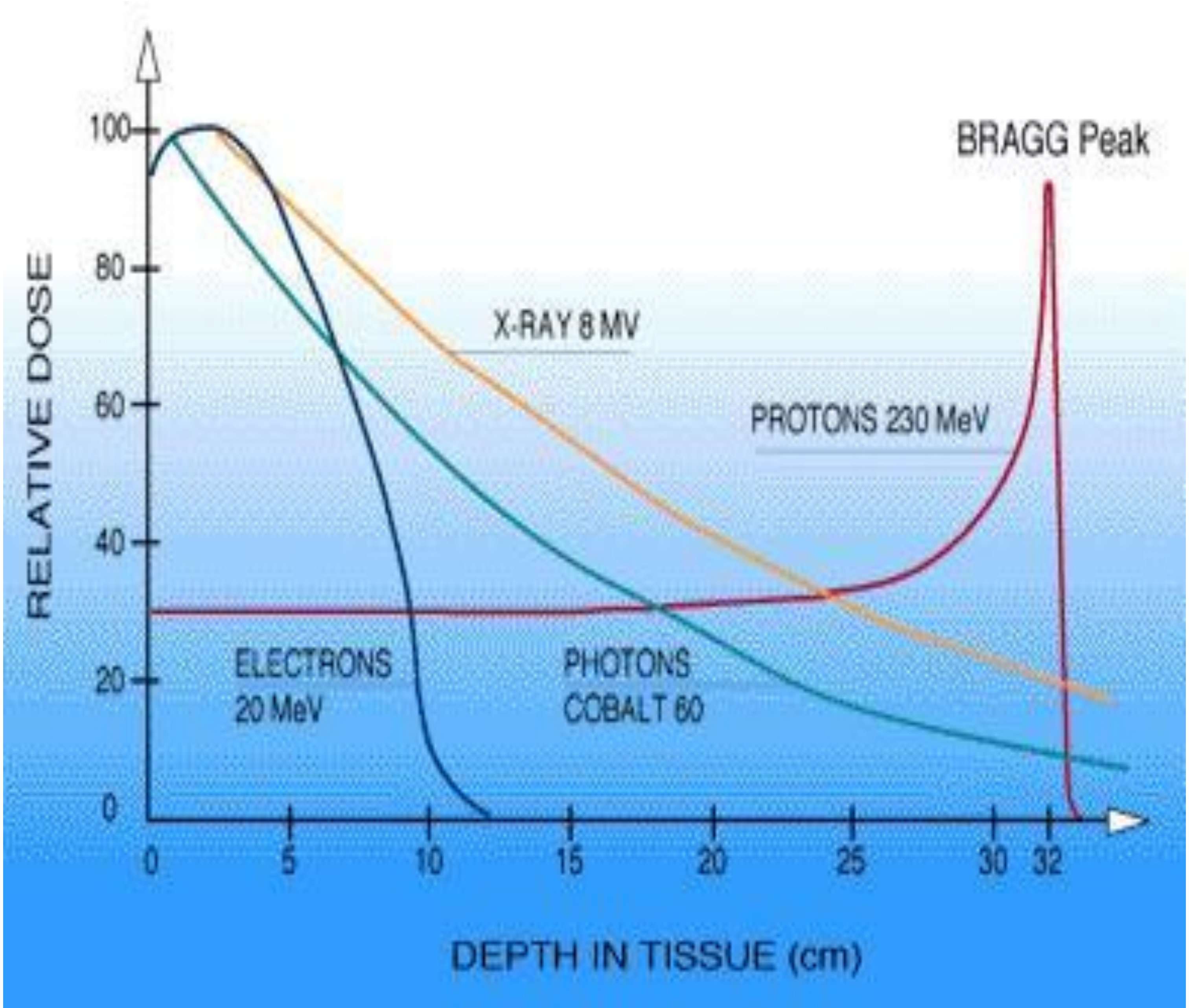
- **Ion Beam Therapy (protons, carbon):**

  Spatially well localized tumors.

- **Boron Neutron Capture Therapy (BNCT) with accelerators:**

  Diffuse and infiltrating tumors.

Protontherapy: physical selectivity



LINEAR ENERGY TRANSFER = LET = dE/dx

Energy loss per unit length of traversed path

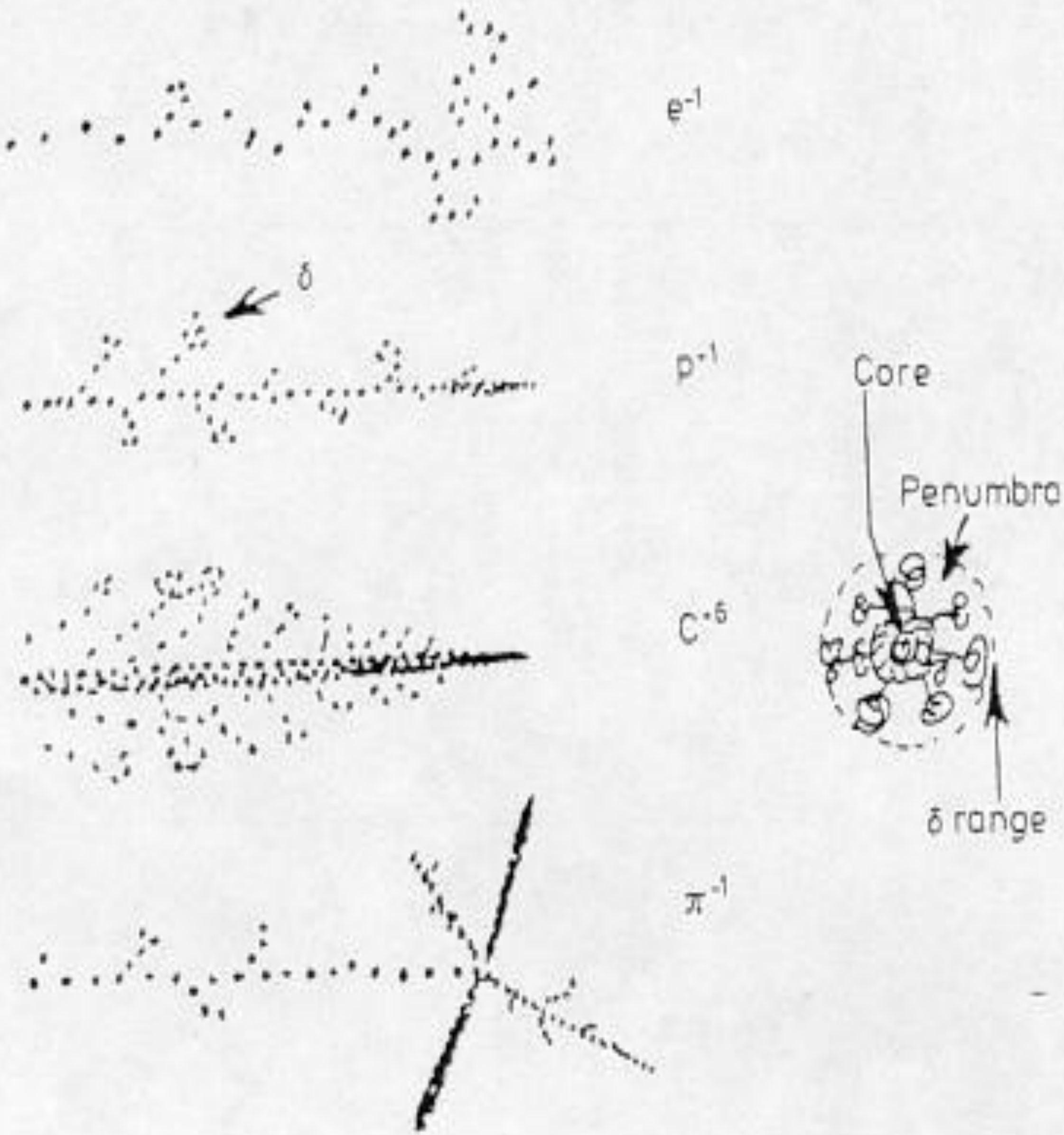
$dE/dx \propto Z^2 n/v^2$ (Bethe-Bloch theory)

Z = projectile atomic number (ion nuclear charge)

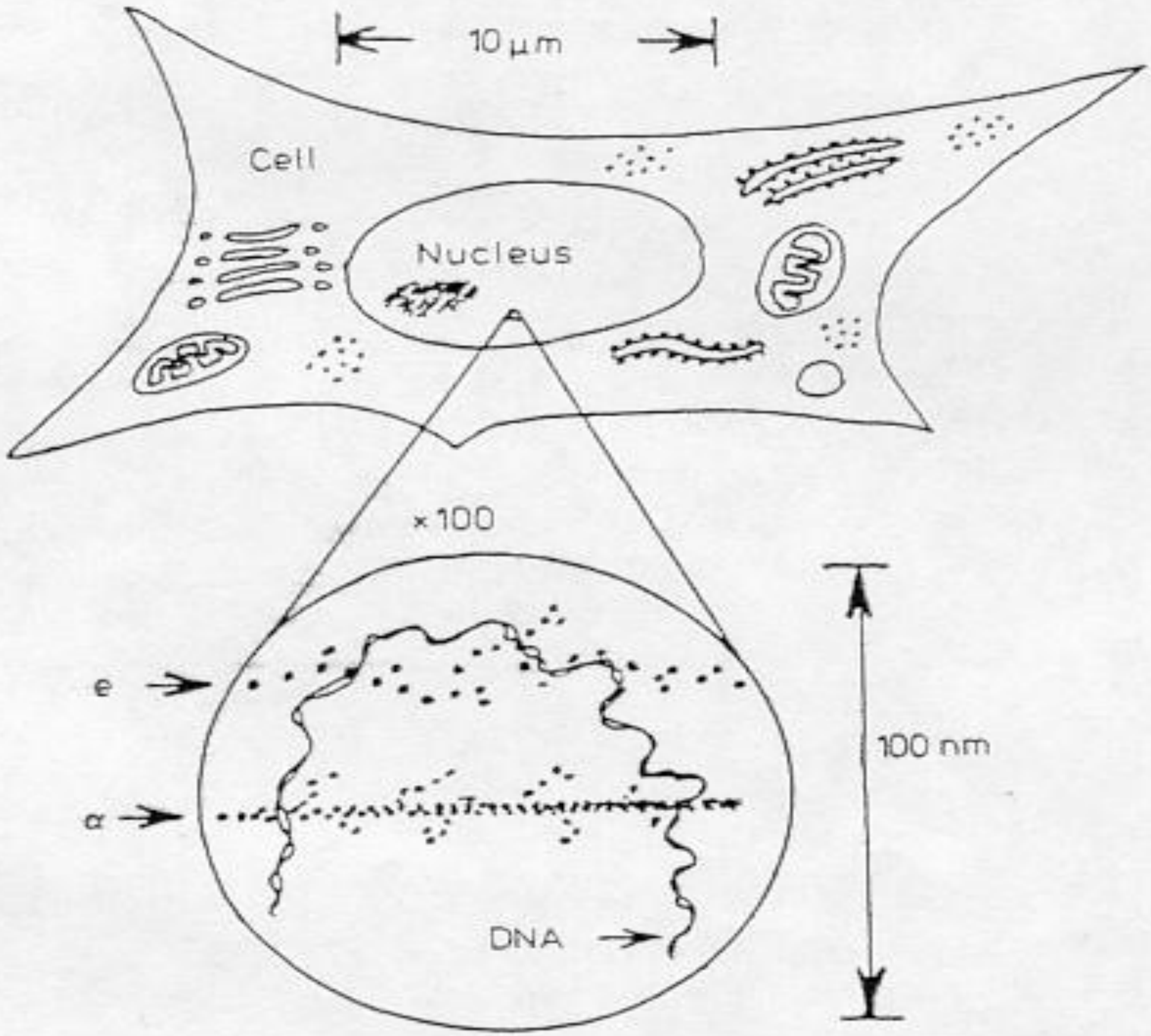
n = electronic density of medium

v = projectile velocity ($v^2 = 2E/m$)

High LET implies High RBE (Relative Biological Effectiveness)

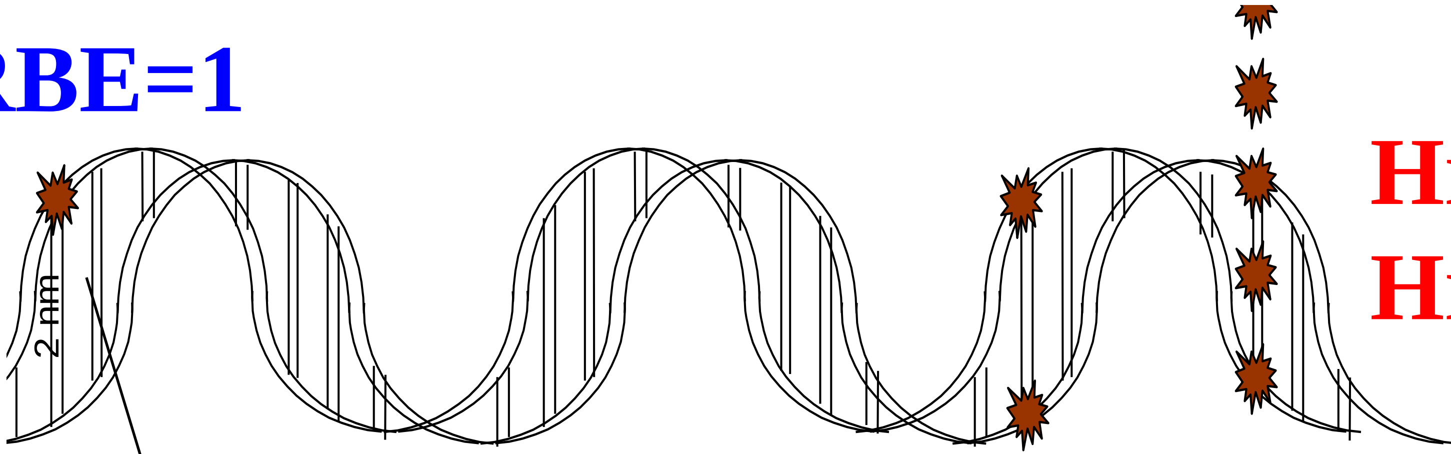


Tracks of e^-, p, C and pions. One observes the straight trayectory for the heavy particles and the Bragg peak (higher density on track) as a function of the ion charge.


10 µm
Cell
Nucleus
×100
e
α
100 nm
DNA

Low LET

RBE=1



High LET

High RBE

Scheme of DNA double helix, showing a single strand break, a double strand break and the effect of radiation of even larger ionization density (complex damage).

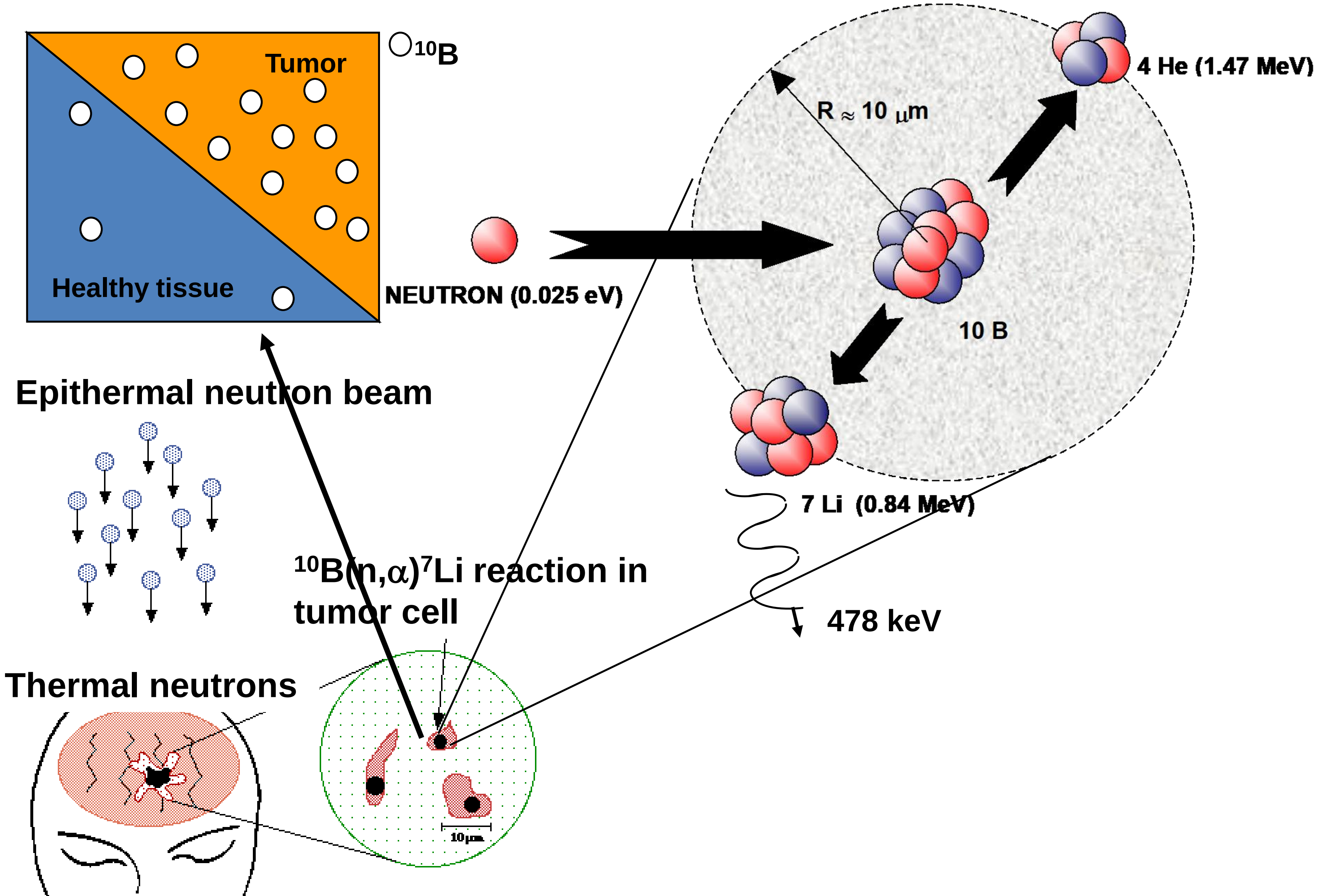
Boron Neutron Capture Therapy (BNCT)

When the tumor is spatially not well defined, i.e. , it has diffuse limits and regions with partial infiltration, a more sophisticated strategy is needed.

1. Selective tumor loading with a neutron capture agent (e.g., ^{10}B). Boron carrier BPA.

2. Irradiation with neutrons. $^{10}B(n,\alpha)^{7}Li$ (high LET/RBE).

With this "binary" approach a cell level targeting may be achieved.



$^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He$ (94%) Q = 2.31 MeV

(γ de 478 keV)

Why Accelerator Based (AB)-BNCT?

- **The advancement of BNCT requires neutron sources suitable for installation in hospital environments.**

  The presence of these devices in specialized cancer centers may be decisive for the future of BNCT:

  HOSPITAL SITING

- **Accelerators offer a number of other major advantages over reactor-based sources for clinical applications:**

  No permanent radioactivity inventory.

  Lower costs.

  Easier licensing.

Active AB-BNCT programs worldwide

1. Japan (x7): Tsukuba, National Cancer Center-Tokyo, Minami-Tohoku, Kyoto,..

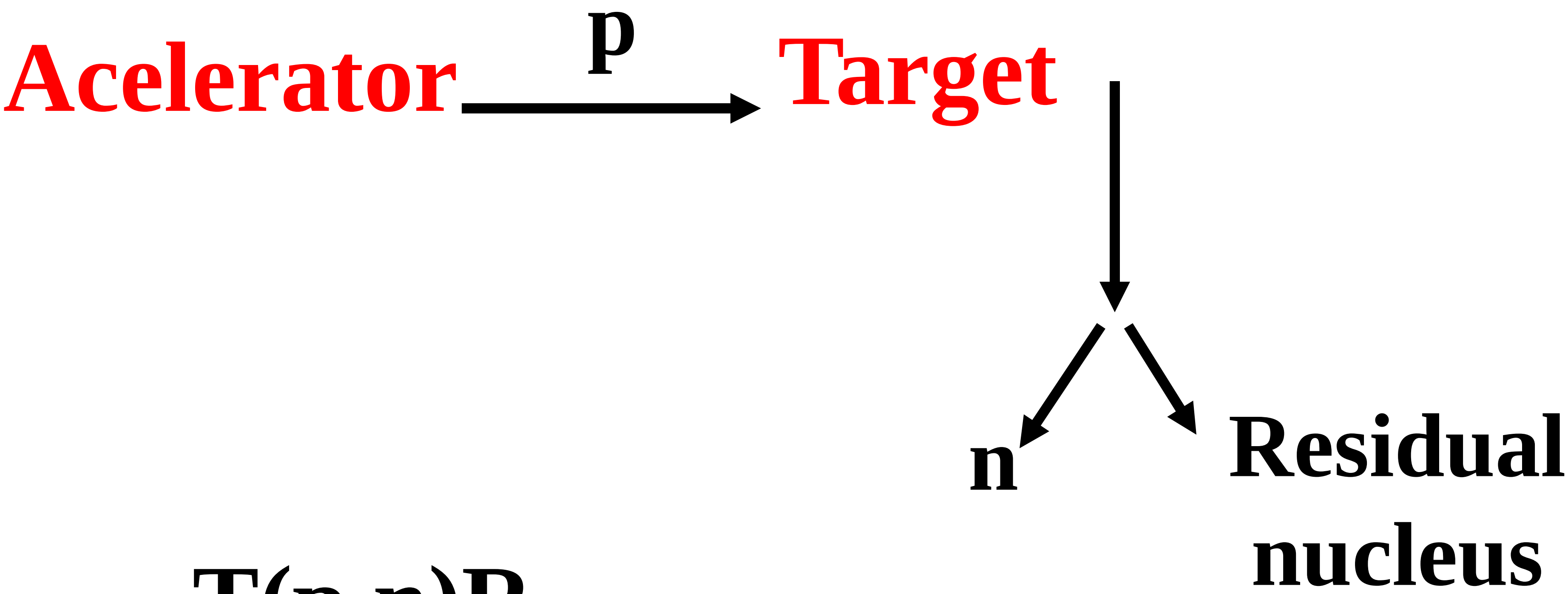
2. Russia: BINP, Novosibirsk .

3. Italy: LNLegnaro & Pavia, INFN-CNAO.

4. Argentina: CNEA.

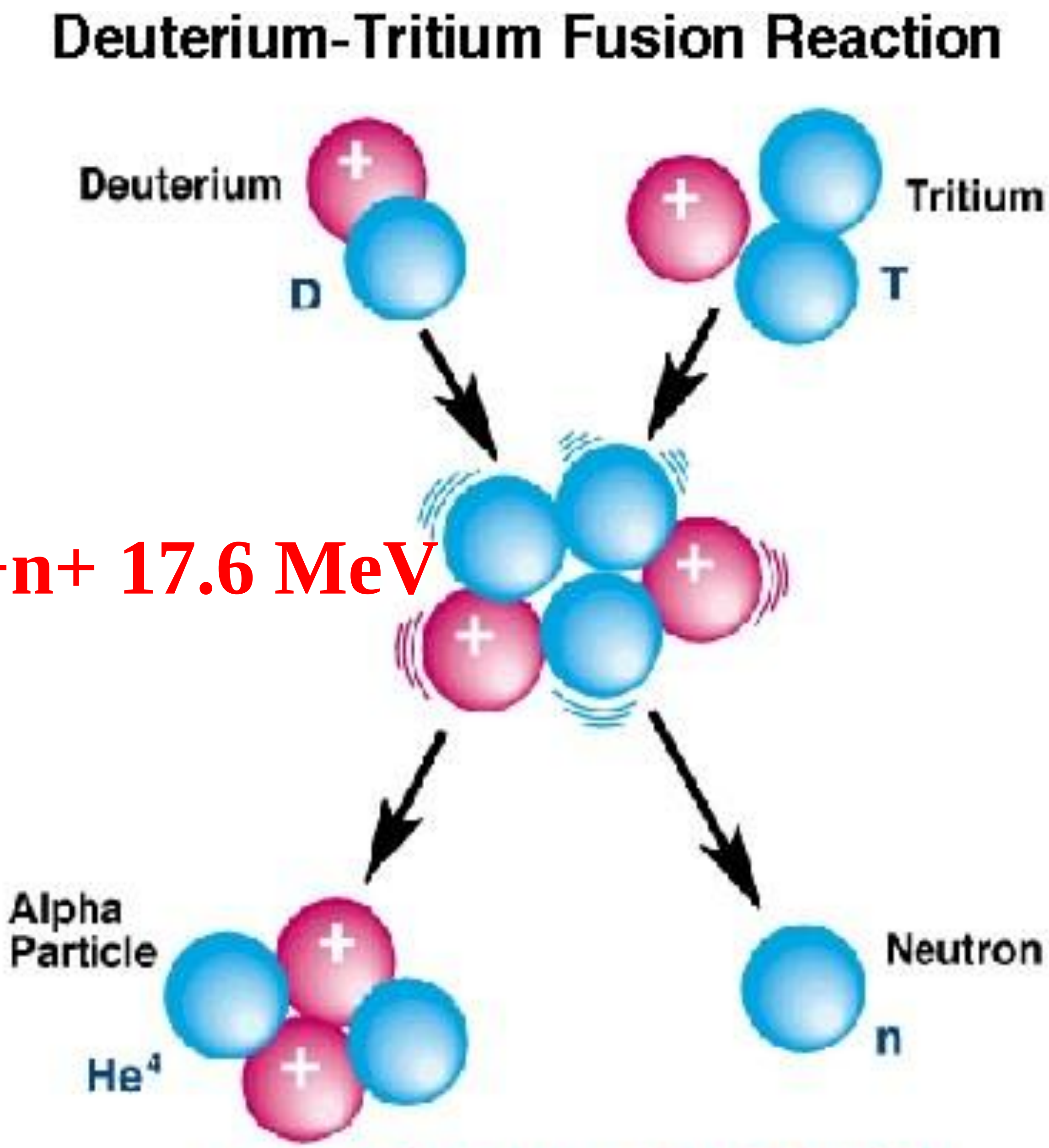
5. Finland (NT). 6. Israel: Soreq-SARAF.

7.China 8.France 9.UK 10. Corea



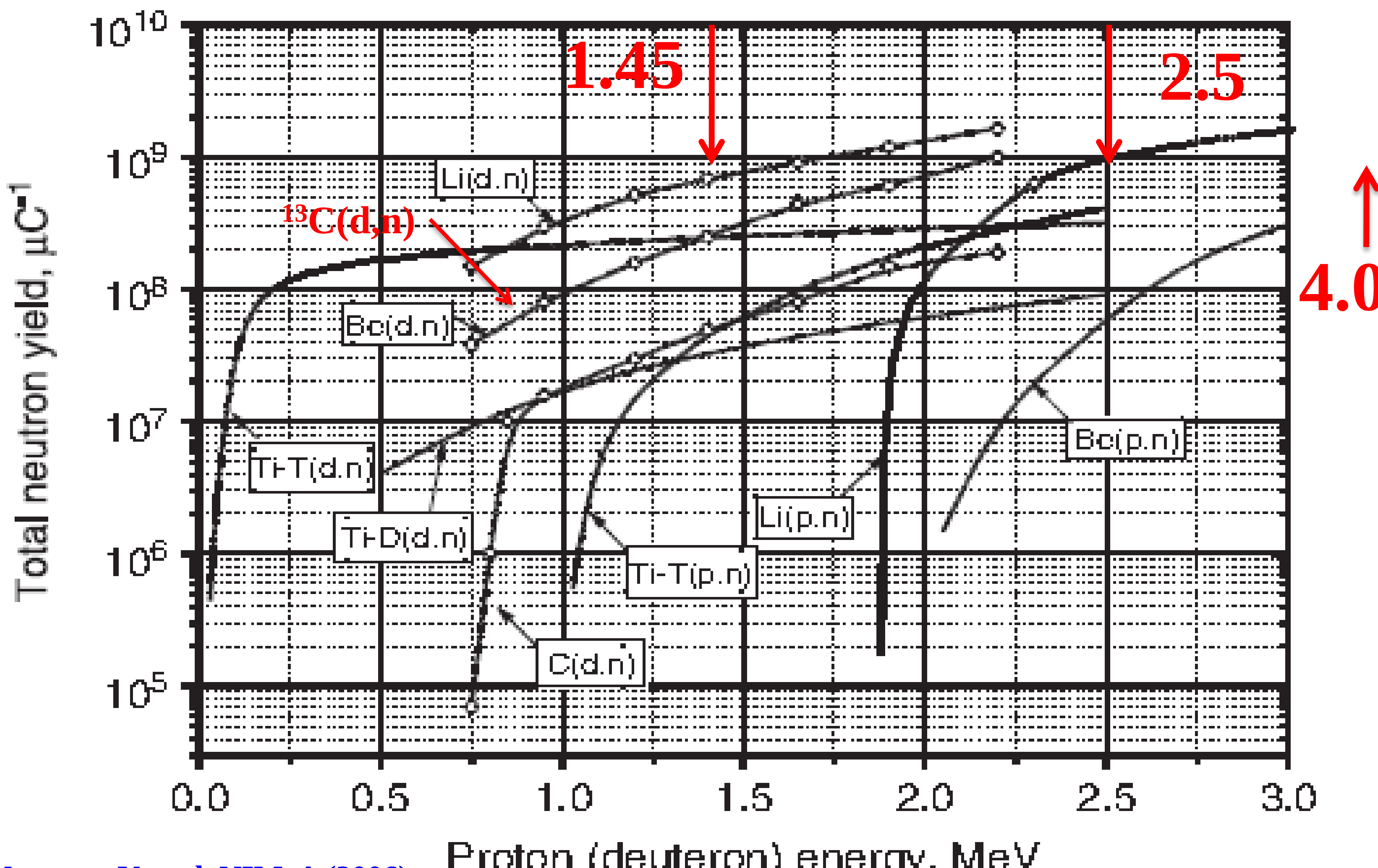
T(p,n)R

Fusion reaction



$$D + T \rightarrow \alpha + n + 17.6 \text{ MeV}$$

Neutron producing reactions



Kononov V et al. NIM. A (2006)

Nuclear reactions & materials

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

[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.

A detailed study of reactions induced by deuterons: $^{9}Be(d,n)^{10}B$ and $^{13}C(d,n)^{14}N$ as neutron sources for the treatment of deep seated tumors.

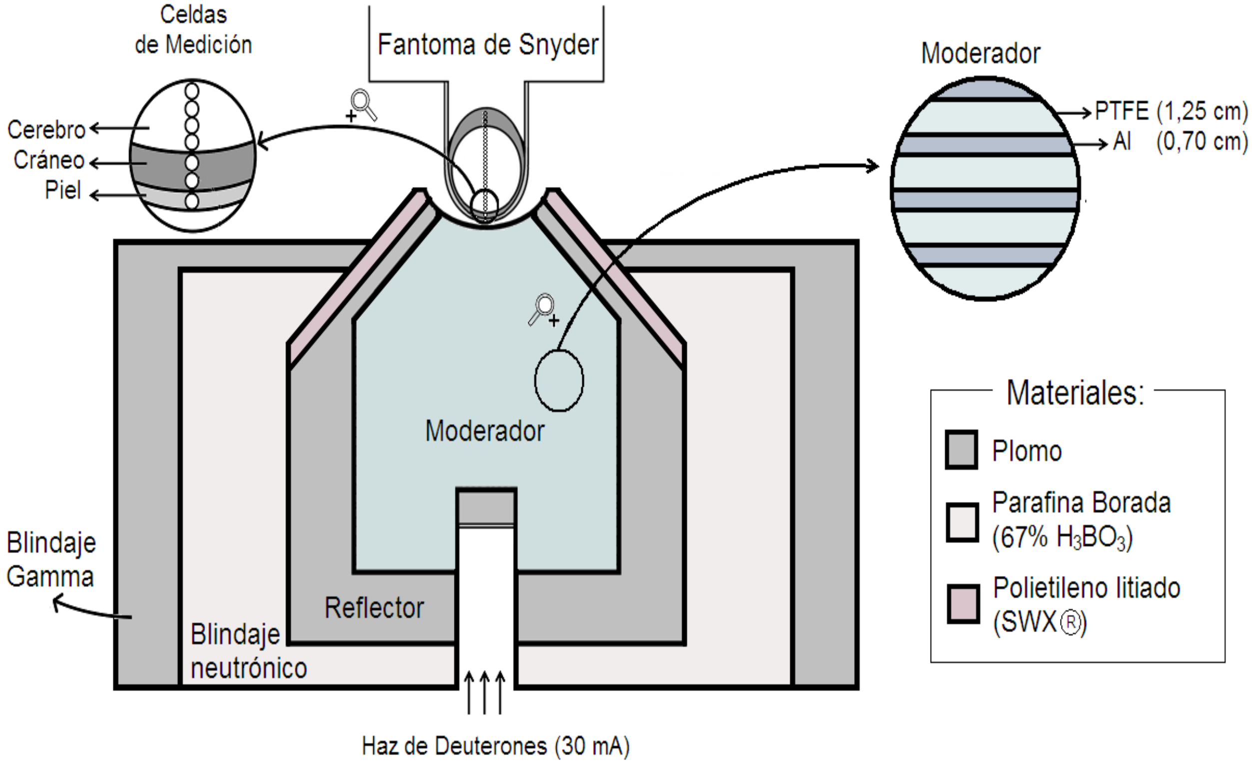
***Computational assessment of deep-seated tumor treatment capability of the $^{9}Be(d,n)^{10}B$ reaction for AB-BNCT*, Physica Medica (Europ. Journal Med. Phys.), 30 (2014) 133-146.**
M.E. Capoulat, D.M. Minsky, and A.J.Kreiner
PhD Thesis M. E. Capoulat.

***A 13C(d,n)-based epithermal neutron source for Boron Neutron Capture Therapy*, Physica Medica 33 (2017) 106–113, M.E. Capoulat, A.J. Kreiner.**

Neutron beam shaping assembly

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, ^{6}Li, ^{10}B

Neutron reflector:
Lead, graphite

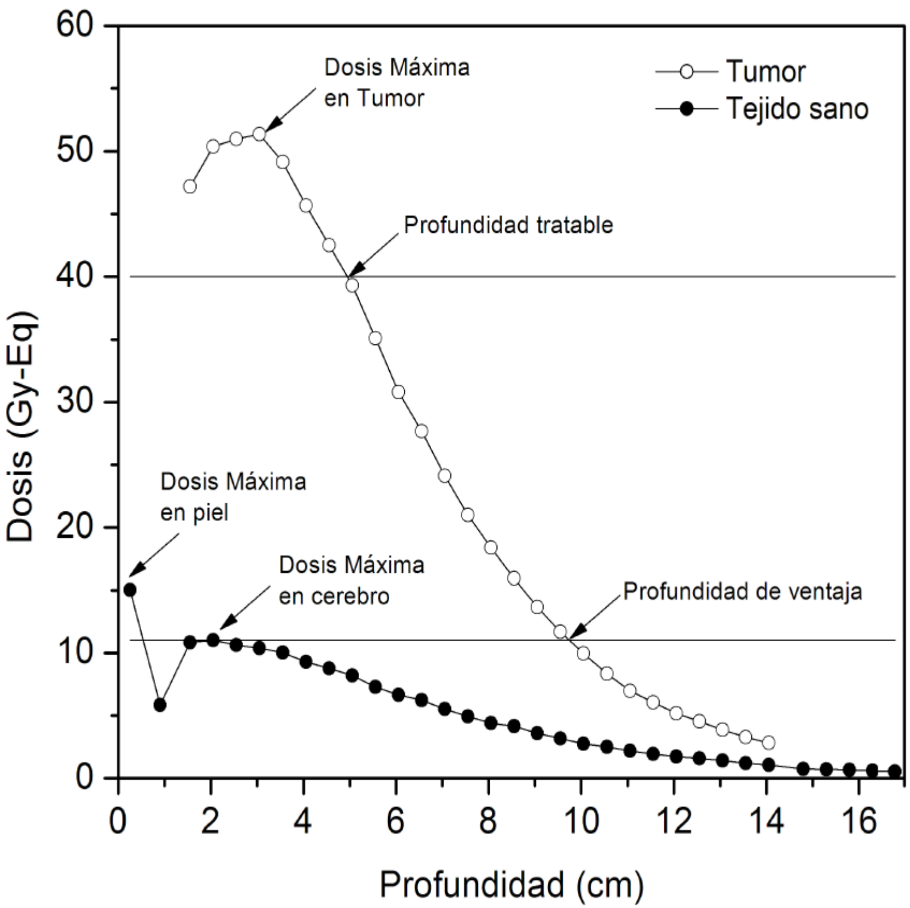
Neutron shielding:
Hidrogenous materials, polyethylene, paraffin

Gamma shielding
High Z materials, Lead.

Beam shaping assembly for ^{9}Be(d,n)

Optimization

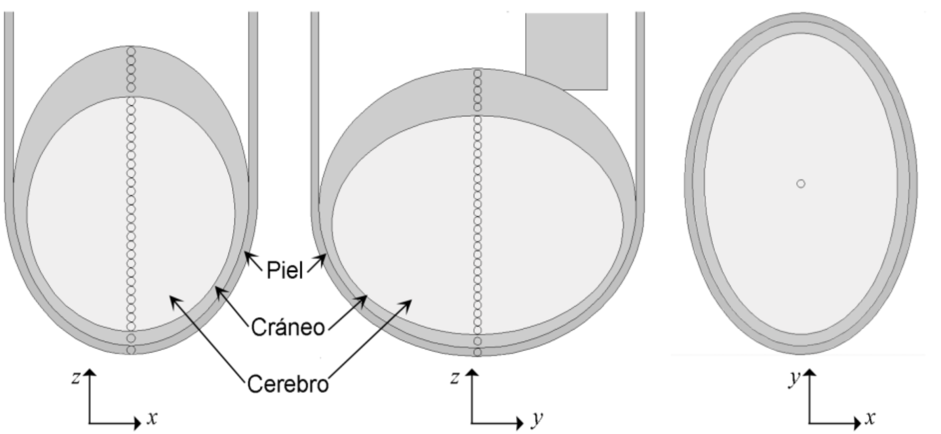
Section (D) and length(L) of moderator were optimized for different configurations using the MCNP code.



Depth dose profile in Snyder phantom.

Optimization Criteria:

- **Maximize tumor dose**
- **Treatment time:** $\leq$ ***60 min***
- **Skin dose:** $\leq$ ***16.7 Gy-Eq***
- **Healthy brain dose:**$\leq$ ***11.0 Gy-Eq***

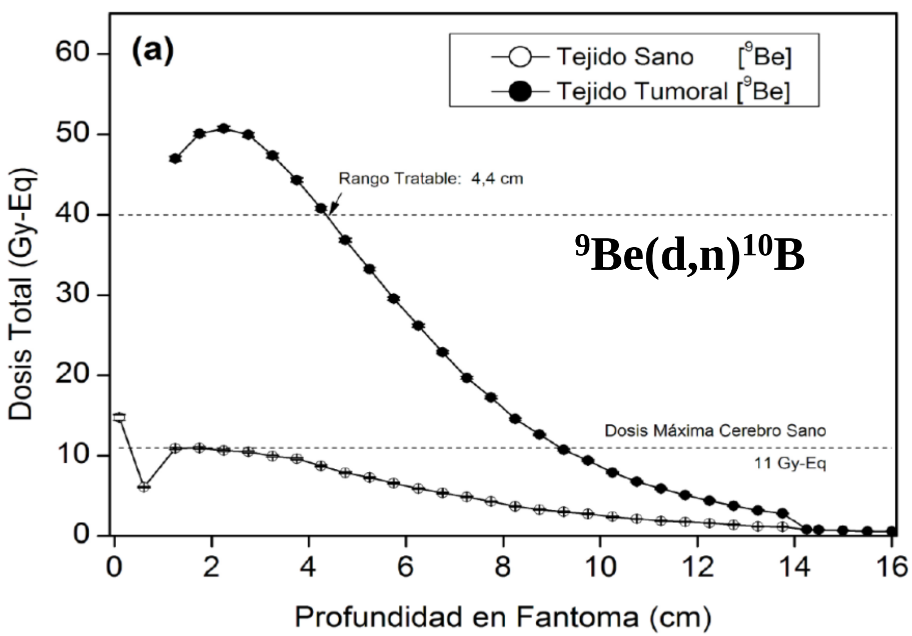


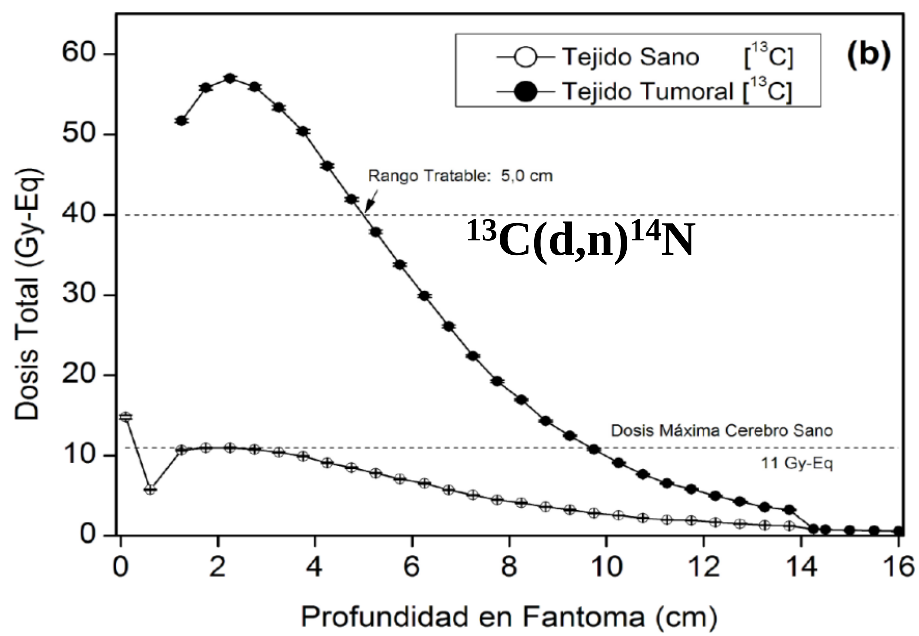
Optimal configurations
$^{13}C(d,n)^{14}N$ & $^{9}Be(d,n)^{10}B$

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

✓ **Dose profiles:**





Development of a Tandem-Electrostatic Quadrupole for BNCT y other types of accelerators.

M. Baldo[1], J. Bergueiro[1], M.E. Capoulat[1,2,3], D. Cartelli[1,2,3], J. Padulo[1], J.C. Suárez Sandín[1], M. Igarzabal[1], M.F. del Grosso[1,3], L. Gagetti[1,2,3], A.A. Valda[1,2], N. Canepa[1], N. Real[1], D.M. Minsky[1,2,3], G. Conti[1], J. Erhardt[1], M.E. Debray[1,2], H.R. Somacal[1,2], A. Bertolo[1], D. Sosa Selaya [1], M. Gun[1], A. J. Kreiner [1,2,3]

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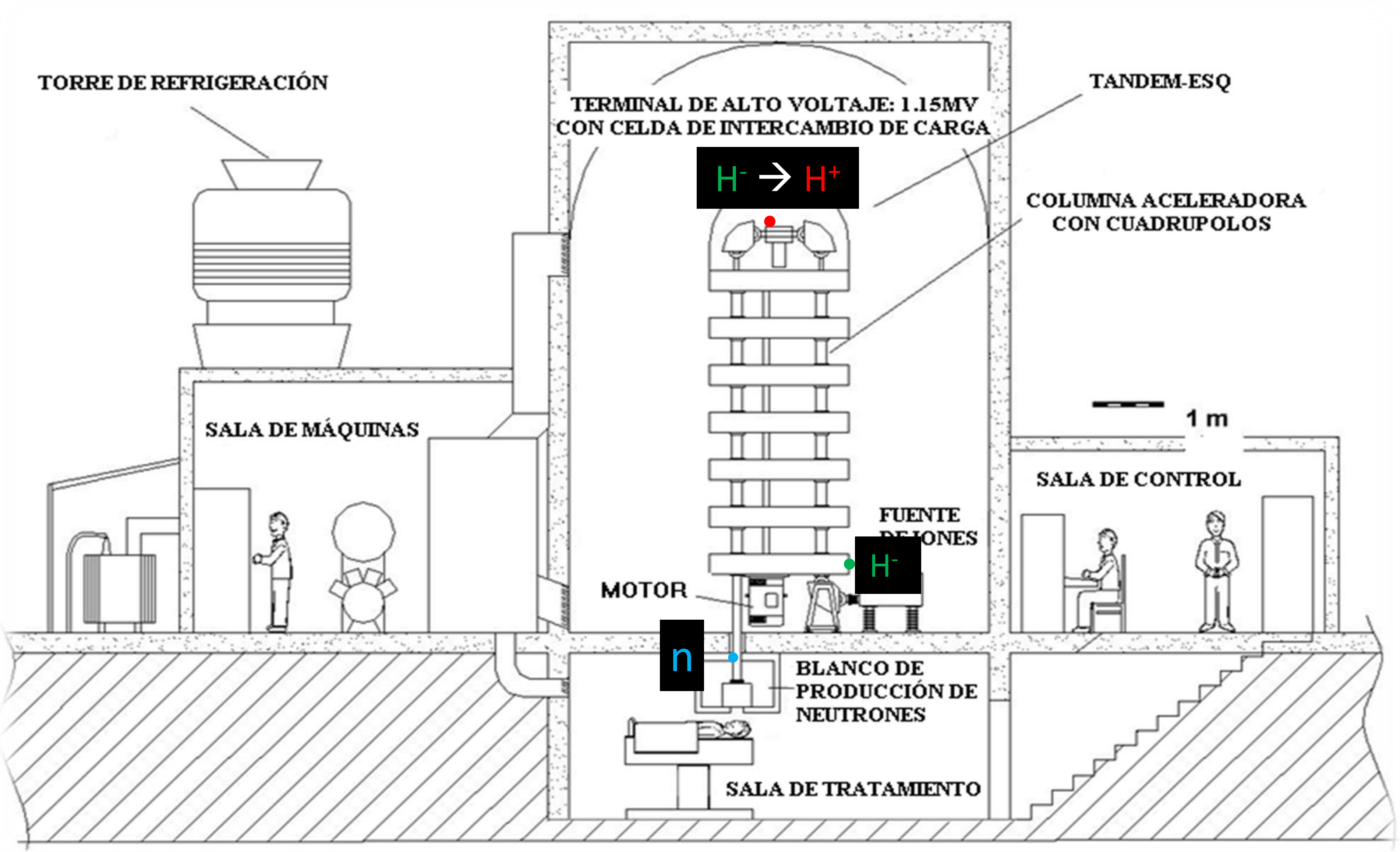
CHALLENGE: large currents

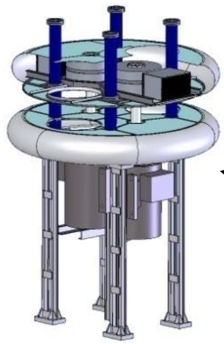
Appl. Rad. & Isotopes 69(12) (2011) 1672–1675, ARI 2013, 2015 & refs therein.

General layout of facility (see Applied Radiation and Isotopes 67 (2009) S266–S269).



Working areas

Mechanical Structure and Components of Module

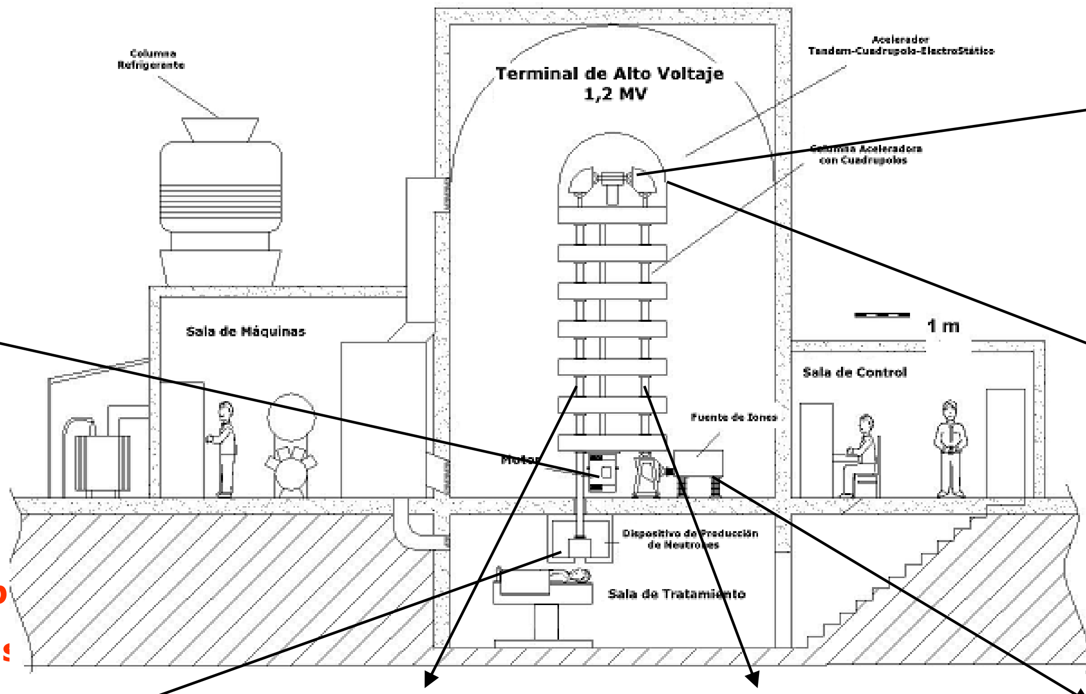


Generators

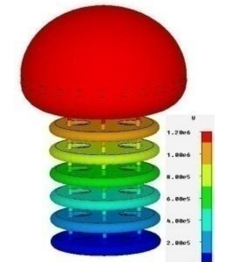
High voltage supp

Insulating Rotating s

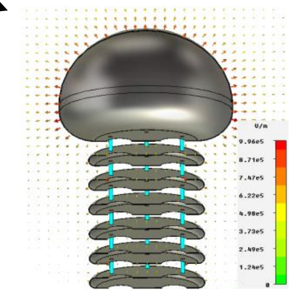
Insulating posts



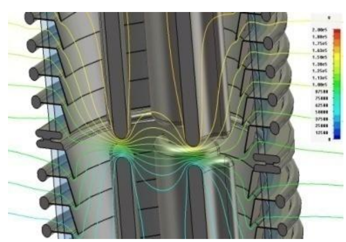
Electric Potential Distribution



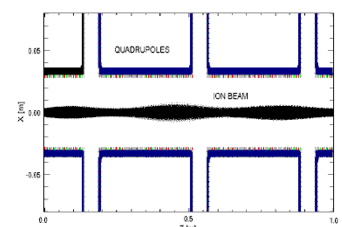
Electric Field Distribution



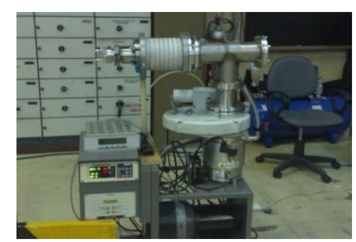
Neutron Production target and Beam Shaping Assembly



Accelerator tubes with Quadrupoles



Beam Transport Simulations



Ion Sources

Working areas

1. **Mechanical design and construction.**
   J.C. Suárez Sandín, M. Igarzábal, J.Erhardt, G. Conti, et al.

2. **Electronic/electromechanical design: High voltage supplies, transformers, etc. M. Baldo, N. Real, M. Gun** et al.

3. **Electrostatics, column, tubes & ion optic (transport of high intensity beams). D. Cartelli, N. Cánepa** et al.

4. **Cooling systems: J.C. Suárez S., M. Igarzábal**,et al.

5. **Vacuum Systems. M.E.Debray, J.C. Suárez Sandín, M. Igarzábal,**et al.

6. **Ion sources. J. Bergueiro, H.Somacal, J.C.Suárez Sandín, M. Igarzábal** et al.

Working areas (Cont.)

- **7. Neutron production targets (neutronics), beam shaping assembly, treatment room. M.E. Capoulat, D.Minsky, A.A. Valda,** et al.

- **8. High power neutron production targets (thermomecanical and materials science & tech aspects).**

  L. Gagetti, M. del Grosso, A. Bertolo, J.C. Suárez Sandin et al.

- **9. Control systems. J. Padulo, M.Baldo** et al.

Working areas (Cont.)

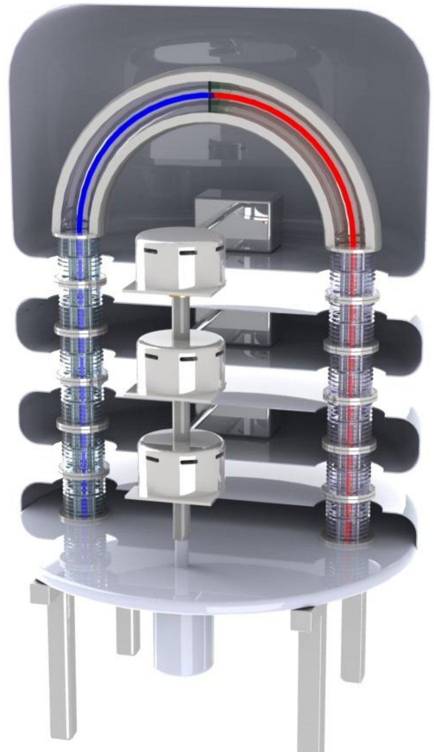
- **10. Licensing, radiation protection: A. A.Valda, M.E. Capoulat, D.Sosa et al.**

- **11. Treatment planning: M. Herrera, S. J. Gonzalez, D.M. Minsky, M.E.Capoulat et al.**

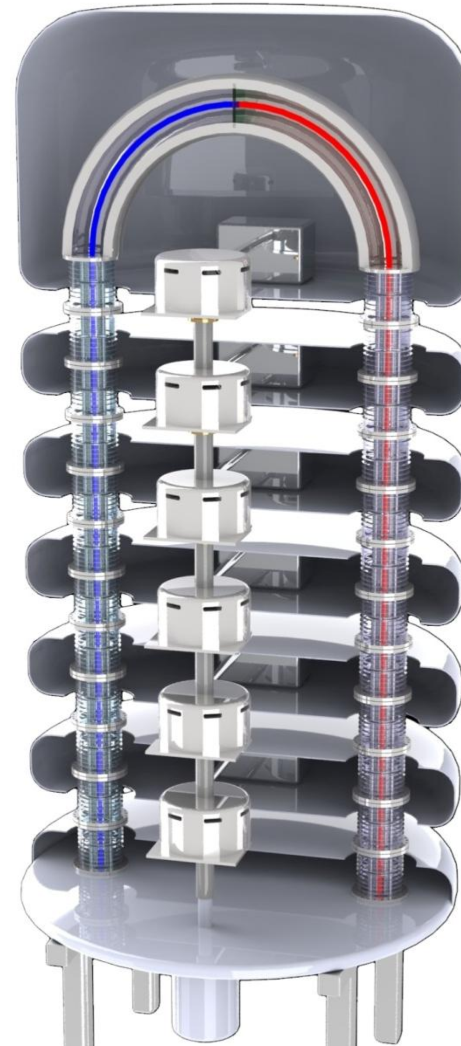
- **12. Development of a SPECT (Single Photon Emission Computed Tomography) : D.M. Minsky, A.A.Valda et al.**

Different accelerators under development

200 kV Accelerator



700 kV Tandem Accelerator



1.4 MV Tandem or single ended

200 kV accelerator completed

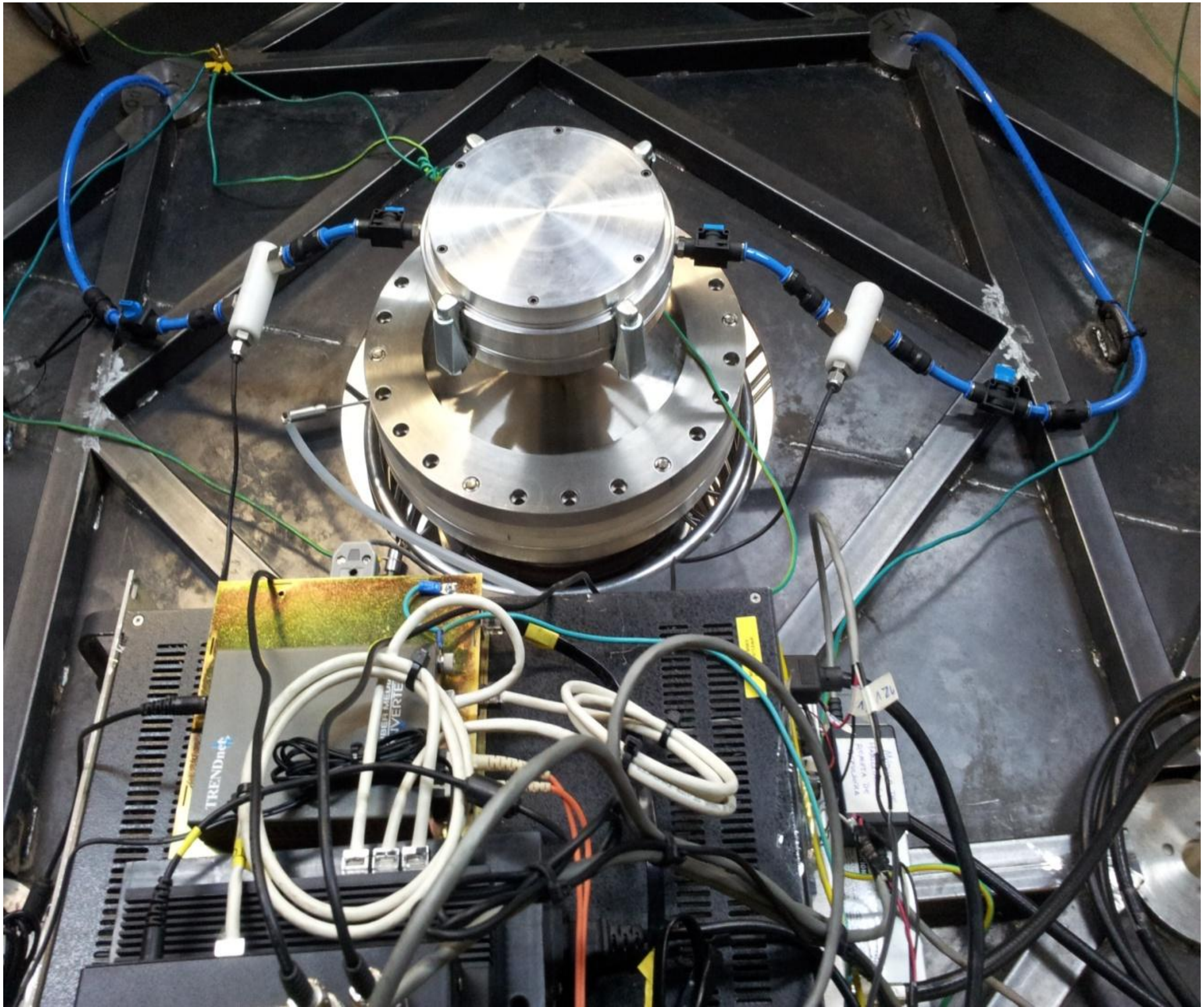
Mounting the tubes

Tubes installed & tested

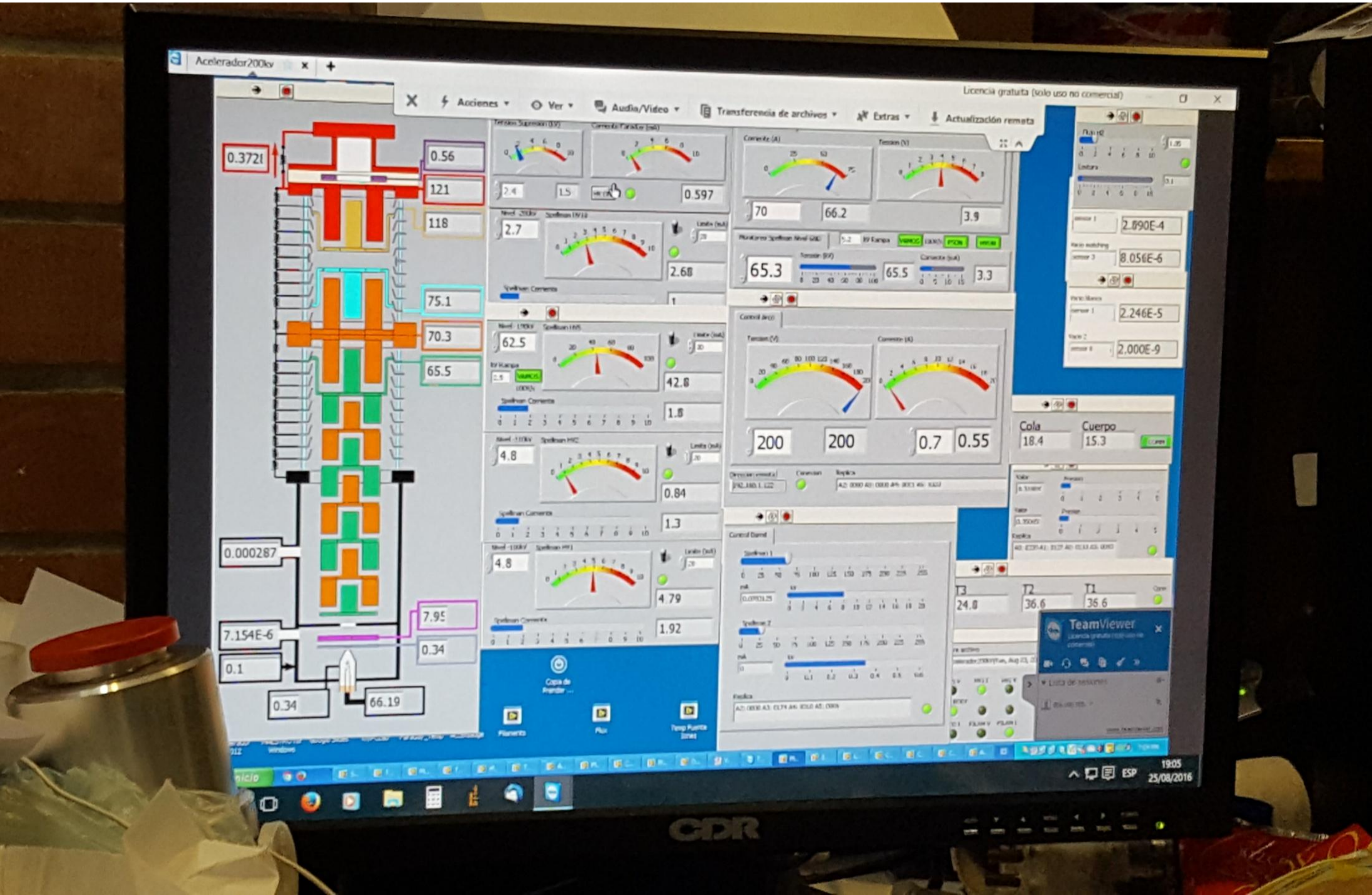
Accelerator with all systems mounted (HV, refrigeration, vacuum, control, ..)

Accelerator column with tubes in vacuum

Neutron production target (refr.)



<u>Control interface:</u> Javier Padulo et al

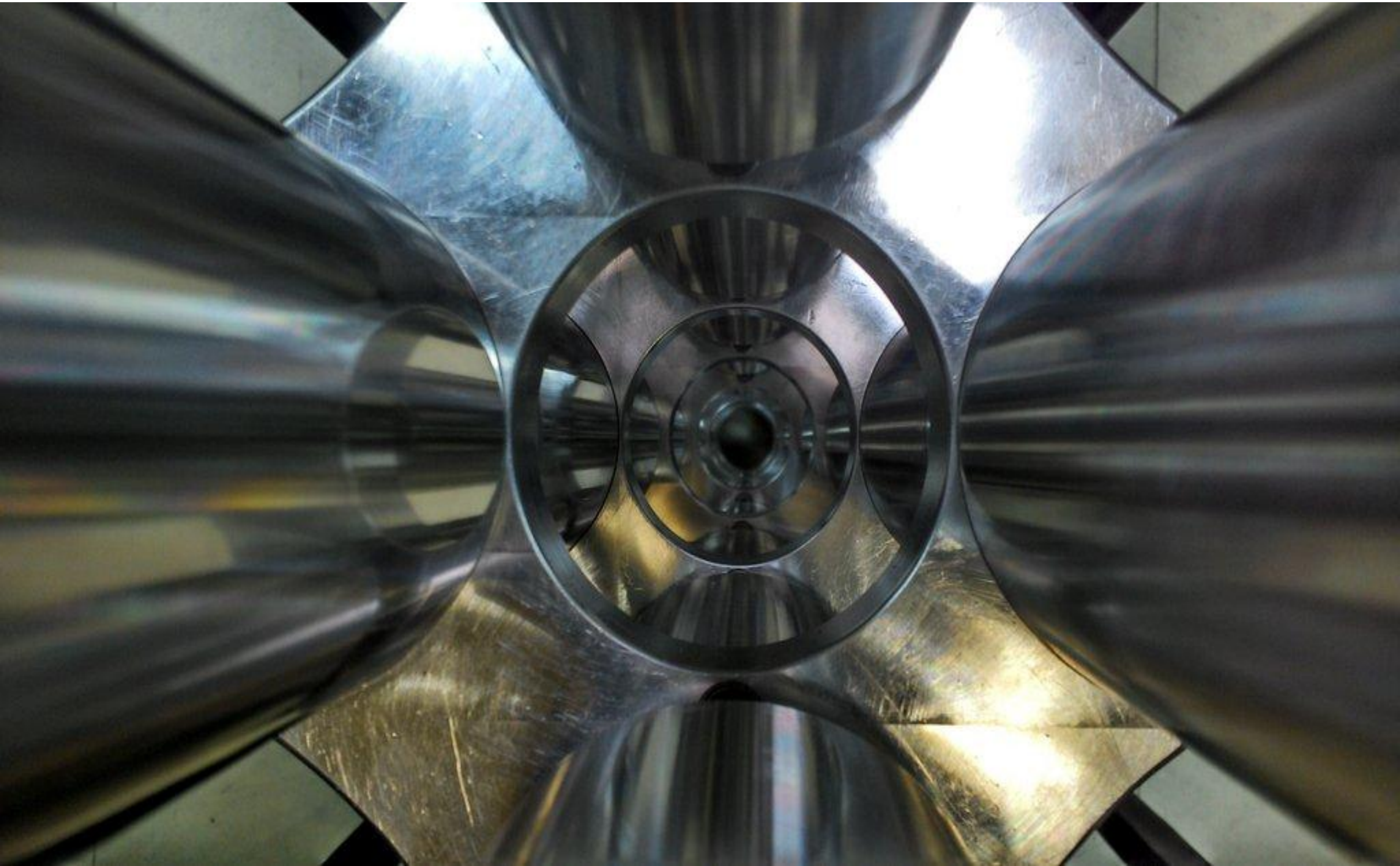


Accelerator tubes & quadrupoles for high currents & strong transverse focusing fields

Daniel Cartelli, N. Cánepa, J. Erhardt, M. Igarzabal, J.C. Suarez Sandín et al.

100 kV tubes, assembled & tested

Looking along the tube axis

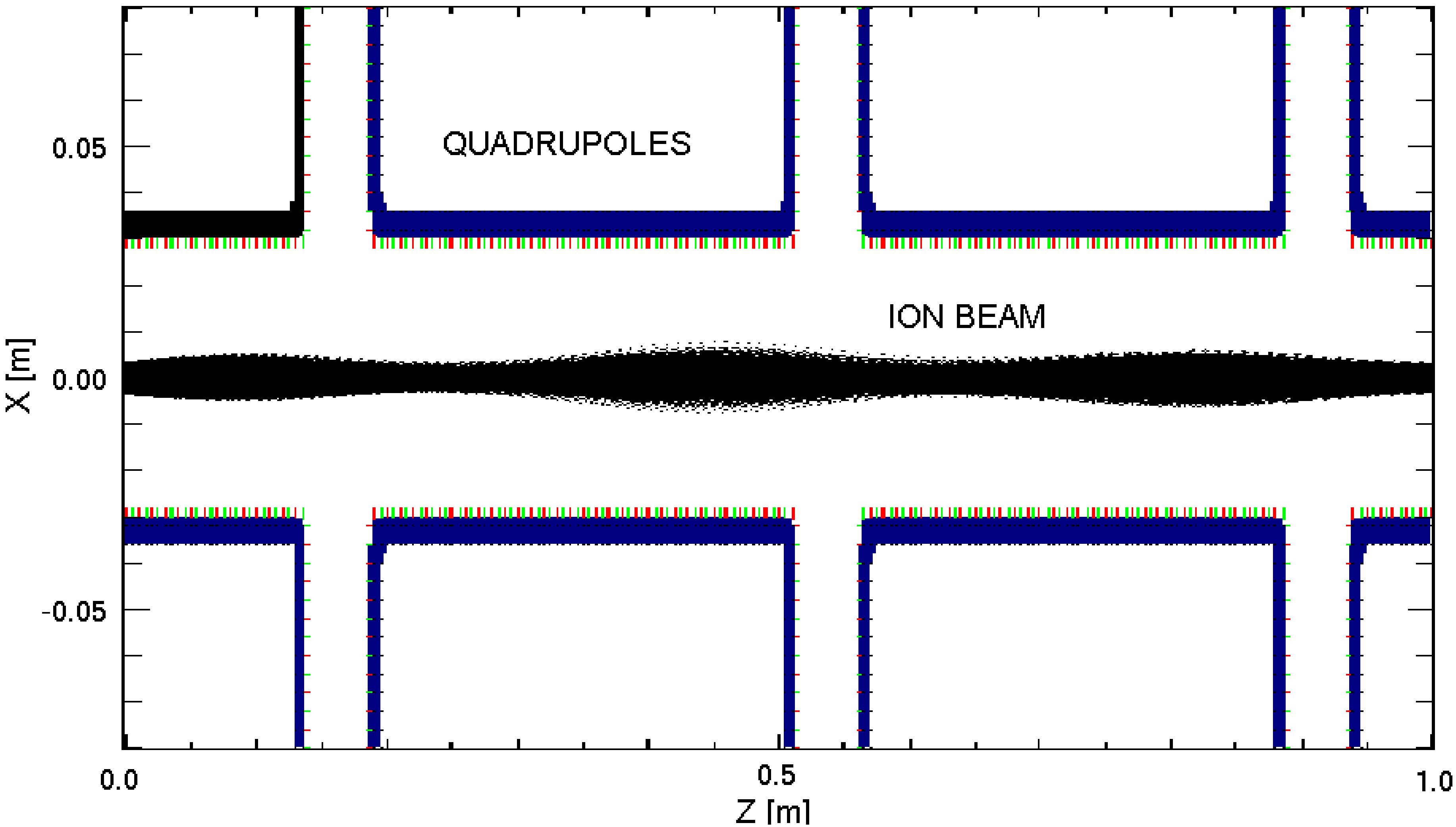


Lifting the tubes on the column

Ion optics (selfconsistent transport of high intensity beam with space charge)

Daniel Cartelli, N. Cánepa et al.

Transport of proton beam (30 mA)

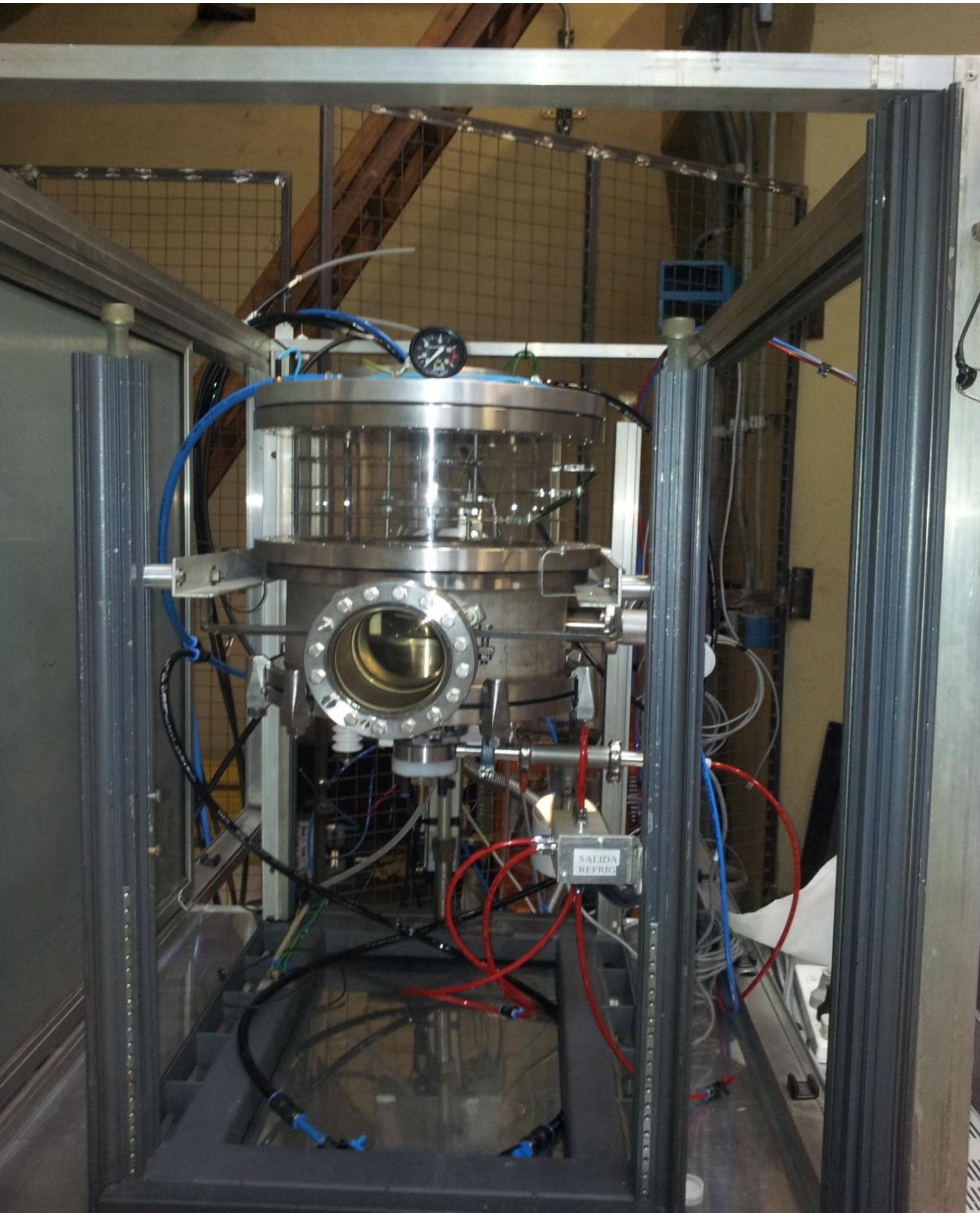


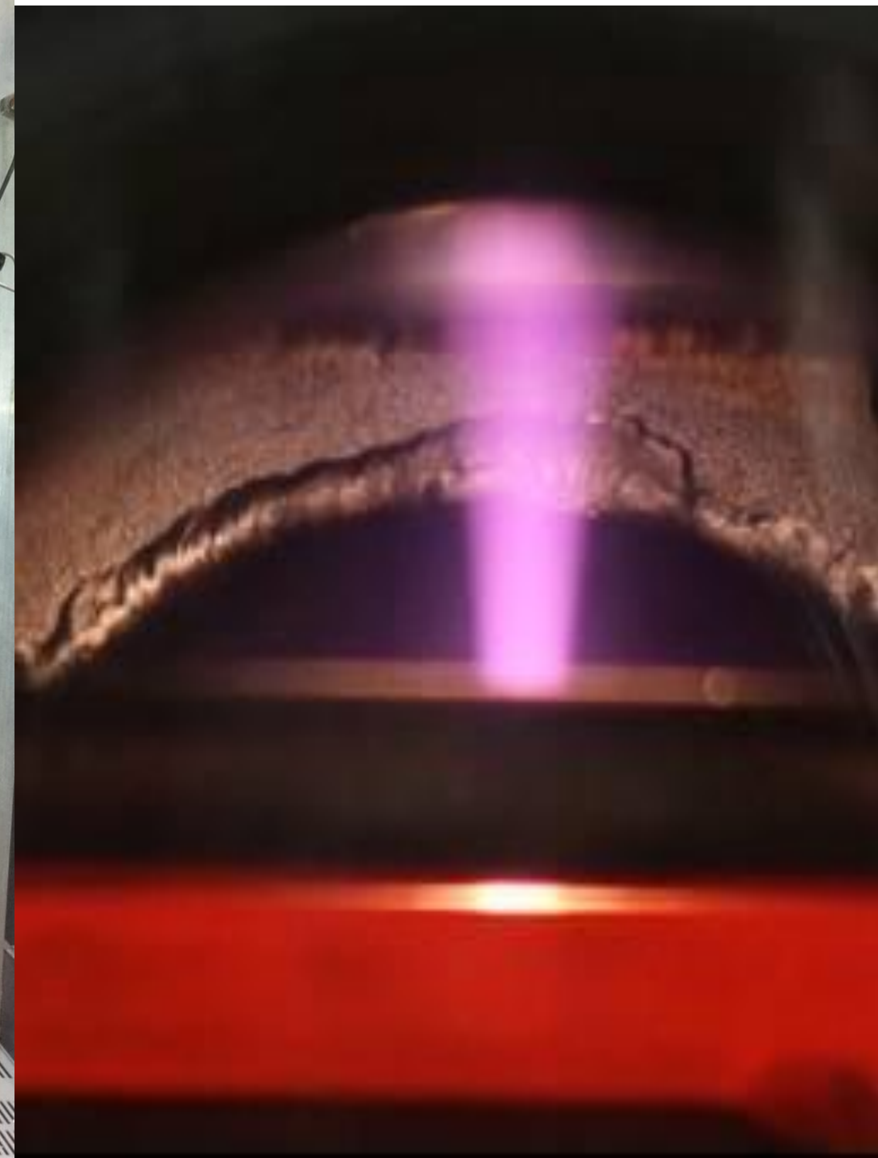
Ion source & injector: plasma volumen excited by filament.

J. Bergueiro, H.Somacal, M.Igarzabal, J.C.Suarez Sandin, et al.

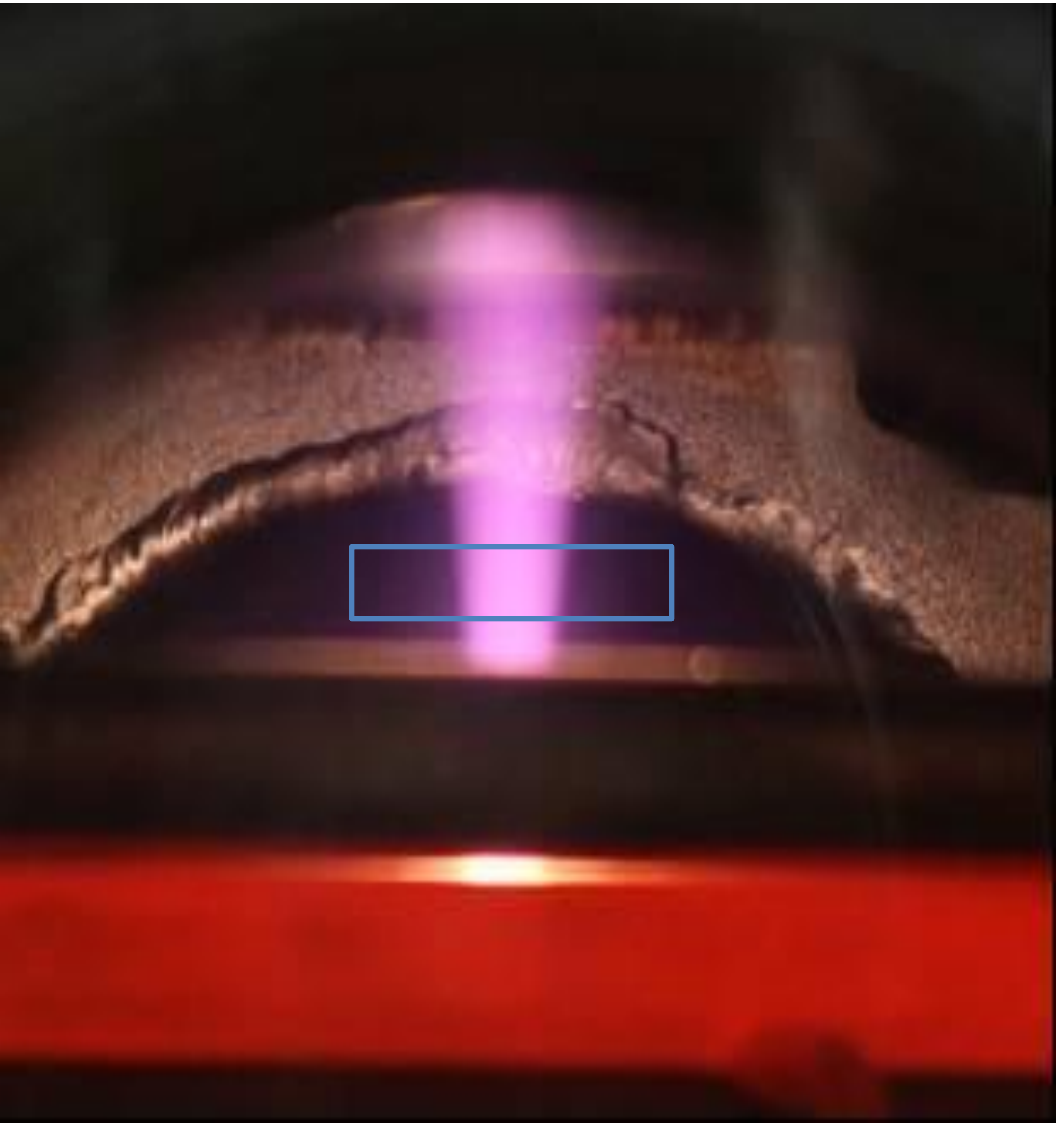
New high power ion source: ready

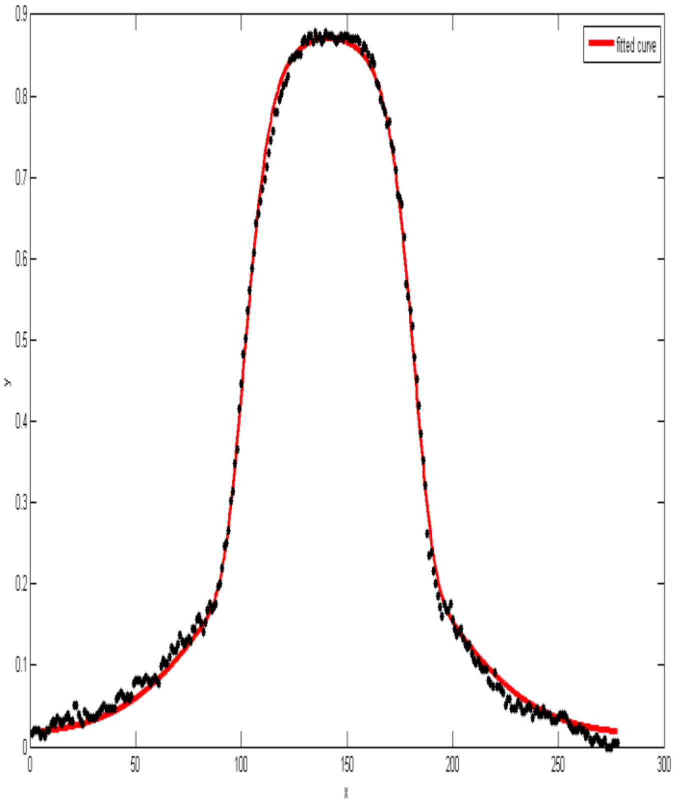
At the test stand: 30 mA proton beam



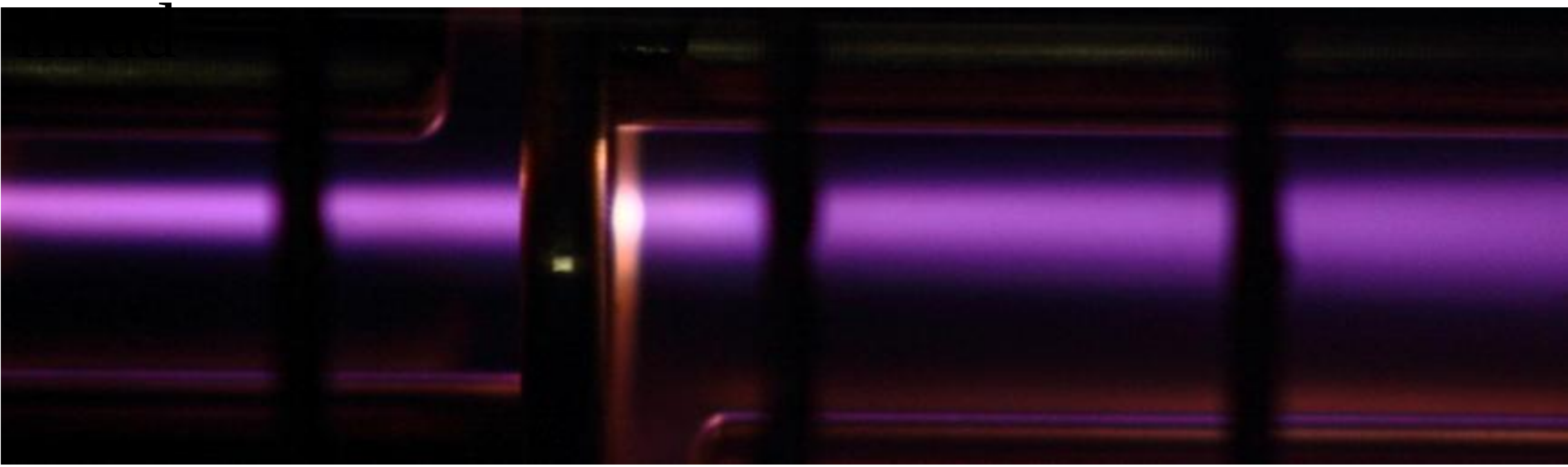


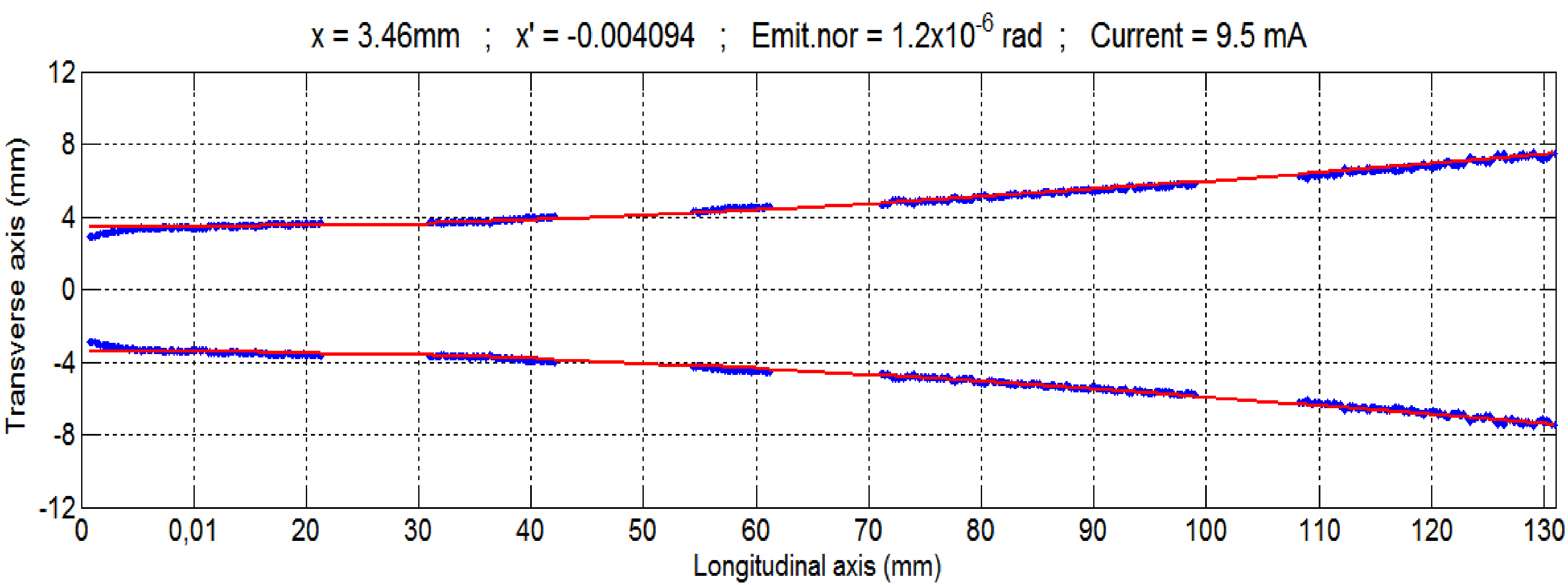
Beam shape analysis through induced fluorescence in residual gas



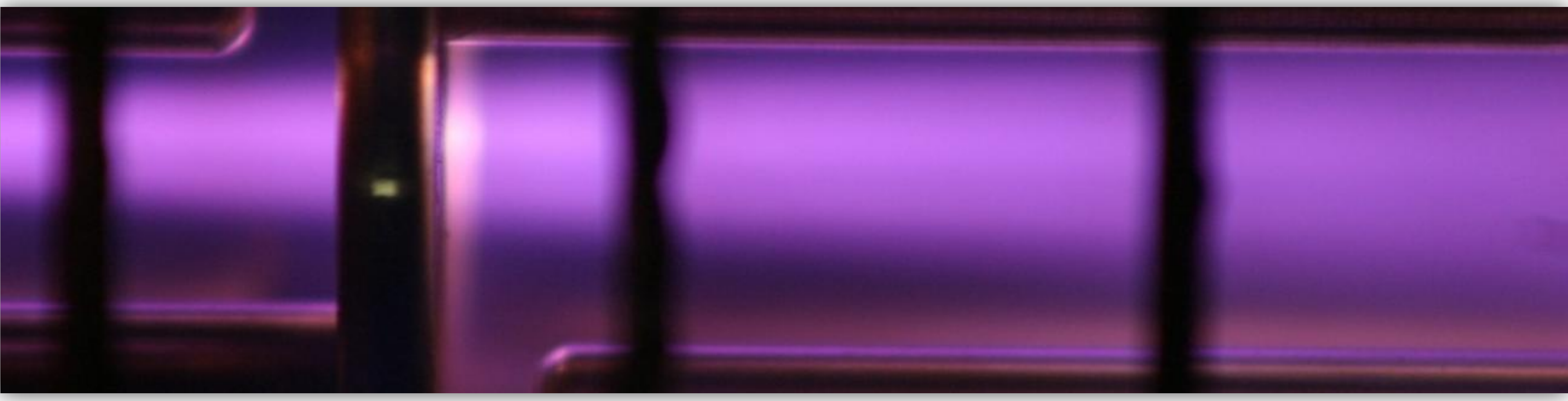


9.5 mA, Radius=3.5 mm; Emittance$_N$=0.38 π mm mrad

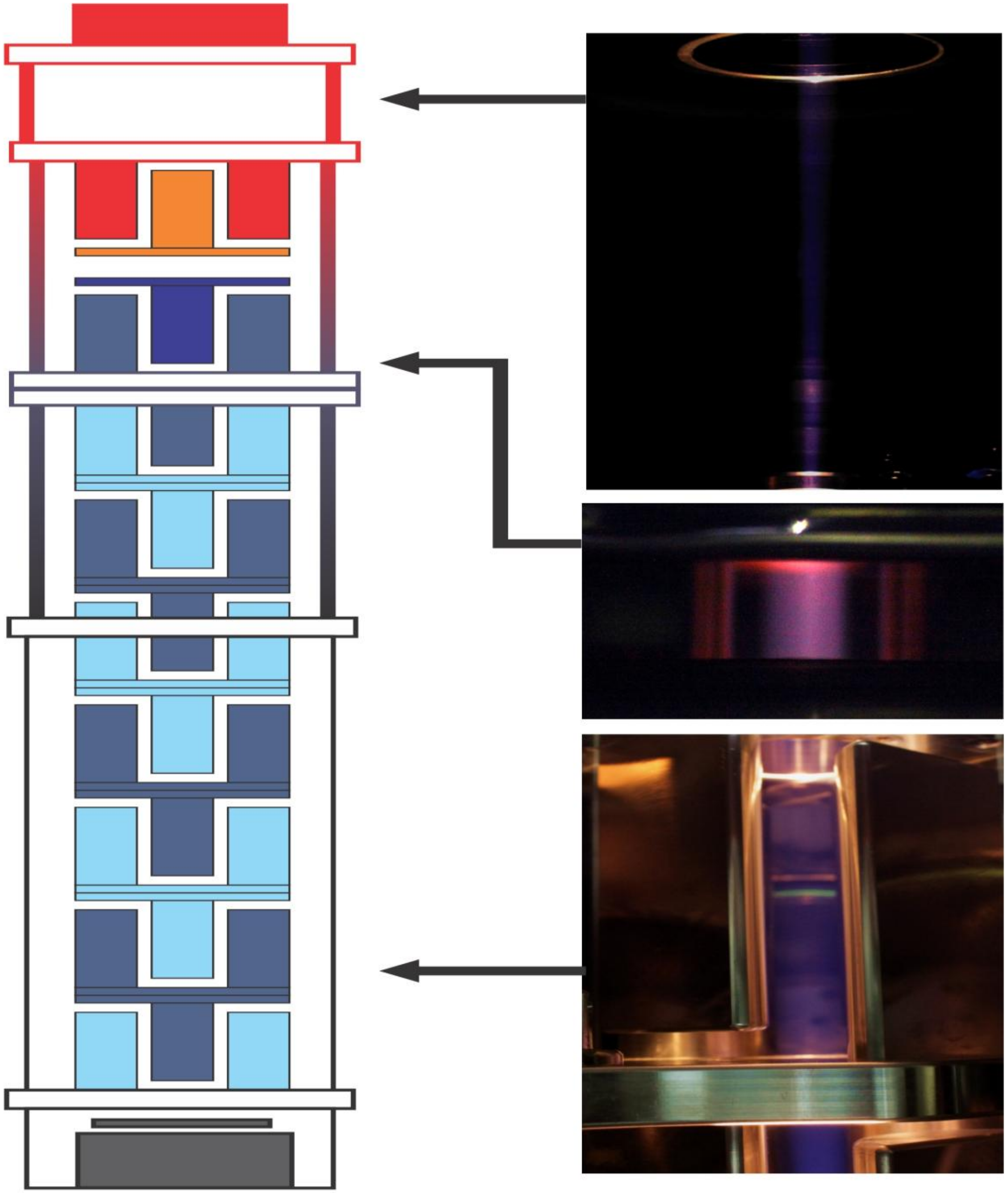




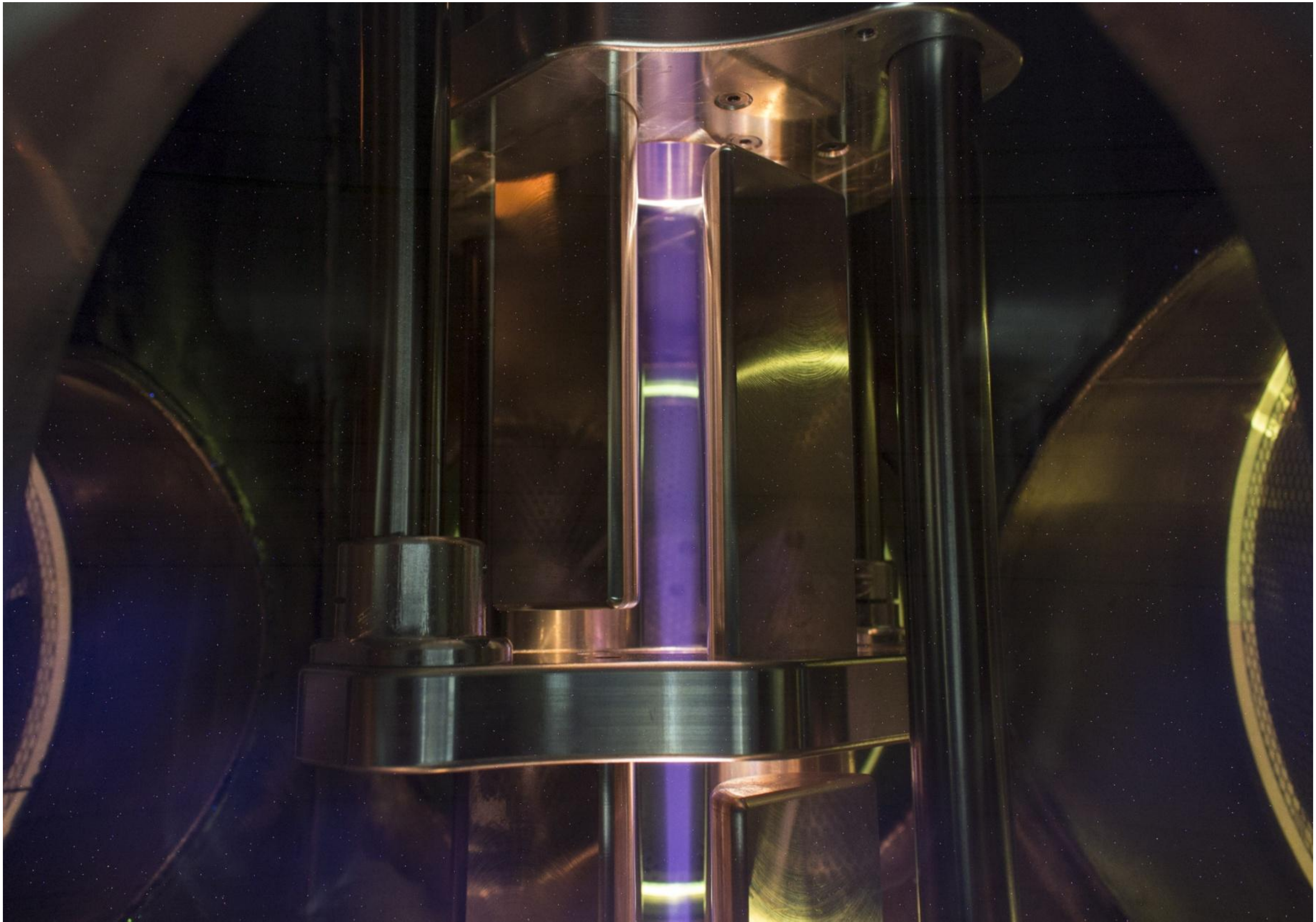
20.3 mA, Radius=6.3 mm; Emittan$_N$= 1.36 π mm mrad



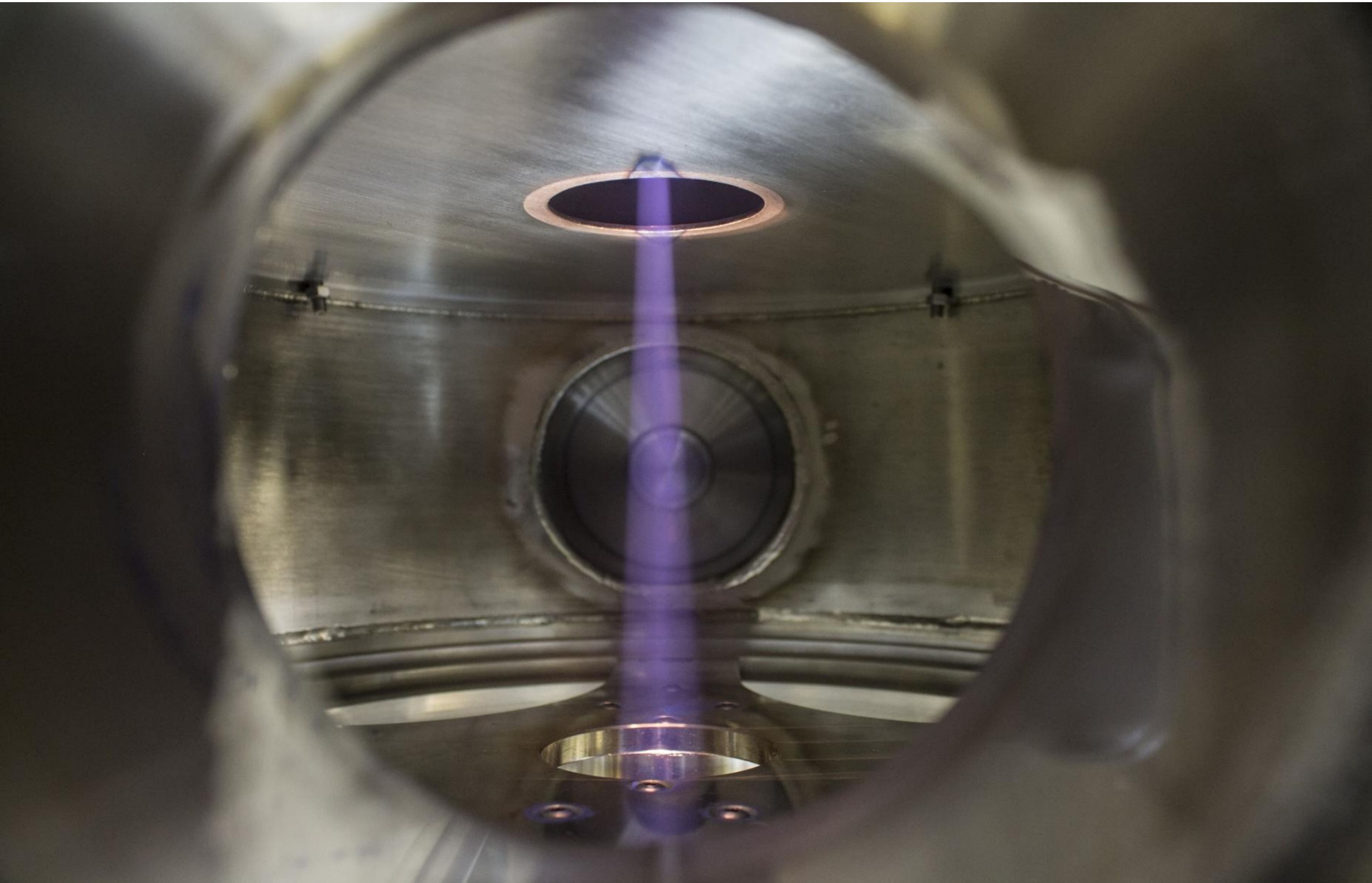
Images of beam through the accelerator

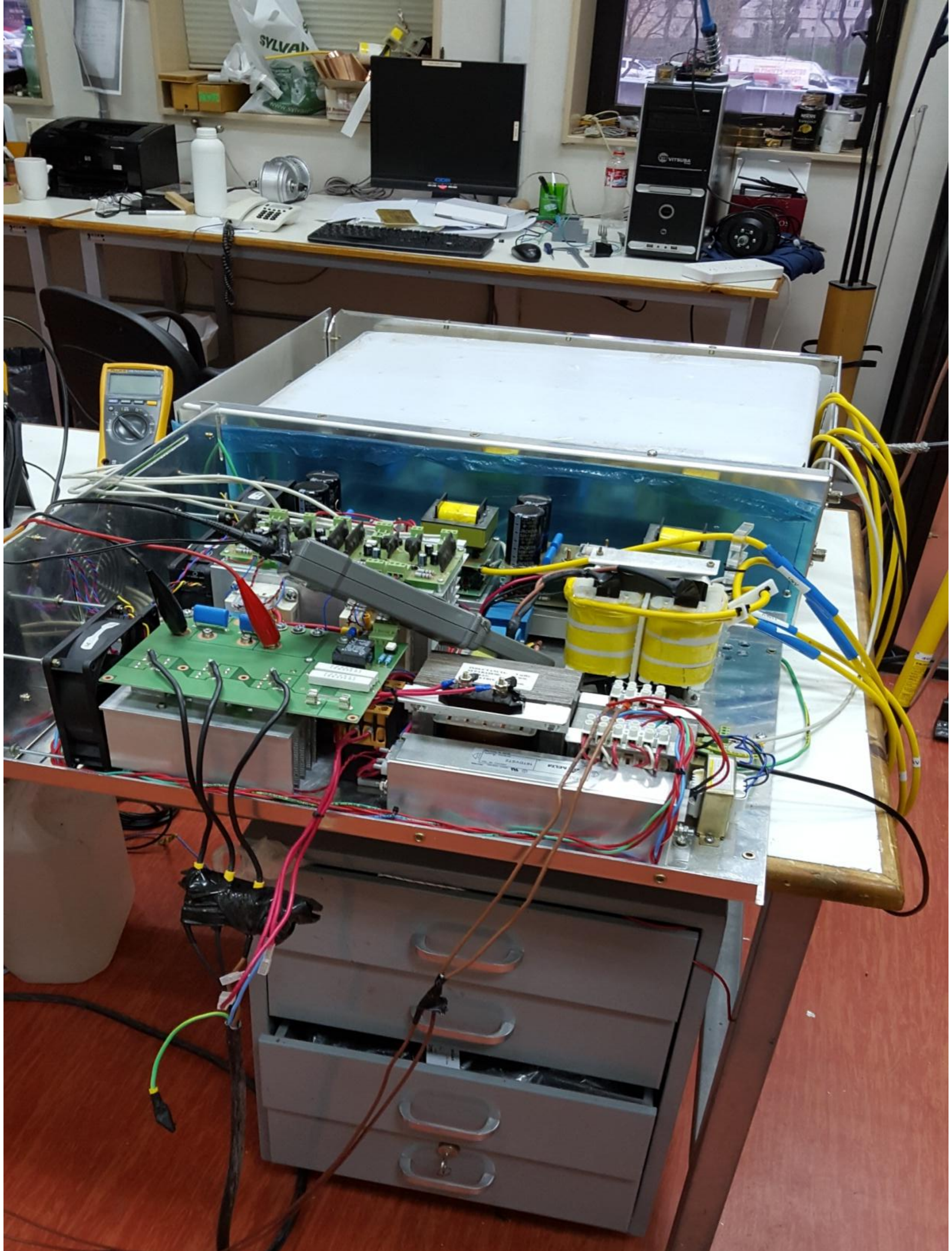


5-10 mA, lower chamber



5-10 mA, upper chamber

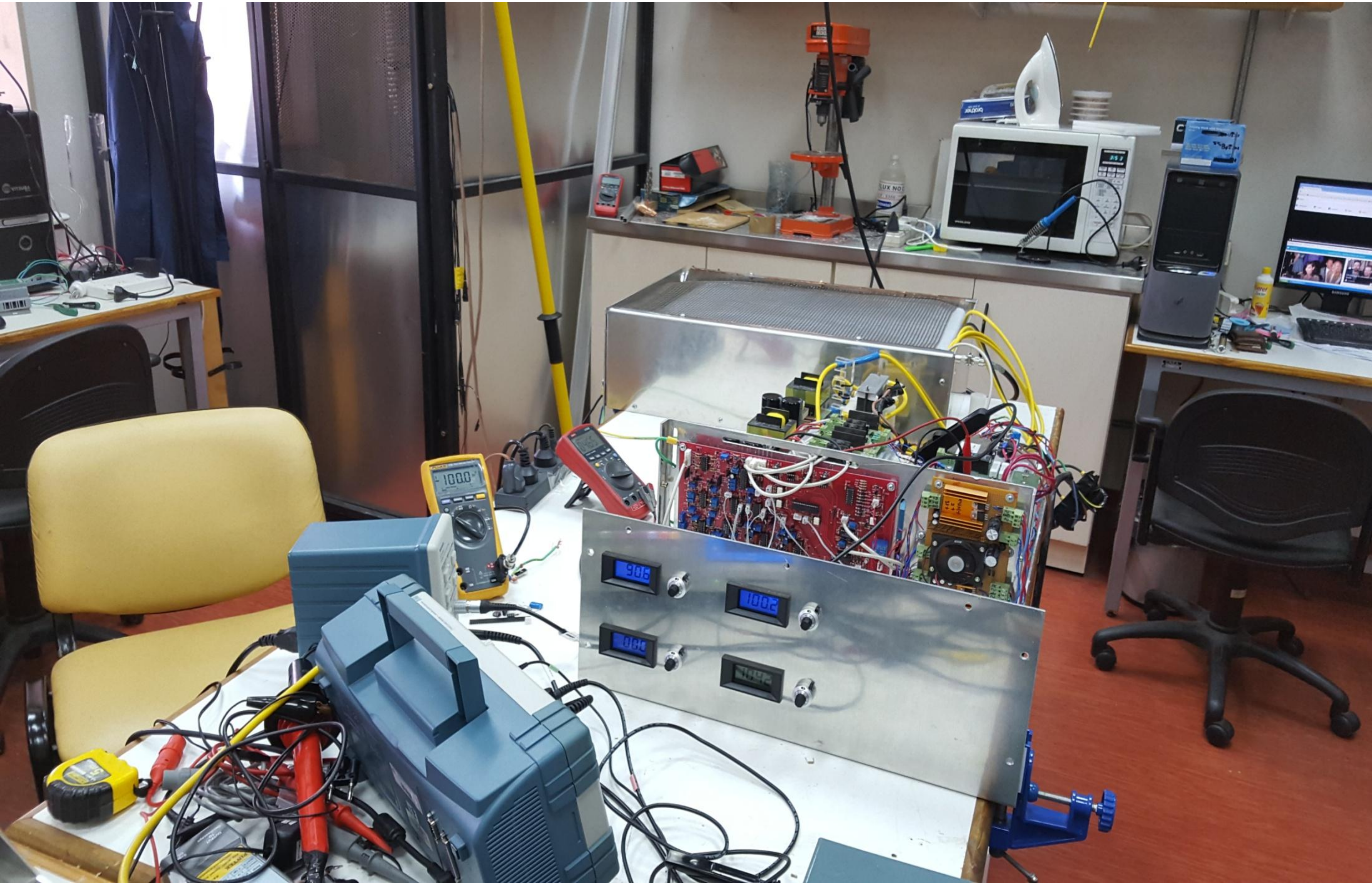




High voltage supplies: 120 kV units

M. Baldo, D. Mercuri, N. Real.

HV supplies, ready & operating

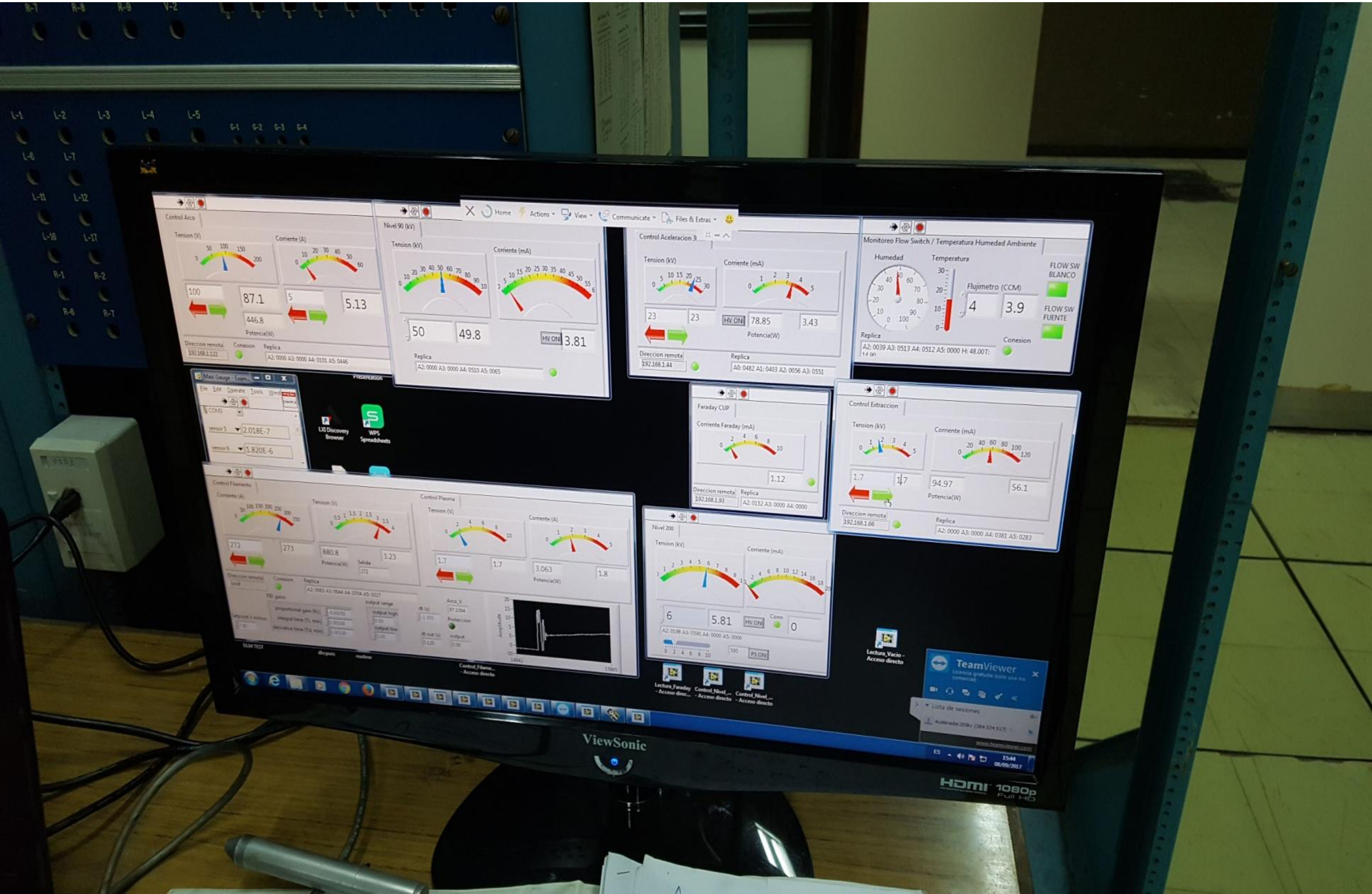


720 kV machine being mounted:

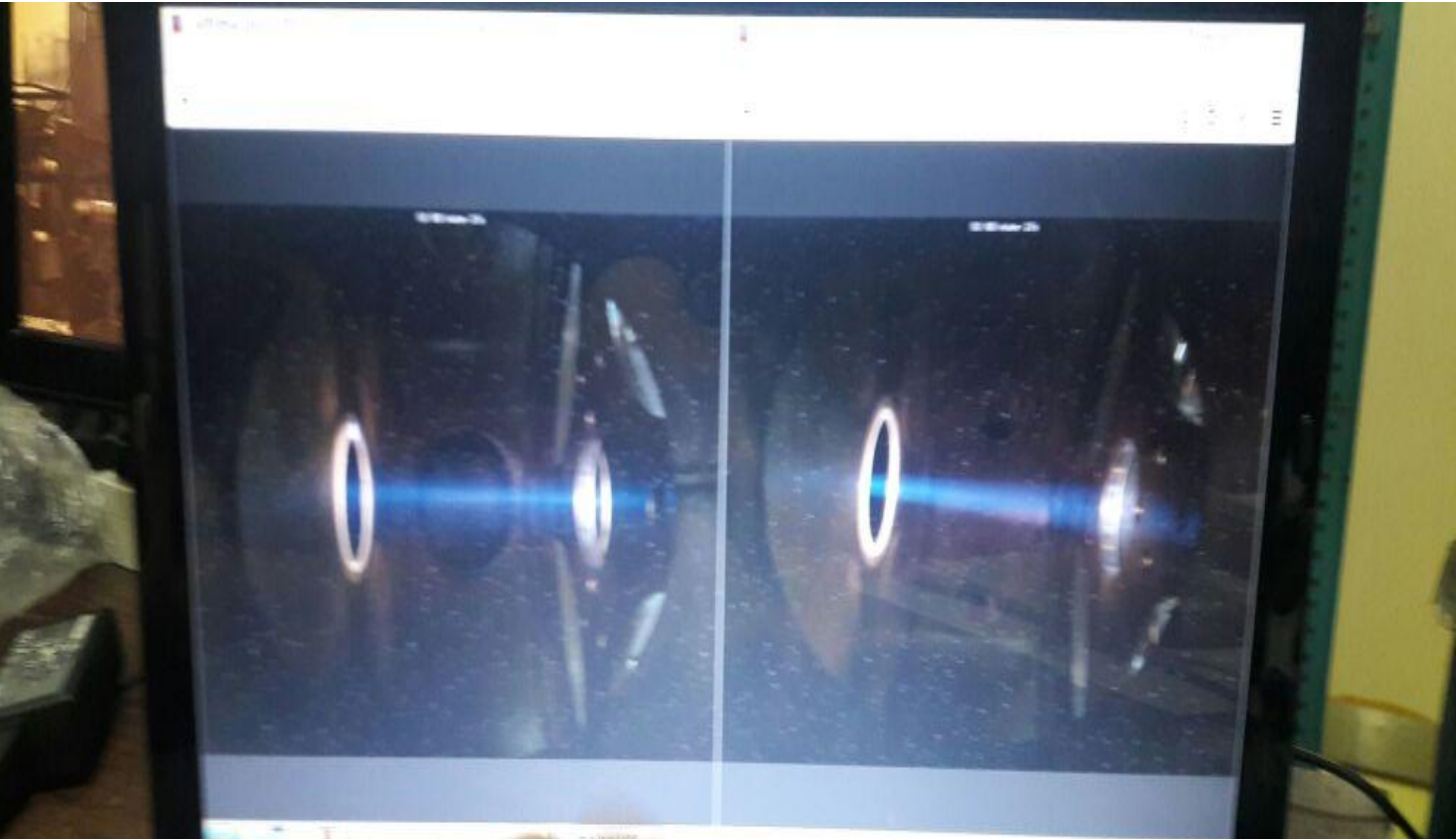
Juan Carlos Suarez Sandin, M. Igarzabal, J. Erhardt, G. Conti

720 kV accelerator mounted

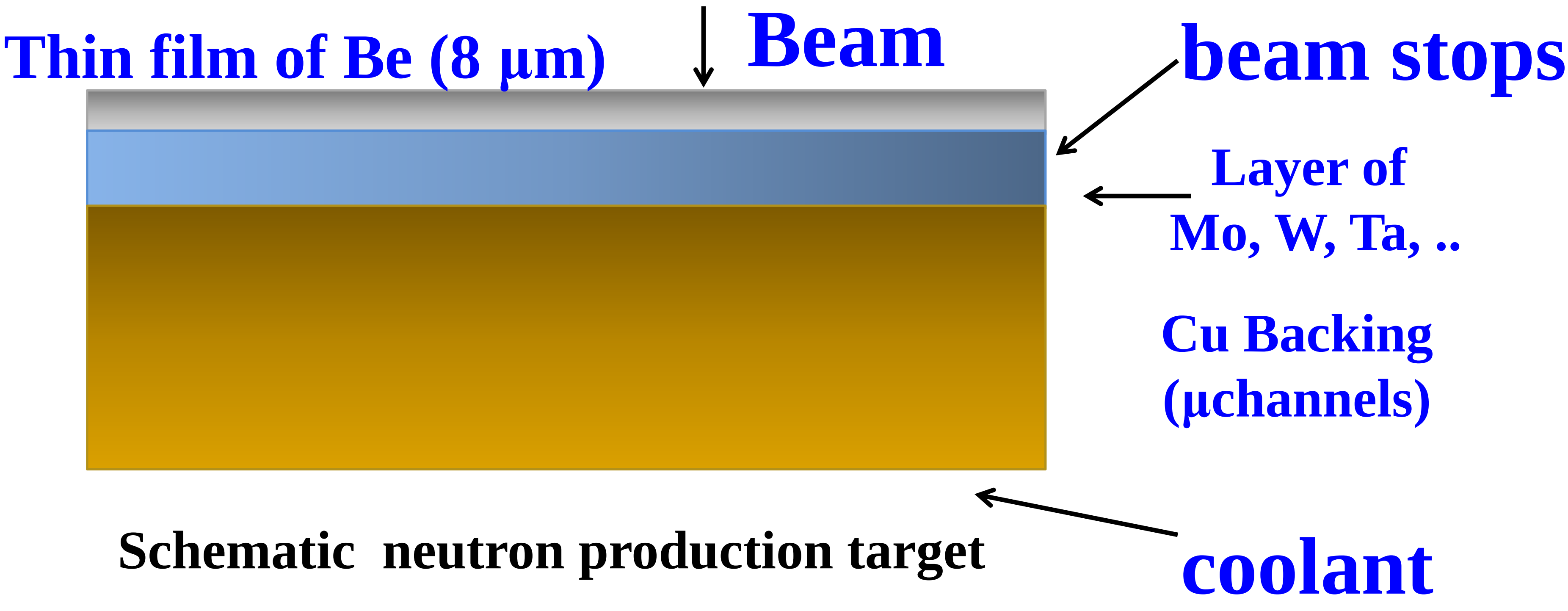
Control interface



Proton beam (5 mA) entering into Faraday cup (xz, yz planes).



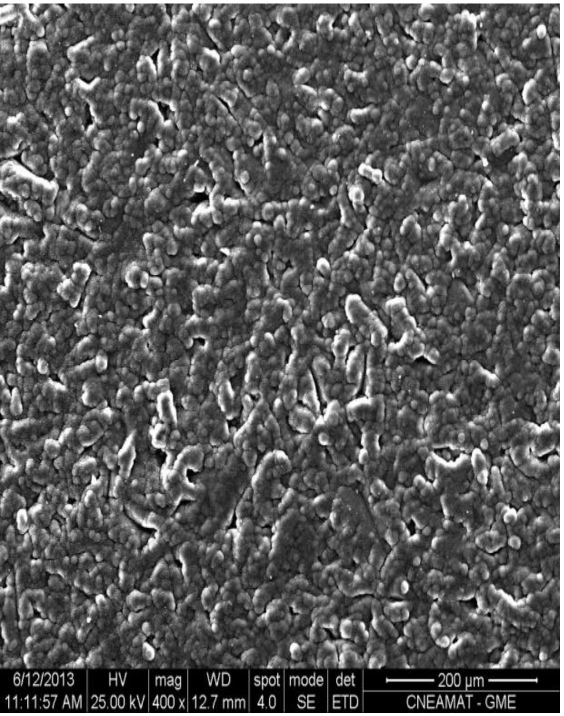
Design & development of a neutron production target for Accelerator-Based Boron Neutron Capture Therapy. L. Gagetti , M. Suarez Anzorena, M.F. del Grosso, A. Bertolo & A.J.K., Int. Cong. of Sc. &Tech. of Metallurgy & Materials,SAM-CONAMET,Argentina (Proc. Mater.Sci. 2015(8), 471/77).



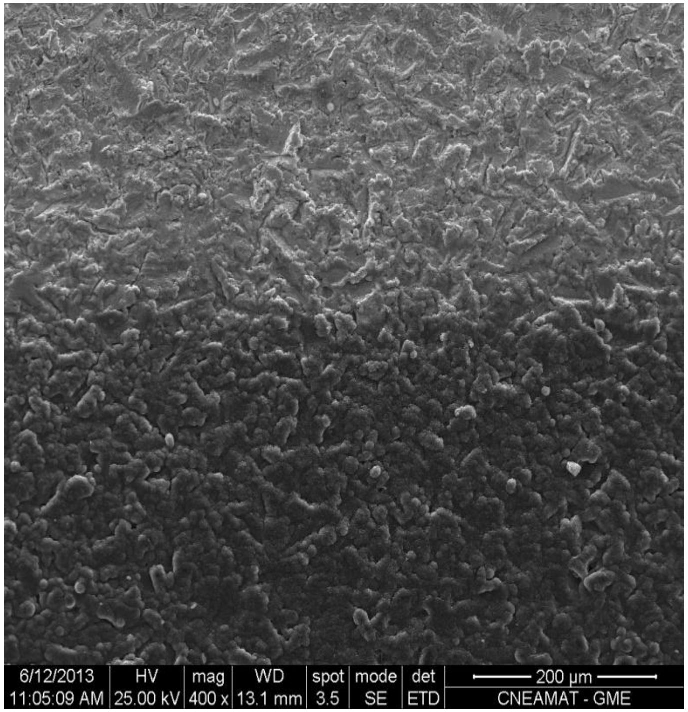
Schematic neutron production target

Be Targets: Gagetti et al., Nuclear Inst. and Methods in Physics Research, A 874 (2017) 28–34

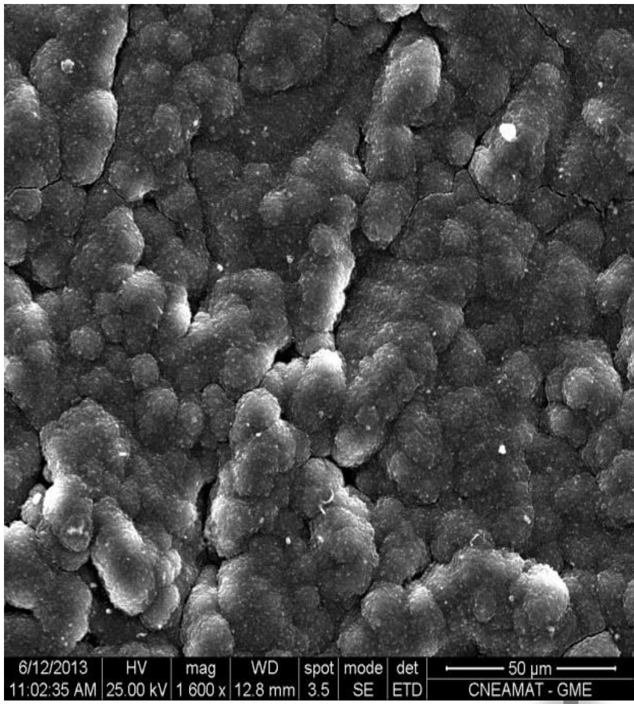
SEM images of Be deposits on different substrates.



Substrate: Tungsten
Thickness: 10 μm

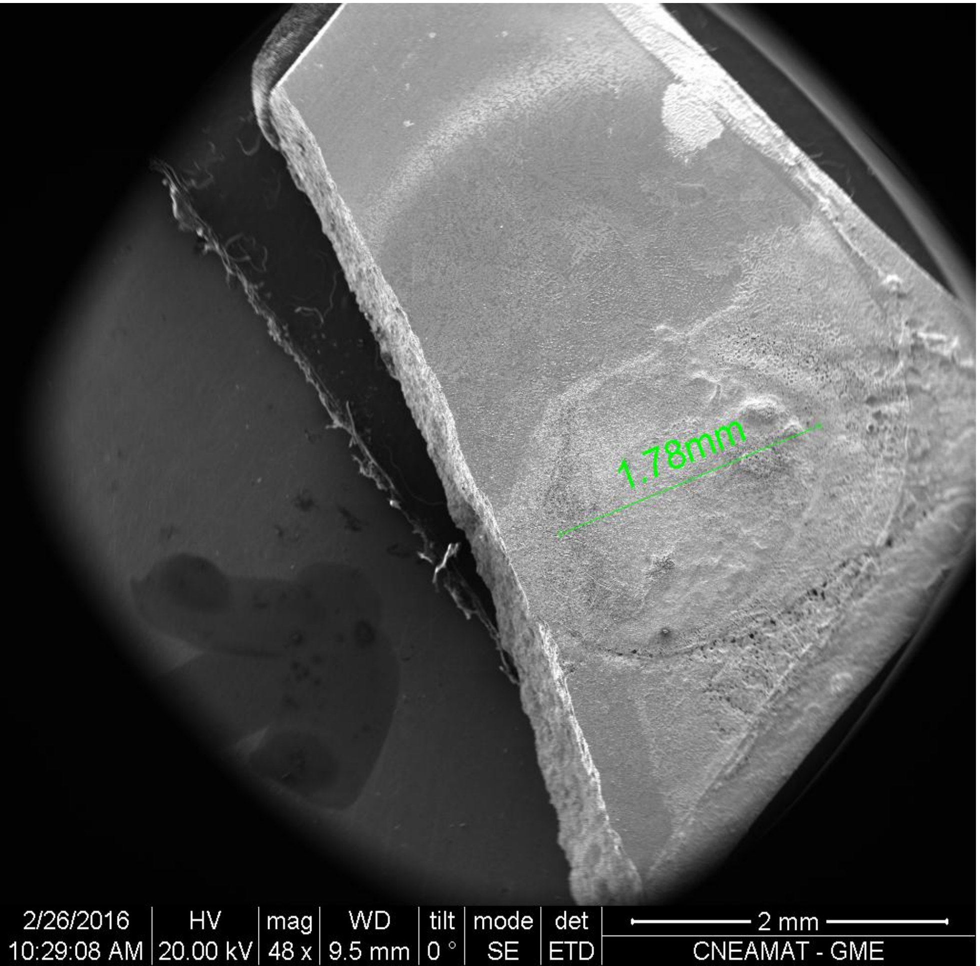


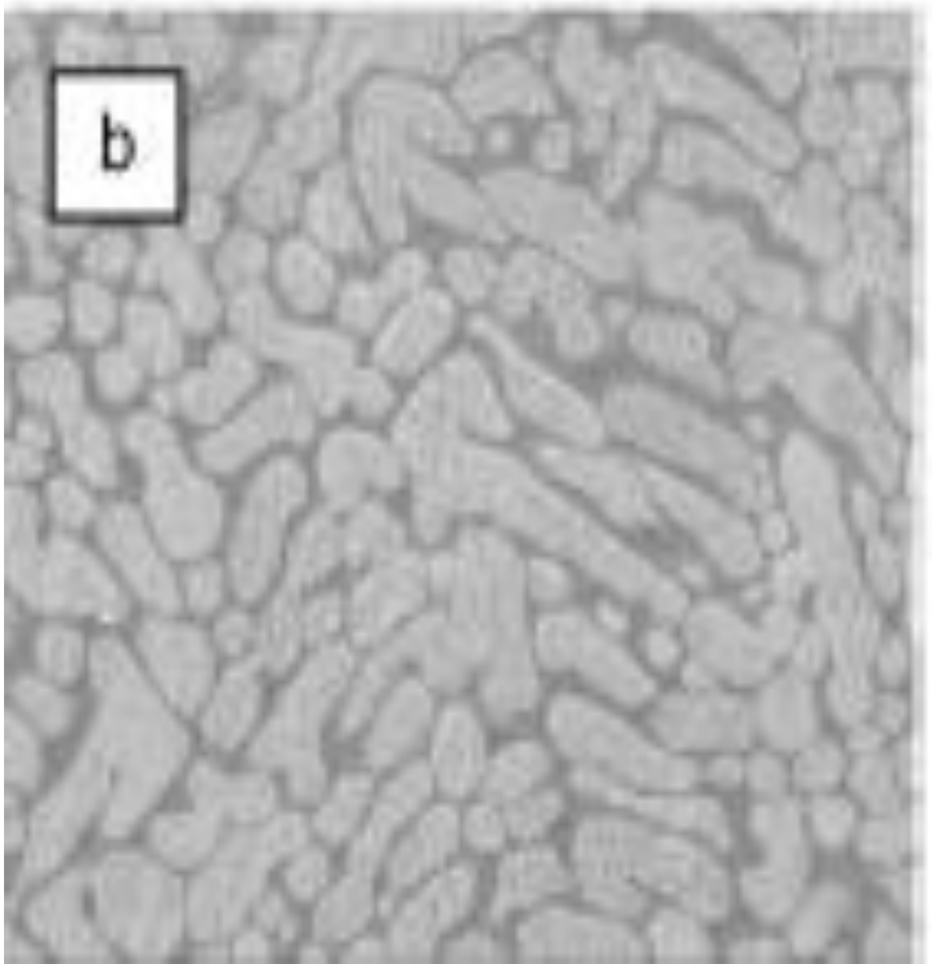
Substrate: Molibdenum
Midlayer: 0.5 μm Ag
Thickness: 10 μm



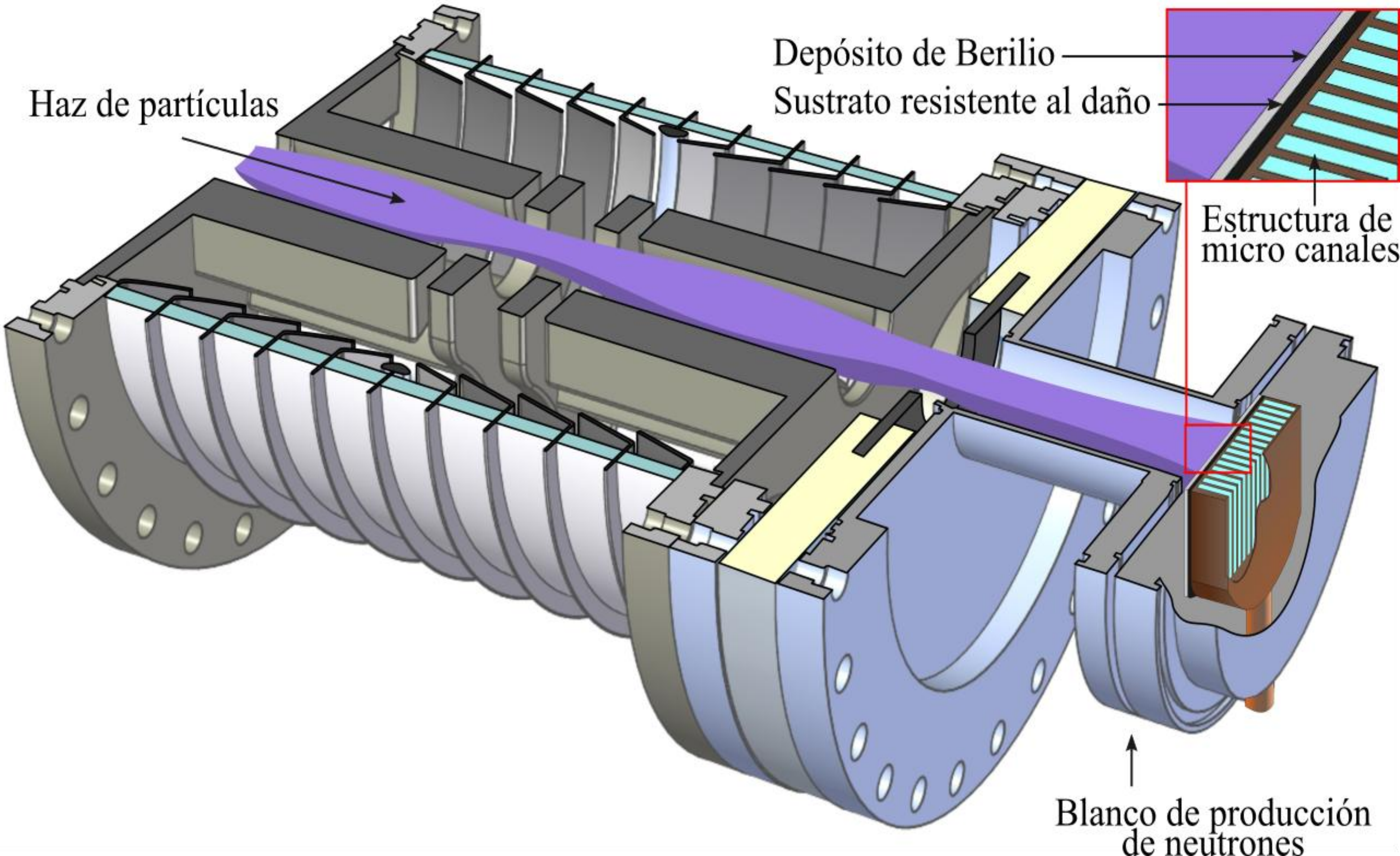
Substrate: Molibdenum
Midlayer: 0.5 μm Ag
Thickness: 10 μm

Caracterization & modeling of MoTaVWZr, high entropy alloy, Suarez Anzorena et al., Materials & Design 111 (2016) 382 **The measured Vickers micro hardness for this alloy (6690 MPa) exceeds the correspon-ding value for pure W (3430 MPa).**

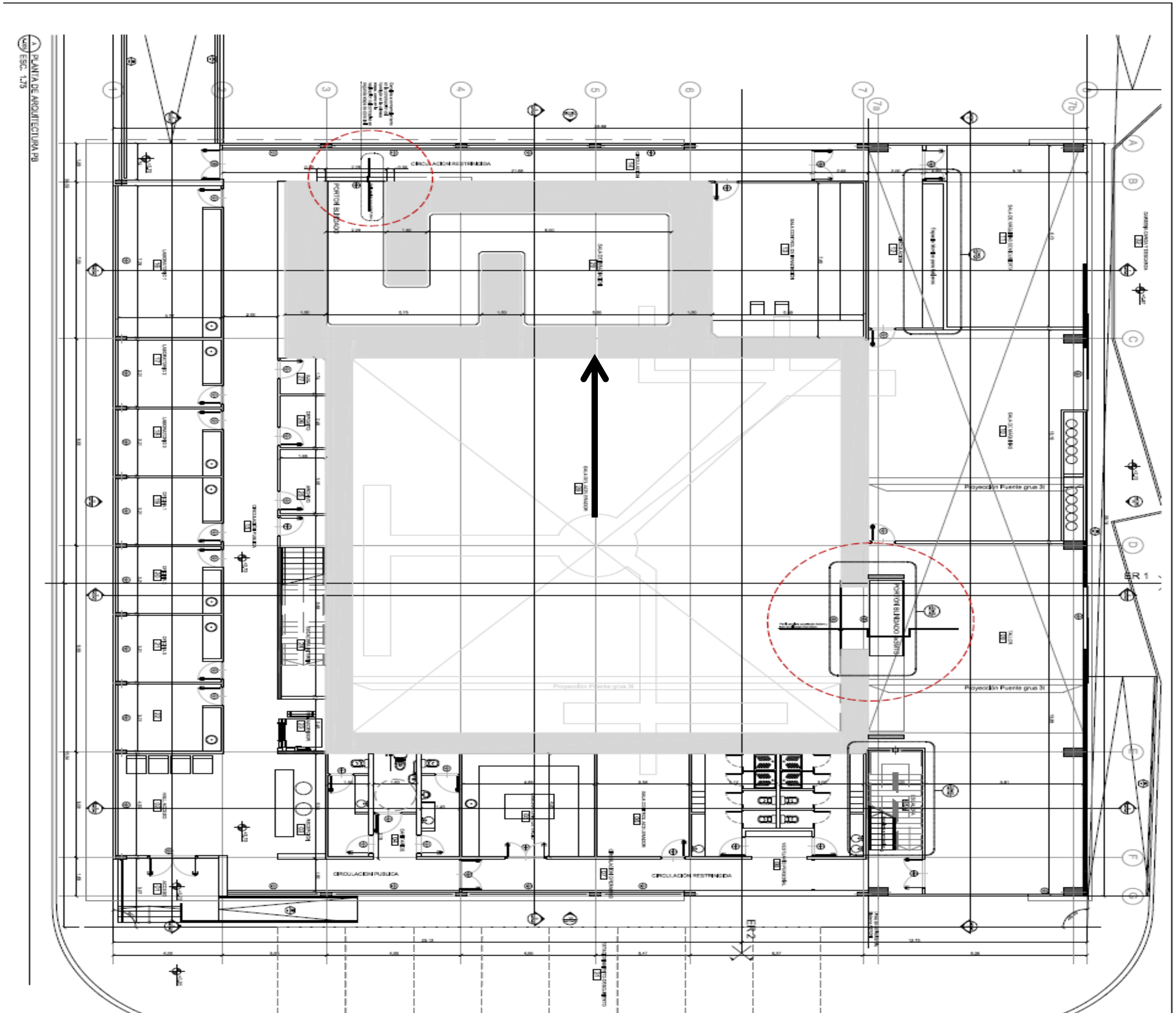




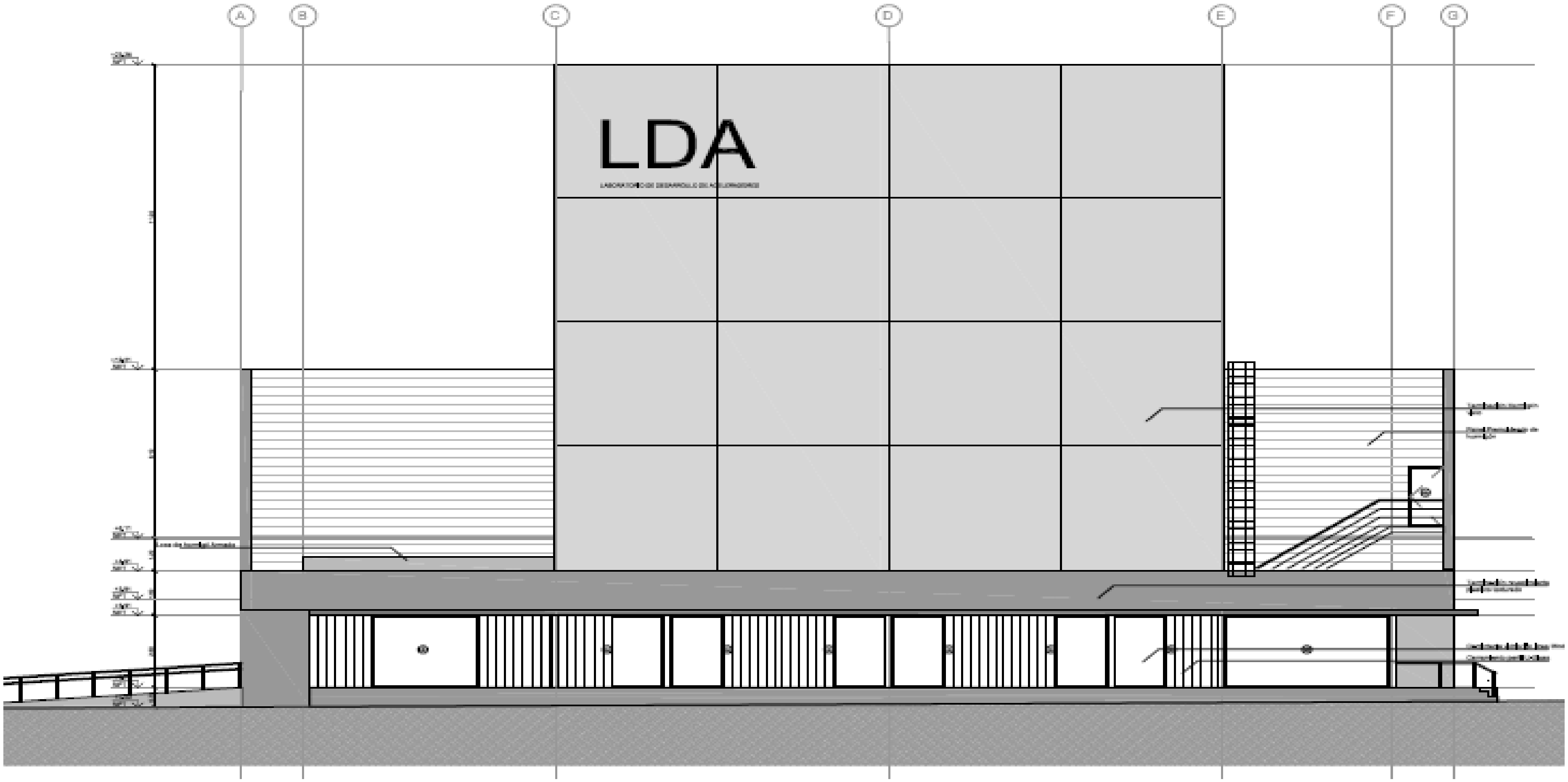
Diseño esquemático del blanco de producción de neutrones, mostrando el haz que sale del acelerador e impacta sobre el mismo.



New Lab & BCNT Centre (CNEA)



Front view of new Centre



FACHADA PRINCIPAL V1
ESCALA 1:75

Starting construction

Laboratory for Accelerator Development and future BNCT Centre

LDA: stand april 2018

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 suitability of $^{9}Be(d,n)^{10}B$ and $^{13}C(d,n)$ @ 1.45 MeV as an epithermal/thermal neutron source has been demonstrated. The technology is well advanced.

- 0.2 MV ElectroStaticQuadrupole (ESQ) accelerator ready. In-air folded 0.72 MV ESQ is being built. Other options (single ended 1.4 MV and 1.4 MV Tandem) are also being pursued. New Lab is being built.