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Cultural Heritage Network

CERN

MACHINA
Movable Accelerator for Cultural Heritage In-situ Non-destructive Analysis

Leonardo - Codex Atlanticus

Lorenzo Giuntini
on behalf of MACHINA collaboration

INFN
Istituto Nazionale di Fisica Nucleare

LES RENCONTRES DE PHYSIQUE DE
LA VALLEE D'AOSTE
Results and Perspectives in Particle Physics
La Thuile, Aosta Valley (Italy)
March 3-9, 2024

Région Autonome Vallée d'Aoste
Regione Autonoma Valle d'Aosta
Assessorat de l'Éducation et de la Culture
Assessorato Istruzione e Cultura

Layout

1. IBA and Cultural Heritage: why a transportable accelerator

2. MACHINA
   a) MAIN FEATURES OF MACHINA
   b) SOURCE
   c) LEBT
   d) ION SOURCE ACCEPTANCE TEST
   e) DUMMY ACCELERATOR
   f) ACCELERATOR
   g) HEBT
   h) CONTROL SYSTEM
   i) TRANSPORTABILITY
   j) RADIO-SAFETY
   k) BEAM
   l) DETECTION SET-UP

3. Status, Activities in progress and Perspectives

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3. Status, Activities in progress and Perspectives

The importance of material composition knowledge in conservation treatments

The Ecce Homo (Behold the Man) in the Sanctuary of Mercy, Borja, Spain, is a fresco (1930) painted by Elías García Martínez depicting Jesus crowned with thorns

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The importance of material composition knowledge in conservation treatments

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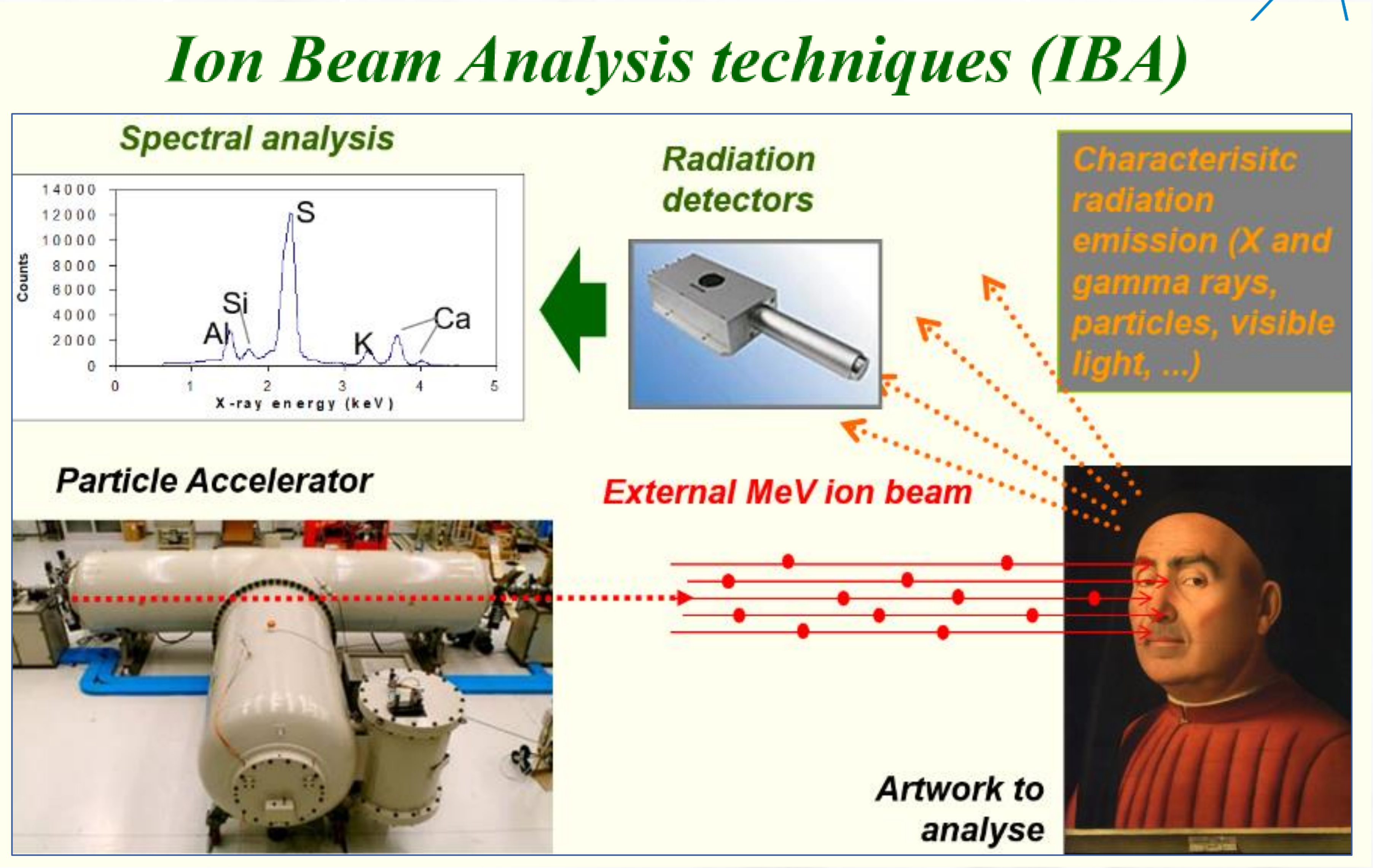
Ion Beam Analysis (IBA) Techniques and Cultural Heritage

- A set of **powerful, complementary techniques for material characterisation (PIXE, PIGE, EBS/RBS, IL, NRA,…)**
- Can be used **simultaneously**
- **Qualitative and quantitative**
- **Very sensitive and fast**
- Beams of **different particles** (mainly p, d, He)
- **Point analysis - 2D and 3D compositional imaging**
- **Variable spatial resolution**, typically down to the 10-μm size
- **Complement and complemented by many widely-used techniques,** such as XRF, SR-XRF, Raman, VIS/OPT/NIR, XRD, X-ray/neutron radiography and tomography, LIBS, AMS, IRMS-AMS, ICPMS, ...
- **Safe analysis (external beams)**

Ion Beam Analysis (IBA) Techniques and Cultural Heritage

- Diagnostics
- Conservation
- Restoration
- Forgeries
- Integrations
- History
- Art History
- Technology history
- Trade route study
- Material origin
- …



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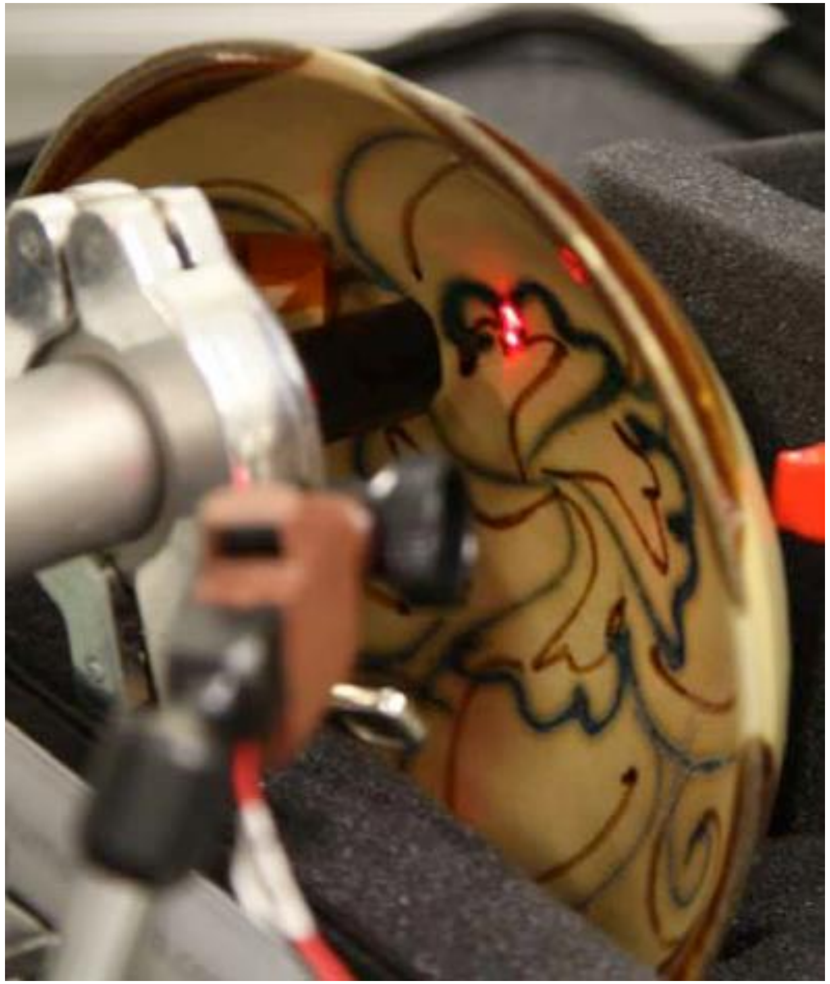
...potteries (authentication)...

Nuclear Instruments and Methods in Physics Research B 406 (2017) 329-333

Tang dynasty (618–907) bowl measured with PIXE

M. Laitinen[a,b,*], M. Käyhkö[a], G. Hahn[c], N. von Uexküll-Güldenband[c], T. Sajavaara[a,b]



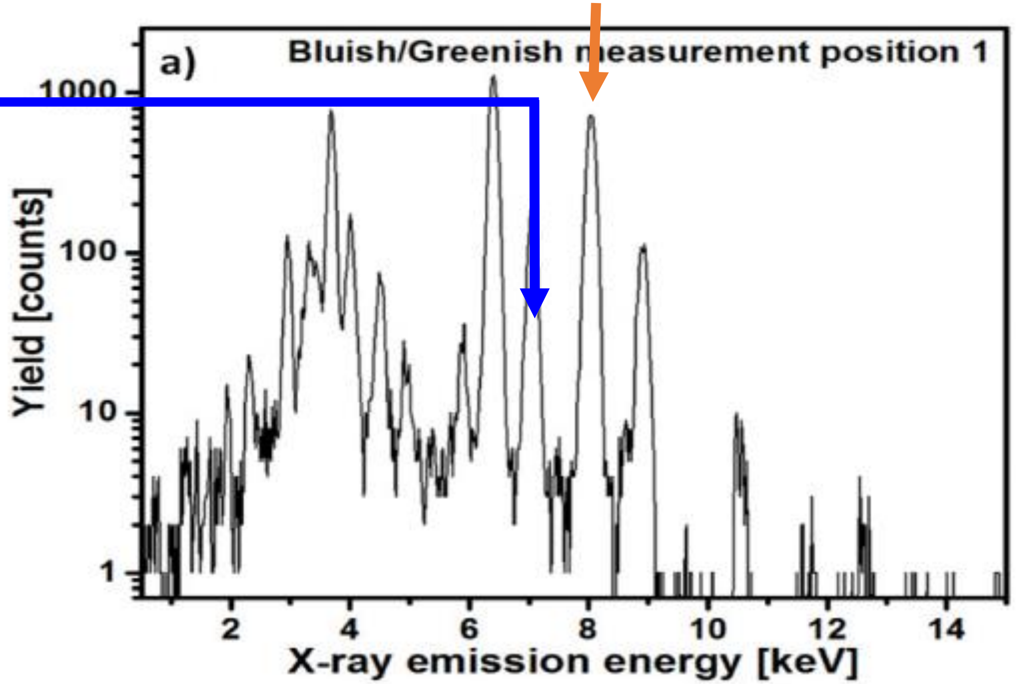
Jyväskylä - 3 MeV proton PIXE
bowl from
Tang Dynasty

Questions:

1. Fake or Tongguan origin?
2. Tang period?
3. Co-blue?

Answers:

1. Tongguan area compatible
2. Tang period compatible
3. No Co-blue: Cu-blue!



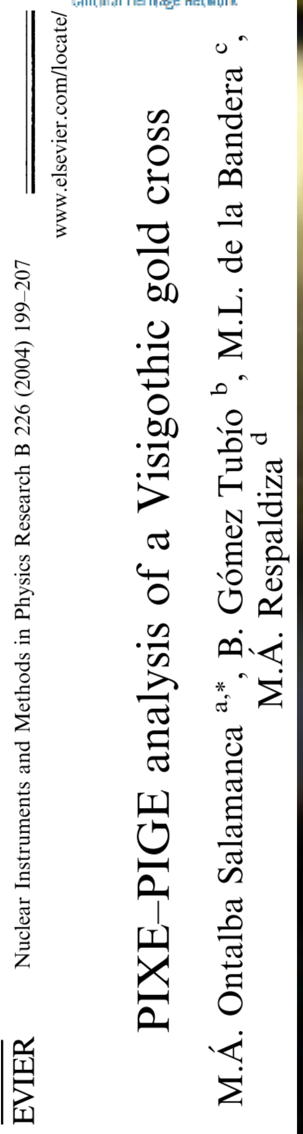
...gold jewels and stones…

CAN Sevilla

IBA external microbeam

Gold Visigotic cross

6–7th century



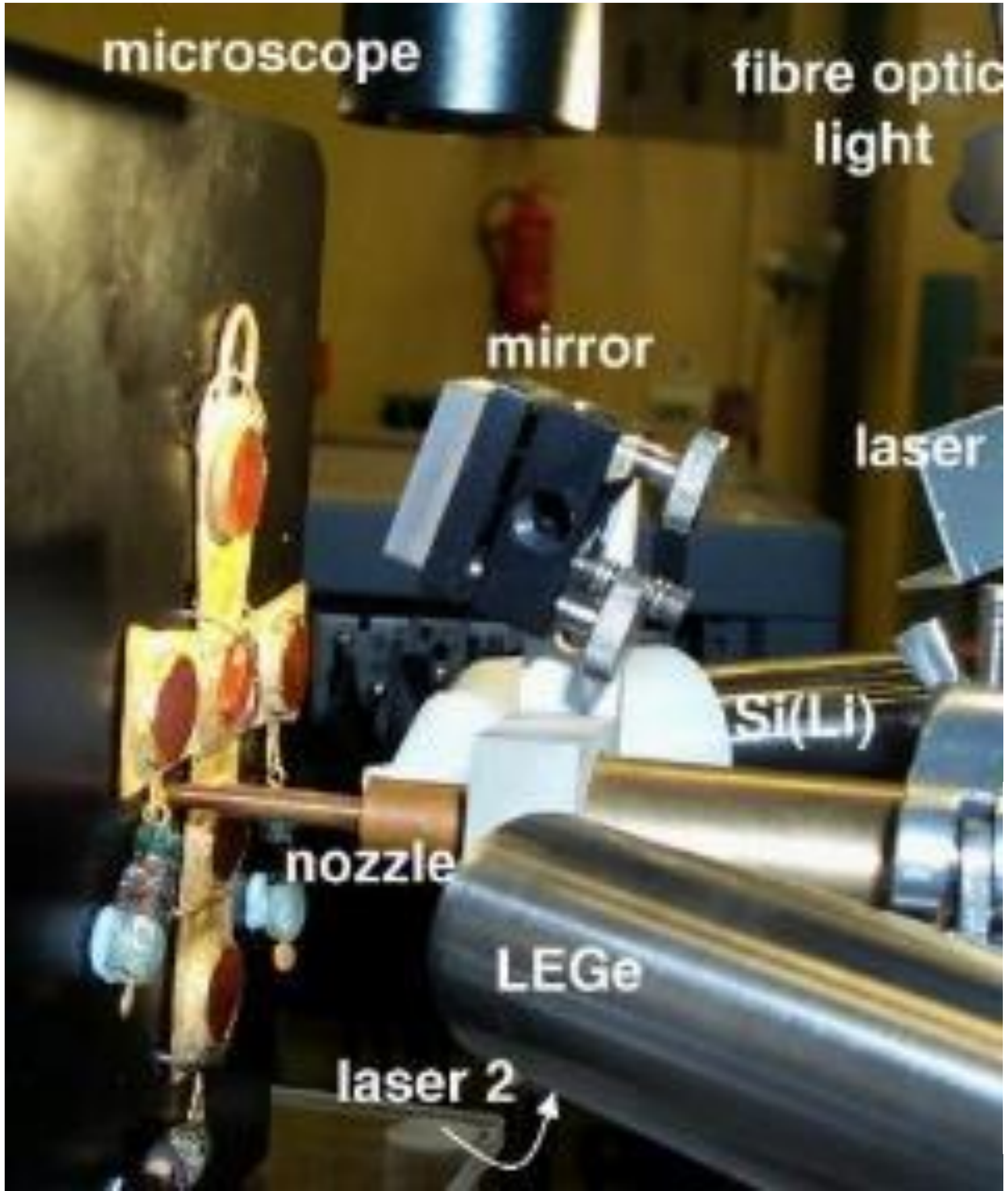
Nuclear Instruments and Methods in Physics Research B 226 (2004) 199–207

www.elsevier.com/locate/

EVIER

PIXE–PIGE analysis of a Visigothic gold cross

M.Á. Ontalba Salamanca [a,*], B. Gómez Tubío [b], M.L. de la Bandera [c], M.Á. Respaldiza [d]



- **distinguish different workshops**
- **study the evolution of the goldsmithery technology**
- **characterisation of mounted stones and beads: glass, not precious stones!**

In our analysis, the absence of Al indicates that, in contrast to Guarrazar Treasure [13], no sapphires or rubies (Al_2O_3, with Ti, Fe or Cr as trace elements, 53 wt.% Al) and no emeralds ($Be_3Al_2(SiO_3)_6$, 10 wt.% Al) were employed to manufacture the jewel.

...precious stones (origin identification)...

AGLAE – external 3 MeV proton beam

Parthian statue of Ishtar

ELSEVIER
Nuclear Instruments and Methods in Physics Research B 136–138 (1998) 846–850

Provenance study of rubies from a Parthian statuette by PIXE analysis

T. Calligaro *, A. Mossmann, J.-P. Poirot, G. Querré

from Burma or Sri Lanka. These results are in agreement with Sanskrit texts written in IV–Xth century B.C. [16,17] stating that rubies were extracted from deposits in India and Sri Lanka.

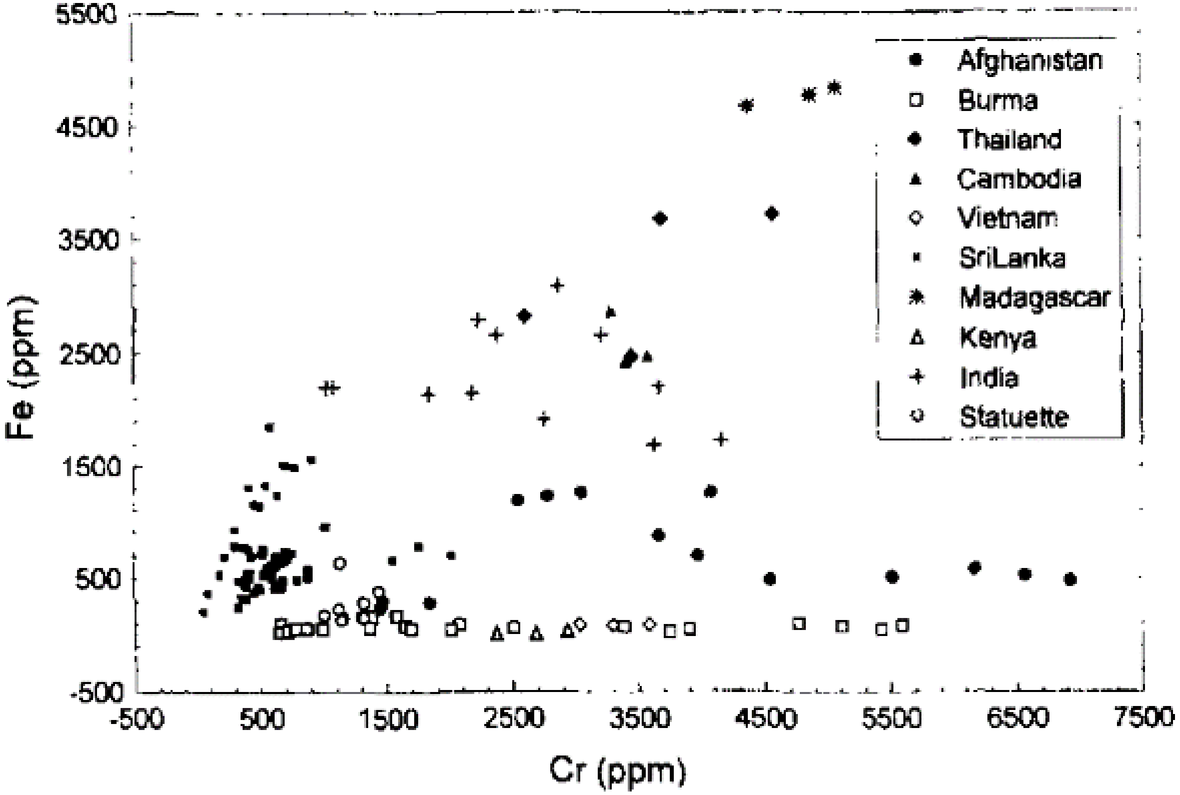
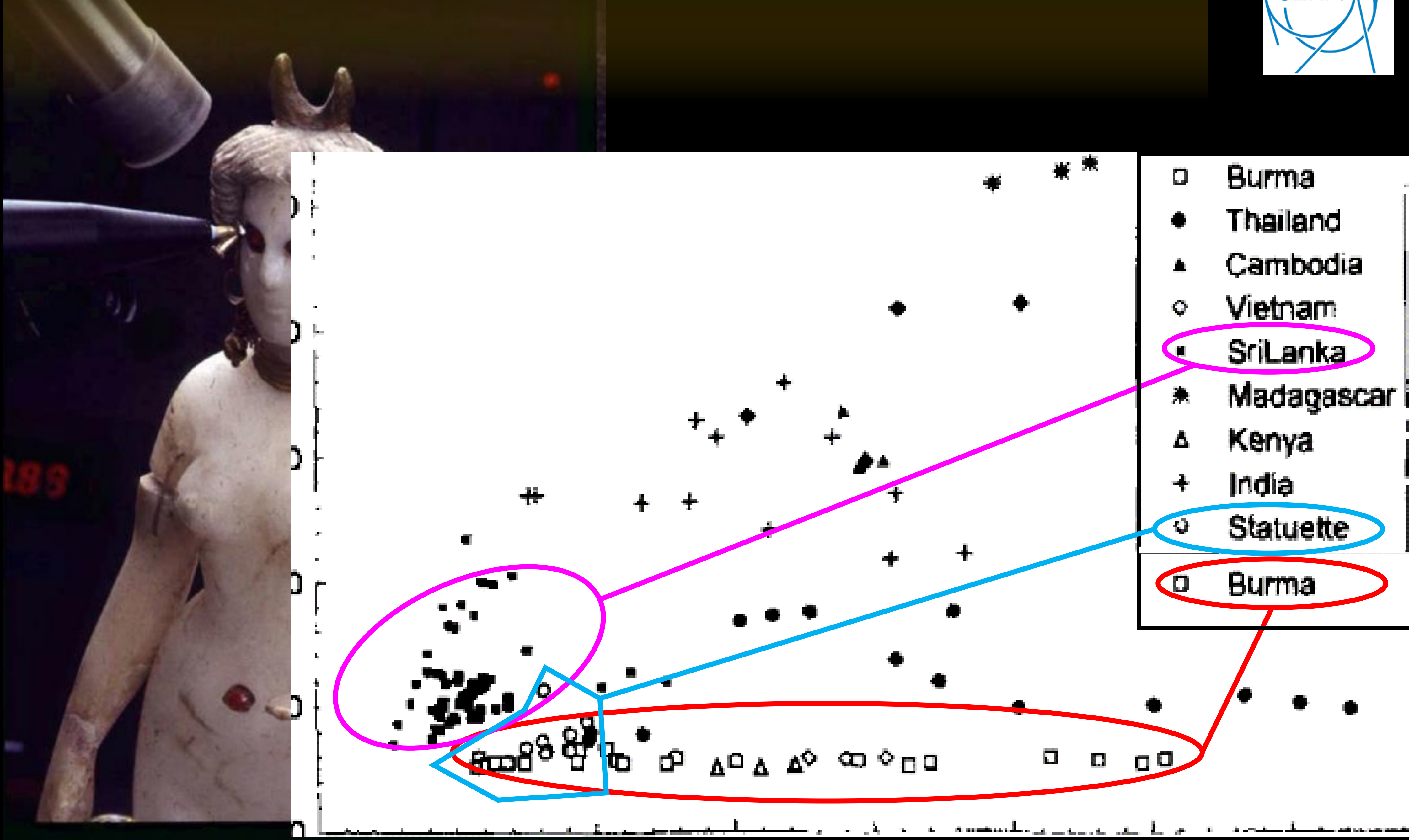


Fig. 4. Plot of Fe vs. Cr for different locations.

...precious stones (origin identification)...



...lost images recovery: imagig by IBA...

https://www.vacuum-uk.org/pdfs/vs5/SurfaceMods/RosslynChapel.pdf

- Long run (overnight) with mechanical scanning
- 2.5 MeV protons with PIXE (particle-induced X-ray emission)
- Particle backscattering and gamma rays also collected

...lost images recovery: imagig by IBA...

https://www.vacuum-uk.org/pdfs/vs5/SurfaceMods/RosslynChapel.pdf

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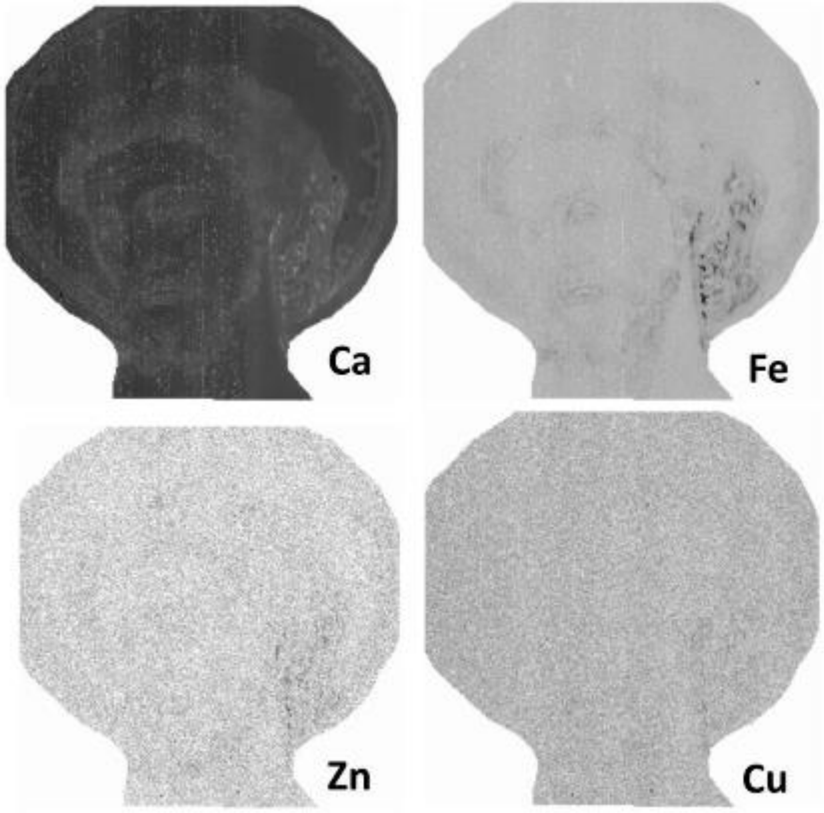
Lead and potassium maps allow recovering details of the lost images



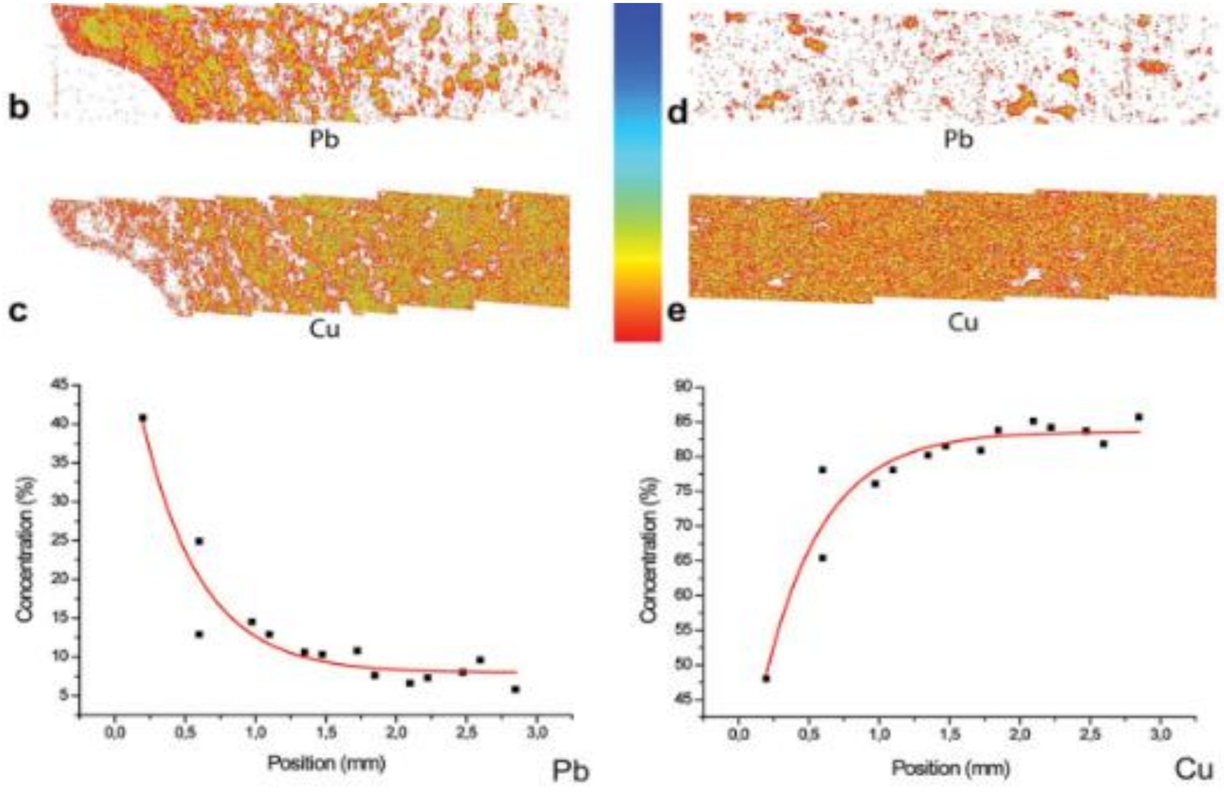
Deus ex Machina !

...bronze statues (corrosion)...

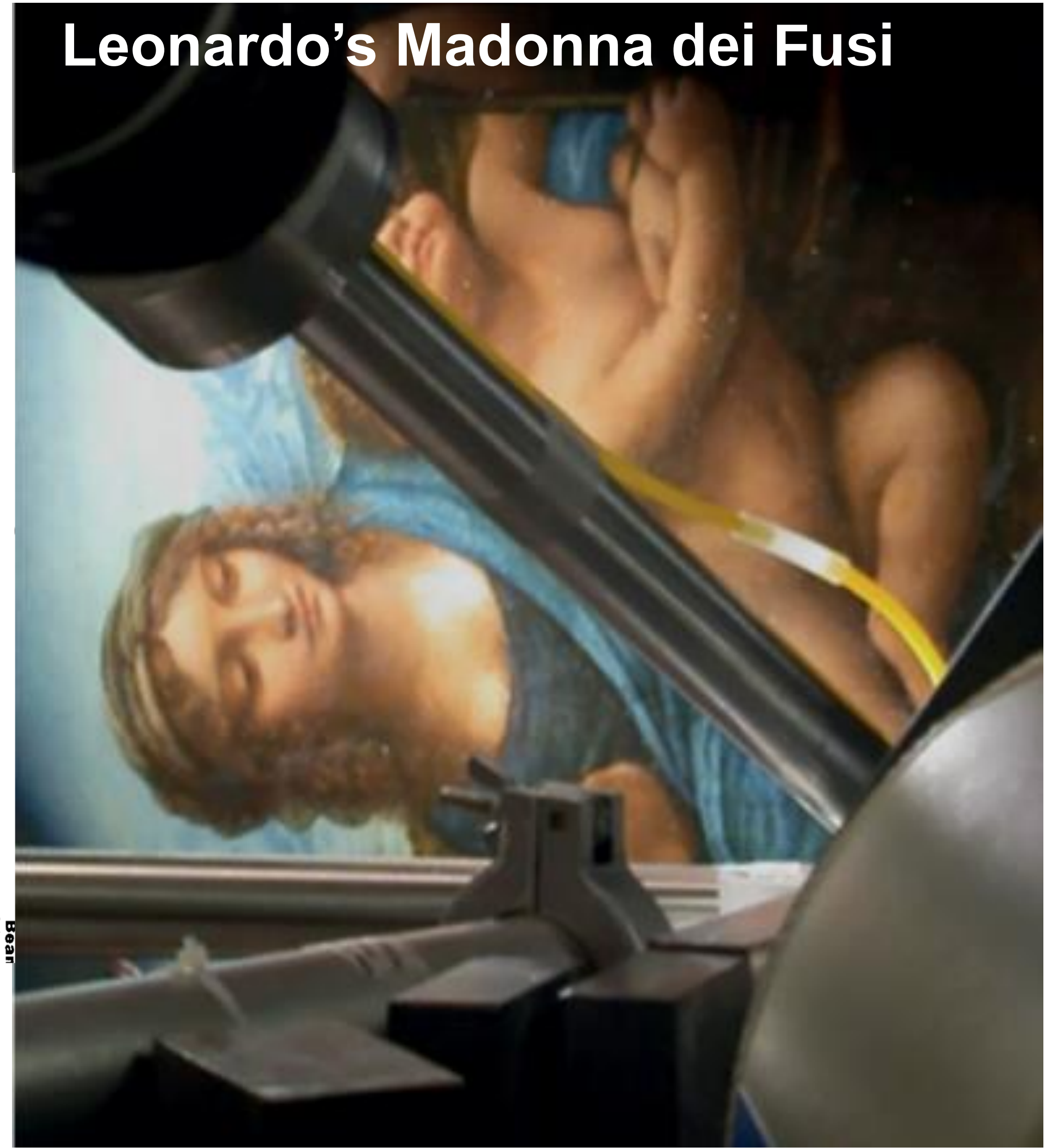
RBI
external PIXE - μPIXE
2/1.6 MeV proton beam


Journal of Archaeological Science 37 (2010) 1396–1402
Contents lists available at ScienceDirect
ELSEVIER
Journal of Archaeological Science
journal homepage: http://www.elsevier.com/locate/jas
Croatian Apoxiomenos alloy composition and lead provenance study
D. Mudronja [a,*], M. Jakšić [b], S. Fazinić [b], I. Božičević [b], V. Desnica [b,c], J. Woodhead [d], Z.A. Stos-Gale [e]

Microprobe PIXE measurements done on alloy cross-sections showed that electrochemical changes made to relative quantities of lead and copper are most apparent in a layer extending approximately 600 μm from the surface.



...pigments in painting: lapislazuli or cobalt blue…

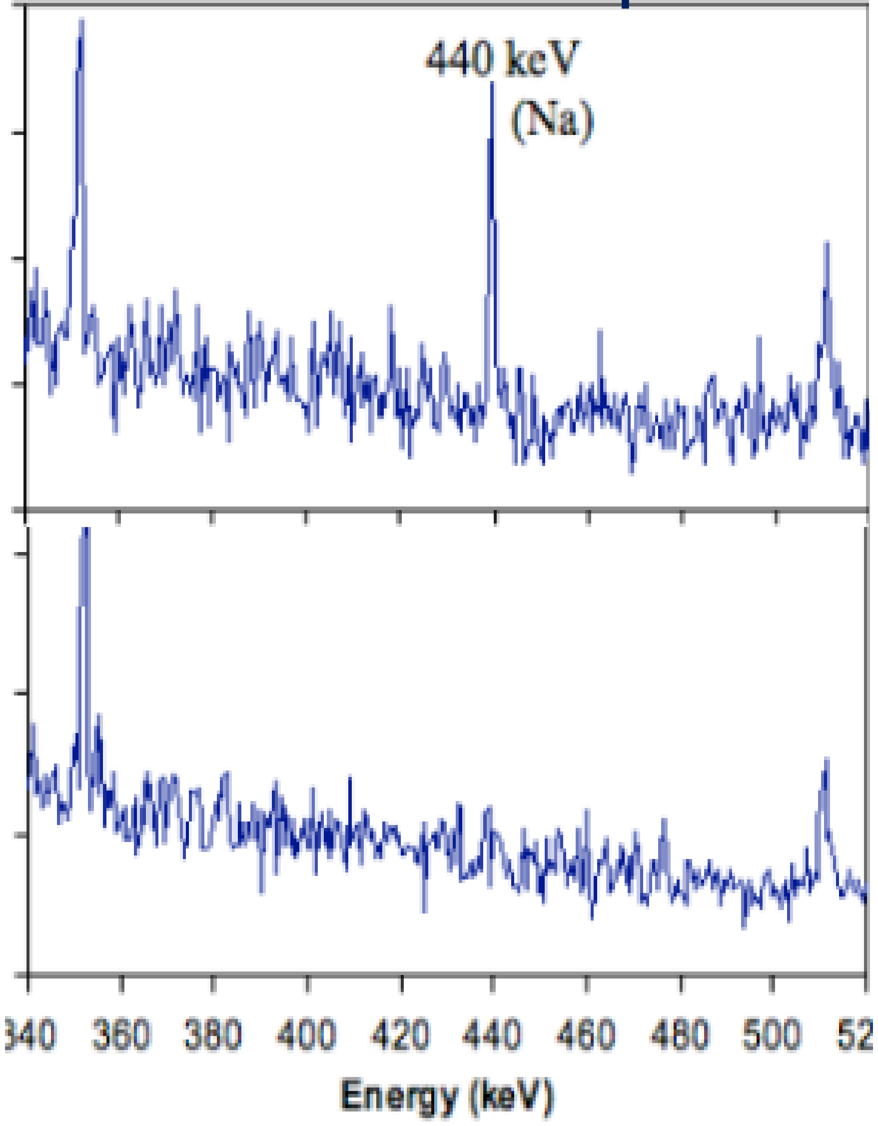


Nuclear Instruments and Methods in Physics Research B 239 (2005) 71–76

Differential PIXE for investigating the layer structure of paintings

P.A. Mandò *, M.E. Fedi, N. Grassi, A. Migliori

PIGE spectra in blue areas:
Presence of Na = Lapis Lazuli
Absence of Na = no Lapis Lazuli

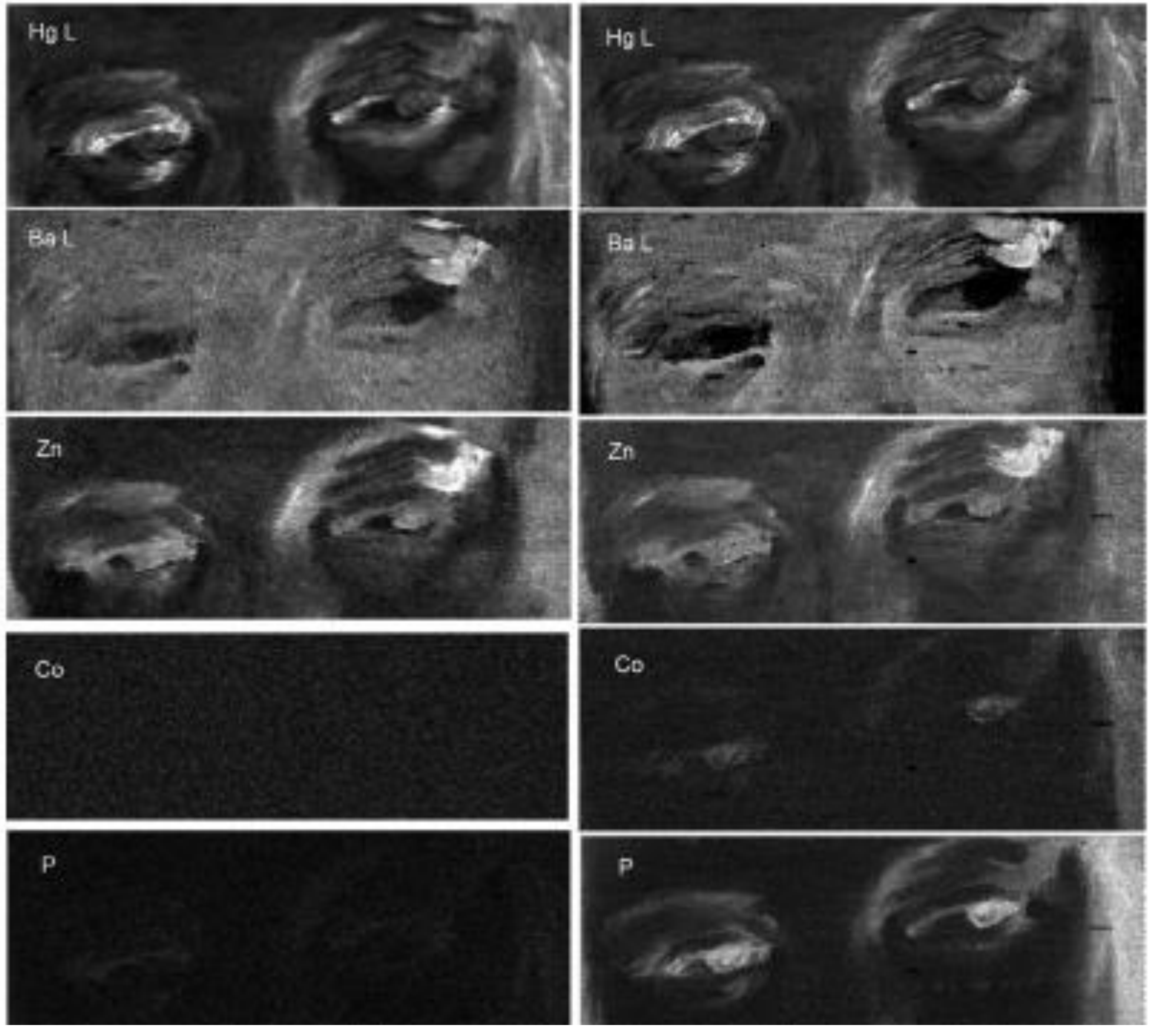


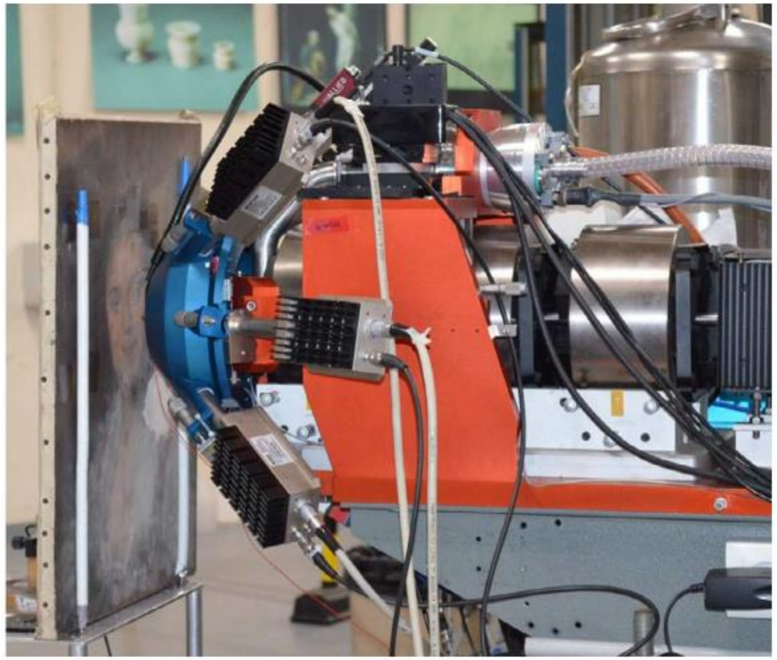
...paintings...

La Bohémienne
by Frans Hals
(19th century copy)

MA-XRF
XRF scanner

PIXE Imaging
particle accelerator





Nuclear Instruments and Methods in Physics Research B xxx (2015) xxx–xxx

PIXE analysis of historical paintings: Is the gain worth the risk?

T. Calligaro [a,b,c,*], V. Gonzalez [a,b], L. Pichon [a,c]

...Egyptian blue...

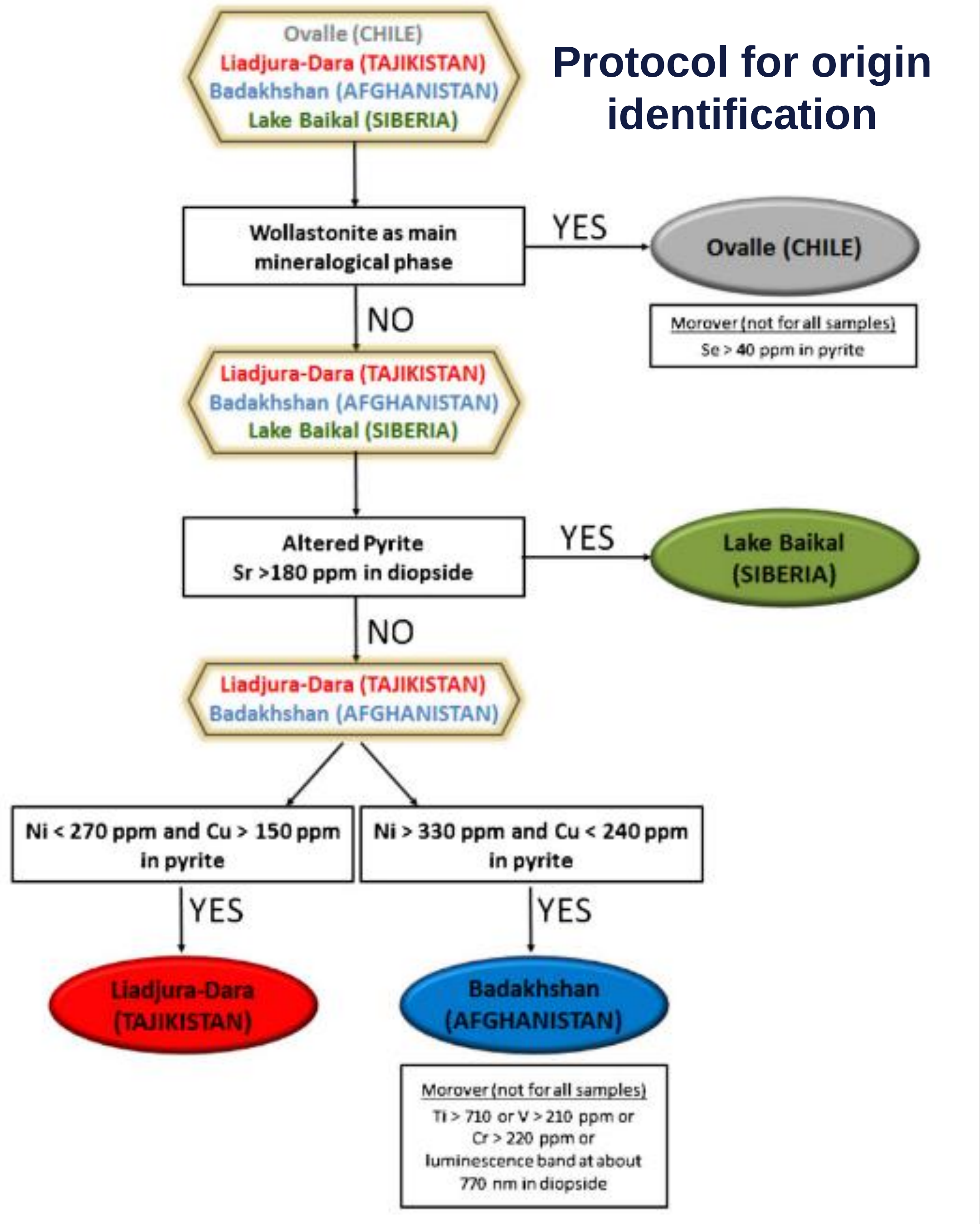
Vacuum 83 (2009) S4–S8

Ion beam analysis of ancient Egyptian wall paintings

PIXE spectra revealed that Si, S, Ca, Fe, Cu are present in the surface layer, this was confirmed by the μ-PIXE analysis. Since Cu, Ca and Si are main components of Egyptian Blue the answer to the question on the blue pigment nature seems to be straightforward. But since one cannot expect Fe-containing compounds in this configuration the large Fe signal in all spectra is quite surprising.

IBA microscopy helped to resolve this puzzle. Dark blue Egyptian Blue grains of the size of 10–40 μm are mixed with light blue grains of more or less the same size.

...lapis lazuli for source identification...



Turin-AGLAE-CHNet_LABEC study using external micro PIXE, PIGE, IL

Over the years, hundreds of crucial applications

of IBA to Cultural Heritage

Look for example:

IBA AND Cultural Heritage

IBA AND Paintings

IBA and Jewels

IBA and Gold

…

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Find articles with these terms

iba AND Cultural Heritage

CERN

sciencedirect.com/search?qs=iba%20AND%20Cultural%20Heritage

- 2024 (6)
- 2023 (26)
- 2022 (27)
- 2021 (22)
- 2020 (33)
- 2019 (32)
- 2018 (25)
- 2017 (29)
- 2016 (14)
- 2015 (38)
- 2014 (21)
- 2013 (15)
- 2012 (11)
- 2011 (20)
- 2010 (13)
- 2009 (12)
- 2008 (12)
- 2007 (11)
- 2006 (13)
- 2005 (22)
- 2004 (19)
- 2003 (2)
- 2002 (5)
- 2001 (3)
- 2000 (5)

461 results

But as IBA are so important for CH, why over the time only **hundreds**

instead of **thousand or more** applications?

Because **artworks are to be moved from the Museum or Conservation Laboratory to the accelerator**

And moving artworks is:

- Expensive
- Time consuming
- Always difficult
- Sometimes **impossible (e.g. frescoes, fragile artworks or big paintings)**

XRF AND in situ AND CH

4,631 results

2024 (205)	2011 (99)
2023 (515)	2010 (94)
2022 (494)	2009 (90)
2021 (454)	2008 (77)
2020 (363)	2007 (88)
2019 (280)	2006 (49)
2018 (243)	2005 (66)
2017 (222)	2004 (57)
2016 (230)	2003 (32)
2015 (170)	2002 (28)
2014 (147)	2001 (32)
2013 (142)	
2012 (114)	

IN SITU measurements are more appealing than those in the accelerator labs and are getting more and more diffused over the time, see for example.

IBA and in-situ measurements for Cultural Heritage:
only at AGLAE in Paris (Louvre)
an IBA laboratory is present close to the conservation site

The idea: if the mountain won't come to you, then you must go to the mountain

https://www.sciencedirect.com/

Overcome this limitation is the basis of the MACHINA project

The idea: a **movable IBA system** for *in-situ* measurements, to use at the Opificio delle Pietre Dure in Florence (a world leader for art conservation)

A realistic compromise between a “perfect” and a “transportable” tool for compositional diagnostics, to try and solve the problems of conservation

The challenge

Maintaining performances comparable to those that can be obtained with *standard* accelerators for the standard analyses in CH with the additional *heavy* constraints:

- **Low power consumption**
- **Low weight**
- **Small form factor**
- **Low emissivity**
- **Low cost**
- **Transportable**

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Cultural Heritage Network

OPD endorsement

CERN

Ministero dei Beni e delle Attività Culturali e del Turismo

OPIFICIO DELLE PIETRE DURE-FIRENZE

Fax 055 287123 e-mail : marco.ciatti@beniculturali.it

Pietre Dure (OPD)* in Florence believe that the project presented by CERN and INFN plays a strategic role in the future of diagnostics applied to the cultural heritage field. The Opificio delle Pietre Dure, therefore, strongly supports the huge importance of such scientific and technological development.

The project aiming to create a new tool for diagnostic investigations, based on a transportable accelerator, will, in future, provide answers so far impossible to achieve by in situ analysis.

A portable accelerator constitutes an achievement of high scientific value and the OPD is strongly convinced that it constitutes a major breakthrough in the world of diagnostics and thus a valuable help for us.

*The Opificio delle Pietre Dure is a public institute of the MIBACT (Italian Ministry for Cultural Heritage).

Florence, February 6th 2017

Marco Ciatti

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Cultural Heritage Network

IAEA support to the MACHINA project (at the time PIXE-RFQ)

CERN

IAEA

Atoms for Peace

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国 际 原 子 能 机 构
International Atomic Energy Agency
Agence internationale de l'énergie atomique
Международное агентство по атомной энергии
Organismo Internacional de Energía Atómica

Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Phone: (+43 1) 2600 • Fax: (+43 1) 26007
Email: Official.Mail@iaea.org • Internet: http://www.iaea.org

In reply please refer to:
Dial directly to extension: (+43 1) 2600-21756

Dr. Giovanni Anelli
Knowledge Transfer Group Leader
Industry Procurement and Knowledge Transfer Department
CERN - European Organization for Nuclear Research
CH-1211 GENEVA 23
SWITZERLAND

Dr. Massimo Chiari
Technological and Interdisciplinary Research Coordinator
INFN Division of Florence
Via B. Rossi 1
I-50019 Sesto Fiorentino, FIRENZE
ITALY

2017-03-16

Dear Dr. Anelli and Dr. Chiari,

With this letter I am very pleased to confirm the interest of the International Atomic Energy Agency (IAEA) in the project "RFQ-PIXE" presented by CERN and INFN.

I believe that the project, based on the development of a portable proton accelerator, will play a strategic role in the future of accelerator-related analytical techniques applied to the cultural heritage field, allowing in-situ analyses so far impossible to achieve by other portable instrumentation.

The IAEA is strongly convinced that a portable accelerator constitutes an innovative diagnostic tool that could be easily deployed in many developing Member States. The IAEA, therefore, strongly supports such scientific and technological development.

Yours sincerely,

Professor Ralf Kaiser
Section Head

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Cultural Heritage Network

AGLAE support to the MACHINA project (at the time PIXE-RFQ)

CERN

Carrousel:
Laboratoire
Palais du Louvre
Porte des Lions
de l'aile Flore
Escalier de l'horloge
14, quai François Mitterrand
75001 Paris
téléphone : 01 40 20 56 52
télécopie : 01 40 20 68 56

Versailles :
Ateliers de restauration
Petite écurie du roi
2 avenue Rockefeller
CS50505
78007 Versailles cedex
téléphone : 01 39 25 28 28
télécopie : 01 39 02 75 45

Flore :
Ateliers de restauration
Palais du Louvre - Paris
Porte Jaujard
téléphone : 01 40 20 24 20
télécopie : 01 40 20 24 47

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RÉPUBLIQUE FRANÇAISE

Ministère
Culture
Communication

Monsieur,

En tant que chef du département recherche du Centre de Recherche et de Restauration des Musées de France, je tiens à vous apporter tout mon soutien ainsi que celui de l'équipe AGLAE au projet PIXE-RFQ.

Dès 1988 le C2RMF a conçu un système d'analyse basé sur un accélérateur de particules dédié aux objets du patrimoine culturel dans les sous-sols du palais du Louvre. Depuis, l'équipe AGLAE n'a eu de cesse de développer et d'optimiser la ligne de faisceau extrait pour une caractérisation totale des matériaux anciens aux propriétés et aux contraintes si particulières. Le projet Equipex New AGLAE, actuellement en cours, s'inscrit dans la même dynamique et l'un de ses objectifs majeurs consiste à concevoir et mettre en œuvre un multi-détecteur PIXE-PIGE-RBS-IBIL capable d'effectuer de l'imagerie chimique systématique. Celui-ci est opérationnel depuis 2012 et les outils de traitement de données et d'image sont actuellement en cours de développement.

L'une des limites actuelles concernent les objets que l'on ne peut déplacer et amener à AGLAE, tels que certains objets de collections de musées trop lourds ou volumineux, ou des éléments de monuments historiques (sculptures, retables, carreaux de parement, sarcophages…). Concevoir un « AGLAE transportable » sur un site du patrimoine culturel est alors un défi qu'il est très intéressant de relever.

Si votre projet voit le jour, l'équipe AGLAE s'engage à apporter ses connaissances et ses compétences dans la réalisation d'un système de détection réunissant plusieurs techniques d'analyse par faisceau d'ions.

Je reste à votre entière disposition pour toute information complémentaire et vous prie d'agréer, Monsieur, l'expression de mes sentiments les meilleurs.

Michel Menu
Chef du Département Recherche

AMC support to the MACHINA project (at the time PIXE-RFQ)

10 March 2017
Dept of Medical Biology, Academic Medical Center,
Amsterdam, The Netherlands

To: KT Fund Selection Committee, CERN.

Subject: Letter of support for the *PIXE-RFQ* project.

Dear members of the Selection Committee,

With this letter, we would like to express our strong support for the *Design & construction of a transportable RFQ for PIXE analysis* (*PIXE-RFQ)* project. Beyond its potential to revolutionize the accessibility of PIXE analysis technology, this project is uniquely positioned to overcome an important obstacle in basic research on biomolecular effects of proton radiation.

Should *PIXE-RFQ* be approved by CERN, we expect that the resulting design can become the foundation for our bioresearch-oriented system. Our team is a broad coalition of industry and leading scientists from multiple disciplines, our research questions are timely and relevant. We are thus confident that based on the *PIXE-RFQ* design our project has a considerable chance for success. This would not only enable basic investigations of high relevance in cancer research, but also open exciting avenues for utilization of the mini-RFQ design developed by CERN.

With best regards,
Przemek Krawczyk, PhD,
on behalf of the project team:

MACHINA timeline

The INFN-CERN MACHINA project financed by the Fondo integrativo Speciale Ricerca (FISR prot. n. 21264, 21 December 2017). The CERN Knowledge Transfer Group financed the cavities (PIXE RFQ project)

1. The MACHINA project is operational since February 2018

2. 2018-19: INFN and CERN proceeded in parallel
   INFN ⇒ source, low energy beam transfer line, high energy beam transfer line, hardware and software of the control system
   CERN ⇒ design, machining and test of the accelerating cavitiy (RFQ), design of the RFQ PS

4. Summer 2020: CERN and INFN completed the subsystems, which are then merged in one single system

5. September 2021: also the RF-PA finished. Start conditioning

6. May 2022: the first 2 MeV proton beam extracted in air at CERN

7. September 2023: we finally got the authorization to switch on the MACHINA 2 MeV proton beam in Italy

a prophetic vision…

IBA 2015

IAEA Panel on

IBT Roadmap

Aliz Simon

IAEA
Division of Physical and Chemical Sciences
Physics Section

The development of **smaller transportable accelerators** would open new fields, in particular in those applications, as cultural heritage, where the vast majority of the world cultural heritage is immovable. The impact of laboratory based analytical techniques could diminish in the future with the advent of more and more performing ED-XRF systems for elemental analysis of cultural heritage objects

Layout

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3. Status, Activities in progress and Perspectives

MAIN FEATURES OF MACHINA

Accelerator:

- Source, LEBT and HEBT: 1.5 m x 1 m, 1 kW, 400 kg
- 2 HF-RFQ accelerating cavities: 1 m x 0.4 m, 100 kg mass
- *Accelerator system: 500 kg, 2.5 m x 1 m, 1 kW*

Ancillaries:

- RFQ Power supplies*: 860 kg, 2.5 m x 1 m, 14 kW*

MACHINA SYSTEM

- 7 independent elements on wheels, can be moved separately
- overall footprint: less than 10 m^2
- Mass ~1400 kg
- Power absorption about 16 kW

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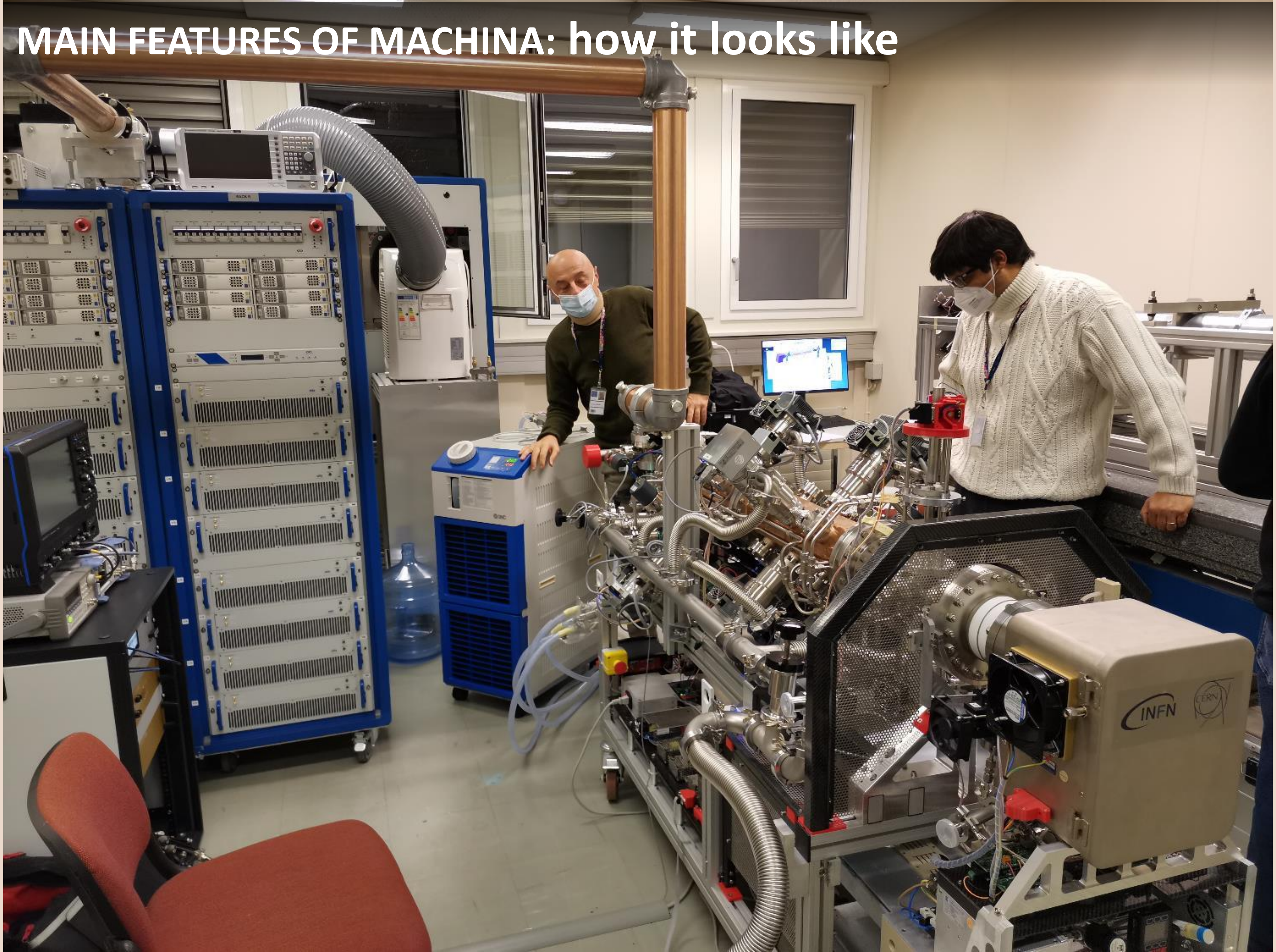
MAIN FEATURES OF MACHINA: how it looks like



CERN

Source

Many possible choices (RF, duoplasmatron, CS sputter, …)

Main requirements (from the accelerator):

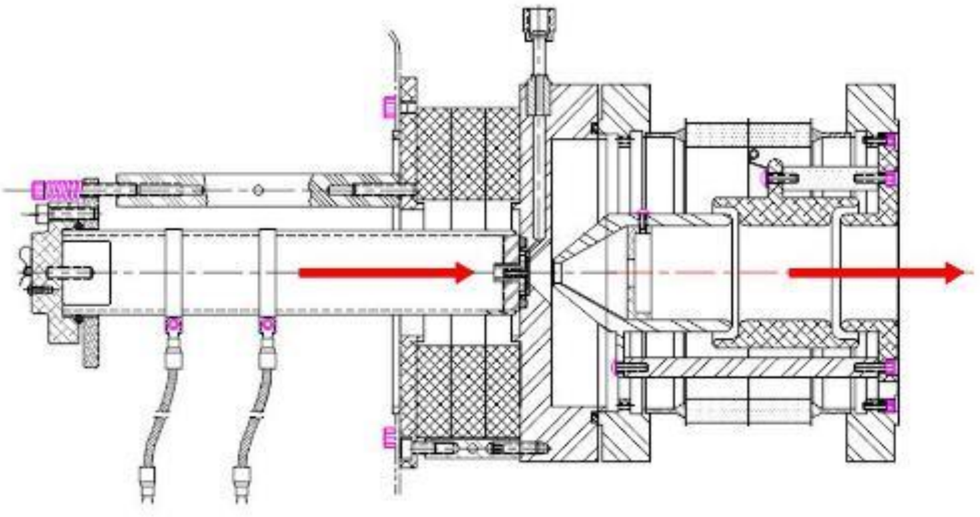
- **20 keV proton beam**
- **± 0.5 mm at the RFQ entrance plane**
- **± 40 mrad at the RFQ entrance plane**
- **No water cooling, low weight and power**

No need of:

- **High beam current**
- **Very low emittance**

The above points can be accounted for by a RF source permanent magnets

Bottle, RF, Screen box and Einzel lens by NEC
All the other parts (gas circuit, HV desk, control electronics and software) developed by the the MACHINA collaboration



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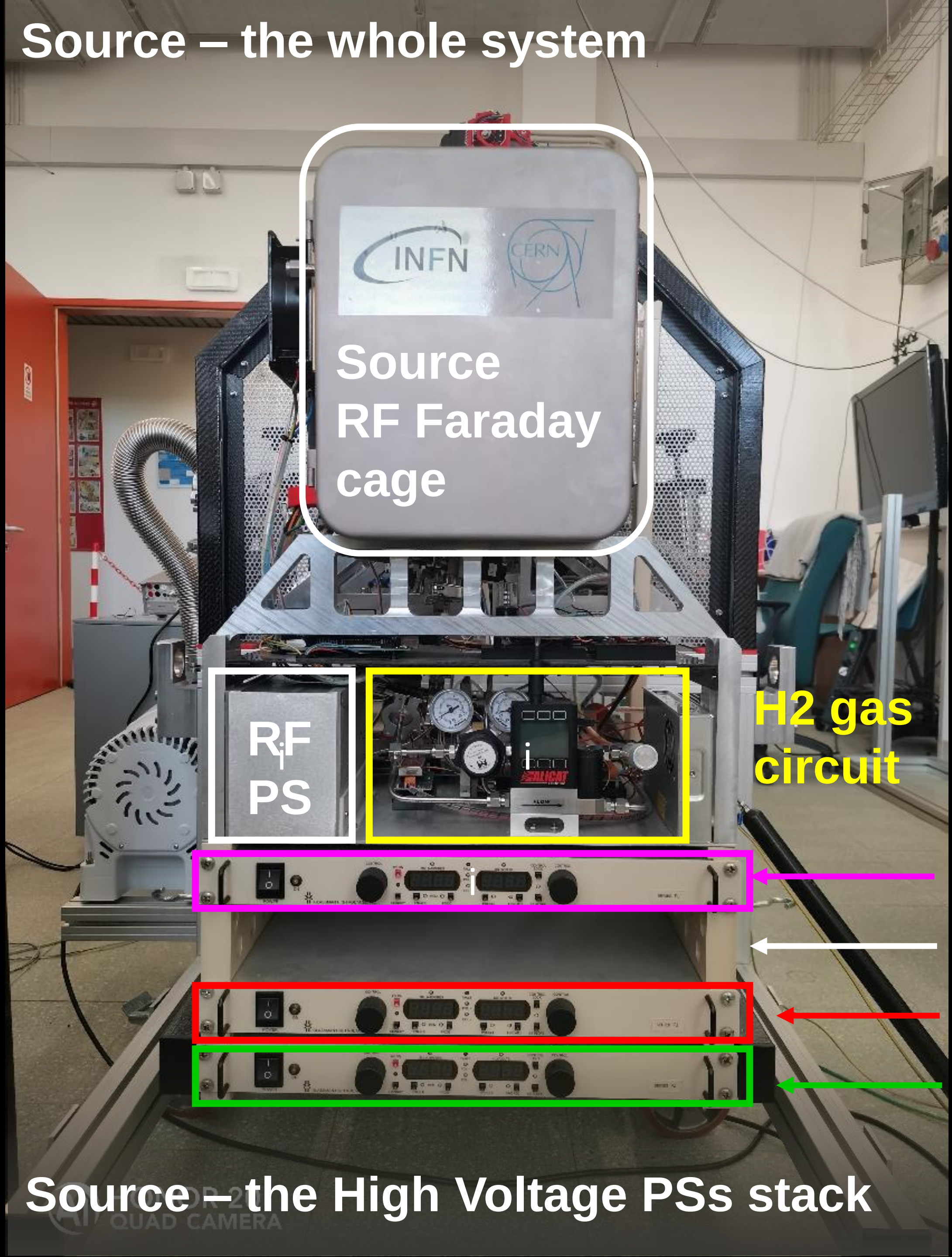
Source – the whole system



Probe PS

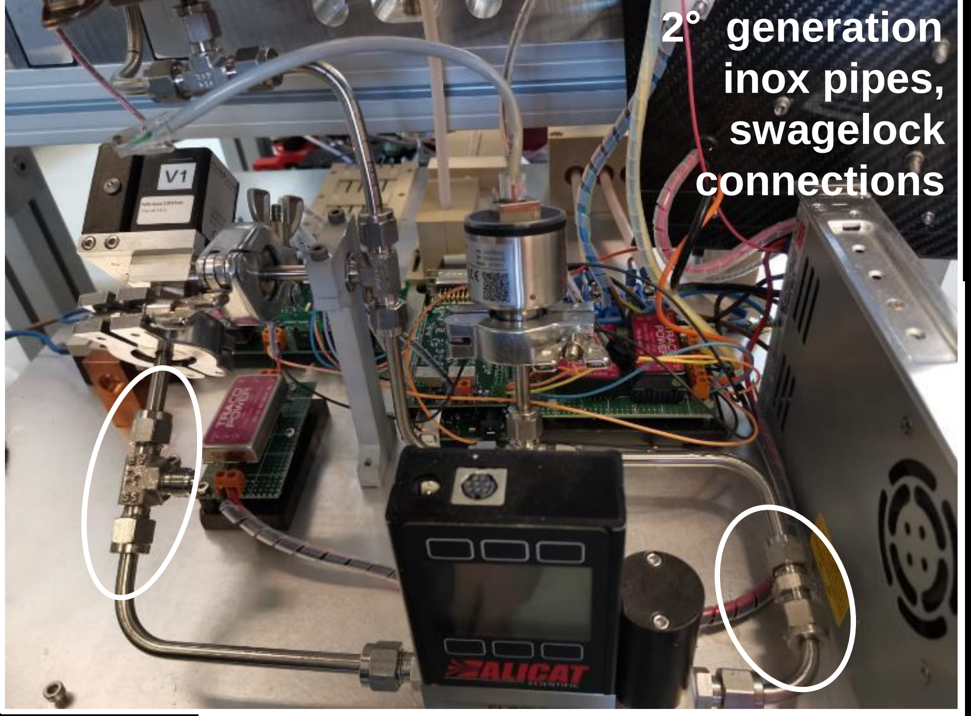
Peek Plates hold the HV Deck

Extraction PS

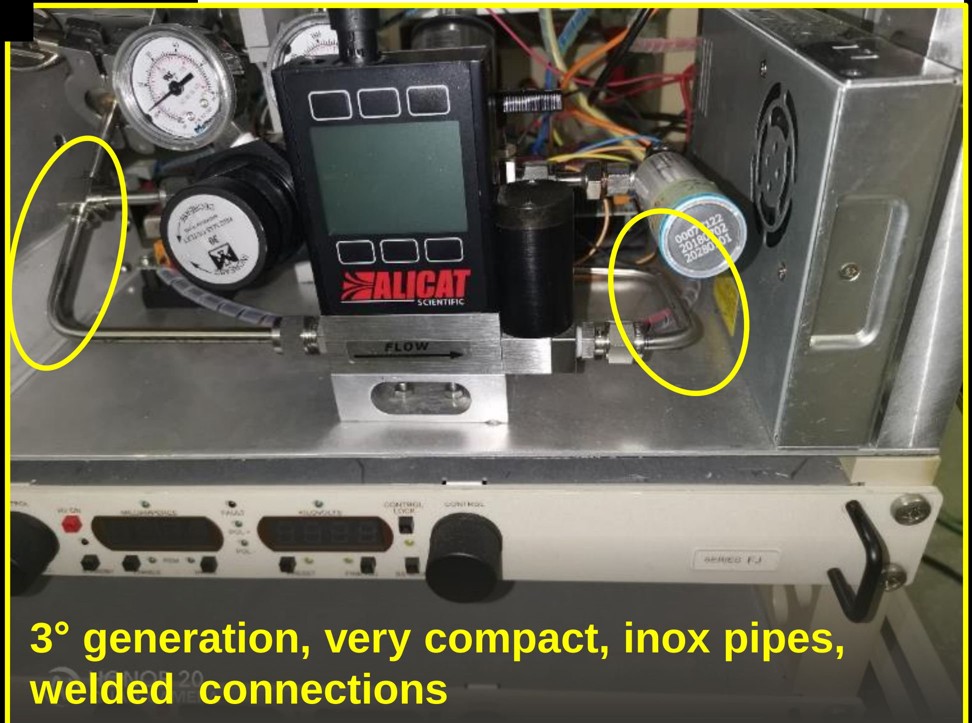
Einzel lens PS

Source - Gas line

Original gas circuit, mostly plastic pipes, big vessel



2° generation inox pipes, swagelock connections



3° generation, very compact, inox pipes, welded connections

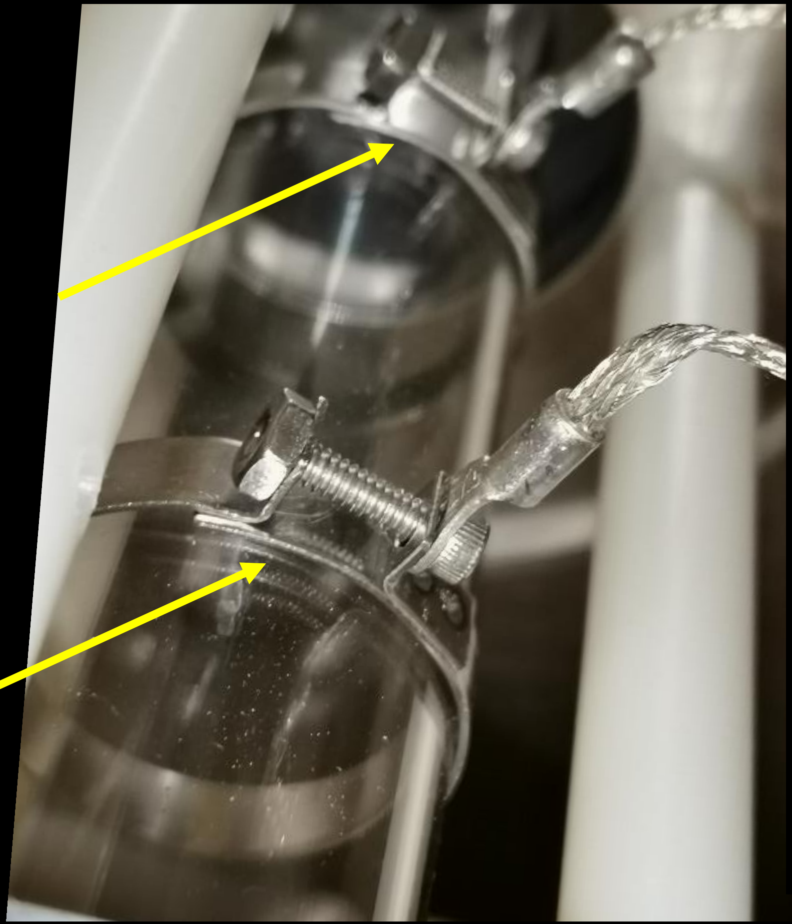
Source – the mass flow controller

Source mass flow controller (light on):
gas flow 0.075 sccm
HV Probe PS: 0.1 mA, 2.30 kV

Source – the quartz bottle for beam creation

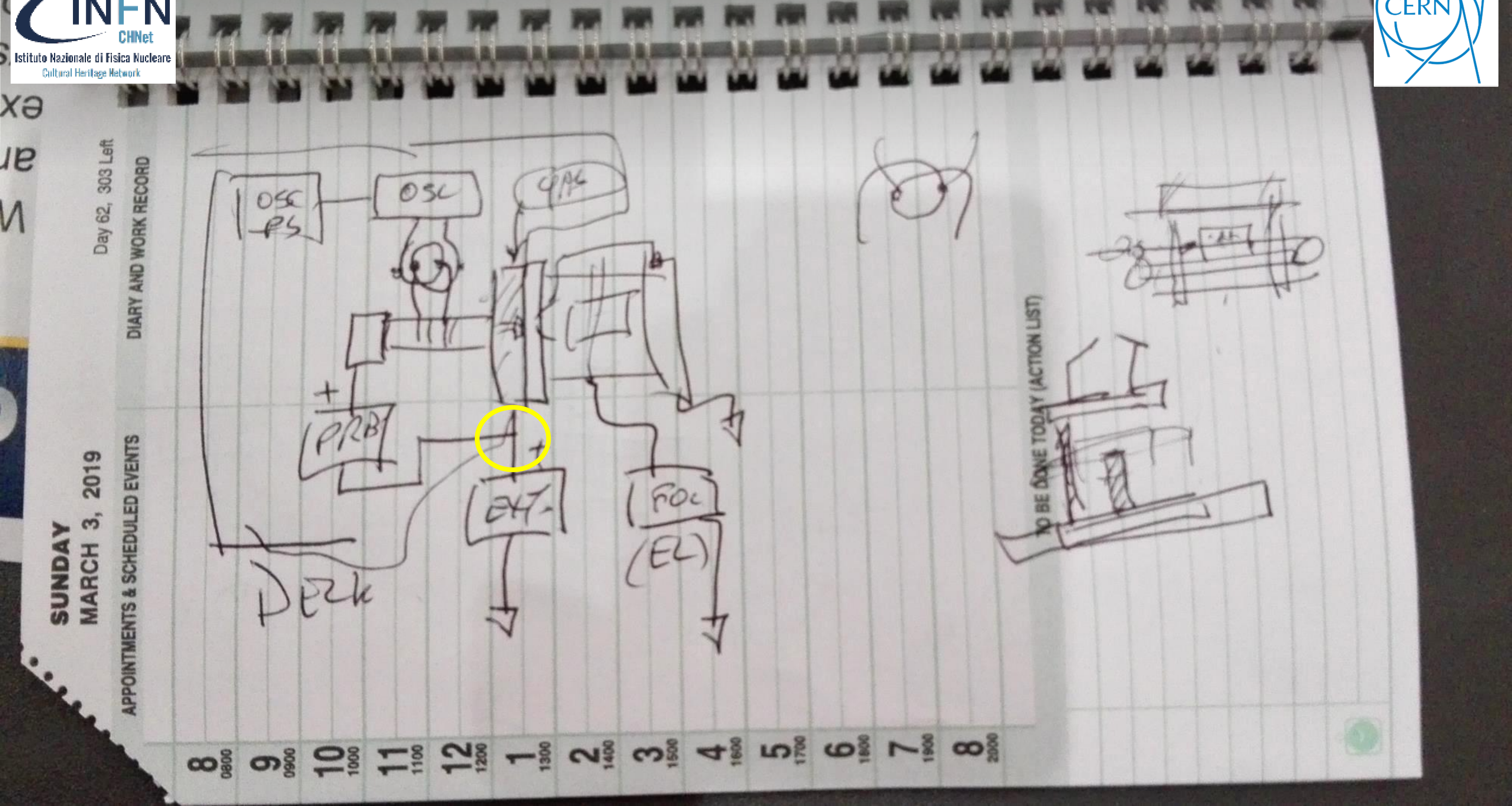
The quartz bottle, with the electron dumper (back metal plate), the white insulating rods holding the probe voltage which moves the particles out of the source

The connections for applying the RF potential to the gas



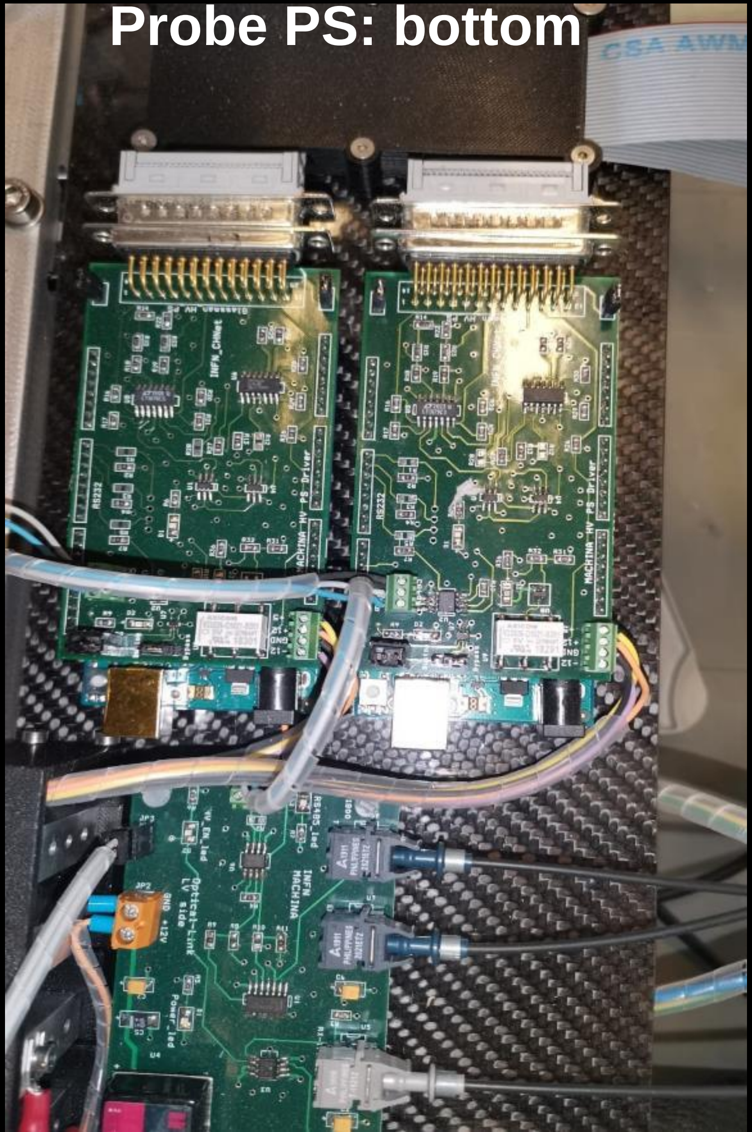
The hole where the beam particles exit from and are injected into the LEBT after acceleration from the extraction voltage

Source – the electrical scheme

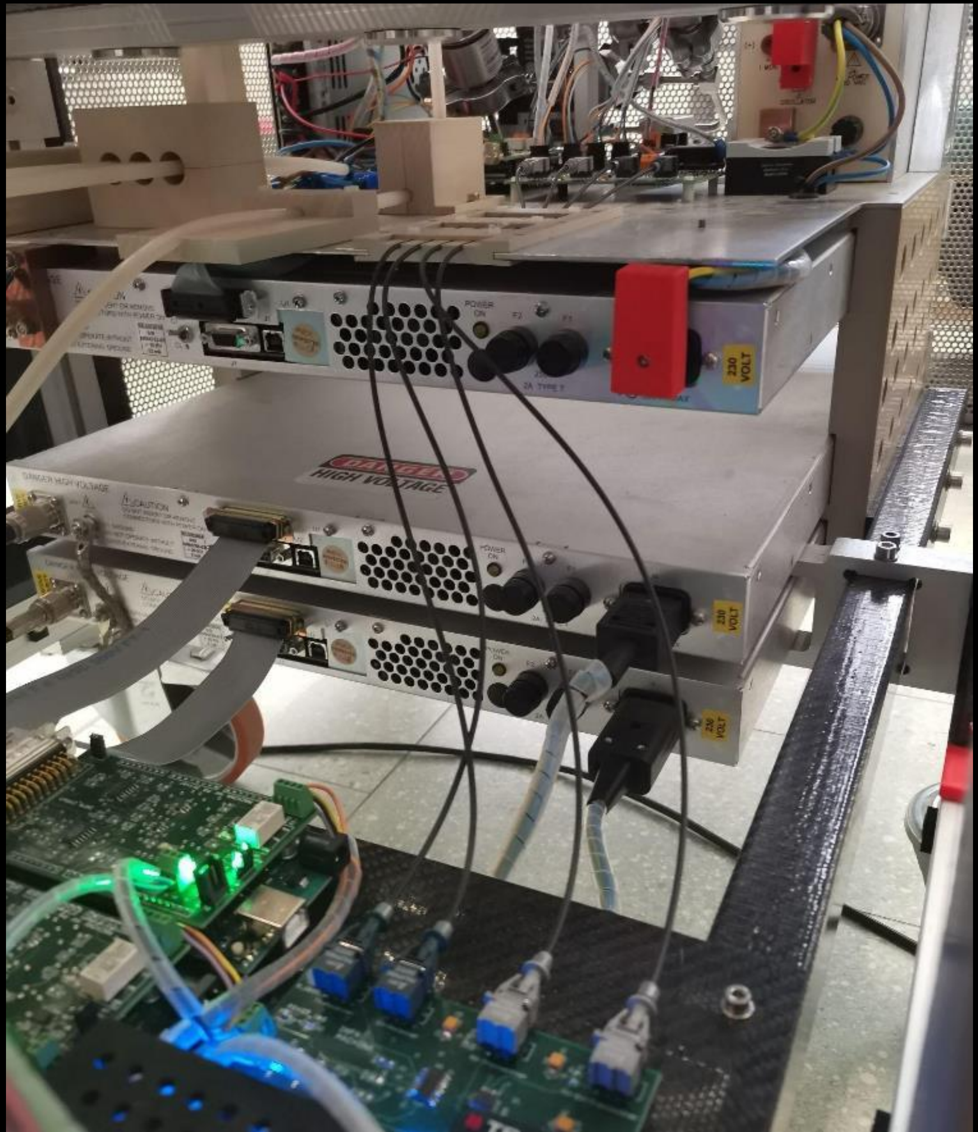


Source – HV PS hardware and control software

Control boards
Extraction PS: up left
Einzel lens PS: up right
Probe PS: bottom

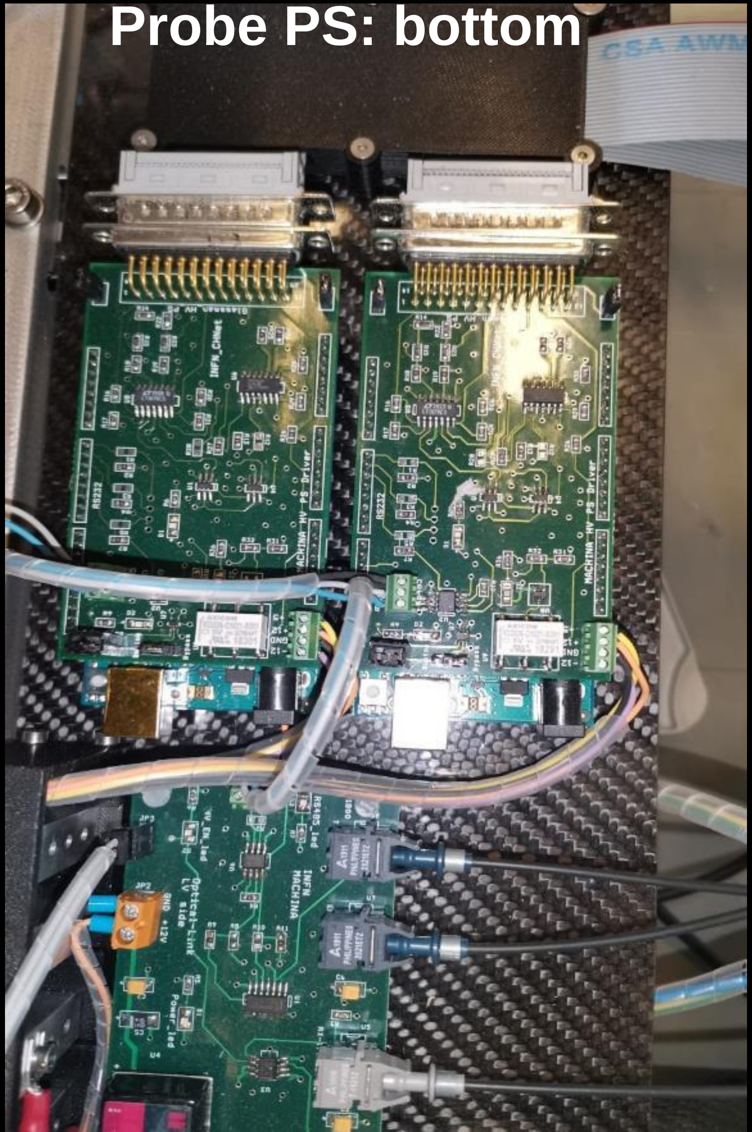


Optical fibres to control the Probe PS@HV

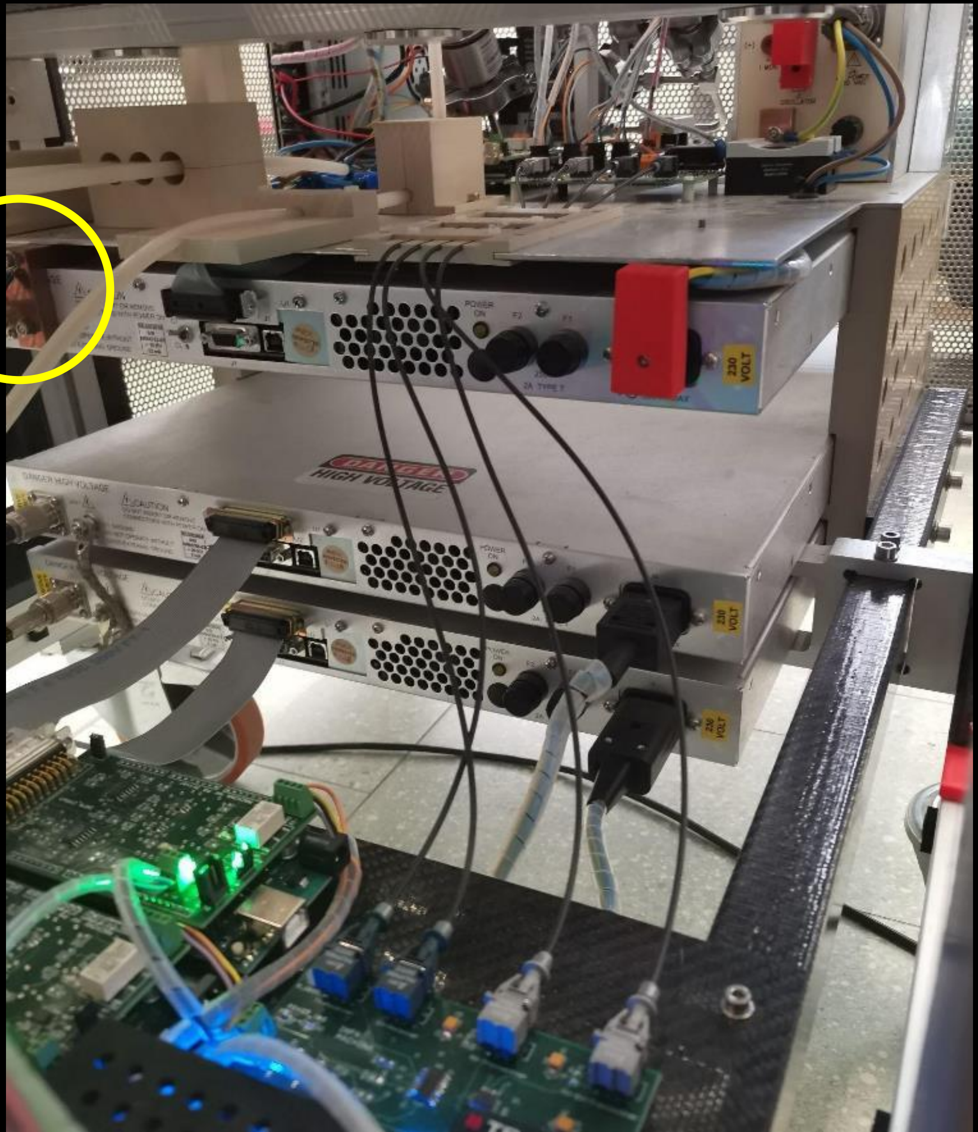


Source – HV PS hardware and control software

Control boards
Extraction PS: up left
Einzel lens PS: up right
Probe PS: bottom



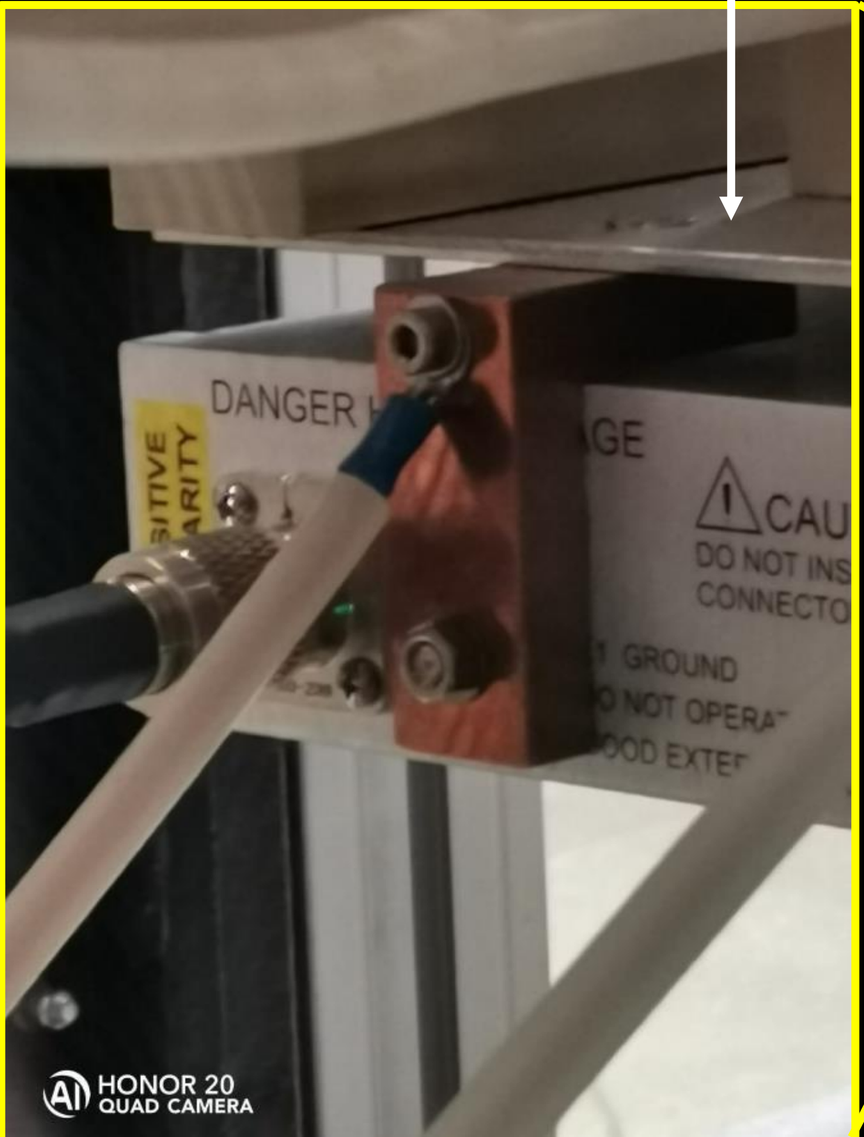
Optical fibres to control the Probe PS@HV

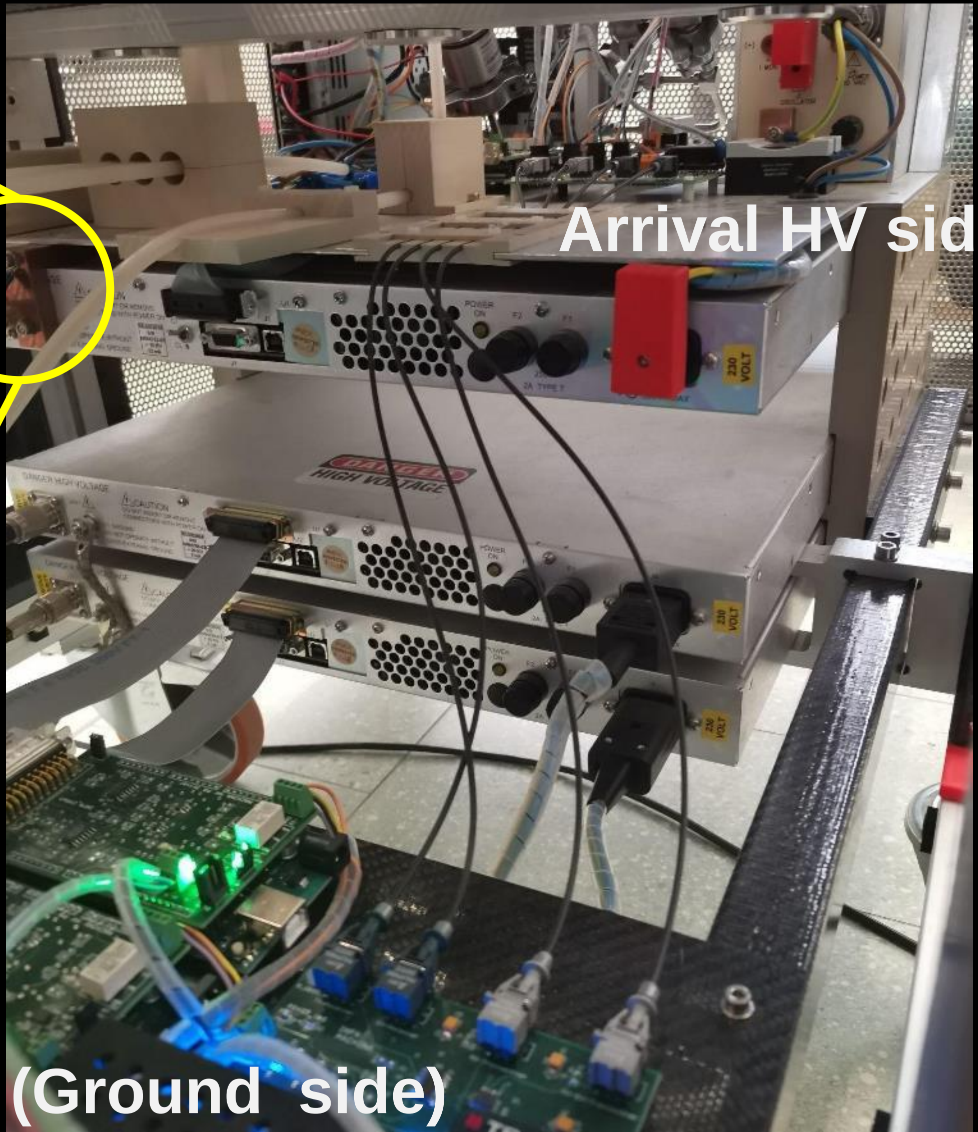


Source – HV PS hardware and control software

Off ground mass connection for the High Voltage deck

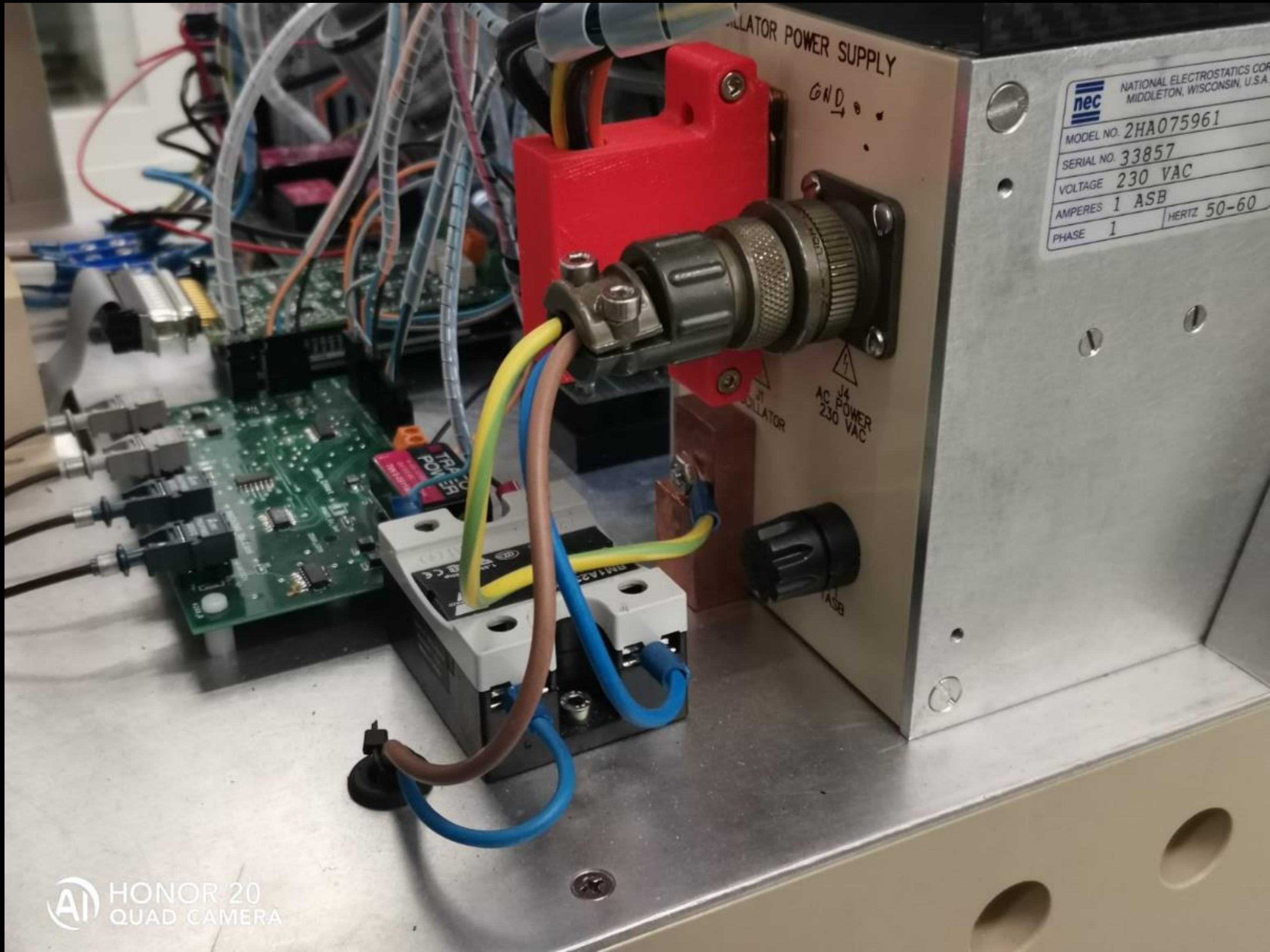
Optical fibres to control the Probe PS@HV



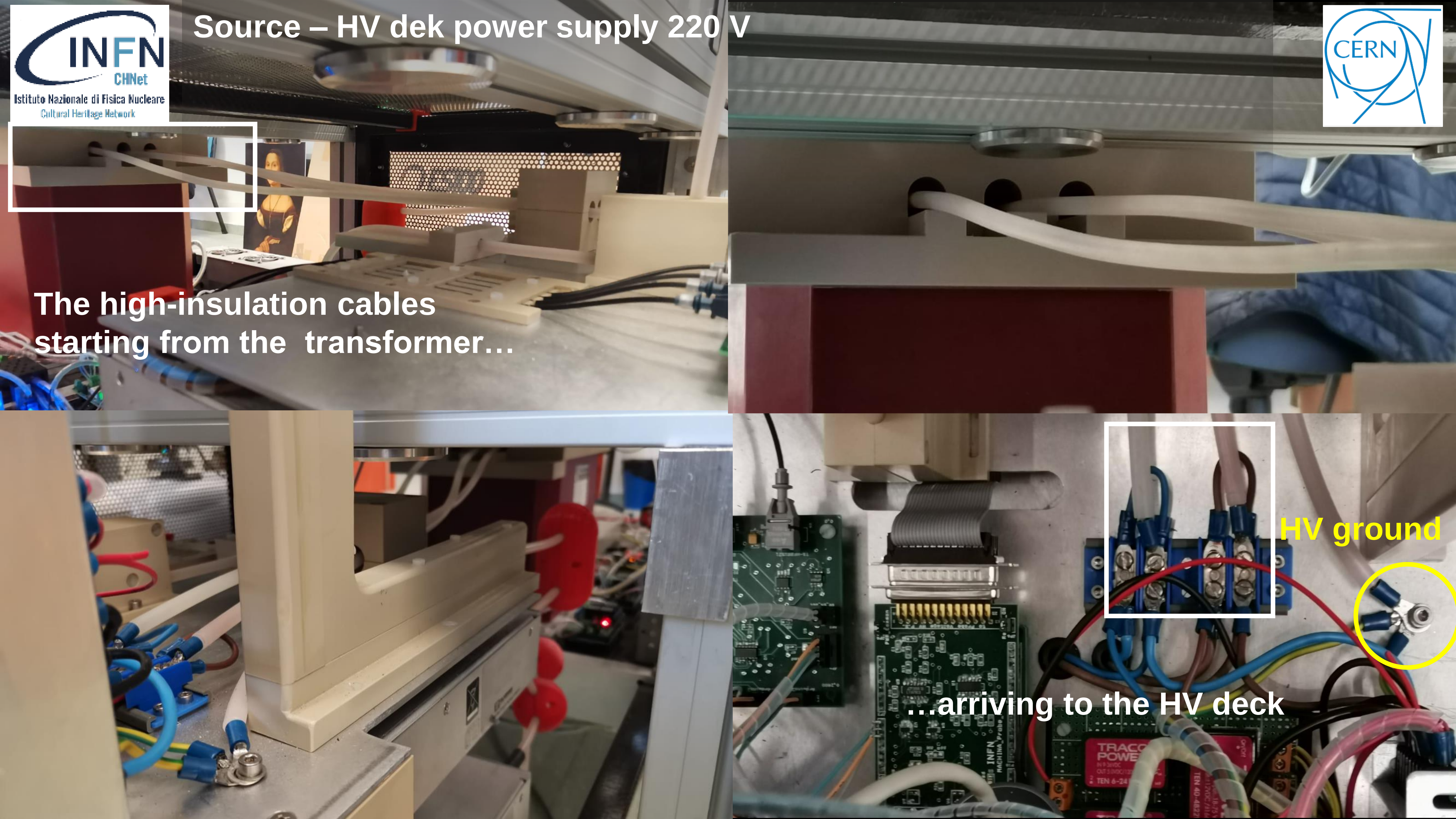


Source – HV PS hardware and control software

HV deck
100 MHz Source RF oscillator power supply and control relay

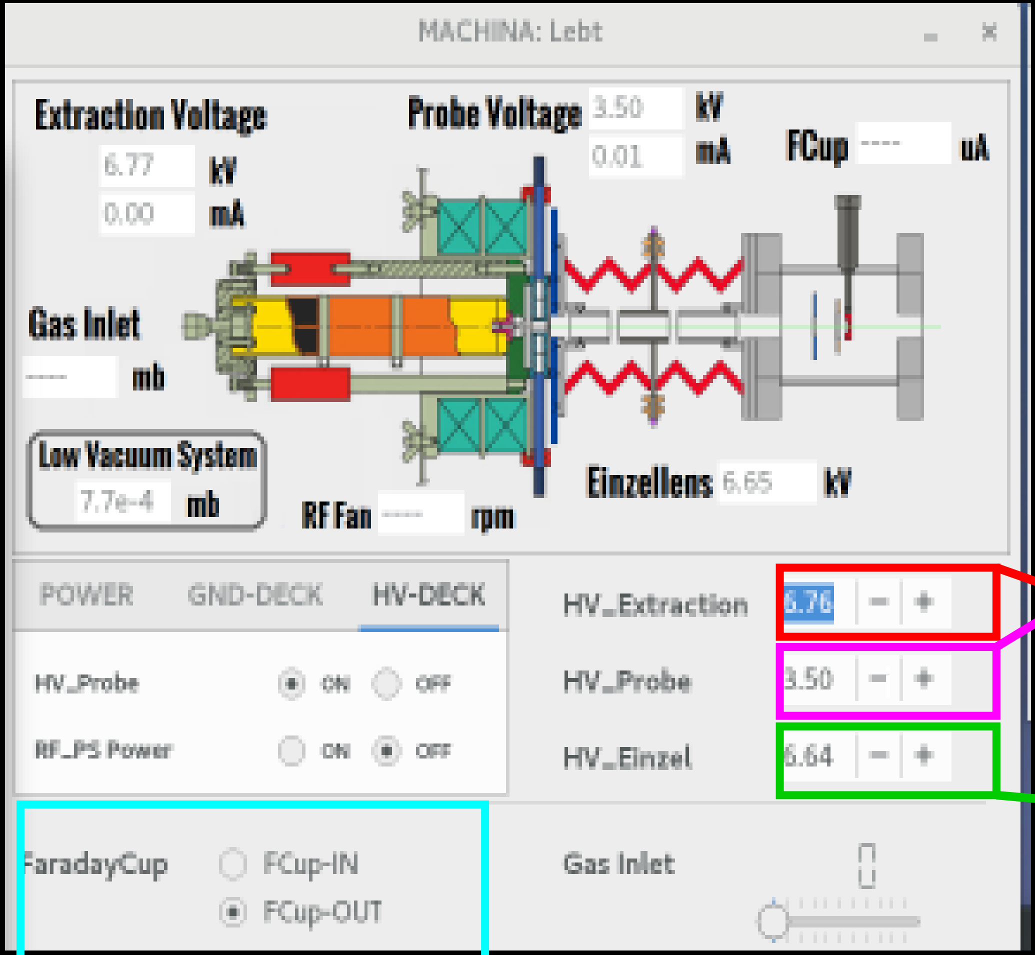


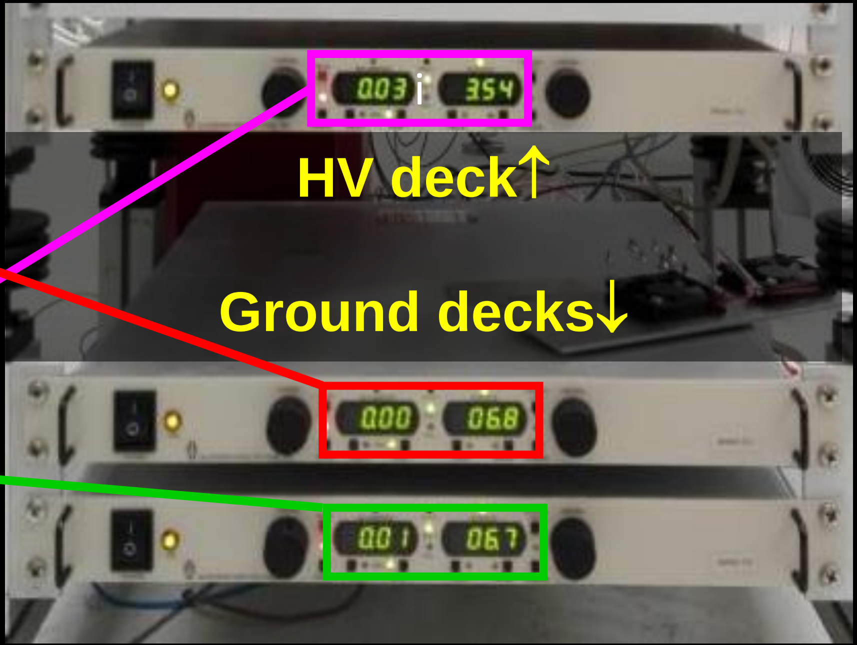
Source – HV dek power supply 220 V



Source – HV PS hardware and control software

extraction, probe, Einzel lens
switch (on/off)
HVs set (kV)
HVs readout (kV & mA)

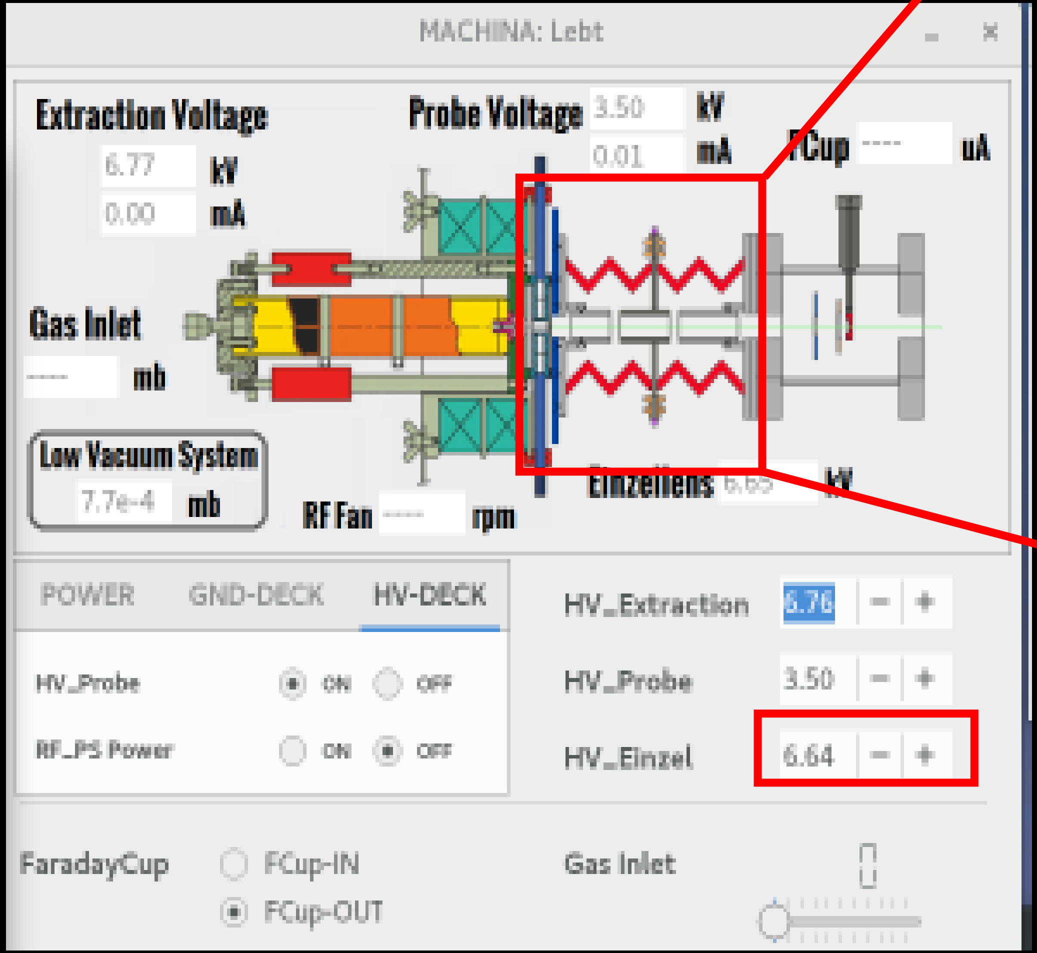


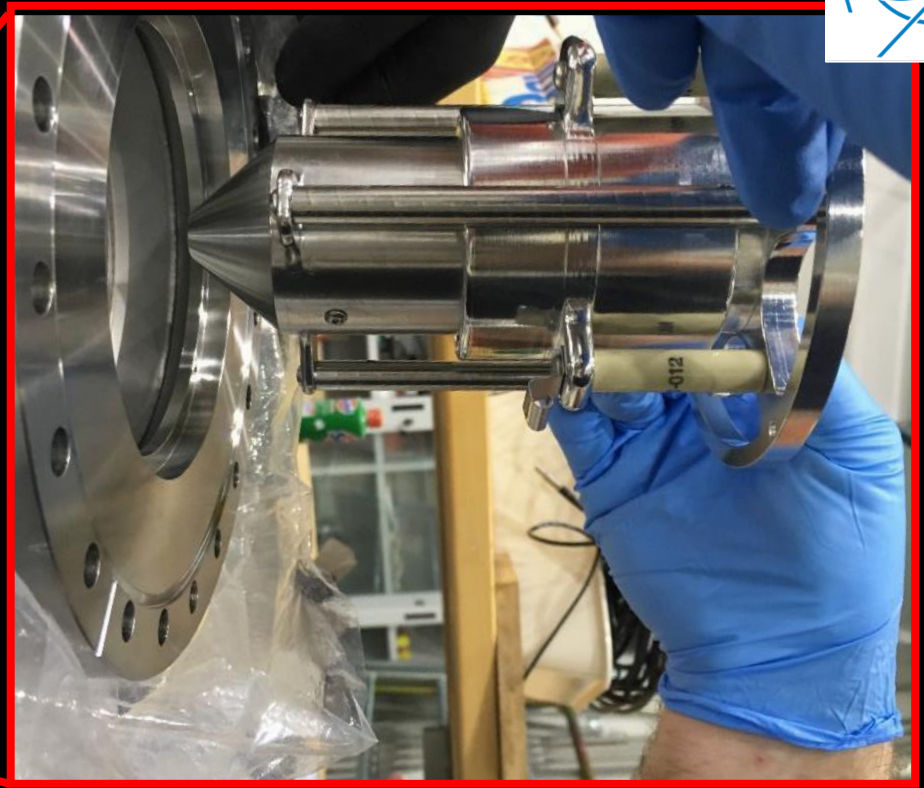


Faraday cup control

Source – Einzel lens

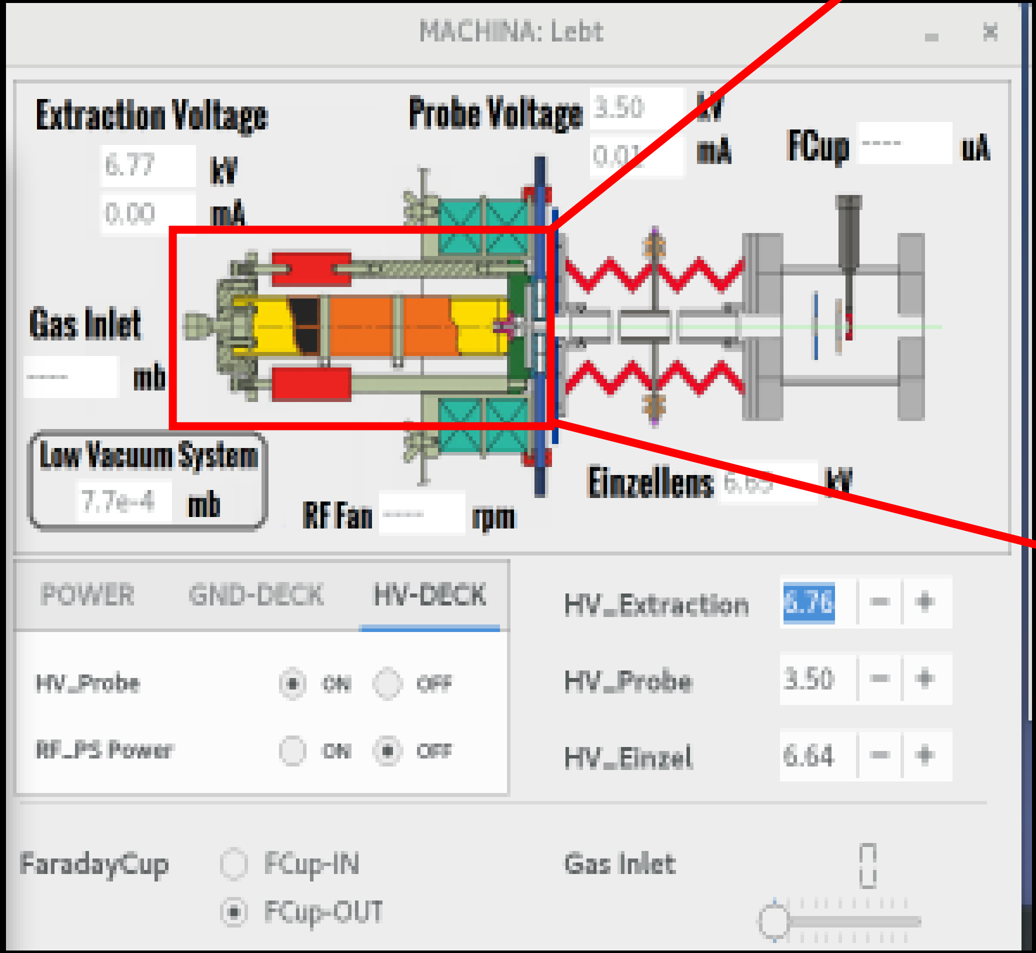
Extraction HV, probe HV, Einzel lens HV switch (on/off)
HVs set (kV)
HVs readout (kV & mA)





Source – probe HV

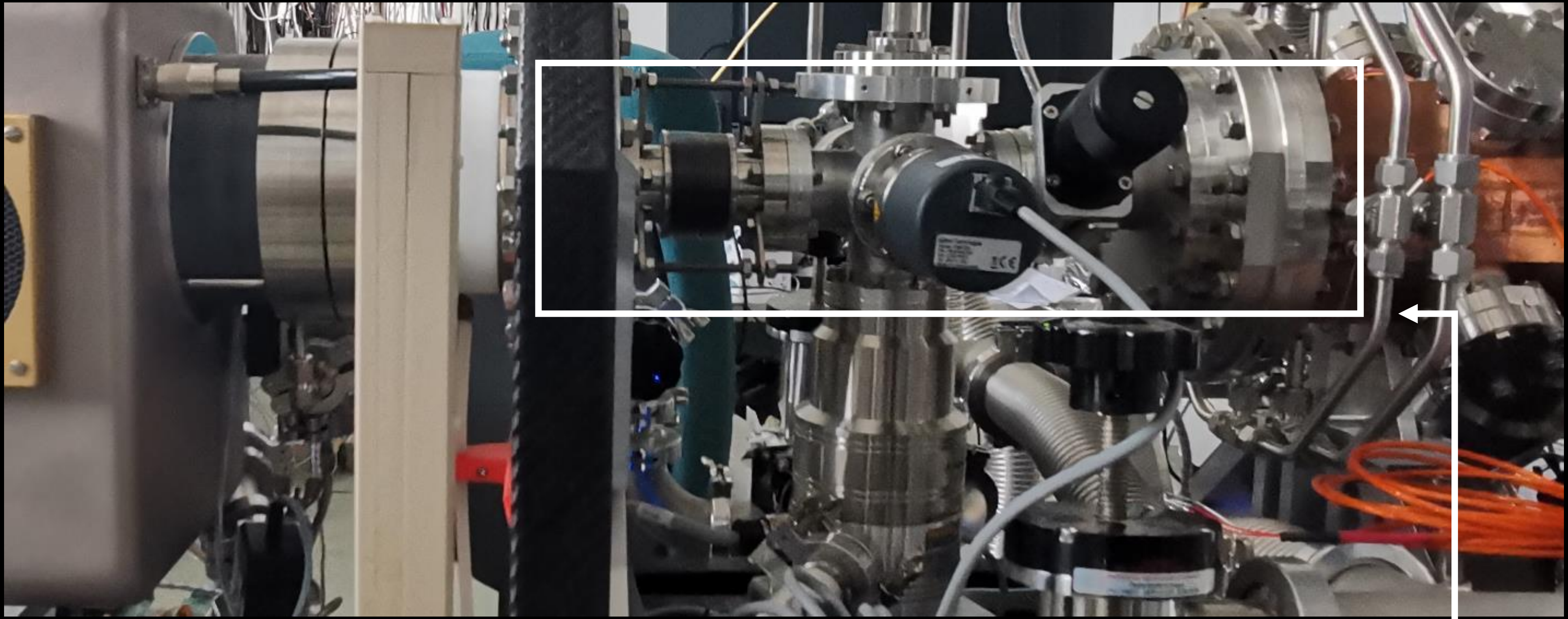
extraction, probe, Einzel lens HV
switch (on/off)
HVs set (kV)
HVs readout (kV & mA)



Source and LEBT – beam injection

Energy 20 keV
Accelerator acceptance $\varepsilon_{acc} = 30\ \pi$ mm mrad
Source emittance is $\varepsilon_{source} = 28\ \pi$ mm mrad.
Direct beam injection into the RFQ is possible,
No active elements required

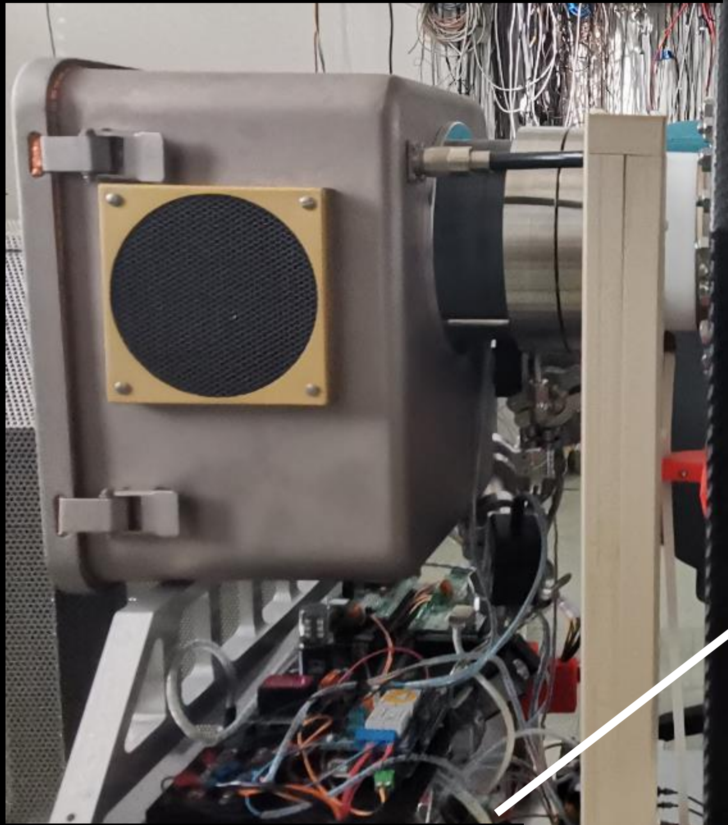
Source and LEBT – beam injection

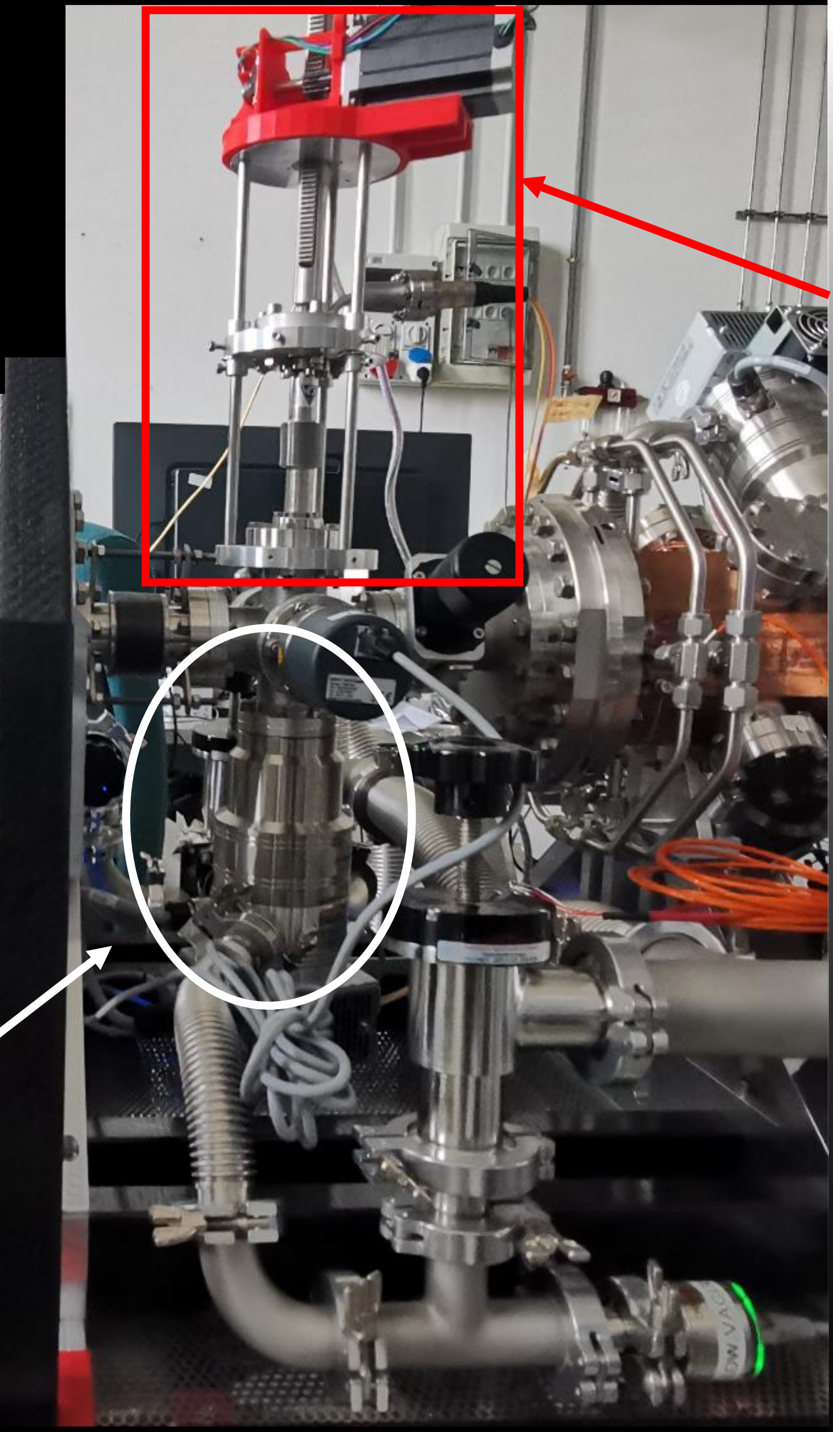


Energy 20 keV
Accelerator acceptance ε_{acc} = 30 π mm mrad
Source emittance is ε_{source} = 28 π mm mrad.
Direct beam injection into the RFQ is possible,
No active elements present:
from left: bellow, 6 way cross (FC, turbo, vac gauge, viewport), gate valve

Source and LEBT – the whole system

The gas load from the source is ~10^{-4} mbarl/s, almost negligible with respect to the turbopump throughput (about 1 mbar l/s)





LEBT control Faraday cup

Thus, a single 84 l/s turbopump, 3.4 kg, is enough to have the LEBT in the 10^{-6} mbar scale when the source is switched on

INFN CHNet
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Cultural Heritage Network

LEBT – the Faraday cup

CERN

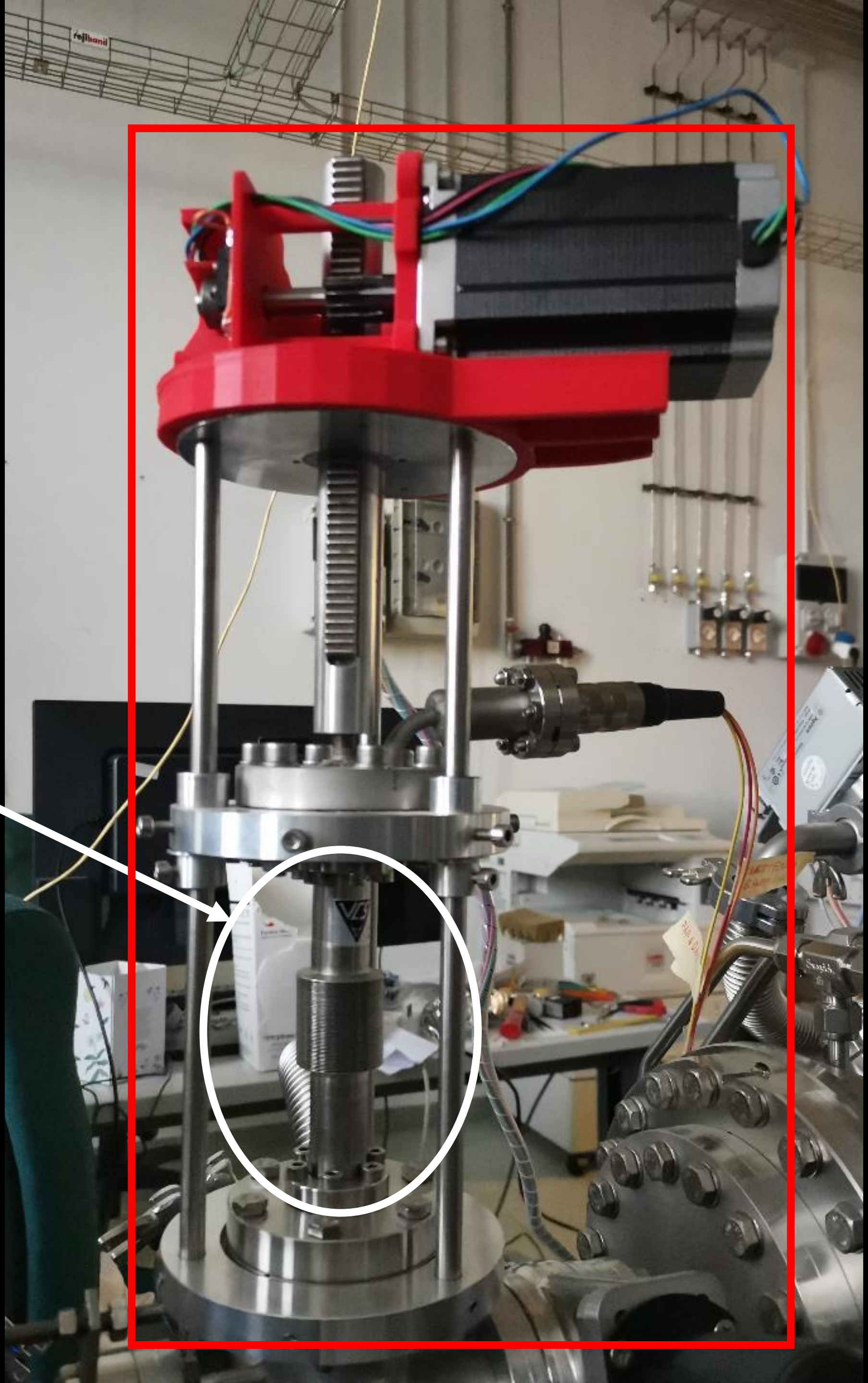
Checking…
Discharge due to beam charging

Connector and cable for screen, guard ring and Faraday cup
Middle: 50 mm long bellow for axial movement

LEBT – the Faraday cup

beam current measurement

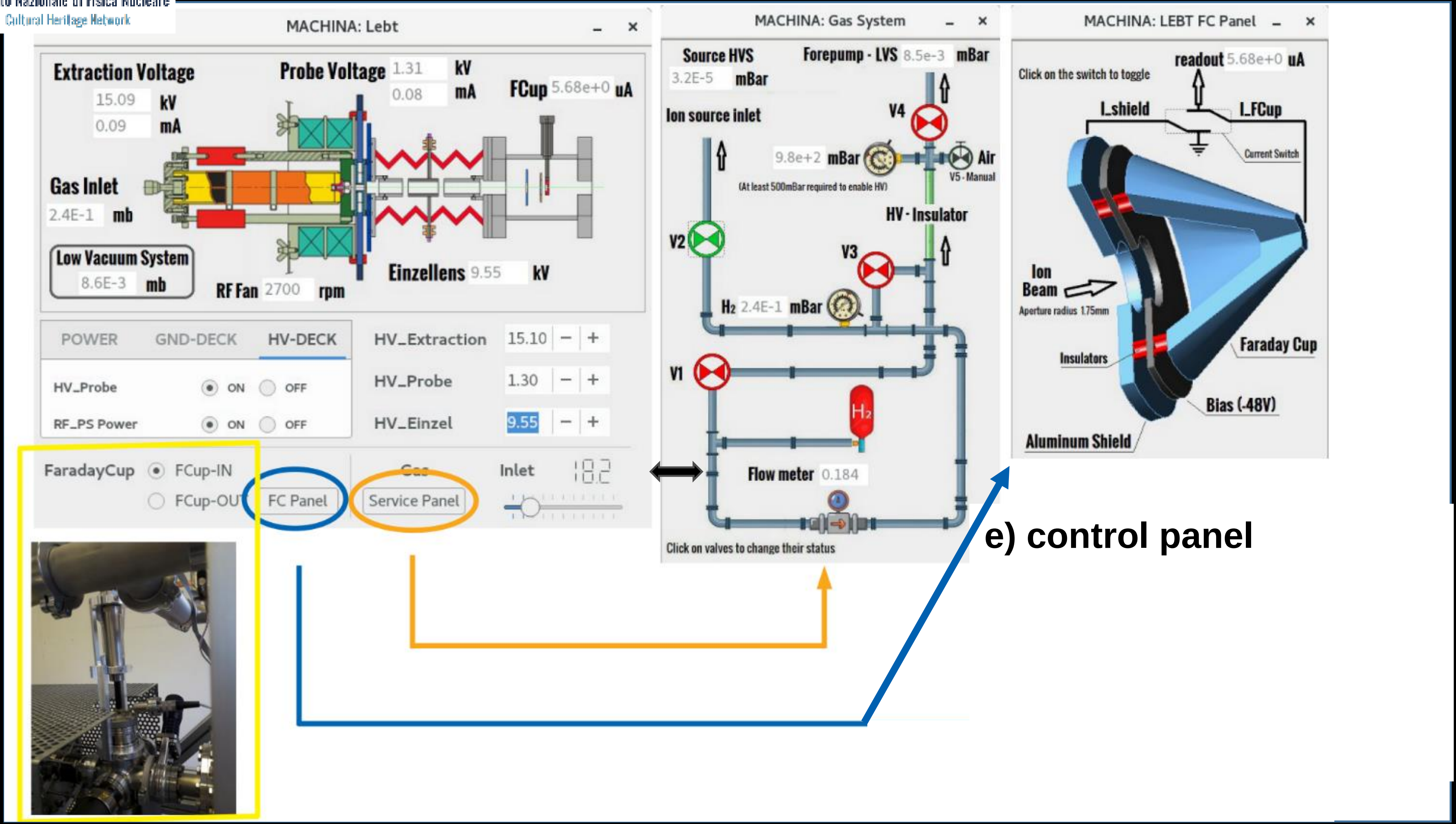
The FC is naturally inserted on the beam path, due to the air pressure.
The FC can be extracted only by activating the FC stepper motor.



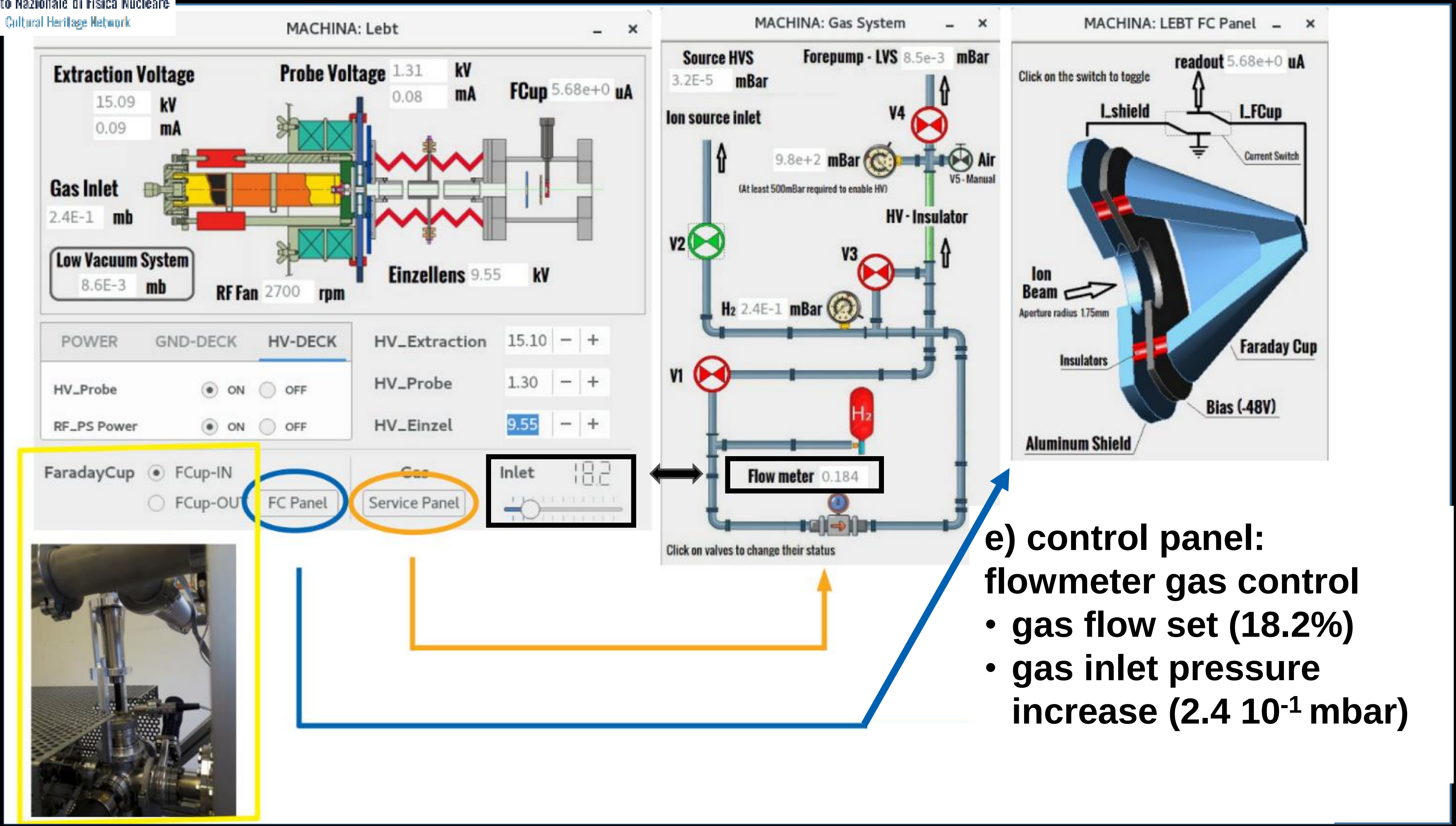
The beam can
be accelerated only if
the radioprotection interlocks
allows powering the FC motor

Radio-safety assured!

Source and LEBT – working



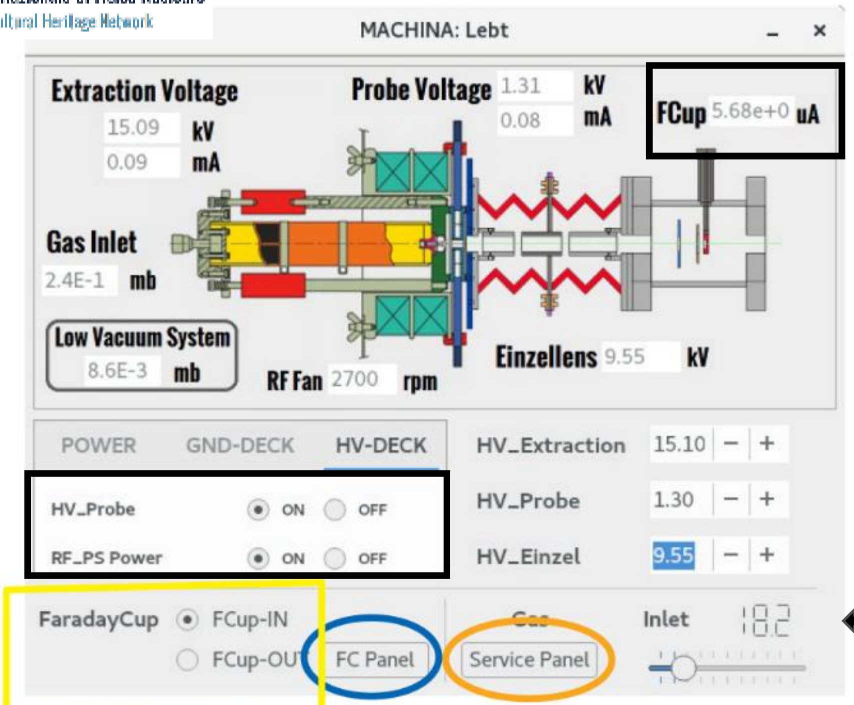
Source and LEBT – working

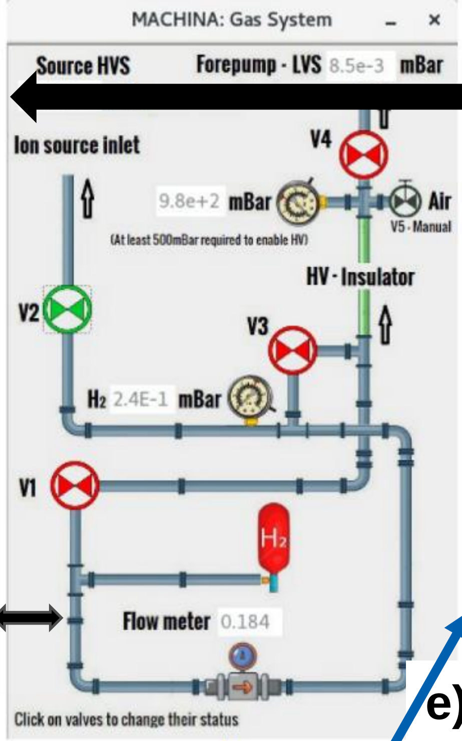


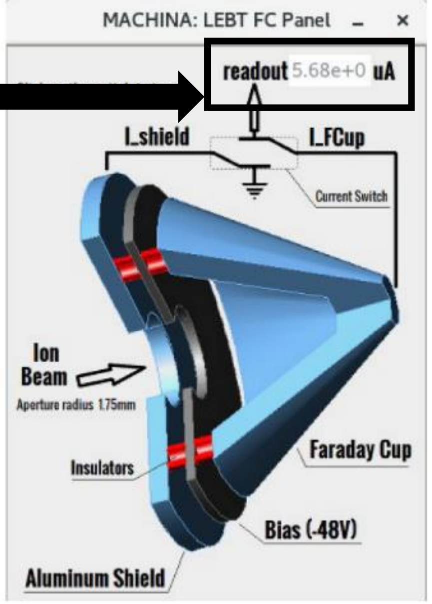
e) control panel: flowmeter gas control

- **gas flow set (18.2%)**
- **gas inlet pressure increase (2.4 10^{-1} mbar)**

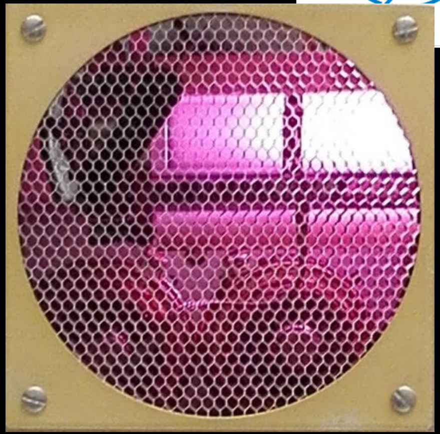
Source and LEBT – working







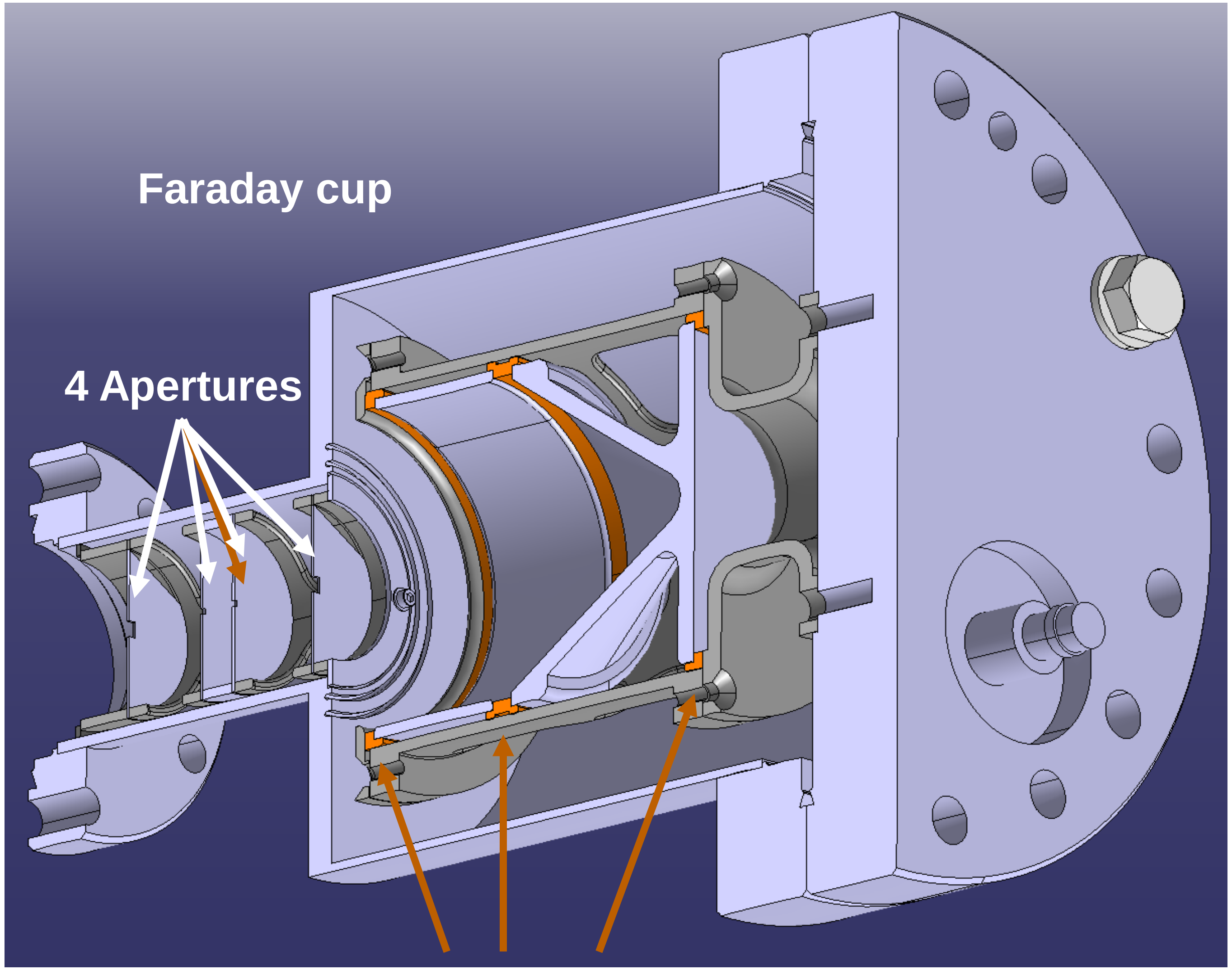
e) control panel: switching on the source
- **RF PS on**
- **current in FC (5 μA)**



the source switched on

Source and LEBT – working

ION SOURCE ACCEPTANCE TEST (02&03/2020)



Bias rings

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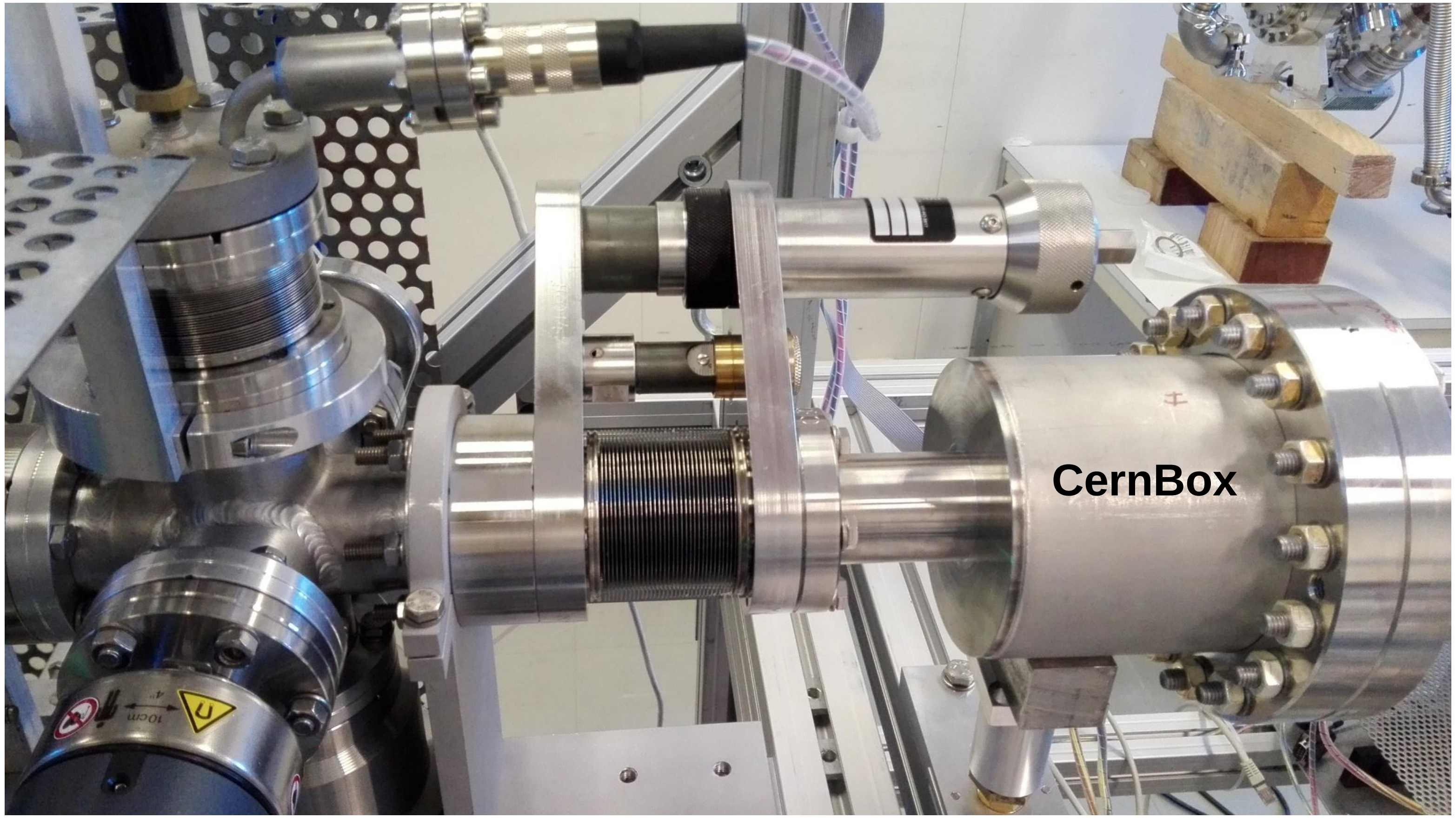
ION SOURCE ACCEPTANCE TEST (02&03/2020)

CERN



TDR: minimum acceptable value for beam current: 400nA

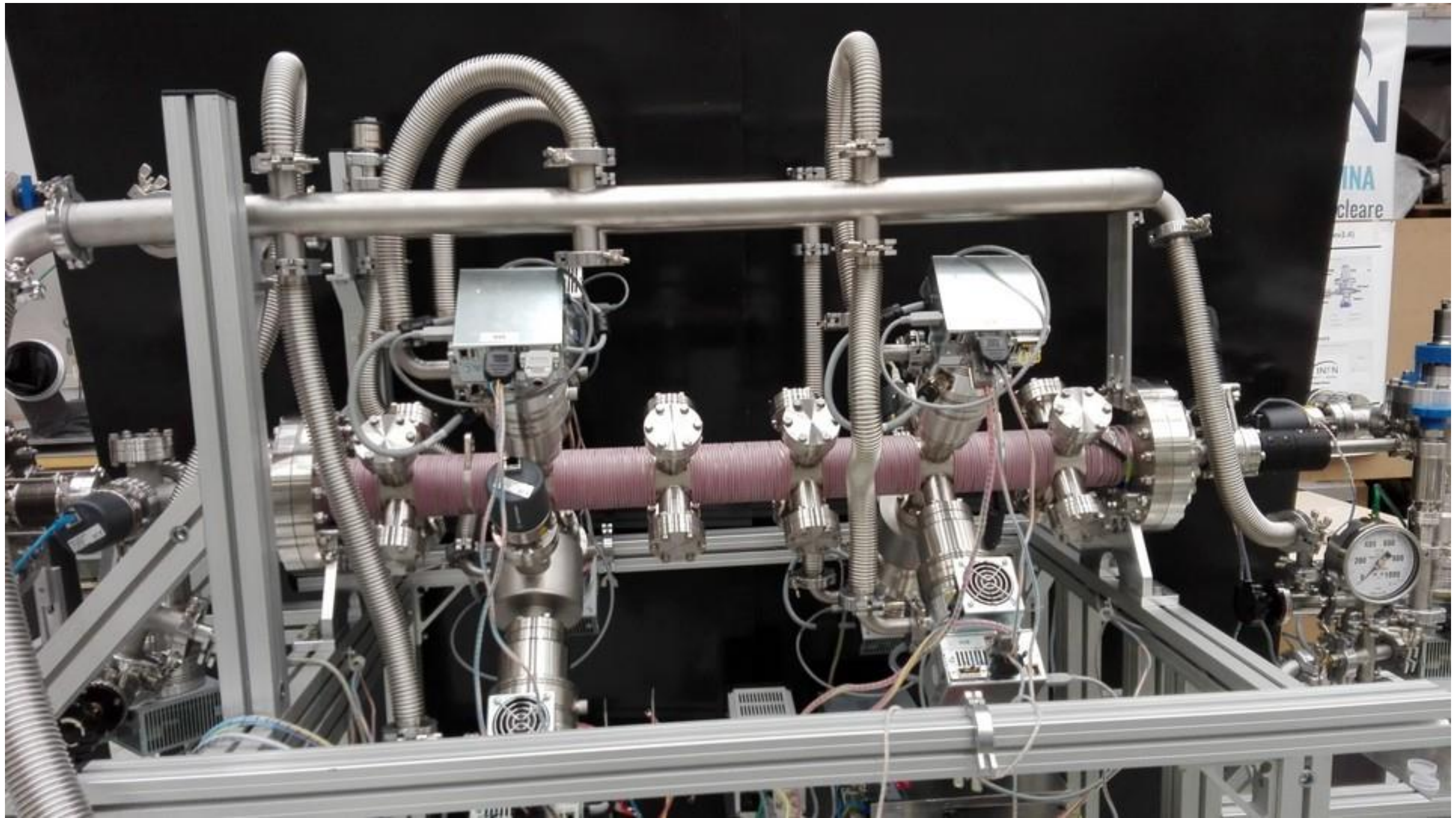
Measured current at RFQ entrance: 1.65 uA

DUMMY ACCELERATOR for testing the VACUUM- and CONTROL-SYSTEM (08/2018 - 12/2018)

a dummy system with the same
- dimensions and volume,
- flanges/ports,
- and the same vacuum conductance as the RFQ system

the vacuum system was subsequently populated with:
- LEBT: 1 turbo pump (1HV Gauge)
- RFQ: 7 turbo pumps (2HV Gauge)
- HEBT: 1 turbo pump (1HV Gauge)
- 1 common LV Gauge

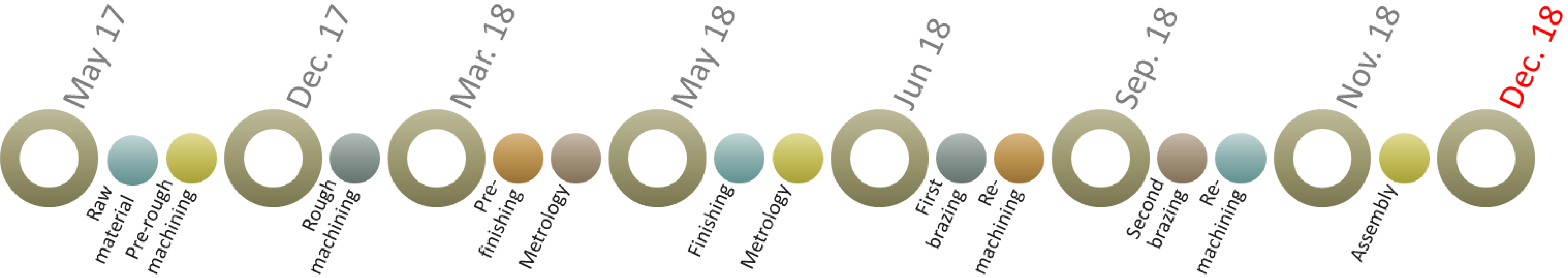
TWIS TOR 74/84



Accelerator

RFQ (production workflow)

the construction of RFQs is a very long and delicate process, because errors are almost always irreversible



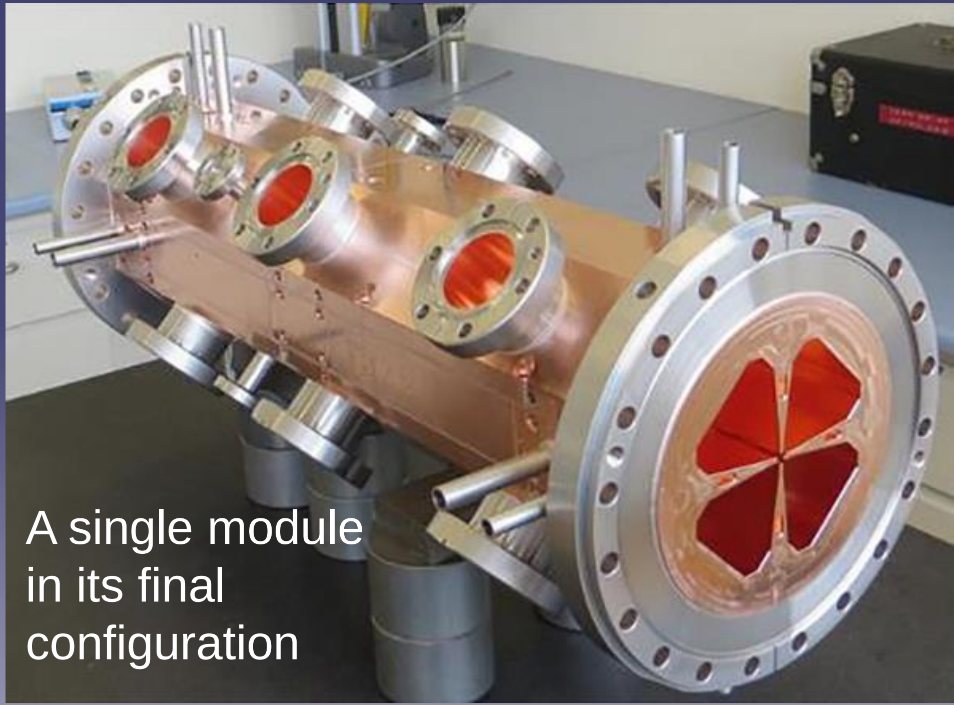
Accelerator

RF Frequency (MHz)	750
Length (mm)	1073
Number of modules	2
Input Energy (keV)	20
Output Energy (MeV)	2
Average Current (nA)	5
Peak Current (μA)	0.2
Repetion Rate (Hz)	200
Pulse Duration (μs)	125
Duty Cycle (%) (Max.)	2.5
Vane Voltage (kV)	35
Min Aperture (mm)	0.7
Max Modulation	2.0
Beam axis/tip dist. (av.)(Ro) (mm)	1.439
Vane tip radius (Rho) (mm)	1.439
Min. modulation rad. (Rhol) (mm)	1.709
Transmission (%)	30
Output Beam Size (mm) (Total)	± 0.25
Accep.(π mrad mm) (Total norm.)	0.2
Energy Spread (keV) (FWHM)	8
RF Peak Power (kW)	80
RF Efficiency (%)	35
Coupler number (#)	1

1 meter long, compact and low cost

- **20 keV input energy**, for a compact proton source
- **2 MeV beam**: Ok for PIXE, below 2.17 MeV (E_{th} $^{65}Cu(p,n)^{65}Zn$), negligible gamma ray production
- **5 nA maximum average current**, 200 nA peak current (challenging parameter – nondestructive, pileup,…)
- 0. 5 mm exit beam diameter
- 8 keV energy spread
- Ultra low power: **less than 6 kVA** for the RFQ

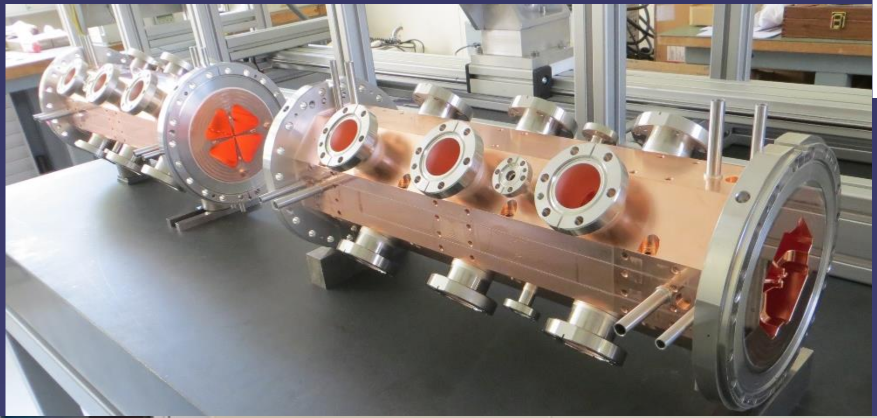
Radio-safe!



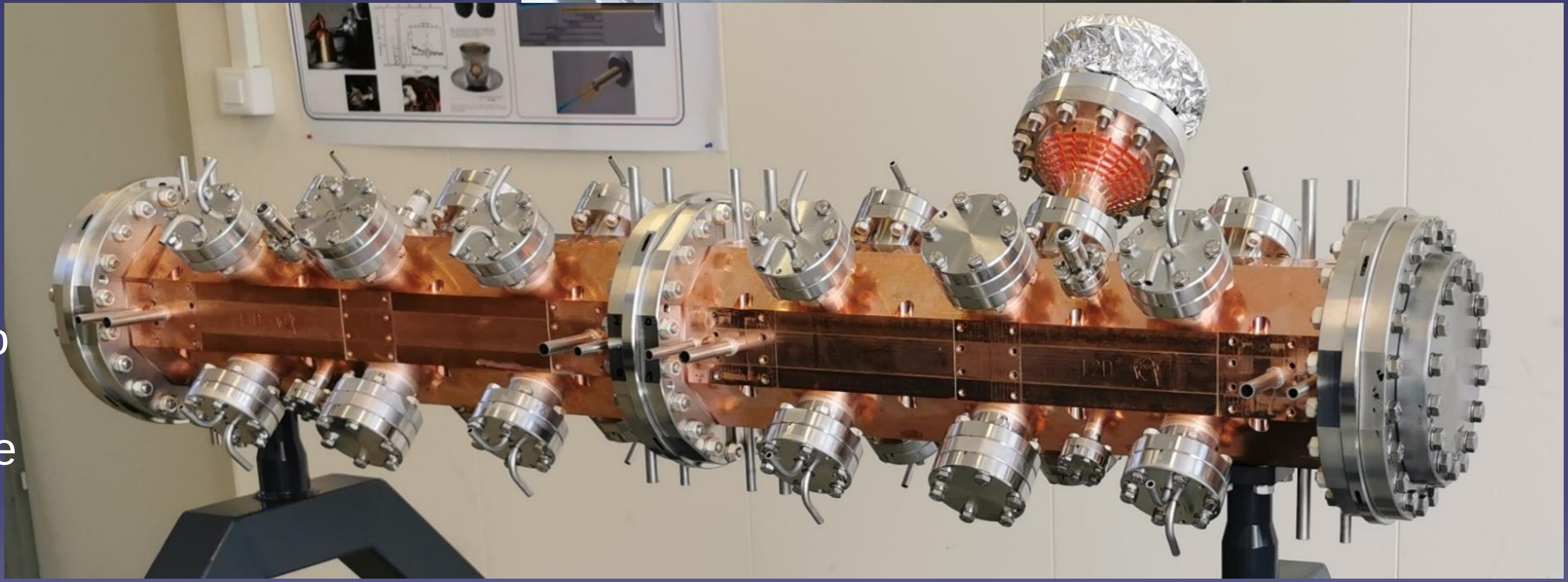
A single module in its final configuration

Accelerator

Individual RFQ modules after final brazing and final machining (Vanes, flanges and cooling tube brazed, end faces remachined).

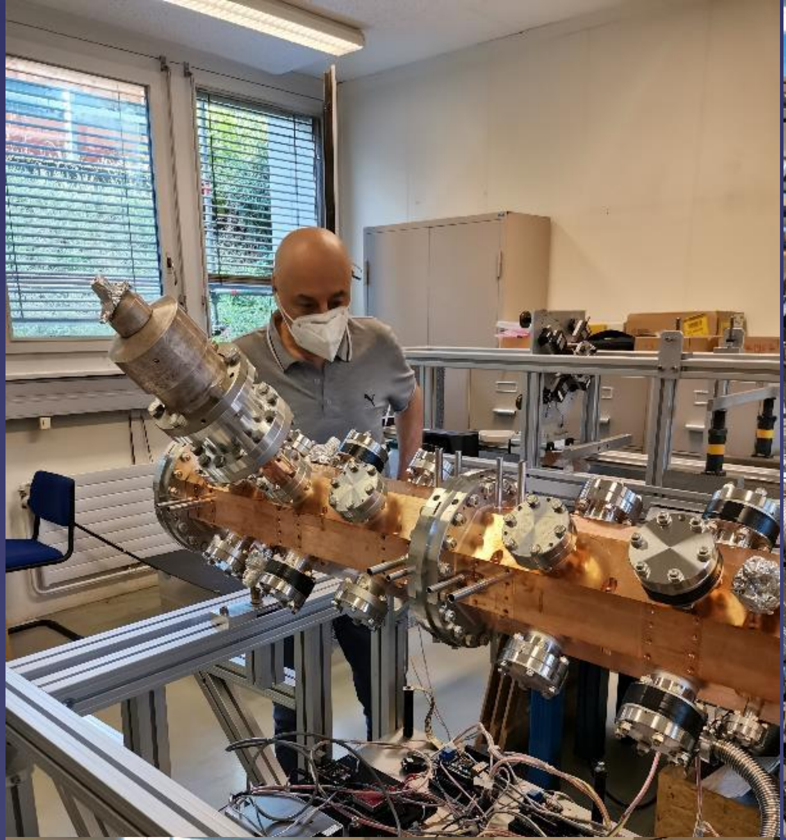


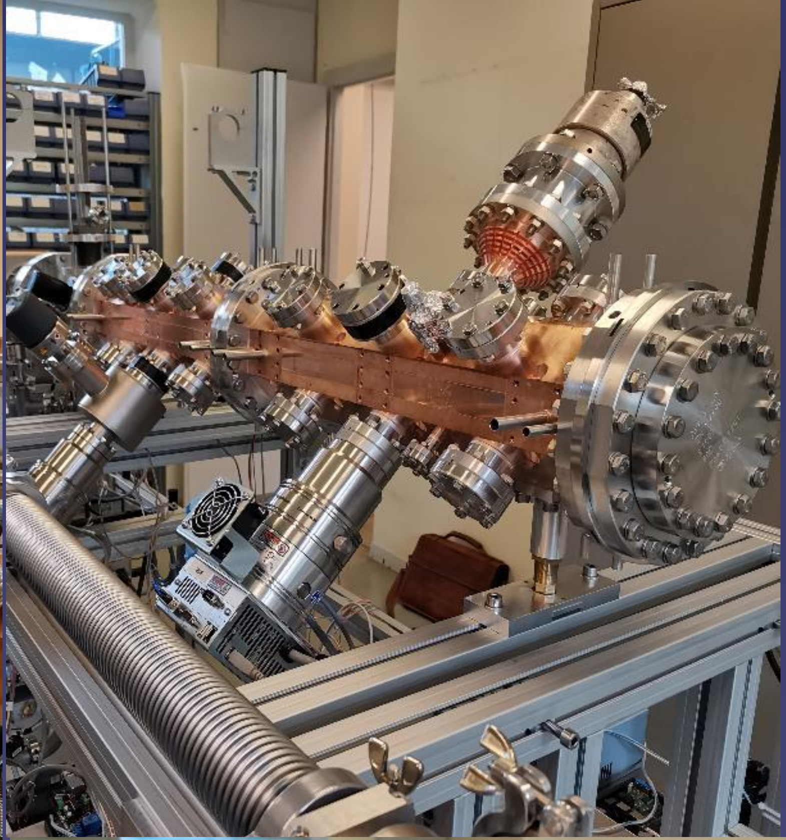
Fully assembled and tuned RFQ (two modules assembled, with tuners (x16), pumping ports (x7), RF coupler (x1), coupling flanges (x2). The RFQ is tuned, i.e. RF field has been measured with the coupler, pumping ports and coupling flanges, the tuners have been machined to minimize the field error and connected to the cavity [Error of less than ±2% along the RFQ with respect of the average quadrupole component. Error of maximum ±60 kHz on the resonant frequency (design value 749,480 MHz)]

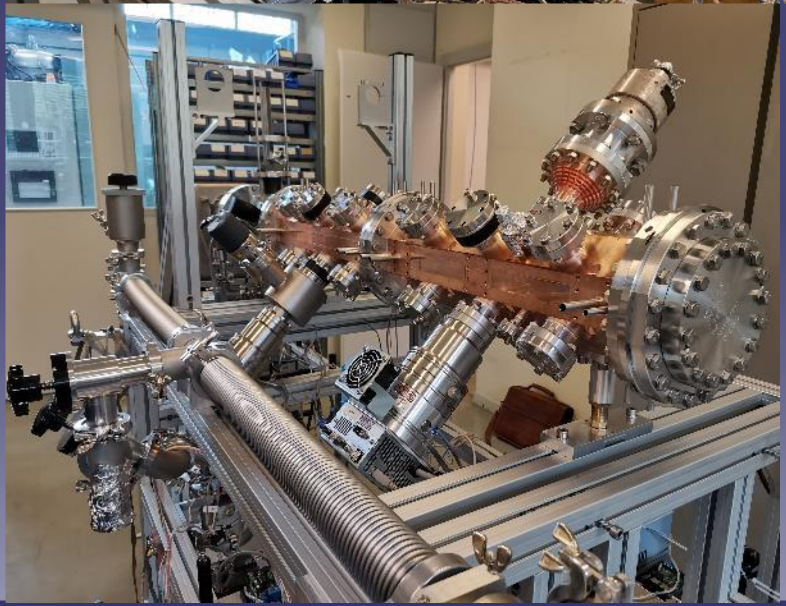


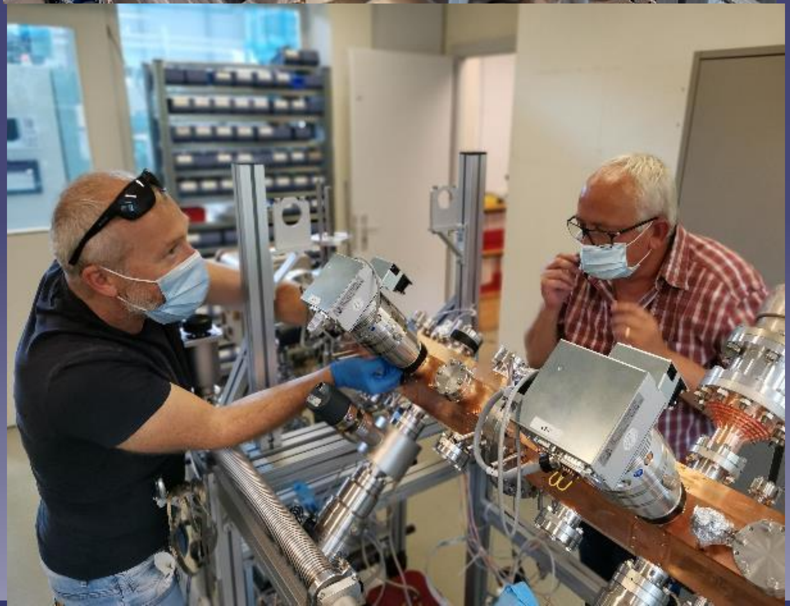
Accelerator

mounting the vacuum system



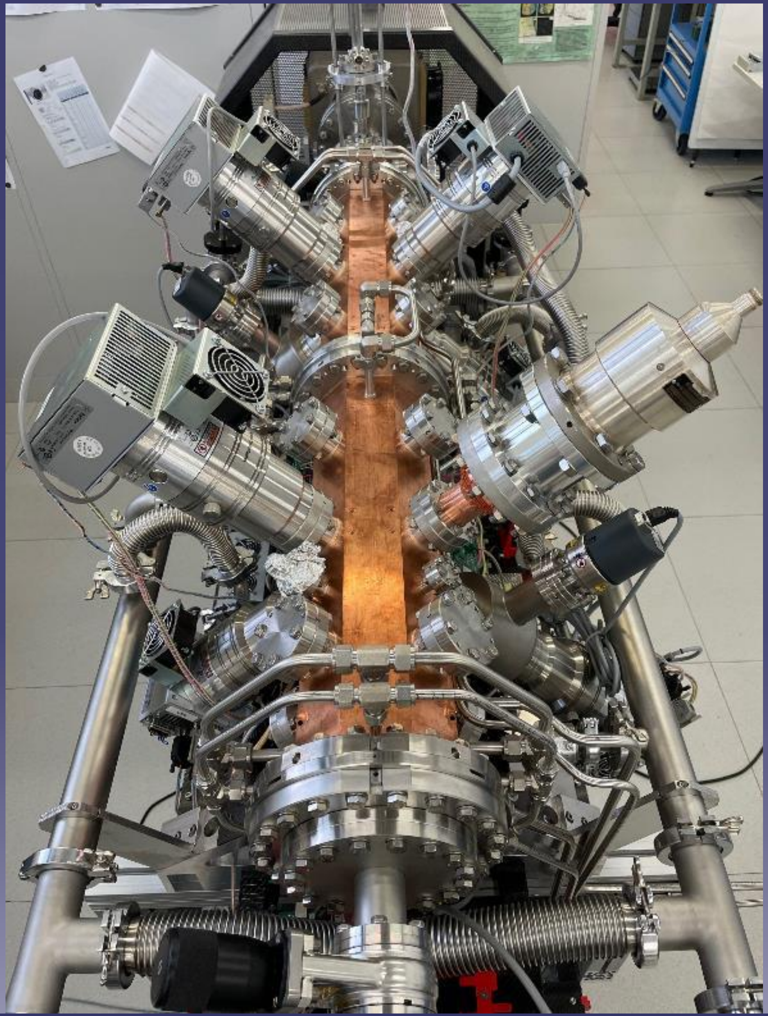


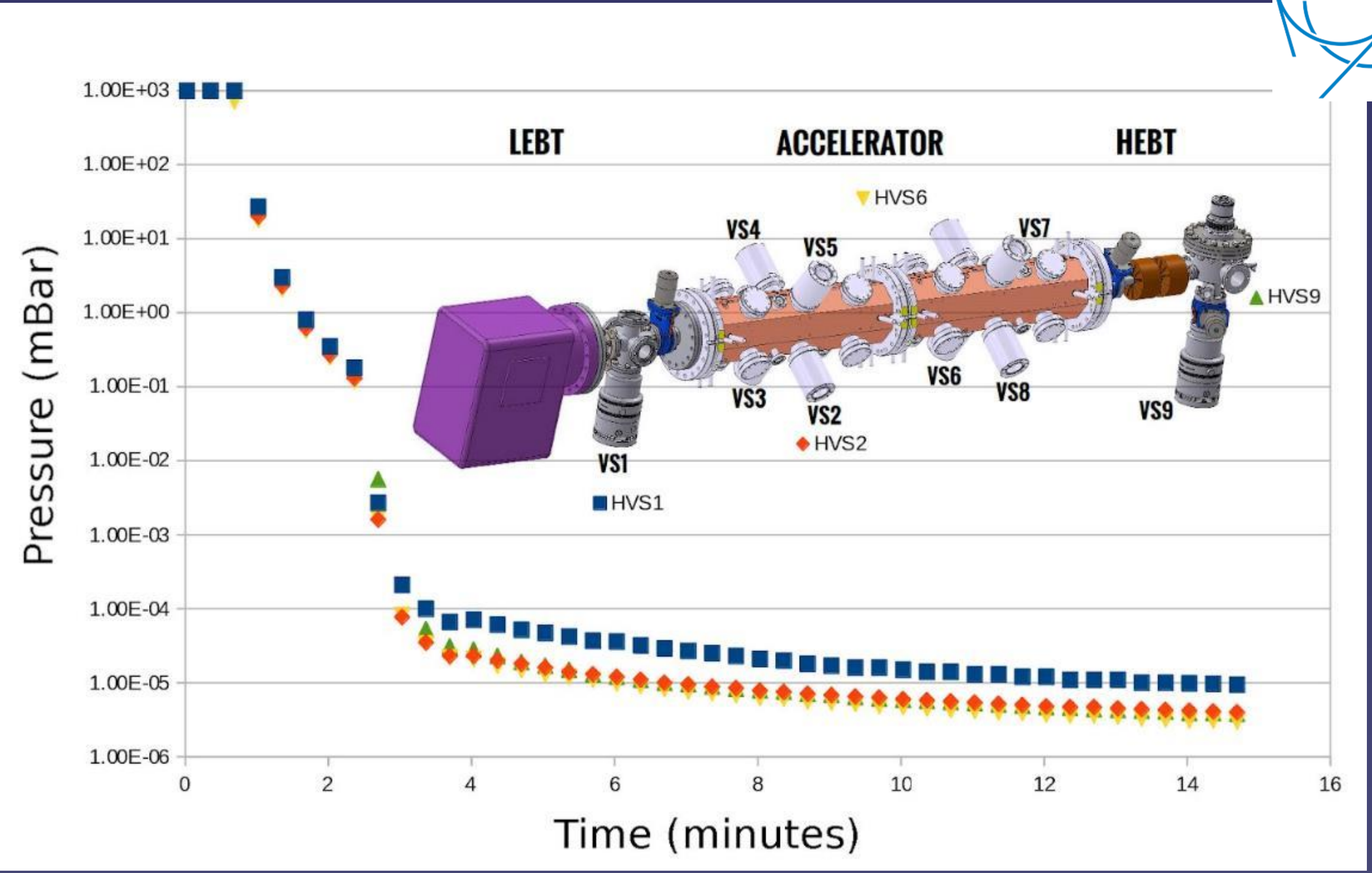




Accelerator

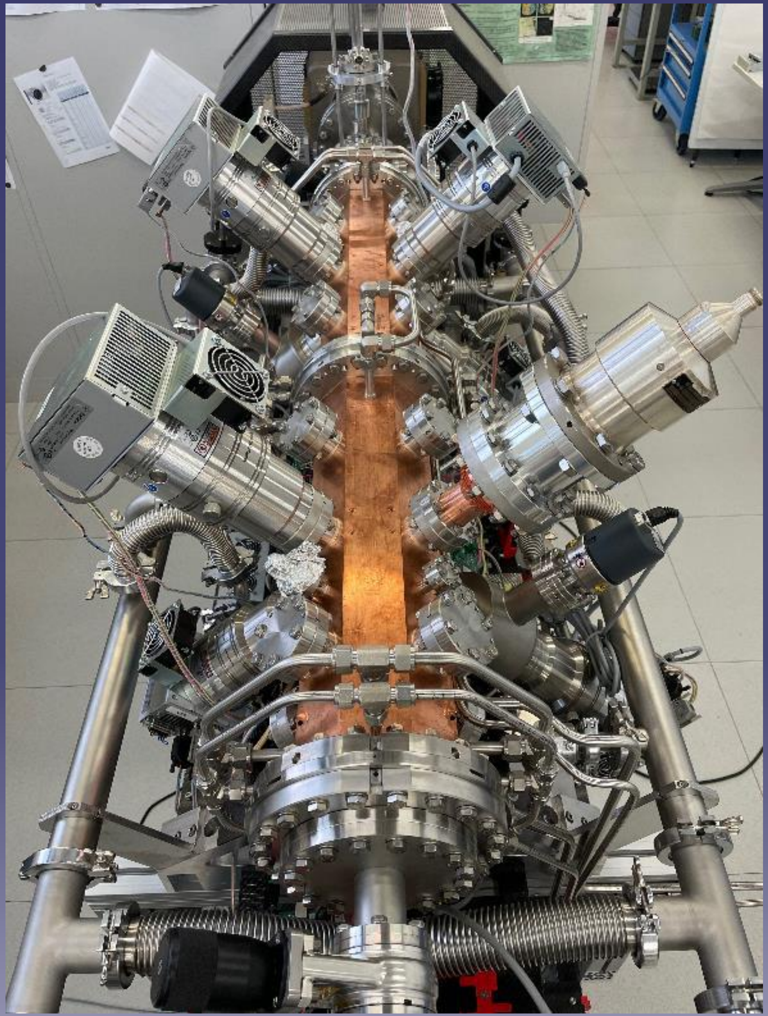
the vacuum system installed:
15 minutes pump down

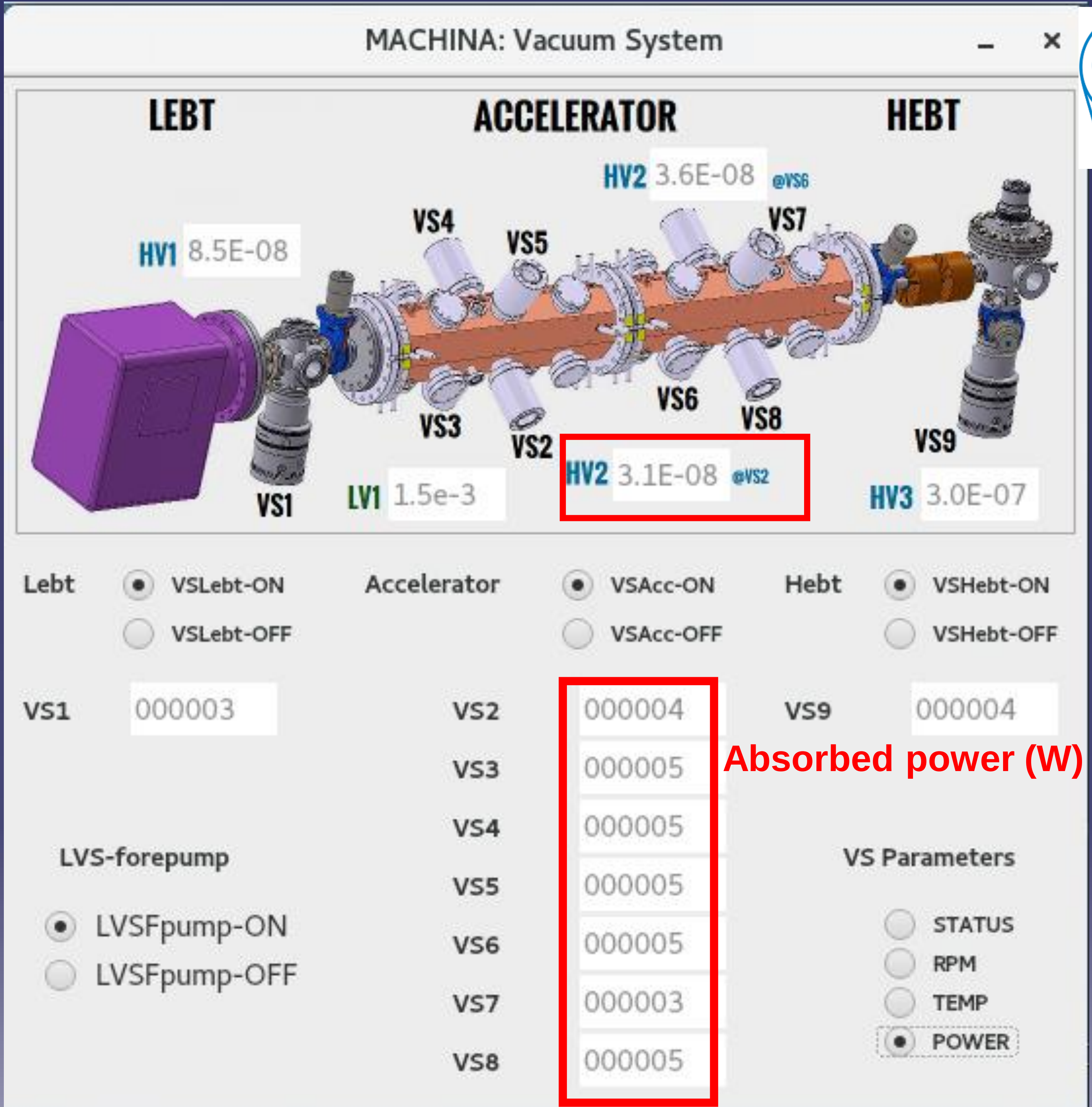




Accelerator

the vacuum system installed: limit vacuum



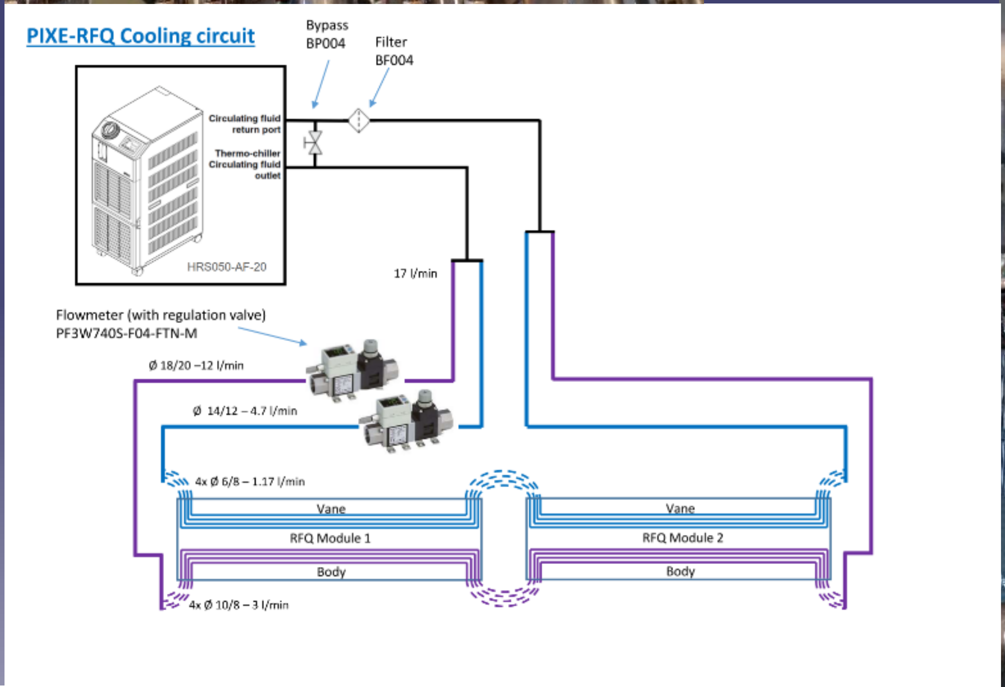


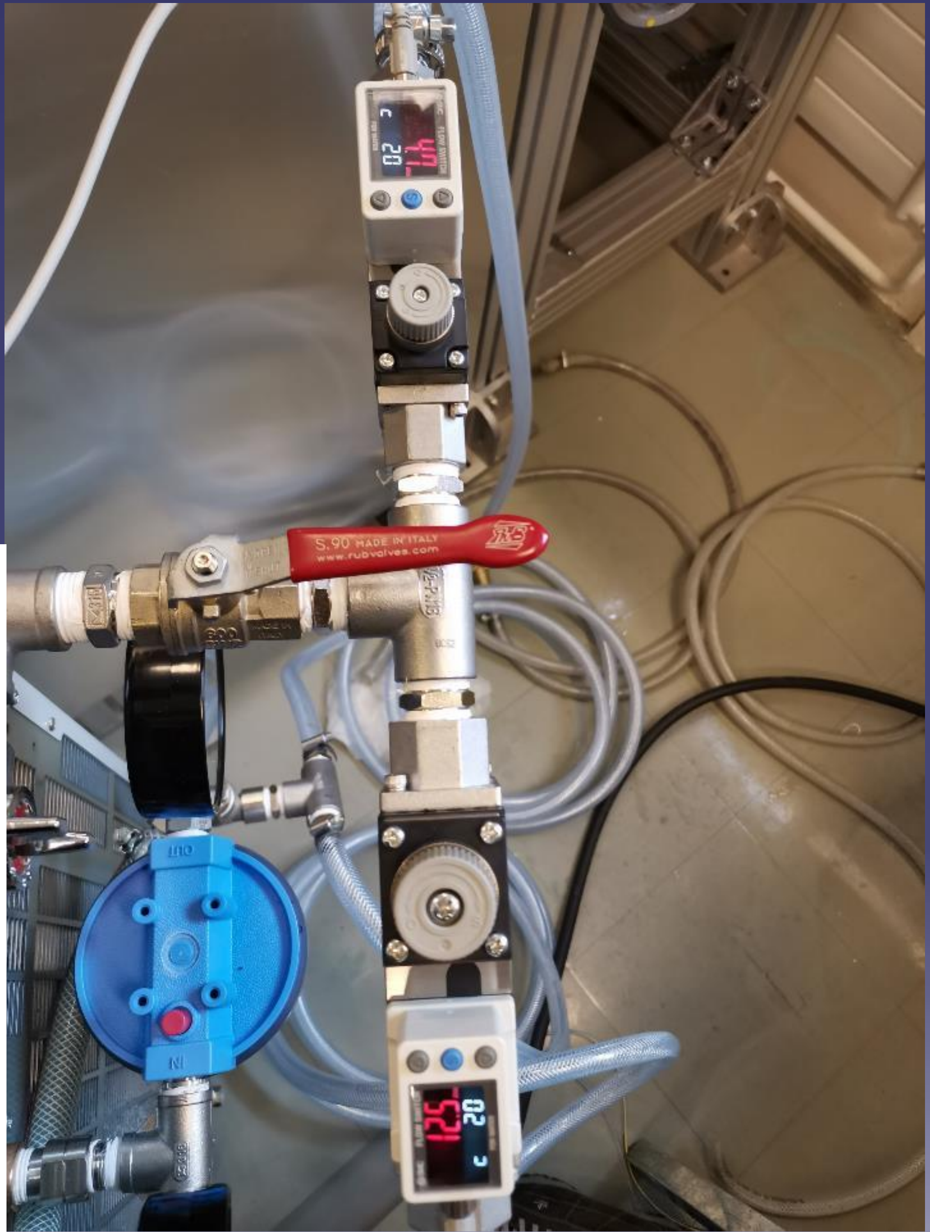
Accelerator

- The chiller of the RFQ power supply
- Two circuits with independent flow regulations

system

RFQ cooling water inlet HE side

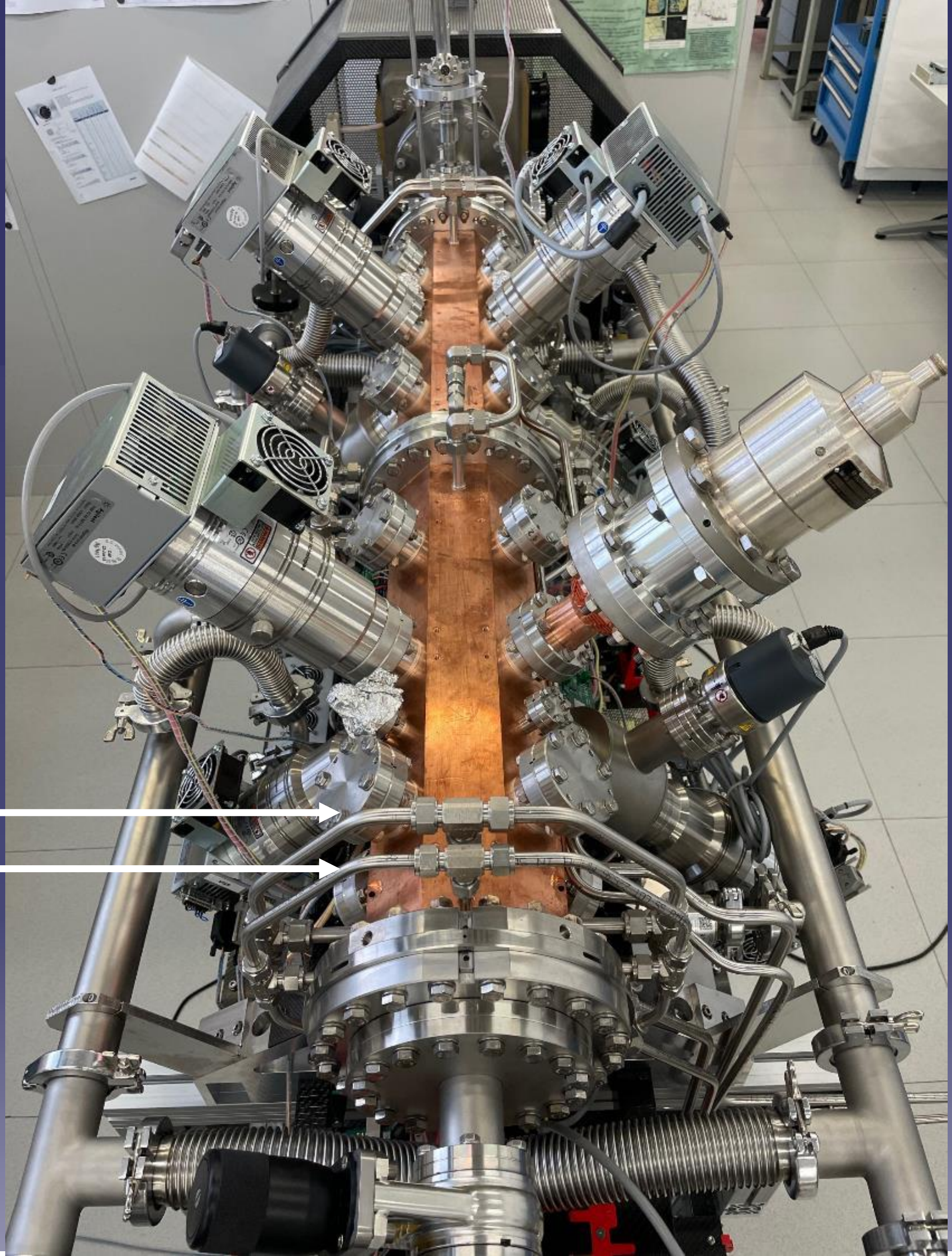




Accelerator

The vacuum system installed
High vacuum
Low vacuum
Pressure gauges
Control system

water ducts
for RFQ cooling

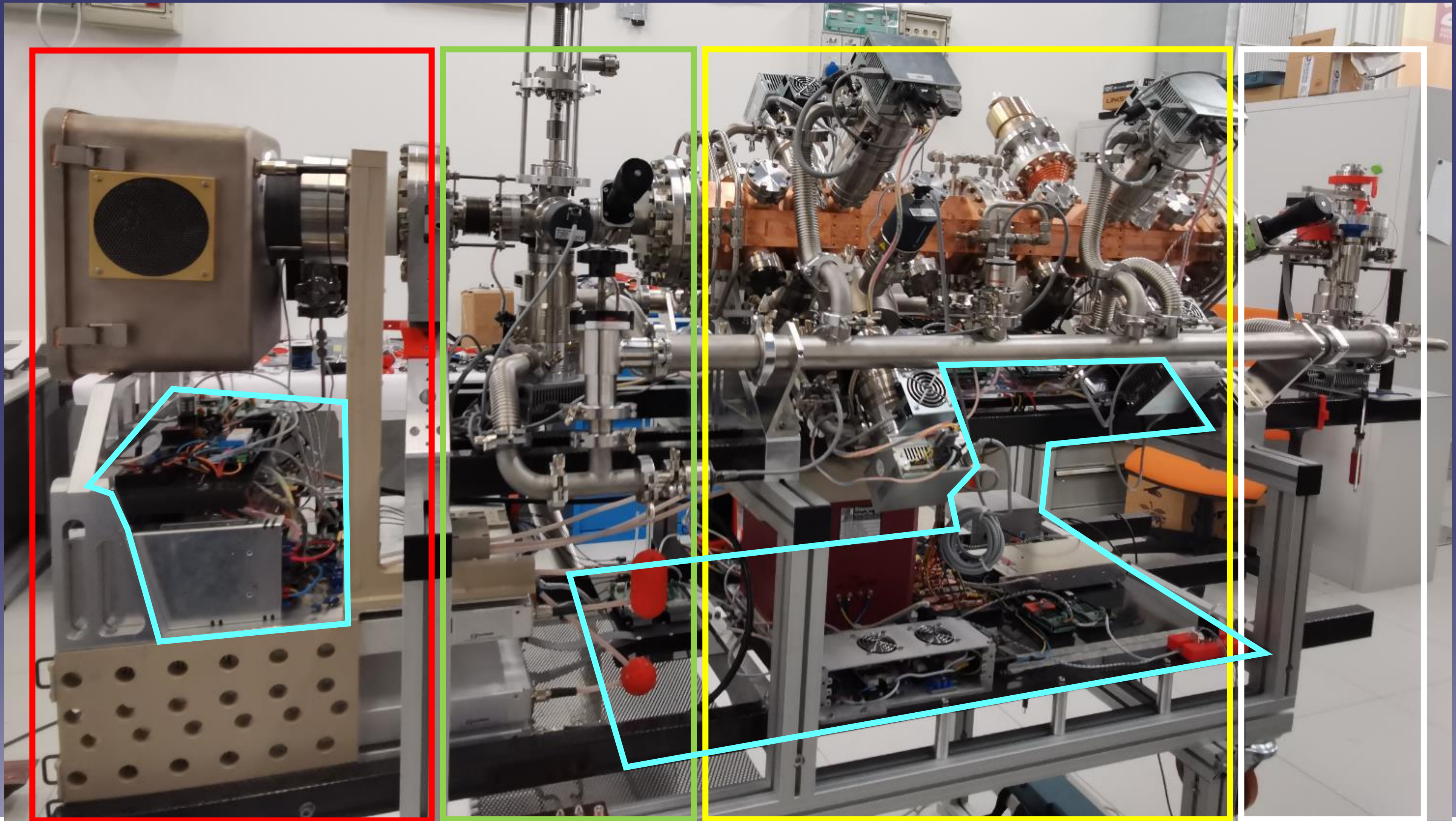


Accelerator

The whole system

CONTROL ELECTRONICS

SOURCE LEBT RFQ ACCELERATOR HEBT



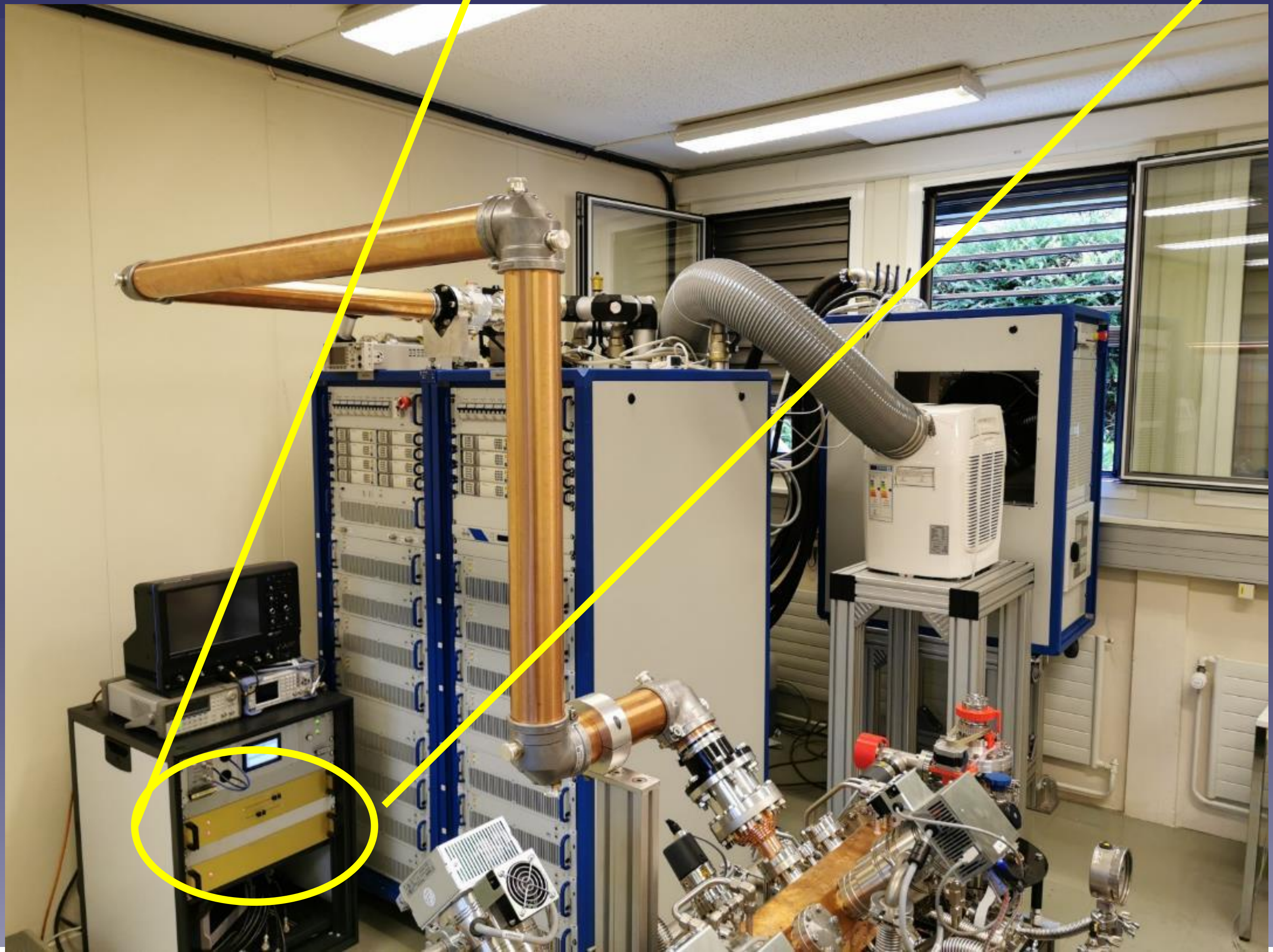
Accelerator

- **RFQ power supplies: big delay due to tender burocracy and covid-19**
- **Arrival on autumn 2021 (due to July 2019)**

Accelerator

The whole PS assembly (from left):

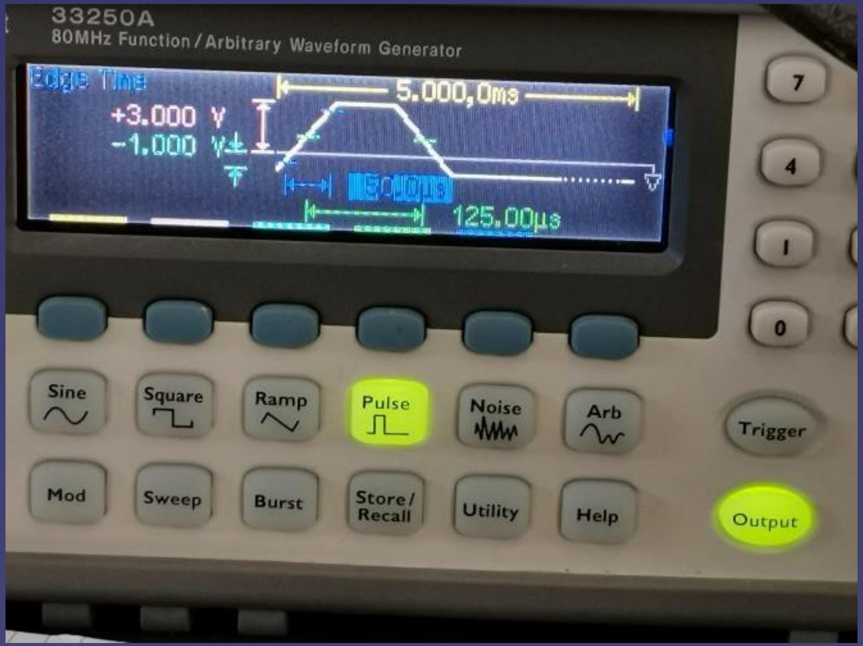
- the half rack for the PS vacuum interlock (supporting the waveform generator and the signal generator)
- The two amplifiers
- The cooling system

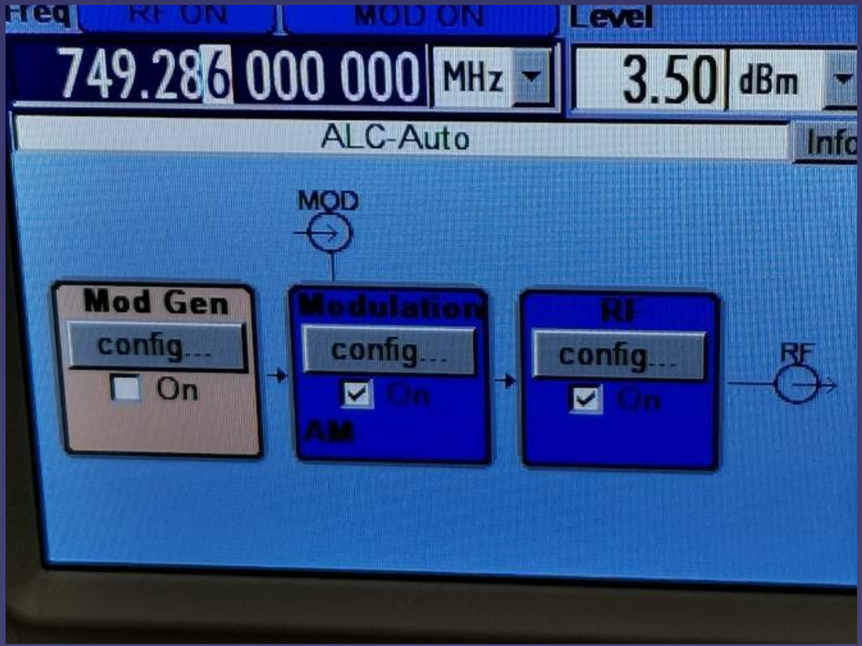


vacuum interlock ⇒ conditioning of the cavities, now able to run in the 10-6 mbar range in continuous operation

Accelerator

The waveform generator defines the duty-cycle parameters: 125 μs pulse every 5 ms





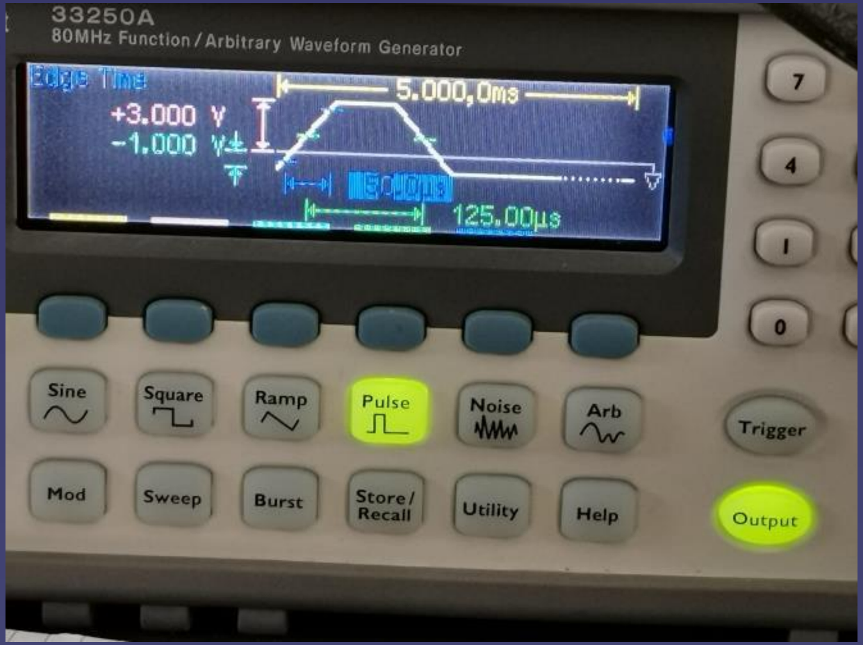
The signal generator, providing the 750 MHz frequency signal

PA

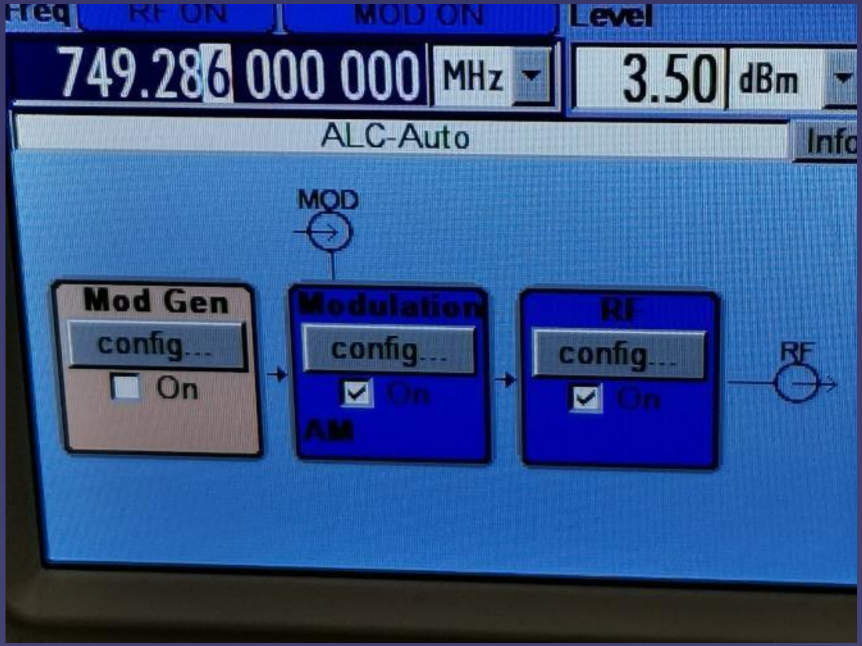
- The system delivers up to 140 kW peak power, greater than the at the time estimated (now measured) 65 kW
- It allows for finding the optimal conditions, whatever the actual power losses (difficult to estimate)
- @65 kW absorbed peak power ⇒ maximum power transferred to the cavities
- next PSs will be less expensive, lighter, more compact, less energy-consuming
- Now: 200 kg for each RF rack, 80 kg for the chiller, 200 kg for materials
- *680 kg* as a whole → 200 kg (1 single rack air cooled)
- 14 kW absorbed power → 7 kW
- *…. strong improvements in MACHINA2!*

Accelerator

The waveform generator defines the duty-cycle parameters: 125 μs pulse every 5 ms



PA



The signal generator, providing the 750 MHz frequency signal

The points that make the new 80kW 750MHz amplifier more efficient:

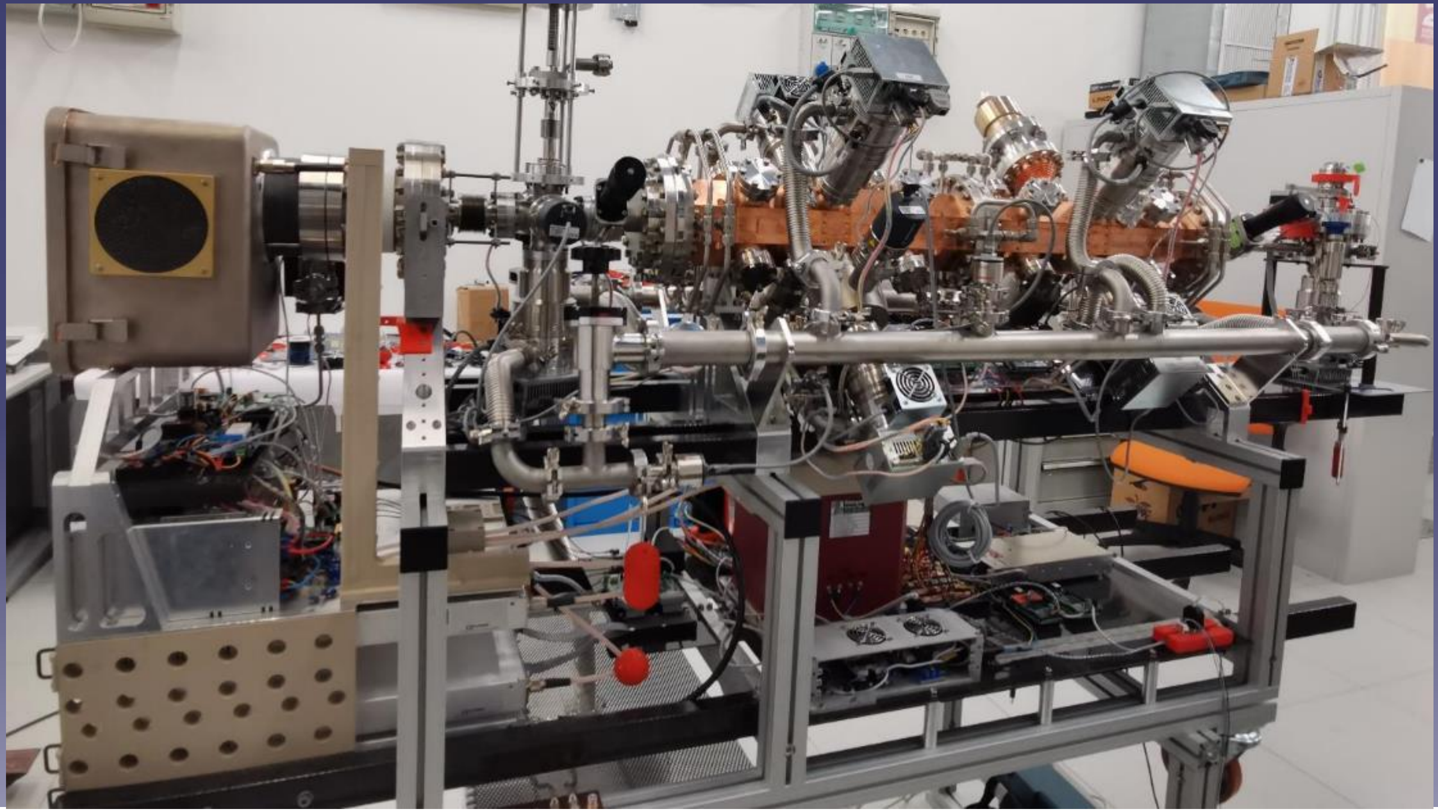
- the 100kW amplifier can deliver up to 140kW, for a 70kW amplifier, the number of modules is reduced by 50%
- The number of RF modules goes from 16 to 8 (50% less consumption).
- The cooling system switches from liquid to air (about 6kW constant absorbed power saved)
- The MOSFET bias, initially set at 200mA will be 50mA (this affects gain linearity, not necessary for our application)
- Synchronizing the switch-on of the modules with the onset of the pulse allows for a total power consumption of 160W for the 8 RF modules, instead of 4800W when the pulse is not present

Accelerator

1.4 A current absorbed by:

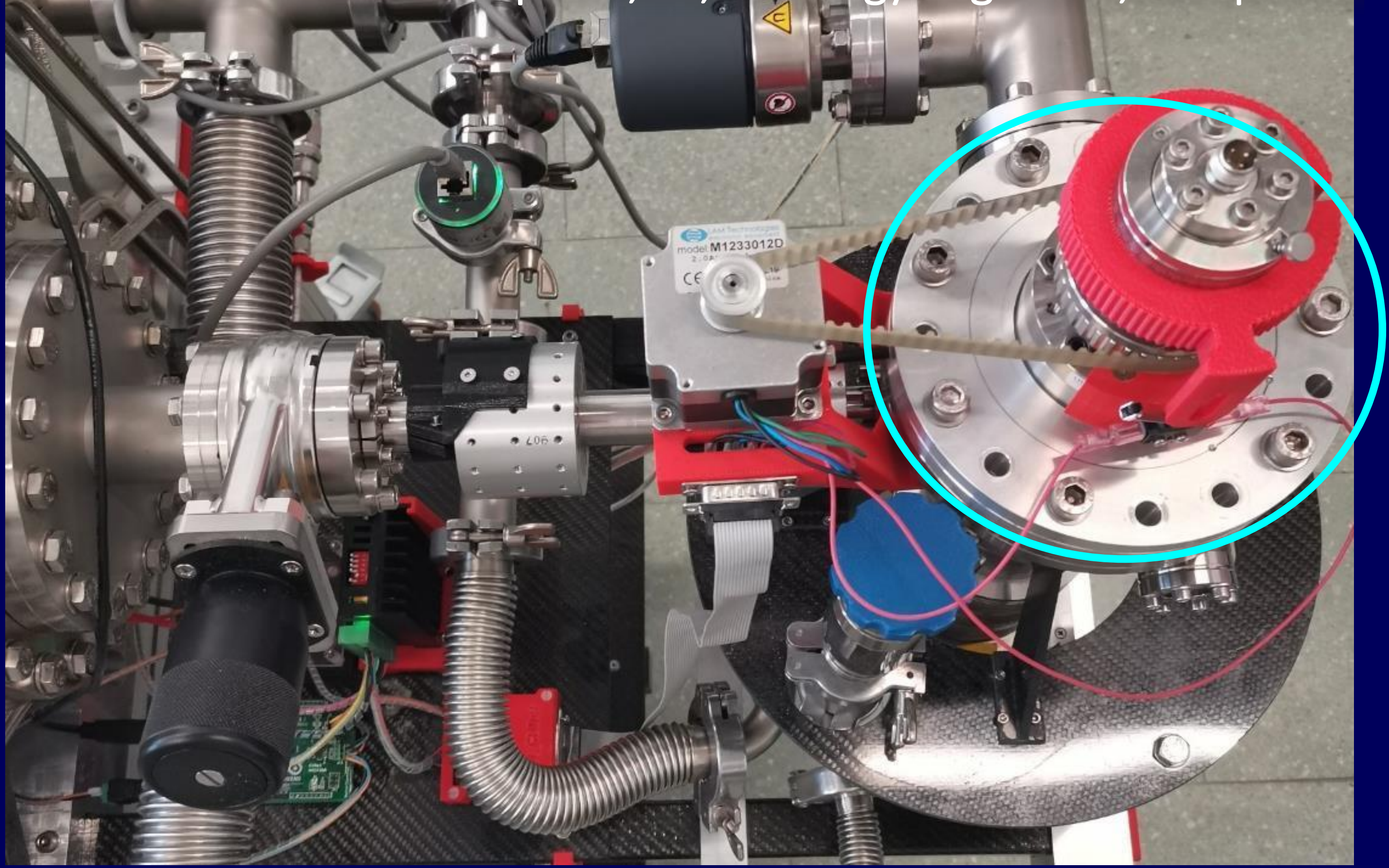
- Source (no beam extracted)
- Vacuum (LV & HV gauges, turbo & forepump)
- Control system (Source, LEBT, services, HEBT)
- ***<u>RFQ PA excluded!!</u>***

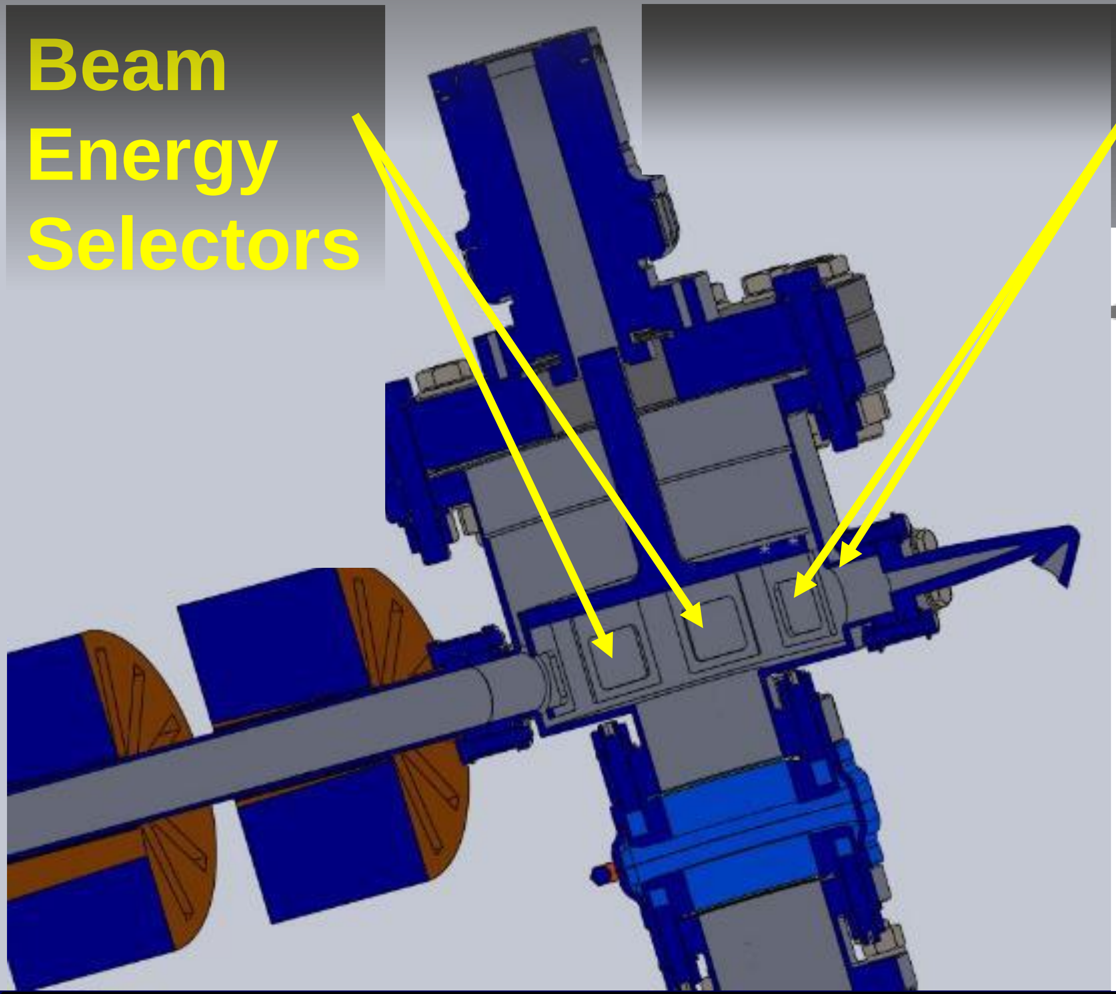
absorbed current



HEBT

The HEBT diagnostic station:
Rotatable carousel with quartz, FC, 2 energy degraders, free path





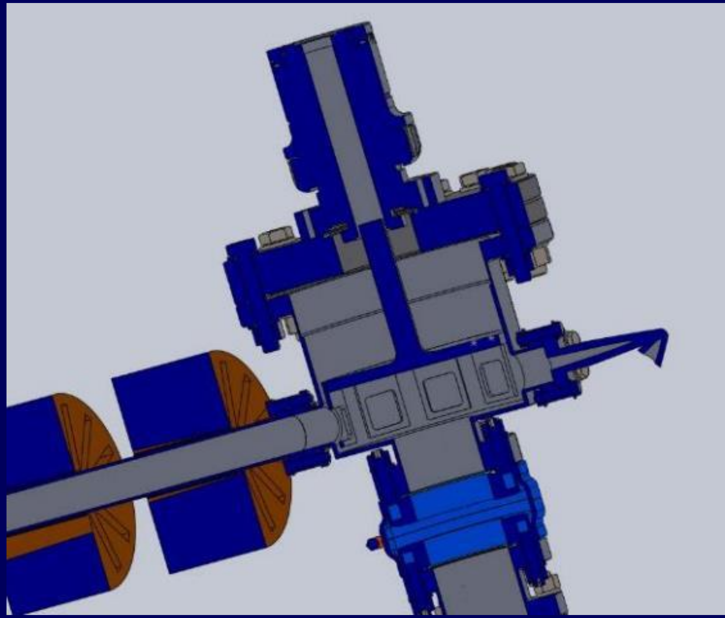
Quartz and Faraday cup

- 2 MeV protons lose about 400 keV passing through 12.5 µm Al foil
  - *2 MeV protons*
  - *Zero, one or two degraders (12.5 µm Al)*
  - *500 nm Si3N4*
  - *1 cm He path*

	No degrader	One degrader foil	Two degrader foils
Proton energy on target	1950 keV	1540 keV	1040 keV
Total energy spread	12.5 keV	44 keV	70 keV

HEBT

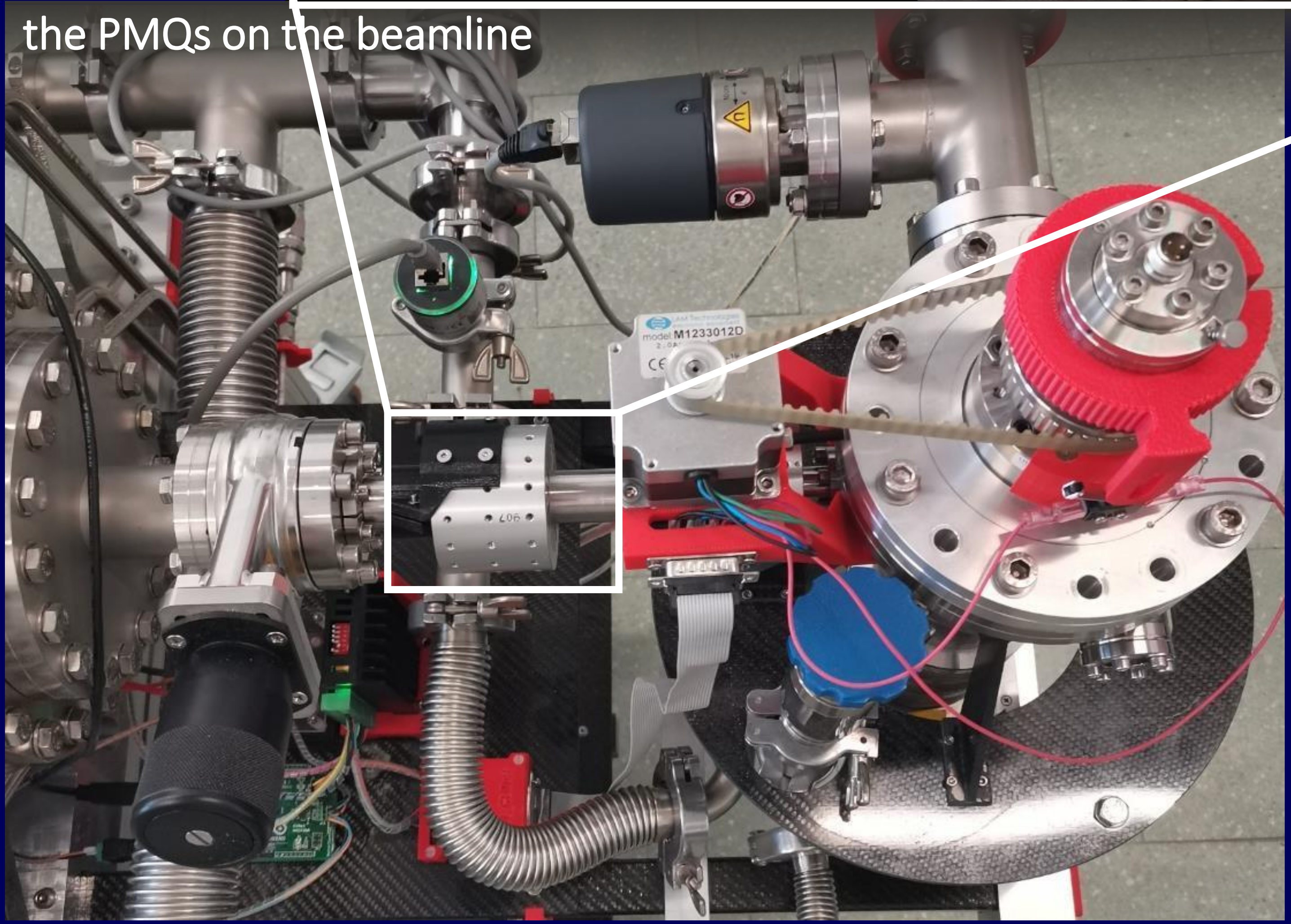
Ein	unit	dE/dx	unit	t (um)	Efin	deltaE Si4N4	E (after Ti+Si3N4)	deltaE 1 cm air	Etarget (6mm))	Etarget (10mm))
2000	keV	41	keV/um	1	1959					
1959	keV	41	keV/um	2	1918					
1918	keV	41	keV/um	3	1877					
1877	keV	41	keV/um	4	1836					
1836	keV	41	keV/um	5	1794					
1794	keV	41	keV/um	6	1753	25	1728	173	1624.2	1555
1753	keV	41	keV/um	7	1712	25	1687	173	1583.2	1514
1712	keV	46	keV/um	8	1667	25	1642	173	1538.2	1469
1667	keV	46	keV/um	9	1621					
1621	keV	47	keV/um	10	1574					
1574	keV	49	keV/um	11	1525					
1525	keV	49	keV/um	12	1475					
1475	keV	49	keV/um	13	1426					
1426	keV	52	keV/um	14	1375					
1375	keV	54	keV/um	15	1321	30	1291	220	1159	1071
1321	keV	52	keV/um	16	1269	30	1239	220	1107	1019



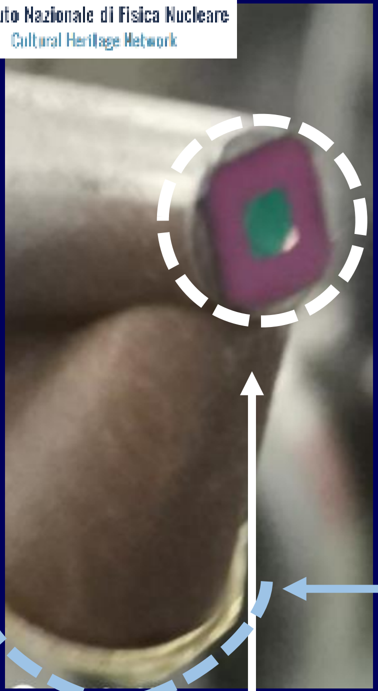
HEBT

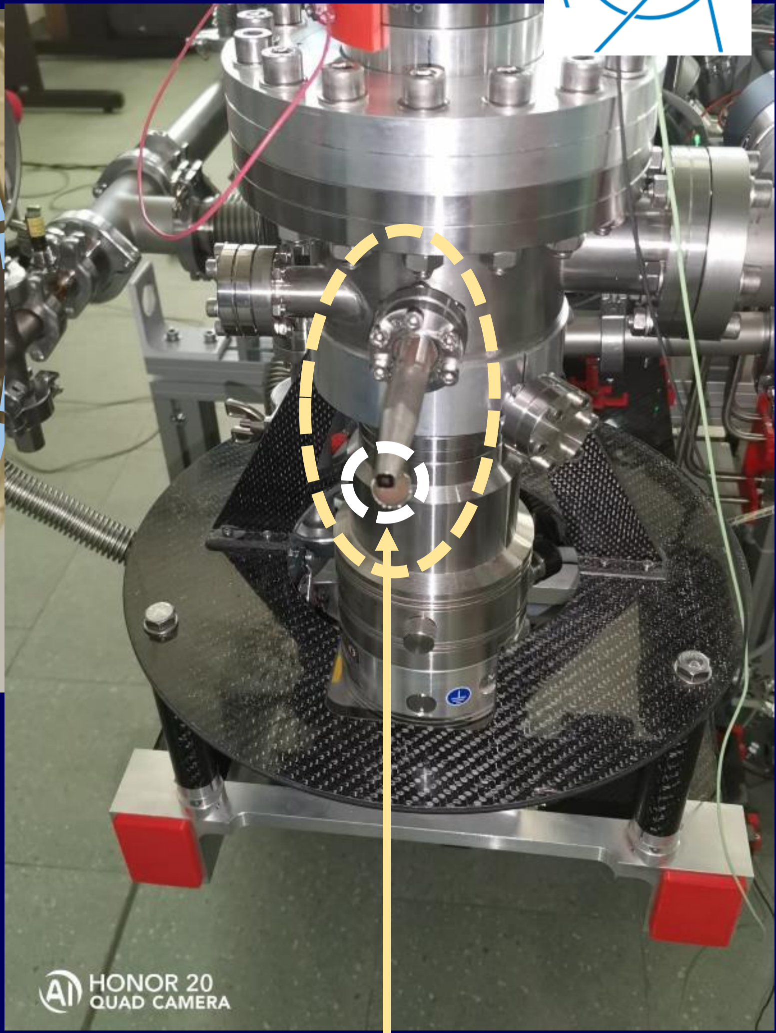
Focusing the accelerated beam by using 2 PMQs

the PMQs on the beamline



HEBT: extracting the beam





500 nm Si3N4 window
on the exit nozzle

HEBT beam extraction:

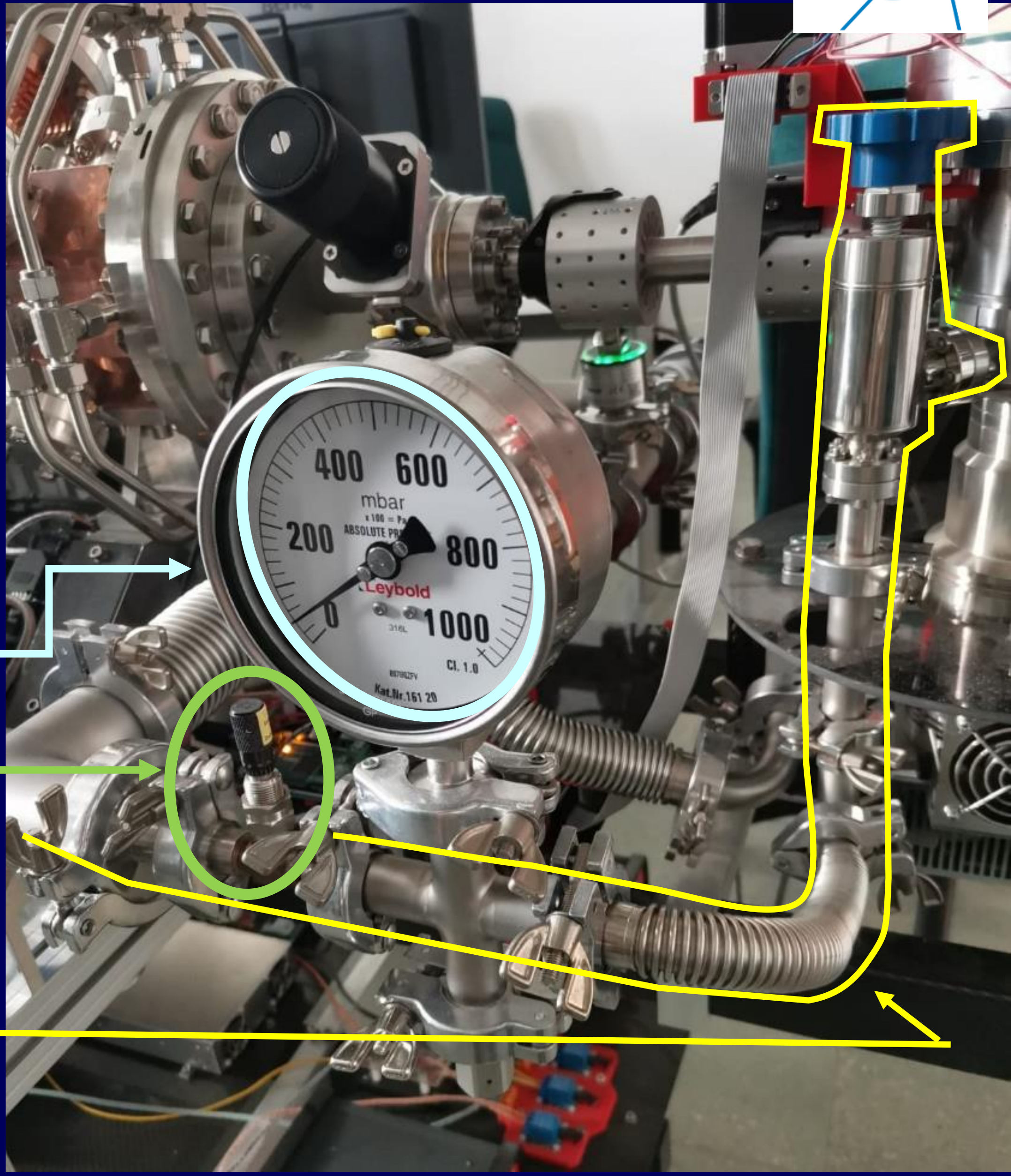
- **Si3N4 beam extraction window**
- **mylar foil for beam intensity normalisation (rear side)**
- **Full view of the exit nozzle installed at the exit of the HEBT diagnostic station**

HEBT: the line for the ultra-smooth pumping down

500 nm Si3N4 window on the exit nozzle

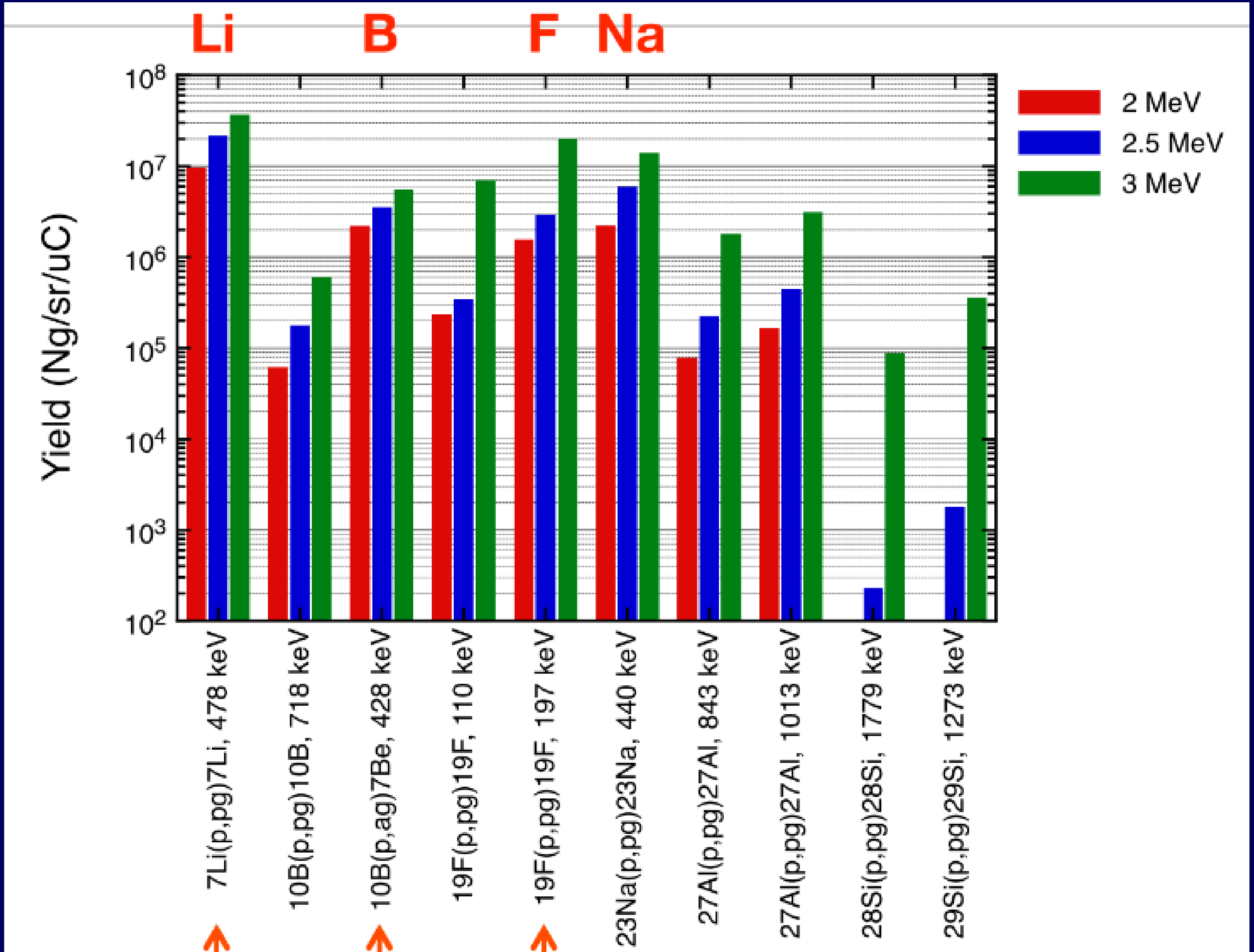
HEBT vacuum:

- UHV: turbo on the chamber
- Big dial vacuum gauge to finely check the pressure dropping behind the Si3N4 window
- Ultra fine valve to control the pressure drop speed
- Dedicated line for ultra-smooth pumpdown



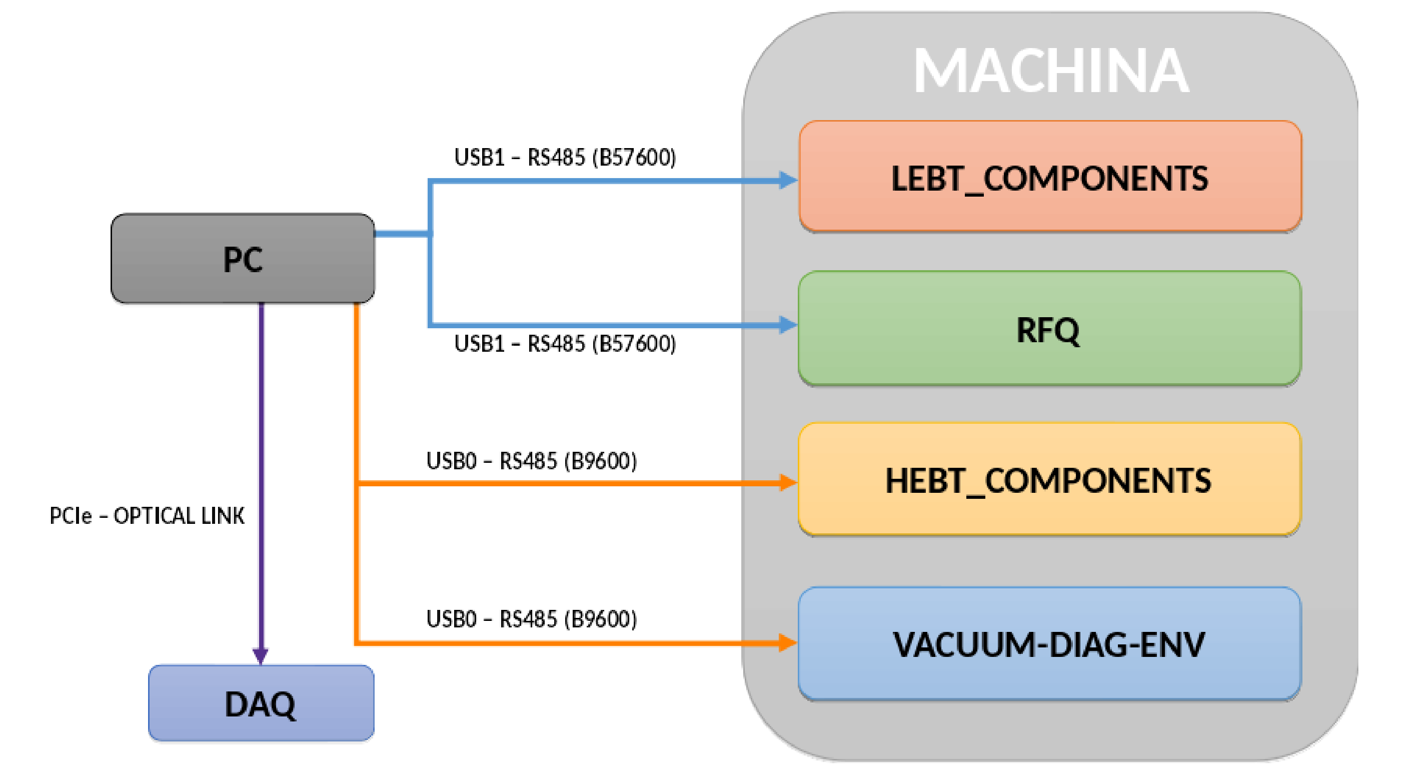
HEBT

PIXE and PIGE analyses



Control System

Scheme of the MACHINA Communication Channels



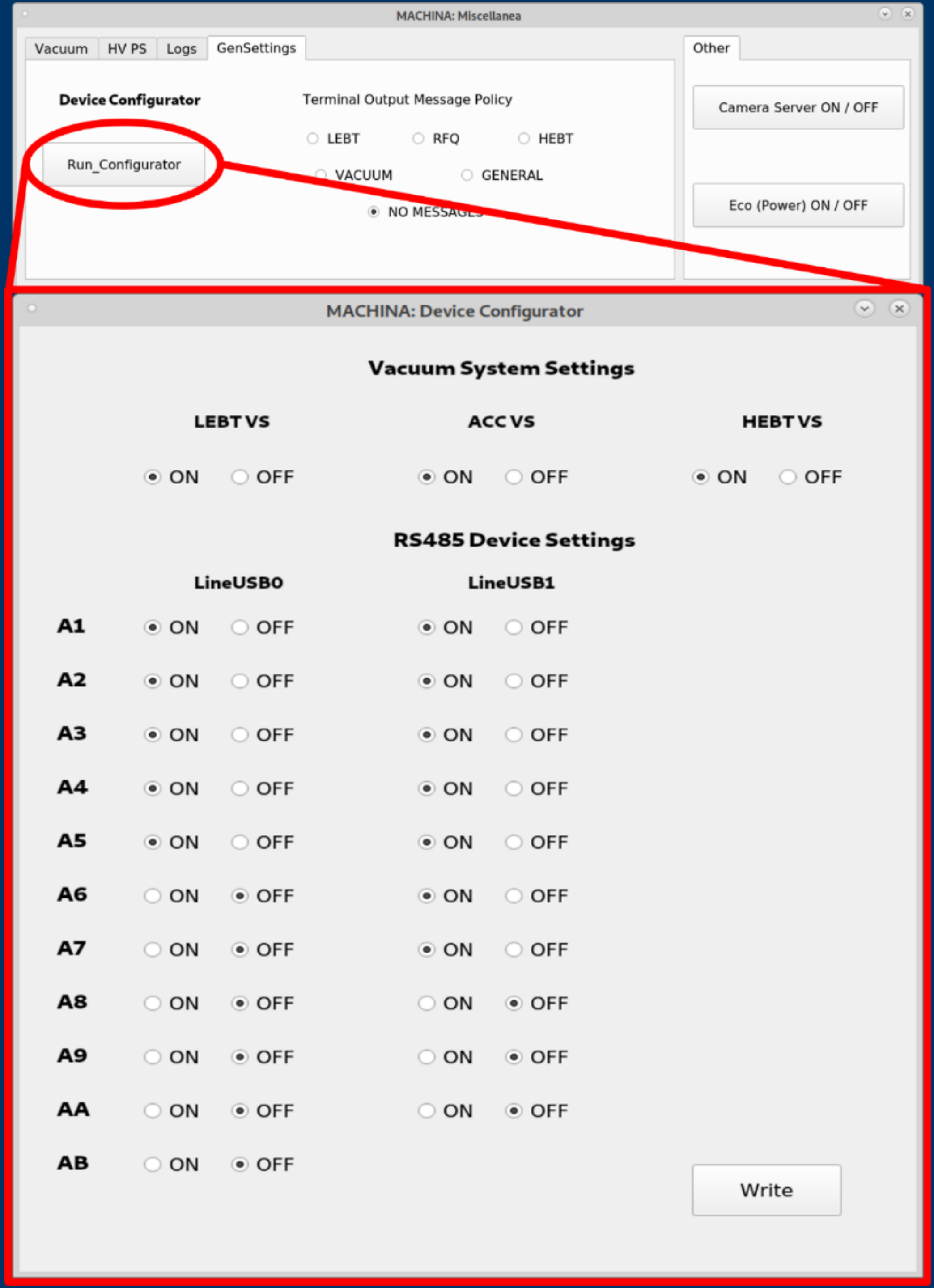
The two USB-RS485 lines allow interacting with the controllers of all the elements of MACHINA (Arduino, turbopump controller)

- LEBT_COMPONENTS: source and low energy beam transport components
- RFQ: radio frequency quadrupole parameters
- HEBT_COMPONENTS: high energy beam transport components VACUUM-DIAG-ENV: vacuum system, beam diagnostic and environmental parameters (temperature, humidity)

Control System

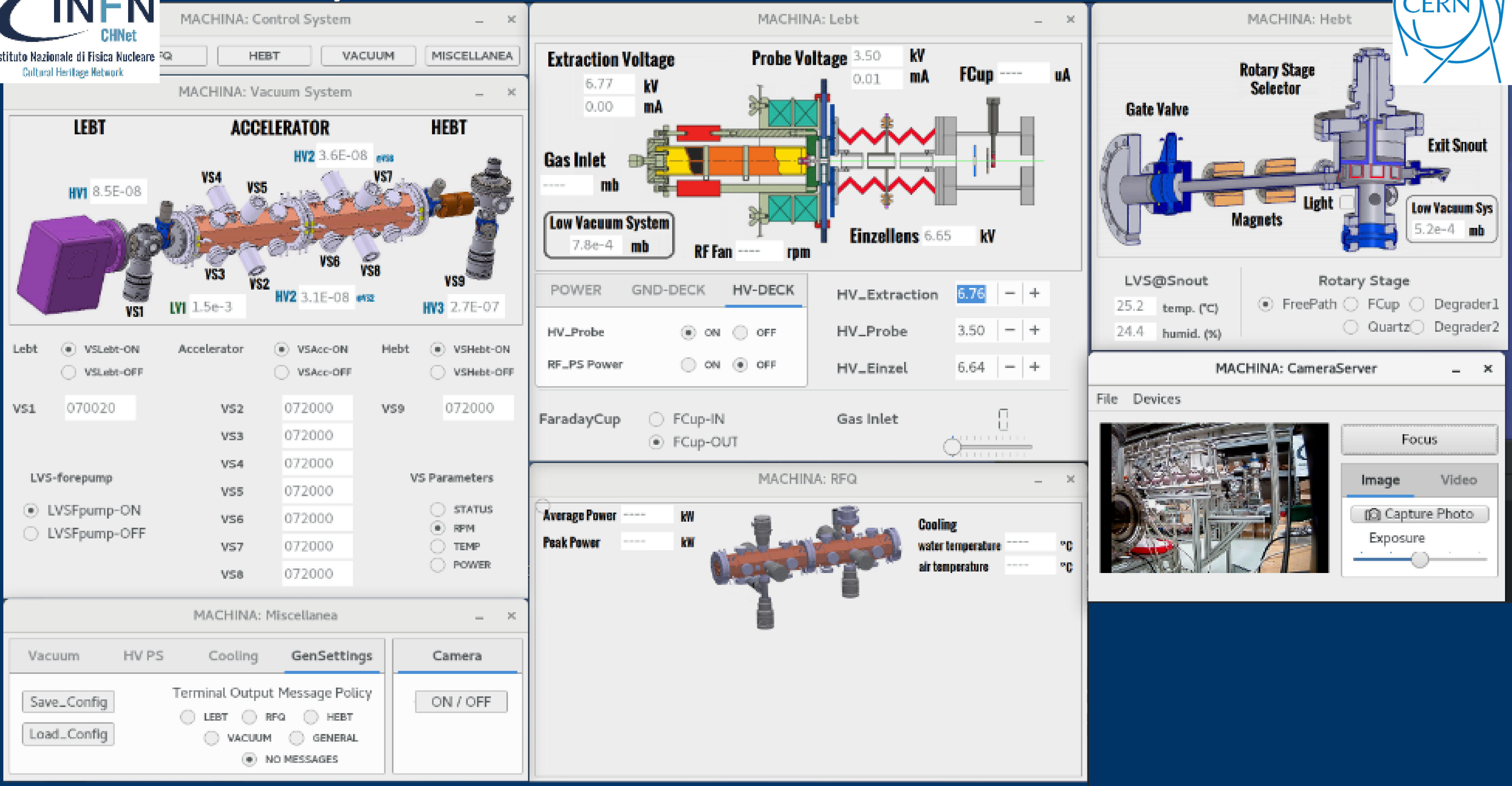
MACHINA device configurator

<u>A tool we are really very proud of!</u>



Allows enabling or disabling the communication to any controller of the installed devices

Control System: overview



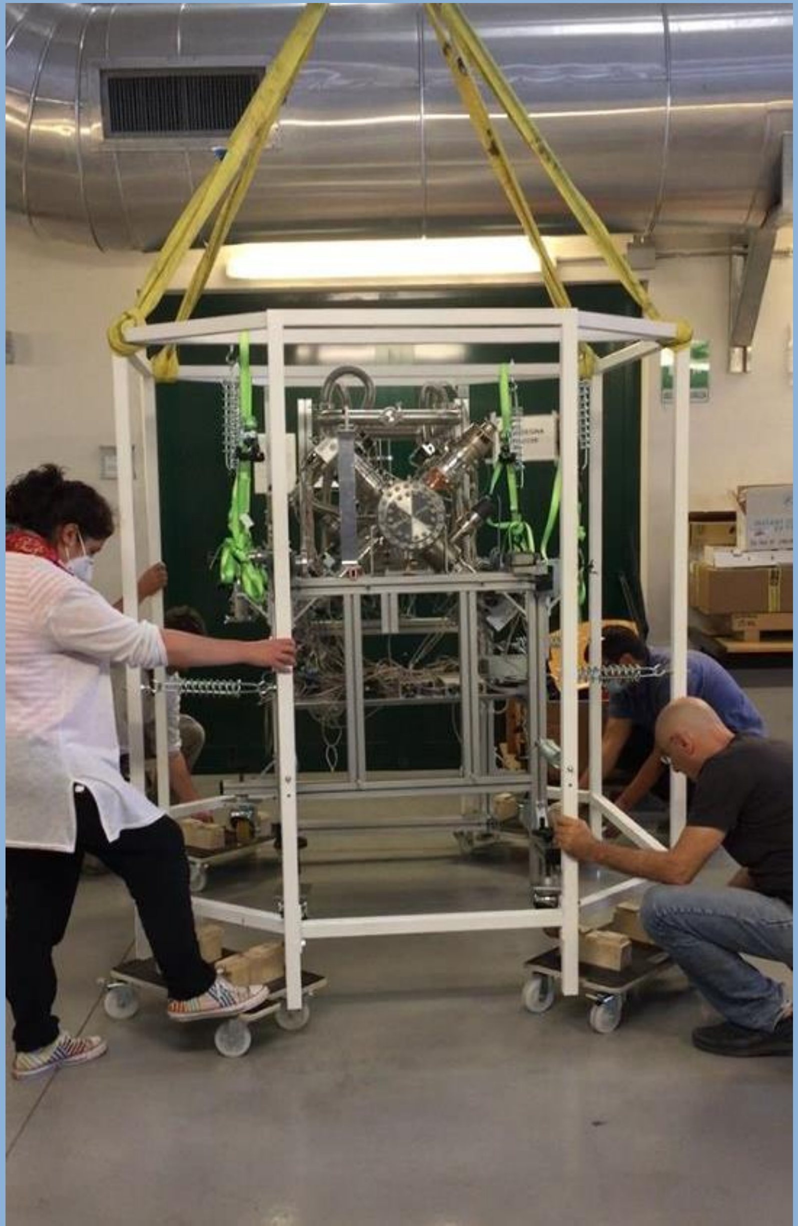
TRANSPORTABILITY

The whole system proved its transportability.
The accelerator system has been moved back and forth from the INFN-LABEC in Florence and CERN in Geneva many times, once including also the PSs

Transport needs:

- 2 small trucks/van (1 for the accelerator and 1 for the PSs), easier than using 1 big lorry
- half a day for packing

TRANSPORTABILITY



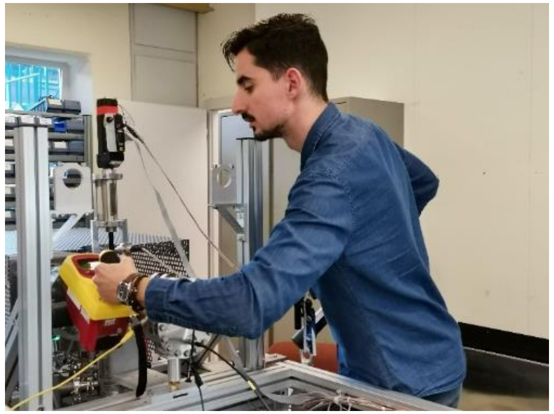
MACHINA has travelled thousands of kilometres back and forth between Florence to Geneve

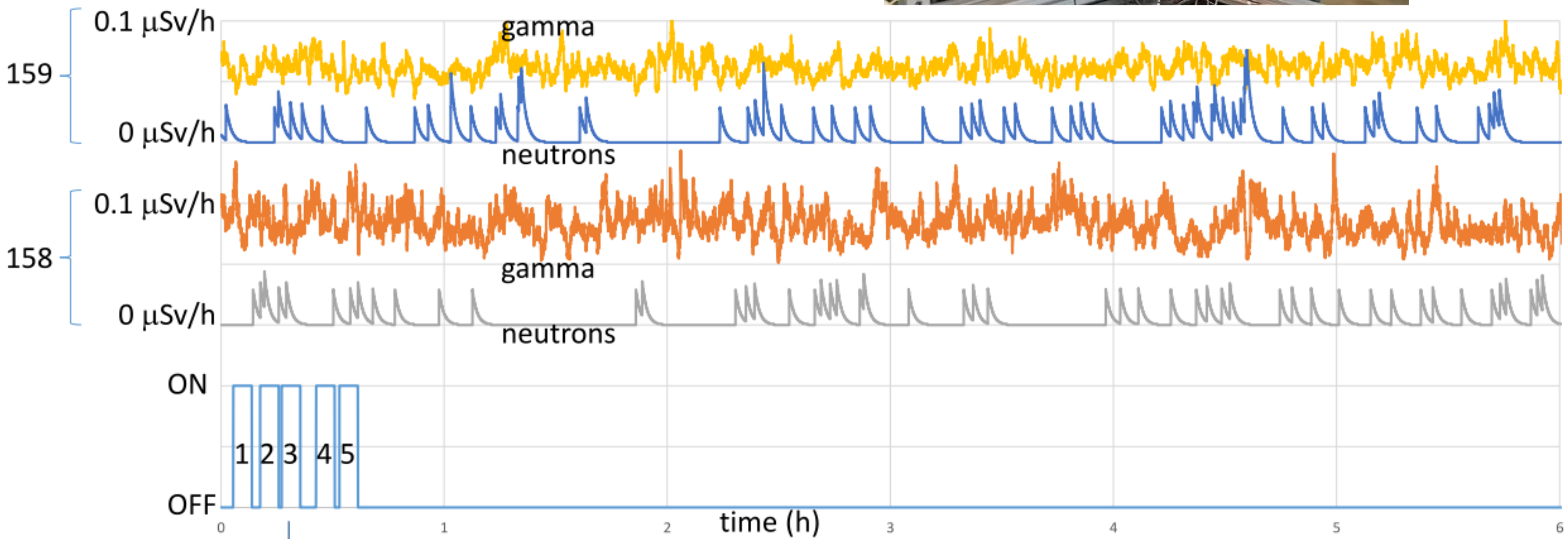
Vibrations are not a problem

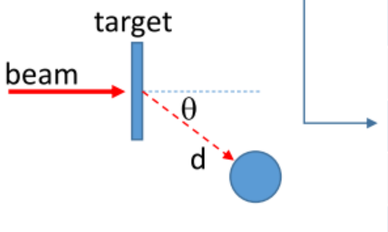
RADIO- SAFETY

MACHINA is intrinsically safe as radiation protection is concerned

- Source+LEBT: X-rays (E<20keV) absorbed in the walls
- Accelerator: lost particle energy < 200 keV. Beam energy < 2 MeV neutrons negligible, even on copper (E_{th} ($^{65}Cu(p,n)^{65}Zn$) = 2.17 MeV)
- HEBT and extracted beam: 2 MeV, @ 100-300 pA on plastics, aluminium, iron and copper: no difference in the X/γ and neutrons dose rates with respect to background (50-100 nSv/h for e.m. radiation and < 100 nSv/h for neutrons)







RUN	Target	Angle	current
1	Fe	50°	0.17 nA
2	Cu	50°	0.17 nA
3	Air	50°	0.19 nA
4	Fe	0°	0.23 nA
5	Air	0°	0.34 nA

Non si evidenzia alcuna correlazione fra l'indicazione dei dosimetri, posti a circa d= 35 cm di distanza dal bersaglio, e l'irraggiamento dei bersagli con protoni da 2 MeV

RADIO- SAFETY

MACHINA is intrinsically safe as radiation protection is concerned

- Source+LEBT: X-rays (E<20keV) absorbed in the walls
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Il Prefetto di Firenze

Prot. n. 170604/2.10/2023/Sost. Rad. (Fasc. n. 8663/2017)

DECRETA

è aggiornata l'autorizzazione, del nulla osta di cat. B. già rilasciato il 16 novembre 2022, dell'Istituto Nazionale di Fisica Nucleare, con sede a Sesto Fiorentino (FI), in via G. Sansone, 1, che comprende:

- l'impiego di un acceleratore Tandetron da 3 MV,
- n. 3 spettrometri portatili/mobili per fluorescenza a raggi X (XRF);
- n. 6 tubi a Raggi X (3 con anodo a cromo e 3 con anodo a molibdeno) - da installare e impiegare uno alla volta su ognuno dei tre sistemi portatili - marca MOXTEK, modello Magnum con tensione massima di 40 kV, corrente massima di 01, mA e potenza massima di 4 W;
- le sorgenti sigillate indicate nella tabella 1 in allegato.
- l'impiego di un acceleratore mobile a radiofrequenza (RFQ), denominato MACHINA, con energia massima dei protoni pari a 2MeV.

La sorveglianza fisica della protezione da radiazioni ionizzanti è stata affidata al Dr.

The use of a radiofrequency (RFQ) accelerator, called MACHINA, with a maximum energy of 2 MeV, **is authorised**

documentazione in atti dovrà essere preventivamente autorizzata nelle forme di legge.

Firenze, 15 settembre 2023

IL DIRIGENTE dell' Area V
(Capecchi)

MARCA DA BOLLO
Ministero dell'Economia e delle Finanze
€16,00
SEDICI/00
Agenzia Entrate
IDENTIFICATIVO : 01220503473999

Per copia conforme all'originale
Il Funzionario Informatico
(Maria Sabrina Giannotta)

Msg

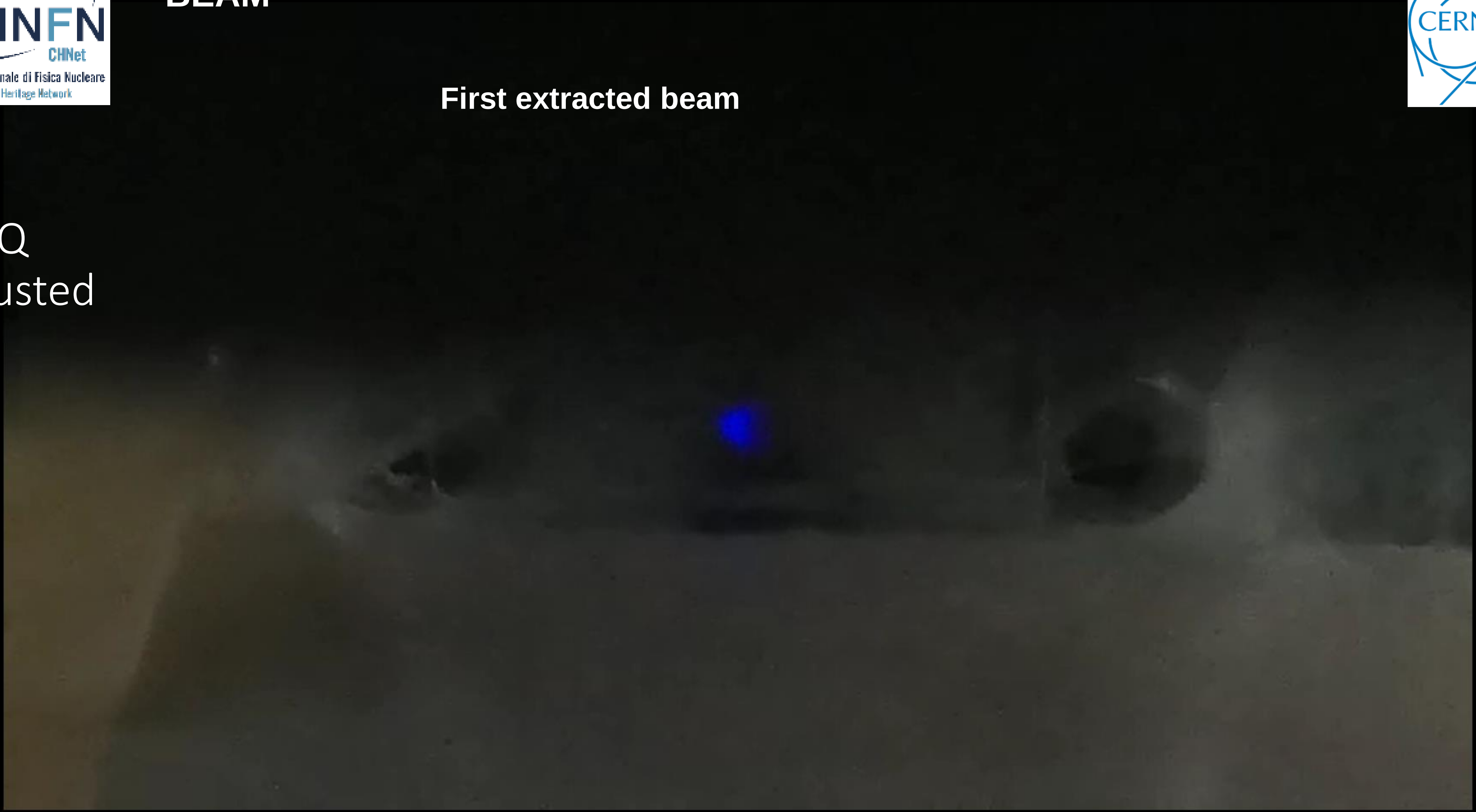
BEAM

First extracted beam

PMQ
randomly set

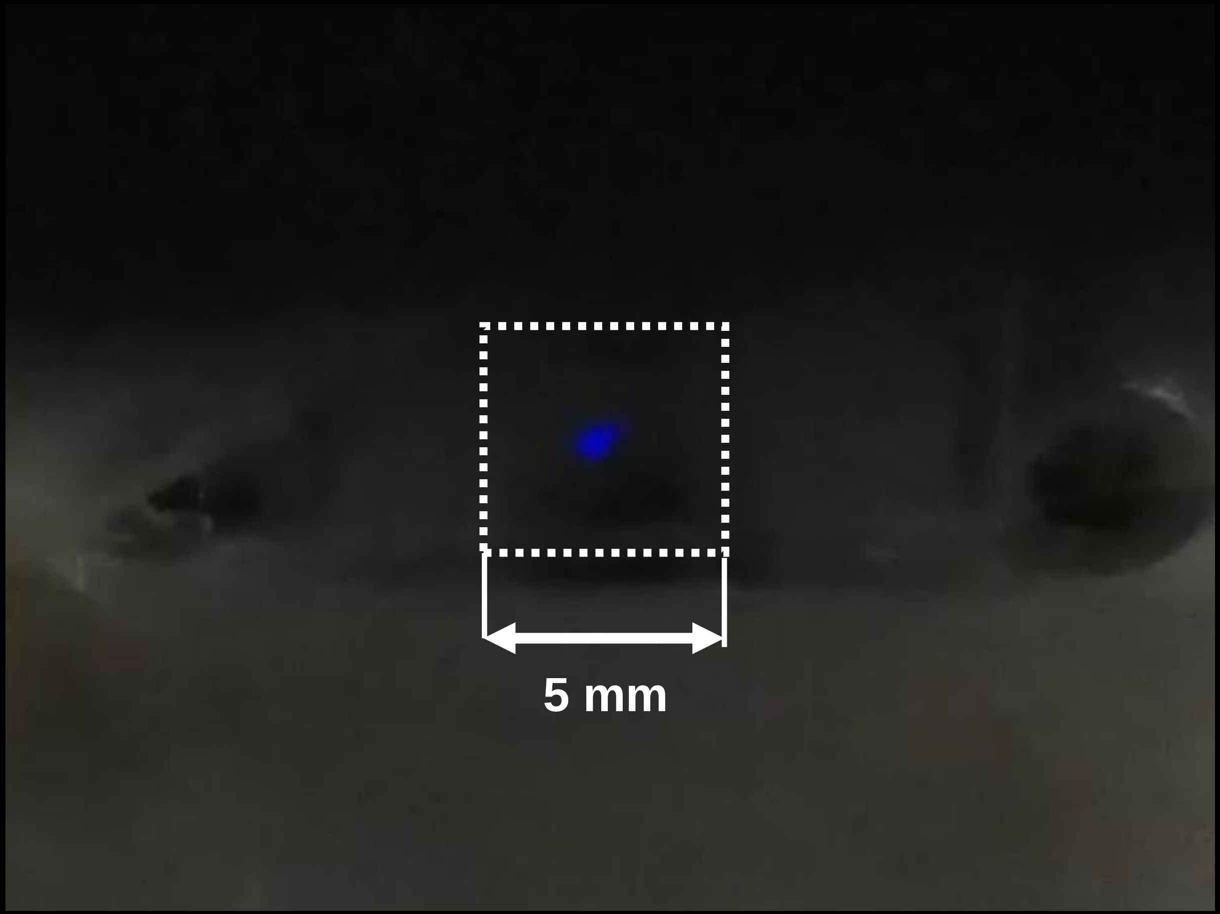
First extracted beam

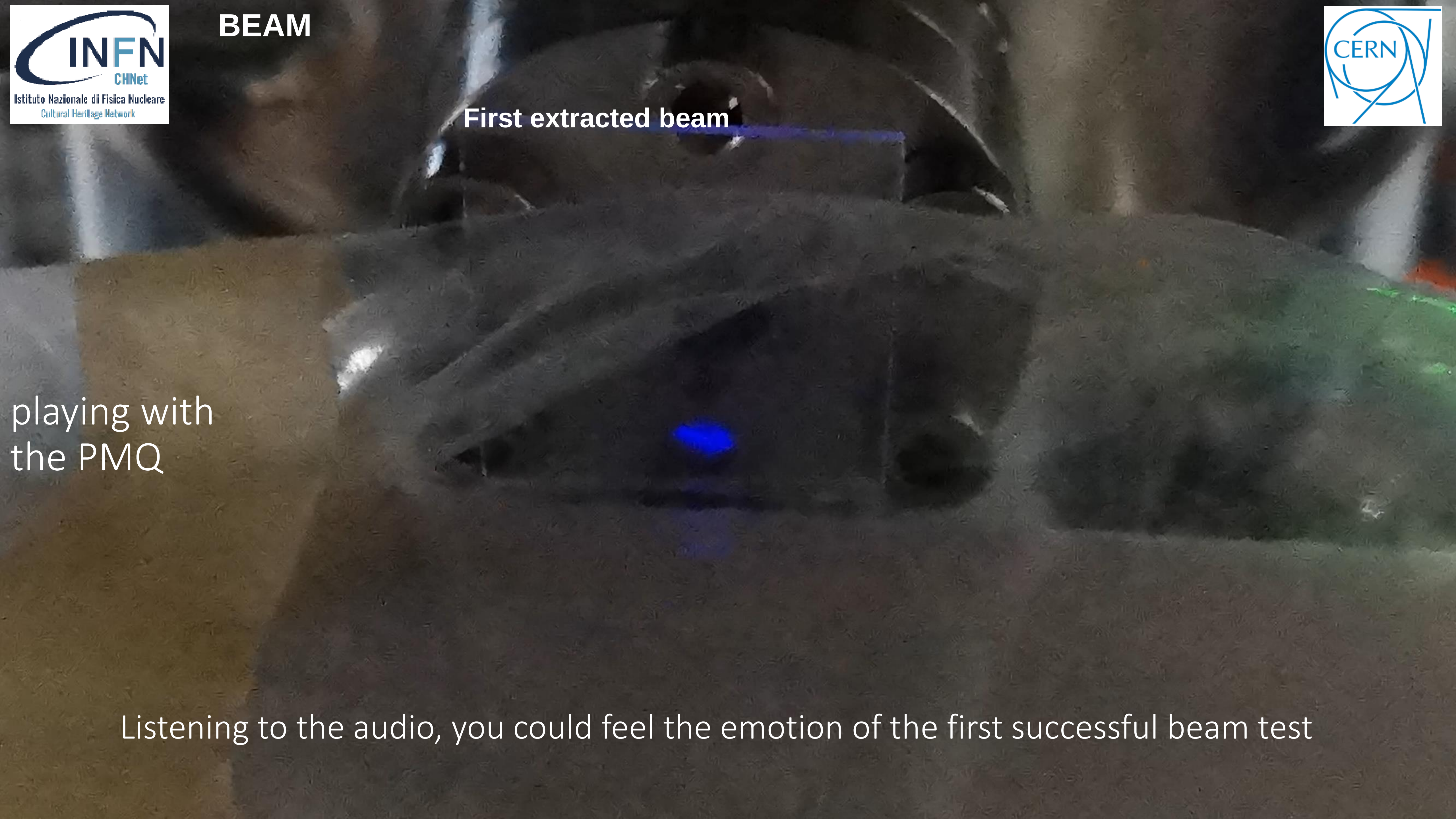
PMQ adjusted



First extracted beam

PMQ optimised



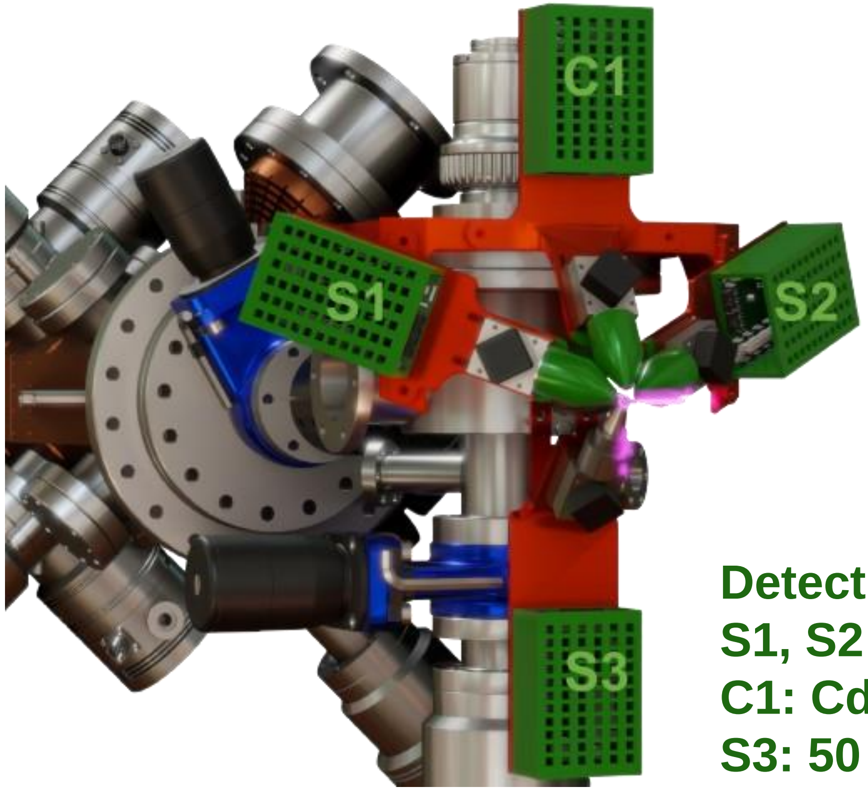

BEAM
First extracted beam
playing with the PMQ
Listening to the audio, you could feel the emotion of the first successful beam test

Detection set-up

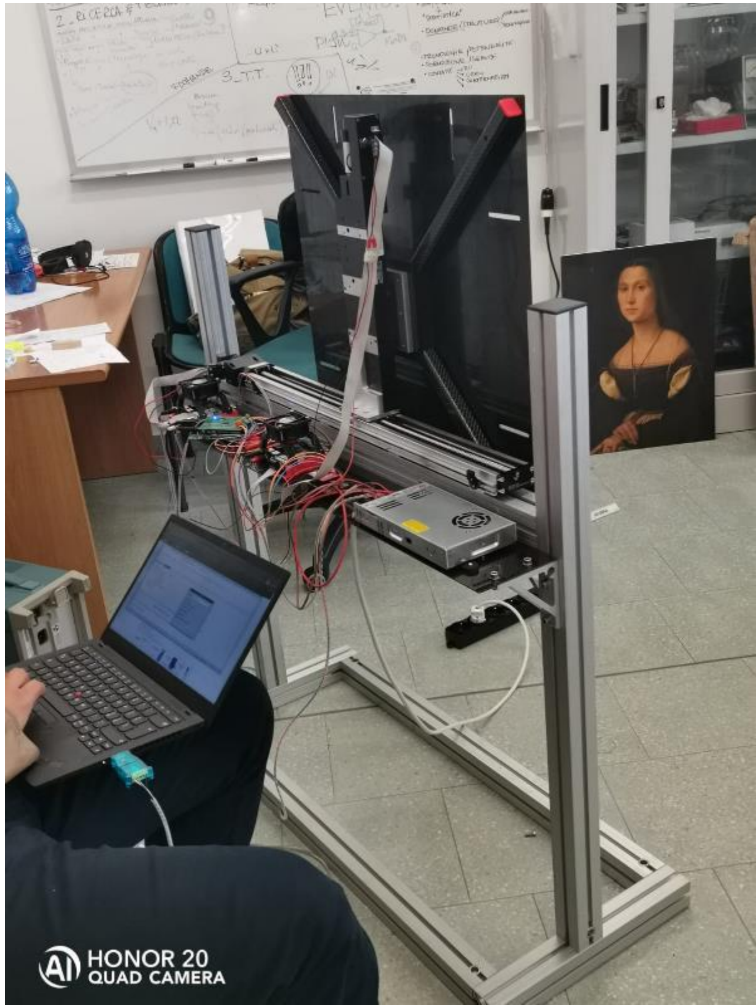
The MACHINA accelerator is working: obtained 2 MeV proton beams, some hundreds pA beam in air

Detection set-up:

- Detectors tested, first generation supporting structure already printed
- ACQ and IMAGING (sample scanning system), both based on the systems already developed at CHNet-LABEC for our XRF scanners tested successfully!



Testing the sample scanning system



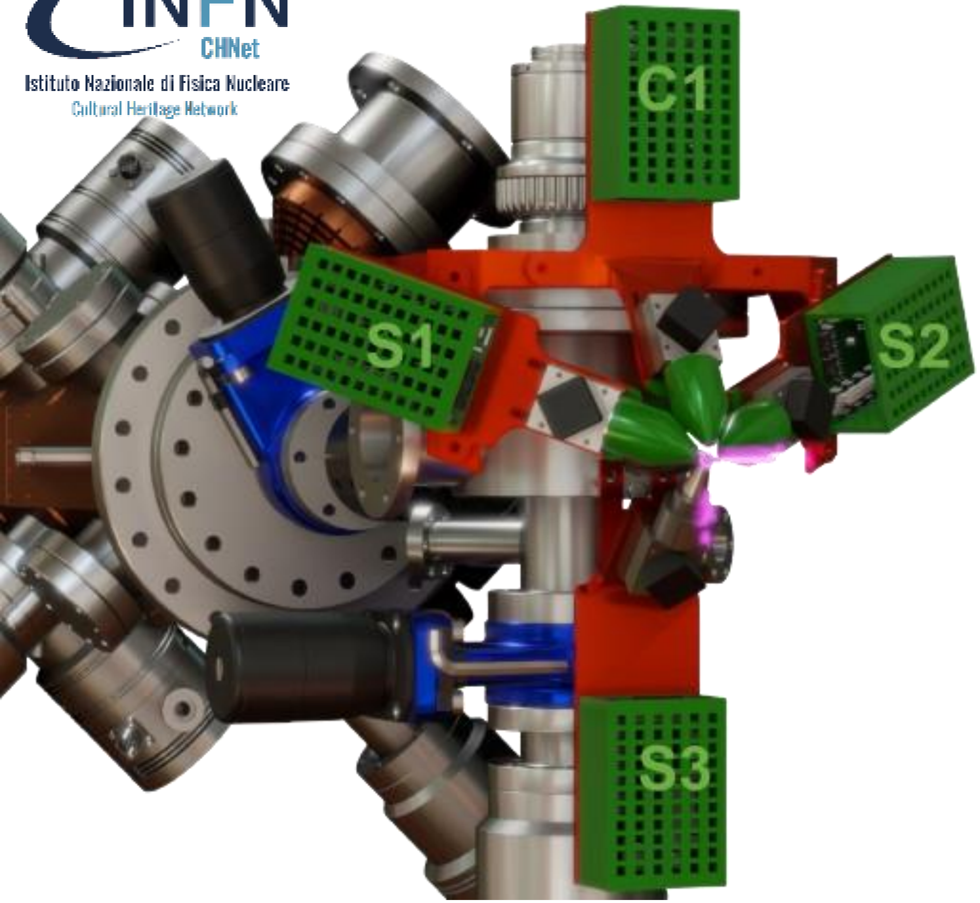
Detection set-up design
S1, S2: 50 mm2 SDD for PIXE
C1: CdTe 25 mm2 area, 1 mm thick, high energy PIXE - low energy PIGE)
S3: 50 mm2 SDD x current (below the beam, upside looking)

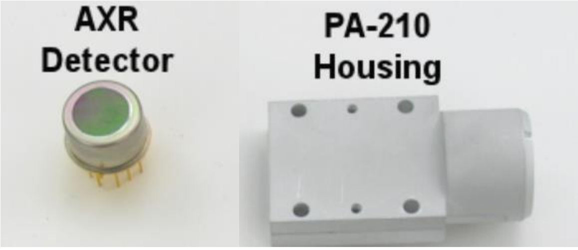
INFN CHNet Istituto Nazionale di Fisica Nucleare Cultural Heritage Network

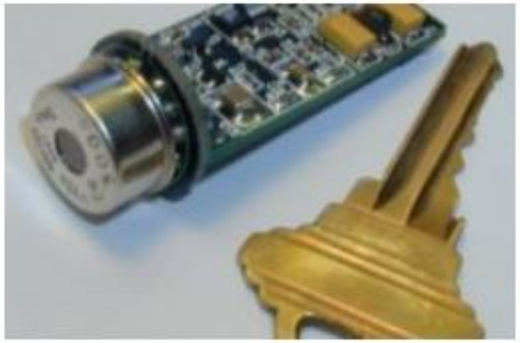
CERN

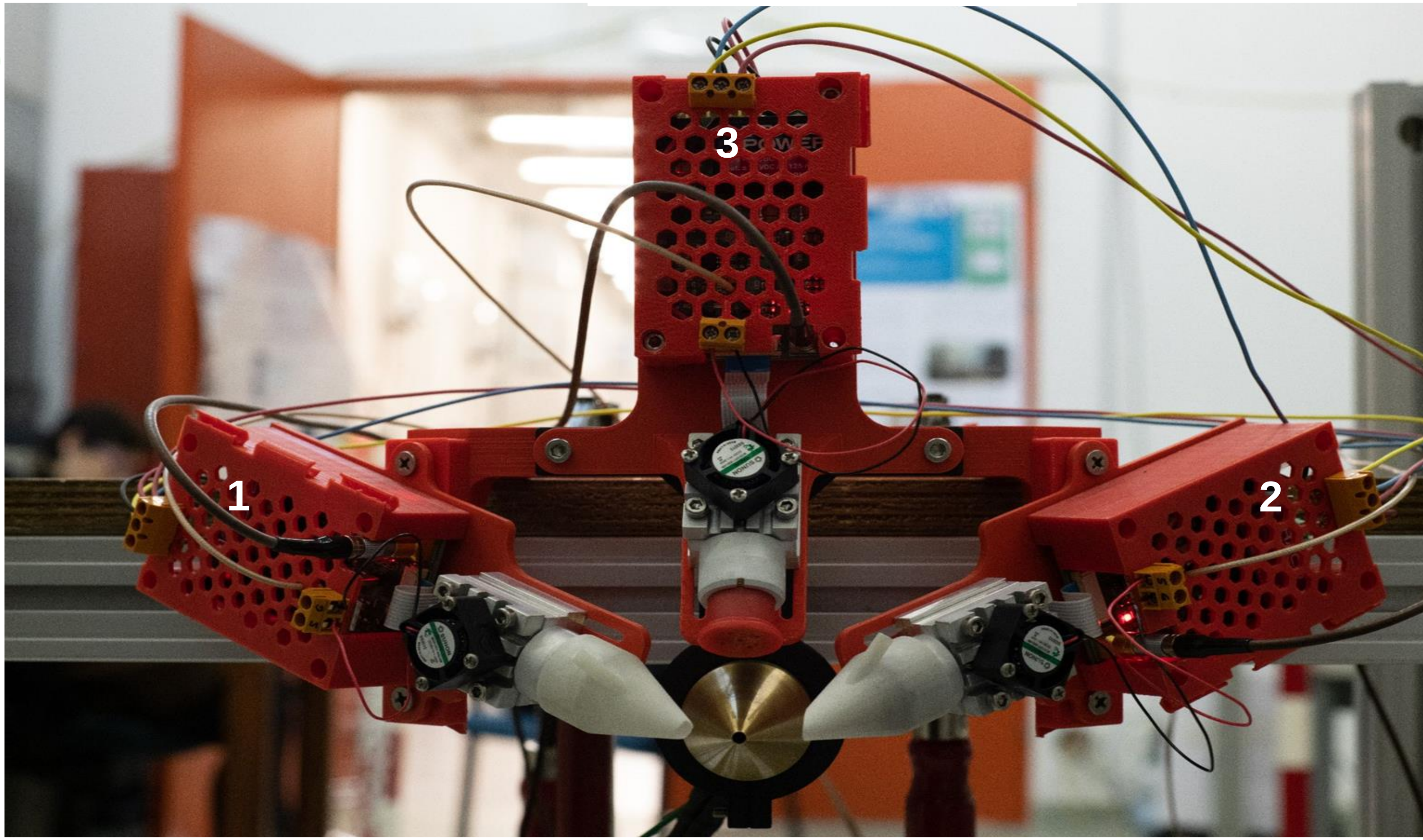
Detection set-up

detection set-up (design)









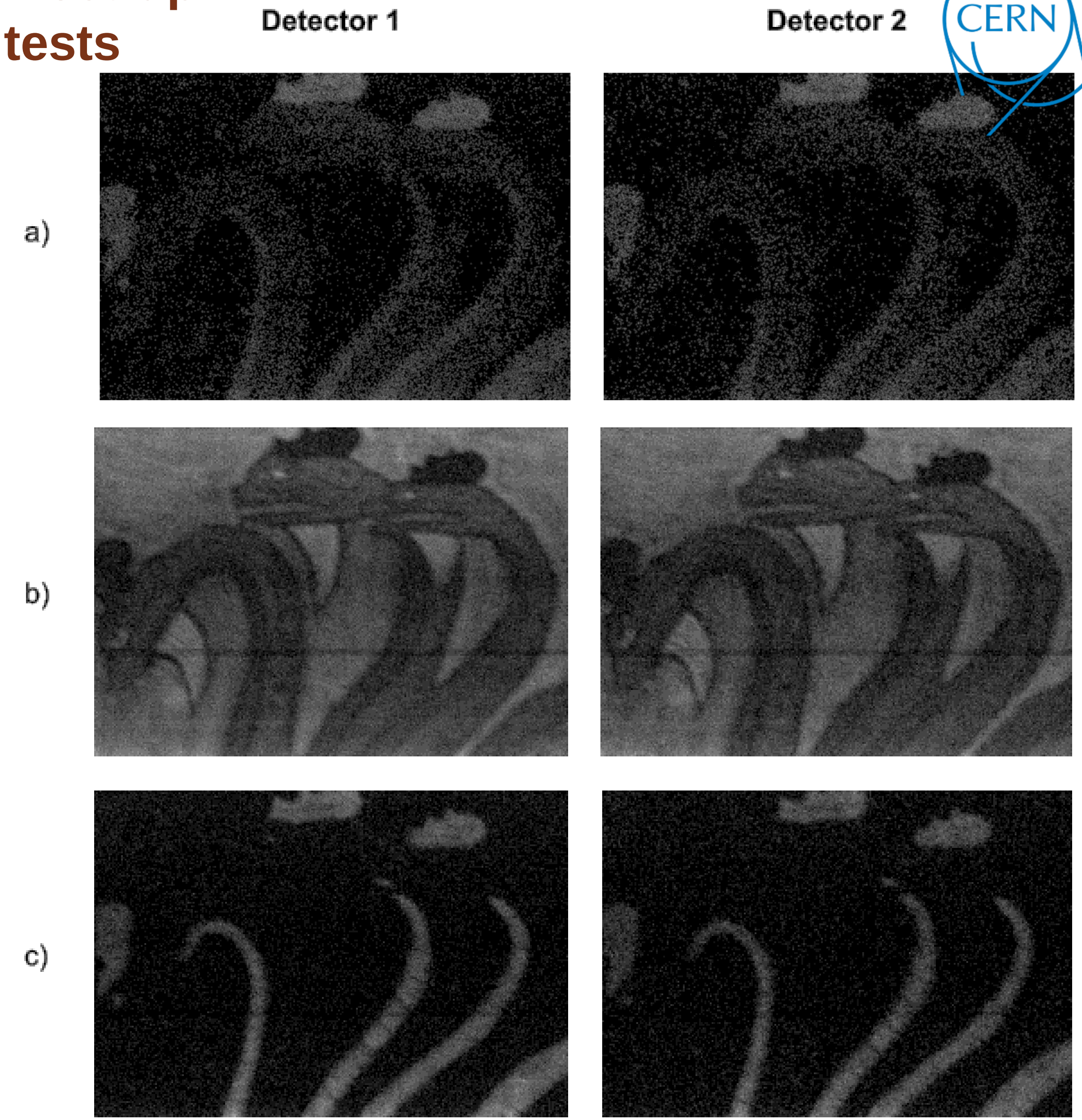
detection set-up (implemented so far)

Detection set-up implemented so far

S1, S2, S3 SDD	50 mm^2
Silicon Thickness	500 µm
Energy Resolution @ 5.9 keV (^{55}Fe)	~130 eV FWHM@t 4 µs peaking time
Detector Window	0.5 mil (12.5 µm) Be

Detection set-up
First tests

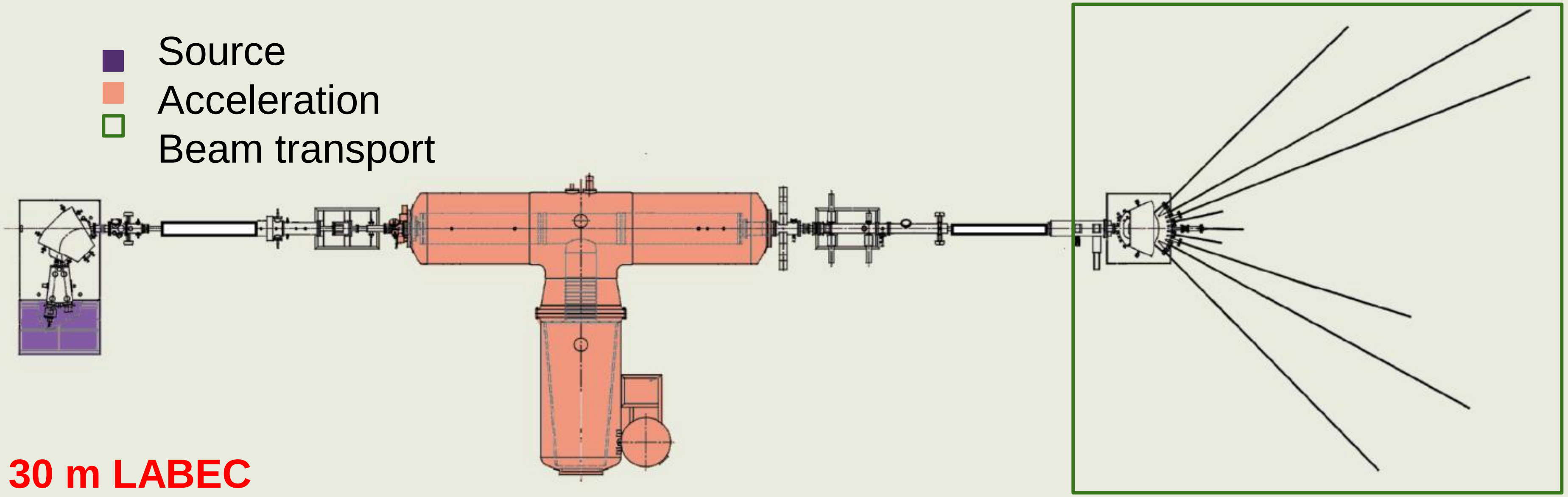
Left-hand side: the modern fresco painting studied with the PIXE technique using the new system described. Right-hand side: the painting during the PIXE measurements installed on the target positioning system (the black carbon fiber sheet) together with the Pb, Au, Fe, Al standards (the small coloured squares inside the red sample holder on the left-hand side).



Intercomparison of the elemental maps obtained with (a) Fe K_α (b) Ti K_α and (c) S K_α, obtained with both detectors used for PIXE imaging.

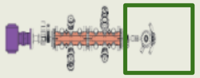
MACHINA footprint compared to the 3 MV tandem electrostatic accelerator

INFN-CHNet LABEC vs. MACHINA



30 m LABEC

2.5 m MACHINA



Layout

1. IBA and Cultural Heritage: why a transportable accelerator

2. MACHINA
   a) MAIN FEATURES OF MACHINA
   b) SOURCE
   c) LEBT
   d) ION SOURCE ACCEPTANCE TEST
   e) DUMMY ACCELERATOR
   f) ACCELERATOR
   g) HEBT
   h) CONTROL SYSTEM
   i) TRANSPORTABILITY
   j) RADIO-SAFETY
   k) BEAM
   l) DETECTION SET-UP

3. **Status, Activities in progress and Perspectives**

Status, Activities in progress and Perspectives

The MACHINA accelerator is working: obtained 2 MeV proton beams, some hundreds pA proton beam in air

Radio-safety: measurements carried on at CERN and at LABEC. Since September 2023, the use of MACHINA is authorised: we can accelerate to full energy a proton beam at the Labec laboratory

Detection set-up:

Detectors tested, first generation supporting structure already 3D-printed

ACQ and IMAGING (sample scan), both based on the systems already developed at CHNet-LABEC, working

Low energy gamma detector still to implement (we got a damaged unit)

Status, Activities in progress and Perspectives

- ✓ **The MACHINA accelerator is working**: 2 MeV proton beams, some hundreds pA proton beam in air:
- ✓ **Radio-safety**: measurements carried on at CERN and at LABEC. Since September 2023, the use of MACHINA is authorised: we can accelerate to full energy a proton beam at the Labec laboratory
- ✓ **Detection set-up:**
- ✓ Detectors tested, first generation supporting structure already 3D-printed
- ✓ ACQ and IMAGING (sample scan) working

  Low energy gamma detector still to implement (we got a damaged unit): **to do!**

- ✓ **First successful 2 MeV beam test at LABEC**
- ✓ **First beam on true artworks at LABEC:** next few weeks
- ✓ **The OPD officially reserved a laboratory to host MACHINA:** now it is an empty space, still to set up from scratch, but we have it!
- ✓ **MACHINA2:** we have been asked to develop a MACHINA twin

Status, Activities in progress and Perspectives

Istituto Nazionale di Fisica Nucleare
CHNet
Cultural Heritage Network

CERN

MACHINA 2

DICHIARAZIONE

Il progetto SEIC (Space and Earth Innovation Campus) guidato dal GSSI prevede l'allestimento di un laboratorio per la diagnostica dei Beni Culturali con *strumentazione mobile* che permetta di effettuare campagne di misure presso musei, centri di conservazione e restauro.

Uno strumento innovativo, sviluppato nei laboratori dell'Istituto Nazionale di Fisica Nucleare (INFN), è un acceleratore di protoni *trasportabile* che permette di svolgere misure diagnostiche su Beni Culturali tramite un insieme di tecniche analitiche molto efficaci che utilizzano fasci di protoni di bassa energia (1-2 MeV). Il sistema ha dimensioni e peso molto inferiori a quelli degli acceleratori utilizzati nei laboratori di fisica, tale quindi da poterlo spostare anche in musei per campagne di misure sulle opere che vi sono conservate.

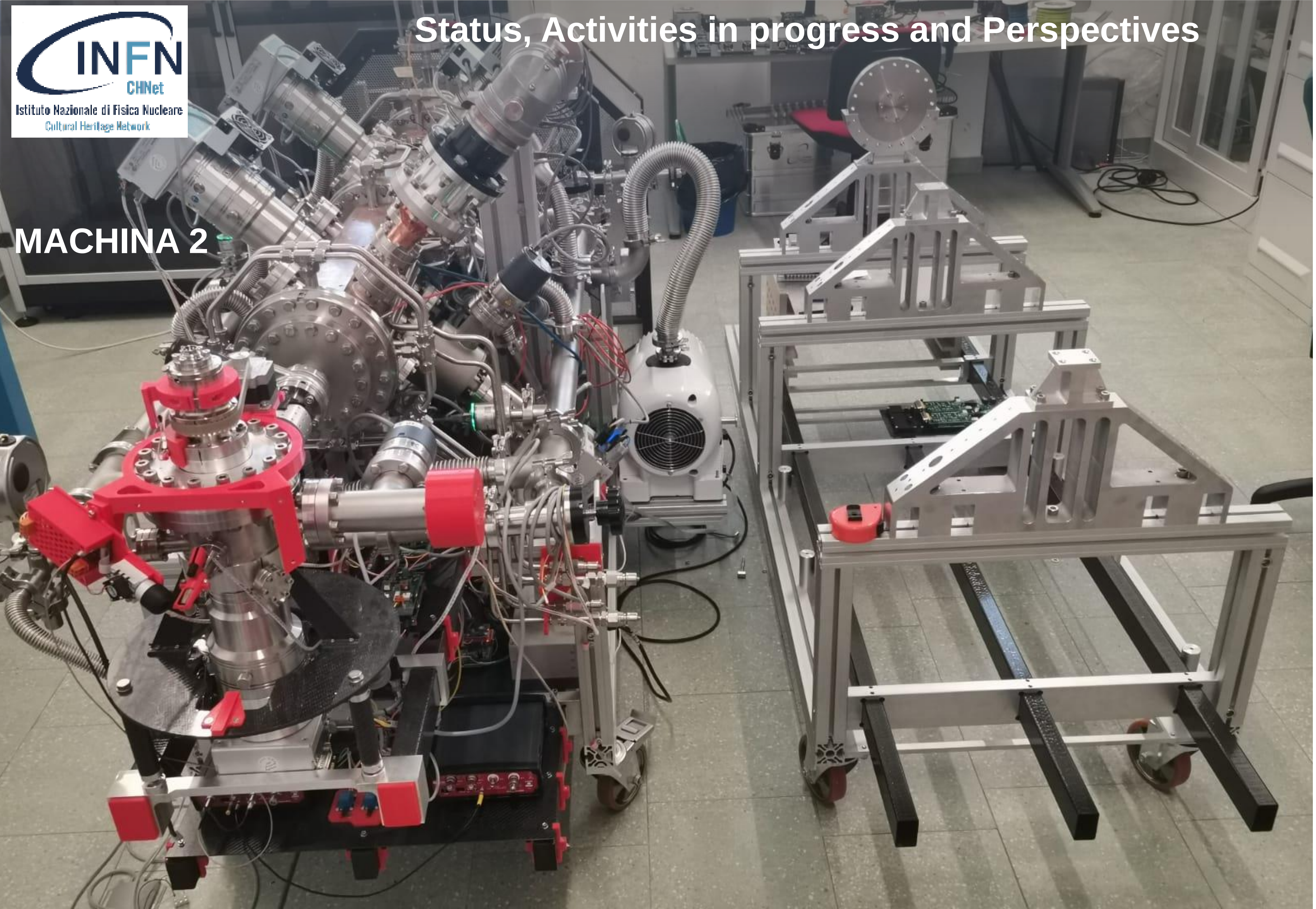
Questa strumentazione, unica nel suo genere in quanto permette di effettuare misure che vengono svolte ad oggi solo con strumentazione fissa (ossia acceleratori di grandi dimensioni non trasportabili), può essere prodotta dall'INFN che si configura come unico fornitore in quanto un'indagine di mercato mostra che uno strumento con caratteristiche simili non è disponibile commercialmente, ma neanche in altri laboratori di ricerca. Si propone pertanto di effettuarne l'acquisto presso l'INFN

L'Aquila 15/04/2023

In fede
Prof. Roberto Aloisio
(Responsabile scientifico progetto SEIC)

Roberto Aloisio

Status, Activities in progress and Perspectives



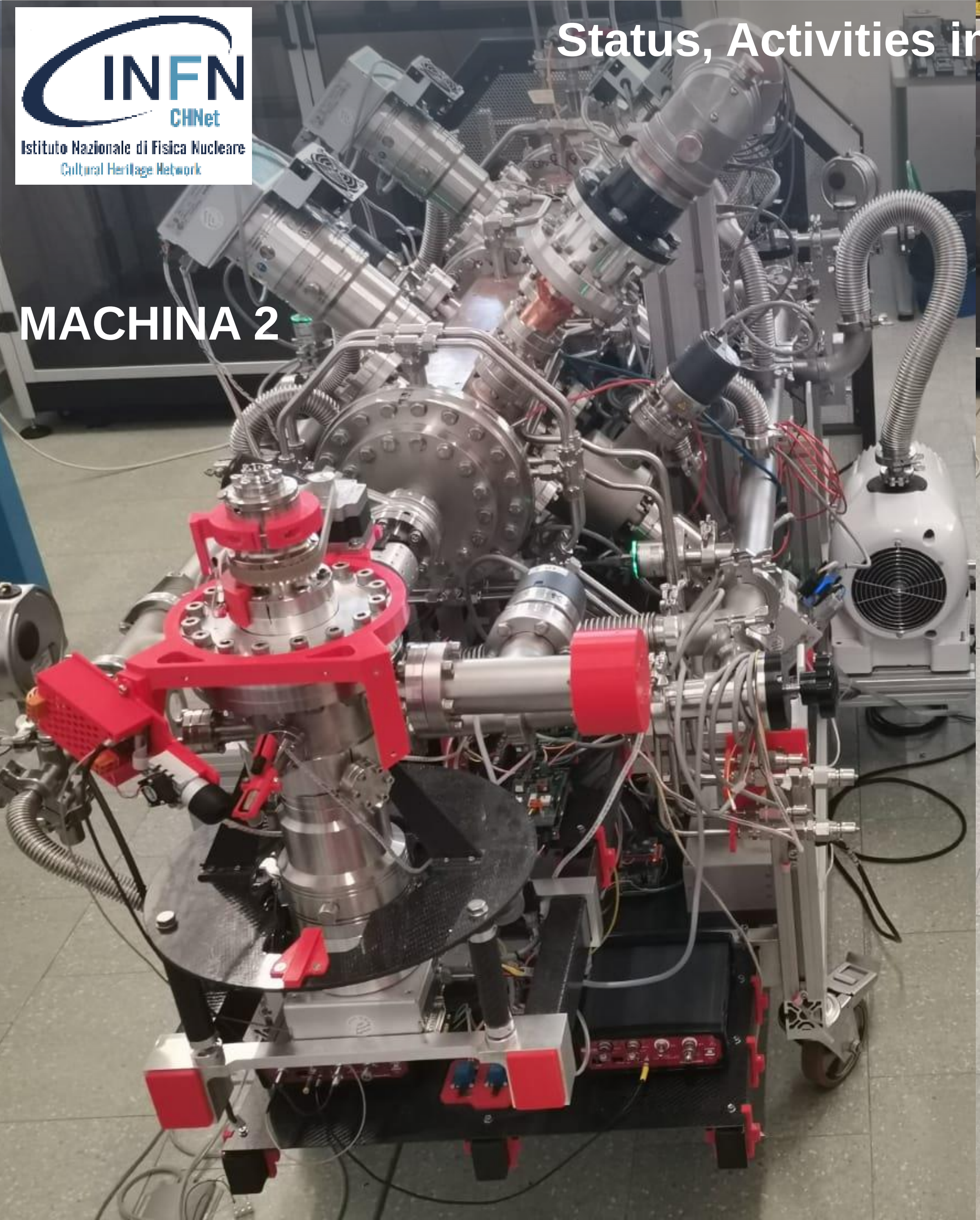
MACHINA2 is coming!

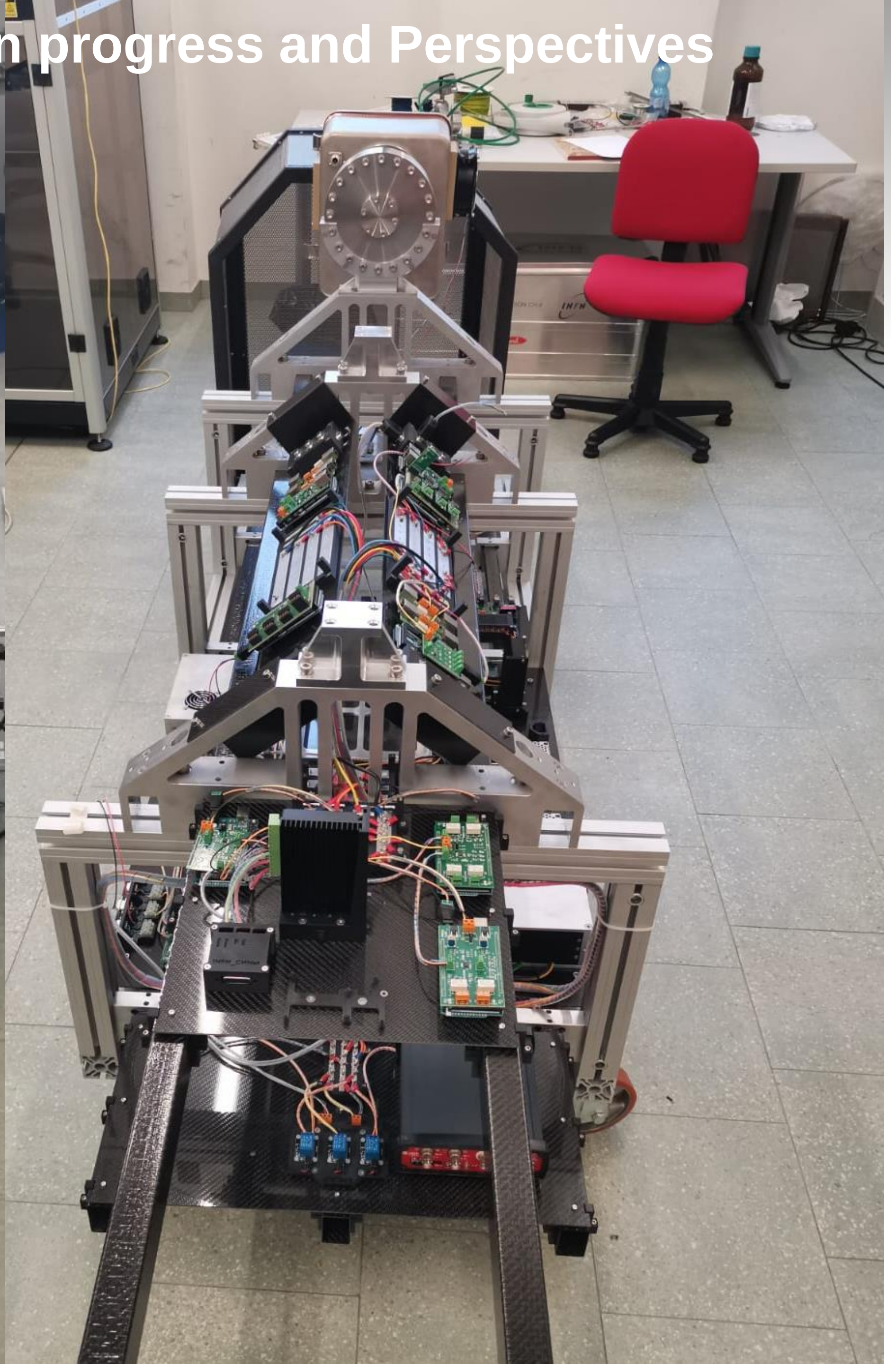
May 2023 GSSI will invest about 2 M€ for MACHINA2

Status, Activities in progress and Perspectives

INFN
CHNet
Istituto Nazionale di Fisica Nucleare
Cultural Heritage Network

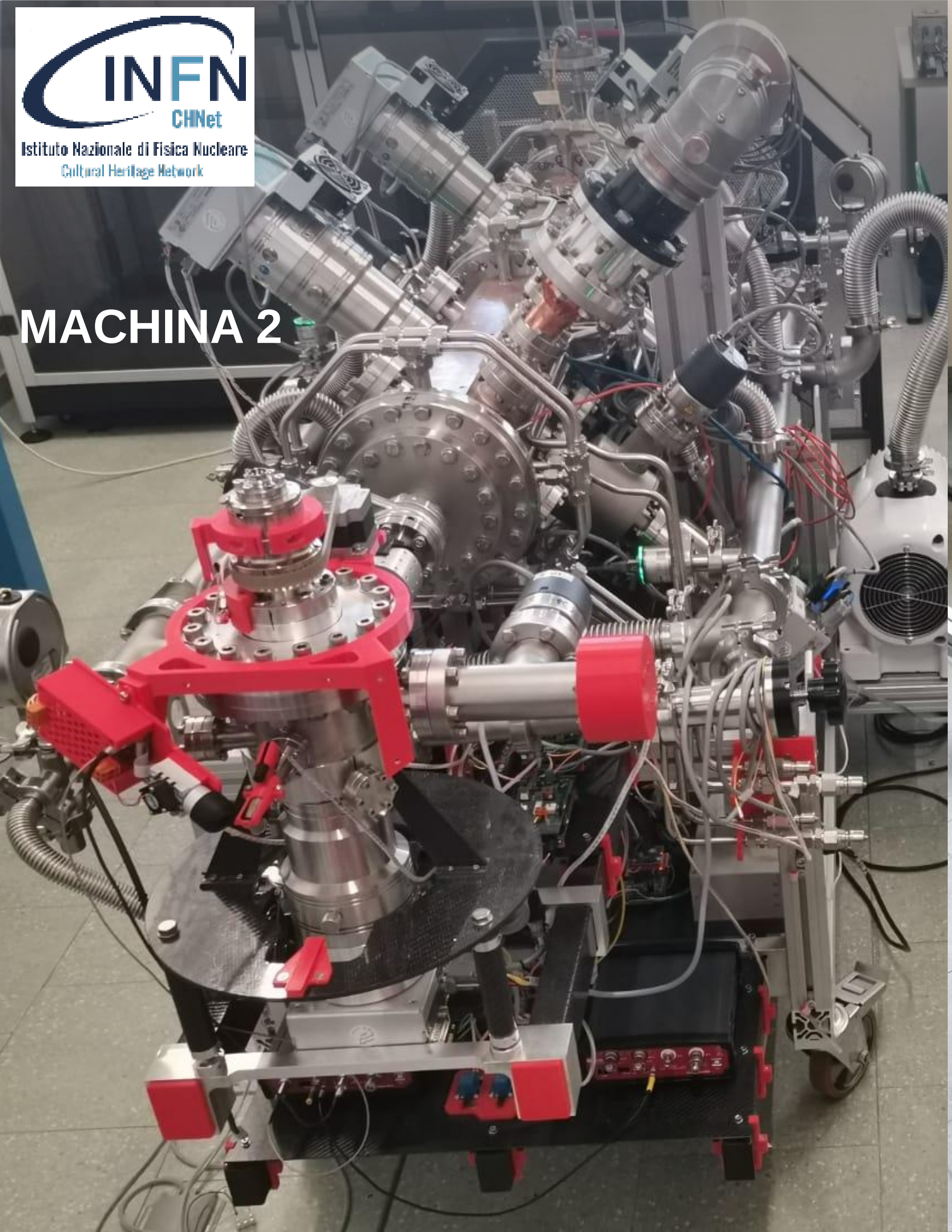
CERN





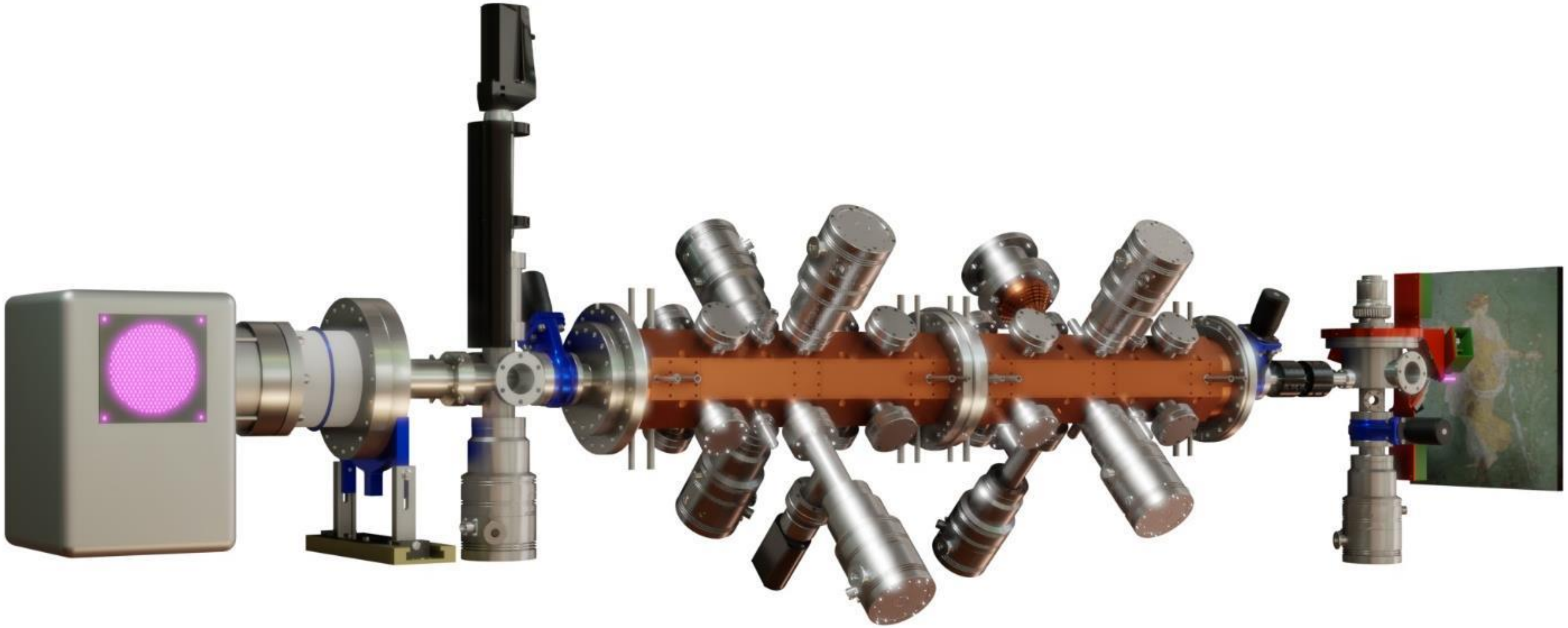
MACHINA2 is coming!

November 2023


INFN
CHNet
Istituto Nazionale di Fisica Nucleare
Cultural Heritage Network
MACHINA 2


CERN
MACHINA2
is coming!
Yesterday!
The
source is
dismounted and
the mock-up
accelerator installed
for upcoming vacuum-
and control-system tests

On behalf of the MACHINA collaboration,



THANK YOU FOR YOUR ATTENTION!

Acknowledgment to the MACHINA collaboration

CERN:

S. Mathot, G. Anelli, G. Cipolla, A. Grudiev, A. Lombardi, E. Milne, E. Montesinos, K. Scibor, M. Vretenar

INFN:

F. Taccetti, F. Benetti, L. Castelli, M. Chiari, C. Czelusniak, S. Falciano, M. Fedi, F. Giambi, P.A. Mandò, M. Manetti, M. Massi, C. Ruberto, L. Giuntini

Funds

MIUR (FISR GU n.277 27-11-2017)
CERN (PIXE-RFQ)