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

Leonardo - Codex Atlanticus

Mirko Massi
on behalf of MACHINA collaboration

TERZA GIORNATA
ACCELERATORI
INFN-LNF
4-5 APRIL 2024

The importance of ascertaining material composition and compatibility

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

The importance of ascertaining material composition and compatibility

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

The importance of ascertaining material composition and compatibility

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

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

…

INFN MACHINA
Istituto Nazionale di Fisica Nucleare

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

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

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**

OPD endorsement

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

IAEA endorsement to the MACHINA project

IAEA
Atoms for Peace
الوكالة الدولية للطاقة الذرية
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

2017-03-16

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

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

AGLAE endorsement to the MACHINA project

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

Liberté • Égalité • Fraternité
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 endorsement to the MACHINA project

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,

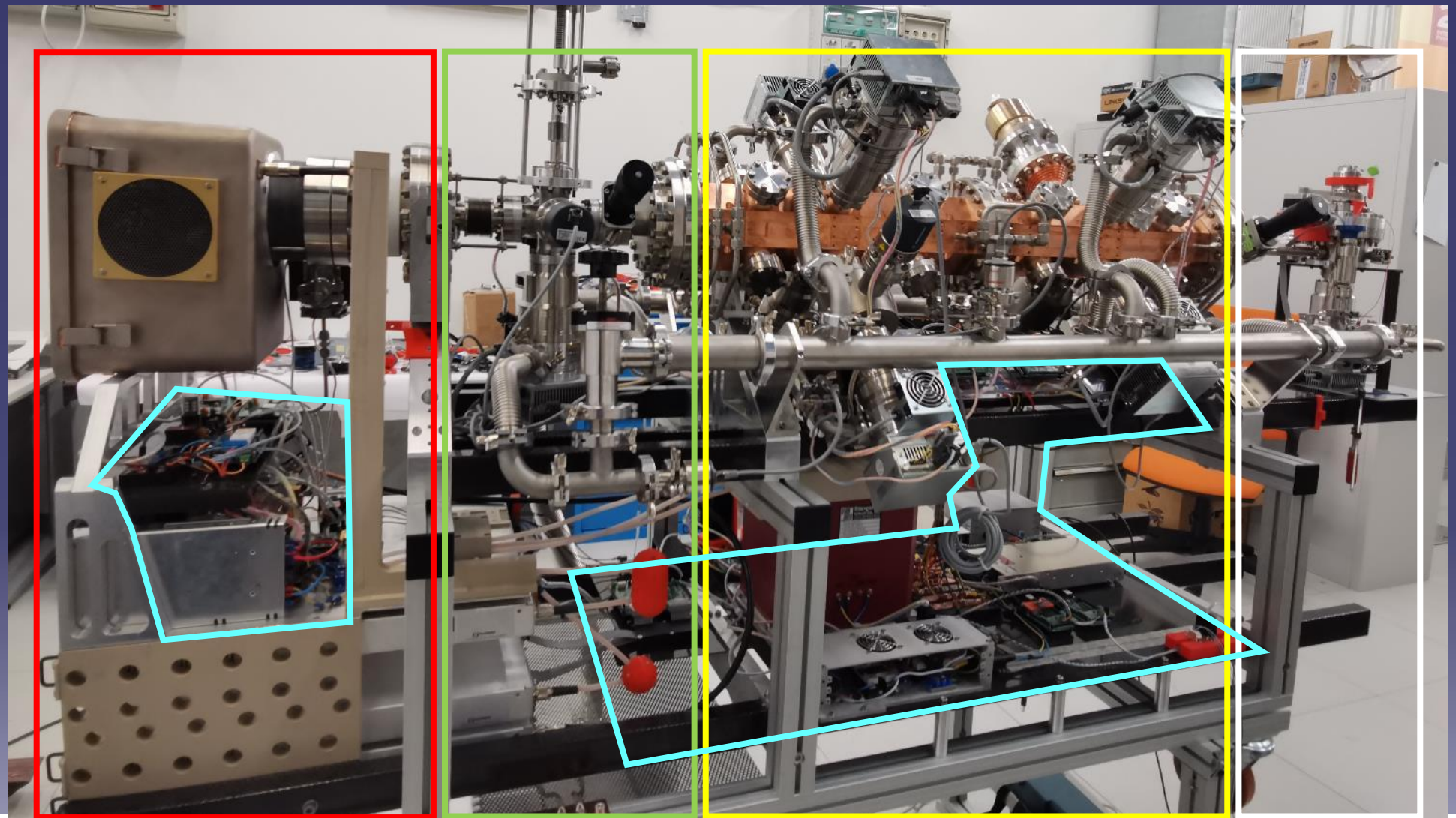
With this letter, we would like to express our strong support for the *Design & construction of a transportable RFQ for PIXE analysis* (*PIXE-RFQ*) project. Beyond its potential to revolutionize the accessibility of PIXE analysis technology, this project is uniquely positioned to overcome an important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

THE WHOLE SYSTEM

SOURCE LEBT RFQ ACCELERATOR HEBT



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

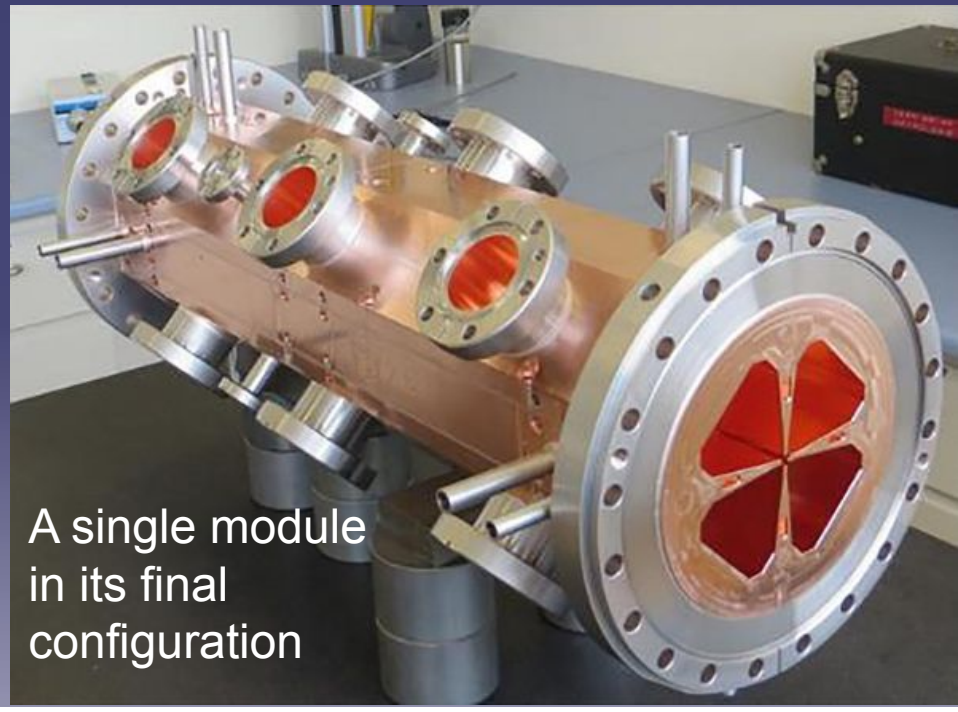
CERN RFQ

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,…)

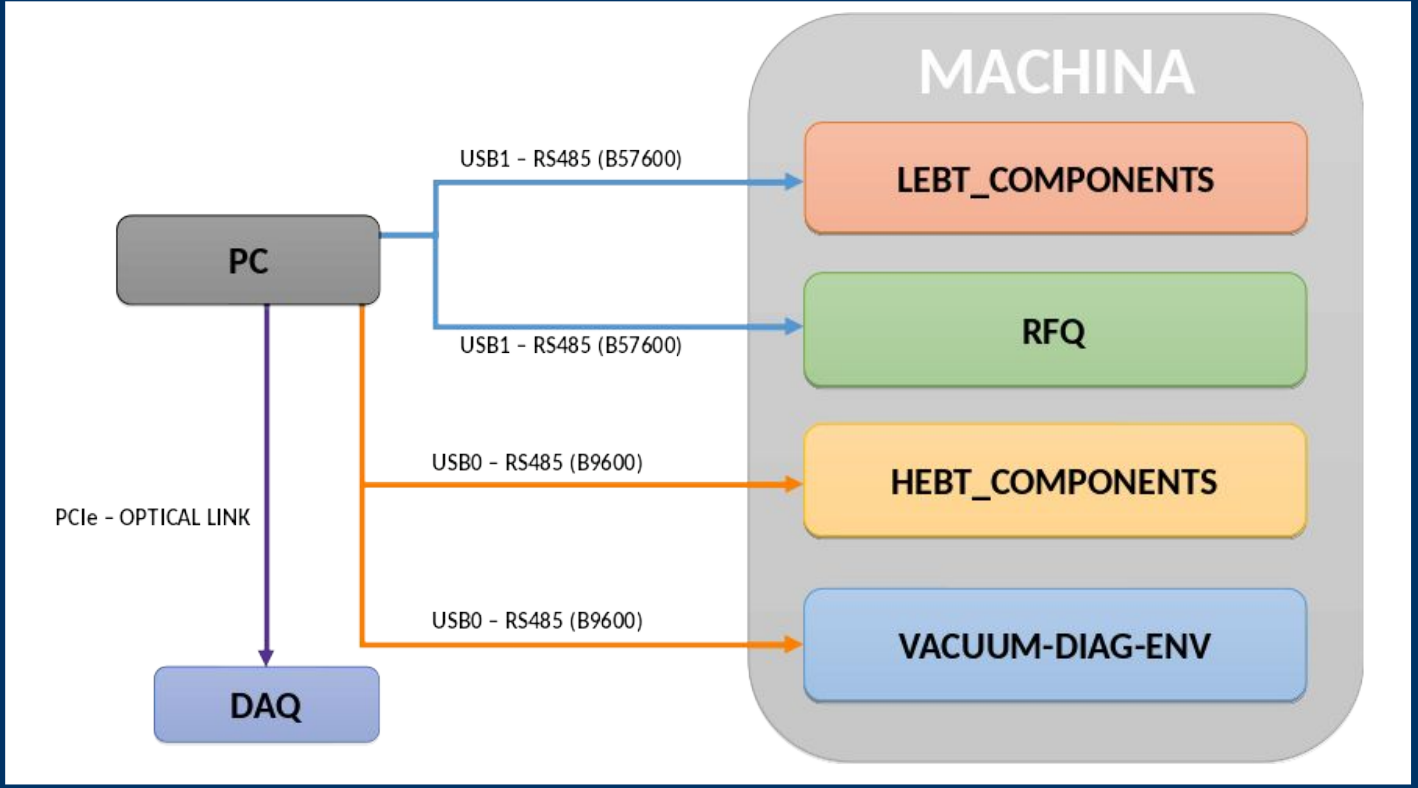
- 0. 5 mm exit beam diameter
- 8 keV energy spread

- Ultra low power: **less than 6 kVA** for the RFQ


A single module in its final configuration

Control System

Scheme of the MACHINA Communication Channels

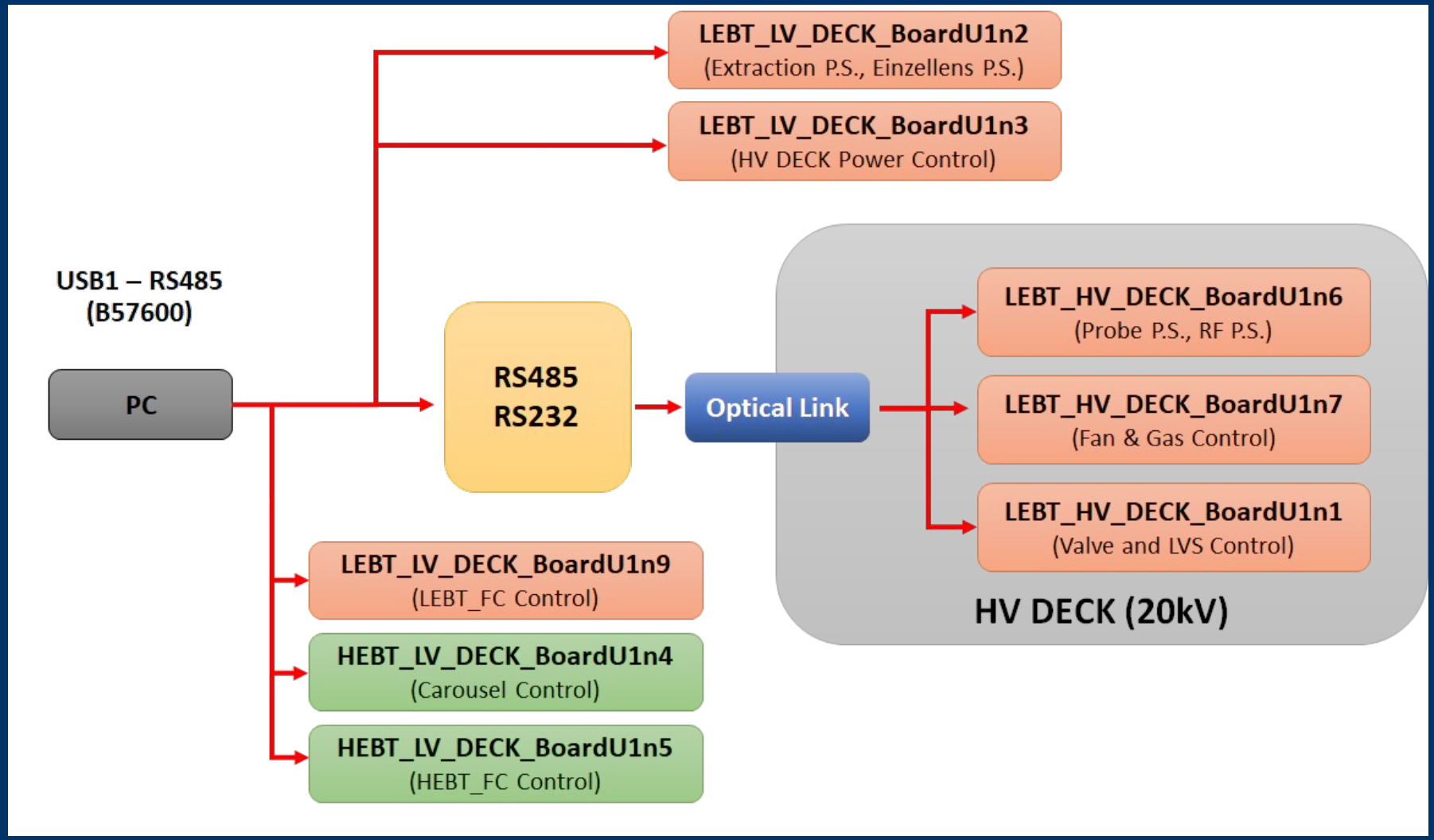


The two USB-RS485 lines allow interacting with the controllers of all the elements of MACHINA (Arduino, turbopump controller)

- 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

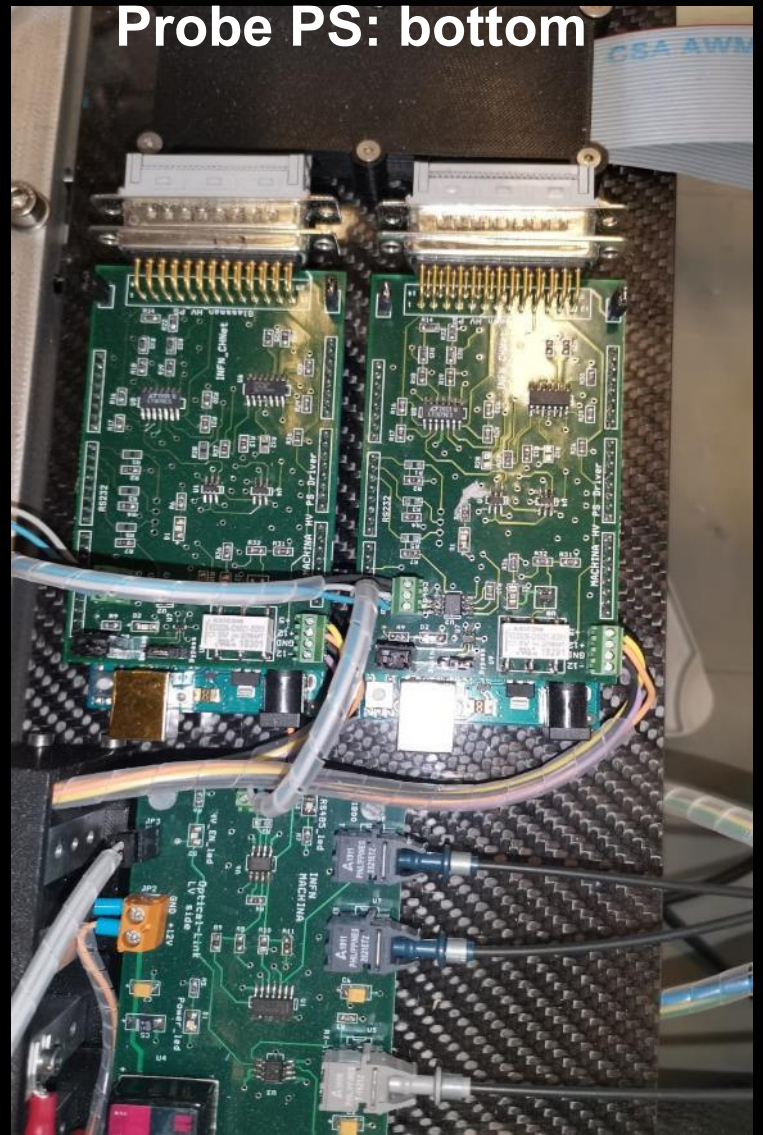
Control System

The control system is based on 25 Arduino Mega 2560R3 board & custom shield

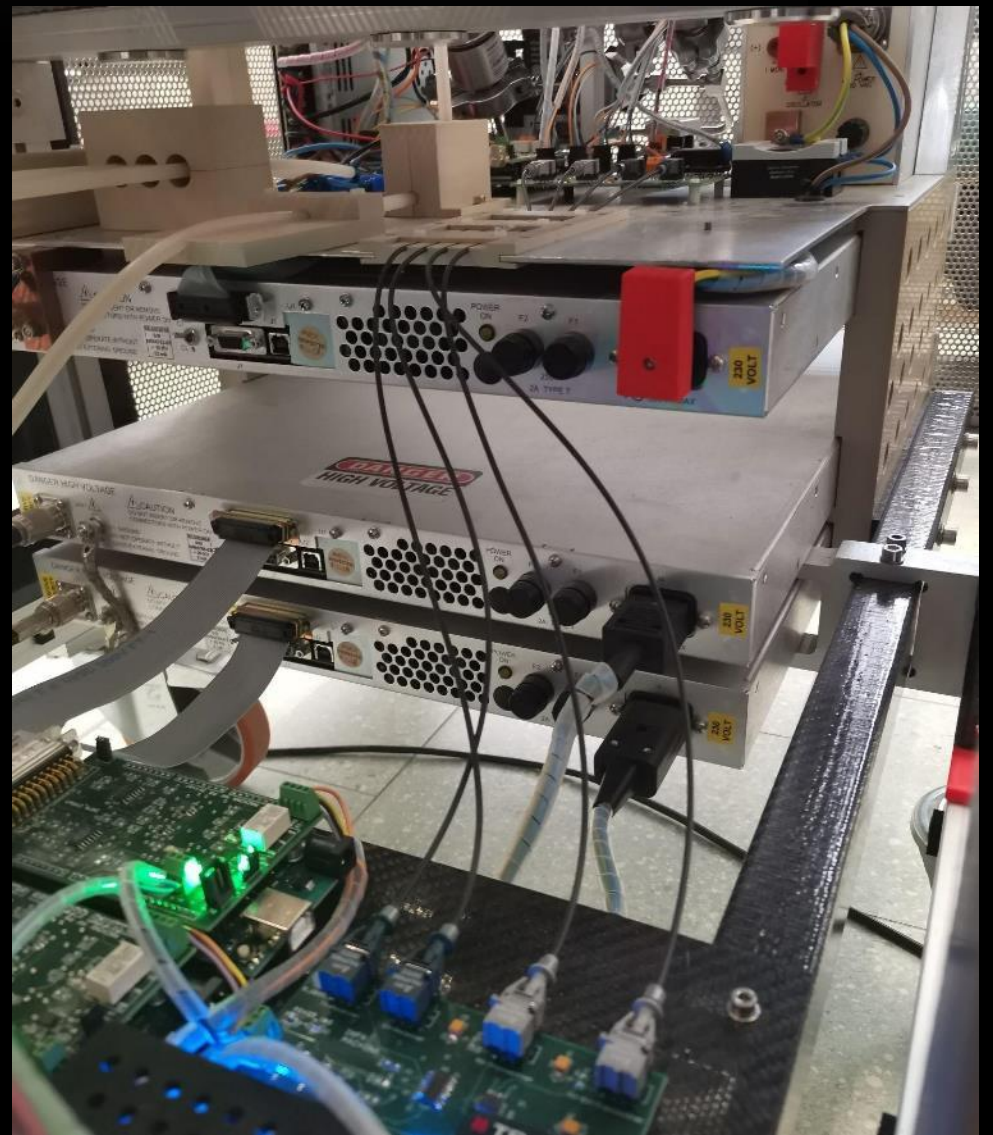


Source – HV PS hardware and control software

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



Optical fibres to control
the Probe PS
Ground Side



Control System: overview

MACHINA: Control System

HEBT | VACUUM | MISCELLANEA

MACHINA: Vacuum System

LEBT ACCELERATOR HEBT

HV1 8.5E-08 HV2 3.6E-08 HV2 3.1E-08 HV3 2.7E-07 LV1 1.5e-3

VS1 VS2 VS3 VS4 VS5 VS6 VS7 VS8 VS9

Lebt VSLebt-ON VSLebt-OFF | Accelerator VSAcc-ON VSAcc-OFF | Hebt VSHebt-ON VSHebt-OFF

VS1	070020	VS2	072000	VS9	072000
		VS3	072000		
		VS4	072000		
		VS5	072000		
		VS6	072000		
		VS7	072000		
		VS8	072000		

LVS-forepump: LVSFpump-ON / LVSFpump-OFF

VS Parameters: STATUS, RPM, TEMP, POWER

MACHINA: Miscellanea

Vacuum | HV PS | Cooling | GenSettings | Camera

Save_Config | Load_Config

Terminal Output Message Policy: LEBT RFQ HEBT VACUUM GENERAL NO MESSAGES

ON / OFF

MACHINA: Lebt

Extraction Voltage 6.77 kV 0.00 mA

Probe Voltage 3.50 kV 0.01 mA

FCup ---- uA

Gas Inlet ---- mb

Low Vacuum System 7.8e-4 mb

RF Fan ---- rpm

Einzellens 6.65 kV

POWER | GND-DECK | HV-DECK

HV_Probe ON OFF

RF_PS Power ON OFF

HV_Extraction 6.76

HV_Probe 3.50

HV_Einzel 6.64

FaradayCup: FCup-IN / FCup-OUT

Gas Inlet

MACHINA: RFQ

Average Power ---- kW

Peak Power ---- kW

Cooling: water temperature ---- °C; air temperature ---- °C

MACHINA: Hebt

Gate Valve | Rotary Stage Selector | Exit Snout | Magnets | Light | Low Vacuum Sys 5.2e-4 mb

LVS@Snout: 25.2 temp. (°C); 24.4 humid. (%)

Rotary Stage: FreePath FCup Degrader1 Quartz Degrader2

MACHINA: CameraServer

File Devices

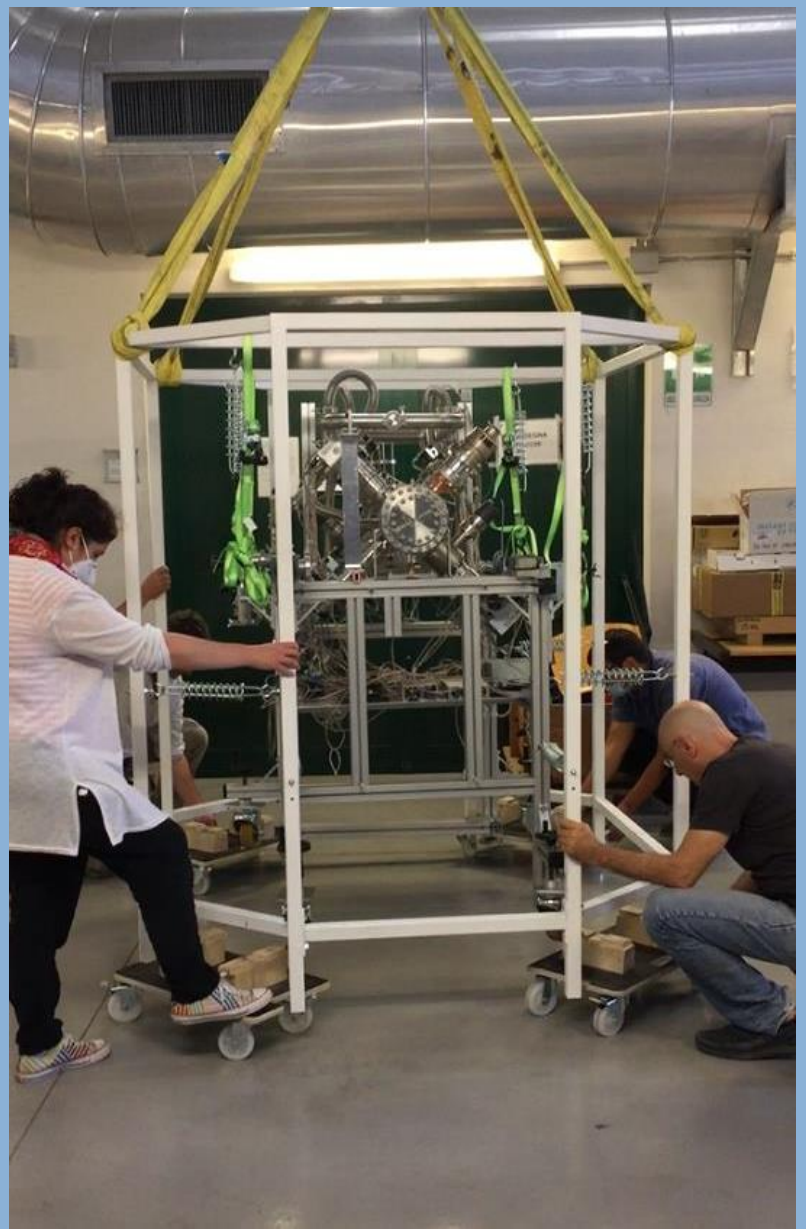
Focus

Image | Video

Capture Photo

Exposure

TRANSPORTABILITY

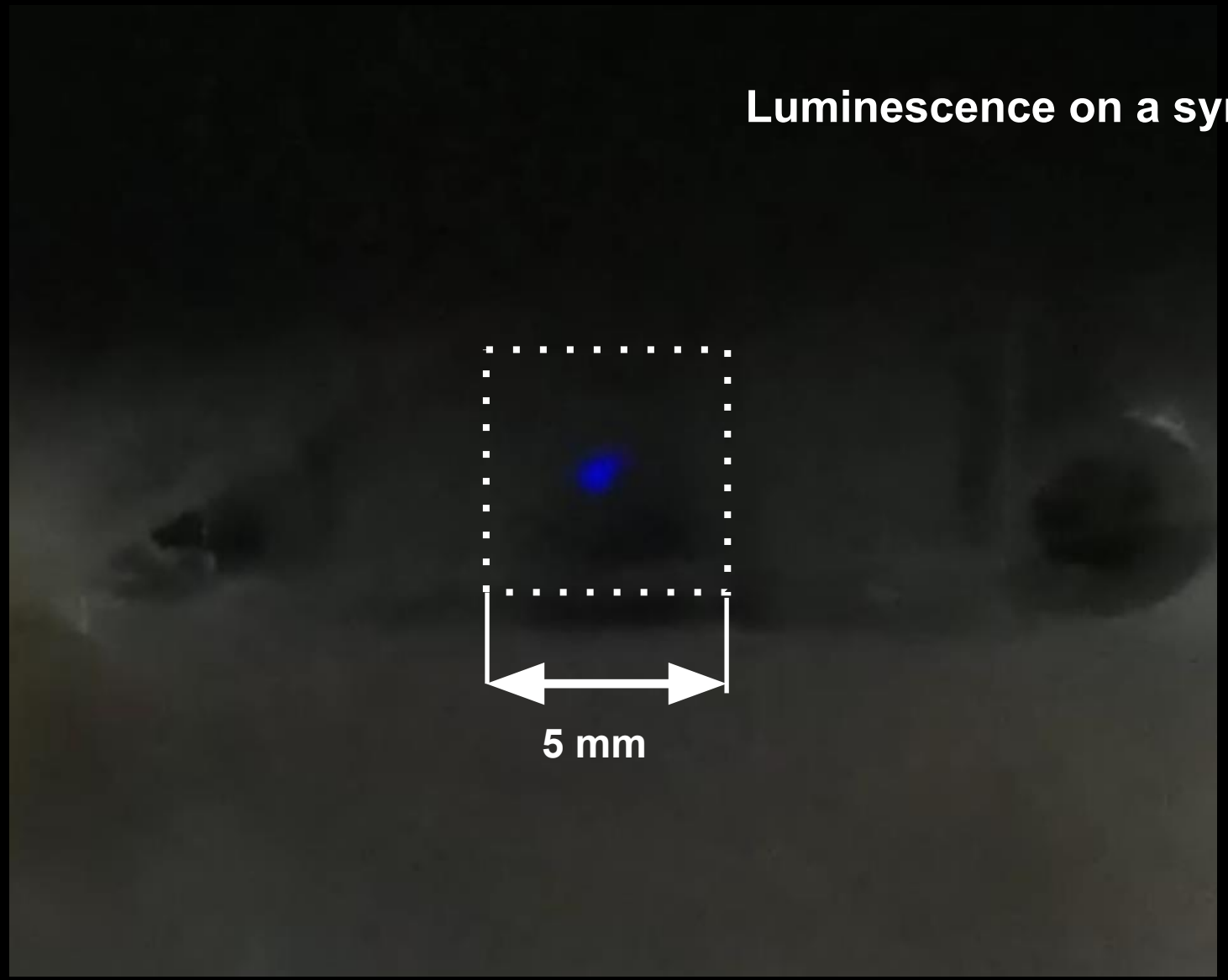


MACHINA has travelled thousands of kilometres back and forth between Florence to Geneve

Vibrations are not a problem

FIRST EXTRACTED BEAM IN AIR - MAY 2022 - CERN

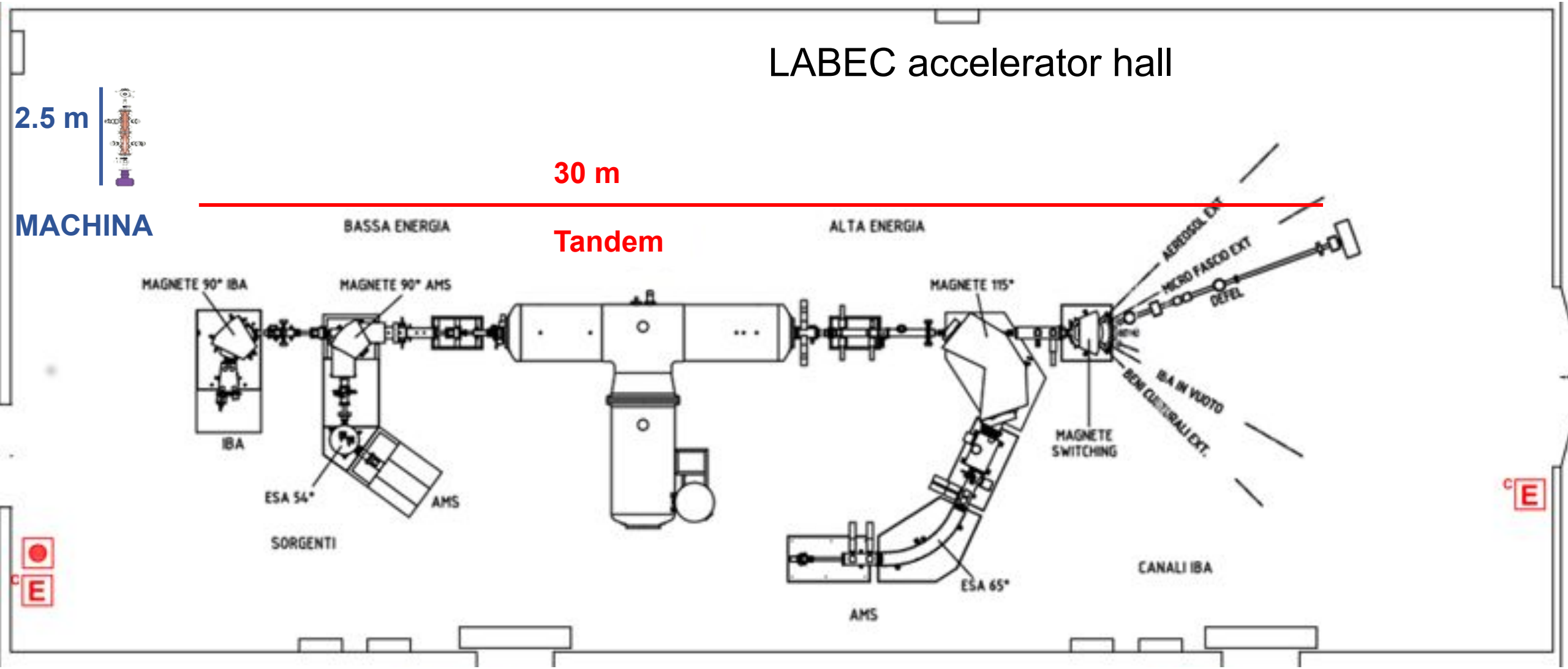
Luminescence on a synthetic sapphire



MACHINA footprint compared to the 3 MV tandem electrostatic accelerator

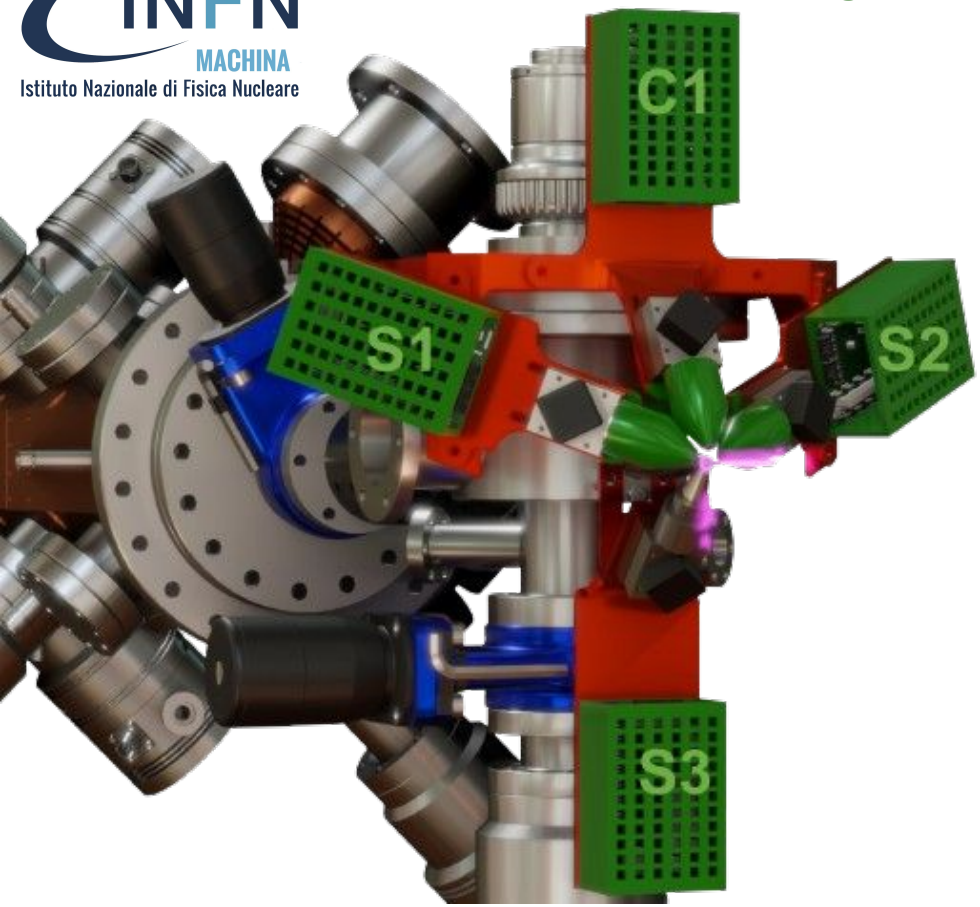
INFN MACHINA
Istituto Nazionale di Fisica Nucleare

CERN

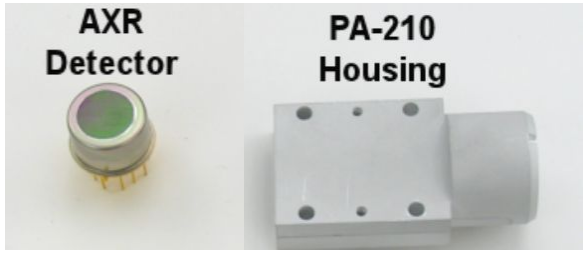


INFN MACHINA
Istituto Nazionale di Fisica Nucleare

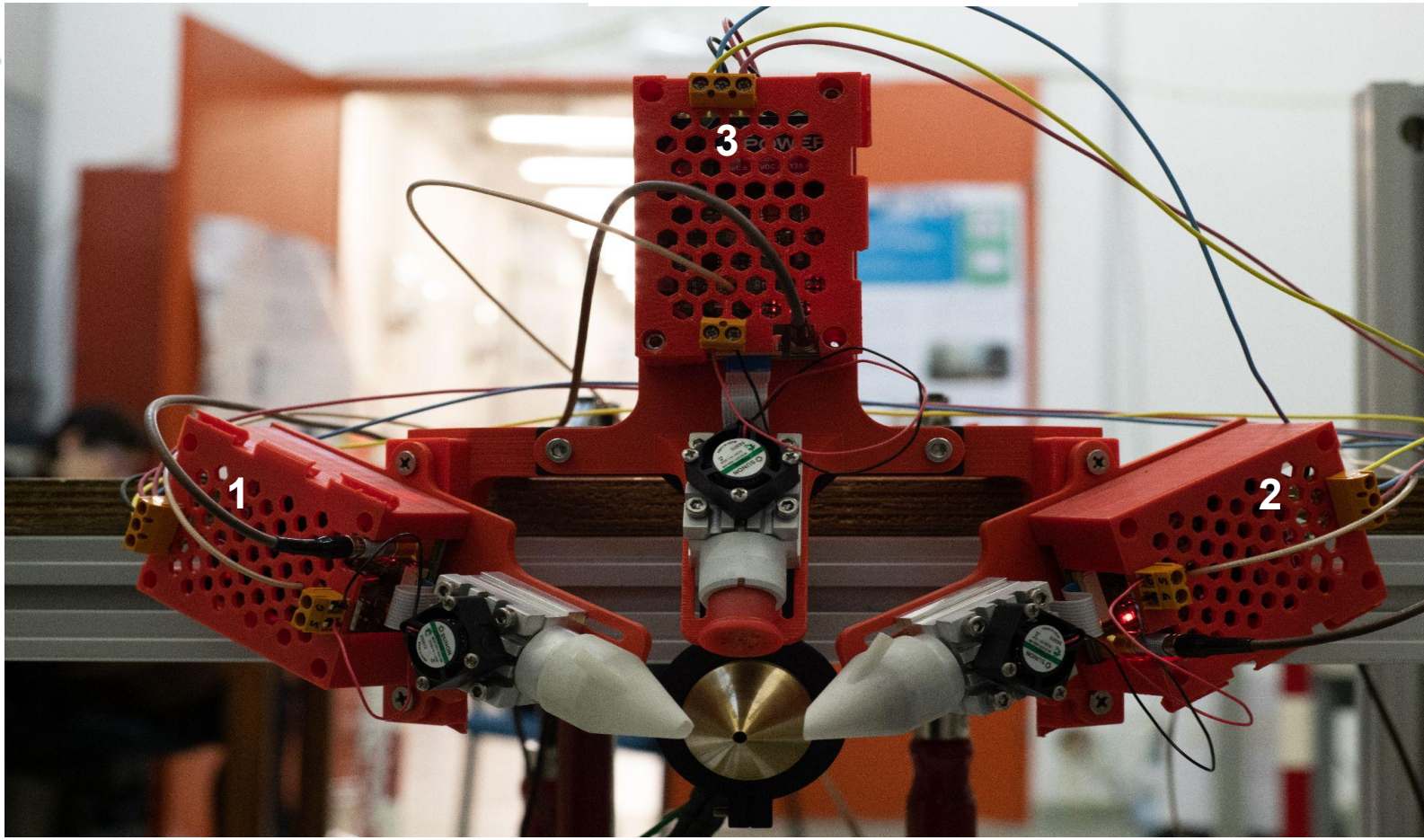
detection set-up (design)



Detection set-up



CERN



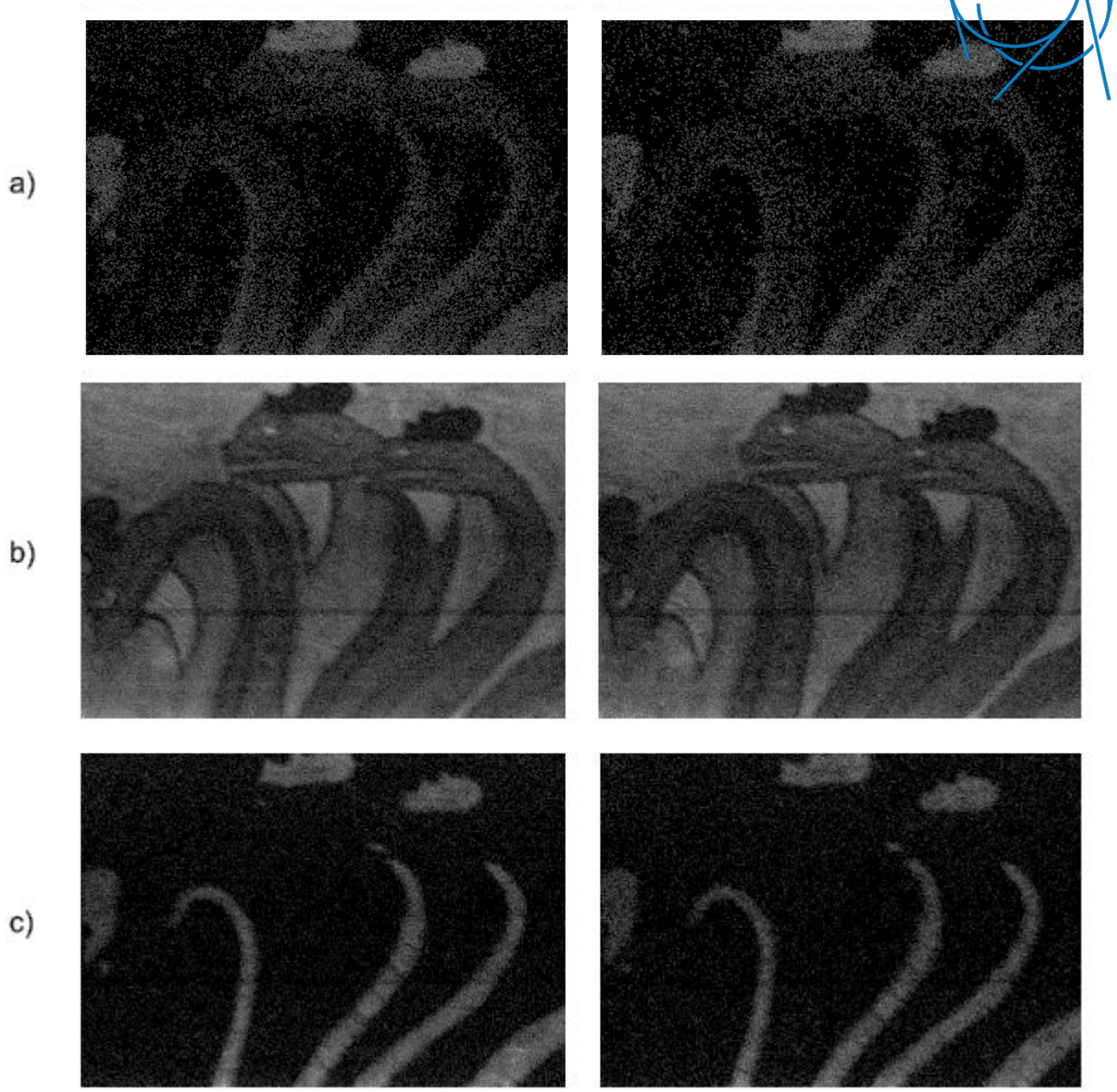
detection set-up (implemented so far)

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

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.

Next steps and Perspectives

MACHINA meeting on the next May 22nd

- First applications to CH
- Next collaboration with CERN KT on developing compact accelerators

MACHINA _MEETING: Agenda

May the 22nd

venue INFN Sezione di Firenze
(50019-Sesto Fiorentino - Firenze)

Session_1 – welcome *(09:00 – 09:30)*

G. Passaleva	(Director of INFN Sezione di Firenze)
D. Bettoni & O. Adriani	(INFN – Executive Board)
C. Hartley,	(CERN, Head of Industry, Procurement and Knowledge Transfer department)

Session_2: Introduction to MACHINA *(09:30 – 10:00)*

09:30 – 09:45	*"The MACHINA concept"*	S. Mathot & F. Taccetti
09:45 – 10:00	*"MACHINA: the accelerated beam and the beam for CH applications"*	A. Lombardi & L. Giuntini

Session_3: visit to MACHINA Accelerator *(10:00 – 10:30)* C.Czelusniak

Coffee break *(10:30 – 10:45)*

Session_4: Example of measurements with MACHINA *(10:45 – 11:30)*

10:45 – 11:10	"Drawings by O. Leoni"	Silvia Castelli (Marucelliana), A. Mazzinghi
11:10 – 11:35	"Painting by scuola fiorentina"	Sandra Rossi (OPD), C. Ruberto

Session_5: Conclusion part 1 and Q&A *(11:35 – 11:50)*

Mathot, Lombardi, Giuntini & Taccetti

Lunch

Visit to Opificio restoration Labs *(14:30 – 16:00)*

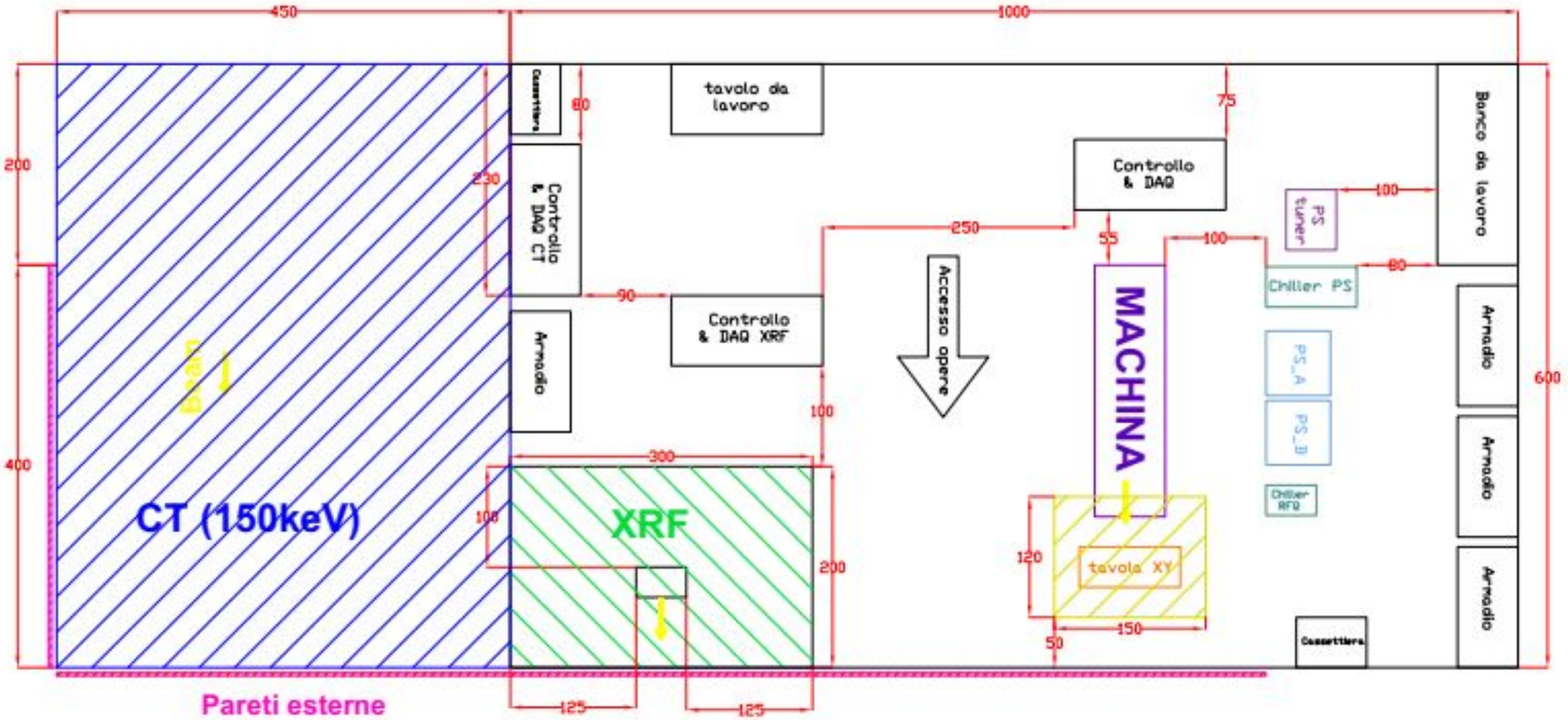
Session_6: Future perspectives and next steps *(16:00 – 16:30)*

Next steps and Perspectives

MACHINA in INFN@OPD Fortezza da Basso

Next steps and Perspectives

MACHINA + CHNet instrumentation in INFN@OPD

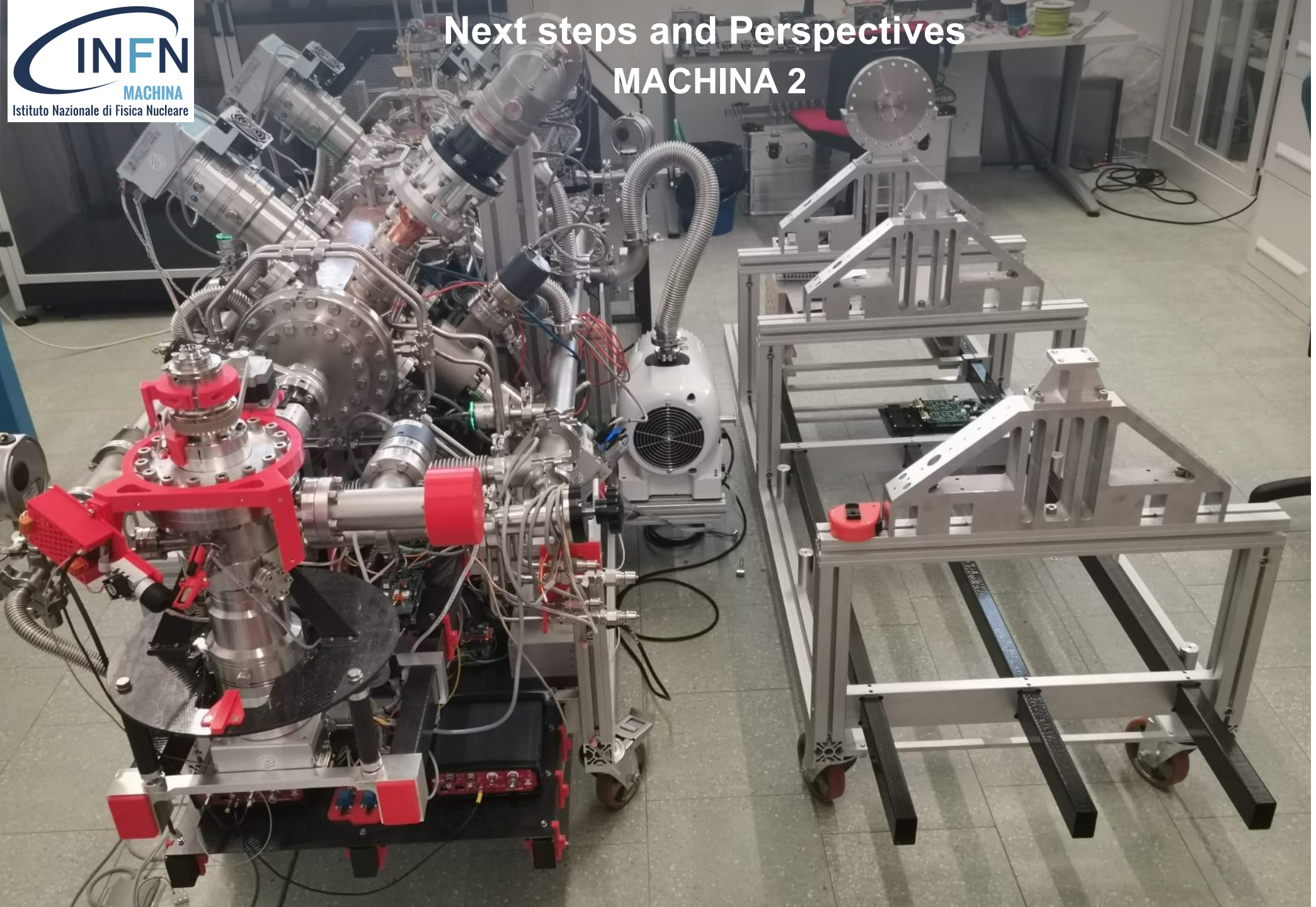


Next steps and Perspectives

MACHINA 2

- A second version of MACHINA to be developed by INFN for Gran Sasso Science Institute (GSSI)
- Funding (about 2 M€) requested by GSSI for MACHINA 2 on the SEIC (Space and Earth Innovation Campus) project, financed with PNRR funds
- GSSI has already submitted a offer request to INFN
- INFN with the resolution of 29/2/2024 has decided to submit an offer to GSSI for MACHINA 2

Next steps and Perspectives
MACHINA 2

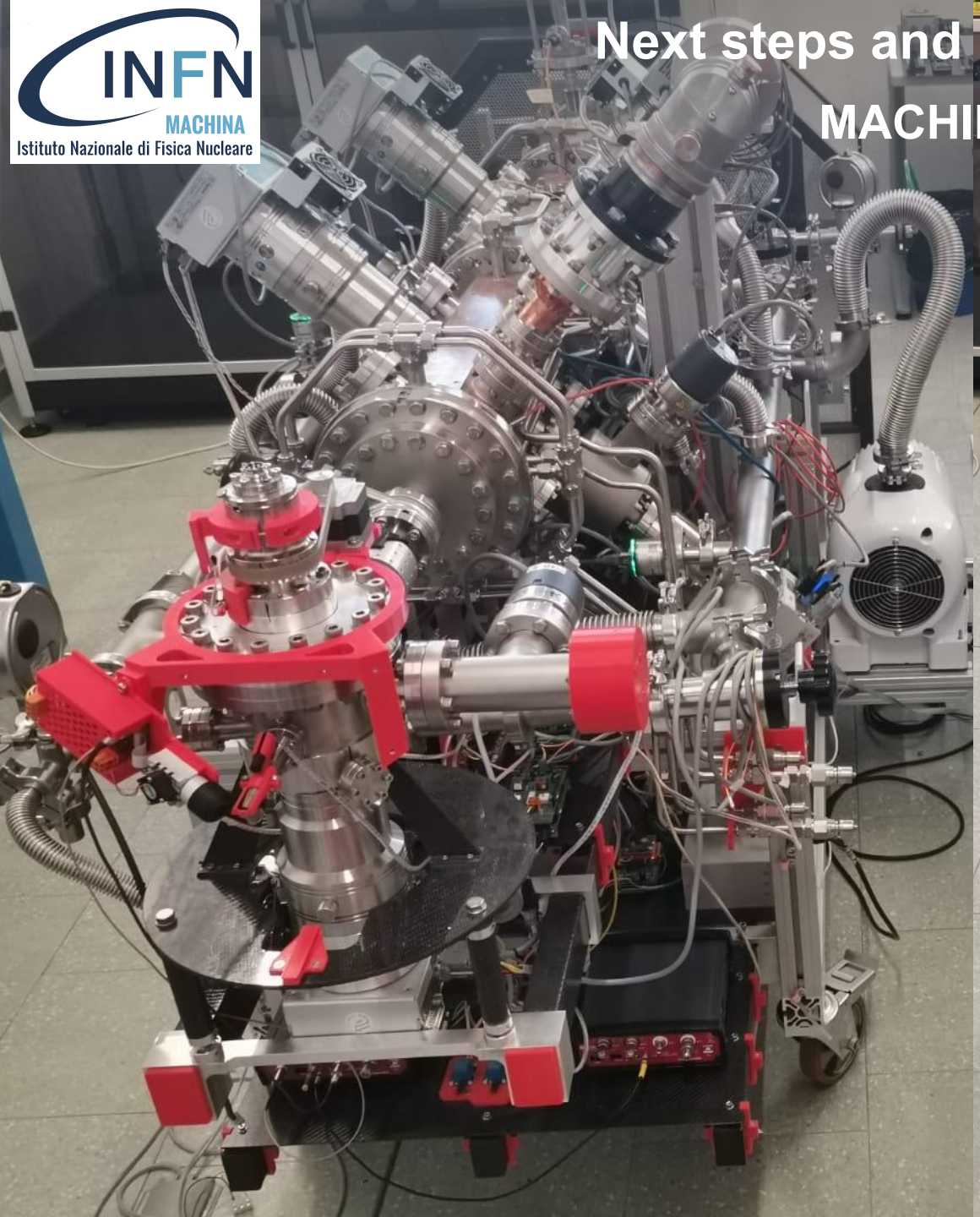


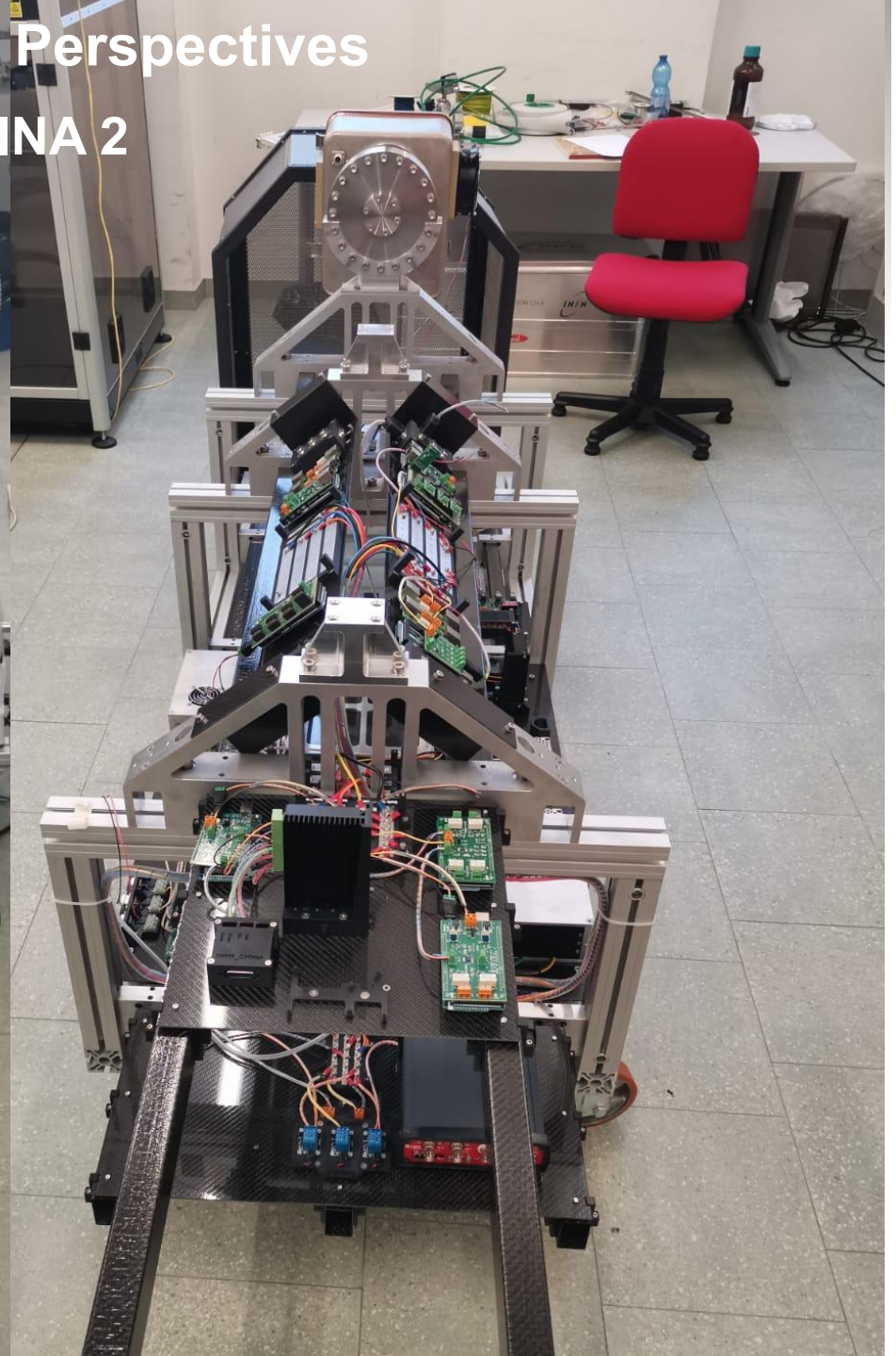
MACHINA2 is coming!

May 2023

Next steps and Perspectives

MACHINA 2





MACHINA2 is coming!

November 2023

Next steps and Perspectives

MACHINA 2

MACHINA2 is coming! Yesterday!

The source is dismounted and the mock-up accelerator installed for upcoming vacuum- and control-system tests

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)