CHNet_IμAGING

*Development of a transmission imaging system for muon applications**

Matteo Cataldo, *PhD*

Proposta per call «Grant Giovani 2025»

29/07/2025

*acronimo e titolo da definire

About me: research fellow @ INFN Milano Bicocca

My Career:

- 2014 – 2019: Science and Conservation for Cultural Heritage @Università degli studi di Firenze
- 2020 – 2024: PhD @Università degli studi di Milano Bicocca/ISIS Neutron and Muon Source
- 2024 – Present: Research fellow @INFN Milano Bicocca

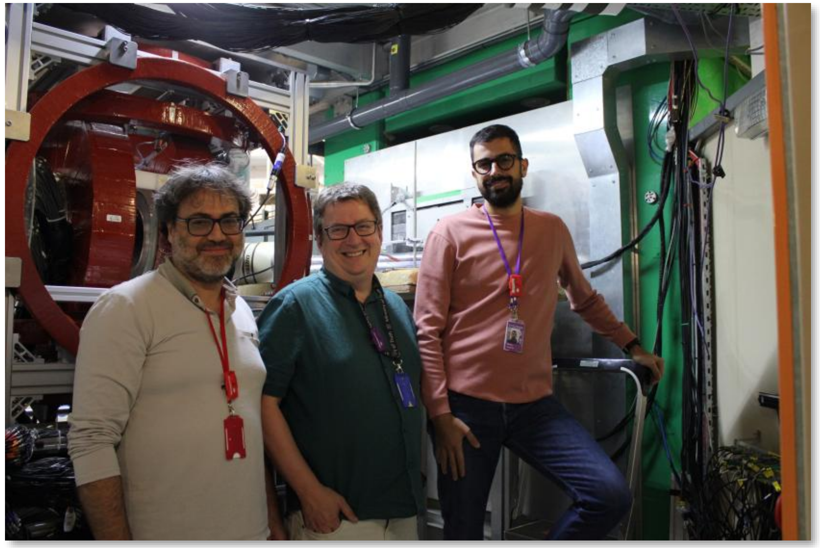
Development of the Muonic atom X-ray Emission Spectoscopy (μ-XES) technique
+
Use of large scale facilities techniques for the characterisation of Heritage artefacts
+
CHNet_MAXI (FTE 0.6)
+
RESNOVA (FTE 0.4)

ISIS Neutron and Muon Source

INFN CHNet Istituto Nazionale di Fisica Nucleare Cultural Heritage Network

CHNet MAXI

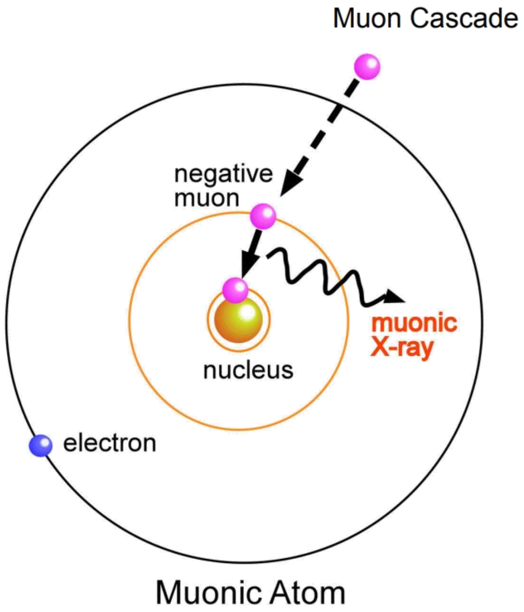
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

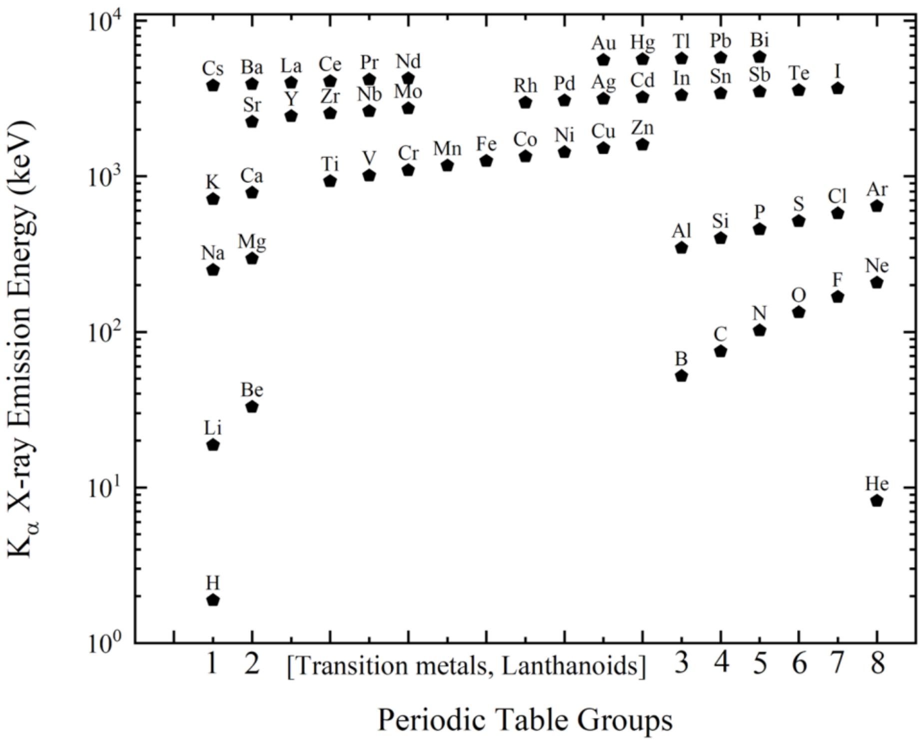


With my PhD supervisors, Massimiliano Clemenza and Adrian D. Hillier

Introduction: negative muon spectroscopy

Muonic atom X-ray Emission spectroscopy (**μ-XES**) is the technique based on the **detection of high energy radiation (X and gamma ray)** emitted after muon interaction with matter





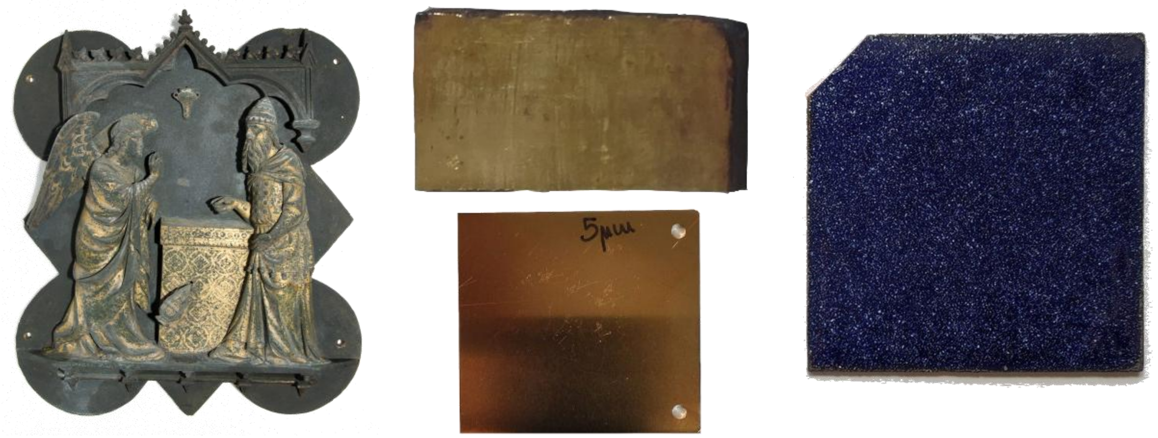
Multi-elemental

Non-invasive probe
No activation of samples

Method for isotopic analysis

Negligible self-absorption effect

Remarkable penetration depth Momentum & Density dependent

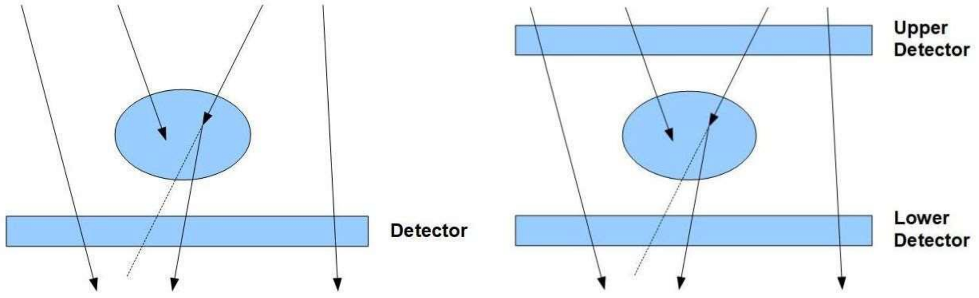


Introduction: bringing cosmic-ray muon imaging to the laboratory scale

Cosmic muons are used **in two ways**[1]:

Muography *(Muon trasmission radiography)*
- Detector is placed below or next to the object
- **The attenuation of the muon flux gives information about the density of the material**
- Observed muon flux *vs* open-sky flux to get a **density map**

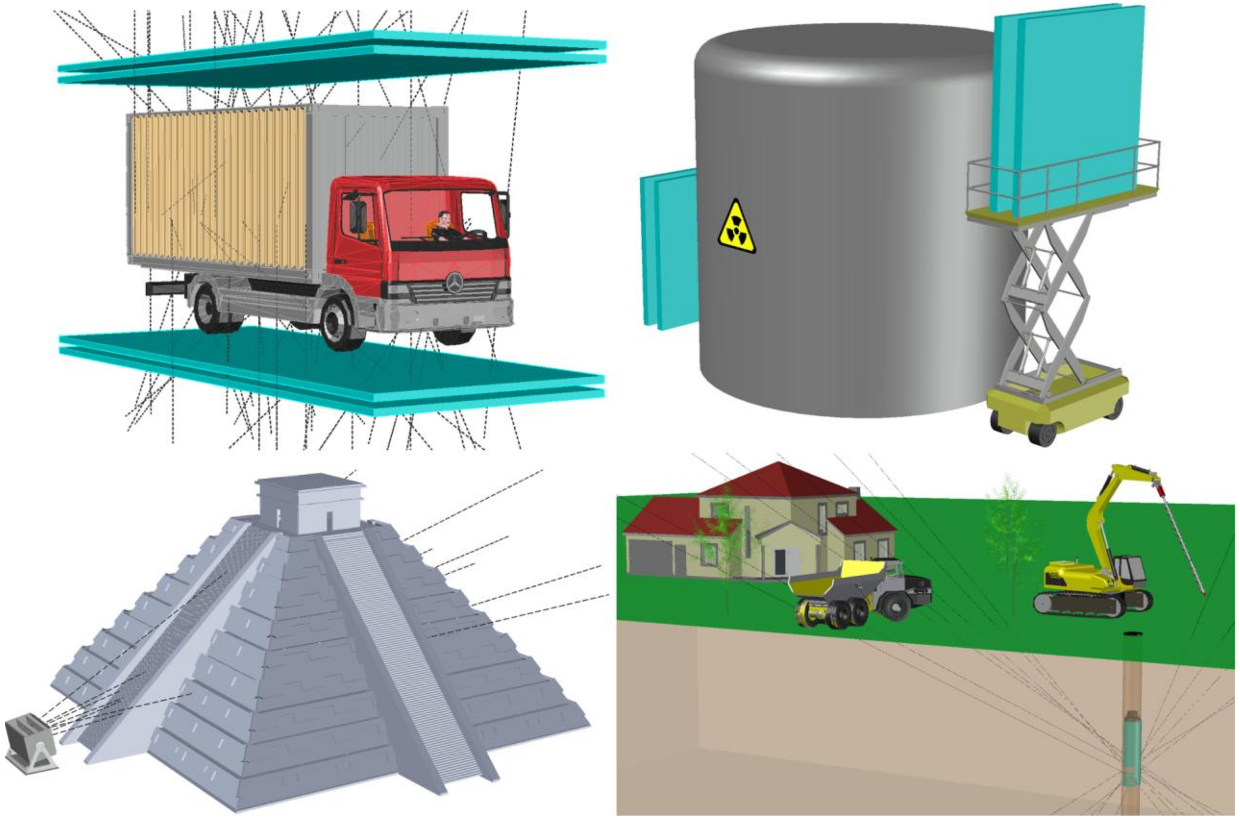
Muon Scattering Tomography *(MST)*
- Muons undergo multiple Coulomb scattering when travelling through matter. **Scattering depends on:**
  - **Atomic number**
  - **Thickness and density of the material.**
  - **Muon energy**
- Collection of muon tracks (in&out with a tracking detector) to produce a **scattering map**

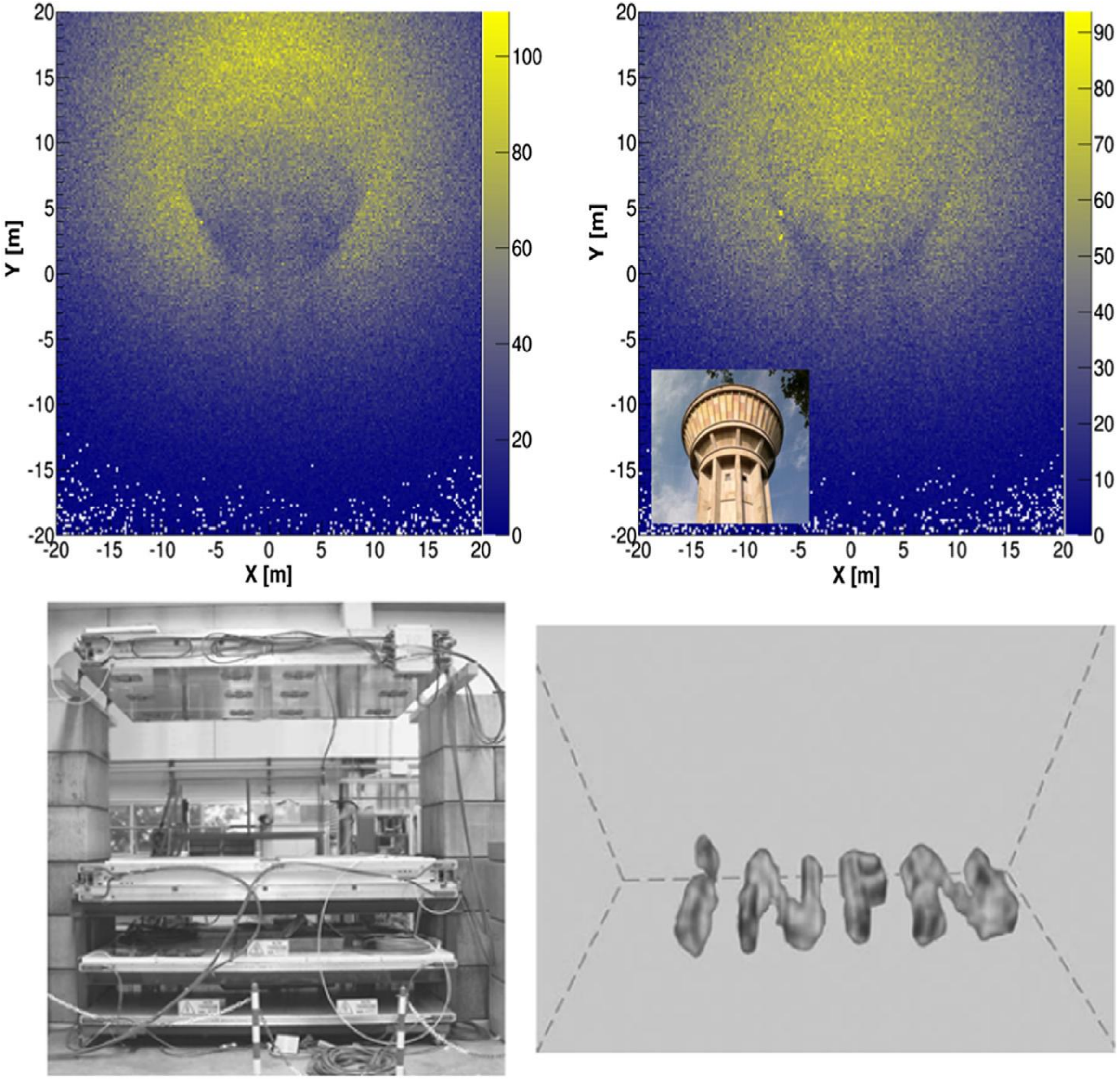


Is it possible to scale down these applications to a muon facility?

[1] Muon imaging: present status and emerging applications (IAEA-TECDOC-2012)

Introduction: bringing cosmic-ray muon imaging to the laboratory scale





Applications of muography and MST:
Archaeology, geosciences, civil engeneering, nuclear waste analysis, border control

We need to scale down the samples too!

[Left] Muon imaging: present status and emerging applications (IAEA-TECDOC-2012)
[Right] S. Procureur, Muon imaging: Principles, technologies and applications, Nuclear Inst. and Methods in Physics Research, A

Goal of the project

Develop a high-resolution, portable muon imaging setup to support Muonic Atom X-ray Spectroscopy (μ-XES) experiments and enable independent, non-destructive imaging.

Where?

INFN Milano Bicocca
+
ISIS Neutron and Muon Source
(Controlled muon beam <u>up to 120 MeV/c)</u>

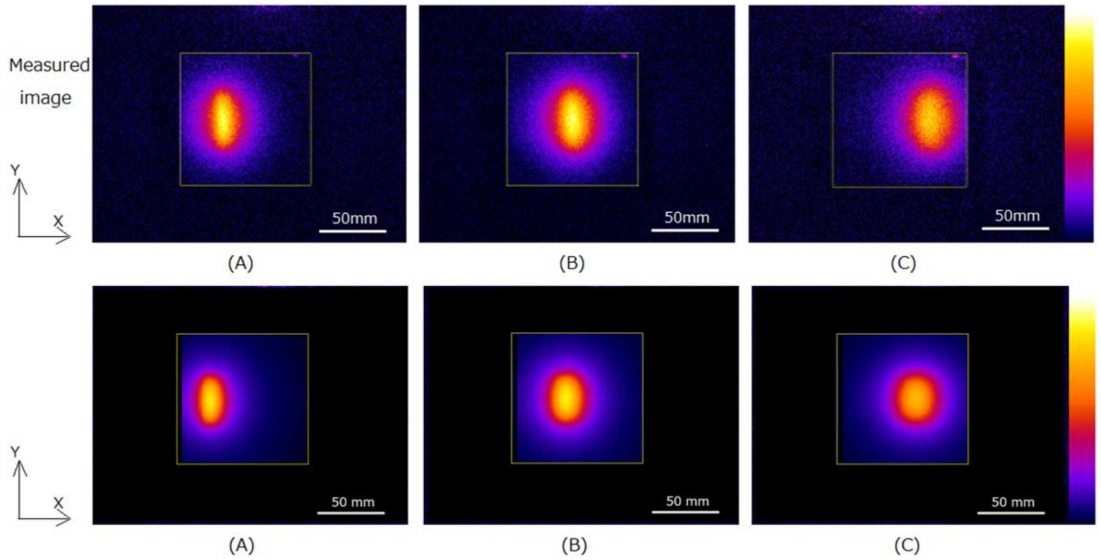
How?

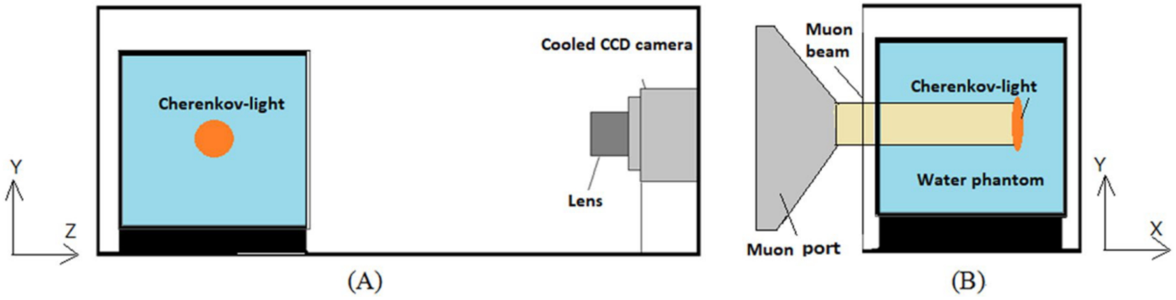
Experimental setup:
Scintillator screen
+
CMOS Camera to record the light

Why?

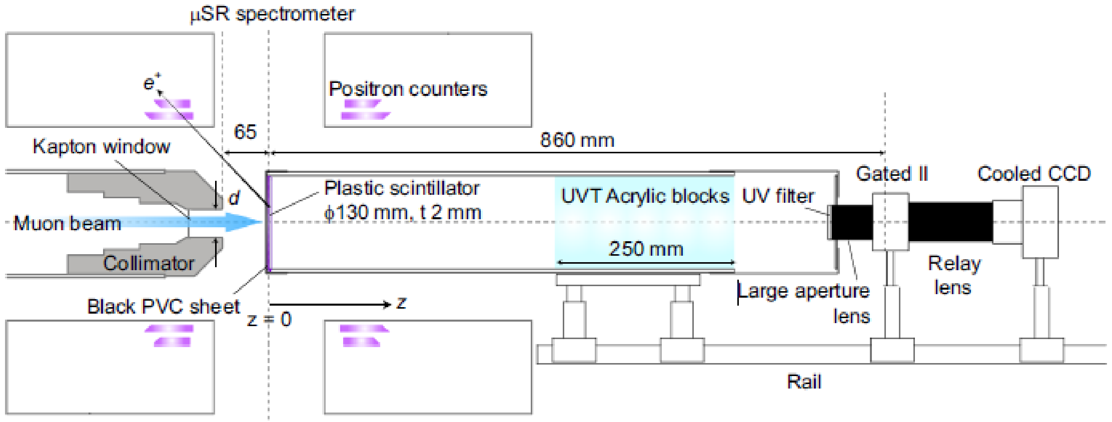
1) **Support and improve μ-XES capabilities, to make it a unique elemental analysis method;**
2) Explore the possibilities offered by muon imaging
3) **Continue INFN experience in developing large scale facility techniques (CHNet Tandem, Niche, Bronze, MAXI)**

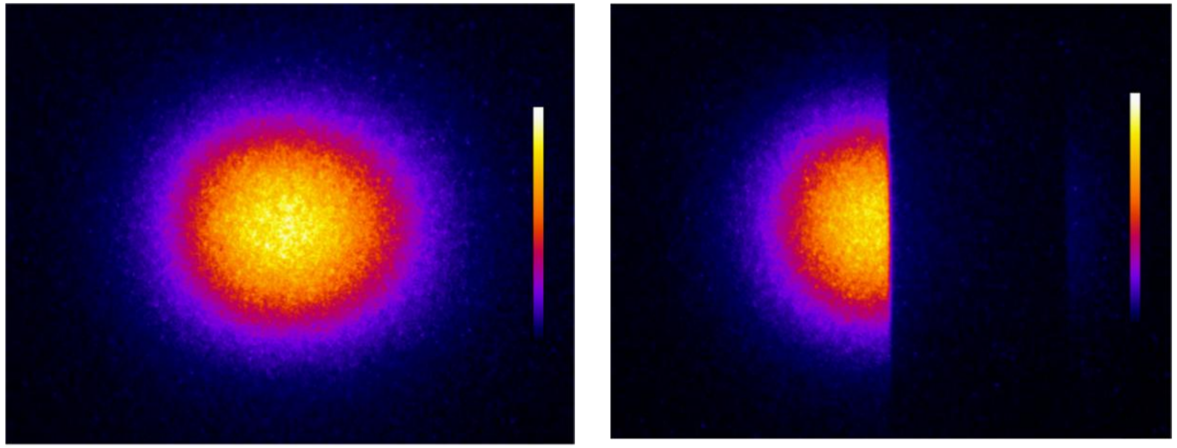
Literature review





@J-PARC: Dose range estimation in water and plastic scintillator



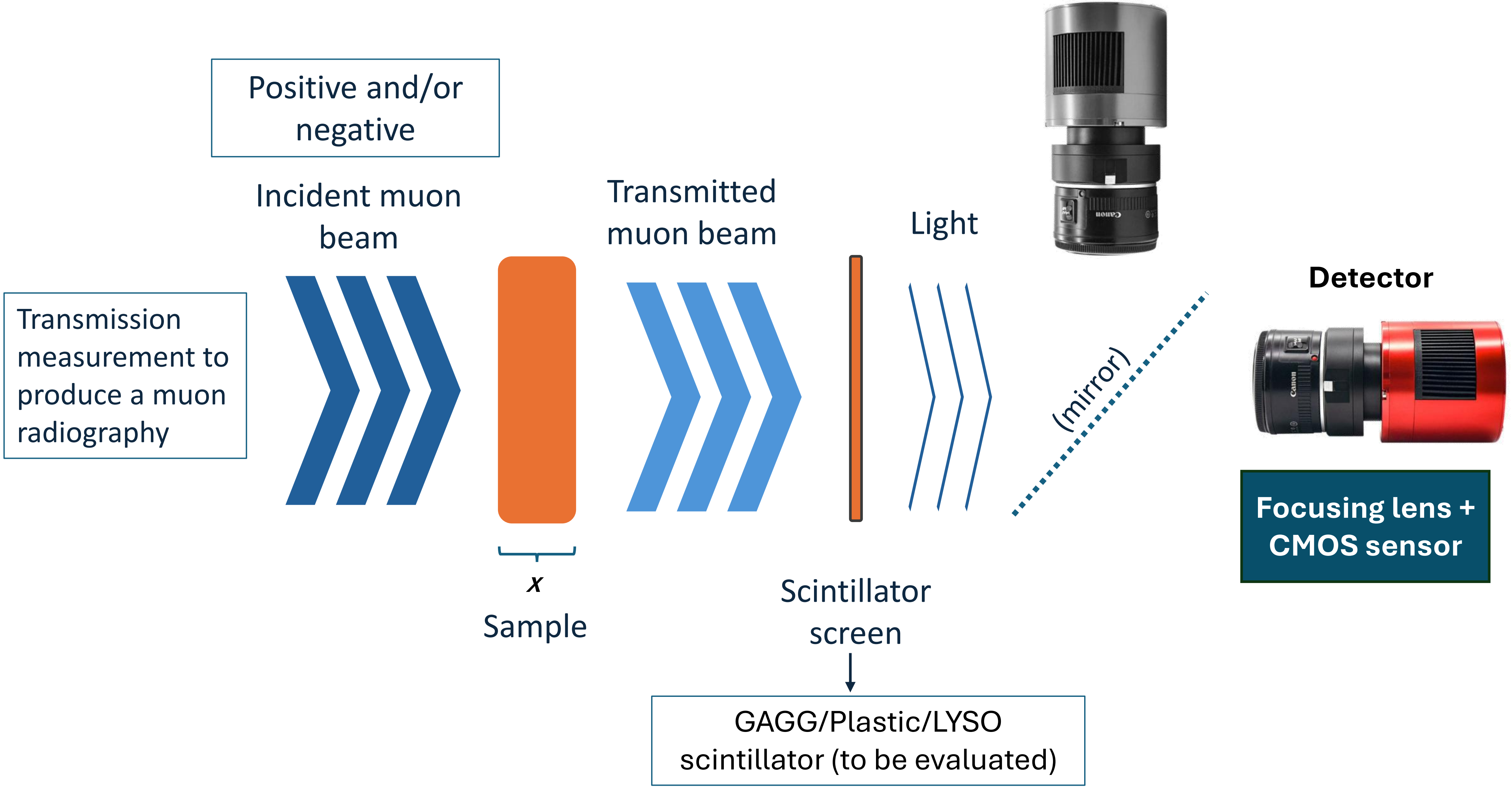


@J-PARC: Development of a beam profile monitor

Yamamoto, S., Ninomiya, K., Kawamura, N. et al. Optical imaging of muons. Sci Rep 10, 20790 (2020).
https://doi.org/10.1038/s41598-020-76652-8

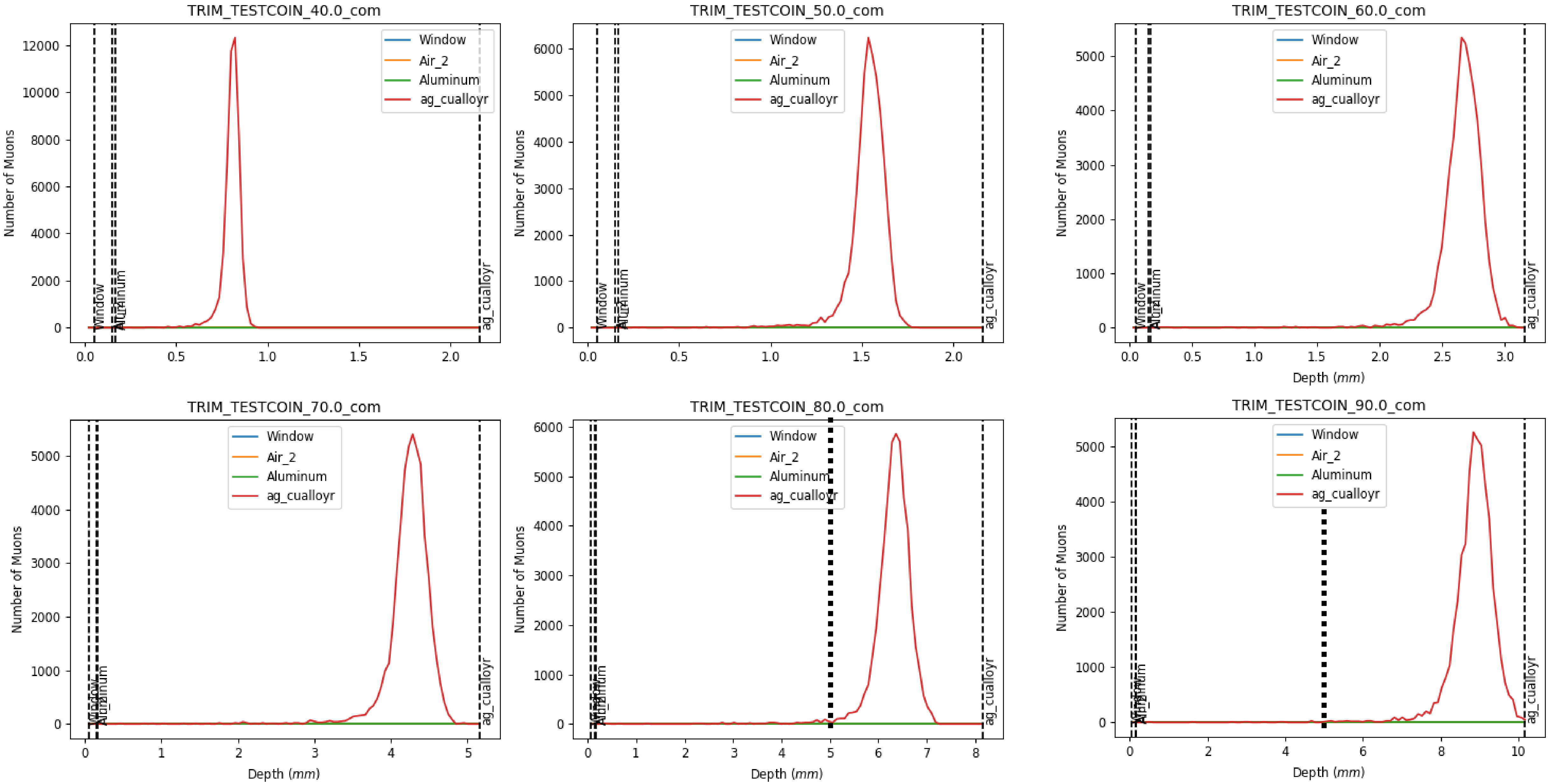
T.U. Ito et al. / Nuclear Instruments and Methods in Physics Research A 754 (2014) 1–9

Proposed experimental setup



Can we get through?

Consider a 5mm thick silver coin (Ag90Cu10 – Density 10.3 g/cm3).
A 80 MeV/c muon beam will travel the entire size of the coin.



Expected outcome

- Enhanced muon experiment accuracy through imaging
- **Safe, non-destructive, activation-free analysis**
- Proof-of-concept for broader muon imaging applications
- Tool for better beam targeting in complex samples or holders
- Estimated sub-mm resolution

Possible application fields:

- Heritage Science
- Battery materials
- Defects identification in materials
- Wood, Paper material?

Pros and Cons

Pros

- **No activation of sample**
- Good penetration depth
- Positive and negative muons can be used
- No radiation damage on sample
- Spatial resolution: sub-mm (in literature, similar setup 300-400 nm)
- High muon flux
- **Multisciplinary**
- **Innovative**

Cons

- Competitors: Neutron and X-ray tomography
- Maximum momentum 120 MeV/c
- Image blurring due Coulomb scattering.
- Scintillator may need to be close to the sample to have a good rate.
- Muon beam spot size (nominal diameter 40mm)
- Few literature examples

Working packages

- **WP1: Scintillators characterisations.** Light output, linearity, decay time, and afterglow test to be performed at the Milano Bicocca. Test will be performed with different scintillator thickness (as it is a trivial parameter for resolution). Modelling of the setup in Geant4. Building of the light-tight box and the XY stage in collaboration with the INFN workshop. The light-tight box will be 3D printed.

- **WP2: CMOS Camera characterisation.** In house test of the setup with known sources and the CMOS camera in place. Evaluation of camera properties. Optimization of setup: mirror and without mirror test. Pinhole configuration test.

- **WP2: First beam acquisition**. Evaluation of the characteristics of the scintillator under a muon beam. Radiation damage evaluation on the scintillator foils. Test with positive and negative muons to evaluate the by-product of the interaction. This test will be performed at the ISIS Neutron and Muon source. Preliminary data treatment

- **WP4: Final beam test.** Analysis of standard materials. Development of a data analysis process (MLEM/POCA algorithms?) and implementation/test of a rotating stage-

WP1 – Scintillator material

Inorganic	GAGG(Ce)	LYSO(Ce)
Density (g/cm3)	6.6	7.25
Light output (ph/MeV)	From 30000 to 54000 (depending on type)	30000
Decay constant (ns)	From 50 to 150 (depending on type)	40
Emission wavelenght (nm)	520-530	420
Hardness (mohs)	8	5.9
Hygroscopic	No	No

Plastic	(Epic 106)	EJ-212
Density (g/cm3)	1.05	1.023
Light output (% Anthracene)	50-60	65
Light output (ph/MeV)	-	10000
Decay constant (ns)	2.4	2.4
Emission wavelenght (nm)	423	423
Hygroscopic	No	No

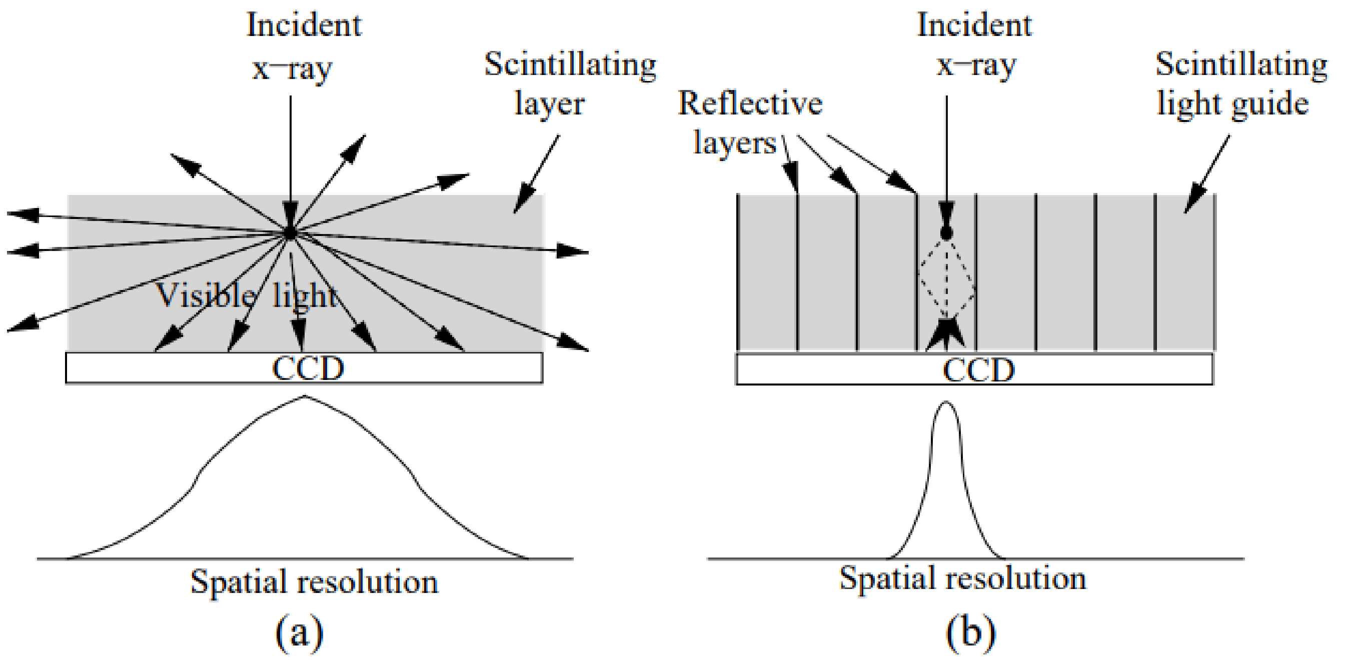
***GAGG**: high light yield, emisssion wavelenght in the best working range of CMOS, radiation hard. But more expensive (1mm 8x8:1.4k€)*

***LYSO**: similar to GAGG, but less exspensive: (1mm 8x8:900€).*

***Plastic**: low density so thickness is an important choice. Quite cheap (1mm 8x8:150€)*

Pixelated array or screen?

WP1 – Scintillator: pixelated or screen?



Screen: Image blurring due to light scattering, potentially reducing spatial resolution.
Low cost and thin size

Pixelated: reduce light scattering for better spatial resolution.
Is it possible to have low thickness?
High cost?

J.G. Rocha et al. / Sensors and Actuators A 110 (2004) 119–123

WP2 – CMOS Camera

ZWO ASI2600MC MONO

Pros:
- Extremely cheap (2k€)
- Easy to use
- Easy to adapt with focal lenses
- Already used in Niche
- Good resolution
- High pixel density
- C-mount
- Pixel 3.75 μm

Cons:
- No possibility of external triggering
- Low frame rate (3.5 fps)

Hamamatsu Orca Fusion

Pros:
- Good low-light performance
- Low read-noise
- High frame rate (up to 89 fps)
- External trigger
- Good resolution
- Pixel binning is feasible
- C-mount
- Pixel 6.5 μm

Cons:
- High cost (about 17 k€)
- Requires vendor software

Milestones and people

- **Milestone 1 (month 6):** From a set of different types of scintillators, choice of the most appropriate one in terms of size, thickness and light yield.
- **Milestone 2 (month12):** Setup optimization. CMOS Camera test and preliminary approach to data processing.
- **Milestone 3 (month 18):**First beam test. Evaluation of the scintillator performance under a muon beam and evaluation of radiation damage and by-product of the muon interaction.
- **Milestone 4 (month 24):** Final test of standard samples and a case study.

People	Sezione	WP	Fte
Matteo Cataldo	Mib	1 to 4	0.8
Paola Monza	Mib	1-2	0.4
Giulia Marcucci	Mib	3-4	0.4
Massimo Rossella	Pv	1	0.1
Massimiliano Clemenza	Mib	1 to 4	0.2
Luisa Vigorelli	Mib	4	0.4
			Total = 2.3
Officina	Mib	1 to 4	1MU

External support	Institution
Adrian Hillier*	ISIS Neutron and Muon Source
Tom Ashton*	UCL
Matt Wilson*	ISIS Neutron and Muon Source
*Will write a support letter	

Funding request

Detailed costs table		
Consumables	Plastic scintillator	1,500.00 €
	GAGG	2,000.00 €
	LYSO	1,500.00 €
	Mirror	100.00 €
Inventoriables	RS travel case	500.00 €
	Hammamatsu Fusion CMOS Camera*	17,000.00 €
	Acquisitoin Laptop	2,500.00 €
	ASI2600MM-PRO CMOS Camera (Mono)*	2,000.00 €
	Camera accessories	1,000.00 €
Travel expsenses	Experimental Activity** (for at least 4 runs for 2 people and eventual run in other facility)	10,000.00 €
	Meeting	2,000.00 €
	Conferences (at least one confernence)	2,000.00 €
	Total	42,100.00 €
*still have two decide between the two. Or if possible to buy both		
**Estimated cost for 3 days of beam time @RAL	3 nights in guesthouse+flights+forfeit+trains	880.00 €

Still thinking on scintillator material, type and number of pieces. Also, we may need to ass some electronic equipment and cables

→ Estimated 50 k€ (?) Dividere in due anni

Risk Evaluation

Risk Chart

Likelihood ↑		Impact → Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
Almost Certain (>1 in 10)	5	*Medium 5*	*High 10*	*Extreme 15*	*Catastrophic 20*	*Catastrophic 25*
Likely (1 in 20)	4	*Low 4*	*Medium 8*	*High 12*	*Extreme 16*	*Catastrophic 20*
Occasional (1 in 200)	3	*Low 3*	*Medium 6*	*High 9*	*High 12*	*Extreme 15*
Unlikely (1 in 2000)	2	*Very Low 2*	*Low 4*	*Medium 6*	*Medium 8*	*High 10*
Rare (<1 in 10000)	1	*Very Low 1*	*Very Low 2*	*Low 3*	*Low 4*	*Medium 5*

Item	Risk	LIKELIHOOD	Effect	IMPACT	RISK SCORE	Mitigation strategies
Scintillator	Delivery delay	3	Delay on WP1 start	3	**9**	The ISIS Facility will made availabe a set of spare scintillators if we experience major delays
Scintillator/ mirror	Radiation damages	4	Material need to be replaces	2	**8**	Test will be performed to evaluate this aspect. If present, it could be mitigated by fluxing argon in the light-tight box and by having spare scintillating material
CMOS Camera	Delivery delay	2	Delay on WP3 start	2	**4**	WP3 is expected to start in the firt half of 2026, so delay can be handled
ISIS Neutron and Muon Source	Proposal refusal	2	No beam test	5	**10**	As a group, we have a long experience of accepted proposal, so it's unlikely to be refused
ISIS Neutron and Muon Source	Shut down for entire 2027	4	No beam time in 2027, WP4 at risk	5	**20**	The facility refurbishment is expected to finish in August 2027, which leaves 2 run of beam time. To mitigate, we could submite proposals to other facilities
Material	Increase in cost	3	increase in cost could affect the funding request	3	**9**	a 10% will be added to the exsisitng quotes to cover increase in costs

Backup - Quotes

INFN MILANO BICOCCA
MATTEO CATALDO
P.ZZA DELLA SCIENZA, 3
20126 MILANO (MI)
ITALY

Offerta n.:	I117478	**Ns. Riferimento:**	Francesco Giovenale
Data preventivo:	11-07-2025	**Tel:**	00390650513454
Revisione n.:	1	**Fax:**	00390293581741
Codice cliente:	HPI000651	**E-Mail:**	francesco.giovenale@hamamatsu.eu
Vs. Rif.:	MATTEO CATALDO		
RFQ n.:			

Pagina 1/1

Pos.	Codice prodotto Descrizione	Quantità (pcs)	Prezzo unit. EUR	Importo netto EUR
1.1	ORCA-FLASH4 V3 USB FUL ORCA-Flash4 V3 with USB3 frame grabber and cable, trigger cable, HCImage Live ROHS:C	1	13.500,00	13.500,00
2.1	ORCA-FUSION USB FUL ORCA-Fusion with USB3 frame grabber and cable, trigger cable, HCImage live ROHS:C	1	14.300,00	14.300,00

RoHS: C = Conforme; L = Può essere utilizzato solo per dispositivi medici, strumenti di controllo e misura; N = Non conforme; U = Contatta l'ufficio vendite Hamamatsu locale

Validità offerta:	11-09-2025
Termini di spedizione:	Porto Franco
Termini di pagamento:	R.D. 30 GG. D.F.
Garanzia:	12 Mesi
Tempi di consegna:	45 GG D.R.O.

I prezzi si intendono al netto dell'aliquota IVA.

ARTESKY SRL
VIA IV NOVEMBRE 103, 20833 Giussano (MB)
Telefono 0362310657
Email AMMINISTRAZIONE@ARTESKY.IT
PEC ARTESKYSRL@PEC.IT
C.F. 12059300967 P.IVA 12059300967
CCIAA e Numero REA: MB 2637730
Capitale Sociale i.v.: € 10.000,00

Spettabile
INFN ISTITUTO NAZIONALE DI ASTROFISICA SEZ MILANO
VIA CELORIA 16
20133 Milano (MI)
C.F. 84001850589
P.IVA 84001850589
Riferimento VS EMAIL DEL 20/06/2025

DESCRIZIONE	QUANTITÀ		IMPORTO	SCONTO	IVA	TOTALE
ASI2600MC-PRO	1,00	pz	1.589,00 €	7	22%	1.477,77 €
ASI2600MM-PRO	1,00	pz	2.120,00 €	7	22%	1.971,60 €
ASI6200MC-PRO	1,00	pz	3.950,00 €	10	22%	3.555,00 €
ASI6200MM-PRO	1,00	pz	3.950,00 €	7	22%	3.673,50 €

Termini di pagamento
Modalità: Bonifico
Scadenze: 30 gg Data Fattura
Banca mittente
Banca: INTESA SANPAOLO SPA
IBAN: IT97P0306951371100000010311

Imponibile	10.677,87 €
Imposta 22%	2.349,13 €
Totale	13.027,00 €
Netto da pagare	10.677,87 €