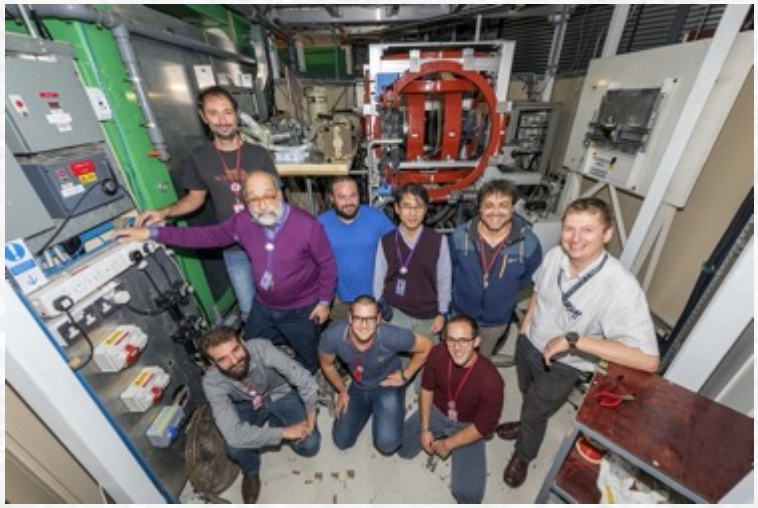
CHNET-TANDEM 2017-2019 sezioni MIB, LNS-UniSS, PV, RM3

Tecniche Analitiche Non Distruttive per l'archEoMetria

The idea behind the experiment called CHNET_TANDEM is to implement, develop, optimize **non-destructive** and **non-invasive** analysis techniques to be used in the archaeometric field for the **elemental characterization** of finds for **Italian Cultural Heritage. Funded and supported by INFN CSNV and Cultural Heritage NET of INFN, LENA, RIKEN-RAL (ISIS-STFC)**

Muonic Atom X Rays Spectroscopy (MAXRS)

PORT4 RIKEN-RAL@ISIS-STFC



PGNAA

TRIGA MARK II @ LENA (UNIPV)

Both techniques are based on the detection of **prompt** electromagnetic radiation emissions in the first case of atomic (muonic) type, in the second of nuclear type.

Muonic Atom X-Rays Spectroscopy (MAXRS)

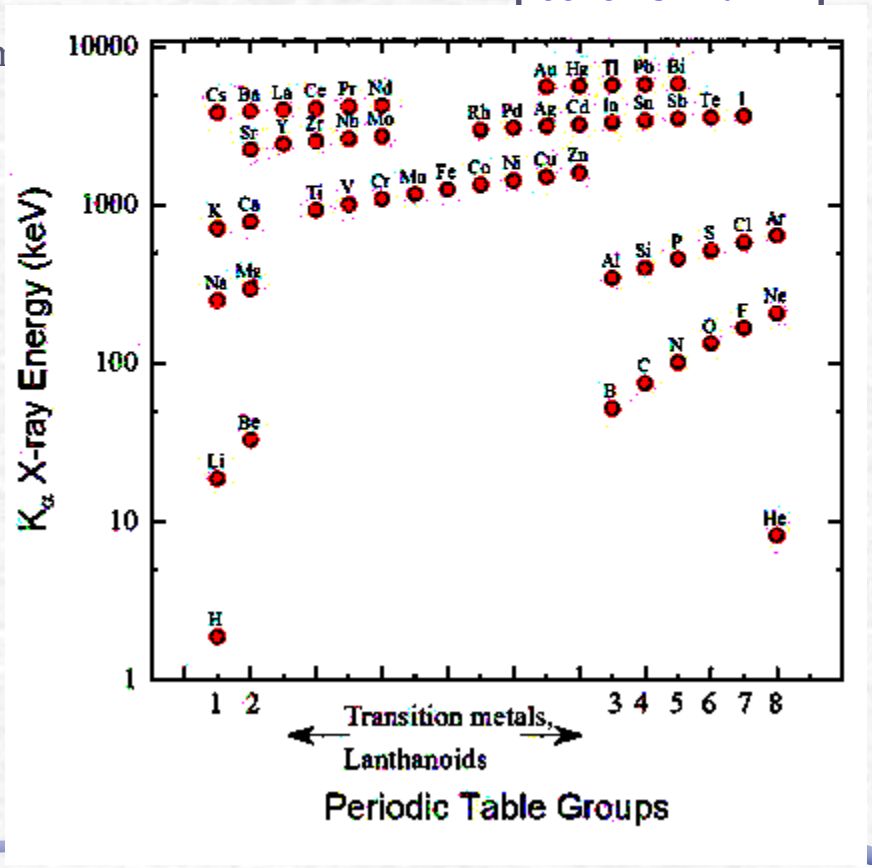
This technique consist in the sample exposure to a **collimated muon beam** (at the ISIS Muon source @Rutherford Appleton Laboratory) and the detection of **characteristic X-rays** emitted following the implantation/formation of **muonic atoms** inside the target.

- High energy **characteritics** X-rays **10 keV** to **10 MeV** observable from outside of sample - No need of vacuun -> applicable to matrices and several shapes;

- Applicable to **every element from (Li to U)** *simultaneous multi-elemental*

- Possibility to perform **depth profile** by changing muon beam momentum/energy, Site selective, 3D mapping

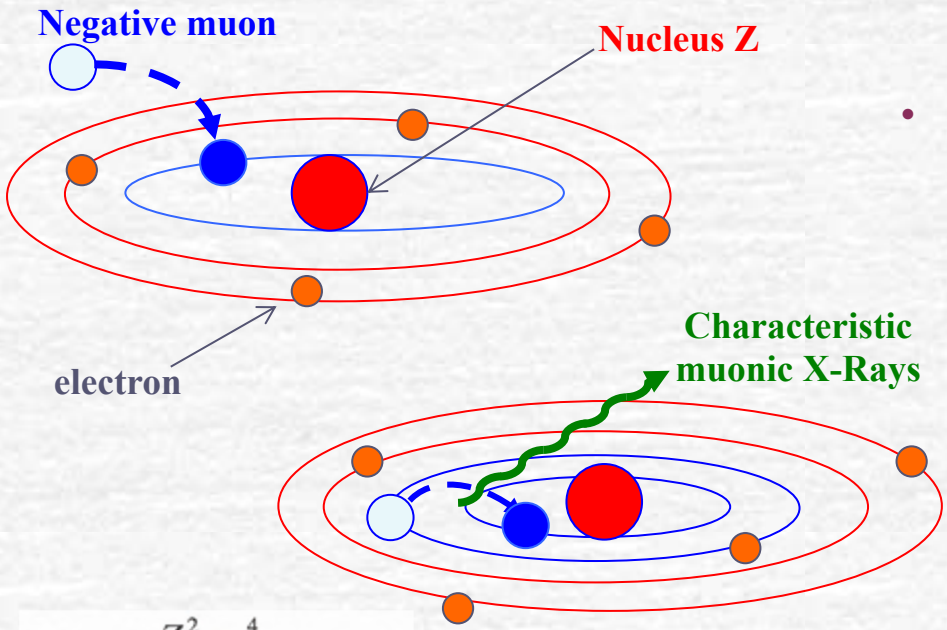
- No sampling - Non-destructive techniques pratically **no activation**



Negative Muon and Muonic Atom

This technique involves **samples exposure** to a **collimated muon beam** (at the ISIS Muon Source @Rutherford Appleton Laboratory) and **characteristic X-rays detection**, emitted following the formation/Implatation of muonic atoms inside the sample.

Muonic atom formation step



$$E_n = -\frac{Z^2 me^4}{8n^2\varepsilon_o^2 h^2}$$

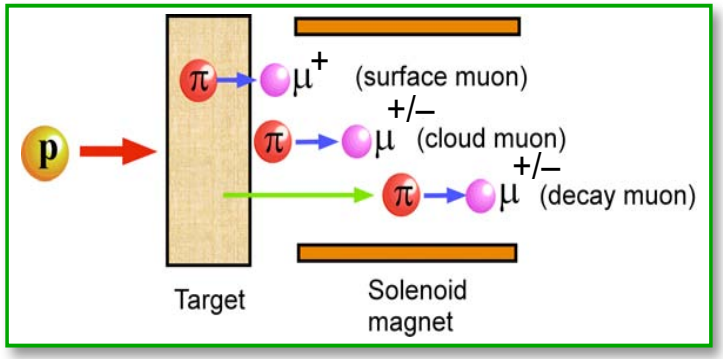
$$r_n = -\frac{4\pi\varepsilon_o n^2\hbar^2}{Zme^2}$$

$$\frac{m_\mu}{m_e} \approx 207 \approx \frac{E_\mu}{E_e} \approx \frac{r_e}{r_\mu}$$

Processes involved

- **Muonic Atom formation**: muon capture in atomic muonic orbital
- **Muonic Cascading process**: emission of high energy **characteristic muonic X-Rays**
- **Natural decay/muon capture** by nucleus with **Prompt Gamma Ray** emission

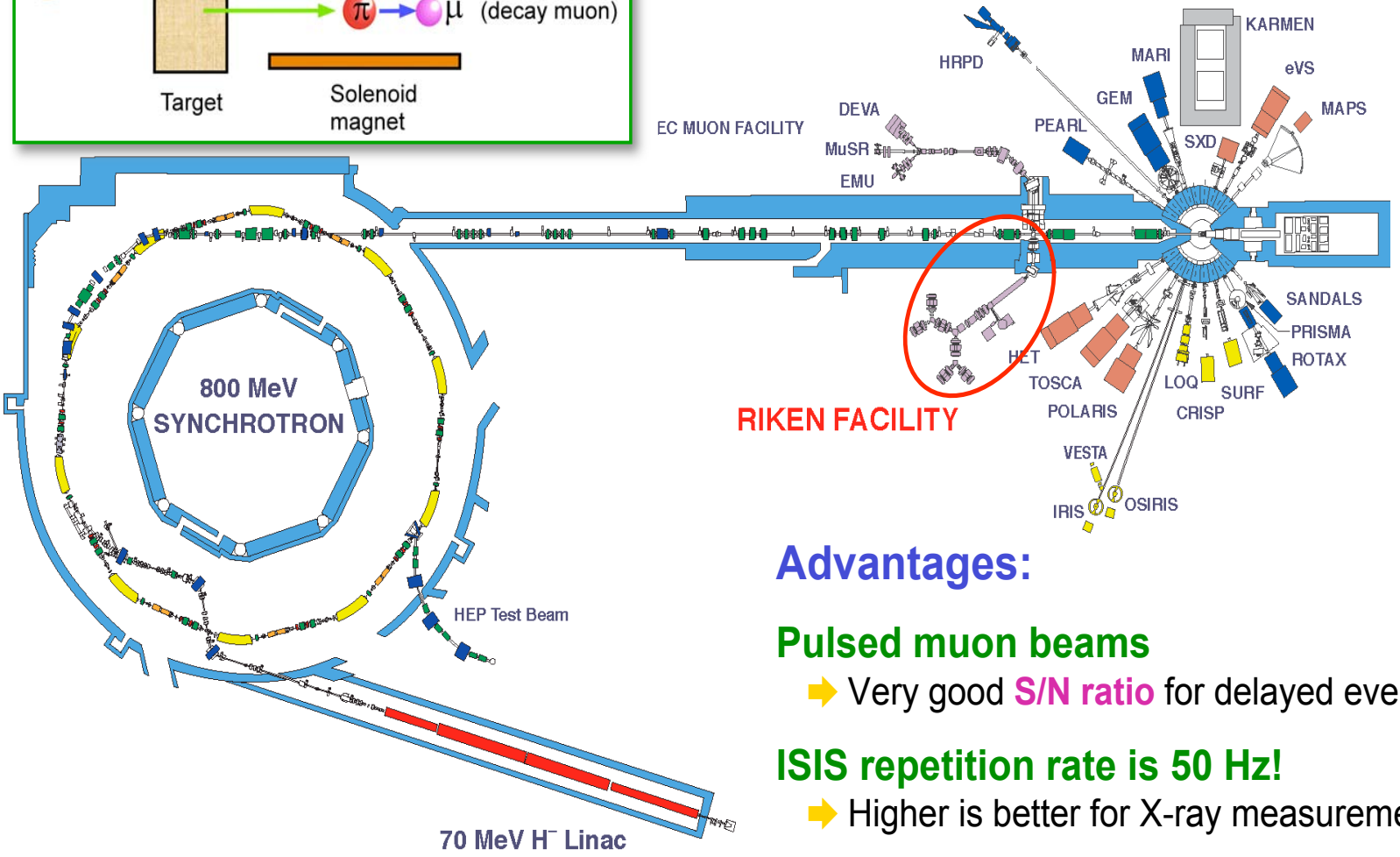
Muonic X-rays: RIKEN-RAL facility (UK)



$\tau_\mu = 2.19703 \pm 0.00004$ μsec.

800 MeV proton
(50Hz, 200 μA, double 70ns pulse)

$\pi^+ \rightarrow \mu^+ \nu_\mu$
$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$



Advantages:

Pulsed muon beams

➡ Very good **S/N ratio** for delayed events.

ISIS repetition rate is 50 Hz!

➡ Higher is better for X-ray measurements.

Muonic X-rays: PORT4 ISIS STFC facility (ex- RIKEN-RAL)

Beam Structure@ PORT4 ISIS Muon source

8 x 10^4 muons /sec @60 MeV/c

Beam properties

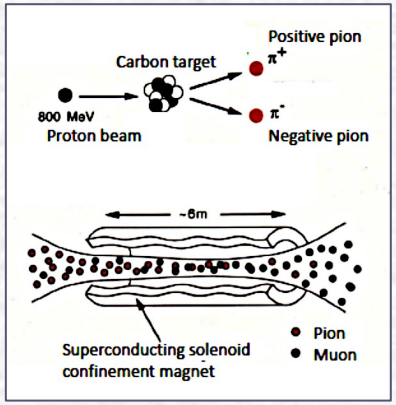
surface μ^+ (20~30MeV/c) and

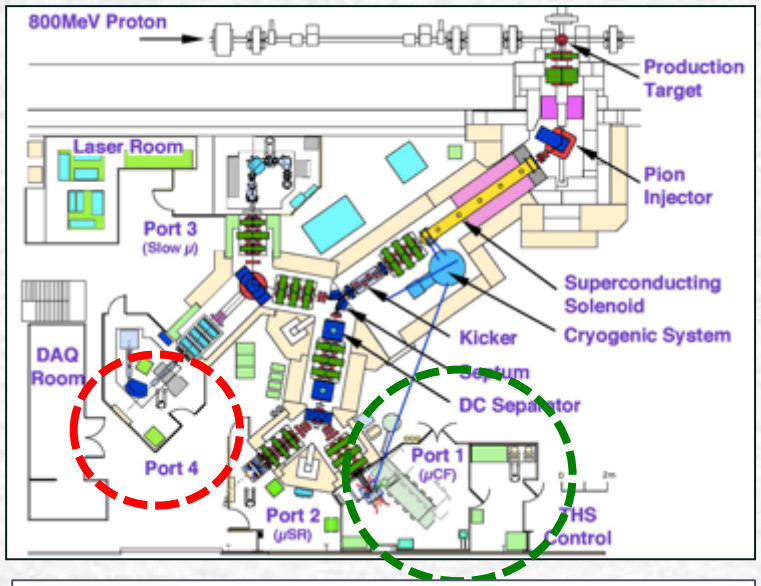
decay μ^+/ μ^- (20~120MeV/c)

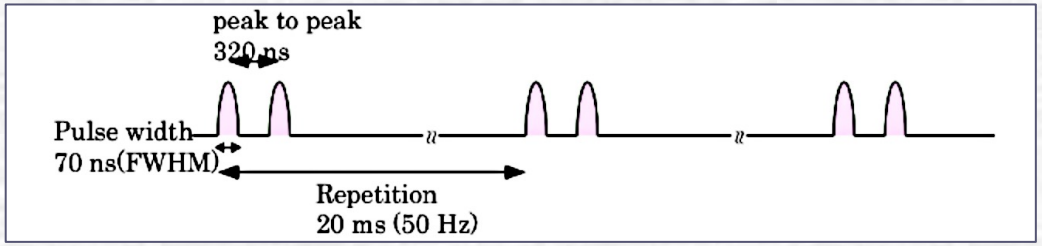
choice of double or single pulse with magnetic kicker (<60 MeV/c)

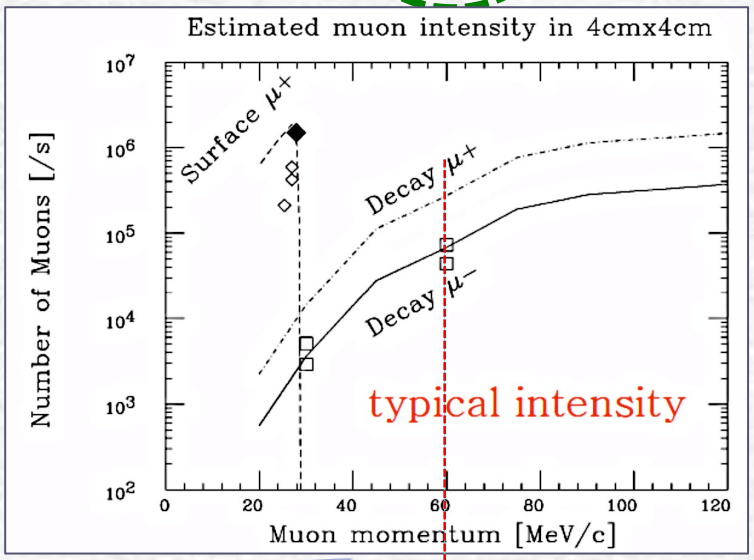
Δp/p FWHM 10%(decay), 5%(surf)

typical beam size 10cm^2





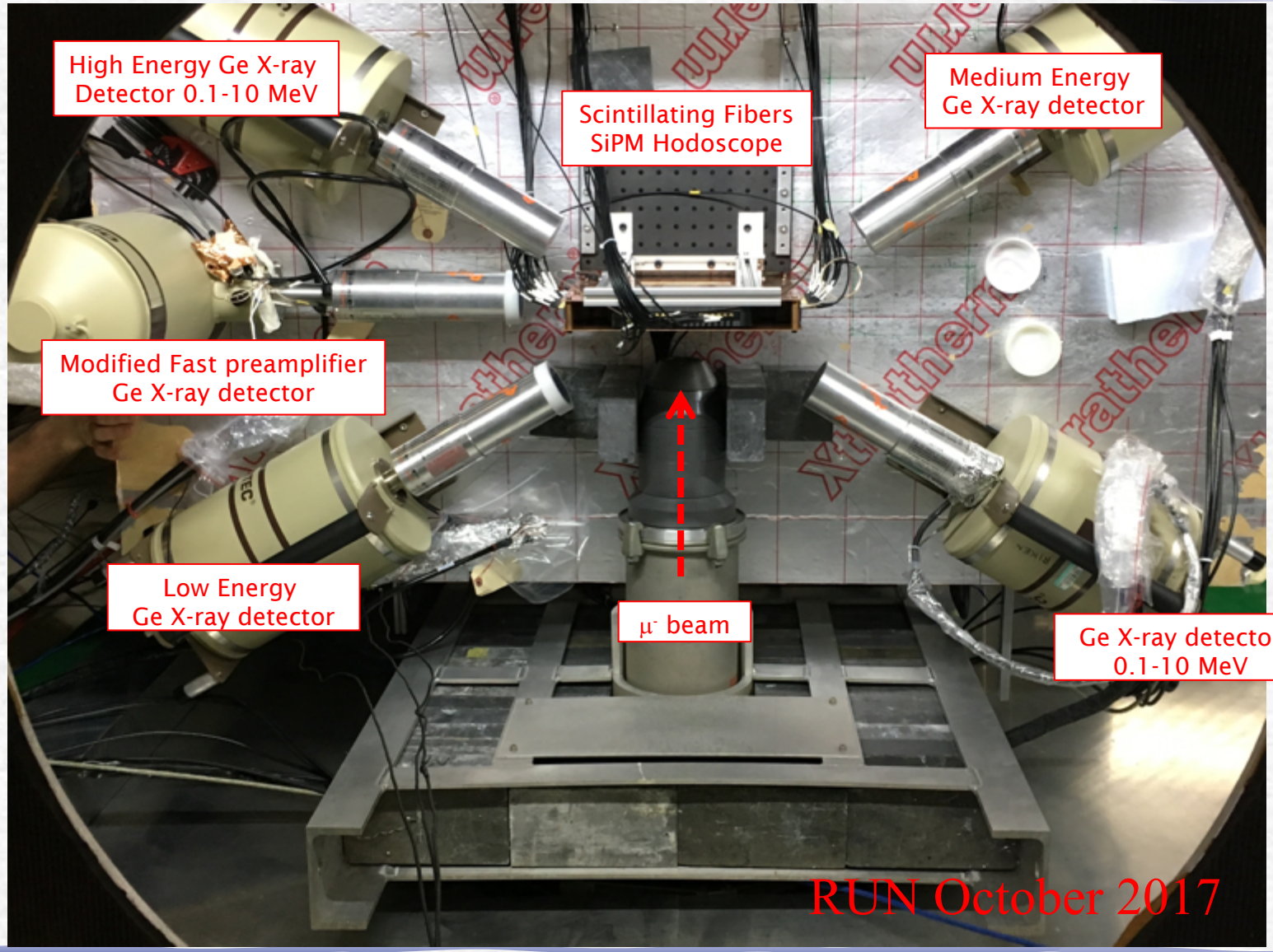




Pulsed proton beam with 50 Hz repetition double pulse with 70 ns width, 320 ns peak to peak on Graphite Target 10 mm thick

Thanks to K. Ishida (RIKEN)

Muon Spectroscopy setup@ RALSet-up of Exp. 1720283 @PORT4 ISIS MUON SOURCE



Spettroscopia Muonica: Attività 2017-2018 presso il RAL

Spin-off dell'Esperimento FAMU CSNIII (raggio di Zeemach del protone tramite spettroscopia laser del μp spokeperson A. Vacchi)

RUN "FAMU" marzo 2017:

- *RUN Esperimento FAMU (sono stati testati Odoscopio e Rivelatori al Germanio in vista del RUN di TANDEM)*

RUN "TANDEM" ottobre 2017:

- *Odoscopio: monitor del fascio e "posizionamento" dei campioni*
- *Germanio con pre-amplificatore "custom", per misure spettroscopia X*
- *Irraggiamento di targhette di materiali certificati*
- *Irraggiamento di un campione multistrato per effettuare lo scan del momento*

RUN "TANDEM" giugno-luglio 2018:

- *Irraggiamento prolungato di 4 frammenti di Navicelle Nuragiche*
- *Implementazione di un nuovo sistema di acquisizione dati DT5780 (Multicanale/Digitizer)*

RUN "TANDEM" giugno 2019:

- *Test beam per misure reperti archeologici "navicelle Nuragiche»*

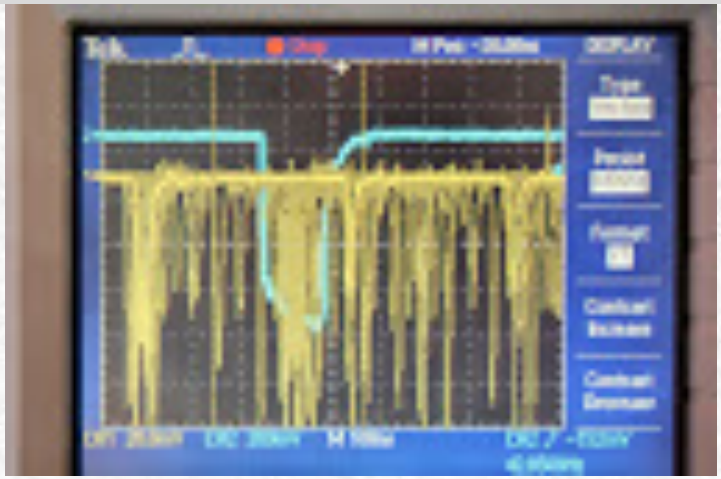
RUN Ottobre 2020:

- *Irraggiamento Moneta Portoghese del XVIII sec intercomparison IAEA*

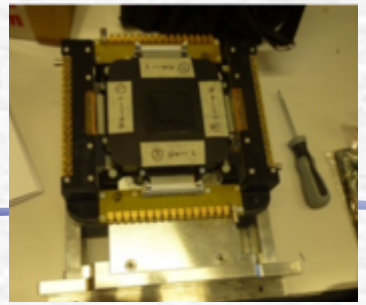
Hodoscope Performances at RiKEN/RAL

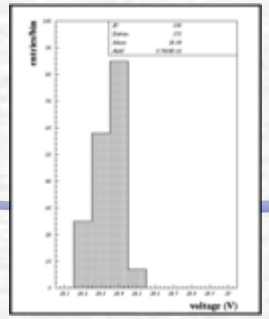
- The system is based **on 2 different hodoscopes** Fiducial area is **3.2 x 3.2 cm^2 (10 x 10 cm^2)** (one with 1 mm and one with 3 mm pitch) with similar design
- Mechanics is realized with a 3-D printer
- 2 X/Y Bicron BCF12 square single clad **scintillating fiber** planes (32+32 channels) read by 3x3 mm^2 (or 1x1 mm2) Hamamatsu (Advansid) **SiPM**
- EMA coating (Al film wrapping) for 1 mm (3 mm) fibers to avoid light cross-talk
- Both have electronics based on CAEN V1742 FADC (waveform → peak, area, time) and common HV for a fiber plane (V_{brk} in a large SiPM sample is very similar)
- **Measure X/Y profile and monitor beam intensity**

Pulsed high intensity muon beam (~70 muons/fiber/70 ns)

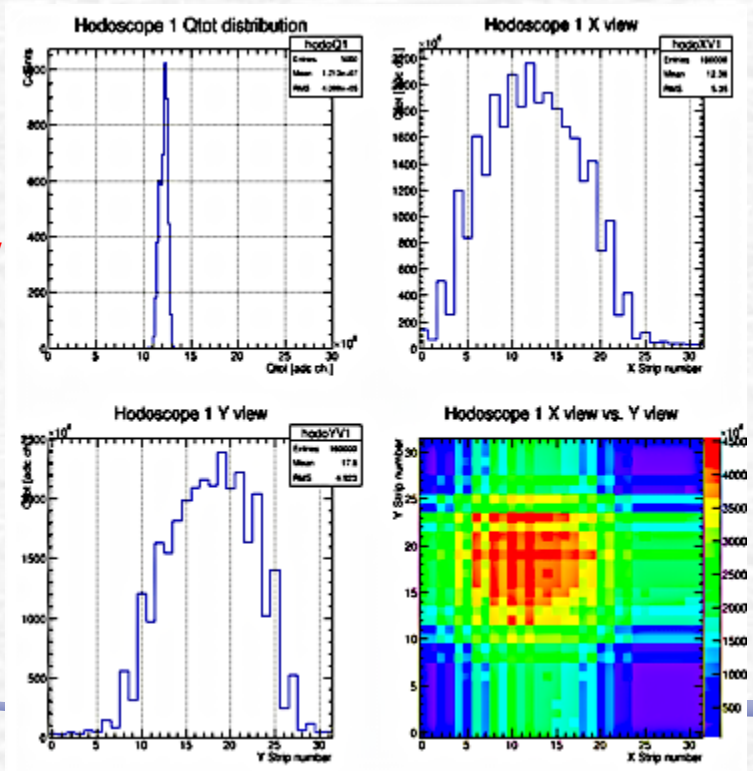


RUN October 2017





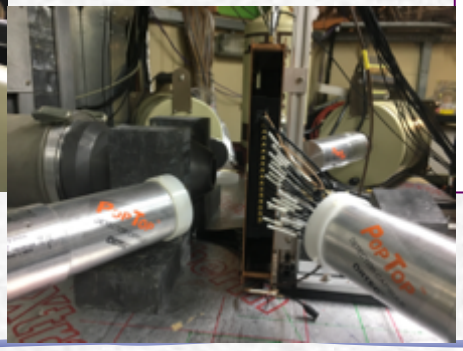
A typical run at 60 MeV/c: 8x10^4 μ^-/sec

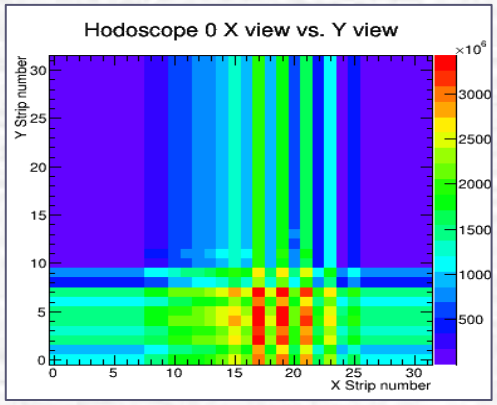


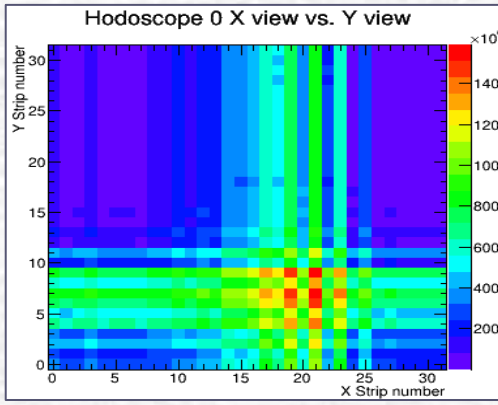
The beam has a 1.10 (0.98) cm r.m.s in x(y) coordinates

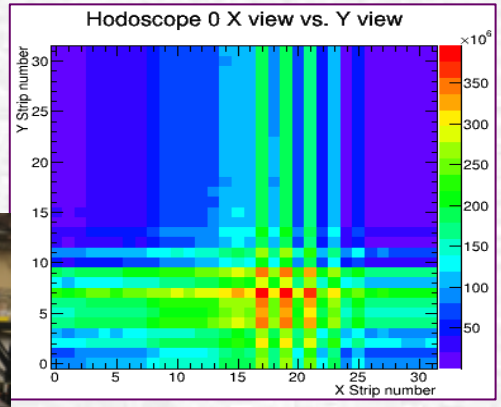
SiPM-Scintillating Fibers Hodoscopes: october 2017

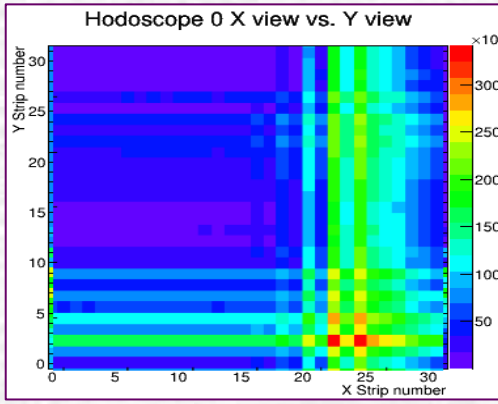
Use of scintillating optic fiber sensors read with SiPM for positioning the sample by measuring the muons flux before and after the sample, allowed us to optimize its position with respect to the center of the beam;





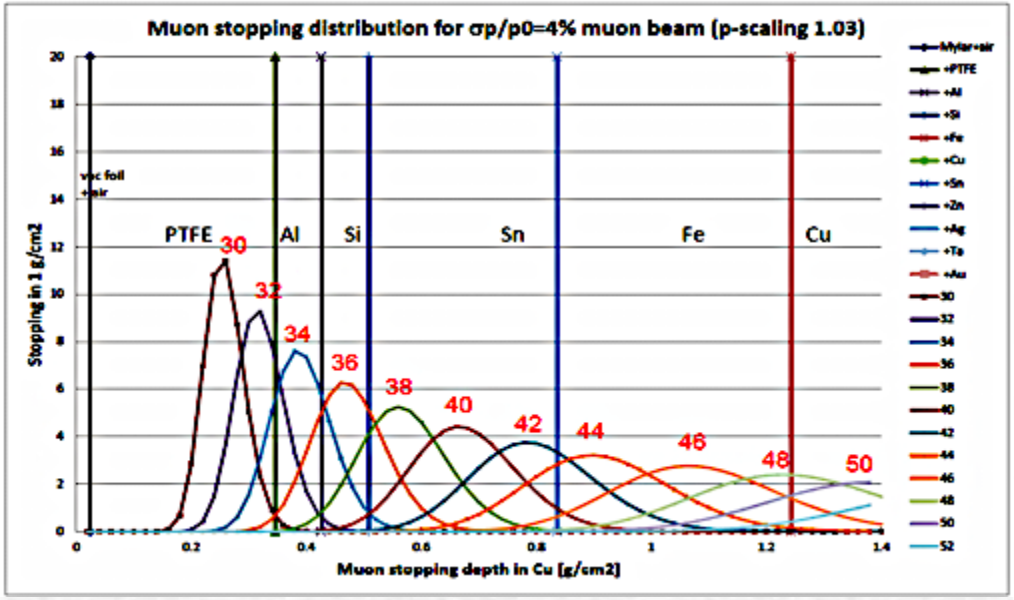


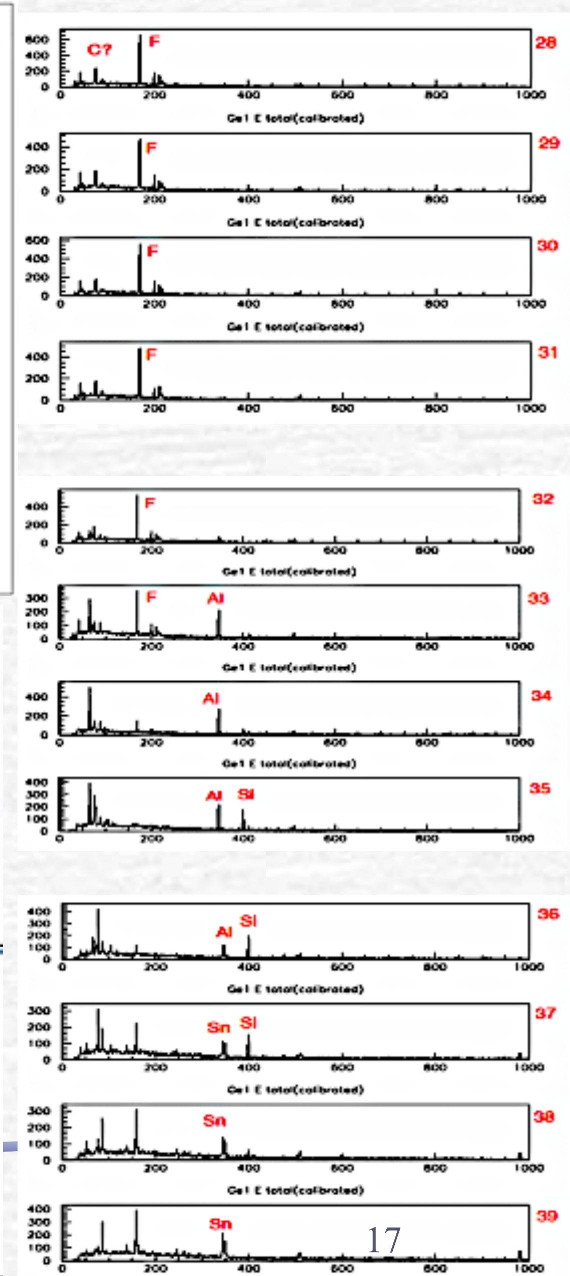


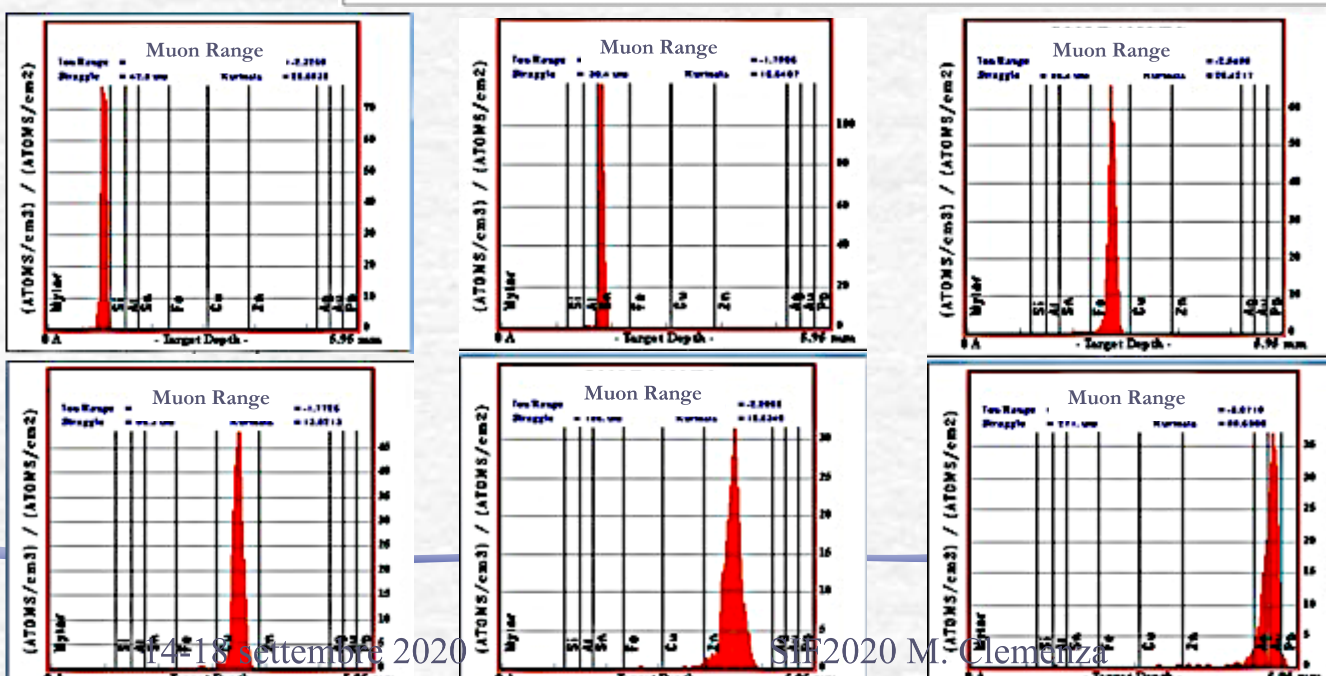


TRIM simulation of a MultilAyered sample: october 2017

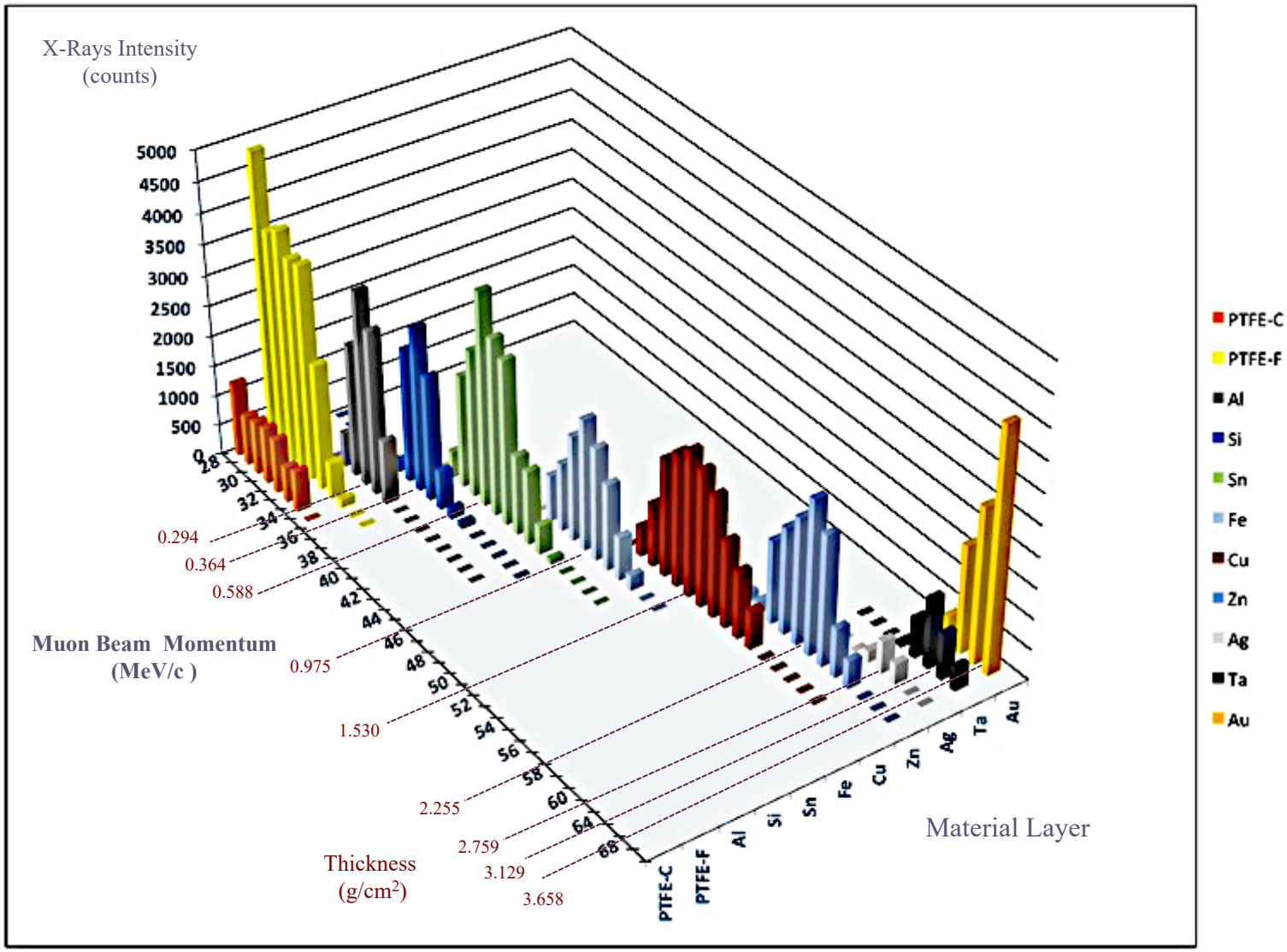
Material	Thickness (mm)
PTFE	1,2
Aluminum	0,25
Silicon	0,3
Tin	0,5
Iron	0,5
Copper	0,8
Zinc	1,0
Silver	0,25
Tantalum	0,25
Gold	0,3





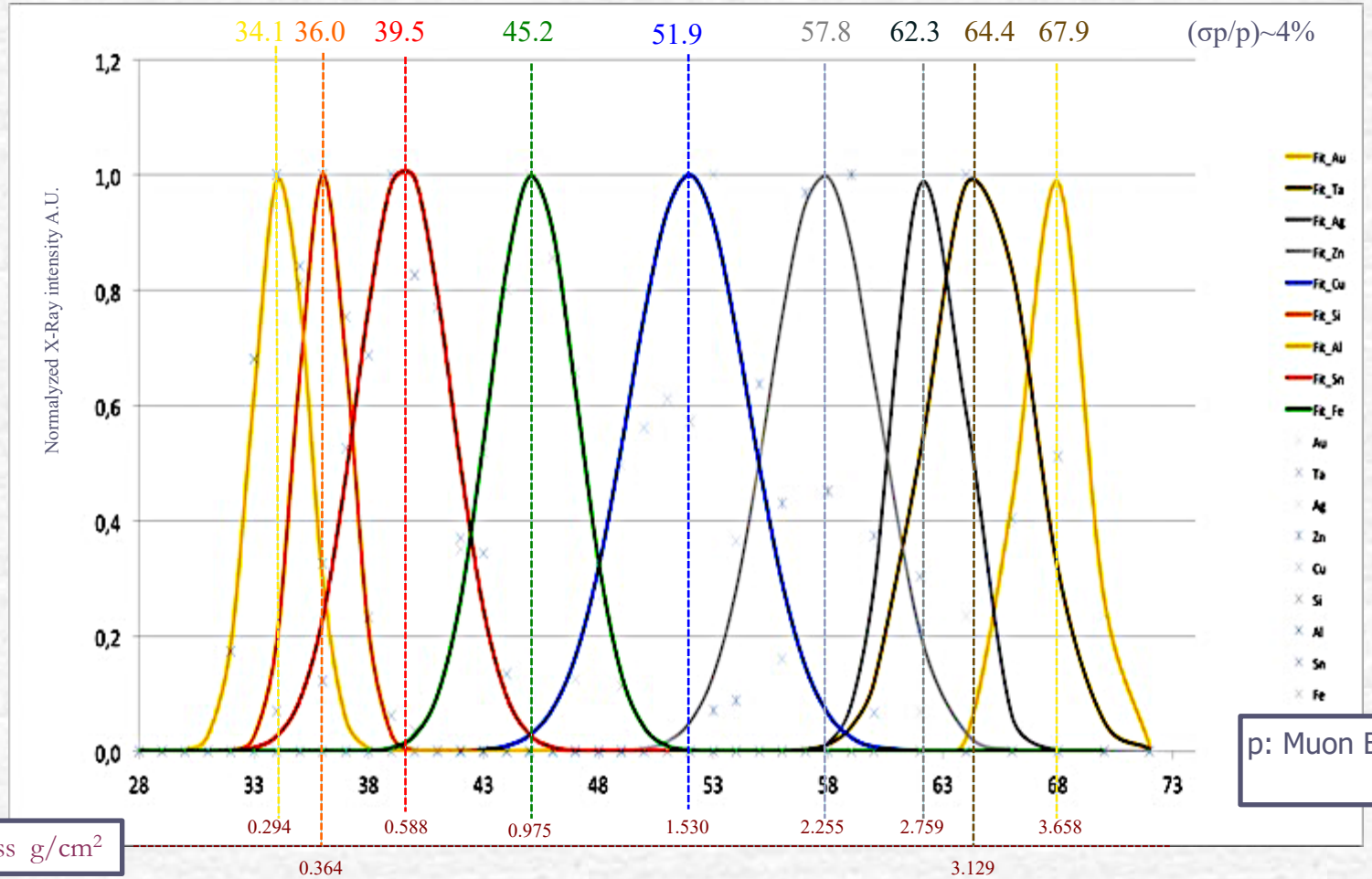


Multi-Layered sample Results october 2017



Multi-Layered sample Results october 2017

Optimization of Beam momentum



Best fit with gaussian curve of the normalyzed intensity of muonic X-rays distributions

June-July 2018: implementation of new DAQ DT5780 CAEN

Dual Digitizer Multi Channel Analyzer - Desktop

CAEN DT5780 DAQ module

The DT5780 is a compact desktop system integrating 2 Independent 16k Digital MCA and featuring HV/Preamp capabilities for digital nuclear Spectroscopy. 2x 100 MS/s 16-bit waveform digitizer (based on 724 series)

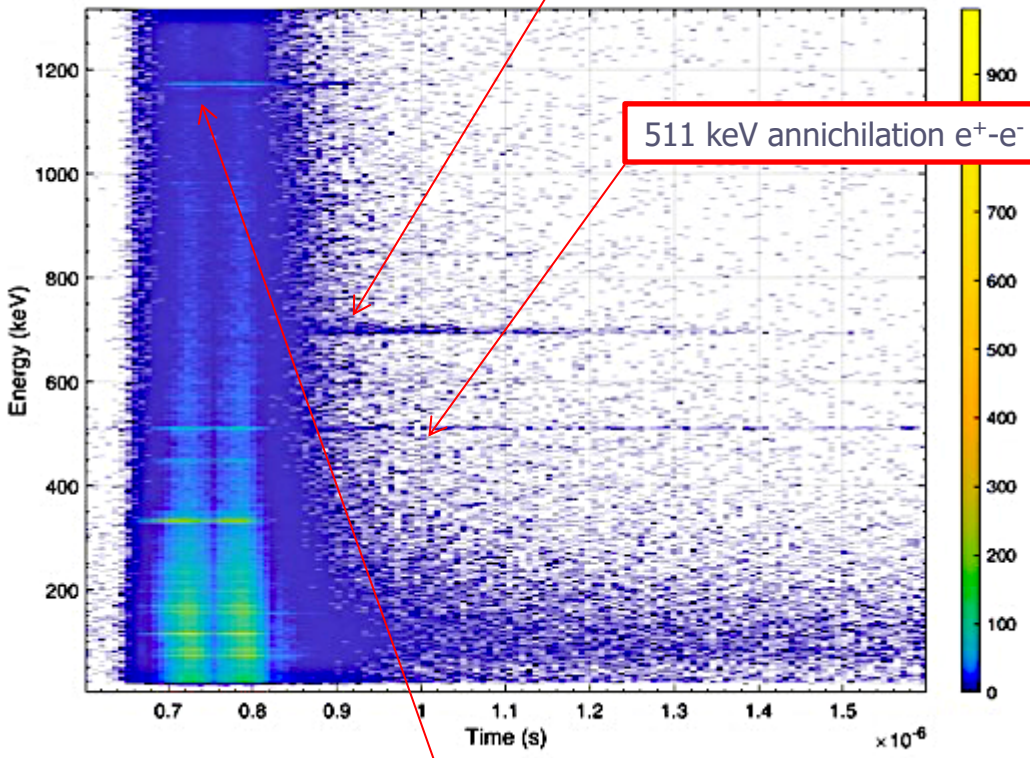
Operating modes:

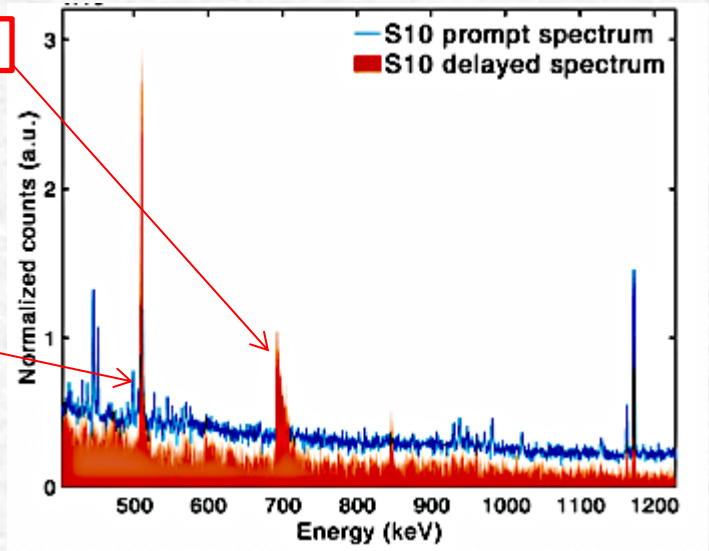
- "Pulse Height Analysis": pulse height histogram (1k-2k-4k-8k-16k) built at software level
- "List": pulse height and time stamp for each event: 10 ns resolution
- "Oscilloscope": input and internal filters waveforms

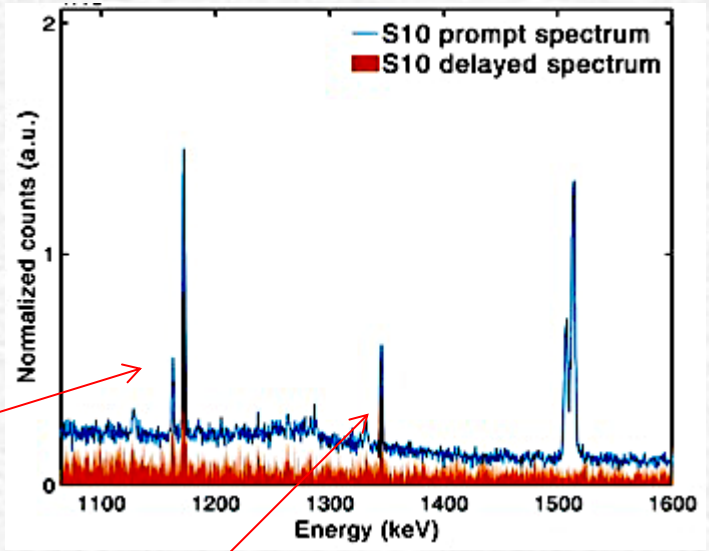
June-July 2018: implementation of new DAQ DT5780 CAEN

interaction of n-Ge (n, n ') (~700keV)

511 keV annichilation e^+-e^-







1173 - 1163 keV from

muon capture reaction
$^{63}Cu + u \rightarrow {}^{62}Ni + n + gamma$.

1345keV from 64Ni
$^{65}Cu+u \rightarrow {}^{64}Ni+n+gamma$

June-July 2018: Calibration Curves

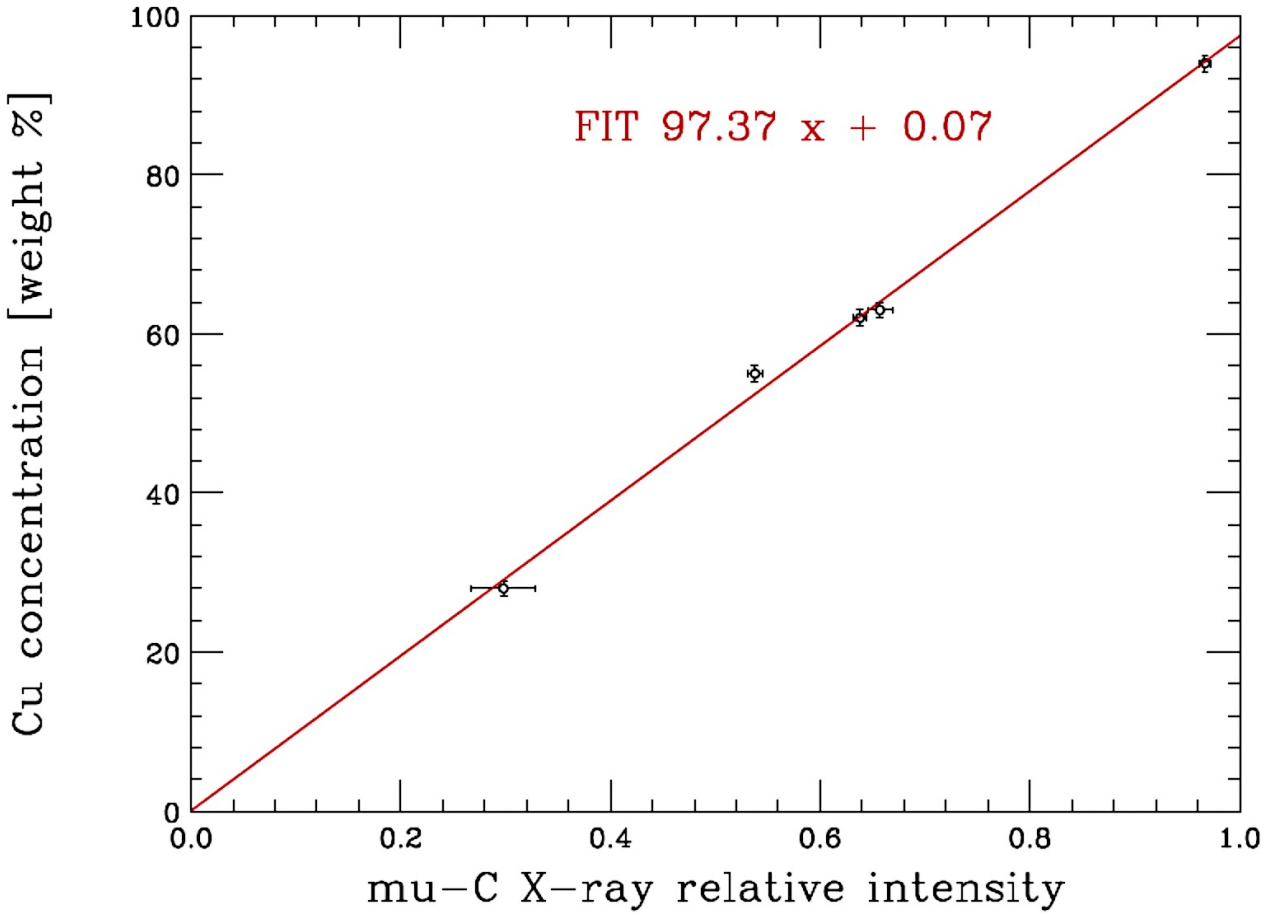
"Reference" Materials:

Silver 99.95
Cu99.9
Al 99.999
Al77.9SiC17.8Cu3.3Mg1.0
Fe65Cr18Ni10Mo3
Fe54Ni29Co17
Carbon 99.95
Cu55/Ni45
Cu63/Zn37
Cu62/Ni18/Zn20
Zn99.95Sn98.8
Ag72/Cu28
Cu94/Sn 6

"N. of values" for Calibration curve

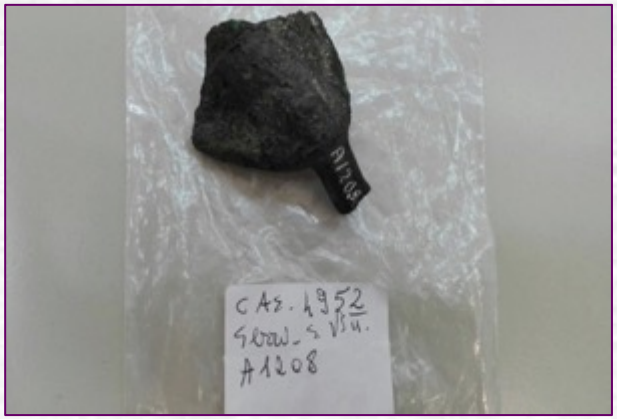
Cu:

99.9-94-63-62-55-28-3.3
Ni: 45-29-18-10
Zn: 99.95-37-20
Sn: 98.8 – 6
Ag: 99.95-72
Al: 99.995-77.9



Elemental Characterization of Nuragic Bronze Age Votive Ships: June-July 2018

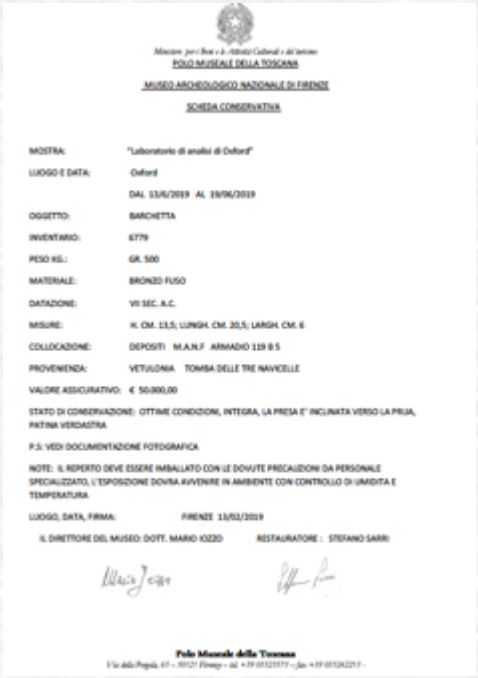
Questo sistema di misura è stato utilizzato per l'analisi approfondita di 4 reperti archeologici (frammenti di navicelle in bronzo votive di età nuragica) che hanno portato all'evidenza dell'utilizzo del piombo come addittivo nella lega di Rame e stagno soprattutto in alcune particolari zone di giunzione (prua della navicella).



Test with "real" Archeological samples

Test beam per misure reperti archeologici "Navicelle Nuragiche" (lucerne a olio)

Museo Archeologico Nazionale di Firenze:
2 navicelle nuragiche in bronzo
«Tomba delle tre navicelle» a Vetulonia (GR)



POLO MUSEALE DELLA TOSCANA

MUSEO ARCHEOLOGICO NAZIONALE DI FIRENZE

SCHEDA CONSERVATIVA

MOSTRA: "Laboratorio di analisi di Oxford"

LUOGO E DATA: Oxford
DAL 13/6/2019 AL 19/06/2019

OGGETTO: BARCHETTA

INVENTARIO: 6779

PESO KG.: GR. 500

MATERIALE: BRONZO FUSO

DATAZIONE: VII SEC. A.C.

MISURE: H. CM. 13,5; LUNGH. CM. 20,5; LARGH. CM. 6

COLLOCAZIONE: DEPOSITI M.A.N.F ARMADIO 119 B 5

PROVENIENZA: VETULONIA TOMBA DELLE TRE NAVICELLE

VALORE ASSICURATIVO: € 50.000,00

STATO DI CONSERVAZIONE: OTTIME CONDIZIONI, INTEGRA, LA PRESA E' INCLINATA VERSO LA PRUA, PATINA VERDASTRA

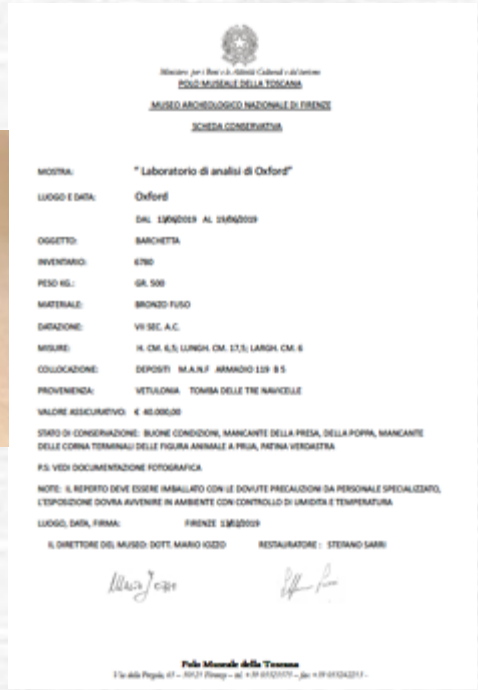
P.S. VEDI DOCUMENTAZIONE FOTOGRAFICA

NOTE: IL REPERTO DEVE ESSERE IMBALLATO CON LE DOVUTE PRECAUZIONI DA PERSONALE SPECIALIZZATO, L'ESPOSIZIONE DOVRA AVVENIRE IN AMBIENTE CON CONTROLLO DI UMIDITA E TEMPERATURA

LUOGO, DATA, FIRMA: FIRENZE 13/02/2019

IL DIRETTORE DEL MUSEO: DOTT. MARIO IOZZO RESTAURATORE : STEFANO SARRI

Polo Museale della Toscana



POLO MUSEALE DELLA TOSCANA

MUSEO ARCHEOLOGICO NAZIONALE DI FIRENZE

SCHEDA CONSERVATIVA

MOSTRA: " Laboratorio di analisi di Oxford"

LUOGO E DATA: Oxford
DAL 13/6/2019 AL 19/06/2019

OGGETTO: BARCHETTA

INVENTARIO: 6780

PESO KG.: GR. 500

MATERIALE: BRONZO FUSO

DATAZIONE: VII SEC. A.C.

MISURE: H. CM. 6,5; LUNGH. CM. 17,5; LARGH. CM. 6

COLLOCAZIONE: DEPOSITI M.A.N.F ARMADIO 119 B 5

PROVENIENZA: VETULONIA TOMBA DELLE TRE NAVICELLE

VALORE ASSICURATIVO: € 40.000,00

STATO DI CONSERVAZIONE: BUONE CONDIZIONI, MANCANTE DELLA PRESA, DELLA POPPA, MANCANTE DELLE CORNA TERMINALI DELLE FIGURA ANIMALE A PRUA, PATINA VERDASTRA

P.S. VEDI DOCUMENTAZIONE FOTOGRAFICA

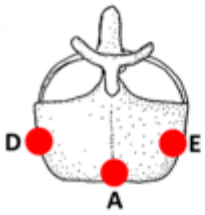
NOTE: IL REPERTO DEVE ESSERE IMBALLATO CON LE DOVUTE PRECAUZIONI DA PERSONALE SPECIALIZZATO, L'ESPOSIZIONE DOVRA AVVENIRE IN AMBIENTE CON CONTROLLO DI UMIDITA E TEMPERATURA

LUOGO, DATA, FIRMA: FIRENZE 13/02/2019

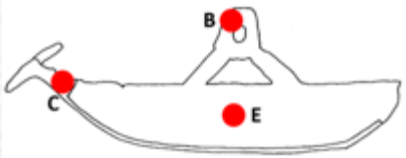
IL DIRETTORE DEL MUSEO: DOTT. MARIO IOZZO RESTAURATORE : STEFANO SARRI

Polo Museale della Toscana

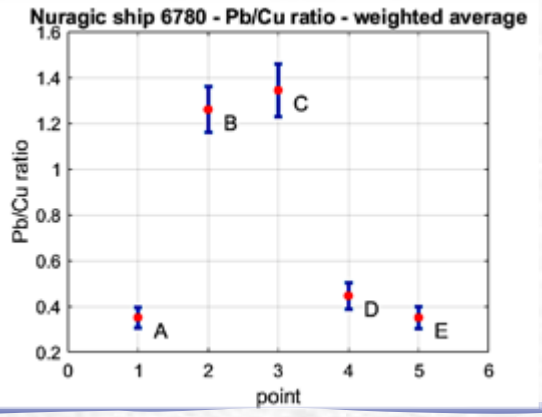
Test beam per misure reperti archeologici "navicelle Nuragiche"

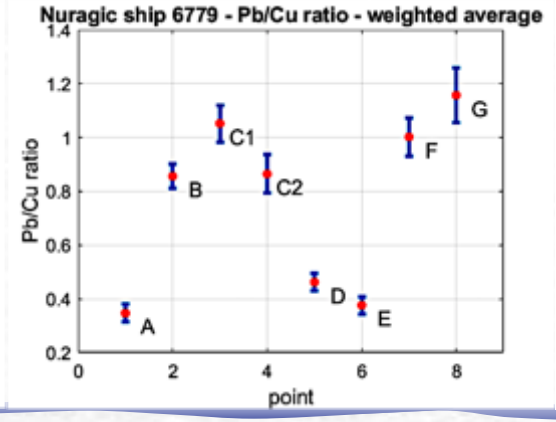


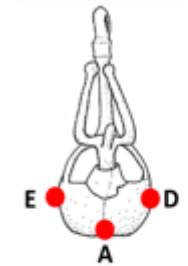
n. inv: 6780



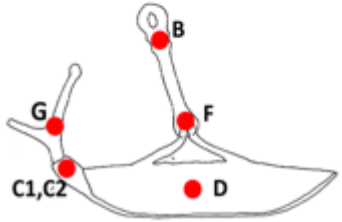
Museo Archeologico Nazionale di Firenze







n. inv: 6779



Summary of features and drawbacks

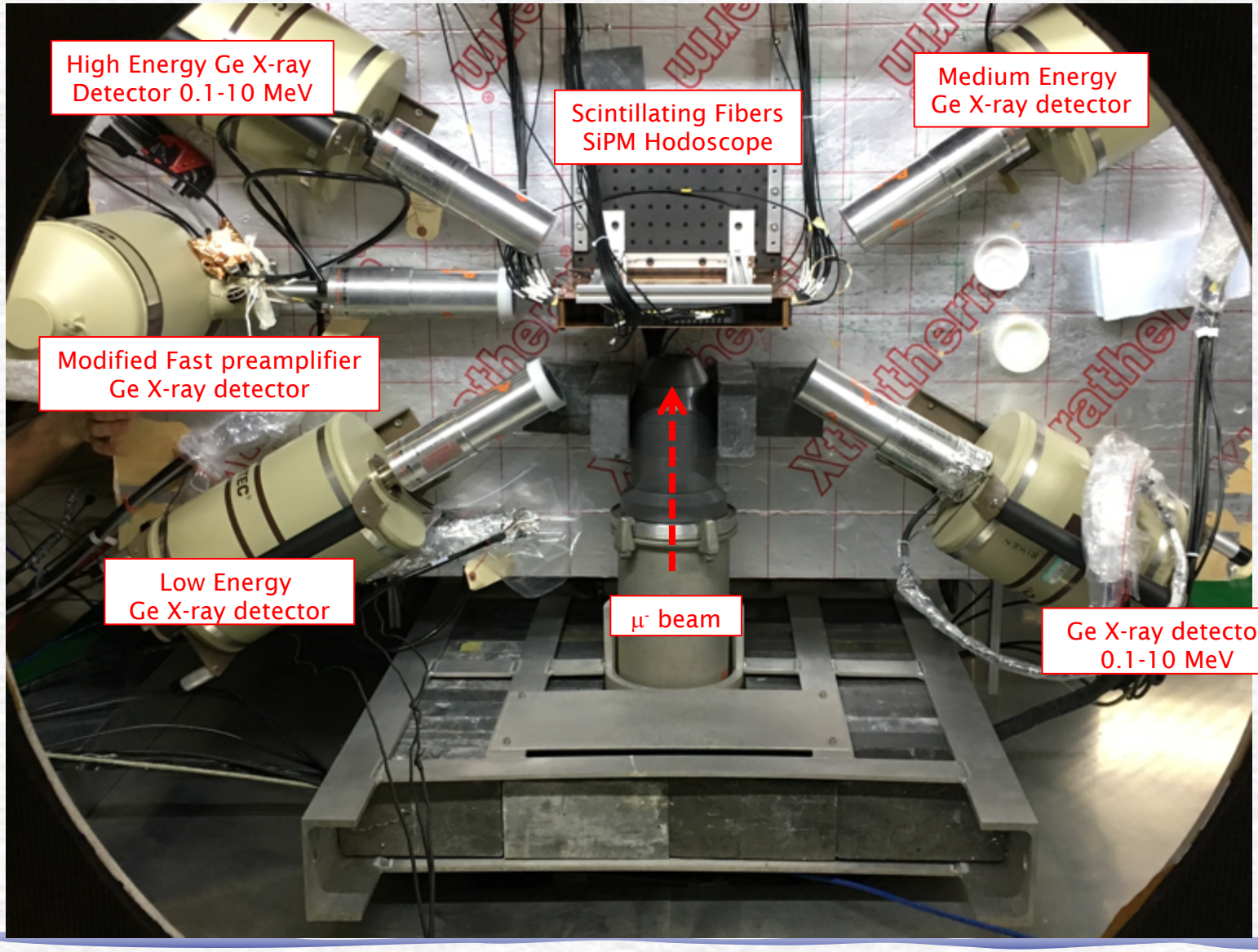
Muonic atom X-rays spectroscopy has proved to be:

- a **non-invasive**, **simoultaneous multielemental** analytical technique
- **High energy characteristic X-rays** emission (**small auto absorption** also for low Z elements) potentially applicable for **all elements** (from Li to U) without vacuum system
- **Depth** (site) **selective** (easy muon beam momentum scan) possibility to perform depth profile elemental characterization (**3D mapping**)
- Very high specifity (**energy** and **temporal signatures**) and **negligible radioactivation**
- **Complementary technique** to other non-invasive analytical techniques for bulk (PGNAA) or surface analysis (XRF)

Drawbacks:

- Poor sensitivity (only major elements)
- Long counting/irradiation time (12-18 h to reach sensitivity to 0,5% m/m !!!)
- Very low solid angle coverage (caused by detector pile-up)

Current experimental Setup



Limitations:

Detector Solid Angle

Data Rate

Squeezed into port 4

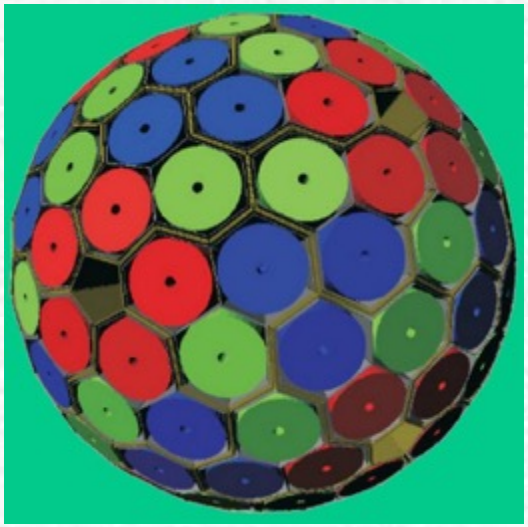
Results in:

Long counting times

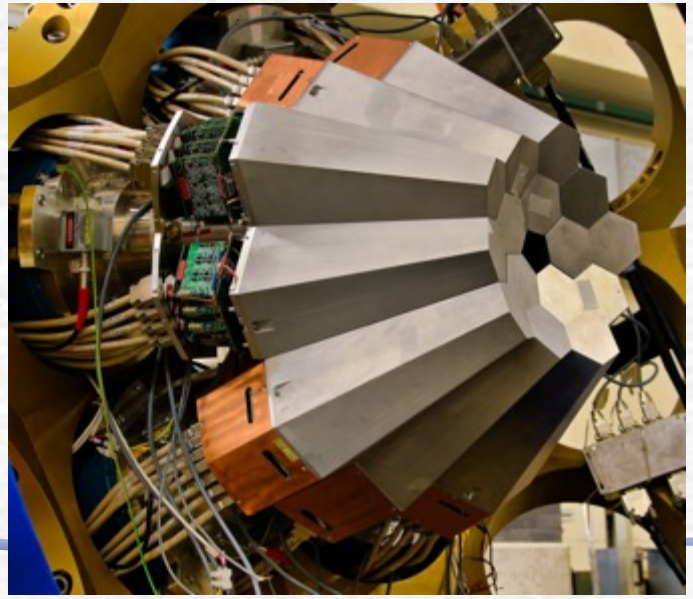
Loss of sensitivity

Time consuming setup

A Possible Solution



By Shantonu Biswas



New set-up like "**AGATA experiment*":

Pixelated Ge detectors

Ge crystals are tapered hexaconical shape electronically into 36 segments

Possible design

upstream and downstream banks gives open access for large cultural heritage samples

*The Advanced GAmma Tracking Array (AGATA) is a European gamma-ray spectrometer used for nuclear structure studies

Spettroscopia muonica: Prospettive future

- ***RUN Ottobre 2020:*** *Irraggiamento Moneta Portoghese del XVIII sec inter-comparison IAEA nuclear techniques*

- ***PhD Novembre 2020****: co-finanziato da RIKEN-RAL e DFO-UNIMIB*

Science & Technology Facilities Council
ISIS

ISIS Facility
STFC Rutherford Appleton Laboratory
Harwell Oxford
Didcot OX11 0QX
United Kingdom

www.stfc.ac.uk

25 November 2019

Dr Clemenza and Dr Hillier

Dear Dr Clemenza and Dr Hillier

ISIS Facility Development Studentship Proposal

Very many thanks for your proposal for an ISIS co-funded Facility Development Studentship.

Proposals were assessed by a panel consisting of ISIS management, senior ISIS scientists and external members of the ISIS user community. We are very pleased to announce that we would like to support your studentship application, and co-fund this project with you.

There was a very strong field of proposals – a total of 30 studentship requests, all with very good science aims and facility development projects. From these submissions we are intending to fund 6 projects, including your proposal.

ISIS

25 November 2019

Dr Clemenza and Dr Hillier

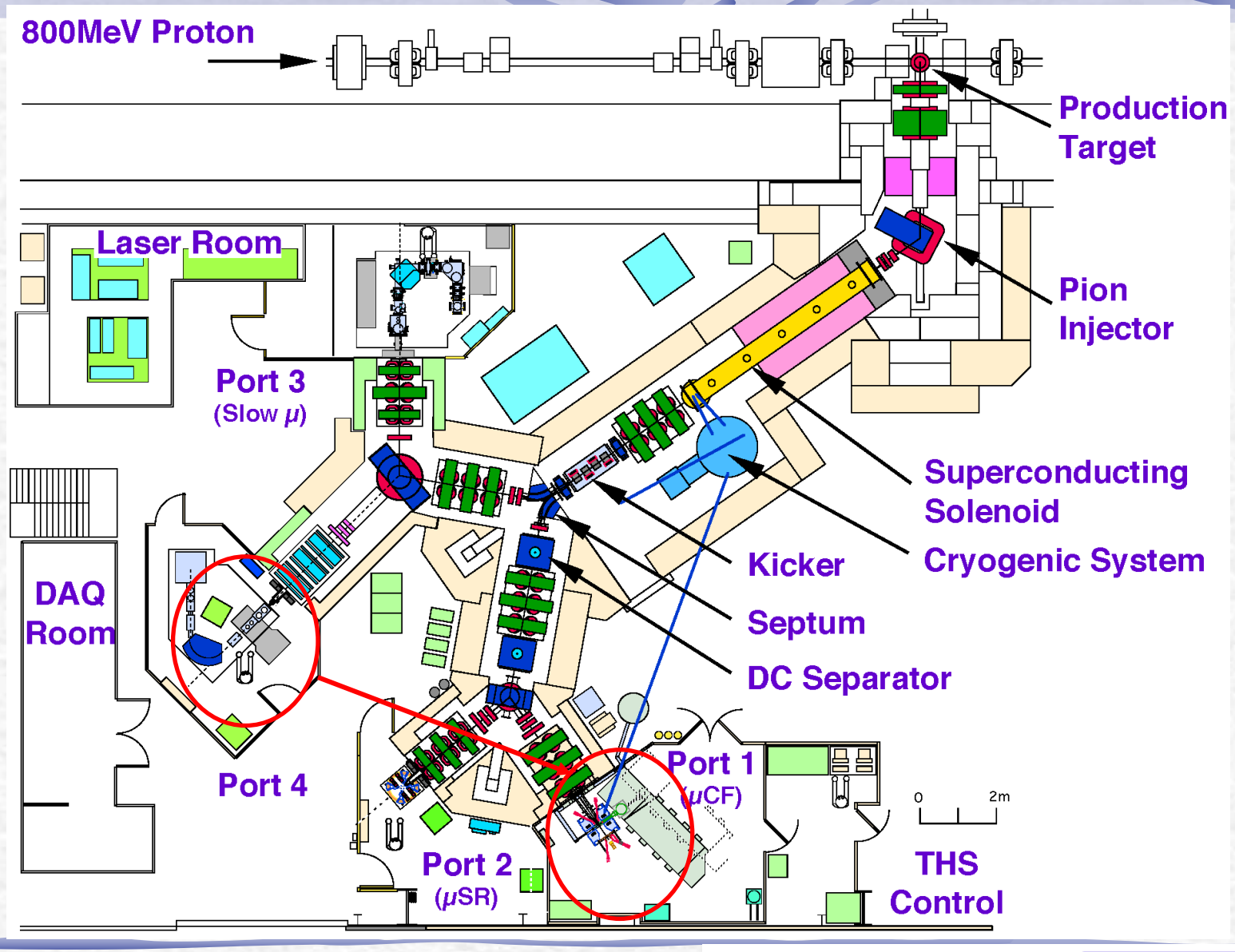
Dear Dr Clemenza and Dr Hillier

ISIS Facility Development Studentship Proposal

Once again, many congratulations on a successful proposal. We very much look forward to working with you over coming years.

With best regards

A Possible solution



Move to Port 1

Science & Technology Facilities Council
ISIS

Dr. Adrian Hillier
ISIS Pulsed Neutron and Muon Facility
Science and Technology Facilities Council
Rutherford Appleton Laboratory
Harwell Science and Innovation Campus
Oxon, OX11 0QX, UK
+44 (0) 1235 446001
adrian.hillier@stfc.ac.uk

23 July 2018

Elemental analysis deep beneath the surface

To whom it may concern.

Science and Technology Facility Councils Rutherford Appleton Laboratory is located on the Harwell Science and Innovation Campus in Oxfordshire, it provides a thriving and collaborative environment for research in different fields like Condensed Matter, Biological system, Chemical analysis, particle physics, space science, materials, astronomy etc... On the campus, we have a neutron and muon facility (ISIS), together with a light source (DIAMOND) and these facilities are used to investigate the material world. This can also be applied to the conservation, preservation and study of cultural heritage that is a field of concern within Italy and Europe.

In particular, it is possible to perform the non-destructive depth analysis of a variety of materials using the intense muon beam @RIKEN-RAL (a 33 year collaboration between ISIS and RIKEN, Japan). By tuning the momentum of the muon the implantation depth can be easily controlled and can penetrate into materials much deeper than electrons without any residual radioactivity. The characteristic muonic X-rays have about 200 times higher energy than that of characteristic X-rays generated by electron beam analysis. Therefore, it becomes possible to obtain information about chemical composition inside materials, from 100 microns to centimetres thick (with a resolution of +/- 20%), in a non-destructive manner.

Currently, a successful collaboration with INFN and other research bodies, in particular with the research group of Massimiliano Clemenza of the University of Milano Bicocca, a series of experiments to optimize muonic spectroscopy as a non-invasive and non-destructive probe for quantitative "bulk" analysis for the use in the archaeometric field for elemental characterization of metal artefacts and ancient objects.

This project aims to perform an in-depth study with a negative muon beam of metallic artefacts from the late Bronze-age found in different area of the Italy (Sardinia, Tuscany, Lazio and Campania regions). The ultimate goal is to achieve a series of measurements on homogeneous type objects from three different areas of the Italian peninsula, all affected by contact with the Sardinian population. In particular, it would be analysed similar objects from different contexts:

The possibility to investigate the miniaturist boat from the grave 74 Montevetrano (Salerno), the miniaturistic shaped pail from Pontecagnano (Salerno), the analogue miniaturist object from the tomb of Sardinian bronzes Cavalupo Vulci and a boat would be of great interest. In addition, possible objects of an interesting study would be from the Tyrrhenian Etruria, one could choose from the Gravisca sanctuary (Viterbo) or that of the recent discovery by the waters of Lake Trasimeno (San Feliciano, Perugia). It would be of great interest to include the analysis of similar objects from the Sardinian territory, with regard to this we propose the following possible artefacts such as pail of Santa Vittoria di Serri and/or that of Santa Cristina of Paulilatino, the miniaturist boat from Villagrande-S'Arcu' and forros and / or the Sorridile boat and / or Baunei boat with a monkey. If there is the possibility of further extending this project thought should be given to the statue of "centaur"

Science & Technology Facilities Council
ISIS

of Nule, as try to provide useful input to the on going research on the technical characteristics of its realization.

The research work is proposed and supported by STFC, INFN, UNIMIB, UNISS and CNR.

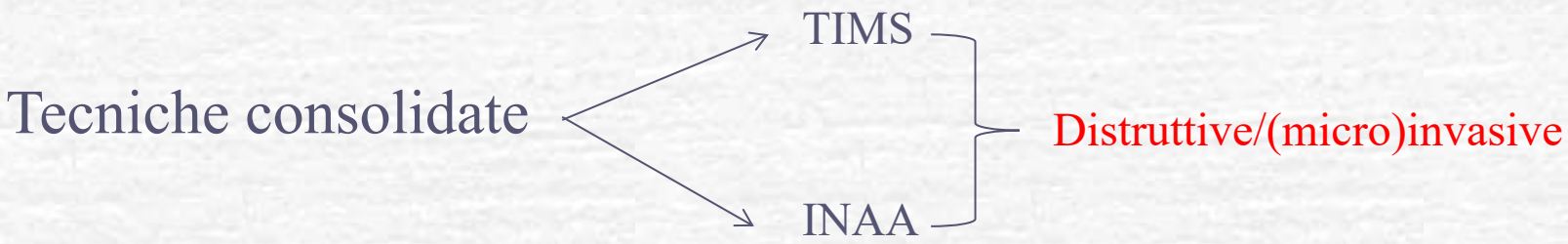
Yours sincerely,

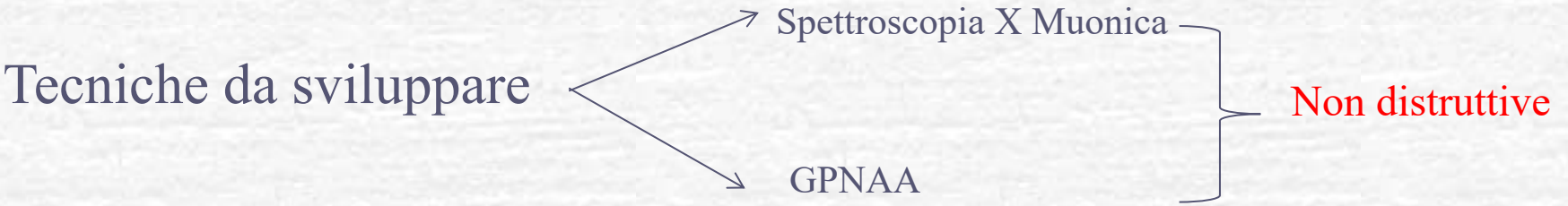
Adrian Hillier
Muon Group Leader
ISIS Pulsed Neutron and Muon Facility
STFC Rutherford Appleton Laboratory

Grazie per l'attenzione

Progetto TANDEM: Tecniche Analitiche Non Distruttive per l'archEoMetria

L'idea che sta alla base del progetto **TANDEM** è quella di implementare, sviluppare e ottimizzare tecniche di analisi da utilizzarsi in ambito archeometrico per la caratterizzazione di manufatti

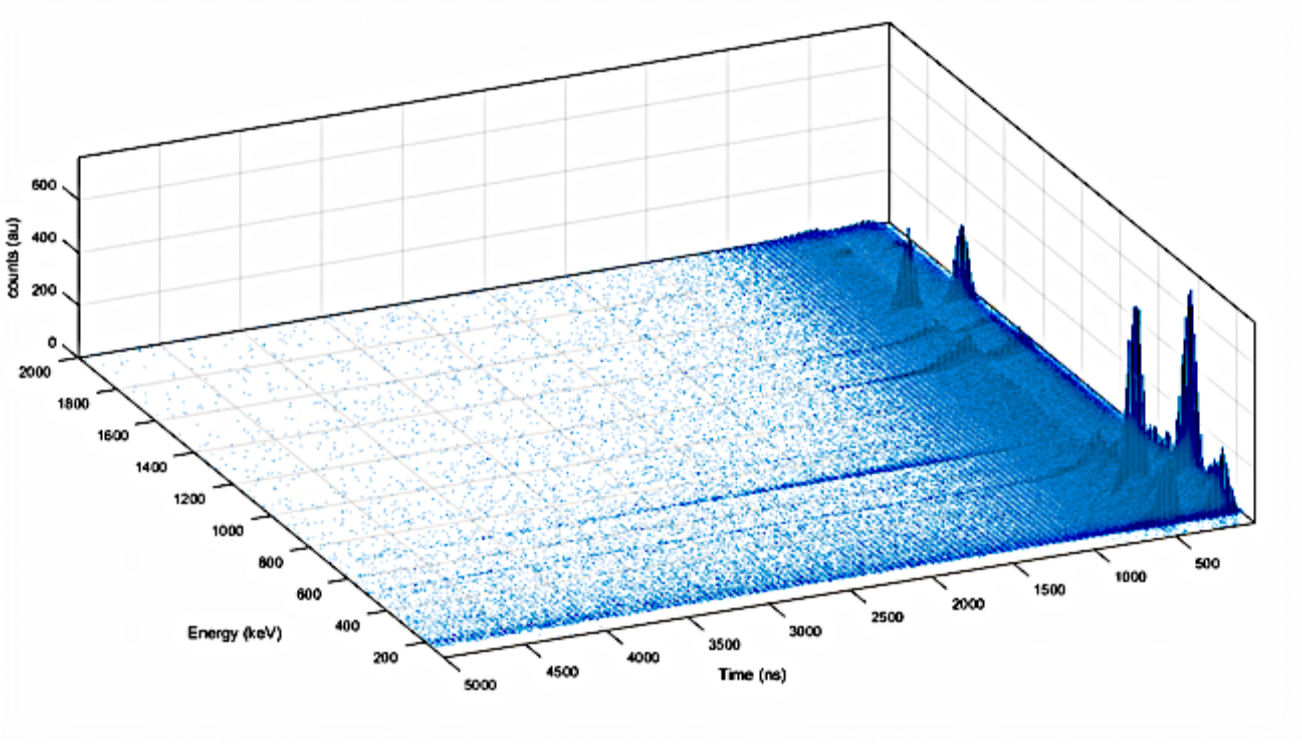




CHNET_TANDEM

June-July 2018: implementation of new DAQ DT5780 CAEN

Energy spectrum and Time distribution



Research and development of analytical techniques

CHNET_TANDEM experiment: X rays spectroscopy with Muonic Atoms

Non-destructive elemental analysis by X-ray spectroscopy of Muonic Atoms

PORT4 RIKEN-RAL@ISIS

Collaboration:
INFN-MIB – LNS- UNISS- UNIPV-LENA – ISIS-RIKEN_RAL

Depth of Implantation as a function of muon beam moment/energy

Surface and bulk elemental characterization without activation!!