CHNET_TANDEM Experiment:

Use of Negative Muons at Port4 of the RIKEN-RAL for elemental characterization of “Nuragic votive ships” samples

Authors: Massimiliano Clemenza (massimiliano.clemenza@mib.infn.it)

G. Baldazzi, G. Ballerini, M. Bonesini, M. Carpinelli, C. Cremonesi, E. Fiorini, G. Gorini, A. Hillier, K. Ishida, A. Menegolli, M. Minoja, E. Mocchiutti, A. Pullia, P. Oliva, L. Rignanese, M. Rossella, M. Prata, G. Salis, V. Sipala, M. Soldani, Tortora L, Vacchi A. E. Vallazza

Experimental Approach

Using the intense double pulsed muon beam at RIKEN-RAL, it is possible to perform the non-destructive bulk analysis of a variety of materials. Muons have high transmission ability and can penetrate much deeper into materials than electrons. The characteristic muonic X-rays have about 200 higher energy than that of characteristic X-rays ones generated by electron/proton beam analysis, without activation of the sample. Then, it becomes possible to obtain information about chemical composition not only for the surface layers, but inside materials up to several millimeters thick in a non-destructive manner. The idea is to develop a non-destructive technique, which allows analysis deep inside the sample with a good spatial resolution, using a negative muon beam. By selecting the primary μ energies appropriately, bulk analysis can be non-destructively performed. The experimental setup used for this experiment, already tested at RAL in Port 1 for the FAMU experiment, (2 hodoscopes and 4 HpGe) it allowed us to collect very interesting preliminary data for scan momentum, positioning and centring of the samples by means of two hodoscopes, analysis of standard material targets and elemental characterization of 4 fragments of Nuragic Bronze Age votive ship.

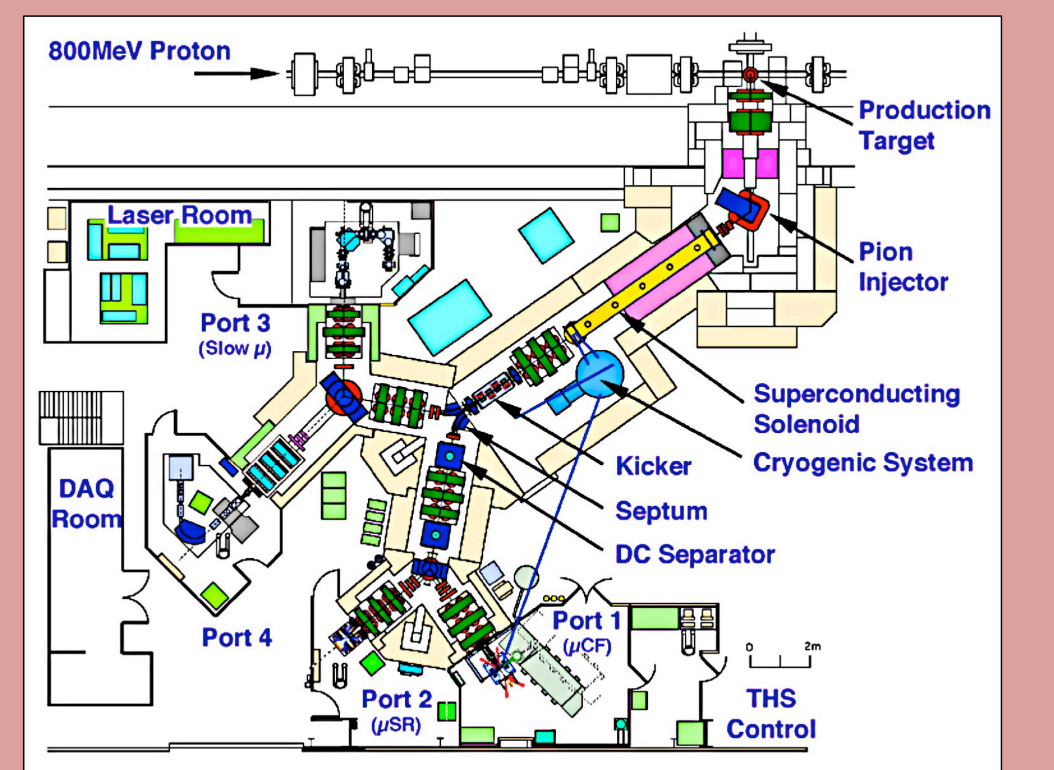
Muonic Atom spectroscopy: Principle

A negative muon can replace an electron in an atom and subsequently transition to lower orbital positions. As with conventional X-ray fluorescence, an X-ray photon is emitted with a characteristic energy to enable the transition between orbitals of an atom. As the mass of a negative muon is much greater than that of an electron, a higher energy X-ray photon is emitted when the negative muon transitions between orbitals compared to conventional X-ray fluorescence. The higher energy muonic X-rays are able to escape large samples even when they are emitted from lower Z atoms, making muonic X-rays fluorescence a unique method to characterize the elemental content of a sample. In a typical experiment a section of a sample will be probed with negative muons with the muon momentum tuned to interact at a desired depth in the sample. A small number of single element high purity Ge detectors are positioned to capture up to one photon each from each of the forty muon pulses per second at the RIKEN-RAL facility. This can provide a high resolution and high dynamic range X-ray energy spectrum when collected for several hours but can only provide a spatial average or single point elemental distribution per collection.

Set-up of Exp. 1720283 @PORT4

During 4 days of beam time from 7 to 11 October 2017, we managed to reach all the objectives expected for the experiment 172028 and very interisting preliminary results in scan momentum and analisys of 4 fragments of *Nuragic votive ships* are emerged. In the following picture the experimental set-up: 1 Fiber Scintillating SiPM Hodoscope and 5 HpGe.

ISIS Rutherford Appleton Laboratory

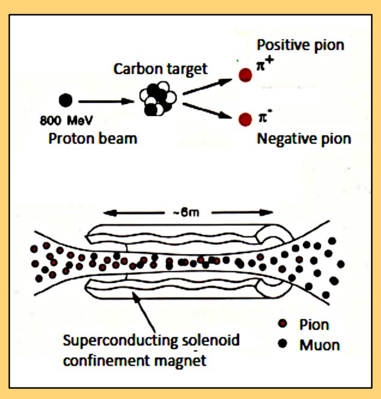


RIKEN-RAL Muon Facility

Uniqueness RIKEN-RAL Beam Facilities

Pulsed proton beam with 50 Hz repetition
double pulse with100 ns width, 320 ns peak to peak
on Graphite Target 10 mm thick

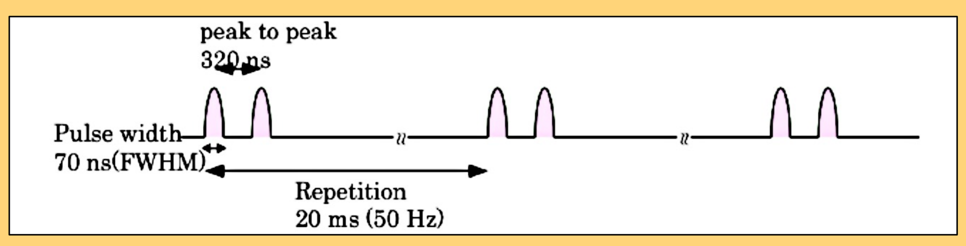
Beam Structure

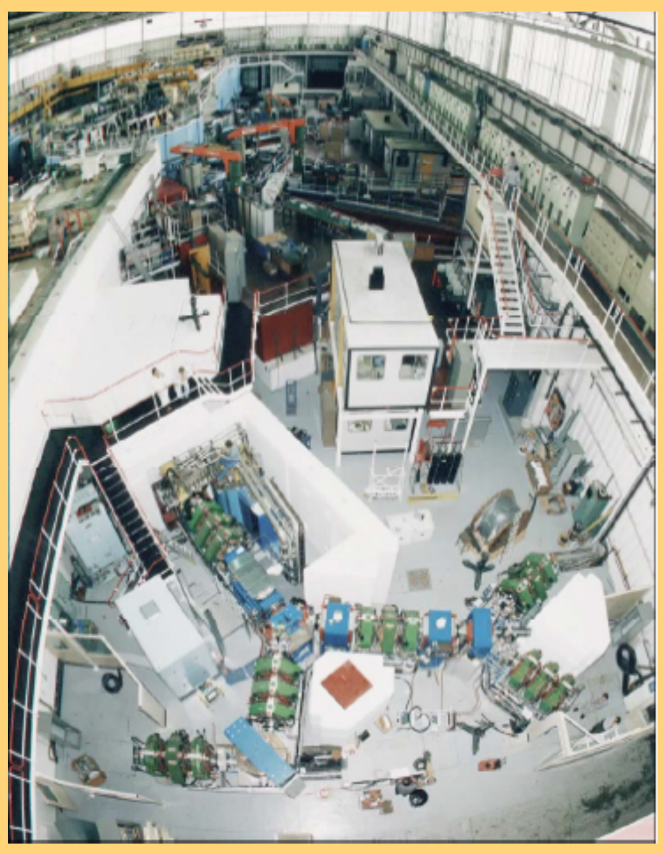


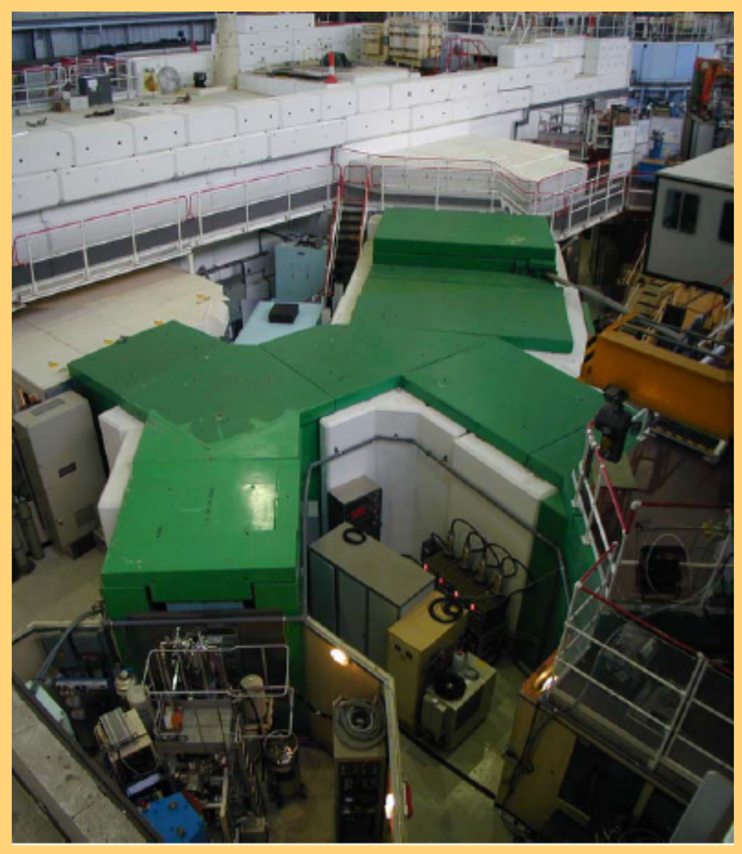
Beam properties

surface μ^+ (20~30MeV/c) and
decay μ^+/ μ^- (20~120MeV/c)

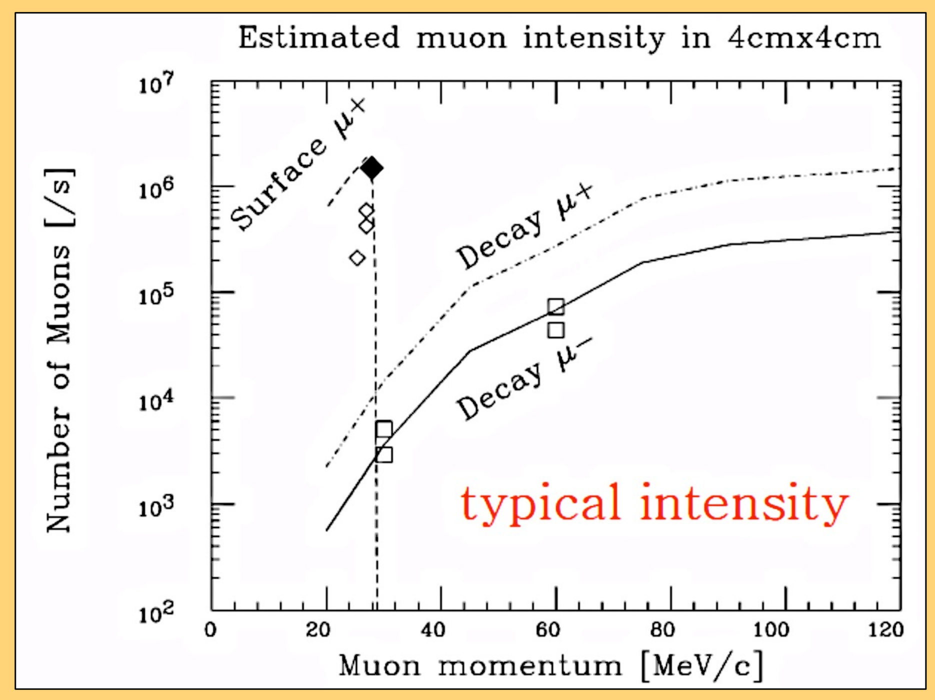
choice of double or single pulse
with magnetic kicker (<60 MeV/c)
$\Delta p/p$ FWHM 10%(decay), 5%(surf)
typical beam size 10cm²





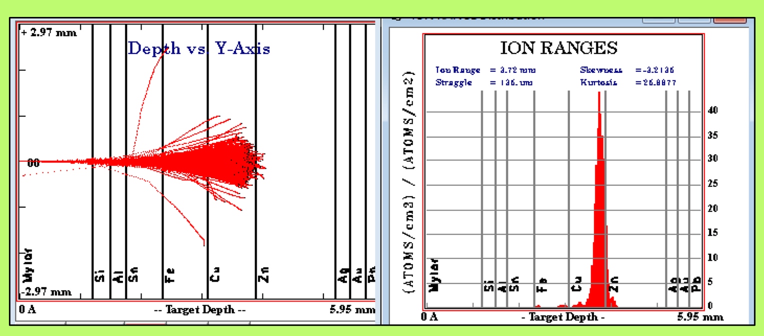


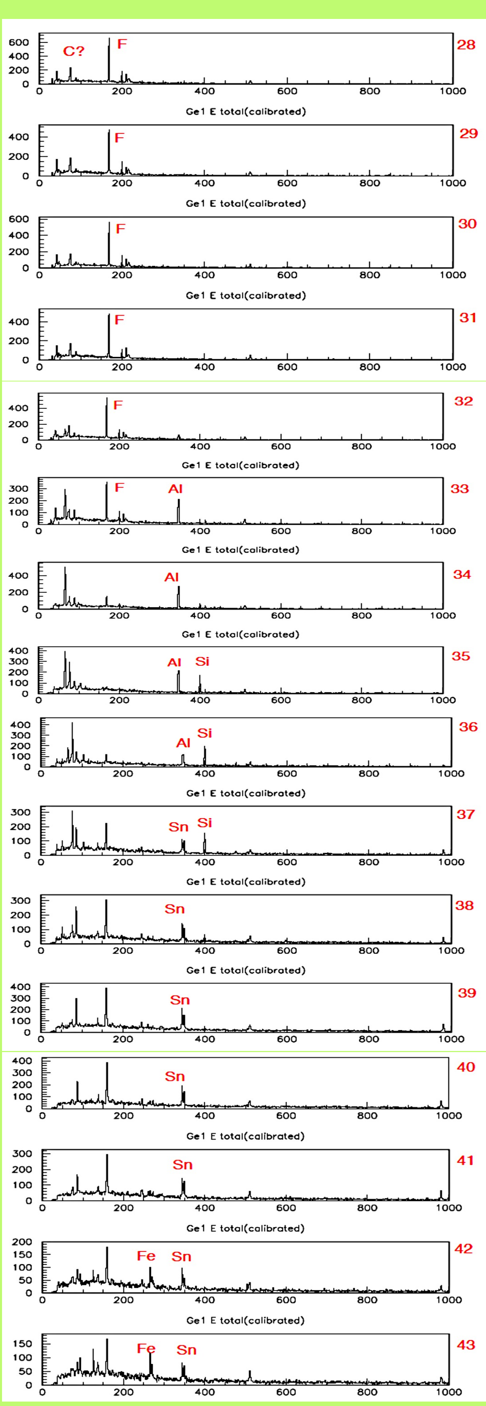
Muons flux Intensity



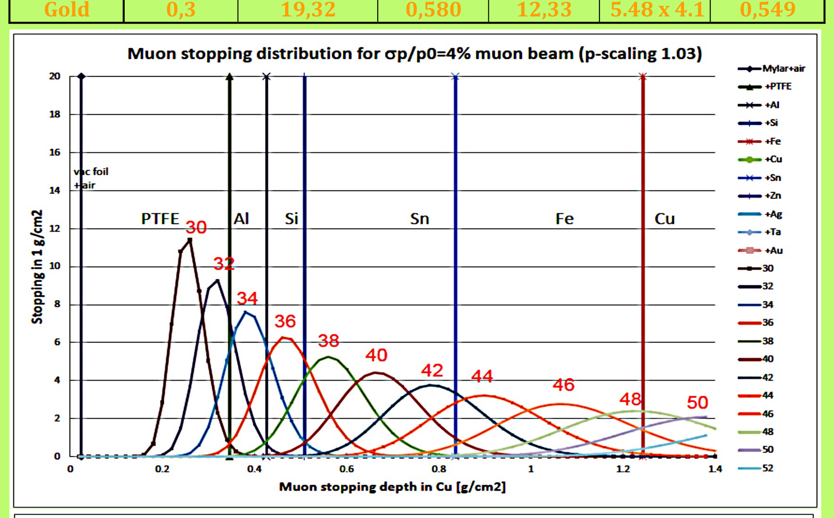
Muon Momentum Scan

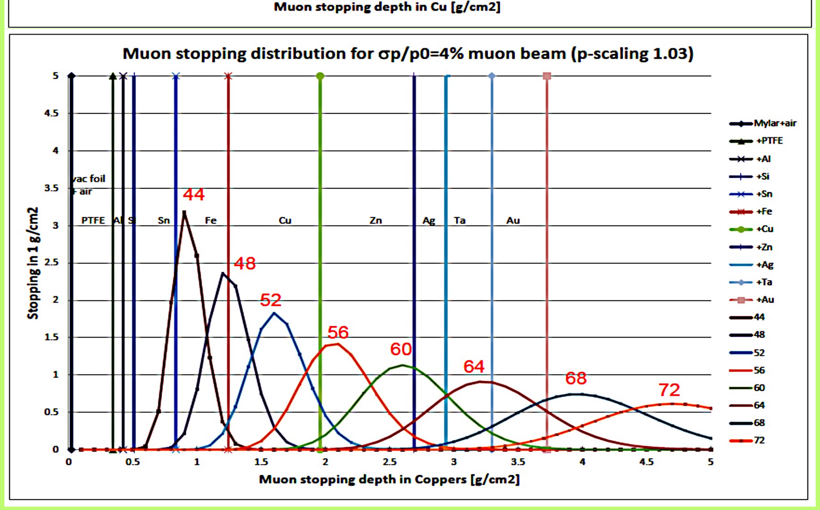
Detailed scanning (from 28 to 72 MeV/c with 1 MeV/c step) of the beam moment with a multi-layer sample consisting of PTFE, Al, Si, Sn, Fe, Cu, Zn, Ag, Ta, Au, layers of variable thickness (250 μm to 1.3 mm) whose results were compared with a simple model for the muon stopping distribution and which highlighted the need to correct the actual moment by factor 1.03. A more detailed quantitative analysis and comparison with the simulations could provide a better understanding of the correct value of the muon momentum and its distribution; such information could also be used profitably by other experiments.

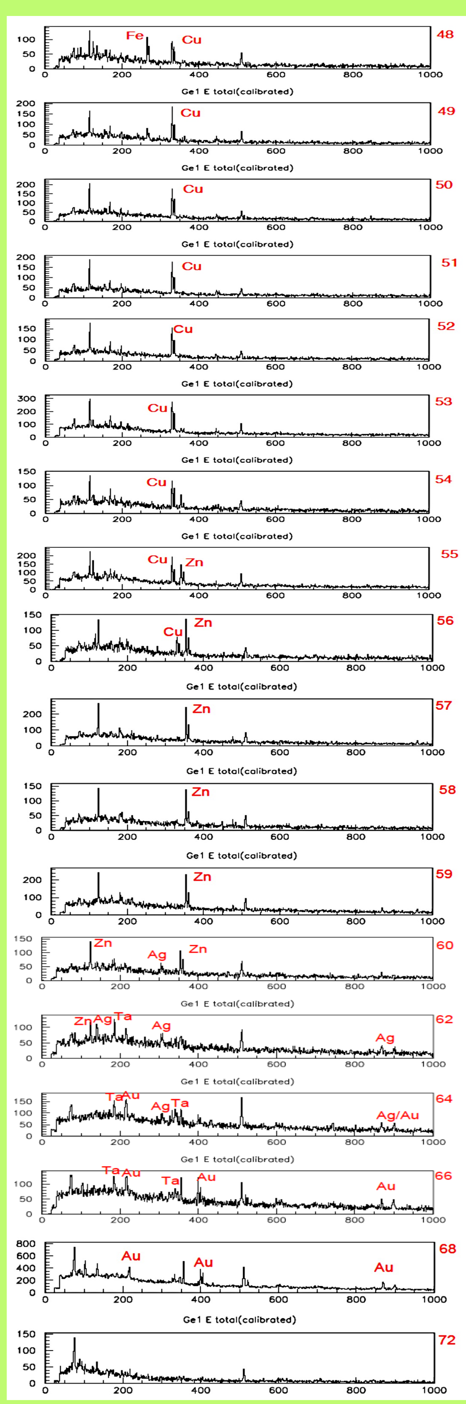




Material	Thickness (mm)	density (g/cm3)	thickness expected (g/cm2)	weight measured (g)	measured size (cm2)	Real Thickness (g/cm2)
PTFE	1,2	2,20	0,264	6,48	5.0 x 5.0	0,259
Aluminum	0,25	2,70	0,068	1,75	5.0 x 5.0	0,070
Silicon	0,3	2,33	0,070	1,48	4.8 x 4.8	0,070
Tin	0,5	7,37	0,368	9,44	5.0 x 5.0	0,378
Iron	0,5	7,87	0,394	9,88	5.0 x 5.0	0,395
Copper	0,8	8,94	0,715	17,82	5.0 x 5.0	0,716
Zinc	1,0	7,14	0,714	18,32	5.0 x 5.0	0,733
Silver	0,25	10,49	0,262	7,18	5.1 x 5.1	0,276
Tantalum	0,25	11,34	0,284	11.63	5.6 x 5.6	0,464
Gold	0,3	19,32	0,580	12,33	5.48 x 4.1	0,549







SiPM-Scintillating Fibers Hodoscope

Use of scintillating optic fiber sensors read with SiPM for positioning the sample by measuring the muons flux before and after the sample, see Figure 1, allowed us to optimize its position with respect to the center of the beam;

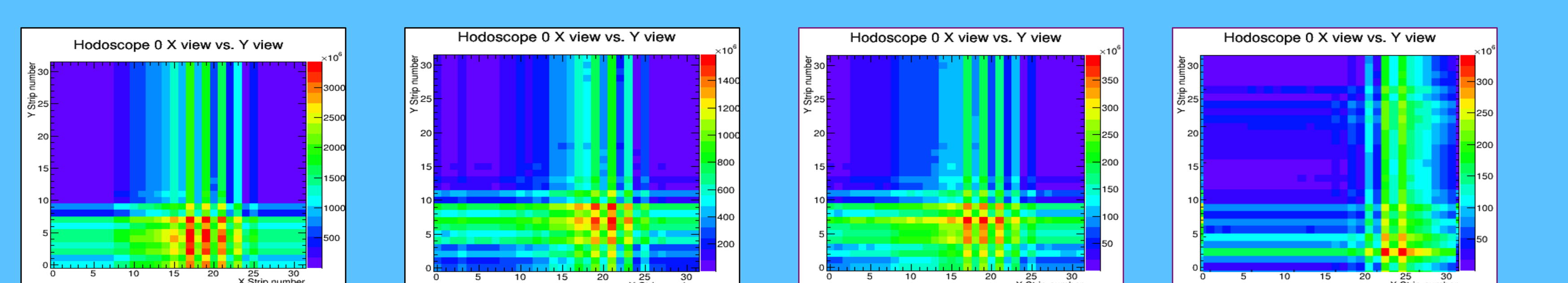


Fig. 1

Elemental Characterization of Nuragic Bronze Age Votive Ships

The irradiation of 4 fragments of Nuragic Bronze Age *votive ship*, from 4 different Sardinian archaeological sites, see fig. 3, whose analysis showed interesting differences in the ratio of Sn/Cu which could disable the possibility of dividing the set of samples into two clusters of common “*fabrication provenence*”, the one with ratios 0.10 ± 0.01 and the other one compatible with a ratio 0.03 ± 0.01.

Fig. 3: 4 fragments of nuragic votive ships

The idea behind the proposed experiment is to use muon negatives spectroscopy as a non-invasive and non-destructive probe for *quantitative "bulk" analysis* to be used in the archaeometric field for elemental characterization of artifacts and ancient objects [2]. This project aims to perform the in-depth study with muons beam of metallic artifacts from the late Bronze-age found in different area of the Italy (Sardinia, Tuscany, Lazio and Campania regions see figure 4. In particular the goal should be 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 analyzed similar objects from different contexts.

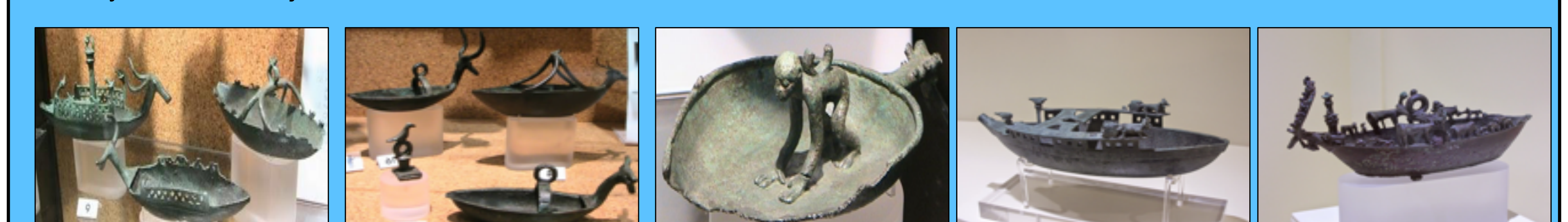


Fig.4: Ornamental/funerary ships from late bronze age (7-8 century BC)

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S6-Applications to Life Sciences and Other Societal Challenges - Abstract ID : 305 -