FUSION

FUsion **S**tud**I**es of pr**O**ton boron **N**eutronless reaction in laser-generated plasma

Responsabile Nazionale: G.A.P. Cirrone (LNS) and F. Consoli (ENEA)

Durata proposta: tre anni (2023-2025)

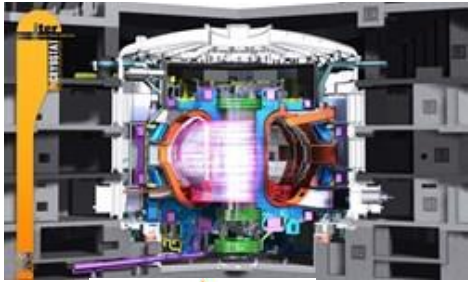
Area di ricerca: Acceleratori e multidisciplinare

INFN sections: Catania, Lecce, LNS, LNGS, Milano, Roma2, Torino, TIFPA, Bologna, Firenze

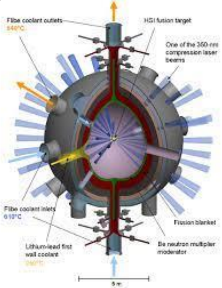
The background: FUSION energy

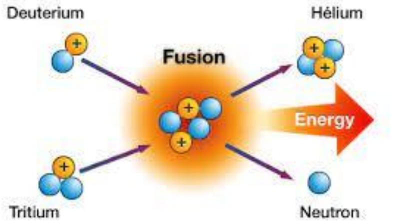
Fusion for energy production:

➢ Magnetical Confinement Fusion



➢ Inertial Confinement Fusion





- One of the approach is using high-power lasers

National Ignition Facility (NIF) of the Lawrence Livermore National Laboratory (LLNL) in the USA

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Burning plasma achieved in inertial fusion

A. B. Zylstra, O. A. Hurricane, ... G. B. Zimmerman + Show authors

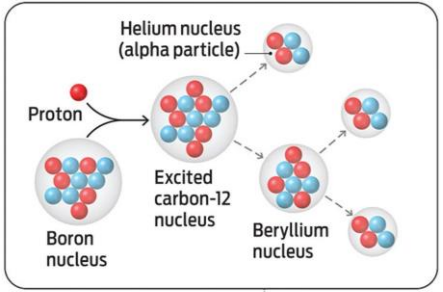
500 TW peak lasers

1.9 MJ total energy from 192 lasers

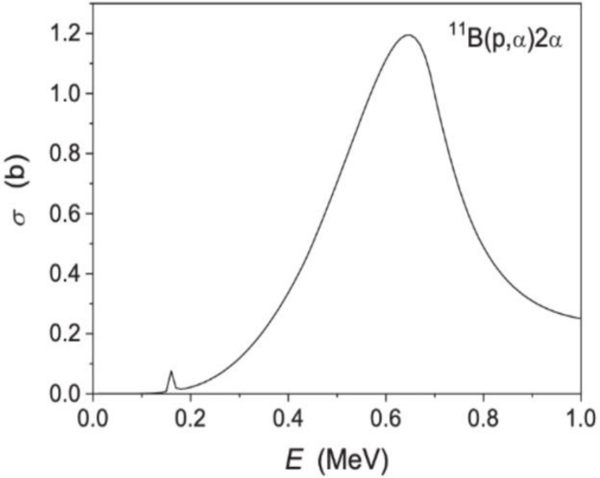
$D + T \rightarrow \alpha\ (3.5\ \text{MeV}) + n\ (14\ \text{MeV})$

1.3 MJ returned (70%)

The background: Interest in the p-11B fusion reaction



$$11B + p \rightarrow 3\alpha + 8.7\ MeV$$



- Two resonance at about 150 keV and 600 keV in the system center of mass
- It is not favourite in thermal equilibrium conditions
- It is considered as a potential candidate in <u>inertial fusion scheme</u>
- Neutronless fusion reactions
- Reagents more abundant in nature with respect to other fusion reactions of interest, and easier to handle (with respect to tritium, for example)
- Interest for astrophysical processes
- Interest for the realisation of intense α sources for applications

ALL THIS HAS BEEN STUDIED IN A CONVENTIONAL FRAMEWORK: AN ACCELERATOR BEAM ON A SOLID TARGET!

The background: Laser-induced p-11B fusion reaction

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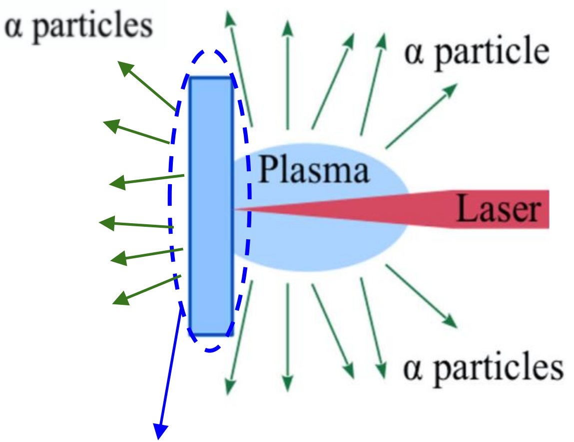
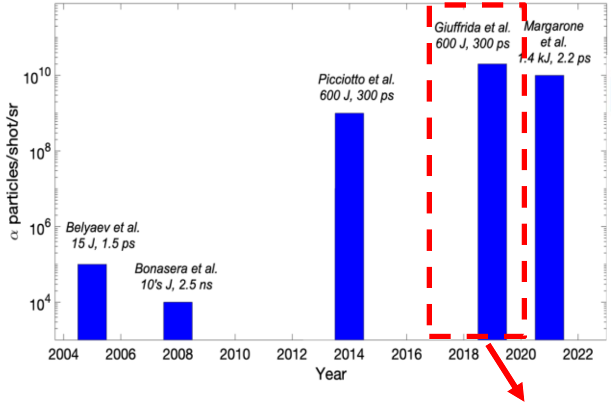
In-target scheme



- Boron (natural or 11B) enriched target on silicon substrate
- NB targets



Experiments	Facility	Target	Diagnostics for alpha particles and protons
Belyaev et al. [6]	10 TW laser facility "Neodymium" 1 (Russia)	$^{11}B + (CH_2)_n$ 300-500 µm containing 50% weight of ^{11}B atoms	CR-39
Bonasera et al. [8]	ABC Frascati (Italy)	Boron doped plastic target	CR-39 TOF detectors
Picciotto et al. [10]	PALS (Czech Republic)	Boron-hydrogen-silicon targets through ^{11}B implantation 500 µm (100 nm Boron layer)	Thomson Parabola, TOF detectors, nuclear-track detectors PM-355
Giuffrida et al. [11]	PALS (Czech Republic)	Natural Boron Nitride (BN) 500 µm	Thomson Parabola, TOF detectors, CR-39
Margarone et al. [7]	LFEX at Institute of Laser Engineering of the Osaka University (Japan)	Natural Boron Nitride (BN) 200 µm	Thomson Parabola, CR-39

PHYSICAL REVIEW E **101**, 013204 (2020)

High-current stream of energetic α particles from laser-driven proton-boron fusion

Lorenzo Giuffrida,[1,*] Fabio Belloni,[2] Daniele Margarone,[1] Giada Petringa,[3] Giuliana Milluzzo,[3,†] Valentina Scuderi,[1,3] Andriy Velyhan,[1] Marcin Rosinski,[4] Antonino Picciotto,[5] Milan Kucharik,[6] Jan Dostal,[7,8] Roman Dudzak,[7,8] Josef Krasa,[8] Valeria Istokskaia,[1,6] Roberto Catalano,[3] Salvatore Tudisco,[3] Claudio Verona,[9] Karel Jungwirth,[8] Pierluigi Bellutti,[5] Georg Korn,[1] and G. A. P. Cirrone[1,3]

Experimental progress in $p^{11}B$ fusion, measured in terms of absolute α-particle flux (particles/sr) in the "in-target" configuration. All experiments are characterized by using lasers with relatively long pulse duration (ps to ns order) and working in a single-shot modality (one shot every 30 minutes or more).

The proposal

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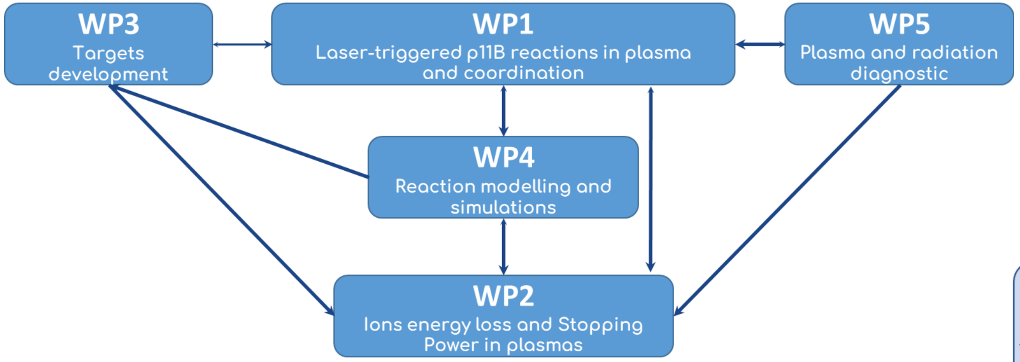
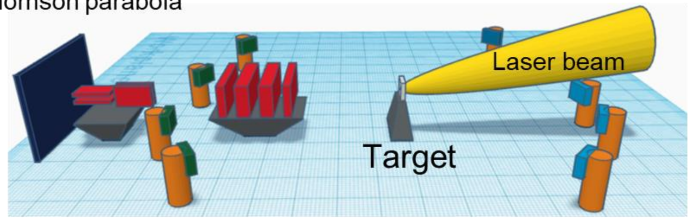
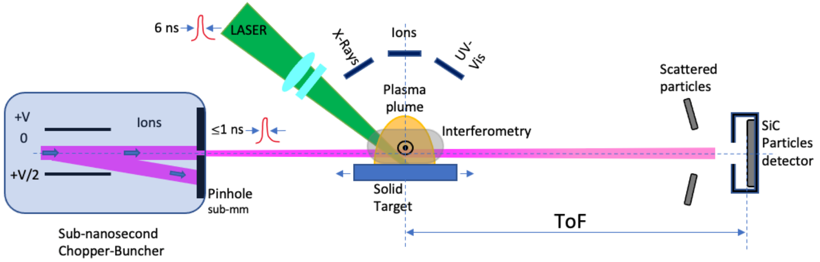
PERT Diagram



Ion detectors in TOF configuration (CR39, diamonds, ICs)

Thomson parabola





Experiments in three laser facilities (using different lasers system: picosecond pulse duration down to never-investigated femtosecond durations and high-repetition rates) will be organized by WP1 using innovative borated targets (WP3) that will be designed, characterized and optimized on the basis of hydrodynamic and Particle in Cell laser-target interaction simulations (WP4). Diagnostic of both plasma parameters (i.e. temperature and density) and the reaction products, optimized to distinguish the alpha particle from the proton background will be developed in WP5. In parallel, the reaction will be also studied using conventional beams interacting with a Boron plasma with the aim of studying and quantifying the stopping power of proton and alpha particles in such a plasma environment (WP2)

The proposal

	WP1 activity			WP2 activity
Laser system characteristics	N°1 High energy, long pulse, low repetition rate	N°2 Medium energy, long pulse, high repetition rate	N°3 Medium energy, short pulse, high repetition rate	N°4 Low energy, long pulse, high repetition rate
Energy per pulse [J]	400 - 700	100	10-30	2
Pulse duration [ps]	300	5000 - 10000	0.03	6000
Intensity at the target [W cm-2]	1-3E16	1E14-1E16	1E19-1E21	1E12-1E13
Repetition rate [Hz]	1 shot per 30 min (8-12 shots per day)	1-10	1-3	10
Maximum proton energy [MeV]	1-3	0.1-0.3	10-30	0.5-3
Target	Thick BN; Si:H B doped; Multifiber foam	Multifiber foam. Bundles of randomly distributed electrospun fibers.	Thin single and multi layer B-functionalized polymers	Thick BN, B(oxide) tablets, foam, Al and Ni plates
Target thickness	Thick BN: bulk 2-3mm;- SIHB: 500 microns - foam	10-100 microns	Frazione micron - qualche micron	Thick-plates 1-3 mm (bulk)
Simulation type/code	MULTI hydrocode and Geant4	MULTI hydrocode and Geant4	EPOCH, SMILEI and Geant4	MULTI hydrocode and Geant4
INFN group	FBK; Roma2; INFN-MI-INFN Lecce	Roma2; INFN Lecce	INFN LNS; INFN CT; INFN-MI, Roma2	FBK; Roma2; INFN-BO; LNGS

Table 2: laser systems that will be used for the project experimental campaign coupled with the targets (orange lines) that will be used for each laser and simulations (green line). The lasers reported in the first three columns will be used in three different campaigns to study and optimize the p11B reaction in plasma (WP1). The laser reported in the fourth column will be used to generate a borated plasma to study the stopping power of protons and alphas in plasma (WP2). Protons and alphas, in the energy range of 0.5-3 MeV for the WP2 study will be available at the Singletron electrostatic accelerator installed at the Physics department of the Catania University.

The proposal

Detector type	Detector/diagnostic type	Description	Advantages	Challenges	Section
Detector for alpha products and reagents of p+11B reaction	Extremely-high sensitivity spectrometer device for univocal determination of alpha particles and for characterization of reagents (p and B) in the specific energy ranges of p-11B fusion reaction.	Complex device integrating 3 techniques: Thomson Spectrometry + advanced adaptive filtering + track discrimination in CR39. Compact stucture with enhanced shielding to X and RF-microwaves; optimized for remarkable proximity to target (30 cm); enhanced resolution in the ion energy ranges of p-11B fusion reaction. Further implementation of scintillating fiber array detector for real-time readout	Efficient discrimination of alpha particles; detection of low particle fluxes with good resolution; high repetition rate in: 1) accumulation mode with CR39 detectors: solution for low yield alpha discrimination in low-medium energy high-rep-rate lasers; 2) real-time operation with scintillating fiber array detector	detection of high energy (>15 MeV) ions	**Roma2**-MI
Thomson Spectrometer	High resolution spectrometer to be placed outside to characterise mainly the proton spectra at the maximum energy for high energy	detector located outside the interaction chamber; reading system based MCP + phospor reading	Proton, ions and contaminants distinguishment also at high repetion rate		LNS
Ion Collector	Ion collector for charge measurements	System able to measure the total charge produced at high repetition rate condition	Charged particle detection at high intensity and high repetition rate	proton and alpha particle distinguishment	LNS & INFN-MI
Pixellated solid-state detectors	Diamond	Matrix of 2x2 diamond detectors nominally identical in terms of size and thickness, overall area of 1 cm x 1 cm, featuring different calibrated foil filters of different thicknesses	Real-time readout systems to 1) distiguish alpha particles from the protons, 2) to measure ions energy spectra and to 3) row estimate the plasma temperature in high repetition rate experiments	EMP suppression and high repetion rate acquisition	**Roma2**
Neutron detection	EJ-309 liquid scintillators	100 mm diameter X 51 mm high + fast Hamamatsu R7725 PMT read out	Neutron detection in ToF configuration + alpha/gamma discrimination with Pulse Shape tecnique	Calibration and high repetion rate acquisition	LNS with ELI-beamlines
Interpherometry	Time-resolved laser Nomarski interpherometry for plasma density measurements	Part of the same laser generating the plasma will be time-reduced by pockels cells and used to illuminate the plasma tangentially at some specific time instants. A pattern of parallel fringes will be set by a Wollaston prism.	Plasma density spatial profile in specific time instants will be retrieved by fringe deflection. Time instant easily tuned by changing path length	no description in regions where plasma density larger than critical density for the used wavelength; diffraction can affect spatial resolution	LNS and **Roma2**
X-ray spectrometry	X-ray spectrometer	X-ray Bragg's diffraction spectroscopy by two planar crystals: ADP e KAP. Ranges: 600-740 eV and 1500-1850 eV. Detector: linear CCD; Be-sheet to separate light from soft X-rays. Customisation of a device developed in the PLANETA experiment (CSN5).	Double X-ray crystal spectra, for description of the X-ray plasma emission and thus estimation of plasma temperature	Operation of CCD in high EMP levels, close to the interaction region; extension of energy range, faced by tests with further crystals to cover around 200 eV and 1 keV	BO & LNGS

The objectives

FUSION goals are:

1. The maximisation of the $p^{11}B$ reaction rate in plasma (WP1). This will be done by studying the interaction of laser systems of different characteristics (Table 2) with targets of different materials and configurations that will be developed (WP3) and optimized (WP4) with both Particle in Cell (PIC) and hydrodynamic simulations.
2. The development of innovative diagnostic (WP5) able to estimate the $p^{11}B$ reaction rate by looking at alphas products or protons, and investigating reaction channels where neutrons are produced. The diagnostic shall also operate in real-time and able to work at laser-shot repetition-rate of at least 1 Hz
3. The understanding of the physics laying at the basis of the observed $p^{11}B$ reaction rate. This will be done by studying the interaction of protons and alphas by conventional accelerators in a Borated expanding plasma (WP2) and modeling them with PIC and Monte Carlo simulations (WP4)

Methodology

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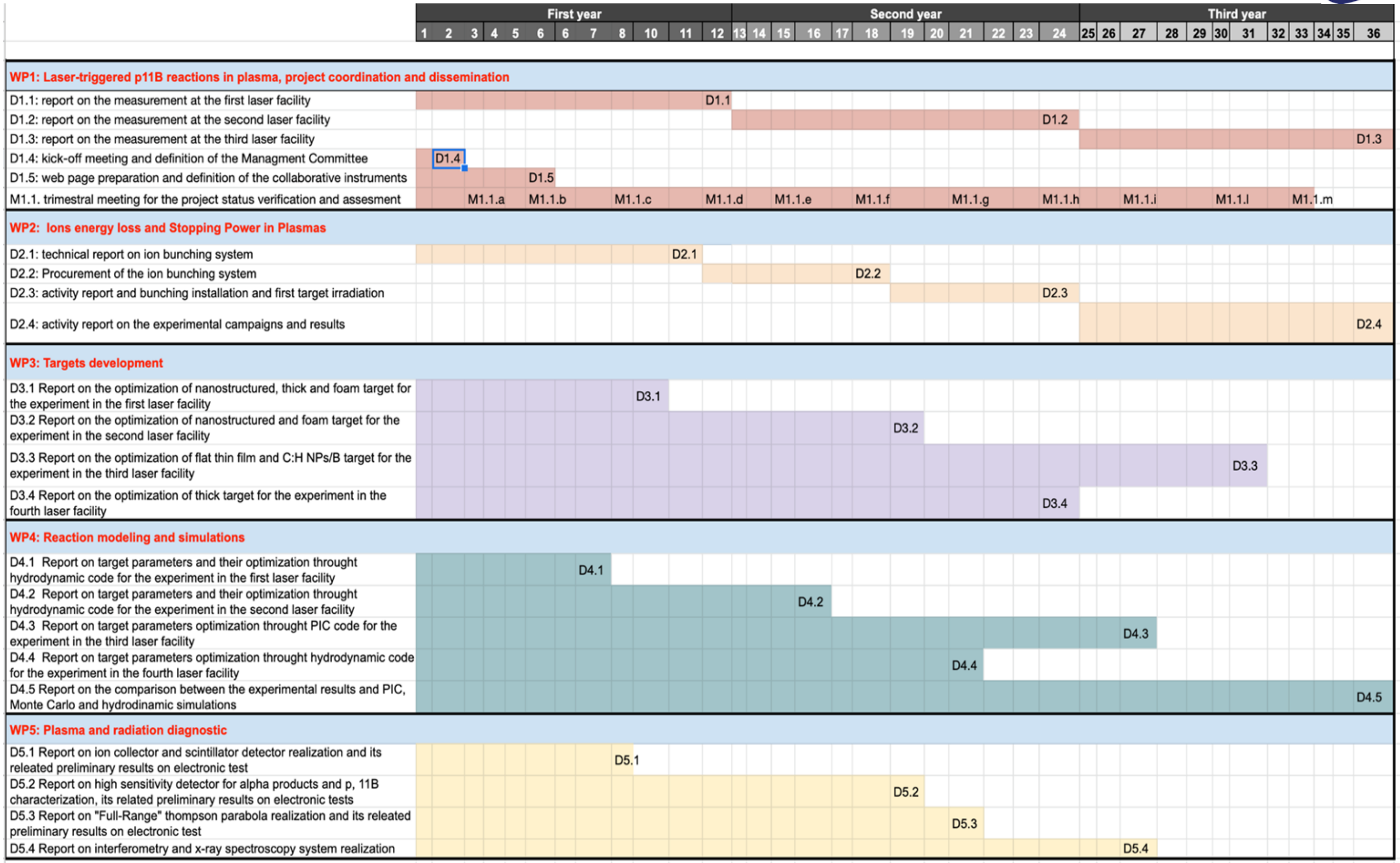

GANTT of the FUSION project

INFN Sections

INFN Sezione di Roma Tor Vergata

INFN sections, with the corresponding local responsibles, their belonging institution and the activity WP

INFN Unit	Local Responsible	Institution	WPs activity
Bologna	Dr Fabrizio Odorici	INFN of Bologna (I)	WP2, WP5
Catania	Prof Antonio Trifiro'	University of Messina (I)	WP2, WP3, WP5
Firenze	Prof Gabriele Pasquali	University of Florence (I)	WP2, WP5
Lecce	Prof Rosaria Rinaldi	University of Salento (I)	WP3
LNGS	Prof Libero Palladino	University of l'Aquila (I)	WP2, WP5
LNS	Dr Giacomo Cuttone	INFN-LNS, Catania (I)	WP1, WP2, WP3, WP4, WP5
Milano	Dr Davide Bortot	Milan Polytechnic, (I)	WP3, WP4, WP5
Roma 2	Prof Claudio Verona	University of 'Tor Vergata', Rome (I)	WP1, WP2, WP3, WP4, WP5
TIFPA	Dr Antonino Picciotto	Fondazione Bruno Kessler, Trento (I)	WP1, WP3
Torino	Dr Raffaella Testoni	Turin Polytechnic (I)	WP4

FUSION participants:

- 10 Sections INFN
- > 47 participants
- ~ 15 FTE

Anagrafica

Name	Institution	FTE
Claudio Verona	UniTV	0.3
Gianluca Verona Rinati	UniTV	0.3
Marco Marinelli	UniTV	0.3
Silvia Palomba	UniTV	0.4
Fabrizio Consoli	ENEA	0.5
Mattia Cipriani	ENEA	0.4
Massimiliano Scisciò	ENEA	0.3
Massimo Alonzo	ENEA	0.3
TOT	**FTE**	**2.8**

INFN - Roma2

UniTV has extensive experience in fabrication and characterization of diamond-based devices for different applications and in laser-generated plasma experiment. In this project, it will contribute to the development of novel diamond diagnostics for p-11B induced by laser (WP5) and to support the experimental campaigns (WP1)

ENEA (FSN-PLAS-PAX) group will contribute to all the WPs and co-coordinate the Units. It has wide expertise in: nuclear fusion (inertial confinement & magnetic confinement), laser-matter interactions, laser-triggered p-^{11}B reactions and related diagnostics.

Budget

FUSION costs are break down into the following categories: Consumables, Instrumentation, Travels etc.. The budget for 2023 is reported in Table for INFN-Roma2.

Cost Category	Item	I anno
Consumabile	#20 Diamond substrates (213 €)	€ 4,500.00
	Mechanical parts (Al plates to be modelled by CNC) and vacuum components (2 x KF50 flange with 4 BNC coaxial feedthrough, grounded shielded) for detector housing to EMP shielding	€ 3,000.00
	Target foam	€ 4,000.00
	MHV vacuum feedthrough (x4)	€ 1,600.00
Attrezzature	Fronte-end electronics (picoscope 1 Ghz)	€ 18,000.00
	2 Wide Band Preamplifier	€ 3,000.00
	4 Bias-Tee	€ 2,500.00
	HV power supply (x2) +-10 kV	€ 3,500.00
Impianti	High Sensitivity alpha-particle detector: Mechanical components for Detector of alpha products and p-11B reagents (incl. parts realization, adjustment and assembly)	€ 12,100.00
Viaggi	Detector characterizations under protons and alpha at CEDAD (University of Salento)	€ 1,500.00
	Meeting	€ 1,500.00
	TOTAL	€ 55,200.00