Report on CSN5 Call projects

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Introduction.

The Calls for Proposals were introduced by CSN5 at the end of 2013 (first projects financed in 2014) with the following objectives:

1. Foster both the aggregation of the scientific community on ambitious projects and the excellence of research.
2. Increase the scientific impact of the research financed by CSN5.
3. Provide CSN5 with an effective tool of scientific policy (address and program resources on strategic items).

This document is prepared in response to the CVI recommendation to CSN5 included in the CVI report of 2017, which stated: "CSN5 should carefully monitor and evaluate the effects and effectiveness of the *Call for Proposals* method". This report is therefore supposed to be updated every year, as the various Call projects conclude their activity in CSN5. Hence, this first version of the report includes the following projects: MAGIX, CHIPIX65, CALOCUBE, AXIOMA and COSINUS.

Structure of the document.

The report summarizes the most relevant information concerning each project, such as scientific line (Detectors, Electronics, Accelerators, Interdisciplinary Applications), period of activity, funds received, scientific production, and so on. The last point (7. Outcome) refers to items such as long term results, possible external funding, increased role of the INFN community in international projects/collaborations, possible transition from the R&D to a full-scale experiment in CSN1/2/3, etc.

MAGIX

Principal Investigator: Giovanni Volpini (MI), Massimo Sorbi (MI)

Participant INFN groups: Milano (LASA), Genova, Napoli (gruppo collegato di Salerno)

1. Title

MAGIX: Magneti Innovativi per futuri acceleratori e detector

2. Scientific line (Detectors, Electronics, Accelerator, Multidisciplinary)

Accelerators and related technologies

3. Period of activity

2014-2018 (4 + 1 yr)

4. Manpower (FTE) and total budget financed by CSN5

- 2014: 2.2 FTE (7 people) 159 k€
- 2015: 3.4 FTE (9 people) 310 k€
- 2016: 3.7 FTE (10 people) 244 k€
- 2017: 3 FTE (9 people) 564.5 k€
- 2018 0.8 FTE (4 people) 29.5 k€
- Total budget: 1307 keur; Average manpower: 3 FTE/y (8 people/y)

In 2017 MAGIX received 374 k€ from GE (74 k€ as extra budget, 300 k€ as a cash advance for the procurement of the equipment for the construction of the high order corrector series.
CERN co-financed the project with 527 k€.

5. Brief summary of the experiment (scientific goals and results)

The future of high-energy physics (HEP) research at hadron accelerators will mark an important step with the High Luminosity LHC (HL-LHC), which will allow to reach an integrated luminosity of 5 10^{23} since 2023,

aiming to gather a total integrated luminosity of 3,000 fb^{-1} by 2035. On a longer timescale, the community is envisaging new hadron machines exploiting dipole magnets with fields up to 20 tesla, which would enable the achievement of the center of mass energy of 100 TeV in a hypothetical FCC (Future Circular Collider) 80 km long. A μ+ μ- collider would require solenoids that reach magnetic fields up to 30-50 T, only feasible by means of high-temperature superconductors. Both these achievements are far beyond the existing technology and represent formidable technological challenges.

MAGIX focuses on the development of prototype magnets characterized by the use of forefront technologies and the search for innovative design solutions, for application to future accelerators, and notably:

• The LHC High Luminosity upgrade;

• Hadron machines requiring bending dipoles with fields in the range of 20 tesla, which would allow the achievement of the center of mass energy of 33 TeV in a hypothetical LHC upgrade in the present tunnel, and require the use of high temperature superconductors;

• Future μ + μ- colliders would require solenoids that reach magnetic fields up to 30 T / 50 T, also by means of high temperature superconductors;

• Fast ramping superconducting magnet technology.

The MAGIX project includes a large number of technological activities. It is organized in four WPs, related to the previous mentioned fields:

WP1 CORRAL: Design and construction of Corrector Magnet Prototypes for High Luminosity LHC;

WP2 PADS: Design of Separation Dipole (D2) for High Luminosity LHC;

WP3 SCOW-2G: High-temperature superconductivity (HTSC) winding development for application to particle accelerators;

WP4 SAFFO: Qualification of low-loss superconducting wires for fast-cycled magnets.

Main result:

- The Higher Order (HO) corrector magnets prototypes for HL-LHC have been developed. They include five different designs, from skew quadrupole to dodecapole. They are based on superferric design; the mechanics allows a modular and easy construction.
- It has been designed, realized and tested an innovative concept of magnet, called "Round Coil Superferric Magnet" (RCSM), a very unconventional concept of magnet that allows to create the desired multipole field through a three dimensional shaping of the iron, which are excited by

simple round coils. The RCSM realized at LASA is particularly innovative also for the use of a coil in MgB_2 (Magnesium di-Boride based superconductor), a prima for the use of this conductor in accelerator magnets.

- The design of the separation dipole (D2) for HL-LHC.
- The development of HTSC coil for application to detectors and accelerators has delivered windings able to produce magnetic field up to 1 kG.

6. Scientific productivity (papers, conference presentations, theses (BS, MS, PhD))

WoS papers:

- IEEE T APPL SUPERCON, **24-3**, 6000404 (2014) 10.1109/TASC.2013.2281465
- SUPERCOND SCI TECH, **27-10**, 104005 (2014) 10.1088/0953-2048/27/10/104005
- IEEE T APPL SUPERCON, **24-3**, 4004204 (2014) 10.1109/TASC.2013.2287635
- IEEE T APPL SUPERCON, **24-3**, 4000205 (2014) 10.1109/TASC.2013.2283814
- IEEE T APPL SUPERCON, **24-3**, 4002205 (2014) 10.1109/TASC.2013.2280733
- IEEE T APPL SUPERCON, **25-3**, 4002605 (2015) 10.1109/TASC.2014.2378377
- IEEE T APPL SUPERCON, **25-1**, 8200107 (2015) 10.1109/TASC.2014.2345339
- IEEE T APPL SUPERCON, **25-2**, 4003605 (2015) 10.1109/TASC.2015.2396931
- IEEE T APPL SUPERCON, **26-4**, 4001504 (2016) 10.1109/TASC.2016.2523060
- COMPOS PART B-ENG, **90**, (2016) 10.1016/j.compositesb.2015.12.023
- IEEE T APPL SUPERCON, **26-4**, 4004804 (2016) 10.1109/TASC.2016.2543468
- IEEE T APPL SUPERCON, **26-4**, 4103505 (2016) 10.1109/TASC.2016.2539150
- IEEE T APPL SUPERCON, **27-4**, 5900104 (2017) 10.1109/TASC.2016.2637360
- CRYOGENICS, **81**, (2017) 10.1016/j.cryogenics.2016.11.001
- IEEE T APPL SUPERCON, **27-4**, 4003205 (2017) 10.1109/TASC.2017.2650957
- IEEE T APPL SUPERCON, **28-3**, 4100205 (2018) 10.1109/TASC.2017.2772887
- IEEE T APPL SUPERCON, **28-3**, 4003305 (2018) 10.1109/TASC.2017.2786267
- IEEE T APPL SUPERCON, **28-4**, 4008705 (2018) 10.1109/TASC.2018.2809561
- IEEE T APPL SUPERCON, **30-4**, 4001905 (2020) 10.1109/TASC.2020.2972219
- IEEE T APPL SUPERCON, **30-4**, 4001305 (2020) 10.1109/TASC.2020.2972212
- IEEE T APPL SUPERCON, **30-4**, 4003805 (2020) 10.1109/TASC.2020.2979159

Talks/posters:

- 2014: 1 poster presentation
- 2015: 1 talk in parallel session; 2 poster presentations
- 2017: 1 talk in parallel session; 1 poster presentation
- 2018: 1 talk in parallel session; 2 poster presentations

Theses:

- 2014: 1 Master Thesis (*Fili Superconduttori a Basse Perdite per Magneti Rapidamente Pulsati*)
- 2017: 1 Master Thesis (*Electromagnetic study and design of superconducting corrector magnet with MgB2 coils*)
- 2018: 1 Master Thesis (*Construction and characterization of a MgB2 round coil for superconducting magnets*)

7. Outcome

The activity carried out in MAGIX has a direct impact on the HEP community. There was a close integration with two EU FP7 programs: **HiLumi LHC** in the case of WP1 and WP2-CORRAL-PADS, **EuCARD2** for the scopes of WP3-SCOW 2G and the related activities for the development of HTSC based magnets, and finally **CRISP** for the activity of characterisation of low loss superconducting wire carried out in WP4-Saffo.

An Italian industry (SAES-RIAL vacuum) participated to the construction of the last two prototypes of High Order correctors, and so it was qualified in superconducting technology.

In 2019, based on the prototyping of these magnets and on the success of the results, the serie production of 54 magnets for High Order Corrector package to be installed in HL-LHC has been launched by INFN. The magnets have to be delivered at CERN by September 2021.

On the base of the design of the separation dipole (D2), subsequently INFN launched the model construction, prototype construction and later will pass to the series construction.

These technological developments of MAGIX have also relevant potential applications in fields outside HEP, such as electric motors and superconducting magnetic energy storage system (SMES) regarding developments in YBCO, and Gantry magnets for hadrotherapy that would benefit from low loss superconducting wires (WP4-Saffo). The use of MgB2, in addition to the technical advantages mentioned before, promotes further a product that is finding applications in increasingly wider areas.

CHIPIX65

Principal Investigator: Natale Demaria (TO)

Participant INFN groups: Bari, Milano, Padova, Perugia, Pisa, Pavia, Torino

1. Title

CHIPIX65 : an innovative CHIP for a hybrid PIXel detector, using CMOS 65nm technology, for experiments with extreme particle rates and radiation at future HEP colliders

2. Scientific line (Detectors, Electronics, Accelerator, Multidisciplinary)

Detectors and electronics

3. Period of activity

2014-2017 (3 + 1 yr)

4. Manpower (FTE) and total budget financed by CSN5

- 2014: 9.85 FTE (35 people) 193 keur
- 2015: 11.05 FTE (40 people) 228 keur
- 2016: 12.45 FTE (41 people) 272 keur
- 2017: 12.25 FTE (41 people) 55 keur
- Total budget: 748 keur; Average manpower: 11.4 FTE/y (39.3 people/y)

5. Brief summary of the experiment (scientific goals and results)

Pixel detectors at HL-LHC experiments will be exposed to an unprecedented level of radiation and particle flux.

The CHIPIX65 project had the purpose of exploiting the CMOS 65nm technology on the very front-end electronics for use at future colliders, building core elements in digital and analog electronics and understanding and solve chip integration issues that are particularly important when a sophisticated chip digital circuitry, with an unprecedented amount of transistors, has to be integrated with the very front end analog electronics.

The radiation hardness of the technology was also characterized, in particular studying how the performance of electronics are modified.

The primary goal of CHIPIX65 was to put the basis for the development of an innovative CHIP for a PIXel detector, using a CMOS 65nm technology for the first time in HEP community, for experiments with extreme particle rates and radiation at future High Energy Physics colliders. This effort was shared at international level with the RD53 Collaboration.

CHIPIX65 was organized in five Working Package:

- WP1: Radiation Hardness
- WP2: Digital Electronics
- WP3: Analog Electronics
- WP4: Chip Integration
- WP5: Project Management

Main Results:

In 2016 the CHIPIX collaboration integrated most of the developments in a demonstrator consisting of a pixel readout ASIC in 65nm CMOS technology fully compliant with HL-LHC conditions and consisting in 64x64 pixel, fully digital IO, low power, low-noise, operating at threshold below 600e-. The pixel readout chip works 100% at specification and it has proven to resist at least to 600 Mrad TID dose.

In the year 2017 the CHIPIX collaboration has made the bump bonding the CHIPIX65 demonstrator with silicon sensors (3D-silicon) and proven that the chip is correctly responding to external signal, with proper signal reconstruction, noise performance and low threshold. Always during 2017, CHIPIX has worked to the design of a large scale prototype of a pixel readout ASIC (RD53A) that have been completed in the frame of the RD53 Collaboration. CHIPIX has contributed with more than 40% of the designers, expressing the lead of the design team and providing several blocks and developments coming from the demonstrator: two out of three analog front-ends, the pixel region digital architectures, the analog bias network and several IP-blocks (DAC,ADC, BandGap). RD53A has an area of $2cm^2$ and 400x192 pixel. This chip has been produced in autumn 2017 and has shown to be fully working, and to be radiation hard up to at least 500 Mrad. RD53A has been extensively characterized, tested in RD53 and used by ATLAS and CMS during 2018 and 2019, to exploit the R&D program and the prototyping phase for the HL_LHC upgrade.

6. Scientific productivity (papers, conference presentations, theses (BS, MS, PhD))

WoS papers:

- J INSTRUM, 9, P10005 (2014) 10.1088/1748-0221/9/10/P10005

- J INSTRUM, **10**, C02004 (2015) 10.1088/1748-0221/10/02/C02004
- IEEE T NUCL SCI, **62-6**, pp. 2899-2905, (2015) 10.1109/TNS.2015.2499255
- IEEE T NUCL SCI, **62-6**, pp. 2398-2403 (2015) 10.1109/TNS.2015.2498539
- IEEE T NUCL SCI, **63-3**, pp. 1762 - 1767 (2016) 10.1109/TNS.2016.2550581
- J INSTRUM, **11**, C12058 (2016) 10.1088/1748-0221/11/12/C12058
- J INSTRUM, **11**, C01069 (2016) 10.1088/1748-0221/11/01/C01069
- J INSTRUM, **11**, C03013 (2016) 10.1088/1748-0221/11/03/C03013
- J INSTRUM, 11, C12044 (2016) 10.1088/1748-0221/11/12/C12044
- J INSTRUM, **11**, C02049 (2016) 10.1088/1748-0221/11/02/C02049
- NUCL INSTRUM METH A, **824**, pp. 371-373 (2016) 10.1016/j.nima.2015.09.103
- J INSTRUM, **11**, C01027 (2016) 10.1088/1748-0221/11/01/C01027
- NUCL INSTRUM METH A, **831**, pp. 265-268 (2016) 10.1016/j.nima.2016.03.096
- CHINESE PHYS B, **25-9**, 096110 (2016) 10.1088/1674-1056/25/9/096110
- 2017 13th Conference on Ph.D. Research in Microelectronics and Electronics (PRIME) 10.1109/PRIME.2017.7974142
- J INSTRUM, **12-**, C02043 (2017) 10.1088/1748-0221/12/02/C02043
- J INSTRUM, **12-**, C03066 (2017) 10.1088/1748-0221/12/03/C03066
- J INSTRUM, **12-**, C02017 (2017) 10.1088/1748-0221/12/02/C02017
- IEEE T NUCL SCI, **64-12**, pp. 2922 - 2932 (2017) 10.1109/TNS.2017.2771506
- IEEE T NUCL SCI, **64-2**, pp. 789 - 799 (2017) 10.1109/TNS.2016.2646908
- IEEE T NUCL SCI, **65-1**, pp. 550 - 557 (2018) 10.1109/TNS.2017.2777741
- IEEE T NUCL SCI, **65-10**, pp. 2699 - 2706 (2018) 10.1109/TNS.2018.2871245
- NUCL INSTRUM METH A, **936**, pp. 319-320 (2019) 10.1016/j.nima.2018.07.065
- NUCL INSTRUM METH A, **936**, pp. 282-285 (2019) 10.1016/j.nima.2018.11.107

Talks:

- 2014: 2 talks in parallel sessions; 1 poster presentation
- 2015: 2 plenary talks; 10 talks in parallel sessions; 3 poster presentations
- 2016: 7 plenary talks; 3 talks in parallel sessions; 4 poster presentations

- 2017: 6 talks in parallel sessions; 3 poster presentations

Theses:

- 2015: 2 Master Theses (Design of CMOS logic gates tolerant of single-event effects for extreme radiation environments; Design of Digital Readout Electronics for Pixel Detectors in 65nm CMOS Technology); 1 PhD Thesis (Design of Electronic Systems Architecture for the Readout of Pixel Radiation Sensors)
- 2016: 2 Bachelor Theses (Caratterizzazione di circuiti integrati sotto effetti singoli; Scheda di test per caratterizzazione di prototipi sotto radiazioni)
- 2017: 3 Master Theses (Caratterizzazione di circuiti analogici del rivelatore a pixel del HL-HLC; Caratterizzazione di un canale di lettura progettato per il rivelatore a pixel di CMS del HL-LHC; Power consumption verification for a new generation pixel readout chip in High Energy Physics); 1 PhD Thesis (Front-end electronics in 65nm CMOS technology for the HL-LHC upgrades)
- 2018 : 1 PhD Thesis (Ultra high-density Hybrid Pixel Sensors for the detection of charged particles and X-rays)

7. Outcome

CHIPIX65 allowed INFN to have a key role within RD53 and has boosted INFN towards the use of CMOS 65nm and to work a real application for a Pixel Phase 2 readout ASIC. The contribution of CHIPIX65 (and hence of INFN) to the RD53A large-scale prototype can be summarized as follows:

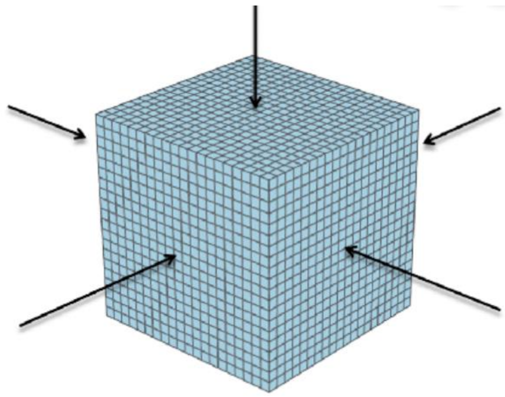
- 50% of all design blocks (almost all of them are IP).
- 10 members of the design team out of 16, F. Loddo (INFN Bari) team leader.

The results achieved in the CHIPIX65 R&D will evolve towards the design of the final CMS and ATLAS pixel chips. Other experiments to future colliders (like ILC) or development for future upgrades of existing experiments, will also profit from of the achievements on the CMOS 65nm technology.

The CHIPIX65 project involved a substantial fraction of INFN expertise on microelectronics, and it has served the purpose of pushing the use of CMOS 65nm in the INFN across a wide community spread across several INFN groups.

Radiation imaging pixel detector systems are vital instruments in a large number of other research and development domains (medical Imaging, synchrotron light, material science, space science, radiation monitoring, x-ray fluorescence spectroscopy and astronomy), often using commercially available pixel detector systems.

CALOCUBE



Principal Investigator: Oscar Adriani

Participant INFN groups: Firenze, Catania, Pavia, Pisa, Trieste

1. Title

CALOCUBE: Sviluppo di Calorimetria Omogenea ad alta Accettanza per Esperimenti di raggi Cosmici nello Spazio

2. Scientific line (Detectors, Electronics, Accelerator, Multidisciplinary)

Detectors and Electronics

3. Period of activity

2014-2017 (3 + 1 yr)

4. Manpower (FTE) and total budget financed by CSN5

- 2014: 7.4 FTE (25 people) 261.5 keur
- 2015: 9.4 FTE (29 people) 314.0 keur
- 2016: 7.8 FTE (23 people) 179.0 keur
- 2017: 11.6 FTE (24 people) 64.5 keur
- Total budget: 819 keur (travel + material); Average manpower: 9 FTE/y (25.3 people/y) (personnel)

5. Brief summary of the experiment (scientific goals and results)

The project was an R&D work for the construction of a calorimeter with an innovative design, with appealing characteristics for next-generation space experiments dedicated to the investigation of high-energy cosmic rays (CR). During the project, a detailed study of all the aspects related to the design of an optimal space based, large acceptance, homogeneous calorimeter was carried out. The design phase was followed by the construction and extensive tests of a reasonable size prototype, built up with space qualified techniques for the mechanical and thermal aspects.

Main results:

The CALOCUBE experiment showed that, in order to extend direct measurements of cosmic rays to higher energies, the next generation of space experiments must rely on a large scale calorimeter. For this purpose, the R&D proved the feasibility of a homogeneous, isotropic and highly segmented calorimeter made of cubic inorganic scintillator crystals. The basic idea is to use cubic crystals equipped with a dual photodiode readout, which can provide the necessary dynamic range of 10^7 when coupled to a front-end electronics with a dynamic range of 10^4-10^5. Based on this concept, we built several prototypes up to a maximum size of 5x5x18 CsI:Tl crystals of 3.6 cm side spaced by 0.3 cm gap, and tested them at CERN SPS facility, using different particle beams. From the analysis of this data, the Collaboration has fully characterized the detector in order to quantify its performances in terms of the following quantities:

1) Gain variation among different channels (crystal+PD+electronics) ~ 20%
2) Energy Linearity (for incident electrons from 50 to 280 GeV) ~ 1%
3) Energy resolution (for incident electrons from 50 to 280 GeV) < 1.5 %
4) Energy resolution (for incident protons from 100 to 350 GeV) ~ 35 %

A comparative study of different scintillating crystals (YAG, YAP, BaF2, LuAG, CsI(Na), BGO, LYSO) has also been done, in terms of single crystal response to ion beams. The energy resolution and the quenching effect have been measured.

All the performance estimated in such a way have been used to develop a realistic model of the instrument. Thanks to this model, it is possible to extend our performance study to the final space design. A first work has been done in this direction, with the purpose of optimizing the detector geometry. The results of this Monte Carlo study, devoted to understand the performances for the detection of high energy protons and nuclei, are:

1) Crystals with low value of nuclear interaction length, like LYSO, are the best candidates
2) Energy resolution is mostly constant for protons between 1 TeV and 1 PeV
3) Mechanical structure must be thin, but not necessarily made by a light material

Finally, we realized a mechanical prototype of the tray structure that has shown to be flexible enough to allow signal extraction to the front end boards while at the same time providing enough rigidity to support a fully loaded matrix of 28x28 Cs:I cubic crystals.

6. Scientific productivity (papers, conference presentations, thesis (BS, MS, PhD)))

WoS papers:

- NUCL INSTRUM METH A, 824, (2016) 10.1016/j.nima.2015.09.073
- NUCL INSTRUM METH A, 845, (2017) 10.1016/j.nima.2016.07.014
- J INSTRUM, 12, (2017) 10.1088/1748-0221/12/06/C06004
- ASTROPART PHYS, 96, (2017) 10.1016/j.astropartphys.2017.10.002
- J PHYS CONF SER, 587, (2015) 10.1088/1742-6596/587/1/012029
- EPJ WEB CONF, 136, (2017) 10.1051/epjconf/201713602011
- J PHYS CONF SER, 928, (2017) 10.1088/1742-6596/928/1/012013
- JINST 14 (2019) P11004 (2019) 10.1088/1748-0221/14/11/P11004

Talks:

- (plenary) CALOCUBE: an approach to high granularity and homogenous calorimetry for space based detectors, 16th International Conference on Calorimetry in High Energy Physics, Giessen, Germany 2014.
- (plenary) Calocube - A highly segmented calorimeter for a space based experiment, 13th Pisa Meeting on Advanced Detectors, La Biodola, Italia 2015.
- (invited) Cosmic rays: direct measurements, 34th International Cosmic Ray Conference, The Hauge, The Netherlands 2015.
- (invited) Future space challenges, IOFD2015, Torino, Italia 2015
- (invited) Acceptance and performance of a large area calorimeter for space applications, 3rd International HERD workshop, Xian, China 2016
- (invited) WHAT WE LEARNED FROM THE CALOCUBE PROJECT, 3rd International HERD workshop, Xian, China 2016
- (parallel) CaloCube: a new-concept calorimeter for the detection of high-energy cosmic rays in space, 14th Vienna Conference on Instrumentation, Vienna, Austria 2016
- (plenary) CaloCube: an innovative homogeneous calorimeter for the next-generation space experiments, 17th International Conference on Calorimetry in Particle Physics , Daegu, Korea 2016
- (plenary) CaloCube: a novel calorimeter for high-energy cosmic rays in space, 6th Roma International Conference on AstroParticle Physics, Roma, Italia 2016
- (poster) Response to relativistic ions of CaloCube: a new 3D crystal array calorimeter for space-borne experiments, 14th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD16), Siena, Italia 2016
- (invited) Future cosmic ray detectors (ground & space), SciNeGHe 2016, Pisa, Italia 2016
- (invited) Studies for a cubic calorimeter for space experiments: the CaloCube project & HERD, 4th International HERD workshop, Pechino, China 2016

- (plenary) CaloCube: a novel calorimeter for high-energy cosmic rays in space, INSTR17, Novosibirsk, Russia 2017
- (parallel) CaloCube: a high perfomances calorimeter for the detection of high-energy cosmic rays in space, IFAE 2017 - XVI Incontri di Fisica delle Alte Energie, Trieste, Italia 2017
- (invited) Development of high dynamic range front-end ASICs for calorimeters in astroparticle physics experiment, Front-End Electronics 2018, Jouvance, Canada 2017
- (parallel) CaloCube: a new homogenous calorimeter with high-granularity for precise measurements of for high-energy cosmic rays in space, EPS Conference on High Energy Physics, Venezia, Italia 2017
- (parallel) Exploring calorimetry new dimensions: a novel approach to maximize the performances of space experiments for high-energy cosmic rays, TAUP 2017 XV International Conference on Topics in Astroparticle and Underground Physics, Sudbury, Canada 2017
- (plenary) Calocube: a novel approach for a homogeneous calorimeter for high-energy cosmic rays detection in space, 18th Lomonosov Conference on Elementary Particle Physics , Moscow, Russia 2017
- (parallel) Calocube: a new homogeneous calorimeter for high-energy cosmic rays detection in space, 2017 Nuclear Science Symposium and Medical Imaging Conference, Atlanta, USA 2017

- (parallel) E. Berti, "Progettazione sviluppo e realizzazione del calorimetro dell'esperimento HERD", 106 congresso SIF, 14 settembre 2020

Theses:

- 2014: 1 Bachelor + 2 Master
- 2015: 1 PhD + 2 Master + 1 Bachelor
- 2016: 1 Master

- 2017: 2 Bachelor

7. Outcome

The results of the CaloCube experiment are of special relevance for other INFN experiments. The R&D activity carried out with Calocube was focused on the design of a large area homogeneous calorimeter for future space experiments devoted to the measurement of high-energy cosmic rays. In particular, this activity is extremely useful for the design and realization of the HERD experiment, planned to start its operations around 2026 on board the future China's Space Station. Exploiting the results of the Calocube collaboration, the HERD detector will be based on a homogeneous, isotropic and finely segmented calorimeter that is expected to lead to the first direct measurement of the knee structure in cosmic rays, to achieve significant result in high-energy gamma-ray astronomy and to search for the indirect evidence of dark matter. Since the beginning of the CaloCube R&D, almost all members were involved in the HERD idea and their expertise in this field was one of the relevant factor that in 2017 lead to an agreement between INFN and IHEP for their participation to the HERD experiment. After that agreement, a new research activity named “HERD_DMP” was opened in INFN CSN2.

AXIOMA

Principal Investigator: Giovanni CARUGNO (PD)

Participant INFN groups: PD, LNL, FE, CA, PI, NA, LNS

1. Title

AXIOMA (AXIOn MAterial)

2. Scientific line (Detectors, Electronics, Accelerator, Multidisciplinary)

Detectors (Thematic Call on Dark Matter)

3. Period of activity

2016 – 2018

4. Manpower (FTE) and total budget financed by CSN5

- 2016: 14.1 FTE (35 people) 331.5 keur
- 2017: 16 FTE (35 people) 289.0 keur
- 2018: 13.1 FTE (33 people) 114.5 keur
- Total budget: 735 keur (travel + material)

Personnel:

- 2 2-yr post-docs,
- 1 1-yr post-doc

5. Brief summary of the experiment (scientific goals and results)

The R&D AXIOMA proposal exploits the interactions of the cosmological axion with the spin of electrons and through far infrared photon detection in rare earth based crystals and rare gases solid crystals doped with alkaline atoms or through electron excitation.

In fact, due to the motion of the Solar System through the galactic halo, the Earth is effectively moving through the dark matter cloud surrounding the Galaxy and an observer on Earth will see such axions as a wind. The effect of the axion wind on a magnetized material can be described as an effective oscillating magnetic field with frequency determined by m_a, and strength related to

f_a. Thus, a detector for the axion wind could be a magnetized sample with Zeeman transition energy tuned to the axion mass by an external polarizing static B field (e.g. 10 T for 280 GHz, corresponding to almost a 1 meV axion mass). The interaction with the axion effective field will drive the M1 transition of the Zeeman state from ground to excited state of the sample, and so sensing such excited state with a laser probe tuned to a specific higher state transition from where a fluorescence photon can be detected. It is worth noticing that the magnetized sample must be cooled to ultra-cryogenic temperature to avoid thermal excitation of the magnetization due to the thermal bath. A similar approach will be followed with the detection of far infrared photons following the Infrared Quantum Counter idea developed by the American Nobel Prize Bloembergen where in this case crystal based on rare earth materials and rare gases doped solid crystal will be used and a much wider possibility to look to low energy excitation into the matter will be accessible so to widening the Dark matter search to a large class of possible constituents.

We have proposed a research activity aimed at the development of a novel type of detector based on an Active Sensing of the Target Material placed into ground state at low temperature where the possibility to detect single atom excitation within a fraction of the mole system would be detected with the aid of laser probe interrogation that will promote such state to a particular level where a photon output will be the signal.

Such type of techniques have been developed in the atomic physics community for the laser cooling of atomic system (Bose Einstein condensate) and for the laser cooling of solids.

Our efforts will concentrate to bridge these optics based techniques to fundamental physics study such as dark matter detection. This Active Target approach could also be used for looking to a much wider range of physical problems such as neutrino physics , neutron and particle detectors, enhancement of electron capture in particular atoms and many other physical subject.

Main Results:

1) A Nature Scientific Report has been published where a preliminary experiment with an Er:YSO doped crystal under a 0,3 Tesla fully immersed in superfluid helium irradiated with a CW tunable laser beam has been probed to detect Zeeman type transitions.
2) Within this type of experiment we got an impressive results related to the creation of Quantum Macroscopic Coherence where a sample of more than 10^{13} atoms are phase locked in the excited state resulting in Super-Fluorescence emission. This result could

open the possibility to address many low cross section phenomena that today are not possible to detect. The article has been submitted recently for publication.

3) Many high luminosity infrared scintillator in rare earth doped crystals and doped low band gap semiconductors has been discovered. One of them, the GaAs:Be doped semiconductor crystal resulted in one the highest Light Yield never reported at cryogenic temperature.
4) Spectroscopy study on rare gases solid, mainly neon and xenon , doped with alkaline atoms and rare earth metals resulted in new molecular structures never reported.
5) Growing of large xenon solid crystals as radiation detection medium crystals where free electron has been evaporated into the vacuum state so to easily detect single electrons and lowering the threshold of such type of detectors.
6) Some preliminary Laser based induced stimulated emission from interacting particle into laser crystals has been performed with optical source where a threshold of MeV could be possible to attain.

All the previously listed results have been published in peer review journals, the subjects have been presented at international conferences and workshops.

6. Scientific productivity (papers, conference presentations, thesis (BS, MS, PhD))

WoS papers:

- NUCL INSTRUM METH A, 855, (2017) **10.1016/j.nima.2017.01.063**
- J LUMIN, 190-, (2017) **10.1016/j.jlumin.2017.05.027**
- SCI REP-UK, 7-, 15168 (2017) **10.1038/s41598-017-15413-6**
- REV SCI INSTRUM, 88-11, 113303 (2017) **10.1063/1.5003296**
- PHYS REV LETT, 118-10, 107205 (2017) **10.1103/PhysRevLett.118.107205**
- J LUMIN, 203-, (2018) **10.1016/j.jlumin.2018.06.035**
- J OPTICS-UK, 20-9, 095502 (2018) **10.1088/2040-8986/aad826**
- SCI REP-UK, 8-, 5193 (2018) **10.1038/s41598-018-23416-0**
- PHYS REV A, 97-4, 042503 (2018) **10.1103/PhysRevA.97.042503**
- PHYS REV A, 98-1, (2018) **10.1103/PhysRevA.98.013849**
- PHYS REV A, 98-4, 042506 (2018) **10.1103/PhysRevA.98.042506**

Talks:

- (invited) Laser-driven scintillation detectors
  ANSRI, Dublin Ireland 2016
- (invited) Quax and Axioma Experiments
  12th Patras Workshop on Axions, WIMPs and WISPs, Jeju Island South Korea 2016
- (invited) Magnetized media as detectors for galactic axions
  Ultralight dark matter at APS Meeting, Washington USA 2017

- (invited) Axioma:rare earth doped materials as detector for galactic axions
  Workshop on axion physics and experiments, Frascati 2017
- (plenary) Axioma: a rare earth based detector for galactic axion
  13th Patras workshop on Axions,WIMPs and WISPs, Thessaloniki Greece 2017
- (invited) Detection of axion dark matter , with a focus on table top scale experiment
  quantum seminar @ Mainz University, Mainz Germany 2017
- (plenary) Optical manipulation of a magnon photon hybrid system
  FISMAT Congresso nazionale di fisica della materia condensata, Trieste Italy 2017
- (invited) Optical control of the magnetization in YIG via multi GHz laser pulses
  Ultrafast magnetism conference, Kaiserslautern Germany 2017
- (plenary) Detection of axion dark matter in solid state materials: exploiting the axion electron coupling
  First international conference on quantum gases, Pisa Italy 2017
- (plenary) Detection of the Unruh effect through radiation-mediated interactions between accelerating atoms
  Fluctuation-induced Phenomena in Complex Systems, Bad Honnef Germany 2018
- (parallel) novel experimental approaches for dark matter detection
  14 Pisa meeting: Frontier detector for Frontier physics, Elba Italy 2018
- (plenary) Axion detection schemes
  Invisible 2018, Karlsruhe Germany 2018
- (plenary) Xenon solid crystal as detector medium
  Xesat, Tokyo Japan 2018

Theses:

- 2016: 2 Bachelor + 2 Master
- 2017: 1 Master
- 2019-2020: 3 PhD

7. Outcome

The obtained results have been fruitful for the following new projects:

- The idea to use the stimulated emission promoted by incident radiation has been submitted to the ATTRACT grant and we have been successful. We received a grant of 100 Keuro starting from May 2019.

- The preliminary exploration within the Axioma Call, within a wide band research spirit, help us to focus on a more promising subject, such as doped rare earth cryogenic crystals, so to concentrate our efforts to build up a radiation detector capable to lower the threshold at few tenth of eV. This line of research has been approved by CSN5 under the DEMIURGOS Project.

- The laser approach has been used to assemble and test a new type of X Ray source where electron current has been emitted at the cathode kept under Negative High Voltage. This method help to solve the thermal release problem encountered in standard X ray Tube. This technology has been presented to our Technological Transfer Division to check the industrial interest of such device.

- The result obtained in the doped rare earth crystals, where a superfluorescence phenomenon involve a large concentration of atoms, has attracted many interests for the possibility to investigate elusive interaction with the matter. We are planning to submit an ERC project on such phenomena so to exploit such Macroscopic Quantum Phenomena into particle physics. On this subject we are collaborating with a Japanese Group to better define the experimental set up and the best crystal to be used.

COSINUS

Principal Investigator: KAROLINE SCHAEFFNER (LNGS, now MPI Munich)

Participant INFN groups: LNGS, Milano Bicocca

1. Title

COSINUS (Cryogenic Observatory for SIgnatures seen in Nextgeneration Underground Searches)

2. **Scientific line (Detectors, Electronics, Accelerator, Multidisciplinary)**

Detectors (Thematic Call on Dark Matter)

3. Period of activity

2016-2019 (3 + 1y)

4. Manpower (FTE) and total budget financed by CSN5

- 2016: 1.9 (8 people) 158.0 keur
- 2017: 1.8 (12 people) 76.5 keur
- 2018: 2.4 (11 people) 42.5 keur
- 2019: 2.2 (5 people) 21.5 keur
- Total budget: 298.5 keur; Average manpower: 2.1 FTE/y (9 people/y)

5. Brief summary of the experiment (scientific goals and results)

The COSINUS project was focused on the development of a bolometric detector based on NaI crystals, to be used in experiments devoted to direct search of Dark Matter. In this field, the annual modulation signal reported by the DAMA/LIBRA collaboration with very high statistical significance, is currently not confirmed by the results obtained by competing experiments. However, these experiments use different detectors with respect to the ultra-pure NaI crystals of DAMA/LIBRA. COSINUS aims at using the same target as DAMA/LIBRA (NaI crystals), but with a different experimental technique. In fact, while in DAMA the crystals are operated at room temperature and coupled to PMTs to detect the scintillation light, in COSINUS the NaI crystals (operated at few mK) are used simultaneously as light detectors and bolometers, using Transition Edge Sensors (TES). This technique allows discriminating event-by-event the nuclear recoils from the β/γ background.
From 2016 to 2019, COSINUS has produced and tested 12 detector prototypes. Already during the first year of activity, the Collaboration implemented and tested the final detector design, which foresees a light detector (Si-beaker) with very high detection efficiency. In the following years, the expected linear relationship between deposited energy and light output has been demonstrated, and the main objectives of the R&D have been met:
1. Threshold of the phonon signal: 5 keV
2. Resolution of the light detector: 15 eV
3. 13% of the deposited energy detected in the light channel
4. Excellent radio purity of the crystals, comparable with that of DAMA/LIBRA.

In the second half of 2018 and during 2019, in parallel with the completion of the R&D activity, the Collaboration started the design phase of the real experiment.

6. Scientific productivity (papers, conference presentations, thesis (BS, MS, PhD))

WoS papers:

- ASTROPART PHYS, **84-**, (2016), 10.1016/j.astropartphys.2016.08.005
- EUR PHYS J C, **76-8**, 441 (2016), 10.1140/epjc/s10052-016-4278-3
- NUCL INSTRUM METH A, **845-**, (2017) 10.1016/j.nima.2016.06.005
- J INSTRUM, **12-**, P11007 (2017) 10.1088/1748-0221/12/11/P11007
- J PHYS CONF SER, **888-**, 012207 (2017) 10.1088/1742-6596/888/1/012207
- J LOW TEMP PHYS, **193-5-6**, (2018) 10.1007/s10909-018-1967-3

Talks/Posters:

- 2016: 2 invited talks, 1 plenary, 2 posters
- 2017: 4 invited talks, 1 plenary, 3 parallel, 2 poster
- 2018: 2 invited talks, 1 plenary, 1 parallel

7. Outcome

In 2018 the Max Planck Institute for Physics (Munich, Germany) granted the PI of COSINUS (Dr. Karoline Schaeffer) with 3.14 M€ for the realization of the COSINUS-1π experiment in the Gran Sasso Laboratory. The Conceptual Design Report of the experiment was submitted to the LNGS Scientific Committee in April 2019, and the Letter of Intent was submitted to CSN2 in June 2019. CSN2 approved the experiment as COSINUS_CSN2.

The COSINUS Collaboration includes currently the INFN units of LNGS and Roma 1, the GSSI, the Physics and Chemistry Department of the L'Aquila University, the Max Planck Institute for Physics (Germany), the Institute for High Energy Physics Austrian Academy of Sciences e Technical University of Vienna (Austria), the Shanghai Institute of Ceramics (SICCAS, China) and the Helsinki Institute for Physics (Finland).