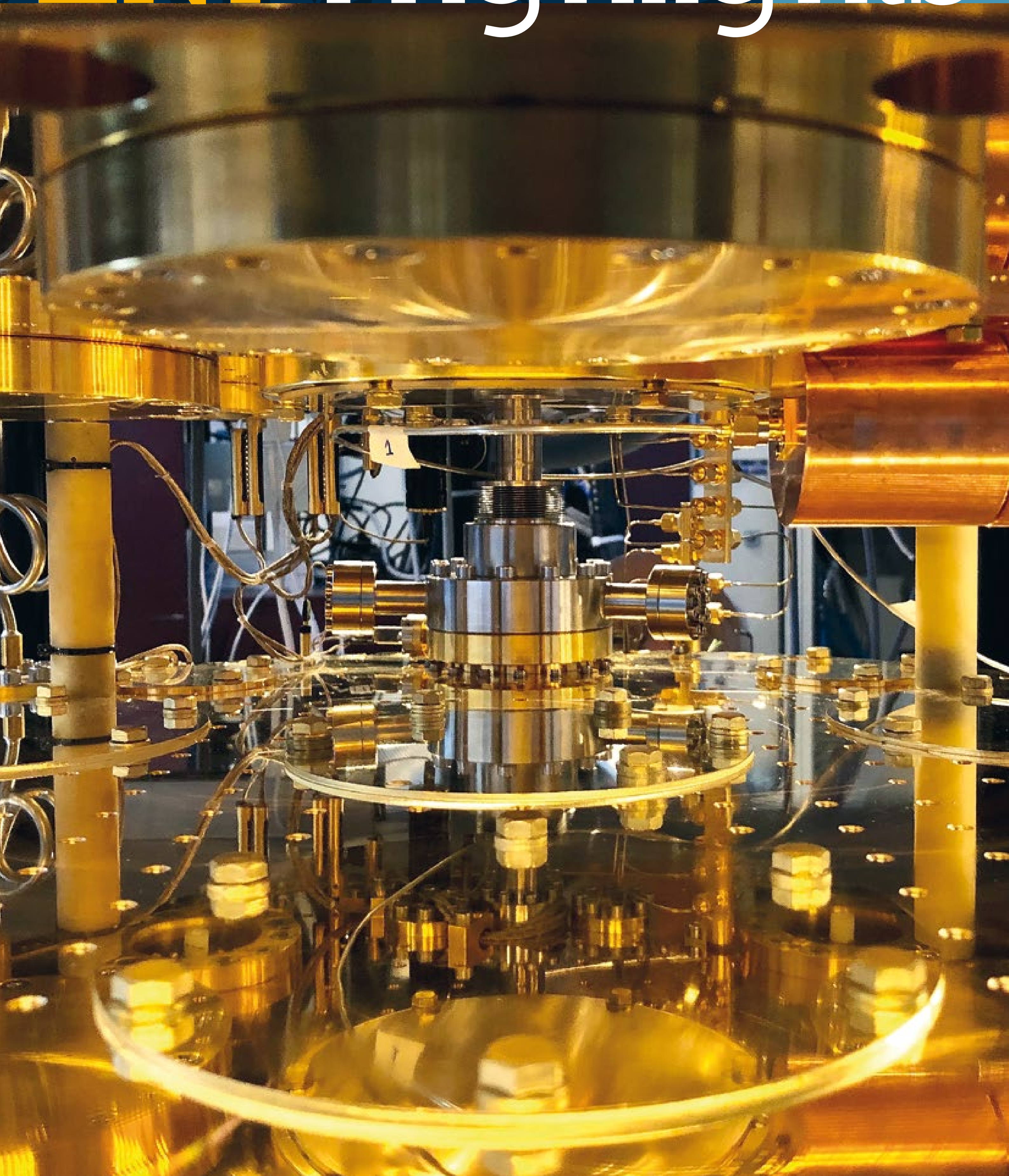
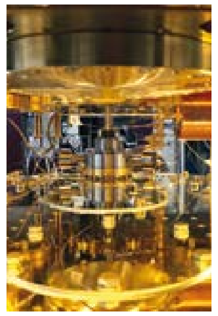
INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

2019

LNF Highlights



2019
ONE YEAR OF RESEARCH AT LNF



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Foreword

Pierluigi Campana
LNF Director

Year 2019 can be considered as the one of the preparation of the European Strategy for Particle Physics (ESPP), which will see in 2020 its final phase. Frascati, being the largest INFN laboratory, and the only one devoted to Particle Physics and to its Accelerators, has been heavily involved. One of the main themes of ESPP is the upgrade of the existing collaboration among HEP institutions, both around large CERN present and future infrastructures (HL-LHC and FCC) and in other large European endeavors, which have to be supported by the community at large. The Laboratory has submitted a specific contribution to ESPP, describing the future research plans for its community.

The progress of diversifying its activities has continued: accelerators for particle and nuclear physics experiments, represented by the restart of DAFNE operation devoted to Siddharta2; the various upgrades of LHC experiments in which LNF is involved (ALICE, ATLAS, CMS and LHCb); new projects for the search for Dark Matter and Axions (CYGNO and COLD lab); the support to the DUNE experiment, with LNF showing its central role as a hub where large detectors can be built; a new acquired regional grant (SABINA) to support technological transfer, together with new infrastructures for photon science at the Laboratory, in connection with SPARC_LAB activities.

The EuPRAXIA@SPARC_LAB project has continued its development and the final EUPRAXIA H2020 Design Study Report has been delivered to the European Commission at the end of 2019. In its last meeting at DESY in October, the EuPRAXIA community has unanimously decided to set the site of the beam-driven leg of the infrastructure in Frascati. This is a fantastic achievement of the whole Laboratory. At the end of 2019, this ambition has been validated by the governmental support, which decided to fund with about 100 ME in a long-term plan investment (2019-2033), the construction of the EuPRAXIA@SPARC_LAB facility. The next goal is to become part of the 2021 ESFRI Roadmap, which would give his "stamp" to the infrastructure, then to be considered as one of the most important of our Continent.

Science Minister, on. Fioramonti, visited Frascati Lab in 2019, providing new impulse to the plan of building a Science Centre in the Lab premises, as a hub of a larger network of outreach initiatives in the south area of Rome, hosting one of the major concentrations of research centers in Europe.

The program of hiring new staff has continued throughout 2019, although with bureaucratic problems which have slowed down the process. We hope to be more efficient in 2020. Given the many new long-term projects ongoing, this represents fresh blood in our arteries.

I feel honored to having led the Lab in these four exciting years. New duties are at the horizon. My term is about to come to the end, and therefore I would like to express my deepest thanks to the whole body of the Lab, who managed to fill my life night and day, providing me with a great excitement.

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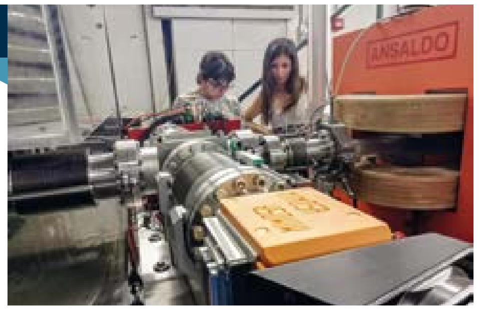

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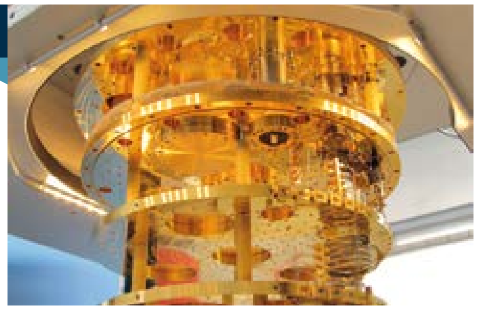
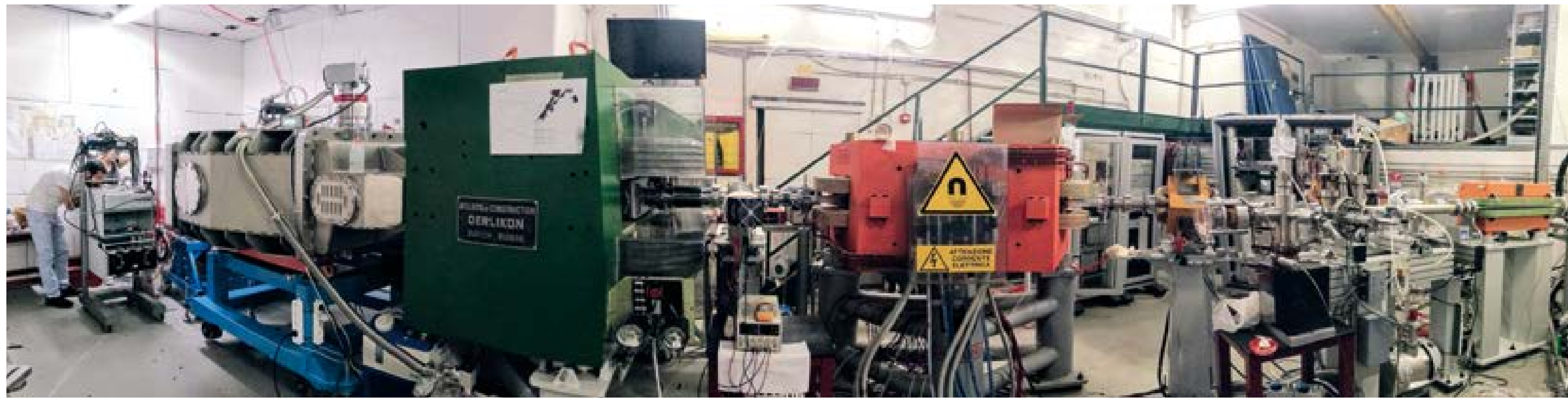


Looking for dark matter



1. Fisheye view of the PADME experimental setup

There are several astrophysical evidences pointing out that in our universe other forms of matter than the baryonic one should exist. Actually, the visible matter accounts only for about 5% of the observed gravity while the rest is due to some other type of non-luminous matter, called dark matter, and a mysterious form of energy, called dark energy.

Among the different theoretical models that try to define what dark matter could be, there are those postulating the existence of a "Hidden Sector" populated by new particles that do not couple with those of the Standard Model (SM). The only connection within these two worlds could be realized by a low-mass spin-1 particle, dubbed with the symbol *A′*, and christened with the name of "Dark Photon", that would possess a gauge coupling of electroweak strength to dark matter, and a much smaller coupling to SM particles [1].

PADME (Positron Annihilation into Dark Matter Experiment) [2] aims at searching for signals of such a Dark Photon by studying the reaction:

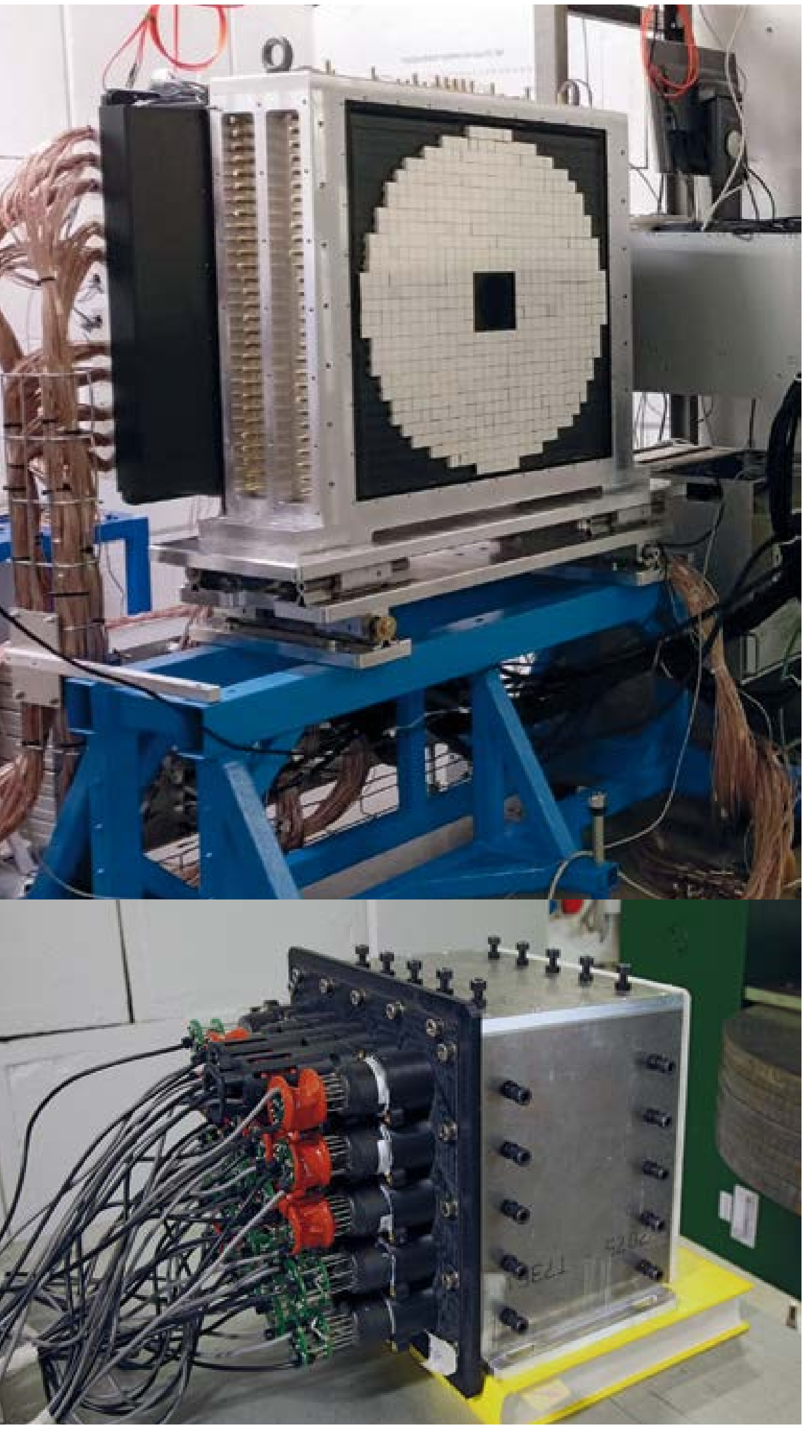
$$e^+ + e^- \rightarrow A' + \gamma$$

A beam of positrons produced by the BTF beamline strikes a target made of polycrystalline carbon. If carbon electrons and positrons annihilate to produce a photon and an *A′*, as in the reaction above, the former is detected by an electromagnetic calorimeter (ECAL) placed a few meters downstream the interaction point, while the latter escapes undetected. By measuring the energy and the direction of flight of the photon, and using the fact that the energy of the incoming positron is known, one can easily infer the "missing mass" of the event, i.e. the mass of the supposedly escaping *A′*.
Unfortunately, life is not so easy. There are several sources of potential background events, i.e. events that can mimic the above signature being instead produced by "ordinary" reactions. For instance, events such as:

$$e^+ + e^- \rightarrow A' + \gamma\,\gamma$$
$$e^+ + N \rightarrow e^+ + N\,\gamma$$

where *N* indicates a nucleus of the target material, are produced at rates much higher than the rate expected for *A′* production, even in the most optimistic scenarios. As soon as one photon in the first class of events, or a positron in the second, escapes detection, we are left with exactly the same signature of Dark Photon production.

The PADME apparatus is therefore designed to minimize the impact of these background events, by adding further subdetectors to catch the max-



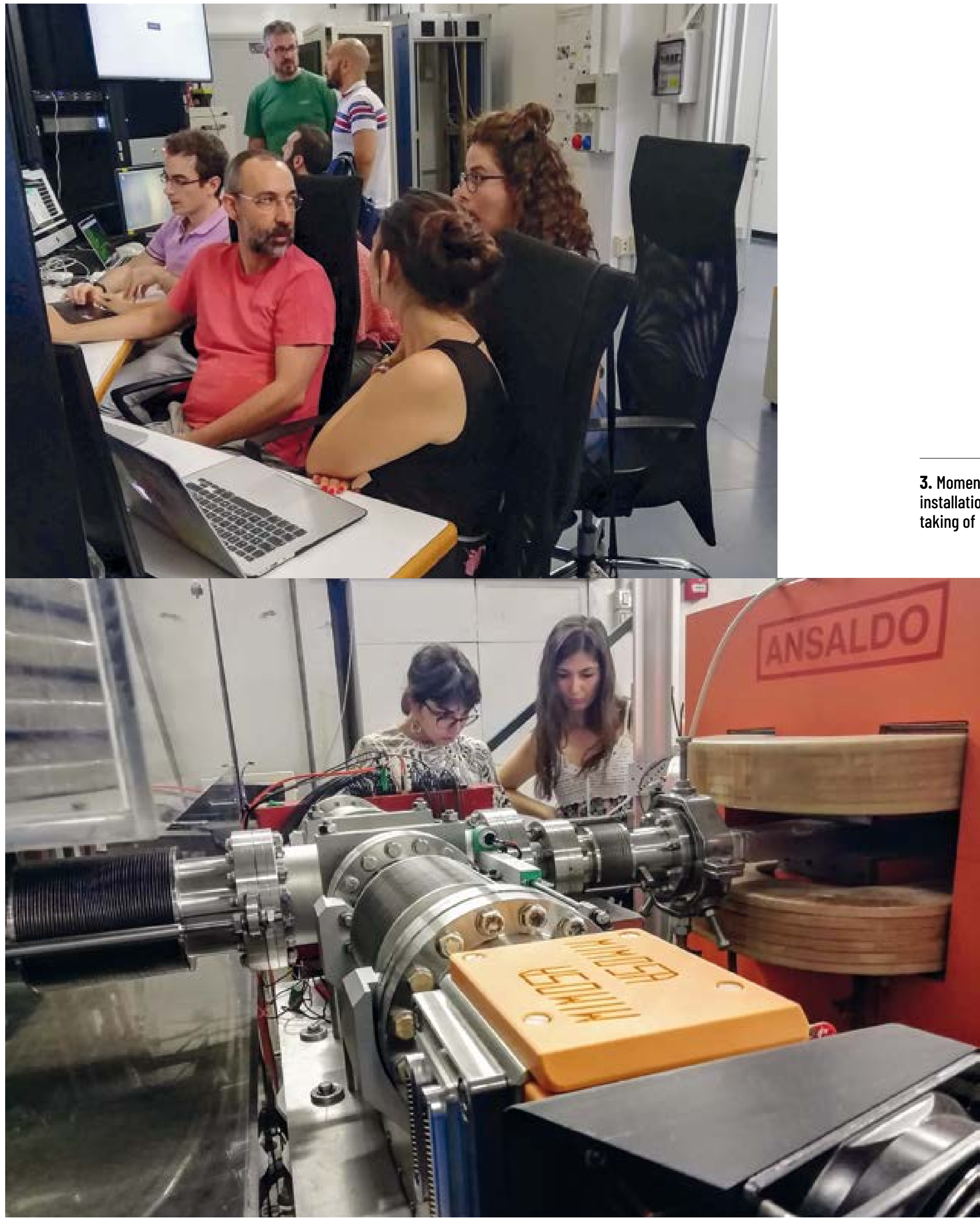
2. The ECAL (top) and the SAC (bottom) of PADME

imum possible number of final state particles. A picture of the experimental setup is shown in fig.1. Besides the ECAL and the target, it consists of a small angle calorimeter (SAC) and a positron veto spectrometer (PVETO). Moreover, an additional detector, the TimePix, is meant to provide information on the quality of the positron beam. Pictures of various subdetector components are shown in fig.2.

Even with the use of all subdetectors, however, some residual background remains. Fortunately, in the case of background events the missing mass can take any value allowed by kinematics, while for *A'* production events it will concentrate around the physical mass of the dark photon. The experiment consists, therefore, in the search for a clear "bump" in the missing mass distribution, peaking over a "flat" background.
PADME is an international collaboration of about 50 people that involves, in addition to LNF researchers, scientists from the INFN sections of Roma1, Roma2 and Lecce, the Sapienza and Tor Vergata Universities of Rome (IT), the Salento University (IT), the Sofia University (BG), the Cornell University (USA), and the Atomki Institute of Debrecem (H).

The apparatus was built and installed in 2018 and had a first data-taking run from October 2018 to February 2019 (see figure 3). These data are presently used for detector commissioning as well as for some preliminary physics analysis. A new source of background, beam induced and not previously accounted for, has been observed and results in additional large energy depositions in the ECAL. These events are generated by unwanted interactions of positrons of the beam with some element of the accelerator placed upstream the target [3]. The collaboration is studying ways to mitigate this background; a few ideas include moving some parts of the accelerator's elements in a "safer" position, and/or adding properly designed shieldings around the target.

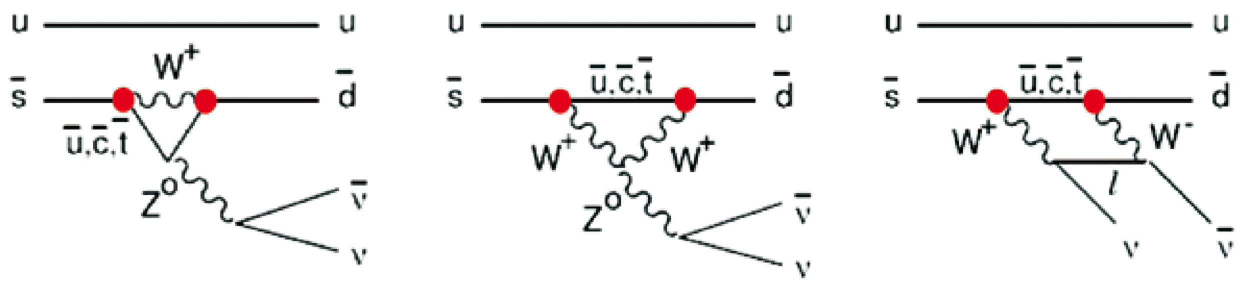
The next PADME data-taking run is expected for summer 2020. The collaboration aims at collecting enough data to explore couplings down to 10^{-6} for *A'* masses up to 23 MeV.



3. Moments of the installation and of the data taking of PADME

1. B. Holdom, Phys. Lett. 166B, 196 (1986).
2. M. Raggi and V. Kozhuharov, Adv. High Energy Phys. 2014, 959802 (2014).
3. A. Frankenthal, contribution to DPF2019, arxiv: 1910.00764 [physics.ins-det].

NA62 experiment @CERN, latest results



1. Feynman diagrams of the $K^+ \to \pi^+\nu\bar{\nu}$ decay

In the Standard Model (SM), the flavour-changing neutral current decay $K^+ \to \pi^+\nu\bar{\nu}$ is forbidden at tree level; it can proceed at the lowest order through electroweak box and penguin diagrams, largely dominated by t quark exchange.

The quadratic GIM mechanism and the small value of the CKM element |Vtd| make this process extremely rare. The theoretical prediction for this decay in the SM is very precise: the expected BR = $(8.4 \pm 1.0)\times10^{-11}$, where the uncertainty is dominated by the current precision on the CKM parameters.

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is sensitive to physics beyond the SM, probing the highest mass scales among rare meson decays. The largest deviations from SM are expected in models with new sources of flavour violation [1, 2]. The E787 and E949 experiments at BNL studied the $K^+ \to \pi^+\nu\bar{\nu}$ decay using a decay-at-rest technique and obtained the measurement BR = $(17.3^{+11.5}_{-10.5}) \times 10^{-11}$. The goal of the NA62 experiment at the CERN SPS is to measure $K^+ \to \pi^+\nu\bar{\nu}$ decays with higher precision, collecting O(100) SM events using a novel decay-in-flight technique.

The experiment makes use of a 75 GeV unseparated positive secondary beam, consisting of 70% π^+, 23% protons and 6% K^+, produced by 400 GeV/c SPS protons on a beryllium target. The decay volume begins 102 m downstream of the production target, with a total beam rate of 800 MHz, and ~50 MHz of K^+s. Approximately 5 MHz kaon decays are observed in a 65-m long fiducial vacuum decay region by means of tracking and particle identification systems (indicated by KTAG, GTK, STRAW, RICH, MUV). Ring-shaped large-angle photon vetoes (LAVs, a LNF group responsibility), are placed at 12 stations along the decay region and provide full coverage for decay photons with 8.5 mrad < θ < 50 mrad. The last 35 m of the decay region host a dipole spectrometer with four straw-tracker stations operated in vacuum. The NA48 liquid-krypton calorimeter (LKr) is used to veto high-energy photons at small angle. Additional detectors further downstream extend the coverage of the photon veto system (IRC, SAC) (e.g., for particles traveling in the beam pipe) [3]. The time resolution of most of the detectors is of the order of 100 ps or better, allowing a high-bandwidth trigger and an efficient association of the signals to each single particle.

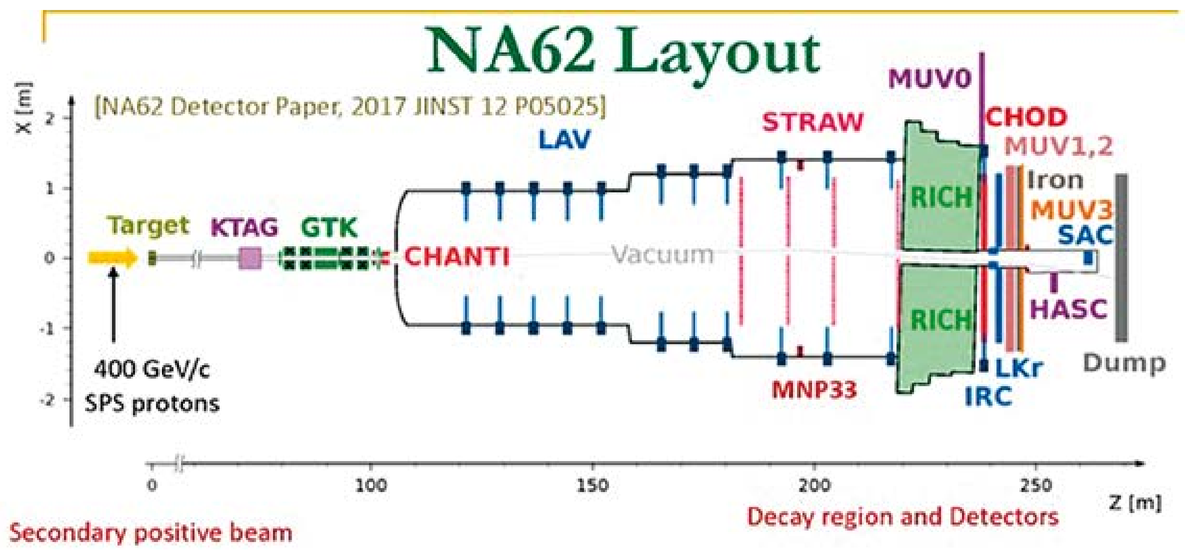
The NA62 experiment collected data throughout the period 2016-2018, for a total of about 6×10^{12} kaon decays in the fiducial volume. Major achievements from the first NA62 run include the following:

- The new in-flight technique to measure the branching ratio of the ultra-rare decay $K^+ \to \pi^+\nu\bar{\nu}$ has been established and proven to work.
- The first NA62 physics result on $K^+ \to \pi^+\nu\bar{\nu}$, based on the 2016 data set, was obtained in 2018 and published in early 2019 [4].

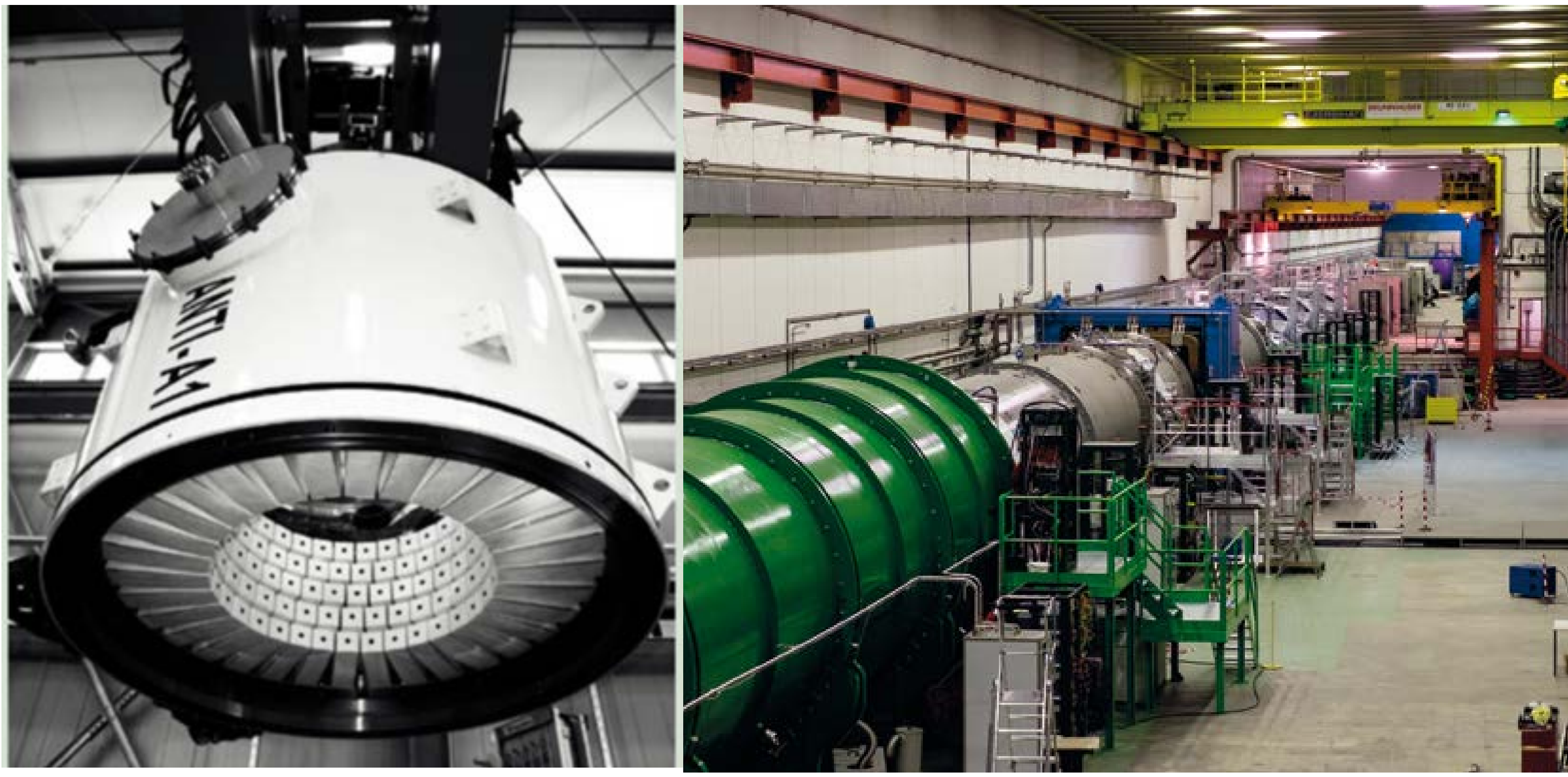
The analysis of the 2017 data set has been completed and the preliminary results shown at major conferences.

The first $K^+ \to \pi^+\nu\bar{\nu}$ analysis was performed on a sample of data taken from mid-September to mid-October 2016. This data set was acquired at an average intensity of 35-40% of the nominal value. In 2016, the spill structure of the SPS beam was irregular, with intensity spikes causing NA62 to sustain running at instantaneous intensities significantly larger than the nominal intensity for periods lasting for several ms.

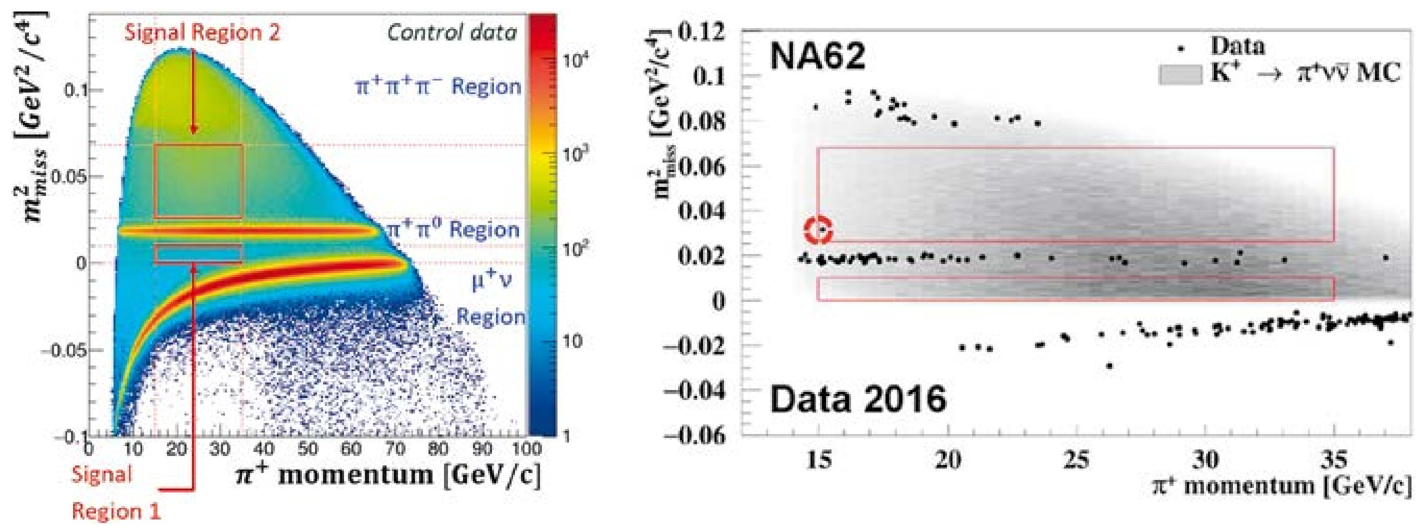
A blind procedure was adopted for the analysis of the data collected, with signal and control regions kept masked until the evaluation of the expected signal and background was completed. Specifi-



2. Schematic top view of the NA62 beam line and detector



3. (Left) one of the Large Angle Veto stations; (Right) NA62 overview.



4. (Left) m^2_{miss} as a function of P_{π^+} for control data after the single charged track K^+ decays selection. The red boxes define the signal regions. (Right) m^2_{miss} as a function of P_{π^+} for $\pi^+\nu\nu$-triggered events (dots) passing the selection. The grey area corresponds to the distribution of MC signal events, with darker (lighter) grey indicating more (less) populated regions. The red (black) lines define the signal (control) regions and are masked. Three background regions are also shown.

cally selected control samples of $K^+\to\pi^+\pi^0(\gamma)$, $K^+\to\mu^+\nu(\gamma)$ and $K^+\to\pi^+\pi^+\pi^-$ decays are employed for background studies. The analysis is mostly based on kinematic cuts and particle identification. The invariant $m^2_{miss} = (p_{K+} - p_{\pi+})^2$ is used to discriminate between the signal and background kinematics, where p_{K+} and $p_{\pi+}$ are the K^+ and π^+ 4-momenta, respectively. Figure (left) shows the distribution of the selected single charged track K^+ decays in the (m^2_{miss}, $P_{\pi+}$) plane, with $P_{\pi+}$ the magnitude of the π^+ 3-momentum. Regions populated mostly by $K^+\to\pi^+\pi^0(\gamma)$, $K^+\to\mu^+\nu(\gamma)$ and $K^+\to\pi^+\pi^+\pi^-$ are visible. Two signal regions are defined: the region at lower (higher) m^2_{miss} is referred as region 1 (2). The m^2_{miss} resolution is of the order of 10^{-3} GeV^2/c^4 for the $K^+\to\pi^+\pi^0(\gamma)$, and this drives the choice of the boundaries of these regions. The analysis is restricted to 15 < $P_{\pi+}$ < 35 GeV/c. This cut reduces the signal acceptance by half, but ensures that there is at least 40 GeV/c of missing energy, improving significantly the π^0 detection. The calorimeters and the Ring Image Cherenkov (RICH) provide π^+ identification and the photon veto system ensures rejection of photons with angles from 0 up to 50 mrad with respect to the beam axis.

The single-event sensitivity SES is defined as $1/(N_K\, \varepsilon_{\pi+\nu\nu})$, where N_K is the number of K^+ decays in the fiducial volume and $\varepsilon_{\pi+\nu\nu}$ is the signal efficiency for the selection. Both are derived from the data using control samples and from simulation. The final measured SES and the corresponding total number of SM expected $K^+\to\pi^+\nu\nu$ events in signal regions 1 and 2 are

SES = $(3.15 \pm 0.01_{stat} \pm 0.24_{syst})$ x10^{-10};
N_{exp}(SM) = $0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$.

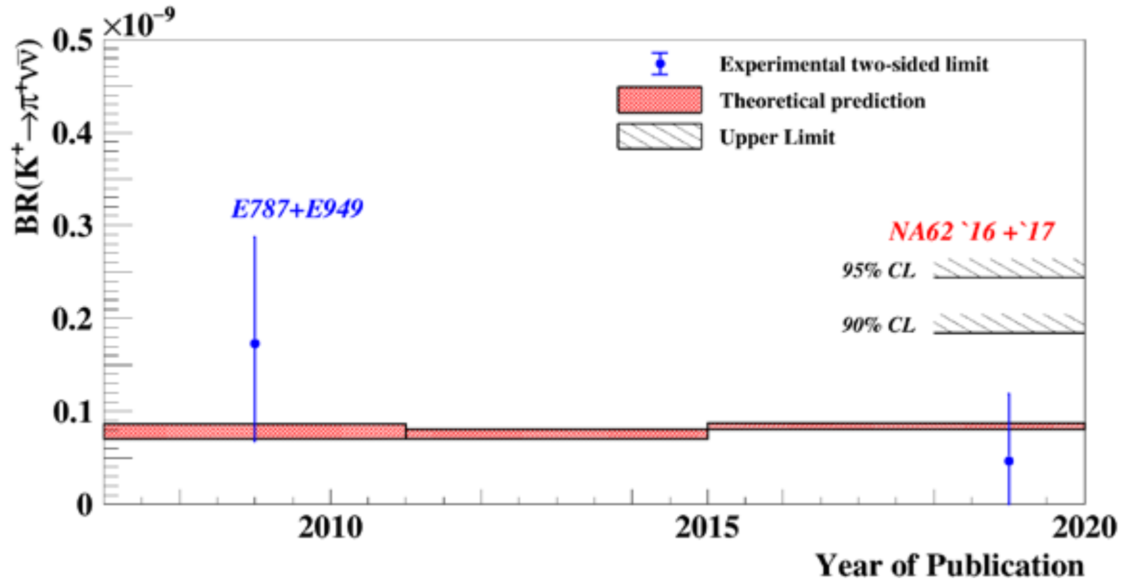
The fraction of background events entering each signal region via the reconstructed tails of the corresponding m^2_{miss} peak is modelled with data control samples and corrected with MC simulation for biases induced by the selection criteria. The total background is estimated to be $0.15 \pm 0.09_{stat} \pm 0.01_{syst}$ events. After un-blinding the signal regions, one event is found in region 2. The corresponding π^+ has a momentum of 15.3 GeV/c. The RICH clearly indicates that it is a pion. A preliminary upper limit on the branching ratio of the $K^+\to\pi^+\nu\nu$ decay is derived from these results using the CLs method: BR($K^+\to\pi^+\nu\nu$) < 14 x 10^{-10} @ 95% CL.

The same analysis has been performed on the 2017 data set, with 2 events found in signal region 2. Combining the 2016-2017 results we obtain:

S.E.S.	(0.346±0.017) x 10^{-10}
Expected background	1.65±0.31
Observed events	3
BR ($K^+\to\pi^+\nu\bar{\nu}$) < 1.85 x 10^{-10} @ 90% CL	
BR ($K^+\to\pi^+\nu\bar{\nu}$) = $0.47^{+0.72}_{-0.47}$ x 10^{-10} @ 68% CL	

The LNF group has made fundamental contributions to this analysis, in particular in the measurement of the photon-veto rejection capability and the determination and improvement of the photon-veto efficiency.

The LNF group has also carried out a search for the invisible decays of the π^0 in NA62 data. Historically, the decay $\pi^0\to\nu\nu$ has been of interest for the study of neutrino properties such as mass, helicity and number of families. At present, the main interest in the search for a π^0 decay to any invisible final state is in testing new-physics scenarios involving feebly interacting or long-lived particles. Any observation of $\pi^0\to$ invisible at the sensitivity currently achievable would be a clear indication of new physics. The direct experimental limit on the tau neutrino mass and the stringent limit set by cosmological constraints on the sum of the neutrino masses corresponds to BR ($\pi^0\to\nu\nu$) < 5 x 10^{-10} at 90% confidence level (CL) and BR ($\pi^0\to\nu\nu$) < 10^{-24}, respectively; the latter is well below the achievable experimental sensitivity. The current experimental limit is 2.7 x 10^{-7} at 90% CL.
The search for $\pi^0\to$ invisible is performed with the decay chain $K^+\to\pi^+\pi^0(\gamma)$, $\pi^0\to$ invisible, inclusive of radiative corrections to the K^+ decay.
With a sample of 4 x 10^9 tagged π^0 mesons with an expected background rejection of 3x10^{-9}, no signal is found. The resulting 90% CL upper limit on the branching ratio $\pi^0\to$ invisible is BR($\pi^0\to$ invisible) < 4.4 x10^{-9}. This limit improves on the present literature by a factor of 60 [5].



5. NA62 result compared with previous measurements and theoretical prediction

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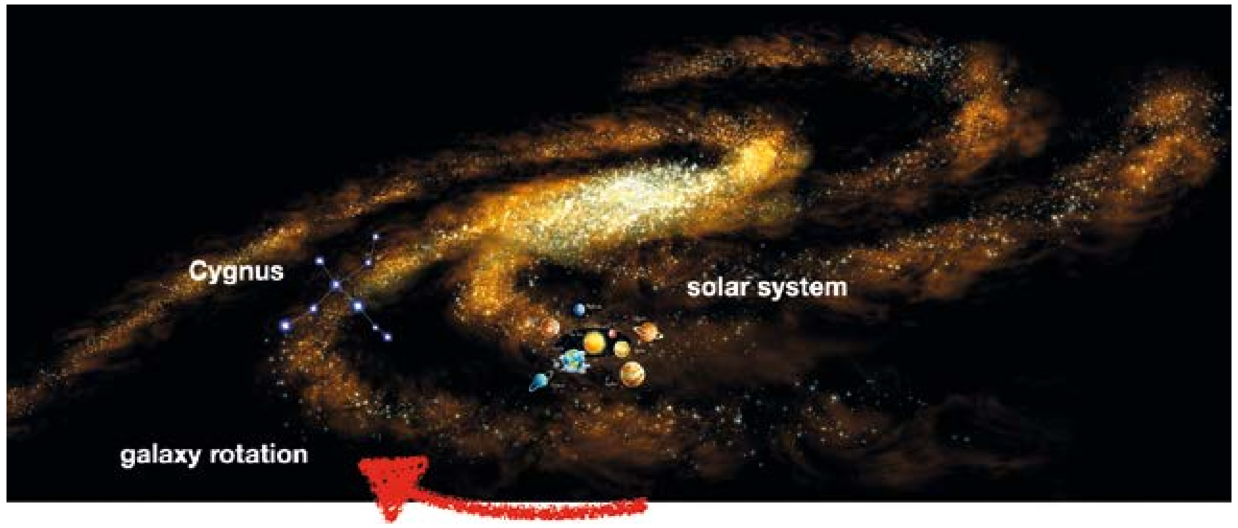
The CYGNO project, a telescope for Dark Matter and Neutrino Physics

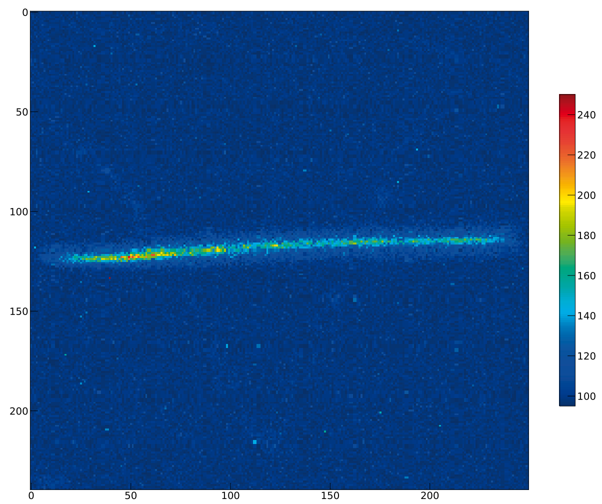
Dark Matter (DM) and neutrinos are today probably the most unknown topics of astroparticle physics: more than 80% of the matter in our Universe is unseen, and neutrinos have mysterious properties all to be understood. To this extent many detectors all around the world, especially in Italy, are taking data or are under construction. Among these is the CYGNO project with a different and innovative approach with respect to today's panorama. Firstly this detector is designed not only to be sensitive to dark matter and neutrinos but hopefully also to their direction, aiming at becoming a "telescope" able to identify the direction of a given source. Moreover, it is based on a new technological implementation of particle detectors with higher granularity and sensitivity with respect to present detectors.
The project foresees the construction of a cubic meter gaseous helium-based Time Projection Chamber (TPC) within the international proto-collaboration CYGNUS with the goal to realize a large distributed array of such telescopes *shared* among the most important underground laboratories of the world. CYGNUS [1] is the constellation in the sky towards which our planet is moving and from which we expect a sort of dark matter wind, modulated by Earth rotation around the Sun (fig. 1). At the same time, in the future, such a detector could achieve the sensitivity to investigate the properties of very low energy neutrinos coming from the Sun. CYGNO will be a demonstrator and is nowadays under construction at LNF in collaboration with the Gran Sasso Science Institute (GSSI), Sapienza and Roma TRE, Brasilian and English institutions, and will be hosted in the tunnels of Gran Sasso National Laboratory of INFN (LNGS). In 2019 LNF researcher Elisabetta Baracchini, now associate professor at GSSI, has been granted and funded by the European Research Council (ERC) program for this project also supported by MIUR-PRIN and INFN funds.
CYGNO is based on TPC technology, developed for High Energy Physics experiments [2], that can provide complete information about interactions occurring in the sensitive volume:
- 3D reconstruction of particle tracks;
- evaluation of the energy release profile along the particle trajectory;
- acquisition of large volumes with a relatively small amount of readout channels.

1. Location of the Cygnus constellation in our galaxy

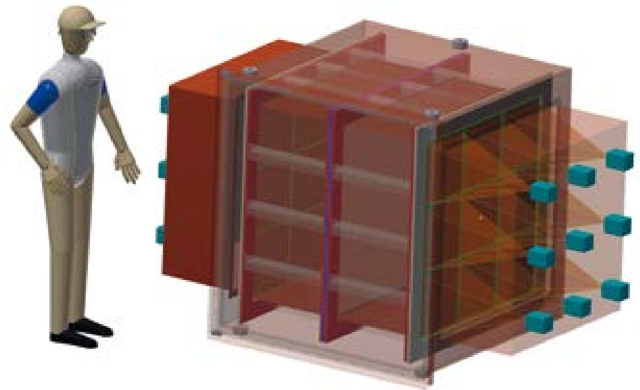


The Optical Readout of Gas Electron Multipliers (GEM) [3], integrated with a readout based on commercial sCMOS sensors, is used.
CYGNO group played a fundamental role in proposing this innovative technology and is keeping a leading role in its development which represents a very promising opportunity for rare and low-energy event studies:
- sensors can be placed outside the sensitive volume reducing the interference with the GEM high voltage operation and reducing the gas contamination;
- the use of suitable lenses allows to image large surfaces onto small sensors;

Figure 2. shows a nuclear recoil (proton) obtained with one of the latest prototypes developed at LNF tested at the neutron test ENEA FNG facility. The picture is a zoom of the 2048x2048 sCOMS pixels and each pixel is 125 micron.
The large granularity and very high sensitivity of the sCMOS technology allows the detection of a few photons per pixel, providing [4] a sensitivity to events with energy releases in the gas of a few keV. The use of helium-based gas mixtures allows an efficient momentum transfer for DM particles with masses in the GeV range, making it possible to explore mass ranges still not covered by other experiments. Moreover, the application of this technology for DM searches will provide high efficiency in the identification of nuclear recoils induced in the gas by DM scattering. Indeed, the possibility of reconstructing the recoil direction offers a crucial handle to reject background events due to natural radioactivity [5].
After about two years of R&D activity, during 2019 the CYGNO collaboration is finalizing the design of the one cubic meter detector and will start its construction soon.
The apparatus (fig. 3) will be composed of a cubic meter gas volume filled with a He/CF$_4$ 60/40 gas mixture (1.6 kg total mass) kept at atmospheric pressure and subdivided into two 50 cm long parts separated by a central cathode with a drift electric field of about 1 kV/cm.
Each gas volume will be equipped with a 3x3 matrix of triple-GEM structures and sCMOS sensors. The active apparatus will be contained in a massive structure, to shield it from external gamma rays and neutrons. The underground installation at LNGS is foreseen for 2022. CYGNO will be a demonstrator of the innovative optical readout technology in order to prepare then a proposal for a 30-100 m^3 experiment.



2. Track produced by a nuclear-recoil (proton) in the detector prototype



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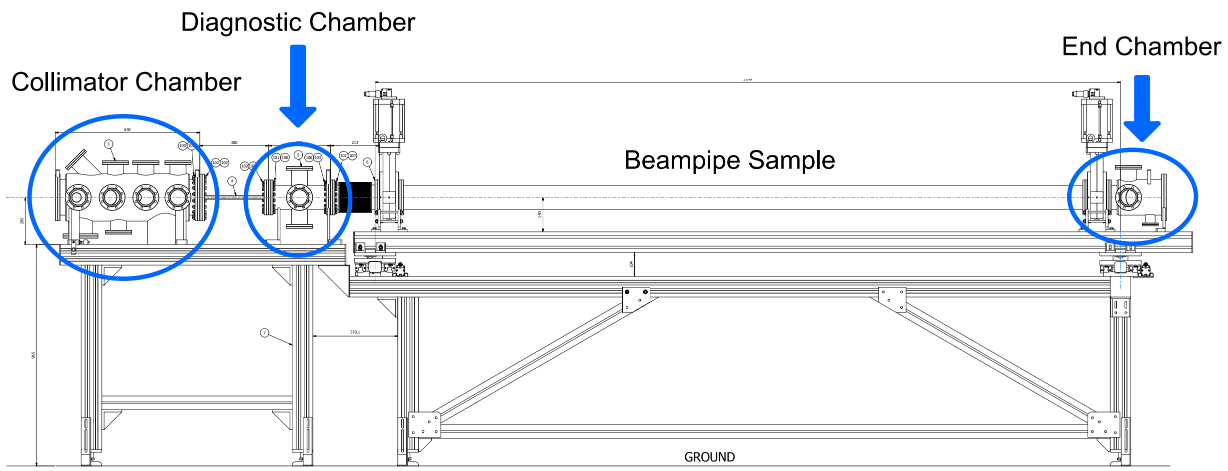
The new beamline WINDY@ DAΦNE-L

In 2017, a Memorandum of Understanding (MoU) between CERN and INFN-LNF (addendum n. 4 MoU INFN / CERN n. KN3083) has been signed. The general purpose of the project is to study the effects of the interactions between synchrotron radiation and technical surfaces.
In circular accelerators like LHC or FCC-hh and in all Synchrotron Radiation Facilities, the accelerated particles emit a high number of photons interacting with the wall of the vacuum beam-pipe. These interactions produce different detrimental effects: gas desorption, secondary electron emission, heat load on cold surfaces, etc.. They may contribute to the instabilities and affect beam lifetime and the overall accelerator performances [1-5]. These effects are directly connected to material properties such as Photon Yield (PY), Reflectivity and Photon Stimulated Desorption (PSD).
The aim of the project is to extract quantitative information about reflectivity, photon yield and photo induced desorption on representative samples using the Synchrotron Radiation White Light (WL) at DAΦNE.

These parameters have a fundamental role in the optimization of existing particle accelerators, like LHC and its upgrade (HL-LHC and HE-LHC), and in the realization of the Future Circular Collider (FCC). Such parameters must be studied not only on realistic "technical materials", but also in conditions as close as possible to the operative ones.

1. 6 Schematic view of the WINDY beamline setup



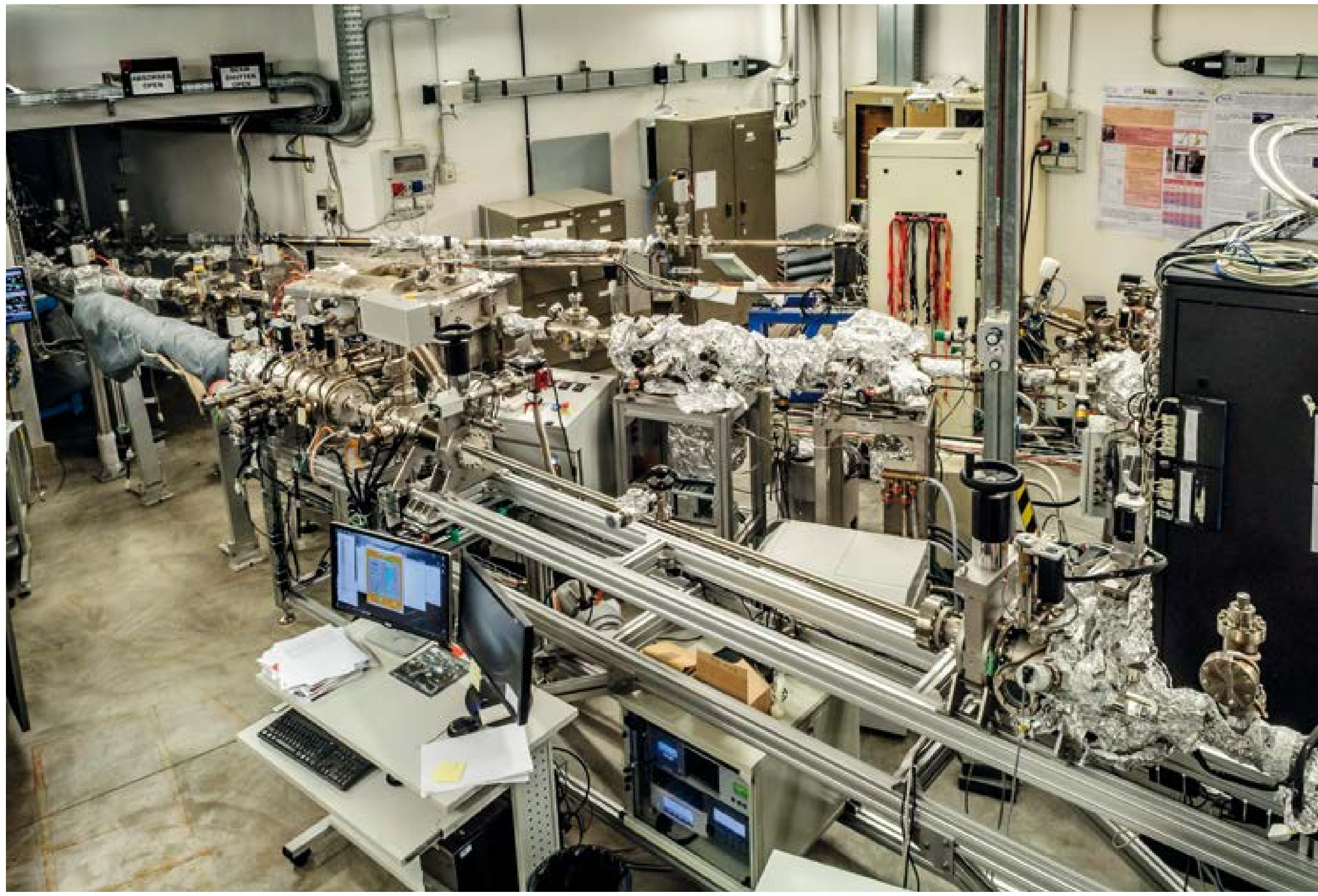
This implies that a significant effort is needed to go, whenever possible, at very grazing angle of incidence (as low as 0.08°) and at very low operating temperatures (from 10 to 70 K).
An ideal setup, where all required information can be simultaneously obtained on the same surface, is not yet available and the agreed strategy was to divide the research in two branch lines: the first studying small samples at cryogenic temperatures (down to 10 K) but not at grazing incidence angles (only above 30°); the second to study long beampipes (up to three meters-long) at grazing incidence (down to less than 1°) and at Room or Liquid Nitrogen Temperature. Studying small samples (~ 8 x 8 mm^2) gives the possibility to analyse the temperature effects on the parameters of interest and it also allows to correlate them with other important properties determining accelerator's performances like the surface chemical state (by X ray Photoelectron Spectroscopy – XPS), Secondary Electron Yield (SEY), Electron Stimulated Desorption (ESD), Temperature Programmed Desorption (TPD), etc. These techniques are available at the existing "Material Science" laboratory built, over the years, with the help of various grants obtained from the INFN National Scientific Committee V and DAΦNE-L. This does represent a significant added value to the research, especially in periods where DAΦNE does not produce any usable SR.

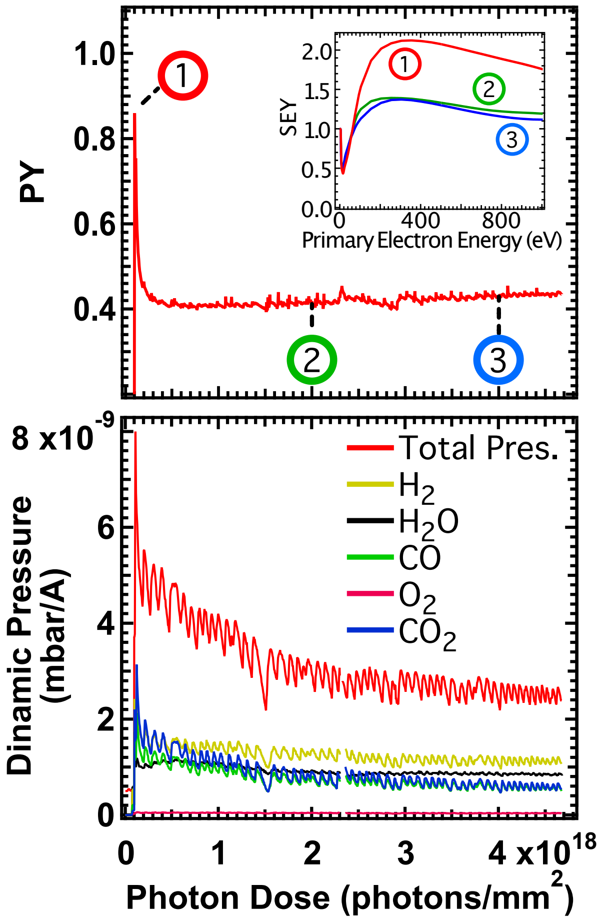
In order to study long beampipes, the agreement foresaw the construction of a dedicated beamline and, in 2017, we started the realization of the new beamline WINDY. The WINDY setup (fig. 1) is divided into three different parts:

- the chamber for collimating and analysing the incoming beam;
- the diagnostic chamber for the analysis of the photo induced desorption;
- the end station for stopping and analysing the reflected beam.

Between the diagnostic chamber and the end station, the beampipe samples

2. 7 WINDY beam-line ready to operate





3. Behavior of total and partial pressure (bottom panel), PY (top panel) during photon irradiation of a small Copper sample. The inset shows SEY measured, on this surface, after three photon doses (1, 2 and 3)

can be inserted. The setup can host samples with a maximum length of 3 meter.

The beamline, shown in fig. 2, is ready since the beginning of 2019 and we are eagerly waiting for some stable operation of the DAΦNE accelerator to start commissioning it and performing first experiments at WINDY with SR.
Meanwhile, the first preliminary measurements with DAΦNE-WL of photo-stimulated desorption and photon yield on small samples have been performed using the existing High Energy Beamline and are shown in fig. 3. With these data, we can qualify and quantify the gas desorbed from the "technical" surface under irradiation, as well as measure its PY. From fig. 3, top panel, we see that PY significantly changes with irradiation. Contemporary XPS (not shown) and SEY (see inset in fig. 3, top panel), performed on the same surface, after various irradiation steps, allow us to correlate, for the first time in this context, photo desorption, PY, SEY and photo induced surface chemistry (by XPS). This combined approach paves the way to a more detailed understanding of the processes governing vacuum walls behavior during accelerator operation. Electron and thermal desorption, that can be performed even in absence of SR, will complete the puzzle, allowing for measurement calibration and rendering the laboratory an ideal tool to study material vacuum behavior at cryogenic temperature. The study of photons and electrons interaction with cold surfaces and ices is also of interest to Astrophysics [6]. Also, some of the experimental set-up was used to study properties of solar cell materials [7], highlighting the interdisciplinary nature of the laboratory.

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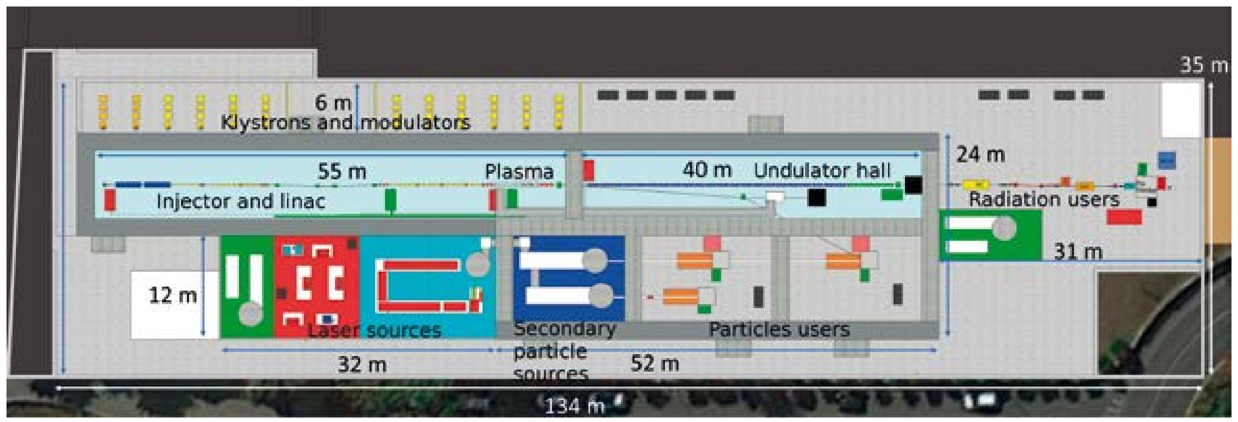
EuPRAXİA @ SPARC_LAB

Recent years have seen spectacular progress in the development of innovative acceleration methods based on high gradient RF accelerating structures and advanced accelerator techniques based on plasma. These novel developments are at the interface of laser, plasma and accelerator physics and may potentially lead to much more compact and cost effective accelerator facilities. While primarily focused on the ability to accelerate charged particles with much larger gradients (up to 10 GV/m) than state of the art RF structures, (about 40 MV/m), these new techniques have yet to demonstrate high performances in terms of both beam parameters and reproducibility. To guide the developments beyond the necessary basic R&D and concept validations, a common understanding and definition of required performance and beam parameters for an operational user facility is now needed [1].
In this context the EuPRAXIA@SPARC_LAB project is a pilot facility, aiming to demonstrate the usefulness of advanced accelerator techniques and their capability to drive a reliable user facility. A conceptual design report has been delivered in 2018 [2] where the entire facility is described in detail. To summarize the main features of the EuPRAXIA@SPARC_LAB facility is worth mentioning that it is a unique combination of a high brightness GeV-range electron beam generated in a X-band RF linac, and a 0.5 PW-class laser system both designed to drive a plasma accelerator module able to boost the beam energy up to factor 5 (in the 1 to 5 GeV final energy range). In its first configuration it will drive a Free Electron Laser user facility able to produce high photon flux in the range of 2-4 nm wavelength, as the one required to penetrate the so called "water window". As specific example of applications, it is worth remarking that the FEL radiation, in the foreseen soft X-ray spectrum, opens possibilities for novel imaging methodologies and time-resolved studies in material science, biology and medicine using samples in "living" condition, where a water solution may represent an obstacle [2] for longer (shorter) wavelength radiation sources. In particular, it will allow investigations of Cells and Viruses structures as the one required to support the R&D effort against the current COVID-19 pandemic [3].
The layout of the EuPRAXIA@SPARC_LAB infrastructure is schematically shown in fig. 1.

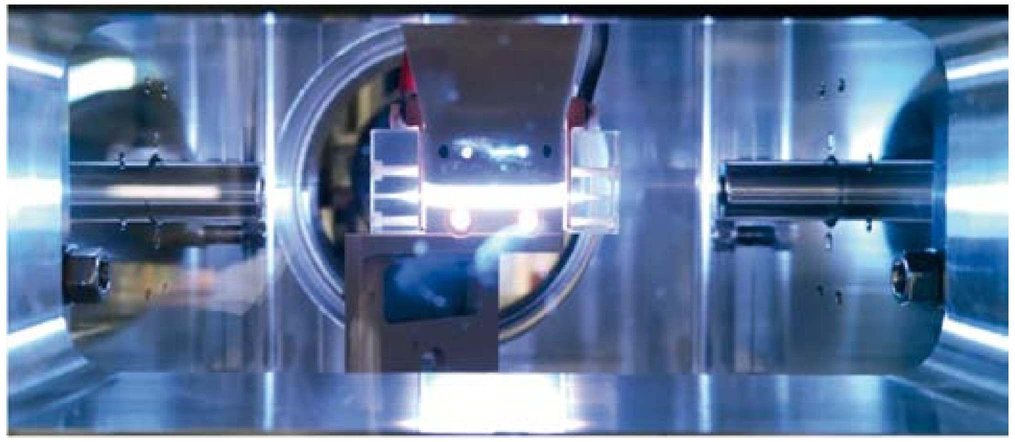
The EuPRAXIA@SPARC_LAB Conceptual Design Report has received in 2019 the endorsement of an international scientific committee and it has been submitted to the INFN management for approval. Consequently, the project has been awarded with a funding of about 100 Million Euros, distributed along 10 years from 2019, from the Italian Ministry of Science (MIUR) [4]. It is a remarkable financial support that will be devoted to the realization of an entirely new facility inside the Laboratori Nazionali di Frascati. The executive design of the new building will be delivered by the end of

1. Layout of the EuPRAXIA@ SPARC_LAB infrastructure. From left to right one can see a 55 m long tunnel hosting a high brightness 150 MeV S-band RF photoinjector and a chain of high gradient X-band RF cavities. At the linac exit a 5 m long plasma accelerator will be installed. In the downstream tunnel a 40 m long undulator hall is shown, where the undulator chain will be installed. Further downstream after a 31 m long photon diagnostic section the users hall is shown. The upper room is dedicated to Klystrons and Modulators to drive the X-band linac. In the lower light-blue room will be installed the 300 TW FLAME laser eventually upgraded up to 500 TW. In addition FLAME is supposed to drive plasma targets in the green room in order to drive electron and secondary particle sources that will be available to users in the downstream 30 m long user area



2021 and after the completion of the tenders and the delivery of the Technical Design Report the building construction could start by the end of 2023. We expect to begin the commissioning of the machine with the beams starting from 2026 and to deliver photons to the users by the end of 2027.
In view of the work plan illustrated above, the EuPRAXIA@SPARC_LAB team is now committed to the Technical Design Study preparation phase which is expected to last about 3 years. The entire design study is currently subject to a careful review with a detailed analysis of the machine layout and the needed hardware together with a detailed cost estimate.
In parallel to that, during 2019, the LNF team has also strongly contributed to the preparation of the European design study EuPRAXIA [5], a distributed European facility whose Conceptual Design Report has been delivered by the end of the year [6]. In the European document is also stated that the EuPRAXIA@SPARC_LAB facility will be one of the 2 main pillars of the EuPRAXIA project where the beam driven plasma acceleration will be tested and made operational as user facility. The next step will be the preparation of the application for the ESFRI [7] road map endorsement that will open up, if successful, additional financial and technical support from the European Community.
In the meantime, R&D activities have been pushed forward with the SPARC_LAB facility at LNF [8] aiming to demonstrate the effectiveness of the plasma acceleration technique to produce high quality electron beams [9]. A dedicated laboratory has been also devoted to the development of the plasma accelerator module itself, where is possible to characterize the plasma behavior and its stability under operational conditions. A picture of the plasma module currently under test is shown in fig. 2.

In addition a formal agreement has been signed with the CLIC group at CERN, in the framework of another European Design study called XLS_CompactLight [10], with the common goal to develop and test at LNF high gradient X-band accelerating structures, as the one required to operate the beam driven plasma accelerator module. It is a challenging and important R&D by itself that might consolidate the international effort towards a compact and cost-effective X-band RF linac with a wide range of applications in the scientific, medical and industrial sectors.



2. Picture of the discharge capillary adopted at SPARC_LAB. A hydrogen gas discharge is produced inside a 3 cm long 1 mm diameter sapphire capillary between 2 electrodes producing a 15-20kV voltage drop

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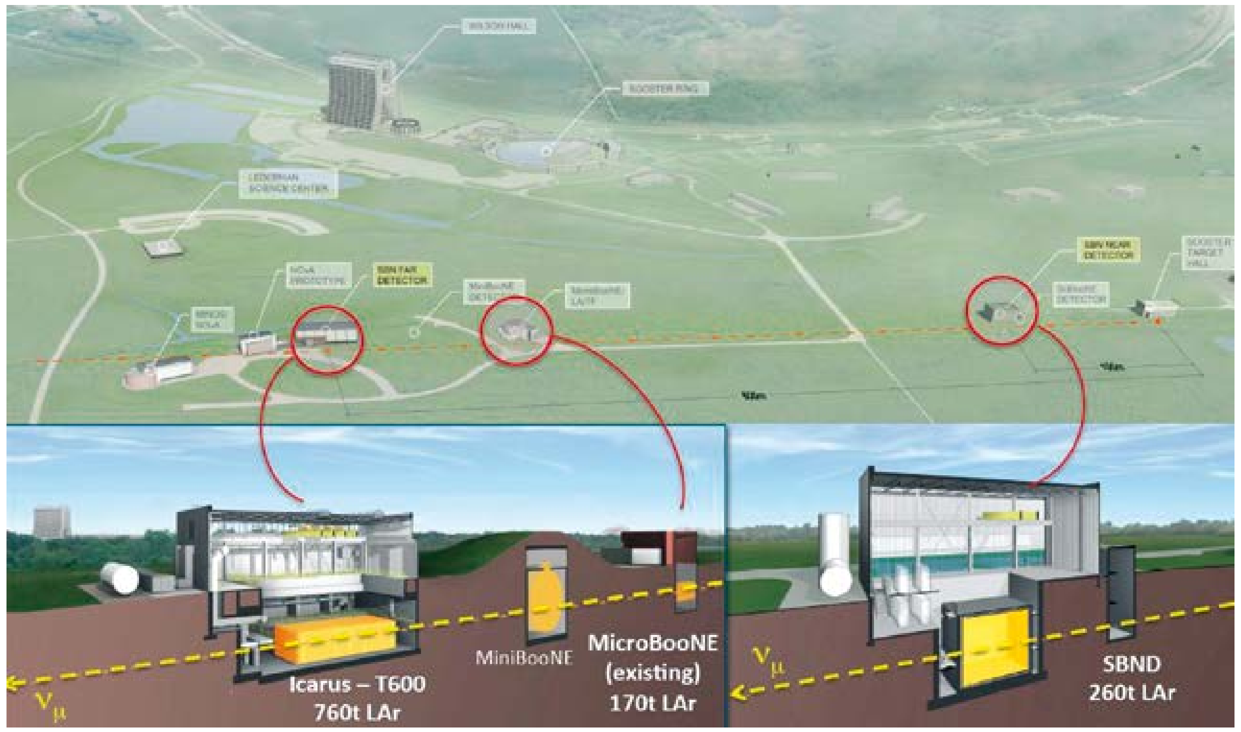
A cosmic ray tagger built for the Fermilab neutrino program

The *Short Baseline Neutrino* (SBN) experiment at Fermilab aims to discover, or rule out, the existence of an additional neutrino mass state ("sterile" neutrino) at the eV scale [1]. The sterile neutrino hypothesis is driven by a set of anomalous results in existing neutrino oscillation data, most notably from the LSND and MiniBooNE experiments that cannot be described by a three-neutrino model [2,3]. Sterile neutrinos – so-called because they do not interact weakly – would mix with active neutrinos leading to new oscillations among standard neutrinos.
The SBN will observe neutrino interactions using three Liquid Argon TPCs located along the Booster Neutrino Beam (BNB) line: the Short Baseline Near Detector, 112 t (total mass), at 110 m from the neutrino source, MicroBooNE, 170 t (total mass), at 470 m, and ICARUS-T600, 600 t (total mass), at 600 m (fig. 1). The BNB neutrino beam is created by impacting 8 GeV protons from the Booster accelerator on a beryllium target. Secondary charged hadrons, mainly pions, are focused to propagate down a 50m long decay tunnel producing muon- and electron- (anti) neutrinos. The focusing horn can be pulsed with either polarity. The Booster spill length is 1.6 μs with nominally 5 x 10^{12} protons per spill. The neutrino energy spectrum peaks at 0. 8 GeV extending up to 3 GeV. The SBN will search for sterile neutrinos in both the $\nu_\mu \rightarrow \nu_e$ appearance channel and $\nu_\mu \rightarrow \nu_\mu$ disappearance channel, reaching 5 σ discovery sensitivity in three years of data taking.
Due to the shallow depth of the detectors' location – few meters underground – the SBN TPCs are continuously exposed to a sizable flux of cosmic ray

1. The SBN experimental area at Fermilab, with the locations of the SBND, MicroBooNE and ICARUS-T600 TPCs along the neutrino beam line



2. ICARUS-T600 in the SBN Far Detector hall at FNAL

muons. Electrons and positrons from secondary showers could be misidentified as part of neutrino interactions. In order to mitigate cosmic muon induced background, SBN Near and Far detectors are surrounded by external Cosmic Ray Tagger systems allowing the identification of muons entering the TPCs.

The construction and testing of the Top CRT of the ICARUS-T600 was carried out at the LNF. The T600, after completing its physics program at LNGS, underwent an extensive overhauling at CERN, it was then moved to Fermilab and installed in its detector hall in 2018 (fig. 2). The detector is divided into two identical, adjacent cryostat modules (T300). Each T300 houses two TPCs sharing a common cathode. The dimensions of the active volume in each T300 half module are 18.0 m (L) X 3.2 m (H) X 3.0 m (W). At the time of this writing the TPCs are being filled with liquid argon. The detector commissioning is planned during fall 2020.

The CRT system will ensure 4π coverage of LAr TPCs, with the Top part collecting more than 80% of the cosmic muon flux [4]. In 1 ms TPC readout time window, 11 cosmic muons are expected to enter the T600 volume, in coincidence of every 1.6 µs neutrino beam trigger window. A 95% cosmic ray track identification efficiency with a time resolution of few ns is required to achieve the experiment analysis sensitivity.

The Top CRT covers a surface of about 426 m^2 and is segmented in 123 modules (84 horizontal + 39 vertical modules). Each module is placed inside an aluminum case, 1.9 x 1.9 m^2, containing two orthogonal layers of 8 plastic scintillator slabs. Each slab is 23 cm wide and 184 cm long. Bottom/top scintillator slabs are 1.5 cm/1 cm thick and were produced by the Institute for Scintillation Materials (ISMA) in Ukraine and the NUVIA company in the Czech Republic, respectively. The scintillator slabs are coated with reflective paint. The scintillation light is collected by two WLS fibers Kuraray Y-11 (200)[5] glued into grooves to the scintillator slab. One fiber end is coupled by a custom optical connector to a SiPM (Hamamatsu S13360-1350CS [6]), while the other end is mirrored with aluminum film. The module SiPMs' signals are read out by a 32-channels CAEN DT5702 Front-End Board [7]. For minimum ionizing particles crossing 15 mm scintillator slabs the Light Yield in each fiber is 15-20 photoelectrons.

The design of CRT modules was based on Monte Carlo simulations [4]. Tests were performed at CERN for the selection of the module components (scintillators, WLS fibers, SiPMs, FrontEnd Boards). The CRT module case, the SiPM and microcoaxial cable patch panels were designed at INFN Bologna, as well as the construction of the CRT Module 0 prototype. The prototype was tested to assure mechanical resistance, light tightness, electrical functionality and to define the construction procedure for the final mass production. Timing, light yield and efficiency measurements with Module 0 completed the prototyping phase.

At LNF over 40 people, including physicists, technicians and engineers from the INFN sections of Bologna, Genova, Lecce, LNF, LNS, Milano, Milano Bicocca, Padova, and from CERN, contributed by weekly shifts to the construction and testing of the 125 CRT modules. The gluing of the fibers was performed at the "LHCb" clean room. The construction of the Aluminum cases, the assembly, cabling and testing of the modules were carried out in the "Gran Sasso" halls (figs. 3-4).

An average muon detection efficiency exceeding 96% was obtained (a planned upgrade of the FEB firmware will increase the efficiency to ~ 99%). A timing resolution better than 2 ns was achieved, well within the SBN requirements. The Top CRT modules will be shipped to Fermilab; their installation, commissioning and integration in the SBN DAQ system will take place by the end of 2020.

The SBN Far detector will thus be ready to start its search for physics beyond the Standard Model.

3. (left) Construction of a CRT aluminum case at the construction hall of Bd. 8 of LNF (right) WLS fiber gluing machine located in the clean room of Bd. 28 of LNF

4. Assembling phases of CRT modules at LNF

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A COLD Laboratory

The COLD (*CryOgenic Laboratory for Detectors*) lab is the LNF cryogenic facility. It was set in 2018 and is located in the hall that formerly hosted the NAUTILUS gravitational wave antenna.
Current experimental activity includes the research and development of ultra-sensitive photon detectors in the range 10 – 100 GHz, mainly devoted to the search for Axion field. Novel superconducting resonant cavities operating at 10-20 GHz at one side, and development of Josephson Junction devices for 50-100 GHz microwave photons on the other side, are the topics under study, with the aim of reaching the single photon detection.
Superconductivity implies very low-temperature technology. So, the lab (fig. 1) is equipped with a complete set of cryogenic facilities for measurements down to the milliKelvin range.

1. View of the COLD lab

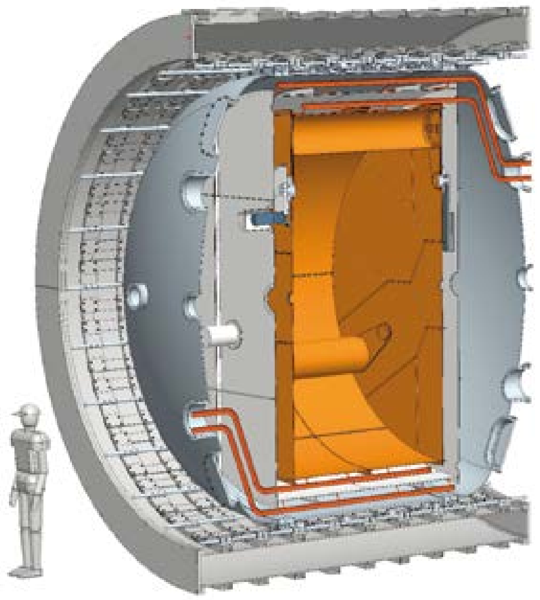
2. Cold side of the CF-CS110 refrigerator

A big-size cryogen-free cryostat from Leiden Cryogenics (CF-CS110 model) was delivered and tested at the end of 2019. It is capable of cooling large devices (up to 500mm diam x 500mm heights) at T below 10 mK, using a continuous-operation dilution refrigerator, with a cooling power of 1 mW @ 120 mK, and a 1.5 W @4.2 K Pulse Tube Cryocooler. This type of refrigerator (fig. 2) allows long-term experimental runs with virtual 100% duty-cycle. The cryostat is equipped with several coaxial RF feedthroughs, and is prepared to host a 9 T superconducting magnet, for application where high-fields are required. The installation of one of these magnets is planned for the beginning of 2021.
The laboratory is also equipped with a small-size liquid helium cryostat with a plastic dilution refrigerator (Leiden Cryogenics MCK50-100), property of CNR-IFN, for DC characterization of small devices down to 40 mK. Another Oxford Instruments Liquid helium cryostat with a superconducting magnet is devoted to measurements at T = 4 K and B up to 5 T.

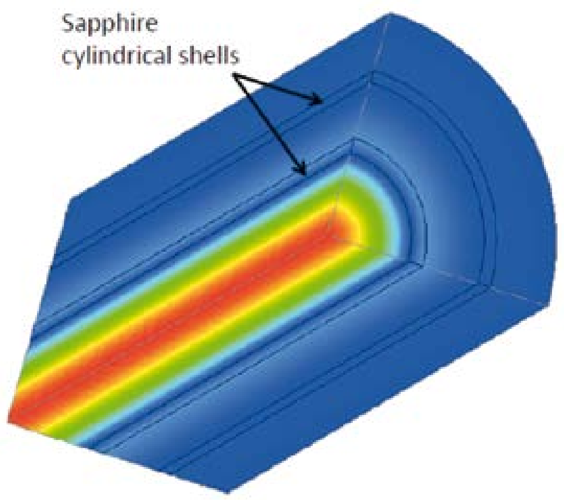
In 2019 it was completed the Conceptual Design Report of **KLASH** (*KLoe magnet for Axion SearcH*) [1], a "haloscope" composed of a large resonant cavity at cryogenic temperatures to search for galactic axions to be inserted inside the KLOE magnet (fig. 3). KLASH could potentially discover Dark Matter particles such as galactic Axions, Dark Photons or other light bosons with a mass of about 1 meV. The CDR summarizes the motivation and physics reach and contains a detailed study of mechanical and cryogenic systems, electromagnetic properties and of the low-noise electronics and signal acquisition. The cryostat can eventually be readapted to be hosted in the bore of the FINUDA magnet.

QUAX (*QUest for AXions*) is an experiment searching for galactic Axions in a mass range around 40 meV with a cryogenic resonant cavity resonating at a frequency of about 10 GHz. The first QUAX haloscope is operated at the INFN laboratory of Legnaro (Padua) [2] and a second one is in preparation at LNF. A large effort has been put in developing resonant cavities able to operate in a magnetic field of several tesla with a high-quality factor, up to 10^6: Superconducting cavity [3,4]; Photonic band gap cavity [5]; Dielectric cavity [6]. Details of the electromagnetic simulation and realization of the dielectric cavity are shown in figs. 4 and 5.

The **SIMP** (*SIngle Microwave Photon detection*) project [7] aims at developing a device sensitive to single microwave photons that would boost the sensitivity of axion experiments. For this scope superconducting Josephson junctions were tested at LNF in a dilution refrigerator. Details of the superconducting chip and of the measured current-voltage curve are shown in figs. 6 and 7.

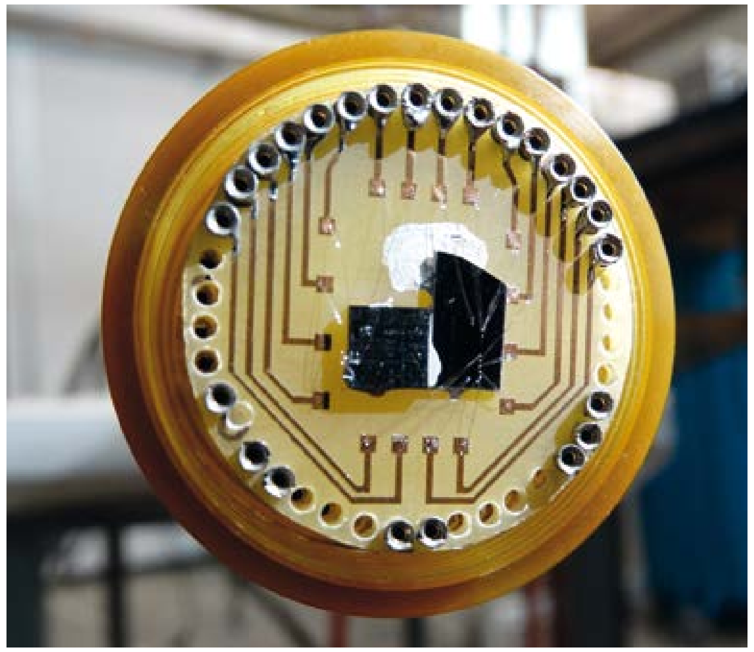


3. Layout of the cryostat and resonant cavity of the KLASH experiment



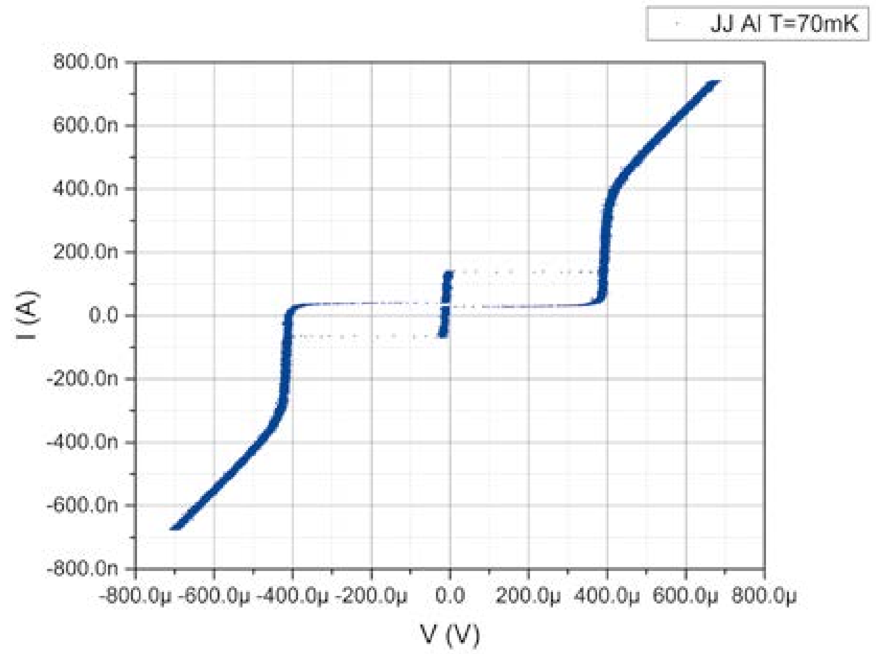
4. Simulation of the electromagnetic field inside the sapphire resonator

5. Picture of the sapphire resonator during the assembly at LNL



The **TERA** (*TeraHertz ERA*) project is investigating the response to microwaves of the Proximity Array Device [8-9], a metamaterial composed of 90,000 Nb superconducting islands on a gold substrate. Its characteristic voltage-current curves, fig. 8, were measured in a liquid-He cryostat at 4 K. By applying an external magnetic field, the number and disposition of flux quanta is varied within the device modifying its superconducting properties. A preliminary measurement of the sensitivity to microwave radiation was done irradiating it with 7.7 GHz microwaves showing a response of about 5 mV/nW.

6. Chip with the superconducting Josephson junctions mounted on the sample holder of the diluitionrefrigerator



7. Current Voltage characteristic curve measured for a Josephson Junction

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LNF Outreach Activity

The education and public outreach activities of LNF are meant to foster the scientific literacy through a wide programme of initiatives addressed to students, teachers and general public. The main mission is to engage the public with science and inform about the latest issues in research conducted at LNF in order to build a network with the society.
In 2019 great attention has been put in communication aspects on web and social media. At present LNF is active on Facebook, Twitter, Instagram and YouTube. Our contacts on these social media are:
- Facebook@lnf.infn.it
- Twitter@infn_lnf
- Instagram@lnf_infn
- YouTubeyoutube.com/user/INFNLNF

Great attention has also been devoted to the realization of outreach material such as multimedia, graphics and photos, without neglecting the traditional program that consists in organizing public events, Lab visits, students and teachers programmes.

1. A hands-on session of the 2019 edition of Incontri di Fisica, a refresher course on modern physics for high school teachers

Tab. 1 reports the list of the 2019 events with the number of participants.

OVERVIEW OF OUTREACH EVENTS ORGANIZED AT LNF DURING 2019	
Events 2019	**Participants**
Visits for kids, high school and university students	800
OpenLabs for the general public	2000
Seminars and Public Lectures	300
IDF and IDFM ("Incontri di Fisica") for high school teachers	203
Stages for high school students	338
"Matinées di scienza" for high school students	350
International Day of Women and Girls in Science	200
Waiting for "Giro d'Italia"	220
European Researchers' Night	720
Visits University - Associations	743
Visitor Centre guided tours	1098

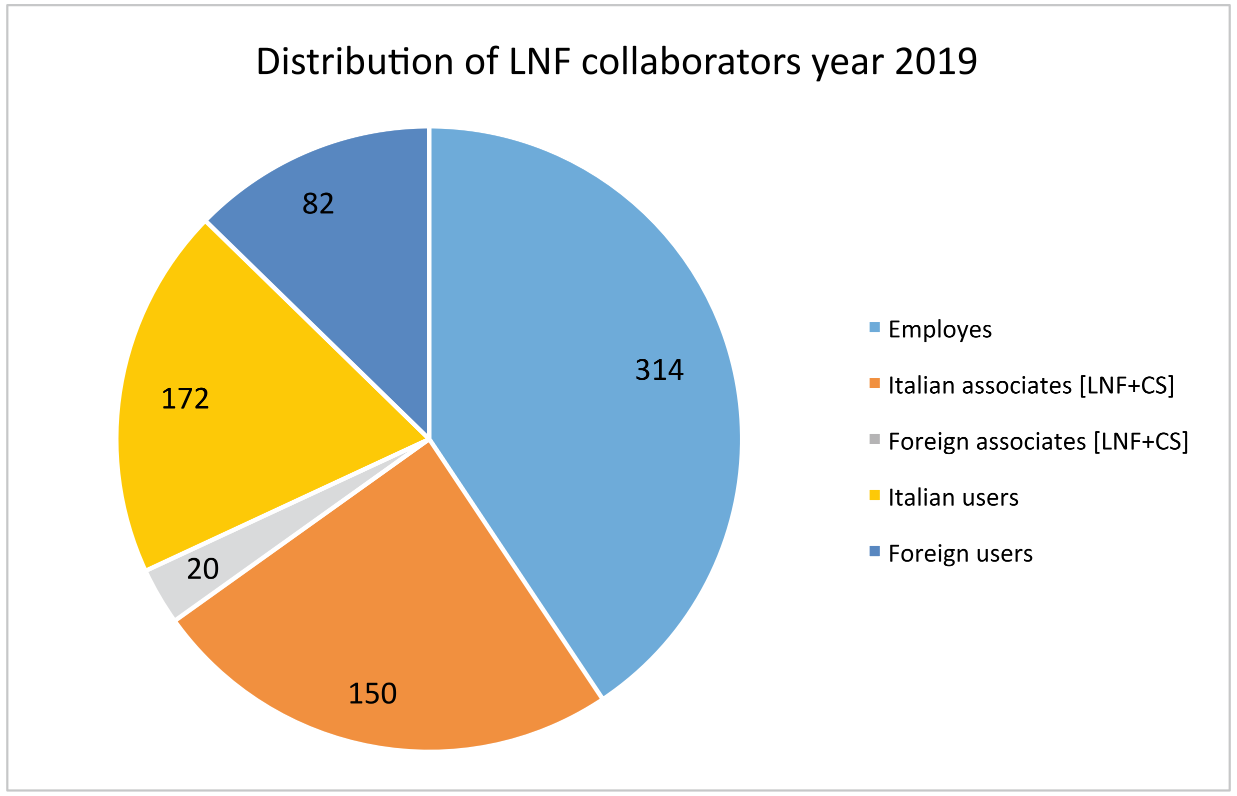
Visiting the Bruno Touschek Visitor Centre, a hub dedicated to the history of LNF, has become a classic of LNF outreach program.
The tours are guided by LNF researchers who present the exhibition and interact with people answering their questions. This visit can be part of a longer itinerary which includes a stage dedicated to the DAΦNE control room and/or a stage at KLOE experimental hall.

On April 12th LNF joined "Frascati in Pink - Science stage" a special public event organized together with the research centres of the Frascati area in the Il Giro d'Italia framework, that in 2019 stopped in Frascati. LNF proposed guided tours to the main experimental apparata and the Visitor Centre. On this occasion about 220 people visited LNF.

LNF in numbers

The LNF personnel, at the end of 2019, consists of 314 units, including 26 with a fixed term contract, plus 170 associate members. Among these, there are university and PhD students, young post-Docs and employees from universities or other research institutions. Associate members work alongside staff members and likewise take part in the Laboratory's activities. Tab. 1 shows the division of the LNF personnel among different profiles.

LNF PERSONNEL AT DECEMBER 2019			
	Staff	**Temp.**	**Tot.**
Researchers	70	5	75
Engineers	54	9	63
Administrative employees	35	2	37
Technicians	129	10	139
Tot.	288	26	314



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