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ARC-ETCRYO and CAOS, two experimental facilities dedicated to Einstein Telescope cryogenics and suspensions

Mateusz Bawaj,[c,d] **Eugenio Benedetti,**[b] **Tommaso Chiarusi,**[l] **Angelo Cruciani,**[a,b] **Aniello Grado,**[h,i] **Van Long Hoang,**[a,b] **Ettore Majorana,**[a,b,*] **Valentina Mangano,**[b] **Luca Naticchioni,**[a,b] **Marco Orsini,**[a] **Andrea Paoli,**[p] **Roberto Passaquieti,**[n,o] **Stefano Pirro,**[e] **Michele Punturo,**[d] **Paola Puppo,**[a,b] **Piero Rapagnani,**[a,b] **Fulvio Ricci,**[a] **Marco Ricci,**[a,b] **Alessio Stollo,**[c,d] **Matteo Tacca,**[m] **Takayuki Tomaru,**[g] **Riccardo Travaglini,**[l] **Flavio Travasso**[f,d] **and Helios Vocca**[c,d]

[a] *Dep. of Physics, Università di Roma "Sapienza", P.le A. Moro 2, 00185, Roma, Italy*
[b] *INFN Sez di Roma, P.le A. Moro 2, 00185, Roma, Italy*
[c] *Dep. of Physics and Earth Sicence, Università di Perugia, Via Pascoli snc, 06123, Perugia, Italy*
[d] *INFN Sez di Perugia, Via Pascoli snc, 06123, Perugia, Italy*
[e] *INFN Laboratori Nazionali del Gransasso, Assergi, Italy*
[f] *Scuola di Scienze e Tecnologie, Università di Camerino, I-62032 Camerino, Italy*
[g] *National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan*
[h] *INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131, Napoli, Italia*
[i] *INFN-Sezione di Napoli, Complesso Universitario di Monte S. Angelo ed. 6, Via Cintia, 80126, Napoli, Italia*
[l] *INFN, Sezione di Bologna, v.le C. Berti-Pichat, 6/2, 40127 Bologna, Italy*
[m] *Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands*
[n] *INFN, Sezione di Pisa, Largo B. Pontecorvo, 3 I-56127 Pisa, Italy*
[o] *ISPRA - Istituto Superiore per la Protezione e la Ricerca Ambientale, Via Vitaliano Brancati 48 00144 Roma*
[p] *European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*

E-mail: ettore.majorana@uniroma1.it

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[*] Speaker

The ETIC consortium will provide the R&D framework to investigate and validate possible configuration and solutions to be adopted for third generation gravitational-wave detector Einstein Telescope. The two facilities are dedicated to the implementation needed for cryogenics application for the low- frequency interferometer (ET-LF) as well as those for the high-frequency interferometer (ET-HF), which are the concept components of Einstein Telescope detector.The main, in common to the two facilities, is the development of 1:1 scale payloads, investigating cryogenics versus test mass suspension, low- mechanical dissipation issues. Cryogenics dedicated to test mass payloads will be the main objective of ARC-ETCRYO facility in at Roma Sapienza University, and the interferometric control of seism-isolated payloads at room temperature will be the topic of CAOS, in Perugia.

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1. Introduction

In the context of the Italy's recovery and resilience plan (PNRR), by the European Commission, [1], a specific project dedicated to third generation gravitational wave detectors called ETIC, - Einstein Telescope Infrastructure Consortium - was funded in December 2022 with 50 M€. The project is meant to provide an R&D distributed infrastructure, articulated through six workpackages: Optics, Electronics and Photonics (WP2); Vacuum and Cryogenics (WP3); Suspensions and large interferometric facilities (WP4); Computing and DAQ (WP5); Sustainable Design (WP6); Outreaching, Dissemination, training (WP7). ETIC is intended to boost R&D activities focused on ET [2] by setting up a suitable experimental infrastructure framework in Italy. A significant characteristic of this investment is the aggressive and short timeline, which implies the completion by 2025. In this report we describe the scientific motivation comment the project description concerning two facilities, ARC-ETCRYO and CAOS, dealt in ETIC workpackages WP3 and WP4.

2. ARC-ETCRYO

The aim of this part of the project is the development of a cryogenic facility with a cooling system inspired to that successfully tested by KAGRA [4], even though with some unavoidable differences imposed by the location and the size of the laboratory. We remark that the rescaling KAGRA system to ET purposes is not trivial, especially if constrained by the size and the location the civil infrastructure; nevertheless, we plan to setup a system dedicated to testing the main elements of a cryogenic payload with double stage suspension, sized quite closely to the ET case. The system will adopt solid conduction heat extraction for both cryostat and payload.

2.1 The cooling line

In 2018, after the first gravitational wave observations, the Sapienza University selected the Amaldi Research Center (ARC) project, granted at the Department of Physics, and aimed to develop an interdisciplinary context, pivoting on the newly born branch of fundamental physics based upon gravitational wave physics. Direct data analysis of current detectors, multi-messenger astrophysics, quantum photonics, surface physics and Cryogenic developments for ET were the five research lines of ARC, whose accountancy ended in 2022. In the context of the latter line of ARC, the civil infrastructure of the laboratory, equipped with cranes for positioning and assembling of large mechanical structures, was delivered. Moreover, a prototype of solid conduction cooling-line prototype equipped with two Cryomech 420 pulse tube cryocoolers was studied, designed and delivered. The system is meant to supply heat extraction from an hypothetical cryostat dedicated to cool-down a realistic payload inspired to the solid conduction case of [3]. The system was delivered in 2023 but in order to assemble it, the ARC team waits for the completion of main laboratory servicing. However, some crucial components of the cooling line have still to be fully developed.

They are the soft thermal links to be installed in the cooling line, connecting the thick cooling bar made of Al5N5 and the radiation thermal shield on one site do the cryocoolers stages and on the other to the cryostat. The need of soft thermal links is related to the need of insulating the cold fingers into the cryostat from cryogenics vibrational noise and to attenuate the seismic noise injected into the cryostat through the thermal extraction path. Indeed, the finalisation of the soft thermal links strongly depends on both the cryostat and payload designs and without a suitable study of the overall system cannot be committed. This R&D activity, initially approached by ARC, is one of the main tasks of ETIC ARC-ETCRYO project; the steady state and the transient modelling is planned to be completed by 2024.

The assembled drawing of the heat extraction duct is shown in Fig.1. The ARC-ETCRYO cryostat is meant to use two cooling lines. The first one will be the one already developed before ETIC, Fig.1-left) and the second one in the context of ETIC, derived from the ARC prototype, but adopting two Cryomech PT425, more recent cryocoolers providing 2.4 W at 4.2 K. Their second stages will be connected to the cold finger dedicated to payload cooling. Notice that in the prototype the hammer shaped cooling duct is obtained by EBW performed at CERN and, differently from KAGRA, is not rigidly connected to the structure hosting the cryocoolers. In fact, both the cooling duct are suspended by suitable steel wires and not seated by means of rigid insulating posts. Such a design explains the need of the third chamber from the left in Fig.1. It must be remarked that studying with FEM the steady state of a single cooling line prototype, a thermal superinsulation, in between the thermal shield connected to the first stage of the cryocoolers and the vacuum chamber, is mandatory, even if the terminal thermal load is due just to the jig chamber shown in Fig.1. This is consistent with the scheme adopted by KAGRA [4]. In Tab.1

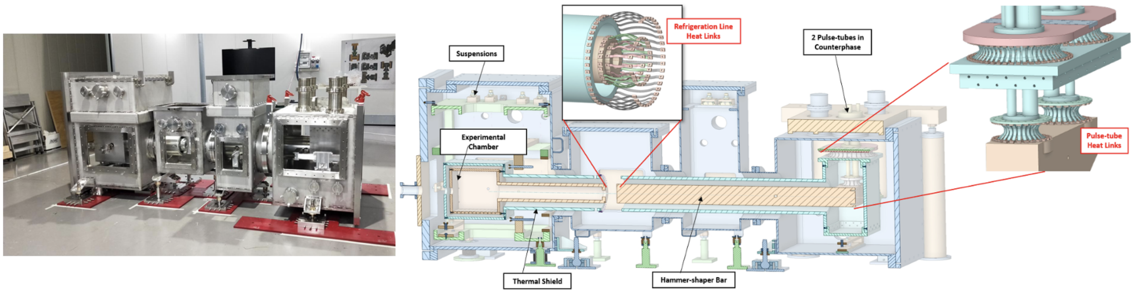

Figure 1: Left: mechanical assembling validation of the cooling duct prototype developed at ARC. On the left side the test-jig chamber, dedicated to cryogenics and vibration tests is shown. Right: assembled drawing of the cooling duct prototype developed at ARC. The soft links are enlightened. Their design will be adapted to match the prototype constructed after the complete cryogenic modelling.

2.2 The *C75* cryostat

The overall size of the cryostat under development, sketched in Fig.2, will be suitable to host a payload with vertical and horizontal dimensions close to those envisaged for the actual ET case. The design will be completely parametrised upon cryogenics purposes.

The prototype cryostat under development adopts solid conduction, as done for KAGRA [4], but at ARC-ETCRYO we plan to implement a significantly different superinsulation scheme in order to prevent particle and gaseous contamination arising from the standard multilayer thermal radiation superinsulation, needed in between the outer thermal shield (OTS) connected to the first stage of cryocoolers and the vacuum chamber. Its relevance, given the large of the cryostat is easily enlightened upon the considerations done in Sec.2.1. We remark that the cooling lines mentioned above will be equipped with standard maylar superinsulation, and the test mass hosted into the

		without multilayer	with multilayer
I stage	PT	67.5 K	29.7 K
I stage	Test chamber	156.7 K	32.7 K
I stage	ΔT	89.2 K	3 K
II stage	PT	4.1 K	2.3 K
II stage	Test chamber	4.1 K	2.3 K
II stage	ΔT	0 K	0 K

Table 1: Preliminary steady state estimation with and without a mylar 50-layer superinsulation to attenuate the room radiation heat load along the cooling line.

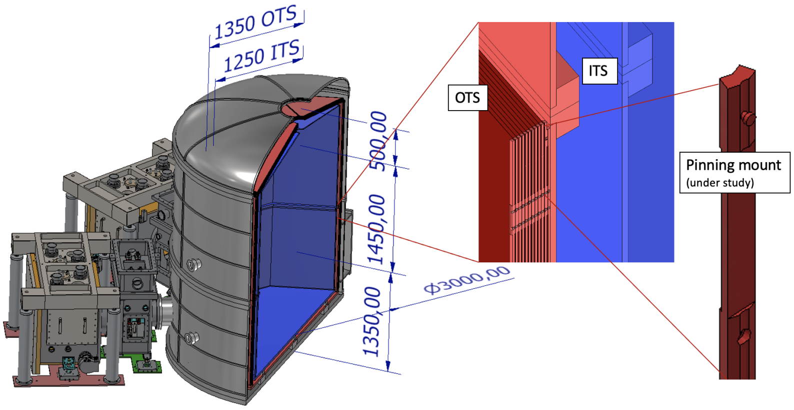

Figure 2: *C75* prototype design, Outer Thermal Shield (OTS) size must be optimised to host the rigid multilayer (RML) radiation insulation under study and Inner Thermal Shield (ITS) size, to allow the payload assembling and the cold finger links to cool down the payload.

payload prototype will be similar to the final one only concerning its size. Nevertheless, given the potentially harmful contamination due to large multilayer surfaces, present in the same volume hosting actual optical elements, the subject of further superinsulation R&D deserves a major effort, leading to actual ET cryostat designs. A dedicated parametrised feasibility study is being performed on RML (Rigid MultiLayer), adopting rigid Al layers separated by insulating rigid mounts 2. The overall modelling takes in account the material of the mounts and the emissivity optimisation, with the aim of reducing the number of layers and the outgassing characteristics.

The cryostat will be installed in a civil infrastructure that which has an overall height under the crane close to 5 m at most and there is not any possibility to design a cryostat with the envisaged access from the bottom flange through a trapdoor. This has two main consequences. The first concerns the cryogenic design. Indeed, both the set of vacuum chamber sections and the the sets of thermal shield sections have to be wisely designed, considering the overall room available and optimising the thermal contacts between isotherm mechanical structures (including the RML). The second concerns the impossibility to install a seismic insulation system to suspend the overall payload. A room-temperature technical chamber at the top of the cryostat vacuum chamber dome will serve to pull-up the payload by a few centimetres from the assembling frame located into the internal thermal shield (ITS). This aspect is not so dramatically crucial, as in our payload design modelling we assume that it is suspended to a high performance seismic attenuation system. We plan to measure the dynamical behaviour concerned by just the mechanical elements involved in heat extraction; they belong to two categories:

- high stress elements, as penultimate mass (usually referred as *marionette* in Virgo and KAGRA cases) suspension, test mass suspension and hydroxide catalysis bonded elements; so far they are envisaged as made of crystalline materials (mainly sapphire, but in principle also Silicon).
- low stress elements, namely heat links, so far envisaged as made of Al6N.

A systematic research dedicated to payload designing is being performed in the context of ARC-ETCRYO tasks and the overall cryostat design is carried out in order to be consistent with it.

3. CAOS

CAOS is the Italian acronym for R&D center for Applications on Gravitational wave and Seismology. The objective of this project at the University of Perugia is to create an international innovative and unique laboratory in which bringing together the skills and the research developed in other national and international laboratories, creating a facility with a 10m-scale interferometer with a 1:1 ET scale passive seismic isolation systems (about 15 m tall) that can serve both as a development test-bench for specific technologies for the third-generation gravitational waves detectors, and as a technological follow-up in other sectors, first of all that of seismology. The nature of the investment, the creation of a laboratory that includes its civil infrastructure is different with respect to ARC-ETCRYO. The relevant aspect is the availability of a space fully dedicated to the seismic isolation hardware servicing and operation. The laboratory is suitable to be gradually populated by apparatuses. Since the seismic isolation system for ET is supposed to be at room temperature for both low-frequency and high-frequency ET interferometers, the lab will host a wide range of possible devices.

3.1 The building

The building (Fig.3), with a square plan of 21 m by 21 m and a total height of about 25 m, is made of a bigger area for the Laboratory itself and a smaller one for other services. The Laboratory is suitable to install three passive seismic attenuation chains, hosted by dedicated vacuum chambers. The initial budget of CAOS is consistent with the construction of two complete towers, fully equipped of digital controls and then capable to constitute the core of a short Fabry-Perot (FP) cavity, but thanks to the room available in the building, also a Michelson interferometer could be hosted in future by means of further investment. The smaller area is divided in four floors, where at the ground level is present a mechanical workshop and the services, on the first floor an electronic workshop and the control room, at the second one a meeting room and some space for the offices for the personnel, while at the third floor is a wide open space for the storage of laboratory equipment and vacuum components. This last floor will be open on the Laboratory itself with the possibility

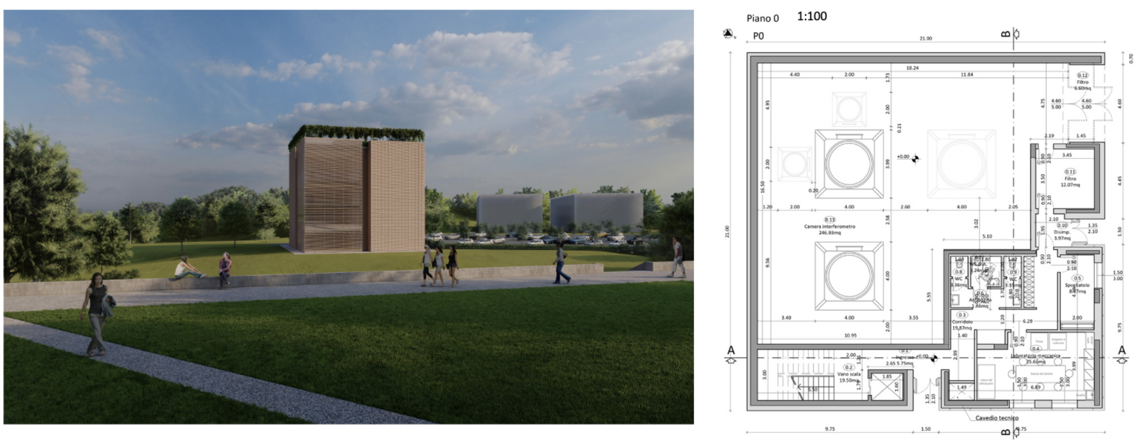

Figure 3: CAOS laboratory at the Perugia University. The building is divided in a large volume to host the 15-m tall passive seismic isolation systems and a smaller one divided in several floors.

to access it with the crane that serves the whole building. The basement of the Laboratory will be seismically decoupled from the rest of the building and strongly reinforced, for hosting the big mass of the vacuum and suspension systems.

3.2 The seismic isolation system

The CAOS Laboratory will be able to host three 15 m tall suspensions as shown in Fig.**??**. At this stage, because of the limited budget and time constrain of the ETIC project, only two suspensions will be realized with the same structure as the Virgo one [6], but with a total high of about 15 m to lower the seismic isolation frequency. A future evolution of the suspensions is foreseen, based on a further investment. The complete mechanics and geometry will be defined in the next months, while for the lower stage suspension the complete design is still under study. The dimension and material of the optics and of the monolithic suspension will be decided in the next months because of its technological evolution, but the goal is to design a complete monolithic silicon suspension.

3.3 The vacuum system

A scheme of the vacuum system is shown in Fig.**??**, it is a standard UHV chamber able to include the whole suspension system similar to the one present already in Virgo, but with two major differences: the lower stage access in Virgo is from below, while in CAOS it is foreseen from the side through a rectangular flange, and the vacuum tube connecting the towers is smaller in diameter (200 mm) but with the possibility to accomplish the 1000 mm tube in future. The inter-axis distance between the two towers is 6.6 m and the towers diameter is 2000 mm. In the final design one of the two towers will be an end mirror one, while the other one will be the beam splitter, for this reason the present FP configuration will be able to easily pass from this configuration to the final one.

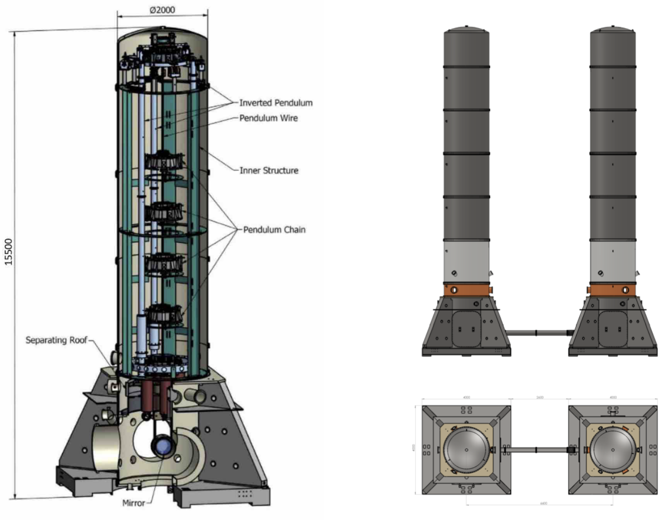

Figure 4: Left: the 15-m tall passive seismic isolation system. Right: scheme of the vacuum system dedicated to host a Fabry-Perot cavity.

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