Politecnico di Torino

PHYSICS

INRIM - Advanced Metrology for physics applications

Funded By	I.N.RI.M. - ISTITUTO NAZIONALE DI RICERCA METROLOGICA [P.iva/CF:09261710017]

Supervisor	TRIGIANTE MARIO - mario.trigiante@polito.it

Contact	Cecilia Clivati (INRiM) (Topic 9, c.clivati@inrim.it) Marco Tarallo (INRiM) (Topic 6, m.tarallo@inrim.it) Michaela Kuepferling (INRiM) (Topic 2, m.kuepferling@inrim.it) Alessandro Sola (INRiM) (Topic 4, a.sola@inrim.it) Carlo Sasso (INRiM) (Topic 8, c.sasso@inrim.it) Andrea Sosso (INRiM) (Topic 3, a.sosso@inrim.it) Cecilia Clivati (INRiM) (Topic 7, c.clivati@inrim.it) Carlo Sias (INRiM) (Topic 5, c.sias@inrim.it) Emanuele Enrico (INRiM) (Topic 1, e.enrico@inrim.it)

Context of the research activity	The Thematic Grant includes 9 research Topics (listed below), with a specific title and proponent Supervisor/s. The applicants have the possibility to identify the specific topic they are interested in.

	Topic 1: Development of a cryogenic quantum computing testbed for the measure, characterization, and validation of superconducting qubits Background: Quantum computing promises a significant increase in computational power for various scientific and commercial applications. Superconducting qubits are one of the most promising platforms for quantum computing. However, their performance is highly sensitive to environmental noise, making it challenging to achieve the necessary levels of coherence and fidelity required for useful quantum computations. Therefore, it is essential to develop reliable and accurate methods for measuring and characterizing the performance of superconducting qubits. Objective: The aim of this PhD project is to design and build a cryogenic quantum computing testbed that can measure, characterize, and validate superconducting qubits. This testbed will be used to evaluate the performance of superconducting qubits under various conditions, including different temperatures, magnetic fields, and noise levels. The testbed will be designed to operate at cryogenic temperatures to minimize environmental noise and to improve the coherence and fidelity of the qubits. Methodology: The project will involve the following steps: • Design and build a cryogenic quantum computing testbed • Fabricate and test superconducting qubits • Characterize the performance of superconducting qubits using the testbed • Develop and implement protocols for measuring and minimizing environmental noise

• Validate the performance of superconducting qubits under different conditions

The outcomes of this project are:

• A fully functional cryogenic quantum computing testbed capable of measuring, characterizing, and validating superconducting qubits

• A detailed characterization of the performance of superconducting qubits under different conditions

• Development and implementation of protocols for measuring and minimizing environmental noise

• Improved understanding of the behavior of superconducting qubits under different conditions

• Potential applications for the testbed in the development of quantum algorithms and quantum computing systems.

Conclusion: The proposed PhD project aims to design and build a cryogenic quantum computing testbed that can measure, characterize, and validate superconducting qubits. The project's expected outcomes include the development of protocols for measuring and minimizing environmental noise and the improved understanding of superconducting qubits' behavior under different conditions. The testbed's potential applications in the development of quantum algorithms and quantum computing systems make it an exciting area of research with promising outcomes.

Topic 2: Development of novel quantum based magnetic field sensors

Magnetic field sensors are ubiquitous in smart mobility applications such as the magnetic encoders able to test the wheel velocity in real time. The most popular magnetic field sensor, based on the Hall effect, is not always appropriate for harsh environments and has a limited sensitivity; novel spintronic sensors based on the tunnel magnetoresistance (TMR) are characterized by much higher sensitivity, however the nano-metric multilayer structure is highly complex to manufacture and large magnetic fields can influence the permanently magnetized reference layer (polarizer), which alters the reading of the sensor [1]. In this project we investigate two promising concepts able to become a disruptive technology: sensors based on the spin Hall magnetoresistance (SMR) and on the magnetic resonance of Nitrogen-Vacancy (NV) centers. These two effects permit to address the need of small sensing areas going from the micrometer down to the nanometer scale and possibly to the atomic scale.

Objective 1: Recently angular sensors and 3D magnetometers based on another spintronic effect, the spin-orbit torque (SOT), were proposed [2,3]. With respect to the TMR, they have a simplified architecture (Hall crosses of heavy metal/ferromagnet bilayers) and the SOT replaces the effect of the polarizer. Recently it was shown that the efficiency of a SOT device can be characterized through the SMR [4], which can be easily measured by electrical means, allowing the development of a novel type of sensor. The aim of the project is to develop a SMR prototype sensor from the deposition of the layers, the lithographic fabrication to the testing in a real case.

Objective 2: NV centers in diamond can be employed to measure a magnetic field because of their magnetic resonance properties [5]. In principle, this effect allows us to reach the ultimate atomic scale resolution by employing the single photon fluorescence coming from a single NV center. In practice, it is exploited by using optically probed diamond nanocrystals or microstructures as sensing elements. The expected high sensitivities of the magnetic field measurement [6] were already demonstrated and the aim of the project is to improve and assess the sensitivity by using quantum optimal control [7] and quantum logic schemes that use the Nitrogen nucleus as an ancillary Qubit [8].

Objective 3: Both prototype sensors will be tested in practical conditions, as for example the reading of the magnetic field generated by magnetic encoders of the type used in the electric mobility field, and their performance will be compared.

[1] P. Ripka and M. Janosek, IEEE SENSORS JOURNAL, 10, (2010)
[2] Z.Luo, et al., APL 112, 262405 (2018)
[3] R.Li et al., Nat. Electron. 4, 179–184 (2021)
[4] A. Magni et al. IEEE Trans. Magn. 58, 4400205 (2022)
[5] Rondin et al 2014 Rep. Prog. Phys. 77 056503
[6] Moreva et al 2020 Phys. Rev. Appl. 13, 054057
[7] Poulsen et al 2022 Phys. Rev. B 106, 014202
[8] Arunkar et al 2022 arXiv:2203.12501

Topic 3: Quantum Volt

In science and technology the most accurate measurements are derived from electrical standards. The central role of the electrical quantities is also motivated by the high accuracy of quantum devices based on fundamental constants of physics. INRiM has long been engaged in research on devices and novel measurements methods.

The doctorate is aimed at forming a highly qualified scientist in Primary Quantum Metrology, targeted to a research career in National Metrological Institutes, as well as to manage a secondary calibration laboratory or a metrological lab in industry.

To mention a few scientific objectives:

• engineering He-free Josephson standards with advanced cryogenic temperature controls;
• realization of an optical driven Josephson standard;
• study of high speed biasing techniques and dedicated analog to digital conversion solutions

The student will be involved in all experimental activities of the Josephson laboratory, partly on leave in laboratories of a foreign Institute.

Topic 4: Heat flux sensors based on Nernst effects

The need to increase the efficiency in processes like thermal cycles, computing and energy storage and transportation has recently increased the focus on heat management, extending the field of interest to the reduced dimensions. In this framework, the design of thermal sensors based on new concepts towards higher versatility and reliability is of great interest for research and industry and has to be supported by metrological traceability. As a heat flux sensor, thermoelectric thermopiles represent an optimal choice in terms of sensitivity. However these devices are plagued but several drawbacks, as for example they are rigid structures, their sensing area has geometrical constrains and the miniaturization of devices is limited. A promising way to overcome these limitations is the realization of active sensing surfaces based on transverse thermoelectric effects [1], in particular the Nernst effect of metals and the anomalous Nernst effect (ANE) of ferromagnets [2]. Although the Nernst effect is smaller then the Seebeck effect, its geometry permits the realization of a sensor as a uniform surface, without the need of the two planes of junctions. The Nernst geometry, in which the thermoelectric voltage is perpendicular to the heat flux, simplifies the architecture of thermoelectric generators and therefore allows for higher integration towards the design of nanostructured devices and MEMS. A further advantage is the use of ANE materials, i.e. ferromagnets with a large remanence and a high coercivity such as MnBi [3,4].

Moreover, the possibility of using magnetic nano-particles and thin films as active elements allows the realization of flexible sensors, nano-structured devices and heat-sensitive coatings for sensors and energy harvesting devices.

Objectives	The main objectives of the research on transverse thermoelectric effects are the optimization of the properties of materials for the preparation of devices, the experimental investigation of their transverse thermopower and the development of models related to the experimental findings. These activities can support the investigation on more fundamental and exotic phenomena like the thermal counterpart of the quantum Hall effect that is expected to be found in Corbino geometry in a 2D electron gas (2DEG) [5]. [1] Boona, Stephen R., et al. Journal of Applied Physics 130.17 (2021): 171101 [2] Mizuguchi, Masaki, and Satoru Nakatsuji. "Energy-harvesting materials based on the anomalous Nernst effect." Science and technology of advanced materials 20.1 (2019): 262-275 [3] He, Bin, et al. "Large magnon-induced anomalous Nernst conductivity in single-crystal MnBi." Joule 5.11 (2021): 3057-3067 [4] Sola A., et al. AIP Advances 13, 035231 (2023); https://doi.org/10.1063/5.0135578 [5] Kavokin, A. V., et al. Proceedings of the National Academy of Sciences 117.6 (2020): 2846-2851 Topic 5: Quantum technologies with atom-ion mixtures Experimental quantum physics relies on the ability to realize and control quantum systems that can be isolated from the environment. Among the many physical systems that are currently studied, ultracold atoms and trapped ions are probably the most formidable sources of coherent matter available in a laboratory. In a hybrid quantum system of atoms and ions, ultracold atoms and trapped ions are combined in a single experimental apparatus, thus realizing an innovative platform to experimentally investigate open problems of quantum physics from a new standpoint. The aim of the project is to implement quantum technologies in a novel atom-ion hybrid system in which full control of atom-ion interactions is achieved by entering in the so-far unexplored regime of ultracold temperatures. The key point of our strategy is to use a new type of ion trap that will allow us to realize for the first time an energetically closed atom-ion system, so that atom-ion physics in the quantum regime will be explored. In this regime, the atom-ion mixture will be used to realize quantum simulations of impurity physics model, such as the Anderson orthogonality catastrophe, in which the ion plays the role of a controlled impurity immersed in a many body state composed by a few thousands of ultracold atoms. Additionally, we will explore the formation of two-dimensional crystal of ions. Currently, all quantum computers and simulators based on trapped ions work with one-dimensional string of particles. However, this limits the number of qubits that can be encoded. A possible way out is to form two-dimensional crystal of ions, in which a much larger number of particles can be confined. However, this search has been limited so far by heating effects occurring in conventional ion traps. In our setup, we have developed an innovative ion trap that aims at surpassing current limitations, thus making it possible to form ultracold two-dimensional crystal of ions. During the Ph.D. project, the formation of these innovative quantum hardware will be studied, including the role of the ultracold atoms as an ultracold bath that can continuously cool the two-dimensional crystal. Moreover, fundamental thermodynamics effects, like orientational melting of the crystal, will be simulated by looking at the role of quantum fluctuations. All these experiments will be performed in an experimental apparatus that has been recently developed by INRIM researchers at LENS, in Sesto Fiorentino, Italy. This apparatus is the first one in Italy for the production of trapped ions. "

Topic 6: Engineering quantum states in hybrid atom-cavity coupled systems for quantum enhanced metrology

The interplay between a quantized photonic field and collective atomic states can be engineered to investigate and study new methods to progress optical clocks beyond their classical limits towards a new generation of quantum-enhanced optical clocks.

State-of-the-art optical clocks are now limited by the thermal noise from the local laser oscillator and the quantum projection noise due to destructive measurements. Cavity-coupled atomic ensembles can be measured by the detection of the quantum state of the cavity field, while quantum backaction ensures the creation of quantum-correlated collective states with uncertainty lower than the classical (shot-noise) limit, i.e. spin squeezed states. On the other hand, the strongly coupled atomic ensemble can supersede the coherence of the cavity itself and generate laser radiation with spectral purity beyond the technical limits (a.k.a. superradiance) imposed by mirror displacement noise, enabling the prospect of an ""active optical maser"".

We propose the experimental study of an hybrid atom–cavity coupled system based on laser-cooled ultracold strontium atoms and high-finesse resonator working at the intercombination and clock transitions at 689 and 698 nm respectively. The clock setup also includes the development of ultra-stable laser sources and spectral purity transfer techniques.

Hence, the candidate will be faced with the challenges of an ultra-cold atomic experiment coupled with a high-finesse optical resonator generating non-linear and non-classical features with the prospect of new engineered light-atom coupled states useful for quantum matter, quantum information, quantum metrology and sensing.

Topic 7: The optical frequency comb: a crucial tool in quantum technologies

Octave-spanning mode-locked lasers (optical frequency combs) produce femtosecond-long optical pulses at microwave repetition rates and coherently bridge the optical and radio-frequency electromagnetic spectrum. 20 years after their Nobel-winning demonstration, these peculiar features found application in disparate fields, from high-resolution spectroscopy for fundamental physics and chemical sensing, to laser ranging and LIDAR, attosecond science and atomic clocks for both Earth and Space applications [S. Diddams, Science 369, 267 (2020)]. In addition to being at the heart of such applications, the optical comb is also an essential tool for the development of emerging quantum technologies based on optical clocks, chip scale photonics, single-photon transmission for the quantum distribution of encryption keys. In these applications, it enables accessing unconventional states of light for operating and characterizing devices.

The Quantum Metrology and Nanotechnology division at INRIM develops narrow linewidth laser sources for spectroscopy and operates atomic clocks based on cold cesium, ytterbium and strontium atoms, as well as compact rubidium cell clocks; it is developing an integrated clock prototype making use of structured chip-scale devices; it built and operates a thousand-km fiber link for ultrastable lasers distribution and remote clock comparisons and demonstrated the application of these technologies to the quantum key distribution over fiber [M. Pzzocaro et al., Nat. Phys. 17, 223–227 (2021); C. Clivati et al., Phys. Rev. Applied 18, 054009 (2022)].

This research proposal focuses on the use of mode-locked-lasers frequency comb in all such applications. The candidate will learn its use in precision-frequency-measurements and comparisons between various species of atomic clocks, both within iNRIM and in the framework of international optical clock comparisons campaigns in collaboration with other European Metrology Institutes; he/she will use the optical comb to support the realization and characterization of microresonator-based chip-scale atomic

clocks and will investigate its use for multimode single-photon transmission over fiber, with application to quantum key distribution.
In each application, the candidate will be introduced to the physical context and will be responsible for the design and implementation of experimental setups for light beam manipulation and analysis, both including free-space and fiber optical circuits, and electronics chains.
This activity will provide strong capabilities in precision frequency measurements, optical beam manipulation, nonlinear optics and integrated photonics. Based on the candidate attitude, the project also offers the possibility to focus on aspects related to digital electronics for the control of optical signals, or on advanced data processing for real-time generation of optical timescales based on the optical comb outputs.
Topic 8: X-ray phase contrast imaging
The objective of the PhD will be the development of X-ray phase-contrast tomography to investigate the possibility to use it either as a research tool (as in the field of cultural heritage or bio-medical studies) or industrial exploitation (for non-destructive testing or the quality/failure inspection in a production line). In the PhD course, a set of X-ray phase-contrast imaging techniques using conventional X-ray sources will be investigated. To extract the refraction index of the medium traversed by the X photons, the imaging techniques will use both grating interferometry of the Talbot-Lau type and speckle interferometry. [1,2]. First, it will be necessary to gain control of the different imaging techniques and weigh their advantages and drawbacks, with an eye to their use in industrial applications. Next, the work will look at the realization of prototypes reaching at least a TRL 6. With this aim in mind, the PhD student will collaborate with two Italian companies, stakeholders in the field of X-ray computed tomography (XCT): XNext SpA, involved in the production of systems for X inspection on production lines; Gilardoni SpA for the production of tomographic systems and customized X-ray sources.
The main activities carried out will be:
a) studying the scientific literature on phase-contrast imaging to acquire a knowledge of the techniques, their practical realization and the mathematical tools necessary to solve the relevant inverse problems;
b) numerical implementation of the models and algorithms. These tools will be applied first in the optical range to increase confidence in this theory;
c) production of the absorption/phase gratings and random masks by the nanofabrication facility PIQUET hosted inside the INRIM’s campus through a funded NextGen project;
d) realization of a test bench where to characterize the different techniques to estimate their pros and cons, also concerning the possibility to use them in an industrial application (costs, flexibility, speed, etc.), in collaboration with the companies involved;
e) study and evaluation of the development of custom X-ray sources for these applications;
f)development of a roadmap to the engineering and the increase of their TRL to 7/8
The PhD student will have the possibility to develop a set of theoretical-practical competencies as:
a) the use of X radiation and the related technology for the inspection of materials and substances containing atoms with low atomic number. These technologies can be potentially employed in the field of food safety, non-destructive testing, bio-medical applications, and systems for quality monitoring in a production line or the security field.
b) the nanofabrication using lithographic techniques of gratings with a high aspect ratio and absorbing power of the X-rays
c) the mathematical tools and algorithms for tomographic reconstruction.

	[1] T Weitkamp et al., Optics Express, 13, 6296, (2005) [2] K M Pavlov et al., PhysRevApplied, 13, 054023, (2020) Topic 9: Chip-scale optical clocks for space applications Today, atomic clocks based on optical transitions reach unprecedented accuracy at the 1E-18 level, that translates into improved measurement capabilities and in turn enables steps forward in fundamental physics experiments on Earth and in Space, precision atom spectroscopy, satellite navigation. Atomic clocks are based on a laser or microwave oscillator that probes an atomic ensemble and is kept on resonance with it by active feedback, and a clock-work that coherently down-converts the local oscillator field into a usable radiofrequency output. As these devices are mostly based on bulky and lab-scale equipment, research focuses now on miniaturization to enable full exploitation of their performances in out-of-lab applications. This requires on-chip integration of the laser source and the related phase-manipulation equipment, of the atom confinement region and the clockwork. While architectures for the atom confinement and optical-to-microwave conversion based on microresonator Kerr frequency combs have been demonstrated [Z. Newman, Optica 6, 680 (2019)], several steps are yet to be achieved and require hybrid research at the forefront of laser physics and nonlinear optics, atom physics and material science and technology. The present project sets in this framework and concerns the realization of an integrated optical clock prototype, based on an infrared laser stabilized to the two-photon transition in Rubidium atoms and its down-conversion to a radio-frequency output using a self-referenced microresonator Kerr frequency comb. The activity includes the realization of the clock's building blocks and the optical and electronics equipment for the laser beam manipulation, as well as the study of strategies for interrogating atoms, accessing and stabilizing nonlinear optical soliton regimes. The characterization of the realized clock in terms of accuracy, stability and sensitivity to external environment will finally be pursued. Based on the candidate attitude, the project also offers the possibility to perform fundamental studies on light-resonator interactions, design of novel atom-confinement schemes and microresonator geometries, that in the future could be fabricated and tested in collaboration with the INRIM Piquet facility for micro and nanofabrication [https://piquetlab.it/]. "

	Topic 1 The successful candidate will need a strong background in quantum mechanics and experimental physics, experience in designing and building complex experimental setups, programming (Phyton preferred), and data analysis. They should also have expertise in measurement techniques such as microwave spectroscopy, time-domain reflectometry, and noise spectroscopy, as well as experience working with superconducting materials. Strong problem-solving and critical thinking skills are required, particularly in troubleshooting experimental issues and optimizing experimental parameters. The ability to work independently and collaboratively with other researchers and engineers is essential. Topic 2 Master in physics or engineering; experience in programming (Python, C++, etc.) and electronics; attitude towards experimental work The student will perform experimental laboratory activity, preparation of patterned magnetic multilayers and HF antennas in a clean room environment, electrical measurements for device characterisation and NV magnetometry. The student will be involved in the sensor design, construction, assembly and testing. To this aim the student should take active

Skills and competencies for the development of the activity	part in a research team composed by researchers and PostDocs working on spintronics and quantum sensing by NV centers. At the end of the PhD the student should have acquired experimental skills as well as theoretical understanding. Topic3 Master degree in Physics or Electronics Engineering or Energy and Nuclear Engineering Basic electronics Familiarity with at least one programming language Interest for laboratory/experimental physics work" Topic 4 A scientific master is required (physics, engineering, material sciences) with a prevalence of experimental subjects. A good attitude for the experimental activities is required for this project, ranging from the preparation of materials to the development of specific measurement systems and code for data analysis. These skills have to contribute to the achievement of independence in the laboratory. Topic 5 The most important quality for a Ph.d. candidate is her/his strong motivation in learning new physics and new experimental methods. Basic knowledge in either electronics, optics or programming (i.e. Mathematics, C/C++, etc.) would result in a smoother approach to the project, but this should not be consireded a pre-requisite. The thesis work will be carried out in a small team (currently formed by the PI, one researcher and two more senior Ph.D. students) and the student will be supervised and trained in learning all the techniques that are necessary for the lab operation. Considered the research topic, a master thesis in Physics or Engineering is preferrable. Topic 6 Scientific skills: Quantum mechanics, Optics, Electronics, Data analysis. Favourite computer skills: basic knowledge of Python. Latex. Topic 7 The activity is predominantly experimental. Interest in experimental laboratory activity is thus required. Basic background in optics and laser physics, signal processing and spectral analysis. Basic knowledge of a programming language for data analysis and control of lab equipment (Python preferred but not strictly required). The motivated candidate will have the chance to fill initial background gaps during the activity. Basic knowledge of digital electronics and FPGA programming could be exploited in this research, but is not mandatory. Topic 8 Due to the wide spectrum of applications in different fields of the phase-contrast imaging, we think that the activity could be of interest and tackled by students having different scientific background but with a strong interest in developing technological tools for their activity. One of the following master degree is welcome: Physics, Material Science, Biomedical engineering, Industrial Production and Technological Innovation engineering, mechanical engineering. Interest in experimental job, software for applications that require test