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### 4DPHOTON: INNOVATIVE TECHNOLOGIES FOR "PHOTOGRAPHING" SINGLE PHOTONS

*Interview with Massimiliano Fiorini, Associate Professor at the University of Ferrara, INFN researcher and winner of an ERC Consolidator Grant in 2018*

*In autumn 2018, Massimiliano Fiorini, Associate Professor at the University of Ferrara and INFN researcher, was awarded an ERC Consolidator Grant worth 1,975,000 euros, with the 4DPHOTON project (Beyond Light Imaging: High-Rate Single-Photon Detection in Four Dimensions). The project envisages the development of a tool to detect single photons, in time and space, with combined resolutions hitherto never obtained.*

*The European Research Council funding, awarded each year to outstanding researchers of any nationality or age who have at least 7 and up to 12 years of post-doctoral experience and a promising academic CV, is targeted at implementing high-risk high-gain projects and strengthening recipients' research groups.*

*The project proposed by Massimiliano Fiorini envisages the development of an innovative tool able to detect photons with spatial resolutions of just a few micrometres and temporal resolutions of some tens of picoseconds, with flows of up to 1 billion photons per second with negligible background noise. It is a technological leap that will have a great impact in high energy physics, but also in biology and in many other disciplines. The project, which will be developed over five years, will be carried out by scientists from INFN Ferrara division, the University of Ferrara, and CERN in Geneva (with the application of the new detector in future experiments at the Large Hadron Collider).*

*We asked Massimiliano Fiorini to explain the investment strategy for the grant that he was awarded, as well as the aims and development prospects of the project.*

**In your opinion, why was your project considered promising by the ERC?**

The project envisages the development of very innovative technology for the imaging of single photons, with a high potential for impact in many disciplines. I believe that the ERC panel positively evaluated not just the detector's applications in the field of particle physics, but also its repercussions in several other research

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fields, like life sciences, quantum optics, and others. In particular, the project envisages the use of this detector to identify charged hadrons (charged particles made of quarks, like protons) in experiments with high-luminosity accelerators (accelerators that are capable of producing a great number of interaction events per second) by taking advantage from the Cherenkov effect, which takes place when a charged particle travels in a medium that is not the vacuum at speeds higher than the light speed in the same medium. The Cherenkov ring of light is produced when a small number of photons distribute themselves in a ring in the detector's focal plane. By measuring the radius of these circles, you can reconstruct the particle's speed and, when you also know its momentum, you can identify it. With the increase in accelerators' luminosity, and the consequent increase in the number of particles that accumulate in the detectors, the addition of the temporal coordinate, with an accuracy of tens of picoseconds, is essential. It is fundamental because it allows researchers to group the particles that come from the same collision event in the accelerator (and which, therefore, arrive simultaneously) and to discard those that arrive at different times and therefore belong to different events.
In addition, the detector will be used in the field of fluorescence microscopy to explore new imaging techniques, thanks to the unique combination of excellent temporal and spatial resolutions in a single tool capable of detecting single photons at a high rate. This detector will be used, for example, to measure the average half-life of fluorescent markers, special molecules used in microscopy techniques that - thanks to their fluorescence - permit to visualize particular biomolecules to which they bind chemically. A very precise determination of the temporal coordinate, together with the spatial one, allows us to tell the difference between different markers that have similar fluorescence spectra but different average half-lives. Furthermore, the temporal coordinate will allow us to study the temporal evolution of biochemical processes on timescales of tens of picoseconds, opening new possibilities for research.

**The technology that you are developing promises, therefore, to "photograph" single photons with an exceptional resolution in time and in space. What differentiates it from existing technologies?**
The detectors currently available, capable of detecting a single photon, can be grouped into several categories according to their performance. There are detectors that are capable of measuring the arrival time of a photon with a high resolution, but with little precision in terms of its position; or detectors that have a high spatial resolution but low temporal precision; or detectors with good spatial and temporal resolutions, but which are very “noisy”.
The detector we proposed is based on a "hybrid" approach: it is constructed from components that come from different technologies, each of which is optimised to obtain the best possible performance. The heart

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of this tool is an integrated circuit developed in 65nm CMOS (Complementary Metal-Oxide Semiconductor) technology, capable of processing signals and of measuring position and time using hundreds of thousands of electric channels that work independently. This technology, which is based on silicon and was developed for applications related to particles' tracking and radiation dosimetry, is embedded within a vacuum tube, equipped with a photocathode (which allows a photon to be converted into an electron) and an electron multiplier, which was initially developed for night vision.

**How are you investing the funds and what results do you expect in five years? What are the main difficulties you think you will have to face, in terms of technological limitations but also obstacles in the research as well as personal and team motivation process?**
The funds will be dedicated to strengthening the research group with at least two post-doc positions. At the moment, the group is composed of researchers and technologists of the Ferrara INFN division, the University of Ferrara, and CERN. And, of course, they will go towards constructing the detector, the electronic reader and the data acquisition system. The main difficulty will be that of being able to develop a detection system for single photons with the anticipated performance. This entails improving the performance of every single component that the final system will be composed of, working both with partners of other research institutes and with industrial partners, to whom the detector's assembly will be entrusted.

**You are also national head of the AEQUO experiment, which is financed by INFN and carried out in collaboration with the department of morphology, surgery and experimental medicine at the University of Ferrara. It is, then, an interdisciplinary project: what exactly is this project about?**
In 2017, I submitted the AEQUO experiment proposal to the INFN 5th National Scientific Committee, and it was approved and financed. This project envisages collaborating with biology and medicine colleagues to develop a data acquisition and detection system for the measurement of visible photons emitted in luminescence processes for biomedical applications. It's all about measuring the concentration of calcium ions in intracellular compartments using the photoprotein aequorin, which has the property of emitting photons when it binds to calcium ions. We have developed a first tool that allows us to very precisely measure the number of photons emitted by cell samples, and we are developing another to improve sensitivity in measuring samples with a limited number of cells, like, for example, with those taken for biopsy. Measuring calcium concentration is hugely important because it allows us to study the physiological state of the cell: the concentration of this ion has an essential role in the regulation of cell death, and these measurements are often used - for example - in research for anticancer drugs.

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**Your research, therefore, has promising applications in fields of great public interest and social utility. Do you think it is possible to bridge the inevitable knowledge gap between researchers and non-experts, in order to create greater awareness regarding the themes and repercussions of scientific research?**

One of the most important tasks for us as researchers is certainly that of the dissemination of research results to young students and to the public in general. It is essential that people are made aware of the importance of research, both fundamental research and applied research. The results of the first, in particular, are typically more difficult to be understood by non-scientists, and explaining complex arguments in a thorough but clear way is not an easy task. It is particularly important, therefore, to organise public engagement events. For some years, I have been involved in organising the Ferrara edition of the International Masterclass, an initiative that is organised, at an international level, by the International Particle Physics Outreach Group (IPPOG) and, in Italy, by INFN with a large number of participating divisions. Since its first edition, in 2005, the initiative has had great international success, and, in Ferrara, around 160 high school students participate every year. They come from different provinces and regions and are invited to play the role of an elementary particle physics researcher over a day. Moreover, I enjoy collaborating with many high school teachers in the Ferrara area in the context of particle physics dissemination activities.

Public engagement is, in addition, evaluated as an important activity for all projects financed by Europe. In this context, I envisage to organise specific activities about my project that aim to show how the investment in frontier, *high-risk high-gain* research is of vital importance for the progress of society.

**The ERC Grant is a longed for recognition, which can give great boost to the carrers of researchers. What would you recommend to a young scientist willing to udertake a research path?**

The evaluation of an ERC project is a competitive process in which a great weight is given to the CV of the proposer, in addition to the idea underlying the project. It is very important for a young researcher to experience recognized responsibilities in experiments or scientific collaborations, in addition to managing research projects. It is also important, I believe, to apply to competitive calls for the funding of research projects as soon as the opportunity arises. For example, for those involved in technological or applied research, an excellent opportunity is represented by the grants for young researchers of the INFN 5$^{th}$ National Scientific Committee. Moreover, it was very useful to me to talk with some of the winners of previous ERC calls. They proved to be very helpful and generous with advices. One of these was particularly valuable: it suggested to address to the External Funds Service of the INFN, which followed me with great competence in the various phases of the proposal and interview preparation, and in the following post-approval phase. ■