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The INFN-LNF present and future accelerator-based light facilities

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Abstract The INFN-Frascati National Laboratory (LNF) is nowadays running a 0.51 GeV electron-positron collider, DAΦNE, that also represents the synchrotron radiation source of the beamlines of the DAΦNE-Light facility. Not being DAΦNE dedicated to synchrotron radiations activities, the DAΦNE-Light facility can use it mainly in parasitic mode. Particle accelerators and high energy physics (HEP) have been and are the main core of the LNF research activity, but like other HEP international laboratories also LNF is now moving in the direction of developing a dedicated free electron laser (FEL) user facility, EuPRAXIA@SPARC_Lab, based on plasma acceleration. This new facility in the framework of the EuPRAXIA (European Plasma Research Accelerator with eXcellence in Applications) EU project should produce FEL radiation beams for a wide range of applications using a smaller accelerator compared to actual radio frequency-based accelerator sources dimensions.

1 Introduction

INFN or Istituto Nazionale di Fisica Nucleare [1] is the Italian national public research institution devoted to the study of the fundamental constituents of matter from an experimental and theoretical point of view. In the 50s, INFN built the first of its four big National Laboratories, the Frascati National Laboratory (LNF) [2], to host a 1.1 GeV electron synchrotron. The activity of LNF in the accelerator field went on with the development of the first prototype of electron-positron collider, AdA (Anello di Accumulazione or storage ring) that was the starting point of storage rings [2]. After the colliders, AdA and ADONE [2], the present electron-positron collider is DAΦNE (Double Annular Φ-factory for Nice Experiments) [3] having low energy (0.51 GeV) but very high electron current (I_e >1.5 A) that makes it also a high flux synchrotron radiation source.

LNF has also a long tradition in the use of synchrotron radiation and the construction of facilities dedicated to its use. This tradition started with ADONE [4], after its life as high energy physics (HEP) accelerator ended, and continued with DAΦNE. Being DAΦNE still in use as electron-positron collider, its use as synchrotron radiation source is mainly in parasitic mode with the assignment of dedicated periods when needed.

The actual synchrotron radiation facility, DAΦNE-Light [5], that will be described in the next section, hosts more than 30 experimental teams per year, in presence or mailing-in their samples, coming from Italian, European and non-EU countries, Universities and Research Institutions and third parties.

Concerning new radiation sources and advanced accelerators concepts, the LNF laboratory has developed also the SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam) [6] test facility that consists in a conventional high brightness radio frequency (RF) photo-injector, SPARC, and a multi-hundred terawatt laser, FLAME (Frascati Laser for Acceleration and Multidisciplinary Experiments) [7]. Having SPARC_LAB an energy per pulse up to 40 μJ and a pulse duration shorter than 100 fs rms, these characteristics make it also an appealing source for nonlinear THz spectroscopy [8].

Using this test facility, within the EuPRAXIA EU project [9] whose aim is the realisation of compact European plasma accelerators, experiments have been performed to demonstrate the quality of beam-driven plasma wakefield accelerators (PWFA), to investigate the possibility to realise an ultra-bright linac with plasma accelerator modules and a multi-disciplinary facility with a free electron

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laser (FEL) in the soft X-ray region. This research integrated in the framework of the EuPRAXIA@SPARC_LAB project [10] that has been included in 2021 in the European Strategy Forum on Research Infrastructures (ESFRI) roadmap [11] will bring to the realisation of a plasma-based user facility at the LNF that will be described in the next sections together with some focused scientific applications.

2 The present status of the INFN synchrotron light facility

DAΦNE-Light [5] is the INFN-LNF synchrotron radiation facility that uses the high photon flux, in the energy range that goes from IR to soft X-rays, produced by the DAΦNE electron ring. This small facility has five beamlines that run independently and a white beam XUV branch line. Of these five beamlines, only three are opened to external users. In 2021, the facility hosted 35 experimental teams, some in presence and some using the sample mail-in service, offered due the COVID-19 travel restrictions from 2019 and still being used. The DAΦNE-Light facility has been successfully involved in EU projects offering transnational access (TNA) to external users the last one being the CALIPSOplus project [12] ended in October 2021.

Of the three beamlines opened to external users, the one mainly requested is the SINBAD (Synchrotron Infrared Beamline At DAΦNE)-IR beamline that was also the first Italian beamline operating in the infrared range [5]. Its end station is a Bruker Vertex 70v interferometer coupled to a Hyperion 3000 IR microscope that was upgraded with a high-resolution visible camera, together with a faster image acquisition board. The most required detector is the 64x64 pixel focal plane array (FPA) one to perform chemical imaging with diffraction-limited spatial resolution. Also in the last years, many important studies have been performed in different fields including cultural heritage [13], biology [14, 15] and material science [16].

Both the DXR2 UV-VIS and DXR1 soft X-ray beamlines have one of the DAΦNE 6-pole wigglers as synchrotron radiation source [5]. The DXR2 beamline covers the energy range from 2 eV to 10 eV, and it can work using the white beam or two different monochromators depending on the energy range of interest [5]. The DXR1 beamline is dedicated to X-ray absorption spectroscopy (XAS) and works in the energy range 900 eV–3000 eV [5, 17].

The last two XUV LEB (30 eV–150 eV) and HEB (60 eV–1000 eV) beamlines and the WINDY (White lIgth liNe for Desorption Yields)) white beam branch line of the HEB beamline collect the radiation produced by a bending magnet, are dedicated to surface studies and are still under commissioning. Two end stations equipped to perform X-ray photoelectron spectroscopy (XPS) and secondary electron yield (SEY) studies are already in use [5].

2.1 DAΦNE-Light: some highlights

Improving tools available to the scientific community for medical diagnostics is one of the objectives of the research carried out by INFN also through projects related to the physics of accelerators. The SINBAD-IR beamline was used for the study of materials including biological tissues, to identify their characteristics and define new strategies for the diagnosis and treatment of tumours. Researchers from the Institute of Nuclear Physics, Polish Academy of Sciences have developed an innovative methodology for diagnosis of early head and neck cancers [15]. Their studies explore the potential of Fourier transform IR (FTIR) and Raman spectroscopies to study the biochemical alterations responsible for the development of these types of cancers. The main finding of the research was that within tumour tissues (see Fig. 1), there are regions that differ significantly in biochemical content, identifying the crucial role of lipids in physiology and carcinogenesis. These findings are particularly important for timely and accurate diagnosis and for guiding appropriate treatment decisions which can reduce the chance of recurrence [15].

Of great importance is also another study performed at the SINBAD-IR beamline related to 2D functional materials that have induced a growing interest on the possible extension of their properties to three-dimensional structures [16]. The random light scattering of a three-dimensional graphene network achieved from the interconnection of high-quality layers of graphene was characterised in the THz to UV range. The optical properties of these 3D networks can be useful in the development of new

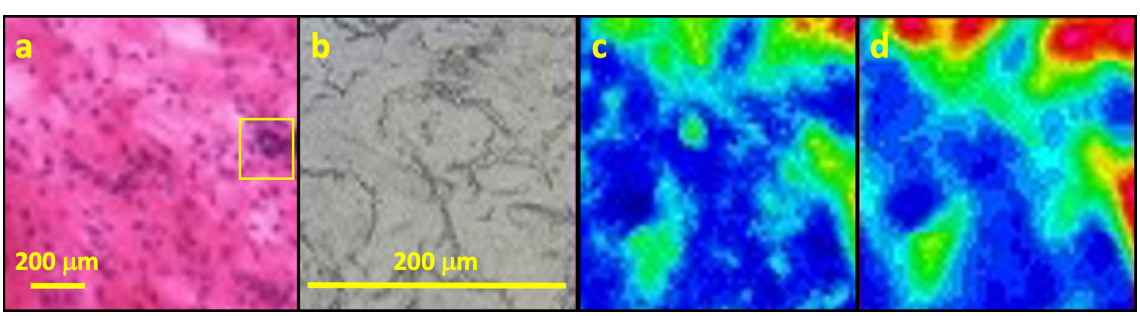

Fig. 1 Microphotographs of a stained tumoural tissue biopsy with different magnifications **a**, **b** and FTIR chemical map distributions of **c** lipids (vCH_2/CH_3) and of **d** proteins (amide I and II) related to the same area shown in panel **b**

optoelectronic devices having observed, in this specific case, a behaviour related to the generation of a high-pass optical filter. With the study performed, it was demonstrated that the observed behaviour came from the random scattering due the pores and branches present in the graphene 3D structure [16].

3 Future INFN accelerator based light facility

The LNF SPARC_LAB [6] research team has recently demonstrated that plasma-based acceleration technique can produce sufficiently high-quality particle beams able to drive a FEL in SASE (self-amplified spontaneous emission) and seeded configurations [18]. This research paves the way to the realisation of compact particle accelerators that can be used for research in different fields but also in other contexts like hospitals and industries. Plasma-based accelerators represent a revolution in the field of particle accelerators giving the possibility to let particles reach high energies in short distances. Despite the high acceleration gradients produced in a plasma (up to three orders of magnitude higher than the conventional machines based on RF technology), their use has been limited by the low quality of the beams produced. At SPARC_LAB for the first time, using a high-quality beam, accelerated by a plasma wave, a FEL coherent radiation in the infrared range was generated. This result was achieved using a 3-cm-long capillary where a plasma was created, ionising hydrogen gas using a high voltage discharge, and after two electron bunches were injected, the first one used as driver to excite the plasma accelerating wave and the second as witness to be accelerated [18]. The high quality of the witness at the entrance of the plasma was preserved along the acceleration process and, in addition to the high current, was capable of driving a FEL to generate coherent light pulses that reached the energy of 30 nJ. The achieved result has not only a great scientific relevance, but represents also a milestone towards the realisation of the EuPRAXIA EU project [9]. This project yearns for the construction of research infrastructures addressed to users, based on plasma acceleration like the LNF EuPRAXIA@SPARC_LAB [10] facility financed also by a contribution of the Italian Ministry of Research and University (MUR) and included in the ESFRI, the EU strategic forum for research infrastructures, roadmap [11]. The EuPRAXIA@SPARC_LAB facility, whose schematic view is shown in Fig. 2, 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. The infrastructure will be user-oriented, and at the forefront of new acceleration technologies. EuPRAXIA@SPARC_LAB is conceived as an innovative and evolutionary tool for multi-disciplinary investigations in a wide field of scientific, technological and industrial applications. Looking at Fig. 2, from left to right, one can see a 55-m-long tunnel hosting a high brightness 150 MeV S-band RF photo-injector equipped with a hybrid compressor scheme based on both velocity bunching and magnetic chicane. The energy boost from 150 MeV up to a maximum of 1 GeV will be provided by a chain of high gradient X-band RF cavities [10]. At the linac exit, a 5-m-long plasma accelerator section will be installed, which includes the plasma module ($\backsim$ 0.5 m long) and the required matching and diagnostics sections.

After a 40-m-long undulator hall, where the undulators chain will be installed, there will be a 31-m-long photon diagnostic section and at the end the experimental hall. Additional radiation sources as betatron and gamma-ray Compton sources are foreseen. In a dedicated space, the 300 TW FLAME laser that in the future can be upgraded to 500 TW will be installed. The plasma accelerator module can be driven either by an electron bunch driver (PWFA scheme) or by the FLAME laser itself (LWFA or laser-driven scheme). A staged configuration of both PWFA and LWFA schemes will be also possible in order to boost the final beam energy to 5 GeV. In addition, the FLAME laser will also be used to drive plasma targets to produce other usable secondary particle sources. Using the studies performed at SPARC_LAB, within the EuPRAXIA collaboration [9], the technical design report of the beam-driven plasma wakefield accelerator giving a FEL emission in the soft X-ray region is being prepared. Some specific tests are ongoing

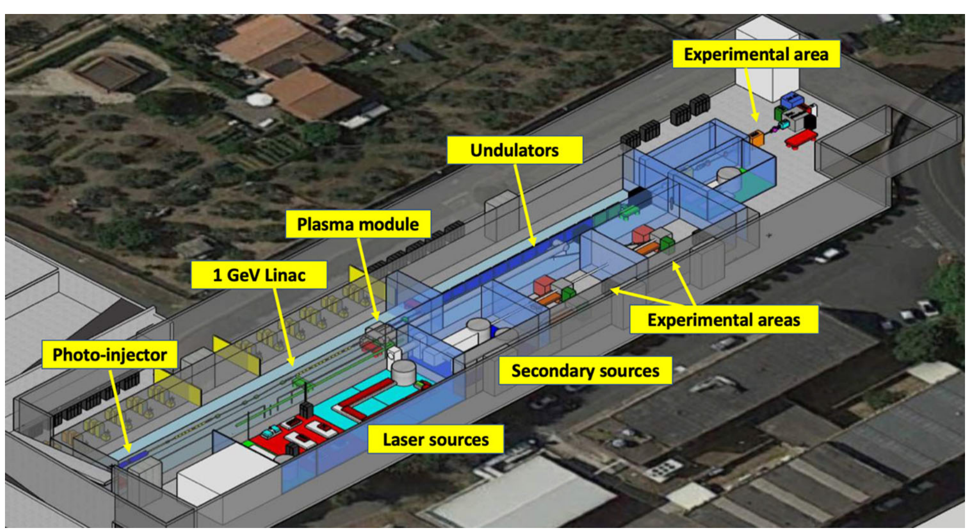

Fig. 2 Schematic view, not to scale, of the EuPRAXIA@SPARC_LAB facility

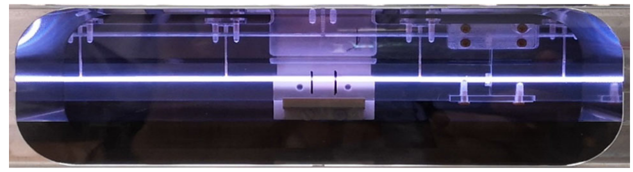

Fig. 3 Sections of a 40-cm-long capillary having a diameter of 2 mm installed inside a vacuum chamber to accommodate large plasma sources. The applied voltage pulse was 9 kV and the peak current reached about 500 A

including the first discharge in the EuPRAXIA plasma acceleration module, created to accommodate large plasma sources, turned on in March 2022 that resulted in the formation of plasma in a 40-cm-long capillary, and part of it is shown in Fig. 3.

Together with the driving motivation to host the EuPRAXIA facility, the realisation of the EuPRAXIA@SPARC_LAB infrastructure at the LNF by itself will allow INFN to consolidate a strong scientific, technological and industrial role in a competing international context. A national multi-purpose facility not only paves the road for a strong role of the Italian contribution to the European EuPRAXIA project, but also to possible future large HEP international projects. Hopefully, this project will represent a further step forward of a long-lasting history of successes in particle accelerators development in Frascati.

3.1 EuPRAXIA@SPARC_LAB scientific applications

According to the design parameters, the EuPRAXIA@SPARC_LAB FEL [19] will provide more than 10^{11} photons/pulse with a pulse duration of less than 50 femtoseconds. A wide class of experiments will benefit from these brilliant, soft X-ray FEL pulses using X-ray absorption and emission spectroscopies and X-ray resonant Raman scattering. The energy range of this FEL beam will allow performing spectroscopic experiments looking at the K-edges of "light" atoms, such as carbon and nitrogen, and at the L-edges of "heavy" atoms, including some *3d* transition metals. The applications are manyfold and include the study of superconductors, magnetic systems, warm-dense matter, bio-metallic complexes, and metalloproteins, just to provide some examples [20].

The photon wavelengths of EuPRAXIA are particularly suitable for the study of biological samples since they lie in the so-called water window (this is the reason for terming a dedicated beamline "AQUA" which stands for "water" in Latin), i.e. the wavelength range between carbon (4.40 nm) and oxygen (2.33 nm) K-edges. Since biological samples are mainly composed by light atoms (mostly carbon, but also nitrogen and oxygen) and find their native environment in aqueous solutions, the absorption contrast between the carbon atoms of the biological samples and the oxygen of the water surrounding them is the highest in the water-window. For this reason, coherent diffraction imaging measurements of unstained cells, viruses and organelles in their hydrated, native state become feasible [20]. Besides photon spectroscopy and imaging experiments, resonant inelastic X-ray scattering, electron spectroscopies and photo-fragmentation measurements will also be possible at the AQUA beamline.

At present, the possibility of building a second accelerator branch line called ARIA (which stands for "air" in Italian), producing seeded FEL radiation in the VUV (50 nm−180 nm) range, is being evaluated [21]. The reason for terming this beamline ARIA is that it will be mainly devoted to pump-probe measurements of molecules and clusters in the gas phase. Given the low number of particles in gas phase, great advances are expected to come from the high brightness of this VUV-FEL photon source.

Since the electrons accelerated in the plasma will also produce, as a "by-product" of their acceleration, brilliant, ultra-short, X-ray betatron pulses, EuPRAXIA@SPARC_LAB will also foresee applications of this radiation and explore the possibility of performing coupled FEL-betatron experiments [22].

Multi-purpose experimental chambers containing the necessary sample delivery systems including injection systems for both liquid jets and aerosols and motorised hexapod devices to control and orient with micron-level precision the positioning and orientation of solid targets and different detectors are under study [20]. There will be the possibility to install energy-sensitive photon detectors for spectroscopy measurements, 2D photon detectors for imaging measurements, and electrons/ions detectors for electron spectroscopies. Since most spectroscopic experiments performed at FELs exploit short pulses to perform time-resolved measurements, different pump-probe schemes will be made available including a split-and-delay unit to allow to pump the sample into an excited state using a fraction of the FEL pulse and then probe it by using a delayed part of the same pulse. Standard and high-power external lasers will be instead used to pump the samples using femtosecond laser pulses and then perform FEL probe measurements [20].

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