The EuPRAXIA@SPARC_LAB project

Executive Summary

Abstract:

It is widely accepted by the international scientific community that a fundamental milestone towards the realization of a plasma driven future Linear Collider (LC) will be the integration of a high gradient accelerating plasma modules in a short wavelength Free Electron Laser (FEL) user facility. To this end the Horizon2020 Design Study EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) will in October 2019 propose a first European Research Infrastructure that is dedicated to demonstrate usability of plasma accelerators delivering high brightness beams up to 1-5 GeV for users. In this report we discuss the EuPRAXIA@SPARC_LAB project, intended to put forward LNF as host of the EuPRAXIA European Facility. The EuPRAXIA@SPARC_LAB facility will equip LNF with a unique combination of a high brightness GeV-range electron beam generated in a state-of-the-art X-band RF linac, a 0.5 PW-class laser system and the first 5th generation light source driven by a plasma accelerator. These unique features will enable at LNF new promising synergies between fundamental physics oriented research and high social impact applications, especially in the domain of key enabling technologies (KET) and Smart Specialisation Strategies (S3).

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1. EXECUTIVE SUMMARY

1.1. Introduction

Advancement in particle physics has historically been linked with the availability of particle beams of ever increasing energy or intensity. For more than three decades the collision energy in particle colliders has increased exponentially in time as it is described by the so-called Livingston curve. A recent version [1] of the Livingston curve is shown in Figure 1. It includes achievements with conventional and novel accelerators and indicates the present plans beyond 2014. It is seen that particle accelerators are a remarkable success story with beam energies having increased by 5 – 8 orders of magnitude since the first RF based accelerators in the 1920s. However, it is also evident that the exponential increase of beam energy with time has leveled off in conventional RF accelerators since the 1980s. Limits in conventional accelerators arise from technical limitations (e.g. breakdown effects at metallic walls of RF cavities, synchrotron power losses, maximum fields in super-conducting magnets) but also practical issues (size and cost).

At the same time a new technology emerged, based on the revolutionary proposal of plasma accelerators by Tajima and Dawson in 1979 [2], and the invention of amplified chirped optical pulses (CPA) by Mourou and Strickland in mid 1980s [3].

Plasma-based concepts presently offer not only the high beam energies shown in Figure 1, but also the highest acceleratiing gradient compared to other novel acceleration techniques like high-frequency W-band metallic RF structures, dielectric wakefield structures or direct laser acceleration**.** Plasma-based accelerators in fact replace the metallic walls of conventional RF structures with an ionized gas, or plasma, see Figure 2 [6].

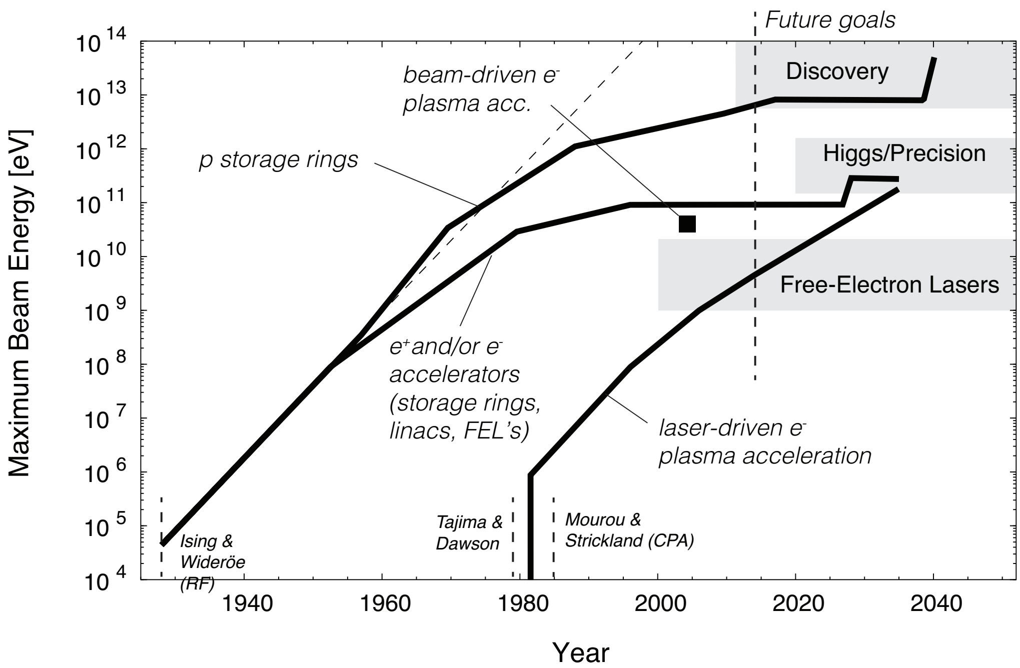

Figure 1: Livingston curve for accelerators [1], showing the maximum reach in beam energy versus time. Grey bands visualize accelerator applications. The left fork shows the progress in conventional accelerators from the first ideas in the 1920s. This main fork splits into two lines for electron/positron machines and for proton accelerators. A new fork of laser-driven plasma accelerators has emerged in 1980, reaching multi-GeV energies by now. Beam driven plasma acceleration results are indicated by the square point. Data beyond 2014 (vertical dashed line) indicate goals for the various technologies.

This revolutionary change permits one avoiding metallic or dielectric structure damage problems encountered in high-gradient operation. Laser beams (laser wakefield accelerator LWFA) or charged particle beams (particle wakefield accelerator, PWFA) may be adopted to excite space-charge oscillations in plasma. The resulting fields can be used for particle acceleration and focusing. Plasma accelerators have been built with active length ranging from the mm to the meter scale. Accelerating gradients up to 160 GV/m have been demonstrated in experiments [4] with improvements in accelerated beam quality that let us expect that advanced light sources (FEL, Compton, etc.) based on plasma-accelerators can be realized in the next decade [5]. To proceed towards high-energy physics (HEP) applications, however, one must demonstrate progress in beam quality and control [7].

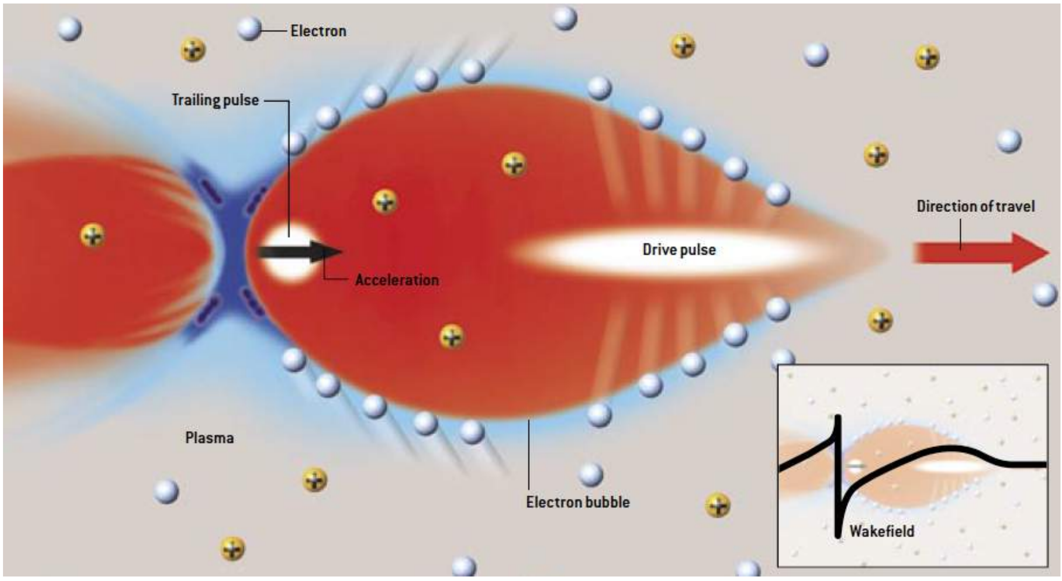

Figure 2: Wakefield accelerator relies on a charge disturbance known as a wakefield to provide the driving force. The drive pulse, which can be a short pulse of either a laser (LWFA) or an electron beam (PWFA), blows the electrons (blue) in an ionized gas, or plasma, outward, leaving behind a region of positive charge (red). Along the axis where the beam propagates, the electric field (plotted below) causes a trailing pulse of electrons injected near the rear of the bubble to feel a very strong forward acceleration. [6]

It is widely accepted by the international scientific community that a fundamental milestone towards the realization of a plasma driven future Linear Collider (LC) will be the integration of a high gradient accelerating plasma modules in a short wavelength Free Electron Laser (FEL) user facility [1]. The capability of producing the required high quality beams and the operational reliability of the plasma accelerator modules will be certainly certified when such an advanced radiation source will be able to drive external user experiments. It is further expected that there will be unique photon-beam characteristics that give notable advantages to such a plasma based 5th generation light source. These include enabling ultra-short photon pulses based on high brightness electron beams that break the attosecond barrier and, when used in combination with next generation undulators, shorter wavelength photons at notably lower electron beam energy. The realization of such a 5th generation light source thus serves as a required stepping stone for HEP energy applications and is a promising new tool for photon science in its own right.

1.2. The EuPRAXIA Design Study

The Horizon2020 Design Study EuPRAXIA (European Plasma Research Accelerator with eXcellence In Applications) will in October 2019 propose a first European Research Infrastructure that is dedicated to demonstrate usability of plasma accelerators for users. EuPRAXIA is devoted to establish the scientific and technological basis required to build a compact and cost effective high energy (up to 5 GeV) machine based on plasma accelerator technology. As stated in the ongoing Horizon 2020 European Design Study proposal [1]: “EuPRAXIA is supposed to bring together for the first time novel acceleration schemes, modern lasers, the latest correction/feedback technologies and large-scale user areas. It is of significant size, but significantly more compact than a conventional 5 GeV beam user facility. If the design study will be successful, EuPRAXIA could be constructed in the early 2020’s. It would be the required intermediate step between proof-of-principle experiments and ultra-compact accelerators for science, industry, medicine or the energy frontier (“plasma linear collider”). Such a research infrastructure would achieve the required quantum leap in accelerator technology towards more compact and more cost-effective accelerators, opening new horizons for applications and research.

The EuPRAXIA design study will cover three major aspects:

- The technical focus is on designing accelerator and laser systems for improving the quality of plasma-accelerated beams.
- The scientific focus is on developing beam parameters, two user areas and the use cases for a femto-second FEL and High Energy Physics (HEP) detector science.
- The managerial focus is on developing an implementation model for a common European plasma accelerator. **This includes a comparative study of possible sites in Europe, a cost estimate and a model for distributed construction in Europe and installation at one central site.**”

Figure 3: EuPRAXIA partners and associated partners.

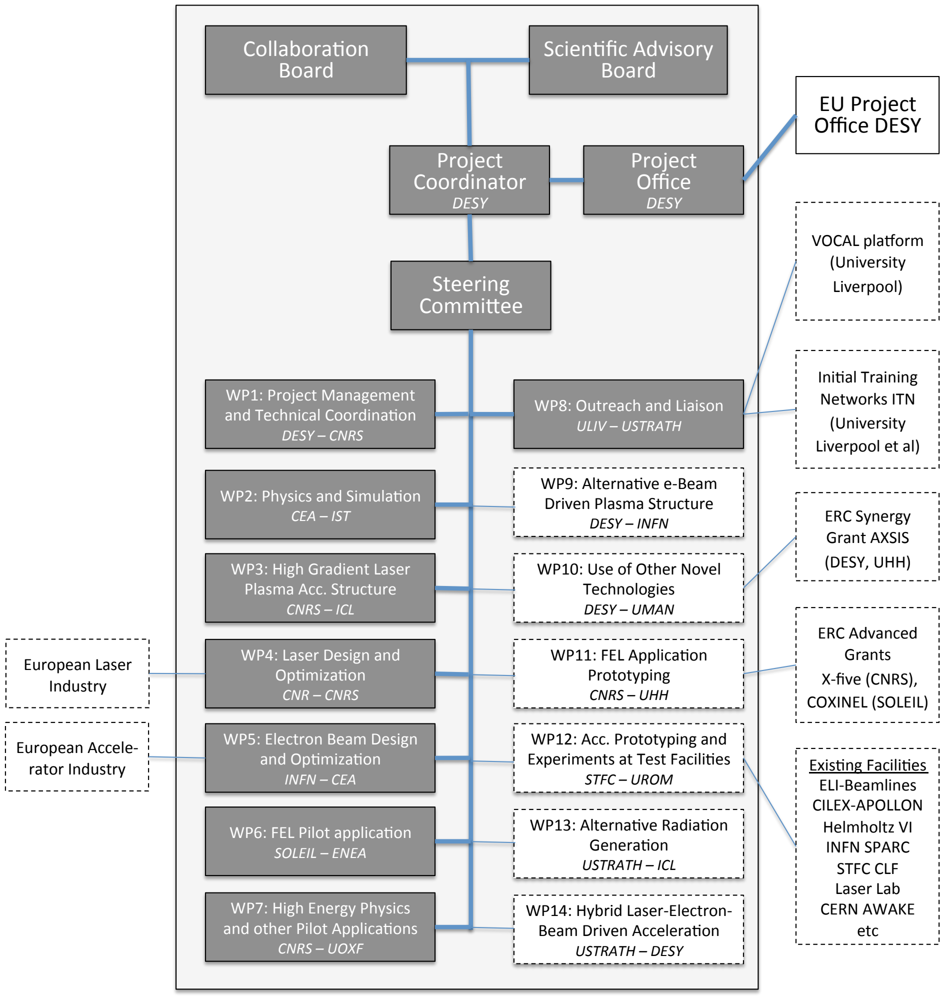

Figure 4: Structure of the EuPRAXIA project, including management bodies.

The EuPRAXIA Design Study started its work in November 2015 and will produce by the end of 2019 a conceptual design report for a 5 GeV plasma-based accelerator with industrial beam quality and user areas. The study will design accelerator technology, laser systems and correction/feedback systems for improving the quality of plasma-accelerated beams. Several user areas will be developed for a novel Free Electron Laser, High Energy Physics detector science and other applications (health, industry).

The EuPRAXIA collaboration, coordinated by R. Assmann (DESY), is the first plasma accelerator collaboration on this scale bringing together 16 European partner laboratories and additional 22 associated partners from the EU, Israel, China, Japan, Russia and the USA [1], see Figure 3.

EuPRAXIA is structured into 14 working packages each headed by two work package leaders from different institutions. Eight work packages receive EU funding and their topics include: plasma and laser simulations (WP2), plasma accelerator structures (WP3), laser design (WP4), conventional beam physics (WP5), FEL radiation (WP6), and a table-top test beam for HEP and other applications (WP7). Two further EU work packages are concerned with the management of the collaboration (WP1) and the outreach to the public (WP8). In-kind work packages (WP9 - WP14) include additional approaches: beam driven plasma acceleration PWFA (WP9), hybrid acceleration schemes (WP14), alternative radiation generation (WP13) and laser sources such as fiber lasers (WP10). WP11 and WP12 connect to prototyping on plasma-based FEL’s and facility access for experiments until 2019. Industry partners Amplitude Technologies, Thales and TRUMPF

Scientific take part in the scientific advisory board and contribute their experience towards a successful completion of the design report. The Structure of the EuPRAXIA project, including management bodies is shown in Figure 4.

The Italian contribution cover a wide range of topics included mainly in WPs from 1 to 12, with significant responsabilities as co-leaders in WP4 (L. Gizzi, CNR-Pisa), in WP5 (E. Chiadroni, INFN-LNF), in WP6 (G. Dattoli ENEA-Frascati), in WP9 (M. Ferrario, INFN-LNF) and in WP12 (A. Mostacci Univerity of Roma "La Sapienza"). A. Cianchi from University of Roma "Tor Vergata" has been recently charged of the coordination of the "Electron Beam Diagnostics" sub-task of WP5. M. Ferrario has been also elected chairman of the EuPRAXIA Collaboration Board.

The first iteration of the design parameter goals were defined in October 2016 [8] and approved by the EuPRAXIA Collaboration Board. The Self Amplification of Spontaneous Radiation (SASE) FEL operational mode has been considered in detail. The parameters in the first study version for the electron beam at the entrance of the undulator are shown in Table 1 together with the expected photon beam characteristics. These parameter goals and estimates are being evaluated and studied with the goal of establishing a second and more refined study version by the end of 2017.

Table 1: Target Values for the 1 and 5 GeV electron beam parameters

	Units	1 GeV Case	5 GeV Case
Bunch charge	pC	30	30
Bunch length rms	fs	10	10
Peak current	kA	3	3
Rep. rate	Hz	10	10
Rms Energy Spread	%	1.	1.
Slice Energy Spread	%	0.1	0.1
Peak current	kA	3	3
Rms norm. emittance	μm	1.	1.
Slice norm. emittance	μm	<1	<1
Slice Length	μm	0.75	0.75
Radiation wavelength	nm	4.	0.1
ρ	x 10^{-3}	> 1	> 1
Undulator period	cm	1.5	1.5
K		0.872	0.872

The first parameter column targets at a SASE-FEL design at 1 GeV electron beam energy with comparable long wavelength in the soft x-ray range to allow a proof of principle demonstration. The 1 GeV operation aims at a very compact version of soft x-ray FEL's like FLASH [9] in Hamburg or FERMI [10] in Trieste. This would be a first breakthrough offering interesting light pulses for first pilot users. The second, more demanding parameter column, leads the way for a plasma-based SASE-FEL design at 5 GeV electron beam energy in the hard x-ray range. Practical realizing of such an FEL however necessarily requires the experience from a previous iteration. One major figure of merit for electron beam quality is the beam energy spread. Especially for driving an FEL, this is an essential quantity, which directly defines the performance of the FEL design. Developing a consistent set of beam parameters produced by a plasma accelerator able to drive a short wavelength FEL is one of the major commitments of the EuPRAXIA Design Study.

The site selection for EuPRAXIA will be performed during the Preparatory Phase (expected in the years 2020-2022), following the delivery of the Conceptual Design Report by the Consortium (2019) and the inclusion of EuPRAXIA into the European Strategy Forum on Research Infrastructures (ESFRI) roadmap (expected in 2020).

1.3. The EuPRAXIA@SPARC_LAB concept

In this report we discuss the EuPRAXIA@SPARC_LAB project, intended to put forward LNF as host of the EuPRAXIA European Facility. In order to achieve this goal and to meet the EuPRAXIA requirements, some important preparatory actions must be taken at LNF:

- provide LNF with a new infrastructure, shown in Figure 5, with the size of about 130 m x 30 m, as the one required to host the EuPRAXIA facility;
- design and build the first-ever 1 GeV X-band RF linac and an upgraded FLAME laser up to the 0.5 PW range;
- design and build a compact FEL source, equipped with user beam line at 3 nm wavelength, driven by a high gradient plasma accelerator module.

Figure 5: The layout of the EuPRAXIA@SPARC_LAB infrstructure at LNF.

We are convinced that the completion in the shortest possible time of the above mentioned program, will represent a formidable boost for the EuPRAXIA facility and will allow LNF to be in an excellent position for being chosen as the site hosting the infrastructure. Synthetically, we call this project **EuPRAXIA@SPARC_LAB**.

The collaboration is carried out with the support of groups from INFN (LNF, LNS, Milano, Rome 1 and Rome 2), Universities of Rome Sapienza, Rome Tor Vergata and Milano Statale, ENEA Frascati, CNR-INO Pisa, and CERN CLIC team. Associated partners are also University of California at Los Angeles (UCLA) and the Hebrew University of Jerusalem (HUJ).

The new infrastructure will be able to accommodate any machine configuration resulting from the EuPRAXIA Design Study. At present, five different EuPRAXIA configurations are under investigation [11], based on a laser and/or a beam driven plasma acceleration approach that will find within the LNF infrastructure the necessary technological background.

The EuPRAXIA@SPARC_LAB facility ***by itself*** *will equip LNF with a unique combination of a high brightness GeV-range electron beam generated in a state-of-the -art linac, and a 0.5 PW-class laser system. Even in the unfortunate cases of LNF not being selected and/or of a failure of plasma acceleration technology, the infrastructure will be of top-class quality, user-oriented and at the forefront of new acceleration technologies. Indeed, this project will allow the establishment of a FEL user community, interested to exploit the proposed radiation source and the possible future extentions of the radiation spectrum, from the water window (4-2 nm), down to shorter wave lengths.*

These unique features will enable at LNF new promising synergies between fundamental physics oriented research and high social impact applications, especially in the domain of key enabling technologies (KET) and Smart Specialisation Strategies (S3), as supported by EU research funding programs. EuPRAXIA@SPARC_LAB is in fact conceived by itself as an innovative and evolutionary tool for multi-disciplinary investigations in a wide field of scientific, technological and industrial applications. It could be *progressively* extended to be a high brightness "particle beams factory": it will be able to produce electrons, photons (from THz to γ-rays), neutrons, protons and positrons, that will be available for a wide national and international scientific community interested to take profit of advanced particle and radiation sources. We can foresee a large number of possible activities, among them:

- X-band RF technology implementation in the framework of the CLIC and CompactLight collaborations,
- Science with short wavelength Free Electron Laser (FEL),
- Physics with high power/intensity lasers and secondary particle generation,
- R&D on compact accelerators and radiation sources for medical applications,
- Detector development for X-ray FEL,
- Science with THz radiation sources,
- Nuclear photonics with γ-rays Compton sources,
- R&D on polarized positron sources,
- Quantum aspects of beam physics including the Quantum-FEL development,
- R&D in accelerator physics and industrial spin – off

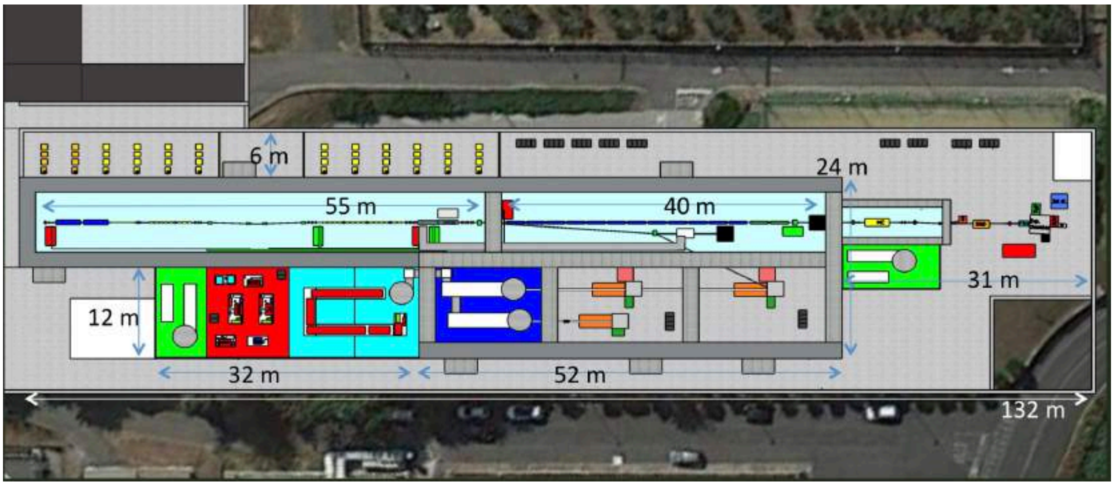

Figure 6: The layout of the EuPRAXIA@SPARC_LAB infrastructure.

In this summary, we will focus the attention to the core of the facility, i.e. the linac, laser, plasma and undulator complexes, leaving to more detailed future studies the wide range of applications of the proposed facility. The layout of the EuPRAXIA@SPARC_LAB infrastructure is schematically shown in Figures 5 and 6.

From left to right one can see a 55 m long tunnel hosting a high brightness 150 MeV S-band RF photoinjector equipped with a hybrid compressor scheme based on both velocity bunching and magnetic chicane. The energy boost from 150 MeV up to 1 GeV will be provided by chain of high gradient X-band RF cavities. At the linac exit a 5 m long plasma accelerator section will be installed, which includes the plasma module (~1 m long) and the required matching and diagnostics sections. In the downstream tunnel a 40 m long undulator hall is shown, where the undulator chain will be installed. Further downstream after a 12 m long photon diagnostic section the users hall is shown. Additional radiation sources as THz and γ-ray Compton sources are foreseen in the other shown beam lines. The upper room is dedicated to Klystrons and Modulators. In the lower light-blue room will be installed the existing 300 TW FLAME laser (eventually upgraded up to 500 TW). The plasma accelerator module can be driven in this layout either by an electron bunch driver (PWFA scheme) or by the FLAME laser itself (LWFA scheme). A staged configuration of both PWFA and LWFA schemes will be also possible in order to boost the final beam energy beyond 5 GeV. In addition FLAME is supposed to drive plasma targets in the dark-blue room in order to drive electron and secondary particle sources that will be available to users in the downstream 30 m long user area.

The most innovative component of the project is the plasma accelerating module, shown in figure 7 in one of its possible configurations. It consists in a 10 cm long, 0.5 mm diameter Saffire capillary tube [12] in which the plasma is produced by a high voltage discharge in Hydrogen. As discussed later in this report plasma density ranging from 10^{16} - 10^{19} cm^{-3} have been already tested [13] producing accelerating gradients exceeding 100 GV/m in both LWFA and PWFA configurations.

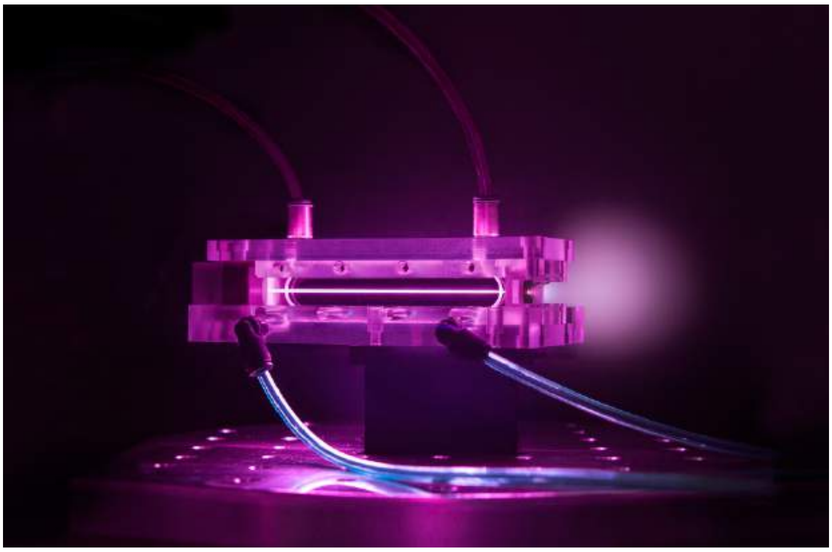

Figure 7: The plasma cell used at LBNL.

Another fundamental component included in the EuPRAXIA@SPARC_LAB proposal is the X-band accelerating technology adopted for the 1 GeV RF drive linac [14]. It is a very interesting option because it allows to reduce the overall drive linac length, taking profit of the high gradient (up 80 MV/m) operation of the X-band accelerating structures. In addition it will allow implementing at LNF in the next 2 years the state of the art high gradient RF technology. This technology has already shown its usefulness for medical and industrial applications but it is also another possible technological option for compact radiation sources and for the future Linear Collider [15]. As stated in the support letter addressed to the LNF Director by the CLIC collaboration leaders:

"*We wish to provide our very strong support for the EuPRAXIA@SPARC_LAB project being proposed by INFN Frascati. We sincerely believe that this is an excellent choice for the future of the laboratory. It is also very important for the CERN and the CLIC collaboration. We have discussed with INFN leaders and elaborated a mutually beneficial program of exchange of hardware and staff to advance both the LNF and CLIC projects. One of the key areas of the CLIC is the high-gradient, X-band radio frequency accelerator of the main linac. Significant resources have been invested to develop the necessary technology and considerable progress has been made and demonstrated by testing prototype systems in test stands at CERN.*

The LNF proposal is an opportunity to now implement this accelerator technology on a much larger scale than is possible in our test facilities. EuPRAXIA@SPARC_LAB will provide important benefits for high-gradient X-band technology including industrialization, larger-scale series production and long-term user operation. For these reasons, we have identified an initial set of collaboration activities. At the core is the loan to Frascati of a 50 MW X-band klystron in order to jointly set up a local high gradient testing facility. INFN would complete the test stand including the modulator and supporting infrastructure and then carry out high-gradient testing. Preparation for the test stand in Frascati would involve training INFN staff at CERN on the existing test stands. The experts would return to Frascati to build and operate the test stand there, experience that is directly applicable to the EuPRAXIA@SPARC_LAB linac. Overall this would be part of the strategy to introduce this innovative accelerator technology that will become a core component of the LNF facility. EuPRAXIA@SPARC_LAB, with its high gradient accelerator and very low emittance beam, will in the longer term provide a unique and important opportunity for the CLIC study for beam testing. This includes experiments and tests in a number of areas including beam dymanics, RF system and beam instrumentation. Finally, the LNF based test stand and then the EuPRAXIA@SPARC_LAB facility will provide important continuity for a long standing and very productive collaboration which extends back to the early days of CTF3."

We expect to install and run at LNF the X-box test stand, shown in Figure 8, by the end of 2018. This facility will allow RF cavities test and personnel training well before the beginning of the linac operations.

Together with the driving motivation to candidate LNF to host the EuPRAXIA facility, the realization 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, along the scientific applications discussed in the following sections, not only paves the road for a strong role for the Italian contribution to the European EuPRAXIA one, but also to possible future large high energy physics (HEP) international projects. This project will represent a further step forward in the mainstream of a long lasting history of success in particle accelerators development in Frascati.

Figure 8: The klystrons of the CERN X-band facility.

1.4. The EuPRAXIA@SPARC_LAB design goals

The EuPRAXIA@SPARC_LAB scientific program has foreseen three main directions:

- High gradient acceleration techniques for the next FEL and e+e- collider generations.
- Advanced radiation sources for photon science (FEL, Betatron, Compton, Channeling).
- Physics of high field interactions with matter.

The main required components enabling the accomplishment of the program are:

- The RF Linac upgrade up to 1 GeV
- The FLAME laser upgrade up to 0.5 PW

The experimental activity will be initially focused on the realization of a plasma driven short wavelength FEL with one user beam line, according to the beam parameter reported in the first column of Table 1, "1 GeV case". This goal is already quite challenging but it is affordable by the EuPRAXIA@SPARC_LAB collaboration and will provide an interesting FEL radiation spectrum in the so called "water window" whose application are described in a dedicated chapter. The first foreseen FEL operational mode is based on the Self Amplification of Spontaneous Radiation (SASE) mechanism [16]. More advanced schemes like Seeded and Higher Harmonic Generation configurations will be also investigated.

In the PWFA scenario driven by a single electron bunch, the peak accelerating field is, in principle, limited to twice the value o the peak decelerating field within the bunch (transformer ratio R=2). Therefore the maximum possible energy gain for a trailing bunch is less than twice the incoming driver energy. In this regime a driver bunch energy of 500 MeV is enough to accelerate the witness bunch up to 1 GeV. A method to increase the energy gain is the so called *ramped bunch train* [17] and consists of using a train of N_T equidistant bunches, see Figure 9, wherein the charge increases along the train producing an accelerating field resulting in a higher transformer ratio. For this application, it is essential to create trains of high-brightness tens of femtosecond long microbunches with stable and adjustable length, charge and spacing. A lot of efforts are now ongoing worldwide to produce the required bunch train configurations [18]. The method we will use to achieve the required bunch train quality is based on the *Laser Comb Technique* [19] that has been recently tested with the SPARC_LAB photoinjector [20]. Higher witness bunch energy will be accessible when the Comb technique will be implemented. With a transformer ratio of 6 the 5 GeV threshold will be also achievable with a 1 GeV driver bunch energy, thus exploiting the full energy provided by the X-band linac.

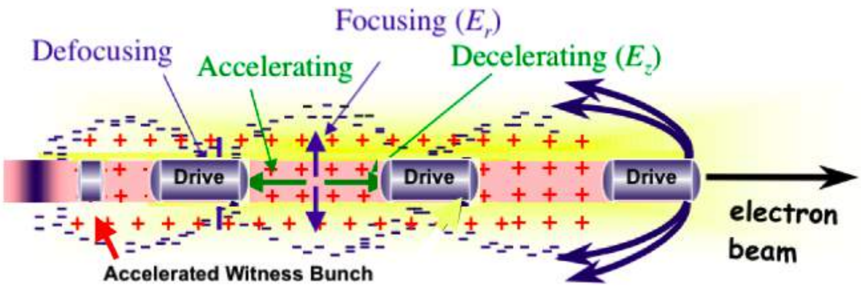

Figure 9: Multibunch excitation of a plasma wave

In the LWFA scenario the 0.5 PW upgrade of the FLAME laser, temporally in the existing dedicated building, is a necessary step to keep the FLAME laser in the group of leading installations and further establish expertise on advanced laser sciences. High energy staging in combination with high brightness beam external injection will be the main application of the upgraded FLAME system, leading to multi-GeV high brightness electron beam production as required by EuPRAXIA applications.

In addition, it will make it possible to implement a new scientific program based on lasers at the highest competitive level. Many laboratories worldwide have recognized the need for a major upgrade of their respective laser systems to the PW-scale power and, in several cases to the 10 PW power. These upgrades are driven by scientific motivations of paramount importance, which are emerging thanks to the parallel major effort in predictive numerical modeling of phenomena never approached so far in the Laboratory.

In this scenario, the upgrade of the FLAME laser system to 0.5 PW power and dual beam capability will enable new regimes of plasma-based particle accelerators and will enable to access the region of high electromagnetic fields of non-linear and quantum electrodynamics (QED) where new fundamental physics processes and promising new radiation emission mechanisms can be explored. The science cases that will be developed with the FLAME 0.5 PW upgrade includes:

- Electron acceleration beyond the GeV (including external injection and/or Trojan horse scheme, high energy staging, etc.);
- QED and generation of high energy radiation;
- Proton and ion acceleration beyond the TNSA regime.
- Coherent (betatron and Compton scattering) radiation sources

In fact, advances in laser-plasma acceleration are already being achieved with PW laser systems recently commissioned elsewhere and the 10 GeV barrier of electron energy gain is now within reach. At such a high energy, intense, hard X-ray emission from betatron radiation is expected [21] which is currently seen as an advanced source for a wide range of applications, including phase contrast imaging and 3D X-ray tomography [22].

Among the other phenomena, the most far reaching ones concerns the possibility of entering the radiation-dominated regime of electron dynamics. Besides its impact on basic physics issues involving the fundamental nature of the electron charge distribution, this regime may lead to the realization of extremely powerful and controllable sources of high-energy radiation. These sources may revolutionize many areas of great societal interest, from Health to Security, from Environment to Safety. In fact, a PW-scale laser system makes it possible to create conditions in which the electromagnetic field is so strong that electron motion no longer follows the laws of classical mechanics. In the classical view, an electron entering an intense laser field will be scattered away by the strong ponderomotive force and will not experience high fields. This regime is well explored in ultra-intense laser fields and is the basic mechanism that, for example, initiates the wakefield in a laser-driven acceleration scheme. When laser intensity is further increased, quantum processes govern the interaction of the electrons with the electromagnetic field and the force assumes a stochastic behavior. In this case, an electron approaching an intense laser field may be able to experience a strong acceleration that will make it radiate much more efficiently [23] than in the classical regime. Based on this principle, a powerful gamma-ray source can be conceived in a compact, all-optical configuration. This is a key example of the physical processes, so far unexplored in the laboratory, that can be addressed with a PW-scale laser.

Table 2: Beam parameters for a plasma driven FEL.

	Units	**1 GeV PWFA with Undulator Tapering**	**1 GeV LWFA with Undulator Tapering**
Bunch charge	pC	29	26.5
Bunch length rms	fs	11.5	8.4
Peak current	kA	2.6	3.15
Rep. rate	Hz	10	10
Rms Energy Spread	%	0.73	0.81
Slice Energy Spread	%	0.022	0.015
Average Rms norm. emittance	μm	0.6	0.47
Slice norm. emittance	μm	0.39-0.309	0.47
Slice Length	μm	1.39	1.34
Radiation wavelength	nm	2.79	2.7
ρ	x 10^{-3}	2	2
Undulator period	cm	1.5	1.5
K		0.987	1.13
Undulator length	m	30	30
Saturation power	GW	0.850-1.2	1.3
Energy	μJ	63	63.5
Photons/pulse		8.8 x 10^{11}	8.6 x 10^{11}
Bandwidth	%	0.35	0.42
Divergence	μrad	49	56
Rad. size	μm	210	160
Brilliance per shot	(s mm^2 $mrad^2$bw (‰))$^{-1}$	0.83 x 10^{27}	1.22 x10^{27}

We have investigated the possibility to fulfill the 1 GeV EuPRAXIA scenario by using both plasma acceleration options (LWFA and PWFA) and we have reported in a dedicated chapter the Start To End Simulations to support both design. In Table 2 the achieved parameters are reported.

We have investigated also the possibility to drive the FEL with higher charge/bunch i.e. 100 pC and 200 pC, in order to produce a larger number of photons as required by some application. This is possible in a conventional configuration, i. e. exploiting the full X-band RF linac energy (1 GeV) without using the plasma module and the results of Start To End simuations are shown in Table 3.

Table 3: Beam parameters for a FEL driven by conventional linac.

	Units	**1 GeV with X-band linac only 100 pC**	**1 GeV with X-band linac only 200 pC**
Bunch charge	pC	100	200
Bunch length rms	fs	38.2	55.6
Peak current	kA	2.	1.788
Rep. rate	Hz	10	10
Rms Energy Spread	%	0.1	0.05
Slice Energy Spread	%	0.018	0.02
Average Rms norm. emittance	μm	0.5	0.5
Slice norm. emittance	μm	0.35-0.24	0.4-0.37
Slice Length	μm	1.25	1.66
Radiation wavelength	nm	2.4 (0.52 keV)	2.87(0.42 keV)
ρ	x 10^{-3}	1.9(1.7)	1.55(1.38)
Undulator period	cm	1.5	1.5
K		0.987	0.987
Saturation length	m	15-25	16-30
Saturation power	GW	0.361-0.510	0.120-0.330
Energy	μJ	48-70	64-177
Photons/pulse		5.9-8.4 x 10^{11}	9.3-25.5 x 10^{11}
Bandwidth	%	0.13-2.8	0.24-0.46
Divergence	μrad	17.5-16	28-27
Rad. size	μm	65-75	120-200
Brilliance per shot	(s mm^2 $mrad^2$bw (‰))$^{-1}$	Fx3.8-2.2 10^{28}	Fx2.5-1.4 11^{27}

The reported EuPRAXIA@SPARC_LAB FEL performances show that our FEL, driven by a plasma accelerator in SASE configuration, is expected to meet the challenging requests for the new generation synchrotron radiation sources. The peak brilliance will exceed of about 10 orders of magnitude that produced by the undulators of the 3rd generation sources. In addition the pulse duration could be very short (of the order of fs scale) with respect to what is currently attainable with storage ring based radiation source (ps scale). Possible applications of the EuPRAXIA@SPARC_LAB FEL source at 3 nm are described in the next paragraph.

1.5. The FEL scientific program within EuPRAXIA@SPARC_LAB facility

The advent of Free Electron Lasers (FELs) opened up the way for an unprecedented, wide class of experiments exploiting the peculiar features of these radiation sources. Key elements are the high peak brilliance and the short pulse duration, which is of the order of tens of femtoseconds. FELs can therefore allow high time resolution measurements and may provide a high signal-to-noise ratio. By exploiting the high peak brilliance and the extremely short FEL pulses the so-called diffract-and-destroy regime can be explored, in which interpretable data are collectable before the sample is destroyed by the FEL pulse radiation [24] thus overcoming one of the main limitations of synchrotron radiation based experiments that is the sample radiation damage. This principle has been proven in several experiments on various samples, both biological [25-29] and non-biological [30, 31], at different wavelengths ranging from the UV to the hard X-rays region. Actually, this issue is particularly relevant since coherent diffraction imaging (CDI) of biological system using conventional methods is ultimately limited by radiation damage owing to the large amount of energy deposited in the sample by the photon beam [32].

The unique FEL features (energy range, time resolution and brilliance) can be exploited in several branches of physics, chemistry, material science and biology. The EX-TRIM (Eupraxia X-ray Time Resolved coherent IMaging) users endstation of EuPRAXIA@SPARCLAB FEL will be designed and built to allow performing a wide class of experiments using the schematic apparatus displayed in Figure 10. Details about the main research lines, requirements for FEL beam parameters and the EX-TRIM experimental end-station are described in Chapter X.

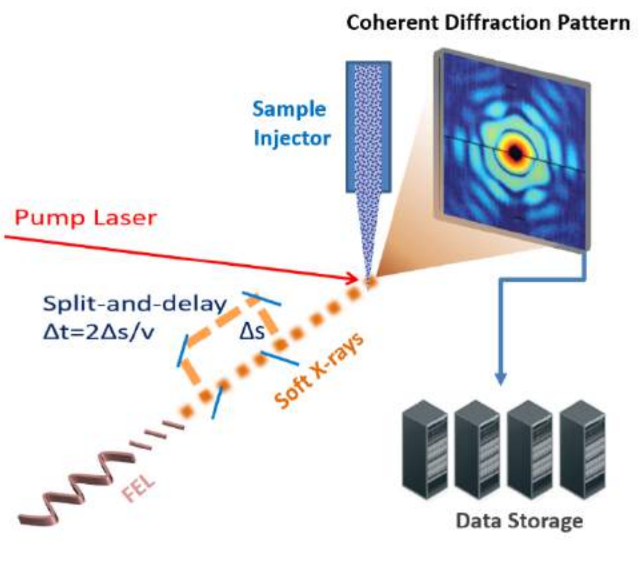

Figure 10 - Simplified layout of an imaging experiment using the EuPRAXIA@SPARC_LAB FEL.

As specific example of EuPRAXIA@SPARC_LAB applications its worth remarking that the FEL radiation in the soft X-ray spectrum open possibilities for novel imaging methodologies and time-resolved studies in material science, biology and medicine, along with non-linear optics applications, among them:

Coherent Imaging of Biological samples in the water window Exploiting the coherence of the EuPRAXIA@SPARCLAB FEL beam and its wavelength falling within the "water window", 2D and 3D images of biological samples in a wet environment can be obtained with high contrast with respect to the surrounding medium. This means that a wide class of biological objects, including protein clusters, viruses and cells can be profitably studied at the EuPRAXIA@SPARCLAB facility.

Clusters and nanoparticles Considerable attention is continuously being addressed to the study of free clusters, since they are known to be a bridge between the gas and the condensed phases of matter. In particular, great interest arises in the correlations between the geometric structure and electronic properties of variable size clusters, underlying changes in optical, magnetic, chemical and thermodynamic properties. In the spectral range from 3 to 5 nm envisaged for the EuPRAXIA@SPARCLAB FEL source, physical processes involving core levels are important. Clusters, as a form of matter intermediate among atoms and bulk solids, are ideal samples to study these processes.

Laser ablation plasma Laser ablation/desorption techniques are utilized extensively across a diverse range of disciplines, including production of new materials, and both extrinsic and in situ chemical analysis. Laser interactions may occur via direct absorption or through non-linear mechanisms such as multi-photon and avalanche excitation. In the case of ablation the use of ultra-fast laser pulses provides a powerful means of machining a wide variety of materials, including biological tissue. The absence of thermal relaxation of the energy allows unprecedented precision and essentially no associated damage, a fact that has stimulated considerable interest also for industrial processes and applications. Electronically induced surface reactions in semiconductors, metal/adsorbate systems and multiphase composite materials could be investigated. Moreover, surface studies of the irradiated area with chemical sensitivity of CDI diagnostics of the ablated species may elucidate the mechanism of the electronic melting, desorption, and multi-photon ablation.

Condensed Matter Science A Free Electron Laser capable to deliver pulses in the 3 nm region is a great asset for Coherent Diffraction Imaging (CDI) experiments tackling many open questions in Condensed Matter physics.
For instance, the quest for smaller and faster magnetic storage units is still a challenge of the magnetism. The possibility to study the evolution of magnetic domains with nanometer/femtosecond spatial/temporal resolution will shed light on the elementary magnetization dynamics such as spin-flip processes and their coupling to the electronic system. Moreover, the possibility to exploit different L-edges resonances would allow introducing the chemical selectivity necessary to account for the complex composition of technologically relevant magnetic media.

Pump and probe experiments The possibility of inducing changes in a sample via a pump pulse such as the stimulation of a chemical reaction or the generation of coherent excitations would tremendously benefit from intense and extremely short pulses in the soft X-ray region. As an example, resonant experiments with pulses tuned across electronic excitation will open up the way towards stimulated Raman or four wave mixing spectroscopies.

1.6. Experience with SPARC_LAB

The EuPRAXIA@SPARC_LAB facility will address new technological challenges at LNF. Nevertheless a wide experience in the development of Advanced Accelerator Concepts and Technology has grew up at LNF in the past decade thanks to the strong involvement of LNF scientist in the design, commissioning and operation (since 2005) of the SPARC_LAB test facility. SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Lasers and Beams) [33] is in fact an inter-disciplinary laboratory with unique features in the world. The SPARC_LAB layout is shown in Figure 11. It was born from the integration of a high brightness photo-injector (SPARC) [34-39], able to produce high quality electron beams up to 170 MeV energy with high peak current (> 1 kA) and low emittance (<2 mm-mrad), and of a high power laser (> 200 TW) (FLAME) [40, 41], able to deliver ultra-short laser pulses (<30 fs).

In Autumn 2015 a long shutdown was foreseen to prepare the facility to host plasma acceleration experiments. The last 3 m long low gradient (~15 MV/m) S-band TW accelerating section has been replaced by a 1.4 m long structure operating in the C-band at 5.712 GHz, with an average accelerating field of ~ 35 MV/m [42], and a plasma chamber for PWFA experiments, hosting diagnostics, permanent magnet quadrupoles and the capillary, which represents the plasma accelerating structure [43]. The recent layout of SPARC is displayed in Figure 12.

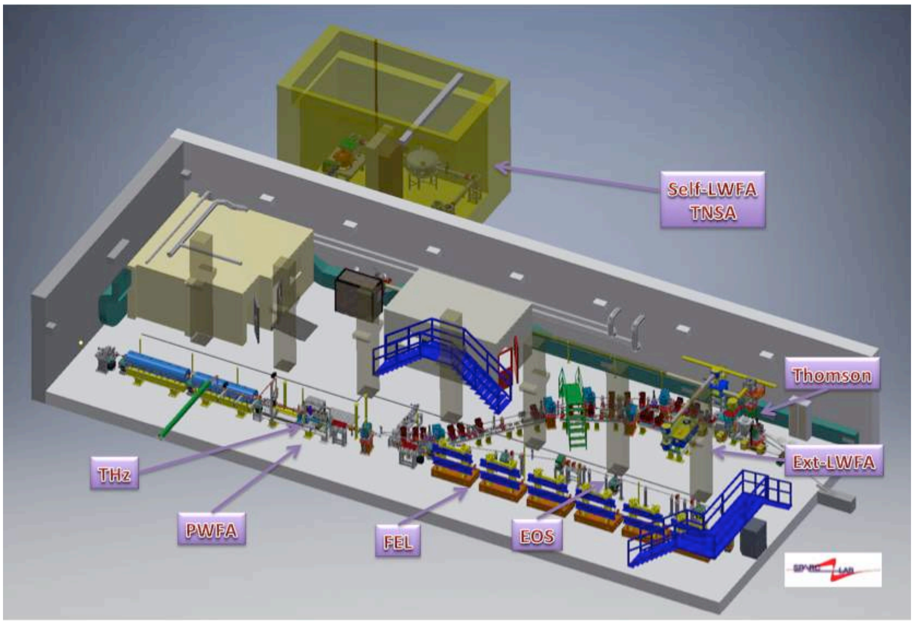

Figure 11 - Layout of SPARC_LAB beam lines.

The plasma interaction chamber, placed at the end of the linac, is fully equipped with diagnostics, both transverse and longitudinal, based on Electro-Optical sampling [43] and THz radiation [44, 45], with a H_2 plasma discharge capillary [46] and permanent quadrupole magnets for beam matching in and out from the plasma. At the end of the linac a diagnostics and matching section allows to characterize the 6D electron beam phase space and to match the beam to the beamlines.

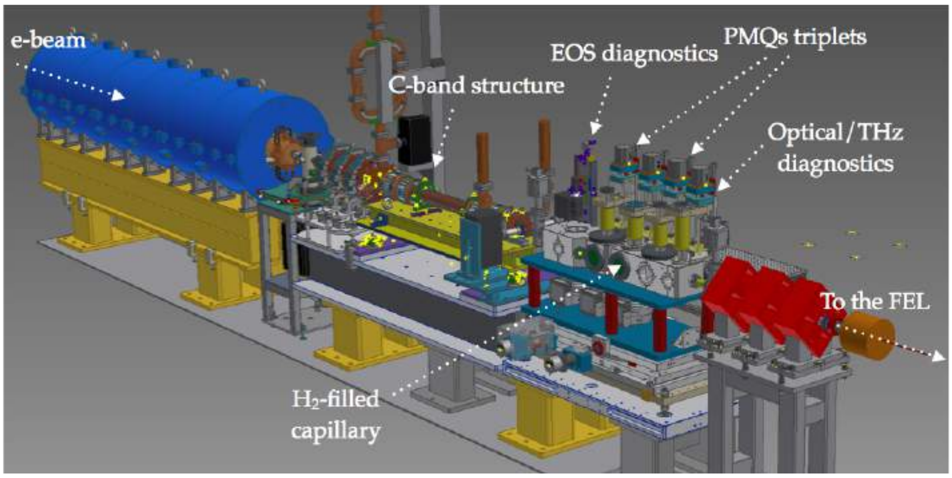

Figure 12 - Update layout of the photo-injector. The third S-band structure has been replaced by a C-band structure and the plasma interaction chamber, fully equipped with beam and plasma diagnostics and permanent quadrupole magnets.

SPARC_LAB has already enabled the development of innovative radiation sources and the test of new techniques for particle acceleration using lasers. In particular the following highlight results have been achieved so far:

- A new electron bunch compression scheme, called Velocity Bunching, has been succesfully demonstrated [47,48] together with the possibility to generate a train of short electron pulses, the COMB scheme [49,50], as the one required to drive PWFA experiments with high transformer ratio [51].
- A Free Electron Laser has been commissioned producing coherent radiation tunable from 500 nm down to 37 nm (with harmonics) and new regimes of operation like Seeding, Single Spike, Harmonic Generation and Two Colors have been observed [52-61];
- A source of both broad band, narrow band (<30%) and high energy (> 40 μJ) THz radiation has been tested, experiments with users have been accomplished [44,45,62] as reported also in a recent Nature Communication paper [63];
- Gamma-rays from Thomson back-scattering have been observed [64],
- Electrons have been accelerated up to 400 MeV in 2-4 mm long plasma wave excited by the high power laser FLAME [40] with less than 20% energy spread;
- Electrons and photons beams have been synchronized at the scale of <50 fs [65], an essential requirement for the recent successful operation of the X-rays (~50 keV) Thomson back-scattering source [66-68] and for the future investigation of new ultra-compact acceleration techniques (> 1 GV/m) based on external injection of high quality electron beams in a plasma wave.
- Reduction of relative arrival time jitter down to 19 fs (rms) between the electron bunch and the external photo-cathode laser by control of the longitudinal beam dynamics in a hybrid compression scheme (velocity bunching and dogleg) has been demonstrated [69].
- Active Plasma Lens experiments have been succesfully performed [70]. Experimental optimization of compact Plasma Lens is underway.
- Innovative electron beam transverse [71-73] and longitudinal diagnostics [43] have been tested.

- Ion acceleration by Target Normal Sheath Acceleration (TNSA) has been tested [74] and plasma diagnostics has been implemented [75].

The external injection beam line for plasma acceleration is also under commissioning and preparatory experiments have been performed to set the electron beam dynamics and the laser transport parameters; in addition, laser-capillary interaction has been investigated [76] and further experiments to characterize the plasma source, study the electric discharge, measure the plasma density and the capillary geometry are underway. *The SPARC_LAB test facility will enable LNF in the next 5 years to establish a solid background in plasma accelerator physics and to train a young generation of scientists to meet all the challenges addressed by the EuPRAXIA@SPARC_LAB project.*

1.7. The EuPRAXIA@SPARC_LAB infrastructure at LNF

The EuPRAXIA@SPARClab project requires the construction of a new building to house the linac, the FEL, the Experimental room and the support laboratories.

The new facility will be built in the South-East part of LNF area. It will cover approximately an area of 4000 m^2 and it will be located at an elevation ranging from 205 to 218 m above sea level.

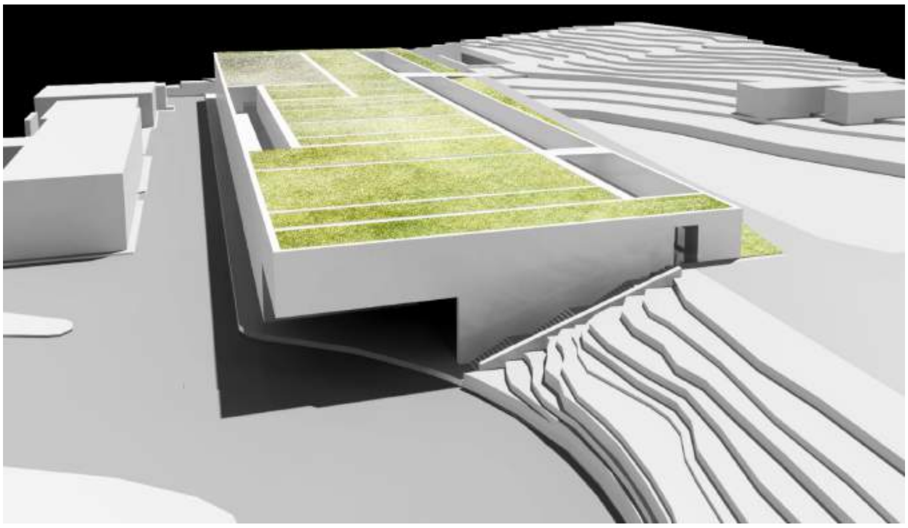

Figure 13: A 3D view (West side) of the EuPRAXIA@SPARC_LAB building.

Figure 13 shows a 3D view of the new proposed building in its surroundings: the foreseen location takes advantage of the difference in height of the soil for a natural schielding from radiation.

The facility will have an L shape and presents a total length of 130 m and a width of 35 m (up to 80 m in a zone reserved for storage and auxiliary plants). It comprises a main building housing the accelerator machine and ancillary equipment, and another one under the natural ground level for plants and storage. Both will be built at the same depth, in cut and cover method.

The main building will be a parallelepiped 130 m long and 35 m wide that will be developed in East/South-West direction. It will have a roof garden for radioprotection reason and to minimize the visual impact on the environment.

The building for auxiliary plants will house a new electrical substation, primary refrigerating plants (dry cooler and pumps) and primary cooling circuit distribution systems. It will also house a parking area and a storage area

The key of the architectural layout is mainly dictated by the requirements of the experiments. The building can be divided into three functional zones. The first includes:

- a Linac tunnel housing the injector, the main linear accelerator, plasma and matching. Its dimensions are approximately 58 x 8 m^2 with a height of 6 m. The tunnel will have the walls and a roof of concrete 2 m thick and two main accesses through shielding doors located on opposite sides;
- a modulator and klystron gallery will be adjacent and parallel to the linac tunnel. Being 9 m wide and 6 m high, it will allow, with proper penetrations, the access of the waveguides feeding the linac sections. In this area a 5 Tons crane will be installed to facilitate the movement of klystrons. The gallery will be extended to the overall length of the building to allow access to experimental rooms and to house the main electrical and cooling distribution;
- some laboratories (THz, Laser Sync, 2x500 TW rooms), with different dimensions, will be distribuited along the linac tunnel. A large corridor allows access into them;
- a radiation users room will be located adjacent the linac, in the opposite side of services gallery. Walls and roof will have the same thickness of linac tunnel (2 m concrete). The entrance will be through a shielding door;
- the part above the ancillary laboratories will be dedicated to the control room, the racks room, a meeting room and offices. The access to the first floor is through a lift and a staircase. The control room will be located approximately midway along the accelerator.

The second functional zone of the building consists of a large hall including the Undulator/FEL hall and 2 HEP rooms.

The Undulator/FEL hall is located downstream the linac tunnel and is at the same level. The dividing wall between the two areas will be a removable wall of 2 m concrete with adequate horizontal holes by means of which the electron beam vacuum chamber passes. The dimensions of this hall are approximately 35 x 10 m^2 with a height of 6 m. The roof will be 2 m concrete. The main access is in the services gallery by a shielding door. Adjacent to the undulator hall, two experimental rooms will be dedicated to HEP. A 1 m thick wall separates the Undulator/FEL hall from HEP rooms, but two chicanes allow the access from side to side.

The third functional zone of the building is the Experimental room. It is a big open space of about 34 x 33 m^2, 8.5 m height. 2 m removable shielding wall separates it from Undulator/FEL hall. The Experimental room will have a little gallery housing a meeting room and some offices for the external users. The first level will be reached by a staircase from ground floor and through an external stairway from *via W. Heisenberg*.

The roof level will be devoted to a garden that must contribute to ionizing radiation shield, and to minimize the impact on the environmental contest.

Another building, completely underground, will be built next to the main building and connected to it. It will be approximately 50 x 35 m^2 and will have two levels.

The first level will be at the same level of the Linac tunnel and will be a big storage area. The second one will be dedicated partly to conventional facilities for the experimental buildings and partly to a parking area. Here an electrical substation and cooling plants (dry coolers, chillers and pumping station) will be installed to feed and support the accelerator machine.

The building will have three main access for people and vehicles: one from *via W. Heisenberg* to the lower level, passes through the EuPRAXIA@SPARC_LAB building, near the linac tunnel; another one from *via W. Heisenberg* but through a sloping road accessing plants area and parking area. The third access will be from *piazzale G. Marconi* to the second level. In addition, an adequate number of emergency exits will be provided, in compliance with the safety rules.

1.8. Preliminary project cost estimate and timeline

The Project is organized in two phases. In the first one (Phase 1), all the elements which are mandatory to operate the infrastructure accordingly to EuPRAXIA requirements (the X band 0.9 GeV linac, the plasma section, and the undulator) must be available at day one, soon after the completion of the Infrastructure. In the second one (Phase 2), the facility will be upgraded in energy (1.3 GeV), in the power of the laser, and equipped with the end user FEL station.

A preliminary evaluation of the costs of the project takes into account the following elements for Phase 1 (all costs are VAT excluded), see Table 4:

- **2,700 k€** for the EUPRAXIA@SPARC_LAB Infrastructure project, including the definitive and executive design, the management of the construction and the trials.
- **16,100 k€** for the EUPRAXIA@SPARC_LAB Infrastructure building, including the hub for services and storage. The cost has been evaluated through a metric estimate made by the building design team. The esteem is preliminary, but conservative, and will be optimized before launching the tenders.
- **4,500 k€** for the EUPRAXIA@SPARC_LAB technical services (ventilation, cooling, power, network, clean rooms, safety controls, shielding doors, etc.). The expected cost is for an assumption of a total installed power of 2 MW, and it is based on the experience of the recently approved bids for the construction of ELI-NP [77];
- **15,400 k€** for the injector and X-band 900 MeV linac. The evaluation is based on the experiences of the SPARC_LAB, STAR and ELI-NP projects, together with the specific expertise of the CERN CLIC team. The quote, for Phase 1, includes the option of using parts from SPARC_LAB laboratory;
- **1,000 k€**, for the plasma beam line;
- **10,000 k€**, for the FEL undulators and associated photon diagnostics. The evaluation is based on recent projects and on SPARC_LAB experience.

At a later stage (Phase 2), and as soon as resources will be available, the following components are necessary to implement the user facility:

- **2,000 k€** for an injector upgrade;
- **5,000 k€** for the FLAME laser upgrade up to 0.5 PW;
- **4,800 k€** for X-band klystron upgrade to bring energy up to 1.3 GeV;
- **1,000 k€** for further photon diagnostics;
- **5,000 k€** for the FEL user end station.

The total cost, VAT excluded, of EuPRAXIA@SPARC_LAB project is **49,700 k€** (Phase 1), and **17,800 k€** (Phase 2).

Table 4 - Preliminary cost evaluation of the EuPRAXIA@SPARC_LAB facility

Infrastructure	**Cost** k€	**Partial Cost** k€	**Incremental Cost** k€
Building Project	2,700		
Building Construction	16,100		
Building Technical Services	4,500	23,300	23,300
Components Phase 1	**Cost** k€	**Partial Cost** k€	**Incremental Cost** k€
Injector	600		
Compressor	300		
4 X-band Linac modules	11,000		
Beam diagnostics	1,500		
LLRF & Synch.	1,400		
Control System	600	15,400	38,700
Plasma module and diagnostics	500		
Plasma beam line	500	1,000	39,700
Undulators	9,000		
Photon Diagnostics	1,000	10,000	**49,700**
Components Phase 2	**Cost** k€	**Partial Cost** k€	**Incremental Cost** k€
Injector upgrade	2,000		
FLAME upgrade	5,000		
X-band Kly upgrade	4,800		
Photon Optics	1,000		
User end station	5,000	17,800	**67,500**

A very preliminary timeline of the project, see Table 5, has been outlined setting the following milestones, for the construction of the infrastructure, and for the realization of the machine, respectively:

- by the end of 2017, the launch of the bid for the realization of the definitive and executive project, including the request for construction approvals;
- by the 1st quarter of 2019, the launch of the bid for the construction;
- by the 1st quarter of 2020, the start of the construction;

- by the 1st quarter of 2022, the building should be available and ready for installation.

- by the 2nd quarter of 2019, the completion of a Technical Design Report;
- in 2020, the launch of bids for the material procurement of the X-band linac, the plasma section and the FEL undulator;
- by the 2nd quarter of 2022, the start of the installation of the machine;
- by the 2nd quarter of 2023, the start of the commissioning of the facility, with the Phase 1 configuration which can satisfy EuPRAXIA requirements.

The separation in time between Phase 1 and Phase 2 will be dictated mainly by the availability of economical resources and not by technical difficulties.

Table 5 - Timeline of the EuPRAXIA@SPARC_LAB project

Year	2017				2018				2019				2020				2021				2022				2023			
Month	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12
EuPRAXIA																												
Design Study & ESFRI	■	■	■	■	■	■	■	■	■	■	■	■																
Preparatory Phase													■	■	■	■	■	■	■	■	■	■	■	■				
EuPRAXIA@SPARC_LAB																												
Machine Conceptual Design Report	■	■	■																									
Machine Technical Design Report				■	■	■	■	■	■	■																		
New building design					■	■	■	■	■																			
New building authorisation requests							■	■	■																			
New building tender										■	■	■	■															
New building construction														■	■	■	■	■	■	■	■							
X-band R&D			■	■	■	■	■	■	■	■																		
X-band LINAC tender											■	■	■	■														
X-band LINAC realization and test													■	■	■	■	■	■	■	■	■							
X-band LINAC installation and commissioning																						■	■	■	■			
Plasma Accelerator R&D	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
Plasma Accelerator Tender																	■	■	■	■	■							
Plasma Accelerator Installation																						■	■	■				
Plasma Accelerator Commissioning																									■	■	■	■
FEL undulator, optics and user tender													■	■	■	■	■	■										
FEL undulator characterisation																			■	■	■							
FEL installation in the new building																						■	■	■				
FEL commissioning																									■	■	■	■
																									■	■	■	■
User Beam Line R&D									■	■	■	■																
User Beam Line Tender and Construction													■	■	■	■	■	■	■	■	■							
User Beam Line Installation																						■	■	■				
User Beam Line Commissioning																									■	■	■	■
FLAME upgrade tender													■	■	■	■												
FLAME components test																	■	■	■	■	■							
FLAME installation in the new building																						■	■	■				
FLAME commissioning up to 500 TW																									■	■	■	■

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