IRIDE: Interdisciplinary research infrastructure based on dual electron linacs and lasers

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1. The IRIDE concept: technological breakthroughs as a basis for new research in fundamental and applied science

The proposed IRIDE infrastructure will enable new, very promising synergies between fundamental-physics-oriented research and high-social-impact applications. Conceived as an innovative and evolutionary tool for multi-disciplinary investigations in a wide field of scientific, technological and industrial applications, it will be a high intensity "particles factory", based on a combination of a high duty cycle radio-frequency superconducting electron linac and of high energy lasers. It will be able to produce a high flux of electrons, photons (from infrared to $\gamma-$rays), neutrons, protons and eventually positrons and muons, that will be available for a wide national and international scientific community interested to take profit of one of the most worldwide advanced particle and radiation sources. We can foresee a large number of possible activities, among them:

- Science with IV generation light sources (IR-X FEL).
- Nuclear photonics with Compton back-scattered $\gamma-$rays.
- Fundamental physics with low energy linear colliders.
- Advanced neutron source by photo-production.
- Science with THz radiation sources.
- Physics with high power/intensity lasers.
- R&D on advanced accelerator concepts.
- International Linear Collider technology implementation.
- Detector development for X-ray FEL and Linear Colliders.
- R&D in accelerator physics and industrial spin off.

The main feature of a superconducting (SC) linac relevant for our facility is the possibility to operate the machine in continuous (CW) or quasi-continuous wave (qCW) mode with high average beam power (<1 MW) and high average current (<500 μA). The CW or qCW choice, combined with a proper bunch distribution scheme, offers the most versatile solution to provide bunches to a number of different experiments, as could be envisaged in a multipurpose facility. In addition, Europe is in a strategic position in the SC RF technology, mainly due to the strong contribution of European countries to the TESLA Collaboration [2]. In particular, INFN strongly participated since the early design stages through the final engineering, shares the know-how with Italian industries (see Fig. 1) and has the recognized intellectual property of several main components (one of which is the cryo-module concept and its evolution [3]).

The realization of such a large facility will allow INFN to consolidate a strong scientific, technological and industrial role in a competing international context both to deploy a national multipurpose facility along the scientific applications discussed in the following sections, and to prepare a strong role for the contribution to possible future large international high energy physics projects such as the International Linear Collider [4].

2. IRIDE layout: staging and upgrade potentials

The backbone of the IRIDE facility is a double superconducting high duty cycle electron linear accelerator, with the required 15 kW at 2 K cryogenic plant, based on the L-band standing wave RF (1.3 GHz) cavities developed by the TESLA collaboration, which currently drive the FLASH FEL facility in DESY and which, with minimal improvements of the cryo-module cooling system, could be upgraded to CW or qCW operation, see Table 1. Both pulsed and CW options rely on existing technology, available on the market by several vendors. Pulsed klystrons at 1.7 MW peak delivering 1.5 ms pulses at 100 Hz repetition rate are for instance available from Thales (TH2104D). Solid State Amplifiers delivering 5–10 kW CW power are available from several Italian or European vendors. XFEL/LC couplers exceed the IRIDE parameter requirements in terms of both peak and average power.

The second core device of the facility is the high average power cryogenically cooled Yb:YAG Laser system operating in a chirped pulse amplification architecture followed by a frequency conversion stage to achieve 515 nm wavelength. This technology allowed achieving recently 1 J at 100 Hz in the picosecond regime with a bandwidth of 0.1%. An upgraded version of the SPARC-LAB [5] laser FLAME [6], based upon a Ti:Sa chirped pulse amplification (CPA) laser, will be also considered, leading to a performance characterized by a total energy of 12 J at 10 Hz, with a bandwidth sufficient to achieve <20 fs and a contrast as high as 10^{12}, suitable to drive advanced plasma wake field acceleration schemes.

Fig. 1. A set of pre-series XFEL cavities at the company E. Zanon.

Table 1
Possible SC linac parameters.

Parameters	Pulsed	qCW	CW
Energy (GeV)	2	2	1.5
I (within pulse) (mA)	2.5	0.26	
I (average) (mA)	0.17	0.16	0.35
RF pulse duration (ms)	1.5	1000	CW
RF Duty cycle (%)	15	60	100
E_{acc} (MV/m)	20	20	15
$Q_0 \times 10^{10}/Q_{ext} \times 10^6$	2/4	2/40	2/40
No. of cavities/No. of modules	96/12	96/12	96/12
Beam average power (kW)	334	309	525

By using standing wave SC accelerating structures, that can accelerate beams in both longitudinal directions, one can see an attractive scheme based on two linacs operating at a maximum energy of 2 GeV each, when working in the collider mode, or used in cascade, as a single longer linac, to boost the electron energy up to 4 GeV for higher energy electron beam applications. In addition when operating in the collider mode both linacs may partially recover the electron kinetic energy of the beam leaving the opposite linac after the interaction, thus increasing the overall efficiency of the system and simplifying the beam dump design.

The IRIDE design options have fundamental implications on the electron injector and on the electron gun. Indeed, the injector accelerating sections must be of the superconducting type, as the rest of the electron linac, while the gun can be in both cases a sub-harmonic, low frequency RF gun, operating at room temperature. The results recently obtained at Berkeley with the CW APEX gun [7], in the framework of NGLS [8], are consistent with the CW option and can also be extrapolated with the required brightness in case the high charge bunch, high repetition rate option is chosen. The possibility to produce polarized electrons with the APEX gun is under investigation.

As indicated in Fig. 2, the first 2 GeV linac system (L1) can drive FEL, Neutron and THz radiation sources, electron-on-target physics experiments and, in combination with the high energy laser, a 10–60 MeV γ-ray Compton source is also possible. With also the second 2 GeV linac installed (L2) one can envisage a low energy linear collider scheme for electron–electron, electron–photon, photon–photon and eventually electron–positron scattering studies. The combination of the two linacs, boosting the electrons up to 4 GeV, could also drive a short wavelength FEL user facility (Exp2).

The *Neutron source* (nT) requires a medium energy electron beam such as the one extracted from L1 driven to impinge on bulk of cooled high-Z target (nT), where it loses energy mainly by bremsstrahlung, producing an electromagnetic shower cascade. The photons of the shower can excite the nuclei of the target with which they interact and these excited nuclei go back into the fundamental state by emitting one or more nucleons. At the state of the art of the project, we have mainly focused on the Tungsten as possible choice for the target of IRIDE: the estimated rate emissions of neutrons (up 10^{15} n/s) and other secondary particles, that are described in Ref. [1], have been obtained for a Tungsten cylindrical cooled target with 7 cm diameter and 6 cm height. A 3 m thick Iron shielding is also foreseen. The beamlines of interest are of three types: short beamlines for Chip Irradiation and Imaging (nL3), long beamlines for applications requiring time of flight measurements, like Bragg Edge Transmission, Diffraction and Nuclear Resonance Capture Analysis (nL1), and even longer beamlines ($\sim$200 m) needed for neutron oscillation studies (nL2). Each beam line needs to be equipped with shielding, diagnostics and detectors.

The main components of the *Compton Source* (CS) are [9]:

(a) The high brightness electron Linac (L1) capable to deliver multi-bunch trains, i.e. working at 100 Hz rep rate with at least 50 electron bunches distributed over the RF pulse duration (from 0.5 up to 1 μs), carrying a fraction of a nC bunch charge at very low *rms* normalized emittances (<1 mm · mrad) and energy spreads ($<0.1\%$).
(b) a high energy, high quality, high repetition rate laser system, delivering pulses carrying at least 1 J of energy (in the fundamental), psec pulse duration, 100 Hz repetition rate, high quality ($M^2 < 1.2$), such to be focused down to typical spot sizes of 10 μm at collision with the electron bunch.
(c) A laser recirculator consisting of a two parabolic confocal mirror set, capable to recirculate the laser pulse a number of times equal to the electron bunches within the train (<50), by focusing it down to the collision point, recollimating and reflecting it back to the other mirror which in turns refocuses it down back to the interaction.

The expected performances for the γ-ray beam delivered are: tunability between 1 and 60 MeV, bandwidth smaller than 0.3%, full control of polarization (linear, larger than 99.8%), spectral density larger than 10^4 photons/s.eV, and peak brilliance larger than 10^{22} (photons/s mm^{2}mrad^2 0.1%).

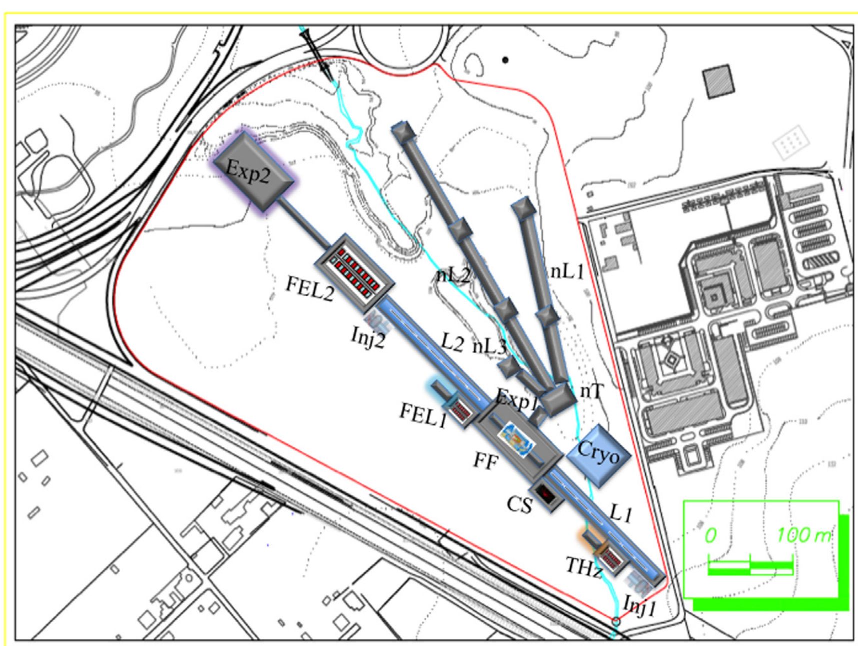

Fig. 2. Schematic layout of the IRIDE accelerators and radiation sources complex. Some relevant components are indicated: the cryogenic plant hall (Cryo), the electron injectors (Inj1, Inj2), the SC linacs (L1, L2), the FEL devices (THz, FEL1, FEL2) and the user experimental hall (Exp1, Exp2), the laser system for Compton source (CS), the Final Focus beam line (FF) in the experimental hall Exp1 for colliders and nuclear photonics, the neutron source target (nT) with experimental beam lines (nL1, nL2, nL3).

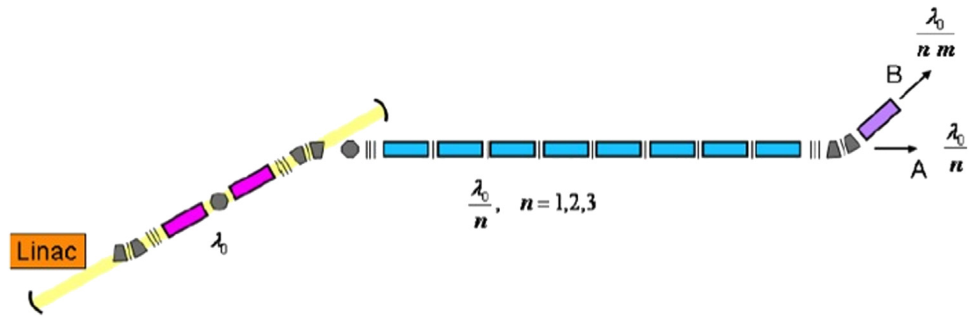

Fig. 3. Undulator chain at the L2 exit, the first component is an oscillator acting also as a micro-buncher driving the downstream SASE FEL.

Table 2
FEL performances at 4 GeV electron beam energy.

	Fundamental	3rd harmonic
λ (nm / keV)	0.6/2	0.2/6
Peak flux (n/s/−0.1% BW)	1.2×10^{25}	5.9×10^{22}
Peak brilliance	1.9×10^{31}	1.8×10^{29}
Photon/bunch	2.1×10^{12}	1.1×10^{10}

Several *FEL source* configurations are possible at IRIDE ranging from IR to X-ray wavelength radiation, as discussed in Ref. [1]. In particular a Seeded configuration is possible at the exit of L1, by using an externally injected laser signal. In this case, the maximum operating energy is fixed by the source exploited as seeding and by the undulator parameters. If we consider the 27th harmonics of the Ti–Sa (26.9 nm), the beam energy is constrained below 1 GeV to drive on resonance an undulator with 2.7 cm period. The FEL tunability could range from 27 nm to 1.65 nm (FEL1). Possible options with shorter undulator period are under investigation including the RF undulator option. User beam lines can be accommodated in the first experimental hall (Exp1).

At the highest energy end of the linac (FEL2) a combination of Oscillator, SASE and Seeded operational mode offers an attractive and unique possibility. As shown in Fig. 3, an oscillator operating in the VUV region is used to produce bunching in the e-beam train, which is successively injected into the downstream sections of the undulator chain tuned at higher harmonics of the oscillator [10]. The rather narrow bandwidth of operation of the cavity provides a constraint for the energy of the e-beam at an energy around 2.28 GeV. In this configuration, a significant amount of third and fifth harmonics allows its use in the successive section to get pre-bunched SASE operation at 4.5 and 2.7 nm. Removing the cavity mirrors and operating at full linacs energy (up to 4 GeV, see Table 2) we get an output wavelength of 0.6 nm, which can be extended to 0.2 nm provided that a segmented undulator is installed and the last sections are replaced by a super-conducting undulator with undulator parameter $K_u = 1$ and period $\lambda_u = 1$ cm. The possibility to operate the IRIDE SASE FEL in a qCW mode with low repetition rate (<1 MHz) will certainly simplify the required X-ray detector performances. User beam lines can be accommodated in the second large experimental hall (Exp2).

Experimental hall 1 (Exp1) will host also the particle detectors for the linear collider options, certainly the most challenging components of the entire project. The *electron–electron collider* option will be essentially based on the final focus (FF) system already operating at ATF2 [11], based on the recently proposed compact final focus optics with local chromaticity correction [12] and where 100 nm electron beam spot sizes have been already achieved. The occurrence of parasitic collisions in the collider mode will be avoided with a crossing angle. The feasibility of the *electron–positron collider* is strongly dependent on our capability to produce low emittance positrons [13,14]. The IRIDE R&D program comprises the development of a positron source based on direct conversion of a 60 MeV γ-ray beam in a solid target. The positron source design goals are reported in Table 3. The *gamma-electron* and *gamma–gamma collider* options will require a careful design and development of the interaction region, see Fig. 4 [15]. In a photon collider in fact two high energy electron beams after the final focus system travel towards the interaction point (IP) and at a distance of about 1–5 mm from the IP collide with a focused laser beam [16]. After scattering, the photons follow their direction to the interaction point (IP) where they collide with a similar opposite beam of high energy photons or electrons. Such a new collider configuration has never been realized so far and is the subject of many design studies around the world. A dedicate design for the IRIDE facility is under way.

Table 3
Comparison between conventional and expected Compton driven positron source performances.

	Conv.	CS driven
Source size (rms) [μm]	400	50
Target thickness [X_0]	6	0.4
Transverse momentum (rms) [MeV]	5	1
Norm. emittance (rms) [mrad]	0.001	50×10^{-6}
Positron yield	1	0.4

Advanced accelerators techniques could be also investigated in the large experimental hall (Exp1). The success of the advanced accelerator activity as a vigorous and intense R&D program focused on the enabling technologies of plasma accelerators, Compton converters, gamma beam focusing, polarized positron source, superconducting RF gun and the associated advanced diagnostics instrumentation, could allow envisaging a convenient energy upgrade of the facility to tens GeV level in a higher energy range of scientific applications.

The IRIDE facility could be hosted in the 30 hectares area on the University of Rome Tor Vergata campus site a few km southeast of the city of Rome as shown in Fig. 2. The total linear extension will be approximately 700 m. The interested area is just alongside of the CNR territory and it is approximately a couple of km away from the ENEA and INFN sites in Frascati, the major Italian research institutes that have already strongly contributed to IRIDE scientific case. IRIDE is also supposed to be realized in subsequent stages of development depending on the assigned priorities and available fundings. An initial stage could include the first linac only, up to a maximum energy of 2 GeV, which could drive the realization within 5 years of the neutron source, the long wavelength FEL, the Compton source and the fixed target nuclear physic studies. Provided that the average beam current is kept constant, all the previous applications could be run concurrently. In the following paragraphs, an overview of the IRIDE scientific case is illustrated, for more details and a complete reference list see Ref. [1].

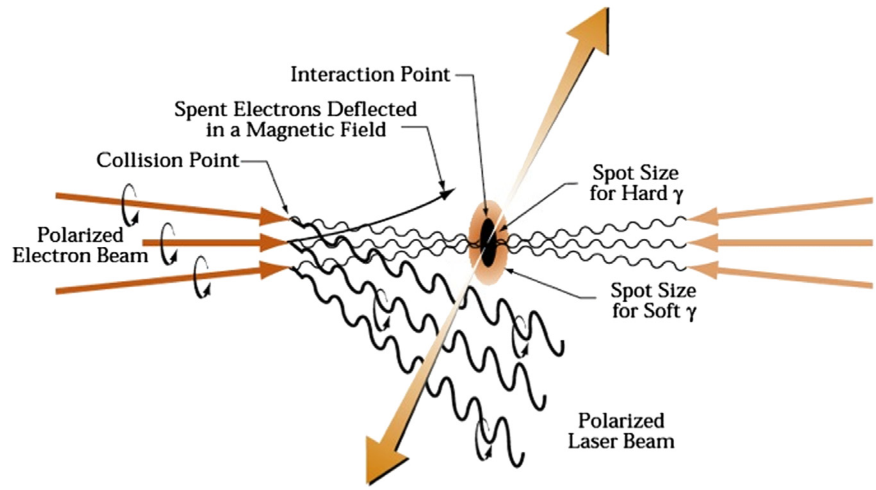

Fig. 4. Scheme of principle of a photon collider. High-energy electrons scatter on laser photons and produce high-energy photon beam which collides with a similar photon or electron beam at the interaction point IP.

3. Science with photons: new insights into the facets of nature and life.

The FEL at the IRIDE facility is a source of coherent X-rays, up to 0.2 nm at fundamental wavelength, depending on the electron beam energy. In some way it covers a radiation region complementary to those of other existing (see for example [17]) or in construction facilities, and will be provided also with an ancillary equipment to produce radiation in to the infrared and THz region [18]. The IRIDE FEL has a wide wavelengths overlap to satisfy users in many different fields of science and to ensure at the same time a beneficial level of competitiveness. The IRIDE FEL will provide radiation with the unprecedented characteristics like:

- Self-seeding: Narrow bandwidth, wavelength stability, higher brightness and energy tunability [10].
- Polarization control: Tunable linear and circular polarization.
- Two color pulses: Simultaneous delivery of independent wavelength pulses [19].
- Delayed pulses: Independent delay of two pulses up to a few ps [20].

The considered scientific case for IRIDE FEL reports experimental proposals ranging from time dependent spectroscopies in condensed matter to imaging for biological applications. Among the highlights of the IRIDE Scientific Case of paramount importance is the *Spectroscopy of flying proteins*. Proteins, long linear chains composed by L-α-amino acids joined together by peptide bonds, rule fundamental functions in life processes. To achieve their functional properties, the interplay between electronic properties and structural properties is crucial. Proteins take their shape spontaneously after the synthesis in the cell, but the structure depends also on the environment properties (solvent, salt concentration, pH, temperatures and molecular chaperones). The chirality influences the assembly, folding and activity of biological molecules: amino acids that form proteins are all in the L configuration, with the exception of (non-chiral) Glycine. So far the task to determine the structure of proteins, and subsequently their electronic properties was carried out by X-ray diffraction and nuclear magnetic resonance in crystals and in solution. The characterization of structural and electronic properties of proteins in the gas phase, as is possible at IRIDE, would provide valuable information to understand the folding. The absence of solvent interaction can reveal the balance of the molecular weak forces that determine the shape of the protein. To bring un-fragmented proteins into the gaseous phase, the state of the art technique is represented by Electro Spray Ionization (ESI) [21]. The ESI technique solved the problem of how to study large molecules in solution by mass spectrometry that needs a high vacuum environment. Pioneering works combining ESI with laser spectroscopies revealed the possible application in the characterization of electronic and structural processes. These preliminary results envisage the application of ion-spectroscopy to proteomics, but this research field is still completely unexplored. The low density of the target (space charge limits the maximum ion density 10^6 ions/cm^3) prevents to extend such experiments in the VUV-soft X-ray wavelength range with the present sources. IRIDE with its high flux and focusing represents an ideal source for these studies. Moreover, the IRIDE wavelength range can cover the excitations to the core states, focusing on bond character and local environment, and providing a rich and detailed description. These results would be complementary with respect to those obtained in crystals or solution, and give insight into the influence of the solvent on the protein shape. In addition, the possibility of reaching wavelength of the order of 1 Å will allow to measure protein crystals of very small dimension, typically of the order of 100 nm edge, which are those produced most of the time in the crystallization trials. The measurement of such samples is outside the capability of any micro focus beam line in the standard Synchrotron Radiation facilities. The fluence of IRIDE in the hard X-ray energy range is still enough to enable structure determination from diffraction measurements of streams of nano-crystals, as recently done at LCLS-FEL facility where diffraction patterns from a large photosystem membrane complex that crystallizes in samples of about 250 nm size have been recorded. The very broad energy range available at IRIDE will allow a complete structural characterization of protein samples in many different physical–chemical conditions. This is crucial to understand the structure/function relationships from a molecular to a cellular level opening new perspective for the treatment of genetic disabilities and diseases and for the design of more effective drugs.

4. Science with γ-rays: a deep view of exotic nuclear structures

Radiation at short wavelength as γ-rays is used to excite the Nuclear Resonant Fluorescence (NRF), so that different nuclei can be identified by the distinct pattern of NRF emission peaks. In nuclear physics, there is large interest at present for the neutron-rich systems. On the one hand, existing and planned radioactive beams facilities aim to locate the position of the neutron and proton drip-lines (i.e. the limits defining whether a nuclear system is bound), and to study the properties of the isotopes in which the neutron/proton ratio differs from the values that characterize stable nuclei. On the other hand, another example of nuclear matter under extreme conditions is the matter that compose the compact astrophysical objects like the neutron stars. In particular, Nuclear Physics will benefit from the availability of new generation γ-rays beams for:

- Studies of the nucleus structure at the Pigmy and Giant Dipole Resonance excitation (to probe the structure and isospin properties of nuclear systems) with unprecedented resolution in reconstructing the nuclear states: this is crucial also to understand some unknown processes in the stellar nucleo-synthesis.
- Studies of two level barionic states in the high energy resonance of the nuclei, above 20 MeV and up to 60 MeV, crucial to reconstruct the equation of state of the nuclear matter.

While new Nuclear Applications will be pursued in several fields like:

- Detection and imaging of fissile and strategic material with isotopic reconstruction of the components (e.g. detection of fissile materials hidden in metallic containers), with large impact on the national security scenario.
- Remote sensing and diagnosis of nuclear wastes in containers, with reconstruction of the isotope and nuclear composition of the waste material, with large impact on the atomic energy scenario.
- Medical imaging and therapy.

The scientific activities foreseen at IRIDE lead to specific and challenging requirements with respect to X-ray instrumentation and in particular to X-ray detectors for FEL and Compton radiation [22]. These requirements ask for detectors that cover a wide energy range, from soft to hard X-ray energies and up to γ-rays, with specification in some cases exceeding the existing technology. Successful exploitation of the unprecedented features of the X-ray radiation that will be available at IRIDE calls for a dedicated and substantial detector R&D program.

5. Science with neutrons: from fundamental physics to industrial applications

Neutrons represent a unique probe for studying matter on the molecular scale, thus opening a wide range of applications: from material science to life science, from engineering and industrial applications to fundamental physics experiments. They cannot compete with electromagnetic radiation in intensity, but they are complementary with it because they penetrate substances that block the electromagnetic radiation (like metals) and are stopped by long radiation length materials, in particular hydrogenated and deuterated ones. Photo-production facilities can be more cost-effective than spallation sources for neutron fluxes up to 10^{15}–10^{16} n/s at the target, even though the neutron yield per primary electron is (depending on the primary beam energy) at least 10–20 times lower with respect to proton-induced spallation. Regarding fundamental physics investigation that are possible with IRIDE neutron facility, *neutron–antineutron oscillations* are very important since they would allow precision testing of the fundamental CPT-symmetry, very closely connected to the quantum field theory through the CPT-theorem. If discovered, neutron–antineutron oscillation will establish a new force of nature and a new phenomenon leading to the physics beyond the SM at the energy scale above TeV. In addition, will help to provide understanding of matter–antimatter asymmetry and origin of neutrino mass. An experiment aimed to improve the present limit on the neutron–antineutron oscillation lifetime (i.e. $\tau > 108$ s) obtained at Institut Laue-Langevin [23], would require, in addition to the possibility of producing cold neutrons with a cryogenic moderator, a dedicated long beam-line with high-vacuum and terrestrial magnetic field shielding, and a detector placed around a thin target in order to reconstruct the anti-neutron annihilation products.

In addition, impinging the electron beam on a target produces also charged pions that decaying produce muons. High intensity μ^+ beams are used among the other things for the search of the lepton violating decay $\mu \to e\gamma$. Preliminary simulations show that with a not yet optimized carbon target a rate of 10^9 μ/s, exceeding the beam performances on which the Muon Electron Gamma (MEG) experiment [24] at PSI is currently operated, can be achieved. This solution offers a huge potential in the search for lepton-flavor-violation.

Possible applications of the IRIDE neutron source in the field of applied physics are:

- Neutron Resonance Capture Analysis (NRCA): Each resonance is the fingerprint of a nuclear specie (isotopical recognition) thus allowing for the elemental material analysis (qualitative and quantitative) especially on metallic samples (e.g. cultural heritages).
- Bragg Edge Transmission (BET): By means of this technique, stresses and strain in bulky samples can be analyzed. This analysis is very important for both industrial and cultural heritages applications.
- Chip irradiation: In order to test the robustness of electronic devices to neutron field in a few minutes, neutron beams produced at facilities are desirable as they may provide an almost atmospheric-like neutron spectrum but several order of magnitude more intense.
- Radiography and Tomography (NR, NT): By means of radiography it is possible to obtain an image of a object that evidences the internal structure, by rotating the sample with respect to the incident beam and collecting images for each angular position a 3D image of the object is obtained (tomography).
- Neutron metrology: In this context, the Italian National Institute of Ionization radiation Metrology (INMRI) is interested in having in Italy (and especially in Roma area) a high energy neutron source in order to develop primary standards for neutron emission rate and energy spectrum calibration.

The characteristics of the neutrons that make them of interest for applied research can of course be used in industrial research. Examples of industrial field with known applications with neutrons are:

- Efficient and cost-effective fabrication of a variety of advanced materials: Neutron scattering techniques can be used for the development of novel transformation-induced plasticity steels or precipitation-hardening Al and Ni alloys, to be used, for example, in aeronautics.
- Pharmaceutical products: The development of new drugs and drug delivery systems, which is strictly related to the detailed understanding of the mechanisms of disease, as well as the improvement of the product shelf-life can be carried out by the employment of neutron techniques.
- Thermoelectric materials: Here, neutrons allow to identify efficient and non-pollutant systems for the development of innovative thermoelectric devices combining low thermal

conductivity with high electrical conductivity, to be employed for waste-heat recovery and in the refrigeration industry.

- Renewable energy sources: In such a field, more and more effective engines, materials for lower heat loss and less energy spill and greener processes for industry are requested. Novel materials for solar and fuel cells, as well as hydrogen storage materials can be developed thanks to neutrons.
- Agro-food systems: Plant strategies and metabolism in resistance to drought can be characterized by neutron methods.

Finally, a neutron facility of the kind we are proposing, can have a positive impact on other two important points: training and education of young scientists, and development of new detection techniques.

6. Particle physics opportunities: assembling the Standard Model puzzles

Recently the experimental results from the Large Hadron Collider at CERN have provided us with very important information on the mass of the Standard Model higgs-like particle. However, the existence of this particle with a given mass does not solve, by itself, all the long-standing puzzles of the SM, such as a problem of the SM hierarchy, the naturalness of the higgs boson and the electroweak (EW) symmetry breaking. Even though all the SM parameters are now measured to a high accuracy, the necessity of the New Physics (NP) existence for explaining the SM puzzles is still an open question. From a theoretical point of view, precise and complicated calculations are required to answer these questions, and high-precision input information on the SM parameters is a must. Due to the intrinsic complexity of the calculations, as one needs to study the running of the non-abelian gauge theory parameters over a dozen of orders of magnitude up to the Planck scale, even small experimental uncertainties in the SM parameters have a drastic impact on the conclusions, which can be drawn from such computations. The implications affect our understanding of the fundamental issues of the *conspiracy* between the SM couplings, the EW phase transition, Universe inflation, the cosmological constant, and also the nature of the Dark Matter (DM). It is important to stress that the precise values of the SM parameters, due to the renormalization group evolution, can be obtained only by simultaneous studies at high-energy and low-energy scales. The former point highly motivates the International Linear Collider (ILC) initiative, while the IRIDE project can pursue the latter one and serve as an accelerator-technology test installation and a research facility. The latter point motivates the possible use of the IRIDE facility as a precision tool for the SM exploration at low- and medium-energy scales, with a high priority on the information about the EW couplings of SM, which drives the evolution of the electromagnetic running coupling and the squared sine of the weak angle. Also a rich hadron phenomenology is accessible at these scales, which allows to study issues of the QCD confinement, where the ordinary perturbation theory approaches fail to work. It is anticipated that the construction of the IRIDE facility will be realized step-by-step starting with the physics program that can be pursued with an electron beam on target, further will be possible to investigate electron–photon collider, photon–photon collisions and finally electron–positron and electron–electron collider.

The electron-on-target physics program makes IRIDE a discovery and also a precision physics machine. Among the searched candidates there are the hypothetical particles, like the very-weakly interacting massive U(1) gauge boson (U-boson) as a DM particle candidate and the non-hypothetical, well investigated theoretically, but yet undiscovered, *true muonium* states (TM), which are the bound states of muon and anti-muon with the lifetime of an order of a picosecond. Utilizing the polarized electron beam dumped onto the proton target, one can measure the left–right parity violating asymmetry of electron–proton scattering at the per cent level, and thereby extract precisely the electroweak mixing angle.

The electron–photon collider allows to utilize the elementary Primakoff process to produce the light pseudoscalar (and scalar) mesons in order to precisely measure their two-photon decay widths and thus to tackle the triangle anomaly of QCD. In addition, one can perform the U-boson search in the lepton triplet production channel. A special feature here is the availability of the highly polarized photon beam. This allows to use the lepton triplet production at IRIDE as a research laboratory for development of the methods of polarimetry to be used in astrophysics to measure the polarization directions of incoming high energy γ-rays. Finally, triple Compton effect can be used to study the properties of entangled states. These measurements, which provide important tests of the SM, are not possible with present Compton Sources facilities [25] due to the low photon intensities of the machines.

Low-energy photon–photon collisions with a luminosity of $10^{30}\,cm^{-2}\,s^{-1}$ give a direct view into the vacuum properties of Quantum Electrodynamics (QED), allowing for precision tests of QED in the MeV range, and more generally of Quantum Field Theory (QFT) [26]. The IRIDE accelerator complex can generate for the first time colliding photon–photon beams by Compton back-scattering (for example with a 160 MeV electron beam back-scattering a 515 nm (2.4 eV) wavelength laser beam), and this opens the fascinating field of low-energy photon–photon physics, see also [27]. The technology needed to carry out a photon–photon physics program at energies close to 1 MeV would disclose new developments at higher energies, where a photon–photon Higgs factory could be a nearly ideal discovery machine.

The high-luminosity electron–positron and electron–electron collider with variable energy would be an extremely useful tool for the study of hadronic vacuum polarisation effects, measurements of the effective electroweak mixing angle and contributing to the description of the muon anomalous magnetic moment and the running QED coupling constant by providing the hadronic cross-sections with high accuracy. In addition, these measurements can contribute to the extraction of the light quark masses, flavor symmetry breaking pattern in the light meson sector and allow to study precisely the meson mixing phenomenology through the various meson decays produced with high statistics in lepton collisions. The gamma–gamma fusion sub-processes in the positron/electron–electron inelastic scattering give us the opportunity to investigate the two-photon couplings and form-factors of the various hadronic resonances (and also the many-particles states, like $\pi^+\pi^-$ or $\pi^0\pi^0$), which is important for the understanding of the quark contents of these resonances, of hadron phenomenology and for improvement in the estimate of the hadronic light-by-light scattering contribution to the anomalous magnetic moment of the muon. The LHC, or a future e^+e^- International Linear Collider (ILC), will answer already many questions. However, their discovery potential may be substantially improved if combined with more precise low energy tests of the SM. In this framework, an electron–positron collider such as IRIDE with luminosity of $10^{32}\,cm^{-2}\,s^{-1}$ with center of mass energy ranging from the mass of the ϕ-resonance (1 GeV) up to ~3.0 GeV, would complement high-energy experiments at the LHC and a future linear collider (ILC). The direct competing project is VEPP-2000 at Novosibirsk which will cover the center-of-mass energy range between 1 and 2 GeV with two experiments. This collider has started first operations in 2009 and is expected to provide a luminosity ranging between $10^{31}\,cm^{-2}\,s^{-1}$ at 1 GeV and $10^{32}\,cm^{-2}\,s^{-1}$ at 2 GeV. Other *indirect* competitors are the higher energy e^+e^- colliders (τ-charm and B-factories) that can cover the low energy region of interest by means of radiative return (ISR). However, due to the photon emission the *equivalent* luminosity produced by these machines in the region between 1 and 3 GeV is much less than the one expected in the collider discussed here.

It is important to stress that a synergy of all the proposed measurements can lead to a very reliable and cross-checked experimental exploration of the SM. In addition to the expected luminosity of IRIDE, in the electron–positron mode the operational time required for the physics program would be limited and well in accordance with the beam requests for the other functioning modes (e.g., FEL) of the machine.

References

[1] D. Alesini, et al., IRIDE White Book, arXiv:1307.7967 [physics.ins-det].
[2] B. Aune, et al., Physical Review Special Topics – Accelerators and Beams 3 (2000) 092001.
[3] C. Pagani, et al., Construction, commissioning and cryogenic performances of the First TESLA Test Facility (TTF) cryomodule, in: P. Kittel (Ed.), Advances in Cryogenic Engineering, vol. 43, Plenum Press, New York, 1998, p. 87.
[4] T. Behnke, et al., The International Linear Collider Technical Design Report – vol. 1: Executive Summary, arXiv:1306.6327 [physics.acc-ph].
[5] M. Ferrario, et al., Nuclear Instruments and Methods in Physics Research Section B 309 (2013) 183.
[6] L. Gizzi, et al., Nuclear Instruments and Methods in Physics Research Section B 309 (2013) 202.
[7] F. Sannibale, et al., Physical Review Special Topics – Accelerators and Beams 15 (2012) 103501.
[8] J.M. Byrd, et al., Design concepts for the NGLS linac, in: Proceedings of IPAC13, Shanghai, China.
[9] A. Bacci, et al., Journal of Applied Physics 113 (2013) 194508.
[10] G. Dattoli, P.L. Ottaviani, Journal of Applied Physics 86 (1999) 5331.
[11] Sha Bai, et al., Physical Review Special Topics – Accelerators and Beams 13 (2010) 092804.
[12] P. Raimondi, A. Seryi, Physical Review Letters 86 (2001) 3779.
[13] K. Floettmann, Positron source options for linear colliders, in: Proceedings of EPAC 2004, Lucerne, Switzerland.
[14] E. Sabia, et al., Free electron laser and positronium stimulated annihilation, in: Proceedings of FEL 2010, Malmo, Sweden.
[15] K.-J. Kim, A. Sessler, Gamma-Gamma Colliders, Beam Line, Spring/Summer, 1996.
[16] V. Telnov, et al., International Journal of Modern Physics A 19 (30) (2004) 5097.
[17] C.J. Bocchetta, et al., Conceptual Design Report for the FERMI@Elettra project, ST/F-TN-07/12 (2007).
[18] E. Chiadroni, et al., Review of Scientific Instruments 84 (2013) 022703.
[19] V. Petrillo, et al., Physical Review Letters 111 (2013) 114802.
[20] M. Ferrario, et al., Nuclear Instruments and Methods in Physics Research Section A 637 (1) (2011) S43.
[21] M. Yamashita, J.B. Fenn, Journal of Physical Chemistry 88 (1984) 4451.
[22] A. Castoldi, et al., Nuclear Instruments and Methods A568 (2006) 89.
[23] M. Baldo Ceolin, et al., Zeitschrift fur Physik C 63 (1994) 409.
[24] J. Adam, et al., European Physical Journal C 73 (2013) 2365.
[25] The White Book of ELI Nuclear Physics, ⟨http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf⟩.
[26] E. Milotti, et al., International Journal of Quantum Information 10 (2012) 1241002.
[27] A. Torre, et al., Journal of the Optical Society of America 30 (October (10)) (2013).