Strong Field Physics and QED Experiments with ELI-NP 2x10PW Laser Beams

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Abstract. The ELI-NP facility will focus a 10 PW pulsed laser beam at intensities of ~10^{23} W/cm^2 for the first time, enabling investigation of the new physical phenomena at the interfaces of plasma, nuclear and particle physics. The electric field in the laser focus has a maximum value of ~10^{15} V/m at such laser intensities. In the ELI-NP Experimental Area E6, we propose the study of Radiation Reaction, Strong Field Quantum Electrodynamics (QED) effects and resulting production of Ultra-bright Sources of Gamma-rays which could be used for nuclear activation. Two powerful, synchronized 10 PW laser beams will be focused in the E6 Interaction Chamber on either gas or solid targets. One 10 PW beam is the Pump-beam and the other is the Probe-beam. The focused Pump beam accelerates the electrons to relativistic energies. The accelerated electron bunches interact with the very high electro-magnetic field of the focused Probe beam. The layout of the experimental area E6 will be presented with several options for the experimental configurations.

1. STRONG FIELD PHYSICS AND QED PROCESSES

At intensities above 10^{21} W/cm^2 available from the ELI-NP lasers [1, 2, 3, 4], electrons in the electromagnetic field are highly relativistic and the normalized transverse vector potential (giving the electron transverse momentum), $a_0 = eA/m_e c^2 >> 1$, which is the work done by the laser field on the electron in the Compton wavelength, λ_c in units of photon energy.

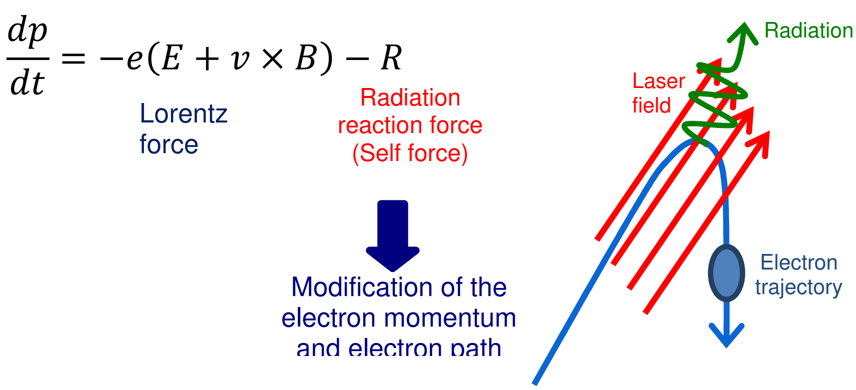

FIGURE 1. Radiation Reaction force becomes important at high laser intensities: the electron radiates a large amount of its kinetic energy.

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Electrons gain a longitudinal drift momentum $\approx a_0^2$. Several interesting phenomena can be studied for fields with $a_0 \gg 1$. One of the outstanding problems in physics is understanding how charged particles react to their own radiation field. Fig. 1 shows that 'Radiation Reaction' (RR) becomes important when the electron radiates large amounts of energy. If the radiated energy, during acceleration time in the laser field, is smaller than the electron kinetic energy, the radiation reaction is negligible. If the radiated energy during the acceleration is close to the kinetic energy, the radiation reaction is important. This becomes important at intensities $>10^{22}$ W/cm^2. The importance of the synchrotron emission is determined by the parameter 'η'. When $\eta \to 1$, many high energy photons are emitted by the electron.

$$\eta = \gamma \cdot \Theta \cdot \sqrt{\frac{I_L}{I_S}} \qquad 1)$$

Where: γ is the electron Lorenz factor; I_L is the focused laser intensity; I_S=2x10^{29} W/cm^2 is the Schwinger intensity for spontaneous generation of electron-positron pair from vacuum. Θ is a geometrical factor. Presently the Schwinger intensity cannot be achieved even with the planned high power lasers of the future. However the equation above shows how we can lower the laser intensity requirement.

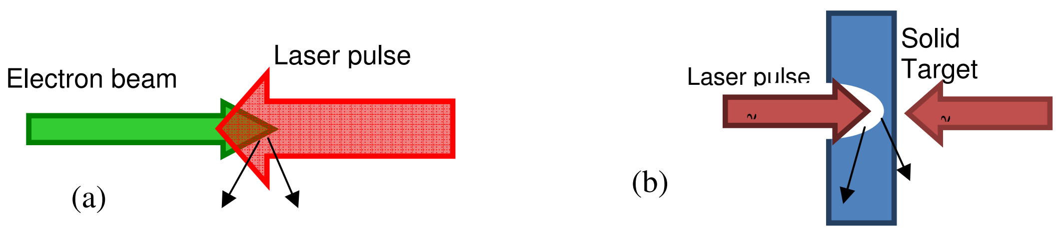

FIGURE 2. Strong field physics and QED with: (a) gas target in which the pump-laser beam generates the relativistic electron-beam which interacts with the counter-propagating probe-laser beam. (b) solid target in which the electrons are produced by the pump-laser beam and interact with the probe-laser beam or with the pump-beam itself. The pump and probe lasers are synchronized and delayed with respect to one another as required.

We can achieve η ~ 1 when γ is large and Θ ~ 1. This is the case for relativistic electrons (γ>>1) and counter-propagating beams of laser and electrons (Θ ~ 1) [5].

The ELI-NP Working Group #2 (WG2) is responsible with designing experiments for 'Strong Field Physics and QED' and has proposed two complementary experimental methods summarized in Fig. 2.

In the first method, Fig. 2a, we generate relativistic electrons ($\gamma \gg 1$) with a 10 PW pump-laser focused by a long focal length mirror (F:20) into a gas jet or a gas cell. The second, 10PW probe-laser is focused to high intensity by an F:3 mirror on the relativistic electron pulse and the electrons are exposed to the strong EM field in the laser focus producing the effects we plan to study. Since the beams are counter-propagating the geometric factor is Θ ~ 1. The intensity of the 10 PW focused to a focal spot of 5μm diameter is expected to be bigger than 10^{22} W/cm^2. The pump and probe lasers are synchronized and delayed with respect to one another as required.

In the second method, Fig. 2b, the 10PW pump-laser is focused tightly by an F:3 mirror on a solid-foil target generating hot electrons in the target. The second, 10PW probe laser is also focused tightly by an F:3 mirror on the solid target and delayed with respect to the pump laser as required. The probe laser provides the strong EM field to which the electrons are exposed. The solid-target method is complementary to the gas-target method. The number of relativistic electrons is very large because the target is a solid. This is much larger than in the gas-target or 'beam-beam' method above. On the other hand the kinetic energy of the electrons is not as large as in the 'beam-beam' method.

The new area of 'Strong Field Physics and QED' is presently based on theoretical predictions of exiting new science and at ELI-NP we plan to use the unprecedented laser power being installed to test these theories. Here are some examples of the predicted new science: nonlinear production of cascades of electron-positron pairs from vacuum [5], gamma-ray production by inverse Compton scattering of the probe-laser beam off the electron beam [6, 7], classical and quantum kinetic radiation reaction effects [8], investigation of collective electron effects in radiation production [9], a new state of matter named the 'QED plasma regime' characterized by 'relativistic hole-boring' and 'induced transparency of target' [10]. We plan to verify these new theoretical predictions using the unprecedented laser power which will be available at ELI-NP.

2. ELI-NP EXPERIMENTAL AREA E6 FOR STRONG FIELD PHYSICS AND QED

The planned High Power Laser Interaction Areas of ELI-NP are shown schematically in Fig. 3 and the Interaction Area E6 is shown in more detail in Figs. 4 and 5. The Interaction Areas in Fig.3 are: E1 with 2x10PW lasers for Nuclear Physics with Lasers, E6 with 2x10PW lasers for Strong Field Physics and QED, E7 with 2x10PW lasers for Combined High Power Laser and Brilliant-Gamma-Beam experiments, E4 with 2x1PW (at 1Hz) and E5 with 2x0.1PW lasers (at 10Hz) for applications of secondary laser radiation in science and technology. The two 10PW laser beams (named A and B in Fig. 3) propagate from the Laser-Area in the North toward the E7 Interaction Area in the South. We plan to ‘condition’ one of the laser beams with ‘polarization control’ and ‘adaptive optics’ for optimal focusing. The beams go through a switch-yard placed between the E1 and E6 Interaction Areas. This allows the switching of the two 10 PW laser beams between the three interaction chambers. The two 10PW laser beams are synchronized because they are amplified starting from the same laser-oscillator. A variable delay between the two beams will be available for pump-probe experiments.

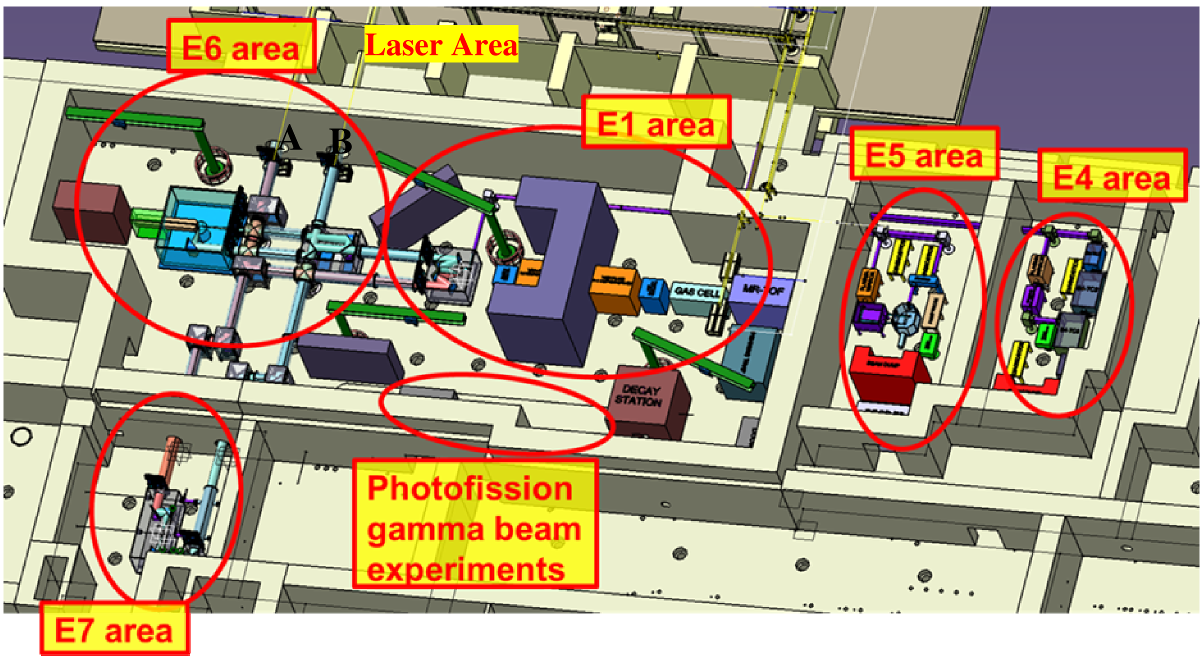

FIGURE 3. ELI-NP High Power Laser interaction areas: E1 with 2x10PW lasers for Nuclear Physics with Lasers, E6 with 2x10PW lasers for Strong Field Physics and QED, E7 with 2x10PW lasers for Combined High Power Laser and Brilliant-Gamma-Beam experiments, E4 with 2x1PW, 1Hz, and E5 with 2x0.1PW lasers at 10Hz for applications of secondary laser radiation in science and technology.

The conceptual design of E6 Interaction Area for Strong Field Physics and QED is shown more detail in Figs. 4 and 5. The interaction chamber is almost octagonal, with the laser-plasma interaction point in the center of the chamber. The octagon allows diagnostics to point naturally to the plasma in the chamber center. The inner ‘diameter’ and the height of the chamber are planned for 4.5 m and 2.2 m respectively in order to accommodate the two-beam pump-probe focusing geometry and the large turning mirrors and toroidal focusing mirrors. The laser beams propagate in a horizontal plane at a height of 1.5 m above the floor. The 10PW laser beam diameter is ~ 550 mm. The floor is supported on spring-loaded pillars and the scroll vacuum-pumps are in the cellar in order to reduce vibrations.

The ‘beam-beam’ counter-propagating focusing geometry for a gas target is shown in Fig. 4. The 10PW East-Laser-Beam is directed to the E6 Interaction Station in the Switchyard. A long focal length mirror F:20 focuses the Pump-Beam on the gas jet or gas cell inside the Station generating the pulse of relativistic electrons. The 10 PW West-Laser-Beam is directed to the E6 Station and focused with a short focal length F:3 parabolic mirror on the electron pulse in the interaction point. The Probe-Beam provides the strong EM field to generate the Strong-Field effects we want to study. The energy spectrum of the electron pulse is measured with the electron spectrometer in order to resolve the changes in the electron energy spectrum due to the electron interaction with the strong EM field. The spectrometer needs to be close to the Interaction Point because of Radiation-Reaction can change the direction of propagation of the electron pulse. The spectrometer design is being developed. A 4 m long permanent magnet spectrometer has been proposed with a field of 1 Tesla. A modular approach with a 2 m long spectrometer inside the Interaction Station and a second section outside the station is being considered [11]. A large, 4 m long Beam-Dump ensures that the relativistic electrons are stopped within the Interaction Area. We envisage electron energies up to ~30 GeV may be generated in the future in which case the muons ($\mu^{\pm}$ particles) would be generated in the Beam-Dump. To protect from this radiation, the Beam-Dump is continued on the other side of the West-wall of E6 with a 7 m long iron Beam-Dump (for attenuation of $\mu^{\pm}$) [12]. A second focusing configuration for gas targets will be available providing same direction pump-probe laser beams focused on the gas-jet.

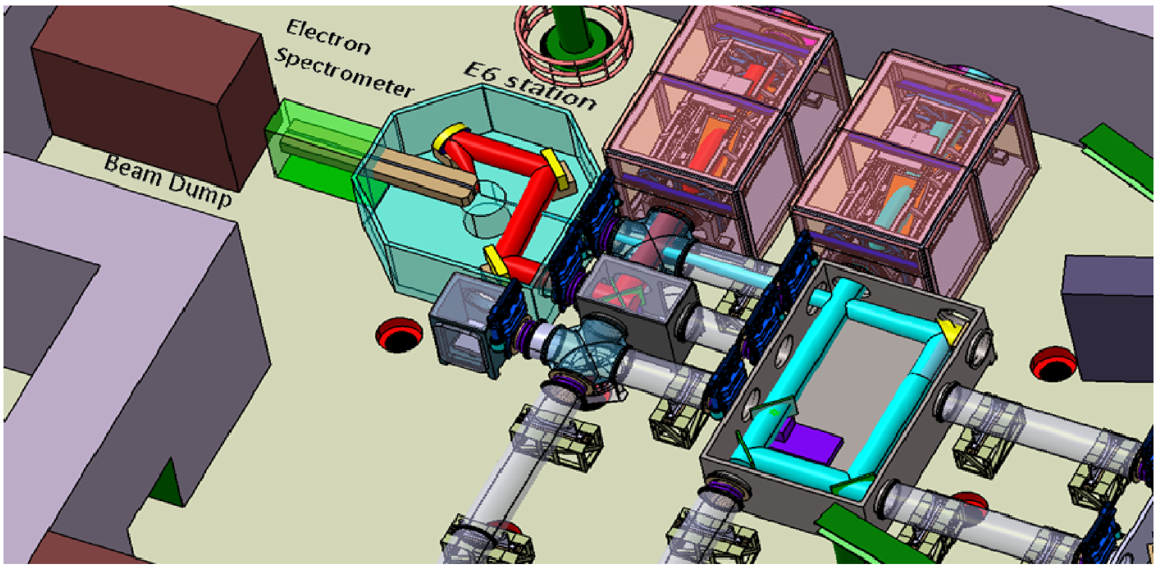

FIGURE.4. ELI-NP E6 interaction area for 2x10PW lasers. Gas target counter-propagating focusing configuration. F:20 mirror focuses the pump-laser (blue) beam on the gas-cell or jet generating the relativistic electron-beam. F:3 mirror focuses the probe laser (red) beam to provide the strong EM field interacting with the e-beam. Same direction pump-probe focusing will also be available.

The counter-propagating focusing geometry for solid foil targets is shown in Fig. 5. The 10PW West-Laser-Beam (the Pump-beam) and the 10PW East-Laser-Beam (the Probe-beam) are tightly focused in the E6 station with short focal length F:3 parabolic mirrors on the solid target at the interaction point. The Probe-Beam provides the strong EM field to generate the Strong-Field effects we want to study. A number of diagnostics will be available for measuring: gamma-rays, electrons, positrons, ions, scattered laser light, etc. Since large energy protons/ions could be generated in the solid target by mechanisms other than Target Normal Sheath Acceleration, the proton/ion beam direction will always be along the axis of the Beam Dump. A second focusing configuration for gas targets will be available providing same direction pump-probe laser beams focused on the gas-jet.

3. CONCLUSION

In conclusion ELI-NP facility will provide for the Romanian and European User Community, for the first time, a 'Strong Field Physics and QED' Interaction Area, E6, with two synchronized laser beams of unprecedented power: 10PW each in each beam. Experiments with both gas and solid targets are planned. Four focusing geometries are planned with counter-propagating or same direction Pump-Probe 10PW laser beams for each of the targets: gas or solid.

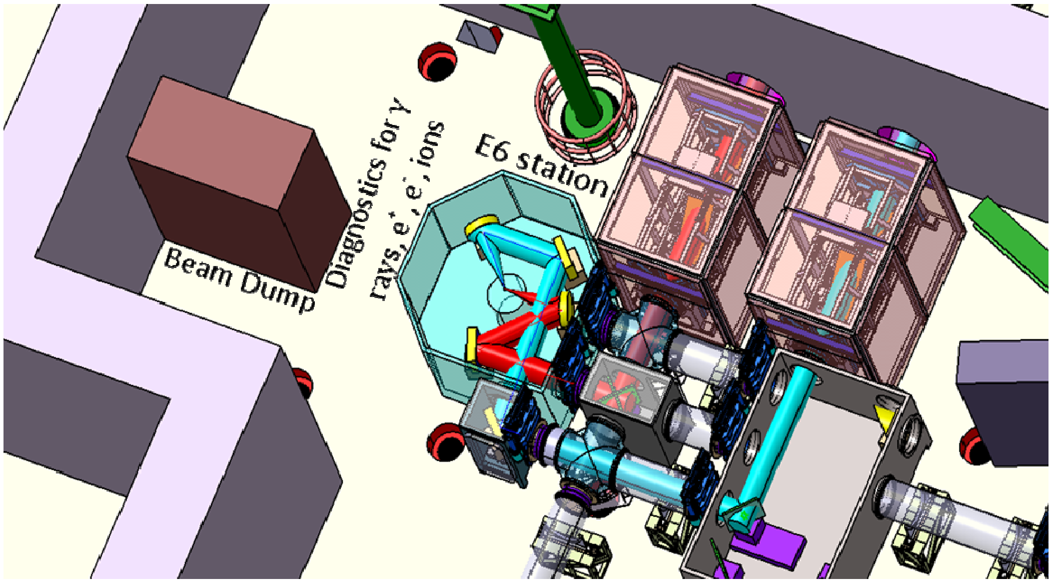

FIGURE 5: ELI-NP, E6 interaction area for 2x10PW lasers. Solid target counter-propagating focusing configuration. F:3 mirrors focus both the pump-laser (red) beam and the probe-laser (blue) beam on the solid foil target. The pump-beam generates the hot electrons and the probe beam provides the strong EM field interacting with the relativistic electrons. Same direction pump-probe focusing will also be available.

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