Investigation of radiation reaction at ELI-NP

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Introduction

With the rapid development of high-power and high-intensity lasers in the world, the maximum laser power and intensity will reach O(10 PW - 10^{23} W/cm^2). Extreme Light Infrastructure - Nuclear Physics (ELI-NP; Figure 1) is one of the research centers which has the two arms of the 10PW lasers to create such extremely high-intensity light and the electron linear accelerator (LINAC) up to 720 MeV to create gamma photons of O(~ 19.5 MeV) via the inverse Compton scattering [1]. Radiation reaction (RR), the back-reaction acting on a radiating electron, becomes important in laser-plasma experiments by these high-intensity lasers. There is its typical prediction that more than 80% of the electron's energy is emitted via the RR effect in head-on collision of a high-intensity laser and a highly energetic electron [2]. That work was performed in purely classical dynamics, however in the recent studies, the importance to include its quantum correction depending on laser intensities has been suggested by several authors [3, 4]. It is regarded as a new regime of physics by high-intensity lasers. For the investigation of this new regime, we plan to examine the effects of RR by the head-on collision between the high-energy electrons ($>$ 600 MeV) extracting from GBS-LINAC and the high-intensity laser ($>10^{21}$ W/cm^2) at ELI-NP [5].

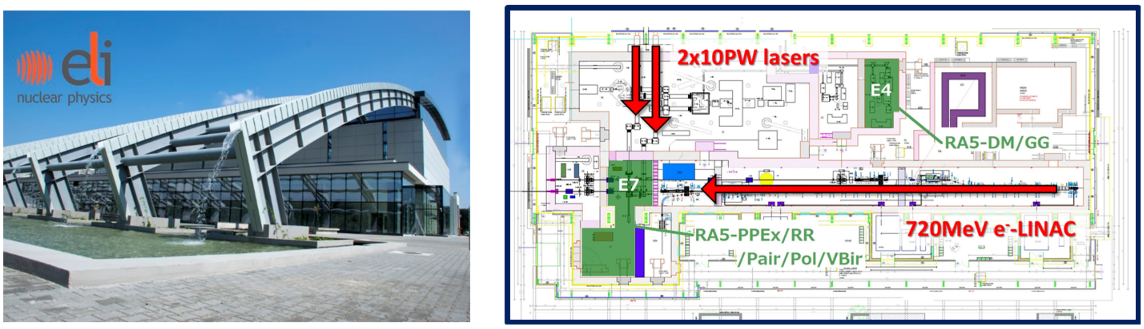

Figure 1: ELI-NP; 10 PW laser facility.

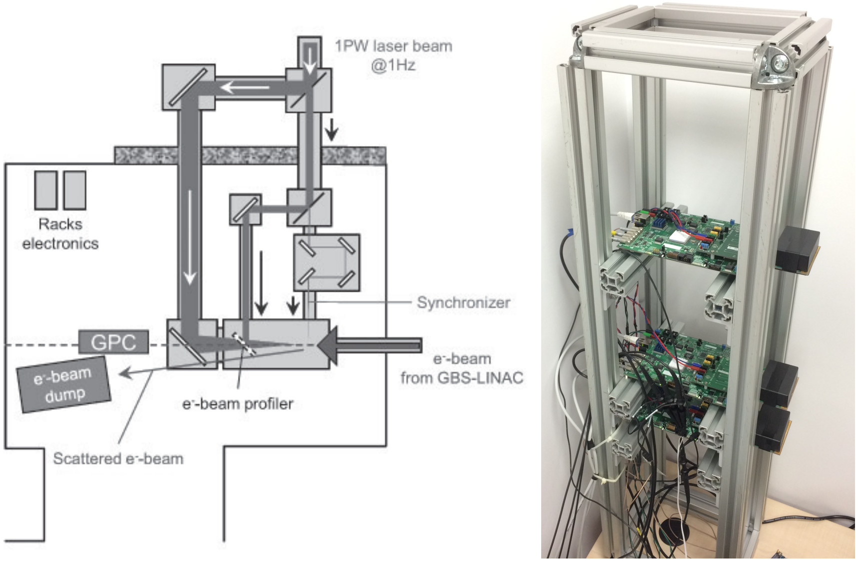

Figure 2: Schematic design of RR experiment at ELI-NP (right panel) and Gamma Polari-Calorimeter (GPC) for radiation detection (left panel).

RR experimental project at ELI-NP

The RR effect in relativistic regime of an electron has been treated in classical electrodynamics in laser-plasma science – the Lorentz-Abraham-Dirac (LAD) equation [6] as the original model of RR, the Landau-Lifshitz (LL) [7], Sokolov models [8] as approximations of the LAD equation, etc. Recently, the RR models including its quantum correction have been proposed [3, 4] by employing the cross-section of non-linear Compton scattering [9, 10]. Their essential difference appears in the radiation energy formula below [11]:

$$\frac{dW_{\text{QED}}}{dt} = q(\chi) \times \frac{dW_{\text{Classical}}}{dt} \tag{1}$$

The factor $q(\chi)$ is the quantumness of RR depending on $\chi \propto (\text{electron energy}) \times (\text{laser intensity})^{1/2}$, namely, it is the running coupling for the radiation process on laser intensities.

The basic idea of our RR experiment is on the confirmation of $q(\chi)$, namely, the detection of radiation correlating with an energy of a scattered electron after the interaction of RR [1, 5]. Figure 2 shows that schematic design of its early stage experiment. We propose the head-on collision between a 1PW laser beam [12] and an electron bunch (with an electron energy of 600 MeV) from GBS-LINAC [13]. The 1 PW laser will be operated by the following characteristics: wavelength $= 0.82\,\mu$m, pulse duration $= 22\,$fsec, spot size $= 5.6\,\mu$m and laser intensity $= 2 \times 10^{21}\,\text{W/cm}^2$ with repetition rate of 1 Hz [14]. In this setup, we expect to detect the energy difference of $O(100\,\text{MeV})$ of a scattered electron between ones in quantum and classical models. At the same time, the radiation spectrum has to be observed. We have developed Gamma

Polari-Calorimeter (GPC) for the detection of radiation [14, 15].

Stochastic mechanics for RR

Can we find the non-perturbative regime in QED? In fact, the appearance of non-perturbative effects in QED is not apparent in mathematical physics since its coupling constant is samall enough. Therefore, we have investigated a non-standard expression of quantum dynamics for it – relativistic stochastic mechanics by a Brownian motion, equivalent to the Klein-Gordon equation. It imposes a similar dynamics to the LAD equation of the classical RR model as we see it below. In this model, the quantum uncertainty appears as the randomness of a quanta's trajectory: $d_\pm \hat{x}^\mu = \mathscr{V}_\pm^\mu d\tau +$ (randomness). This kinematics is coupled with the following dynamics including RR [16]:

$$m_0 \mathfrak{D}_\tau \mathscr{V}^\mu(\hat{x}(\tau,\omega)) = -eF_{\mathrm{ex}}^{\mu\nu}(\hat{x}(\tau,\omega))\mathscr{V}_\nu(\hat{x}(\tau,\omega)) - e\mathfrak{F}^{\mu\nu}(\hat{x}(\tau,\omega))\mathscr{V}_\nu(\hat{x}(\tau,\omega)) \tag{2}$$

$$\mathfrak{F}^{\mu\nu}(\hat{x}(\tau,\omega)) = -\frac{m_0\tau_0}{ec^2}\int_{\Omega_{(\tau,\omega)}} d\mathscr{P}(\omega') \begin{bmatrix} \dot{a}^\mu(\hat{x}(\tau,\omega'))\cdot \mathrm{Re}\{\mathscr{V}^\nu(\hat{x}(\tau,\omega'))\} \\ -\dot{a}^\nu(\hat{x}(\tau,\omega'))\cdot \mathrm{Re}\{\mathscr{V}^\mu(\hat{x}(\tau,\omega'))\} \end{bmatrix} \tag{3}$$

$$\dot{a}(x) := \frac{c^4}{[\mathrm{Re}\{\mathscr{V}(x)\}\cdot\mathrm{Re}\{\mathscr{V}(x)\}]^2}\mathrm{Re}\{\mathfrak{D}_\tau^2\mathscr{V}(x)\} - \frac{27}{8}\frac{c^4\mathrm{Re}\{\mathscr{V}(x)\}\cdot\mathrm{Re}\{\mathfrak{D}_\tau\mathscr{V}(x)\}}{[\mathrm{Re}\{\mathscr{V}(x)\}\cdot\mathrm{Re}\{\mathscr{V}(x)\}]^3}\mathrm{Re}\{\mathfrak{D}_\tau\mathscr{V}(x)\} \tag{4}$$

The each variables are defined in Ref.[16]. Where, $-e\mathfrak{F}^{\mu\nu}(\hat{x}(\tau,\omega))\mathscr{V}_\nu(\hat{x}(\tau,\omega))$ denotes the interaction of RR. The readers may find the similarity to the LAD eqution:

$$m_0\frac{dv^\mu}{d\tau} = -e(F_{\mathrm{ex}}^{\mu\nu} + F_{\mathrm{LAD}}^{\mu\nu})v_\nu \tag{5}$$

$$F_{\mathrm{LAD}}^{\mu\nu} = -\frac{m_0\tau_0}{ec^2}\left[\frac{d^3x^\mu}{d\tau^3}\cdot\frac{dx^\nu}{d\tau} - \frac{d^3x^\nu}{d\tau^3}\cdot\frac{dx^\mu}{d\tau}\right] \tag{6}$$

Equations (2-4) are the quantization of the LAD equation (5-6). Ehrenfest's theorem of Eqs.(2-4) imposes

$$m_0\frac{d^2\langle\hat{x}^\mu\rangle_\tau}{d\tau^2} = -eF_{\mathrm{ex}}^{\mu\nu}(\langle\hat{x}\rangle_\tau)\frac{d\langle\hat{x}_\nu\rangle_\tau}{d\tau} - e\left[\mathscr{P}(\Omega_\tau^{\mathrm{ave}})\times F_{\mathrm{LL}}^{\mu\nu}(\langle\hat{x}\rangle_\tau)\right]\frac{d\langle\hat{x}_\nu\rangle_\tau}{d\tau}, \tag{7}$$

where, F_{LL} is the RR field in the LL model. The existence probability $\mathscr{P}(\Omega_\tau^{\mathrm{ave}})$ at its average trajectory $\{\langle\hat{x}\rangle_\tau\}_{\tau\in\mathbb{R}}$ is replaced by $q(\chi)$ when an external laser field is a plane wave. This agrees with the numerical results in Ref.[4]. Equation (7) is useful to estimate RR with its quantumness in laser-plasma similations.

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