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Status for 2018, CERN NA63

C.F. Nielsen and U.I. Uggerhøj
Department of Physics and Astronomy, Aarhus University, Denmark

T.N. Wistisen and A. Di Piazza
Max Planck Institute for Nuclear Physics, Heidelberg, Germany

NA63

Abstract

In the NA63 experiment of April 2018 the purpose was to look for the effect of the derivative term, the so-called Schott-term, in classical radiation reaction as described in [3]. Data was taken for 20, 40 and 80 GeV electrons and positrons aligned to the ⟨100⟩ axis of a diamond crystal of thickness 1.5 mm, as well as for 40 and 80 GeV electrons on a 1.0 mm thick diamond aligned to the ⟨100⟩ axis. The data which was taken during the run shows encouraging results, but await a thorough analysis. For the 2017 data, the analysis is still ongoing, but expected to be finished within the coming few months. The results look very promising, but no final conclusion can be drawn at the present stage. For the 2016 results on quantum radiation reaction obtained by CERN NA63, the results have been published in Nature Communications [5].

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1 Test of the radiation reaction using single crystals

With a setup very similar to the one used in 2016 and 2017, and two thicknesses of axially aligned diamond crystals, we have attempted to test the derivative term, the so-called Schott-term, in classical radiation reaction. At the time of writing this test seems to have been succesful, although it is too early to say if the impact of the Schott-term can be ascertained.

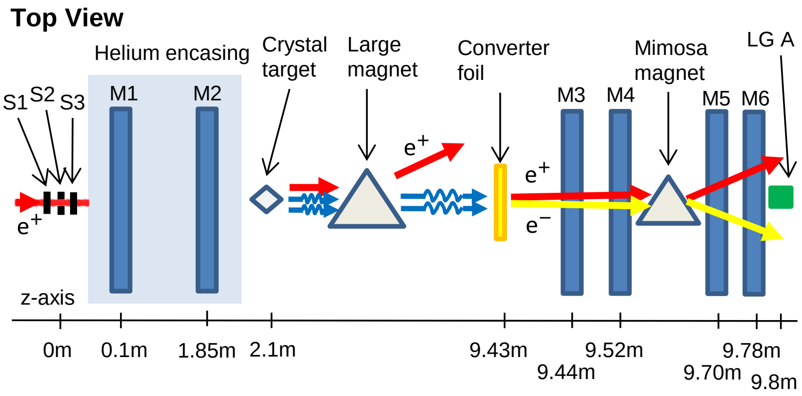

Figure 1: A schematic of the 2018 experimental setup.

A schematic of the setup used – which is almost identical to the one used in 2016 and 2017 – can be seen in figure 1. We use MIMOSA detectors, with a position resolution of about 5 μm, the first two of which – both kept in helium to reduce multiple scattering – are used to determine the entry angle to the crystalline target. The detectors have a sensitive area of 1×2 cm^2. Following emission of photon(s) in the crystalline target, the primary particle – in this case a positron or an electron – is deflected in a single MBPL magnet supplied by CERN. The photon(s) are then incident on a thin Ta converter foil, the thickness Δt of which corresponds to approximately 5% of a radiation length, $\Delta t/X_0 \simeq 5\%$, i.e. the probability that two photons convert is kept low. The pair generated from the conversion is then tracked in two additional MIMOSA detectors, and subsequently separated in a 'Mimosa magnet', a magnetic dipole produced from permanent magnets that generates a field of approximately 0.12 T over a length of 0.15 m. The 'Mimosa magnet' is kindly supplied by DANFYSIK, and represents an essential component of the setup, given that it neither requires cooling nor current supplies, which means that it is an extremely compact device allowing a very short distance to the next MIMOSA detectors. These MIMOSA detectors are then used to determine the momenta of the produced electron and positron, allowing the energy of the originally emitted photon to be determined. Finally, a lead glass detector (90×90 mm^2 and 700 mm long, corresponding to 25 X_0) at the end enables a cross-check of the energy/momentum of the pairs, and is used for alignment of the crystallographic planes to the beam.

2 Classical radiation reaction

Classically, radiation emission is calculated using the Lienard-Wiechert potential of a point particle. This procedure calculates the radiation based on its trajectory and results in the differential energy emitted per frequency interval per solid angle as

$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2} \left| \int_{-\infty}^{\infty} \vec{f}(t,\vec{n}) e^{ikx} dt \right|^2, \tag{1}$$

where

$$\vec{f}(t,\vec{n}) = \frac{\vec{n} \times [(\vec{n} - \vec{v}) \times \dot{\vec{v}}]}{(1 - \vec{v} \cdot \vec{n})^2} \tag{2}$$

with $\vec{n}$ giving the direction of emission and $\vec{v}$ is the particle velocity. The velocity is usually calculated from the Lorentz force equation

$$\frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{H}) = \vec{F}, \tag{3}$$

where $\vec{E}$ and $\vec{H}$ are the external electric and magnetic fields respectively. This however neglects the fact that the emitted radiation carries away energy. This is most easily seen in the case of a constant magnetic field. In this case the trajectory obtained from equation (3) is an indefinite circular motion where the particle energy is conserved, and yet we know that using equation (1) for this motion leads to the classical formula of synchrotron radiation.

For many years, there was controversy connected to the solution of the equation of motion including the emission of radiation, which was shown by the use of the Larmor formula for the irradiated power – see e.g. [2] – to lead to the Lorentz-Abraham-Dirac equation

$$\vec{F}_{\mathrm{rad}} = \frac{2}{3}\frac{e^2}{c^4}\dddot{\vec{v}} \tag{4}$$

which has solutions conflicting either with energy conservation or causality.

Currently the Landau-Lifshitz (LL) equation – see below – is seen as a possible solution to this problem, but it has never been experimentally tested since strong electromagnetic fields of an appreciable extension are necessary. During the past decade, many papers have appeared discussing possible routes to testing the radiation reaction in ultra-intense laser fields, but generally speaking the theoretical suggestions require intensities several orders of magnitude higher than those achievable even at the proposed fourth pillar of the Extreme Light Infrastructure (ELI). On the other hand, due to the immense effective fields available in a crystal upon the penetration of an ultrarelativistic particle, measurements of the radiation reaction may be an ideal case for high-energy electrons or positrons in crystals. In the restframe of the particle, the crystalline fields may in fact become comparable to the QED critical field, $E_0 = m^2c^3/e\hbar \simeq 1.32 \cdot 10^{16}$ V/cm [4].

The Landau-Lifshitz equation introduces additional terms in the force on a charged particle such that

$$\frac{d\vec{p}}{dt} = \vec{F} + \vec{f}, \tag{5}$$

where

$$\begin{aligned}\vec{f} = \frac{2e^3}{3m}\gamma\left\{\left(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla\right)\vec{E} + \vec{v}\times\left(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla\right)\vec{H}\right\}\\ + \frac{2e^4}{3m^2}\left\{\vec{E}\times\vec{H} + \vec{H}\times(\vec{H}\times\vec{v}) + \vec{E}(\vec{v}\cdot\vec{E})\right\}\\ - \frac{2e^4}{3m^2}\gamma^2\vec{v}\left\{\left(\vec{E} + \vec{v}\times\vec{H}\right)^2 - (\vec{E}\cdot\vec{v})^2\right\}\end{aligned} \tag{6}$$

In the case of a time-independent electric field as found in a crystal this reduces to

$$\vec{f} = \frac{2e^3}{3m}\gamma\left\{(\vec{v}\cdot\nabla)\,\vec{E}\right\} + \frac{2e^4}{3m^2}\left\{\vec{E}(\vec{v}\cdot\vec{E})\right\} - \frac{2e^4}{3m^2}\gamma^2\vec{v}\left\{\left(\vec{E}\right)^2 - (\vec{E}\cdot\vec{v})^2\right\}. \tag{7}$$

Based on equation (7) the radiation spectrum can be calculated numerically using equation (1). In [1] this is described in greater detail and shows such a calculation done for 10 GeV electrons hitting diamond. In equation (7) the first two terms of the RR force originate from the Schott term in the Lorentz-Abraham-Dirac equation, whereas the last 'damping' one corresponds to the Liénard formula.

The final aim of the experiment performed in 2018 is to test the influence of the Schott-term in equation (7) for a particle subjected to fields that are so strong that the radiation emission severely affects its equation of motion. A direct test of the influence of the Schott-term seems not to be possible with optical processes, not even with the planned ultra-intense lasers of the fourth pillar of ELI. In short, this is because the derivative term is only significant for variations of field strengths over short distances, and even for crystals where the strong field varies over distances of Å, its influence is only up to about 10%. For lasers, where the field varies over distances at least three orders of magnitude larger, the influence is correspondingly smaller, and thus likely to be impossible to detect.

3 Preliminary results from the 2017 run.

As seen in figure 2 the measured photon enhancement spectra from the 2017 show features which can only be explained theoretically by including radiation-reaction effects. Moreover, the agreement between theory that includes the radiation reaction effect and data is remarkably good, with generally large factors separating the data from the theory that disregards radiation reaction. We emphasize, though, that the figure is still preliminary, with a known problem in the analysis routine which has not been solved yet.

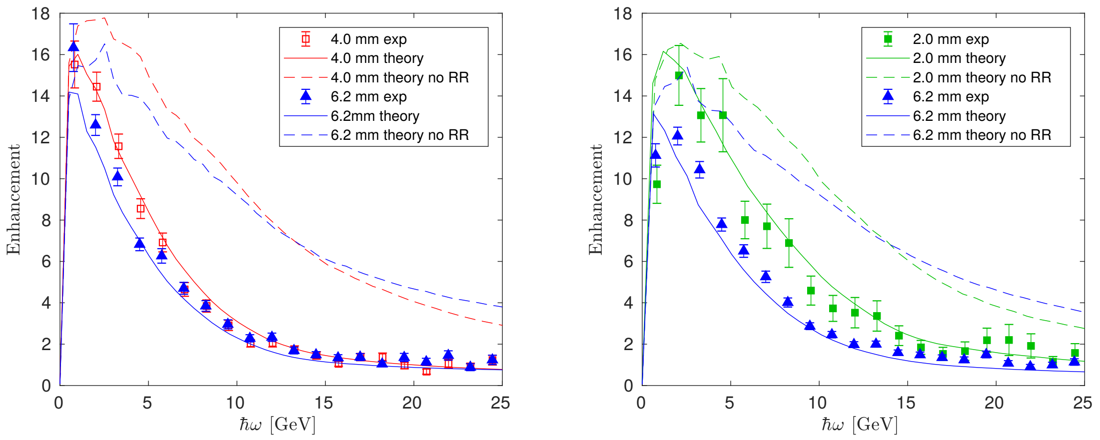

Figure 2: Preliminary results for the enhancement spectra, i.e. the radiation obtained for 50 GeV positrons passing 2.0, 4.0 and 6.2 mm thick silicon crystals aligned to the (110) plane, divided by the corresponding amorphous/'random' yield. On the left is shown experimental data and calculations obtained for a beam with a divergence of $\sigma_\perp = 85$ μrad in the direction transverse to the plane, while on the right for a beam with a divergence of $\sigma_\perp = 100$ μrad. The dashed lines show the theoretically expected values excluding the radiation reaction, the full-drawn lines the theoretically expected values with full inclusion of the radiation reaction and the filled symbols show the experimental data with statistical error bars. The experimental preference for including the effect of radiation reaction is clearly visible, even in this case where detection efficiencies and selection criteria are unimportant.

4 Preliminary results from the 9th April – 18th April 2018 run.

We have investigated diamond crystals of thicknesses 1.0 and 1.5 mm, both aligned to the $\langle 100 \rangle$ axis. Our calculations show that the influence of the Schott-term is negligible at 80 GeV, maximum at 40 GeV and still significant at 20 GeV, so we measured with electrons and positrons of these energies. Without multiple Coulomb scattering the relative influence of the Schott-term would increase with falling energy, which is why we have chosen to also measure at 20 GeV. For electrons the Schott-term is expected to be strongest, but we also measured with positrons to have an additional check.

The preliminary results shown above appear very promising, but a more firm conclusion awaits accurate calculations of the theoretically expected spectra for the particular crystallographic orientation used in the experiment, and a final analysis of the experimental spectra.

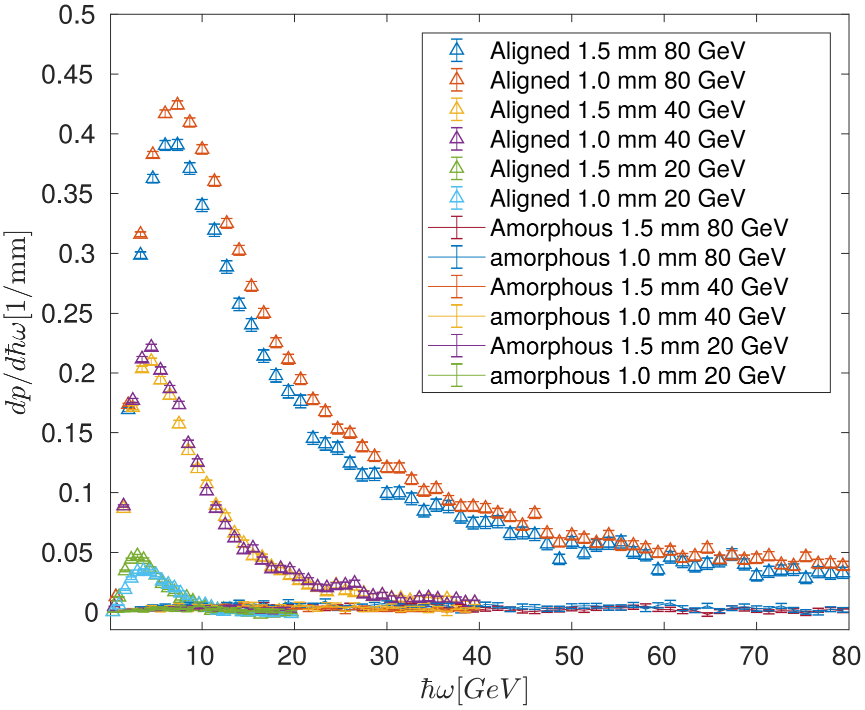

Figure 3: Preliminary experimental data for diamond crystals of thicknesses 1.0 and 1.5 mm, both aligned to the $\langle 100 \rangle$ axis as well as 'random'/amorphous, for energies 20, 40 and 80 GeV.

5 Status of publications

Publications related to the activities of NA63:

1. T. Virkus, U.I. Uggerhøj, H. Knudsen, S. Ballestrero, A. Mangiarotti, P. Sona, T.J. Ketel, A. Dizdar, S. Kartal and C. Pagliarone (CERN NA63): *Direct measurement of the Chudakov effect*, Phys. Rev. Lett. **100**, 164802 (2008)
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3. H.D. Thomsen, K. Kirsebom, H. Knudsen, E. Uggerhøj, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar, M. Dalton, S. Ballestrero and S. Connell (CERN NA63): *On the macroscopic formation length for GeV photons*, Phys. Lett. B **672**, 323 (2009)
4. J. Esberg and U.I. Uggerhøj: *Does experiment show that beamstrahlung theory - strong field QED - can be trusted?*, Journal of Physics Conference Series, **198**, 012007 (2009)
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6. K.K. Andersen, J. Esberg, K.R. Hansen, H. Knudsen, M. Lund, H.D. Thomsen, U.I. Uggerhøj, S.P. Møller, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar and S. Ballestrero (CERN NA63): *Restricted energy loss of ultrarelativistic particles in thin targets - a search for deviations from constancy*, Nucl. Instr. Meth. B **268**, 1412 (2010)
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8. H.D. Thomsen and U.I. Uggerhøj: *Measurements and theories of the King-Perkins-Chudakov effect*, Nucl. Instr. Meth. B **269**, 1919 (2011)
9. A. Mangiarotti, P. Sona, S. Ballestrero and U.I. Uggerhøj: *A general semi-analytic method to simulate discrete bremsstrahlung at very low radiated photon energies by the Monte Carlo method*, Nucl. Instr. Meth. B **269**, 1977 (2011)
10. A. Mangiarotti, P. Sona, S. Ballestrero, K.K. Andersen and U. I. Uggerhøj: *Comparison of analytical and Monte Carlo calculations of multi-photon effects in bremsstrahlung emission by high-energy*

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12. K.K. Andersen, J. Esberg, H. Knudsen, H.D. Thomsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar and S. Ballestrero (CERN NA63): *Experimental investigations of synchrotron radiation at the onset of the quantum regime*, Phys. Rev. D **86**, 072001 (2012)
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17. K.K. Andersen, S.L. Andersen, J. Esberg, H. Knudsen, R. Mikkelsen, U.I. Uggerhøj, T.N. Wistisen, A. Mangiarotti, P. Sona and T.J. Ketel (CERN NA63): *Measurements of the spectral location of the structured target resonance for ultrarelativistic electrons*, Phys. Lett. B **732**, 309-314 (2014)
18. J. Esberg, U.I. Uggerhøj, B. Dalena and D. Schulte: *Strong field processes in beam-beam interactions at the Compact Linear Collider*, Phys. Rev. Spec. Top. Acc. Beams **17**, 051003 (2014)
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22. A. Di Piazza, T.N. Wistisen and U.I. Uggerhøj: *Investigation of classical radiation reaction with aligned crystals*, Phys. Lett. B **765**, 1-5 (2016)
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[3] A. D. Piazza, T. N. Wistisen, and U. I. Uggerhøj. Investigation of classical radiation reaction with aligned crystals. *Physics Letters B*, 765:1 – 5, 2017.

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