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Status for 2017, CERN NA63

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NA63

Abstract

In the NA63 experiment of May-June 2017 the purpose was to look for the effect of classical radiation reaction as described in [3] but for 50 GeV positrons aligned to the (110) plane of silicon crystals of varying thicknesses in the range 1-6 mm. The data which was taken during the run shows promising results, but the final verdict awaits accurate calculations of the theoretically expected spectra, and a final analysis.
For the 2016 results on quantum radiation reaction obtained by CERN NA63, we have submitted a manuscript, which is presently under refereeing [5].

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1) On behalf of the collaboration.

1 Test of the radiation reaction using single crystals

With a setup very similar to the one used in 2016, and several thicknesses of Si (110) planar aligned crystals, we have attempted to test classical radiation reaction using single crystals. At the time of writing this test seems to have been succesful.

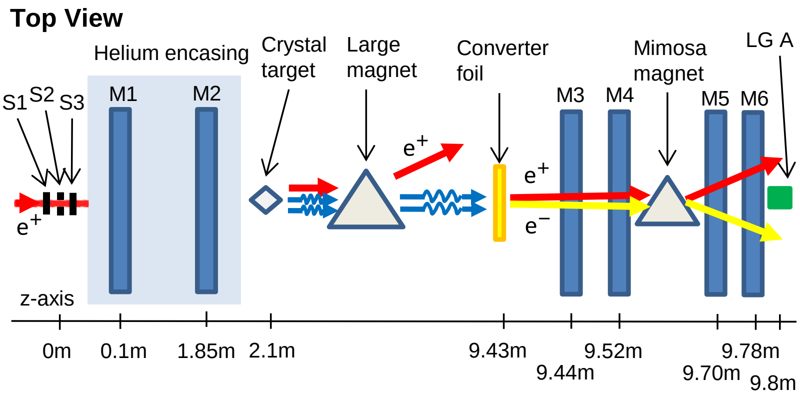

Figure 1: A schematic of the 2017 experimental setup.

A schematic of the setup used – which is almost identical to the one used in 2016 – 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 – is deflected in two MBPL magnets 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

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

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 2017 is to test whether or not equation (7) provides a sufficient description of the trajectory of a particle subjected to fields that are so strong that the radiation emission severely affects its equation of motion.

3 Preliminary results from the 24th May – 7th June 2017 run.

We have investigated silicon crystals of thicknesses 1.0, 2.0, 4.0 and 6.2 mm, all aligned at an angular distance of 10.3 mrad from the ⟨100⟩ axis, on the (110) plane.

In figure 2 is shown the counting spectra obtained for the (110) aligned 6.2 mm thick Si crystal, in both aligned and non-aligned (so-called 'random') angular positions, as well as the background spectrum obtained with the target crystal removed. The background – which has also been verified by means of measurements performed with the lead glass detector – is in agreement with expectations, based on the known amount of material in the beam.

In figure 3 is shown the power spectra obtained for the (110) aligned 6.2 mm thick Si crystal, in aligned and non-aligned configurations. Clearly, there is a strong enhancement of radiation for the aligned case compared to the non-aligned case. This is due to the coherent action of the crystal nuclei on the penetrating particle which – even in the planar case where the field is about a factor 10 smaller than in the axial case – leads to a significant enhancement.

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.

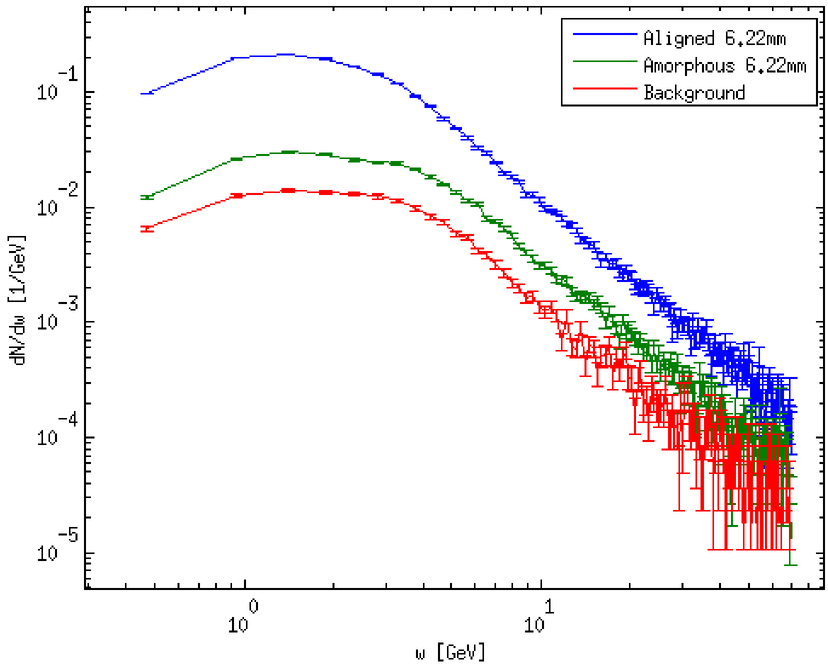

Figure 2: Counting spectra for the (110) aligned 6.2 mm thick Si crystal (blue curve), for the non-aligned case (green curve) and for the background (red curve).

4 Plans for 2018

Given that the 2017 run seems to have been a success, we are in the process of developing plans for a run in 2018, to investigate in more detail the Schott contribution (the first two terms in 7) in the (classical) radiation reaction. This requires a parallel beam of electrons at energies in the regime 10-100 GeV, and probably about 2 weeks of beam time, preferably at SPS H4. A more elaborate request for beam time in 2018 will be submitted to the SPSC by the end of 2017.

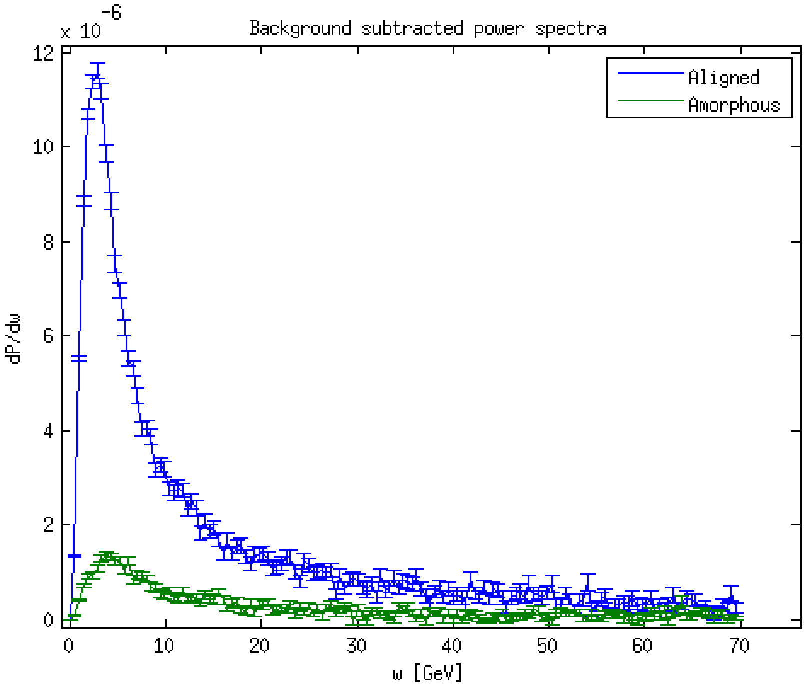

Figure 3: Power spectra for the (110) aligned 6.2 mm thick Si crystal (blue curve), and for the non-aligned case (green curve).

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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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)
7. H.D. Thomsen, J. Esberg, K.K. Andersen, M. Lund, H. Knudsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar, S. Ballestrero and S.H. Connell (CERN NA63): *Distorted Coulomb field of the scattered electron*, Phys. Rev. D, **81**, 052003 (2010)
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 electrons*, Nucl. Instr. Meth. B **289** 5-17 (2012)

11. K.K. Andersen, S.L. Andersen, J. Esberg, H. Knudsen, R. Mikkelsen, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel and S. Ballestrero (CERN NA63): *Direct measurement of the formation length of photons*, Phys. Rev. Lett. **108**, 071802 (2012); see also accompanying Physics Synopsis and Science Daily.
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)
13. K.K. Andersen, J. Esberg, H.D. Thomsen, U.I. Uggerhøj and S. Brock: *Radiation emission as a virtually exact realization of Heisenbergs microscope*, Nucl. Instr. Meth. B **315**, 278 (2013)
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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)
19. T.N. Wistisen, K.K. Andersen, S. Yilmaz, R. Mikkelsen, J.L. Hansen, U.I. Uggerhøj, W. Lauth and H. Backe: *Experimental realization of a new type of crystalline undulator*, Phys. Rev. Lett. **112**, 254801 (2014)
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21. R.E. Mikkelsen, A.H. Sørensen and U.I. Uggerhøj: *Elastic photonuclear cross sections for bremsstrahlung from relativistic heavy ions*, Nucl. Instr. Meth. B **372**, 58-66 (2016)
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)
23. T.N. Wistisen, A. Di Piazza, H.V. Knudsen and U.I. Uggerhøj: *Experimental Evidence for Quantum Radiation Reaction in Aligned Crystals*, subm. to Nature Physics (2017)

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[5] T. Wistisen, A. D. Piazza, H. Knudsen, and U. Uggerhøj. Experimental evidence for quantum radiation reaction in aligned crystals. *Nature Physics*, 2017. submitted.