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Status for 2016 and plans for 2017, CERN NA63

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NA63

Abstract

In the NA63 experiment of May 2016 the purpose was to look for the effect of radiation reaction as described in [4] but for positrons. The 180 GeV positron data which was taken during the run shows promising results, despite the fact that essentially half the useful time for pure data-taking, 5 days, was lost due to an incident in the PS. We are in the process of finalizing a manuscript to submitted, with the aim of publishing these results on quantum radiation reaction.
For the next beam-time, in 2017, we will look at a different parameter range to enter the regime of classical radiation reaction instead of quantum radiation reaction which was seen in the 2016 experiment.

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1) On behalf of the collaboration.

1 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

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

where

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

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

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

where $\boldsymbol{E}$ and $\boldsymbol{H}$ 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. Currently the Landau Lifshitz equation is seen as the solution to this problem, but has never been experimentally tested since strong electromagnetic fields of an appreciable extension are necessary: an ideal case for electrons or positrons in crystals.

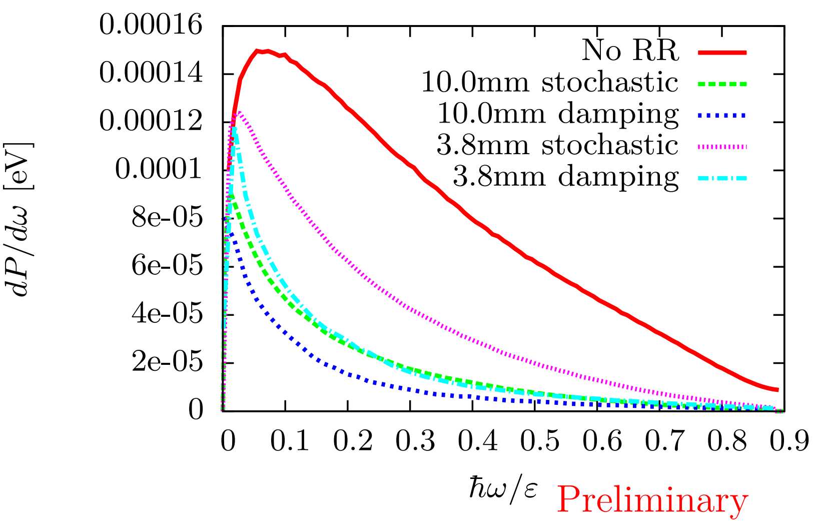

Figure 1: The theoretical power spectra in the case of no kind of radiation reaction 'No RR' and for the stochastic and damping approaches described in the text.

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

$$\frac{d\boldsymbol{p}}{dt} = \boldsymbol{F} + \boldsymbol{f}, \tag{4}$$

where

$$\boldsymbol{f} = \frac{2e^3}{3m}\gamma \left\{ \left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla \right) \boldsymbol{E} + \boldsymbol{v} \times \left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \nabla \right) \boldsymbol{H} \right\} + \frac{2e^4}{3m^2} \left\{ \boldsymbol{E} \times \boldsymbol{H} + \boldsymbol{H} \times (\boldsymbol{H} \times \boldsymbol{v}) + \boldsymbol{E}(\boldsymbol{v} \cdot \boldsymbol{E}) \right\} - \frac{2e^4}{3m^2}\gamma^2 \boldsymbol{v} \left\{ (\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{H})^2 - (\boldsymbol{E} \cdot \boldsymbol{v})^2 \right\} \tag{5}$$

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

$$\boldsymbol{f} = \frac{2e^3}{3m}\gamma \left\{ (\boldsymbol{v} \cdot \nabla) \boldsymbol{E} \right\} + \frac{2e^4}{3m^2} \left\{ \boldsymbol{E}(\boldsymbol{v} \cdot \boldsymbol{E}) \right\} - \frac{2e^4}{3m^2}\gamma^2 \boldsymbol{v} \left\{ (\boldsymbol{E})^2 - (\boldsymbol{E} \cdot \boldsymbol{v})^2 \right\} \tag{6}$$

Based on equation (6) the radiation spectrum can be calculated numerically using equation (1). In [3] this is described in greater detail and shows such a calculation done for 10 GeV electrons hitting diamond. In figure 1 we compare two approaches to the radiation reaction, a damping force calculation and a stochastic one, as described in [1]. It is seen that the stochastic approach generally predicts more radiation than that of the damping force approach and that this difference is larger for the 3.8mm case. There is a significant difference wrsp. to the 'no RR' case, though, in both approaches.

2 The 2016 run - experimental details

The experiment directed towards measuring the radiation reaction was conducted in May 2016 in the CERN NA63 collaboration in the SPS North Area. Here secondary beams of electrons or positrons are available. In this experiment high energy positrons of 178.2 GeV were used. Such high energies are necessary to reach appreciable values of the quantum parameter $\chi = \gamma E/E_0$, where $E_0 = m^2c^3/e\hbar = 1.32 \cdot 10^{16}$ V/cm is the critical field.

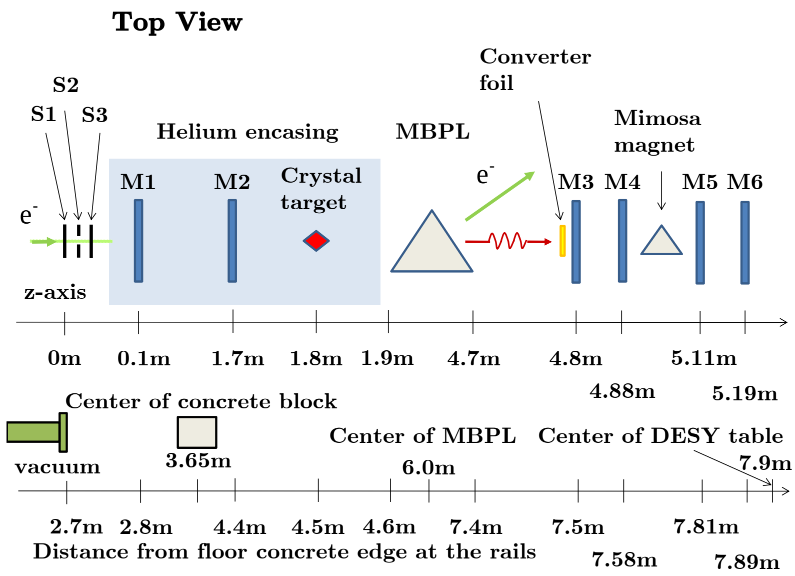

Figure 2: A schematic of the 2016 experimental setup. The setup in 2017 will be identical, except for a differently aligned crystal (planar orientation instead of axial), and an additional calorimeter.

Positrons were chosen since the effect of dechanneling is much smaller than for electrons. An estimate for the dechanneling length in the case of axially channeled positrons of 178.2 GeV gives 52cm, meaning that dechanneling can be neglected, even when the thickest crystal is 1cm.

In figure 2 a schematic of the experimental setup is shown. The incoming positron encounters the scintillators S1, S2 and S3 which are used to make the trigger signal. The positron then enters a helium chamber where the two first position sensitive 2cm $\times$ 1cm MIMOSA-26 detectors are placed. Shortly after the helium chamber the crystal target is placed. The helium chamber reduces multiple scattering of the positron such that the incoming particle angle can be measured precisely using detectors M1 and M2. After the positron enters the crystal, multiple photons and charged particles will leave the crystal. To sweep away the charged particles, two large magnets were placed before the final set of tracking detectors. The photons emitted from the crystal then reach a thin converter foil, 200μm of Ta, corresponding to approximately 5% of the radiation length X_0. The thickness is chosen such that most of the time only a single of the emitted photons converts to an electron positron pair. Such a pair passes through M3 and M4 before entering a small magnet, such that the momentum of the electron and positron can be determined based on this deflection. Finally the deflected electron and positron pass through M5 and M6.

3 Simulation of the setup

To test the tracking code and for comparison of experimental data to theoretical calculations, a Monte-Carlo simulation of the experimental setup has been developed. This code takes the theoretically calculated radiation spectrum of a channeled particle as input which is then sampled when a positron is sent through the setup. If a pair is produced in the converter foil, the energy of the electron and positron is selected, based on the Bethe-Heitler cross section of pair production in amorphous media. Multiple scattering of the produced particles in the detectors and air between the detectors is simulated using normal distributions and the PDG formula [2]. The output of this Monte-Carlo simulation are simulated detector data files which are then sent through the tracking algorithm which is also used for the experimental data. This way potential problems with the tracking algorithm could also be identified.

4 Results from the 2016 run

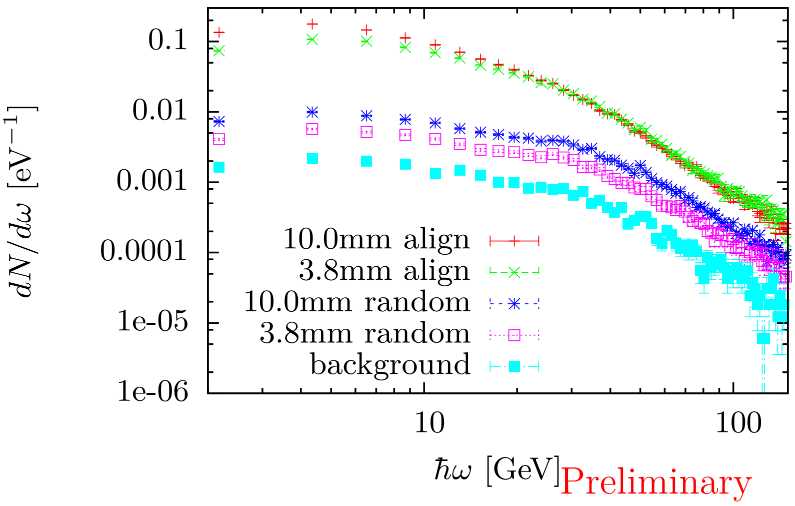

Figure 3: The photon counting spectrum per incoming positron for the two crystal thicknesses in the aligned and random case along with a measurement of the background.

As opposed to using a calorimeter, this setup allows us to measure the single-photon radiation spectrum. In figure 3 we show the experimentally obtained counting spectra for the 'background', when no crystal is in the beam, for 'random' when the crystal is not aligned wrt. the beam and 'align' when the crystals $\langle 111 \rangle$ axis is aligned with the incoming beam. These spectra are, however, not directly comparable with theory due to a photon energy dependent efficiency and broadening in the experimental setup which can be seen clearly in the shape of the curves in the 'random' case which in the absence of such effects should be a straight line in this plot. It is however not difficult to simulate the behavior of the setup. Multiple Coulomb scattering between and in the detectors and converter foil and Bethe-Heitler pair production are well understood processes which can be described with simple formulas.

In figure 4 is shown the background subtracted power spectra for the same cases as in figure 3, compared to the results of a simulation performed as described above. The simulation − based on theoretical expectations propagated through the same analysis routine that is used to examine the experimental data − is in very good agreement with data, except for a slight discrepancy at low photon energies for the 3.8 mm case.

In figure 5 is shown the enhancement spectra − the ratio of the aligned case to the amorphous case where background has been subtracted. As seen, the stochastic approach to the radiation reaction is in better agreement with data than the damping approach. In any case, when comparing the 'no RR' calculation in figure 1 to either approach to the radiation reaction, there is clear evidence for the effect of radiation reaction. Based on this, we can confidently claim that we have obtained experimental evidence for quantum radiation reaction in aligned crystals, and our next step is to submit the paper [1], which is in its final stage of internal discussion.

5 2017 plans

With a setup very similar to the one used in 2015 and 2016, and several thicknesses of Si (110) *planar* aligned crystals, we wish in 2017 to test the classical radiation reaction using single crystals. The setup used can be seen in figure 2.

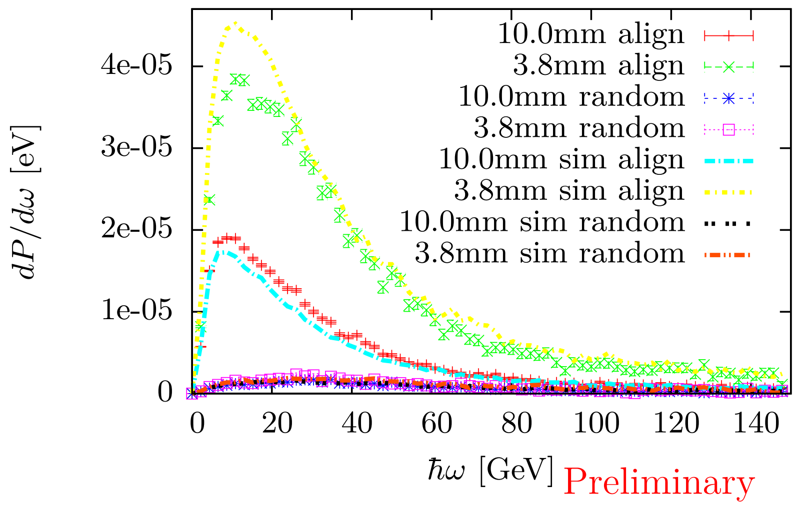

Figure 4: The background subtracted power spectra for the same cases as in figure 3 are shown along with the results of a calculation based on the procedure described in the main text.

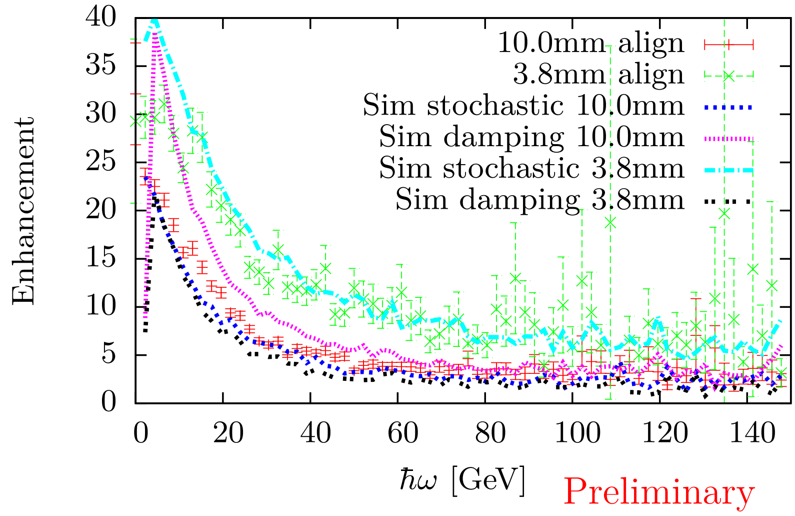

Figure 5: The enhancement spectra which are the ratio of the aligned case to the amorphous case when background has been subtracted.

In figure 6 this calculation has been done for 50 GeV positrons hitting a (110) planar aligned silicon crystal. The drop in the power spectrum seen for thicker crystals is the effect of radiation reaction. In the absence of RR these curves would be identical. In the right figure in figure 6 we show the results for the thin and thick crystal including the simulated experimental response.

In addition to this measurement using a pair spectrometer as in our previous experiment we will add a calorimeter behind the spectrometer to measure to total energy radiated (the sum of photon energies).

As stated in the abstract, due to an incident at the PS on Friday 20th of May in the morning, we lost the remaining 5 days of the total allocated 13 days of beam time, see `http://sps-schedule.web.cern.ch/sps-schedule/`. As setting up and debugging takes about 3 days of beam time, this meant that essentially half our data-taking time was lost. Thus, we could not finish the measurements we had planned/hoped for.

Nevertheless, a full set of measurements on ⟨111⟩ Si were performed, as seen in our previous report. In 2017 we will do a measurement using planar alignment and with a lower beam energy to ensure that we remain in the classical regime and with the full beam time we hope to measure more than the 2 thicknesses as we did last time, preferrably 4 thicknesses.

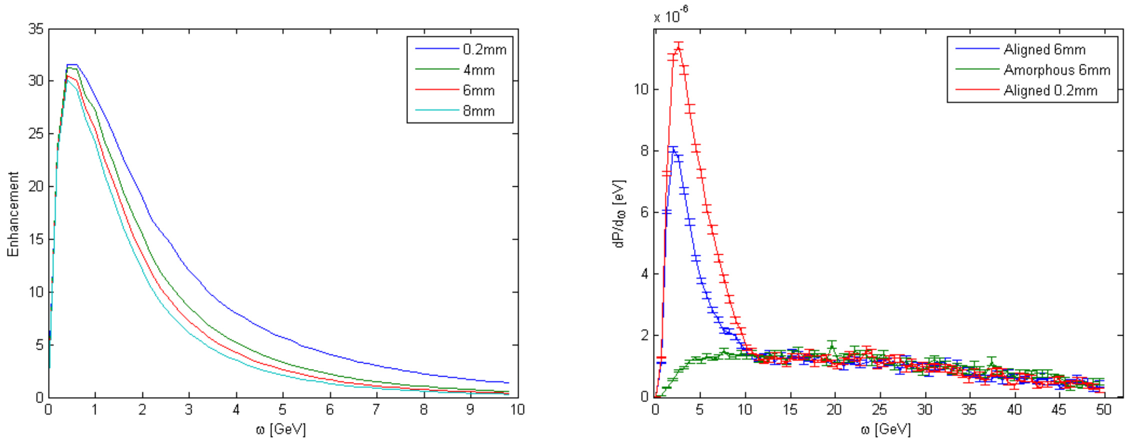

Figure 6: The power spectra (left) for 50 GeV positrons in varying thicknesses of (110) planar aligned Si are shown. In the right figure, the simulated measurement based on these spectra is shown. In the absence of RR the curves for aligned 0.2 and 6.0 mm would be identical.

5.1 Requested beam and beam time

We therefore request in 2017 2 weeks of beam time in H4 with positrons of energy 50 GeV with a beam angular divergence as low as possible, $\sigma_\theta < 50\mu\text{rad}$ is required. Less than 10000 particles per burst are required for the measurement, and we therefore request that any excess compared to this is collimated away to reduce the beam divergence.

Schedule:

Day	Comment
1+2+3	Setup experiment. Alignment of crystal & detectors. Tests of the setup
4	6mm crystal aligned measurement
5	6mm crystal amorphous measurement
6	4mm crystal aligned measurement
7	4mm crystal amorphous measurement
8	2mm crystal aligned measurement
9	2mm crystal amorphous measurement
10	thin crystal aligned measurement
11+12	thin crystal amorphous measurement
13+14	Background measurement

References

[1] T. N. Wistisen, A. Di Piazza, H.V. Knudsen and U. I. Uggerhøj. Experimental evidence for quantum radiation reaction in aligned crystals. to be submitted, 2016.

[2] J. Beringer *et al.*. Review of particle physics. *Phys. Rev. D*, 86:010001, Jul 2012.

[3] A. Di Piazza, T. N. Wistisen, and U. I. Uggerhøj. Investigation of classical radiation reaction with aligned crystals. *arXiv preprint arXiv:1503.05717*, 2015.

[4] 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.

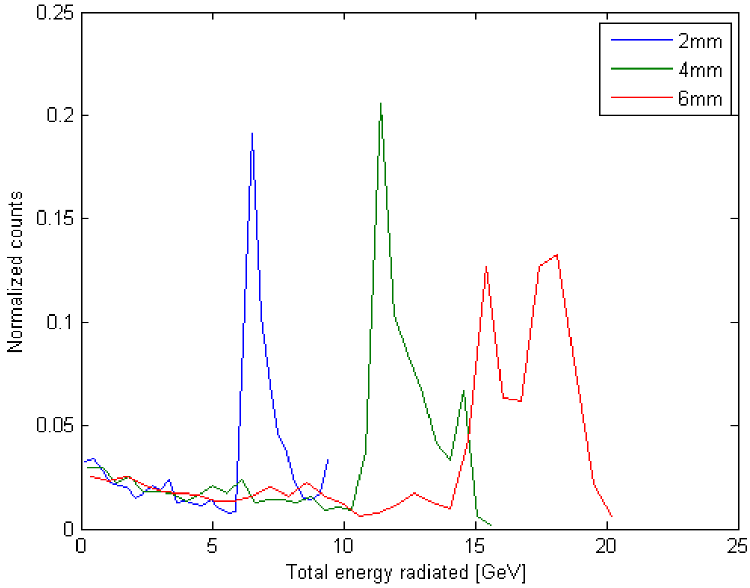

Figure 7: The signal as expected in the calorimeter for different thicknesses of the planar aligned Si crystals.