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Status in 2020 and request for beamtime in 2021 for CERN NA63

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NA63

Abstract

In the NA63 experiment of April 2018 reliable data was taken for 40 and 80 GeV electrons and positrons aligned to the $\langle 100 \rangle$ 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 $\langle 100 \rangle$ axis. A paper has been submitted to Phys. Rev. D, and has received favourable referee comments.
For the 2017 data, a paper has been published in Phys. Rev. Research in 2019, and our experimental findings have inspired another paper published in Phys. Rev. Lett.

For the year 2021 we request 2 weeks of beamtime in the SPS H4 to do a measurement of trident production, $e^- \to e^- e^+ e^-$, in strong crystalline fields. This process is closely related to the production of muon pairs, $e^- \to e^- \mu^+ \mu^-$, and single crystals may prove to be an attractive source to obtain muons of high intensity and small emittance, as required for a muon collider.
The trident results obtained in 2009, and published in 2010, are strongly at odds with theory (factor 3-4 discrepancy). Since then we have acquired and have been using MIMOSA-26 position-sensitive detectors with a resolution about a factor 40 higher than the drift chambers used in 2009, and now with true multi-hit capability, a significant advantage when looking for trident events. Thus we have substantial improvements in our equipment that enable a much more precise measurement.

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1 Radiation reaction in strong fields 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 performed measurements also in 2018 that complement the previously obtained results, and agree very well with strong field theory.

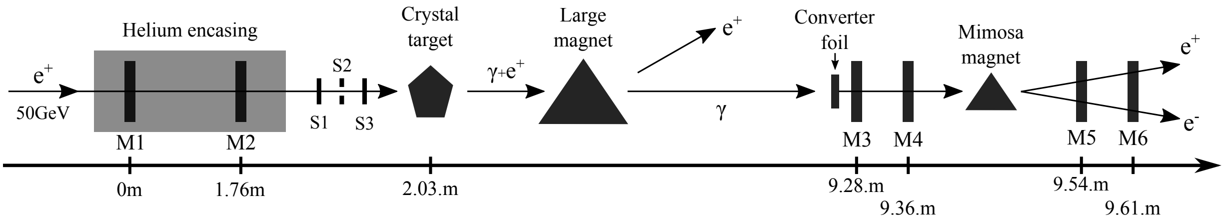

Figure 1: A schematic of the 2018 experimental setup.

A schematic of the setup used – which was almost identical to the one used in 2016 and 2017 – can be seen in figure 1. We used MIMOSA-26 detectors, with a position resolution of about 5 μm, the first two of which – both kept in helium to reduce multiple scattering – were 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 – was deflected in a single MBPL magnet supplied by CERN. The photon(s) were 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 was kept low. The pair generated from the conversion was 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' has been 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 up- and down-stream MIMOSA detectors. These MIMOSA detectors were 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 enabled a cross-check of the energy/momentum of the pairs, and was used for alignment of the crystallographic planes to the beam.

2 Results from the April 2018 run.

The equation of motion for a light, charged particle, in a strong external electromagnetic field, must take into account the reaction of the radiation (or the "radiation reaction") on its dynamics. This is done by the Lorentz-Abraham-Dirac (LAD) equation. The LAD equation, however, has peculiar features because the additional force due to radiation reaction depends on the time-derivative of the electron acceleration, which makes this equation structurally "non-Newtonian". Moreover, the presence of the derivative of the acceleration allows for the existence of unphysical ("runaway") solutions, with the electron's acceleration increasing exponentially even if no external field is present. Runaway solutions can be removed by transforming the LAD equation into an integro-differential equation. However, as a result of this remedy, the electron starts to accelerate before it is acted upon by the external force, which violates the causality principle. These features have rendered the LAD equation one of the most controversial equations in physics.

Provided the radiation-reaction force is much smaller than the Lorentz force in the instantaneous rest frame of the electron a "reduction of order" (a perturbation approach) may be applied with the electron four-acceleration in the radiation-reaction four-force replaced by the Lorentz four-force divided by the electron mass m. This results in the Landau-Lifshitz (LL) equation,

$$m\frac{du^\mu}{ds} = eF^{\mu\nu}u_\nu + \frac{2}{3}e^2\left[\frac{e}{m}(\partial_\alpha F^{\mu\nu})u^\alpha u_\nu + \frac{e^2}{m^2}F^{\mu\nu}F_{\nu\alpha}u^\alpha + \frac{e^2}{m^2}(F^{\alpha\nu}u_\nu)(F_{\alpha\lambda}u^\lambda)u^\mu\right]. \tag{1}$$

Here, $e < 0$ denotes the electron charge, $F^{\mu\nu}$ is the external electromagnetic field tensor, u^μ is the four-velocity, and s its proper time in units with $c = 1$. The LL equation is free of the physical inconsistencies of the LAD equation, and it has been shown to feature all the physical solutions of the LAD equation. For the above reasons, the radiation reaction phenomenon, and its relation to the LL equation, have been under active investigation in recent years both theoretically and to some extent experimentally.

Our measurements address the importance of the radiation reaction by comparing theoretical models, in particular models based on the LL equation, and experimental data recorded for high-energy electrons and positrons penetrating aligned single crystals. An example is shown in Figure 2.

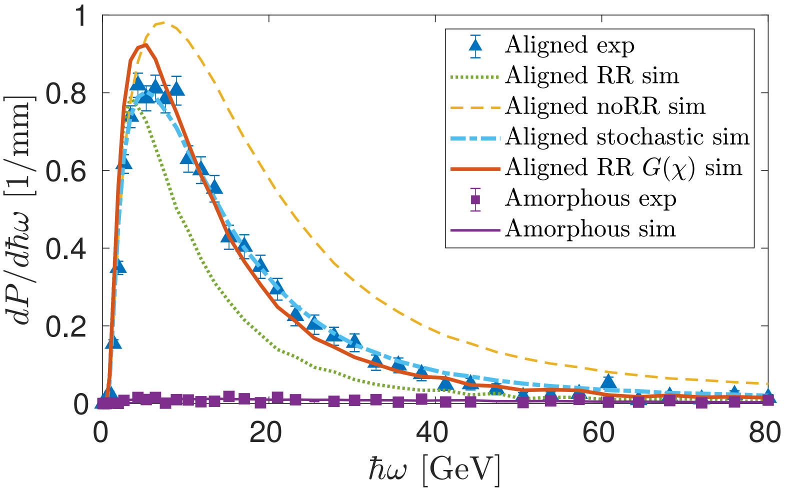

Figure 2: Radiation power spectra obtained for 80 GeV (right) electrons traversing a 1.5 mm (top) thick diamond crystal aligned to the $\langle 100\rangle$ axis, and the corresponding amorphous spectra. This spectrum has angular cuts, meaning that only particles with entry angle less than ψ_1 with respect to the crystal axis are included, where ψ_1 is the Lindhard critical angle with $\psi_1 \approx 35 \times 10^{-6}$ for 80 GeV electrons. The theoretical spectra calculated using the Belkacem, Cue and Kimball (BCK) model in the constant energy scheme are shown for trajectories including the LL equation without the $G(\chi)$ correction (“RR sim”) as a green dotted line, the LL equation with the $G(\chi)$ correction (“RR $G(\chi)$ sim”) as a red solid line and without the LL equation (“noRR sim”) as a yellow dashed line. The spectrum calculated using the BCK model in the stochastic scheme (“stochastic sim”) is shown as a dashed-dotted blue line and the simulated amorphous spectrum (“Amorphous sim”) is shown as a solid purple line. The data from the axially aligned crystal (“Aligned exp”) is shown as blue triangles and the data from the amorphous alignment (“Amorphous exp”) shown as purple squares.

Our measurements and their comparisons with theoretical models, clearly show that the recorded spectra are in remarkable agreement with predictions based on the LL equation of motion with small quantum corrections for recoil and, in the case of electrons, reduced radiation intensity. The results are still in the process of being refereed in Phys. Rev. D, but the following quote from the referee report seems promising: "The results of this work are very important. The experimental is carefully conducted. The data show a marked effect, on the radiation spectrum, of the variation of the e$^{\pm}$ energy inside the crystal. They fit with a model where the slowing down is continuous and given by the Landau-Lifshitz equation modified by a quantum correction $G(\chi)$ (calculated for uniform fields)."

3 Request for beamtime in SPS H4 in 2021.

For the year 2021 we request 2 weeks of beamtime in the SPS H4 to do a measurement of trident production, $e^- \rightarrow e^- e^+ e^-$, in strong crystalline fields. This process is closely related to the production of muon pairs, $e^- \rightarrow e^- \mu^+ \mu^-$. Due to the reduced multiple scattering of positrons channeled in single crystals, such targets may prove to be an attractive source to obtain muons of high intensity and small emittance, as required for a muon collider.

The trident results obtained in 2009, and published in 2010 (J. Esberg *et al.*, Phys. Rev. D **82**, 072002 (2010)), are strongly at odds with theory (factor 3-4 discrepancy, see its figure 13) for the case of an aligned crystal (i.e. in the case where the strong field effects are expected to be prominent), even though the amorphous yield compares favourably with theory (see its figure 11). Since then we have acquired and have been using MIMOSA-26 position-sensitive detectors with a resolution about a factor 40 higher than the drift chambers used in 2009, and now with true multi-hit capability, a significant advantage when looking for trident events. Thus we have substantial improvements in our equipment that enable a much more precise measurement.

In Figures 3 and 5 we show the results of some simulations performed to optimize the setup, by adjusting the distances between target and detectors, and between the detectors themselves.

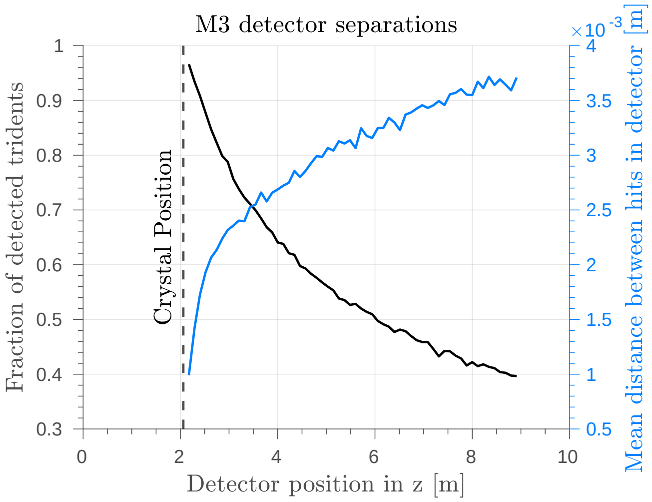

Figure 3: In black, the fraction of detected tridents as a function of distance between the crystal and M3 (and those downstream M3), where the limited transverse size of the detectors favour small distances. With blue, the mean distance between hits in the detector, which should be compared to the MIMOSA-26 resolution of approx. 5 μm.

The simulation results have led to an optimized setup as shown in Figure 4. With this setup, the expected count rates from 150 GeV electrons penetrating a 5 mm thick amorphous silicon target are as shown in Figure 5.

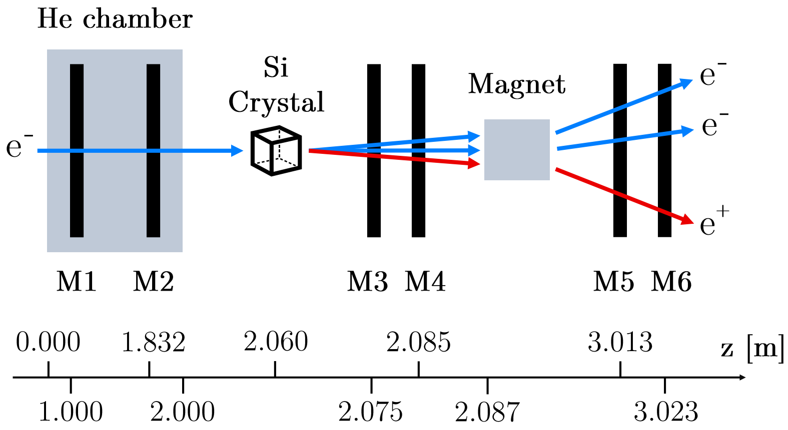

Figure 4: The setup as optimized for the detection of trident events from incoming electrons in targets of the order $1 - 10\% X_0$. Our MIMOSA-26 detectors, M1-M6, enable a setup that is much more compact than for the previous measurement, and their true multihit capability is a significant advantage for the detection of tridents.

As seen in the center subfigure of Figure 5, the expected count rates from a 5 mm thick amorphous silicon target approaches 40 (with the trident positron interval 0-80 GeV divided into 50 bins) per 10^6 incoming electrons. At 150 GeV, and with a nicely collimated beam at SPS H4, a reasonable beam intensity would be an average of $2 \cdot 10^4$ electrons per minute, including down-time. The spectrum thus represents approximately an hour of beamtime. Nevertheless, as we would like to be able to perform angular cuts for the crystalline case, which requires significantly more data, and do measurements for at least three crystal thicknesses (in addition to at least one no-target run), we need 10 days of running time. Experience has shown that for our installations in H4, 3-4 days is needed to install and debug our setup. Thus, we request 2 weeks of beamtime in the SPS H4 to do a measurement of trident production in strong crystalline fields.

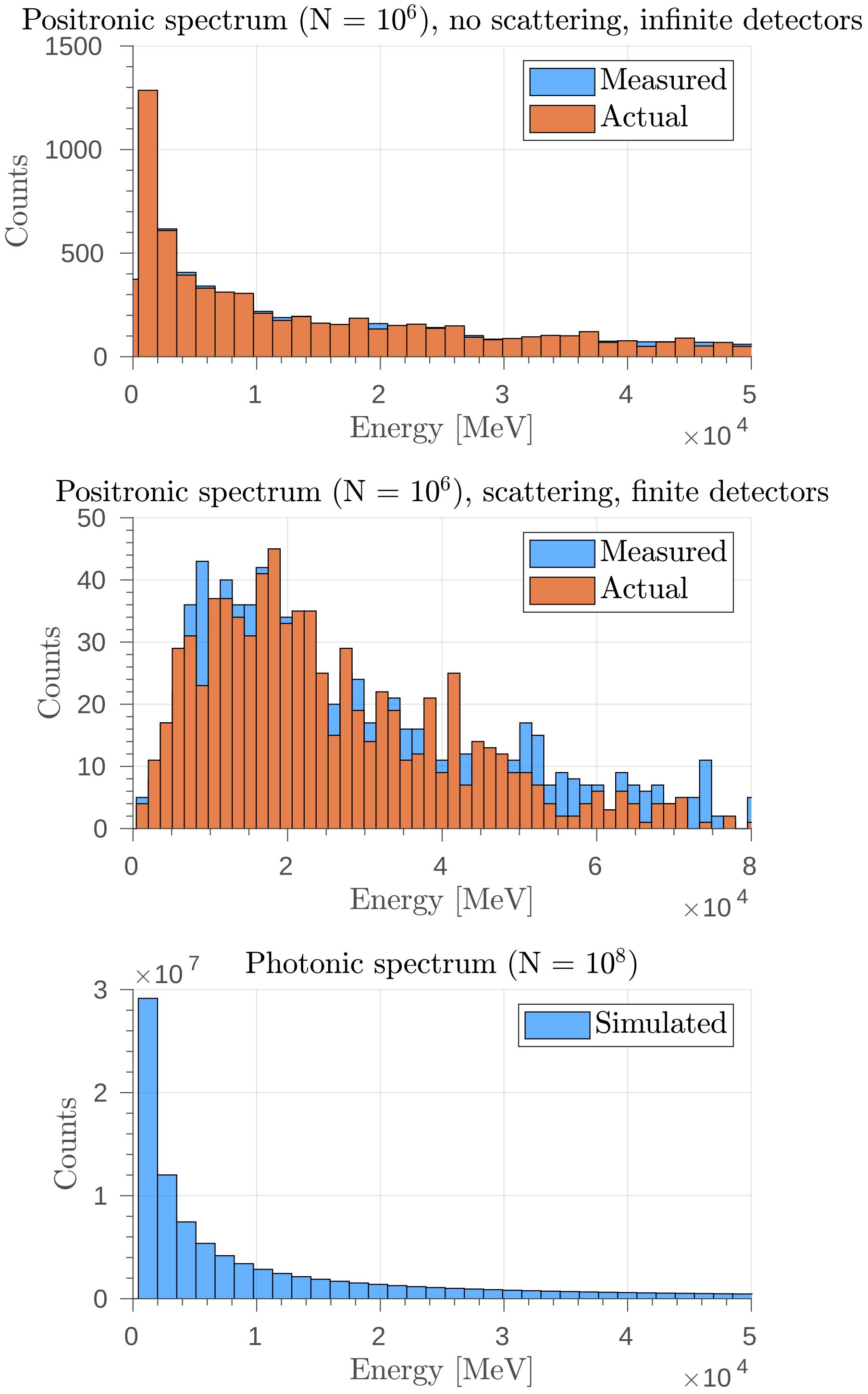

Figure 5: The upper subfigure shows simulated spectra for the number of positrons generated by 10^6 incoming electrons in 5 mm of amorphous silicon, in the ideal case where there is no multiple scattering, and all MIMOSA-26 detectors, M1-M6, are considered infinite in transverse dimensions. With blue is shown the trident events reconstructed from tracks in M5 and M6, while the orange shows the actual tridents (which, of course, are not known in reality, but only in a simulation). The central subfigure shows the same as the upper one, but with the inclusion of the 1×2 cm^2 transverse area of the MIMOSA-26 detectors and including multiple scattering. The lower subfigure shows the simulated photon spectrum (for 10^8 incoming electrons), which compares well with the expected Bethe-Heitler spectrum which scales essentially as $1/\hbar\omega$.

4 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)
2. A. Mangiarotti, S. Ballestrero, P. Sona and U.I. Uggerhøj: *Implementation of the LPM effect in the discrete-bremsstrahlung simulation of GEANT 3 and GEANT 4*, Nucl. Instr. Meth. B **266**, 5013 (2008)
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)
5. J. Esberg, K. Kirsebom, H. Knudsen, H.D. Thomsen, E. Uggerhøj, U.I. Uggerhøj, P. Sona, A. Mangiarotti, T.J. Ketel, A. Dizdar, M. Dalton, S. Ballestrero, S. Connell (CERN NA63): *Experimental investigation of strong field trident production*, Phys. Rev. D **82**, 072002 (2010)
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)
14. U.I. Uggerhøj: *Crystals, critical fields, collision points and a QED analogue of Hawking radiation*, in W. Greiner (ed.): Exciting Interdisciplinary Physics, Springer Verlag (2013)
15. 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): *Experimental investigation of the Landau-Pomeranchuk-Migdal effect in low-Z targets*, Phys. Rev. D **88**, 072007 (2013)
16. T.N. Wistisen and U.I. Uggerhøj: *Vacuum birefringence by Compton backscattering through a strong field*, Phys. Rev. D **88**, 053009 (2013)
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)
20. R.E. Mikkelsen, A.H. Sørensen and U.I. Uggerhøj: *Bremsstrahlung from relativistic heavy ions in a fixed target experiment at the LHC*, Advances in High Energy Physics **2015**, 625473 (2015)
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*, Nature Communications **82**, art. 795 (2018)
24. T. N. Wistisen, A. Di Piazza, C. F. Nielsen, A. H. Sørensen and U. I. Uggerhøj (CERN NA63): *Quantum radiation reaction in aligned crystals beyond the local constant field approximation*, Phys. Rev. Research **1**, 033014 (2019)
25. A. Di Piazza, T.N. Wistisen, M. Tamburini and U. I. Uggerhøj: *Testing strong-field QED close to the fully nonperturbative regime using aligned crystals*, Phys. Rev. Lett. 124, 044801 (2020)
26. C. F. Nielsen, J.B. Justesen, A. H. Sørensen, U. I. Uggerhøj and R. Holtzapple (CERN NA63): *Radiation reaction near the classical limit in aligned crystals*, submitted to Phys. Rev. D