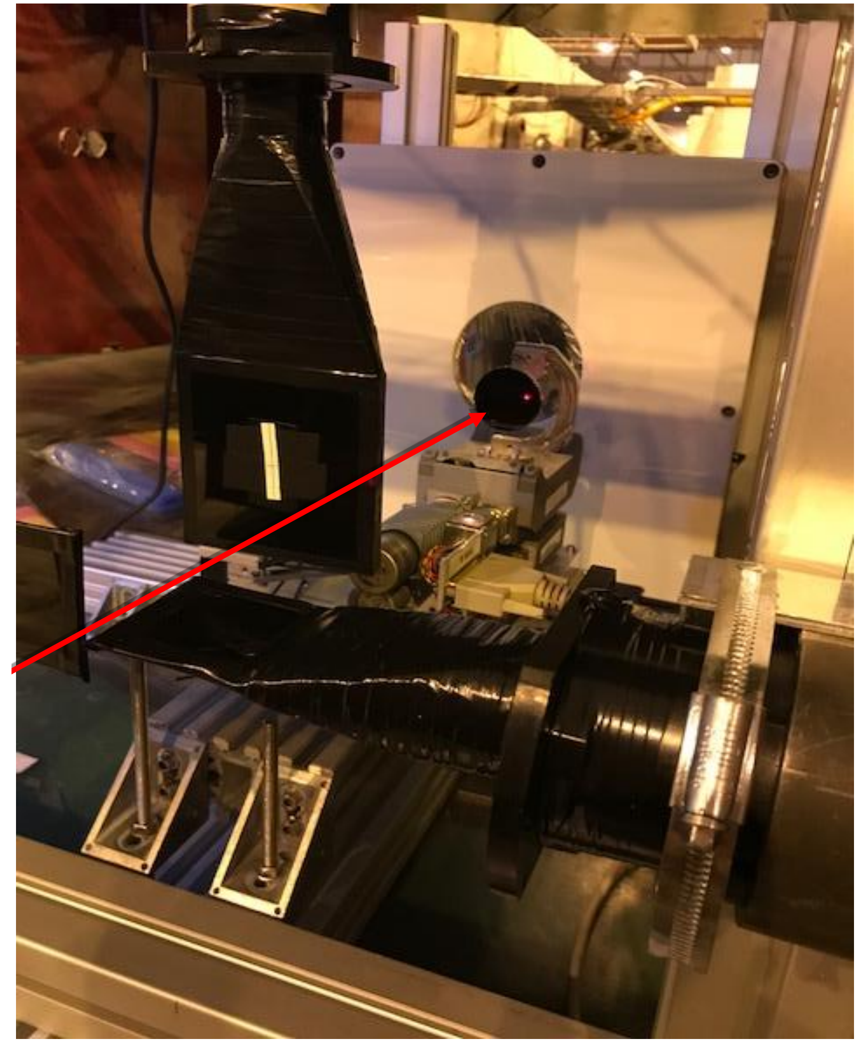
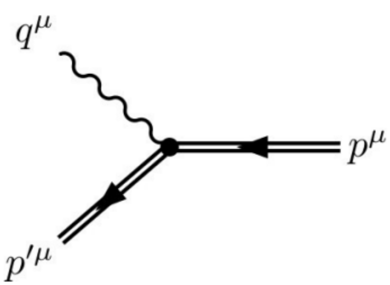
Status in 2022 and request for beamtime in 2023 for CERN NA63

Christian F. Nielsen
on behalf of NA63

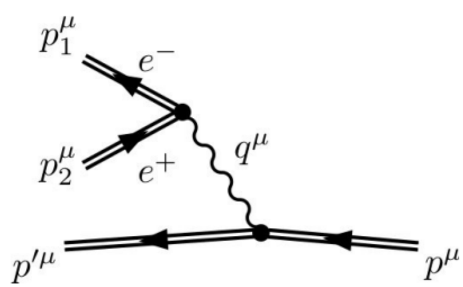
NA63

Studies fundamental strong field effects by means of crystals in GeV e^+/e^- beams

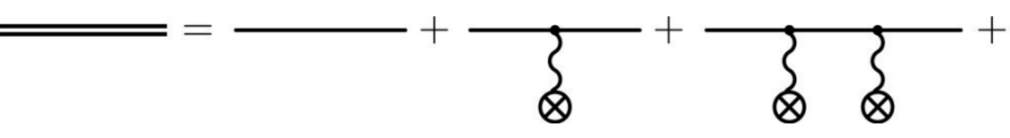




Quantum beamstrahlung



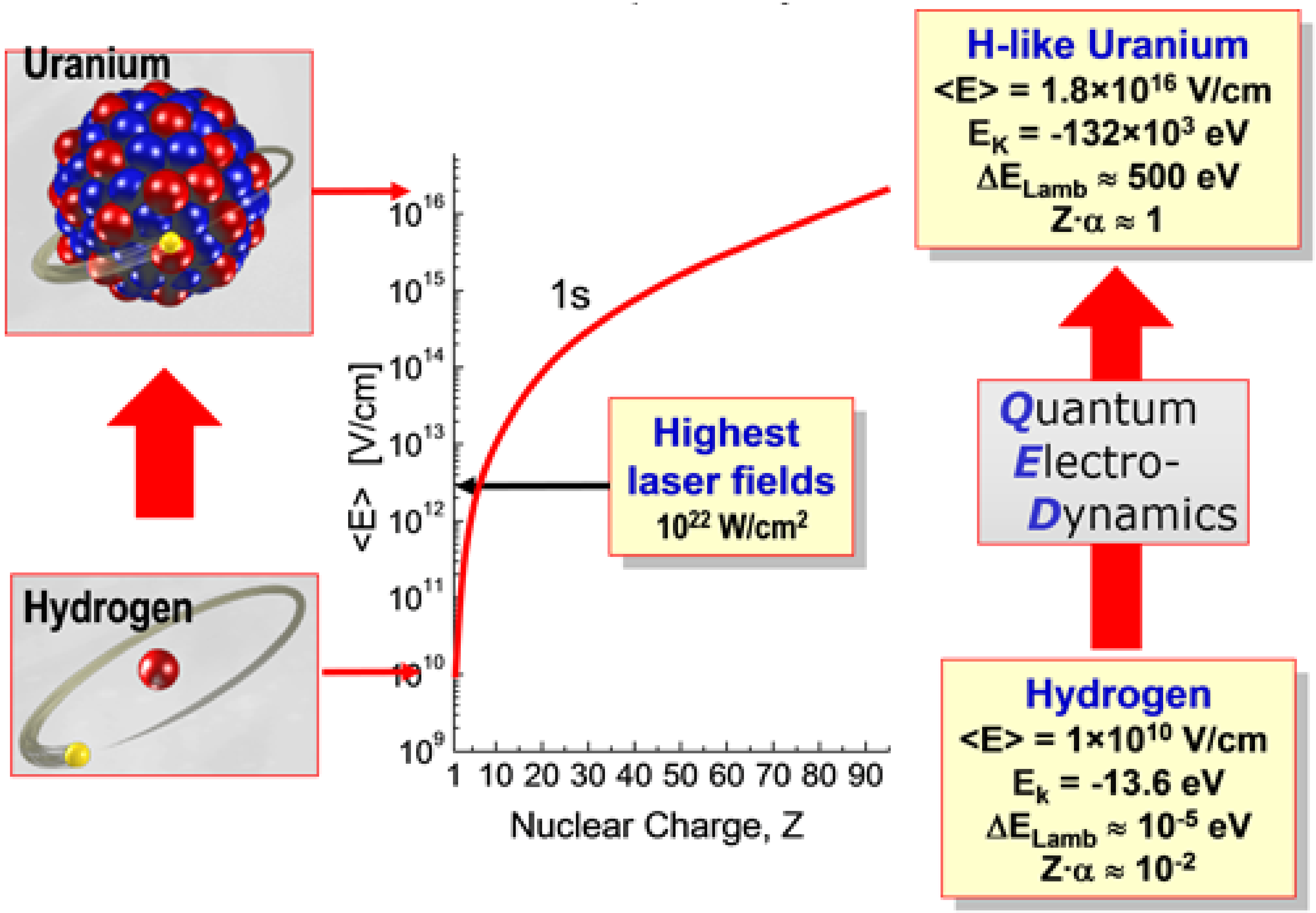
Electron/positron pair production



Strong fields

$\mathcal{E}_{1s}/\mathcal{E}_0 = \alpha^3 Z^3$

$\mathcal{E}_0 = mc^2/e\lambda\!\!\!^{-}_c = 1.32\cdot10^{16}$ V/cm

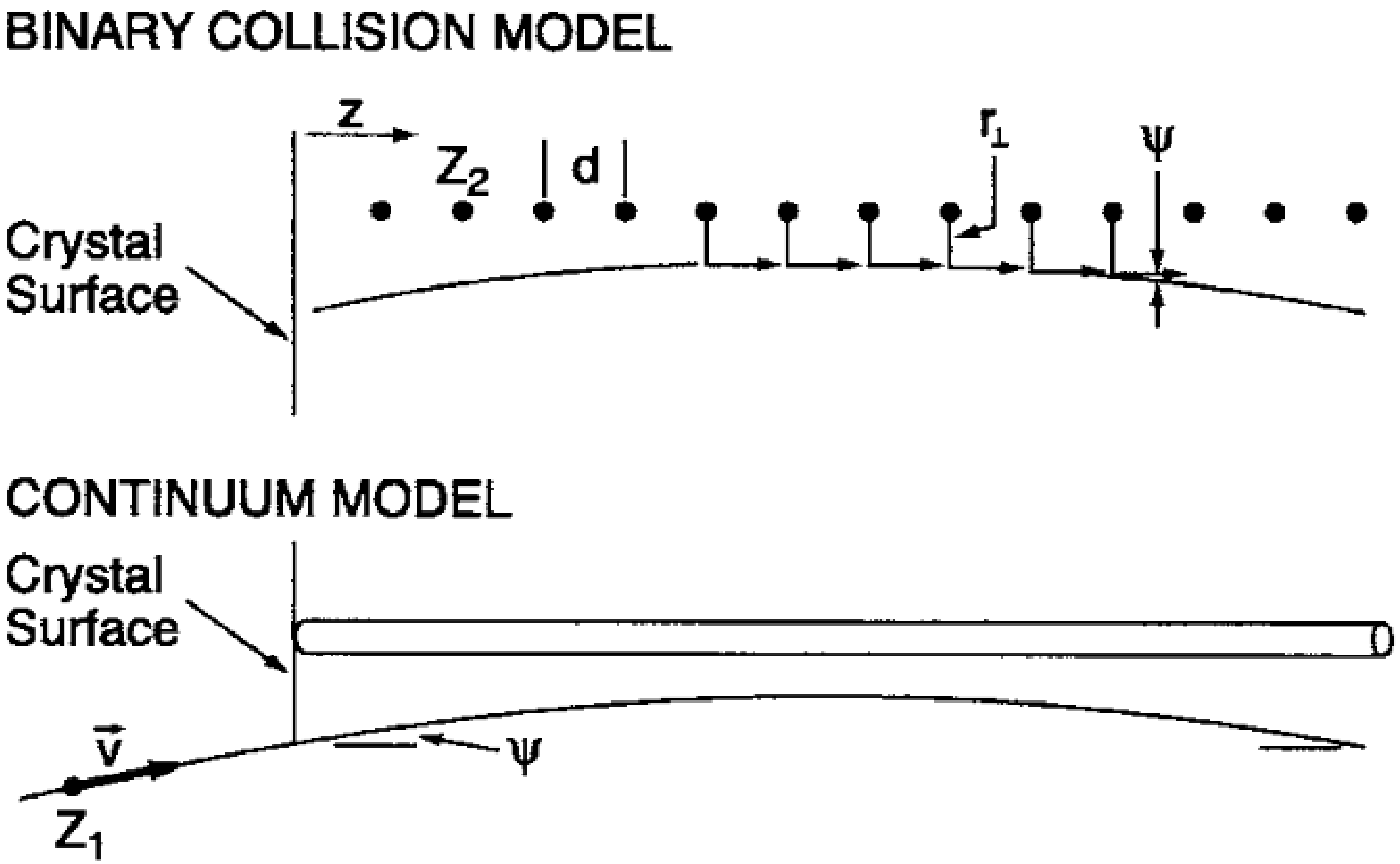


Picture from H.-J. Kluge, presented at the BriX workshop 2008, SCK•CEN, Mol, Belgium

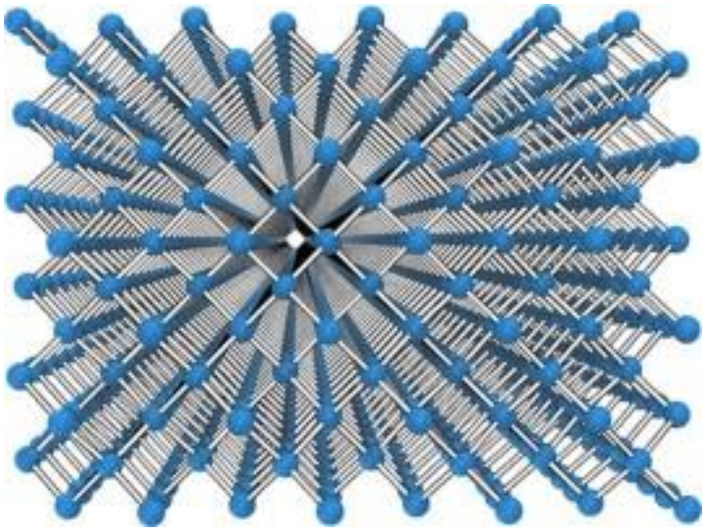
Crystals as a source of strong fields

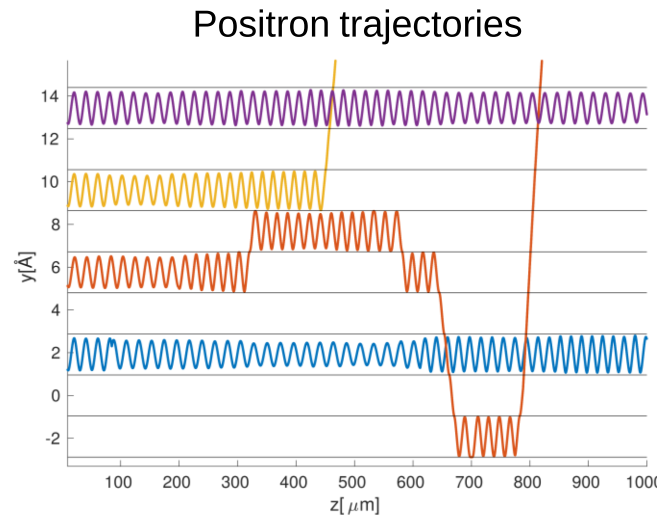
$\mathcal{E}_{1s}/\mathcal{E}_0 = \alpha^3 Z^3$

$\mathcal{E}_0 = mc^2/e\lambda\!\!\!^{-}_c$ =1.32·10^{16} V/cm

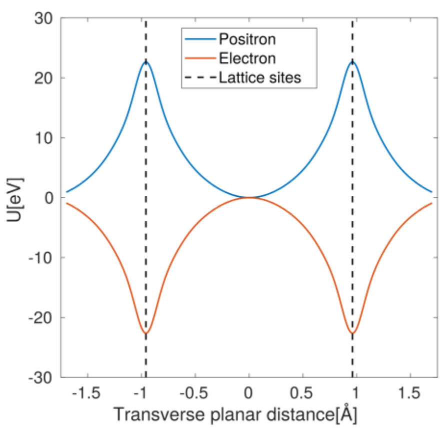


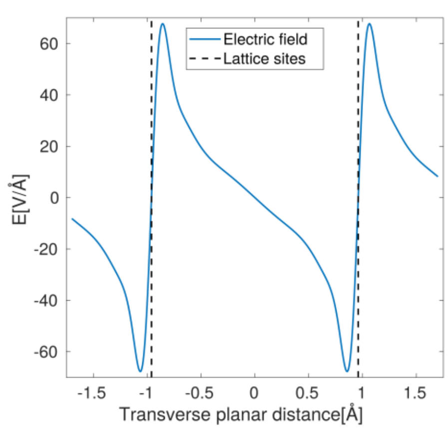
Crystals as a source of strong electric fields

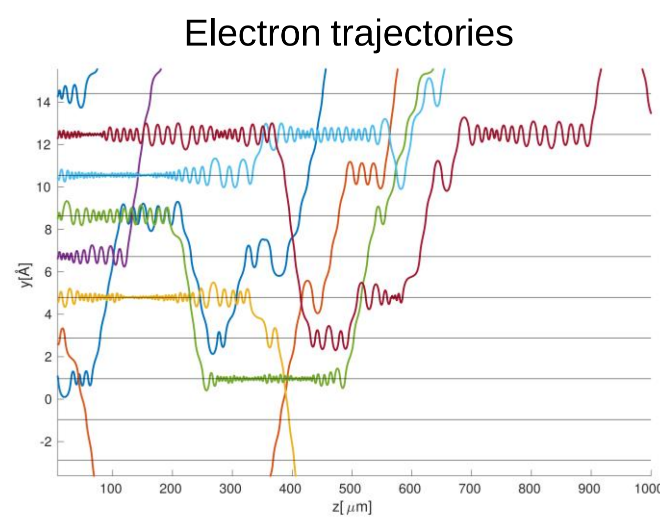




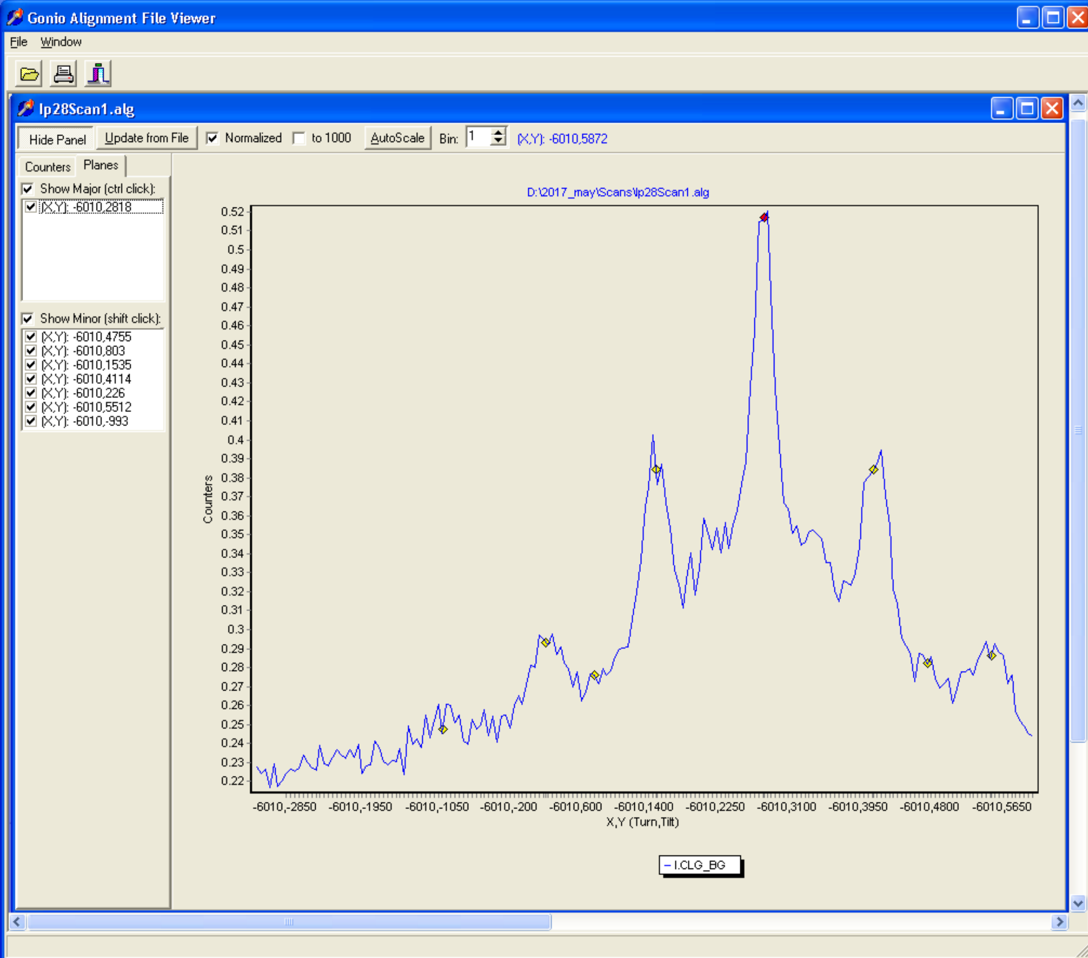
Extremely strong electric fields 10^9-10^{11} V/cm



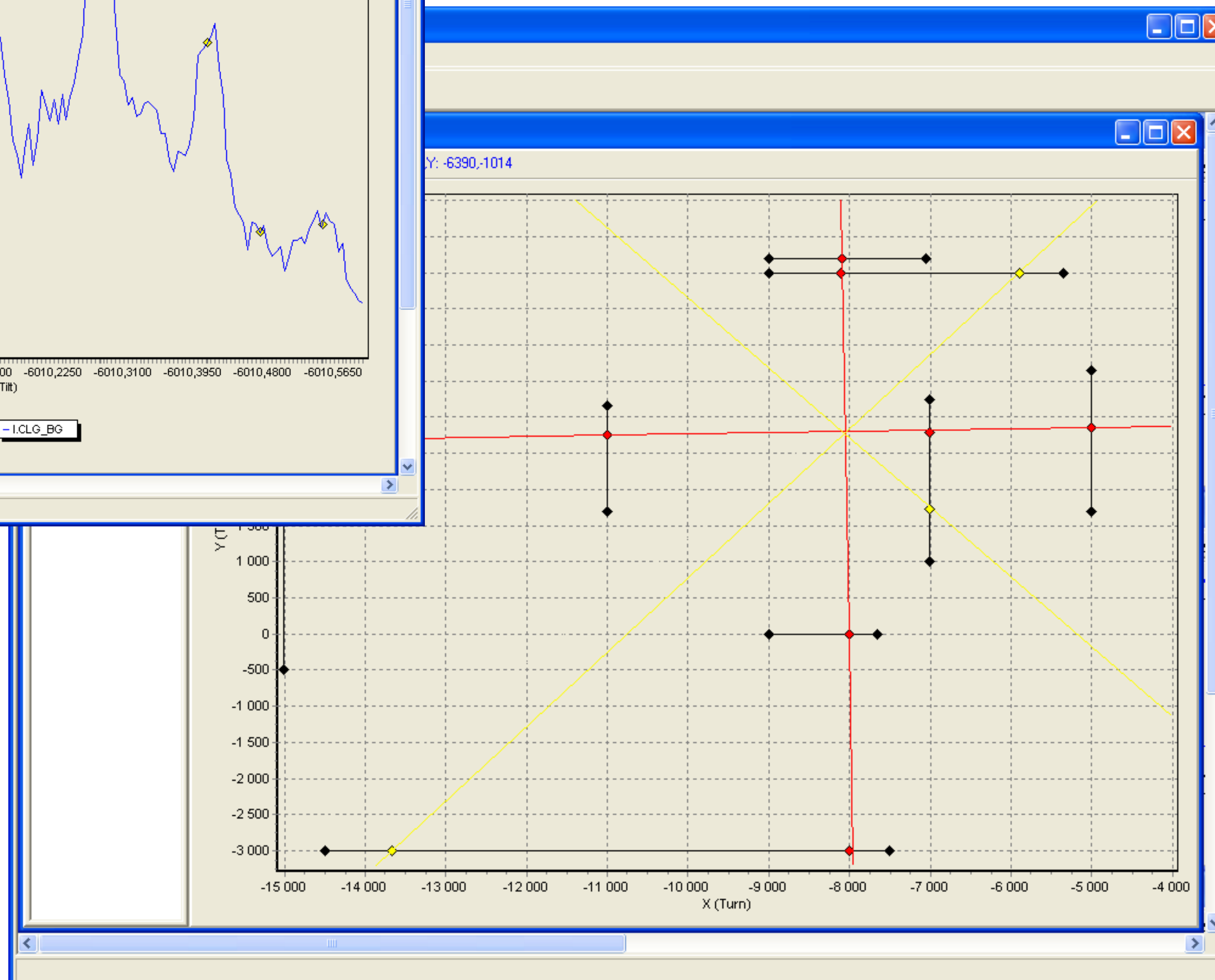




Crystal planar alignment



Lindhard critical angle @ 50 GeV: 23 microrad



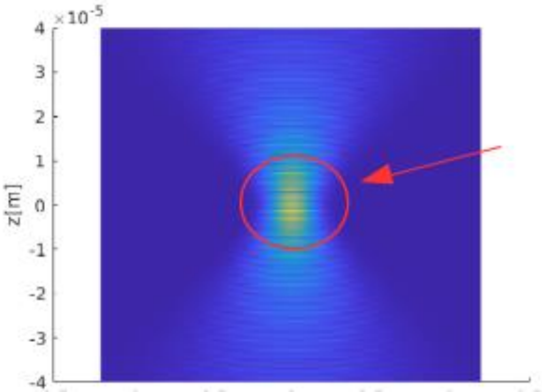
Crystals prealigned with x-rays

2017 data (planar case)

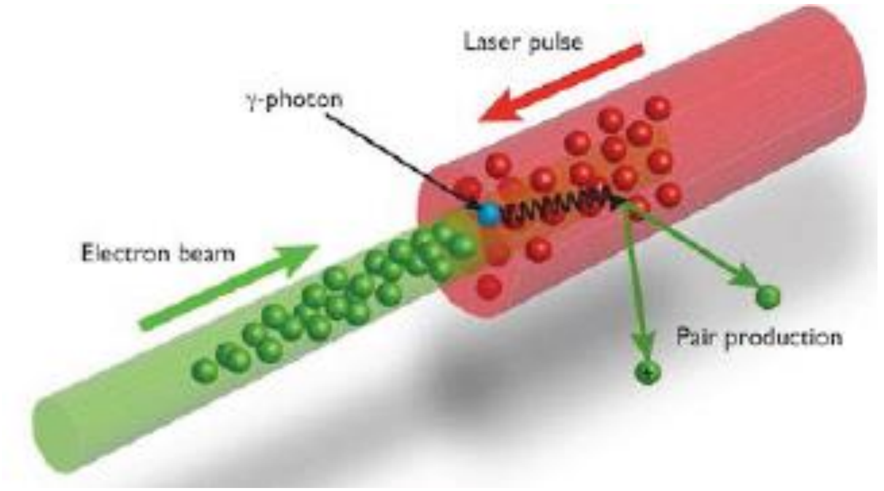
Lasers as a source of strong fields

New development in laser technology → many upcoming SFQED experiments:

SLAC E-144 (mid-90’s, 1 TW laser)
SLAC E-320 (almost ready to run, 10 TW laser)
LUXE @ DESY (ready in 2025, 30 TW laser)



10^{22} W/cm²



- 2-3 micron transverse size
- 40 - 100 fs pulse length
- overlap with counterpropagation bunched electron beam

New radiation reaction experiments with lasers:

Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam

J. M. Cole, K. T. Behm, E. Gerstmayr, T. G. Blackburn, J. C. Wood, C. D. Baird, M. J. Duff, C. Harvey, A. Ilderton, A. S. Joglekar, K. Krushelnick, S. Kuschel, M. Marklund, P. McKenna, C. D. Murphy, K. Poder, C. P. Ridgers, G. M. Samarin, G. Sarri, D. R. Symes, A. G. R. Thomas, J. Warwick, M. Zepf, Z. Najmudin, and S. P. D. Mangles
Phys. Rev. X **8**, 011020 – Published 7 February 2018

Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser

K. Poder, M. Tamburini, G. Sarri, A. Di Piazza, S. Kuschel, C. D. Baird, K. Behm, S. Bohlen, J. M. Cole, D. J. Corvan, M. Duff, E. Gerstmayr, C. H. Keitel, K. Krushelnick, S. P. D. Mangles, P. McKenna, C. D. Murphy, Z. Najmudin, C. P. Ridgers, G. M. Samarin, D. R. Symes, A. G. R. Thomas, J. Warwick, and M. Zepf
Phys. Rev. X **8**, 031004 – Published 5 July 2018

Classical Radiation Reaction

Jackson 1975 p. 786-798

$$m\dot{\mathbf{v}} = \mathbf{F}_{ext}$$ N2

$$P(t) = \frac{2}{3}\frac{e^2}{c^3}(\dot{\mathbf{v}})^2$$ Larmor

$$m\dot{\mathbf{v}} = \mathbf{F}_{ext} + \mathbf{F}_{rad}$$

$\mathbf{F}_{rad}$ "must" vanish if $\dot{\mathbf{v}} = 0$ (no radiation)

$$m(\dot{\mathbf{v}} - \tau\ddot{\mathbf{v}}) = \mathbf{F}_{ext}$$

Lorentz-Abraham-Dirac (LAD) equation

$$\mathbf{F}_{rad} = \frac{2}{3}\frac{e^2}{c^3}\ddot{\mathbf{v}} = m\tau\ddot{\mathbf{v}} \qquad \tau = \frac{2}{3}\frac{e^2}{mc^3}$$

No field, solution to LAD eq.:
(runaway – energy conservation)

$$a(t) = a_0 e^{t/\tau},$$

$$\tau = 6 \times 10^{-24}\text{s}.$$

Possible remedy: 'Landau-Lifshitz equation'

Step-fct. field, solution to LAD eq.:
(pre-acceleration - causality)

Classical Electrodynamics

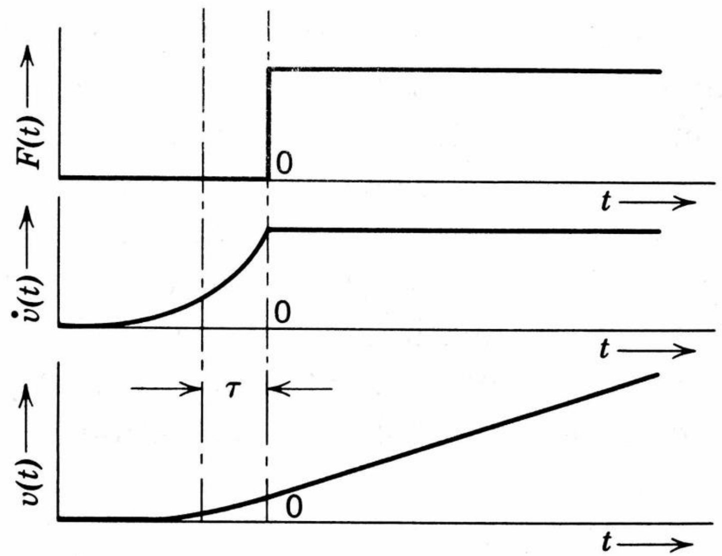


Fig. 17.1 "Preacceleration" of charged particle.

Significant damping in strong fields

quantum nonlinearity/strong field parameter χ

$$\chi^2 = (mF_{\mu\nu}u^\nu)^2/\mathcal{E}_0^2$$

$$\chi \simeq \gamma\mathcal{E}_\perp/\mathcal{E}_0$$

A 'specialty' of NA63 (and NA43) to address strong fields

ratio of damping force to external force

$$\eta = \alpha\gamma\chi = \alpha\gamma^2\mathcal{E}_\perp/\mathcal{E}_0$$

$$\alpha = e^2/\hbar c \simeq 1/137$$

classical for:

$\chi \ll 1$ which means: $\gamma \gg 1$

for significant damping

- Landau-Lifshitz equation, "Reduction of order", valid when $\chi\alpha \ll 1$

experiment: $\chi < 0.1$

Example of results, silicon (2017 data)

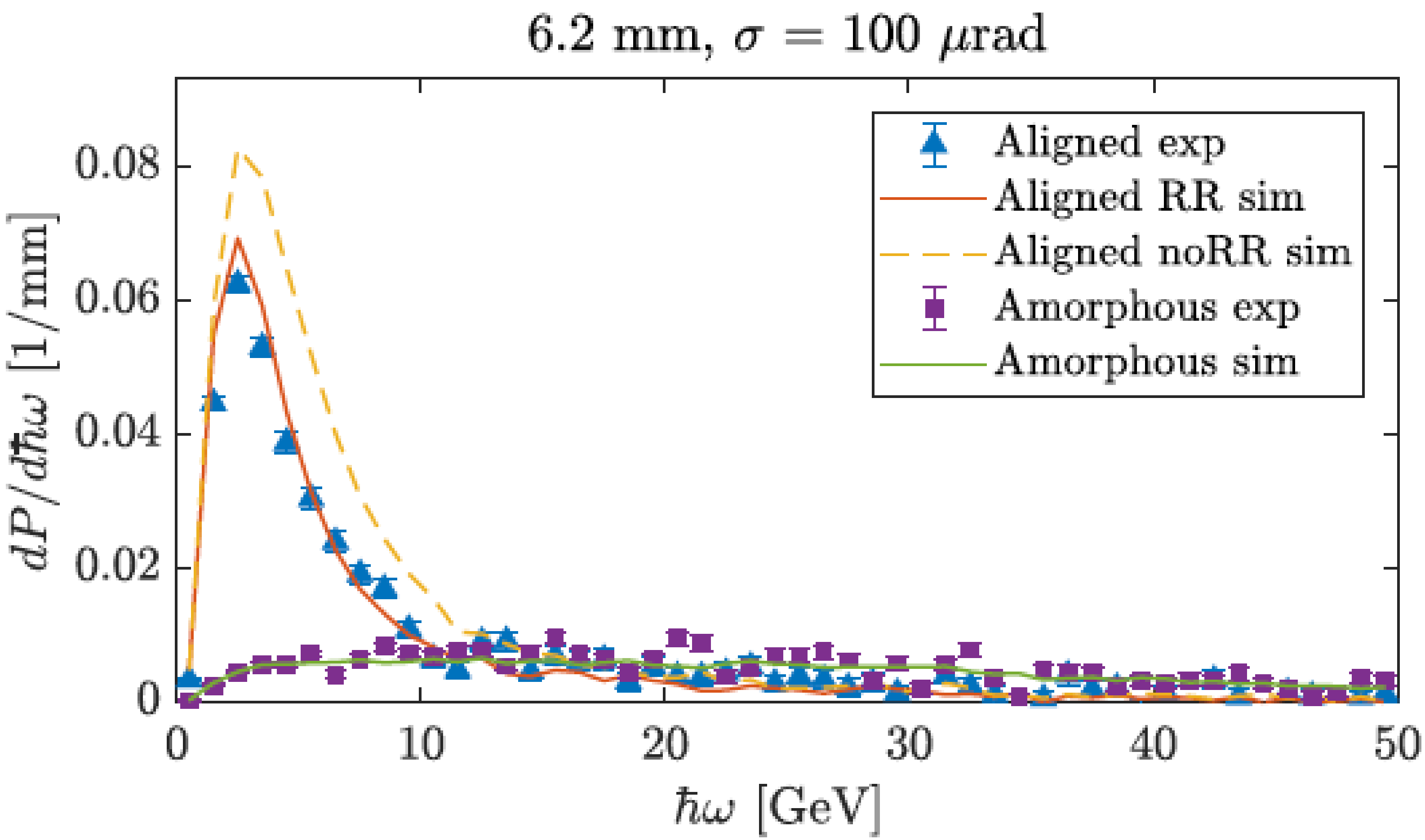


Figure 4: Radiation power spectra obtained for 50 GeV positrons passing 1.1, 2.0, 4.2 and 6.2 mm thick silicon crystals aligned to the (110) plane, and the corresponding amorphous spectra. These spectra has angular cuts, meaning that only particles with entry angle between $\pm$ 30 μrad with respect to the crystal planes are included.

Example of results, diamond (2018 data)

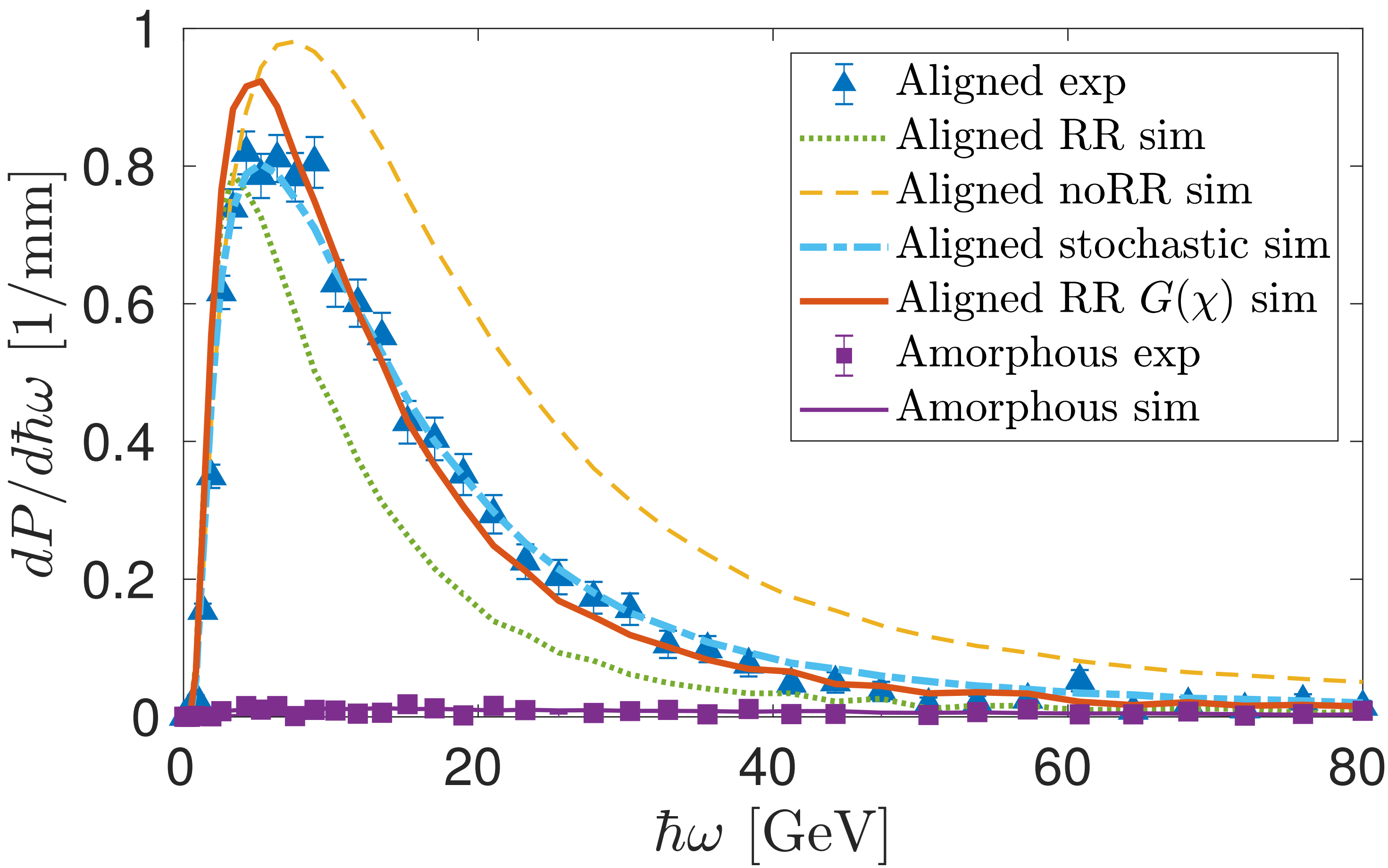


Figure 2: Radiation power spectra obtained for 80 GeV (right) electrons traversing a 1.5 mm (top) thick diamond crystal aligned to the $\langle 100 \rangle$ axis, and the corresponding amorphous spectra. This spectrum has angular cuts, meaning that only particles with entry angle less than ψ_1 with respect 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.

An example from a total of 22 experimental comparisons with theory reported in the paper published in PRD.

3 papers published
(27 NA63 papers published, since 2008)

Published in PRD: 2018 data:

Radiation Reaction near the Classical Limit in Aligned Crystals

C. F. Nielsen,[1] J. B. Justesen,[1] A. H. Sørensen,[1] U. I. Uggerhøj,[1] and R. Holtzapple[2]
(CERN NA63)
[1] *Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark*
[2] *Department of Physics, California Polytechnic State University, San Luis Obispo, California 93407, USA*

Published in Phys. Rev. Research: 2017 data:

PHYSICAL REVIEW RESEARCH **1**, 033014 (2019)

Quantum radiation reaction in aligned crystals beyond the local constant field approximation

T. N. Wistisen,[2,1] A. Di Piazza,[2] C. F. Nielsen,[1] A. H. Sørensen,[1] and U. I. Uggerhøj[1]
(CERN NA63)
[1] *Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark*
[2] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117, Germany*

Newly published in New Journal of Physics, Special issue: 2017 data + 2018 data:

IOP Publishing *New J. Phys.* **23** (2021) 085001 https://doi.org/10.1088/1367-2630/ac1554

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3 August 2021

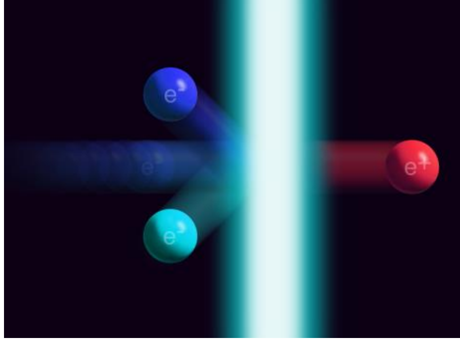
PAPER

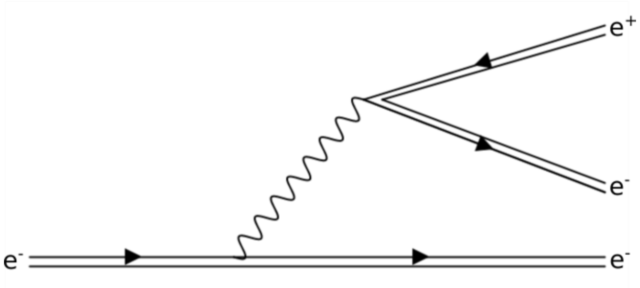
Experimental verification of the Landau–Lifshitz equation

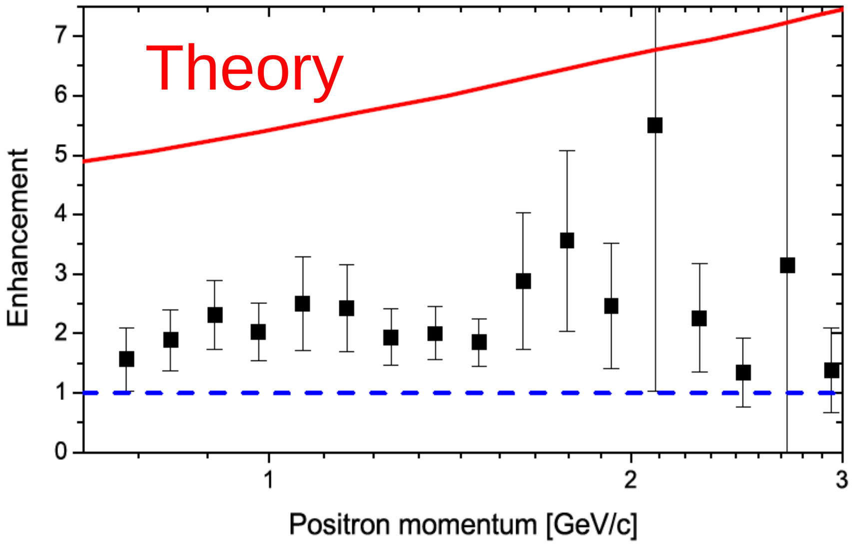
C F Nielsen[1,*], J B Justesen[1], A H Sørensen[1], U I Uggerhøj[1], R Holtzapple[2] and CERN NA63
[1] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark
[2] Department of Physics, California Polytechnic State University, San Luis Obispo, CA 93407, United States of America
[*] Author to whom any correspondence should be addressed.
E-mail: christianfn@phys.au.dk

Keywords: radiation reaction, strong fields, classical electrodynamics

Trident enhancement in strong field







Significant discrepancy!

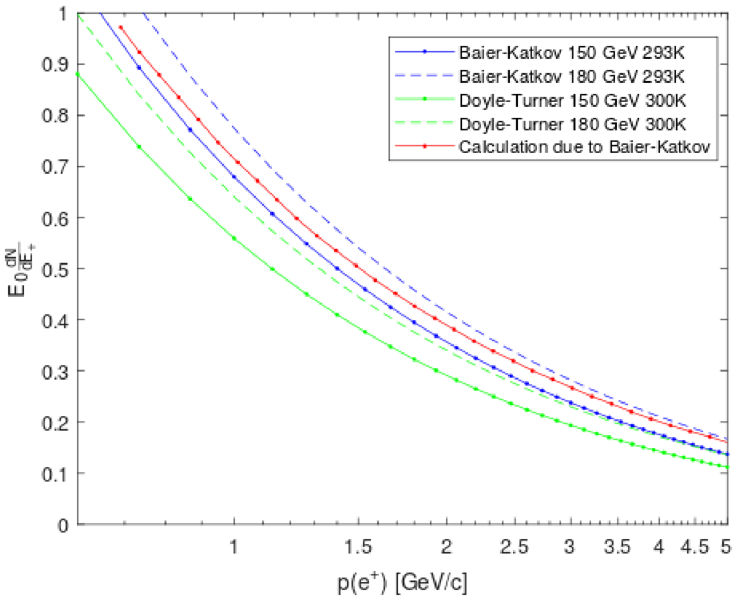
Found in the framework of NA63

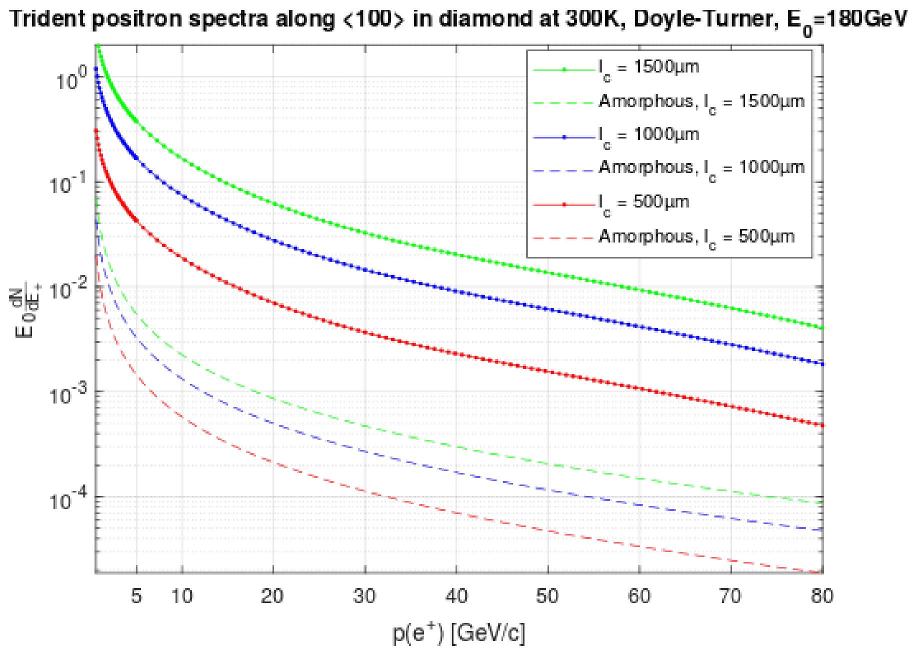
PHYSICAL REVIEW D 82, 072002 (2010)

Experimental investigation of strong field trident production

J. Esberg,[1] K. Kirsebom,[1] H. Knudsen,[1] H. D. Thomsen,[1] E. Uggerhøj,[1] U. I. Uggerhøj,[1] P. Sona,[2] A. Mangiarotti,[3] T. J. Ketel,[4] A. Dizdar,[5] M. M. Dalton,[6] S. Ballestrero,[7] and S. H. Connell[7]
(CERN NA63)

New theoretical simulations of trident production rates is in agreement with 2009 predictions.





- Positron (trident) spectrum for 150 and 180 GeV electrons hitting a 400 micron Ge <111> crystal. Red curve corresponds to the theoretical prediction used in 2009.

- Positron (trident) spectrum 180 GeV electrons hitting a 0.5, 1 and 1.5 mm thick Diamond <100> crystal.

- **Agreement between new and old predictions means that discrepancy in 2009 experiment most likely is experimental**

Simulations by: Jeppe Heering Surrow, Aarhus University 2021

MIMOSA-26 detectors

(M. Winter, Strasbourg)

Vertex detectors for CLIC (?)

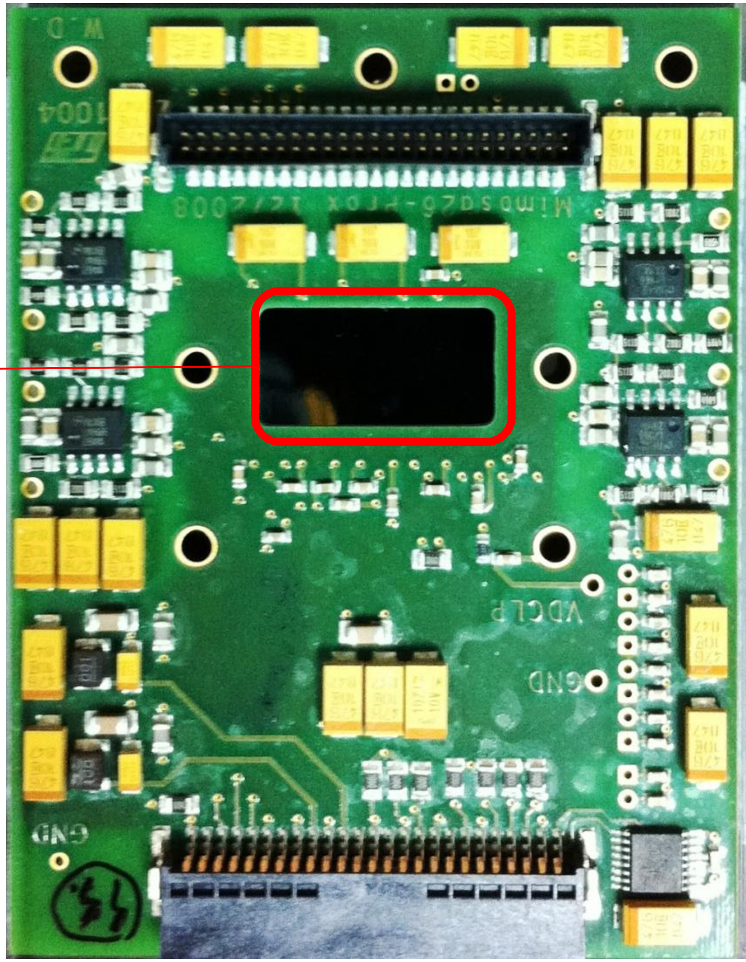
CMOS-based position sensitive detectors

1152 columns of 576 pixels, $\simeq$ 18.4 μm pitch

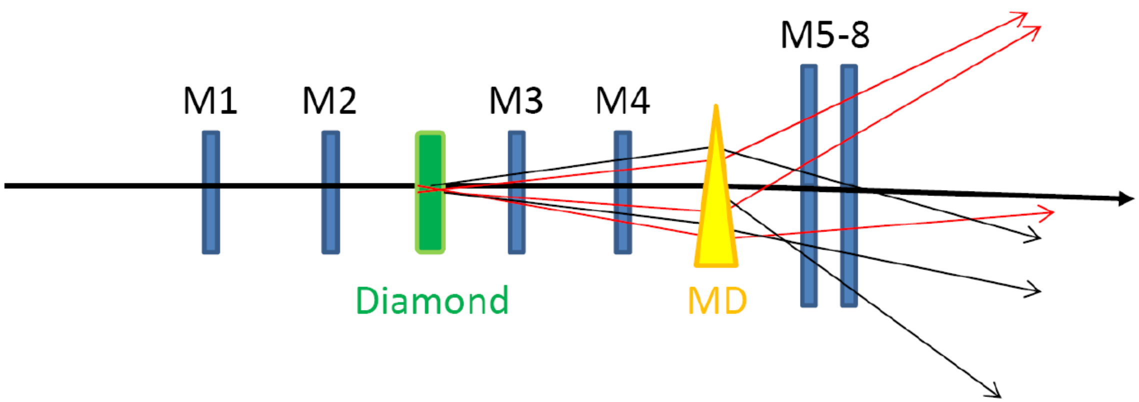
true multi-hit capability

$\Delta t/X_0 \simeq 0.05\%$

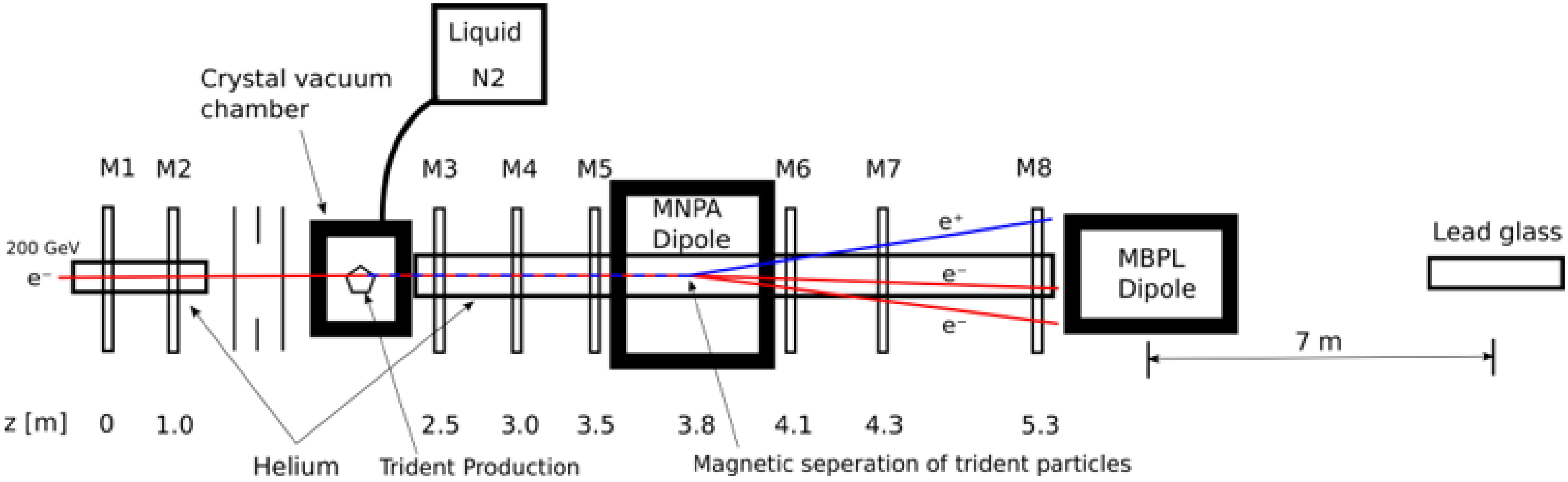
1×2 cm^2



10 k frames/s, resolution 3.5 µm

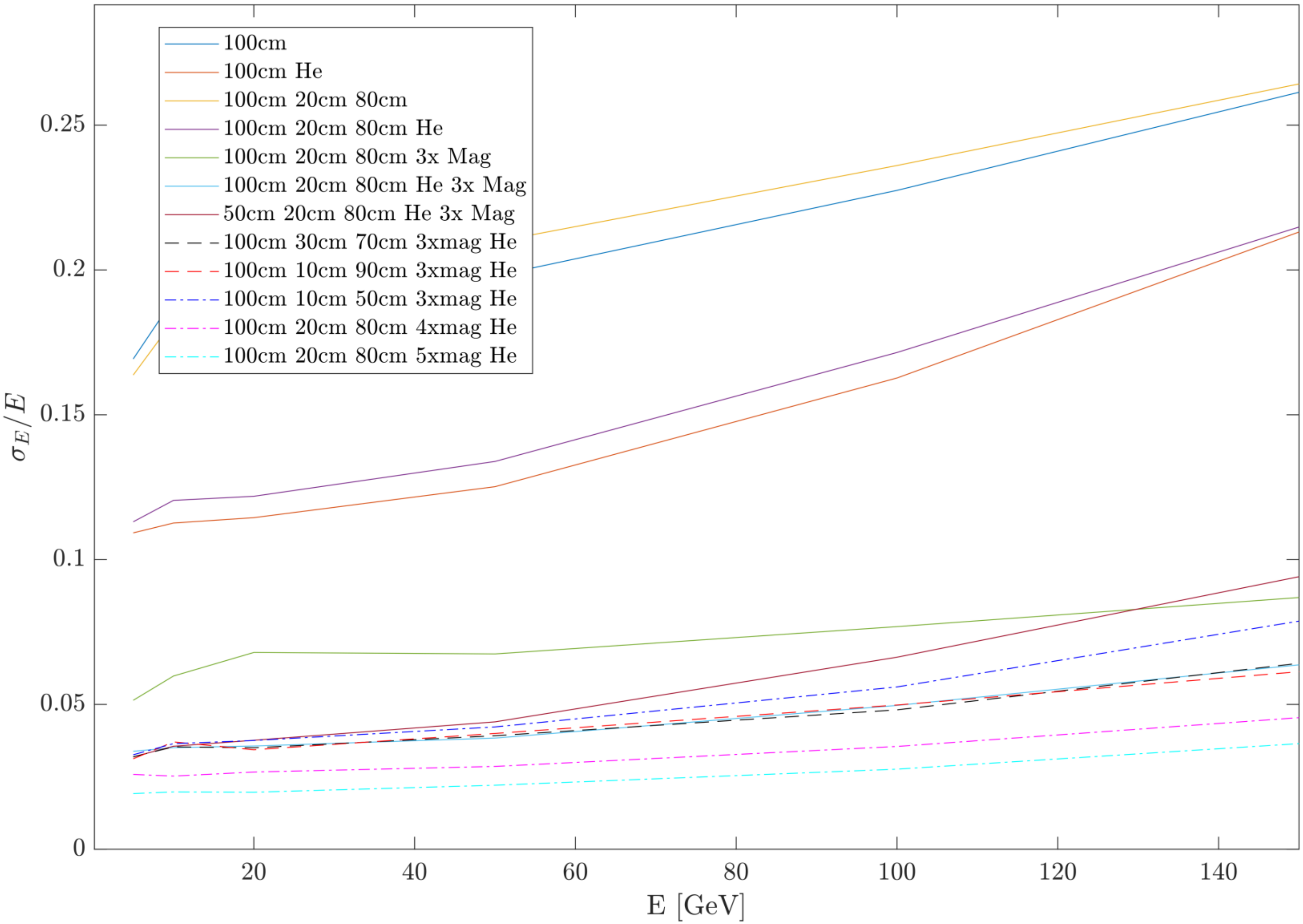


2022 Setup

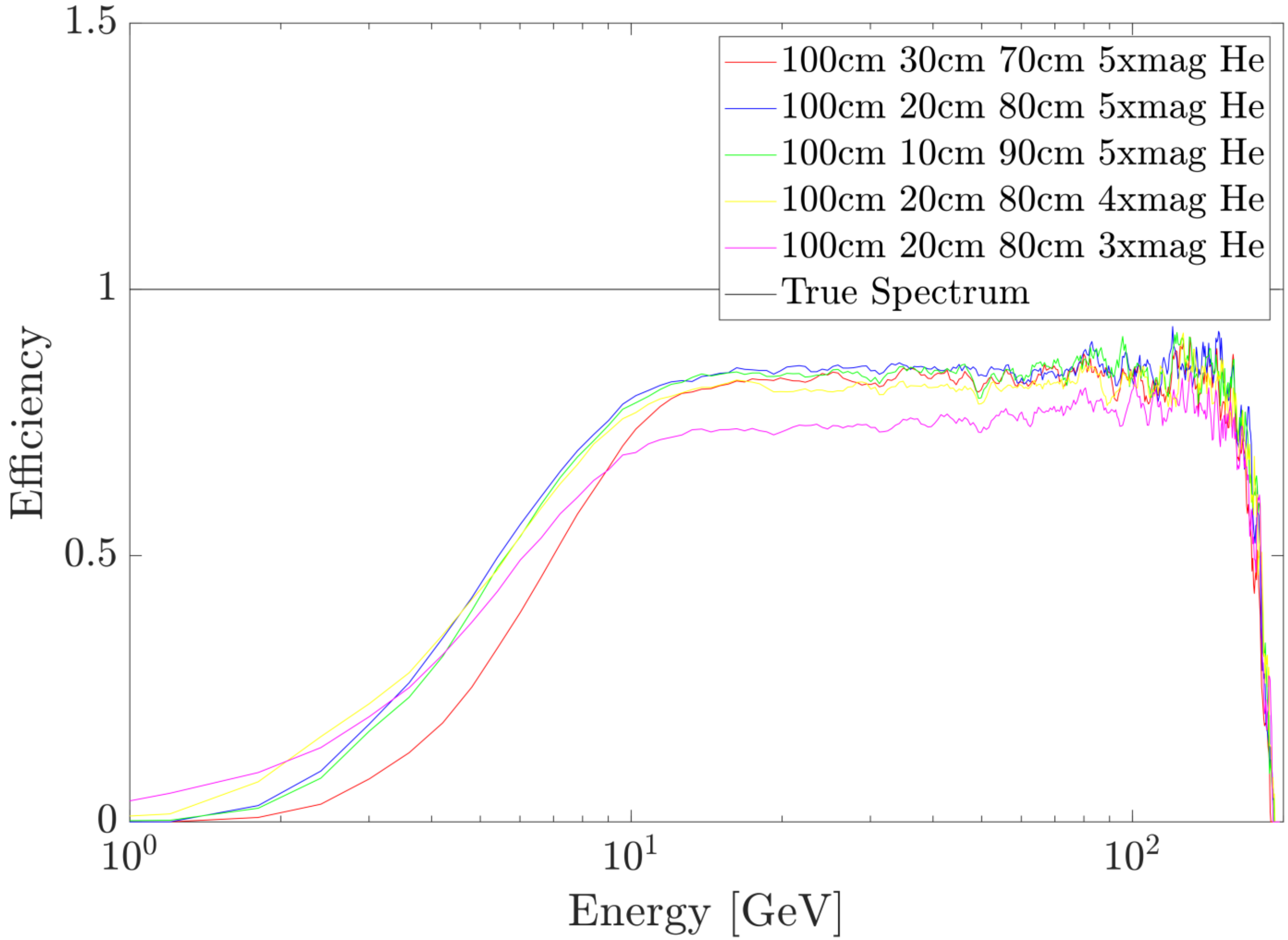


- Minimal background
- 8 mimosas instead of only 6
- LN2 cooled crystal to enhance strong field effects
- Stronger magnet to increase energy resolution

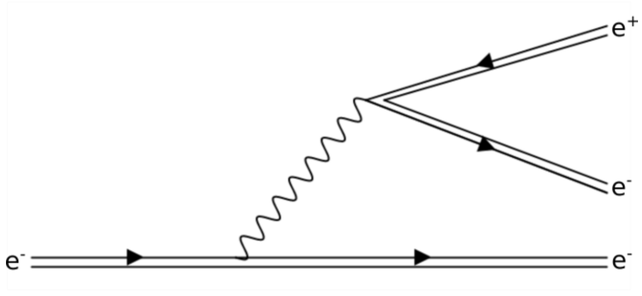
Energy resolution of tracks

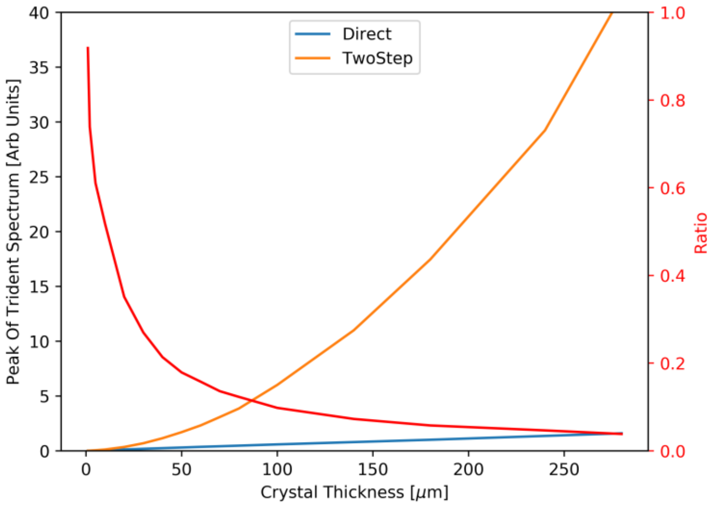


Efficiency of the setup:



Direct vs two step – possible measurement in 2023





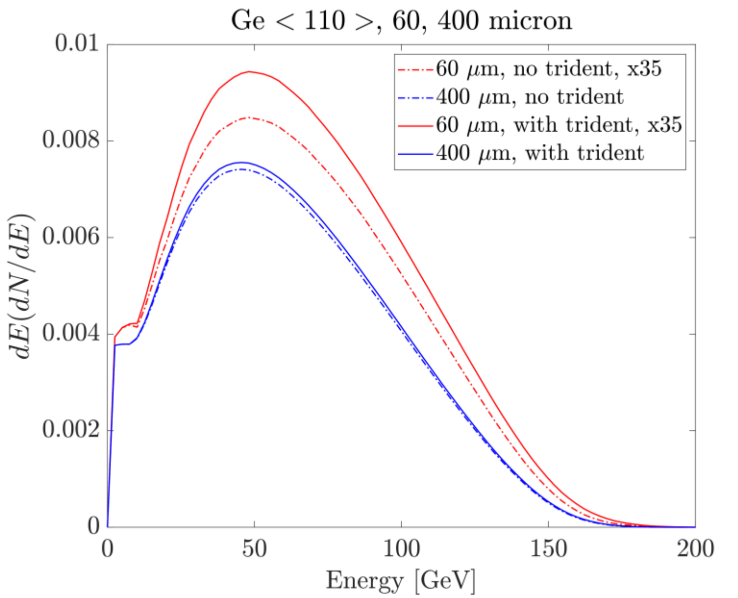
Total signal is comprised of two-step and direct trident.

Depends on the virtuality of the photon.

Two-step: ~ L^2 scaling
Direct: ~ L scaling

Requires thin crystals – lower count rate.

We foresee to request 3 weeks of beam in 2023



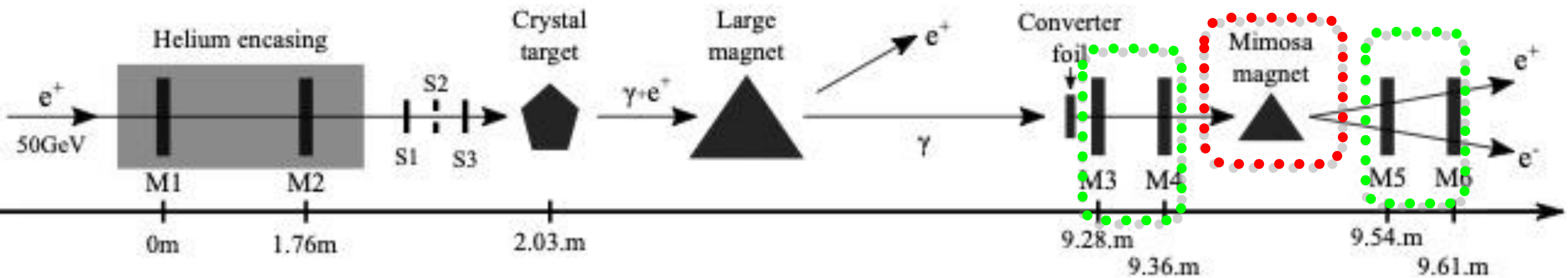
Change in spokesperson:

from: Ulrik I. Uggerhøj
to: Christian F. Nielsen

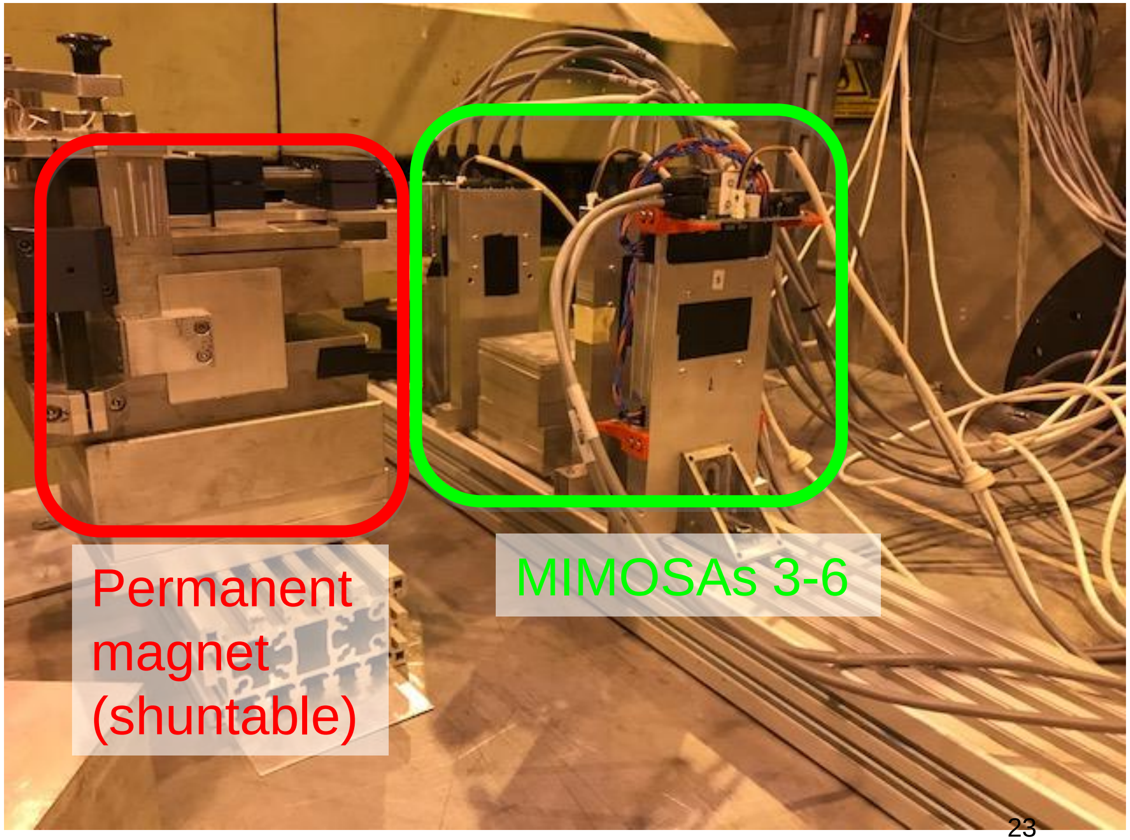
Scientific investigations in the framework of NA63 (full list of publications in report)

- Direct measurement of the Chudakov effect: PRL **100**, 164802 (2008); NIMB **269**, 1919 (2011)
- LPM effect: NIMB **266**, 5013 (2008); NIMB **269**, 1977 (2011); NIMB **289** 5-17 (2012); PRD **88**, 072007 (2013)
- Macroscopic formation length: PLB **672**, 323 (2009); PRL **108**, 071802 (2012); NIMB **315**, 278 (2013); PLB **732**, 309-314 (2014)
- Beamstrahlung in strong fields: JPCS **198**, 012007 (2009); PRST-AB **17**, 051003 (2014)
- Strong field trident production: PRD **82**, 072002 (2010)
- Logarithmic thickness dep. of radiation: PRD **81**, 052003 (2010)
- Quantum synchrotron radiation: PRD **86**, 072001 (2012)
- Strong field vacuum birefringence: PRD **88**, 053009 (2013)
- Quantum/classical Radiation Reaction: PLB **765**, 1-5 (2016); Nat. Comm. **82**, art. 795 (2018); PRR **1**, 033014 (2019); PRL 124, 044801 (2020); PRD submitted

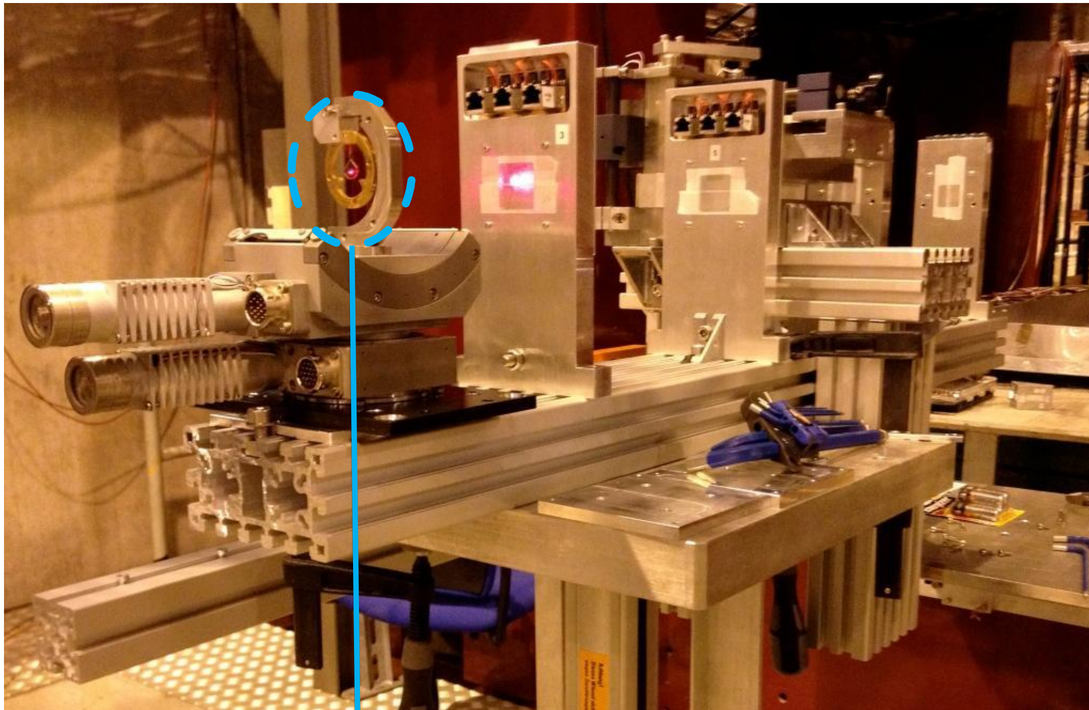
Overview of the experiment

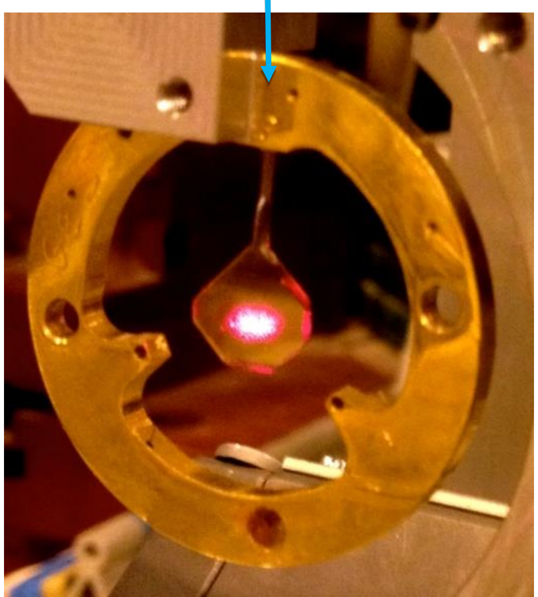


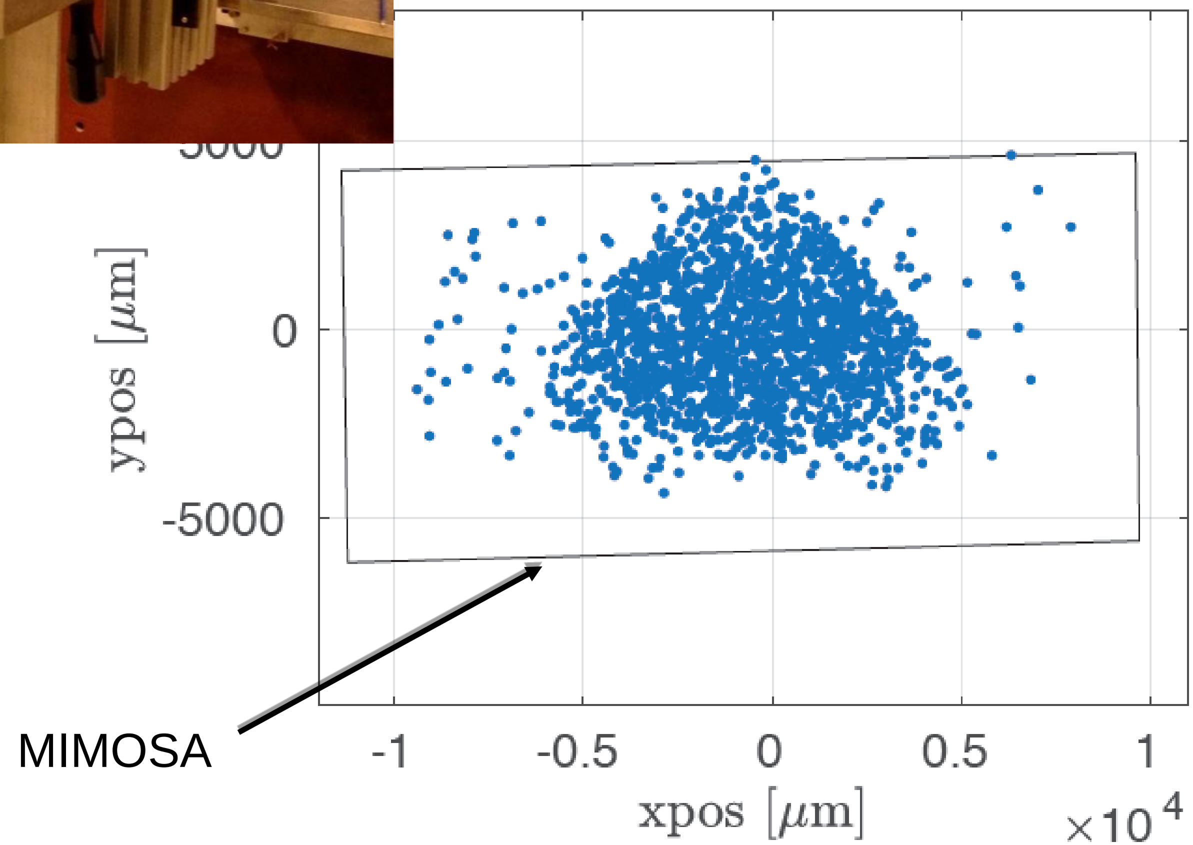
- In RR regime, naturally many photons are emitted per incoming charge
- Sufficiently thin converter foil is required to convert a single photon per event



‘Picture’ of a 1.5 mm thick diamond, taken with tracked e+e- pairs:







What is classical radiation reaction?

- Landau-Lifshitz equation, “Reduction of order”: $\chi\alpha \ll 1$

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

or in 3-vector notation:

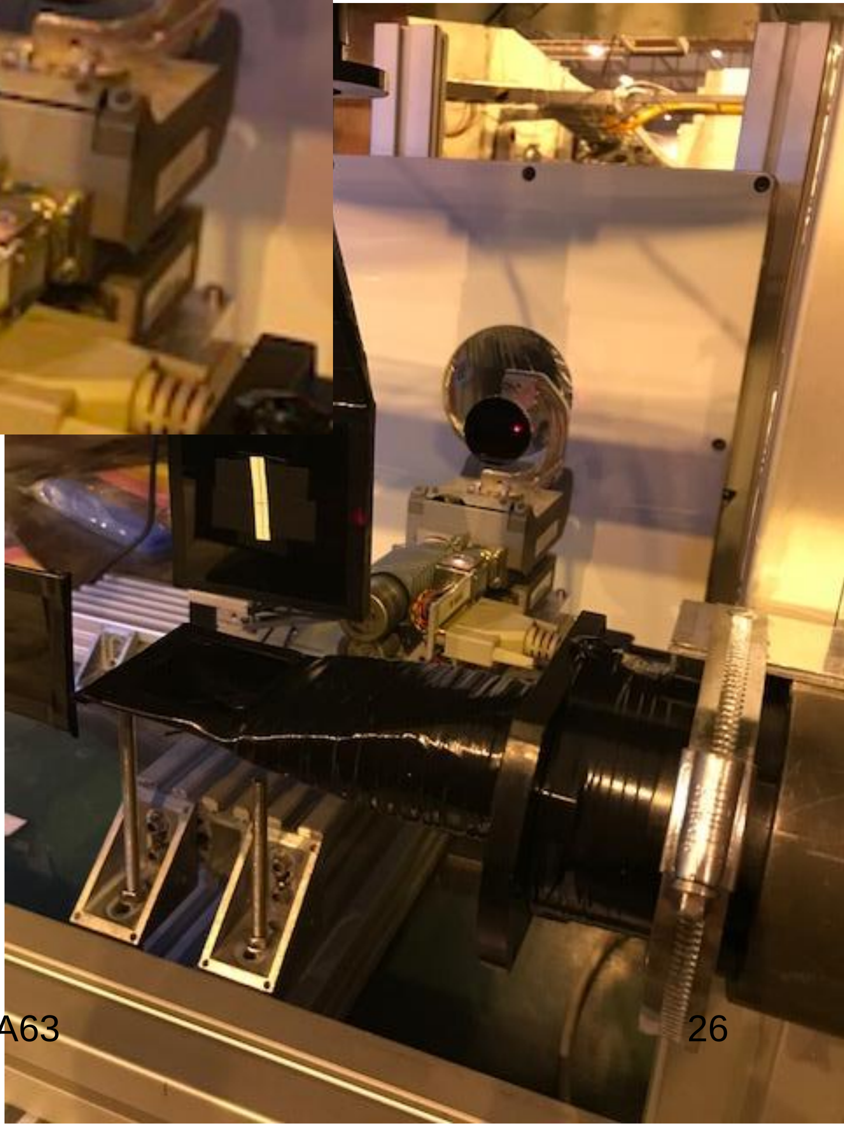
$$\boldsymbol{f} = \frac{2e^3}{3m}\gamma\left\{\left(\frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla\right)\boldsymbol{E} + \boldsymbol{v}\times\left(\frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla\right)\boldsymbol{H}\right\} + \frac{2e^4}{3m^2}\left\{\boldsymbol{E}\times\boldsymbol{H}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

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

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

Schott

Detectors and crystal

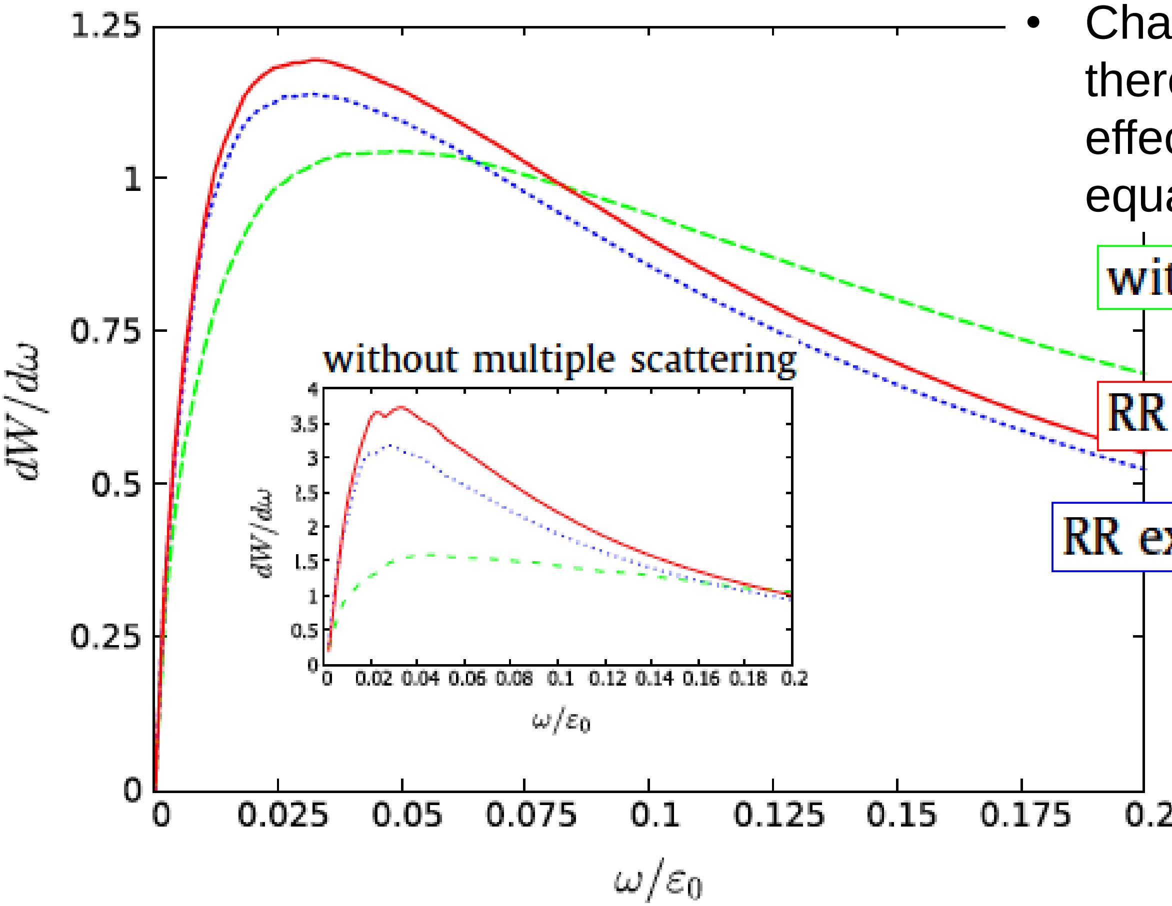


Investigation of classical radiation reaction with aligned crystals

A. Di Piazza [a,*], Tobias N. Wistisen [b], Ulrik I. Uggerhøj [b]

[a] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117, Germany
[b] Department of Physics and Astronomy, Aarhus University, 8000 Aarhus, Denmark

Physics Letters B 765 (2017) 1–5



- Challenging, but the only place where there would be a chance to see the effect of the derivative term in the LL equation.

Derivative term not accessible in laser interactions

In a purely electric field (in the lab frame), 'Landau-Lifshitz' equation :

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

Crystal	d_c	E	Cut	$\overline{\chi}$	$\%E_{\mathrm{LL}}$	$\%E_{\mathrm{LL,G(\chi)}}$
C ⟨100⟩	1.0 mm	40 GeV	No cut	0.0285	47.7%	20.2%
			$2\psi_1 < \psi < 5\psi_1$	0.0274	50.0%	24.0%
			$\psi_1 > \psi$	0.0311	40.8%	8.8%
		80 GeV	No cut	0.0479	59.7%	25.1%
			$2\psi_1 < \psi < 4\psi_1$	0.0470	58.3%	22.3%
			$\psi_1 > \psi$	0.0537	50.6%	6.9%
	1.5 mm	40 GeV	No cut	0.0258	46.4%	20.1%
			$2\psi_1 < \psi < 4\psi_1$	0.0253	48.1%	22.8%
			$\psi_1 > \psi$	0.0278	39.7%	8.9%
		80 GeV	No cut	0.0418	58.3%	25.1%
			$2\psi_1 < \psi < 4\psi_1$	0.0415	56.9%	22.6%
			$\psi_1 > \psi$	0.0576	49.2%	7.0%
Si (110)	1.1 mm	50 GeV	No cut	0.0155	33.5%	25.9%
			$\psi < 30\mu$rad	0.0140	16.1%	5.7%
	2.0 mm		No cut	0.0154	32.8%	24.7%
			$\psi < 30\mu$rad	0.0130	16.2%	6.38%
	4.2 mm		No cut	0.0141	31.8%	24.9%
			$\psi < 30\mu$rad	0.0123	16.7%	7.4%
	6.2 mm		No cut	0.0139	28.9%	21.5%
			$\psi < 30\mu$rad	0.0113	16.3%	7.1%

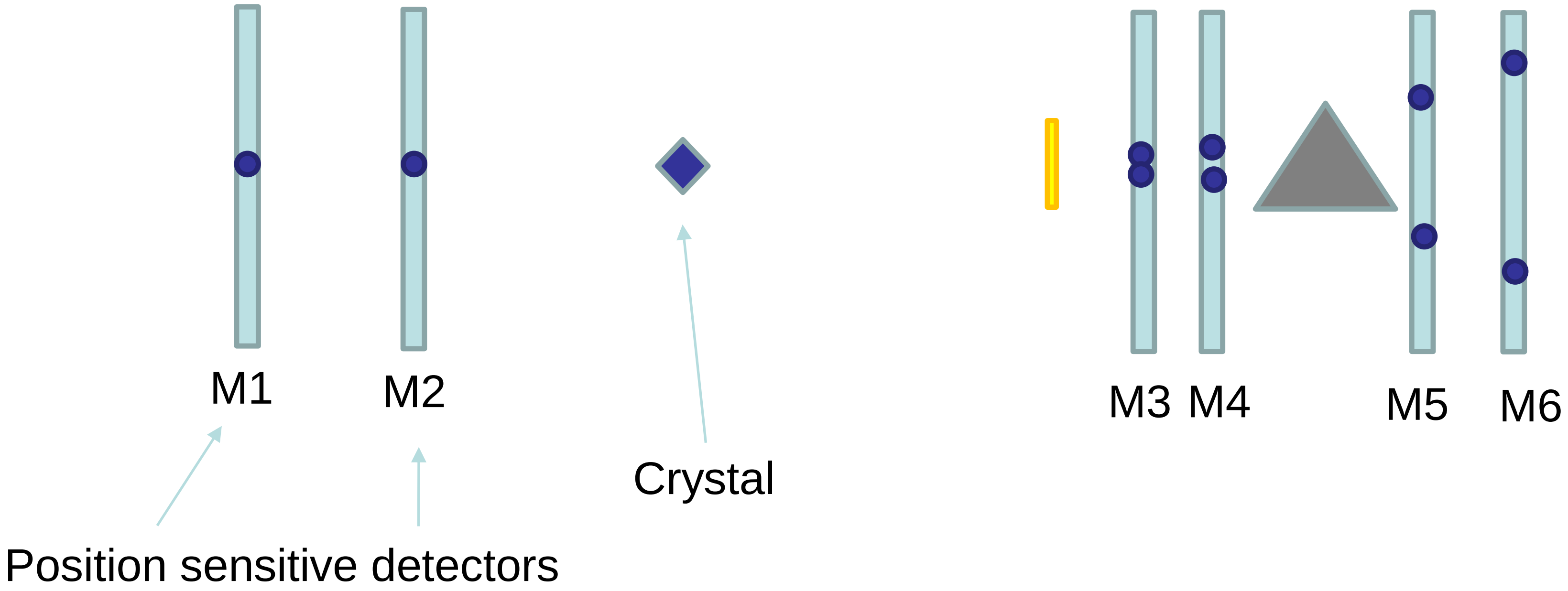
ratio of damping force to external force

$$\eta = \alpha\gamma\chi = \alpha\gamma^2\mathcal{E}_\perp/\mathcal{E}_0$$

This number shows a compromise: with increase of chi the damping becomes more significant, but the validity of the LL becomes more questionable: the fractional difference between energy lost according to the (Lorentz-force with LL damping) trajectory and energy lost according to the full spectrum increases.

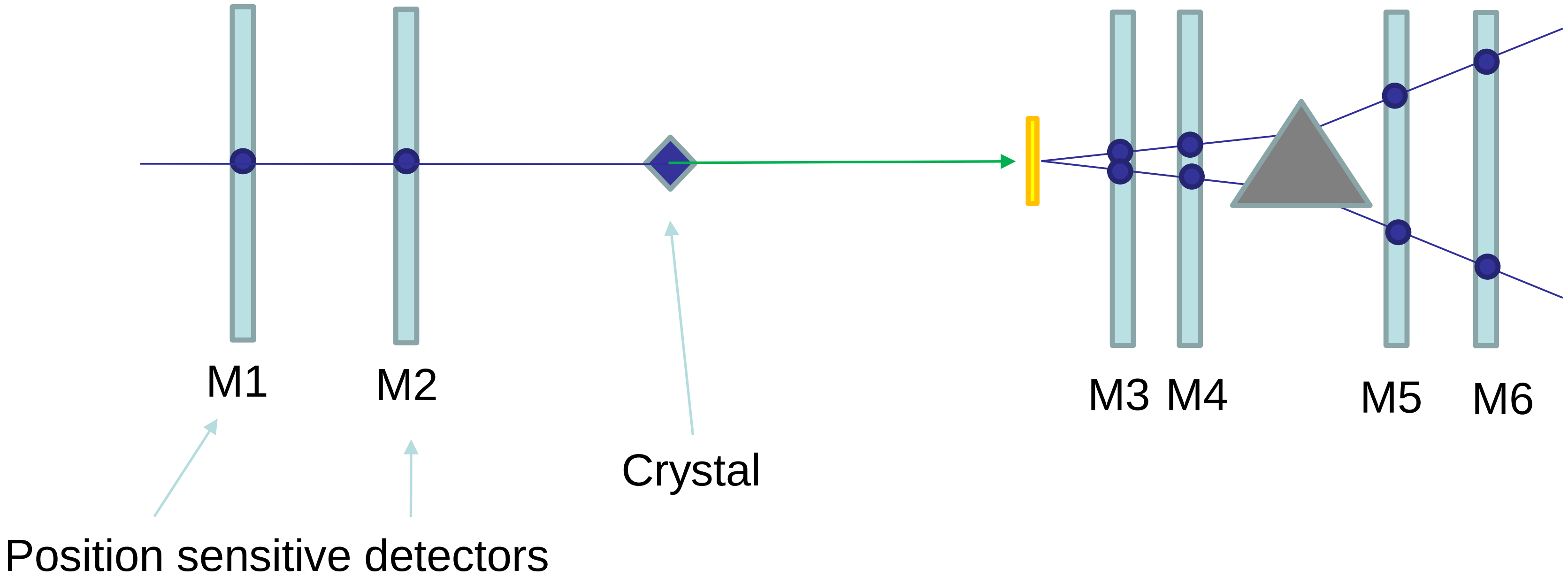
The experimental setup

- How does this setup measure photon energies?
- All you know is the position where some charged particles hit the detector



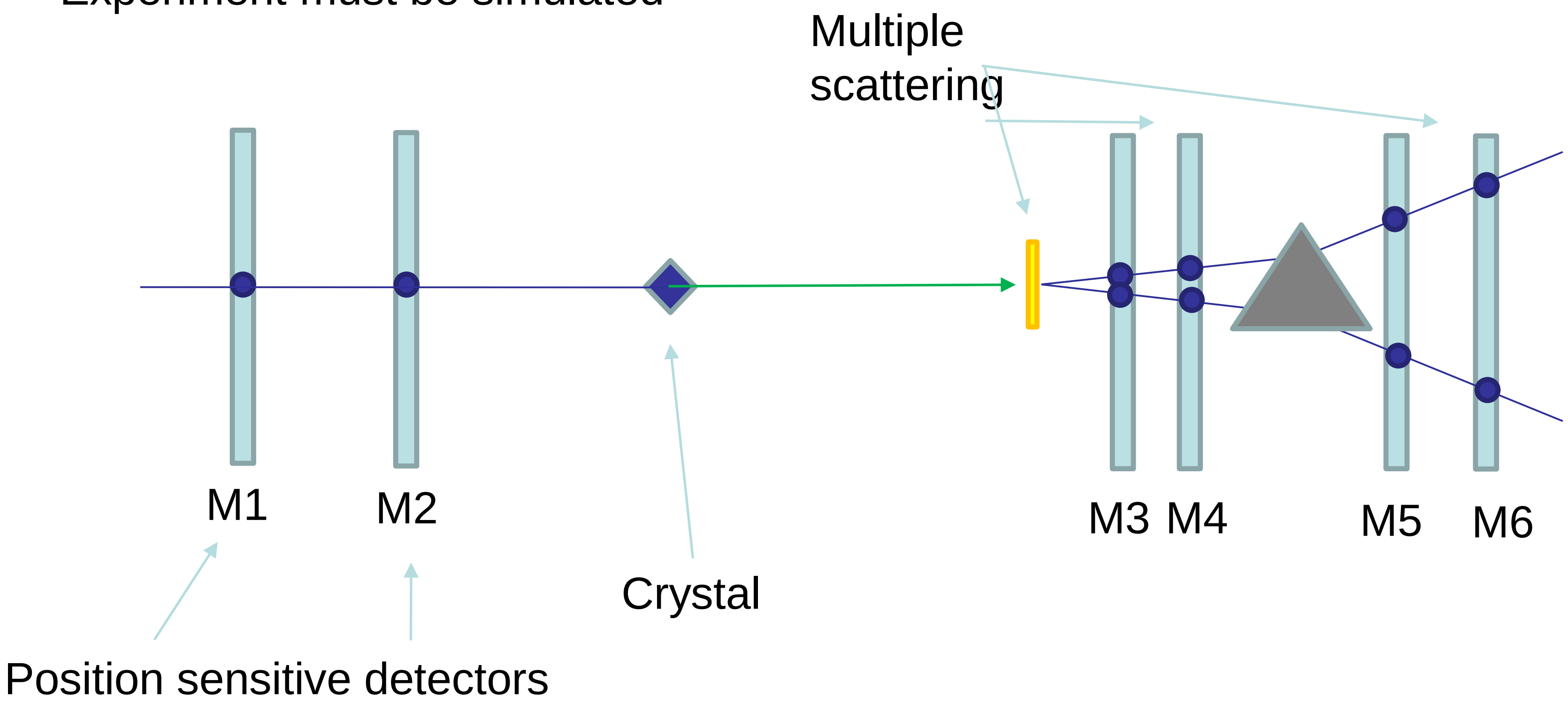
Designing the experiment.

- How does this setup measure photon energies?
- All you know is the position where some charged particles hit the detector



Designing the experiment.

- How does this setup measure photon energies?
- All you know is the position where some charged particles hit the detector
- Experiment must be simulated



Xtras

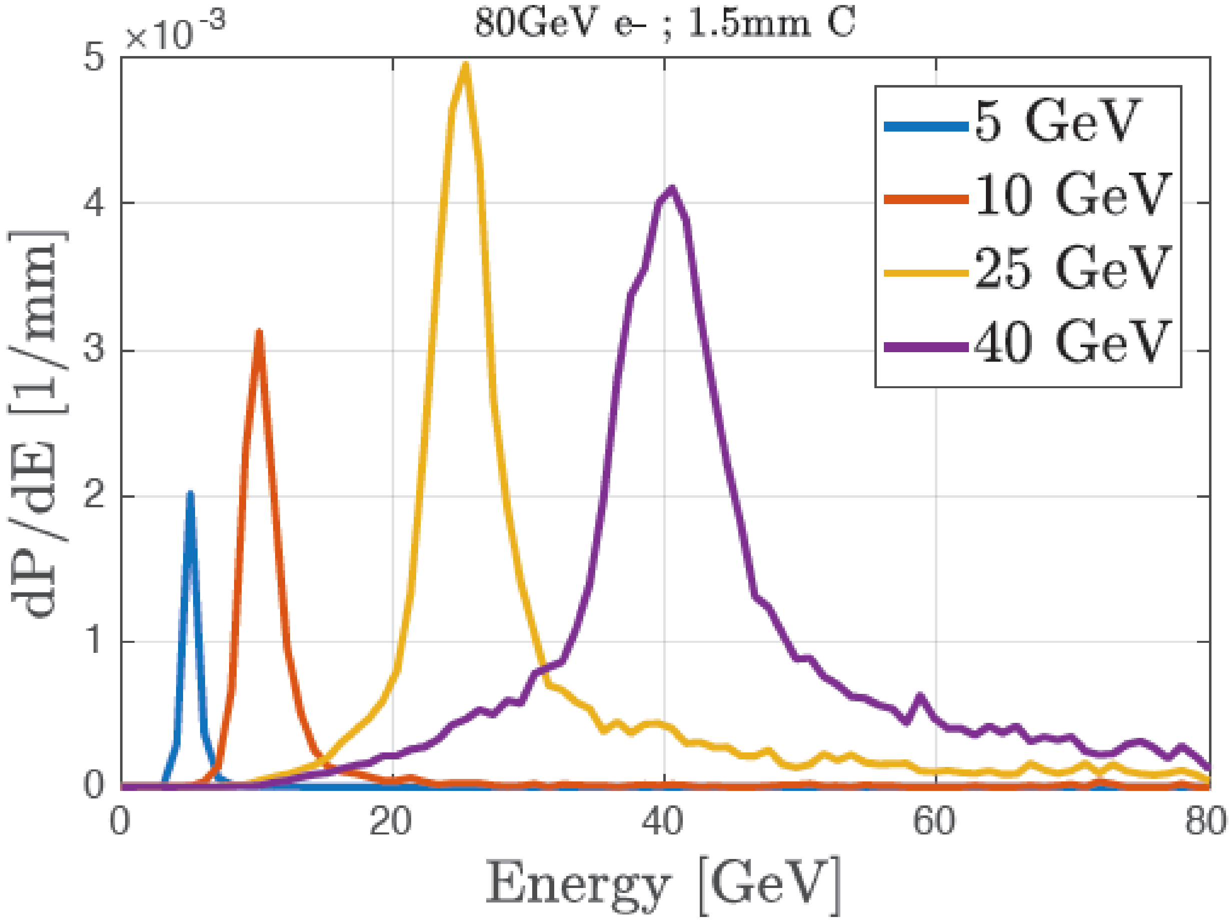


Figure 4.8: Simulations of the experiment assuming a monochromatic light source at 5 GeV (blue), 10 GeV (orange), 25 GeV (yellow) and 40 GeV (purple).