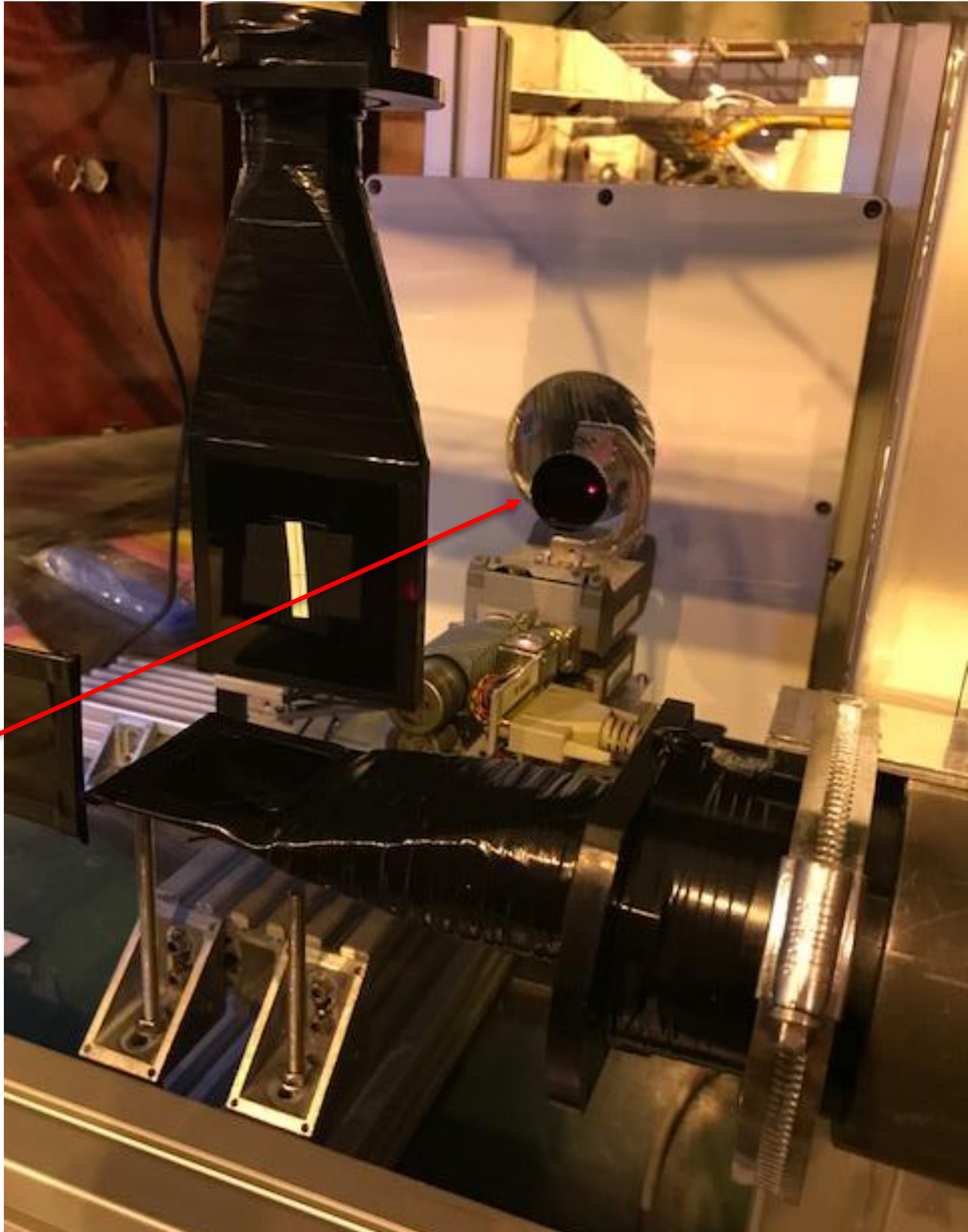
Status in 2020 and request for beamtime in 2021 for CERN NA63

Ulrik I. Uggerhøj
on behalf of NA63

NA63

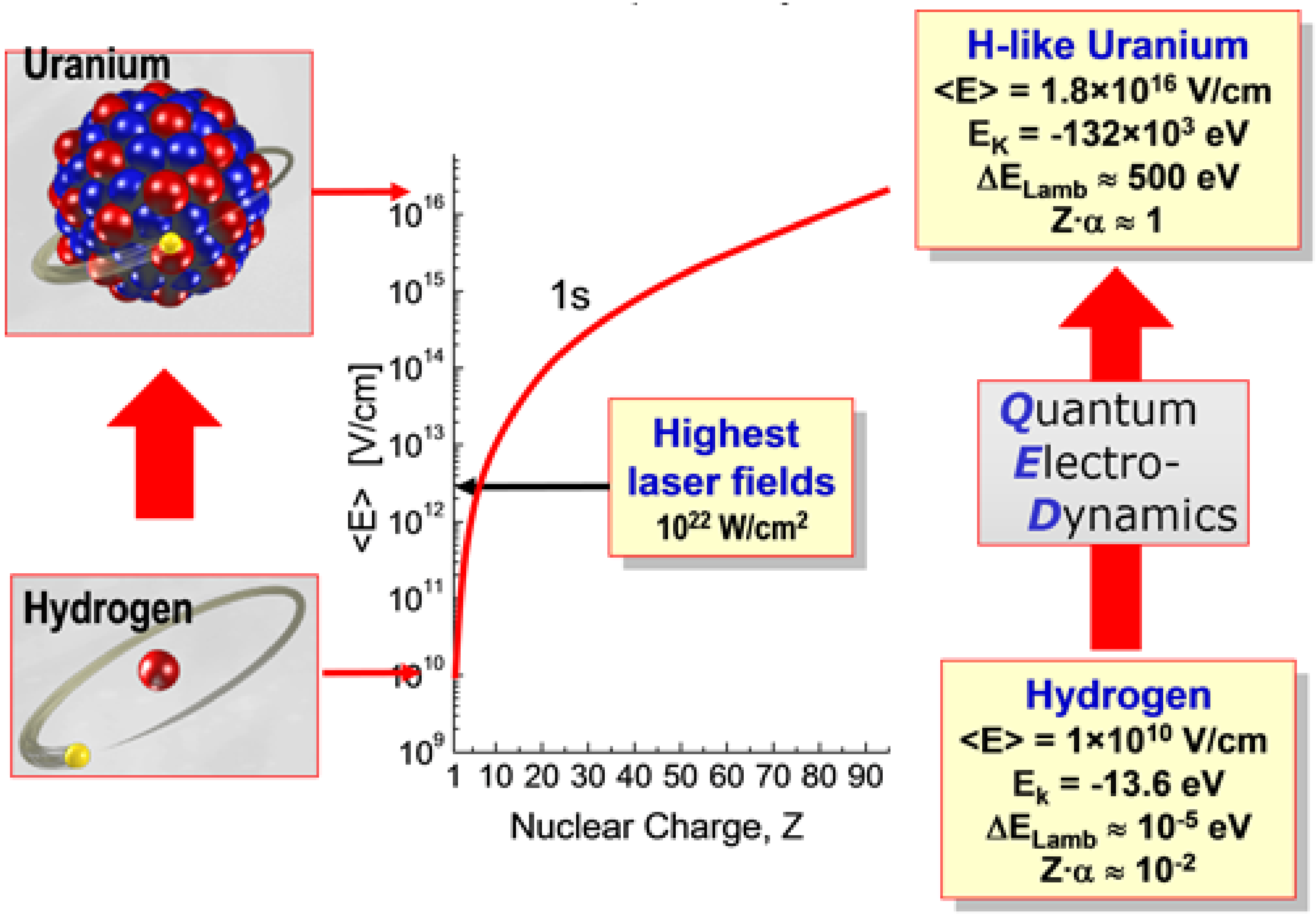
Strong field effects by means of crystals in GeV e^+/e^- beams



Strong fields

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

$$\mathcal{E}_0 = mc^2/e\bar{\lambda}_c = 1.32\cdot 10^{16}\ \text{V/cm}$$

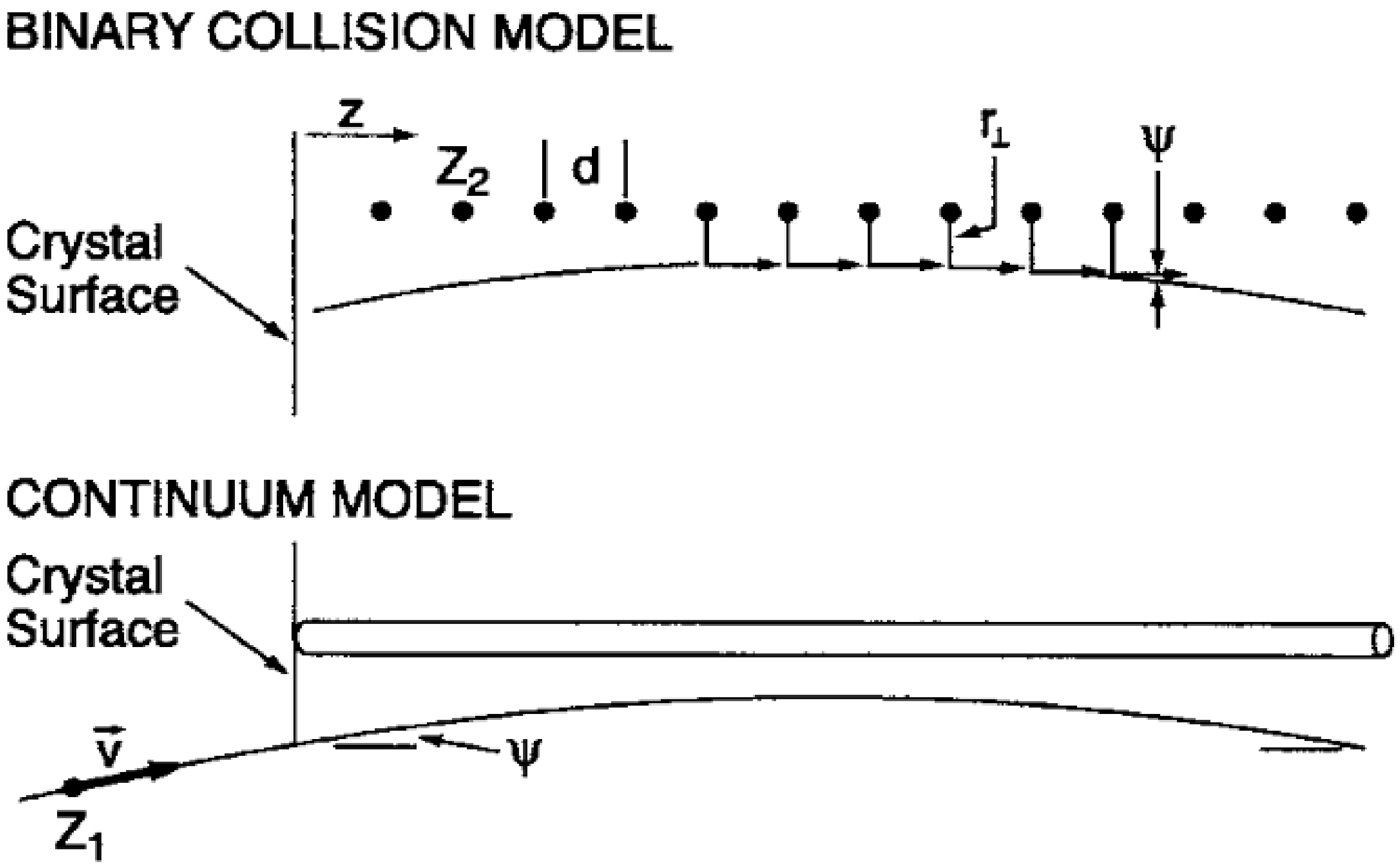


Picture from H.-J. Kluge, presented at the BriX workshop 2008, SCK•CEN, Mol, Belgium

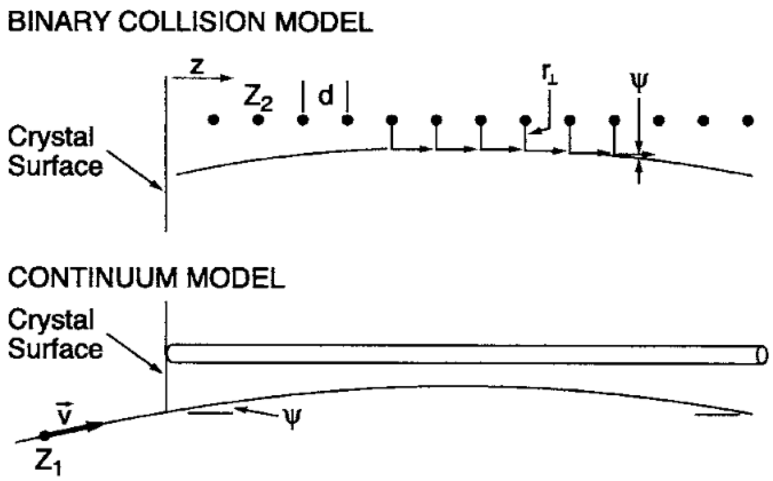
Crystals as a source of strong fields

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

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



Crystals as a source of strong fields



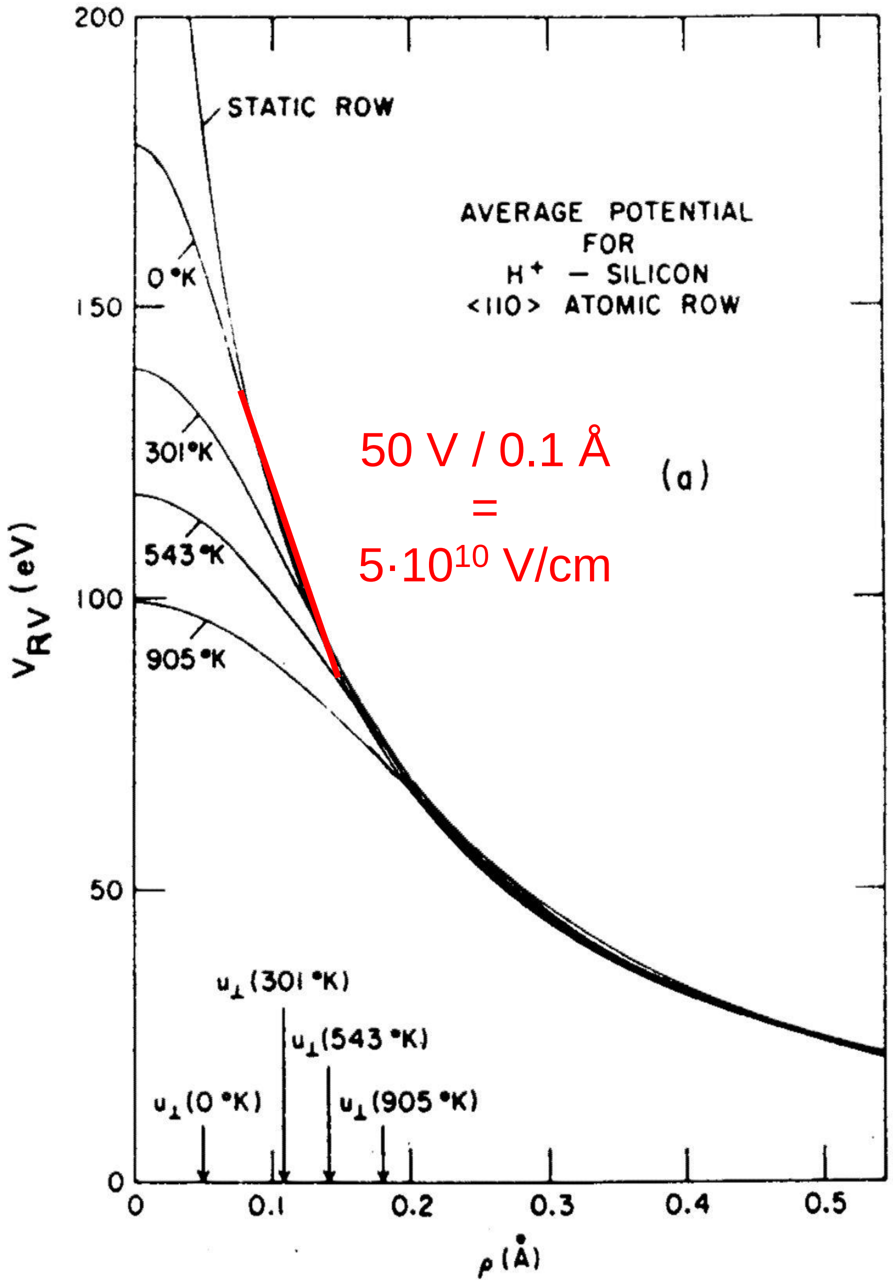
Extremely strong electric fields

10^{10}-10^{11} V/cm

Relativistic invariant: $\chi = \frac{\gamma \mathcal{E}}{\mathcal{E}_0}$

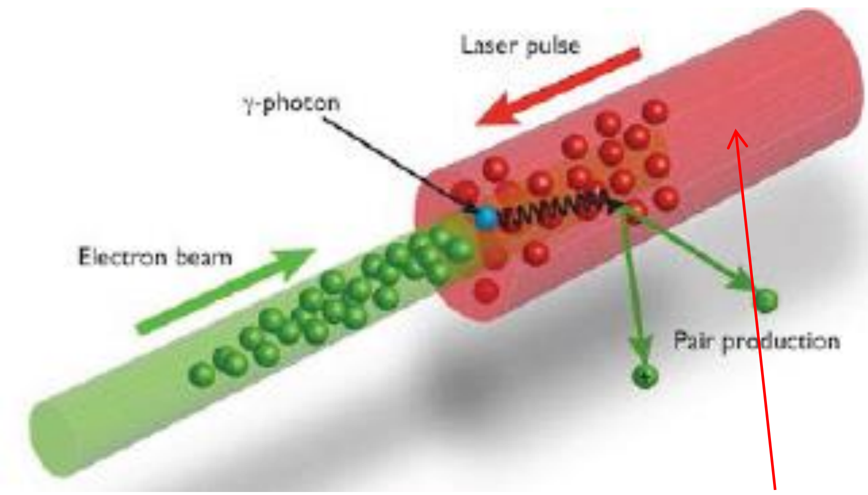
$$\mathcal{E}_0 = mc^2 / e\lambda\!\!\!^{-}_c$$

=$1.32 \cdot 10^{16}$ V/cm



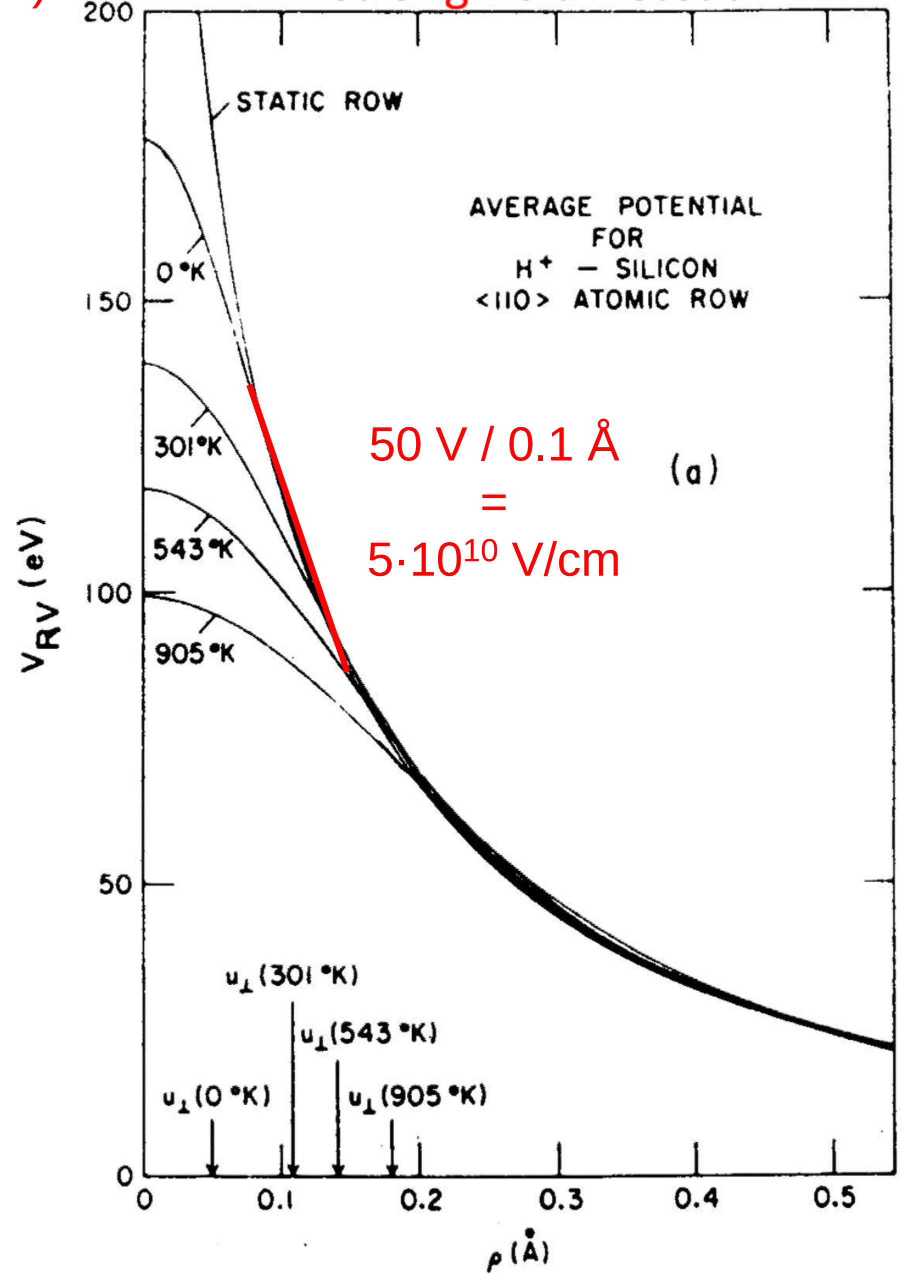
SLAC E-144 (mid-90’s, 1 TW laser)
SLAC E-320 (almost ready to run, 10 TW laser)
LUXE @ DESY (ready in 2022, 30 TW laser)

Why not use a constant strong field instead?



Crystals:

Replace laser-pulse by virtual photons



Extremely strong electric fields

10^{10}-10^{11} V/cm

$$\chi = \gamma \mathcal{E} / \mathcal{E}_0$$

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

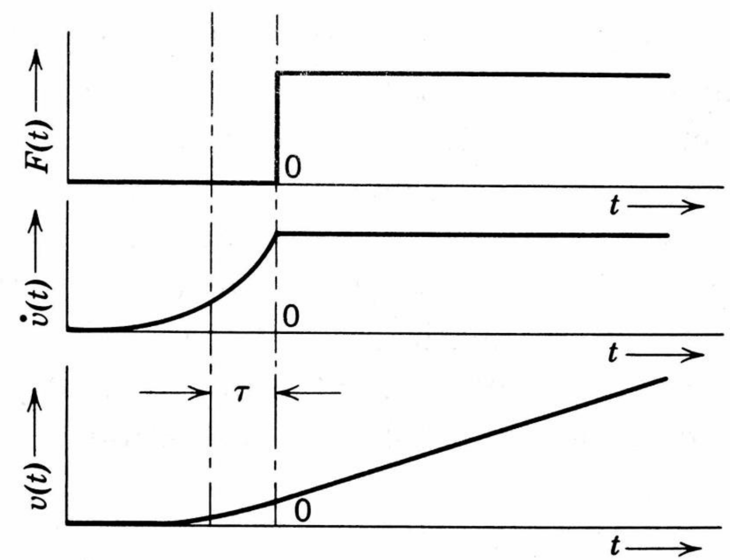


Fig. 17.1 "Preacceleration" of charged particle.

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: $\chi < 0.1$

MIMOSA-26 detectors

(M. Winter, Strasbourg)

Vertex detectors for CLIC (?)

CMOS-based position sensitive detectors

1152 columns of

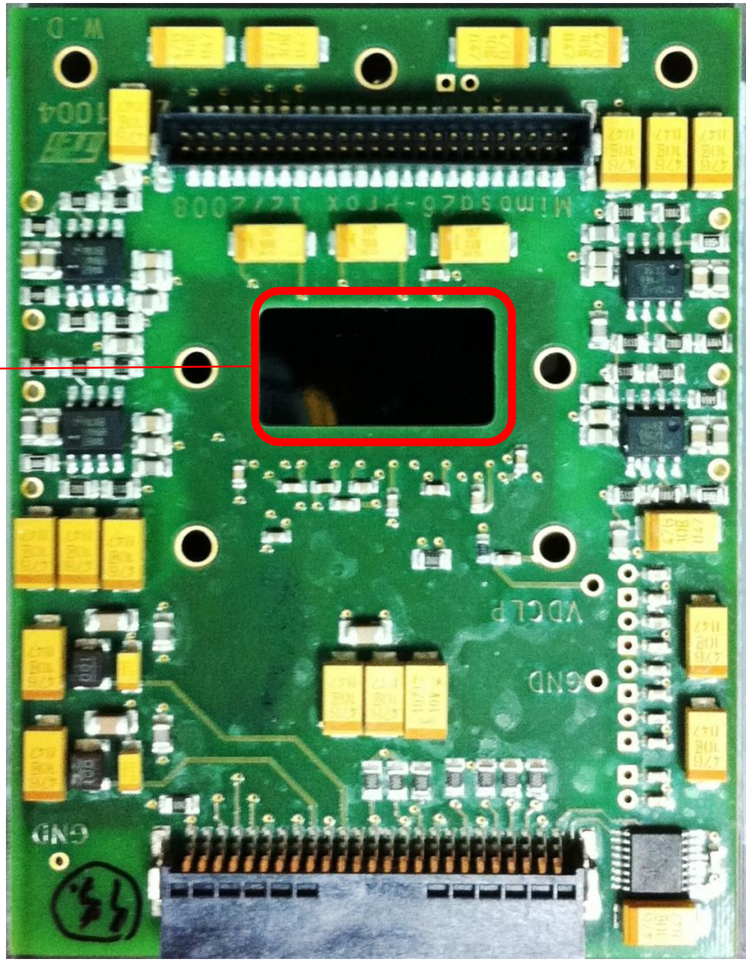
576 pixels, $\simeq$ 18.4 μm pitch

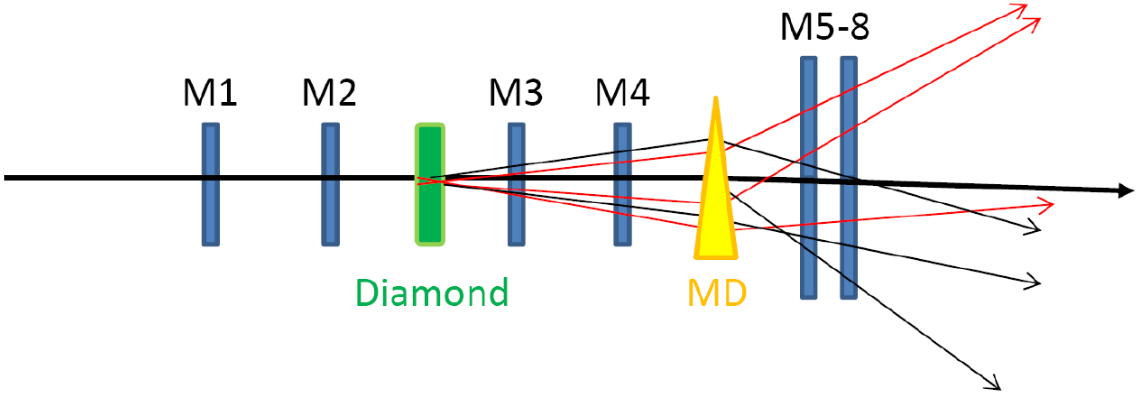
true multi-hit capability

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

$1 \times 2\ \mathrm{cm}^2$

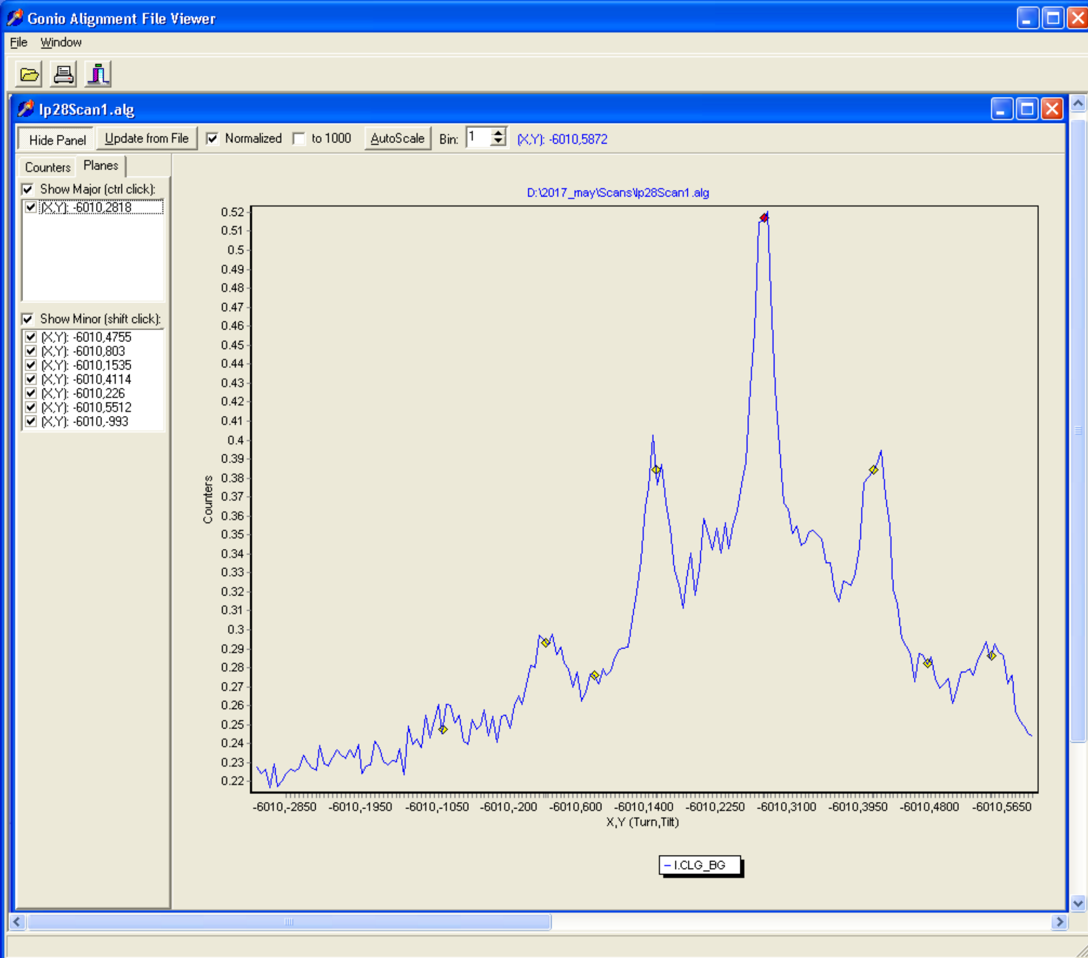
10 k frames/s, resolution 3.5 µm

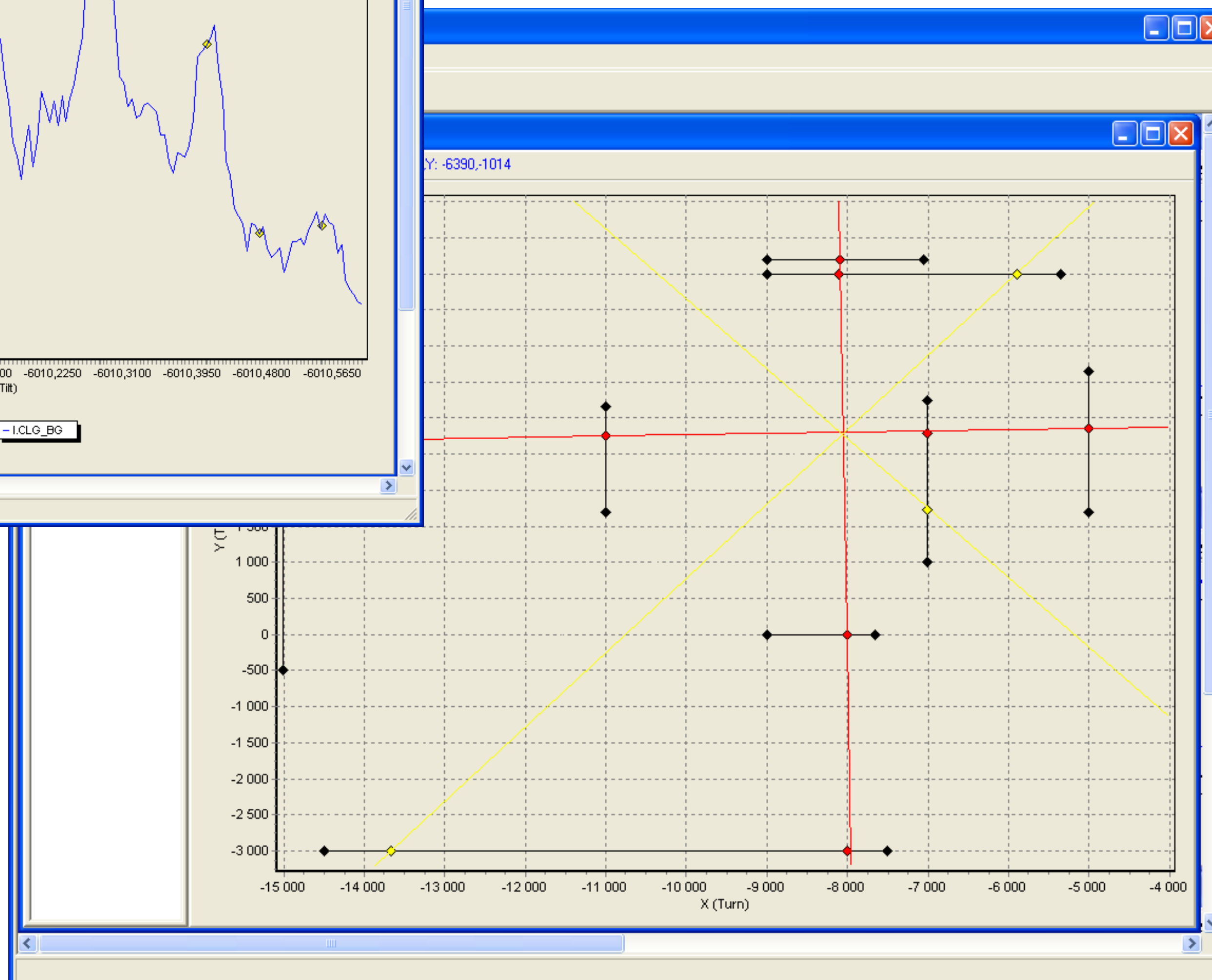




Crystal planar alignment

Lindhard critical angle @ 50 GeV: 23 microrad

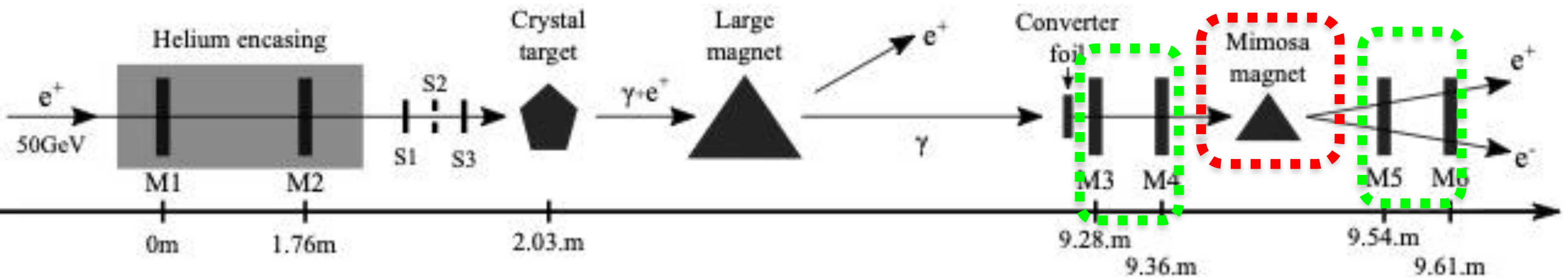




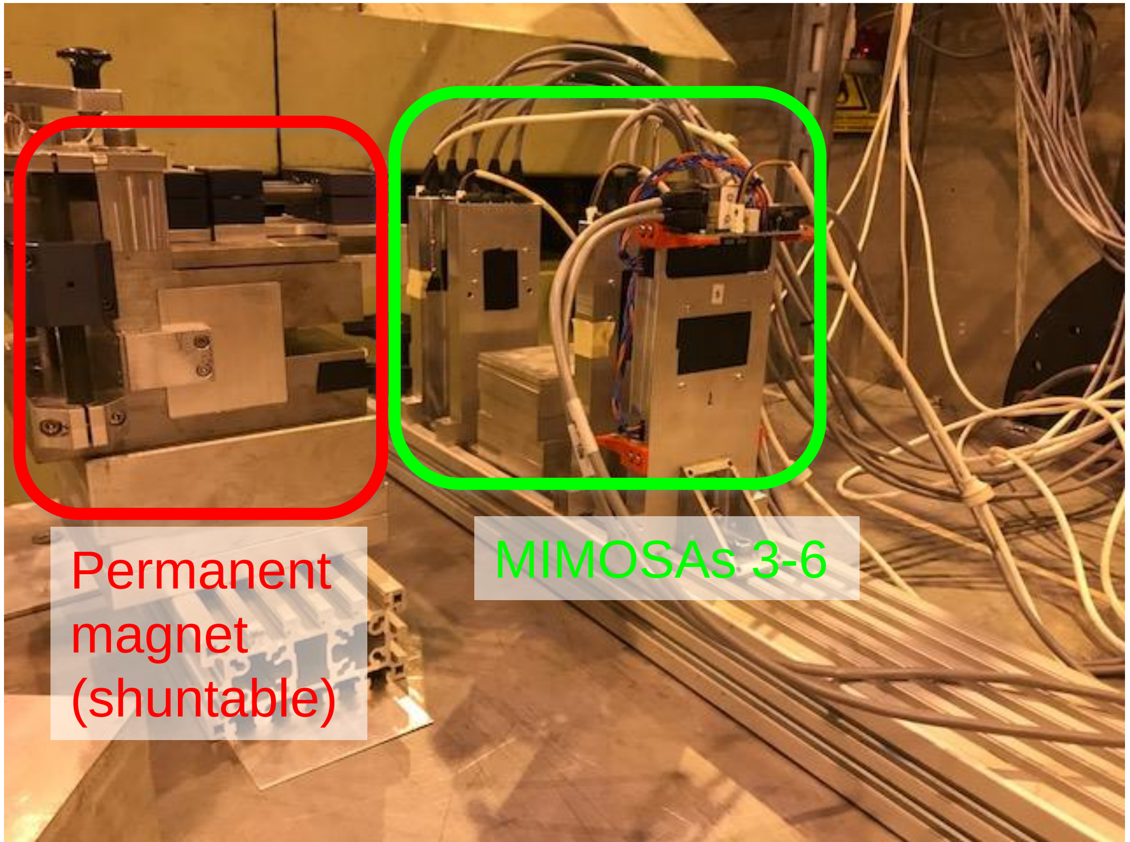
Crystals prealigned with x-rays

2017 data (planar case)

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



Example of results, silicon (2017 data)

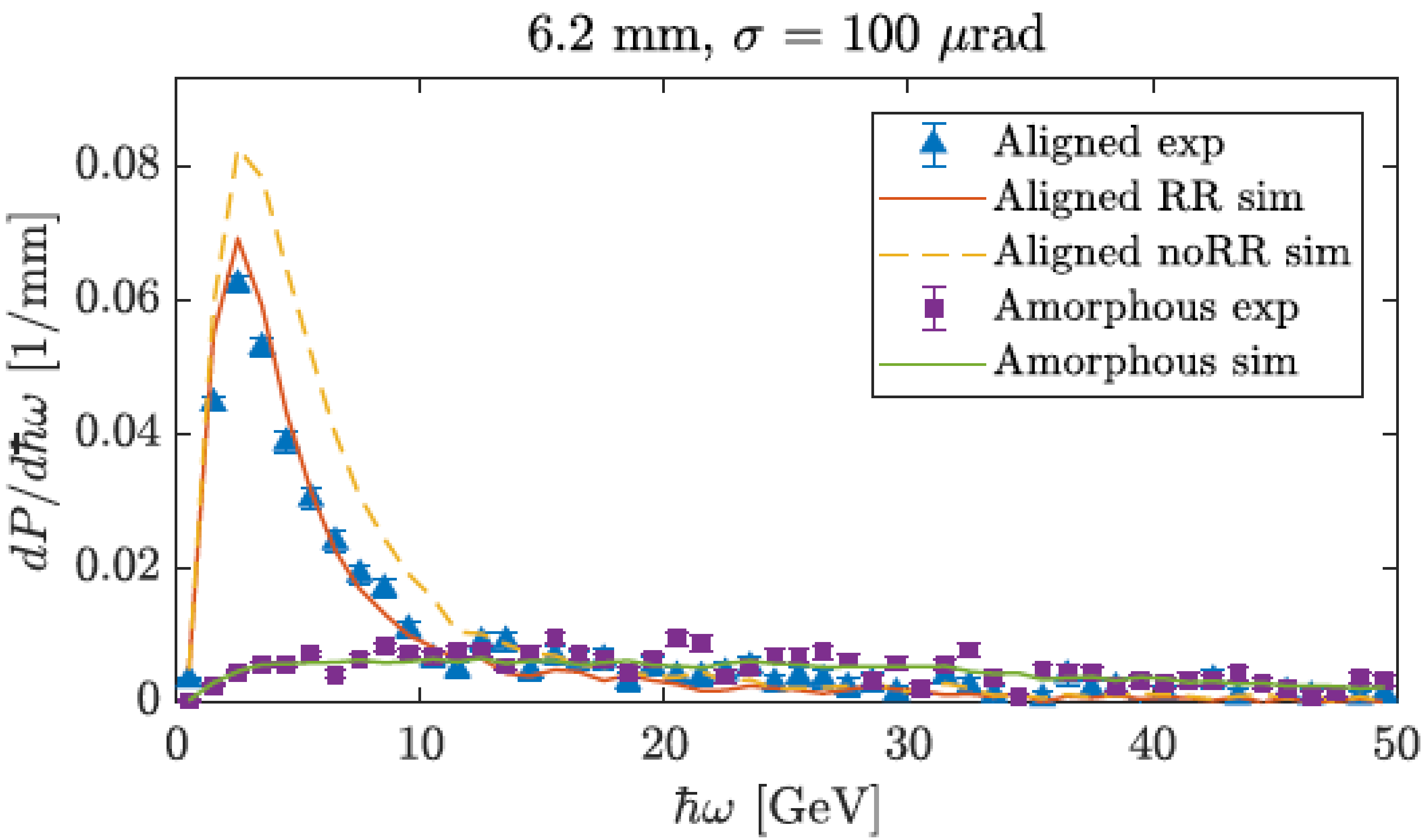


Figure 4: Radiation power spectra obtained for 50 GeV positrons passing 1.1, 2.0, 4.2 and 6.2 mm thick silicon crystals aligned to the (110) plane, and the corresponding amorphous spectra. These spectra has angular cuts, meaning that only particles with entry angle between $\pm$ 30 μrad with respect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

Crystal	Energy	ψ_1	Θ_B
C $\langle 100 \rangle$	40 GeV	50 μrad	175 μrad
	80 GeV	35 μrad	
Si (110)	50 GeV	23 μrad	45 μrad

Substitution method takes account of quantum recoil:

$$\omega \to \omega^* = \omega/(1 - \hbar\omega/E)$$

Correction for quantum suppression of synchrotron radiation:

$$G(\chi) = \left[1 + 4.8(1+\chi)\ln(1+1.7\chi) + 2.44\chi^2\right]^{-2/3}$$

confirmed by:

PHYSICAL REVIEW D 86, 072001 (2012)

Experimental investigations of synchrotron radiation at the onset of the quantum regime

K. K. Andersen,[1] J. Esberg,[1] H. Knudsen,[1] H. D. Thomsen,[1] U. I. Uggerhøj,[1] P. Sona,[2] A. Mangiarotti,[3] T. J. Ketel,[4] A. Dizdar,[5] and S. Ballestrero[6]

(CERN NA63)

Example of results, diamond (2018 data)

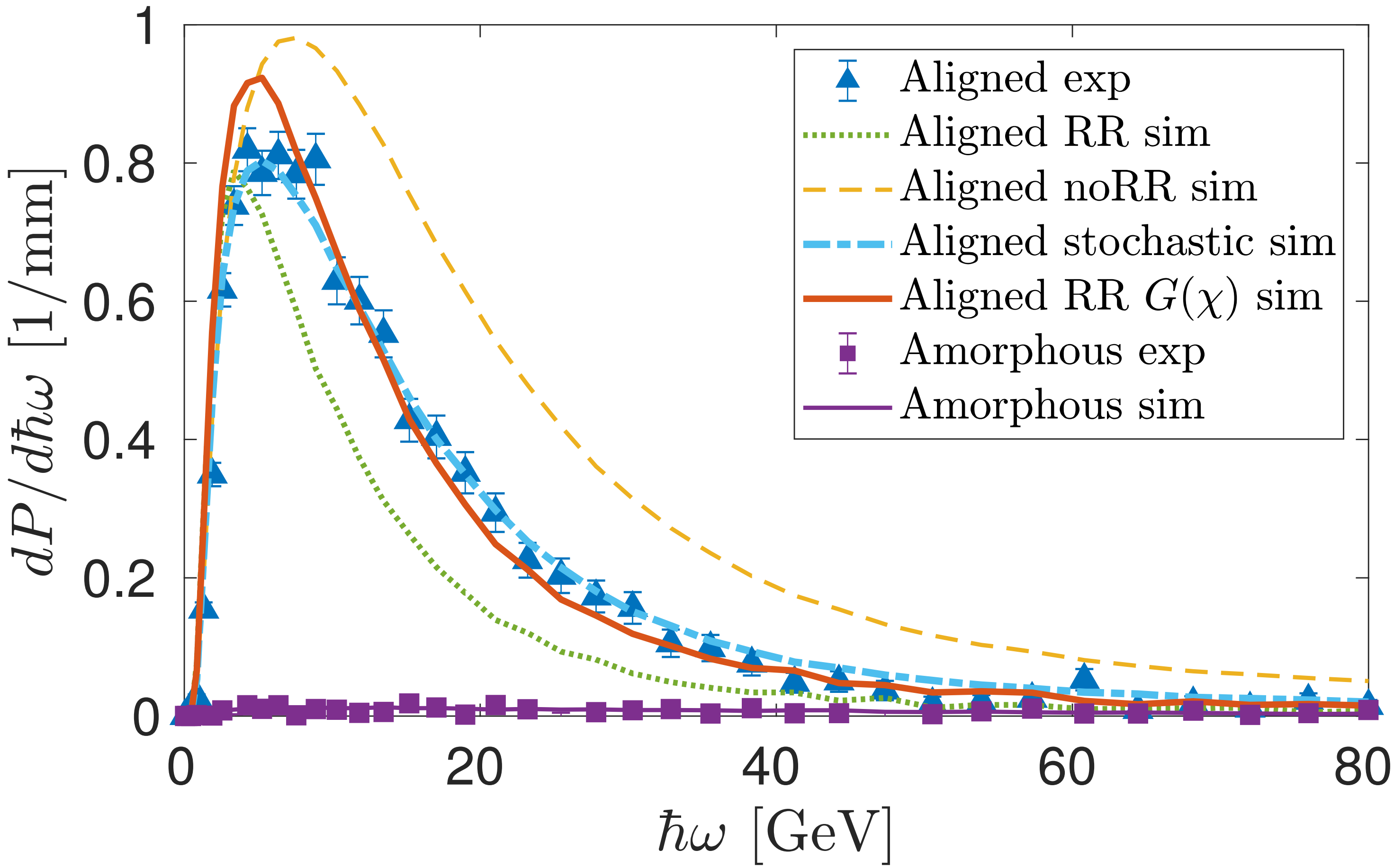
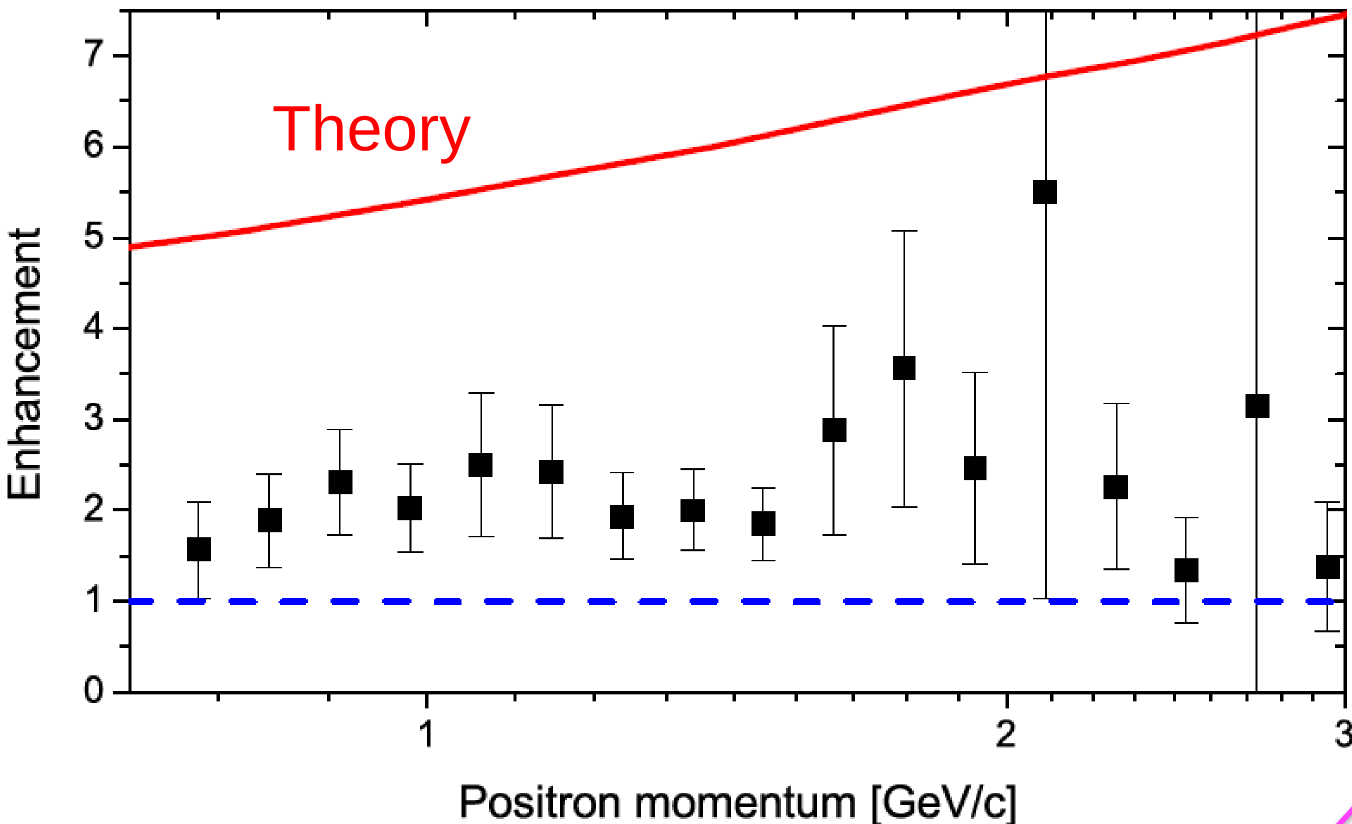
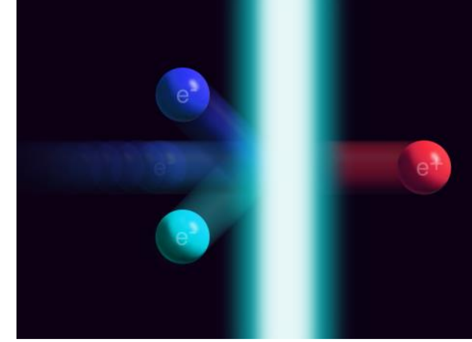


Figure 2: Radiation power spectra obtained for 80 GeV (right) electrons traversing a 1.5 mm (top) thick diamond crystal aligned to the $\langle 100 \rangle$ axis, and the corresponding amorphous spectra. This spectrum has angular cuts, meaning that only particles with entry angle less than ψ_1 with respect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

Trident enhancement in strong field





Significant discrepancy!

Found in the framework of NA63

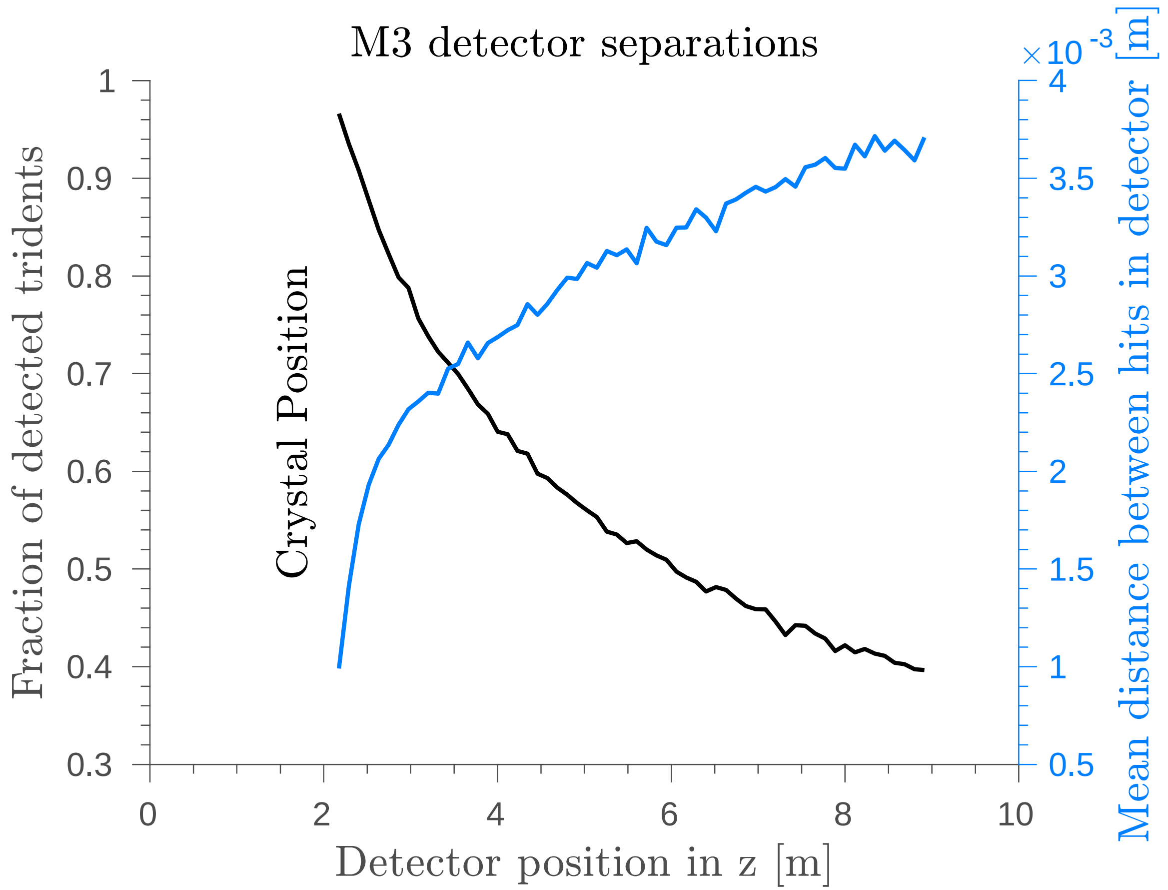
PHYSICAL REVIEW D 82, 072002 (2010)

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]

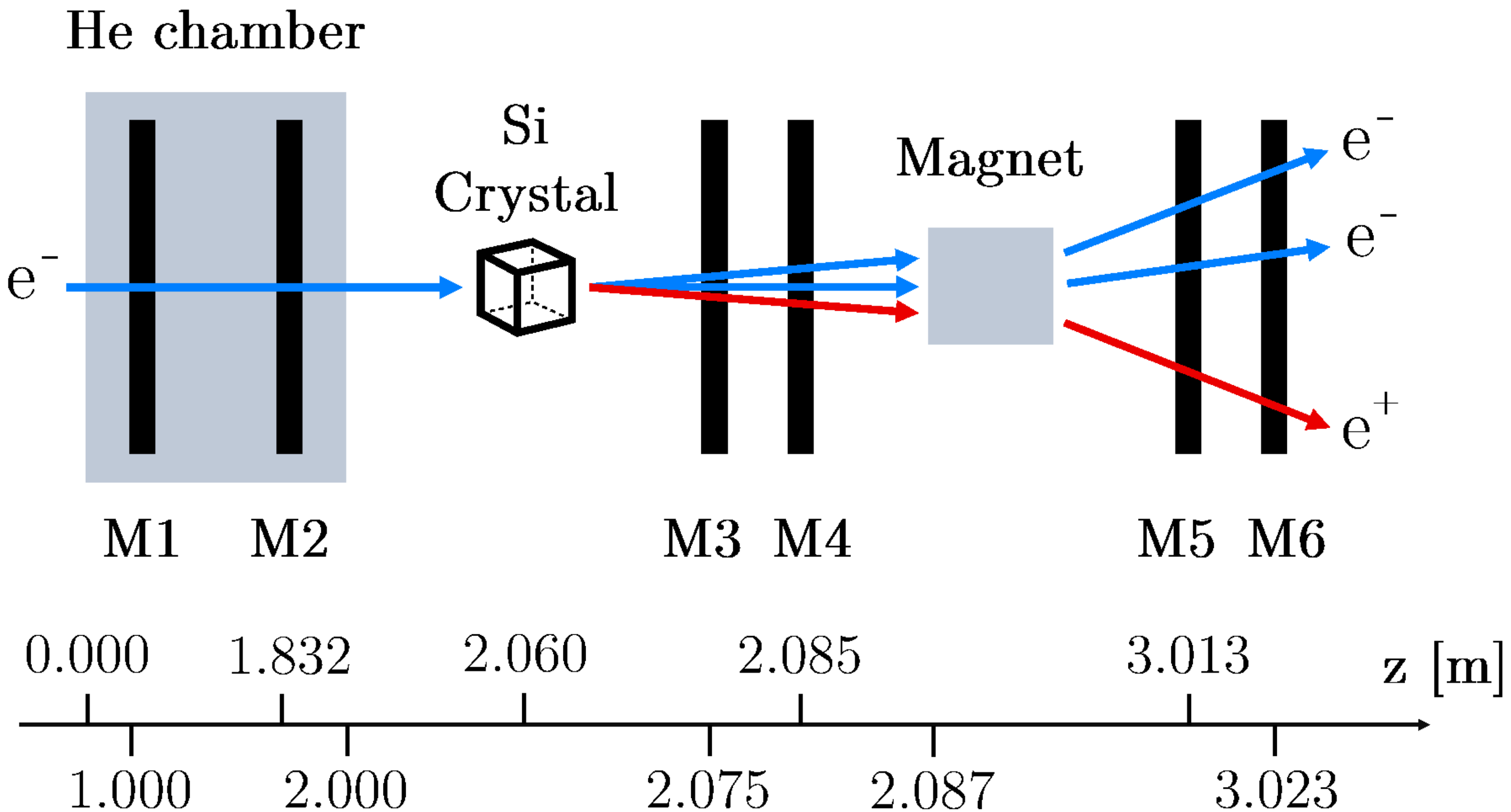
(CERN NA63)

Beam request for 2021: 2 weeks in SPS H4



An example of simulations performed to optimize setup

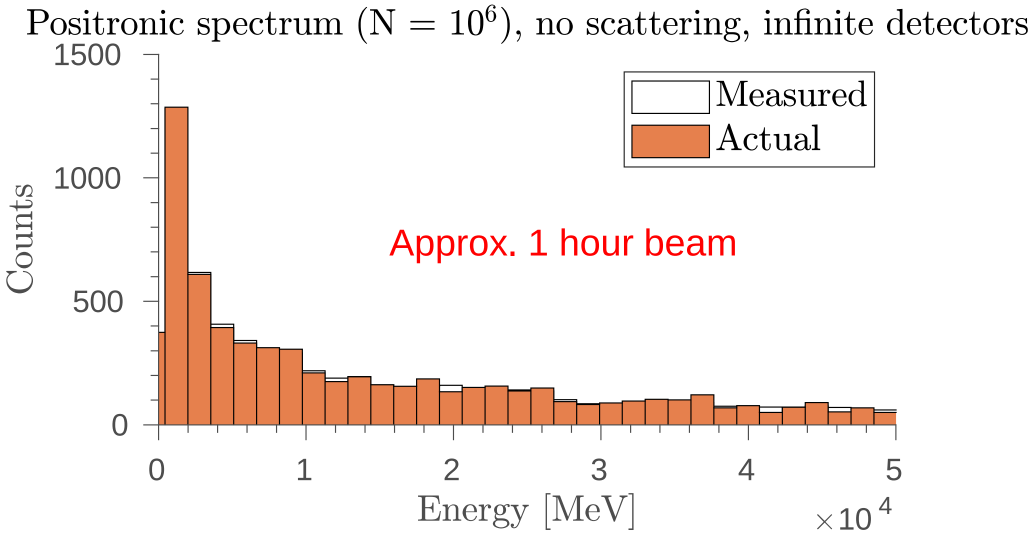
Beam request for 2021: 2 weeks in SPS H4

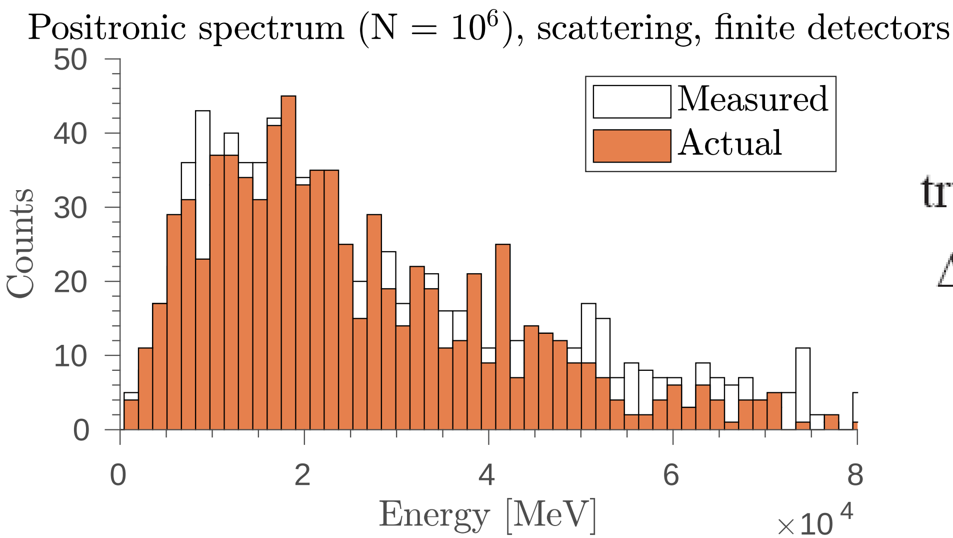


Significant improvements since 2009: MIMOSAs instead of drift chambers

- Factor 40 better resolution
- True multi-hit capability
- Much more compact setup (4 m instead of 80 m, less scattering)

Beam request for 2021: 2 weeks in SPS H4 to (re-)measure trident process





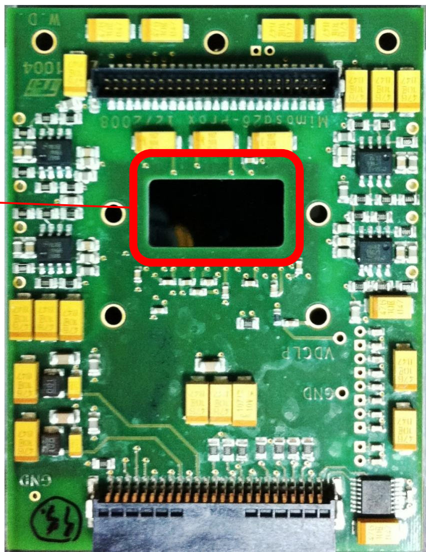
4 days for setting up
10 days run-time

- 3 xtal thicknesses, each takes 12 hrs. to get aligned + no target
- Possibility for off-line cuts in angles and position

true multi-hit capability

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

$1 \times 2\ \mathrm{cm}^2$



10 k frames/s,
resolution 3.5 µm

2 papers ready for submission

(25 NA63 papers published + 1 in review, since 2008)

Under review 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:

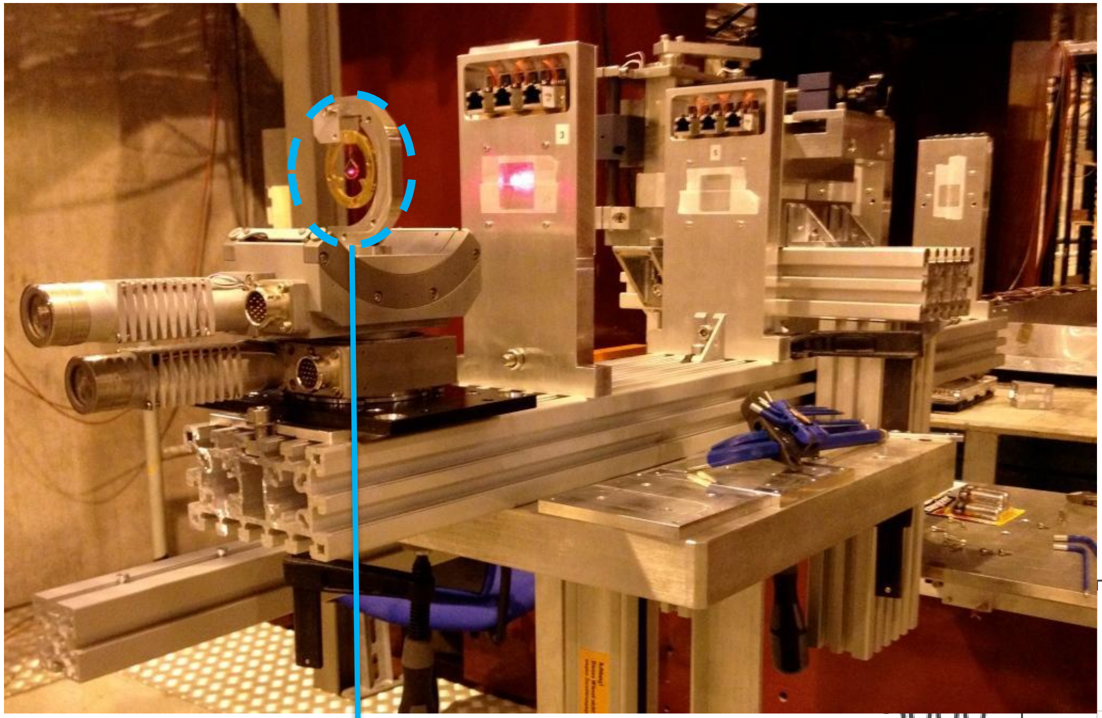
PHYSICAL REVIEW RESEARCH 1, 033014 (2019)

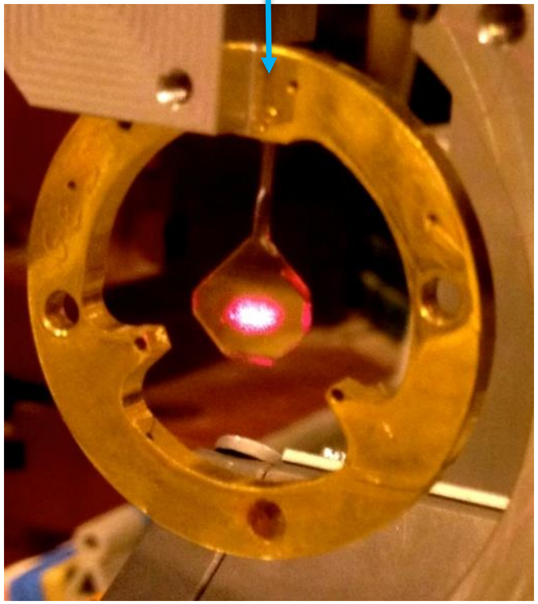
Quantum radiation reaction in aligned crystals beyond the local constant field approximation

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*

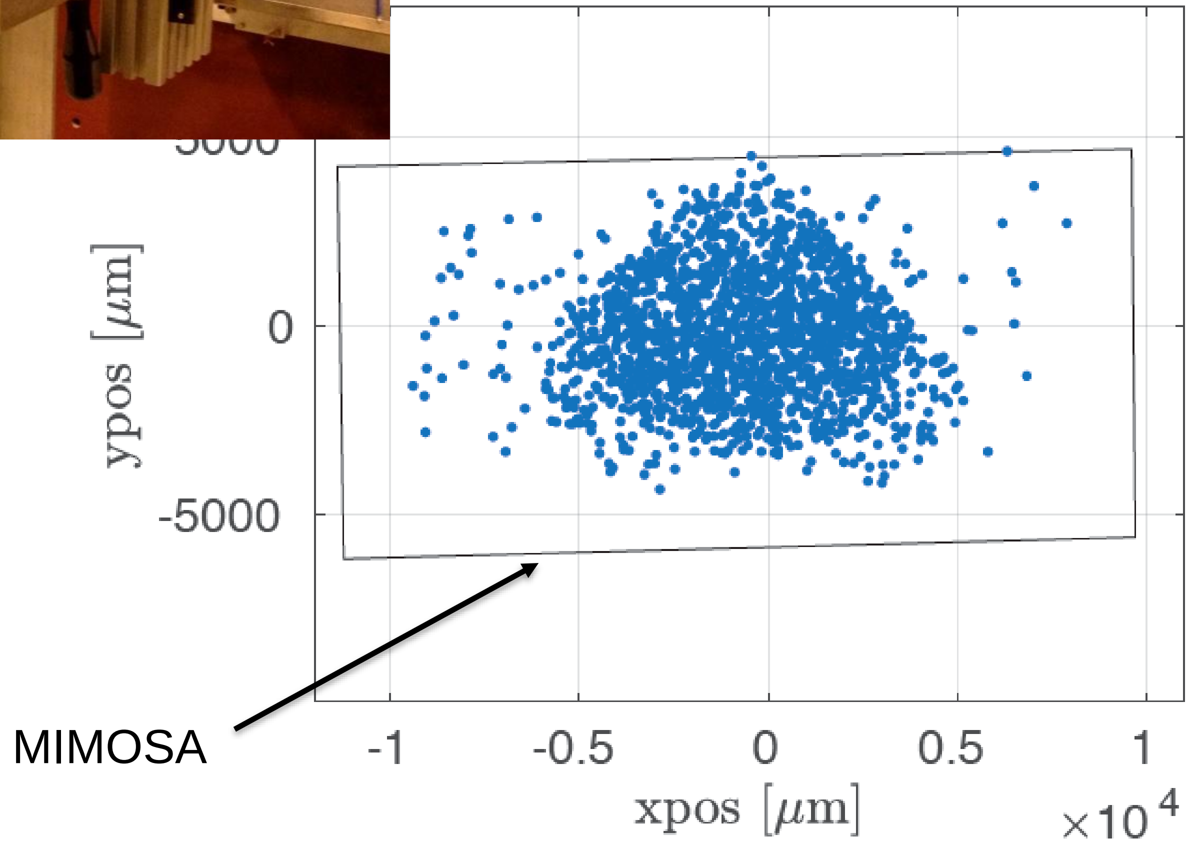
Scientific investigations in the framework of NA63 (full list of publications in report)

- 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





‘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:

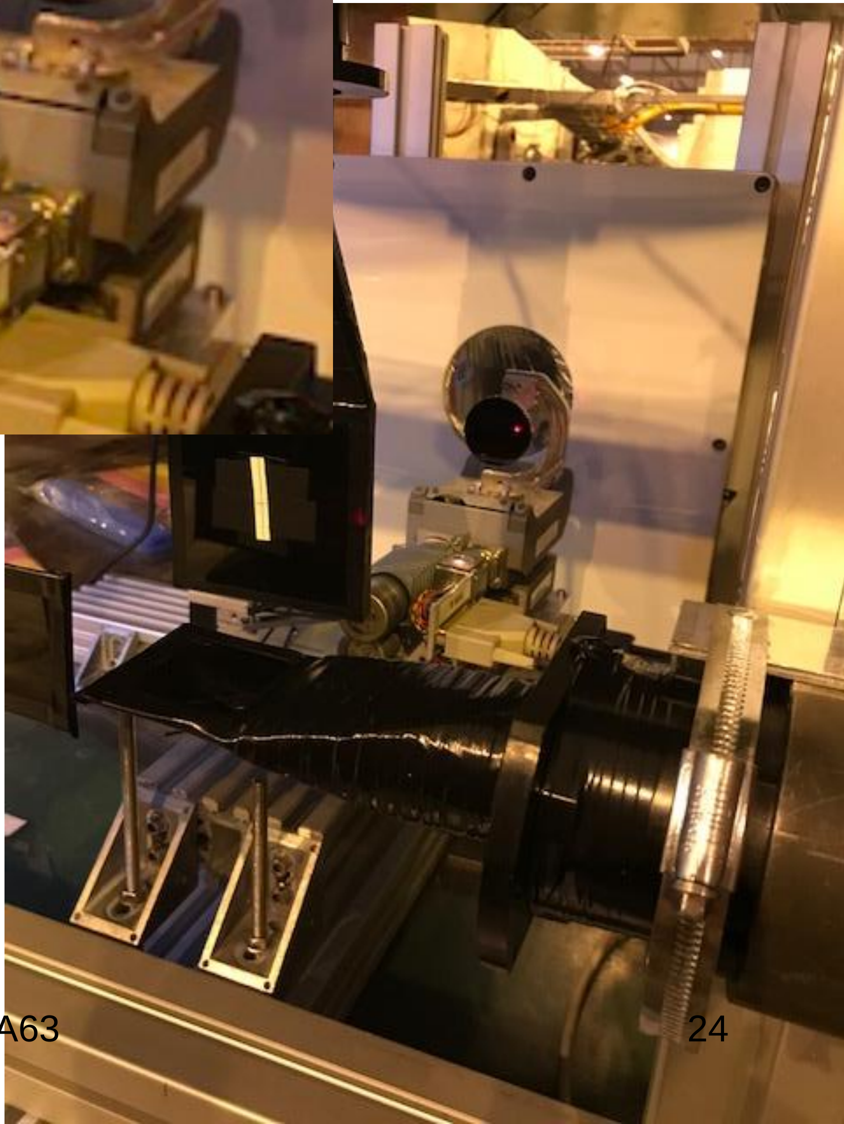
$$\boldsymbol{f} = \frac{2e^3}{3m}\gamma\left\{\left(\frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla\right)\boldsymbol{E} + \boldsymbol{v}\times\left(\frac{\partial}{\partial t} + \boldsymbol{v}\cdot\nabla\right)\boldsymbol{H}\right\} + \frac{2e^4}{3m^2}\left\{\boldsymbol{E}\times\boldsymbol{H}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

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

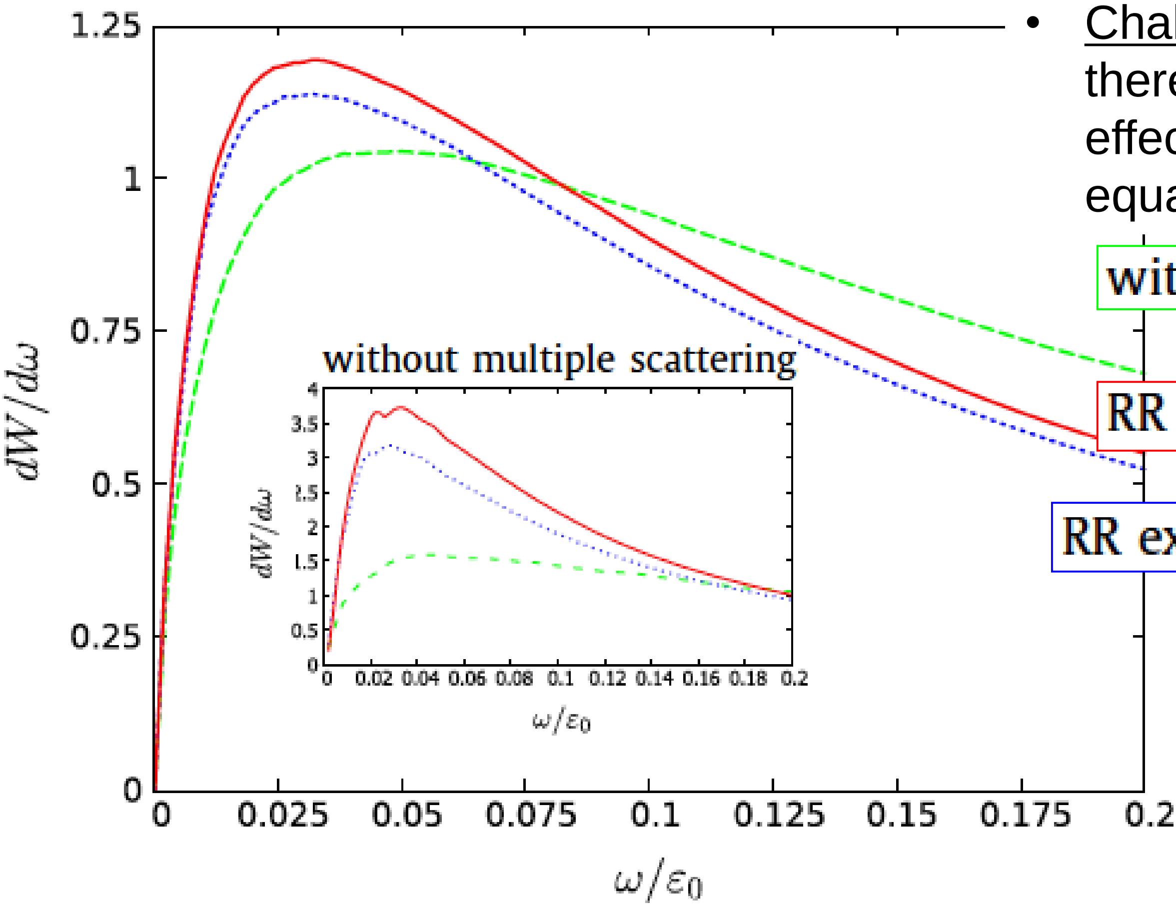


Investigation of classical radiation reaction with aligned crystals

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	$\overline{\chi}$	$\%E_{\rm LL}$	$\%E_{\rm LL,G(\chi)}$
C $\langle 100 \rangle$	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%

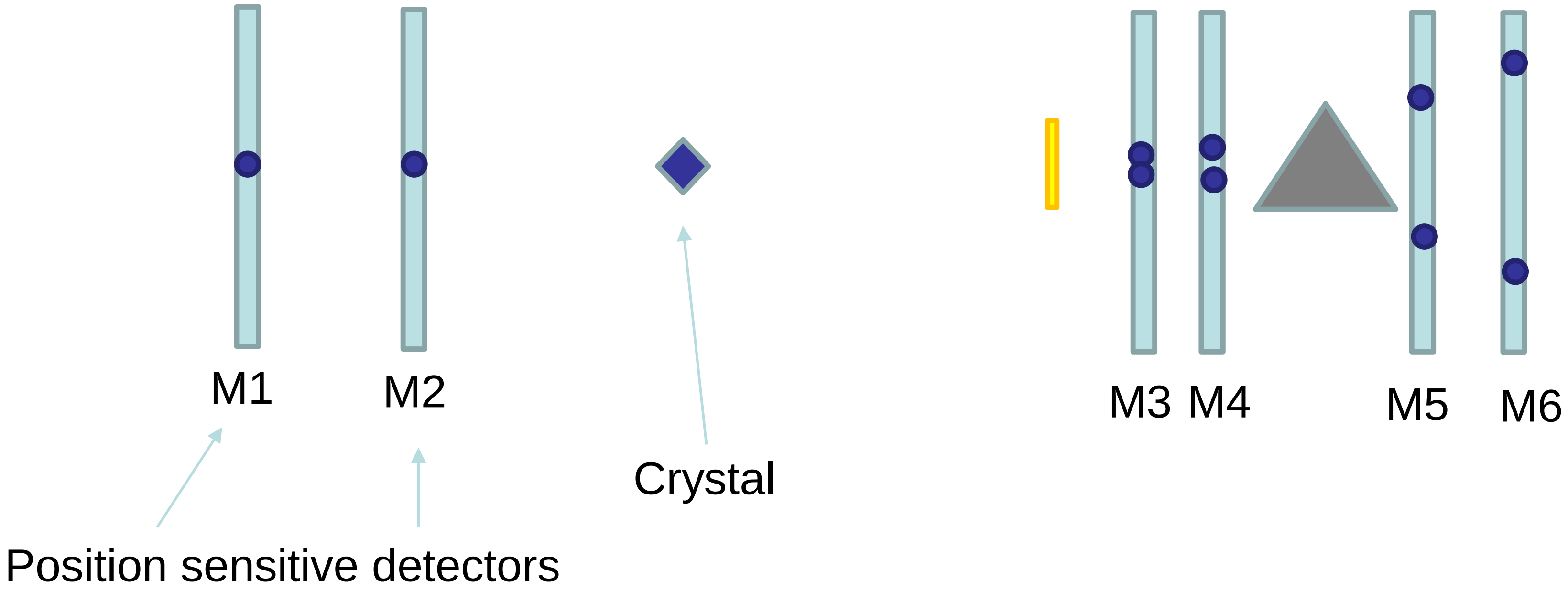
ratio of damping force to external force

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

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.

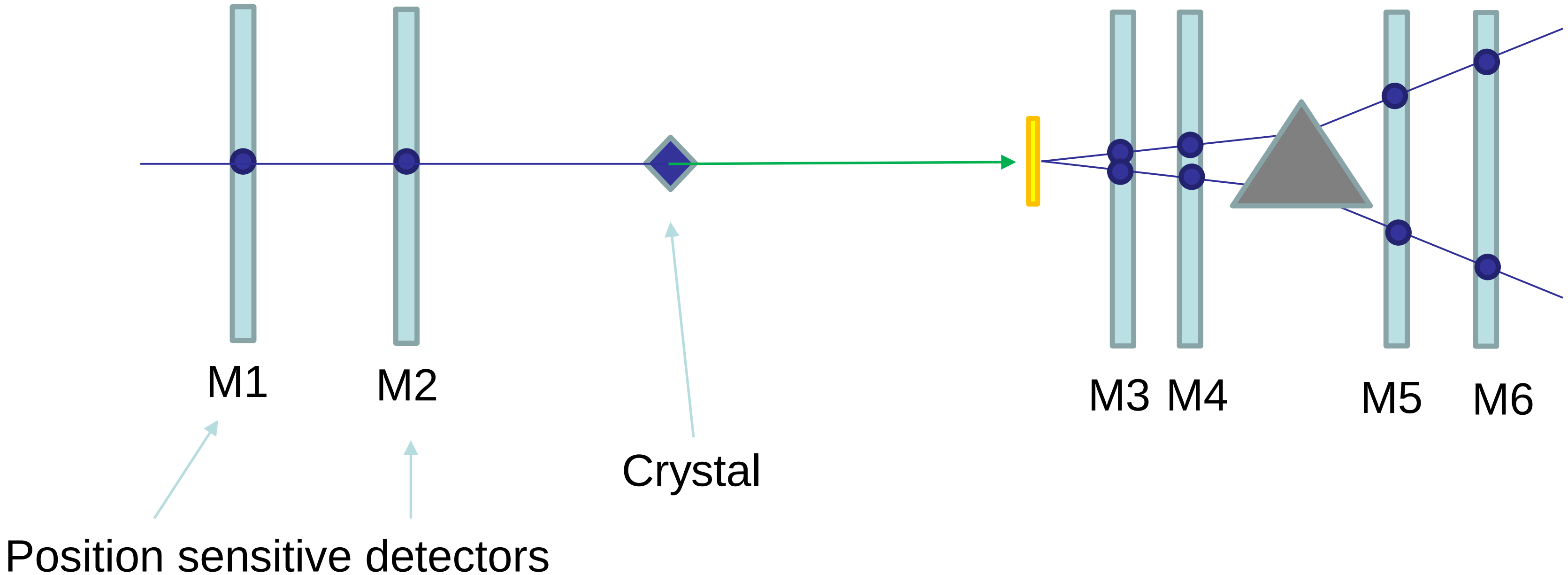
The experimental setup

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



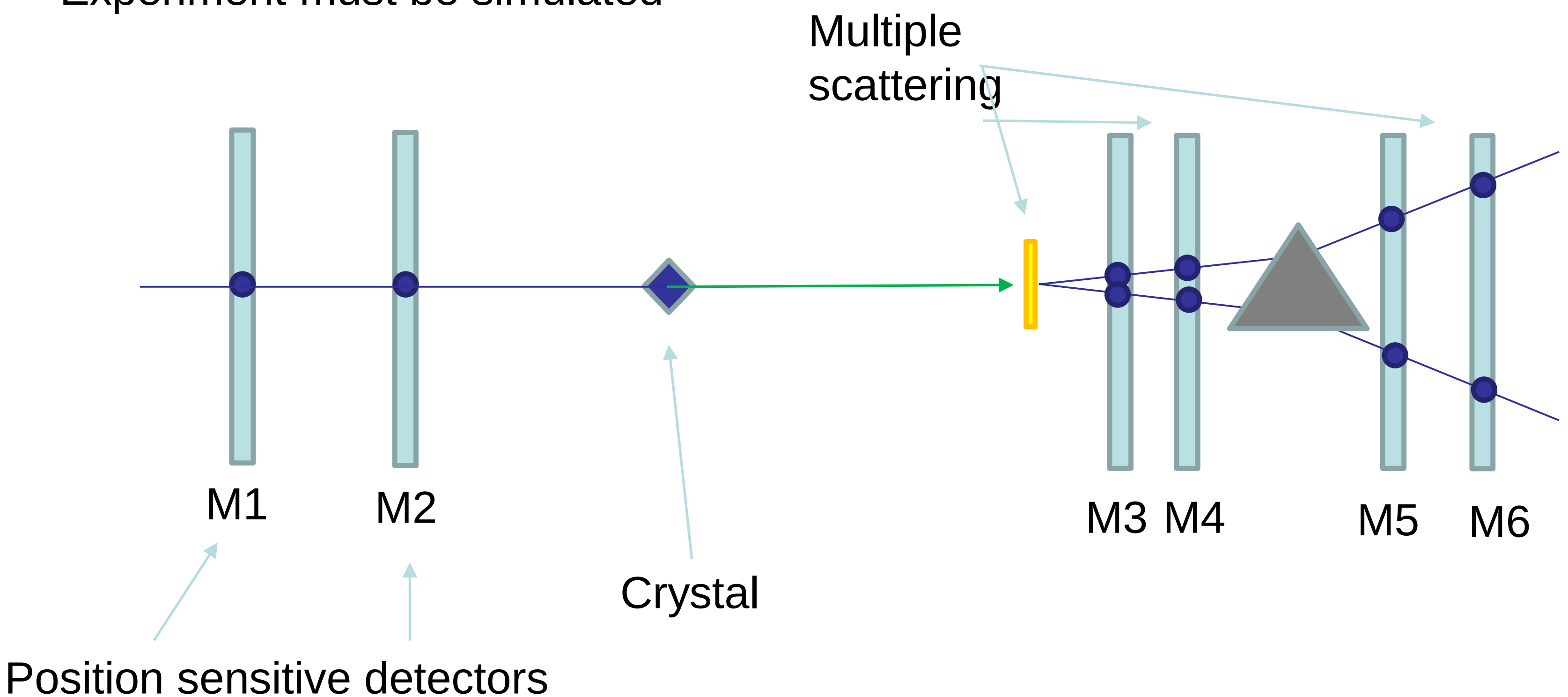
Designing the experiment.

- 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

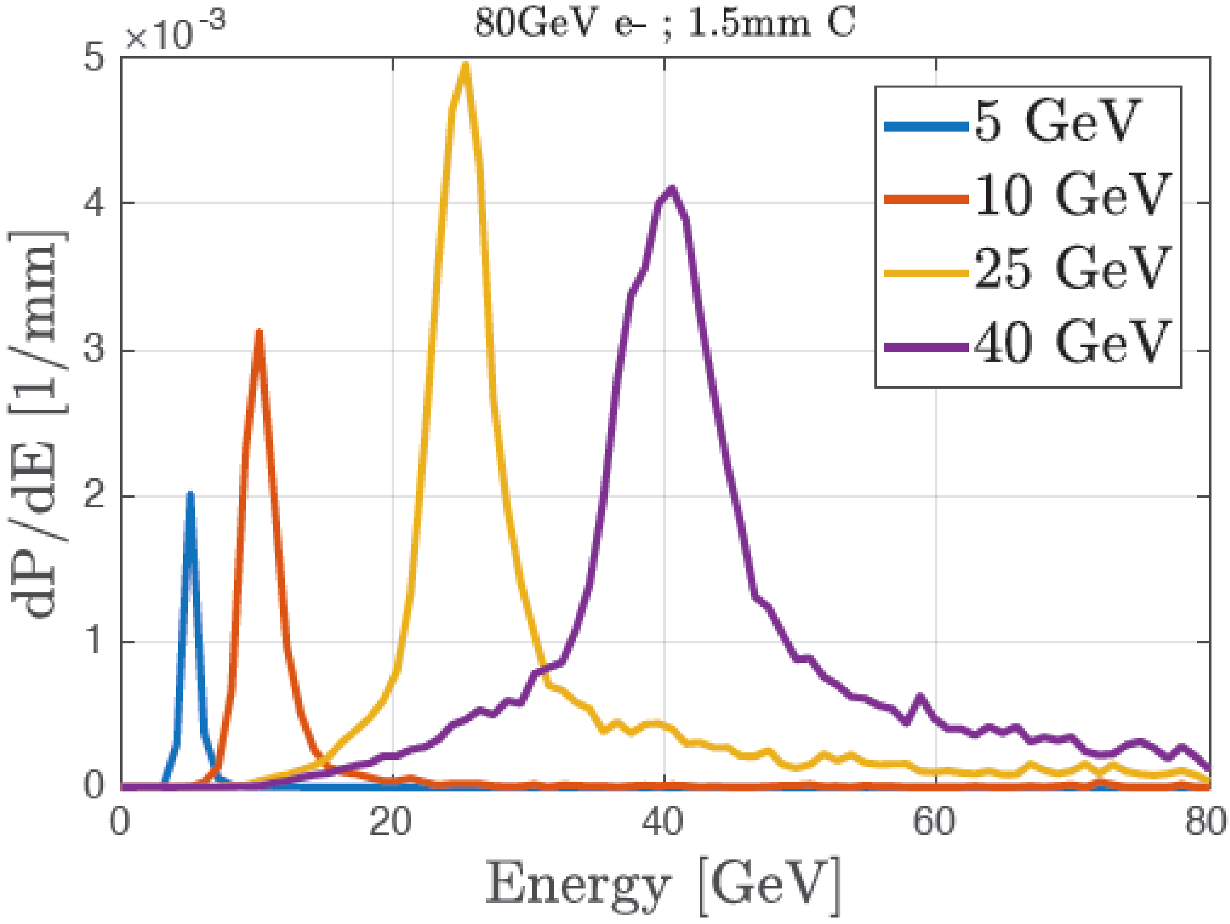


Figure 4.8: Simulations of the experiment assuming a monochromatic light source at 5 GeV (blue), 10 GeV (orange), 25 GeV (yellow) and 40 GeV (purple).