Status and plans of the NA63 experiment

Tobias N. Wistisen
on behalf of NA63

Outline

- Classical radiation emission.
- Channeling as a way to investigate radiation reaction.
- CERN NA63 2016 experiment on quantum radiation reaction.
- CERN NA63 2017 experiment on classical radiation reaction.
- CERN NA63 2018 experiment on the Schott term in classical radiation reaction.
- Ideas for experiments in the future.

Classical radiation emission

- Classical radiation emission refresher $$\boldsymbol{S} = \frac{1}{4\pi}\boldsymbol{E} \times \boldsymbol{B}$$
- From this we obtain the emitted energy differential in solid angle and frequency as

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

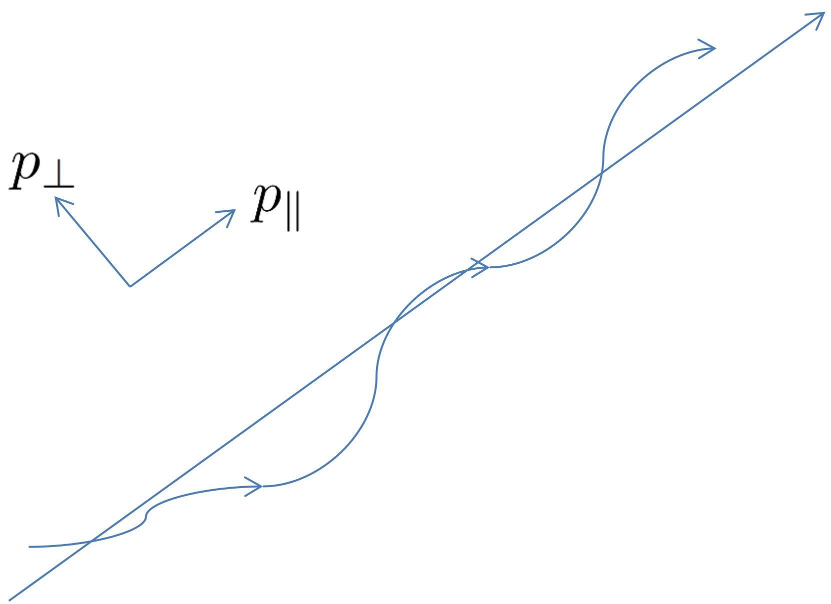
where

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

- So the radiation is obtained from the motion.
- Total instantaneous power $$P = \frac{2}{3} e^2 \gamma^6 \left[(\dot{\boldsymbol{v}})^2 - (\boldsymbol{v} \times \dot{\boldsymbol{v}})^2\right]$$

Classical radiation emission

- Two extreme cases of classical radiation emission



Electron/positron trajectory

Longitudinal is average velocity motion.

Transverse the remainder

Radiation characteristics decided by parameter

$$\xi = \frac{p_{\perp,\mathrm{max}}}{m}$$

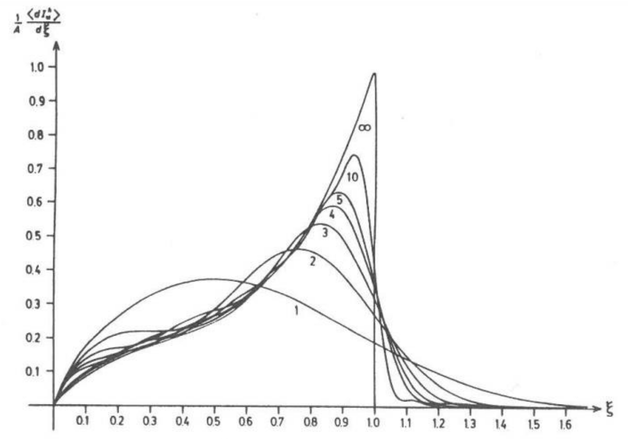
Classical radiation emission

$$\xi = \frac{p_{\perp,\mathrm{max}}}{m}$$

- Two extreme cases of classical radiation emission

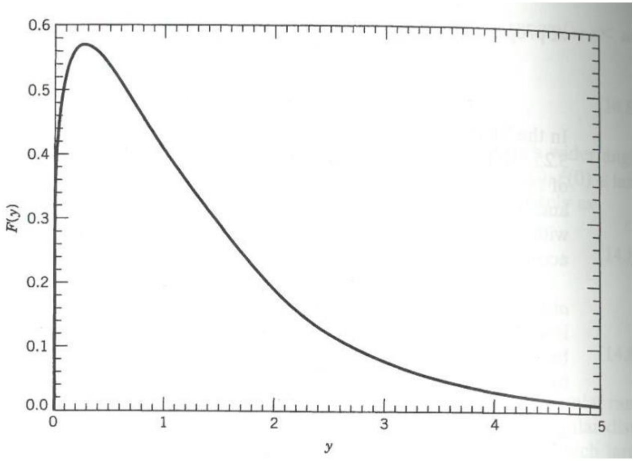
$$\xi \ll 1$$

- Dipole- or scattering-regime
- Undulator



$$\xi \gg 1$$

- Local constant field regime
- Synchrotron

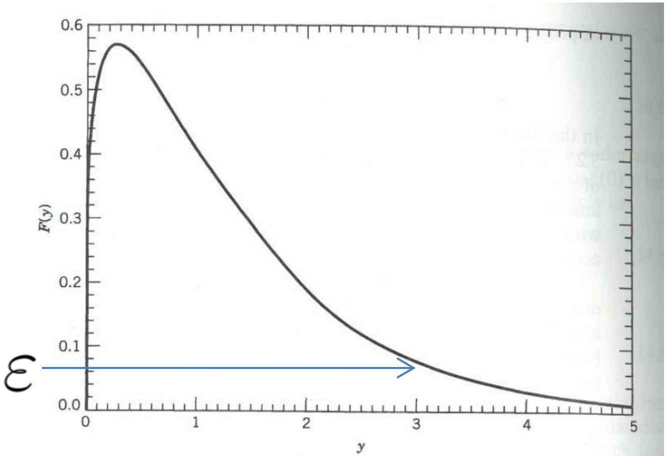


Classical radiation emission

- When can the classical theory be used?
- Two conditions:

1. The notion of trajectory must make sense.
2. Emitted photon momentum must be small compared to that of emitting electron.

$$\hbar\omega \ll \varepsilon$$



- Baier et al. finds 1) to be the case when

$$\frac{B}{\gamma^2 B_c} \ll 1$$

$$B_c = \frac{m^2}{e} = 4.4 \times 10^9 \mathrm{T}$$

- True in realistic scenarios.

- 2) is equivalent to small quantum parameter

$$\chi \ll 1$$

$$\chi = \gamma \frac{B}{B_c}$$

What is classical radiation reaction?

- Now we know classical radiation emission, what's the problem then?
- From the beginning we assumed that the motion was 'fixed' by an external field

$$\frac{dp^\mu}{d\tau} = qF^{\mu\nu}V_\nu$$

$$J^\mu = e\int d\tau V^\mu(\tau)\delta^{(4)}(x' - r(\tau))$$

$$A^\mu = 4\pi \int d^4x' D_r(x - x')J^\mu(x')$$

- The generated field is not taken into account in the equation of motion, but the calculation tells us that energy is emitted:

$$P = \frac{2}{3}e^2\gamma^6\left[(\dot{\boldsymbol{v}})^2 - (\boldsymbol{v}\times\dot{\boldsymbol{v}})^2\right]$$

What is classical radiation reaction?

- The problem is that equations are not solved in a consistent way.
- Attempt at amending this: Lorentz-Abraham-Dirac (LAD) eq.
- Start from Lamor formula $$P = \frac{2}{3} e^2 \gamma^6 \left[(\dot{\boldsymbol{v}})^2 - (\boldsymbol{v} \times \dot{\boldsymbol{v}})^2 \right]$$

(Jackson)

$$\int_{t_1}^{t_2} \mathbf{F}_{\text{rad}} \cdot \mathbf{v}\, dt = -\int_{t_1}^{t_2} \frac{2}{3} \frac{e^2}{c^3} \dot{\mathbf{v}} \cdot \dot{\mathbf{v}}\, dt$$

The second integral can be integrated by parts to yield

$$\int_{t_1}^{t_2} \mathbf{F}_{\text{rad}} \cdot \mathbf{v}\, dt = \frac{2}{3} \frac{e^2}{c^3} \int_{t_1}^{t_2} \ddot{\mathbf{v}} \cdot \mathbf{v}\, dt - \frac{2}{3} \frac{e^2}{c^3} (\dot{\mathbf{v}} \cdot \mathbf{v}) \Big|_{t_1}^{t_2}$$

If the motion is periodic or such that $(\dot{\mathbf{v}} \cdot \mathbf{v}) = 0$ at $t = t_1$ and $t = t_2$, we may write

$$\int_{t_1}^{t_2} \left(\mathbf{F}_{\text{rad}} - \frac{2}{3} \frac{e^2}{c^3} \ddot{\mathbf{v}} \right) \cdot \mathbf{v}\, dt = 0$$

Then it is permissible to identify the radiative reaction force as

$$\mathbf{F}_{\text{rad}} = \frac{2}{3} \frac{e^2}{c^3} \ddot{\mathbf{v}} = m\tau \ddot{\mathbf{v}} \qquad (16.8)$$

What is classical radiation reaction?

- Landau & Lifshitz equation. "Reduction of order".

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

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

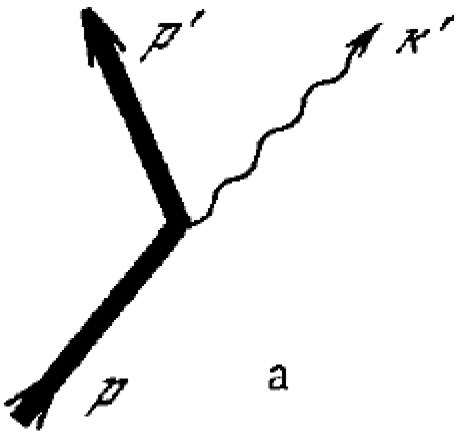
$$f = \frac{2e^3}{3m}\gamma\left\{(\boldsymbol{v}\cdot\nabla)\,\boldsymbol{E}\right\} + \frac{2e^4}{3m^2}\left\{\boldsymbol{E}(\boldsymbol{v}\cdot\boldsymbol{E})\right\} - \frac{2e^4}{3m^2}\gamma^2\boldsymbol{v}\left\{(\boldsymbol{E})^2 - (\boldsymbol{E}\cdot\boldsymbol{v})^2\right\}$$

What is classical radiation reaction?

- Experimental test of the Landau & Lifshitz equation?
- Longstanding fundamental problem. 1905 Abraham
- 1975 Landau Lifshitz
- Channeling in a crystal? A source of a strong electromagnetic field.
- In 2016 when we first pursued radiation reaction and 2017 when we did the experiment we could say that no experiments existed on this topic.
- However, hot topic. Lasers are now at the limit of being able to see radiation reaction. "Experimental Evidence of Radiation Reaction in the Collision of a High-Intensity Laser Pulse with a Laser-Wakefield Accelerated Electron Beam" Phys. Rev. X 8, 011020 – Published 7 February 2018

Quantum radiation emission

- How does one calculate radiation emission quantum mechanically?



$$V_{fi}(t) = -e\sqrt{\frac{2\pi}{\omega}} \int \psi_f^\dagger(t,\boldsymbol{r}) e^{i(\omega t - \boldsymbol{k}\cdot\boldsymbol{r})} (\boldsymbol{e}^* \cdot \boldsymbol{\alpha}) \psi_i(t,\boldsymbol{r}) d^3x,$$

$$dP = \sum_f \left| \int V_{fi}(t) dt \right|^2 \frac{d^3k}{(2\pi)^3},$$

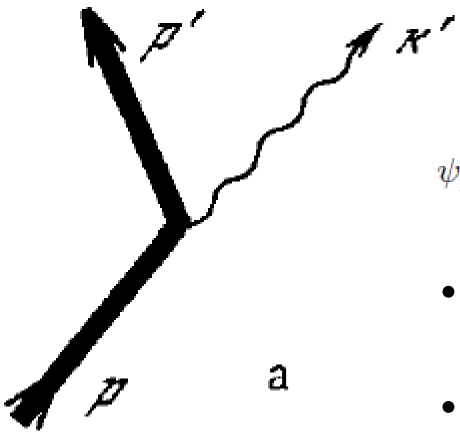
$$\left(\not{p} - q\not{A} - m\right)\psi = 0$$

- Several methods, Volkov, Baier, but all begin here.
- What wave function to use?

Quantum radiation emission

- Solution of the Dirac equation?

$$\left(\not{p} - q\not{A} - m\right)\psi = 0$$



- If you have a field that depends only on phase $\not{A}_{ext}(\varphi)$ $\varphi = k^\mu x_\mu$

$$\psi_{pr}(x) = \left[1 + \frac{e\not{k}\not{A}_{ext}(\varphi)}{2k\cdot p}\right] u_{pr} \exp\left[-i\int_0^\varphi \left(\frac{ep\cdot A_{ext}(\varphi')}{k\cdot p} - \frac{e^2 A_{ext}(\varphi')^2}{2k\cdot p}\right) d\varphi' - ip\cdot x\right],$$

- Exact Volkov solution of the Dirac equation.
- Typical cases are

$A^\mu(\varphi) = a^\mu \cos\varphi$ → Long laser wave

$A^\mu(\varphi) = a^\mu \varphi$ → Constant crossed electric and magnetic field

Quantum radiation emission

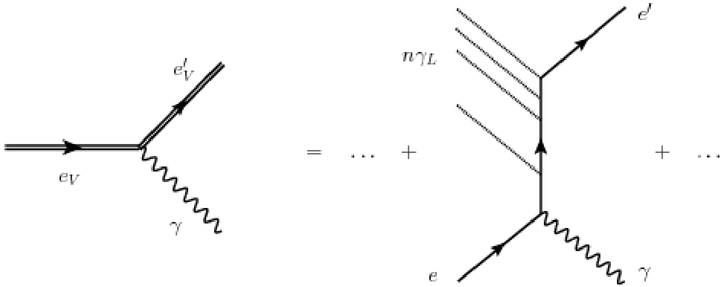
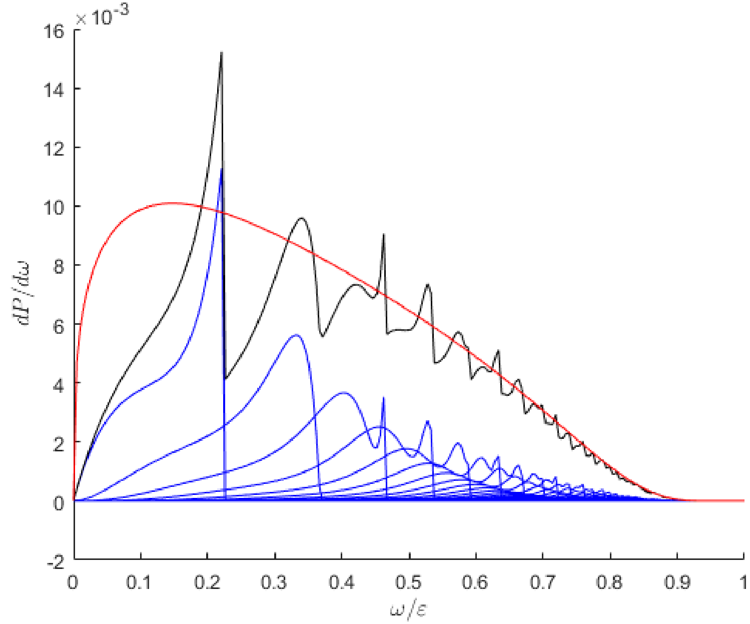


Figure from Heinzl, T. et al. Phys.Rev. A81 (2010)

Seen as multi-photon absorption

$$\frac{dW}{du}(x,\chi) = \sum_{s=1}^{\infty} \frac{dW_s}{du},$$

$$\omega_s = \frac{4s\omega_0\varepsilon^2}{\bar{m}^2 + 4s\omega_0\varepsilon}$$

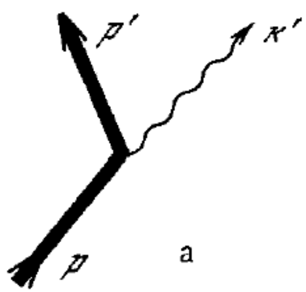


$\chi = 1$

$\xi = 1.5$

Quantum radiation reaction

- In Quantum Electrodynamics, radiation reaction is just the emission of many photons.
- However under general circumstances very difficult to calculate high orders.
- It has only been explicitly shown that one can split the higher order processes into consecutive first order emissions in the local constant field approximation.
- Maybe there is a way, but no established approach.



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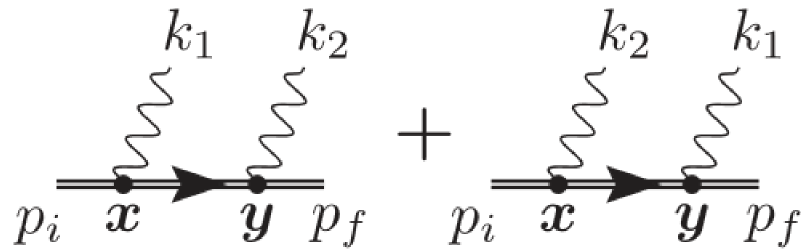
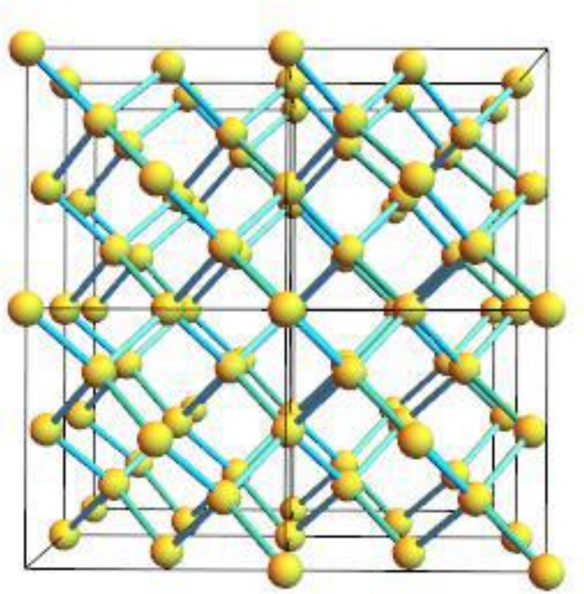
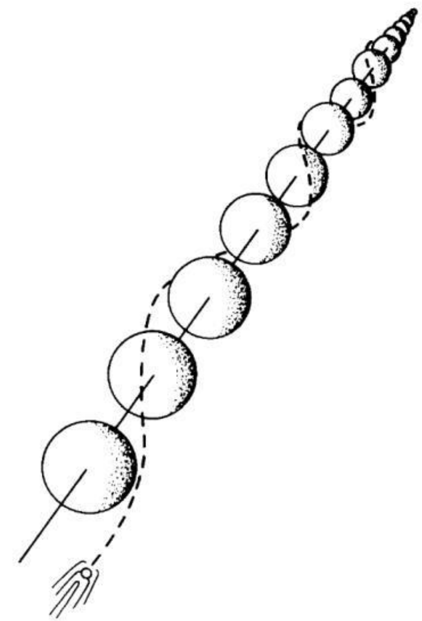


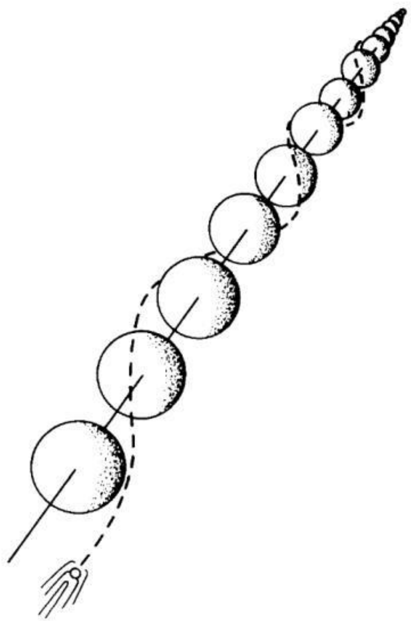
What is channeling?

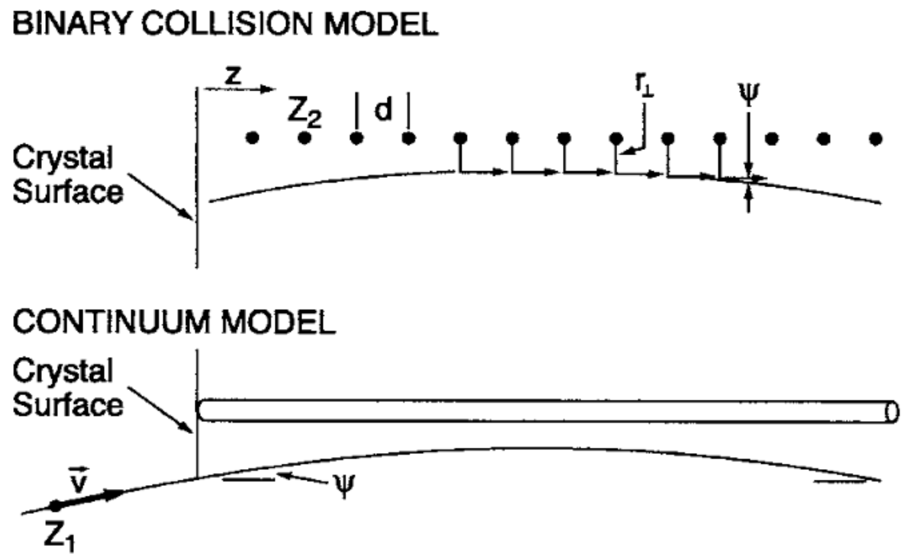




- Channeling is a phenomenon that takes places when a high energy charged particle enters the crystal close to a direction of high symmetry.

What is channeling?



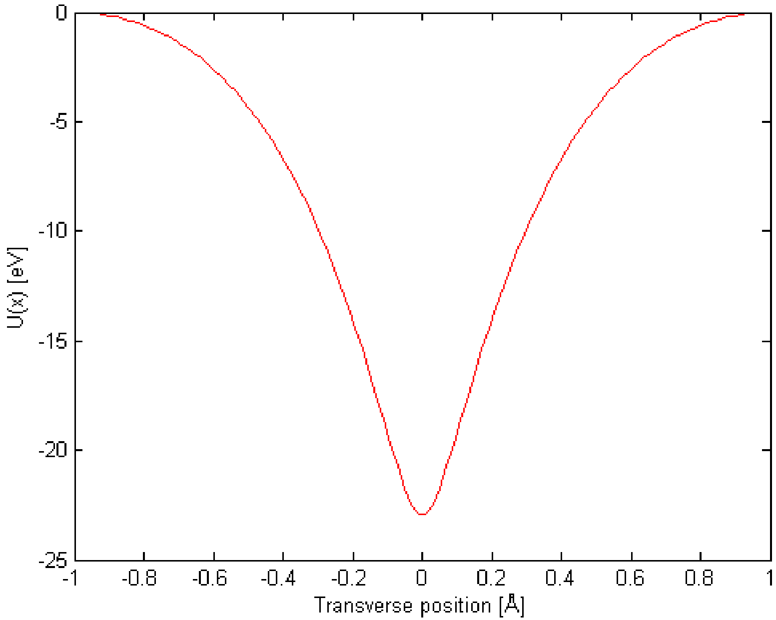


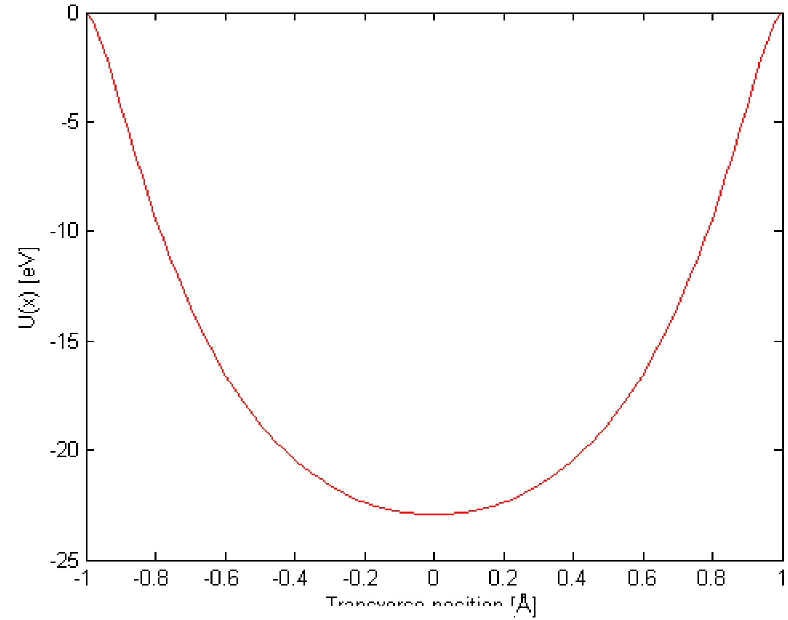
- Often employed is the continuum model of the potential.

What is channeling?

- Model of the (110) planar potential for Si

$$U(x) = V[\cosh(\delta(\sqrt{1+\eta^2} - \sqrt{y^2+\eta^2})) - 1],$$

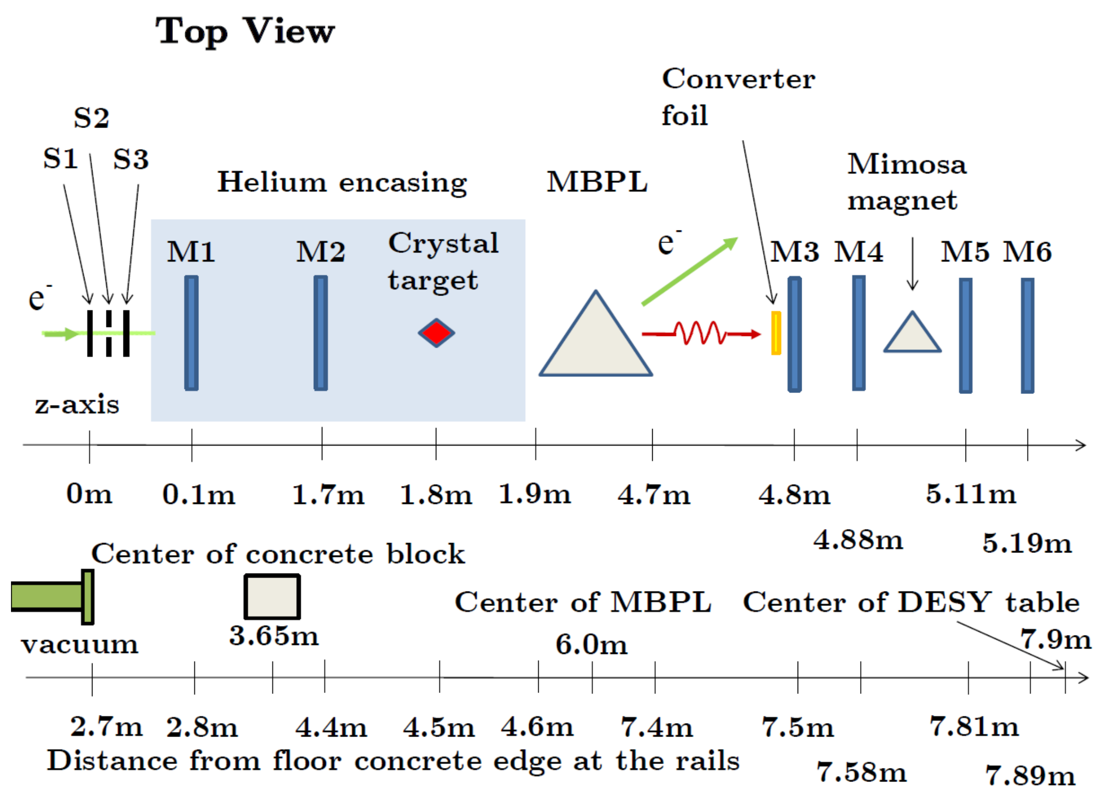




- Important dynamics is transverse

$$E_\perp = \frac{\boldsymbol{p}_\perp^2}{2\gamma m} + U(\boldsymbol{x}_\perp),$$

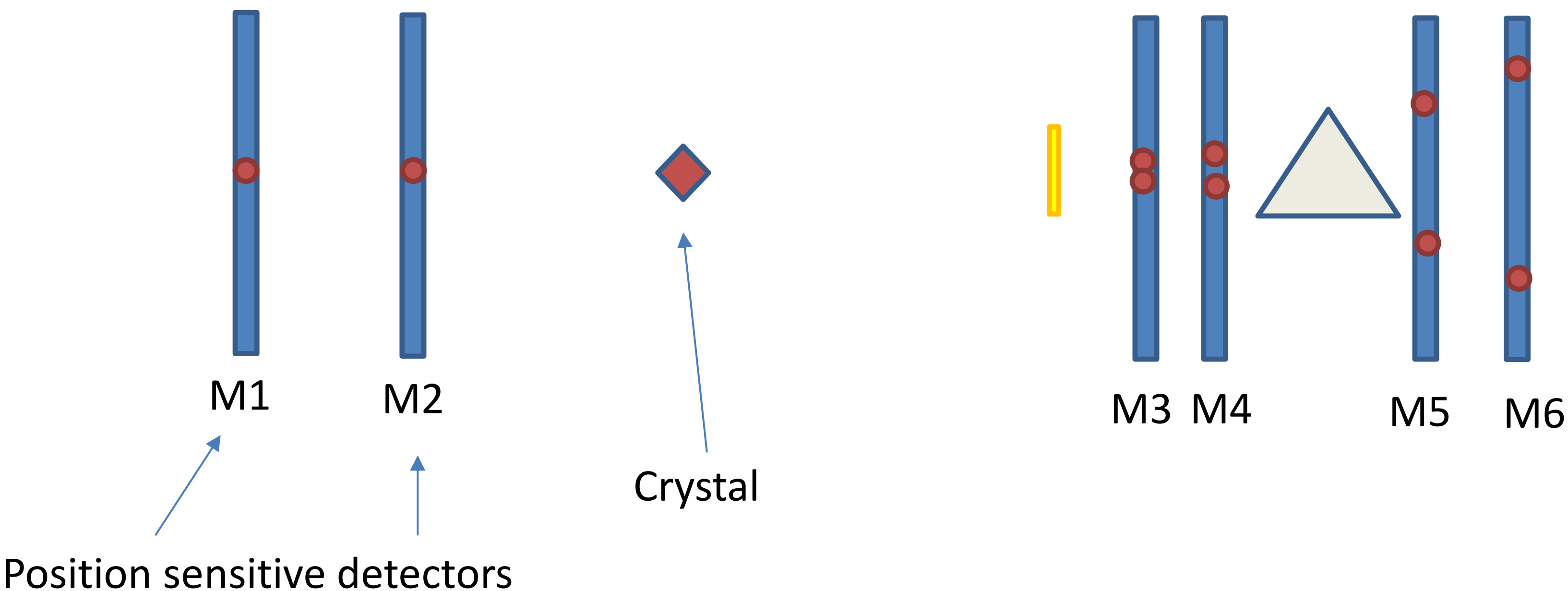
Designing the experiment



- In RR regime, naturally many photons are emitted per incoming charge.. How to deal?
- Converter foil to convert single photon

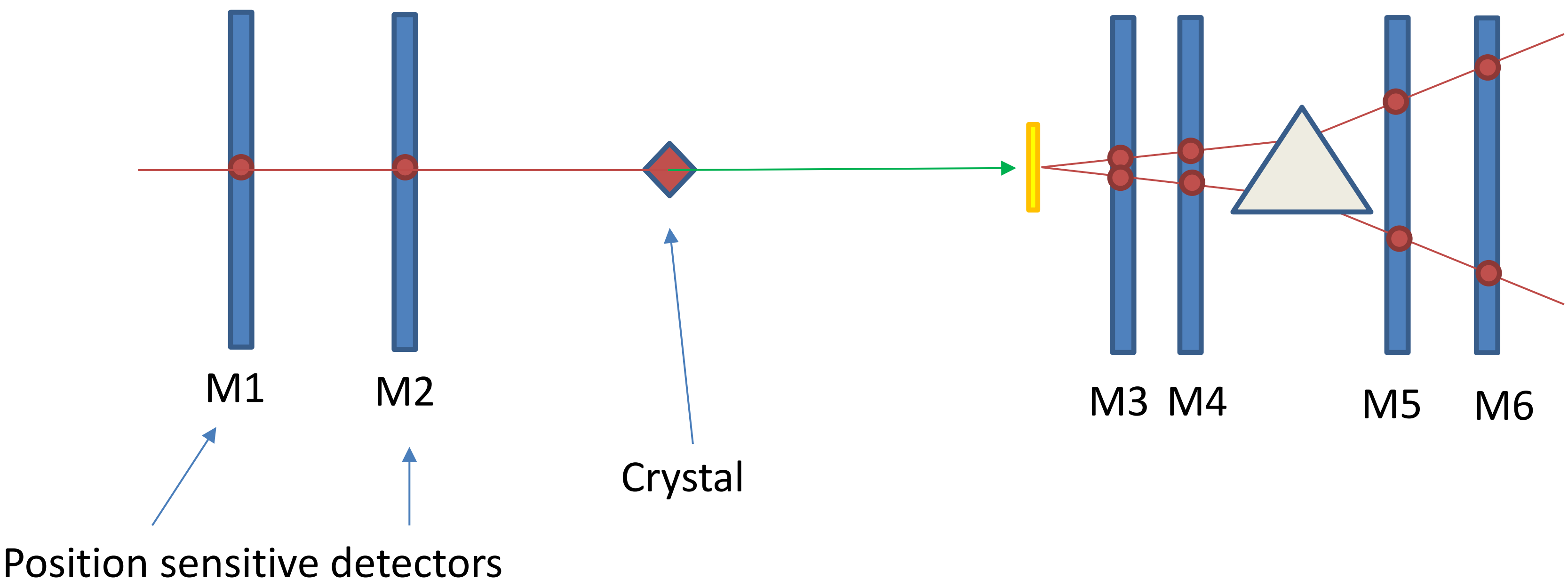
The experimental setup

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



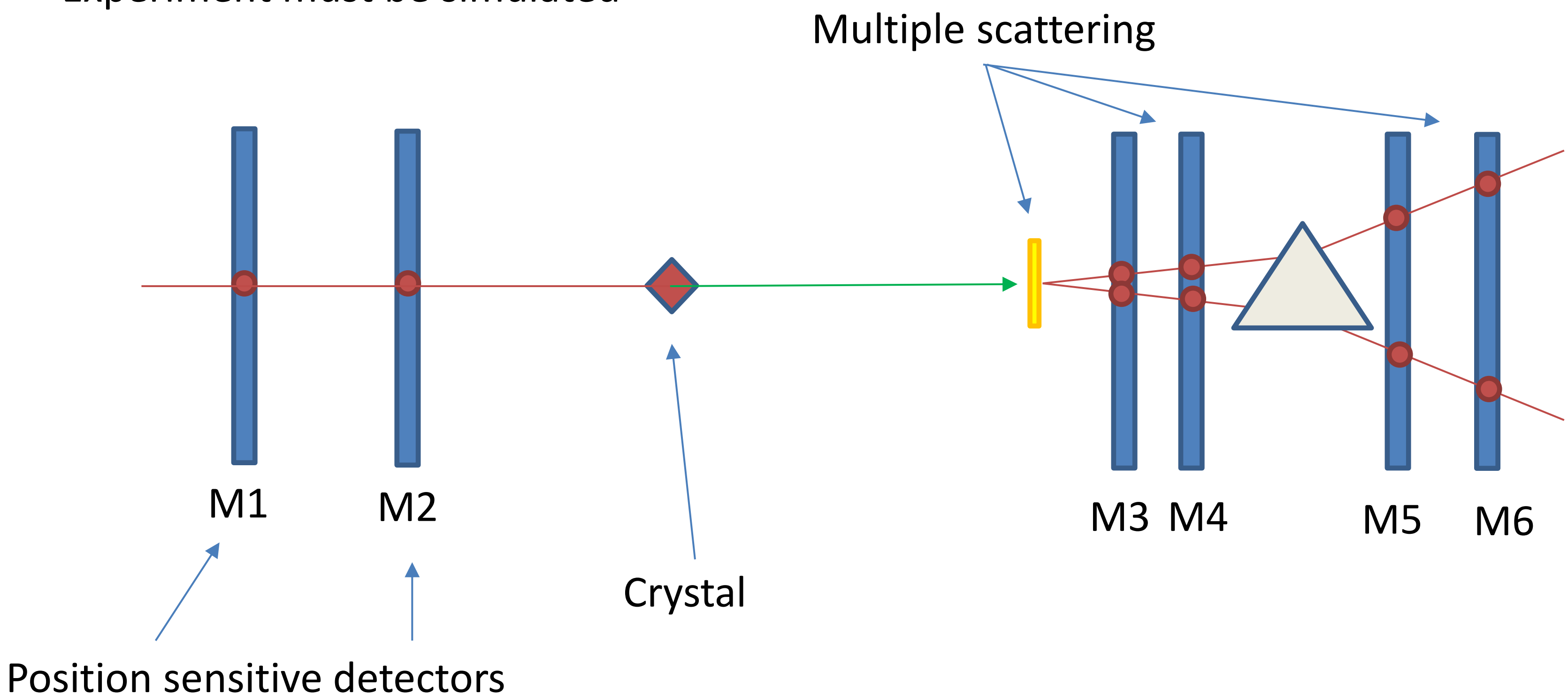
Designing the experiment.

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



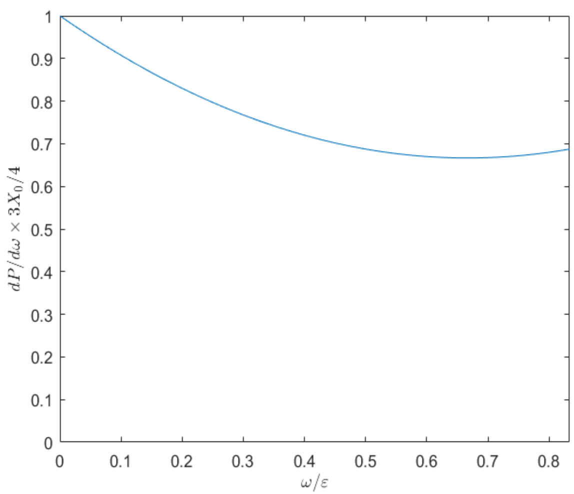
Designing the experiment.

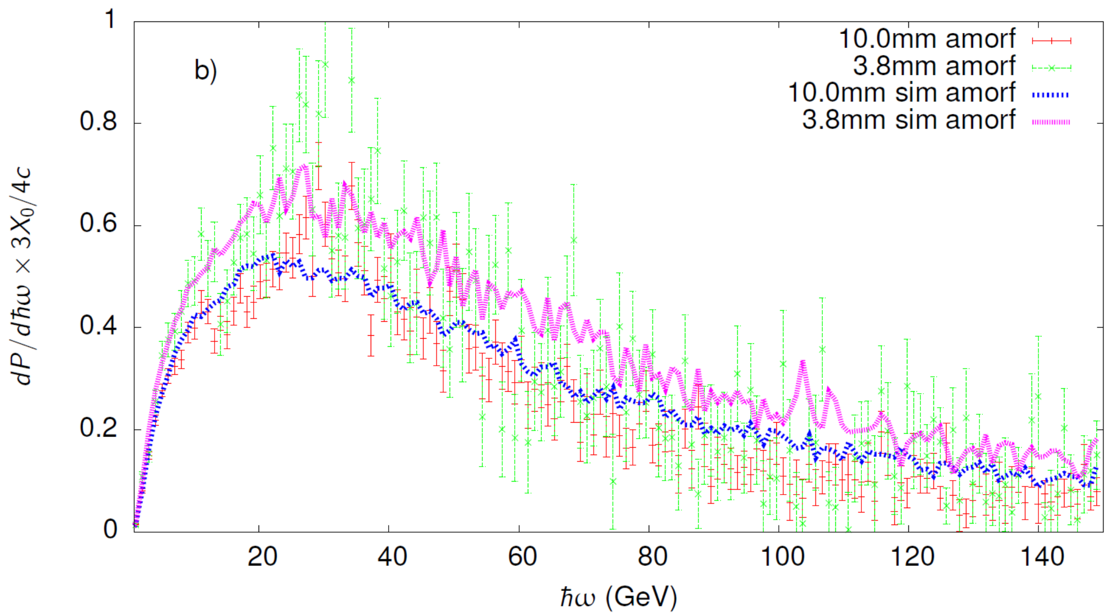
- How does this setup measure photon energies?
- All you know is the position where some charged particles hit the detector
- Experiment must be simulated



Designing the experiment.

Theoretical bremsstrahlung power spectrum

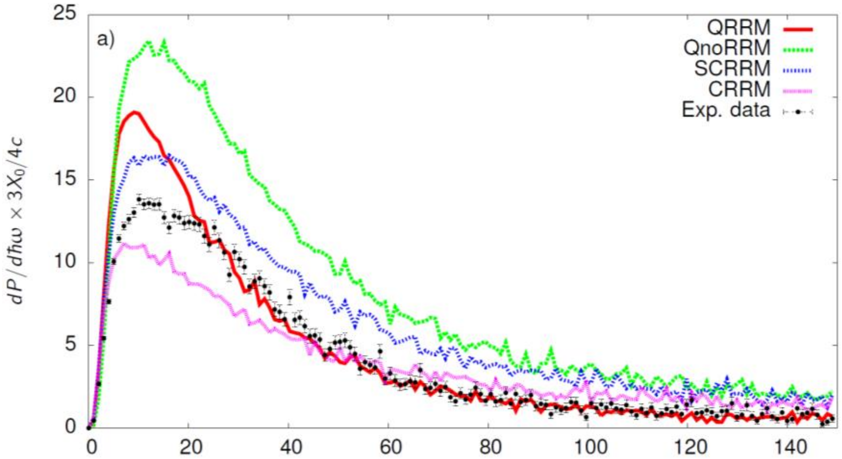




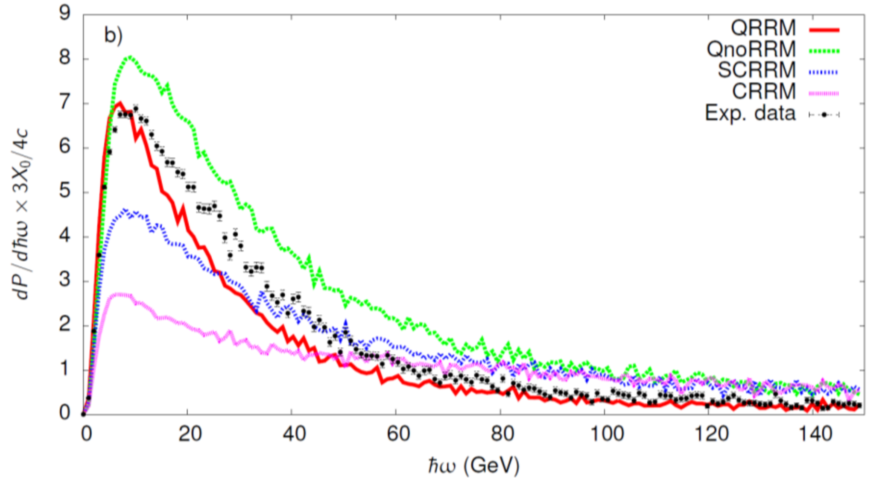
Experimental bremsstrahlung with our setup compared to simulation.

Experimental results from 2016 on QRR

3.8mm crystal



10mm crystal



- Overall best agreement with quantum radiation reaction model (local constant field approximation)
- Cause of the discrepancy?

Quantum radiation emission

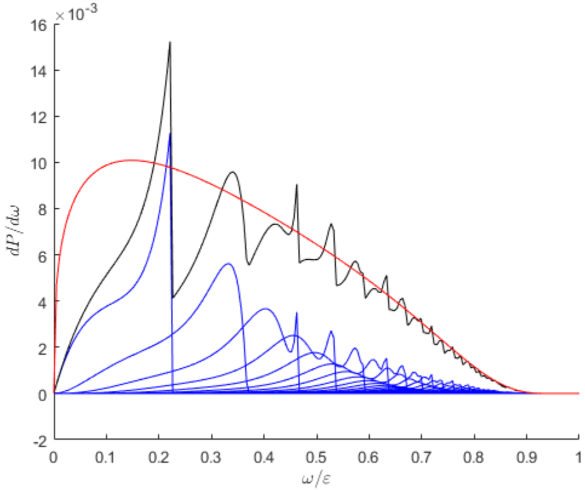
4 models
1) Quantum radiation reaction model (QRRM)

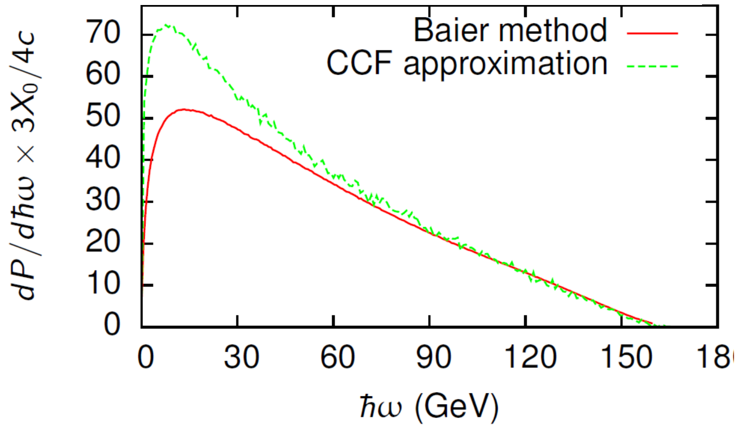
Additional correction at low frequencies.
CCF overestimates spectrum at low frequencies.

$$l_f(\omega) = 2\gamma^2/\omega, \qquad l_f(\omega_c) = a\lambda_0/2$$

λ_0 Is the typical particle oscillation wavelength.

We make a cutoff below the critical frequency and decide the constant a such that the total power matches that of the more accurate calculation





CERN NA63 2017 experiment on classical radiation reaction

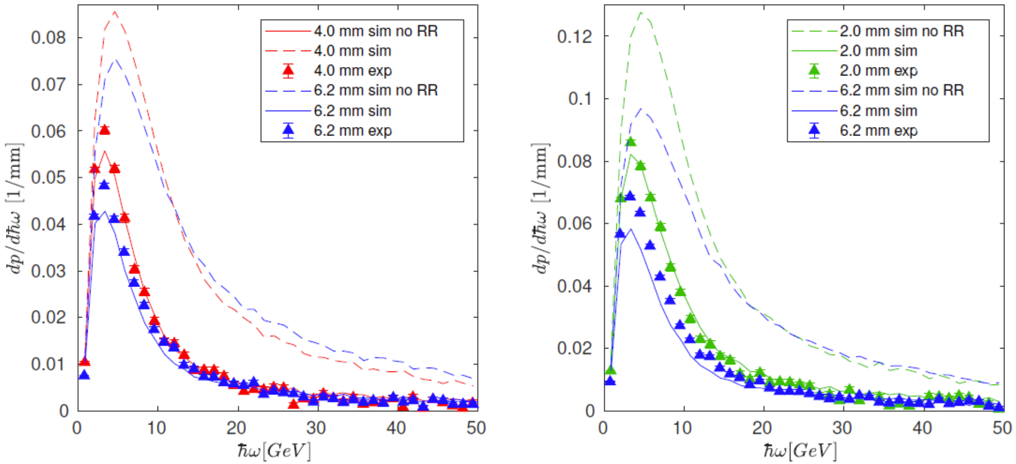


Fig. from MA. thesis of C.F. Nielsen

Preliminary! We know there is an issue with convergence for the theoretical curves which is being corrected.

- Experimental data is sensible.
- We are confident we will obtain useful and important results.
- We did measurements with 50 GeV positrons undergoing (110) planar channeling in Si.

CERN NA63 2018 experiment on Schott term

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

$$+ \frac{2e^4}{3m^2}\{\boldsymbol{E}\times\boldsymbol{H} + \boldsymbol{H}\times(\boldsymbol{H}\times\boldsymbol{v}) + \boldsymbol{E}(\boldsymbol{v}\cdot\boldsymbol{E})\}$$

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

- These terms in the Landau Lifshitz (LL) eq. come from the controversial Schott term in the Lorentz Abraham Dirac (LAD) eq.

$$\frac{dp^\mu}{d\tau} = eF^{\mu\nu}u_\nu + f^\mu$$

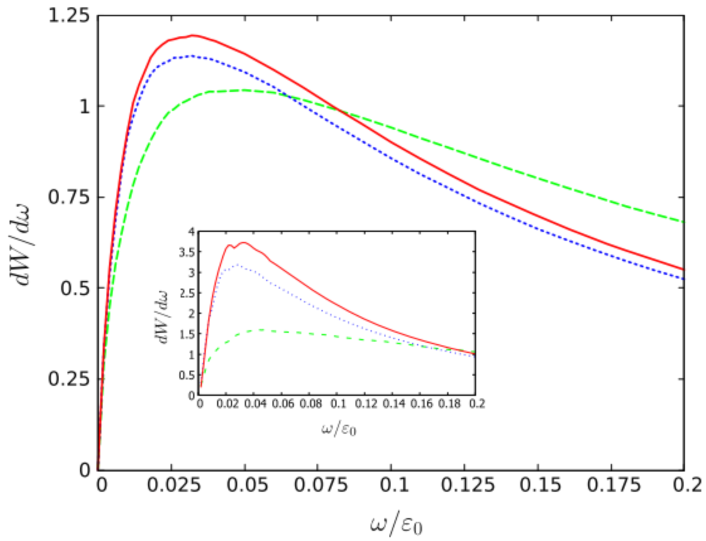
$$f^\mu = \frac{2}{3}e^2\left(\frac{d^2u^\mu}{d\tau^2} + u^\mu\frac{du_\nu}{d\tau}\frac{du^\nu}{d\tau}\right)$$

- Runaway solutions etc.

- Second term in LL must be there for orthogonality, but the derivative of fields could be thrown away.

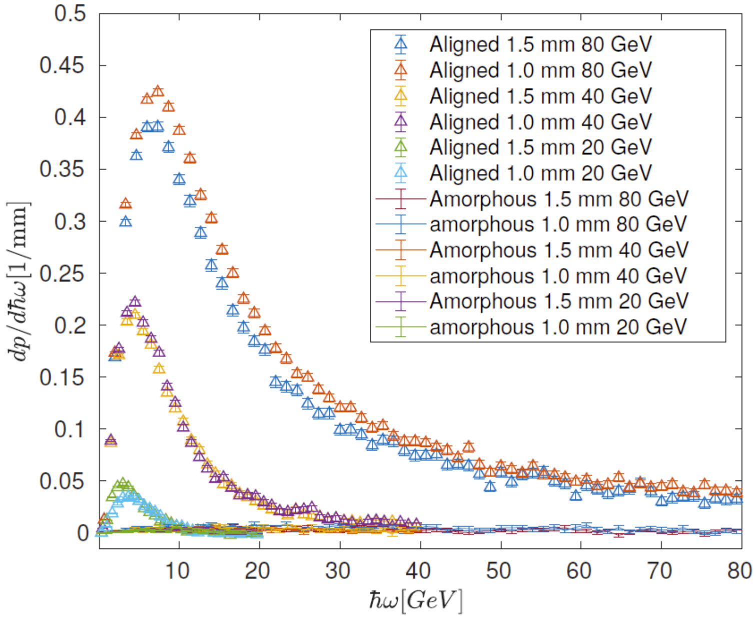
$$f^\mu u_\mu = 0$$

CERN NA63 2018 experiment on Schott term



- Earlier theoretical investigation
- Green curve no RR, blue and red with RR and with/without Schott term
- Small effect, but much bigger than in lasers.
- Challenging, but the only place where there would be a chance to see the effect of the derivative term in the LL equation.

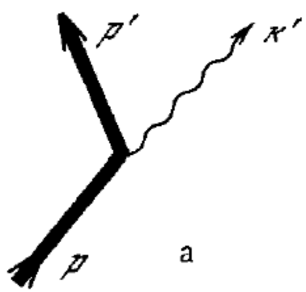
CERN NA63 2018 experiment on Schott term



- For small effect we need high statistics, which we got
- These are spectra including all incoming particles. We will need to make cuts in the angles of the incoming particles, but we should still have enough statistics even when we have done that.
- Can not tell directly from data if we are successful, we need to do the comparison with our theoretical calculations.

Future plans

- SPS beam again in 2021.
- We expect that the experiments from 2017 and 2018 on classical radiation reaction will be conclusive and as such there are no more plans for experiments on classical radiation reaction
- In the quantum regime, currently, we can only do the calculation of many photon emissions in the local constant field approximation



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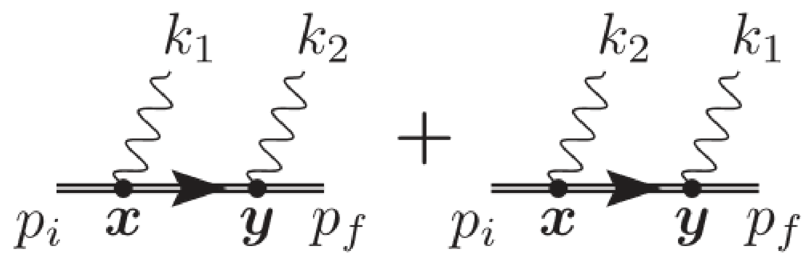
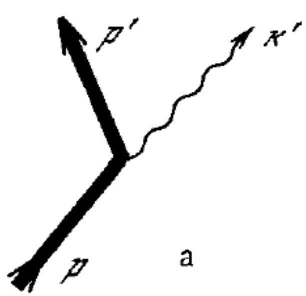


Future plans

- In the local constant field approximation, quantum radiation reaction becomes "trivial" in the sense that many photon emissions reduces to just the first order emission taking place consecutively.

- Could we see two-photon emission in the non-trivial case? I.e. investigate "Nonlinear Double Compton Scattering in the Ultrarelativistic Quantum Regime" (2013 theory with laser) in a crystal?

- That is in the quantum regime, and when the field cannot be considered locally constant.



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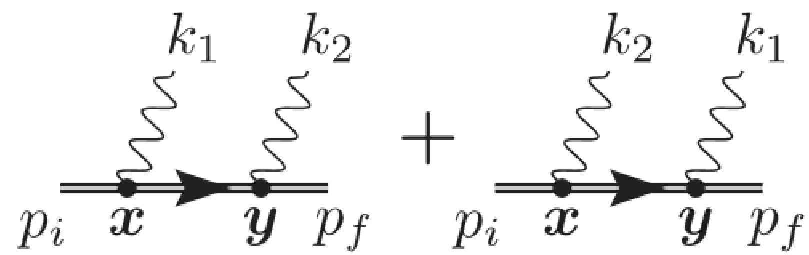
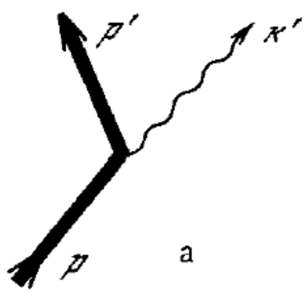


Future plans

- Double compton scattering beyond the local constant field approximation is a topic of investigation for lasers currently.
- We need to do the calculation for the case of a crystal.
- Everything e.g. Baier has done on radiation emission in crystals comes from the first order diagram, the 2nd order diagram is a natural continuation of Quantum electrodynamics in strong fields.



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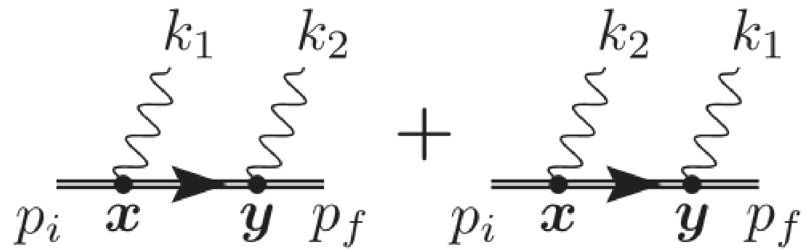

Conclusions

- We have seen quantum radiation reaction in a strong field in a crystal. (Published in Nat. Comm. 2018)
- The 2017 data analysis has come a long way and we can use the data to make a statement on the Landau & Lifshitz equation.
- The 2018 data analysis is still in an early stage. We can see that we have good statistics as required. Accurate calcuations need to be done to make a claim on the derivative term.

Thank you!

What is classical radiation reaction?

- The equations of motion (non-relativistic) become

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

$$\boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\boldsymbol{f} = \frac{2e^2}{3}\dot{\boldsymbol{a}}$$

$$m\dot{\boldsymbol{v}} = \frac{2e^2}{3}\ddot{\boldsymbol{v}}$$

$$v = \text{const} \times \exp(3mt/2e^2)$$

- Higher order, problematic equation

What is classical radiation reaction?

- Solution? Landau & Lifshitz equation

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

$$\boldsymbol{F} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\boldsymbol{f} = \frac{2e^2}{3}\dot{\boldsymbol{a}}$$

$$\dot{\boldsymbol{a}} = \frac{e}{m}\left(\dot{\boldsymbol{E}} + \dot{\boldsymbol{v}} \times \boldsymbol{B}\right)$$

$$\dot{\boldsymbol{v}} = \frac{e}{m}\boldsymbol{E}$$

$$\dot{\boldsymbol{a}} = \frac{e}{m}\dot{\boldsymbol{E}} + \frac{e^2}{m^2}(\boldsymbol{E} \times \boldsymbol{B})$$