Experiments on strong field QED in crystals (CERN NA43 and NA63)

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Strong fields

Motivation

What are the invariants?

Motion perpendicular to an electric field:

$$\chi^2 = \frac{(F_{\mu\nu}p^\nu)^2}{m^2c^2\mathcal{E}_0^2},$$

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

$$\Xi = \frac{F_{\mu\nu}^2}{\mathcal{E}_0^2} = \frac{2(\vec{B}^2 - \vec{\mathcal{E}}^2)}{\mathcal{E}_0^2},$$

$$\Gamma = \frac{e_{\lambda\mu\nu\rho}F^{\lambda\mu}F^{\nu\rho}}{\mathcal{E}_0^2} = \frac{8\vec{\mathcal{E}}\cdot\vec{B}}{\mathcal{E}_0^2},$$

$$\mathcal{E}_0 = m^2c^3/e\hbar = 1.32 \times 10^{16}\ \mathrm{V/cm}$$

$$B_0 = 4.41 \times 10^9\ \mathrm{T}$$

Beamstrahlung

Electric field from one bunch boosted by $2\gamma^2$ as seen by the other

SLC:

χ (or Υ) $\approx 10^{-3}$

NLC (ILC, CLIC):

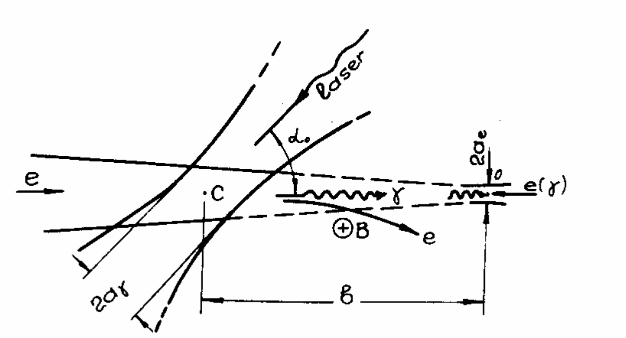
χ (or Υ) ≈ 1

heavy ions

Superstrong field, but of short duration

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

Strong lasers



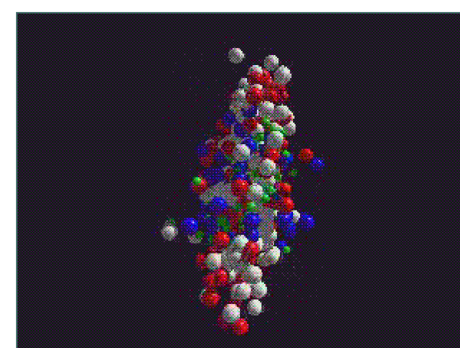
γγ-collision scheme (Telnov *et al.*)

Laser wavelength (and γ energy) limited by non-linear Compton scattering

χ (or Υ) ≈ 1

Extended nucleus:

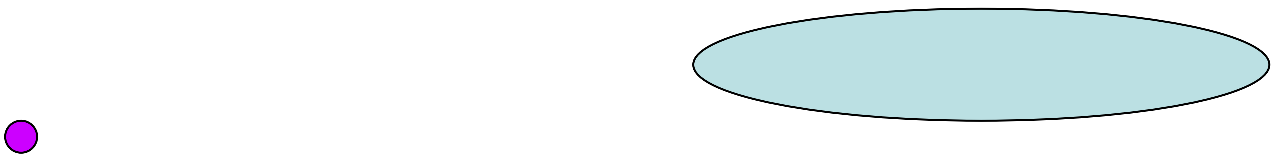
$Z \approx 172$



Similar situations ?

Blankenbecler, Drell (PRD **36**, 277 (1987), Quantum treatment of beamstrahlung:
"Pulse transforms into a very long narrow 'string' of *N* charges."

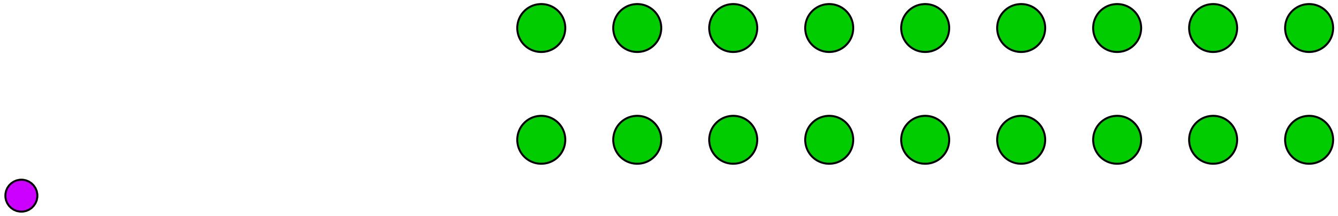
ILC / CLIC



Bunch-size: 300×0.6×0.006 μm^3, 2·10^{10} particles

Density: 0.005 Å^{-3}, 0.6 Å^{-3} (at IP)

Si
crystal



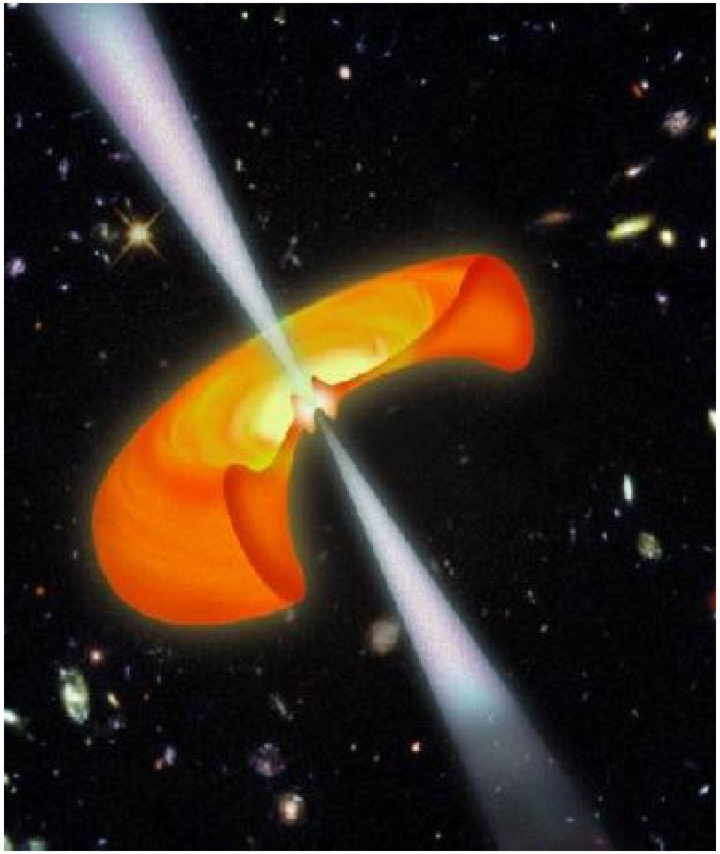
Density: 0.05 Å^{-3}, of Z = 14

Magnetars

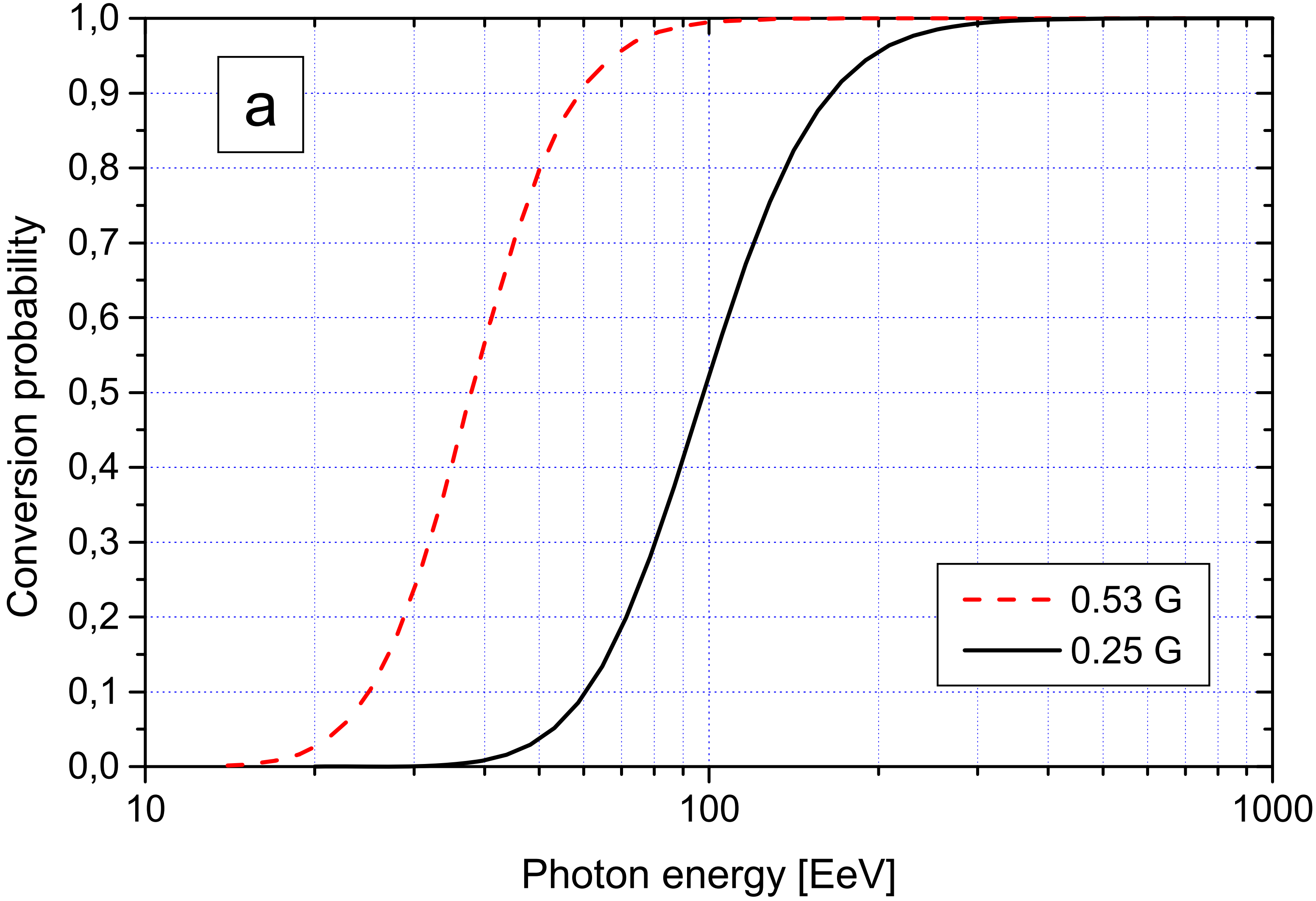
- Magnetars, $B \approx 10^{10}$ T, relativistic gyration:

$$\hbar\omega/mc^2 = \sqrt{B/B_0}$$

- Electrosphere of strange stars – possible signatures from suppressed radiation?

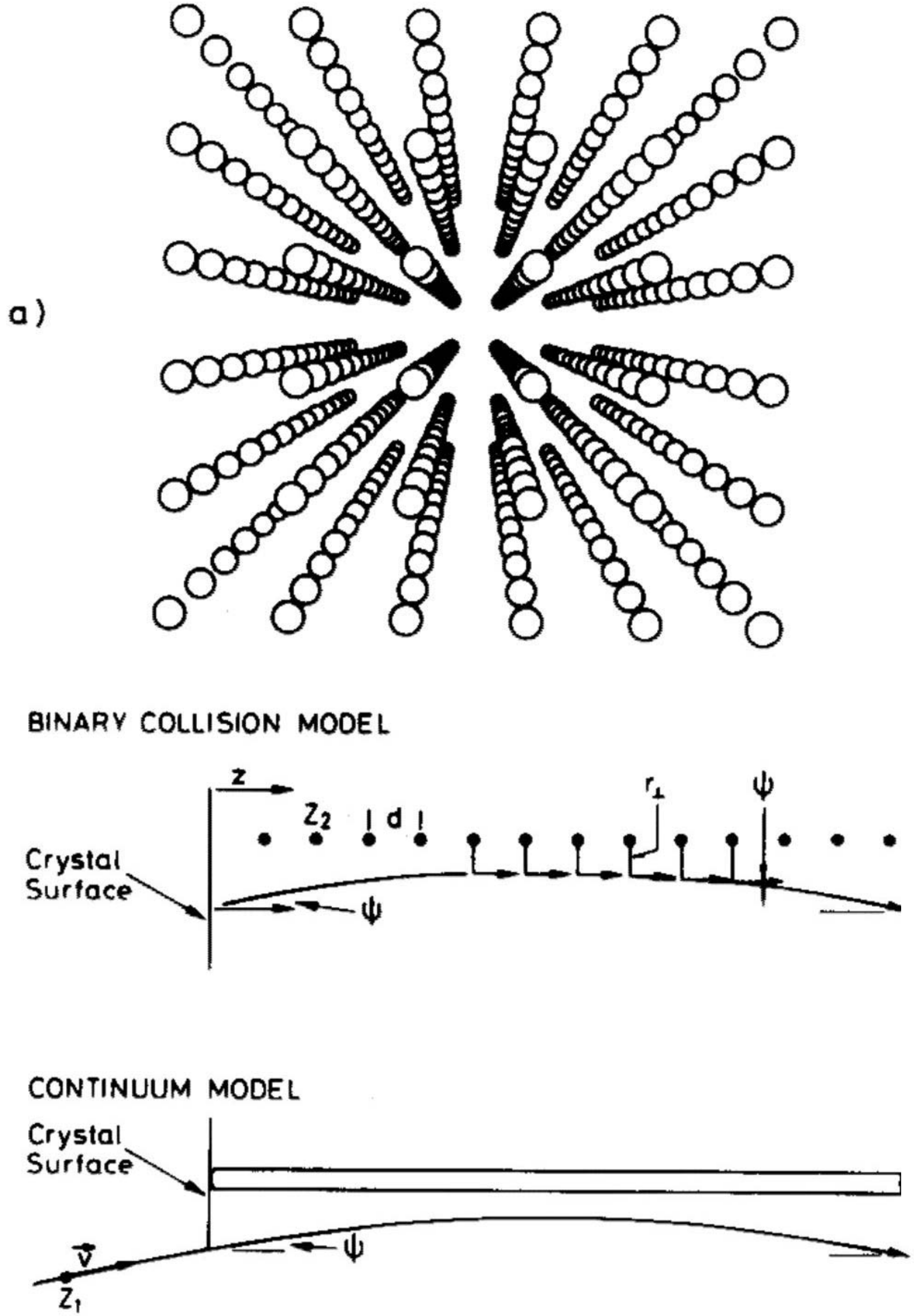


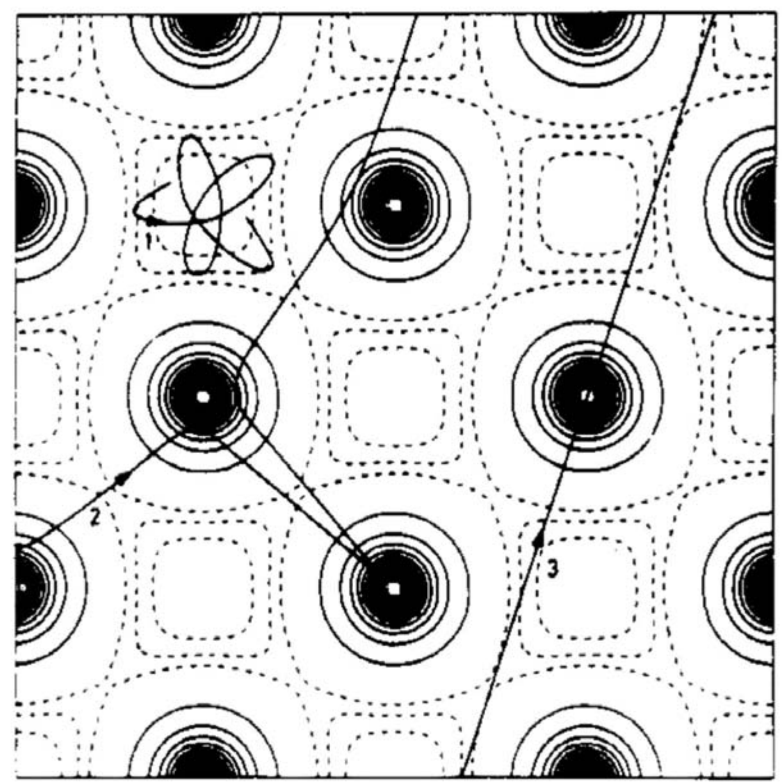
The strong magnetic field of the Earth



Strong fields in crystals

Strong crystalline fields

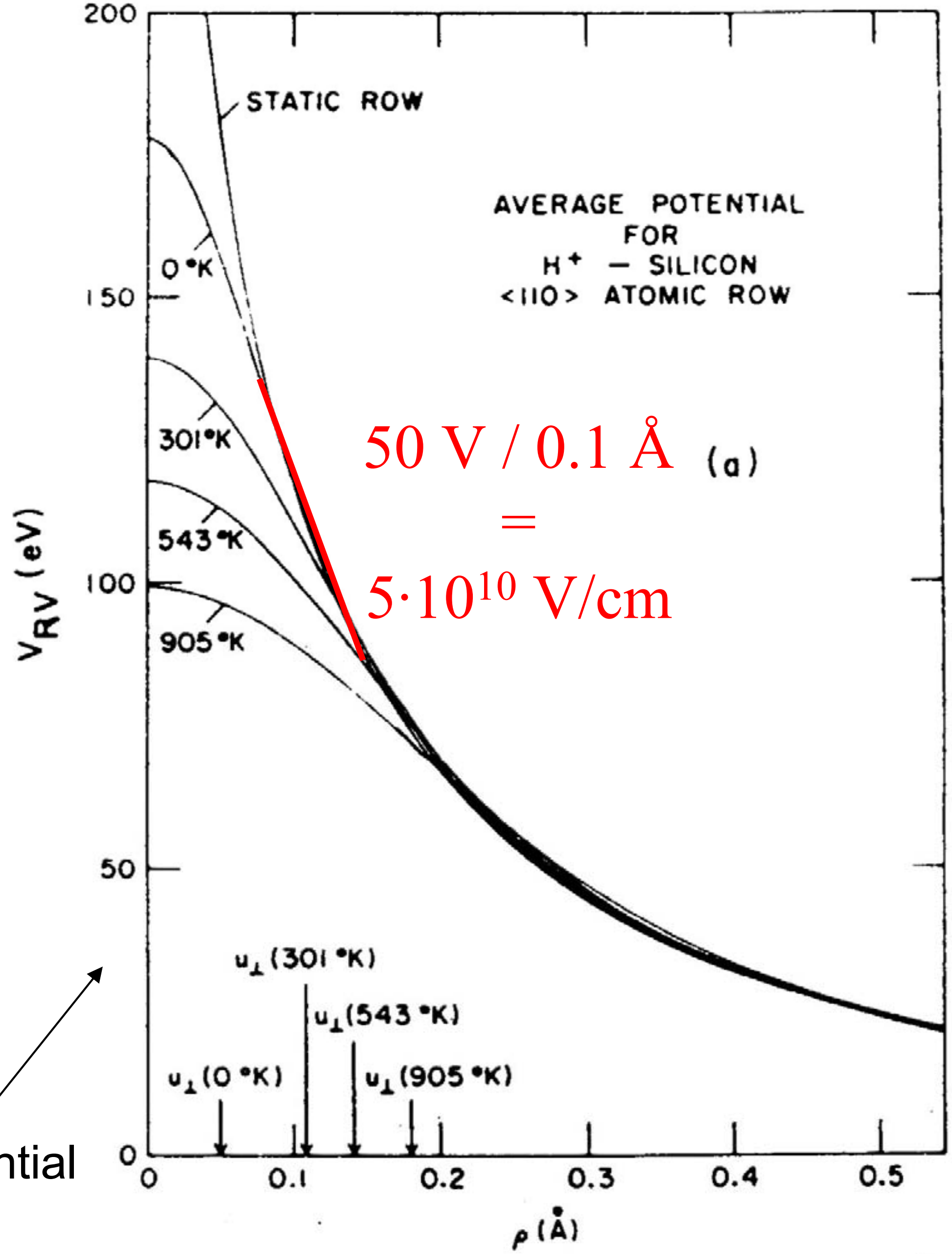




Crystals

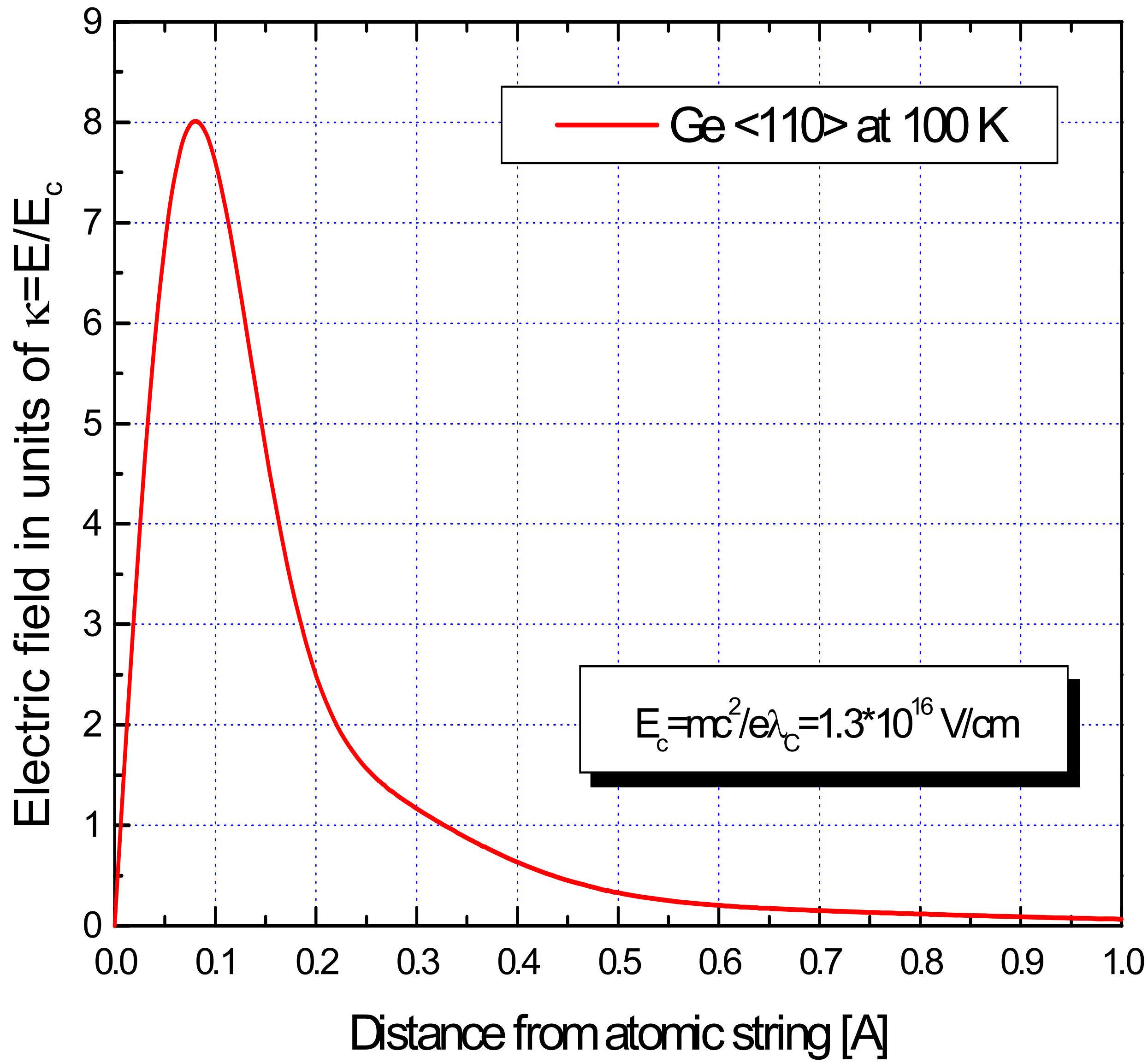
Extremely strong electric fields

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



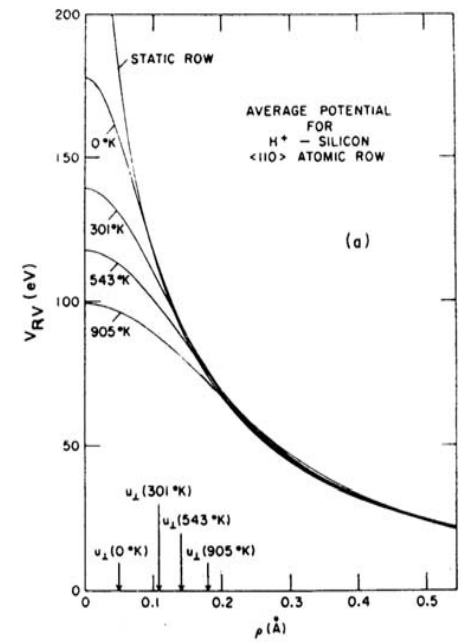
Channeling transverse potential

'Super-critical' fields

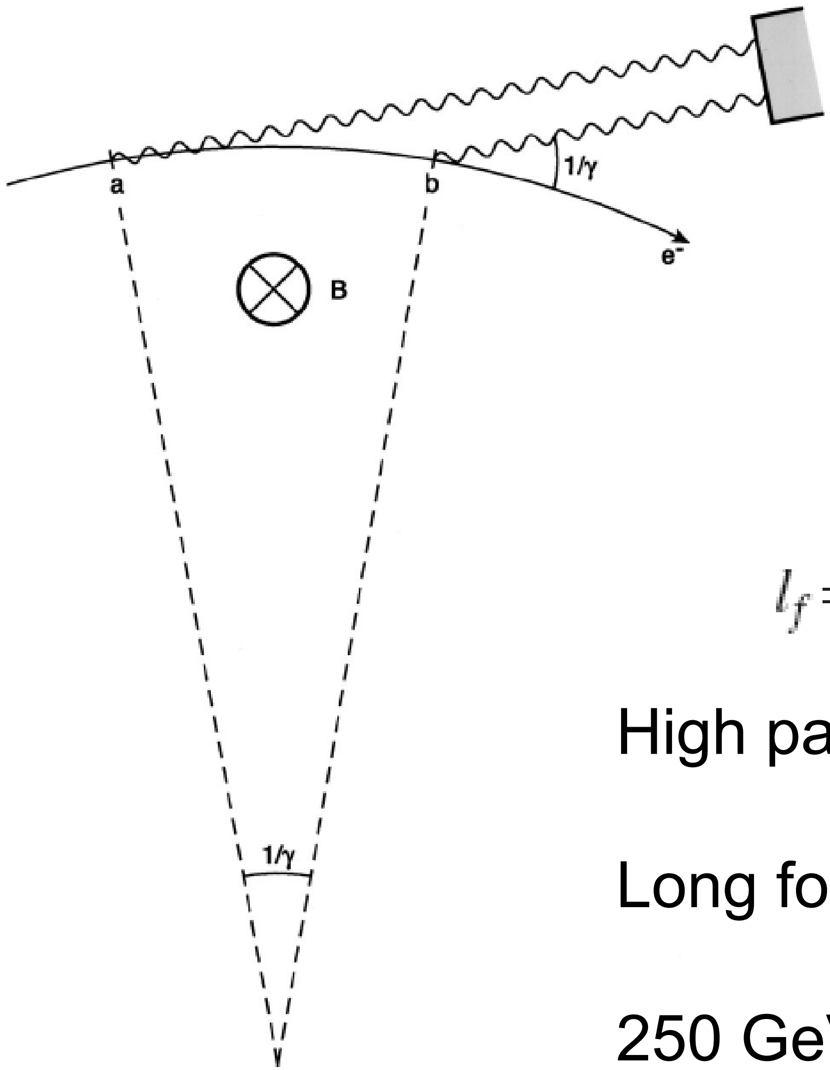


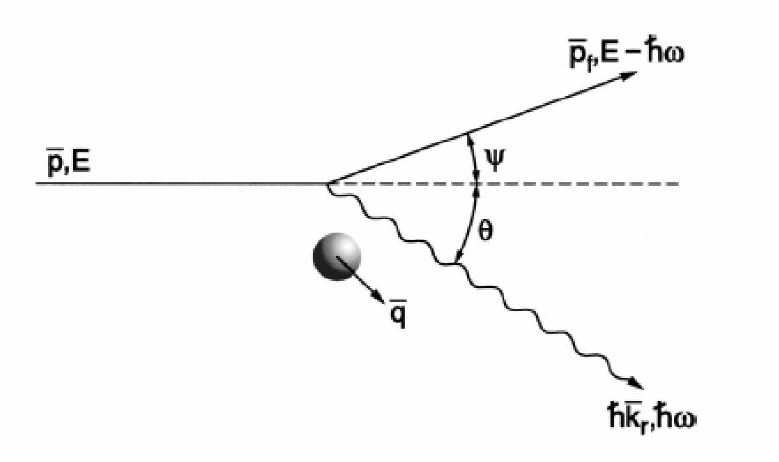
Relativistic invariant:

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



Formation length





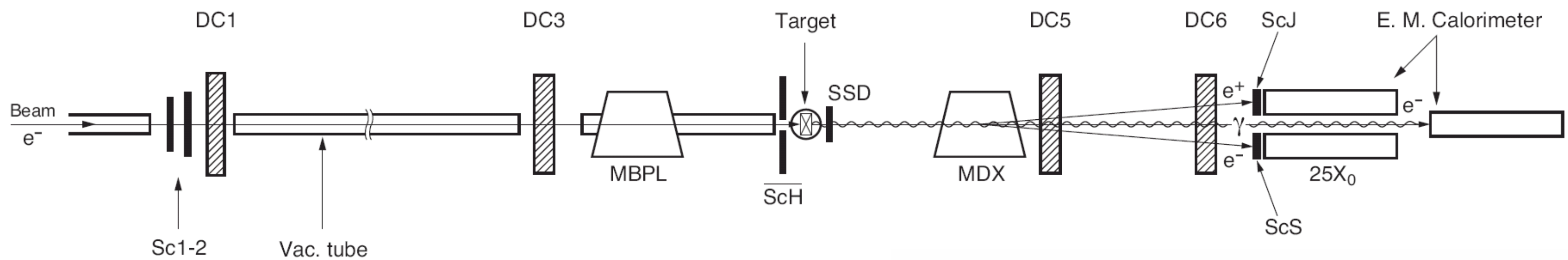
$$l_f = \frac{2\gamma^2 c}{\omega^*} \quad \text{with } \omega^* = \omega\frac{E}{E-\hbar\omega} \simeq \omega,$$

High particle energy, low photon energy:

Long formation length

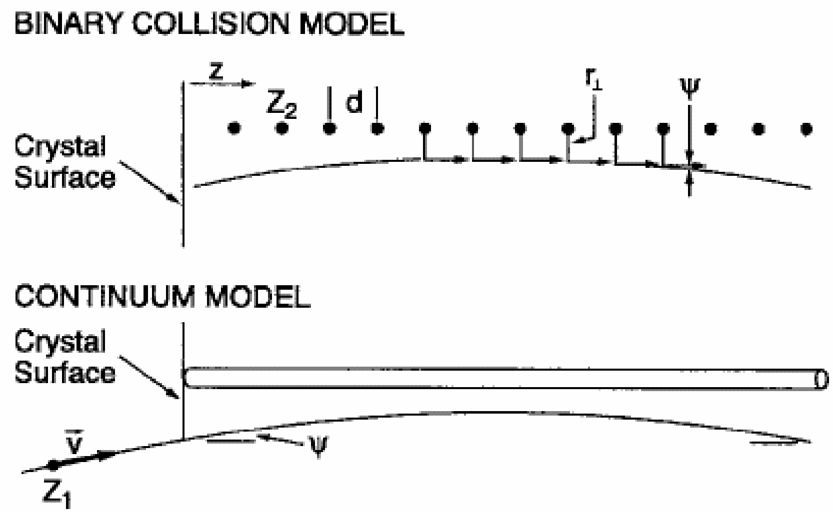
250 GeV e^-, 1 GeV γ: 0.1 mm

NA63 experiment



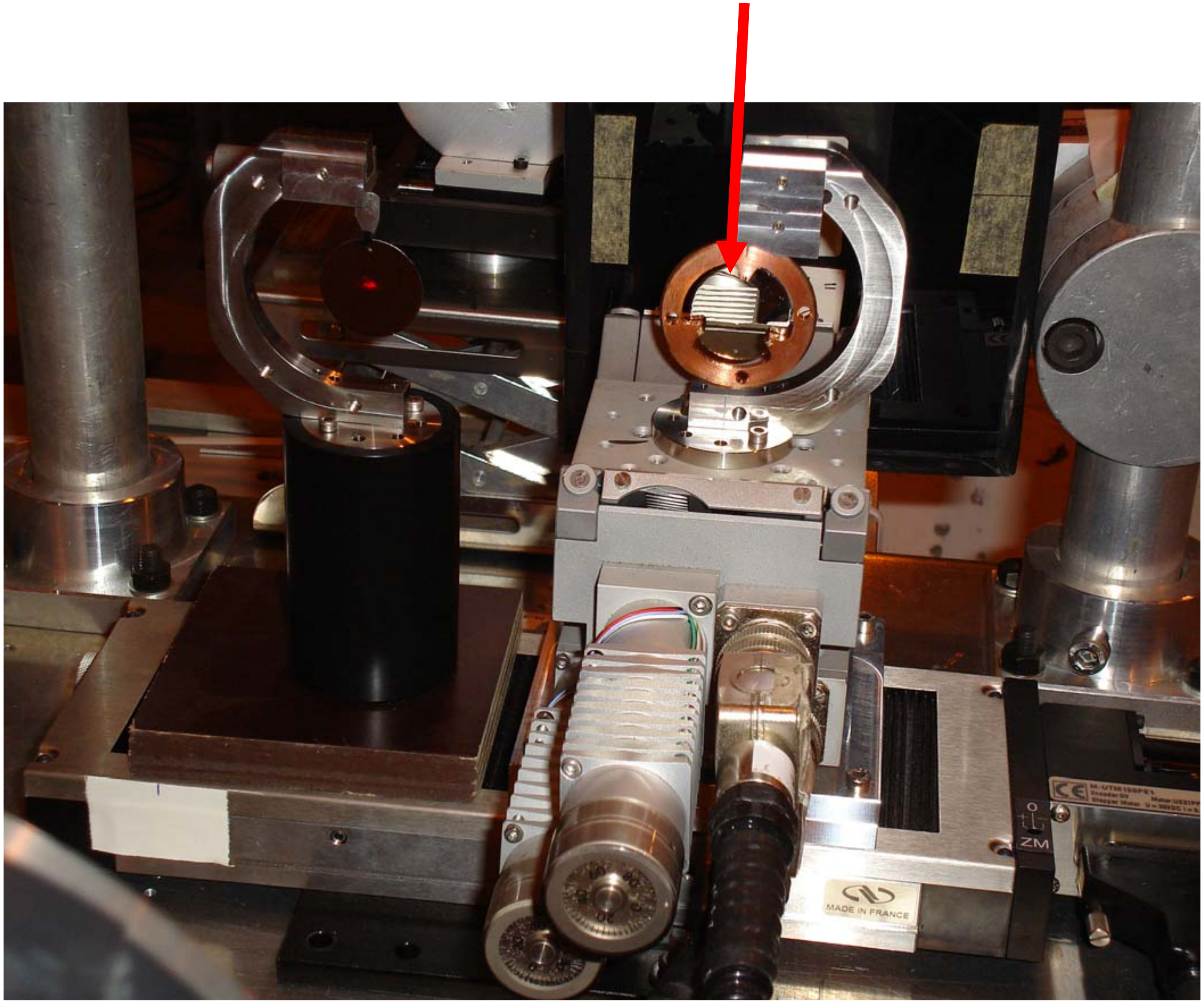
$$\chi = \gamma \mathcal{E} / \mathcal{E}_0$$

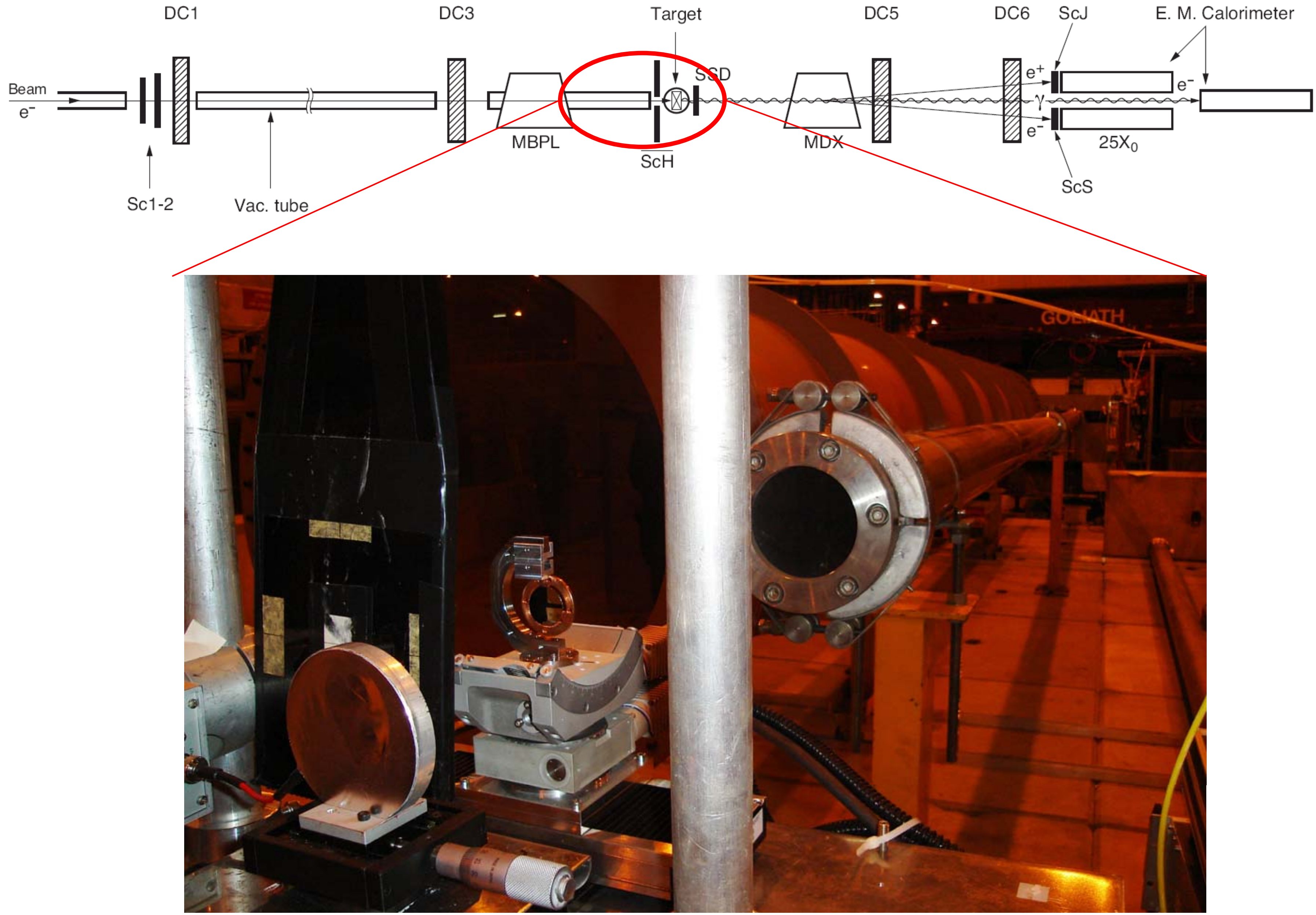
$$\mathcal{E}_0 = mc^2/e\lambda_c = 1.32{\cdot}10^{16}\ \mathrm{V/cm}$$



$$10^{11} - 10^{12}\ \mathrm{V/cm}$$

Crystal on goniometer





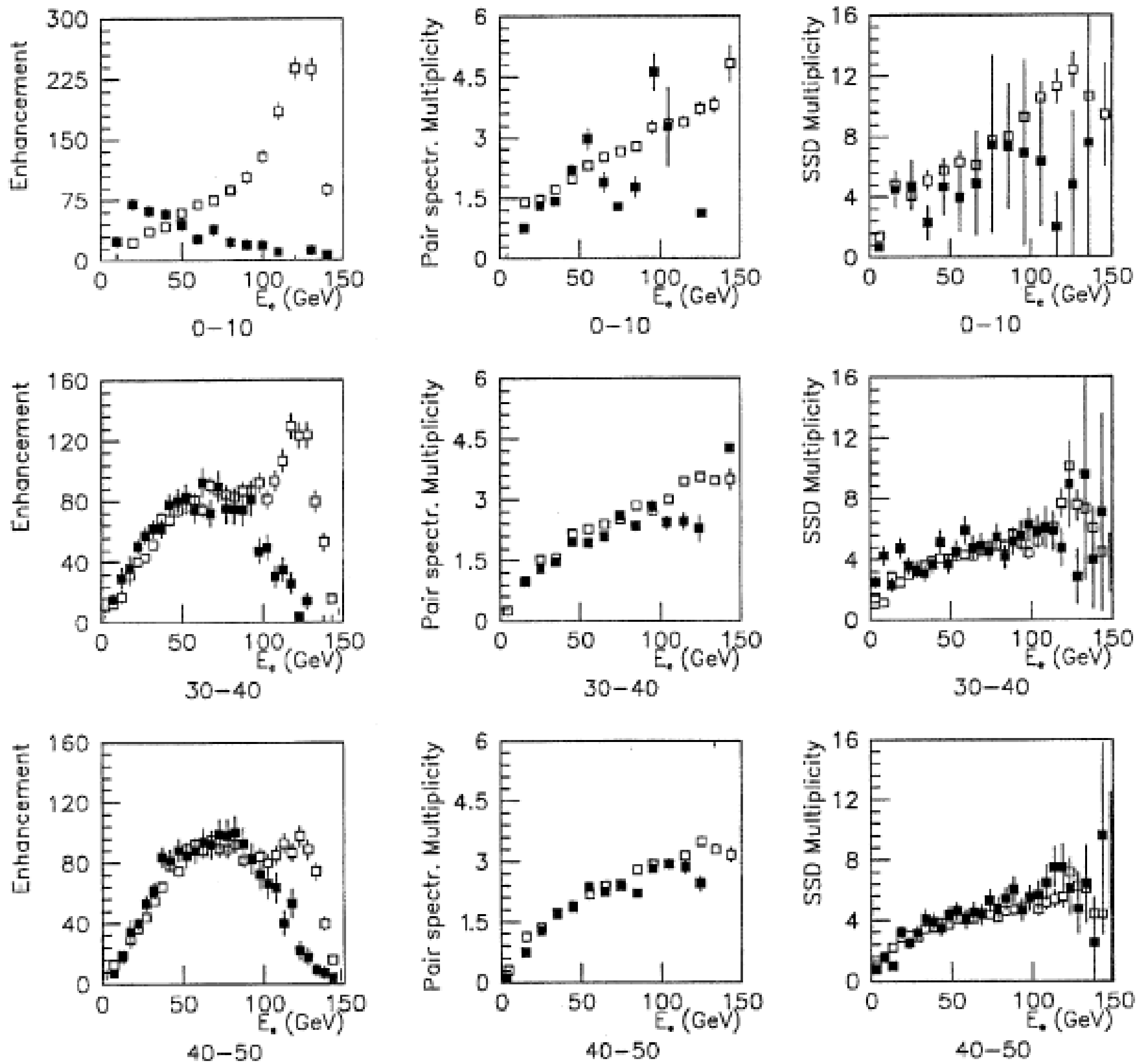
Total length of setup: 65 m => good angular resolution (few μrad)

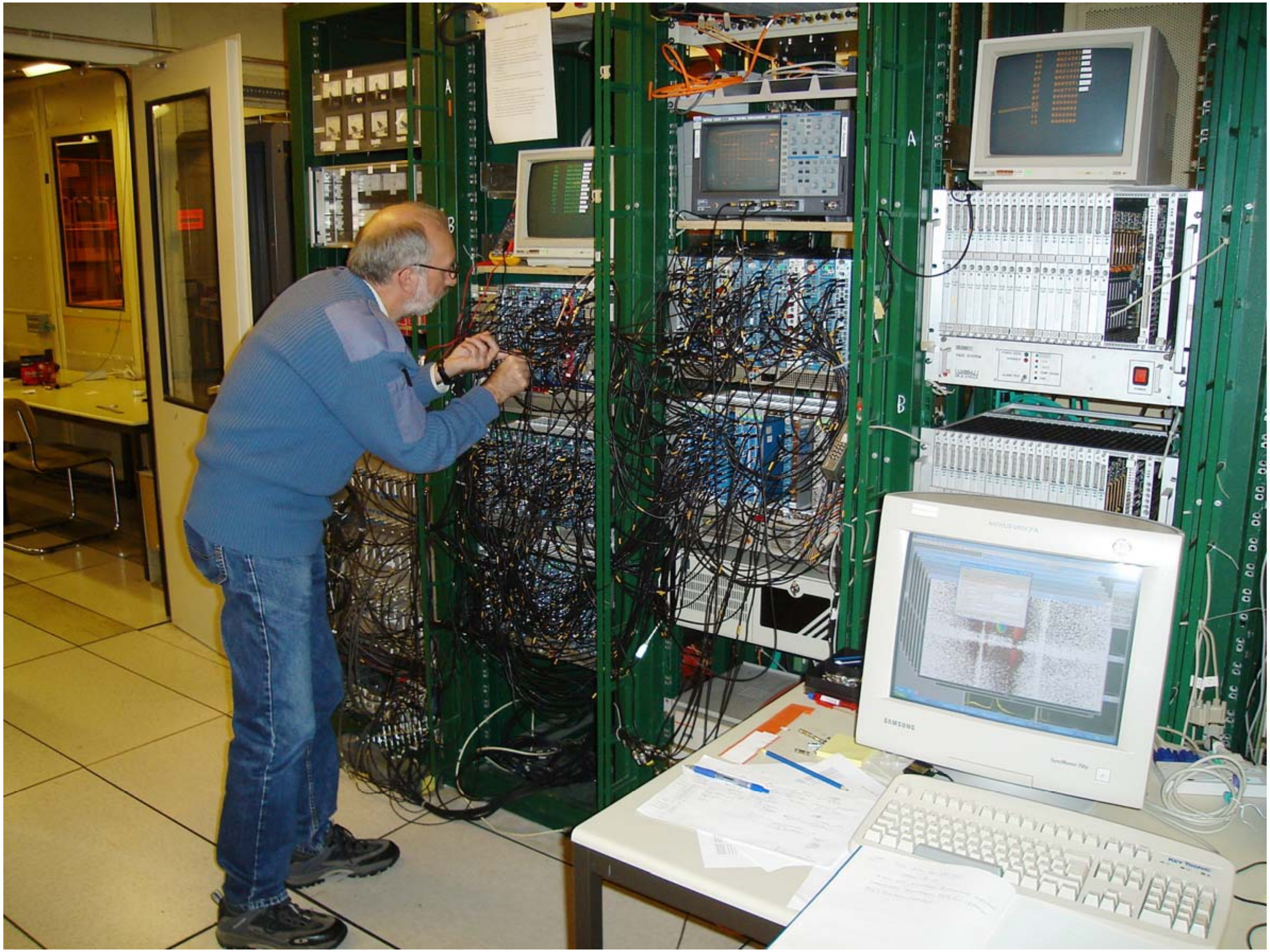
Strong crystalline fields

- Critical fields can be simulated in a crystal.
- Example: Radiation emission in diamond

  (CERN NA43)

K. Kirsebom et al. / Nucl. Instr. and Meth. in Phys. Res. B 174 (2001) 274–296

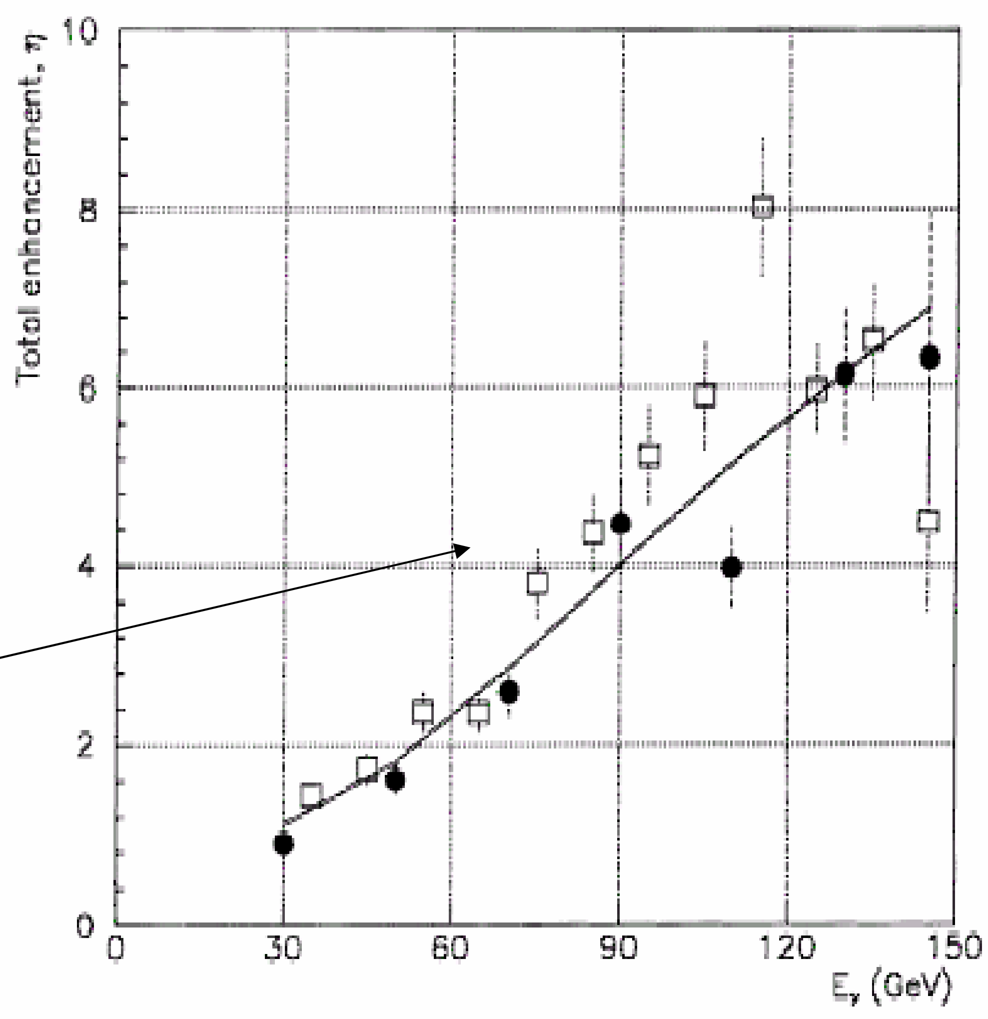




One of the complications -
Setting up within a few days: Electronics, hardware, crystal target….

Strong crystalline fields

- Critical fields can be simulated in a crystal.
- Example: Pair production in Ge (CERN NA43)



Baier: W and Ir

Quantum synchrotron

PHYSICAL REVIEW VOLUME 75, NUMBER 12 JUNE 15, 1949

On the Classical Radiation of Accelerated Electrons

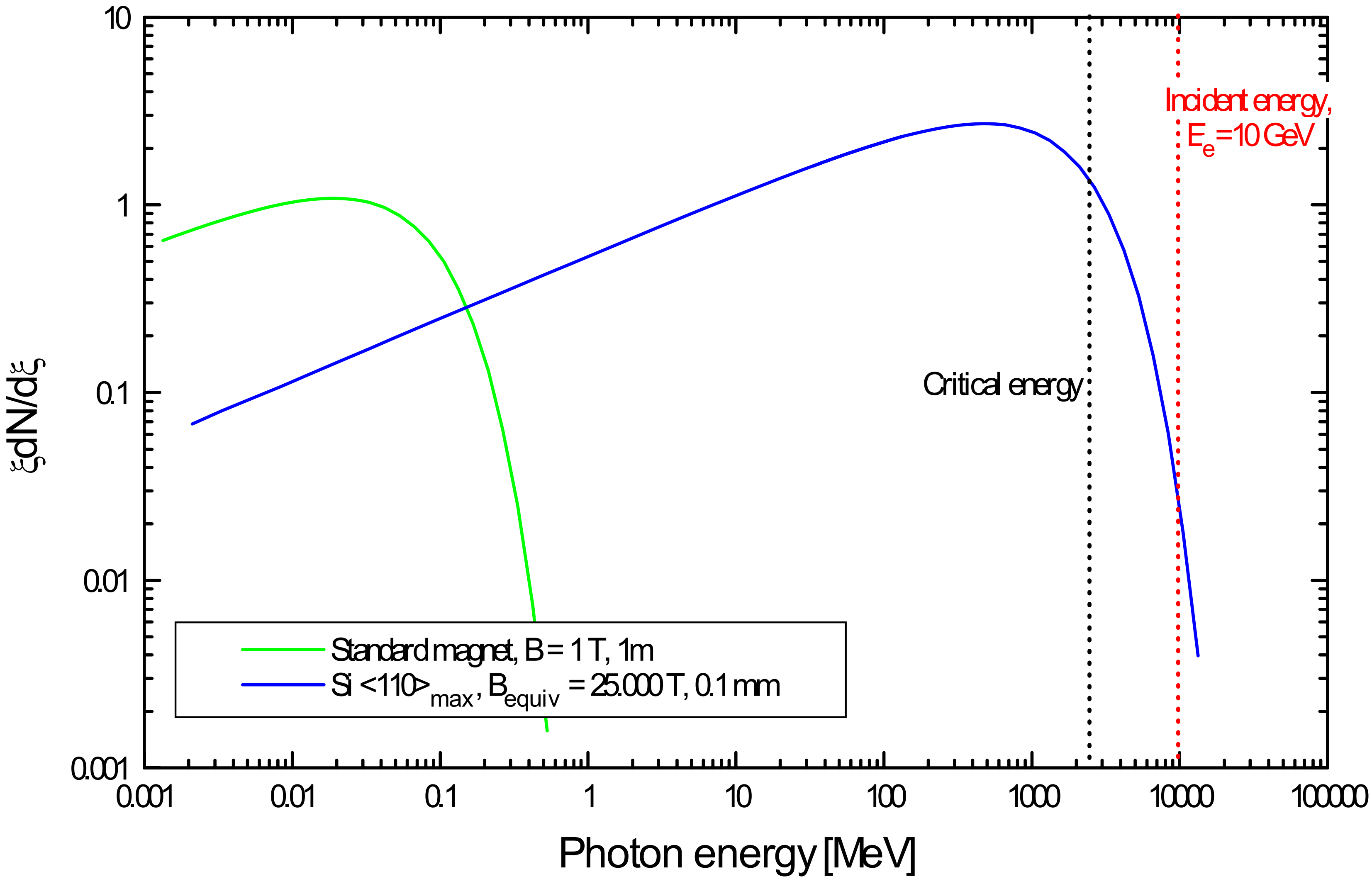
JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts
(Received March 8, 1949)

$\chi << 1$

We shall conclude this section by briefly examining under what conditions quantum phenomena will invalidate the classical considerations we have presented. This will occur when the momentum of the emitted quantum is comparable with the electron momentum. Hence, for the validity of our classical treatment, it is required that

$$\frac{E}{mc^2} \ll \frac{mc^2}{(e\hbar/mc)H}, \qquad \text{(II.56)}$$

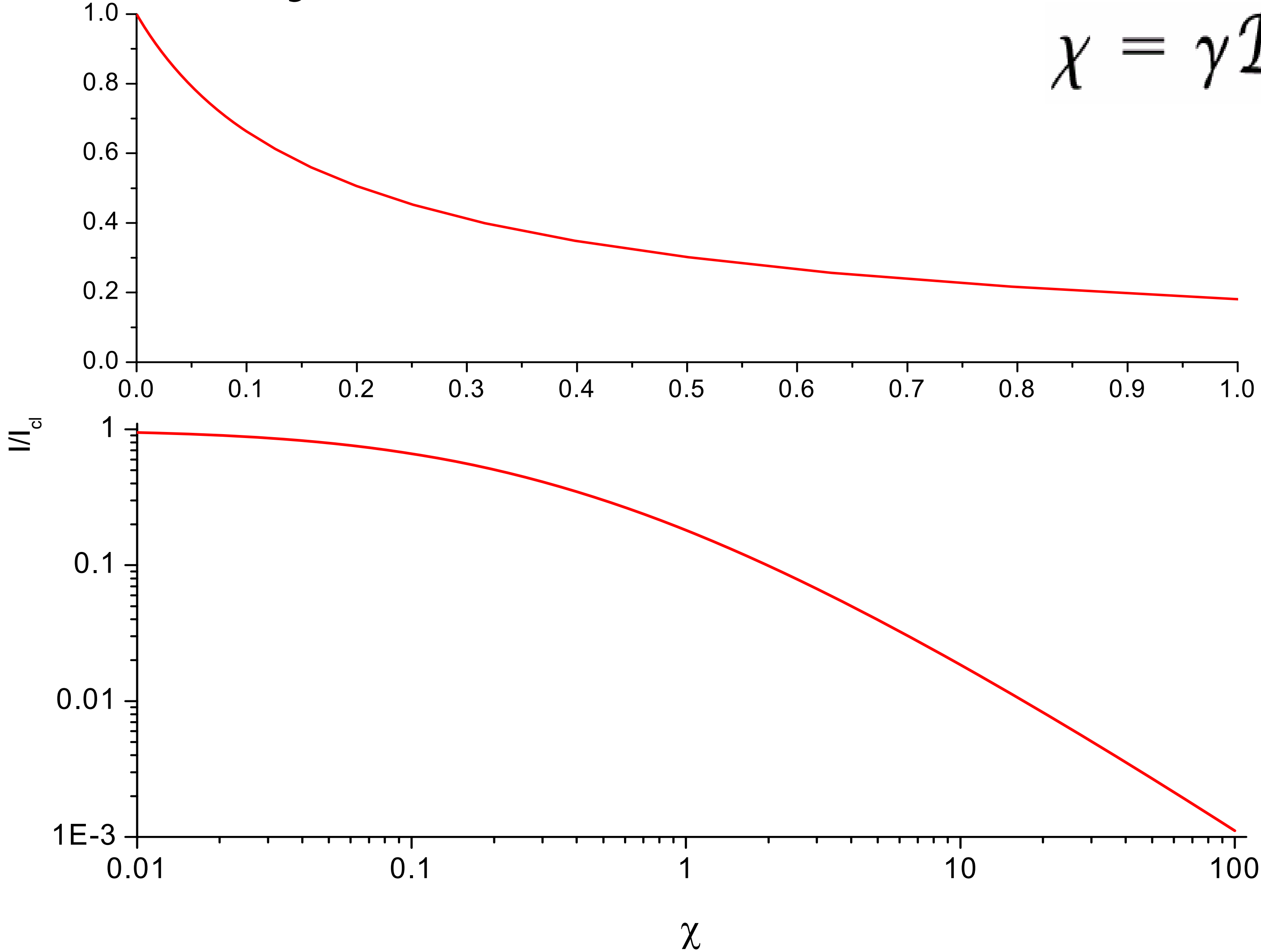
Classical synchrotron-radiation



$$\hbar\omega_c/E_e \simeq 3\gamma^3\hbar eB/2pE_e = 3\gamma B/2B_0$$

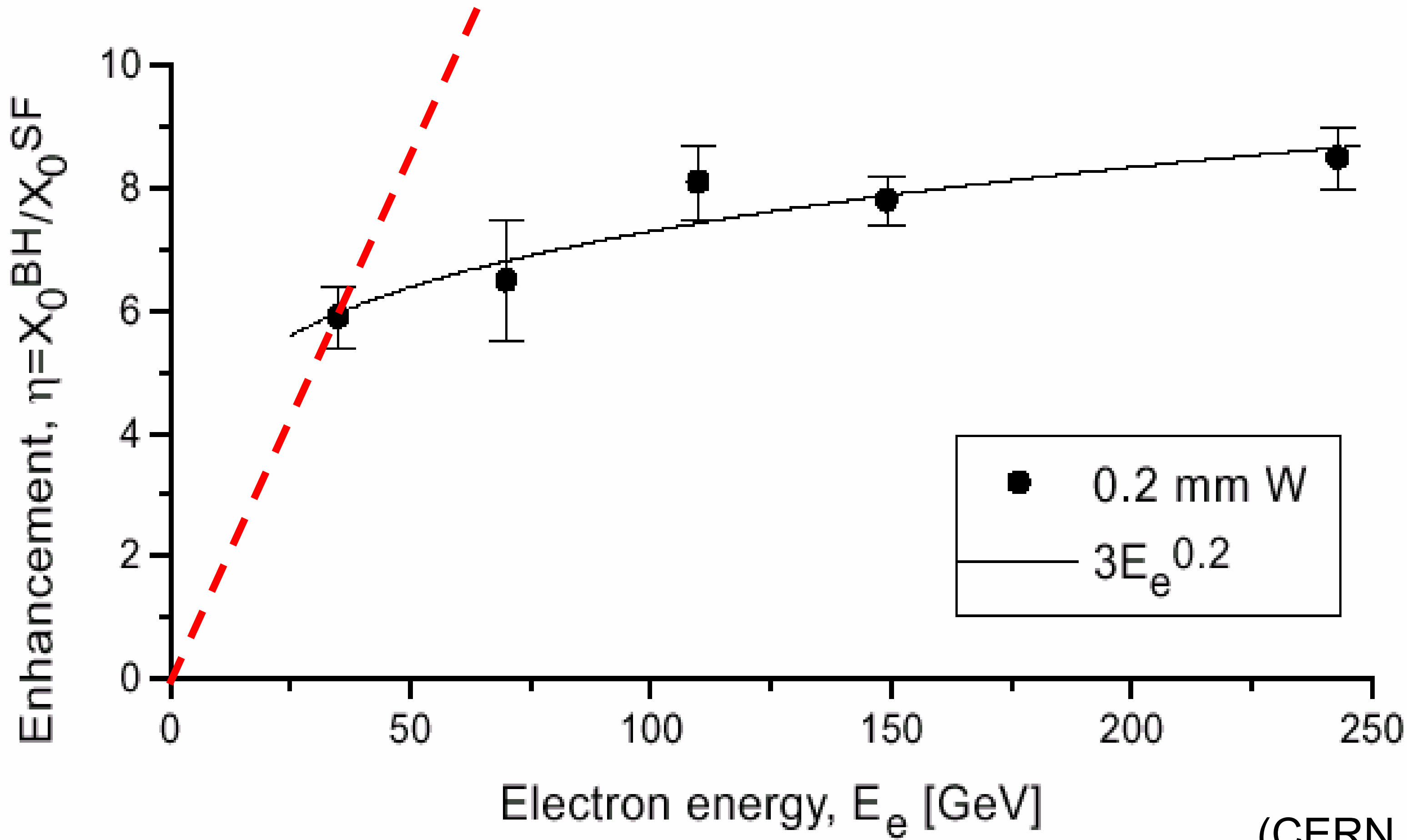
Synchrotron-radiation

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



Schwinger, Proc. Nat. Acad. Sci. 1954; Berestetskii, Lifshitz, Pitaevskii

Quantum-synchrotron



(CERN NA43)

$$\Delta E/\Delta E_{\rm cl} \simeq 1.2\chi^{-4/3} \qquad \chi \gg 1$$

Classical = linear

Coherent and incoherent radiation from high-energy electron and the LPM effect in oriented single crystal

V.N. Baier*, V.M. Katkov

Physics Letters A 353 (2006) 91–97

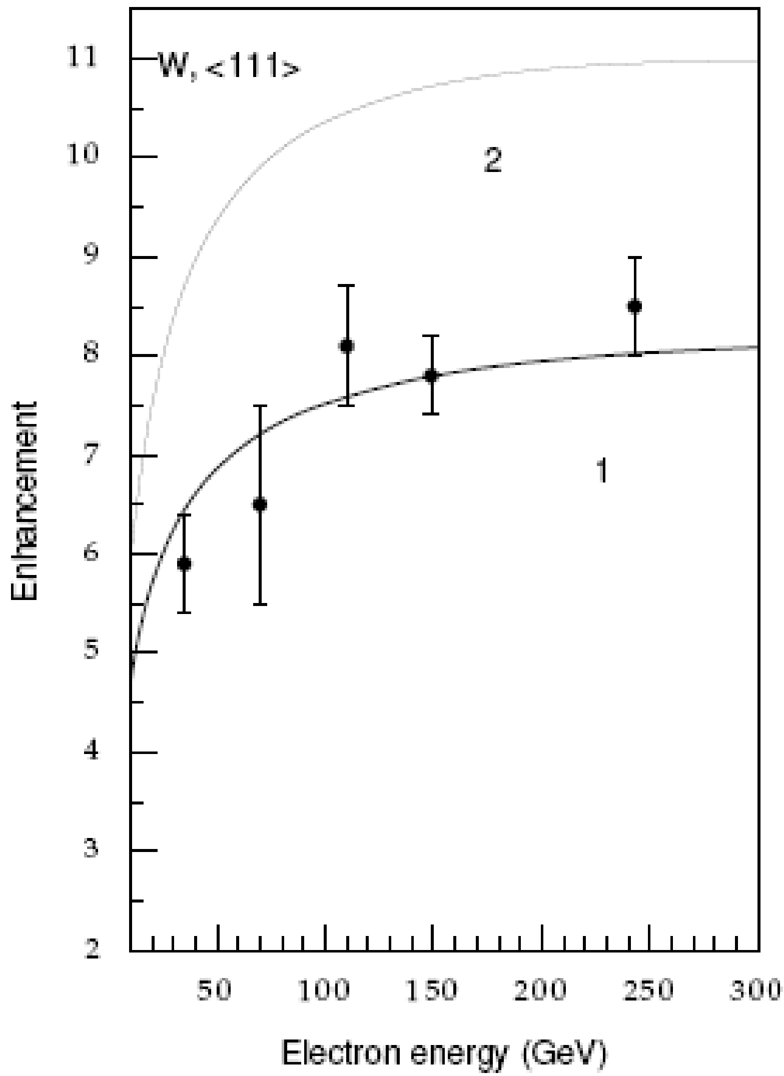


Fig. 2. Enhancement (the ratio L^{BM}/L^{ef}) in tungsten, axis ⟨111⟩, $T = 293$ K. Curve 1 is for the target with thickness $l = 200$ μm, where the energy loss was taken into account (according with Eq. (24)). Curve 2 is for a considerably more thinner target, where one can neglect the energy loss ($L^{ef} \to L^{cr}$). The data are from [8].

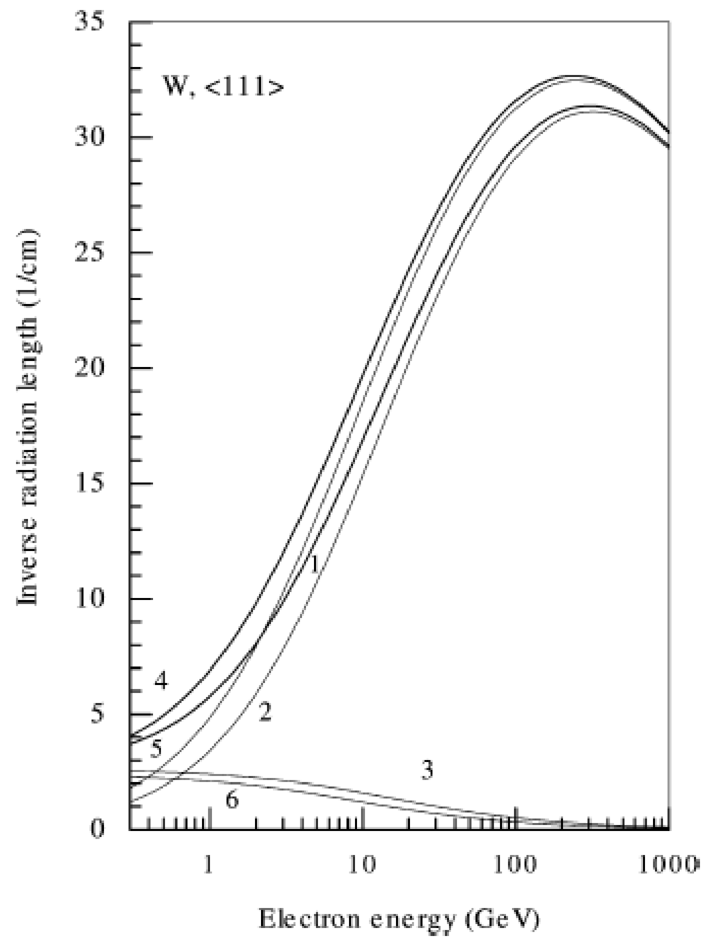
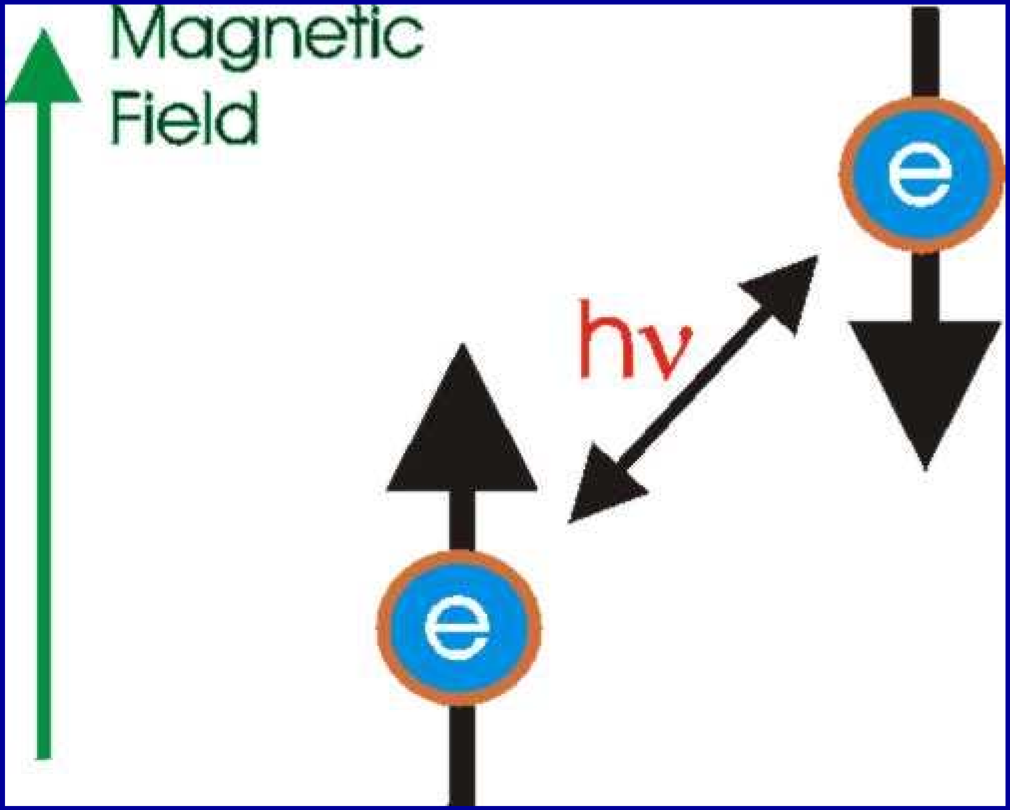
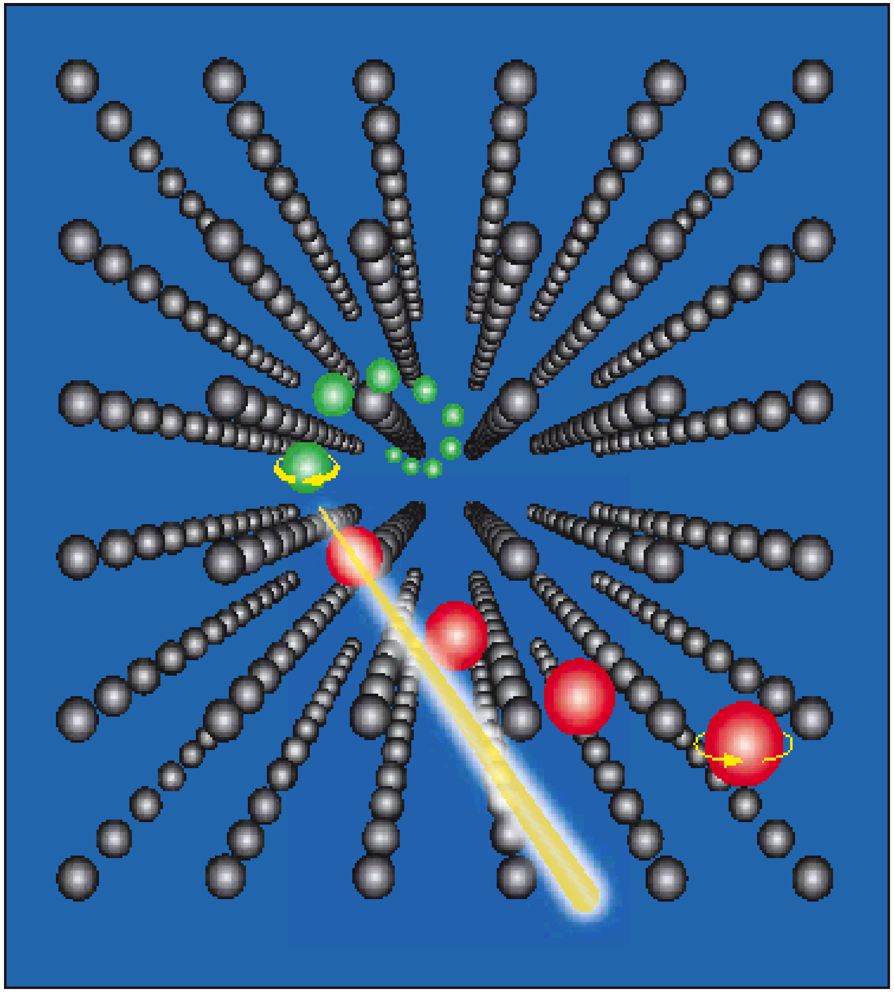


Fig. 1. The inverse radiation length in tungsten, axis ⟨111⟩ at different temperatures T vs. the electron initial energy. Curves 1 and 4 are the total effect: $L^{cr}(\varepsilon)^{-1} = I(\varepsilon)/\varepsilon$ (Eq. (18)) for $T = 293$ K and $T = 100$ K correspondingly, the curves 2 and 5 give the coherent contribution $I^F(\varepsilon)/\varepsilon$ (Eq. (25)), Curves 3 and 6 give the incoherent contribution $I^{inc}(\varepsilon)/\varepsilon$ (Eq. (27)) at corresponding temperatures T.

Spin-flip



Spin-flip



$$B = \gamma \beta \mathcal{E}_{\rm lab}$$

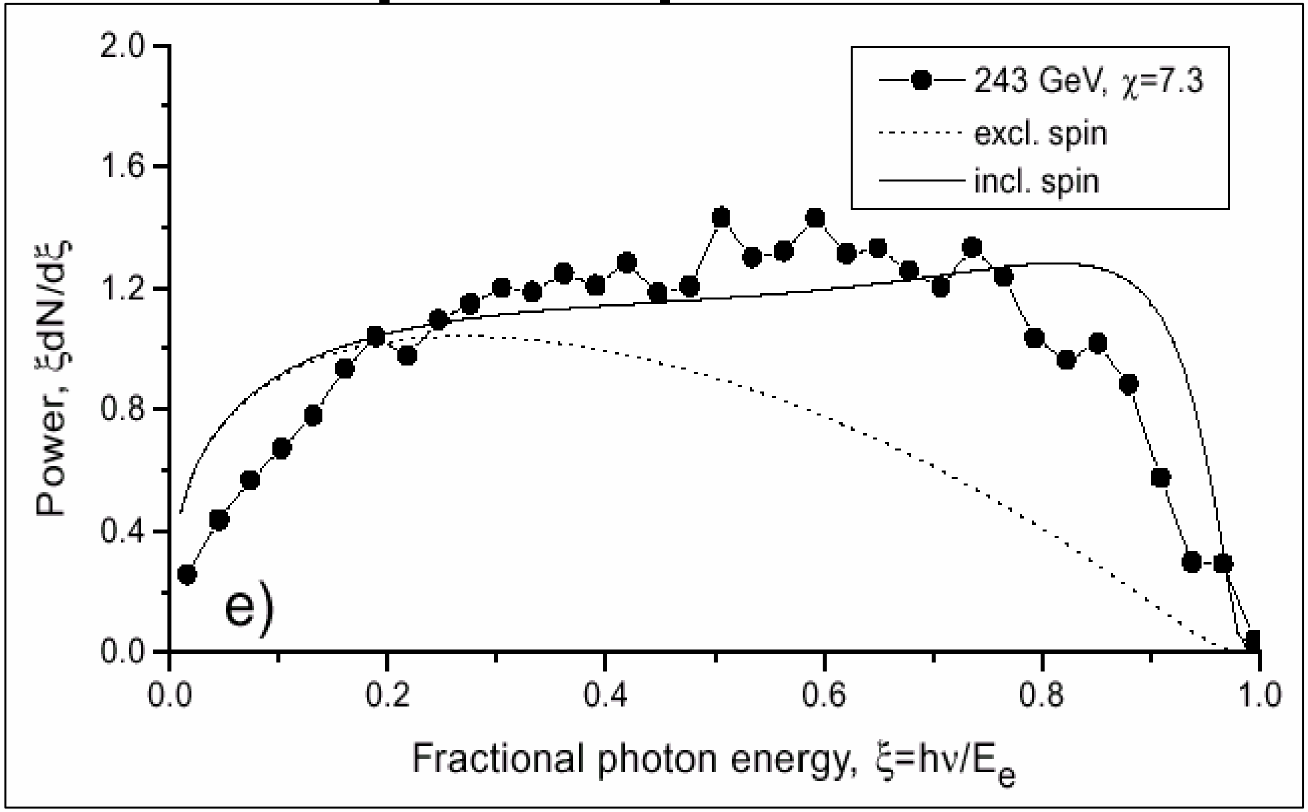
$$W_{\rm mag} = -\overline{\mu} \cdot \overline{B}$$

$$\Delta W = e\hbar B / mc$$

$$\mathcal{E}_0 = m^2 c^3 / e\hbar$$

$$\Delta W = \gamma^2 \beta \frac{\mathcal{E}}{\mathcal{E}_0} mc^2$$

Spin-flip



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

$$\Delta W = \gamma^2 \beta \frac{\mathcal{E}}{\mathcal{E}_0} mc^2$$

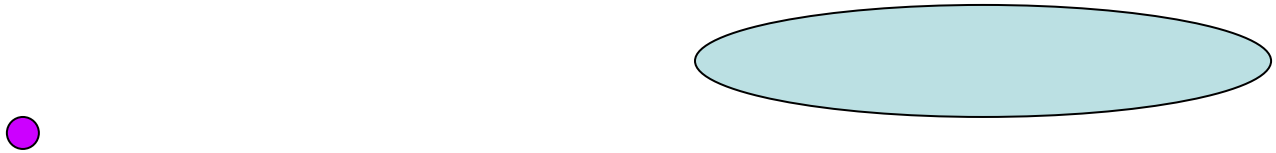
$$\tau = \frac{8\hbar}{5\sqrt{3}\,\alpha m} \left(\frac{B_0}{B}\right)^3 \frac{1}{\gamma^2} = \frac{8\hbar}{5\sqrt{3}\,\alpha m} \frac{\gamma}{\chi^3}$$

'Polarization time'

Similar situations

Blankenbecler, Drell (PRD **36**, 277 (1987), Quantum treatment of beamstrahlung:
”Pulse transforms into a very long narrow ’string’ of *N* charges.”

ILC / CLIC



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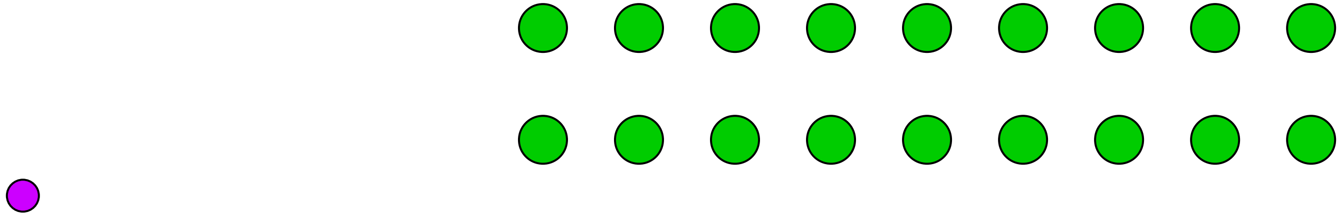
Density: 0.005 Å^{-3}, 0.6 Å^{-3} (at IP)

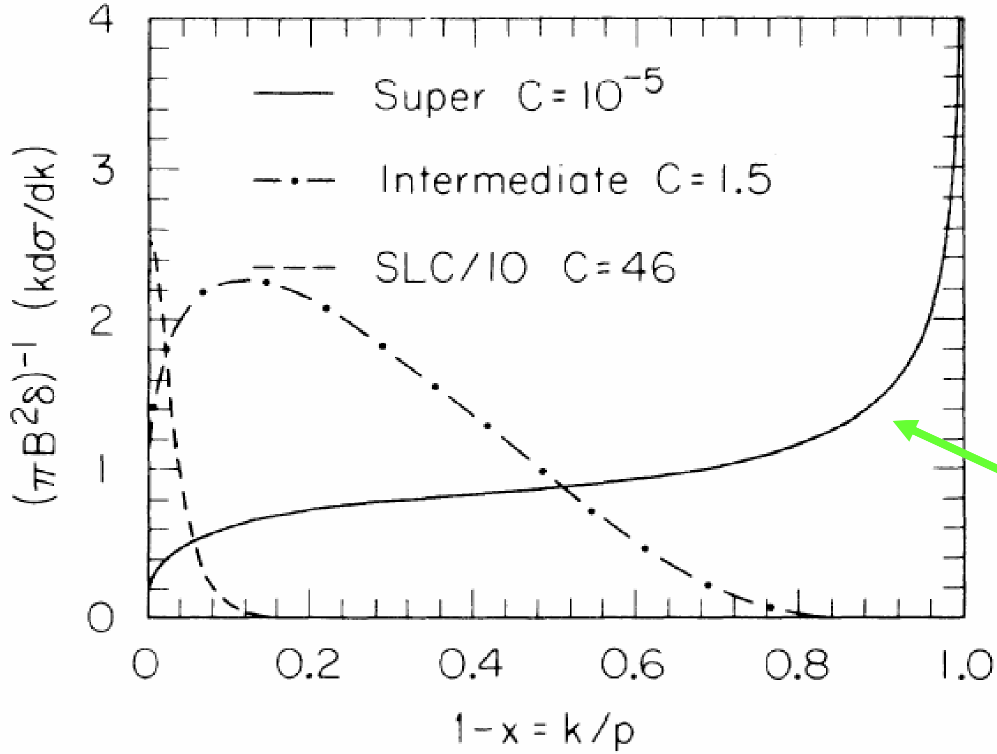
Si crystal



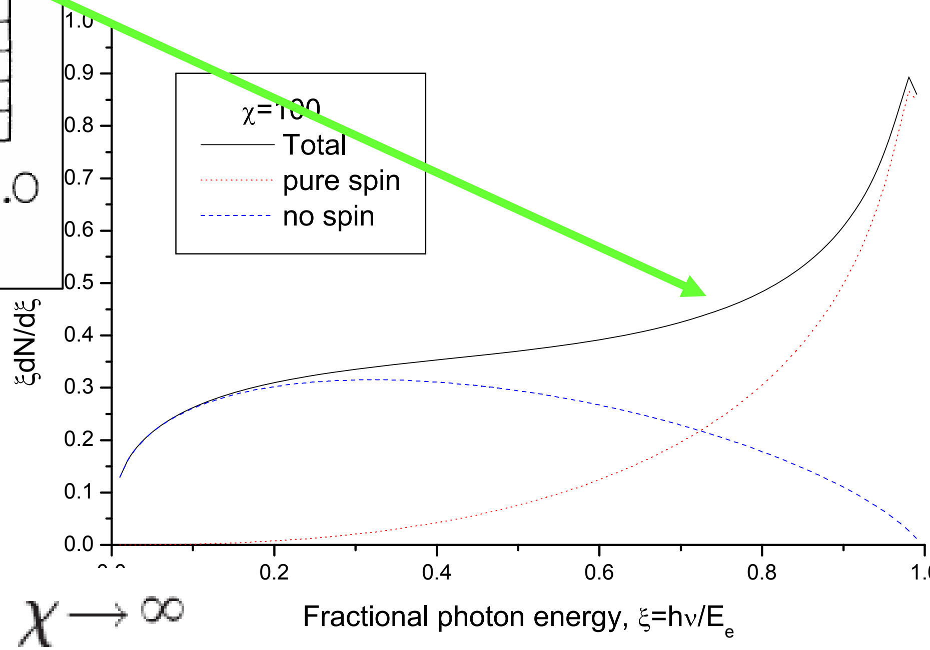
Density: 0.05 Å^{-3}, of Z = 14

Spin contr. to beamstrahlung

Blankenbecler and Drell, "Quantum treatment of beamstrahlung", PRD **36**, 277 (1987)



Radiation from crystal

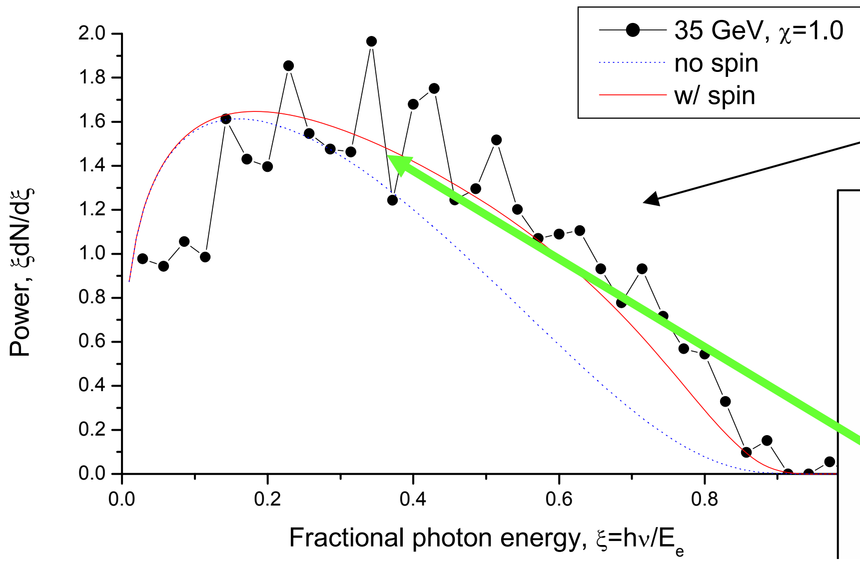


$C \approx 1/\chi$

Spin-flip contribution:

$$\xi dN/d\xi \propto [\xi^7/(1-\xi)]^{1/3}\chi^{2/3} \quad \text{for} \quad \chi \longrightarrow \infty$$

Spin contr. to beamstrahlung



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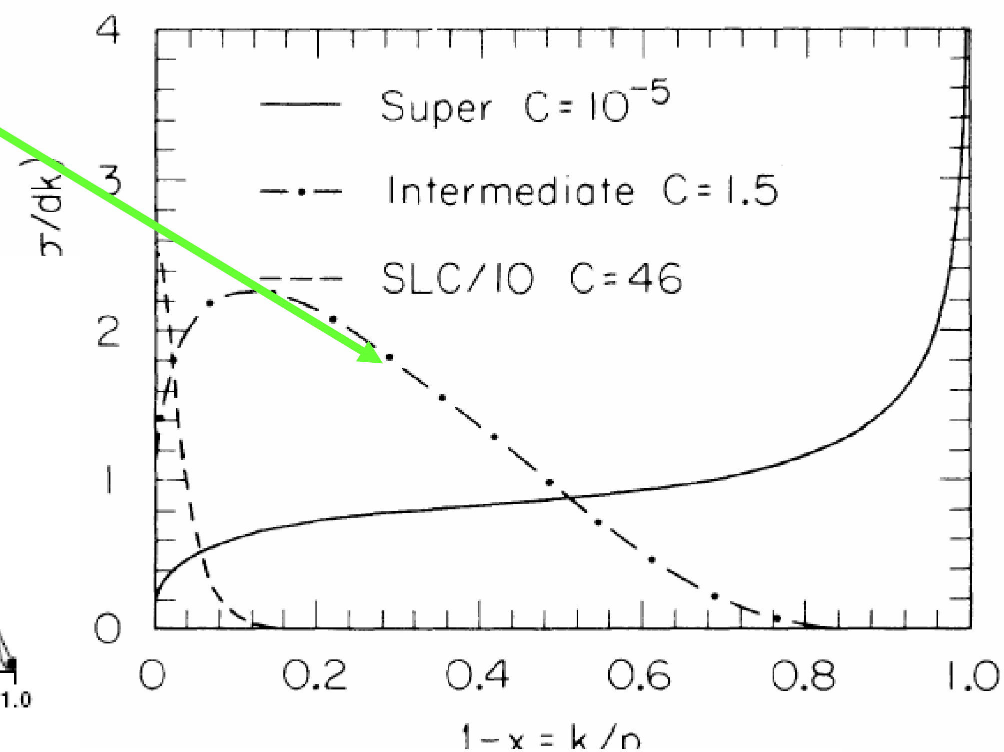
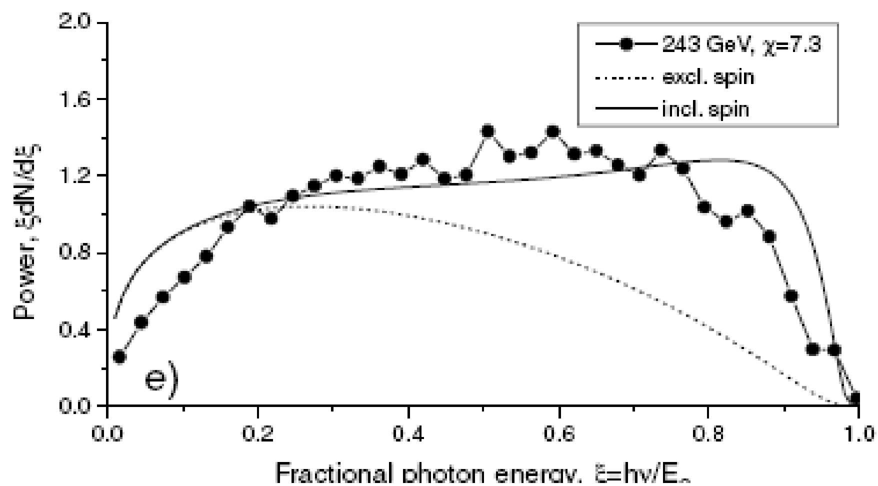




VOLUME 87, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JULY 2001

First Measurements of the Unique Influence of Spin on the Energy Loss of Ultrarelativistic Electrons in Strong Electromagnetic Fields

Trident production

$$e^- \rightarrow e^- e^+ e^-$$

'Coherent pairs'

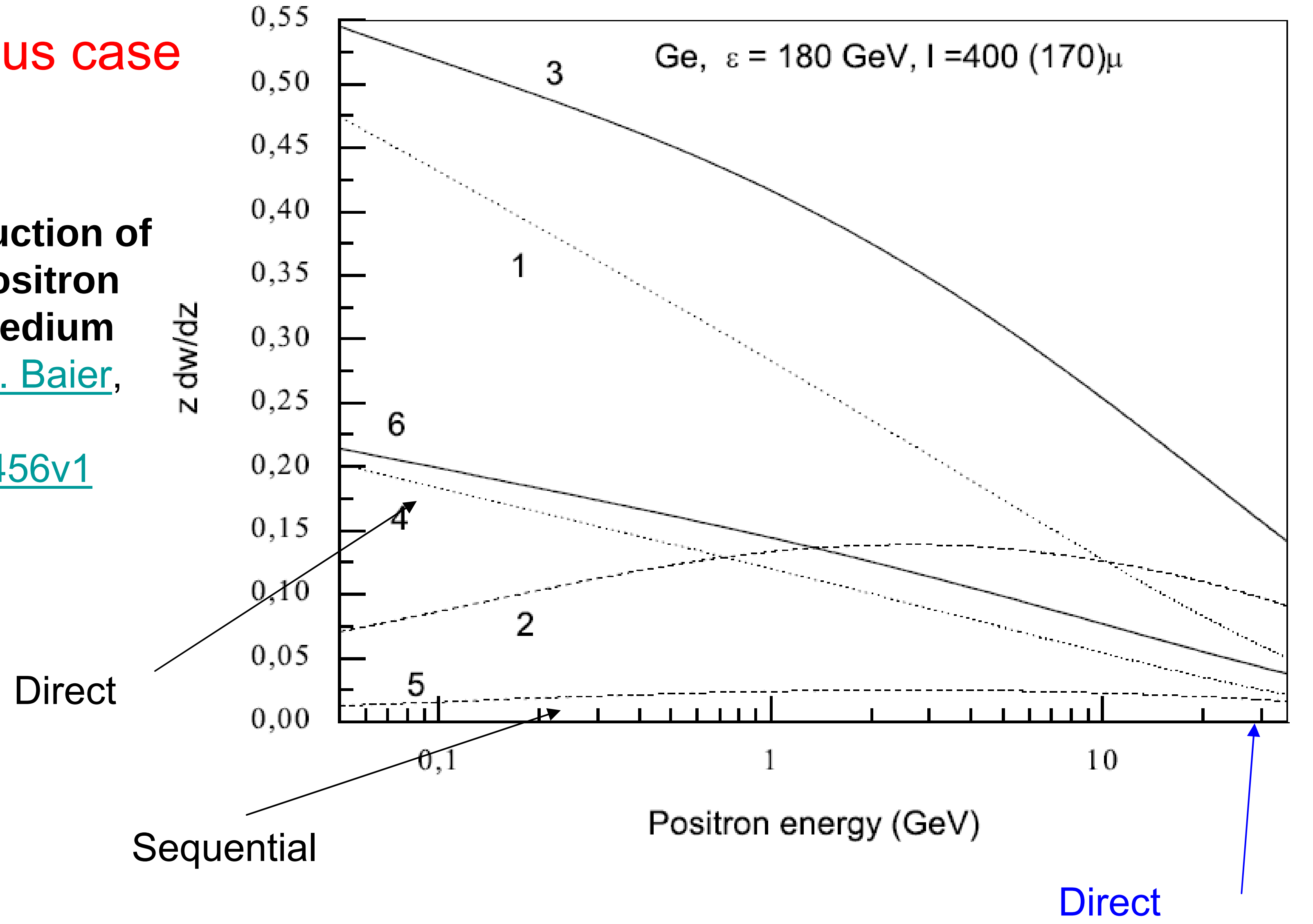
'Landau-Lifshitz process'

Amorphous case

Electroproduction of electron-positron pair in a medium

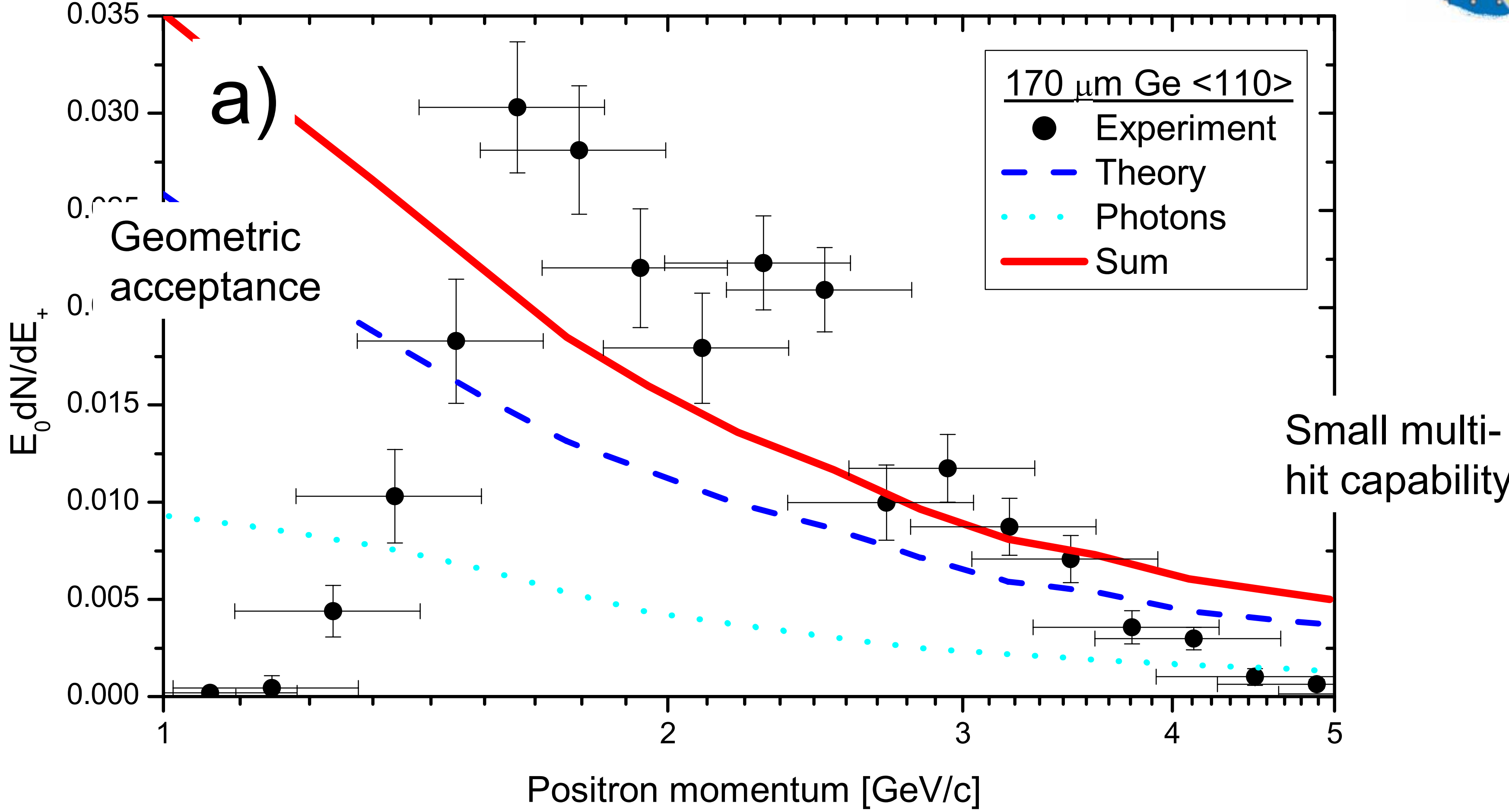
Authors: V. N. Baier, V. M. Katkov

arXiv:0805.0456v1 [hep-ph]



The combination zdw/dz for the pair electroproduction probability in amorphous Ge at the initial electron energy $\varepsilon = 180$ GeV. The dotted curves 1 and 4 are the contributions of two-photon diagrams Eq.(3), the dashed curves 2 and 5 are the contributions of cascade process Eq.(11), the solid curves 3 and 6 are the sum of two previous contributions for two thicknesses $l = 400\ \mu m$ and $l = 170\ \mu m$ respectively. For convenience the ordinate is multiplied by 10^3.

Non-aligned crystal



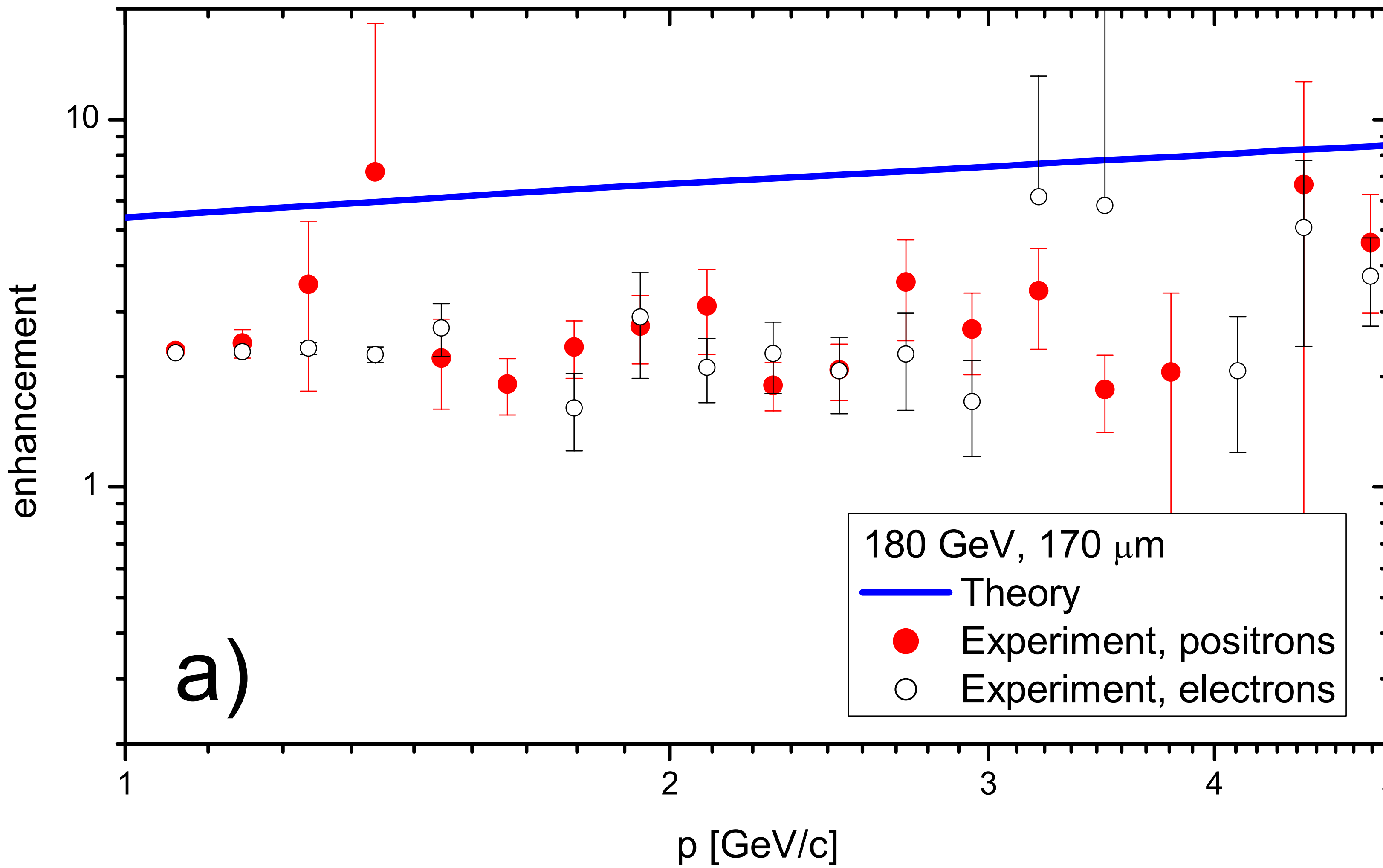
Pis'ma v ZhETF, vol. 88, iss. 2, pp. 88 – 92 JETP Lett.**88**:80-84,2008

Electroproduction of electron-positron pair in a medium

V. N. Baier[1], *V. M. Katkov*

Budker Institute of Nuclear Physics RAS, 630090 Novosibirsk, Russia

Aligned crystal



Electroproduction of electron-positron pair in oriented crystal at high energy

V. N. Baier and V. M. Katkov
Budker Institute of Nuclear Physics, Novosibirsk, 630090, Russia

arXiv:0810.1802v1 [hep-ph] Phys. Lett. A, accepted

October 10, 2008

More about these and related effects in:

NA63

REVIEWS OF MODERN PHYSICS, VOLUME 77, OCTOBER 2005 1131

The interaction of relativistic particles with strong crystalline fields

Ulrik I. Uggerhøj

Department of Physics and Astronomy, University of Aarhus, Denmark

•H.D. Hansen, U.I. Uggerhøj, C. Biino, S. Ballestrero, A. Mangiarotti, P. Sona, T. Ketel and Z.Z. Vilakazi: Is the electron radiation length constant at high energies?, Phys. Rev. Lett. vol. 91, 014801 (2003)

•H.D. Hansen, U.I. Uggerhøj, C. Biino, S. Ballestrero, A. Mangiarotti, P. Sona, T. Ketel and Z.Z. Vilakazi: The LPM effect for multi-hundred GeV electrons, Phys. Rev. D vol. 69, 032001 (2004)

•U.I. Uggerhøj, H. Knudsen, S. Ballestrero, A. Mangiarotti, P. Sona, T.J. Ketel, A. Dizdar, S. Kartal and C. Pagliarone: Formation length effects in very thin targets, Phys. Rev. D vol. 72, 112001 (2005)

•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: On the macroscopic formation length for GeV photons, subm. to Phys. Lett. B (2008)

•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. vol. 100, 164802 (2008)

•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): Addressing the Klein paradox by trident production in strong crystalline fields, in preparation (2008)

Thank you for your attention!