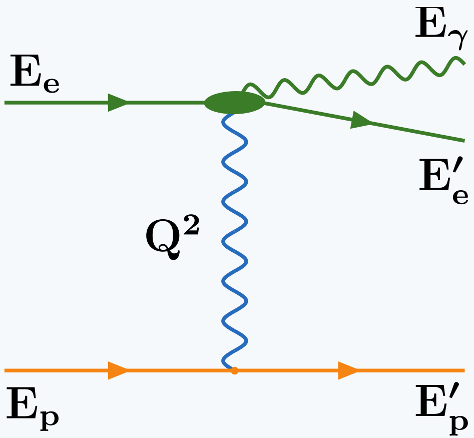
(Coherent) Bremsstrahlung @ CEPC



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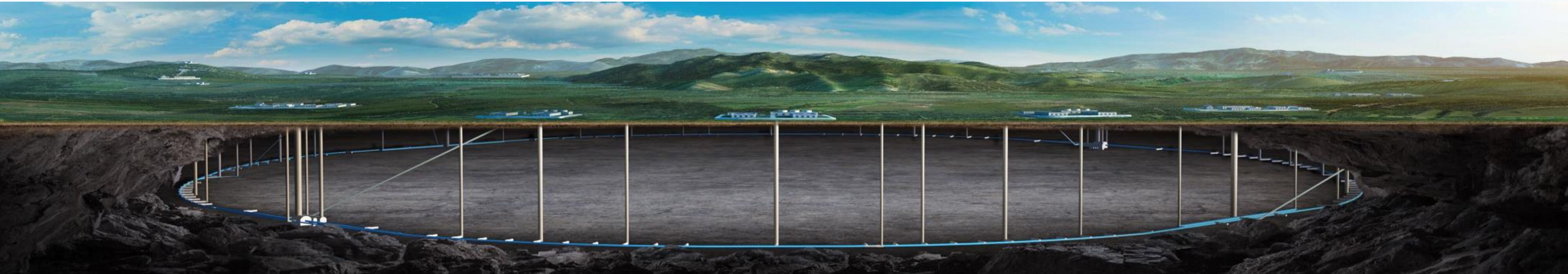
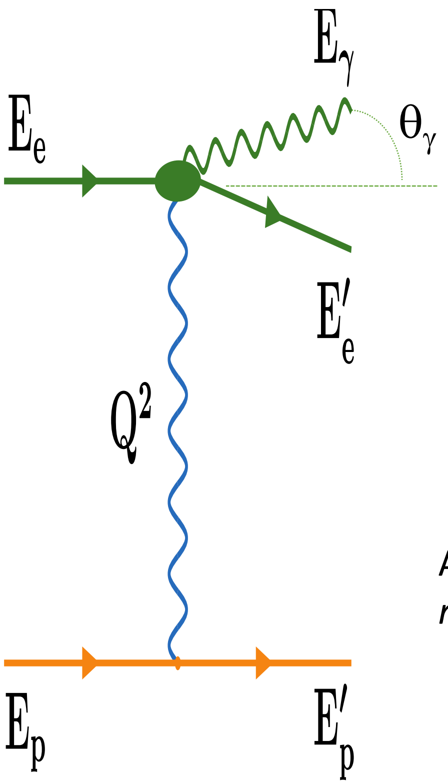


e^+e^- bremsstrahlung *aka* radiative Bhabha scattering at high energies



Bremsstrahlung signatures in ***electron-positron collisons*** $e^- + e^+ \rightarrow e^{-\prime} + \gamma + e^+$:

$E'_e + E_\gamma = E_e$ with very (very) high accuracy, and it is "zero-angle process"

$\Rightarrow$ typ. polar angles for photons/scattered electrons, $\theta_\gamma \approx \theta_e \approx m_e/E_e$

It is kinematically allowed that $\theta_\gamma = \theta_{e'} = \theta_p = 0$ hence there is no transverse momentum transfer, which results in (for variables in LAB):

$$|q_{min}| = m_e^3\, E_\gamma/(4\, E_p\, E_e\, E'_e),$$ where

$$Q^2 = -q^2 \simeq -q^2_{min} + q_T^2$$

At CEPC, for $E_e = E_p = 180$ GeV and $E_\gamma = 2$ GeV, minimal momentum transfer, *in positron rest-frame*, $\Delta p_z = |q_{min}|/c \approx 10^{-8}$ eV/c ! Corresponding to kin. energy transfer $= (\Delta p)^2/2M \approx 10^{-22}$ eV !

That corresponds to coherence length $\boldsymbol{l_c = \hbar/\Delta p_z \approx 20}$ **m** whereas in transverse plane impact parameters can be even larger

Higher beam energies/lower photon energy $\Rightarrow$ **more** extreme it becomes!

Bremsstrahlung and *Beam Size Effect(s)*

$$d^3\sigma/dE_\gamma\, d\theta_e d\theta_\gamma \propto Q^{-4}$$

hence cross-section integrated over angles, that is bremsstrahlung spectrum, is dominated by large distance contributions

$p_T = 0$ → infinite impact parameter!

$p_{T,typ} \approx |q_{min}|/c$ → **Beam-Size Effect** - *apparent* bremsstrahlung *suppression* at colliders, at low E_γ, due to finite beam-sizes

Discovered at VEPP-4 [Phys. Lett. B113 (1982) 423], measured also at HERA I [Z. Phys. C67 (1995) 577] , will be deeply studied at EIC [Phys. Rev. D103 (2021), no. 5 L051901]

Nota bene: This has nothing to do with "environmental effects" – it is present in proper "binary" processes ⇒ collisions of single particles

BSE is directly related to ("text-book") **definition** of cross-sections:

Event rate = Luminosity × σ

where colliding particles are represented by plane waves. But this assumption is invalid if lateral sizes of <u>both</u> beams are comparable to relevant impact parameter of process.

In this case *wave-packet formalism* must be used ⇒ Int. J. Mod. Phys. A7 (1992) 4707

BSE @ FCC-ee

Eur. Phys. J. C (2023) 83:802
https://doi.org/10.1140/epjc/s10052-023-11981-2

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

High energy bremsstrahlung at the FCC-ee, FCC-eh and LHeC

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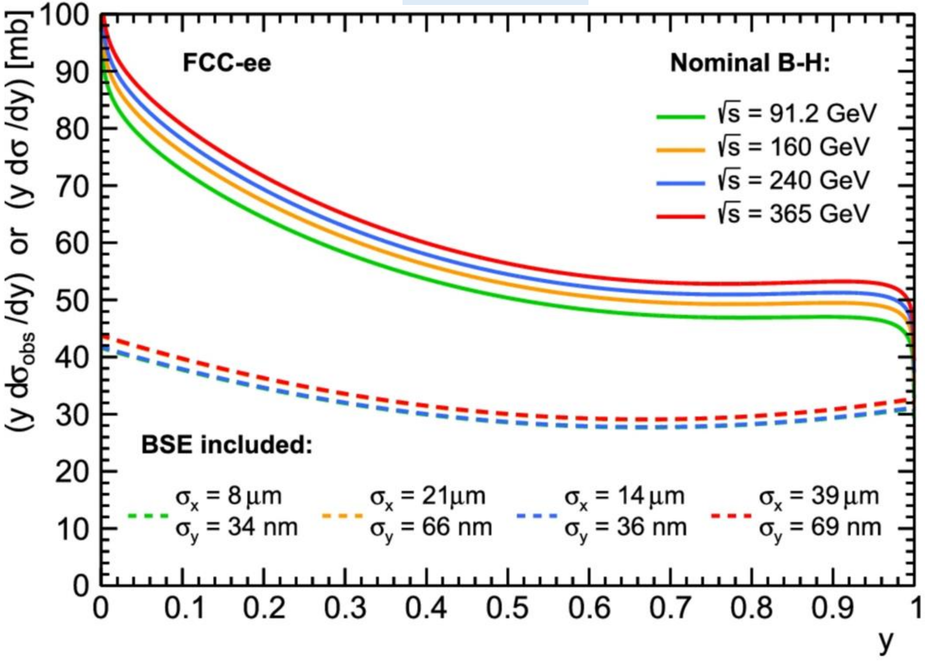
At very high energies, for small flat beams, bremsstrahlung spectrum depends only on vertical beam sizes! ⇒

$y = E_\gamma/E_e$



Bremsstrahlung spectra at the $\sqrt{s} = 91.2$ GeV, 160 GeV, 240 GeV and 365 GeV FCC-ee – solid lines $y\,\mathrm{d}\sigma/\mathrm{d}y$ are for the Bethe–Heitler nominal case and dashed ones $y\,\mathrm{d}\sigma_{\mathrm{obs}}/\mathrm{d}y$ when the BSE is included. Note that the spectra with the BSE included overlap due to similar σ_y: those at $\sqrt{s} = 160$ GeV and 365 GeV, as well as those at $\sqrt{s} = 91.2$ GeV and 240 GeV

NB: In calculations head-on collisions are assumed, and no hour-glass effects (both effects found very small)

BSE and beam lifetime @ CEPC

Radiation Detection Technology and Methods (2024) 8:1–1105
https://doi.org/10.1007/s41605-024-00463-y

IHEP-CEPC-DR-2023-01

Received: 7 March 2024 / Revised: 7 March 2024 / Accepted: 9 March 2024 / Published online: 3 June 2024

IHEP-AC-2023-01

CEPC

Technical Design Report

Accelerator

Table 4.1.1: CEPC baseline parameters in TDR

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
Bunch number	268	11934	1297	35
Bunch spacing (ns)	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Beam current (mA)	16.7	803.5	84.1	3.3
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune ν_x/ν_y	445/445	317/317	317/317	445/445
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.0/1.7	1.05/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	40/40	90/2800	60/195	81/23
Beam lifetime requirement (min)	18	77	22	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5

BSE and beam lifetime @ CEPC

E_{beam} [GeV]	45.5	80	120	180
N_b [10^{13}]	167	17.5	3.5	0.7
L_{tot} [10^{35} cm^{-2}s^{-1}]	23	3.2	1.0	0.1
σ_a [mb] for $a = 0.01$ (0.02)	169 (140)	172 (142)	170 (141)	184 (152)
τ_a [minutes]	71 (86)	53 (64)	34 (41)	63 (77)

Reminder: At very high energies, for very small flat beams, bremsstrahlung spectrum depends (logarithmically) only on vertical beam size ⇒

The integrated cross-section $\sigma_{a,\mathrm{p}} = \int_a^1 \mathrm{d}\sigma_{\mathrm{obs,p}} = 41.77 \times C(r)(a - 5/8 - 3a^2/8 - \ln a)$ [mb], where $a = y_{\min}$ and $C(r) = (1 + 0.074 \ln r)$, $r = \sigma_y/36$ nm

Coherent Bremsstrahlung: HERA case

At HERA I, for $E_\gamma = 10$ keV, $\hbar/\Delta p_z \approx$ **11 cm** at LAB $\Rightarrow$ beam electron interacts with **whole** proton bunch and bremsstrahlung event rate becomes proportional to **number of protons squared**! Hence extraordinary signal **amplification**.

The equivalent photon approximation for coherent processes at colliders

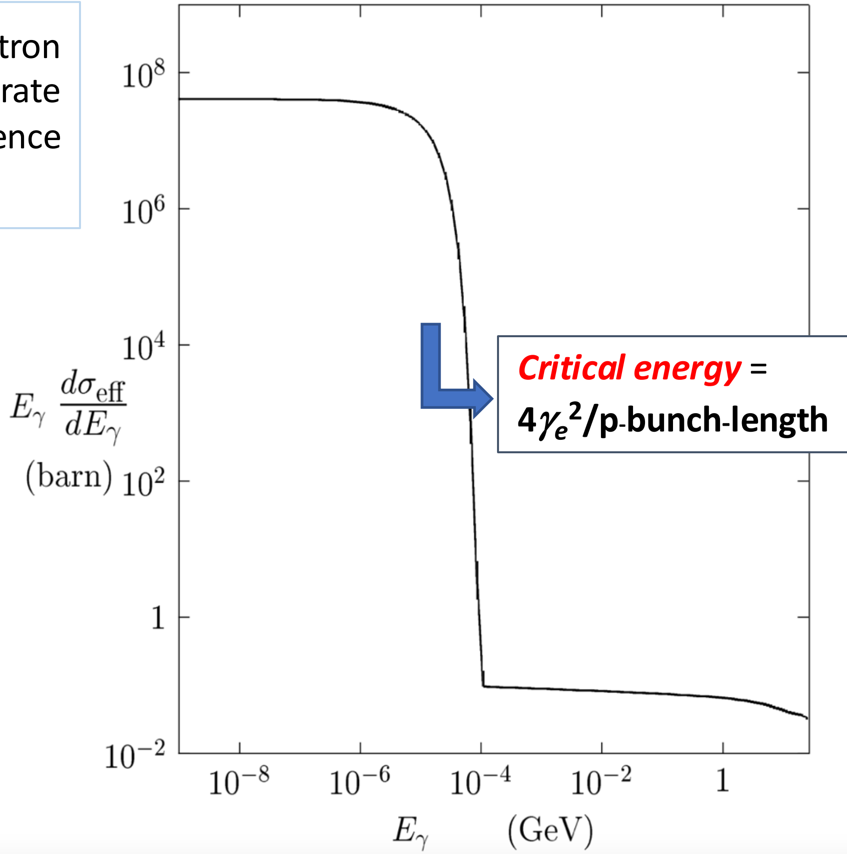
R. Engel, A. Schiller & V. G. Serbo

Zeitschrift für Physik C Particles and Fields **71**, Article number: 651 (1996) | Cite this article

78 Accesses | Metrics

Abstract

We consider coherent electromagnetic processes for colliders with short bunches, in particular the coherent bremsstrahlung (CBS). CBS is the radiation of one bunch particles in the collective field of the oncoming bunch. It can be a potential tool for optimizing collisions and for measuring beam parameters. A new simple and transparent method to calculate CBS is presented based on the equivalent photon approximation for this collective field. The results



Bremsstrahlung ⟷ Coherent Bremsstrahlung ⟷ Beamstrahlung

↳ Synchrotron radiation aka *magnetobremsstrahlung*

Coherence effects turn on when **coherence length l_c > bunch length σ_z** but properties of *coherent radiation* are different for electron average deflection angles α (in magnetic field of opposite bunch) much larger or smaller than radiation angular range $\Delta\theta \approx m_e/E_e$ – as measured by their ratio (for head-on collisions):

$$\eta \coloneqq r_e\, N_p/\sigma_x \approx \alpha/\Delta\theta$$

where r_e is classical electron radius
N_p is number of positrons
σ_x is bunch horizontal size

If $\eta \gg 1$ then corresponding radiation is called *beamstrahlung* and if $\eta \ll 1$ that is *coherent bremsstrahlung* (CBS) case – nota bene: *synchrotron radiation* is special case of beamstrahlung in uniform external field.

Reminder

Again, an important parameter, the beamstrahlung parameter Υ, is introduced. For the case $\Upsilon \ll 1$, typical energy of the photons is much smaller than the initial energy of the radiating particle and this is called the classical regime. On the contrary, when $\Upsilon \gg 1$, photons tend to

AN INTRODUCTION TO BEAMSTRAHLUNG AND DISRUPTION, P. Chen (1987)

In evaluating the spectral resolution of the radiation, the relation between the magnitude of the angular range $\Delta\theta$ and the angle of deflection α of the particle in passing through the external electromagnetic field is essential.

The Classical Theory of Fields, Landau & Lifshitz (1971)

BS vs. CBS

Total radiated energy is, as expected, (almost) **same**:

$$\delta_E = \frac{16\sqrt{3}}{5\pi^{3/2}} \frac{r_e \alpha N_e}{\sigma_x^*} \Upsilon_{ave} = \frac{24}{3\sqrt{3}\pi^{3/2}} \frac{r_e^3 \gamma N_e^2}{\sigma_z \sigma_x^{*2}}$$

$\Delta E = 0.0061\, \eta^2 \gamma^2/\sigma_z$ vs. $0.0067\, \eta^2 \gamma^2/\sigma_z$

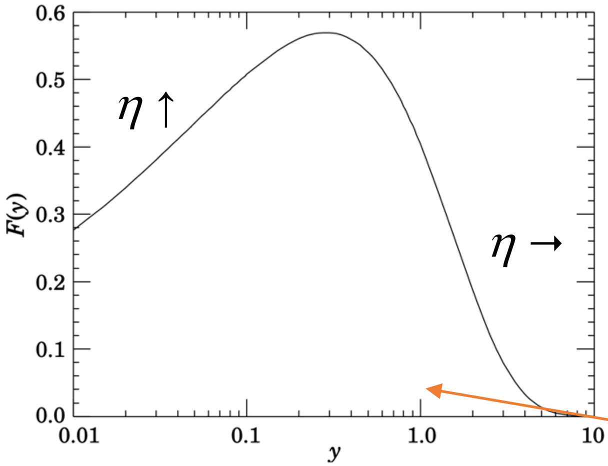
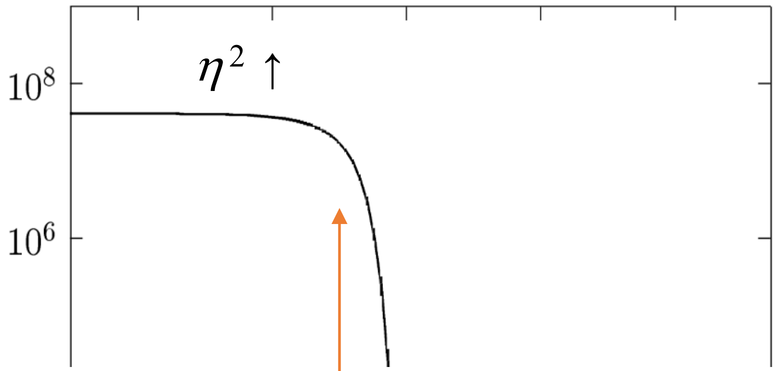


Figure 7.1: The normalized synchrotron radiation spectrum $F(y)$.



$\boldsymbol{E_{cr}}$ (BS) ≈ $\mathbf{1.5}\boldsymbol{\eta\gamma_e^2/\sigma_z}$ vs. $\boldsymbol{E_{cr}}$(CBS) ≃ $\mathbf{4}\boldsymbol{\gamma_e^2/\sigma_z}$

Special case of $\eta \approx 1$

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 011003 (2009)

Emission of low-energy photons by electrons at electron-positron and electron-ion colliders with dense bunches

U. D. Jentschura,[1,2] G. L. Kotkin,[3] and V. G. Serbo[3,2,*]

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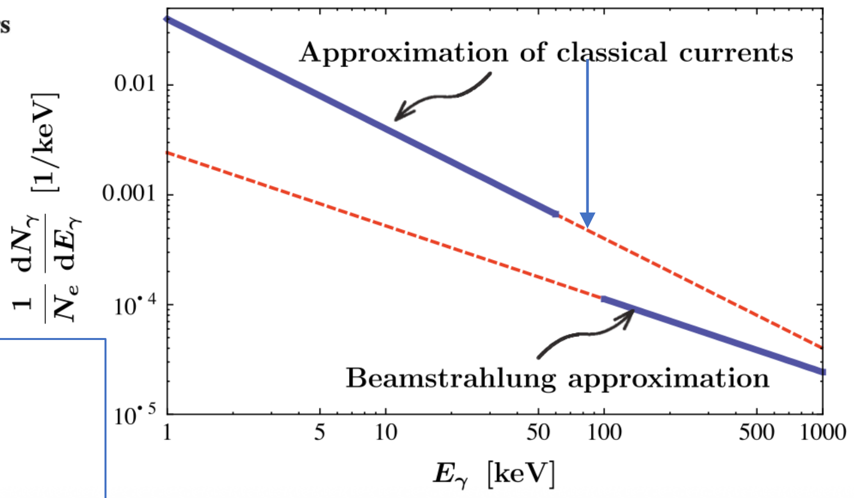
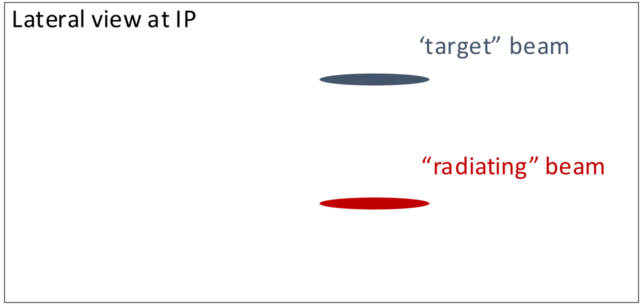


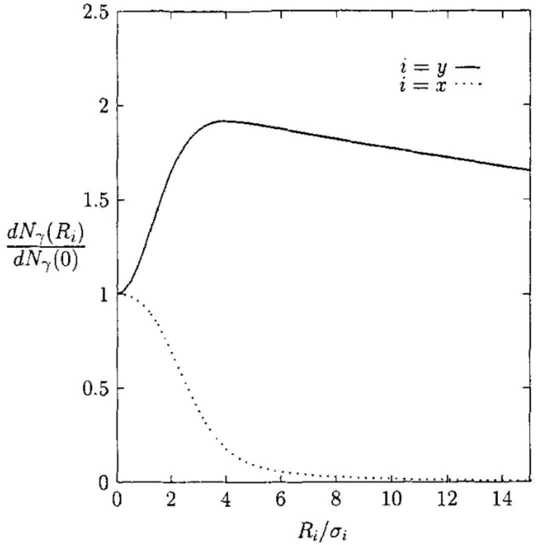
$$E_{cr} = 4\gamma_e^2/[(1+\eta^2)\sigma_z]$$

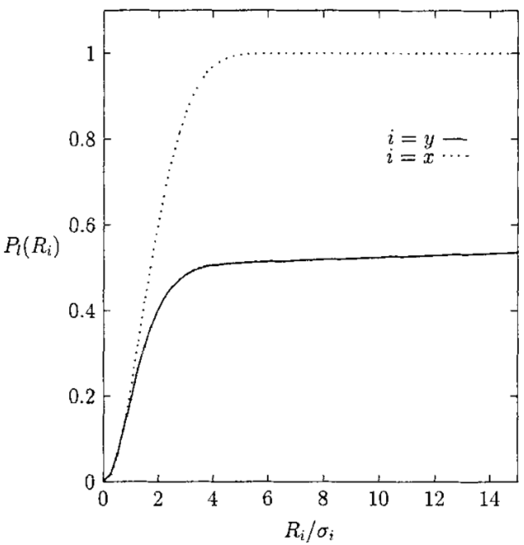
For $\eta \gg 1$ number of emitted CBS photons scales as $\log(\eta^2 + \text{const})$ instead of η^2

NB: for η close to 1 one needs to properly consider CBS effects

CBS and (vertical) beam separation



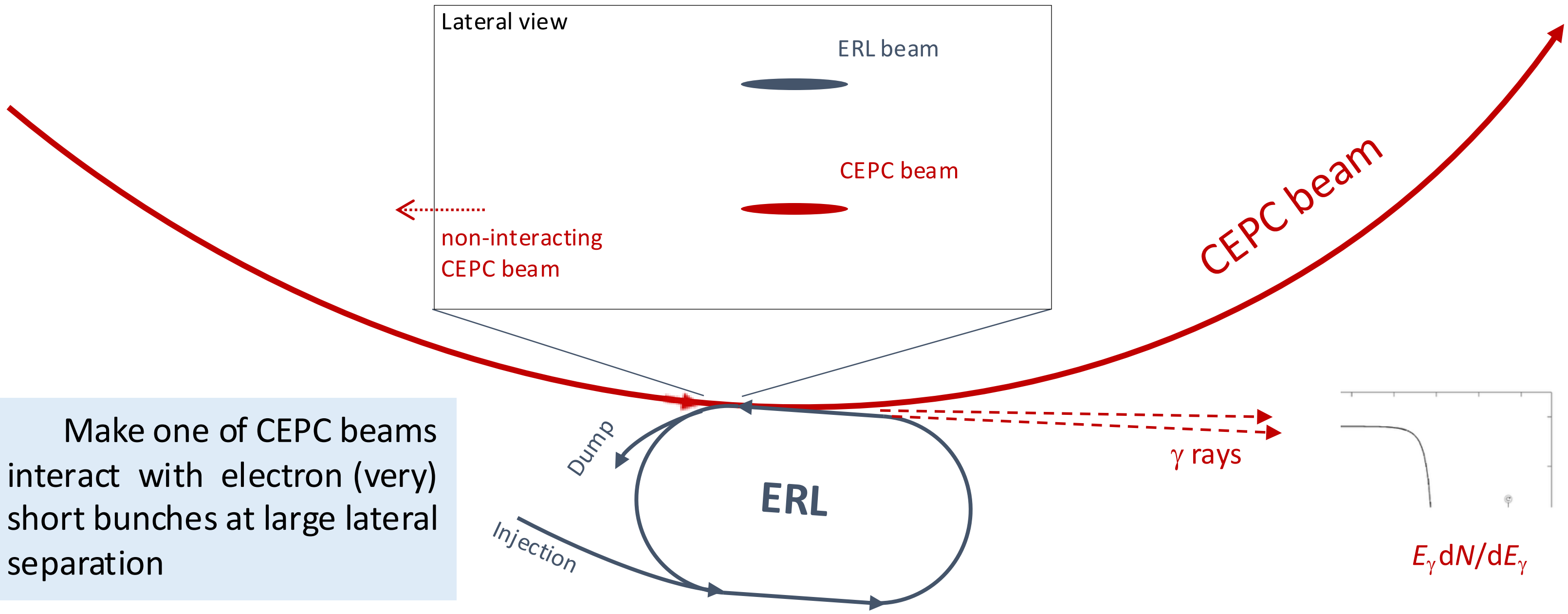




Interesting for beam diagnostics?

https://link.springer.com/article/10.1007/BF02907027

Novel powerful γ-source at CEPC



Make one of CEPC beams interact with electron (very) short bunches at large lateral separation

https://cds.cern.ch/record/2928809

As "target" beam use electron beam of about 5 GeV from *Energy Recovery Linac* (ERL)

Novel powerful γ-source at CEPC

Working conditions:
η = 0.5 and large vertical separation of 20 σ_{vert} between low (LE) and high energy (HE) beams; assume 0.1 mm LE bunch length and nominal luminosity optics for HE beam

E_{beam} [GeV] (Q_b [nC])	E_{crit} [MeV]	Flux Φ [10^{12}/(s 0.1%BW)]	Brilliance [10^{20}/(s mm^2 mrad^2 0.1%BW)]	Peak B [10^{23}/(s mm^2 mrad^2 0.1%BW)]
45.6 (0.15)	50	4	2.7	5.2
120 (0.2)	350	0.084	0.026	2.4

- Total flux of radiated photons above 0.1 MeV is extremely high, about 10^{16} photons/s and close to 10^{15} photons/s for 45.6 and 120 GeV beams, respectively
- Radiated photons are not coherent but are vertically polarised at about 60%

Proposal of powerful γ-source at CEPC

- Proposed facility would produce, **concurrently** (thanks to negligible impact on HE beam dynamics) with nominal operation of CEPC, polarised gamma beams of very high brilliance and flat energy spectra for photon energies from 0.1 to 500 MeV.

- One can envisage also **stand-alone** operation of such gamma-source with much larger ERL bunch charges when $\eta \gg 1$. In this case, source would operate in *beamstrahlung regime*, for which yet much higher photon fluxes and brilliances can be achieved, even larger to those in high-energy e^+e^- interaction regions, with vertical photon polarisation of 75% and better control.

Thank you for attention!

Backup slides

Bremsstrahlung at HERA: Observation of Beam Size Effect

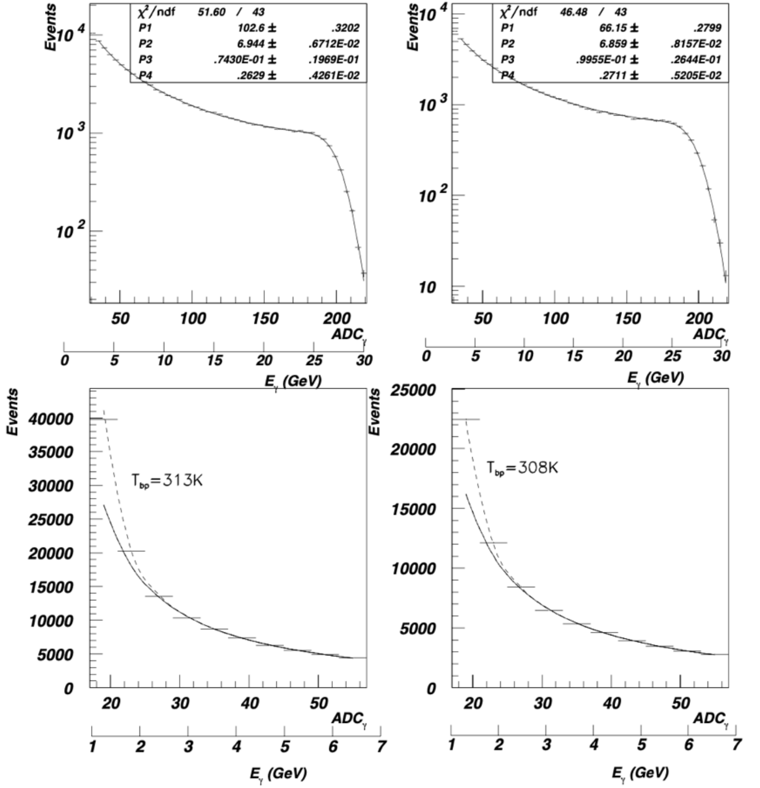
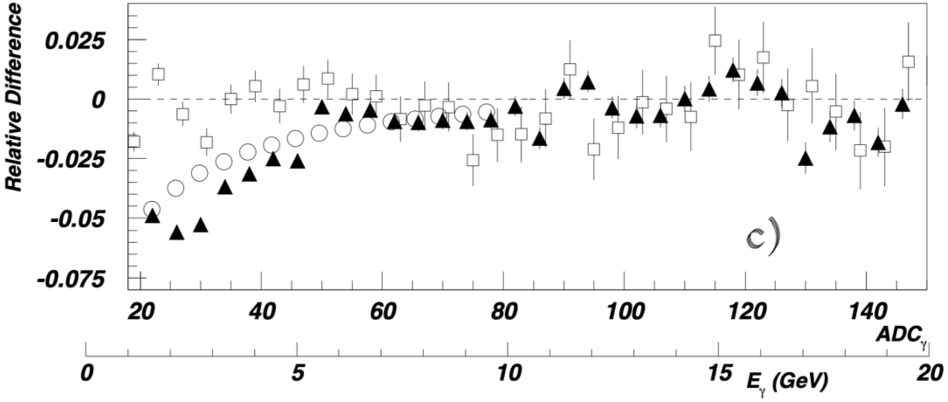


Figure 3: Two spectra of eN bremsstrahlung measured in the luminosity monitor using the electron pilot bunches. The histograms represent the data and the curves are results of fitting the function F (from Eq.1) for $E_\gamma > 3.5$ GeV; in the lower plots the low energy parts of the spectra are shown with extrapolations of the curves obtained from the fits - the excess of events with $2 > E_\gamma > 1$ GeV is well described by adding a contribution from Compton scattering of the blackbody photons off the beam electrons (dashed curves, T_{bp} is the beam-pipe temperature).

K. Piotrzkowski, Zeit. für Physik C **67** (1995) 577,
https://arxiv.org/abs/hep-ex/9504003

electron-gas bremsstrahlung was measured to agree with Bethe-Heitler LO formula but significant suppression of *electron-proton* bremsstrahlung was observed at low photon energies – it was found to agree at 30% level with BSE calculations by G. Kotkin *et al.*, Z. Phys. C **39**, 61 (1988):



Letter Open Access

When invariable cross sections change: The Electron-Ion Collider case

Krzysztof Piotrzkowski and Mariusz Przybycien
Phys. Rev. D **103**, L051901 – Published 5 March 2021

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

In everyday research, it is tacitly assumed that scattering cross sections have fixed values for a given particle species, center-of-mass energy, and particle polarization. However, this assumption has been called into question after several observations of suppression of high-energy bremsstrahlung. This process will play a major role in experiments at the future Electron-Ion Collider, and we show how variations of the bremsstrahlung cross section can be profoundly studied there using the lateral beam displacements. In particular, we predict a very strong increase of the observed cross sections for large beam separations. We also discuss the relation of these elusive effects to other quantum phenomena occurring over macroscopic distances. In this context, spectacular and possibly useful properties of the coherent bremsstrahlung at the Electron-Ion Collider are also evaluated.

AGH

BSE @ EIC

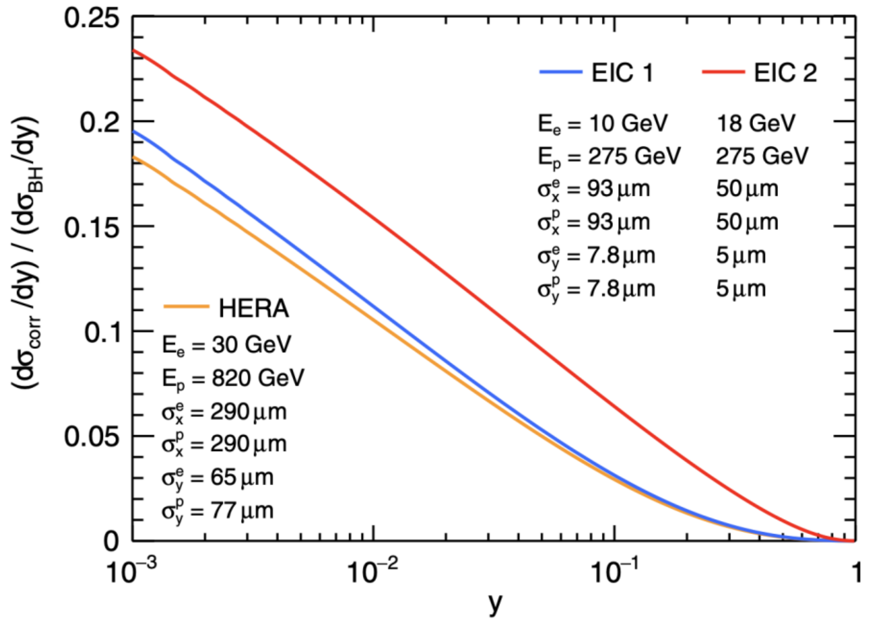


FIG. 2. Relative corrections to the standard Bethe-Heitler cross sections due to the beam-size effect. Relative suppression due to the beam-size effect $(d\sigma_{\mathrm{corr}}/dy)/(d\sigma_{\mathrm{BH}}/dy)$ is shown as a function of $y = E_\gamma/E_e$ for three cases of electron-proton bremsstrahlung.

https://doi.org/10.1103/PhysRevD.103.L051901

Due to very small **vertical** beam sizes bremsstrahlung suppression at EIC is **stronger** than at HERA – BSE must be carefully studied and understood to get required precision on EIC luminosity

BSE @ EIC

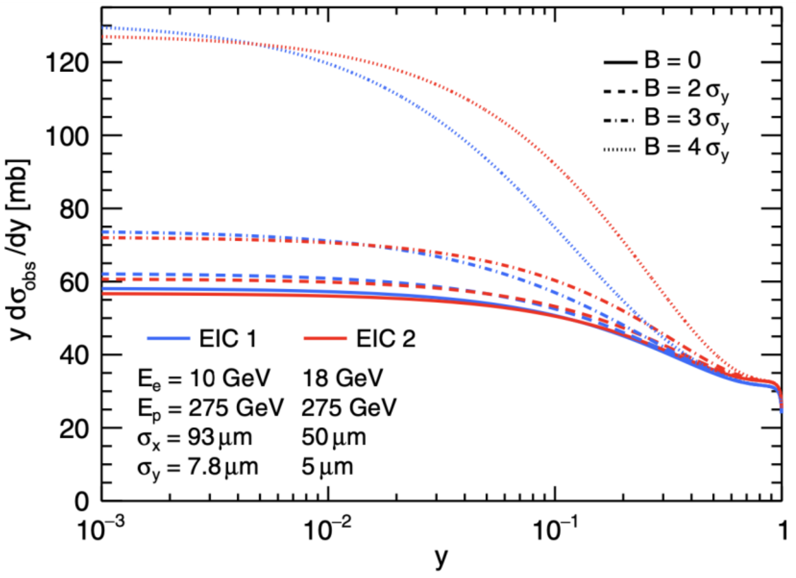


FIG. 4. The predicted spectra of ep bremsstrahlung at the EIC for several vertical beam displacements. The standard Bethe-Heitler cross section $d\sigma_{BH}/dy$ is modified due to the beam-size effect and beam displacements B. The effective cross sections (multiplied by y for better visibility) are shown for two cases of electron-proton collisions at the EIC—the corresponding beam energies and Gaussian lateral beam sizes at the interaction point are listed.

https://doi.org/10.1103/PhysRevD.103.L051901

Original and powerful test of BSE was proposed by measuring bremsstrahlung spectrum while making beam van der Meer scans (vertically).

This will allow for exciting direct studies/ demonstration of very long-range nature of bremsstrahlung process – for large **lateral** beam displacements strong **effective increase** of its cross-section is expected!

Vertical *Van der Meer scans*: