Powerful γ-source at FCC-ee

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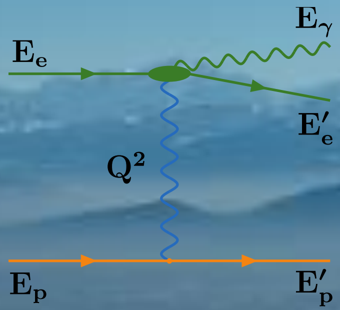
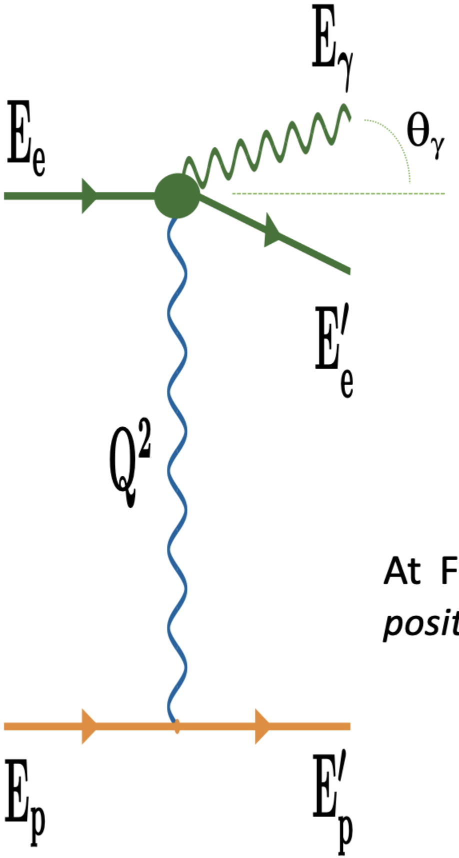


e^+e^- bremsstrahlung *aka* radiative Bhabha scattering at high energies



electron-positron bremsstrahlung $e^- + e^+ \rightarrow e^- + \gamma + e^+$ has following signatures:

$E'_e + E_\gamma = E_e$ to a very (very) high accuracy, and it is a truly "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

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

At FCC-ee, for $E_e = E_p = 182.5$ GeV and $E_\gamma = 2$ GeV, minimal momentum transfer, *in positron rest-frame*, $\Delta p_z = |q_{min}|/c \simeq 10^{-8}$ eV/c (Corresponding energy transfer = $(\Delta p)^2/2m_e \approx 10^{-22}$ eV)

It corresponds to longitudinal *coherence* length $l_c = \hbar/\Delta p_z \approx$ **20 m !**

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

Bremsstrahlung at FCC-ee: Beam-Size Effect

$$\mathrm{d}^4\sigma/\mathrm{d}E_\gamma\,\mathrm{d}\theta_e\mathrm{d}\theta_\gamma\mathrm{d}\phi \;\propto\; Q^{-4}$$

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

$p_T = 0$ → infinite impact parameter

$p_{T,typ} = \mathcal{O}(|q_{min}|/c)$ → **Beam-Size Effect:** *effective* brems-strahlung *suppression* at colliders, at low E_γ , due to small lateral beam-sizes of <u>both</u> beams, hence

FCC-*ee* beam lifetime enhancement →

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Regular Article - Experimental Physics

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

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BSE has nothing to do with "environmental/density effects" – it is present in proper "binary" processes, however if coherence length exceeds bunch length new effect kicks in

HERA CBS case

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

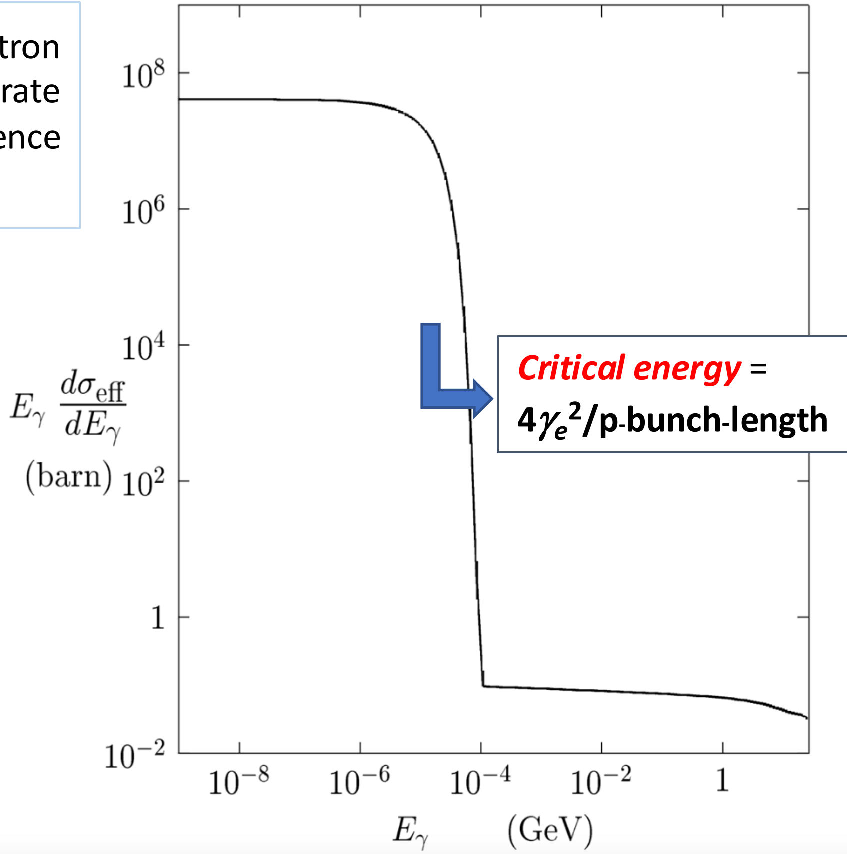
The equivalent photon approximation for coherent processes at colliders

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

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

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 $\eta^2 \gamma^2/\sigma_z$

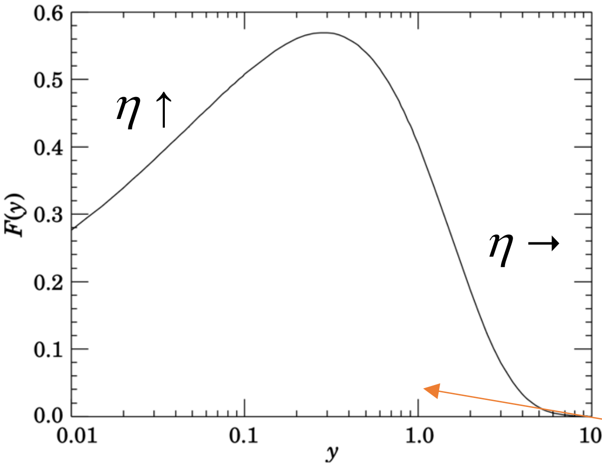
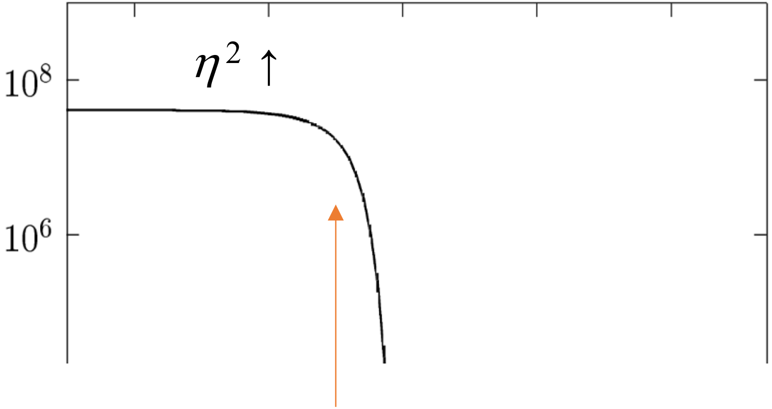


Figure 7.1: The normalized synchrotron radiation spectrum $F(y)$.



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

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

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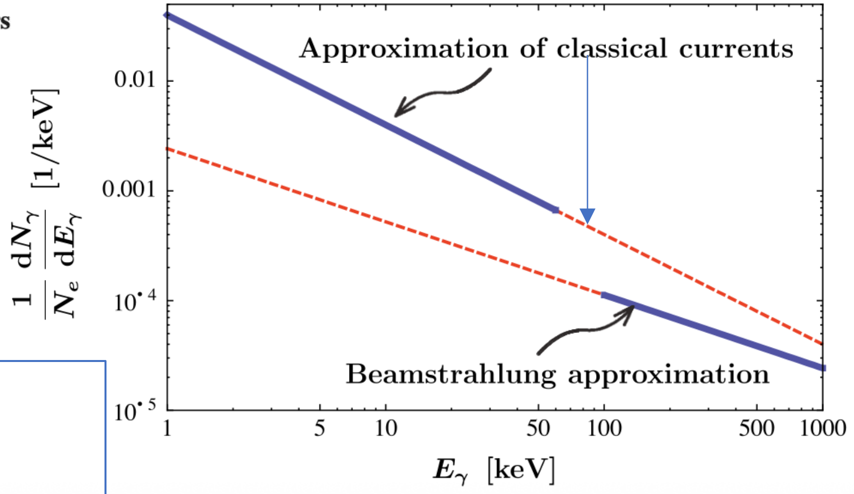
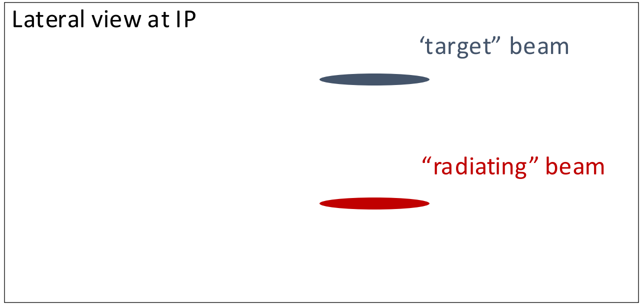
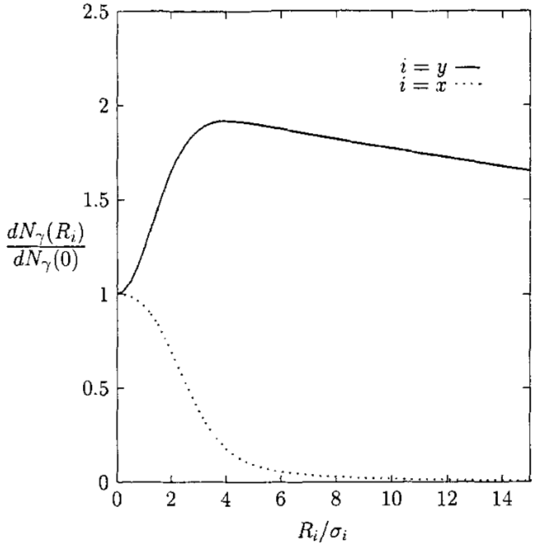


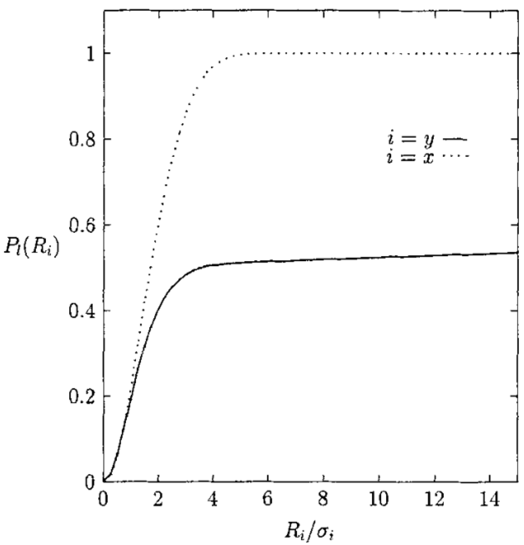
$$E_{cr} = 4\gamma_e^2/[(1+\eta^2)\sigma_z]$$

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

CBS and (vertical) beam separation

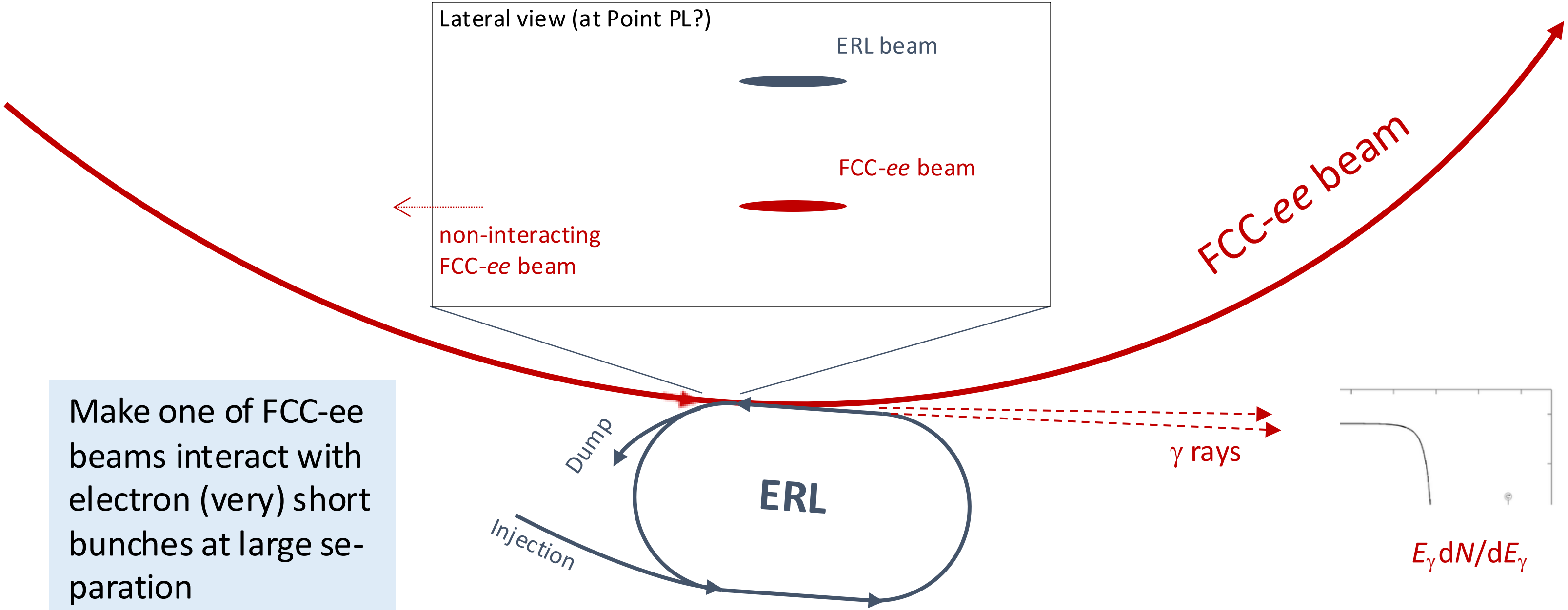






https://link.springer.com/article/10.1007/BF02907027

Novel powerful γ-source at FCC-ee



Make one of FCC-ee beams interact with electron (very) short bunches at large se-paration

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

Novel powerful γ-source at FCC-ee

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	6.6	1.5	0.83
120 (0.2)	350	0.14	0.053	5.8

- Total flux of radiated photons above 0.1 MeV is extremely high, above 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 FCC-ee

- Proposed facility would produce, **concurrently** (thanks to negligible impact on HE beam dynamics) with nominal operation of FCC-*ee*, 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, comparable to those in high-energy e^+e^- interaction regions, but with vertical photon polarisation of 75%.

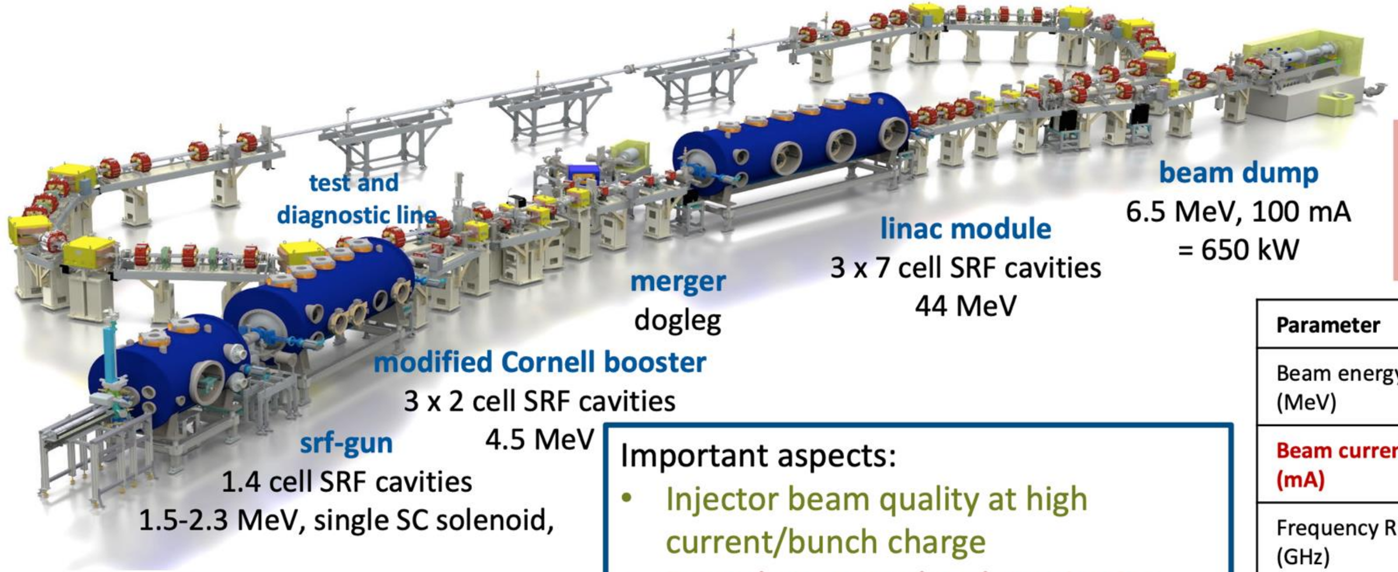
Thank you for attention!

Backup slides

Axel Neumann

Evolution of bERLinPro

From 4th generation light source prototype (2011), via generic high intensity ERL prototype (2012-2020) towards *application driven* facility (today)



Single turn high intensity ERL
5 MW beam power
650 kW injector beam power

Parameter	bERLinPro
Beam energy recirculator (MeV)	50
Beam current ERL mode (mA)	**100**
Frequency RF and Laser (GHz)	1.3
Normalized emittance (mm mrad)	**1 (< 0.6 in simulations)**
Bunch length (ps)	**< 2 (ERL mode), 100 fs @ 10 mA**
Beam losses	<< 10^{-5} @ 100 mA

Important aspects:

- Injector beam quality at high current/bunch charge
- Beam loss control and monitoring → Radiation protection
- Beam break-up in main Linac
- Longitudinal control of beams for recovery process (low power margin)