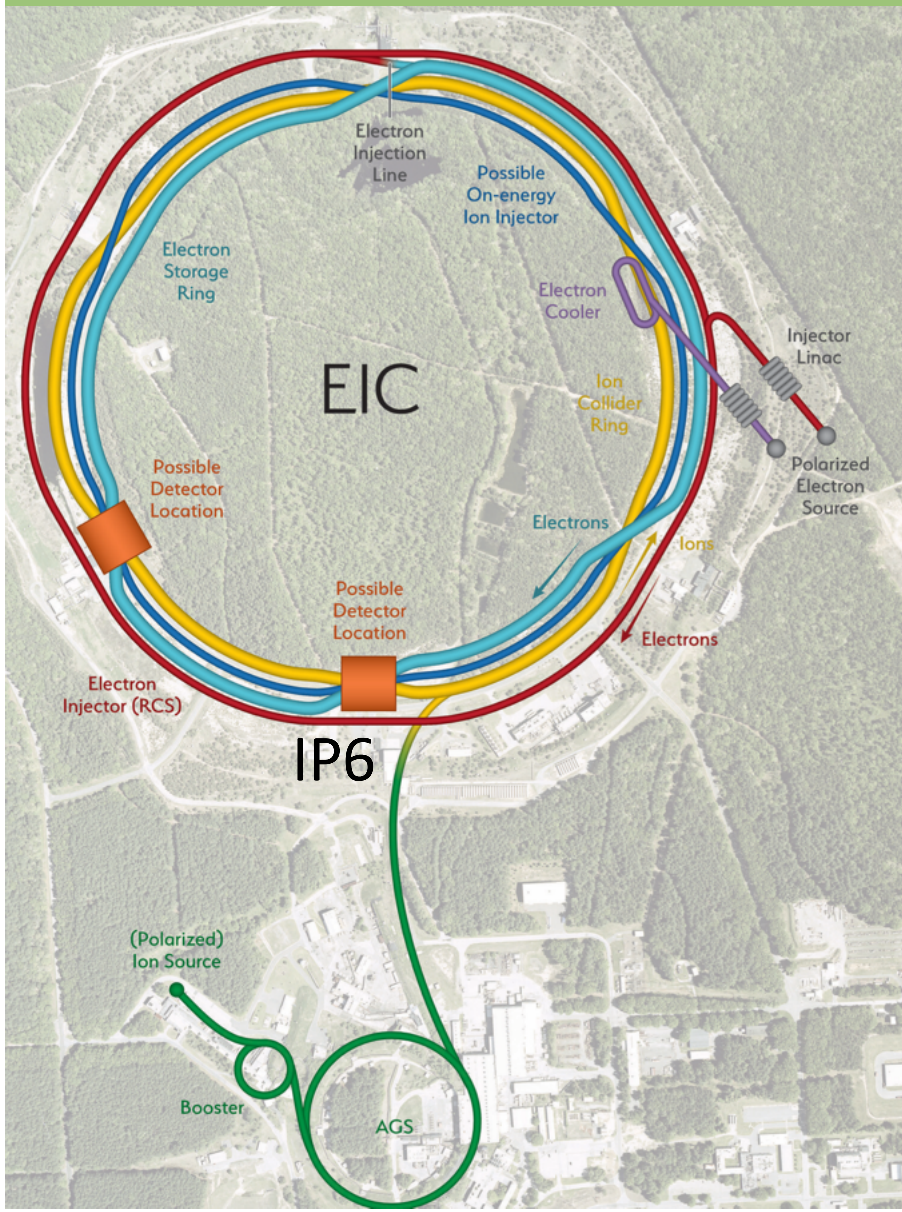
Coherent bremsstrahlung and its observation @ EIC
and at Solaris?



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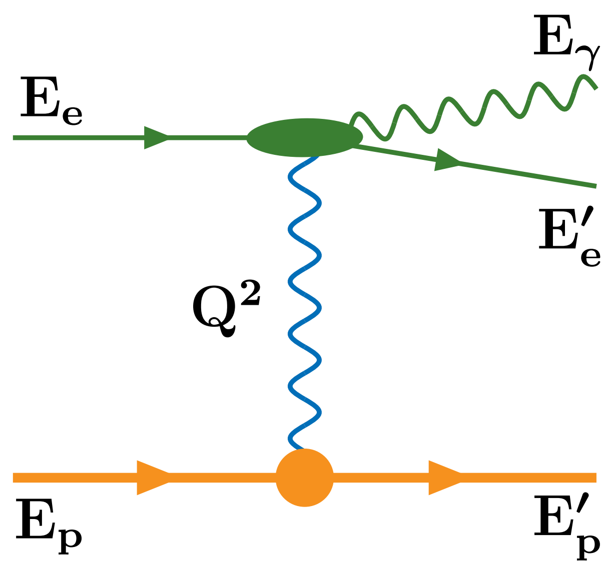
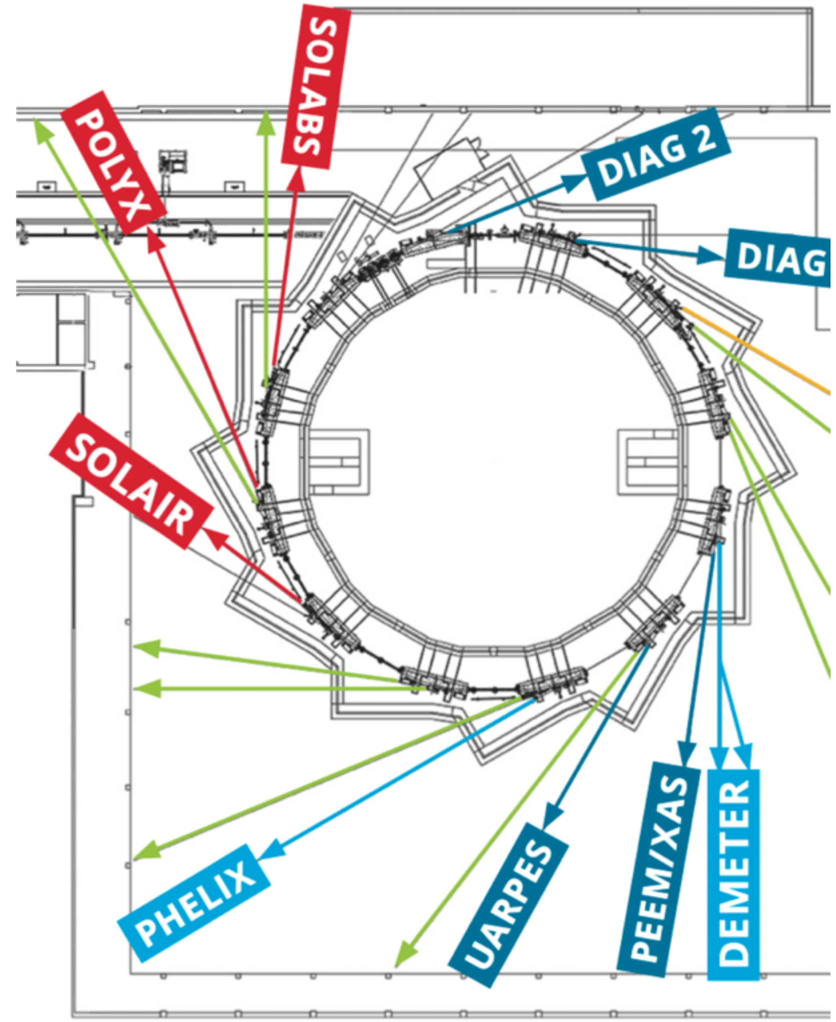
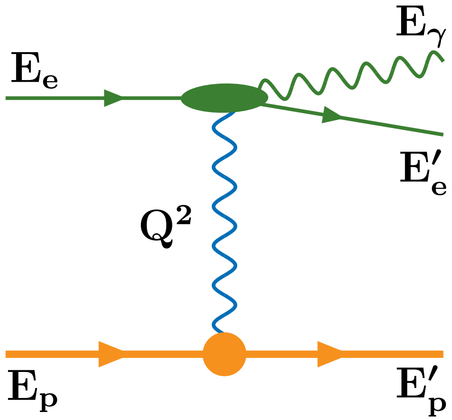


WFiIS seminar

April 28, 2023



Bremsstrahlung *aka* braking radiation is truly unique at high energies



Bremsstrahlung process was first studied by Hans Bethe and Walter Heitl*er* – hence the *Bethe-Heitler* reference still used today – however, its "macroscopically" long-range nature has been quite elusive ever since…

On the Stopping of Fast Particles and on the Creation of Positive Electrons

By H. Bethe, Manchester, and W. Heitler, Bristol

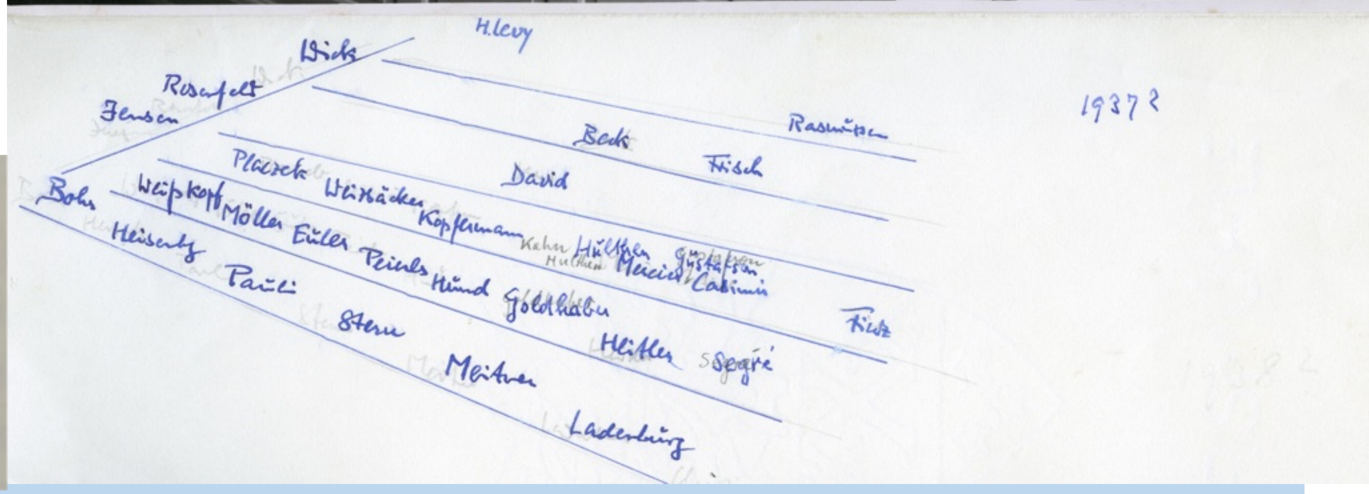
(Communicated by P. A. M. Dirac, F.R.S.—Received February 27, 1934)

For energies large compared with mc^2, *i.e.*, for

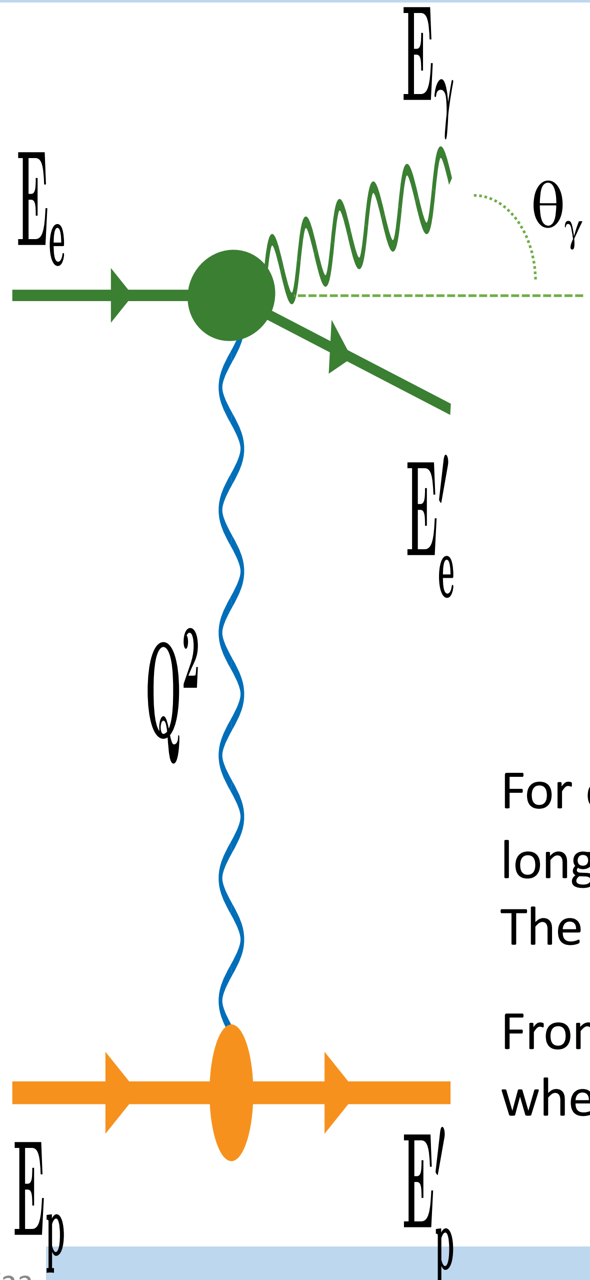
$$E_0 \gg mc^2, \qquad E \gg mc^2, \qquad k \gg mc^2,$$

(15) reduces to

$$\Phi = \frac{Z^2}{137}\left(\frac{e^2}{mc^2}\right)^2 \frac{dk}{k}\frac{4}{E_0^2}\left(E_0^2 + E^2 - \tfrac{2}{3}E_0E\right)\left(\log\frac{2E_0E}{k\mu} - \tfrac{1}{2}\right).$$



ep bremsstrahlung at high energy



electron-proton bremsstrahlung $\boldsymbol{e + p \to e' + \gamma + p}$ has following signatures:

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

⇒ 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):

$$|q_{min}| = m_e^2\, m_p\, E_\gamma/(4\, E_p\, E_e\, E'_e),$$ where

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

For example, at the EIC, for $E_e = 18$ GeV, $E_p = 275$ GeV and $E_\gamma = 1$ GeV, one gets the minimal longitudinal momentum transfer, *in the proton rest-frame*, $\Delta p_z = |q_{min}|/c = 0.00073$ eV/c. The corresponding (kinetic) energy transfer = $(\Delta p)^2/2M \approx 3.10^{-16}$ eV!

From the uncertainty principle it corresponds to a longitudinal distance $\approx \hbar/\Delta p_z \approx$ **0.3 mm** whereas in the transverse plane the impact parameters can be even larger.

Higher beam energies/lower photon energy ⇒ **more** extreme it becomes!

High energy bremsstrahlung – coherence loss

This long-range character of bremsstrahlung has spectacular consequences:

Δp_z → *Landau-Pomeranchuk-Migdal effect** and dielectric/*Ter-Mikaelian effect*** & other "environmental" effects as strong magnetic fields – all that due to extremely small **longitudinal** momentum transfers.

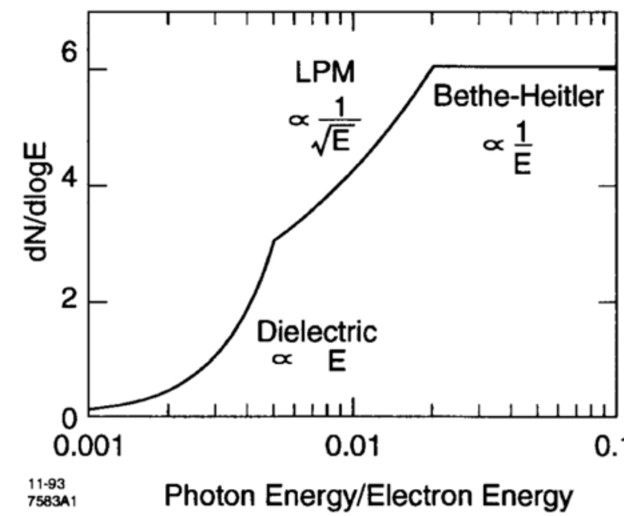
The notion of a coherence length (often called the *formation length* in this context) is introduced – bremsstrahlung is **suppressed**, when the electrons/photons are "perturbated during interaction", leading to *coherence loss.* In dense media bremsstrahlung is not a "binary" process anymore.

Investigation of an Electromagnetic Cascade of Very High Energy in the First Stage of its Development.

M. Mięsowicz, O. Stanisz and W. Wolter

Institute of Nuclear Physics, Department of Cosmic Rays - Krakow

(ricevuto il 17 Settembre 1956)



*) L.D. Landau & I. Pomeranchuk (1953) "Limits of applicability of the theory of bremsstrahlung electrons and pair production at high-energies", *Dokl. Akad. Nauk S. F.* **92**; A.B. Migdal (1956) "Bremsstrahlung and pair production in condensed media at high-energies", *Phys. Rev.* **103**: 1811.
) M.L. Ter-Mikaelian (1954), *Dokl. Akad. Nauk Ser. Fiz.* **94: 1033.

Bremsstrahlung at HERA: Observation of Beam-Size Effect

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

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

$p_T = 0 \rightarrow$ infinite impact parameter!

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

At HERA I, for E_γ = 1 GeV $|q_{min}| \approx$ 0.0001 eV $\Rightarrow$ it corresponded to a 2 mm impact parameter, whereas the HERA colliding beam lateral sizes $\ll$ 1 mm

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

It effectively comes from the ("text-book") **definition** of a cross-section:

Event rate = Luminosity × σ

where colliding particles are represented by PLANE waves **but** this *assumption* is invalid if the lateral beam sizes are **comparable** to the relevant impact parameter of a process.

Bremsstrahlung at HERA: Observation of Beam Size Effect

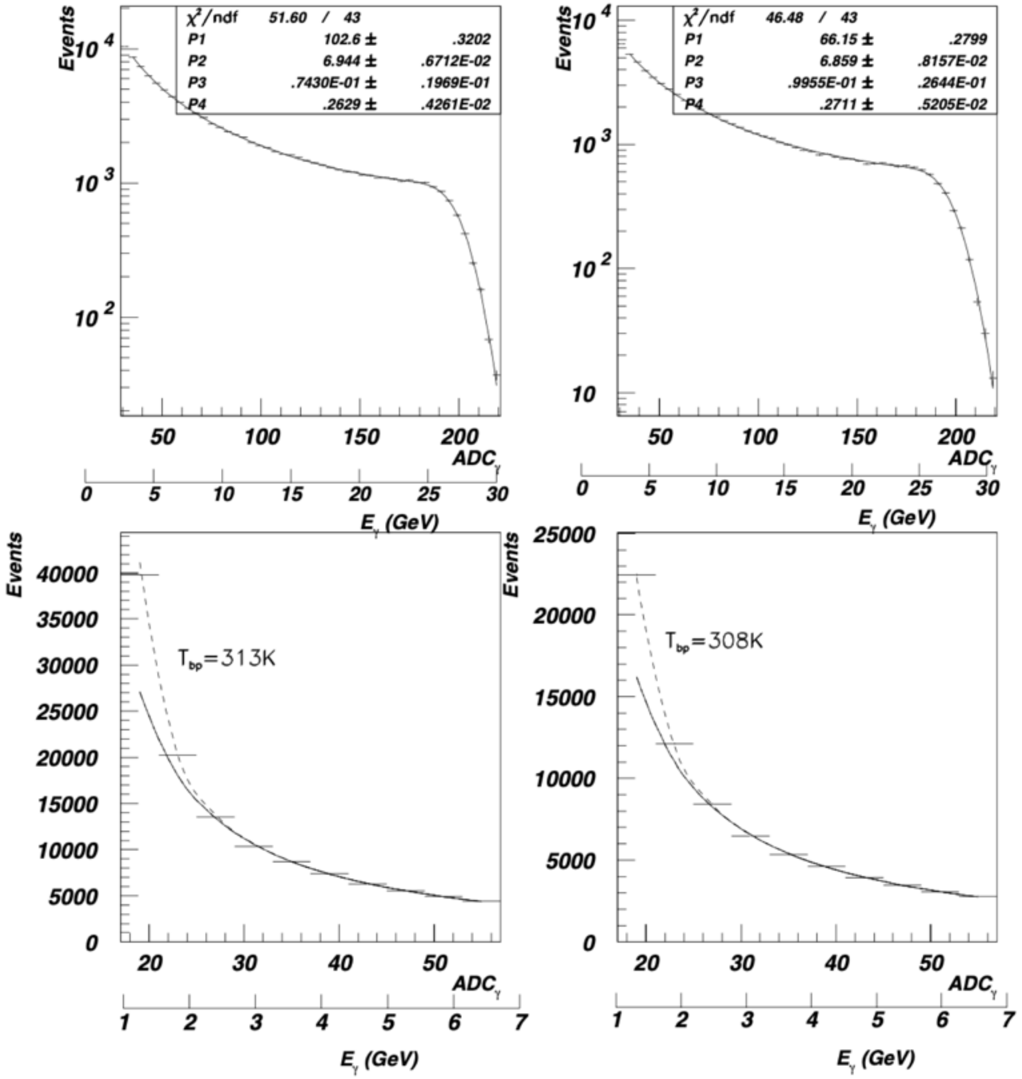
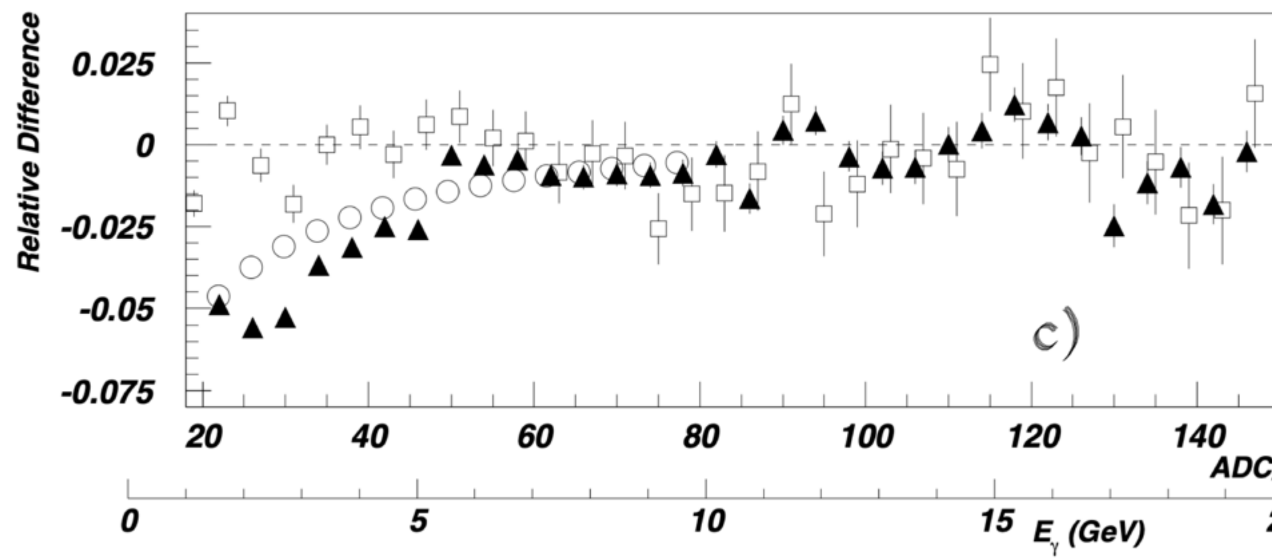


Figure 3: Two spectra of eN bremsstrahlung measured in the luminosity monitor using the electron pilot bunches. The histograms represent the data and the curves are results of fitting the function F (from Eq.1) for $E_\gamma > 3.5$ GeV; in the lower plots the low energy parts of the spectra are shown 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 the Bethe-Heitler LO formula but a significant suppression of *electron-proton* bremsstrahlung was observed at low photon energies – it was found to agree at 30% level with the BSE calculations by G. Kotkin *et al.,* Z. Phys. C **39**, 61 (1988):



Predicted coherent bremsstrahlung (CBS) at HERA

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

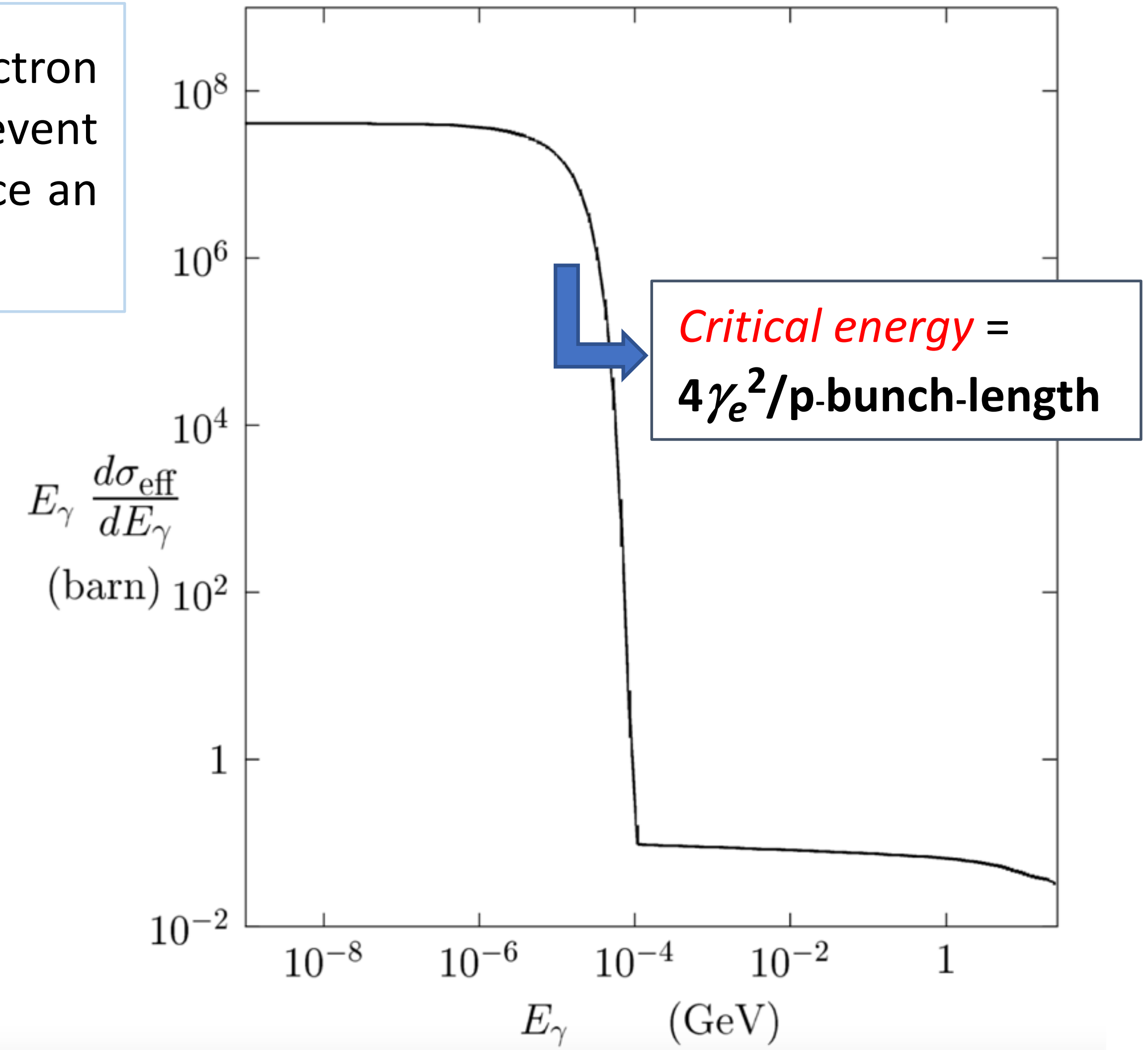
The equivalent photon approximation for coherent processes at colliders

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



It has **same** origin as famous *beamstrahlung,* yet has never been confirmed experimentally…

CBS vs. Beamstrahlung (and SR)

Properties of such coherent radiations are quite different for electron deflection angles θ_d (in magnetic field of proton bunch) much larger or much smaller than typical radiation angle $\theta_r \approx m_e/E_e$ – as measured by their ratio

$\boldsymbol{\eta = r_e\ N_p\ /\sigma_x \approx\ \theta_d\,/\,\theta_r}$ where r_e is classical electron radius, N_p is number of protons and σ_x the bunch lateral size

If $\eta \gg \mathbf{1}$ then corresponding radiation is called *beamstrahlung* and if $\eta \lesssim \mathbf{1}$ that is CBS case

Nota bene: *Synchrotron radiation* (SR) is special case of beamstrahlung in uniform (external) field.

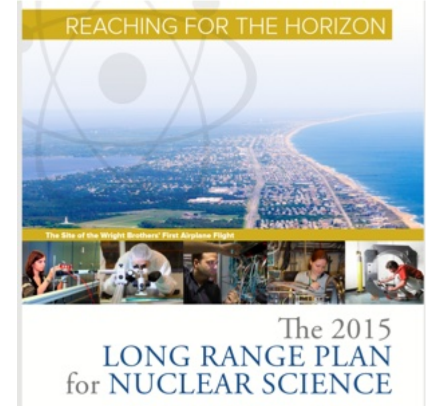
At HERA $\eta \lesssim 1$ but CBS was much smaller than SR generated in the electron beamline close to interaction point (IP) – what about EIC?

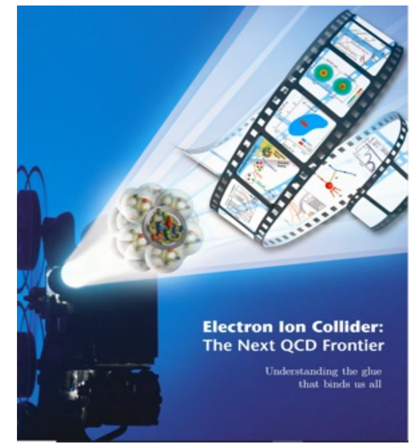
Electron-Ion Collider @ BNL

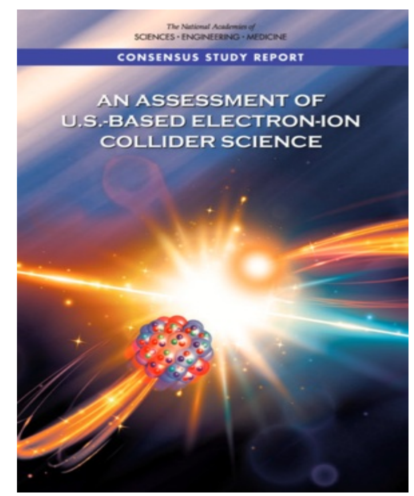
From F. Willeke @ Epiphany'23

- EIC Design Goals
  - High Luminosity: L=(0.1-1)·10^{34} $cm^{-2}sec^{-1}$, need 10 -100 fb^{-1}
  - Collisions of highly polarized e and p (& light ion) beams with flexible bunch by bunch spin patterns : 70%
  - Large range of center of mass energies: E_{cm} = (20-140) GeV
  - Large range of Ion Species: Protons – Uranium
  - Ensure Accommodation of a second IR
  - Large detector acceptance
  - Good background conditions (hadron particle loss and synchrotron radiation in the IR)

- Goals match or exceed requirements of Long-Range Plan & EIC White Paper, endorsed by NAS
- EIC Design meets or exceeds goals and requirements







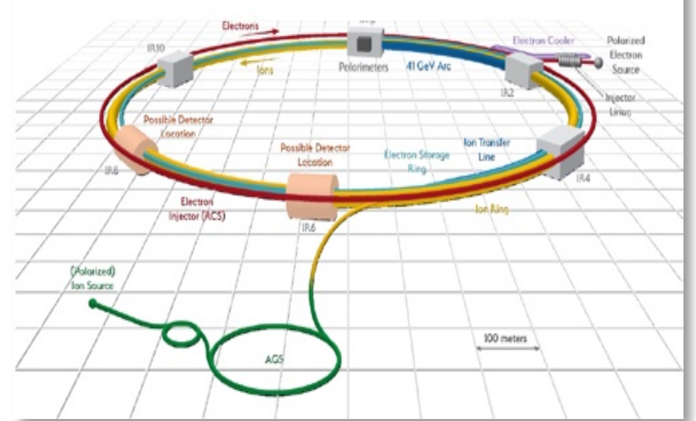
EIC Design Overview

From F. Willeke @ Epiphany'23

- Design based on **existing RHIC Complex**
- RHIC is well maintained, operating at its peak
- RHIC accelerator chain will provide EIC Hadrons
- EIC constructed in Collaboration with **JLab**

- **Hadron storage Ring (RHIC Rings) 40-275 GeV**
  - Superconducting magnets (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - strong cooling (coherent electron cooling)
- **Electron storage ring 2.5–18 GeV**
  - many bunches,
  - large beam current, 2.5 A ➔ 9 MW S.R. power
  - S.C. RF cavities
  - Need to inject polarized bunches
- **Electron rapid cycling synchrotron 0.4- 18GeV**
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)**
  - $L = 10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation

EIC



EIC will start in 2032

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.

Beam-Size Effect (BSE) @ EIC

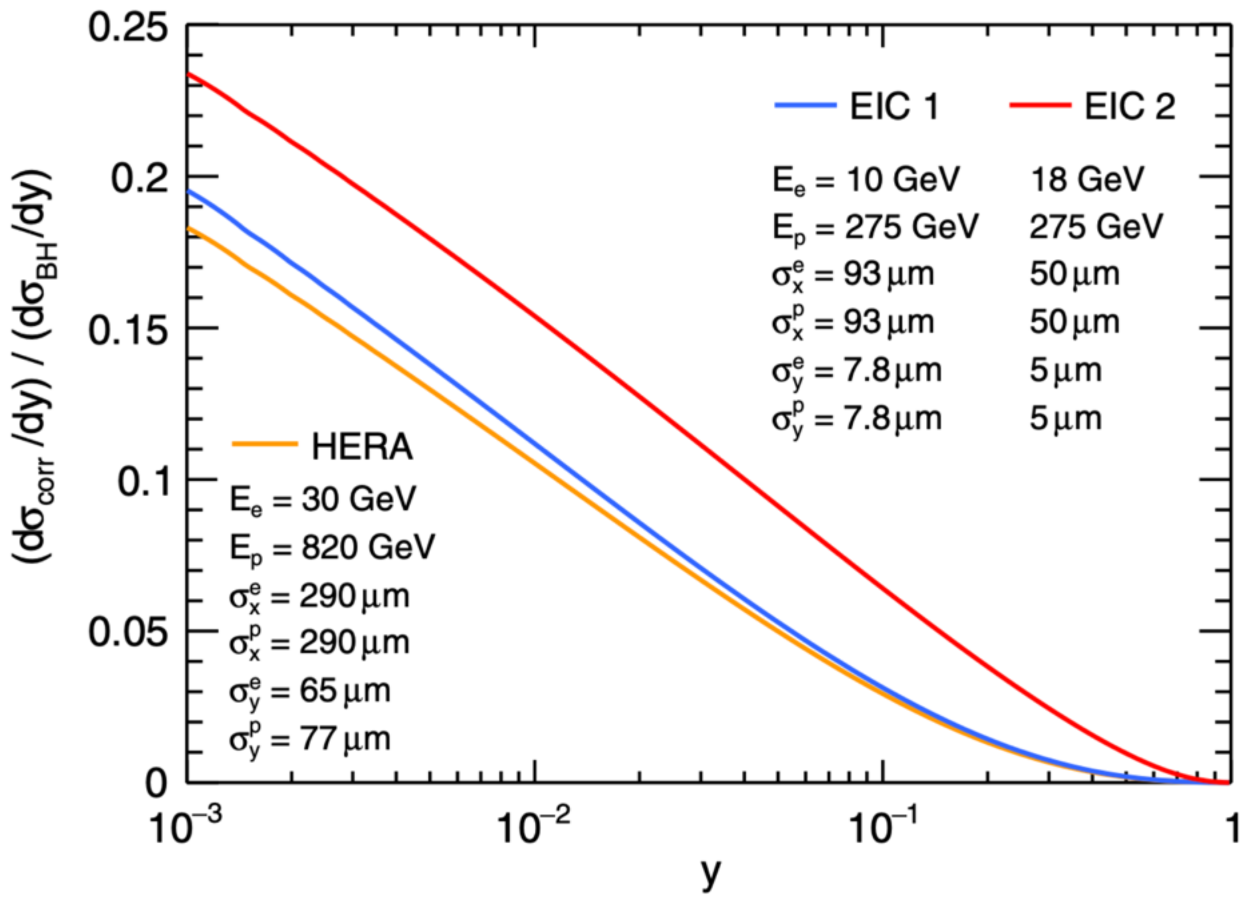
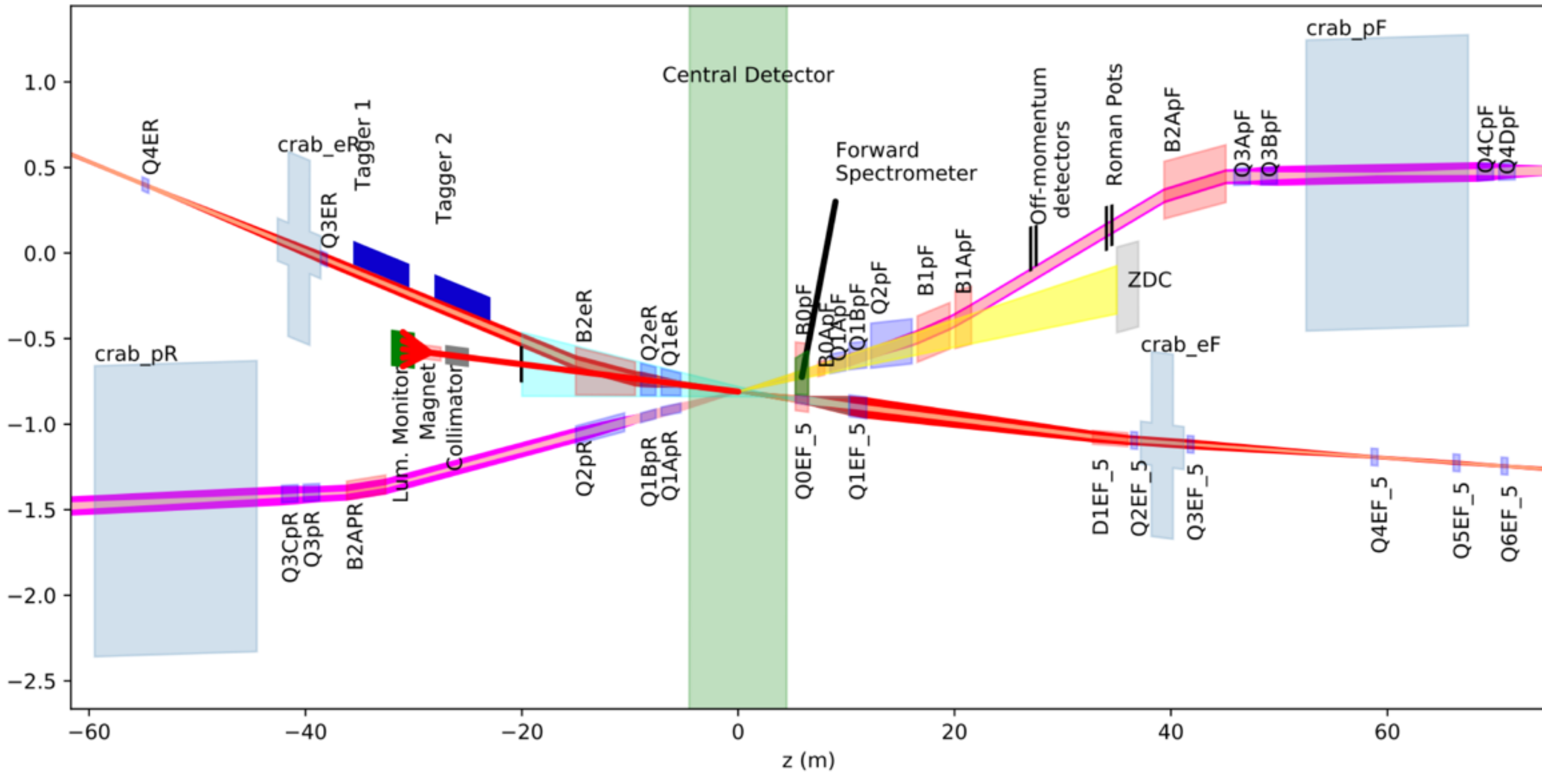


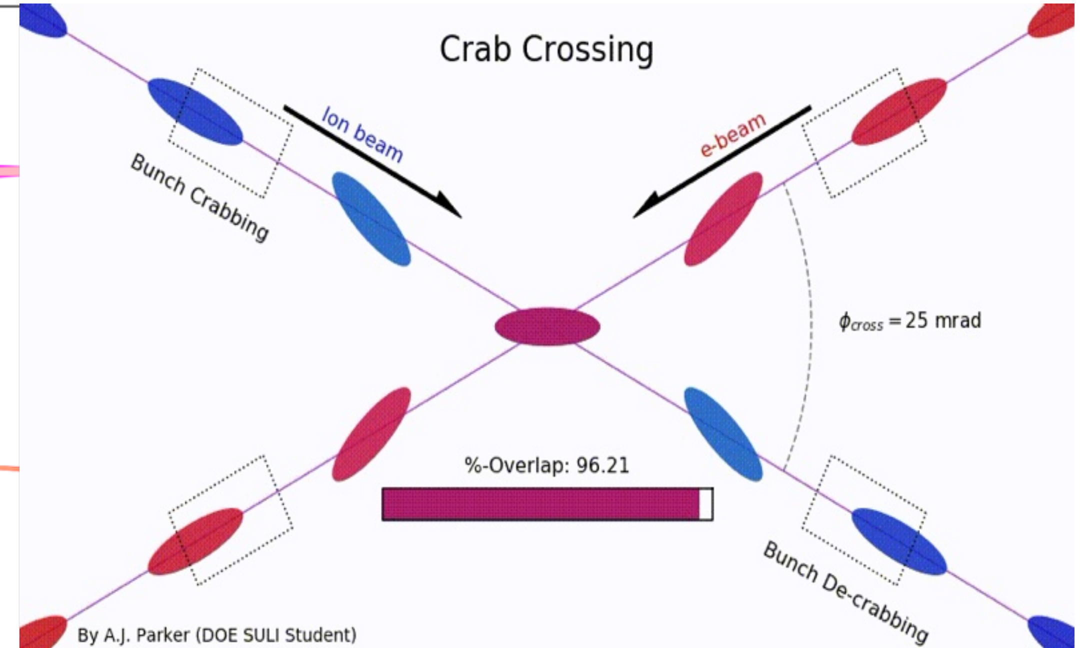
FIG. 2. Relative corrections to the standard Bethe-Heitler cross sections due to the beam-size effect. Relative suppression due to the beam-size effect $(d\sigma_{\rm corr}/dy)/(d\sigma_{\rm BH}/dy)$ is shown as a function of $y = E_\gamma/E_e$ for three cases of electron-proton bremsstrahlung.

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

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

Luminosity measurements at the EIC

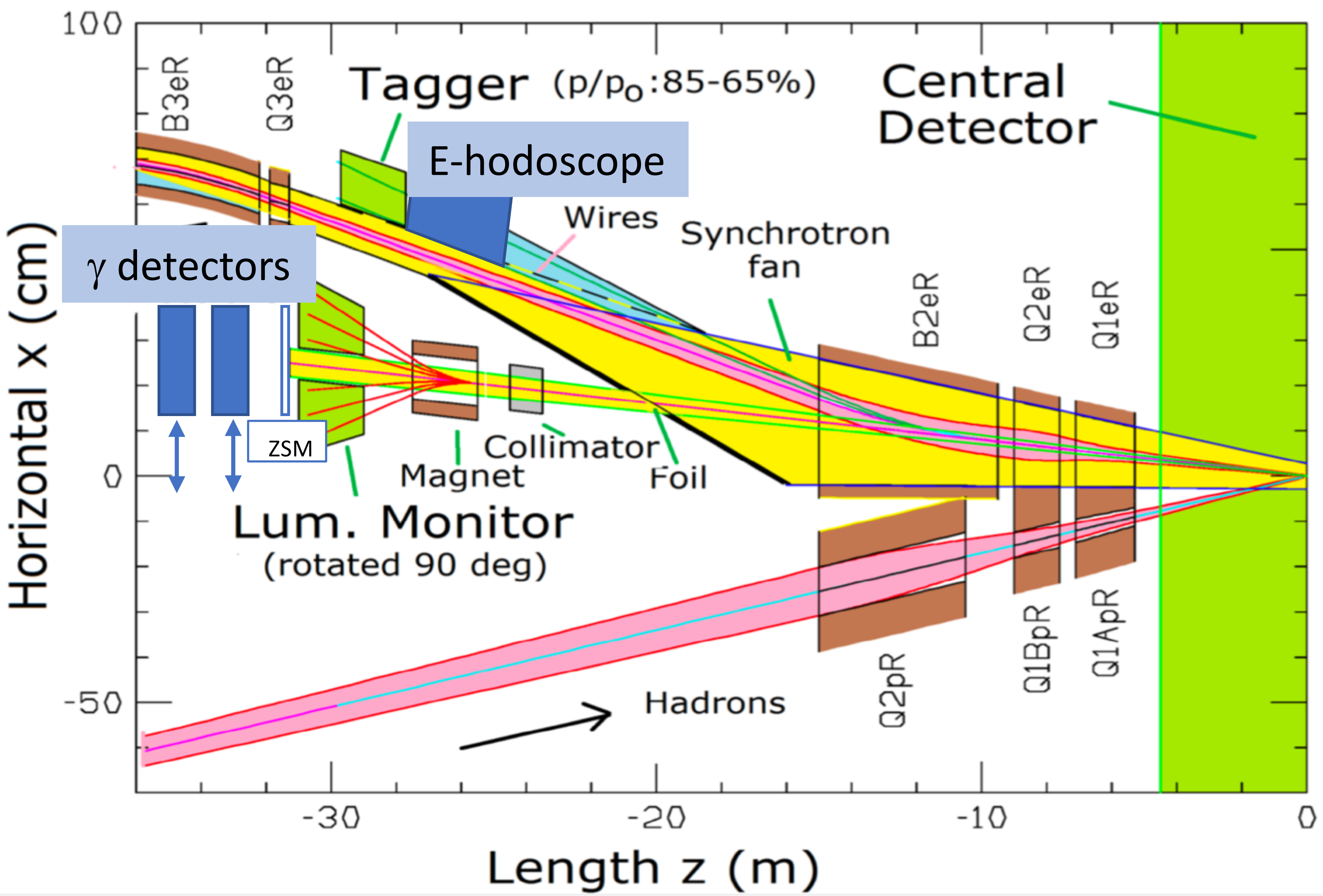




Provisions has been made in the preliminary EIC *Interaction Region* designs for the proper luminosity measurement, as well as for forward electron detectors (photoproduction taggers)

https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf
https://wiki.bnl.gov/eic/

Luminosity measurement vs. coherent bremsstrahlung



Coherent bremsstrahlung will play a major role at the EIC – its power (within a cone of 100 μrad) might even exceed **1 kW!** Therefore, it will be a serious background in the EIC luminosity measurements.

However, it is also a subject of exciting research by itself, and in addition might lead to novel and useful beam diagnostics.

A proposal for the CBS detector at the EIC is being prepared.

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

CBS @EIC

For low energy photons, the CBS spectrum is very simple, for flat beams and single bunch crossing*:

$$dN_\gamma = N_0\, dE_\gamma / E_\gamma \quad \text{where} \quad N_0 = \eta^2 N_e\, 8\alpha/9\sqrt{3}$$

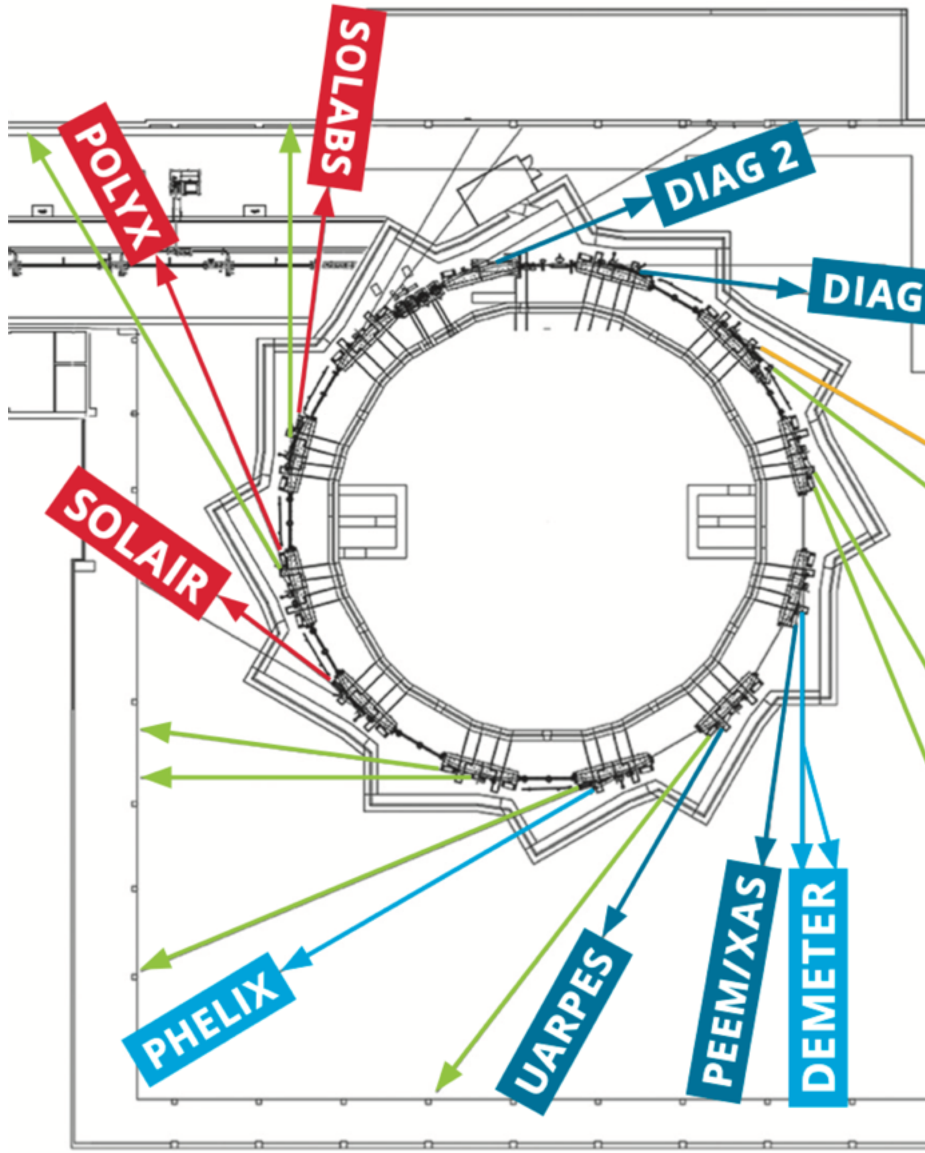
At the EIC, depending on the electron beam energy, $\eta = 0.01\text{–}10$, $N_0 \approx 4\eta^2\, 10^8$ and photon critical energy = 1–20 keV.

Nota bene: EIC bunch crossing rate = 10^8/s

CBS observation should be rather straightforward as **SR background is manageable for visible light**. Conditions are also very favorable for studies of transition between the CBS and *beamstrahlung* regimes.

*) *Z. Phys. C* **71** (1996) 651-658 e-Print: hep-ph/9511262 [hep-ph]

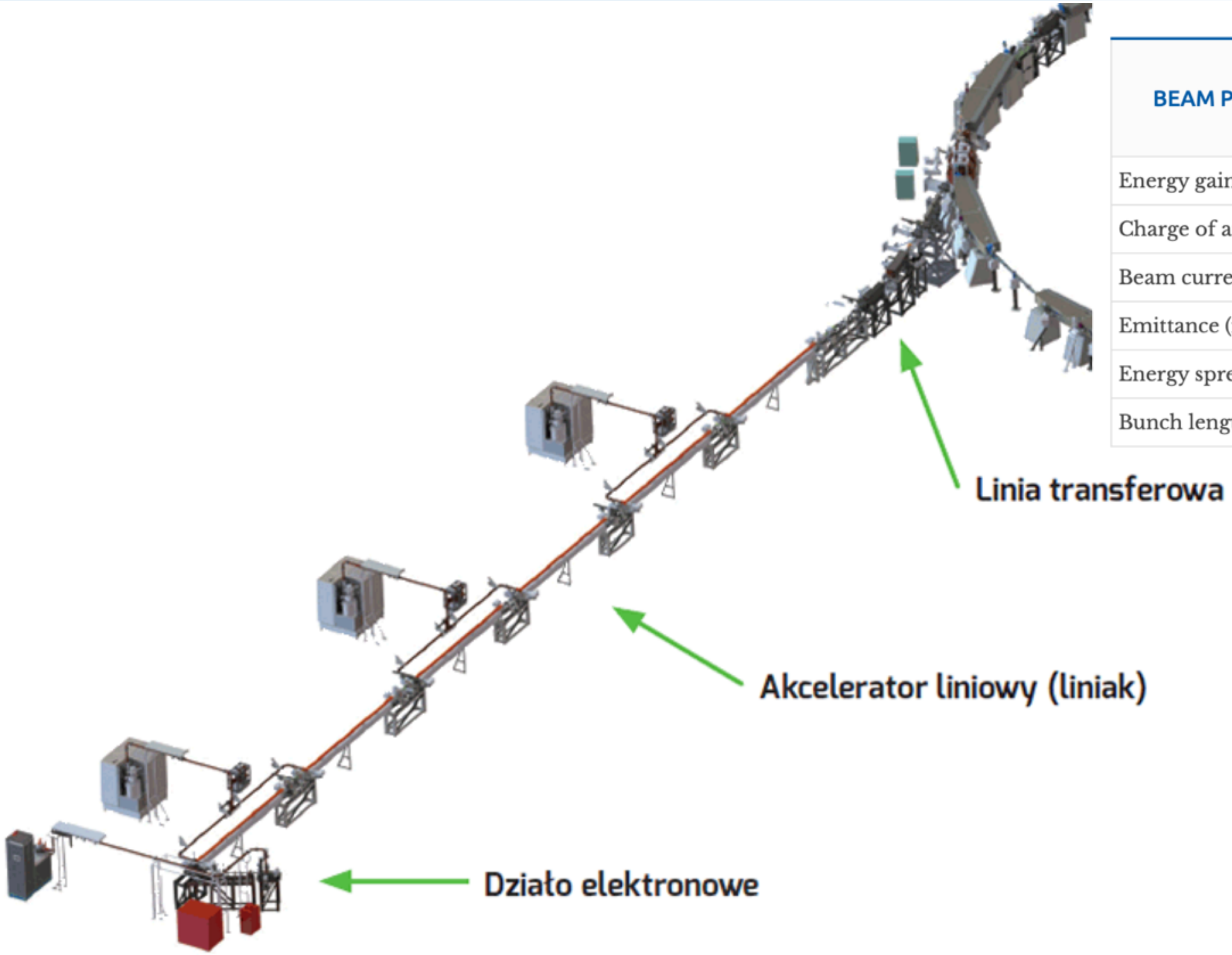
CBS @ Solaris?



Could one bring an e-beam to collide with stored electrons?

Could one use one of free slots?

Linac @Solaris



The beam parameters at the injector exit

BEAM PARAMETERS	VALUE
Energy gain (max.) [MeV]	550
Charge of an electron bunch [nC]	0.2
Beam current [mA]	600
Emittance (norm, rms) horizontal/vertical mm mRad	3,111/2,175
Energy spread [keV]	400
Bunch length [ps]	14

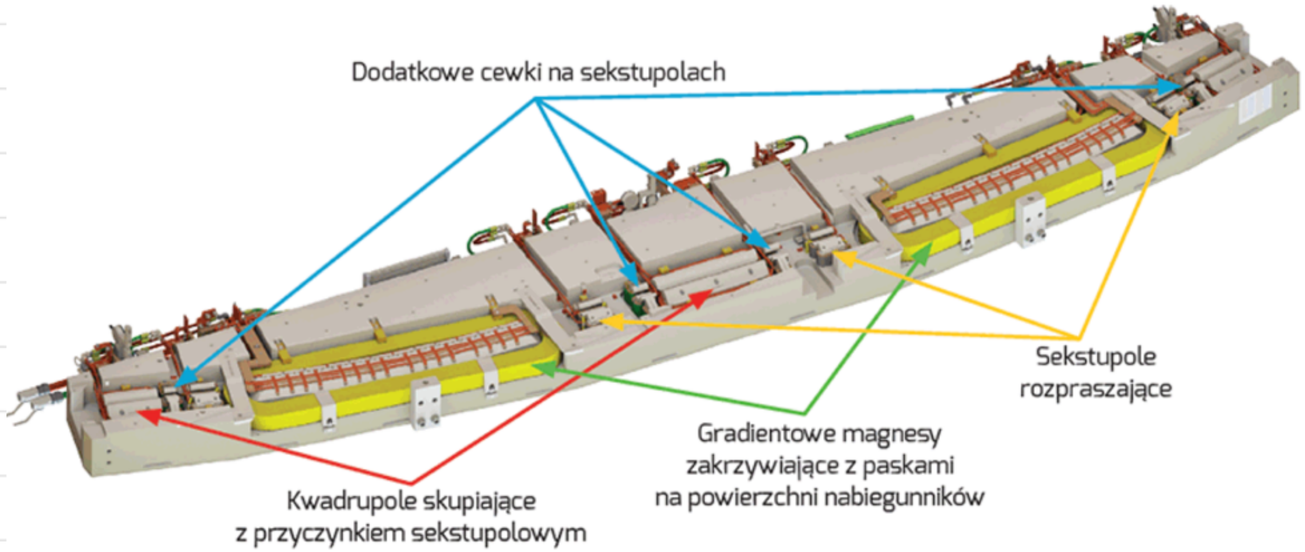
Bunch length (s.d.) $\lesssim$ **1.5 mm**

after planned upgrade ≈ **0.15 mm**

Solaris – storage ring

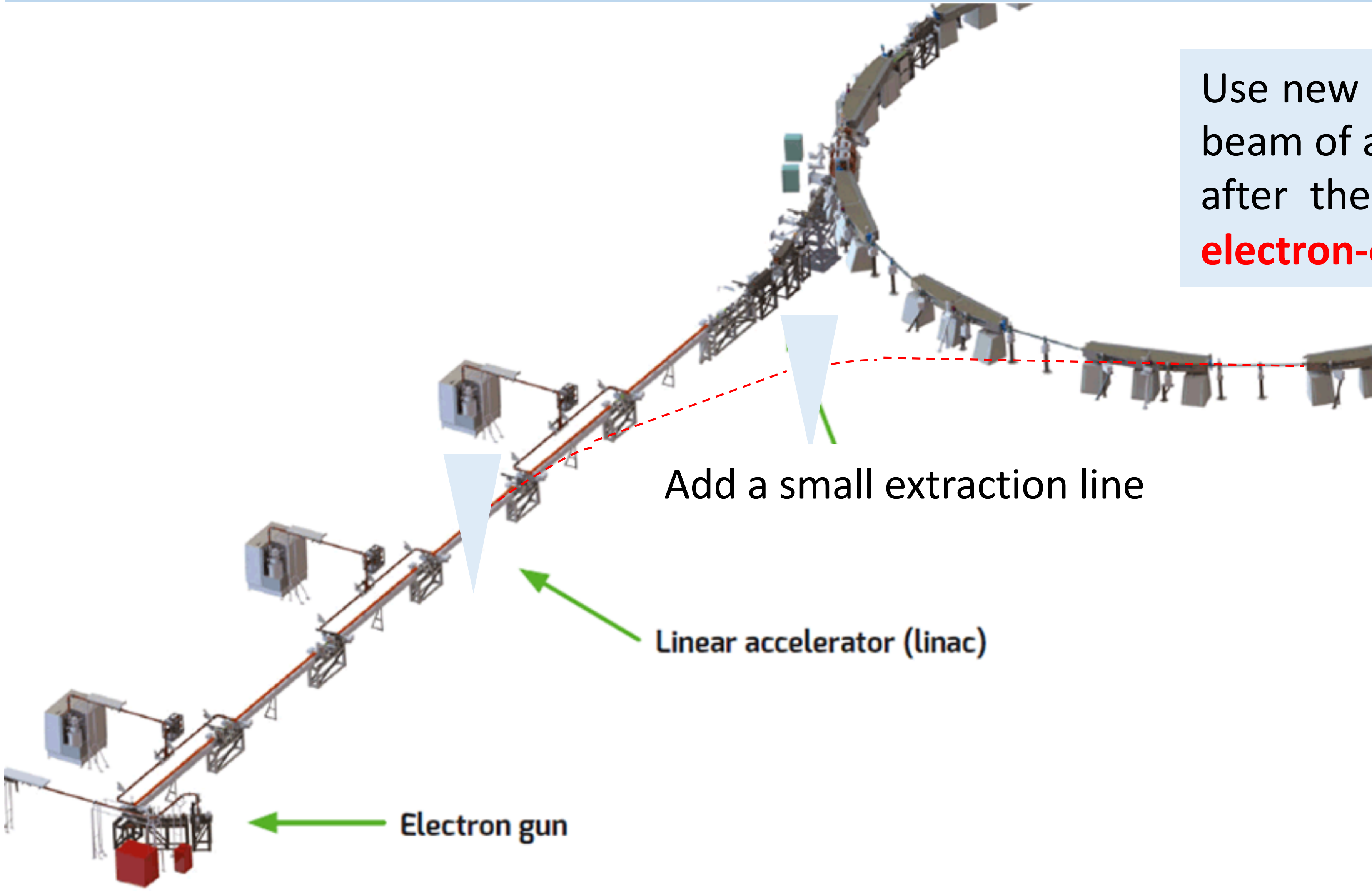
The SOLARIS storage ring main parameters

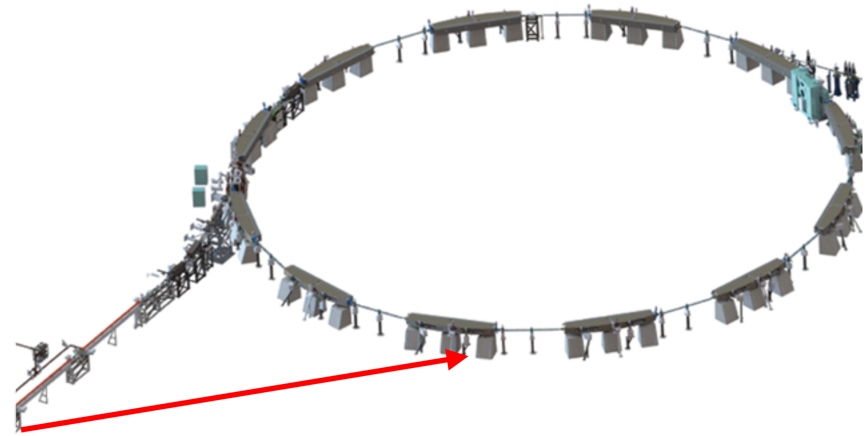
PARAMETER	VALUE
Energy	1.5 GeV
Max. current	500 mA
Circumference	96 m
Main RF frequency	99,93 MHz
Max. number of circulating bunches	32
Horizontal emittance (without insertion devices)	6 nm rad
Coupling	1%
Tune Q_x, Q_y	11.22; 3.15
Natural chromaticity ξ_x, ξ_y	-22.96, -17.14
Corrected chromaticity ξ_x, ξ_y	+1, +1
Electron beam size (straight section centre) σ_x, σ_y	184 µm, 13 µm
Electron beam size (dipole centre) σ_x, σ_y	44 µm, 30 µm
Max. number of insertion devices	10
Momentum compaction	3.055×10^{-3}
Total lifetime of electrons	13 h



CBS @ Solaris: Proof-of-concept proposal

Use new couple of dipoles to extract linac beam of about 200 (or 400) MeV to make, after the storage ring is filled, **parasitic electron-electron collisions** at Solaris!





Solaris: 1st ever CBS observation?

Reminder: For low energy photons, CBS spectrum is very simple, for flat beams and single bunch crossing:

$$dN_\gamma = N_0\, dE_\gamma / E_\gamma \quad \text{where} \quad \boldsymbol{N_0 = \eta^2 N_e\, 8\alpha/9\sqrt{3} = 0.0038\,\eta^2 N_e}$$

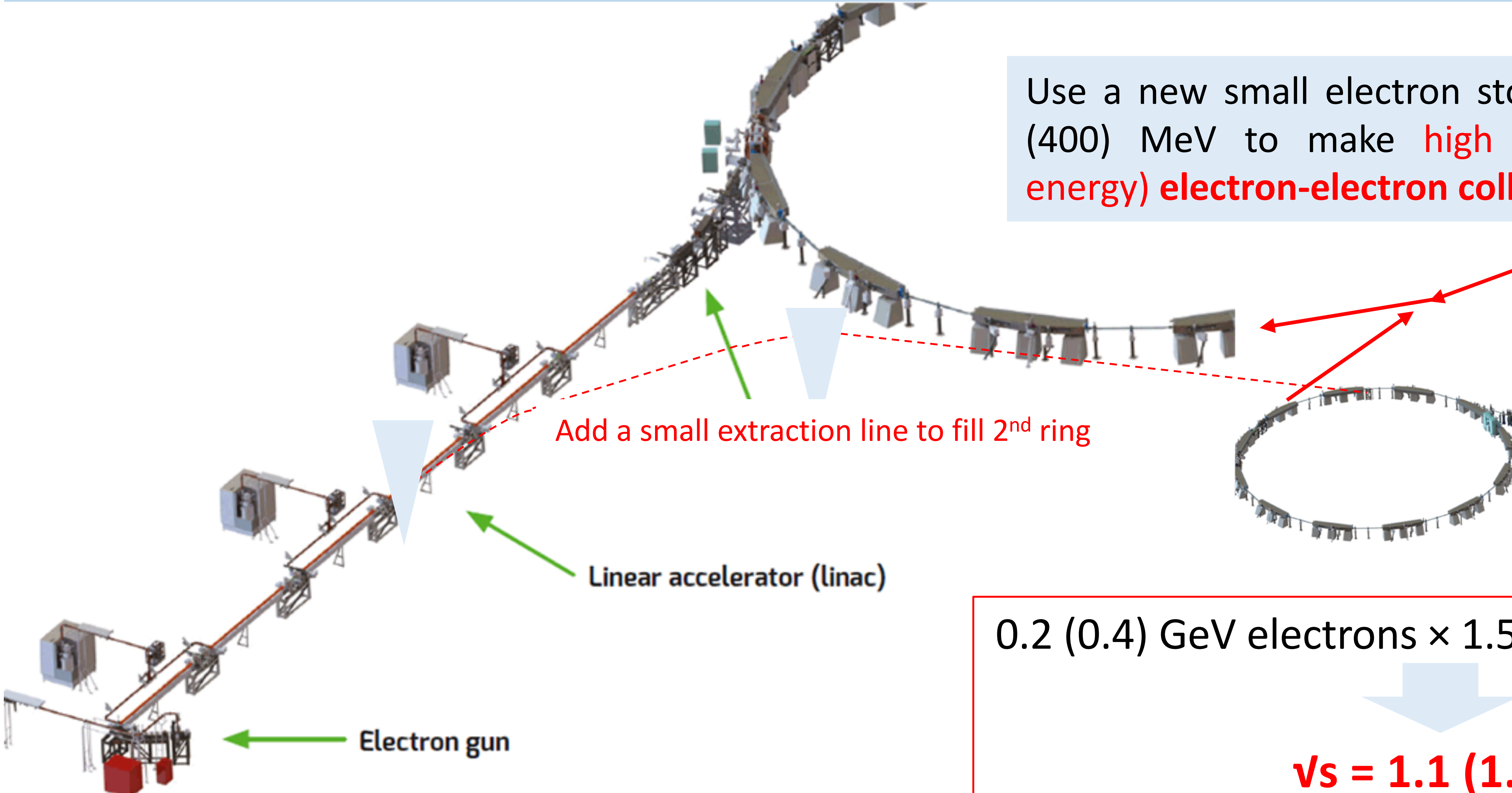
At "Solaris CBS line", low energy (200 MeV?) beam plays the role of protons at the EIC, hence assuming σ_x = 200 μm and "target" bunch charge = 0.2 nC, then η **= 0.02** and $\boldsymbol{N_0 \approx 1.2\,\eta^2\, 10^8}$ for total beam current of 500 mA.

Assuming bunch length of 1.5 (0.15) mm one gets for 1.5 GeV storage ring photon critical energy = **4.6 (46) keV** and number of photons in 0.1–1 (1–10) keV interval **≈ 10^5 per bunch-X** radiated within **0.3 mrad**, for CBS light pulse width of about **10 ps.**

In addition, perhaps horizontal beam-sizes could be significantly reduced at *ee* IP

CBS @ “Solaris+”: Ultimate dream scenario…

Use a new small electron storage ring at 200 (400) MeV to make high luminosity (high energy) **electron-electron collisions** at Solaris!



0.2 (0.4) GeV electrons × 1.5 GeV electrons

$\sqrt{s}$ = 1.1 (1.55) GeV

CBS @ Solaris: Ultimate dream scenario

At "Solaris+", (very) low energy (50 MeV?) beam plays the role of protons at EIC, hence assuming σ_x = 200 μm and bunch charge = 5 nC then η **= 0.5** and $N_0 \approx 1.2\eta^2\, 10^8$ for total beam current of 500 mA.

Nota bene: Assuming bunch length of 1.5 (0.15) mm one gets, for 1.5 GeV storage ring, photon critical energy = **4.6 (46) keV** and number of photons in 0.1–1 (1–10) keV interval ≈ **7×10^7 per bunch-X** radiated within 0.3 mrad, for CBS light pulse width of about 10 ps.

As a result, bright source of **photons up to 1 (10) keV** and above is available:

Spectral brightness = 4×10^{14} $s^{-1}mm^{-2}mrad^{-2}$ @ 0.1% BW (could be boosted **up to 10^{16}**)

+

Very interesting possibility of unique **measurements of light-by-light scattering**!
⇒ peak *ee* luminosity at least of **3×10^{32} $cm^{-2}s^{-1}$** (much higher than at HERA)

Summary

Coherent bremsstrahlung (CBS) has not been ever observed, and conditions for its observation at the Electron-Ion Collider seem very favorable (as well as for in-depth studies of onset of beam-strahlung).

Solaris might offer exciting possibility of observing the CBS before startup of EIC – provided low energy electrons are brought to collisions (“parasitically”) with storage ring beam.

Moreover, installation of “auxiliary” (very) low energy storage ring at Solaris would open new and unique research directions:

- Studies using CBS as high brightness source of X-rays, resulting from intense electron-electron collisions - note it is **green technology, as ALL radiated power in CBS can be used for research**
- Breakthrough studies of light-by-light scattering at crucial $\gamma\gamma$ center-of-mass energies

Thank you!

Basic research is what I am doing when I don't know what I am doing.
-- *Wernher von Braun*

BSE @ EIC

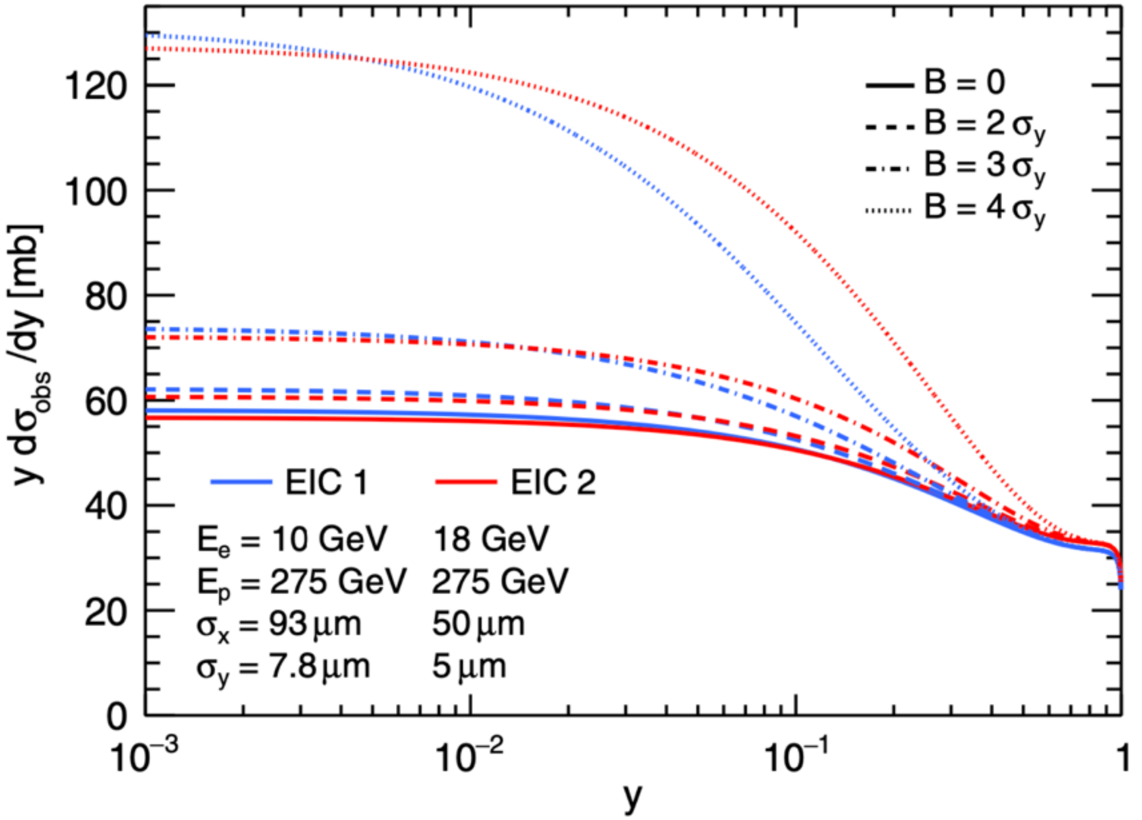


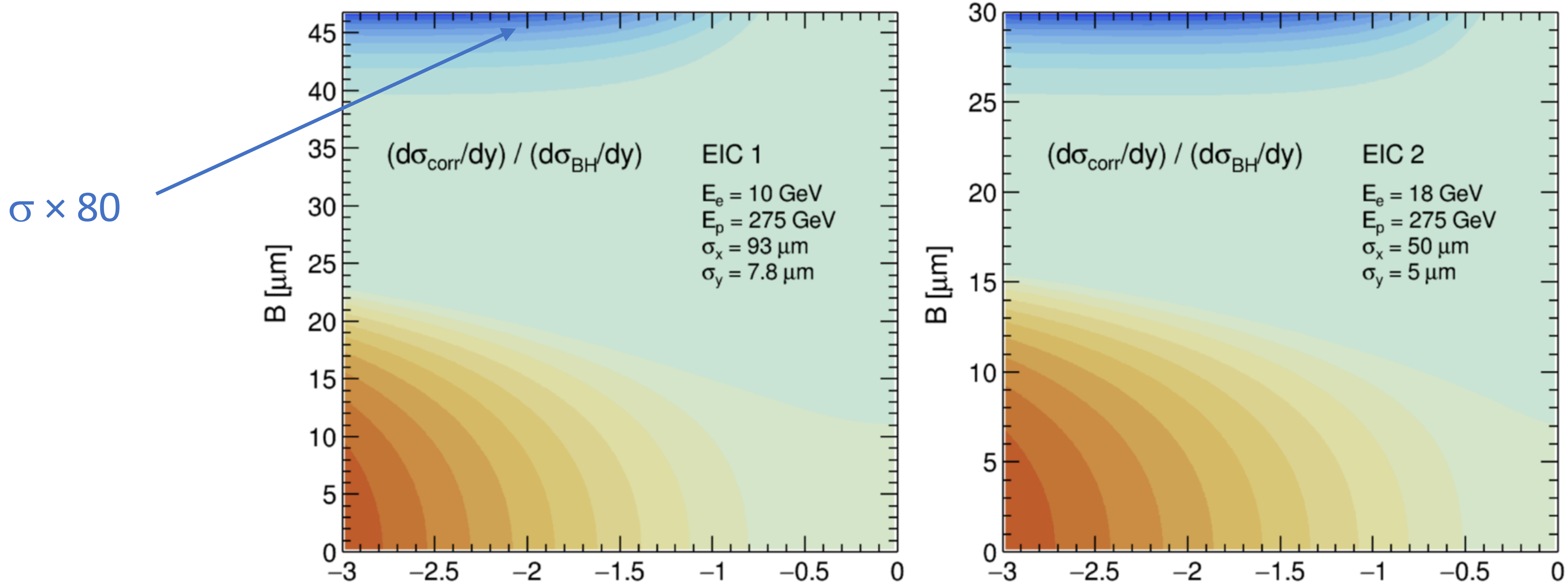
FIG. 4. The predicted spectra of ep bremsstrahlung at the EIC for several vertical beam displacements. The standard Bethe-Heitler cross section $d\sigma_{BH}/dy$ is modified due to the beam-size effect and beam displacements B. The effective cross sections (multiplied by y for better visibility) are 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

We propose an original and powerful test of the BSE by measuring the bremsstrahlung spectrum while scanning (vertically) the beams.

This will be at the same time an exciting direct study/demonstration of very long-range nature of bremsstrahlung process – for large **lateral** beam displacements we predict a strong **effective increase** of its cross-section!

BSE @ EIC



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

FIG. 5. Relative corrections to the standard Bethe-Heitler cross sections, due to both the beam-size effect and vertical beam displacements, as a function of B and y. The ratios $(d\sigma_{\rm corr}/dy)/(d\sigma_{\rm BH}/dy)$ are shown as a function of the vertical beam displacement B and the logarithm of the relative photon energy $y = E_\gamma/E_e$ for the two sets of EIC parameters: EIC 1 and EIC 2. The corresponding beam energies and Gaussian lateral beam sizes at the interaction point are listed. Shown are ten equidistant (in the third dimension) contours for the values above zero (displayed in brown) and ten equidistant contours for values below zero (displayed in blue). For the EIC 1 case, the distribution extends in the third dimension between approximately −84 and +0.2, whereas for the EIC 2 case this range spans approximately from −80.5 to +0.24.