Sensitivity studies for a Compton polarimeter at SuperKEKB

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AG pôle Physique des Accélérateurs
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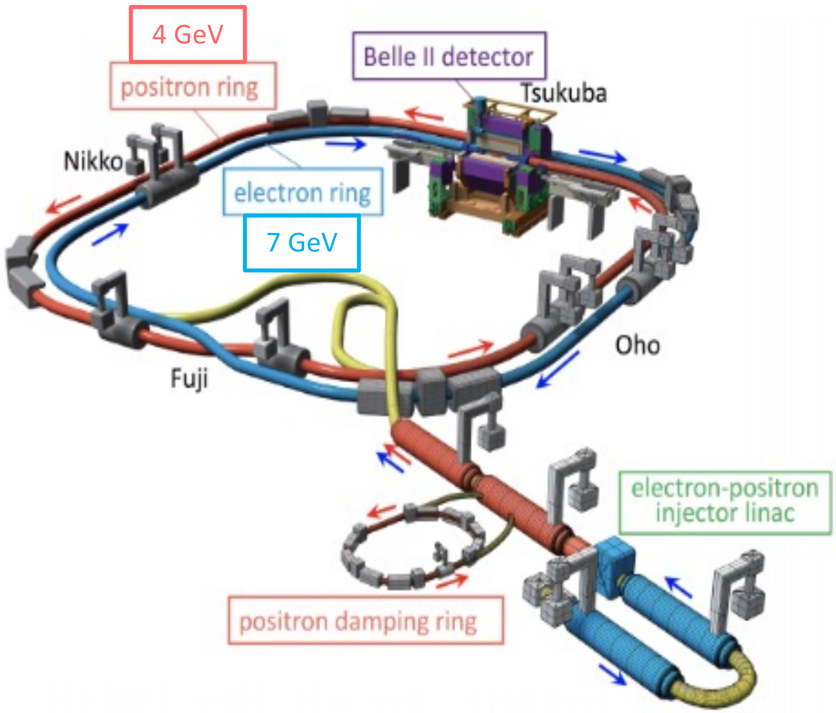
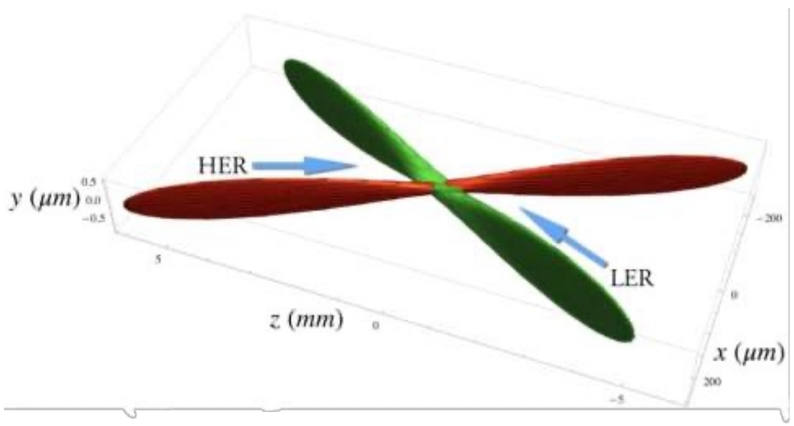
Introduction

- SuperKEKB collider:
  - Description
  - Upgrade
- Compton polarimeter:
  - Compton Cross section
  - Compton Longitudinal and transverse polarimetry
- Sensitivity studies of a photon detector

What is SuperKEKB?

- Asymmetric electron-positron collider of 3 Km circumference in Tsukuba, Japan
- Collision occurs at 10.58GeV in CMS
- Designed to run mainly at the Upsilon (4S) resonance that is a $b\bar{b}$ bound state

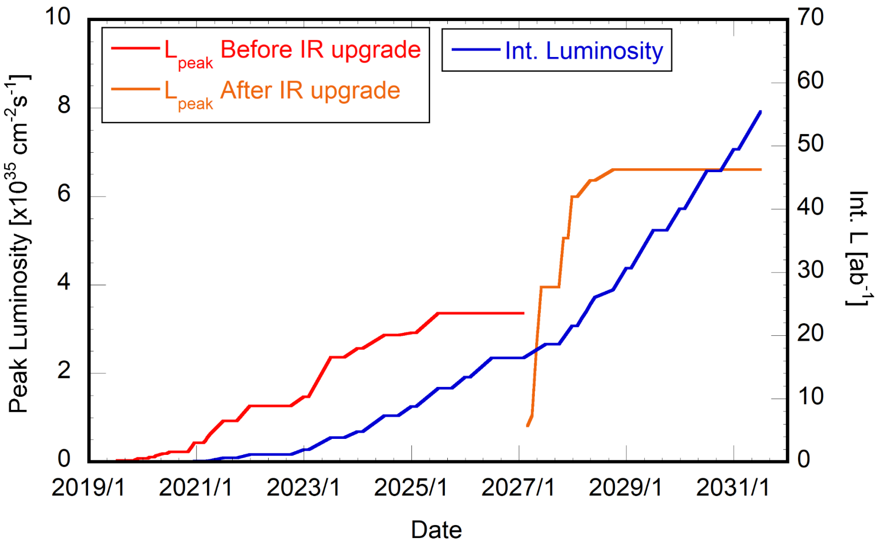


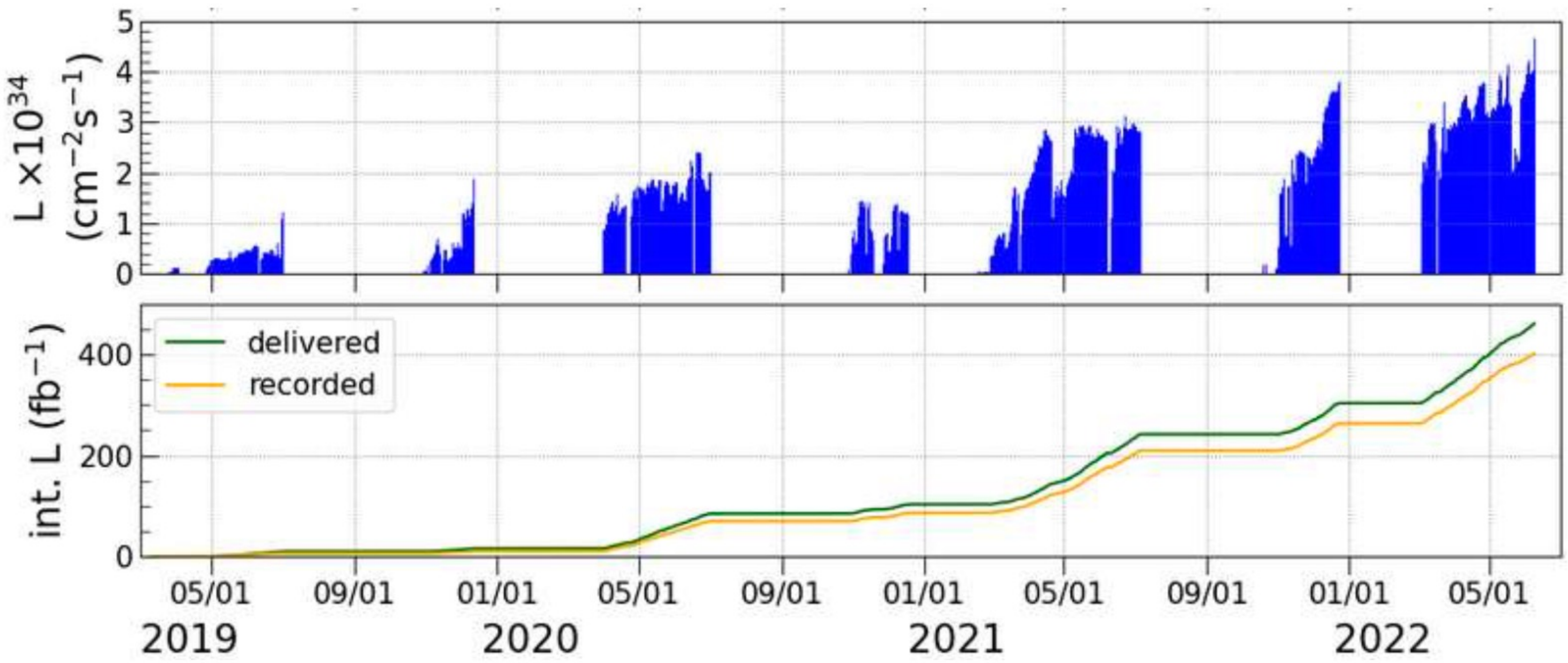


Nano-beam scheme:
10μm x ×50nm y ×250μm(z)
“Crab crossing” shape at the IP

What is SuperKEKB?

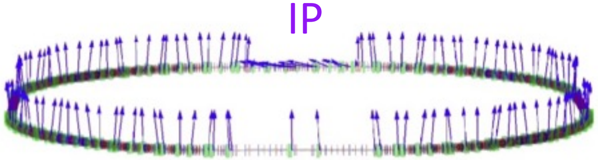
- Integrated luminosity goal: 50 ab^{-1}
- Already collected ~ 0.43 ab^{-1}(~ Babar ~ 0.5 Belle)
- Data taking restarts on Jan 29th 2024 !!! ☺
- High luminosity → precision measurements



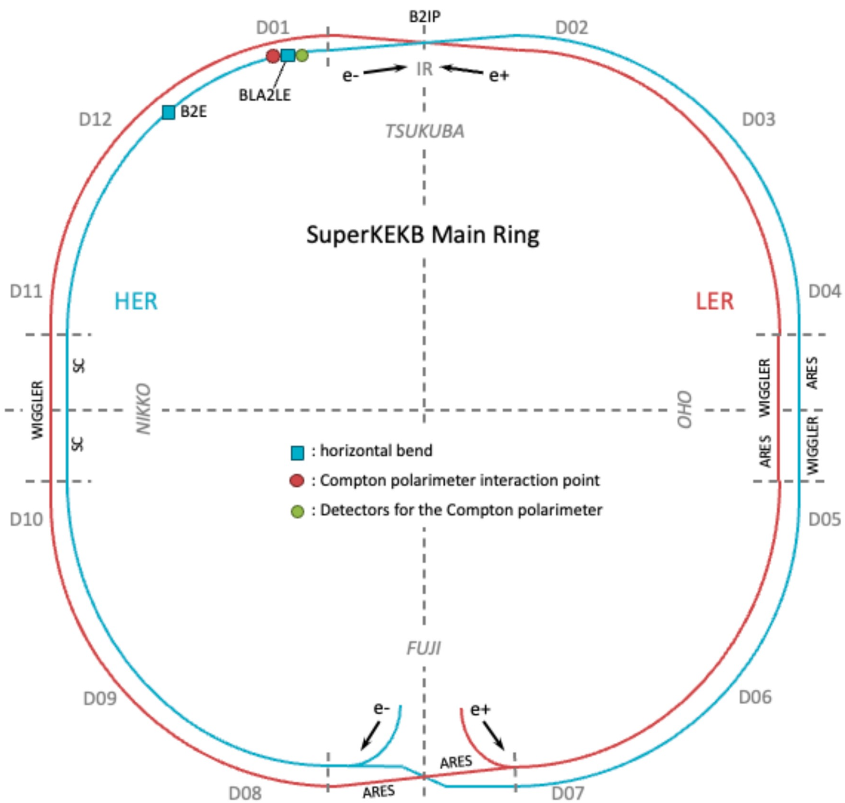


Project: Upgrade SuperKEKB with polarized electrons

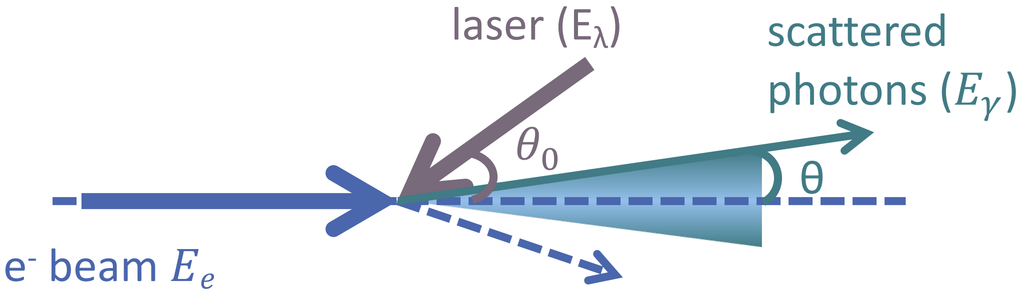
- Why?
  - Possible exploration of the electroweak and dark sectors
  - Unique measurements of Standard Model quantities with sensitivity to potential New Physics
- How?
- With required elements for the upgrade:
  - Injector
  - Spin rotator
  - Polarimeter

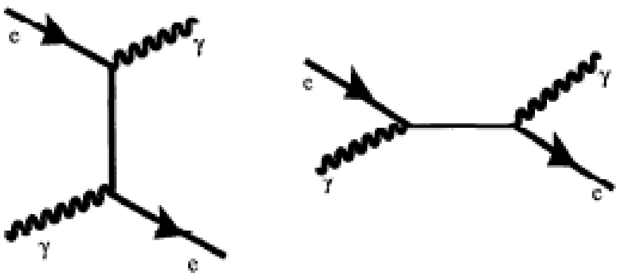


e- spin vector around ring



Compton back-scattering





- Initial electron energy (7 GeV)
- Initial photon energy (2.4eV at 515nm)
- Crossing angle of beams
- Emitted photon energy

Compton back-scattering

$$x = \frac{2E_e E_\lambda}{m^2}(1 + \cos\theta_0) \qquad y = \frac{E_\gamma}{E_e}$$

The Compton cross-section averaged over scattered particles spins:

Differential cross-section

Transverse laser polarisation: nuisance parameter to minimize and keep under control

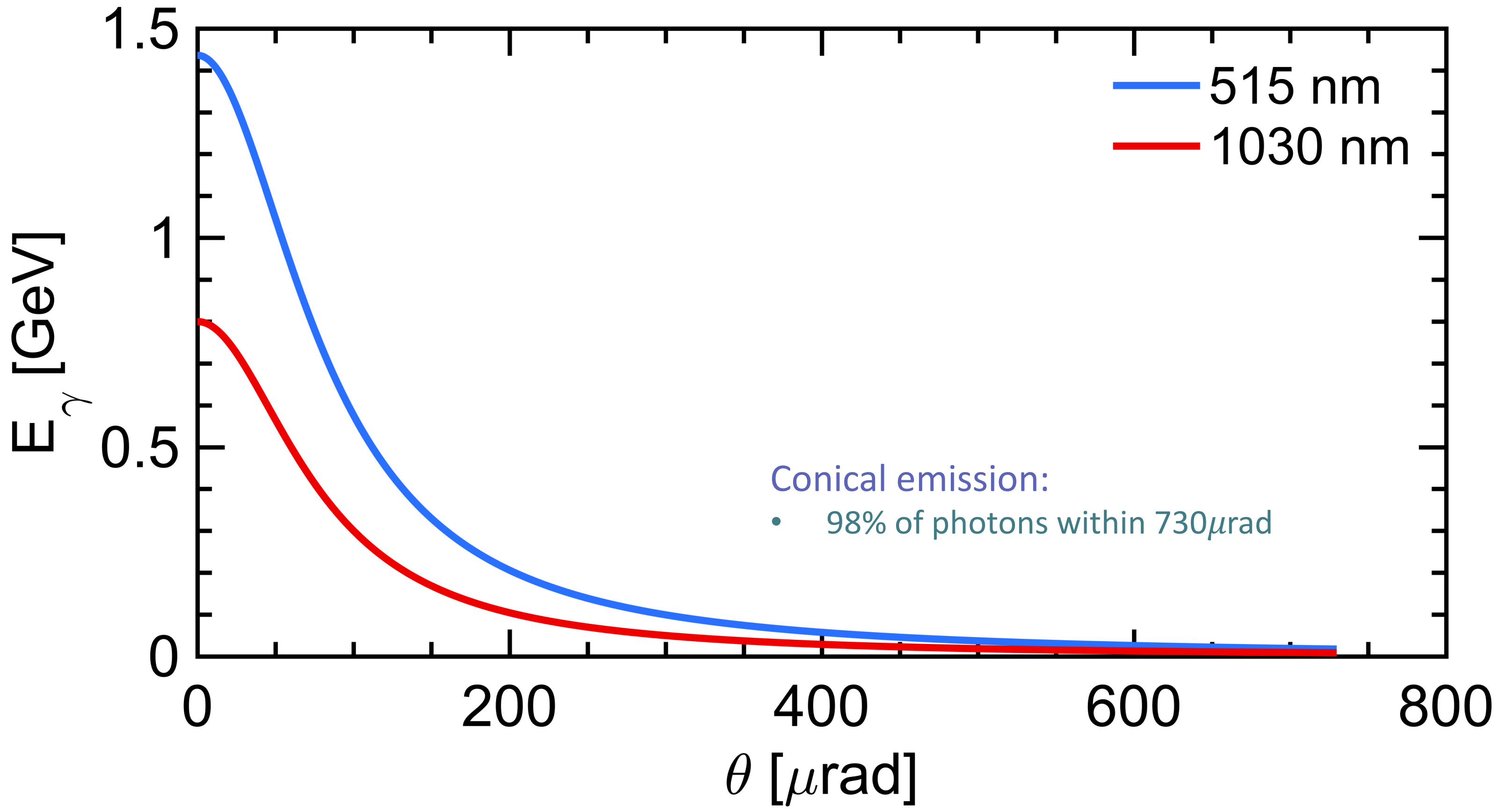
Transverse electron beam polarisation: intervenes as an asymmetry in the transverse plane

$$\frac{d\sigma}{dy d\varphi_{obs}}(x,y) = \frac{d\sigma_0}{dy}(x,y) + \frac{d\sigma_\perp}{dy}(x,y)\cos\big(2(\varphi_{obs} - \varphi_{las})\big)\mathcal{P}_{las}^{lin} + \frac{d\sigma_\parallel}{dy}(x,y)\mathcal{P}_{las}^{circ}(P_T f_T(x,y)\cos(\varphi_{obs} - \varphi_{elec}) + P_Z f_L(x,y))$$

Electron beam polarization independent

Electron beam polarization dependent

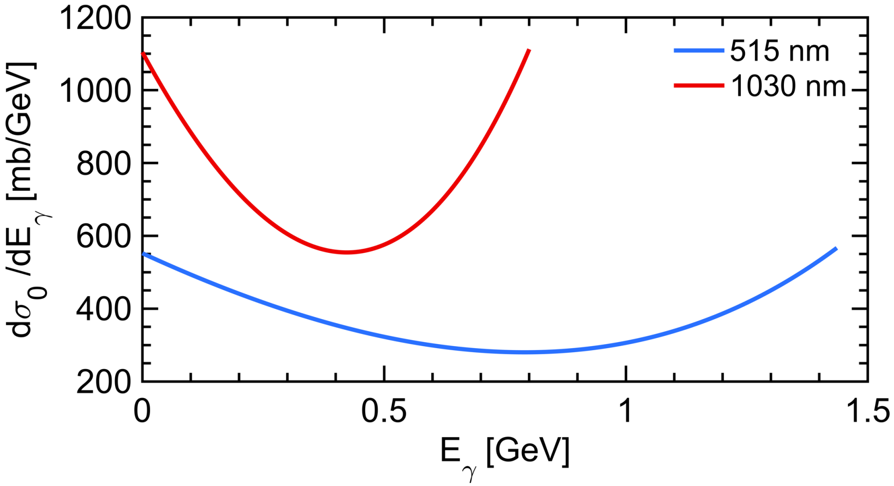
Transverse distribution of photons

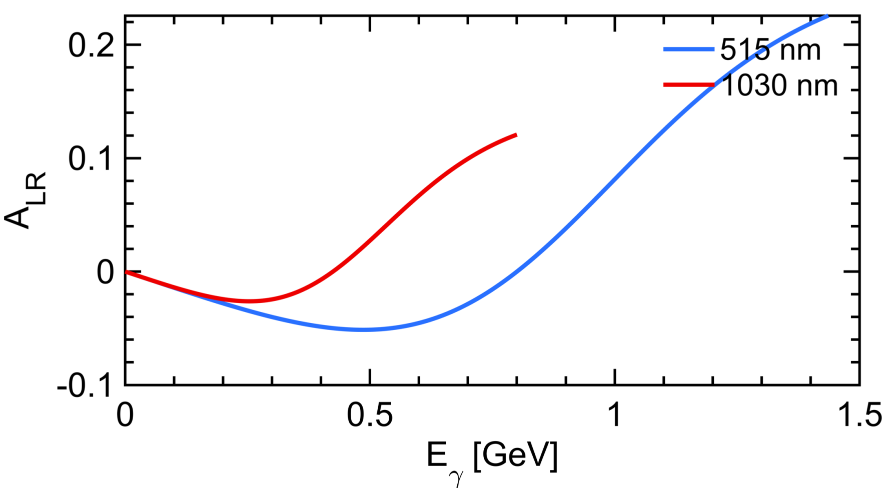


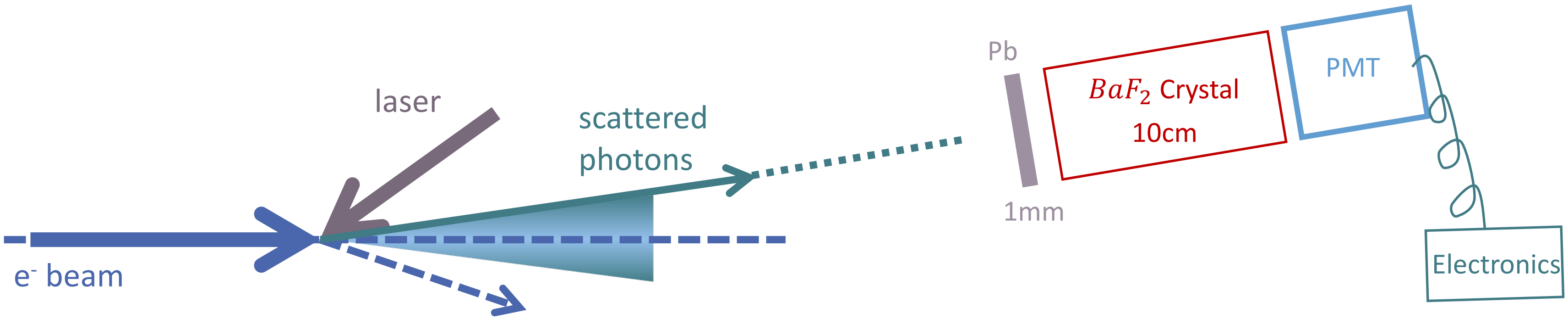
$$\frac{d\sigma}{dy}(x,y) \cong \frac{d\sigma_0}{dy}(1 + \mathcal{P}_z \lambda A_{LR})$$

Longitudinal Compton polarimetry

Polarization dependent term generates a left-right asymmetry function of E_γ







Landau-Lifshitz QED book paragraphs 86 and 87

Toy-MC sensitivity studies

Simulate electron-laser interaction → extract longitudinal polarization of electrons

Electron beam parameters

Parameter	Value	
μ_E	7 GeV	
σ_δ	6.3×10^{-4}	
Q_e	10 nC	
T_{rev}	10 μs	
$P_\perp$	0	
P_z	0.7	
ϕ_e	$\pi/2$	
	horizontal plane (x)	vertical plane (y)
$\epsilon_{x,y}$	4.49×10^{-9} m·rad	4.5×10^{-11} m·rad
$\beta_{x,y}$	96.46 m	127.09 m
$\alpha_{x,y}$	−8.72	9.45
$\eta_{x,y}$	−0.083 m	-1.1×10^{-9} m
$\eta'_{x,y}$	−0.0035	6.8×10^{-11}

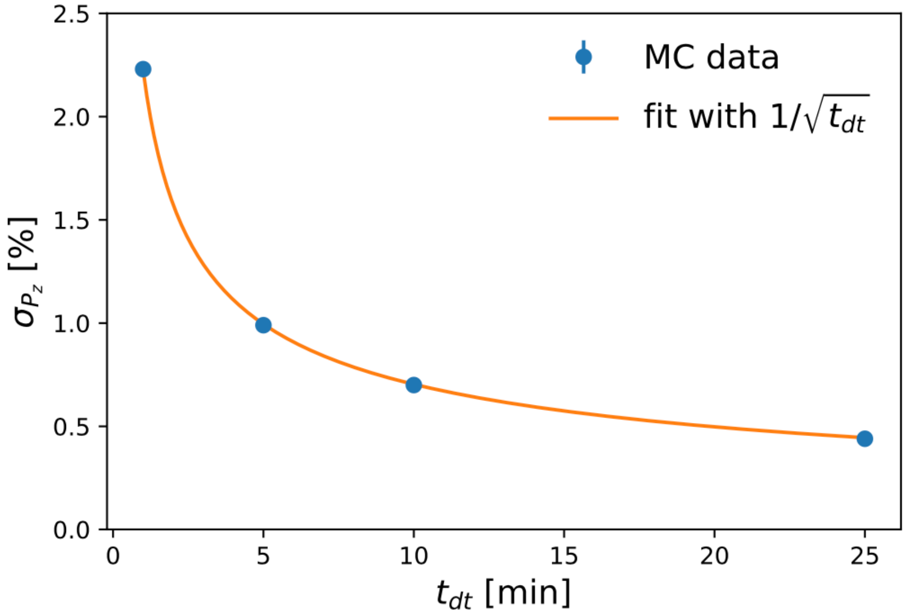
Laser beam parameters

Parameter	Value
P_C	−1
P_L	0
ϕ_l	0
$\sigma_x/\sigma_y/\sigma_z$	500 µm/500 µm/500 µm
λ	515 nm
$f_{\text{rep.}}$	250 MHz
U	20 nJ
θ_{in}	8.9 degrees
ϕ_{in}	28 degrees

Parameters of Compton interaction and the detector

Parameter	Value
L	13 m
$T_{\text{meas.}}$	5 min
$d_{\text{det.}}$	5 cm
$A_{\text{det.}}$	0.1 GeV$^{1/2}$
$B_{\text{det.}}$	0.01

Statistical sensitivity



- For 1 min, there's 2.2% error on the extraction of P_z
- For 25 min, there's 0.5% error on the extraction of P_z

Signal + background Toy-MC

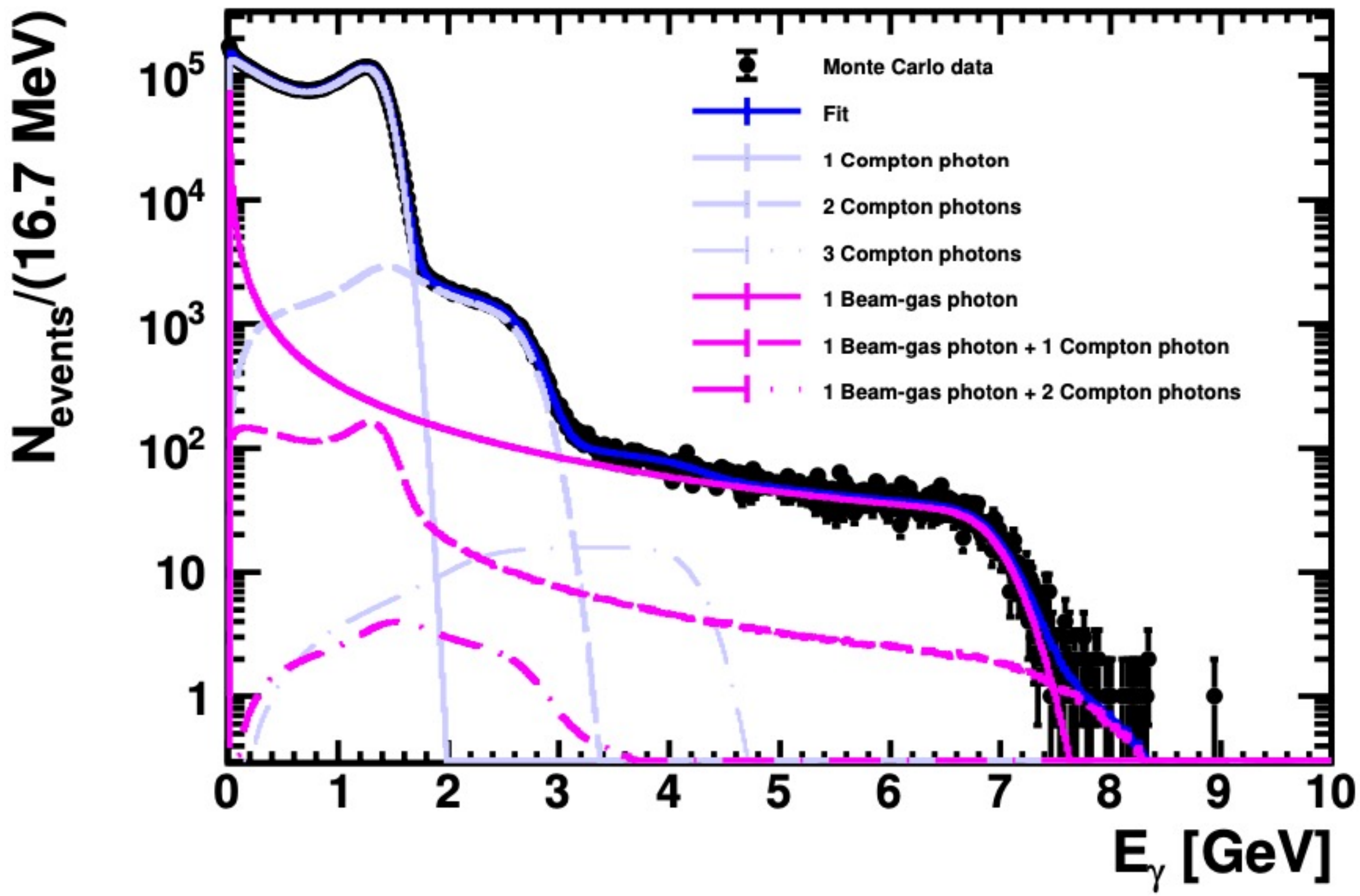


Table of systematics

Source	Uncertainty on P_z(%)
Laser beam polarization	0.30
Backgrounds	0.16
Fit procedure	0.080
Beam energy	0.050
Spatial misalignment	0.015
Angular misalignment	0.015
Longitudinal misalignment	0.015
Transverse electron beam polarization	0.015
Total	0.35

Summary

- Extensive studies based on toy MC have been made
- Systematic uncertainties have been estimated
- JINST publication
- R&D BaF_2 detector + realistic GEANT simulation ← French funding applied (hardware + manpower)

Jinst
Published by IOP Publishing for Sissa Medialab
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Conceptual study of a Compton polarimeter for the upgrade of the SuperKEKB collider with a polarized electron beam

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Abstract: The physics scope of the Belle II experiment currently acquiring data at the SuperKEKB collider will expand with a polarized electron beam upgrade, as recently proposed. Among the required elements for this upgrade, a real time diagnosis of the polarization is necessary to ensure it is large for all bunches in the accelerator during its regular operation. This will be realized by inserting a Compton polarimeter in the accelerator. Its conceptual design is described and no show-stopper for its integration has been identified. An estimation of the sensitivity of the polarimeter is made by means of toy Monte-Carlo studies. The proposed design accounts for the constraint to preserve the performance of the SuperKEKB accelerator and to cope with the short time separation of successive bunches. We show that the polarimeter will measure for each bunch the polarization within five minutes with a statistical precision below 1% and systematic uncertainties below 0.5%. It has the capability of providing this information online on a similar timescale. This work paves the way towards future implementation of real-time Compton polarimetry in several future projects.

Keywords: Accelerator Subsystems and Technologies; Beam-line instrumentation (beam position and profile monitors, beam-intensity monitors, bunch length monitors); Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons)

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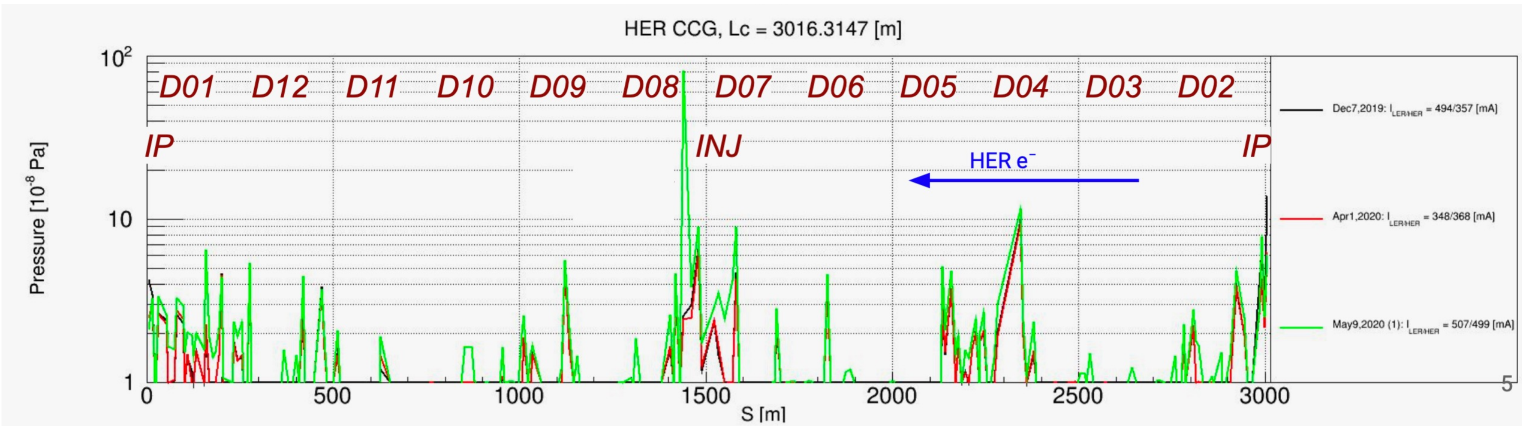
2023 JINST 18 P10014

Backup

Backgrounds

- Bremsstrahlung radiation → Main Contribution
- Synchrotron radiation
- Compton on blackbody radiation



Bremsstrahlung Luminosity

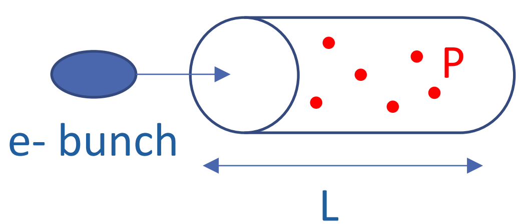
$$L_{brem} = \beta\, N_e \frac{L\, P}{k_B T}$$

L=30m

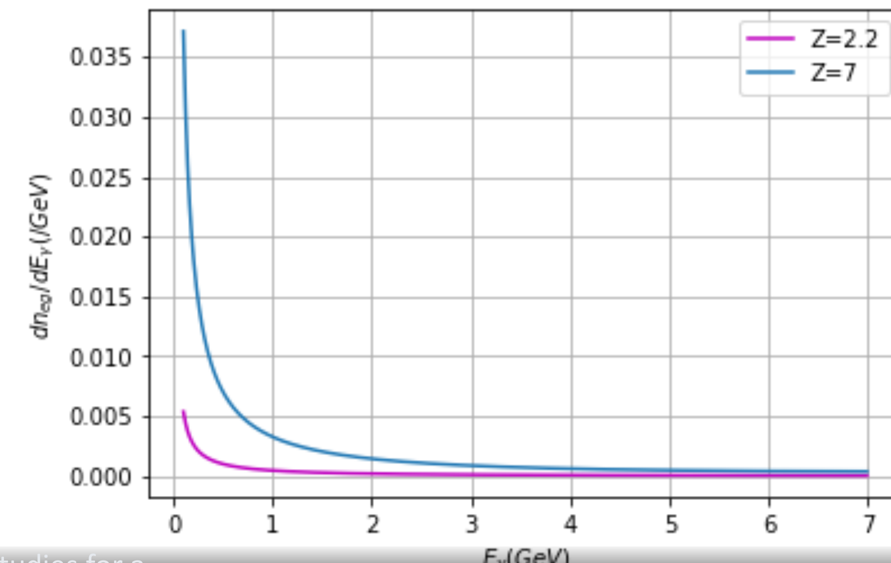
P<$10^{-7}\,Pa$

T=300K

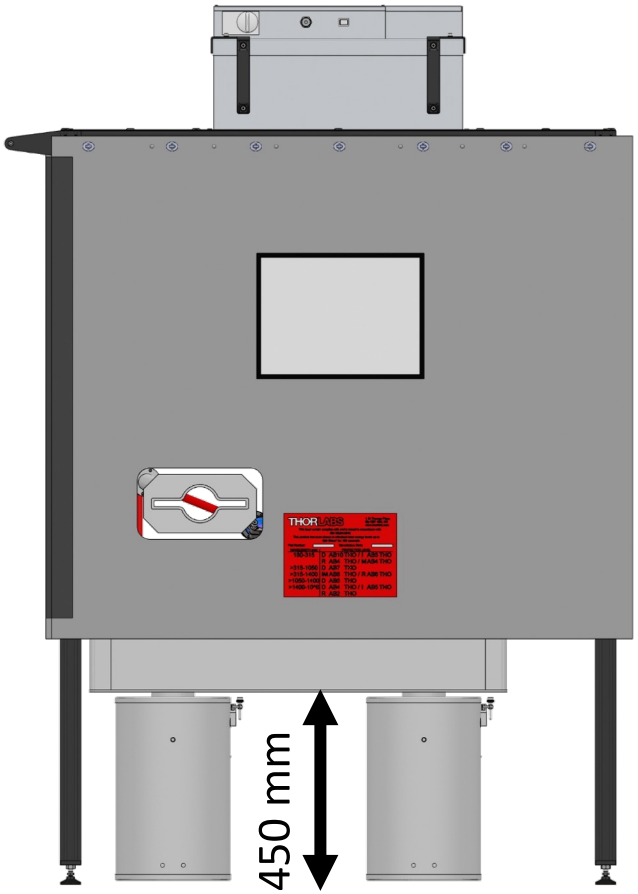
N_e=10nC

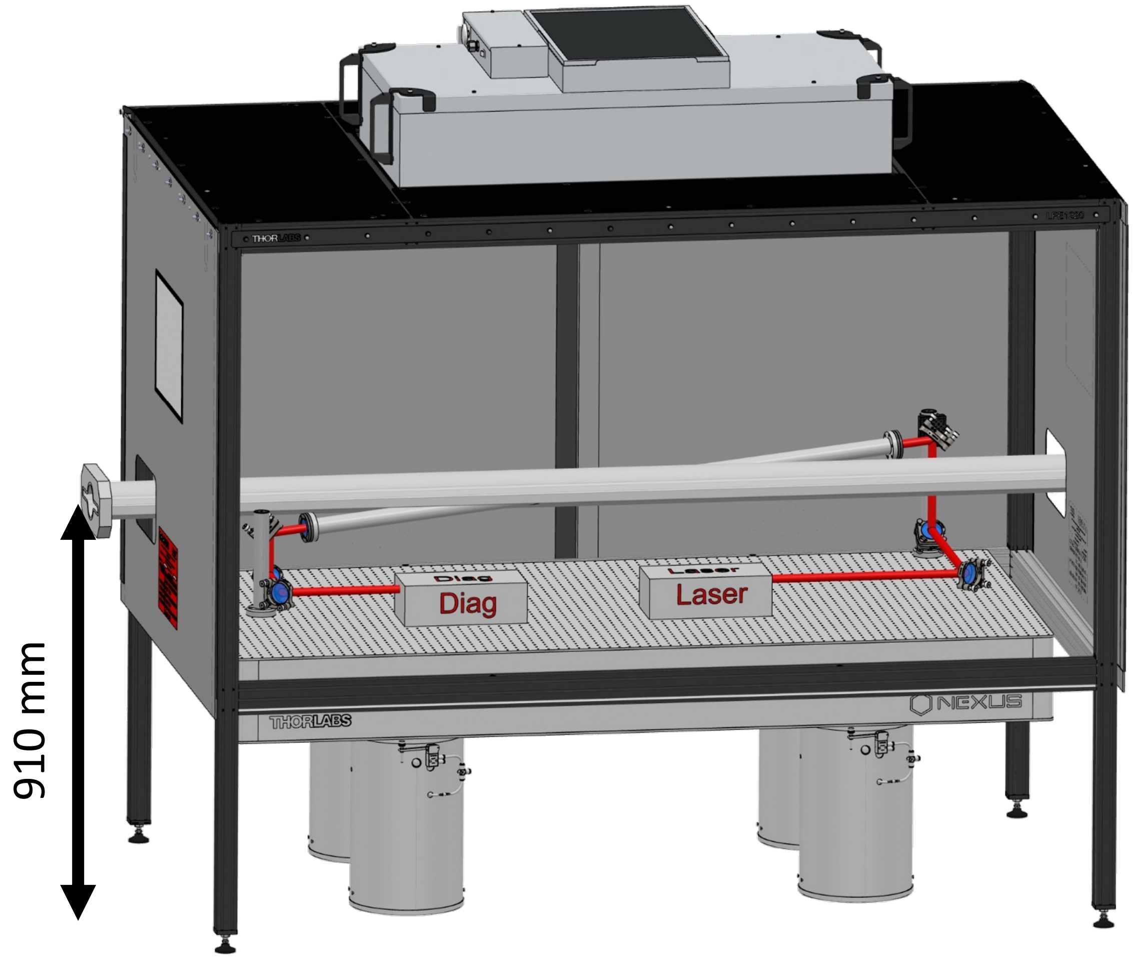


uniformly distributed gas particles in the beam pipe



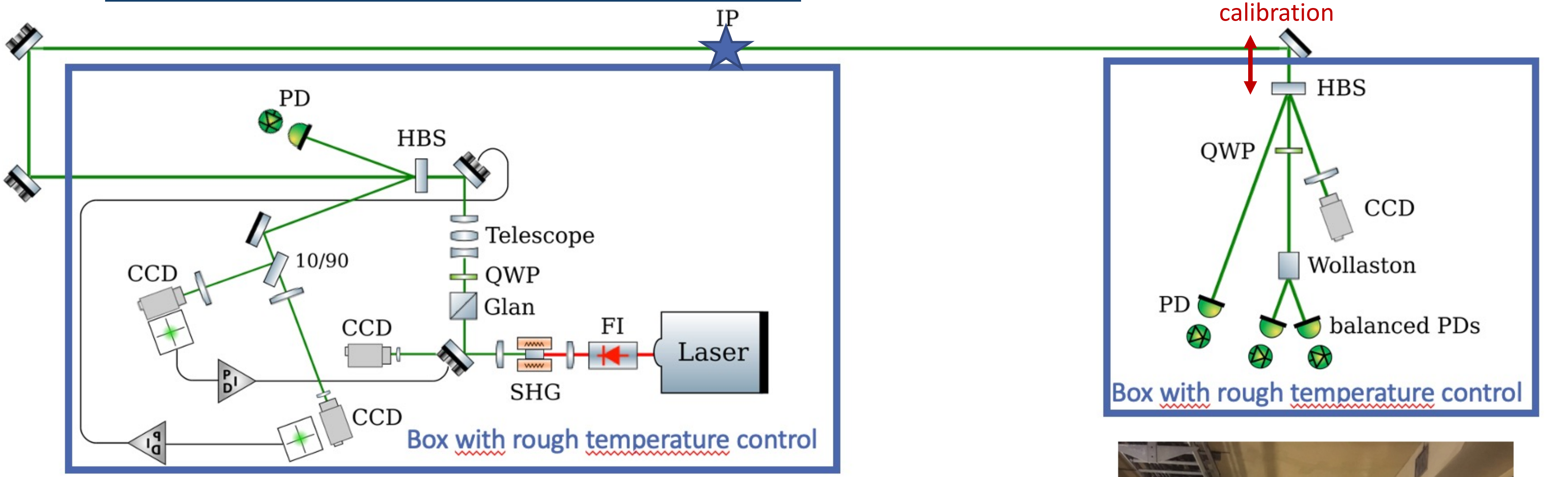
Mechanical system integration



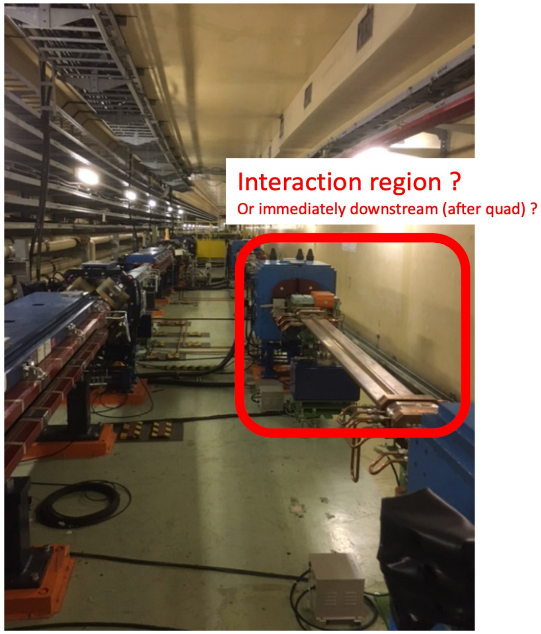


Cross Angle Horizontal : 10 deg
Cross Angle Vertical : 4 deg

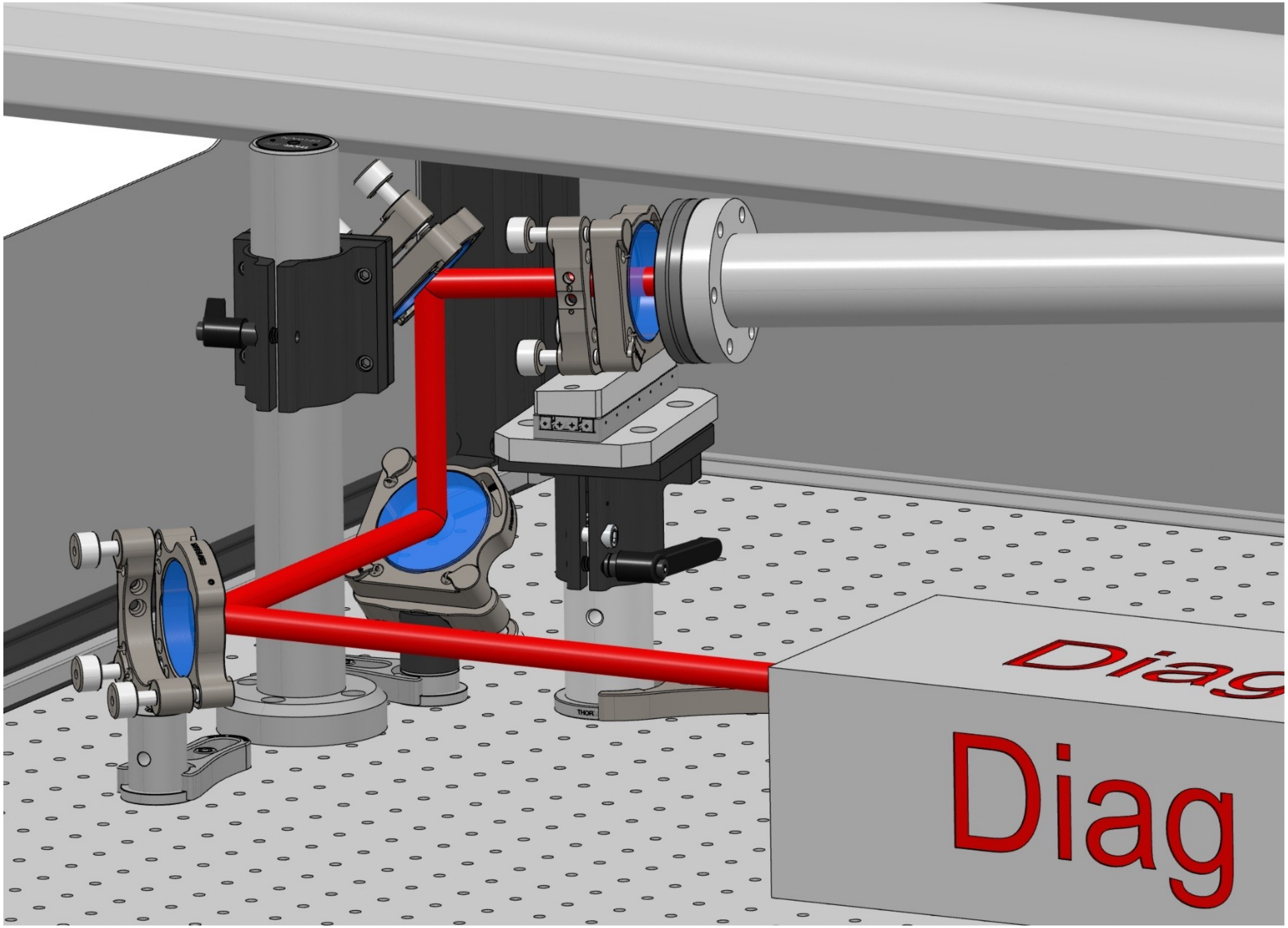
SuperKEKB laser concept



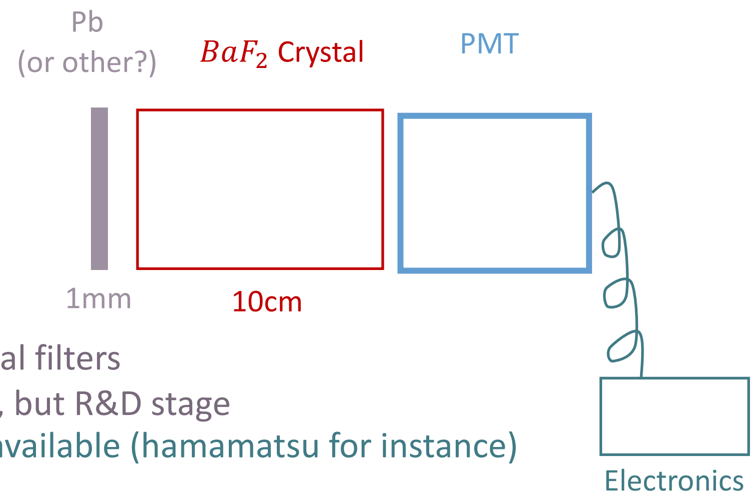
- Laser placed in accelerator bay below beam line
- Pulsed 250MHz green laser with a couple of Watts
- Automatic beam alignment and stabilization
- Currently working on real-time laser polarimetry based on photo-elastic modulation (on-going at IJCLab)
- Laser must be sync-ed to accelerator RF



Insertable mirror

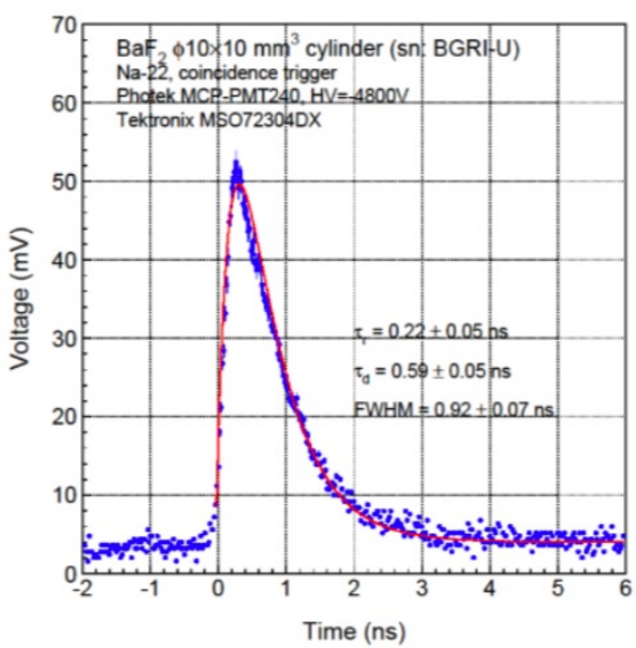


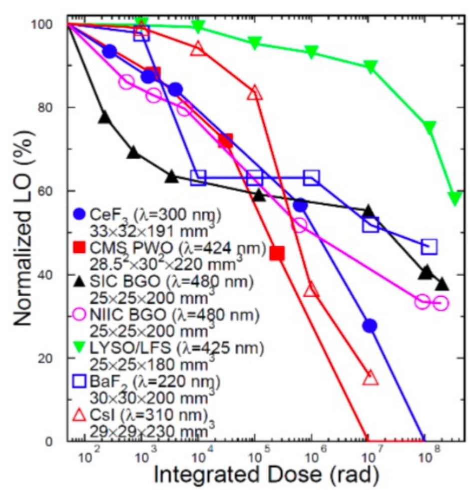
Basic idea of detector



Basic elements

- a VERY FAST radhard scintillating crystal → BaF2
  - Need to filter out the slow component → UV optical filters
  - Interesting: Y doping reduces the slow component, but R&D stage
- a PMT with low transit time dispersion → commercially available (hamamatsu for instance)
- Associated electronics
- Next step: validate detection scheme





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IOP Conf. Series: Journal of Physics: Conf. Series 1162 (2019) 012022 doi:10.1088/1742-6596/1162/1/012022

Ultrafast and Radiation Hard Inorganic Scintillators for Future HEP Experiments

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Abstract. Future HEP experiments at the energy and intensity frontiers require fast and ultrafast inorganic scintillators with excellent radiation hardness to face the challenges of unprecedented event rate and severe radiation environment. This paper reports recent progresses in fast and ultrafast inorganic scintillators, such as LYSO:Ce crystals and LuAG:Ce ceramics for an inorganic scintillator based shashlik sampling calorimeter and yttrium doped BaF_2 crystals for the proposed Mu2e-II experiment. Applications of ultrafast inorganic scintillators in Gigahertz hard X-ray imaging will also be discussed.

1. Introduction

Inorganic scintillators have been used widely in high energy and nuclear physics experiments, medical instruments and homeland security applications. In high energy physics (HEP) and nuclear physics experiments, total absorption electromagnetic calorimeters made of inorganic crystals are known for their superb energy resolution and detection efficiency for photon and electron measurements [1]. An inorganic crystal calorimeter is thus the choice for those experiments where precision measurements of photons and electrons are crucial for their physics missions.

Among all existing crystal calorimeters, the CMS lead tungstate (PbWO4 or PWO) crystal calorimeter, consisting of 75,848 crystals of 11 m^3, is the largest. Because of its superb energy resolution and detection efficiency, the CMS PWO calorimeter has played an important role for the discovery of the Higgs boson by the CMS experiment [2]. Crystal calorimeters currently under construction are: an undoped CsI calorimeter for the Mu2e experiment at Fermilab, a PWO calorimeter for PANDA at FAIR, a LYSO calorimeter for COMET at JPARC and a PbF_2 calorimeter the g-2 experiment at Fermilab.

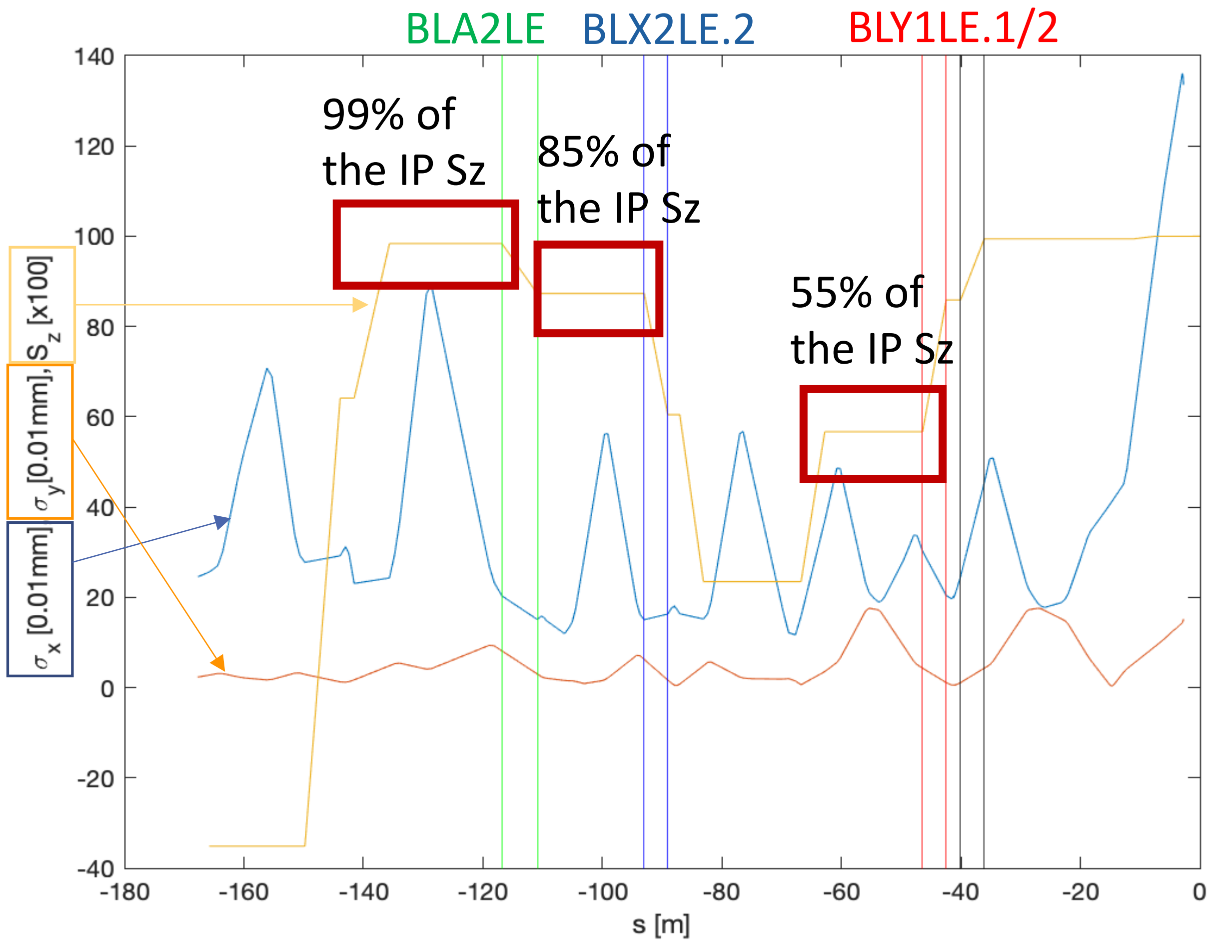
Future HEP calorimeters will be operated under unprecedented luminosity. An important issue is thus the decay time of scintillation light. Table 1 lists the optical and scintillation properties for fast inorganic crystal scintillators with a scintillation decay time ranged from sub-nanosecond to a few tens nanosecond, and compared to plastic scintillator [1]. Among the fast crystals listed in Table 1 the mass-production cost of barium fluoride (BaF_2) and undoped CsI crystals is significantly lower than others because of their low raw material cost and low melting point.

Crystal calorimeters for future HEP experiments at the energy frontier face a challenge of severe radiation environment. Significant losses of light output have been observed in the CMS PWO crystals at large rapidity *in situ* at the LHC caused by both ionization dose and hadrons [3]. Controlling oxygen contamination in halide crystals, e.g. CsI:Tl, or oxygen vacancies in oxide crystals, e.g. PWO, was found effective [4]. Co-doping with yttrium and lanthanum was also found effective for CMS PWO crystals [5]. For experiments to be operated at the HL-LHC with 3,000 fb^{-1}, crystals should survive an environment with an absorbed dose of 100 Mrad, charged hadron fluence of 6×10^{14} p cm^{-2} and fast

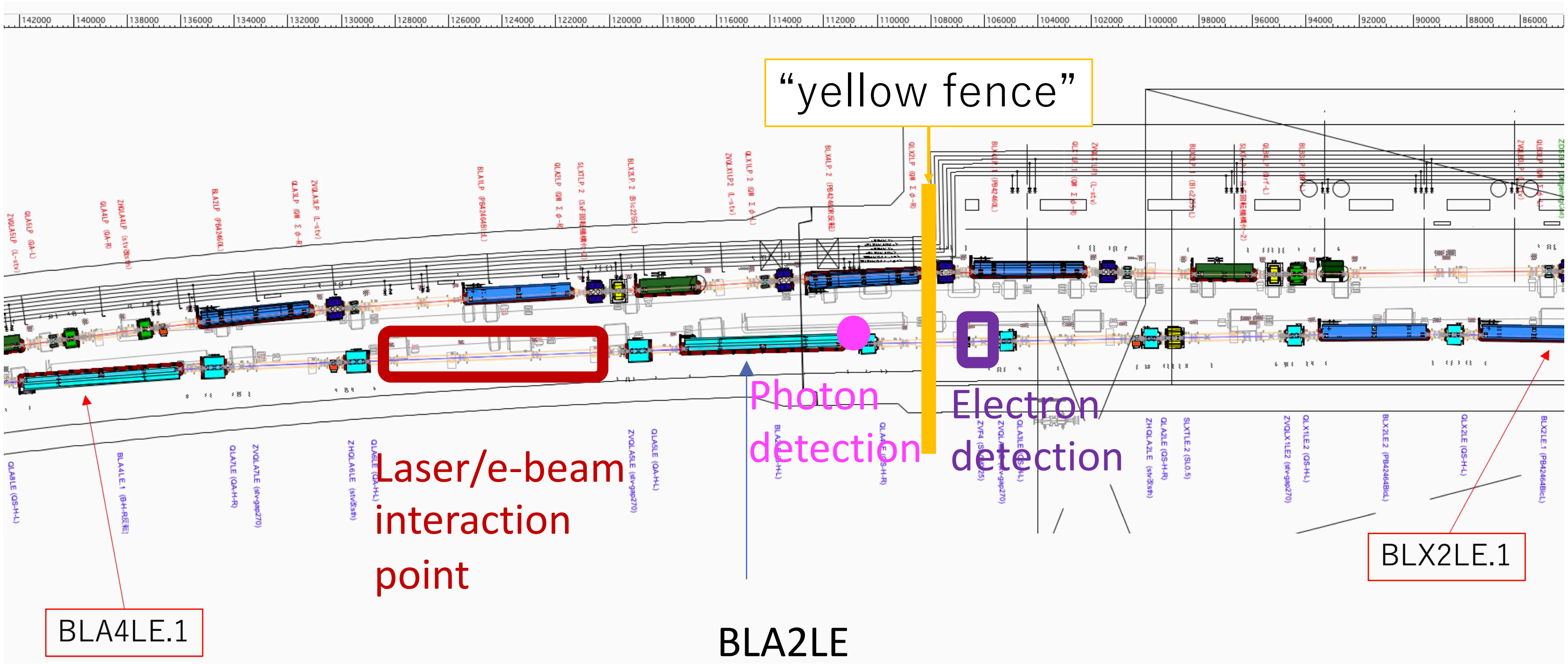
Location

Best candidate location to install polarimeter is before BLA2LE

Beam sizes and spin projection in z:



BLA2LE/BLX2LE.2

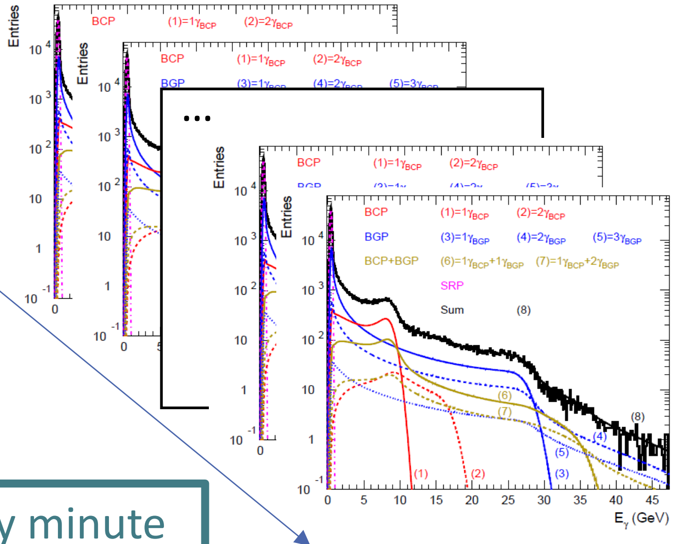


Basic idea of detector

Basic elements

- a VERY FAST radhard scintillating crystal → BaF_2, the only solution ?
  - ☹ Need to filter out the slow component → UV optical filters
  - ☺ Interesting: Y doping reduces the slow component, but R&D stage
- a PMT with low transit time dispersion → commercially available (hamamatsu for instance)
- Associated electronics
- Next step: validate detection scheme

2500 bunches → 2500 histograms
About 1000 bins each (or less ?)
12 bits dynamics ?



30Mb (3.75MB) to transfer every minute

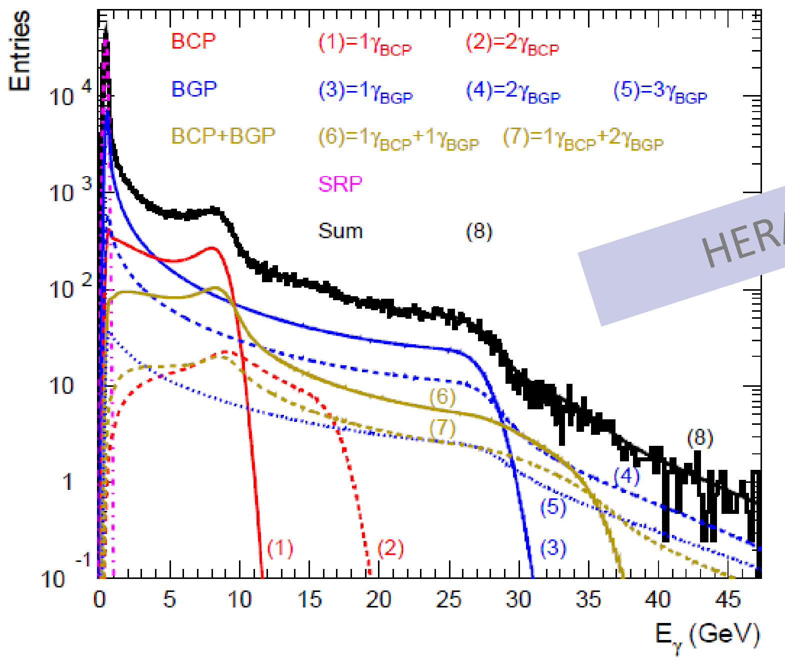
Two options

- Embarked ADC and data processing in the accelerator bay w/transfer link to storage, requires clock (laser also needs it) and bunch identification
- Deported electronics ‘à la’ lumi with diamonds sensors ? (expensive high BW cables)

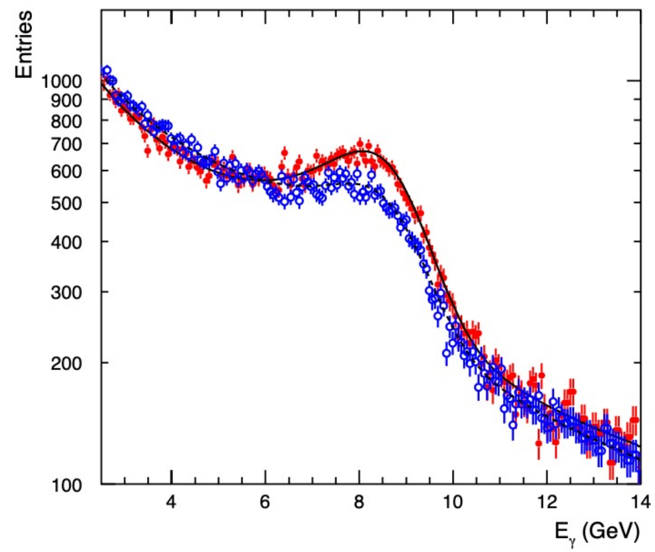
Polarization extraction

Offline: fitter

- Not immediate but can be very precise
- Account for every detail of the experiment → I start by implementing this step by step



HERA



Online: fast approximate/biased extraction

- To be investigated based on HERA work by C. Pascaud et al. (Orsay group)

Synchrotron radiation

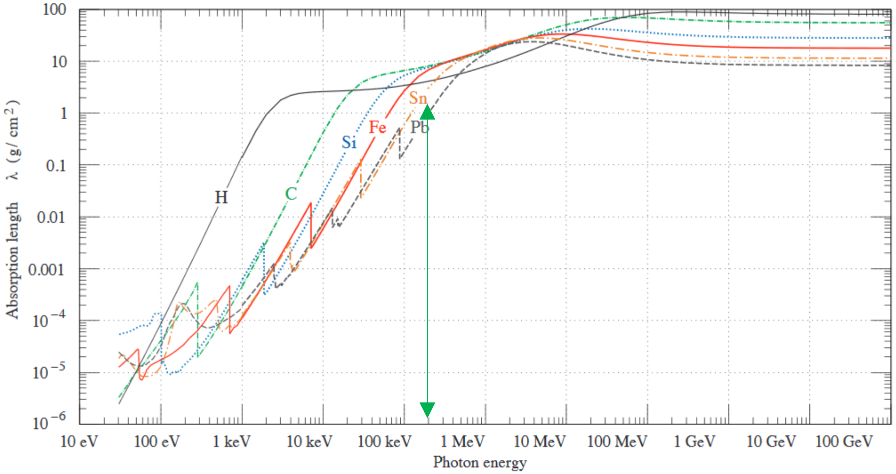
"Critical energy" of synchrotron radiation: $E_c = \frac{3}{2}\gamma^3 \frac{c}{\rho} \sim 5keV$

ρ: radius of curvature ~ 146 m

Total number of synchrotron radiation photons E_0 :

$$N_{tot\ sync}(E_X \geq E_0) = \sqrt{\frac{3\pi}{2}}\alpha\gamma\Gamma(\frac{1}{2}, \frac{E_0}{E_c})\frac{L}{2\pi\rho}$$

E_0~200keV ⟷ $1g\ cm^{-2}$



Jackson Book, Classical Electrodynamics

Density of lead: $11.34g\ cm^{-3}$

Solution: put a ~1 mm (or more) lead plate in front of the detector to get rid of synchrotron radiation

Bremstrahlung

Bremsstrahlung radiation :

Z: mean atomic number of the residual gas nucleus , taken as 2.2 or 7

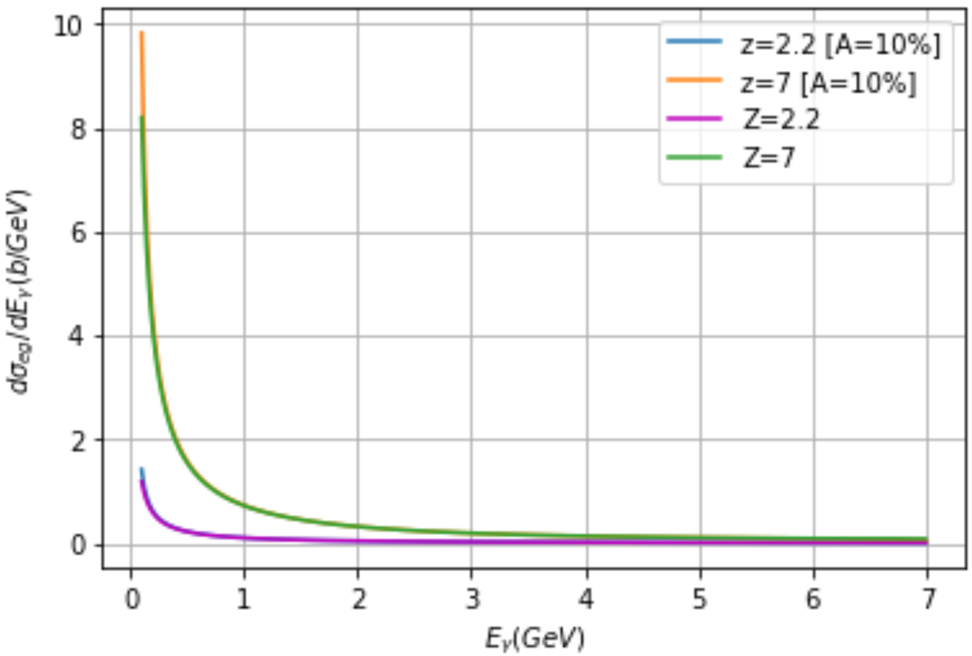
e + g $\longrightarrow$ e + g + γ

The cross section averaged over scattered particles spins :

$$y = \frac{E_\gamma}{E_e}$$

$$\frac{d\sigma}{dy} = \frac{4\alpha r_e^2}{y}\{\left(y^2 - \frac{4}{3}y + \frac{4}{3}\right)\left(Z^2 \ln\left(184.15Z^{-1/3}\right) + Z\ln\left(1194Z^{-2/3}\right)\right) + \frac{1}{9}(Z^2 + Z)(1 - y)\}$$

Detector energy resolution has no effect except for small energies



Yung-Su Tsai: Pair production and bremsstrahlung of charged leptons. Rev Mod. Phys. 46 (1974) 815

P.M Lewis et al. First measurements of beam backgrounds at SuperKEKB. NiMA 914 (2019) 69

Toy-MC sensitivity studies

type	$< Pz >$	σ_{Pz}	μ^{pull}_{Pz}	σ^{pull}_{Pz}	$< m.s. >$	$\sigma_{m.s.}$	$\mu^{pull}_{m.s.}$	$\sigma^{pull}_{m.s.}$	$< E_{resol_A}[\%] >$	$\sigma_{E_{resol_A}}[\%]$	$\mu^{pull}_{E_{resol_A}}$	$\sigma^{pull}_{E_{resol_A}}$	χ^2
A	0.6992	0.0049	-0.1569	1.0150	1.1	0.0001	0.0022	1.011	9.9994	0.0152	-0.0455	1.0040	171.7
C	0.7000	0.0041	-0.0067	0.9952	1.1	6.7e-5	0.0825	1.017	3.0025	0.0081	0.2945	0.9799	150.5
F'	0.6992	0.0049	-0.1519	1.0060	1	0.0001	0.0035	1.004	9.9994	0.0153	-0.0422	1.001	155.4
G'	0.7000	0.0042	-0.0068	0.9947	0.9999	6.2e-5	0.0856	1.020	3.0025	0.0081	0.3022	0.9845	135.6
H	0.6992	0.0049	-0.1597	1.0130	1.1	0.0001	0.0022	1.009	9.9993	0.0152	-0.0356	1.003	171.6
I	0.6992	0.0049	-0.1559	1.0150	1.1	0.0001	0.0047	1.013	9.9993	0.0152	-0.0399	0.9968	171.6
J	0.6992	0.0049	-0.1554	1.0130	1.1	0.0001	0.0022	1.011	9.9993	0.0152	-0.0522	0.9988	171.6
K	0.6992	0.0049	-0.1571	1.0150	1.1	0.0001	0.0058	1.018	9.9994	0.0153	-0.0361	1.012	171.6
L	0.6991	0.0053	-0.1718	1.0230	1.1	0.0001	-0.0033	1.022	9.9992	0.0154	-0.0534	1.029	171.7
M	0.6992	0.0049	-0.1571	1.0100	1.1	0.0001	0.0026	0.9967	9.9993	0.0152	-0.0431	0.9971	171.7
N	0.6992	0.0049	-0.1561	1.0100	1.1	0.0001	0.0019	0.9984	9.9993	0.0152	-0.0438	0.0019	171.7
O	0.7006	0.0057	0.1232	1.0240	1.1125	0.0004	7.1970	1.0240	9.9412	0.0364	-3.9280	0.9998	198.5

We have a fit that can extract the longitudinal electron polarization, the miscalibration energy scale, the energy resolution and the scales for the Compton contributions