Systematic effects simulation studies for an electron beam polarimeter for SuperKEKB

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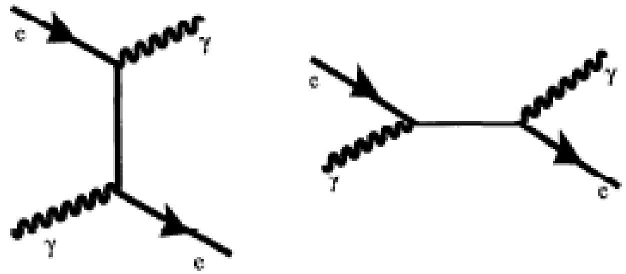
Introduction

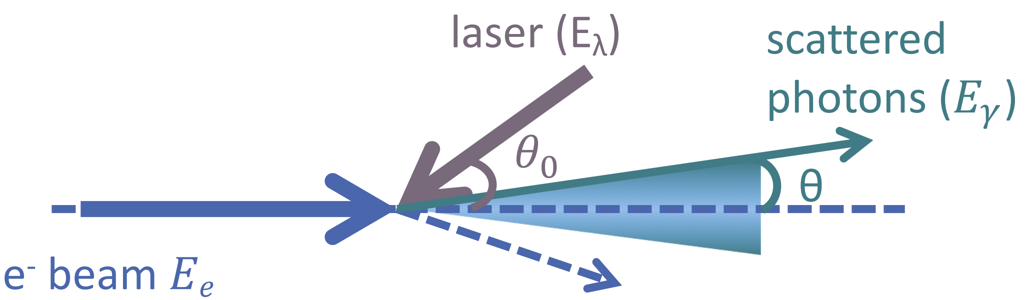
Current status:
Several sensitivity studies shown in the past
Look-up tables (LUTs) introduced to fasten the fit procedure

Purpose of today's presentation:

a) Reminder of Compton scattering and cross section
b) MC sensitivity studies reviewed with LUTs
c) Detector misalignment
d) Beam jittering related to top-up injection
e) Backgrounds

Compton backscattering





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

Compton backscattering

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

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

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

Electron beam polarization independent

Electron beam polarization dependent

Toy-MC sensitivity studies

We simulate the e-/laser interaction and we try to extract the polarization of the electrons

Assumptions:

- 1min data taking (6 10^6 turns)
- Laser: $\mathcal{P}_{las}^{circ}$= -1, $\mathcal{P}_{las}^{lin}$ = 0
  λ = 515 nm
  P = 5W @ 250MHz
  $\sigma_x = 200\mu m, \sigma_y = 200\mu m$

Detector's geometry:

- BaF_2 Crystal size: 2.5cm
- L = 30 m
- Resolution: $\sigma_E \sim A\sqrt{E}$
- miscalibration scale$\sim$1.1

- Electron beam: $\mathcal{P}_Z = 0.7$, $\mathcal{P}_T$= 0
  $Q_e = 10\ nC$
  $\sigma_x = 170\mu m, \sigma_y = 5\mu m$

We concentrate on photon detection only

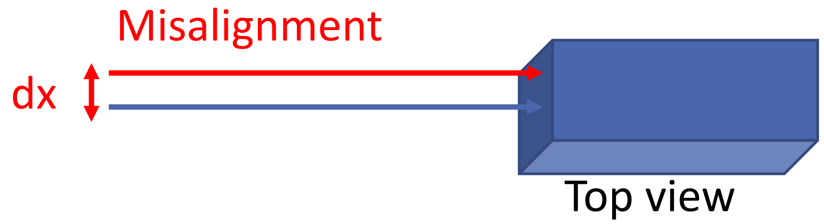
Fixed parameters: e- beam energy and spread, detector energy resolution, $\mathcal{P}_T = 0$, $\mathcal{P}_{las}^{circ}$, $\mathcal{P}_{las}^{lin}$=0

Fitted parameters: $\mathcal{P}_Z$, miscalibration scale, relative scale of each contribution (1 or 2 Compton photons)

Toy-MC sensitivity studies

$$Pull(P_Z) = \frac{P_Z^{gen} - P_Z^{fit}}{\sigma_{P_Z}^{fit}}$$

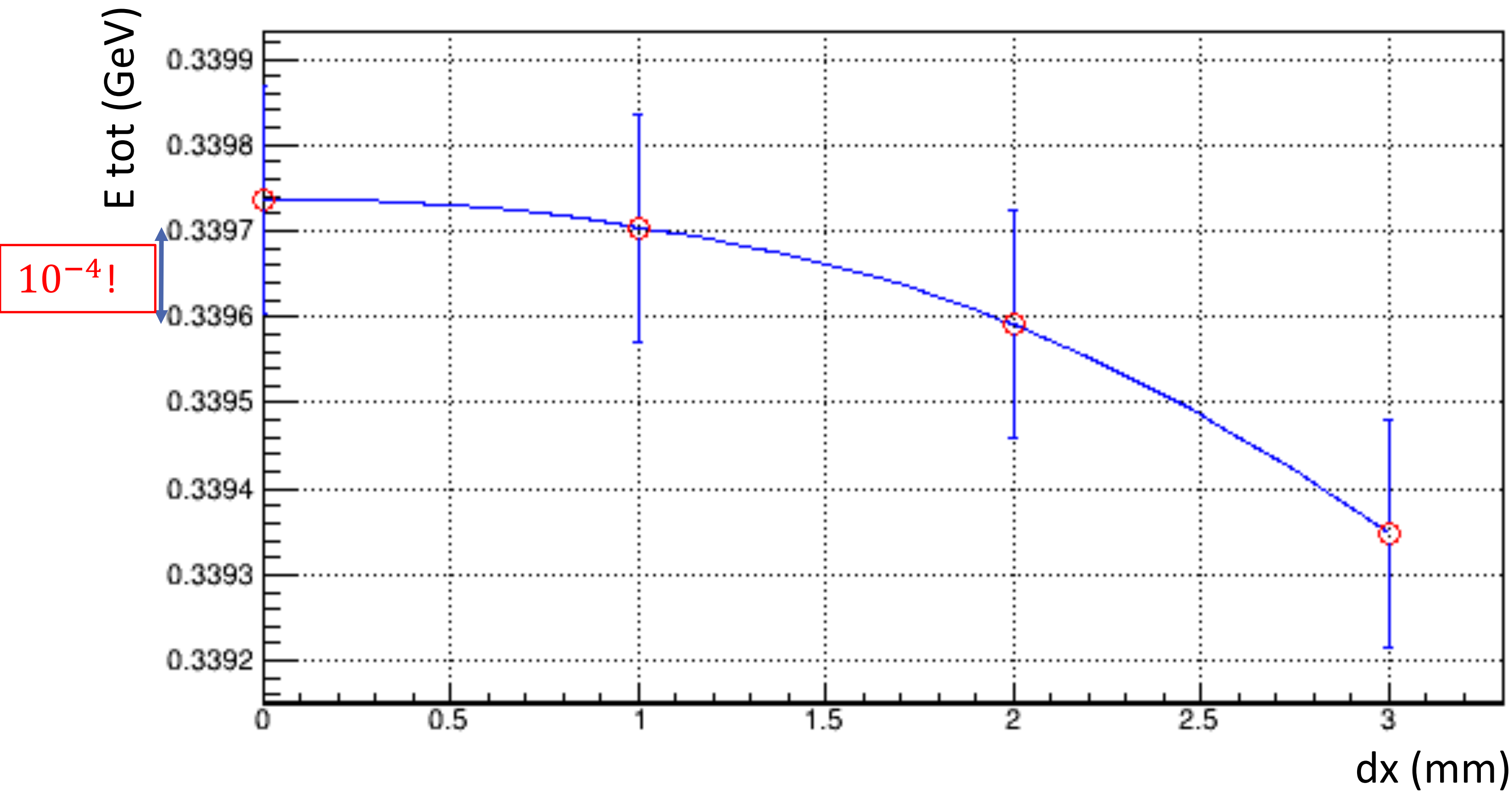
dx and dy: misalignments on the detector



type	Pz^{gen}	A^{gen}	Miscalibration scale	σ_{Pz}	Other parameters	$\mu_{Pz}^{pull,fit}$	$\sigma_{Pz}^{pull,fit}$
A	0.7	0.1	1.1	0.0099	-	-0.0469	0.9583
B	0.7	0.1	1.03	0.0112	-	-0.0130	0.9312
C	0.7	0.03	1.1	0.0088	-	0.0009	0.9594
D	0.7	0.01	1.1	0.0085	-	-0.112	0.9614
E	0.3	0.03	1.1	0.0086	-	-0.0156	1.006
F	0.7	0.1	1.0	0.0095	-	-0.009182	0.9594
G	0.7	0.03	1.0	0.0086	-	0.03982	0.9818
H	0.7	0.1	1.1	0.0099	dx=1mm	0.0600	0.9607
I	0.7	0.1	1.1	0.0099	dx=2mm	0.4189	0.9452
J	0.7	0.1	1.1	0.0099	dy=1mm	-0.0317	0.9574
K	0.7	0.1	1.1	0.0099	$P_T = 0.3$	0.0167	0.973
L	0.7	0.1	1.1	0.0104	$P_{las}^{lin} = -0.05$; $P_{las}^{circ} = -0.95$	-0.0133	0.9622

Basic Alignment of detector

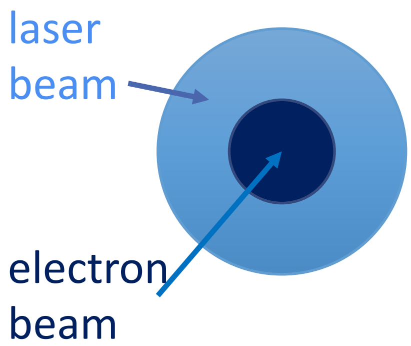
Mean energy deposited in the detector per bunch-crossing as function of the misalignment of the detector:



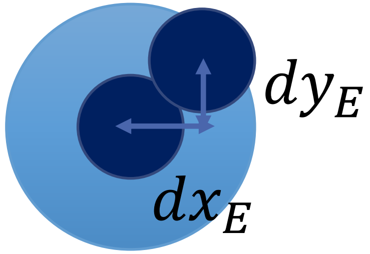
Following e-mail exchange with Oide-san.
Any mistake reflects our misunderstanding.

Beam jitters at injection

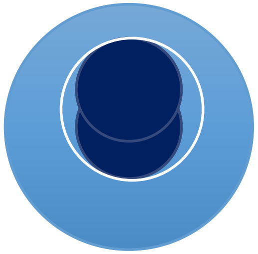
Injection of fresh electrons affects the beam dynamics in two ways:



Shift of the center of gravity of e bunch:
Damped by the feedback in ~100turns



Emittance growth:
Damped by radiation in ~10000turns



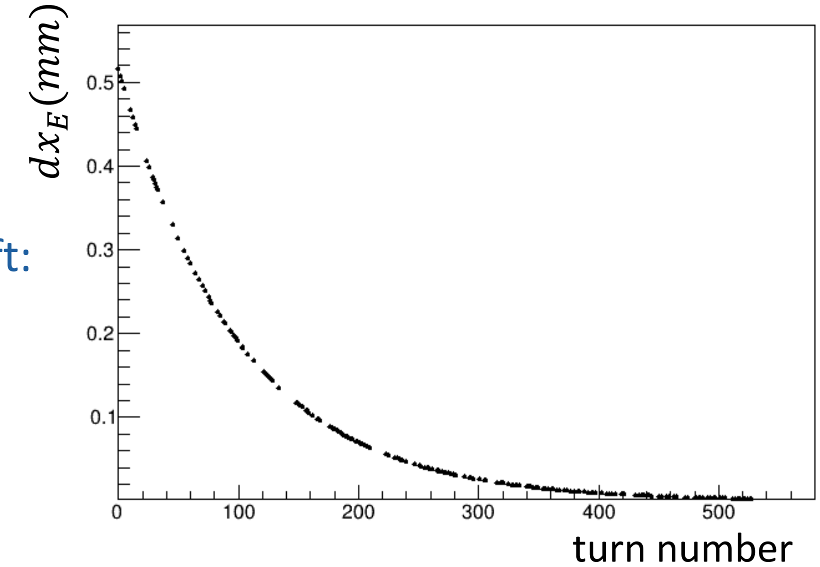
Goal: study the jitters and their impact on the sensitivity of the polarimetry

Center of gravity

Displacement of electron beam:

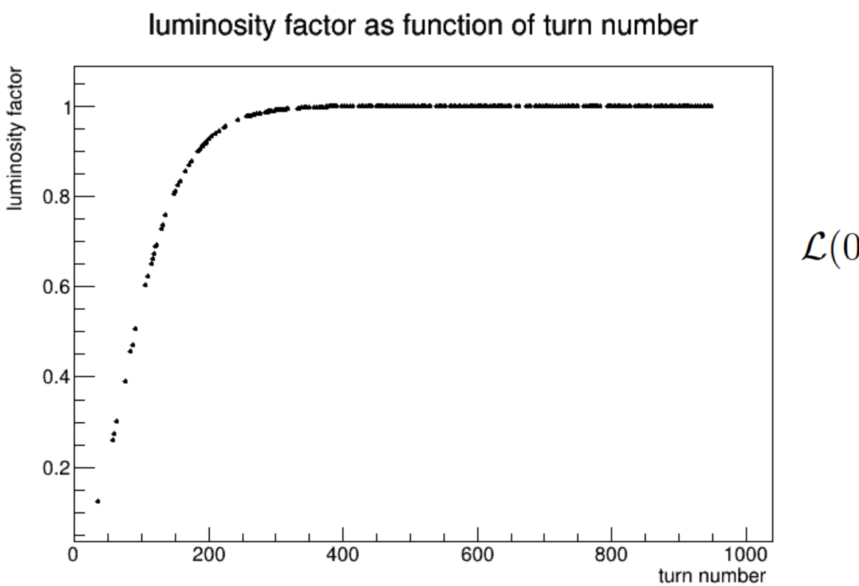
Proposed model of dx_E, dy_E the center of gravity shift:

$$di_E(t) = 3\,\sigma_i\, e^{\frac{-turn}{N_1}} \quad (\mathrm{i=x,y})\ N_1=100$$



Luminosity formula with the center of gravity shift:

$$\mathcal{L}(dx_E, dy_E) = \mathcal{L}(0,0)exp\Big[-\frac{dy_E^2}{2(\sigma_{y_e}^2+\sigma_{y_l}^2)} - \frac{dx_E^2}{2(\sigma_{x_e}^2+\sigma_{x_l}^2+(\sigma_{z_e}^2+\sigma_{z_l}^2)tan^2\phi)}\Big]$$



$$\mathcal{L}(0,0) = \frac{fBN_eN_lcos\phi}{2\pi\sqrt{\sigma_{y_e}^2+\sigma_{y_l}^2}\sqrt{(\sigma_{x_e}^2+\sigma_{x_l}^2)cos^2\phi+(\sigma_{z_e}^2+\sigma_{z_l}^2)sin^2\phi}}$$

Emittance growth

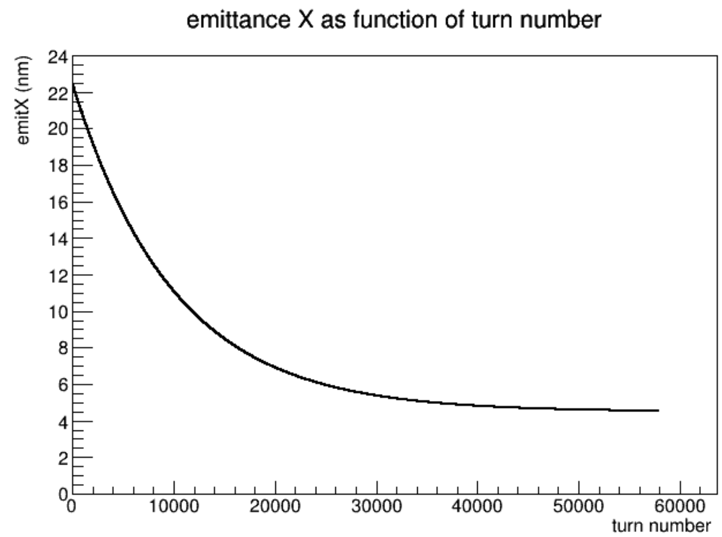
Emittance growth on the x-y plane:

Proposed model:

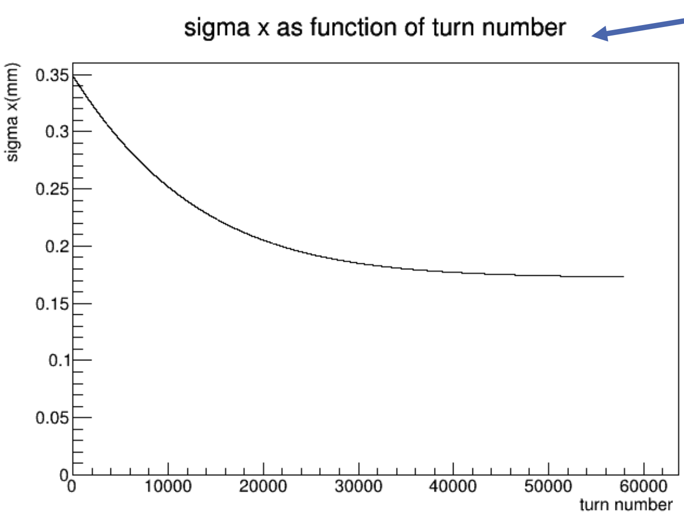
$$\epsilon_x(t) = \epsilon_{0x} + 4\,\epsilon_{0x}\,e^{\frac{-turn}{N_2}}$$

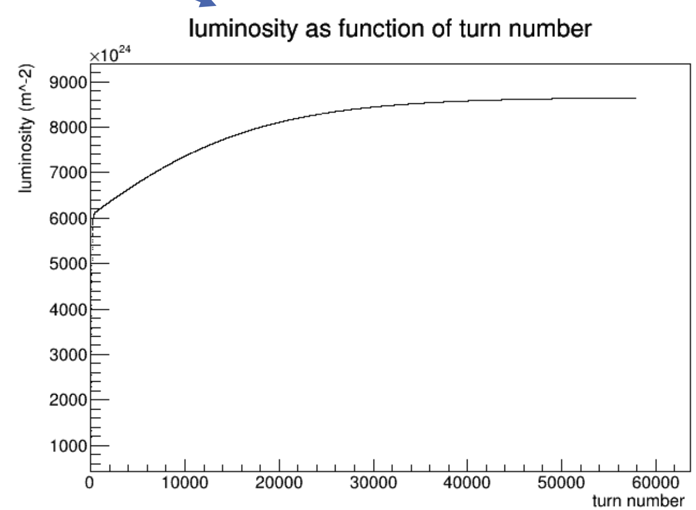
$$\epsilon_y(t) = \epsilon_{0y} + 4\,\epsilon_{0y}\,e^{\frac{-turn}{N_2}}$$

N_2=10000

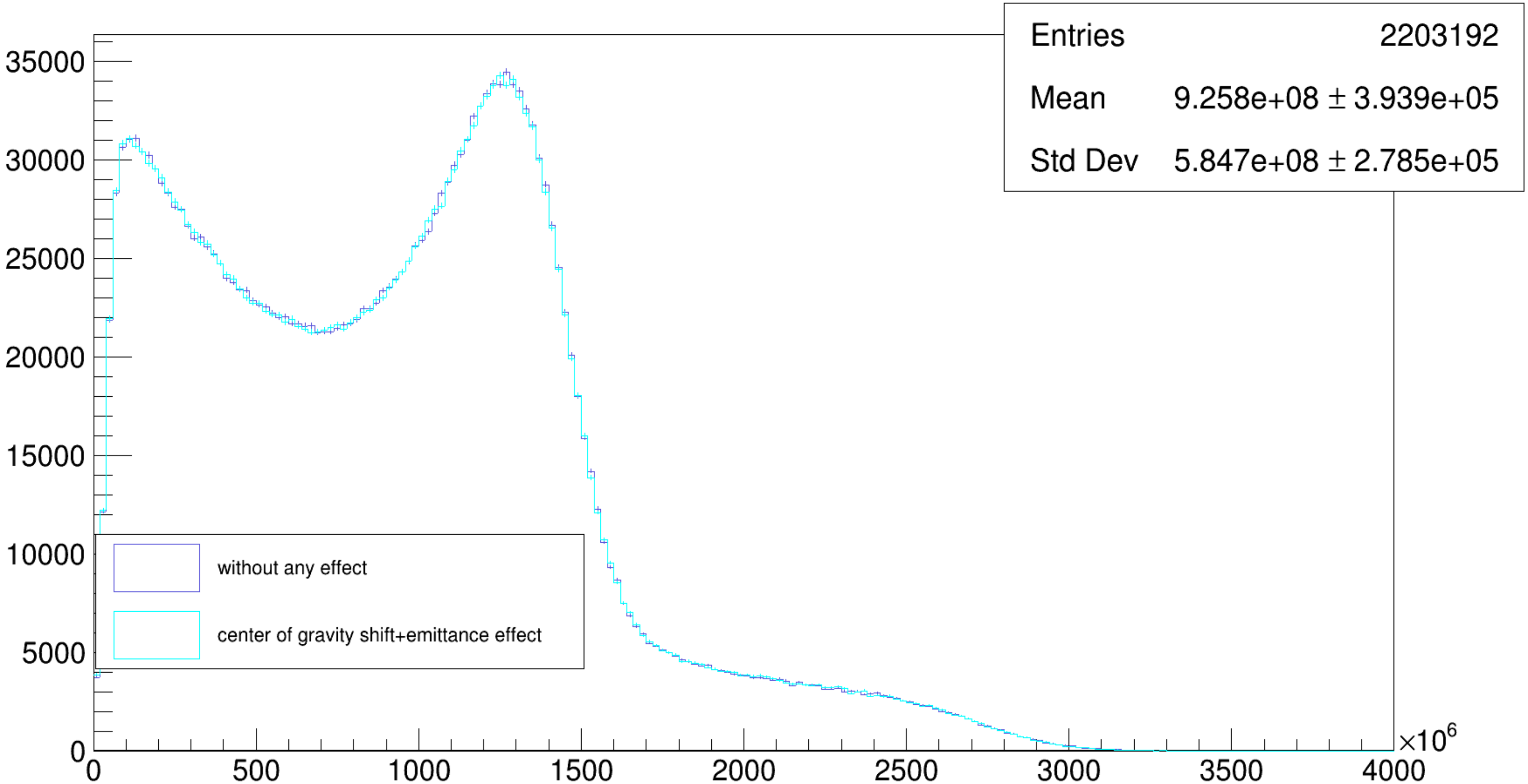


This leads to a change in the e- beam size and the luminosity !





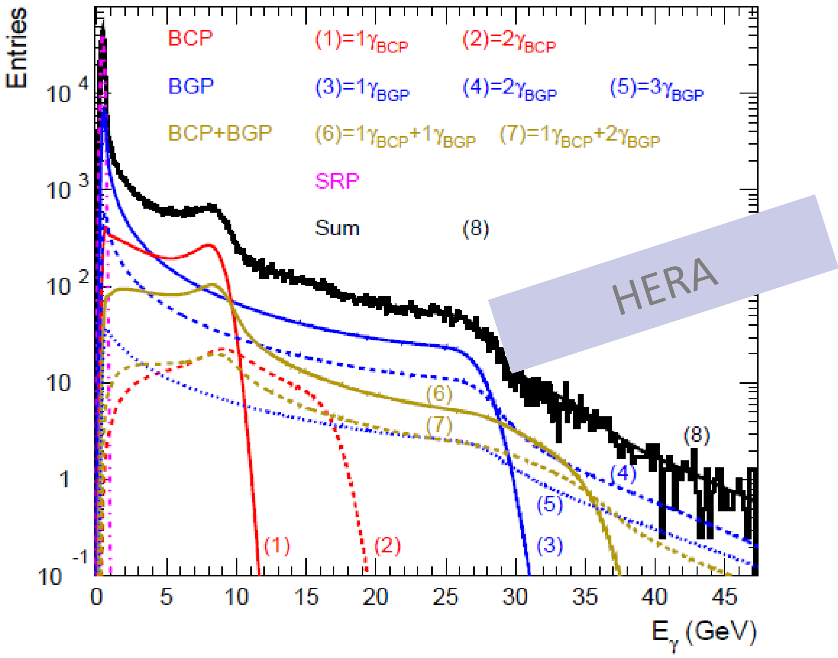
Effect on energy spectrum



Backgrounds

List of background contributions:

- Bremsstrahlung radiation
- Synchrotron radiation
- Compton on blackbody radiation



Main Contribution ?

Just as at HERA, we suppose bremsstrahlung radiation is one of the dominant contributions

We try to make a first rough estimate here

Bremstrahlung

Bremsstrahlung radiation :

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

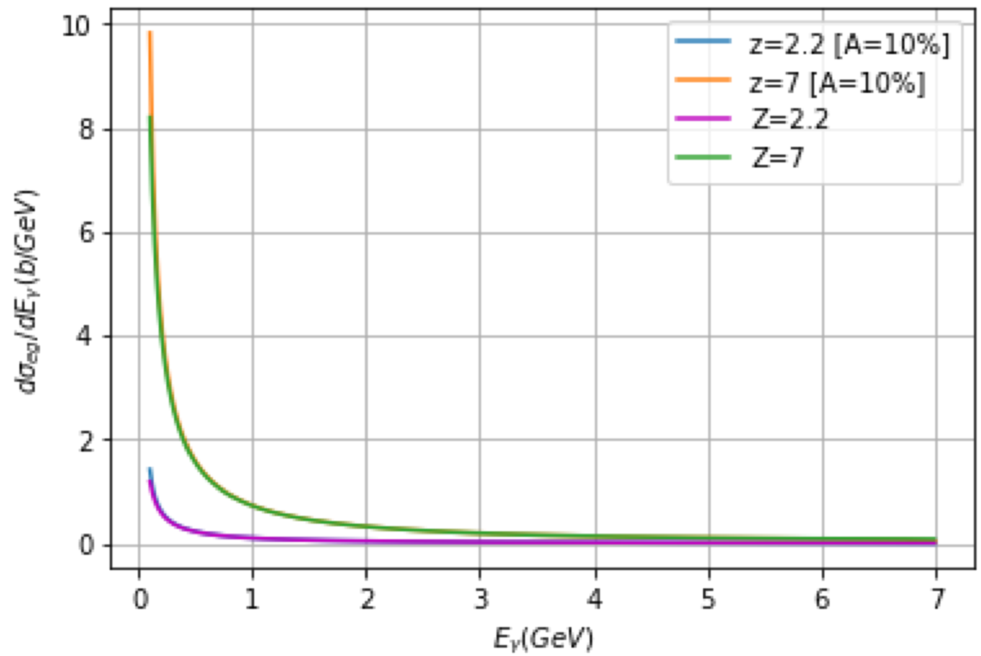
e + g ⟶ e + g + γ

The cross section averaged over scattered particles spins :

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

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

Detector energy resolution has no effect except for small energies



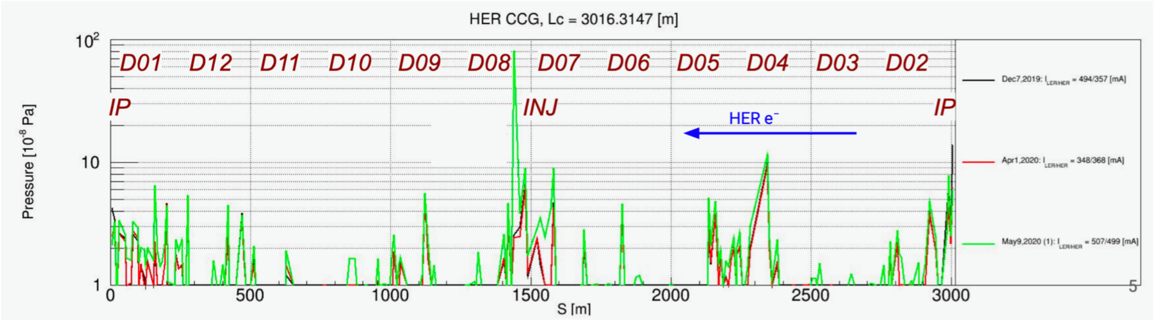
Yung-Su Tsai: Pair production and bremsstrahlung of charged leptons. Rev Mod. Phys. 46 (1974) 815

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

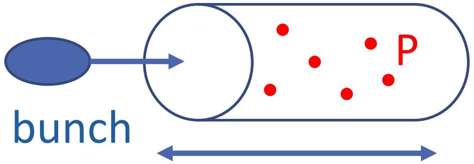
Following e-mail exchange with Andrii Natochi.
Any mistake reflects our misunderstanding.

Bremstrahlung luminosity

Luminosity of the collision between the electron bunch and the gas particles in the beam pipe of length L:

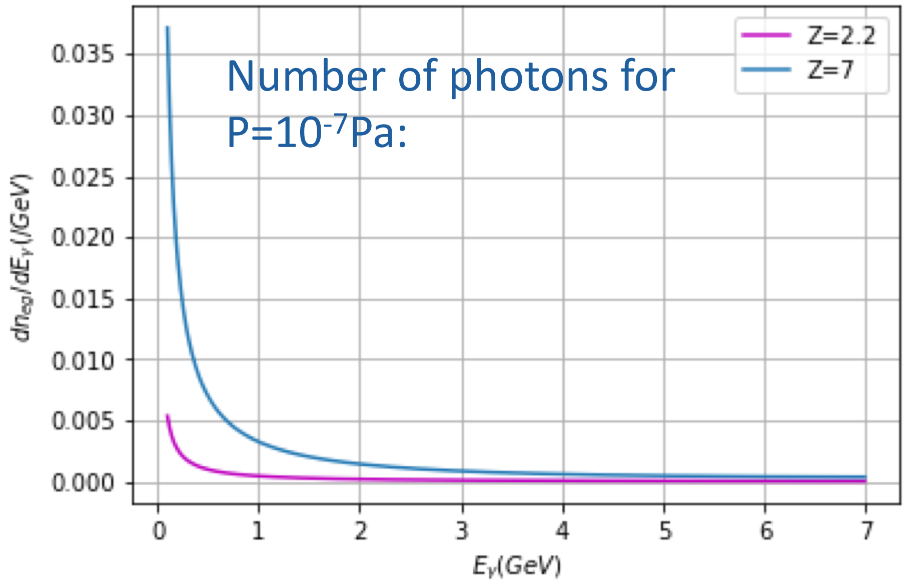


L=30m
$P<10^{-7}Pa$
T=300K
N_e=10nC



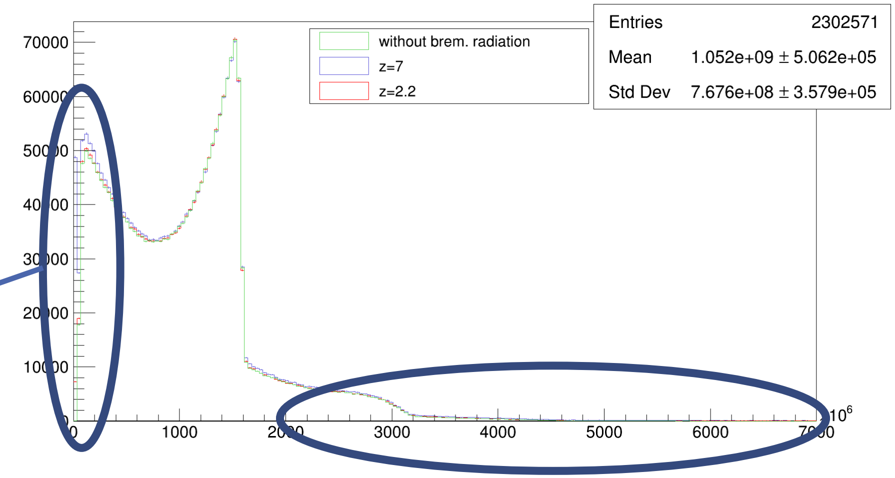
gas particles uniformly distributed in the beam pipe, having pressure P

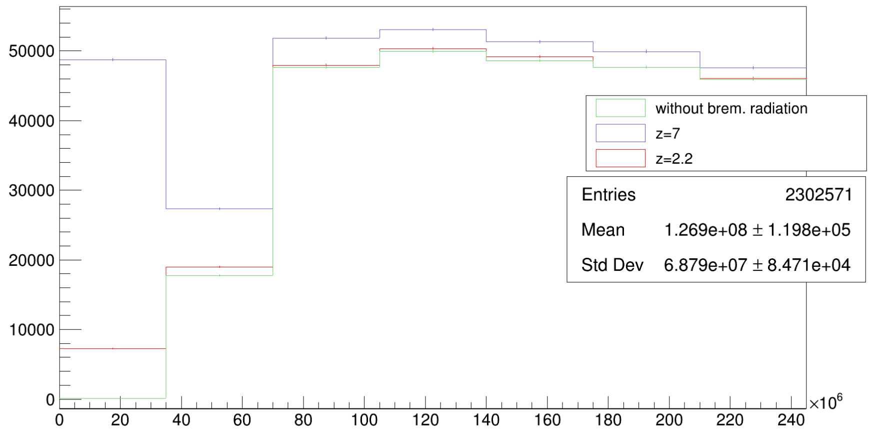
$$L_{brem} = \beta\, N_e \frac{L\, P}{k_B T}$$

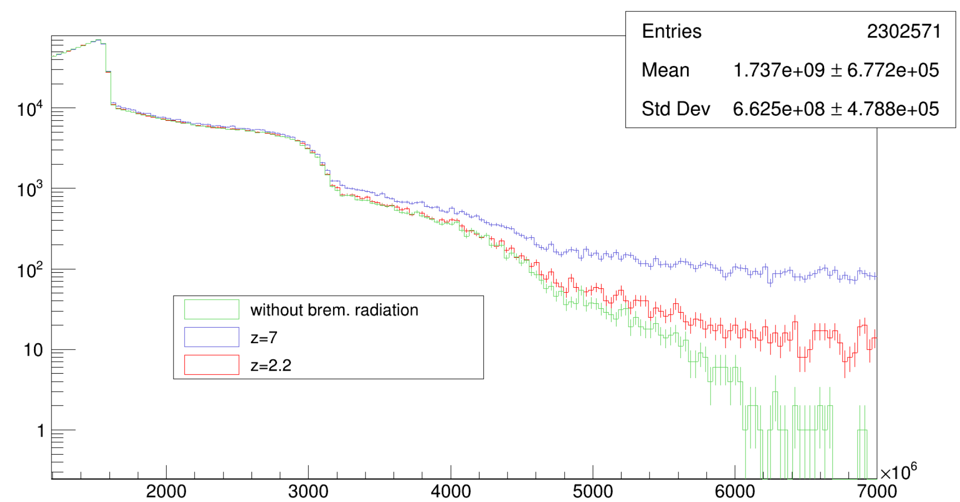


Energy spectrum

At low energy: we see an increase of the number of photons emitted with bremsstrahlung radiation for a beam gas of effective z=7







At high energy, we see photons emitted with bremsstrahlung radiation for a beam gas of effective z=7

Synchrotron radiation

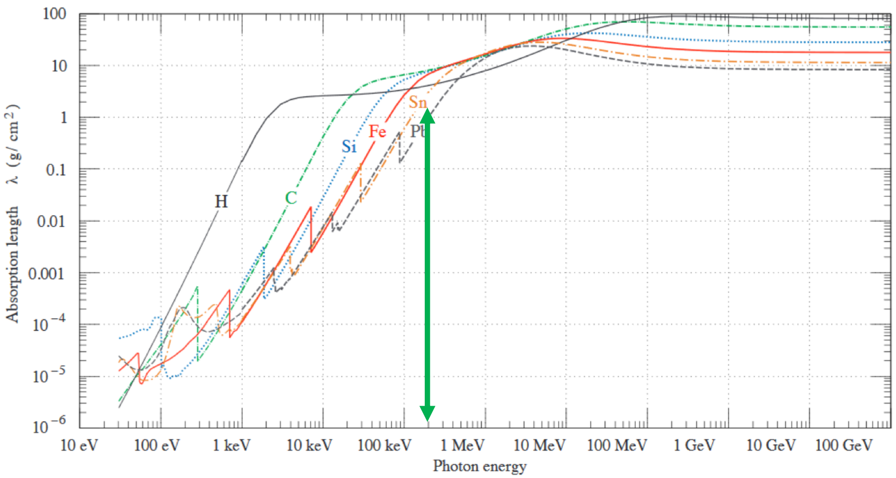
"Critical energy" of synchrotron radiation: $E_c = \frac{3}{2}\gamma^3\frac{c}{\rho} \sim 5keV$

ρ: radius of curvature ~ 146 m

Total radiated energy by synchrotron radiation:

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

~200keV ⟷ $1 g\ cm^{-2}$



Jackson Book, Classical Electrodynamics

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

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

Summary and next steps

Main lessons:

- A 2 mm misalignment of the detector → a 0.4% bias on longitudinal polarization
- Average deposited energy in detector is hardly varying with misalignment
- Extraction of Pz is immune (as expected) against transverse electron polarization
- Extraction of Pz is immune (as expected) against linear laser polarization (as soon as the circular polarization is perfectly known)
- Beam displacement and emittance growth at injection do not affect the energy spectrum of photons significantly (within statistical fluctuations)
- Background contributions seem anecdotic, even bremsstrahlung. May require further consolidation when a location is decided

Next steps:

- Include Bremsstrahlung in the fit
- Test the concept of a BaF_2 detector
- Start mounting a laser R&D setup
- Costing exercise for the laser system

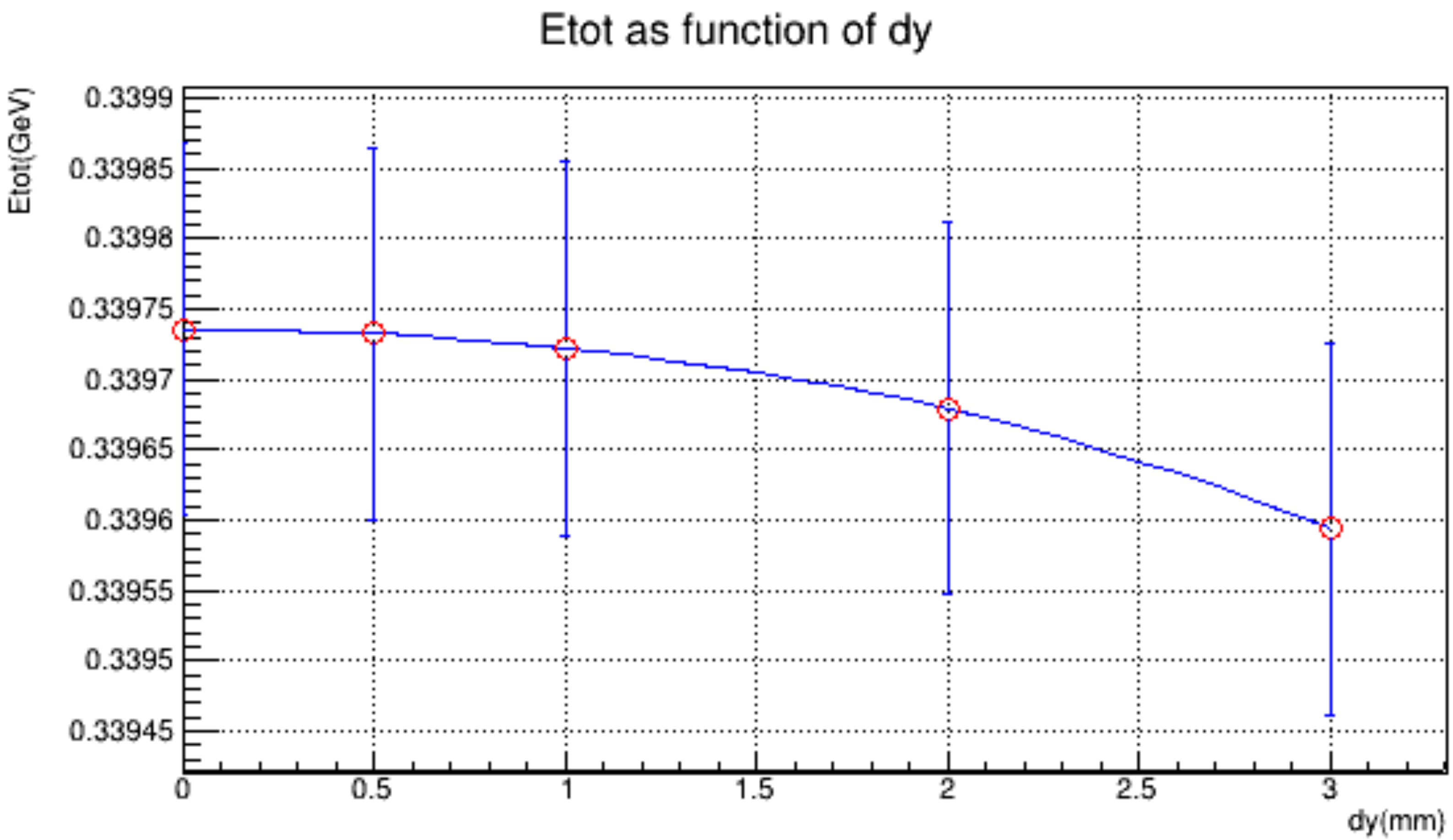
Compton on blackbody

The beam pipe emits photons through blackbody radiation, these photons scatter on the electron beam and the scattered photons contribute in the background effects and have an impact on the energy spectrum.

The blackbody energy spectrum: $\frac{dn(E_\lambda)}{dE_\lambda} \propto \frac{E_\lambda^2}{e^{E_\lambda/k_B T}-1}$

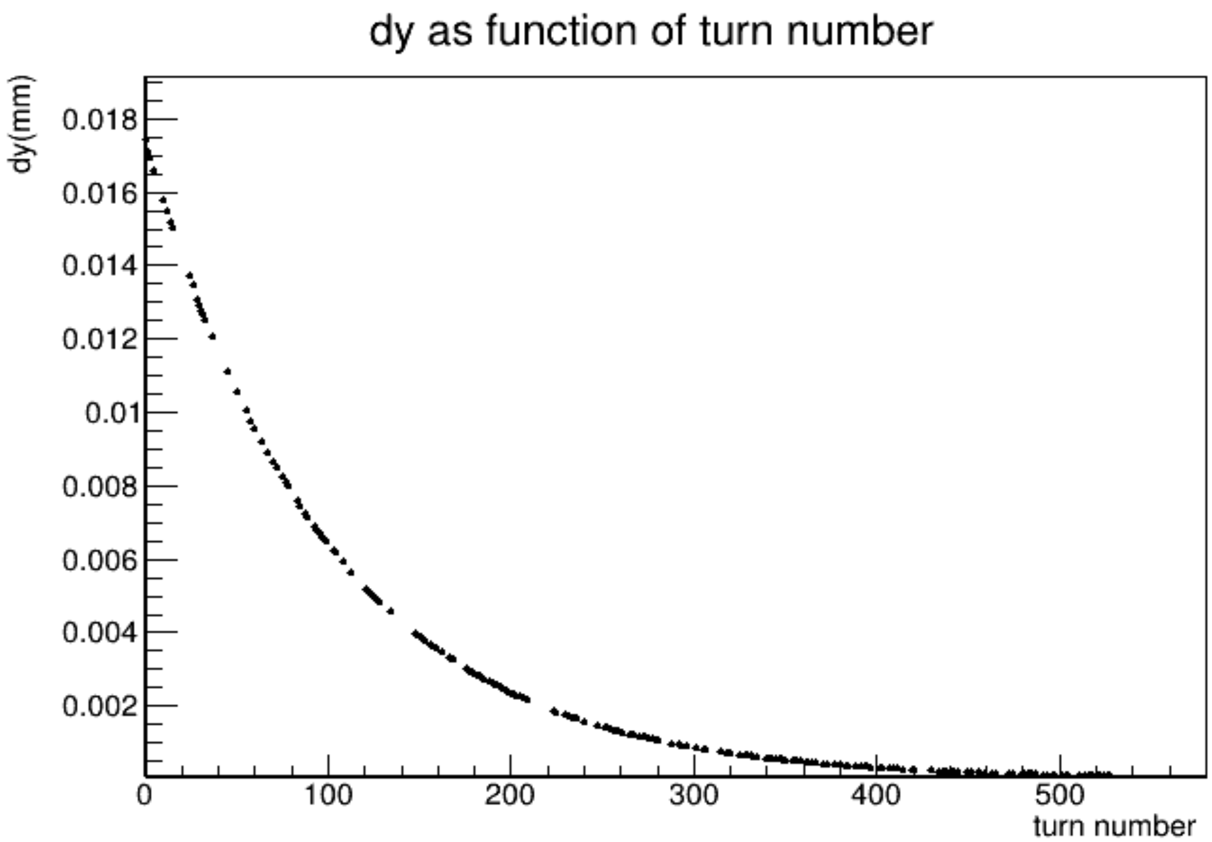
Basic Alignment of detector

Deposited energy in the detector with misalignment :



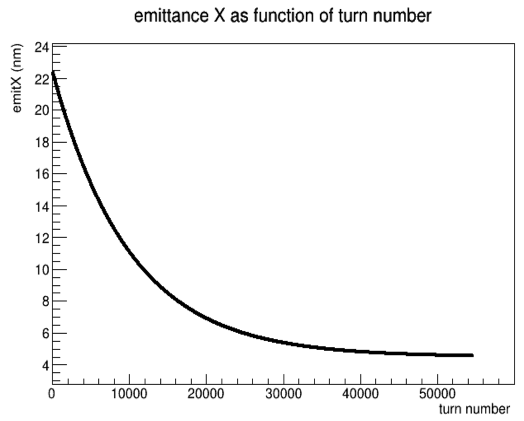
Jitter issues

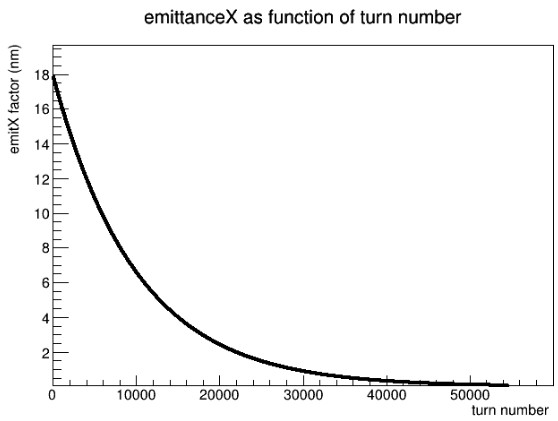
Misalignment of the e beam: (w/o emittance growth)

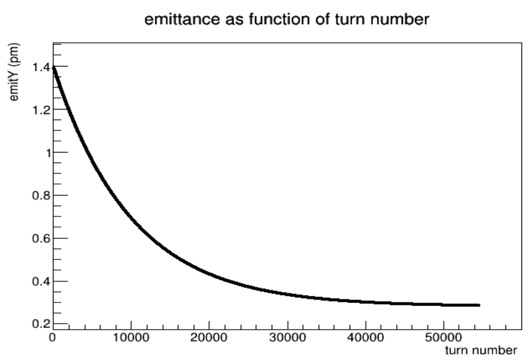


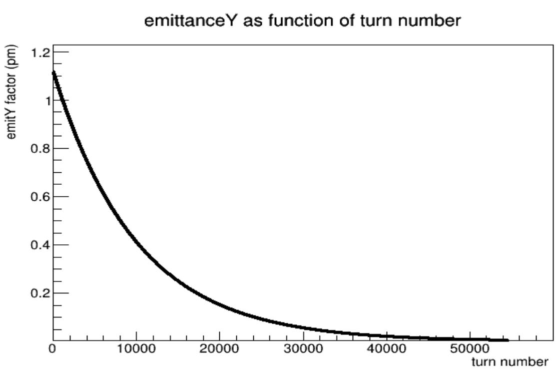
Jitter issues

Taking into consideration misalignment on e- beam + Emittance growth :



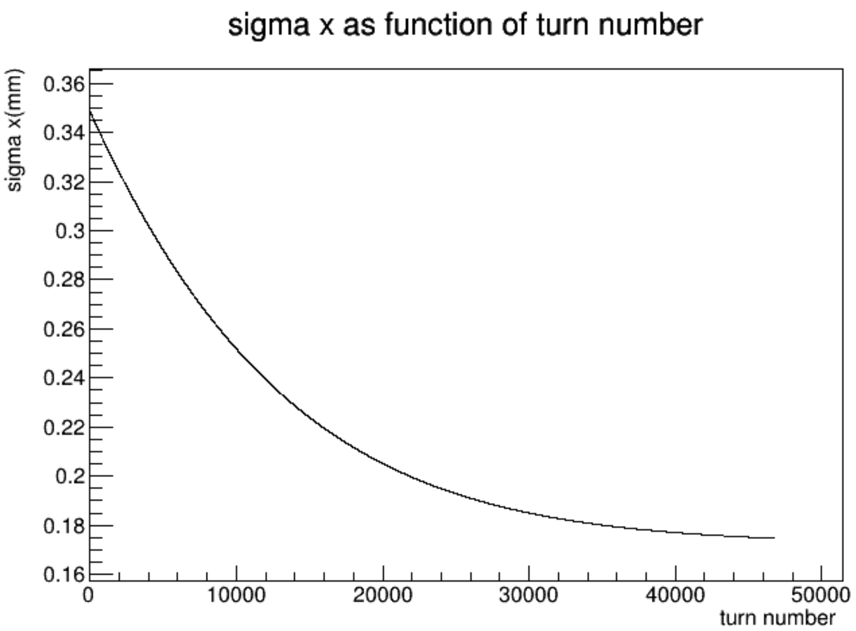


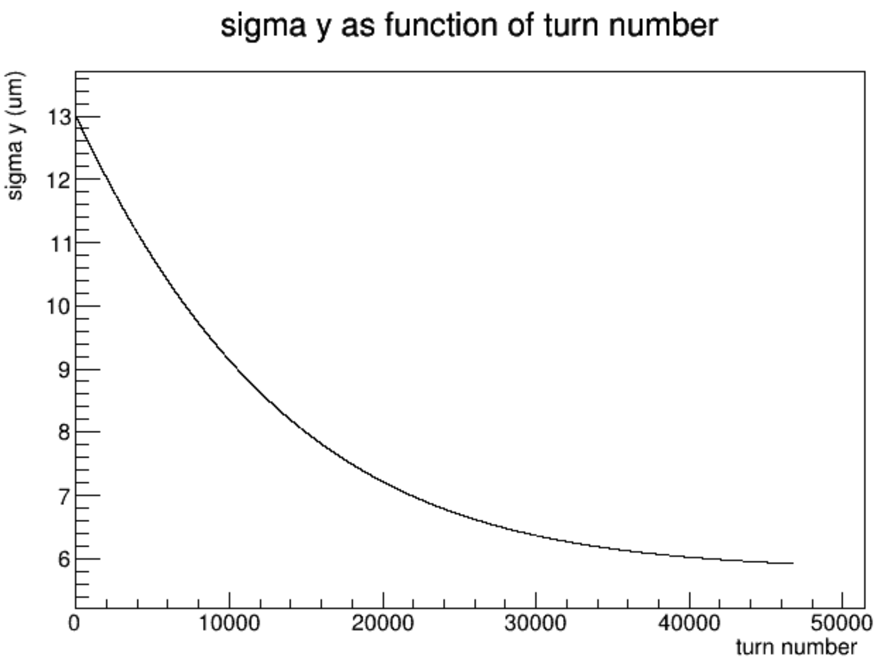




Jitter issues

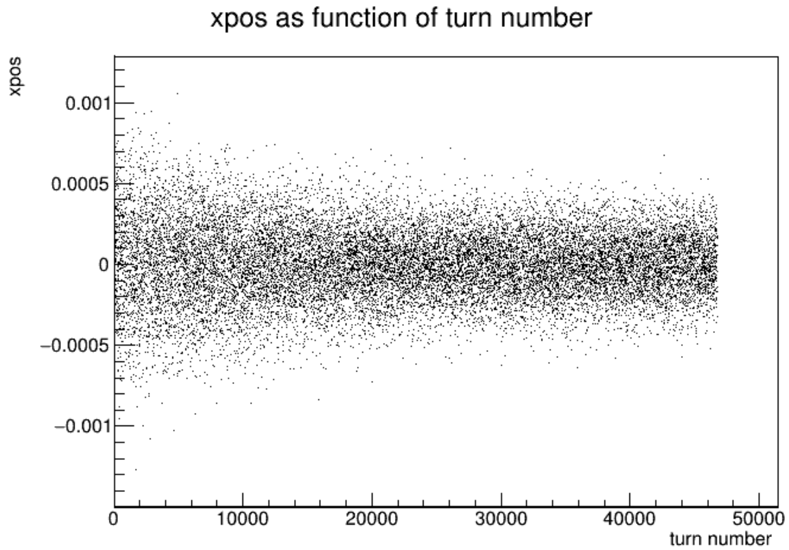
Taking into consideration misalignment on e- beam + Emittance growth :



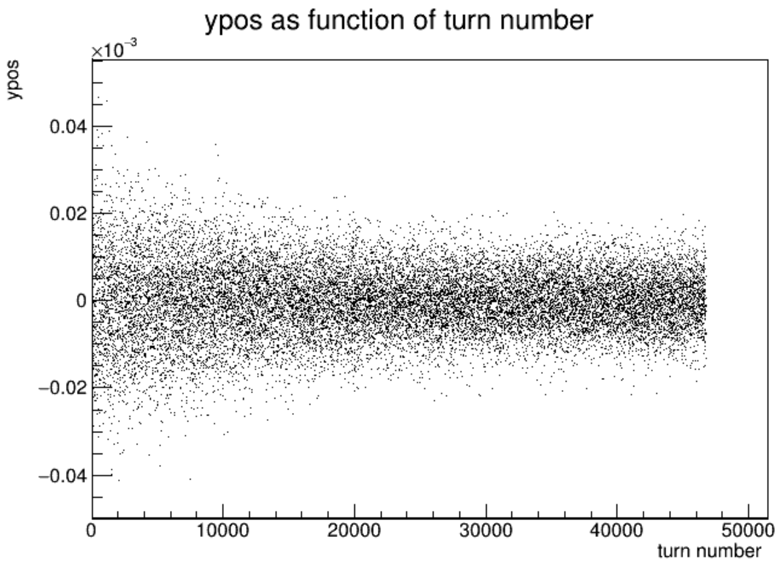


Jitter issues

Taking into consideration misalignment on e- beam + Emittance growth :

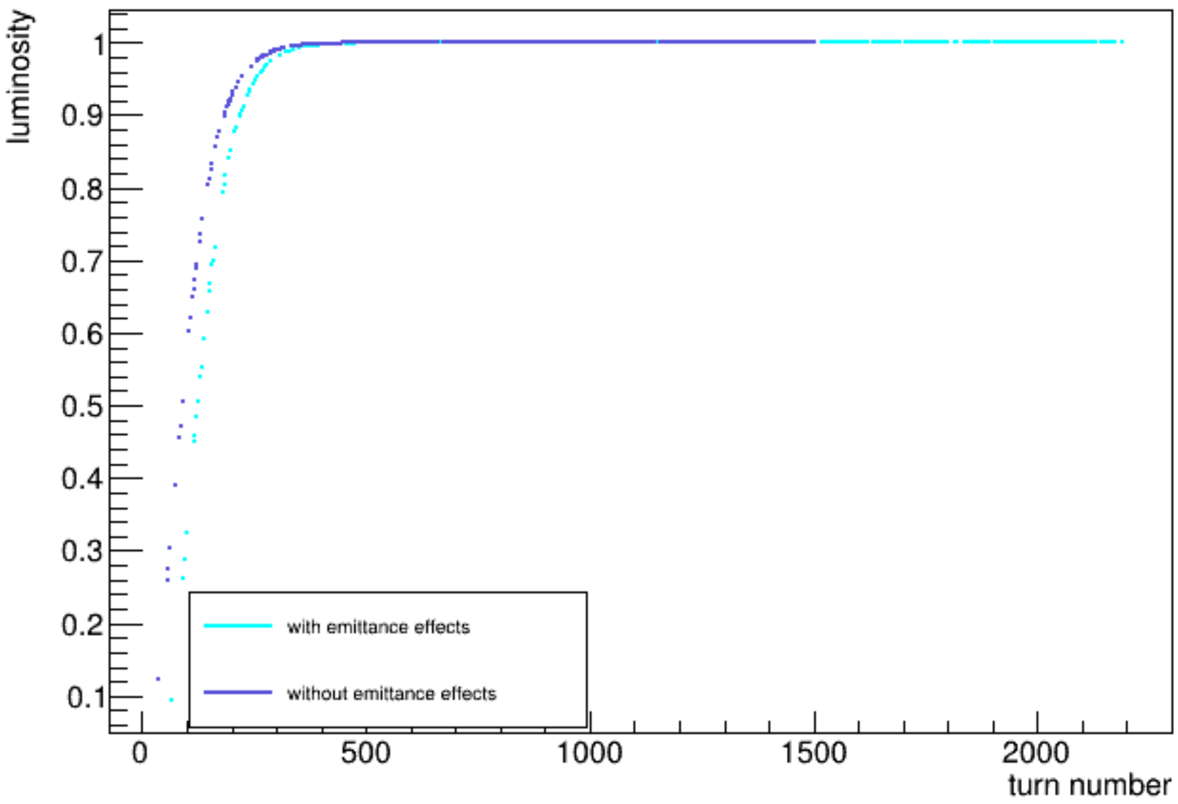


xpos and ypos are the positions of electrons inside the bunch on the x and y axis



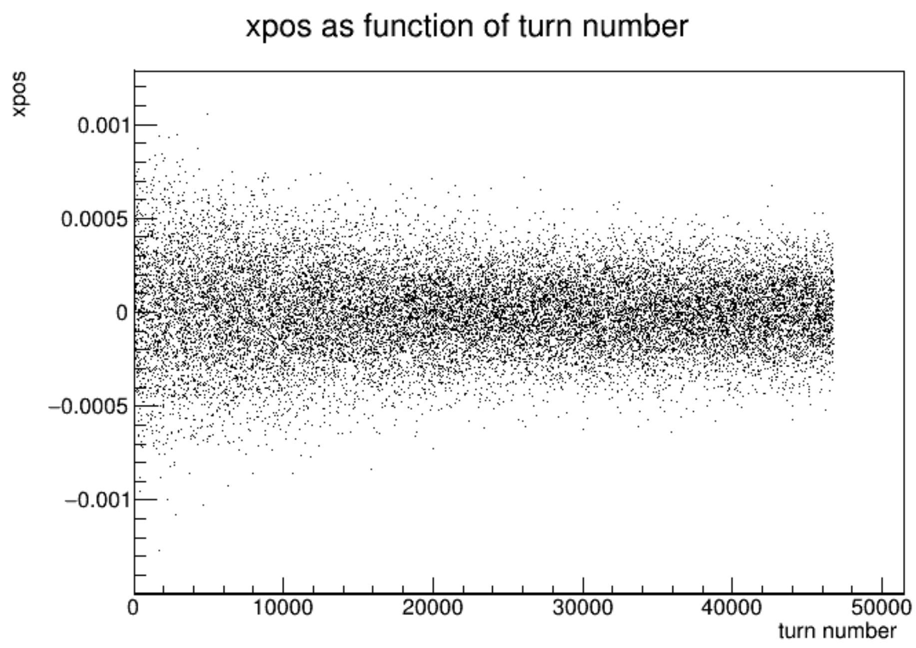
Jitter issues

Comparison:



Jitter issues

Taking into consideration misalignment on e- beam + Emittance growth :
xpos: the positions of electrons inside the
bunch on the x axis



Misalignments on the detector