Fast Luminosity Monitoring Using Diamond Sensors for SuperKEKB

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Outline

1. Fast luminosity monitoring:

a. Motivations / Specifications / Methods
b. Position of DS in both rings and design of vacuum chamber in LER

2. SuperKEKB phase 1: single beam loss measurements

a. Experimental setup
b. Single beam loss simulations and measurements in LER
c. Estimations for luminosity monitoring

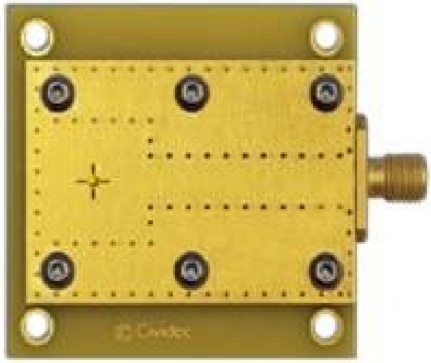
3. Conclusions and perspectives

Fast Luminosity Monitoring

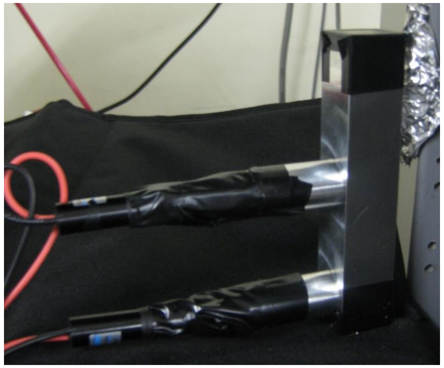
- **Motivations:**
  - Orbit offsets lead to luminosity degradation
  - Orbit feedbacks to minimize luminosity losses

- **Orbit feedback:**
  1) Vertical feedback: by four BPMs (Beam Position Monitors)
  2) Horizontal feedback: lock-in amplifier, dither coils (beam kicks), fast luminosity monitors

- **Luminosity monitor: (collaboration)**
  1) Single crystalline diamond sensors at LAL (sCVD)
  2) Cherenkov and Scintillator detectors by ZDLM group at KEK (S. Uehara)



sCVD



ZDLM

- **Specifications:**
  - The beam is kicked at a frequency of 77 Hz
  - Luminosity sampling at about 10 times faster than 77 Hz (1 KHz)
  - Relative statistical precision of 10^{-3} in 1 ms for integrated luminosity
  - Perform bunch by bunch luminosity monitor (each 4 ns, signal sampling at 1 GSPS), precision of about 10^{-2} in about 1 second

Steps to be done

→ **Search of positions of diamond sensors in the LER and HER to satisfy the precision on luminosity**

→ **Study the signal in the sensors after taking into account the geometry of the beam pipe**

→ **Characterize the diamond sensors and the amplifiers**

→ Prepare fast electronics

→ **Signal need not to be contaminated by backgrounds from single beam losses:**

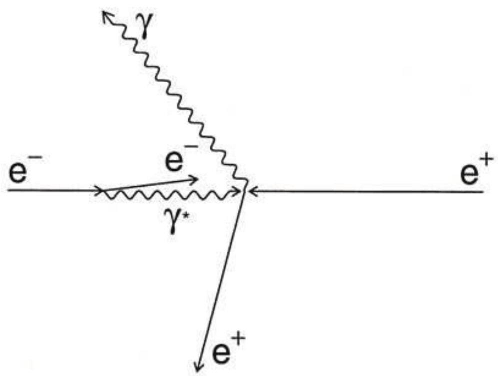
Phase 1

- → **Simulations of single beam losses at position of sensors**
- → Installation of the mechanical setup and sensors in SuperKEKB for phase 1
- → Preparation of data acquisition and processing codes
- → **Data acquisitions and data analysis**
- → **Compare data to simulations to validate the simulations**
- → **Estimate the signal to background ratio for phase 2**

Project: Definition

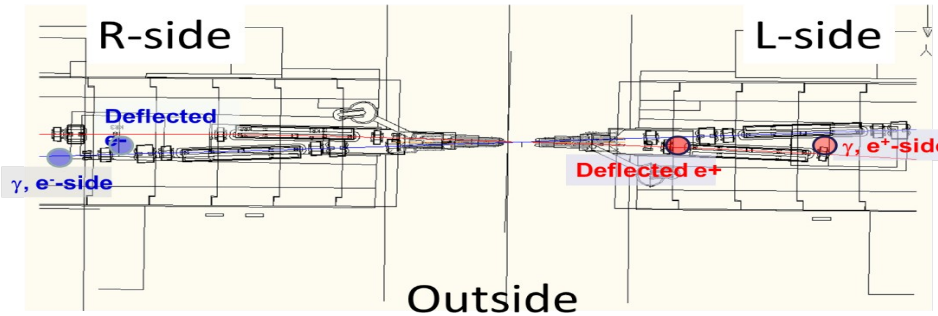
- Fast luminosity monitoring using diamond sensors

- Measure signals from radiative Bhabha at zero photon scattering angle ($\sigma \sim 150$ mbarn for $\sigma_y = 60$ nm): $N_{Bhabha} = \mathcal{L}\,\sigma\,\tau$



- **The process:**

- Beams scatter by exchanging a virtual photon
- Scattered particle loses energy and is deflected and lost downstream of IP (mainly after bends)



- **<u>DS are installed outside the beam pipe:</u>**

1) Detects secondaries of Bhabha EM shower

1) Event rates consistent with the aimed precision

2) Less than 1% contamination by backgrounds from single beam losses

Luminosity ($cm^{-2}s^{-1}$)	Total number of Bhabha produced	Aimed precision	Required fraction
8×10^{35}	1.2×10^{8} in 1 ms	10^{-3} in 1 ms	8.3×10^{-3}

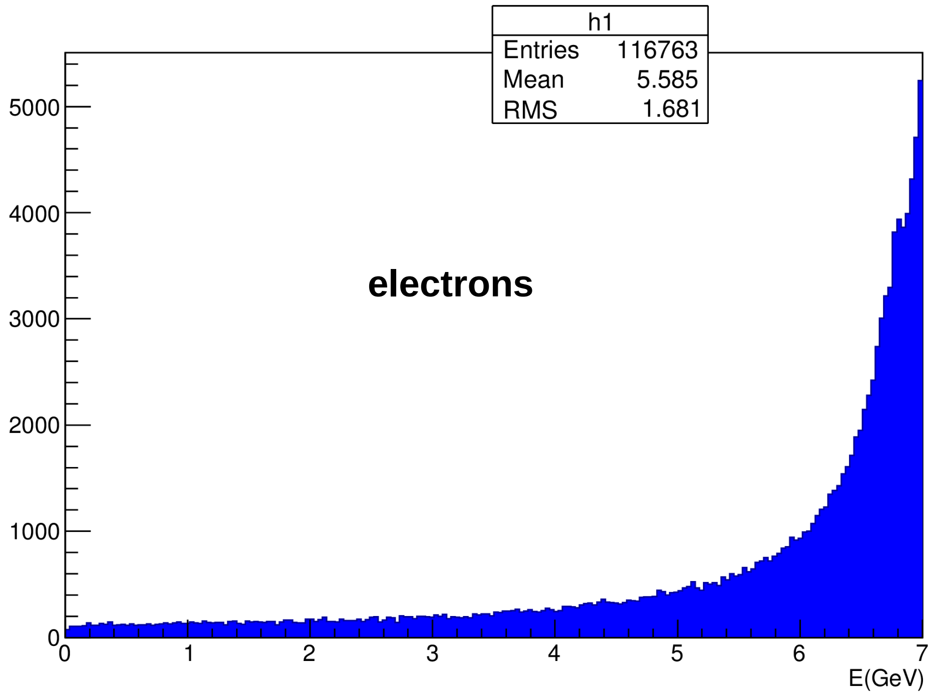
→ For $\mathcal{L}=10^{34}$ $cm^{-2}s^{-1}$, the horizontal beam sizes are twice larger

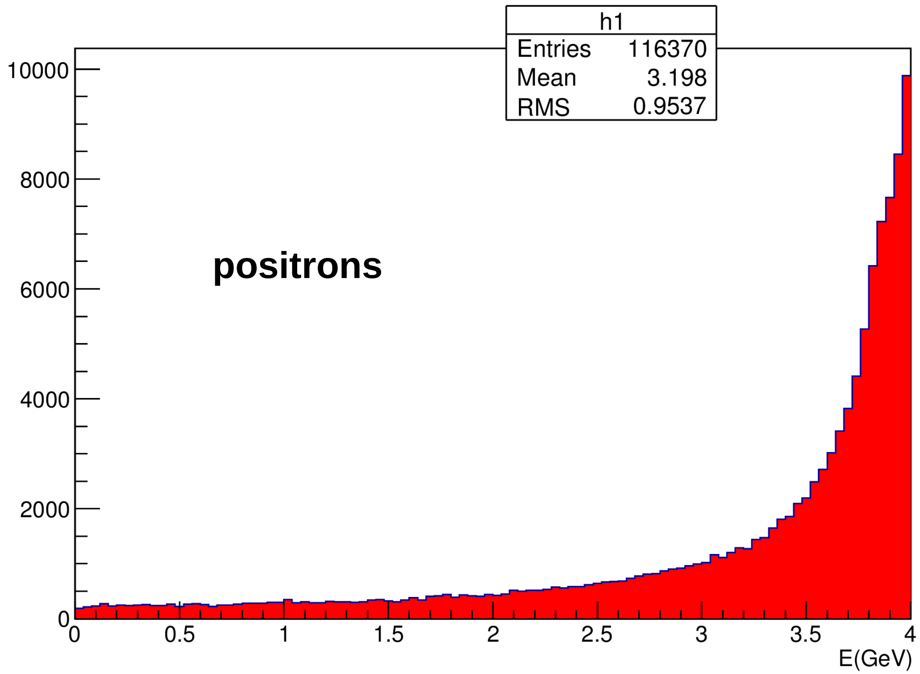
→ Precision on luminosity could be looser by some factor

Bhabha dynamics

- Dynamics of the radiative Bhabha scattering was generated by GUINEA-PIG++

- Energy of Bhabha particles ranges from very low energy to the beam energy (E_{e+}= 4 GeV, E_{e-}=7 GeV)



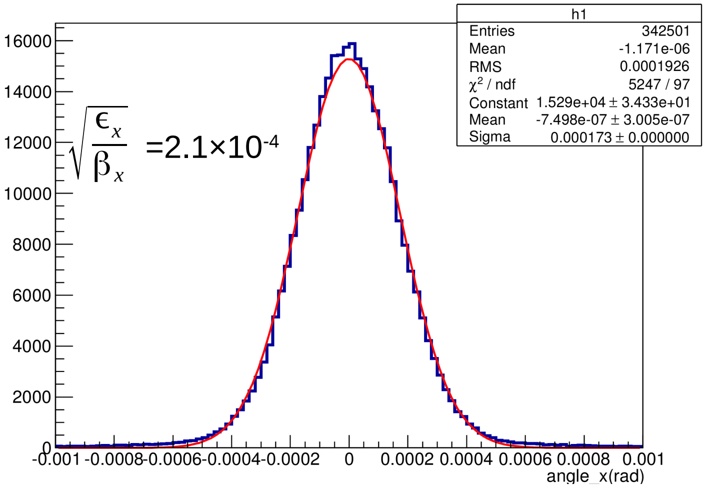


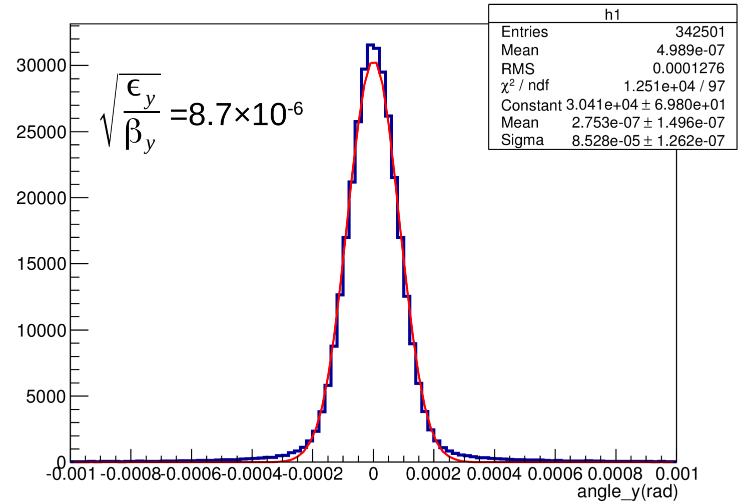
Bhabha dynamics

- Dynamics of the radiative Bhabha scattering was generated by GUINEA-PIG++

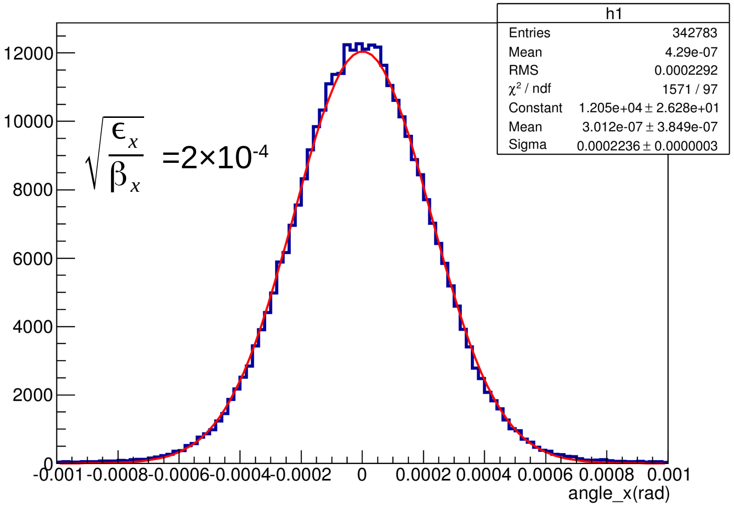
- Energy of Bhabha particles ranges from very low energy to the beam energy (E_{e+}= 4 GeV, E_{e-}=7 GeV)

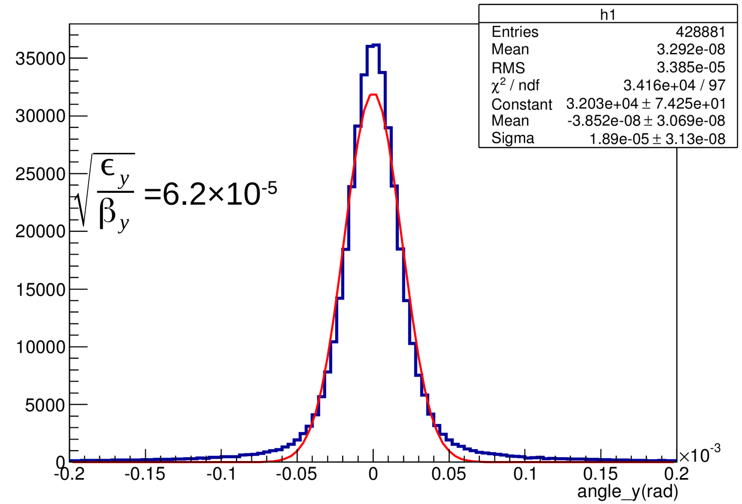
- The angular distributions of the Bhabha particles are the same as the beam distributions $\left(\sqrt{\frac{\epsilon_x}{\beta_x}}, \sqrt{\frac{\epsilon_y}{\beta_y}}\right)$





Bhabha positrons





Bhabha electrons

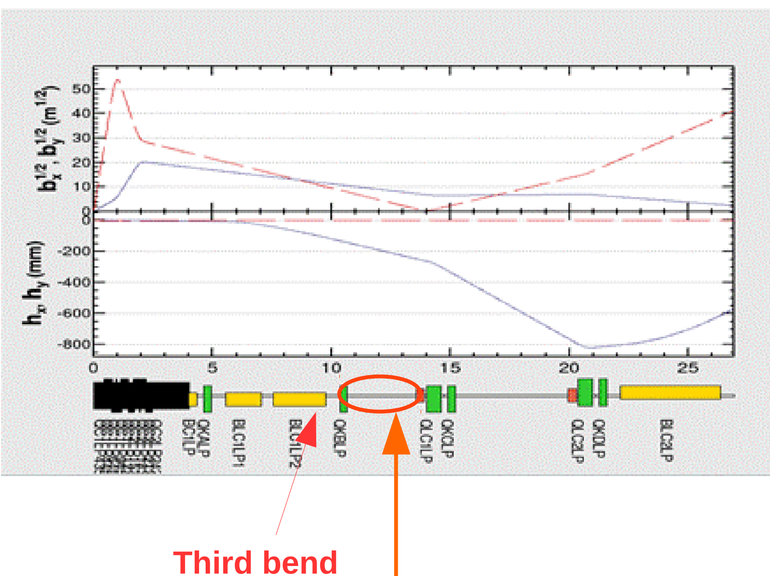
Bhabha Tracking: LER

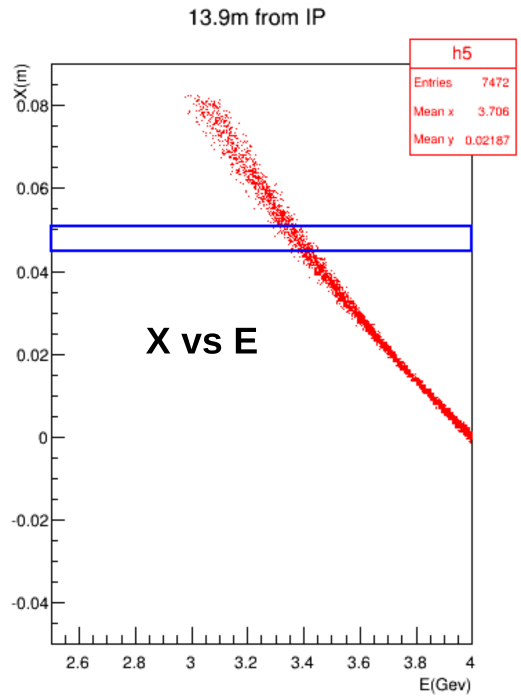
- Bhabha positrons tracked until 30 meters downstream of IP by SAD (tracking code)

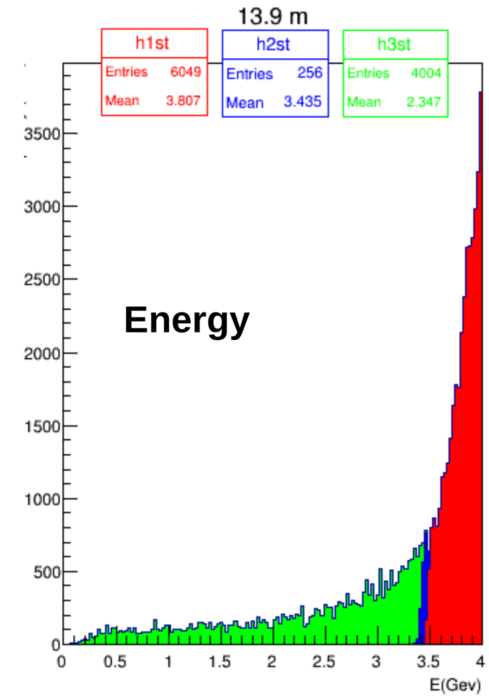
- **Results:**

- Very low rates of detected Bhabhas after first and second bends

- Immediately after third bend: 7.2×10^{-3} of intercepted Bhabha cross section over ~ 50 cm







→ In drift at ~ 13 m: 4.7 % of the total Bhabha cross section are intercepted

→ ~ 3m drift: enough space for the experimental setup and sensors

→ Beam pipe: 6 mm thick Copper cylindrical

→ Lost Bhabha positrons exit at an angle ~ 5 mrad

Signal in sensors

- Shallow exiting angle : absorption of big part of EM shower (very low signal)

- **GEANT4 simulations:**

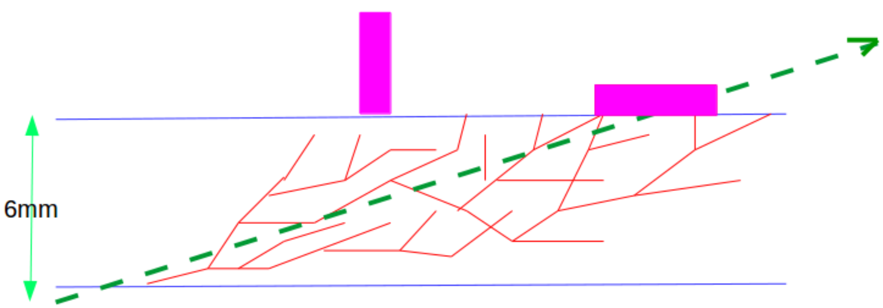
- Precision: $P = \frac{1}{\sqrt{N}}$; N = 4.7 % × $\mathcal{L}$ × σ × f; $f = \frac{N_{diamond}}{N_{exiting}}$

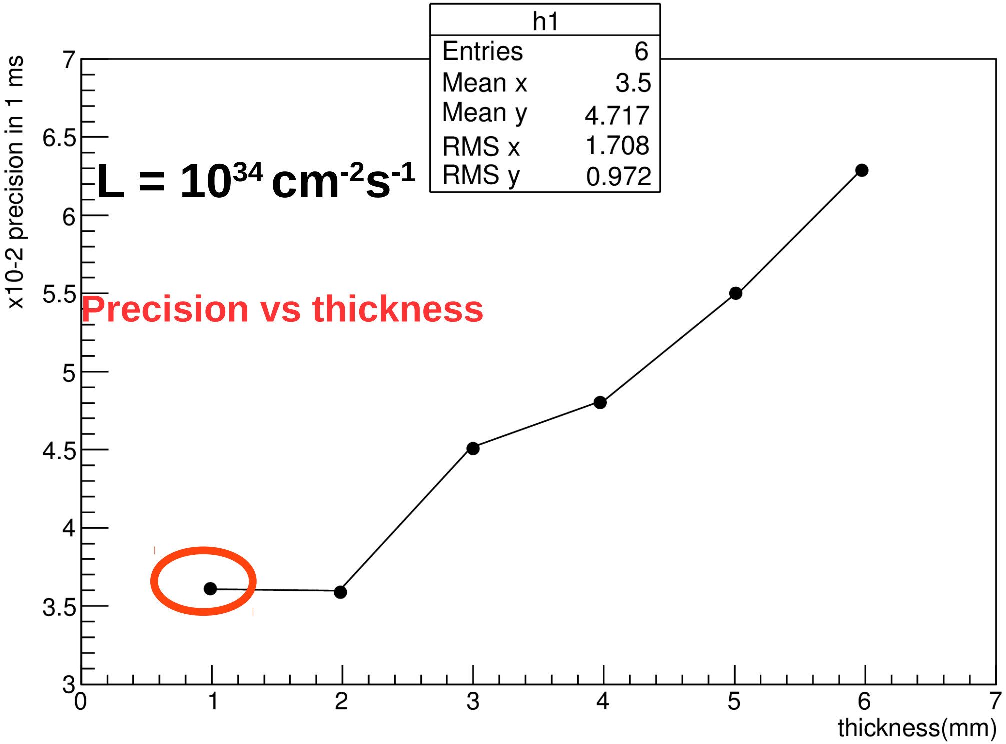
- Fraction of intercepted Bhabha in diamond sensors is **1.4 x 10^{-4}** << 8.3 x 10^{-3}

- Very low precision: 6.3 x 10^{-2}

- Thinner beam pipe: 1 mm thick Cu beam pipe improves the precision by factor 2 (not enough)

- Different materials were simulated (Al, Ti, Be)





Design of beam pipe

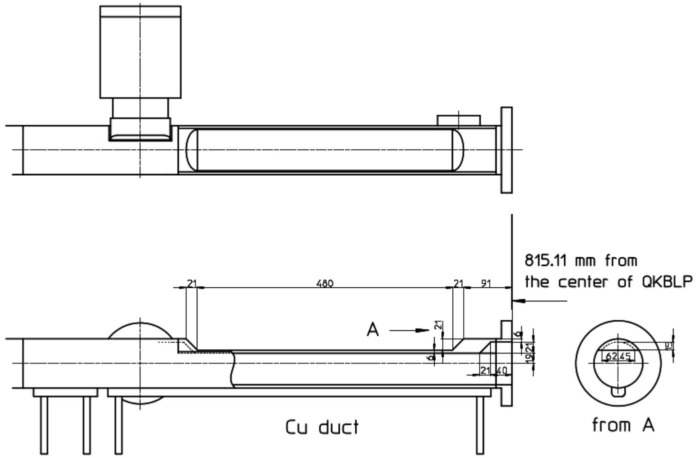
- To increase the signal in DS → Window at 45°

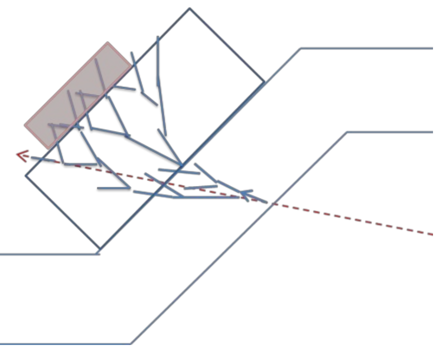
- Radiator: Increase (control) the EM shower

- Fraction of intercepted Bhabha in the diamond sensor is $2.35 \times 10^{-2} > 8.3 \times 10^{-3}$

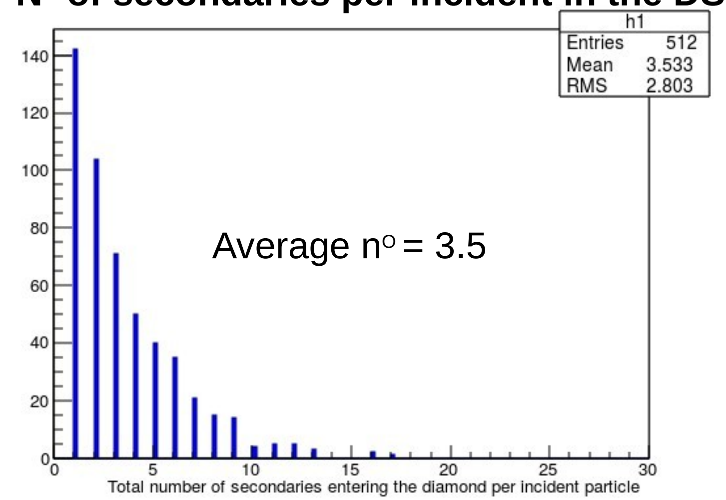
- Results:
- → Improvement of precision by about factor 10

  → **Window is the best design to be installed in spring 2017 for phase 2 commissioning**



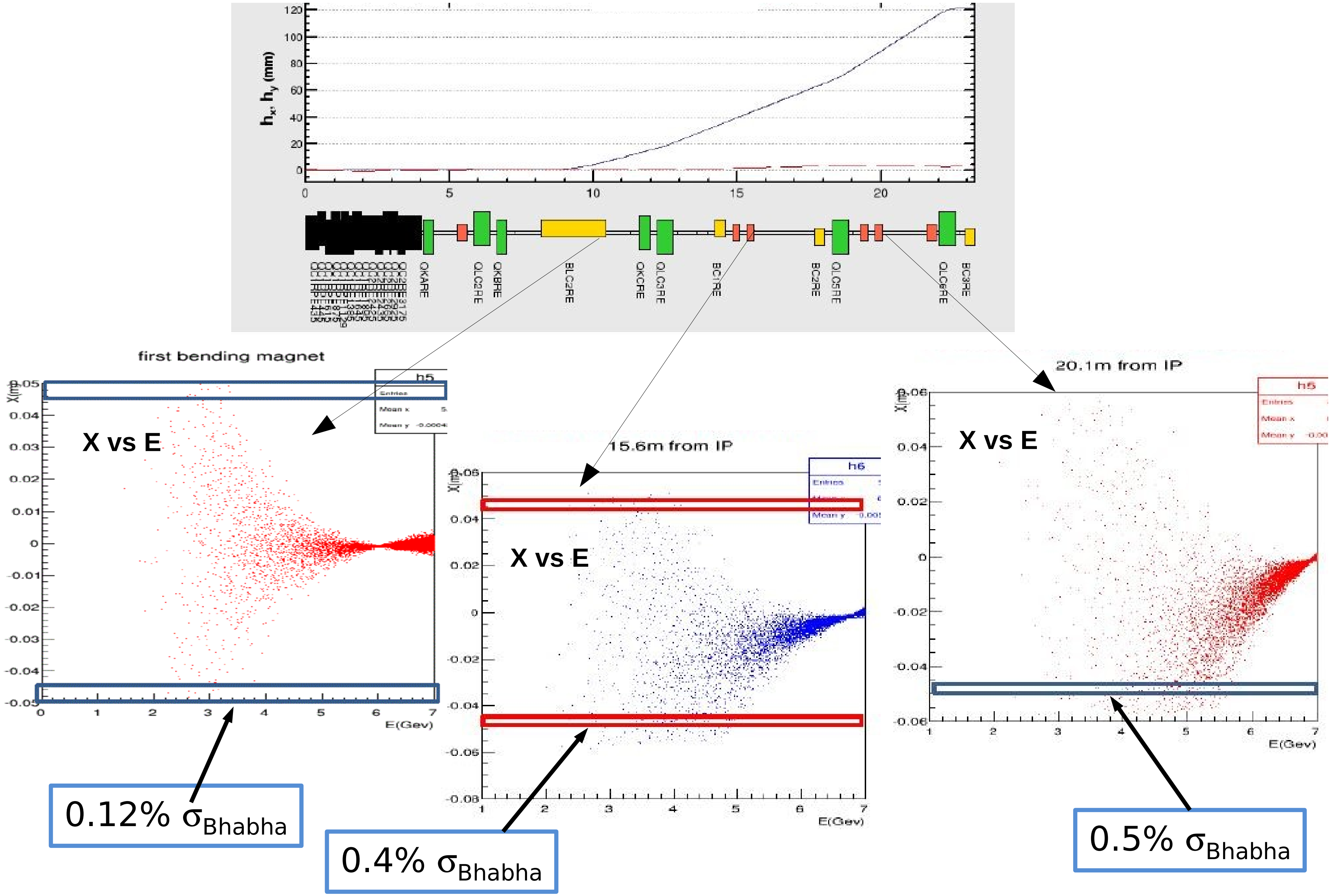


N° of secondaries per incident in the DS



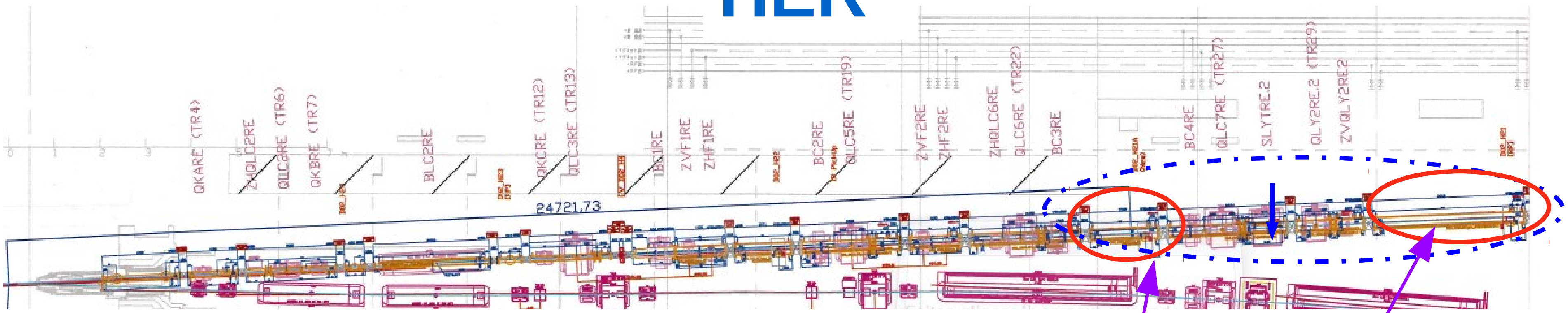
Design	phase 2 (10^{34} cm^{-2}s^{-1})	phase 3 (10^{35} cm^{-2}s^{-1})	design (8×10^{35} cm^{-2}s^{-1})
cylinder 6 mm Cu	6.3×10^{-2}	2×10^{-2}	7×10^{-3}
cylinder 1 mm Cu	3.6×10^{-2}	1.1×10^{-2}	4×10^{-3}
window at 45°	6×10^{-3}	1.89×10^{-3}	6.7×10^{-4}
window + radiator	3.7×10^{-3}	1.2×10^{-3}	4×10^{-4}

HER

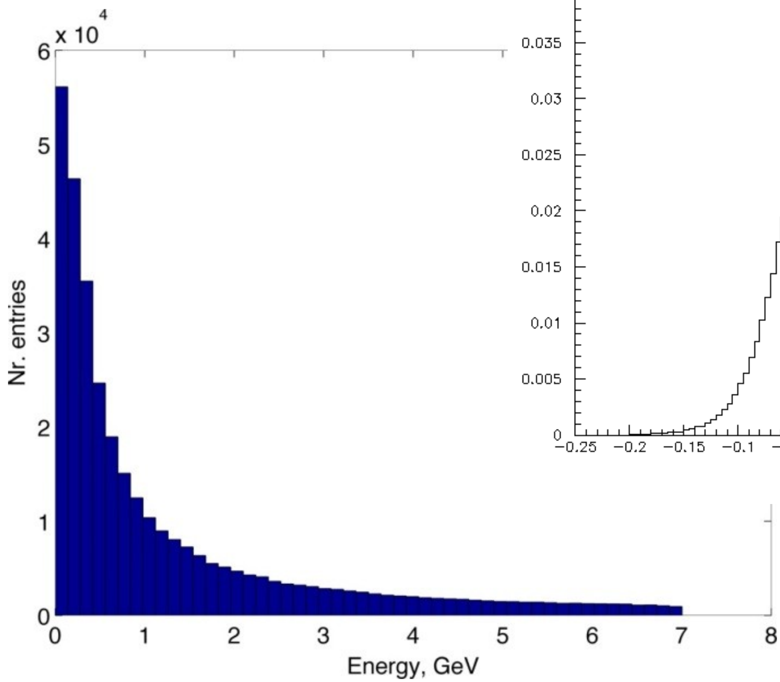


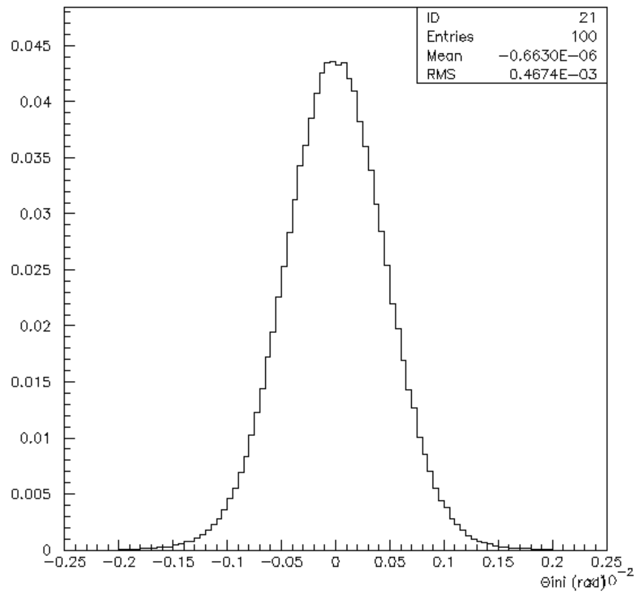
HER: No clear dependence of deflected electrons with their energy

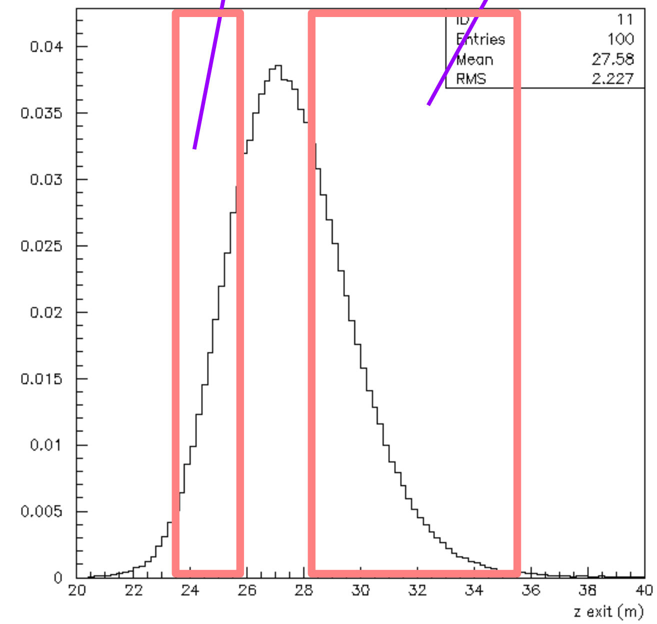
HER

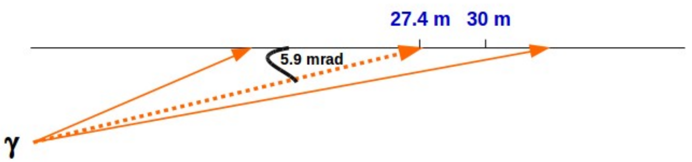


γ initial angle: ± 0.4 mrad









Diamond sensors will be placed at 30 m downstream of the IP

- **LER: Diamond sensors placed in the 3 m drift at 11.9 meters downstream of the IP**

- **A window at 45^{o} achieves the specified precision and will be installed in the drift in phase 2**

- **HER: Diamond sensors placed at 30 meters downstream of the IP to detect Bhabha photons**

Outline

1. **Fast luminosity monitoring:**

   a. Motivations / Specifications / Methods
   b. Position of DS in both rings and design of vacuum chamber in LER

2. **SuperKEKB phase 1: single beam loss measurements**

   a. Experimental setup
   b. Single beam loss simulations and measurements in LER
   c. Estimations for luminosity monitoring

3. **Conclusions and perspectives**

SuperKEKB Commissioning

- **SuperKEKB commissioning stages :**

→ Phase 1 : Single beam commissioning (no collisions, no final focus)

→ Phase 2: Final focus insertion, $\mathcal{L}$= 10^{34} $cm^{-2}s^{-1}$, Belle II commissioning without vertex detector

→ Phase 3: Increase beam currents, $\mathcal{L}$ up to 8 x 10^{35} $cm^{-2}s^{-1}$, physics runs with VXD

- **Goals of our fast luminosity project at phase 1**

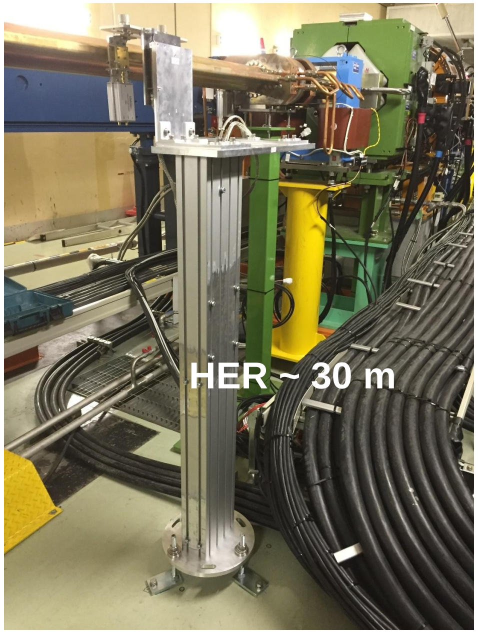
→ check the operation of the sensors and overall installation under beam conditions

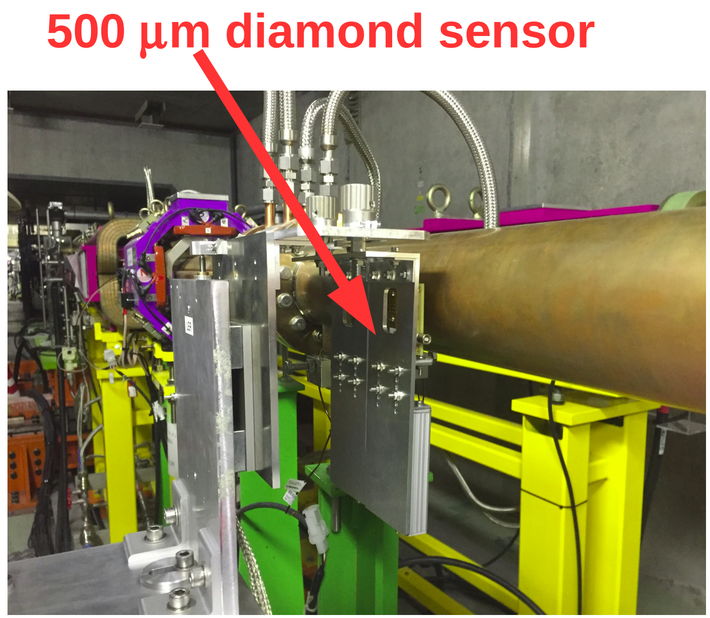
→ measure single beam losses in the sensors

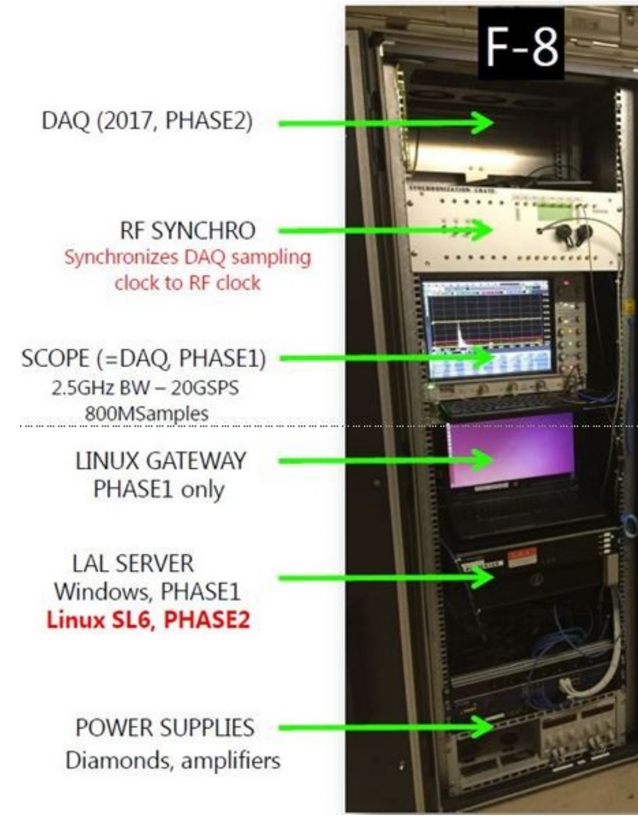
→ compare data to simulation to validate the simulations for luminosity monitoring

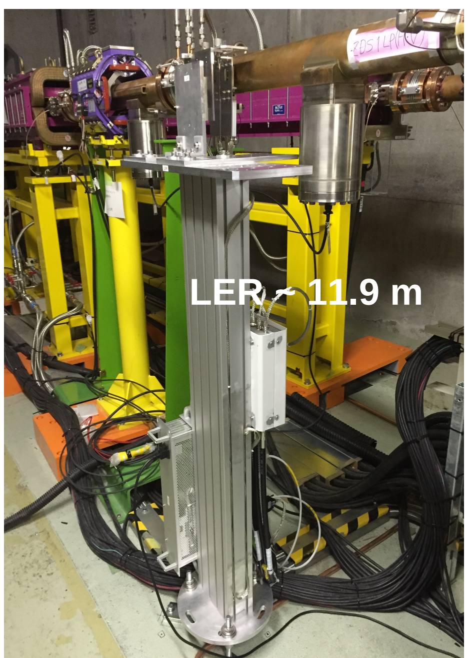
→ estimate the precision on luminosity for phase 2 and the signal to background fraction

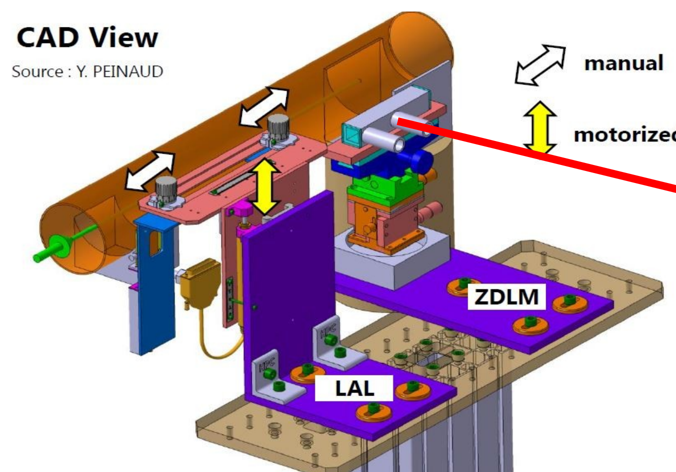
Experimental setup

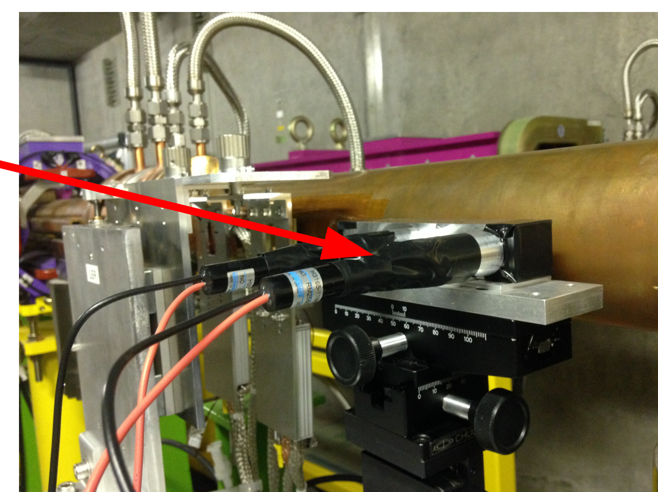












Diamond sensors

- **Properties:**

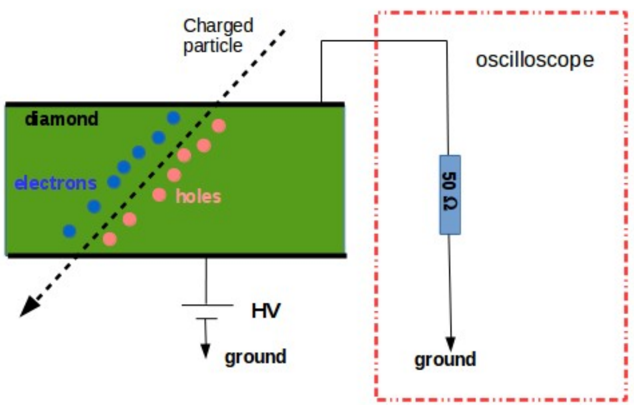
- Highest thermal conductivity among solid state materials
- Very high binding energy → radiation hardness
- Large band gap 5.47 eV → Low leakage current and noise
- High electron and hole mobilities → fast signal (ns)

Compact and simple

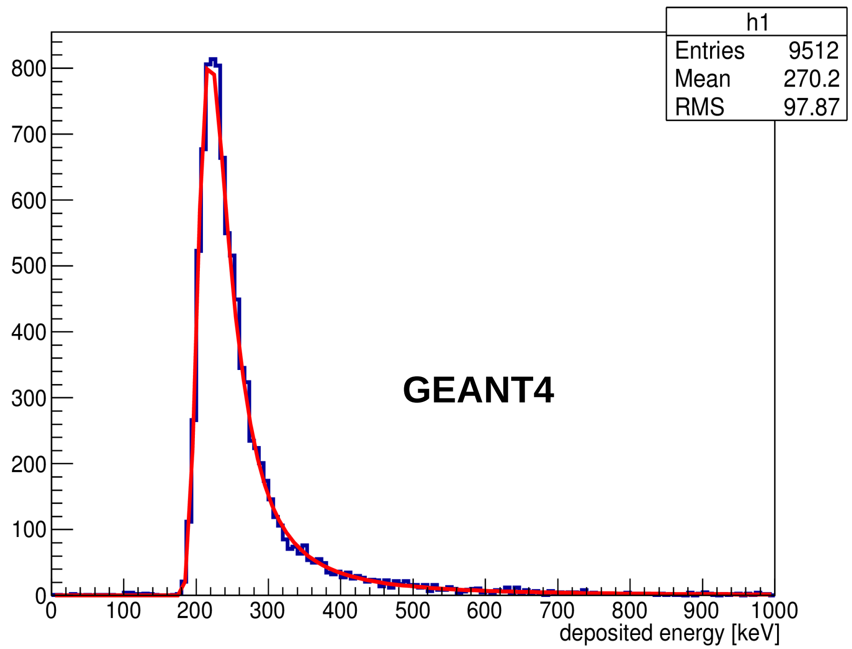
Property	Diamond	Silicon	Germanium
Atomic number Z	6	14	32
Density ρ [g.cm^{-3}]	3.51	2.33	5.33
Radiation length X_0 [cm]	12	9.4	2.3
Relative dielectric constant ε	5.7	11.9	16.3
Band gap E_g [eV]	5.47	1.12	0.67
Resistivity ρ_c [Ω cm]	$>10^{12}$	2.3×10^5	47
Electron mobility μ_e [cm^2 V^{-1} s^{-1}]	1800	1350	3900
Hole mobility μ_h [cm^2 V^{-1} s^{-1}]	1200	480	1900
Energy to create e$^-$h pair E_{eh} [eV]	13	3.6	3 (at 77 K)

- **Operation**

- Charged particle traverses the DS creating e$^-$/h pairs
- High voltage applied at the electrodes: opposite charges drift
- Voltage drop is read by an oscilloscope
- Energy deposition in the DS is a Landau distribution



MIP electron loss in 500 µm DS

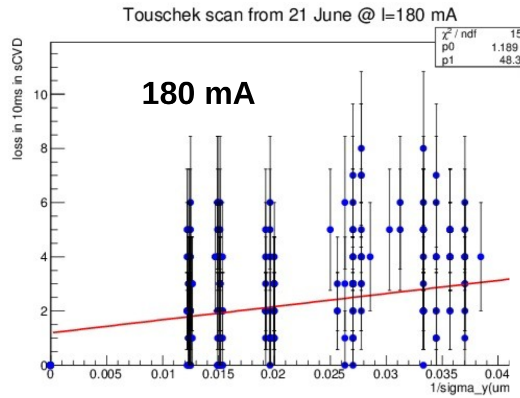


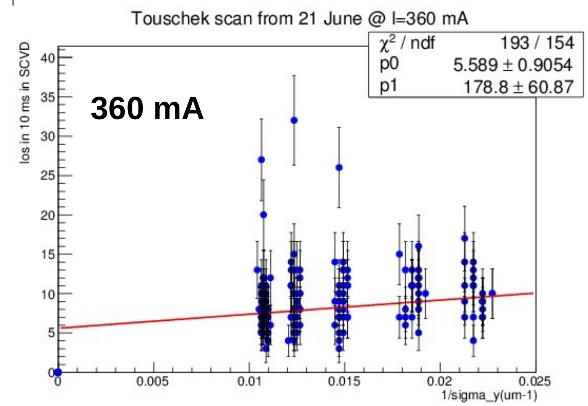
Vertical beam size scan

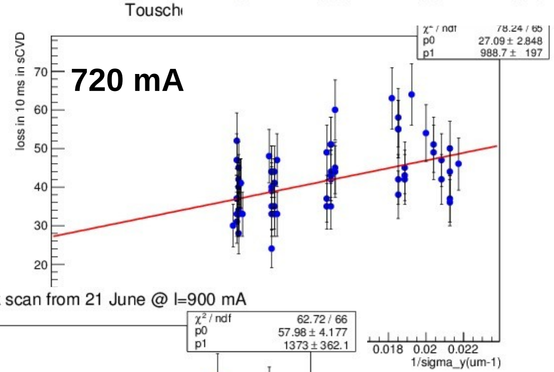
→ The vertical beam size σ_y was varied by varying the ECK (Emittance Control Knob)

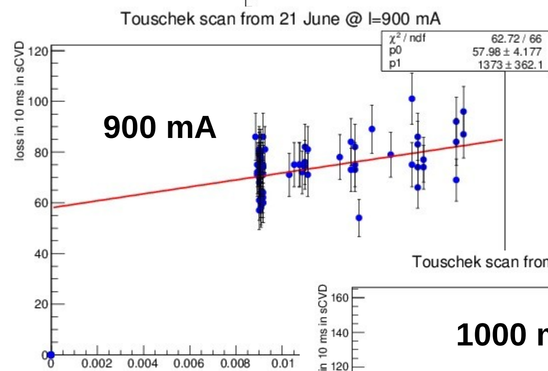
→ Losses in the sCVD were fit as a function of the inverse vertical beam size (σ_y^{-1})

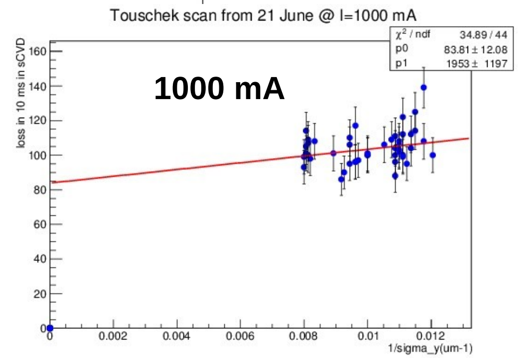
→ Loss= Touschek σ^{-1}_y + Bremsstrahlung

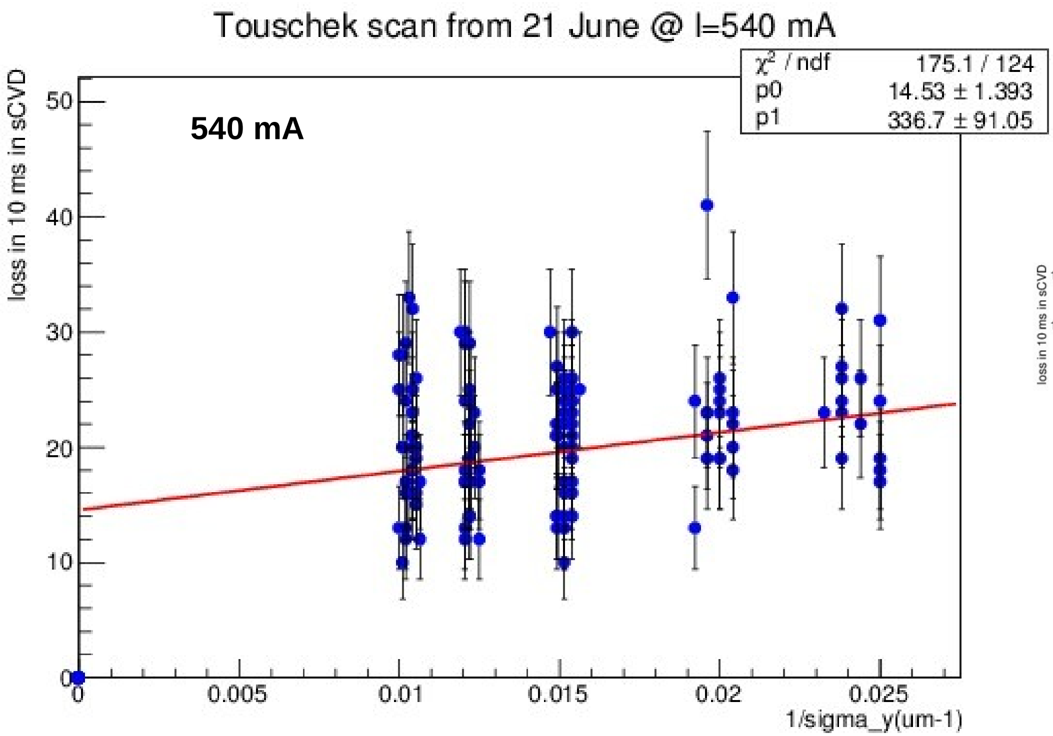








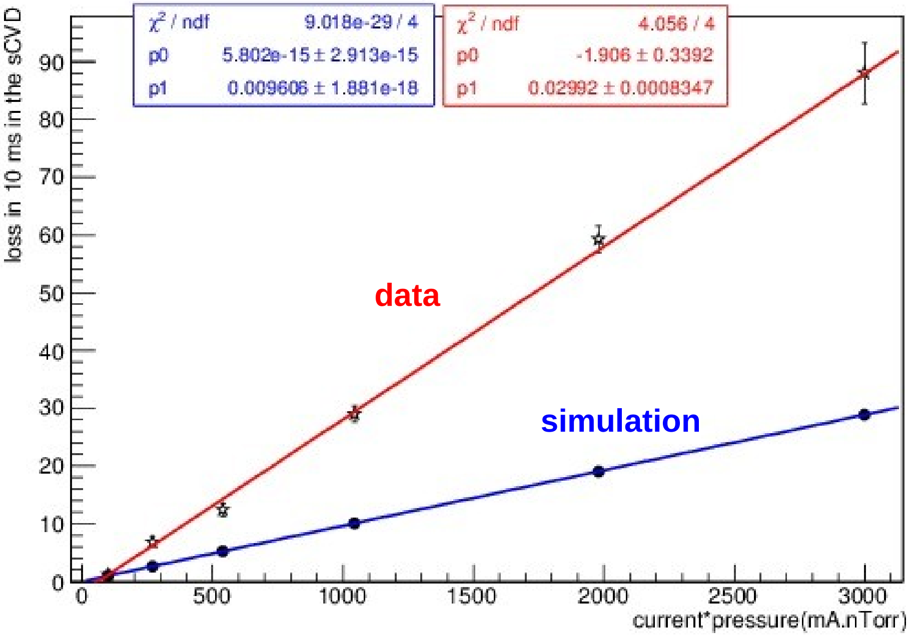


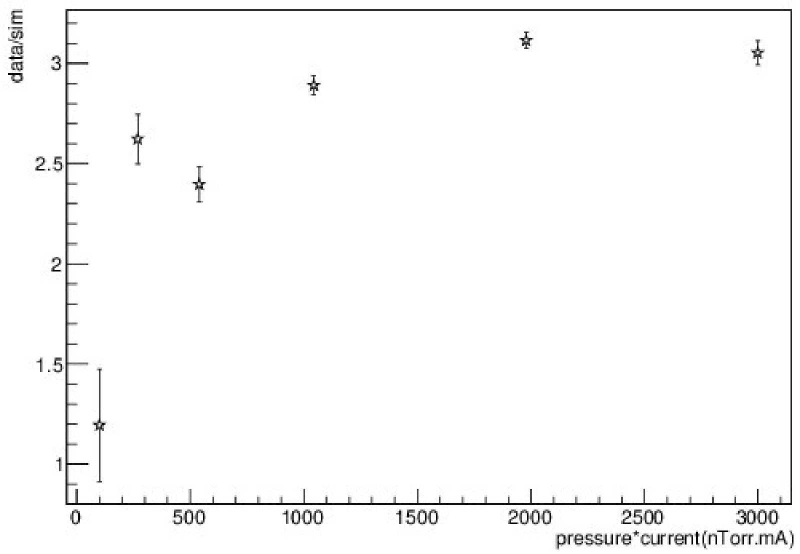


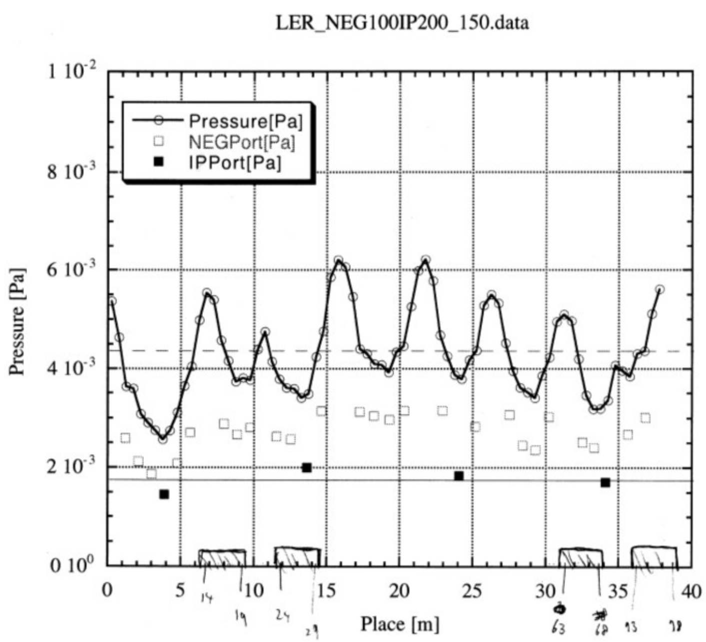
Bremsstrahlung

→ Data is larger than simulation by factor about 3

Current (mA)	Pressure (nTorr)	Beam-gas Bremsstrahlung in DS in 10 ms
180	0.56	1.2 ± 0.3
360	0.75	5.6 ± 0.9
540	1	14.5 ± 1.4
720	1.45	27.1 ± 2.8
900	2.2	58.0 ± 4.2
1000	3	83.8 ± 12.0







→ Factor 3 ± 1.5 was found by vacuum group at KEK (simulation)

→ The pressure measured at Gauges should be multiplied by 3 to represent the pressure at center of beam pipes

Touschek

→ **Slopes and their errors extrapolated quadratically to one current (1 A)**

Current (mA)	Slope ± error
180	0.95 ± 0.10
360	1.1 ± 0.6
540	1.02 ± 0.08
720	1.42 ± 0.55
900	0.97 ± 0.15
1000	0.97 ± 0.10

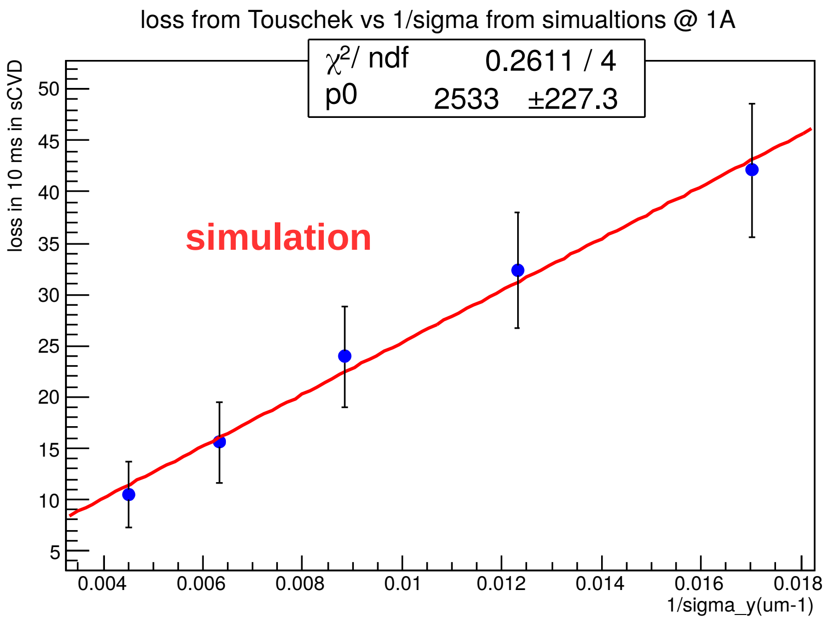
→ Weighted arithmetic mean of the slopes+errors:

$$\bar{x} = \frac{\sum_{i=1}^{n}\left(\frac{x_i}{\sigma_i^2}\right)}{\sum_{i=1}^{n}\frac{1}{\sigma_i^2}} \quad \pm \quad \sigma_{\bar{x}}^2 = \frac{1}{\sum_{i=1}^{n}\frac{1}{\sigma_i}}$$

Simulations:

→ Beam current I = 1000 mA

→ Change x-y coupling $k = \frac{\epsilon_y}{\epsilon_x}$



Touschek	slope	error
data	1530	172
simulation	2533	227

→ **simulation/data = 1.7± 0.74**

→ bunch length is consistent (σ_z= 6 mm)

→ vertical beam size (measurement consistent with modeling)

- Could be ε_x ?

Touschek losses are proportional to $\frac{1}{\sigma_x} * \frac{1}{\sigma_y}$

$\sigma_x = \sqrt{\epsilon_x * \beta_x}$ → Simulation depends 1/ε_x

$\sigma_y = \sqrt{\epsilon_y * \beta_y}$

But no reliable measurements

Estimations for luminosity monitoring

- Estimations of single beam losses for phase 2 for same SAD code
- **Interest : Luminosity signal will be contaminated by single beam loss?**

→ **Phase 2:**

- Final focus quadrupoles are inserted

- Collimators are closed to mitigate beam backgrounds in Belle II detector

- **Preliminary expectations:**

- Luminosity signal from radiative Bhabha is ~ 2 orders of magnitude larger than backgrounds

- This satisfies requirements to achieve a precision of 10^{-3} in 1 ms

Conclusions

→ Fast luminosity monitoring is important to optimize and stabilize the luminosity

→ Simulations performed in SAD:

1) LER: diamond sensors placed at 11.9 meters

2) HER: better to measure signal of Bhabha photons, diamond sensors placed at 30 meters

→ Simulations in GEANT4:

A window at 45^{o} is needed to achieve the required precision (spring 2017)

→ Our diamond sensors operated well and allowed good measurements of single beam losses

→ Data analysis of single beam loss measurements:

1) Bremsstrahlung (dominant) : data and simulation are consistent

2) Touschek: data/simu=1.7 (horizontal emittance?)

→ Preliminary estimations for phase 2: signal / background ~ 200

Perspectives

→ HER: detailed simulation on Bhabha photons signal

→ Window at 45^o : Simulations of signal and background rates

→ Preparation of the fast readout electronics for phase 2 (no dead time)

- Programming of FPGA to monitor integrated luminosity and bunch luminosity

- Use 500 μm diamond sensor for phase 2 and 140 μm for phase 3

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Mika Masuzawa
Hiroyuki Nakayama
Yukiyoshi Ohnishi
Yusuke Suetsugu
Sadaharu Uehara

Merci pour votre attention

Thank you for your attention

Grazie mille

ありがとうございました

شكراً جزيلاً

BACK UP SLIDES

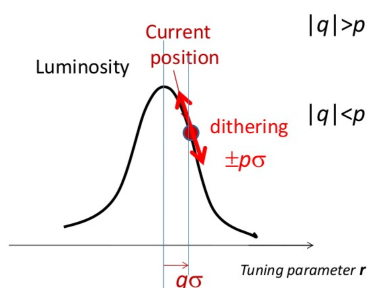
Dithering algorithm

Done by S. Uehara

→ dithering frequency "f_0=77 Hz" modulates the orbit of one of the two beams (e^+) as **r=sin(2πf_0t)**

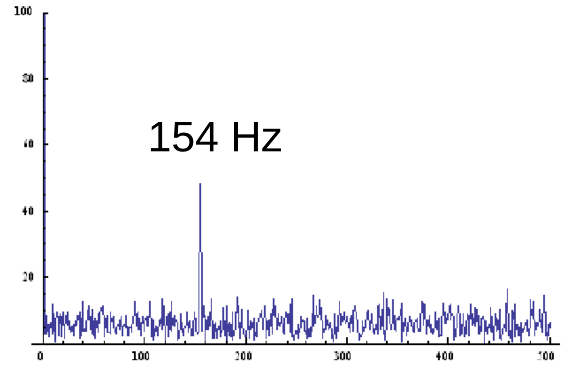
→ Luminosity depends on **r** as a Gaussian function:

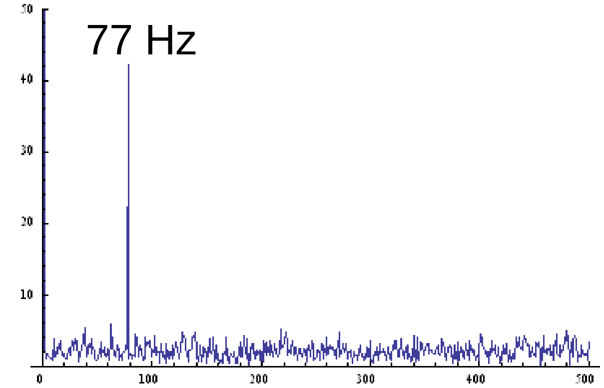
$$\mathcal{L}(t) = exp(-\frac{(q + p \times sin(2\pi f t))^2}{2})$$



→ **aim: increase peak at 2*f_0 and decrease peak at f_0**

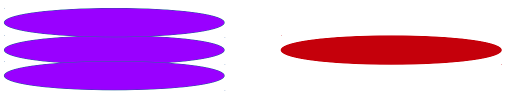
Result: precision 1.6 x 10^{-3} over 1 ms is sufficient (400 KHz in 1 ms) to control the horizontal orbit every 1 s

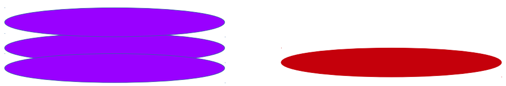




|q|<p, negligible luminosity loss

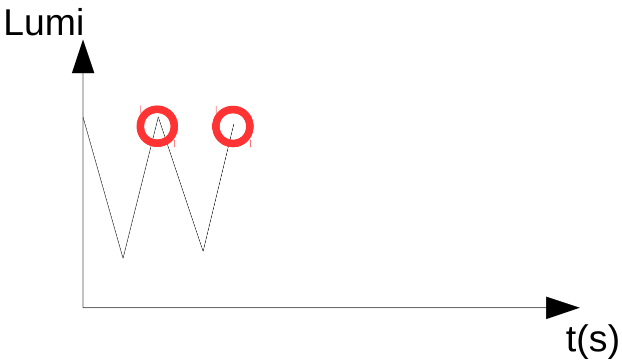
|q|>p, luminosity loss

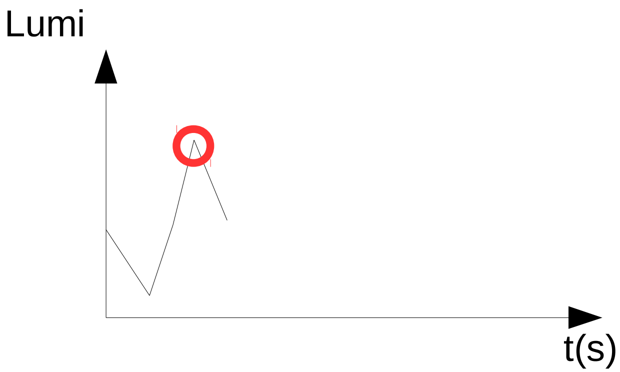




Peak at 2f_0

Peak at f_0





Calibration

→ Maximum of signal of Data were fit by “Landau”

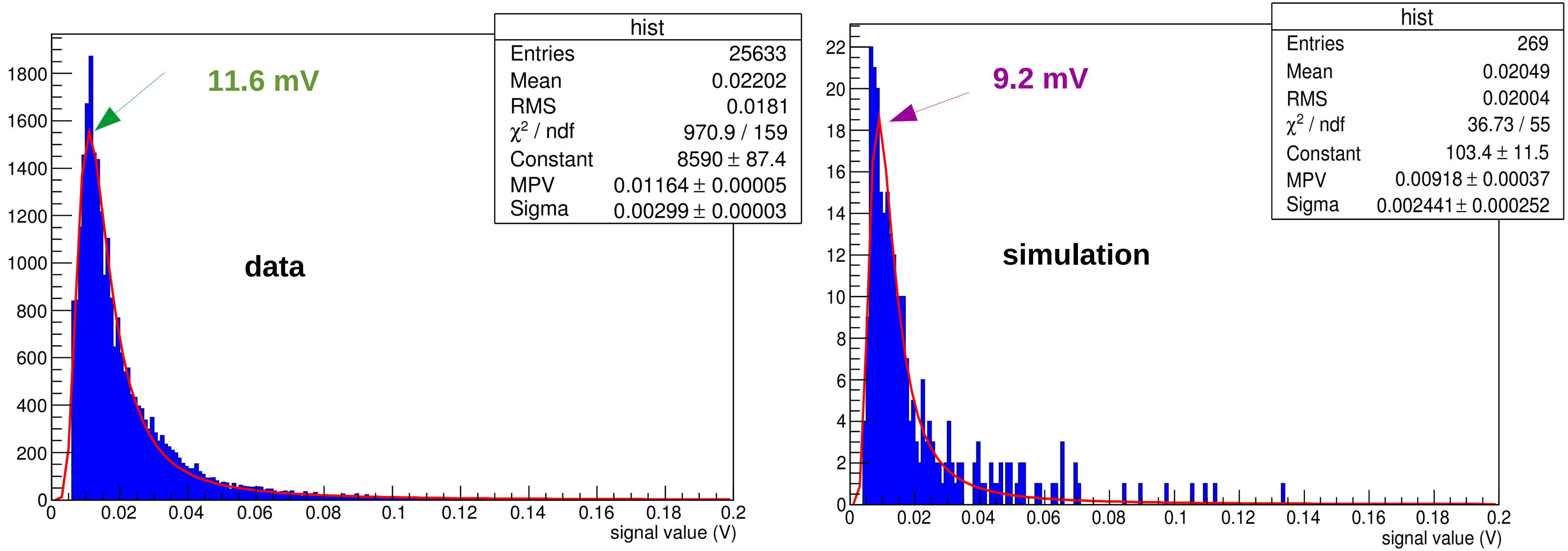
→ A cut at 6 mV separates signal from noise

→ In simulation: minimum of 50 KeV (> 3σ of noise)

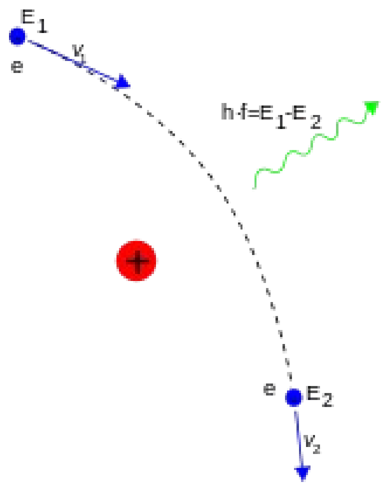
→ MPV= 11.6 mV in data

→ MPV= 9.2 mV in simulations

→ **11.6/9.2 = 1.3 ------------> threshold is at ~ 4.7 mV for simulations**



Beam gas Bremsstrahlung

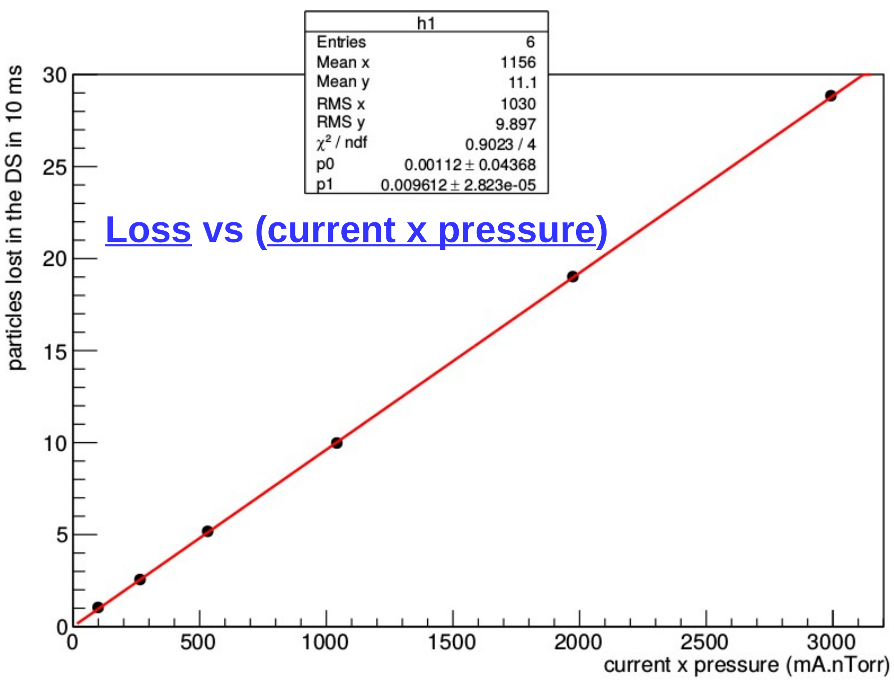


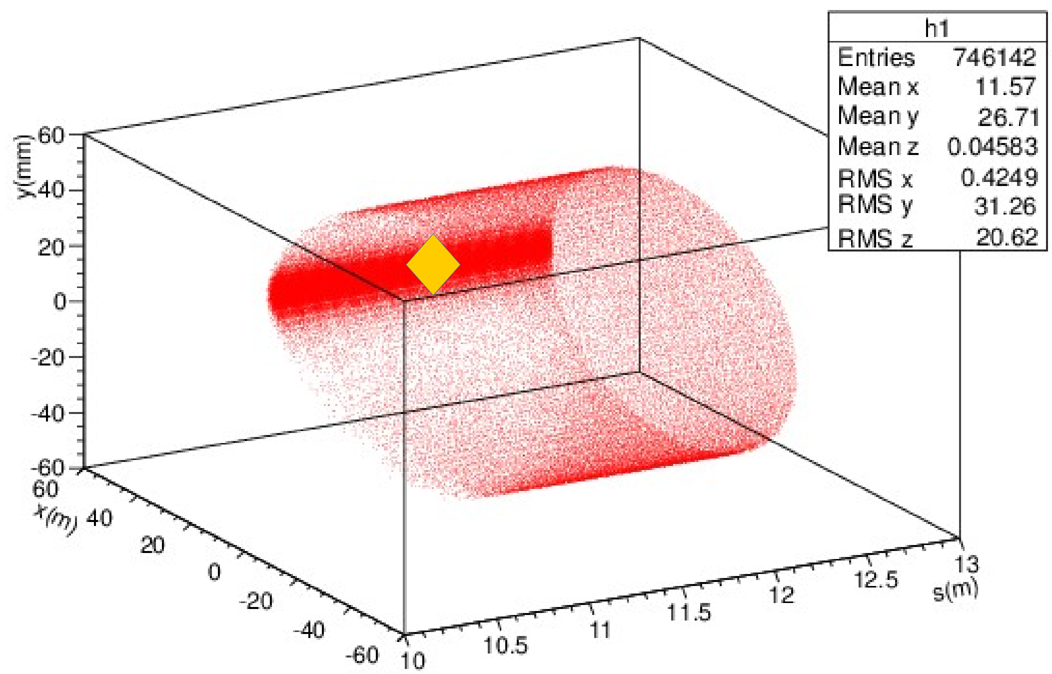
→ Inelastic Coulomb scattering

→ Beam particles pass by EM of nucleus of molecules of residual gas

→ Emission of photon → particle loses energy

→ Particle is lost downstream of emission point





→ **Scattering and loss rates are proportional to beam current and vacuum pressure**

Touschek scattering

→ Scattering of beam particles upon each other

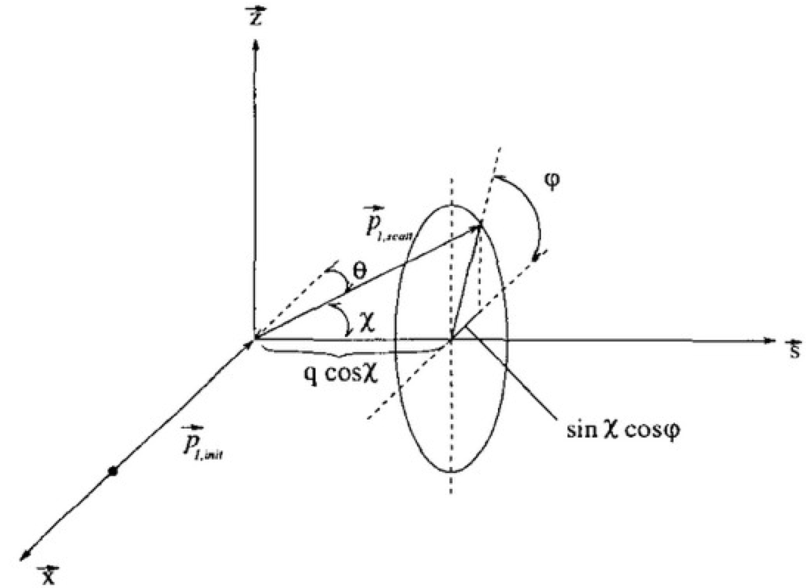
→ In CM; $\vec{p}_{init1,\,2} = (\pm p_x, 0, 0)$

$\vec{p}_{scat1,\,2} = (\pm p_x \sin\chi \cos\varphi, \pm p_x \cos\chi, \pm p_x \sin\chi \sin\varphi)$

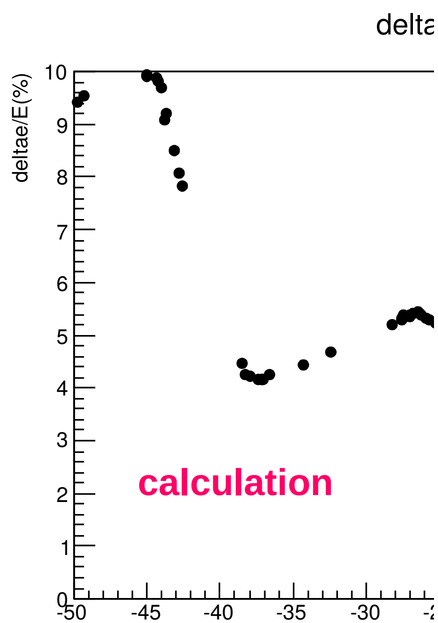
→ In Lab frame: maximum momentum transfer : **$\Delta E = \gamma \times p_x$**

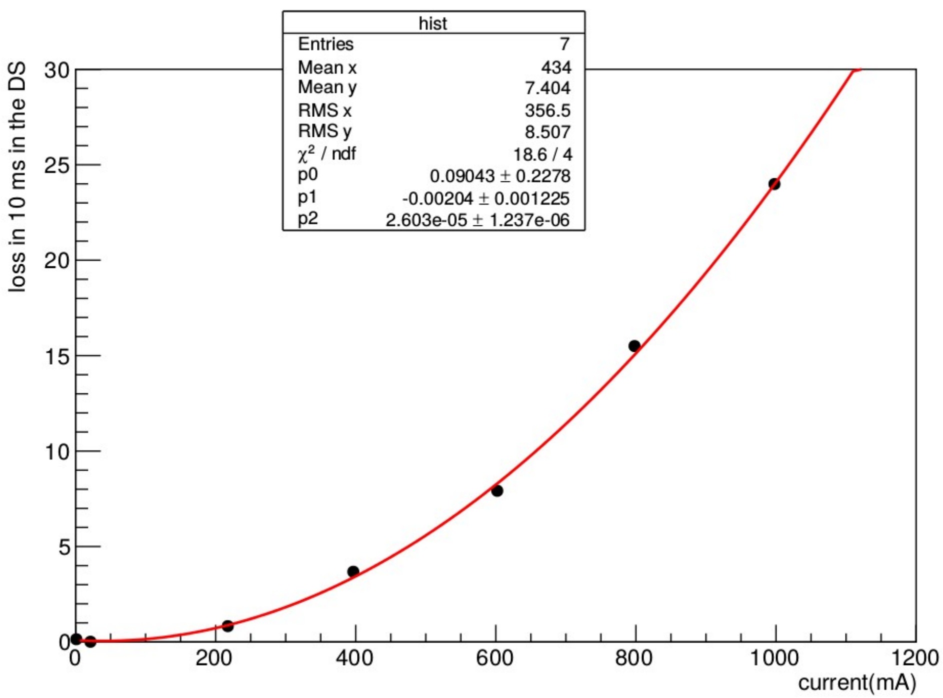
$$\frac{p_x}{p} = \sqrt{\frac{\epsilon_x}{\beta_x}}$$

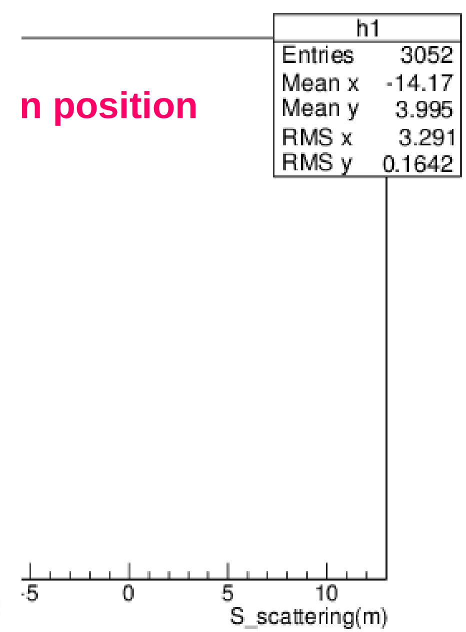
→ One particle loses energy and the other gain energy



→ Scattering and loss rates are proportional to I^2 and inversely proportional to the beam size





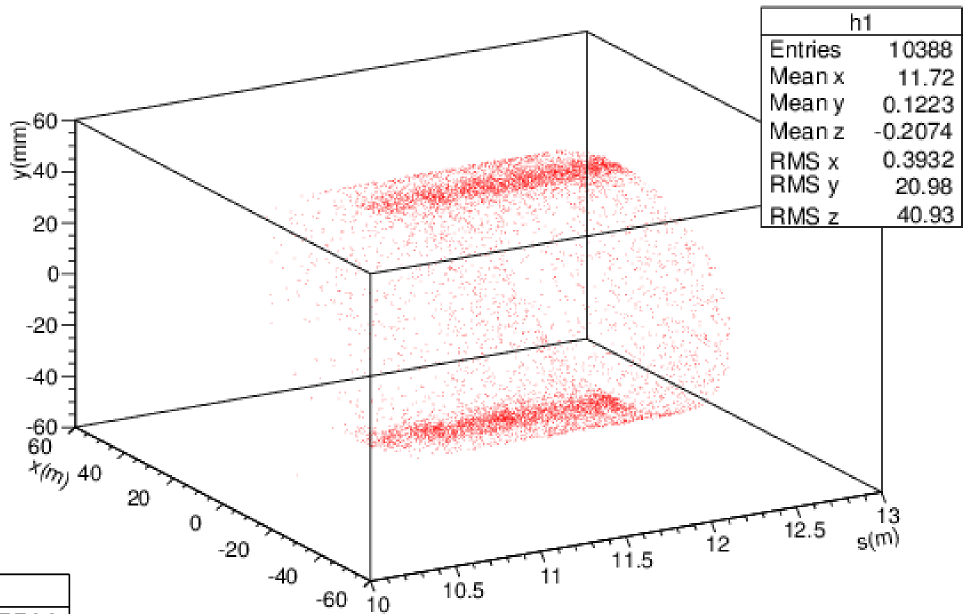


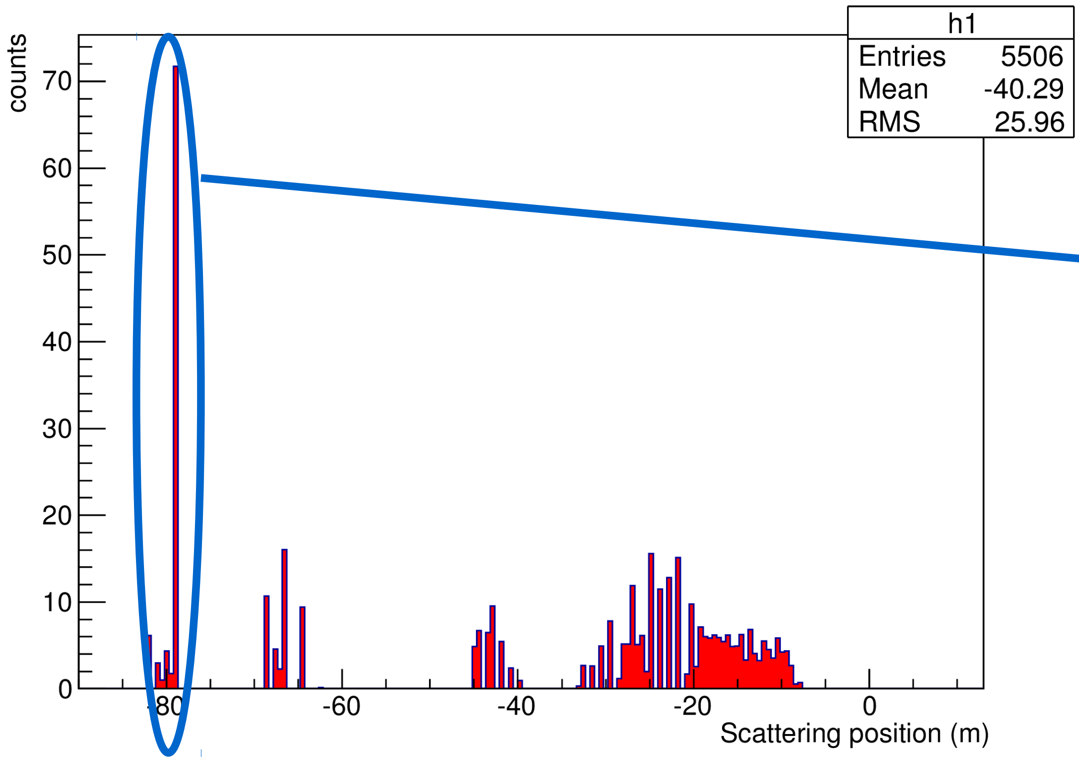
Coulomb scattering

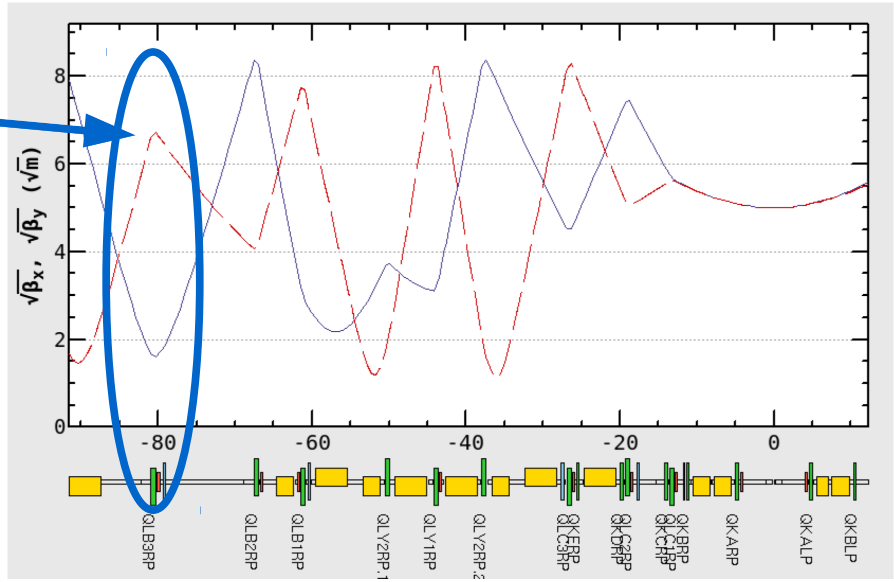
→ Elastic scattering of particle beams on the nucleus of residual gas molecules

→ Particle receives a transverse kick and is lost downstream the emission point

→ Transverse offset of particle lost at position B and emitted at A depends on $\sqrt{\beta_A \times \beta_B}$



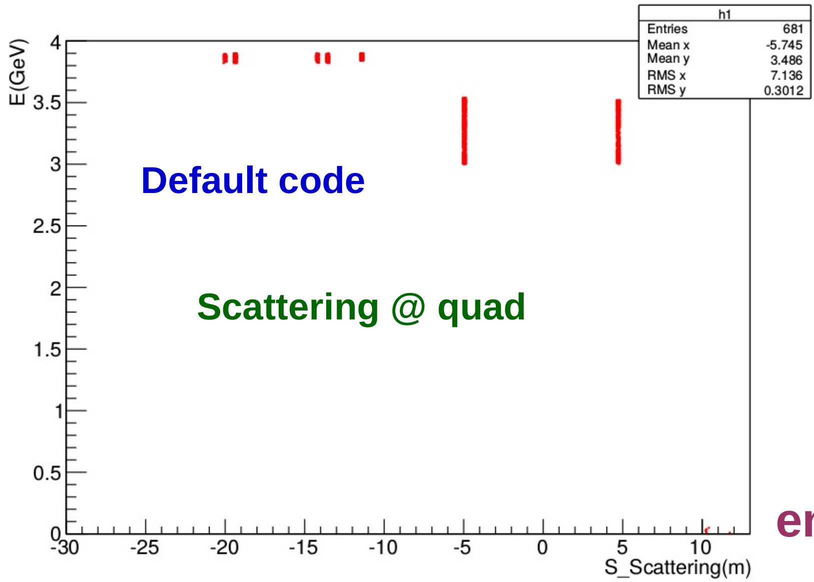


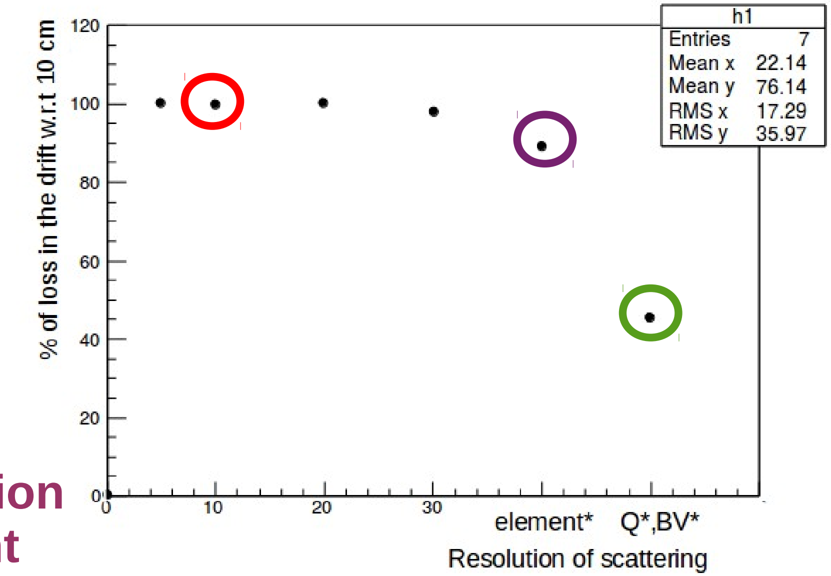


Code Optimisation

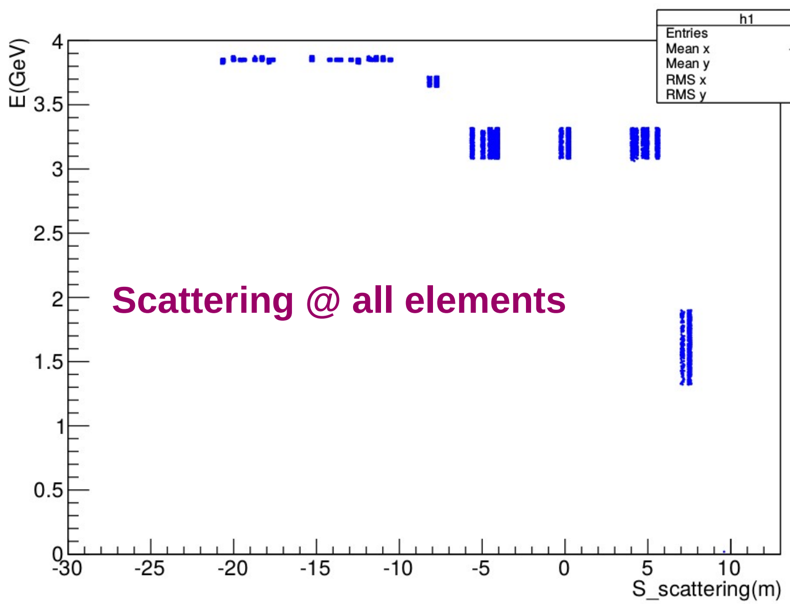
→Code written in SAD by Y. Ohnishi to simulate beam backgrounds in SuperKEKB rings

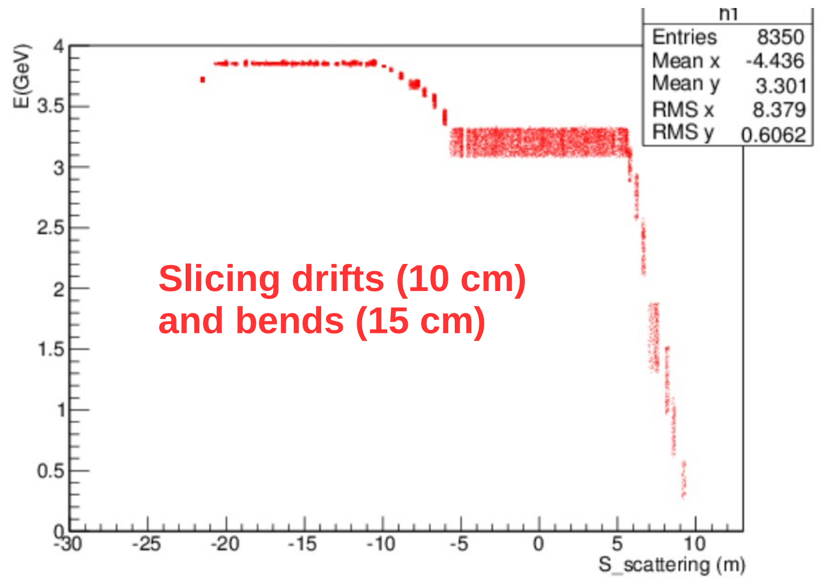
→ Optimization of the code to estimate the loss rates in the DS: scattering resolution





E vs emission point





Vacuum bumps in LER

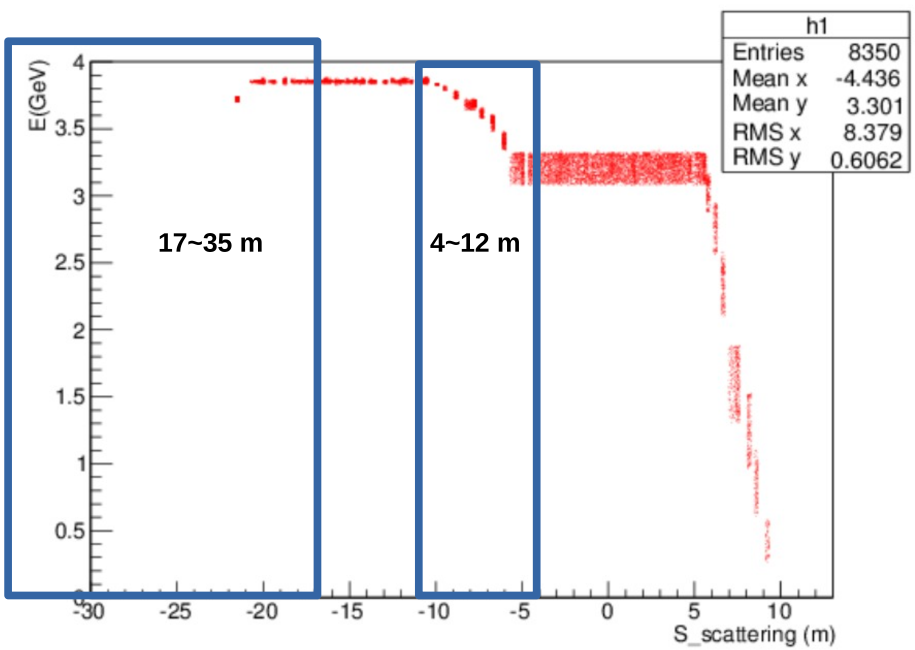
→ Vacuum bumps were performed upstream of the IP

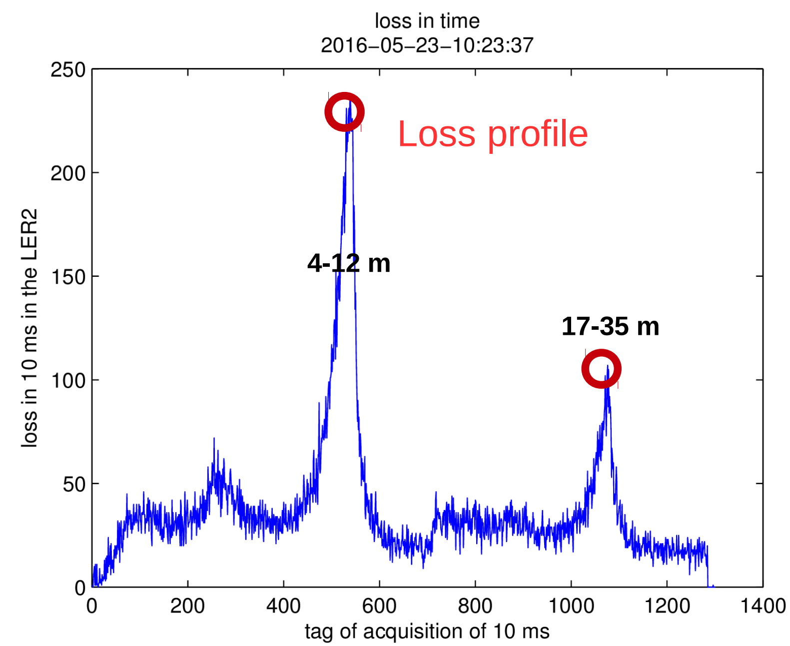
→ Fraction of losses in the sCVD from scattering regions were calculated and compared to data

$$\rightarrow f = \frac{loss_{bump}}{loss_{all-sections}}$$

$loss_{bump}$ → is the loss in the sCVD at the maximum of the bump

$loss_{all-sections}$ → total loss simulated in the sCVD, when pressure everywhere in the ring is equal to that of the maximum of the bump at the given section





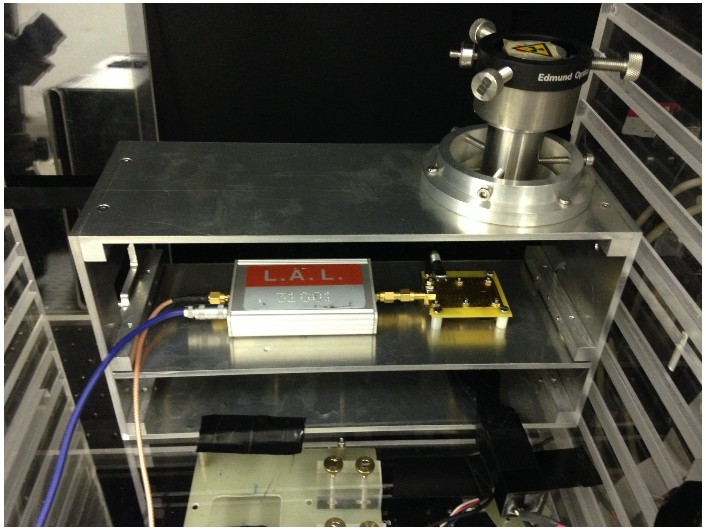
Position of vacuum bump	Average vacuum pressure (nTorr)	f_{data}	$f_{simulation}$
4 to 12 meters upstream of the IP	300	0.17±0.01	0.20±0.02
17 to 35 meters upstream of the IP	275	0.07±0.01	0.09±0.01

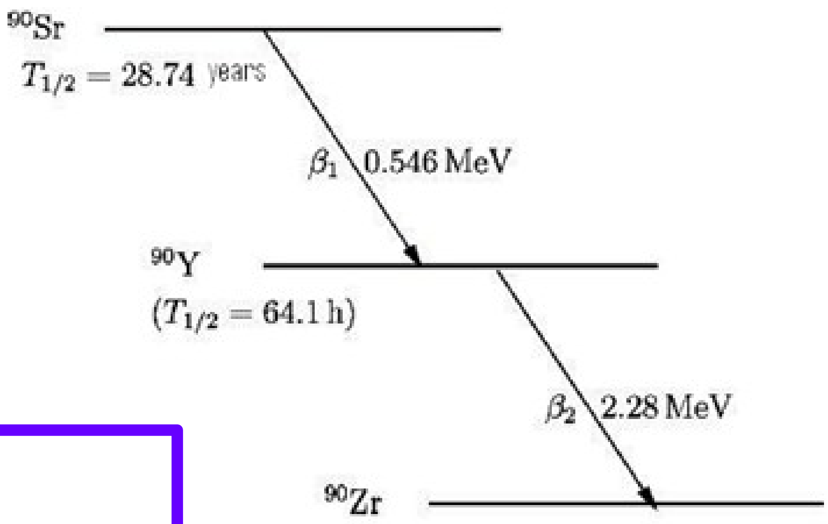
Characterization Tests

- **Characterization tests:**
  - Reconstruct the Landau distribution of the signal
  - Verify that the position of the maximum of the signal doesn't vary significantly in time

- **Experimental setup:**
  - ^{90}Sr β source
  - CIVIDEC DS
  - CIVIDEC charge amplifier (G= 4mV/fC , σ~10 ns)
  - Scintillator for triggering
  - Oscilloscope

→ **Low energy particles get absorbed in the DS**
→ **MIPs exit the DS and creates signal in the scintillator**



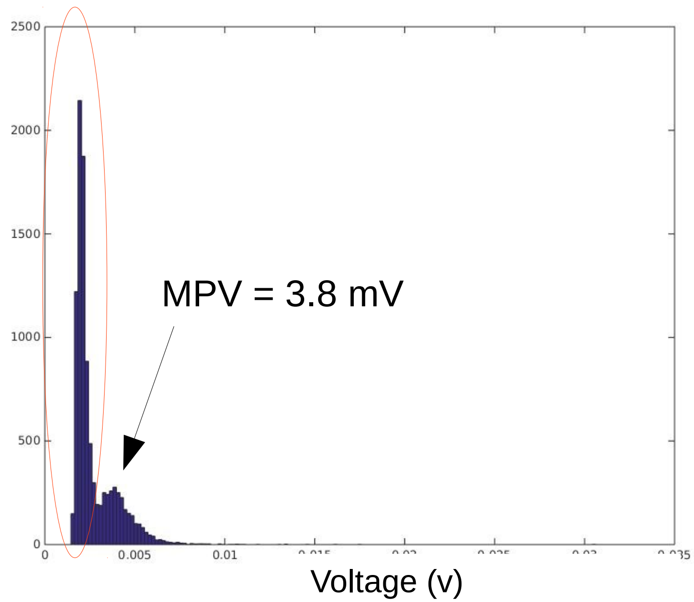


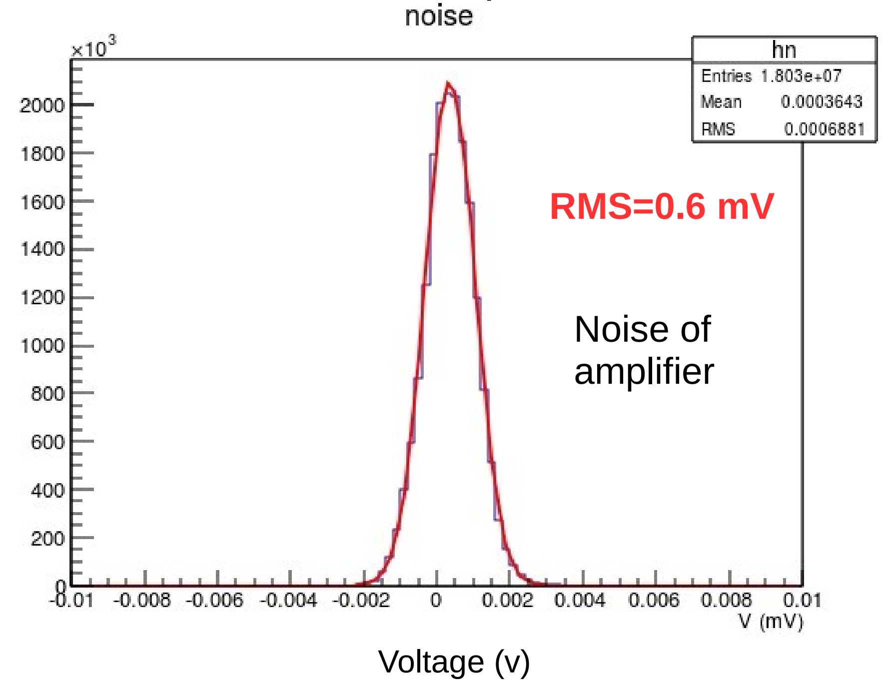
- **Trigger:**
  - Normal trigger: trigger on all the events including noise
  - Multistage trigger: trigger on events of the DS which arrive 6 ns before the rising edge of signal in scintillator

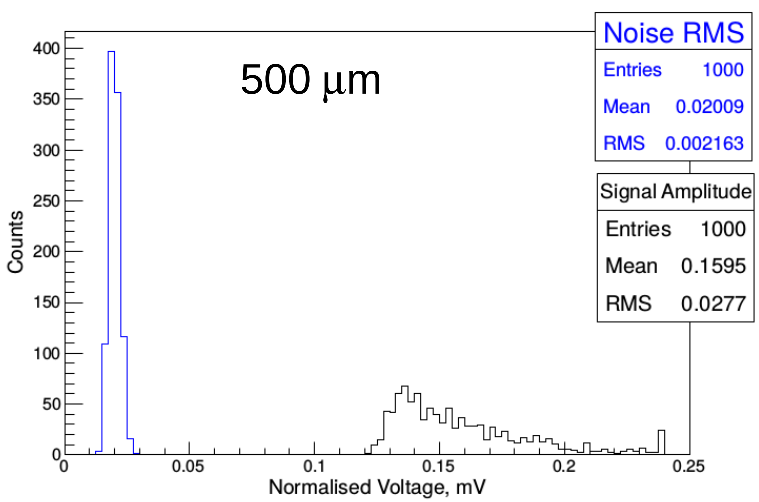
Normal Trigger

- **140 µm, 4x4 mm² DS, normal trigger:**

- The MPV of the Landau distribution of the signal of one MIP in the 140 µm DS is 3.2 mV



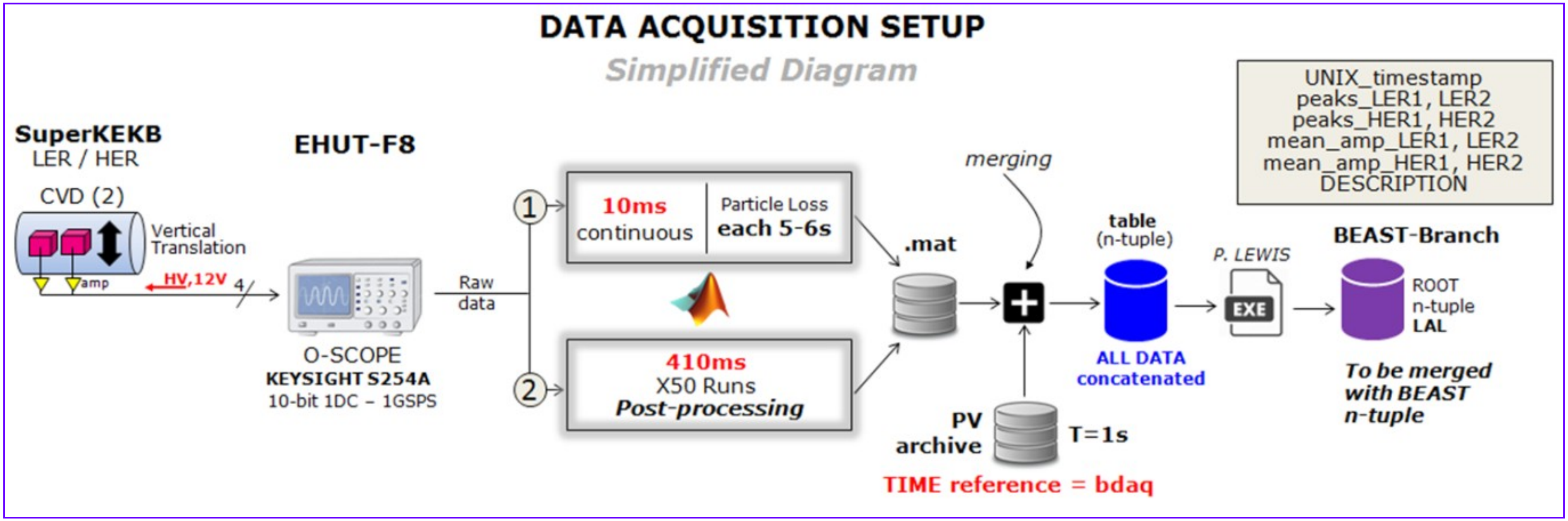




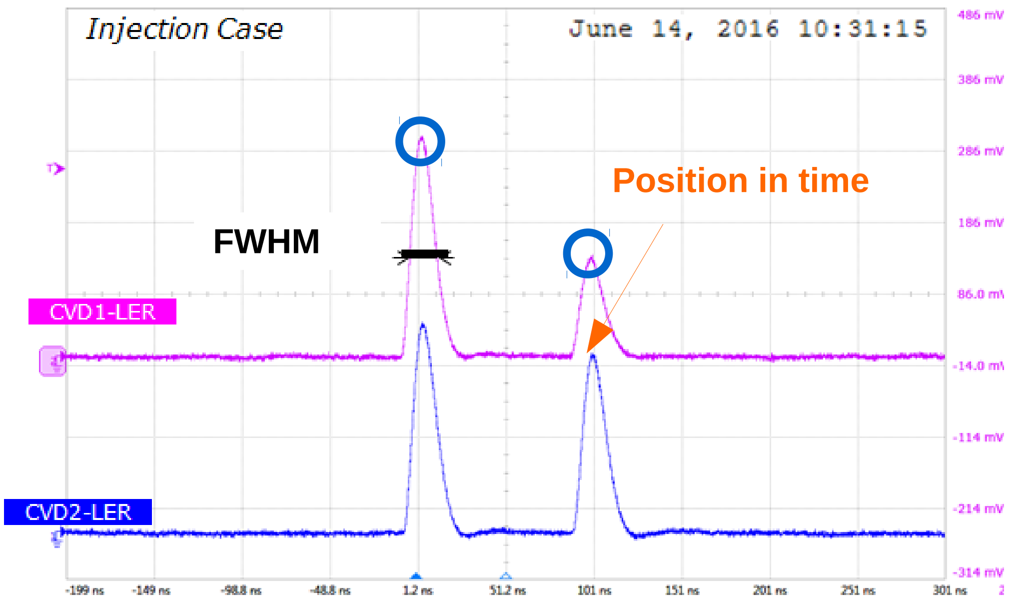
S. Liu PhD thesis

- Noise of charge amplifier ~ 0.36 mV
- MPV (3.2 mV) is 5 times greater than RMS of noise
- Difficult separation of the signal from the noise
- **In phase 2: More than 1 MIP in DS (separation from noise)**
  - **For 500 µm DS: MPV is at 12.3 mV >> 0.36 mV**
  - **Signal is well separated from the noise**

Data acquisition



CVD Signal example (LER)



- **Data processing:**

→ Define waveforms and save them

→ Extract maximum of signal (total integrated charge)

→ Position in time

→ FWHM

→ Save in .mat files

→ Merge them to EPICS

SuperKEKB Commissioning

- **SuperKEKB commissioning stages :**

→ Phase 1 : Single beam commissioning (no collisions, no final focus)

→ Phase 2: Final focus insertion, $\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$, Belle II commissioning without vertex detector

→ Phase 3: Increase beam currents, $\mathcal{L}$ up to $8 \times 10^{35}\ cm^{-2}s^{-1}$, physics runs with VXD

- **Phase 1 achievements: (Feb-June 2016)**

→ Verification of hardware system (magnets, vacuum system, etc …)

→ Successful vacuum scrubbing in both rings (< 1 nTorr at 1 A)

→ Optics measurements and corrections

→ Background measurements and studies by BEAST II

- **Goals for our fast luminosity project at phase 1**

→ check the operation of the sensors and overall installation under beam conditions

→ measure single beam losses in the sensors

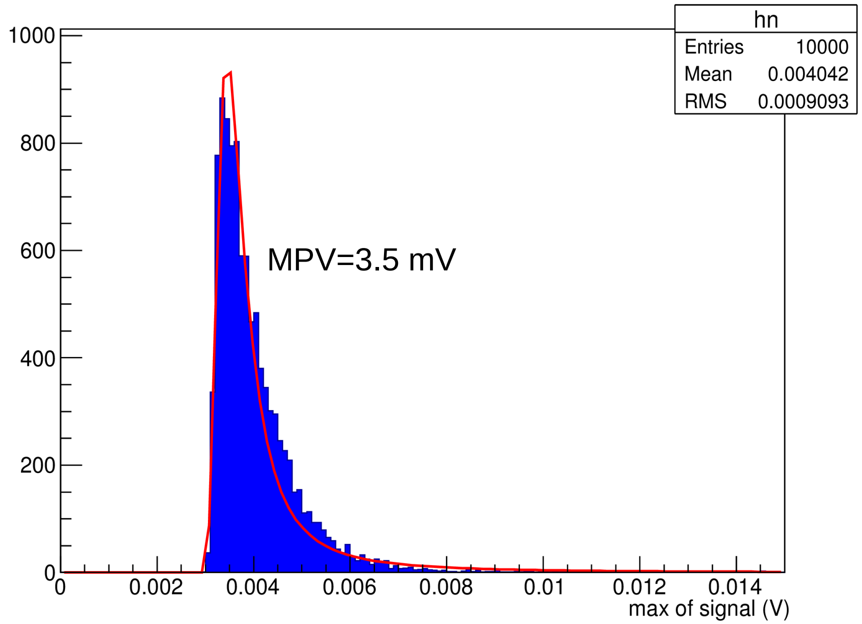
→ compare data to simulation to validate the simulations for luminosity monitoring

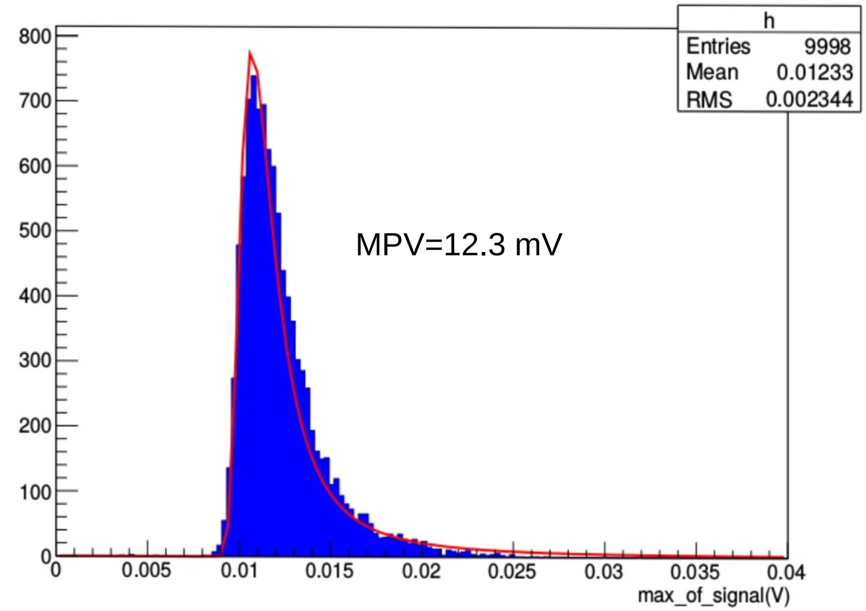
→ estimate the precision on luminosity for phase 2 and the signal to background fraction

Multistage Trigger

140 μm, 4x4 mm² DS

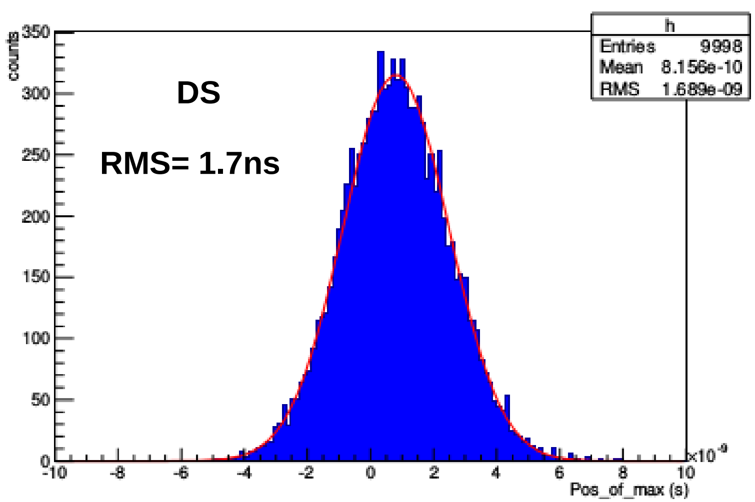
- **500 μm, 4x4 mm² DS**

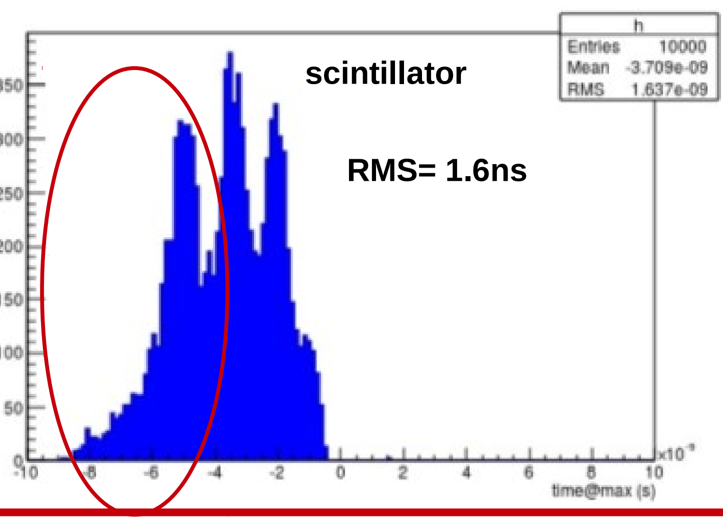




- **Position of maximum in time : 500 μm, 4x4 mm² DS**

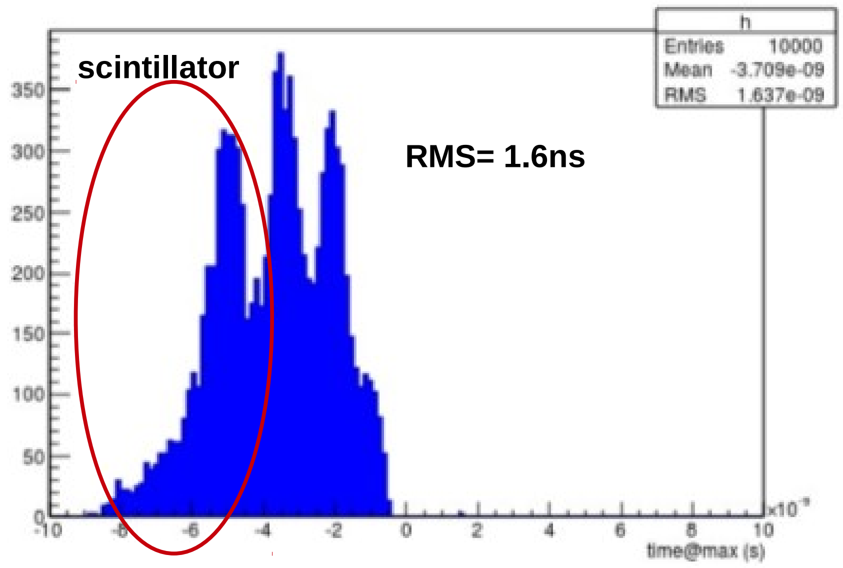
- Electronic sampling at 1 GSPS (Giga sample per second), each 1 ns
- Position of maximum in time should move with an RMS of less than 1 ns

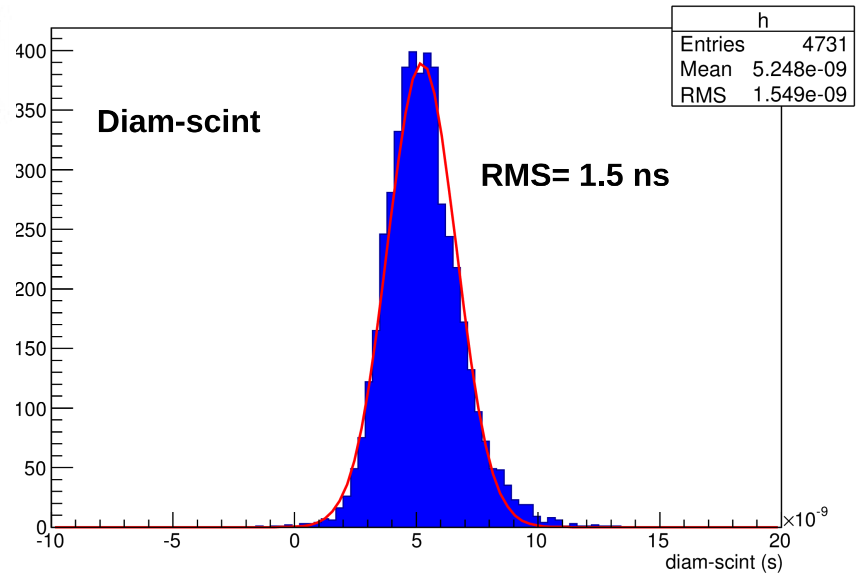




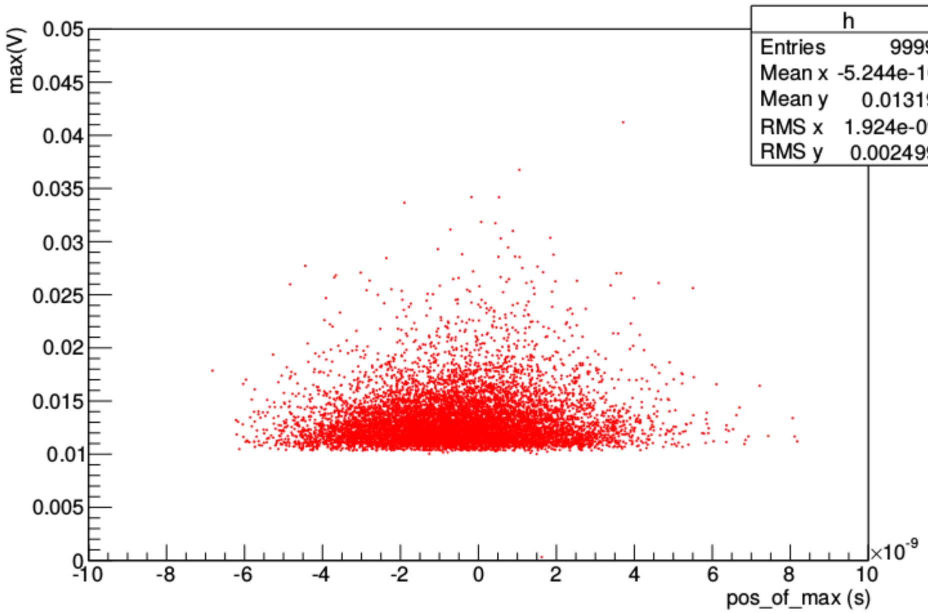
Position in time

- Subtract the positions in time of the maxima in the DS from those of one population in scintillator





- Verification of no correlation between the maximum and its position in time

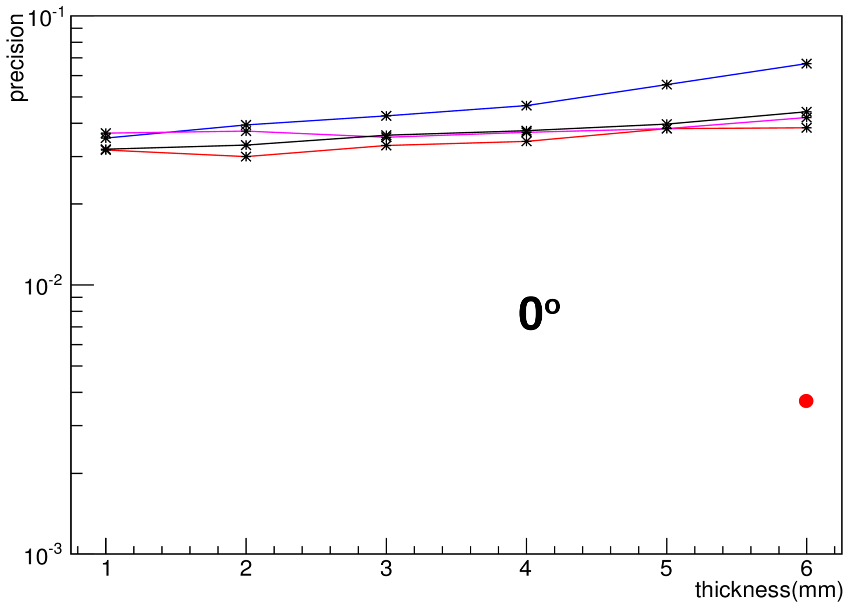


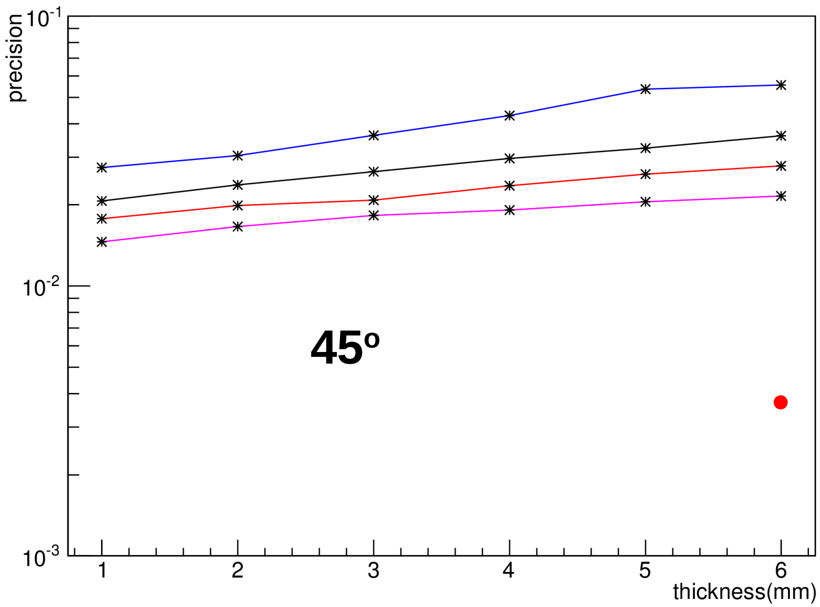
- **Landau distribution was successfully reconstructed for 140 μm and 500 μm diamond sensors**

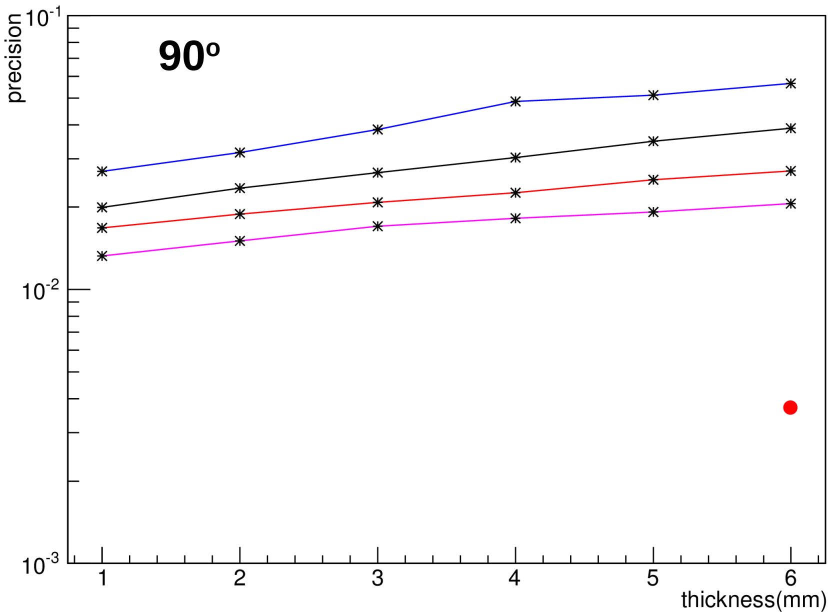
- **The position in time of the maximum of signal in the diamond sensor depends mainly on the trigger**

Material simulations

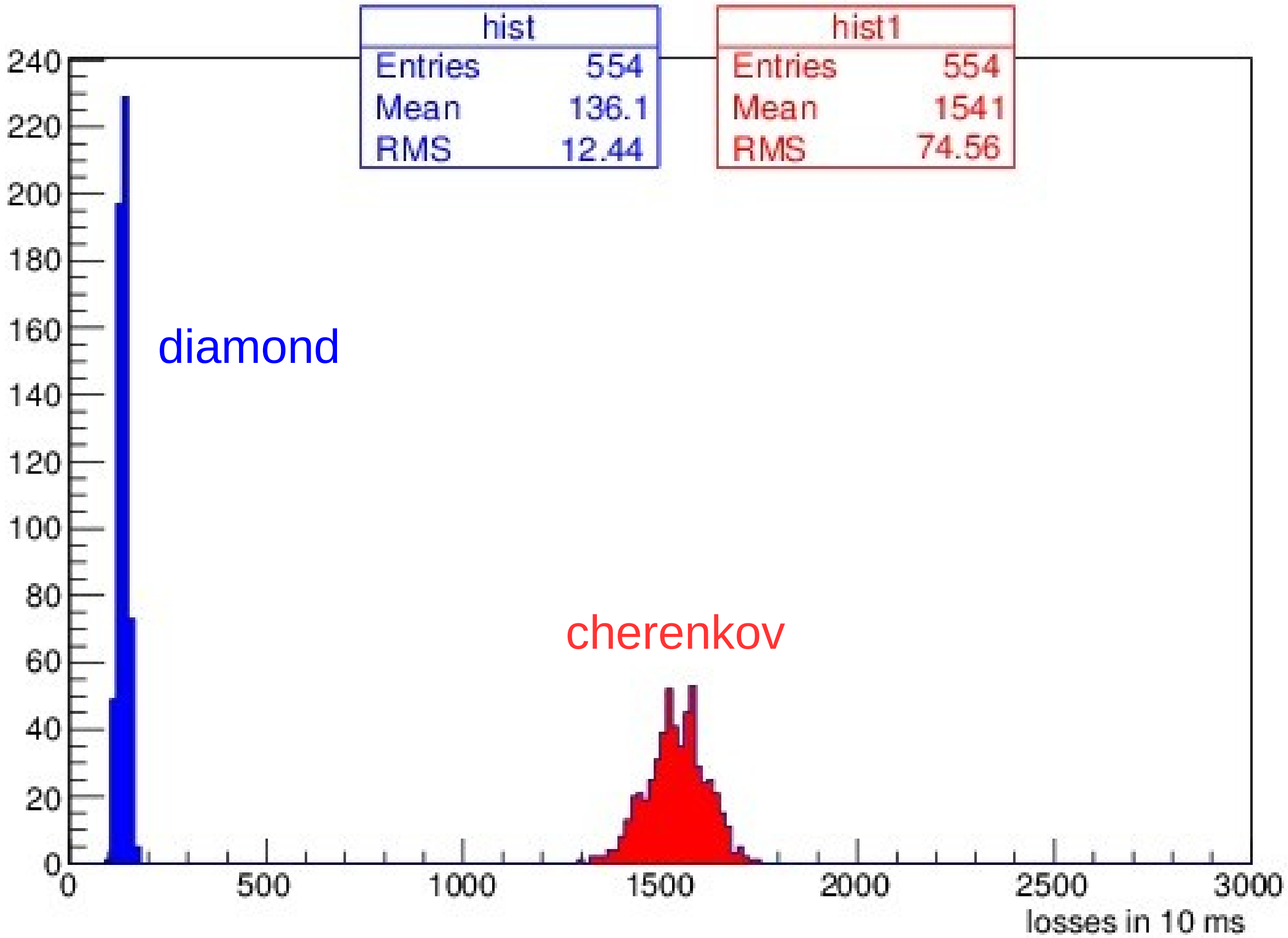
- Different beam pipe materials were considered beside **Cu** : Al, Be Ti
- Different material thicknesses of the beam pipe
- Different DS orientations
- The window gives the best precision
- Window (red dot) will be installed for phase 2 commissioning







Between Diamond and Cherenkov



→ Diamond 5 x 5 mm^2 and cherenkov 50x15x50 mm^3 → factor 30 in area

→ From measurement: factor 11 (< 30)

→ Distance of sensors from beam pipe and efficiency of chosen threshold of signal

Comparison of Parameters

Preliminary

	KEKB Design	KEKB Achieved (): with crab	SuperKEKB Nano-Beam Scheme	LHC
β_y^* (mm)(LER/HER)	10/10	6.5/5.9 (5.9/5.9)	0.24/0.37	550
ε_x (nm)	18/18	18(15)/24	2.8/2.0	0.5
σ_y(μm)	1.9	1.1	0.084/0.072	16
ξ_y	0.052	0.108/0.056 (0.101/0.096)	0.09/0.09	0.0034
σ_z (mm)	4	~ 7	5	75
I_{beam} (A)	2.6/1.1	1.8/1.45 (1.62/1.15)	3.6/2.1	0.6
$N_{bunches}$	5000	~1500	2119	2808
Luminosity (10^{34} cm^{-2} s^{-1})	1	1.76 (2.08)	80	1