Fast Luminosity Monitoring Using Diamond Sensors For The Super Luminous Flavor Factory SuperKEKB

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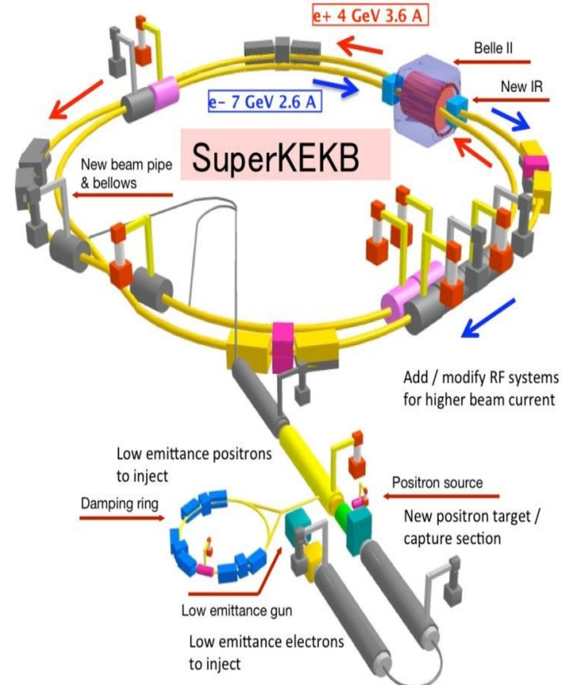
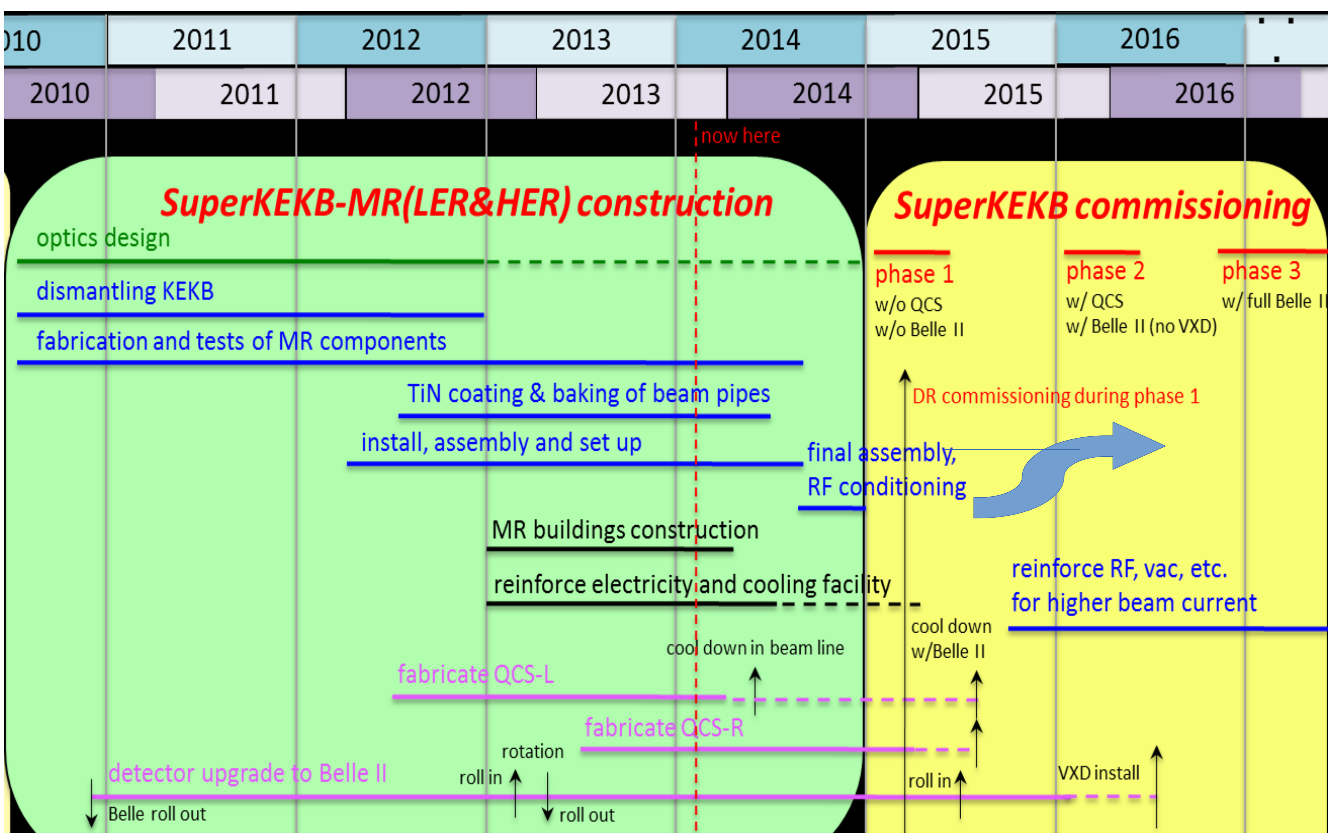
Outline

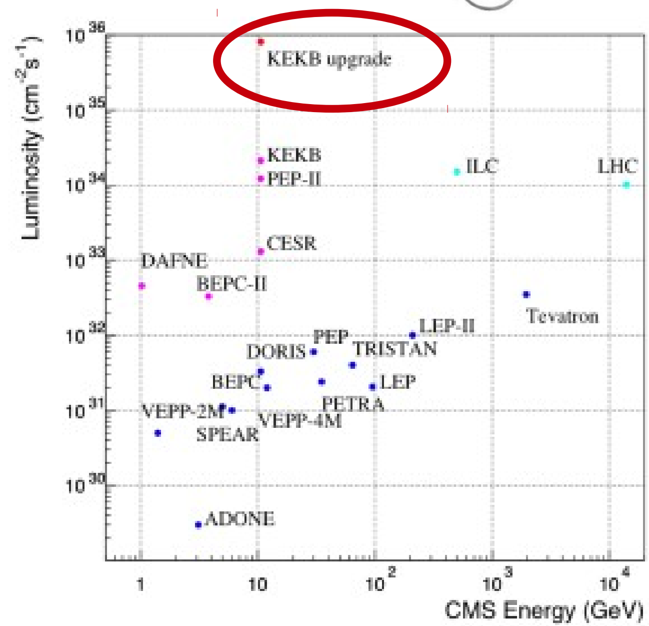
- SuperKEKB: Definition and Status
- Fast luminosity monitoring:
- ✓ Sensor location in LER
- ✓ Geometry of the vacuum chamber
- ✓ Geant4 simulations for Cherenkov and Scintillator detectors
- ✓ HER
- ✓ Simulation analysis of Backgrounds from single beam
- ✓ Primary tests on 140 μm diamond in the clean room @ LAL
- Readout and electronics
- Conclusion & Next Plans

SuperKEKB

- Belle II @ SuperKEKB: e^+e^- collider (e^+ @ 4 GeV (LER) & e^- @ 7 GeV (HER))
- High Luminosity (8 10^{35} cm^{-2} s^{-1})
  - ➔ Nano-beam scheme, very small beam sizes (60 nm)
  - ➔ High currents (beams collide @ 0.25 GHz)

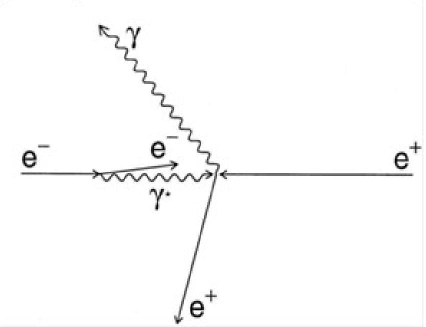






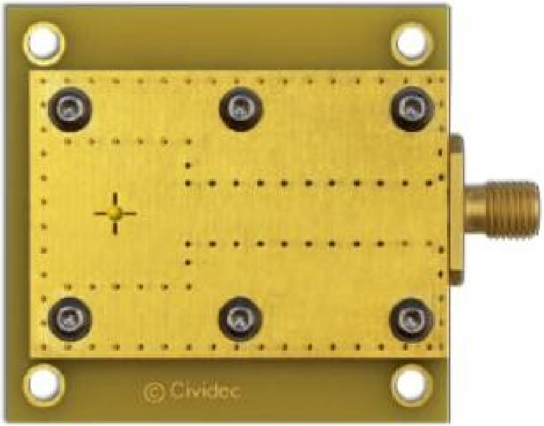
Fast Luminosity Monitoring

- Fast luminosity monitoring is required in the presence of dynamical imperfections, for feedback and optimization.
- Precision $\delta\mathcal{L}/\mathcal{L} = 10^{-3}$ in 1ms
- Lumi monitoring for each bunch crossing: 2500 bunches, collide each 4 ns
- Measurement: Radiative Bhabha process at zero photon scattering angle , Large cross-section ~ 0.2 barn
- Technologies: Sensors set immediately outside beam pipe



- 5x5 mm^2 diamond sensors (Radiation hardness, Fast charge collection)

-Scintillator + Cherenkov detector

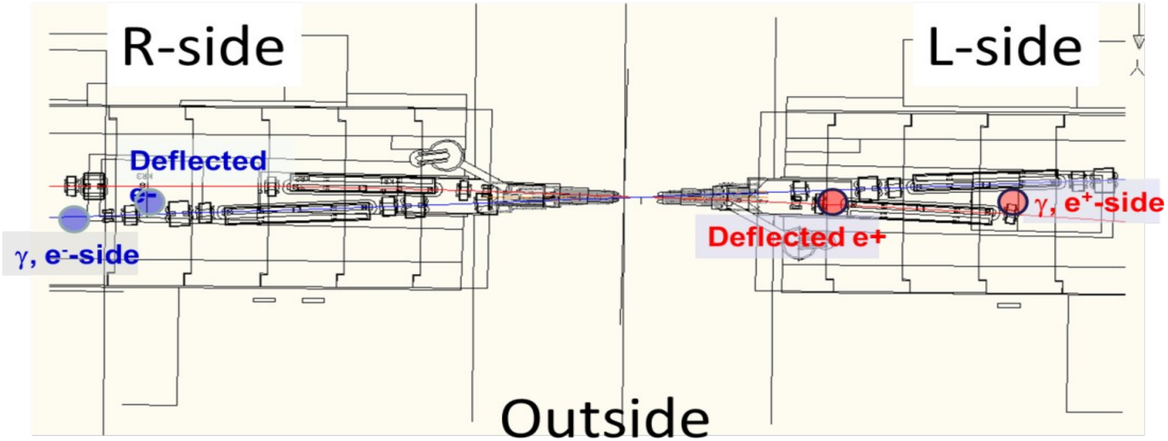


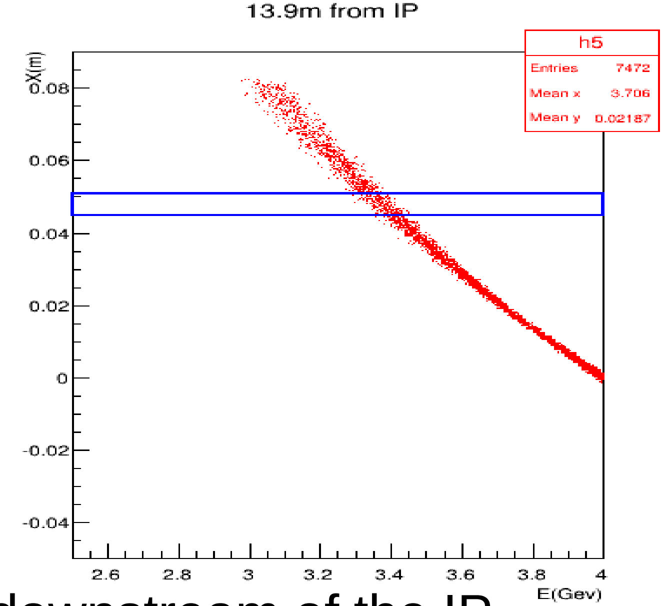
LAL group

ZDLM group at KEK, S.Uehara San

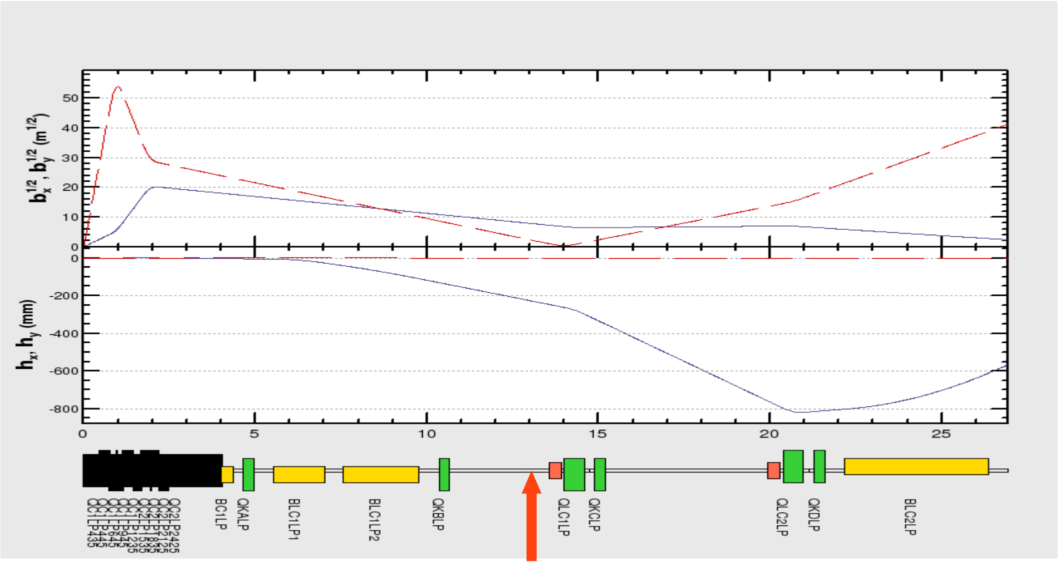
Sensor Location in LER

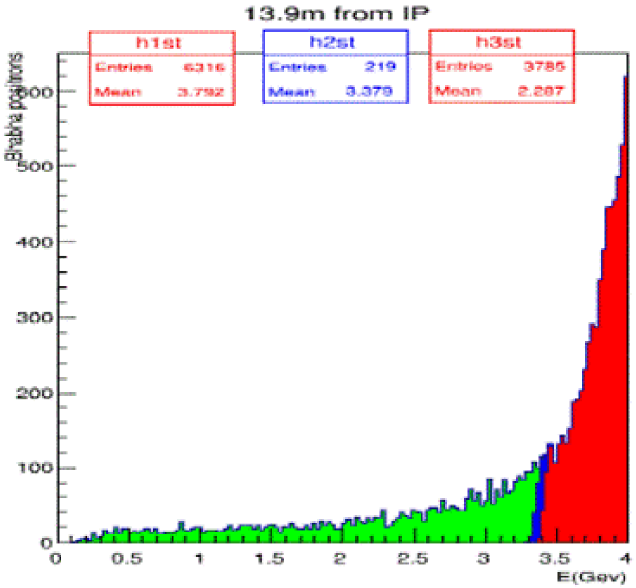
- Bhabha dynamics have been generated by GUINEA-PIG++





- Low energy e+/e- will be deflected mainly in bends downstream of the IP
- Exiting Bhabha rates are studied using SAD tracking code





Sensor Location in LER

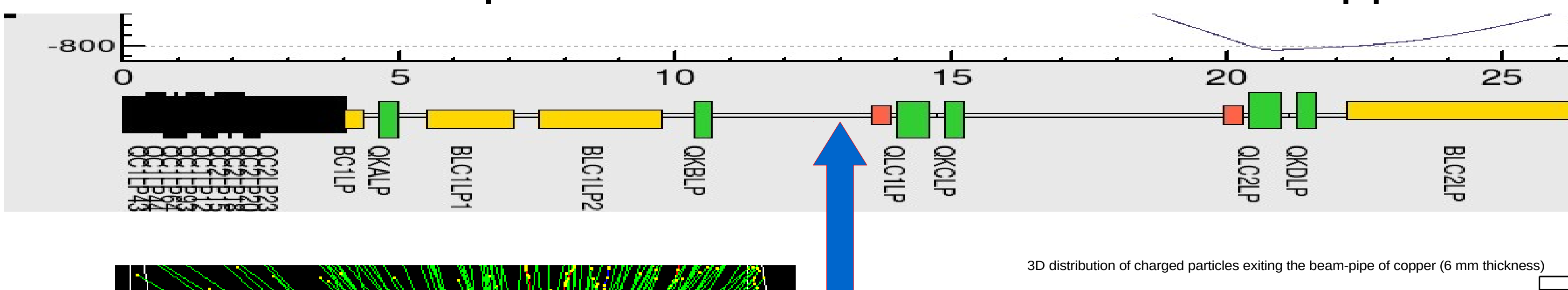
- To reach the aimed precisions, the following counting rates are required:

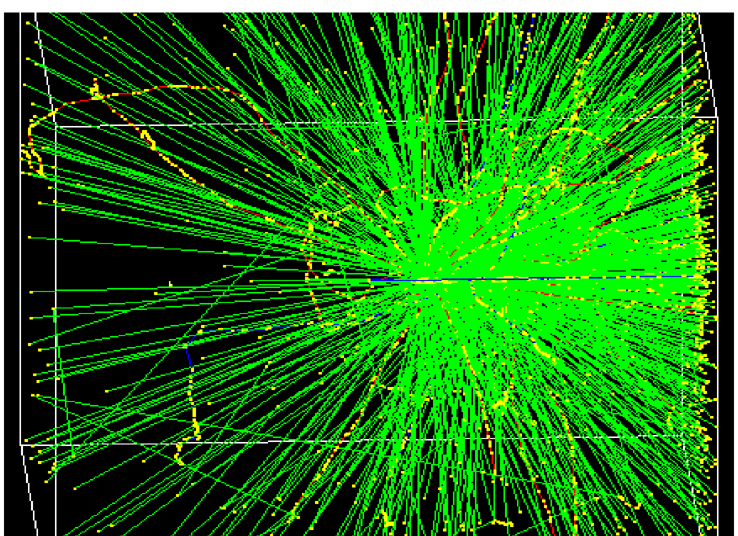
Luminosity ($cm^{-2} s^{-1}$)	Aimed precision (in 1 ms)	Required fraction
10^{34}	10^{-2}	2.1×10^{-3}
$8\ 10^{35}$	10^{-3}	2.6×10^{-3}

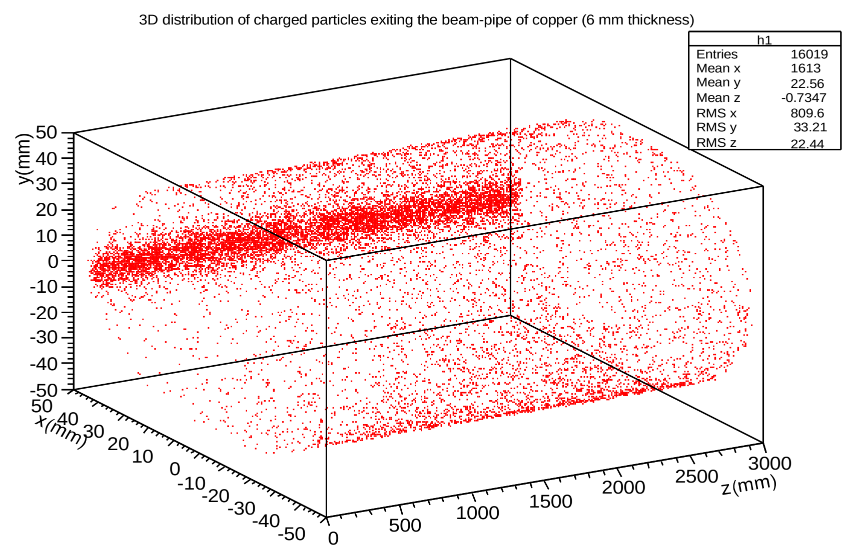
- The best candidate position is chosen to be at 13.9 meters from the IP:

✓ 3 meters drift , adequate to place our sensors

✓ 4.7% of Bhabha positrons will exit the 6 mm thick copper beam-pipe

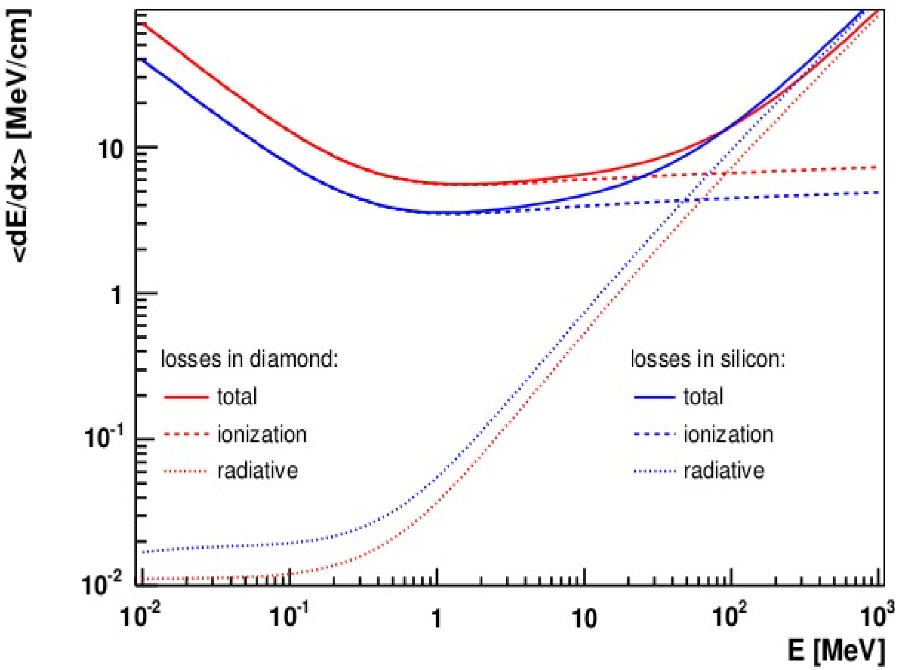




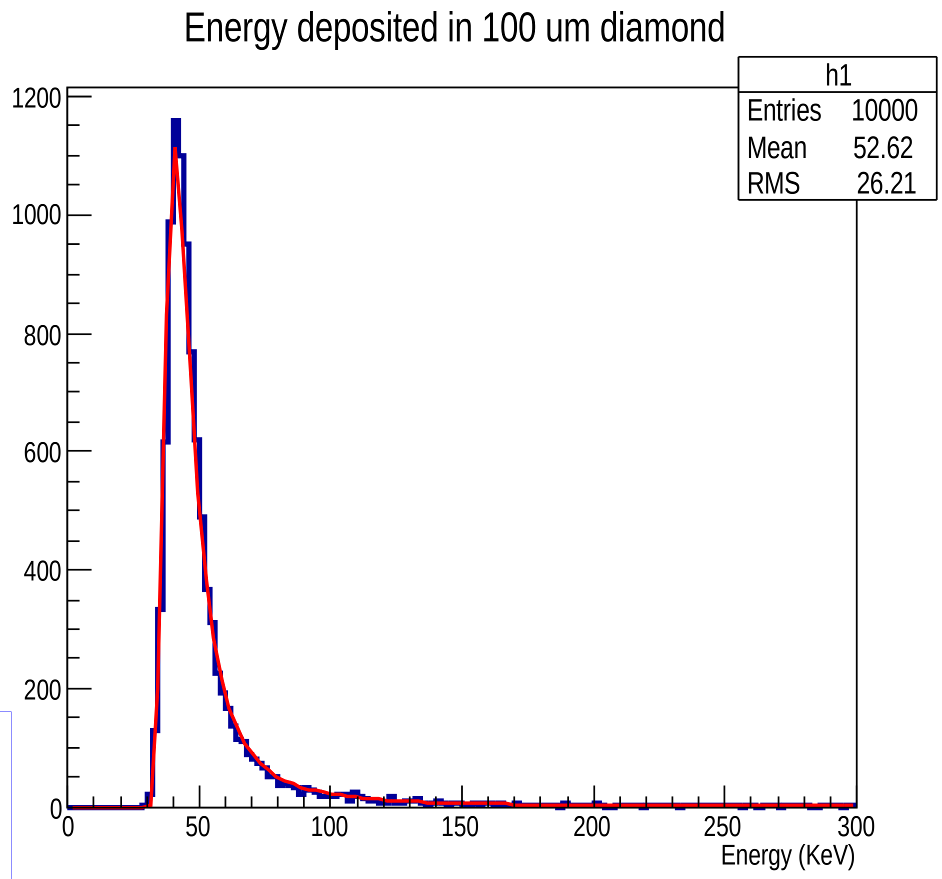


Energy Deposition of e+/e- in a 100um Diamond

- Charged particles like e^+ and e^- will deposit energy in the diamond sensor according to a "Landau" distribution

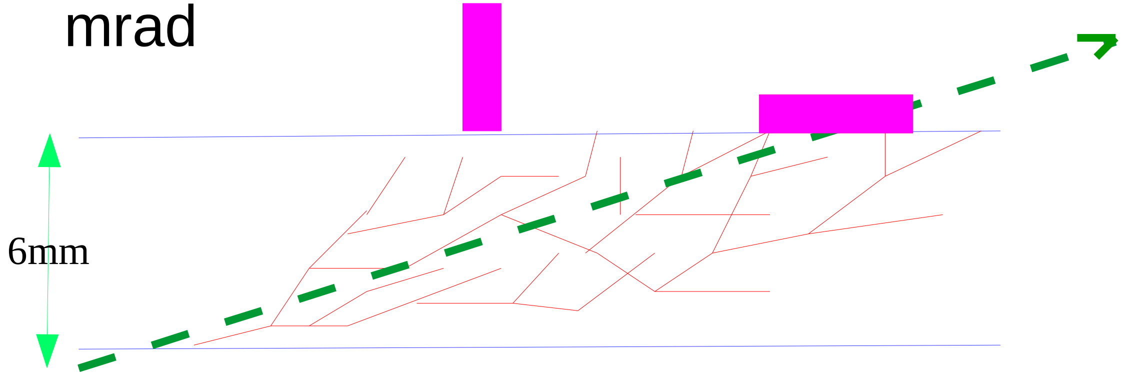


The mean energy losses of an electron in diamond (red curves) and silicon (blue curves)



Geometry of Vacuum Chamber

- Bhabha positrons escape the beam pipe at an average angle of 5 mrad

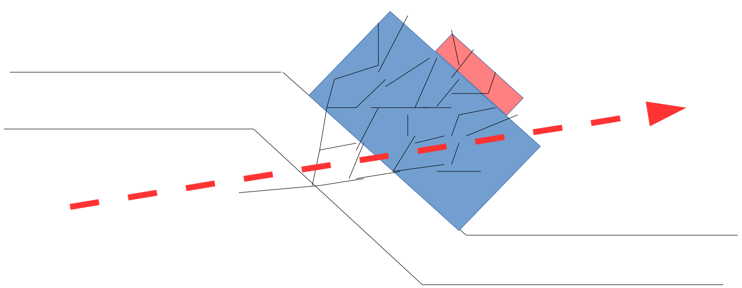


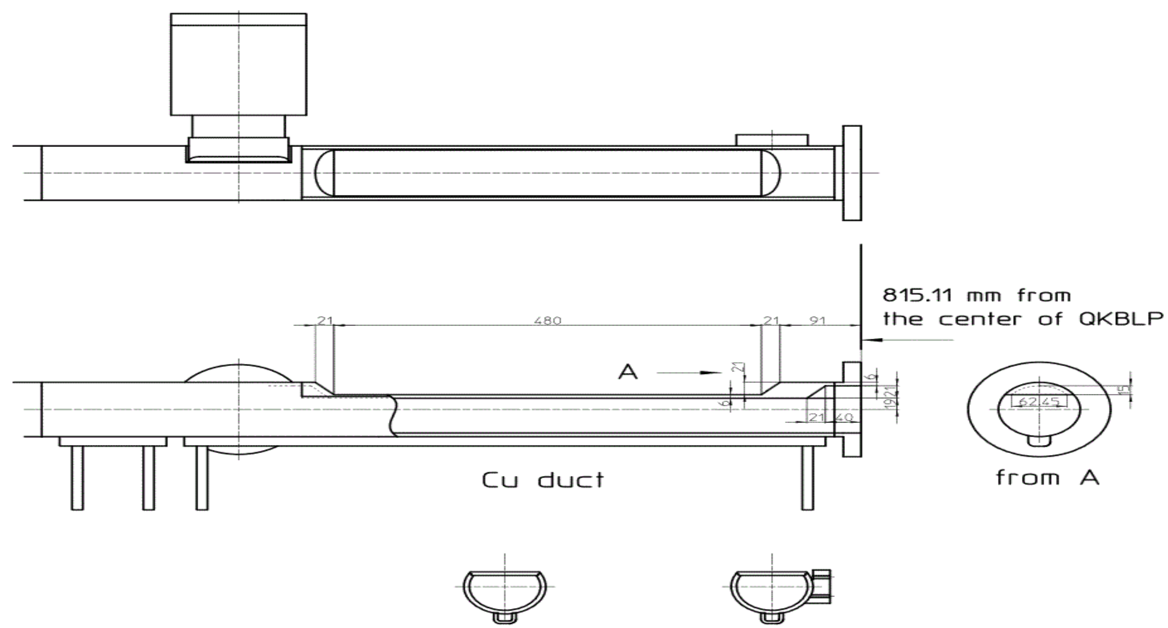
- The particle will cross 1.2 meters in the copper ~ 80 radiation lengths

Signal just from the lateral extent of the shower (R_M= 1.568 cm)

- Modification of the beam pipe is suggested to increase the probability of having exiting showers

A window at 45 degrees is suggested



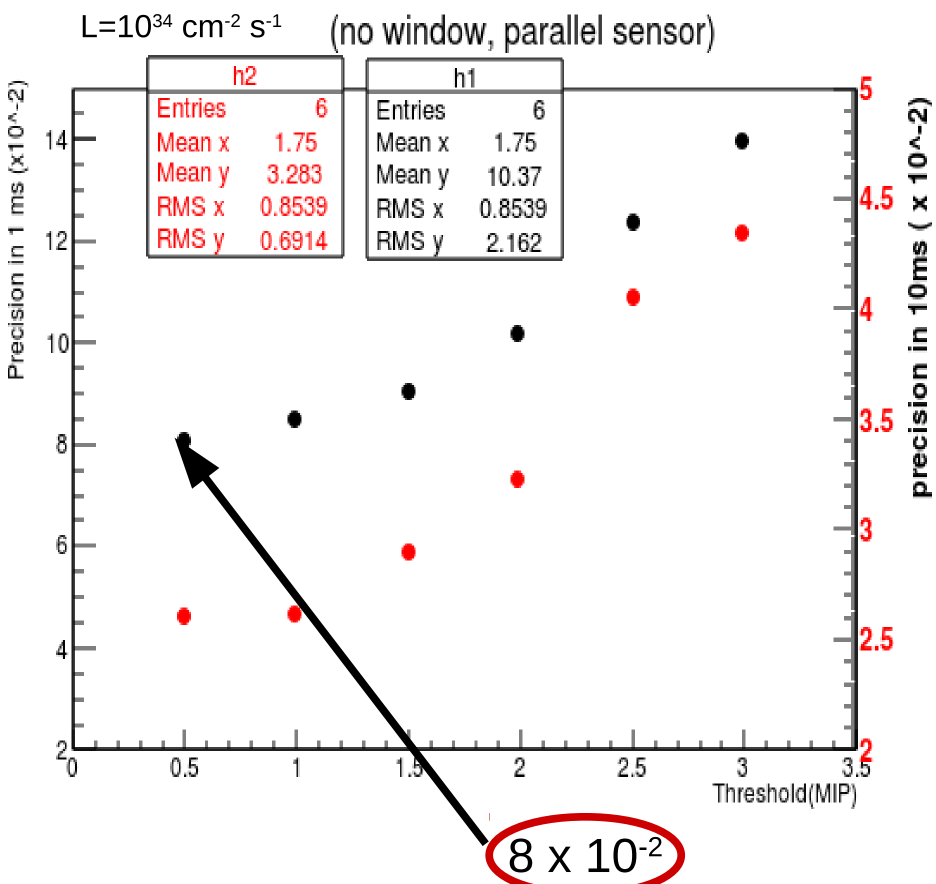


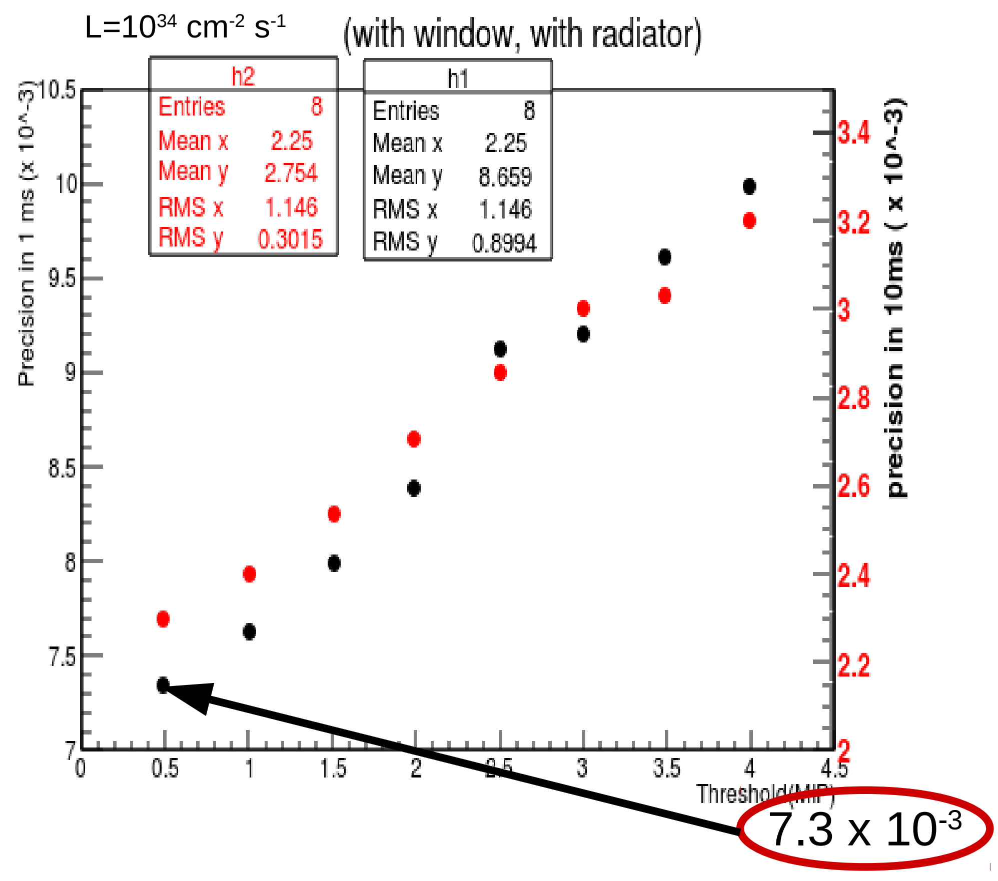
A Summary Table of collected secondaries

	Luminosity ($cm^{-1}s^{-1}$)	Required Precision in 1 ms (Nb of particles)	Number of particles collected in 1 ms
No window	10^{34}	10^{-2} (> 10^4 part)	$1.4\ 10^2$
No window	$8\ 10^{35}$	10^{-3} (> 10^6 part)	$1.3\ 10^4$
Window	10^{34}	10^{-2} (> 10^4 part)	$4.4\ 10^3$
Window	$8\ 10^{35}$	10^{-3} (> 10^6 part)	$3.5\ 10^5$
Window+Radiator	10^{34}	10^{-2} (> 10^4 part)	$1.5\ 10^4$
Window+Radiator	$8\ 10^{35}$	10^{-3} (> 10^6 part)	$1.2\ 10^6$

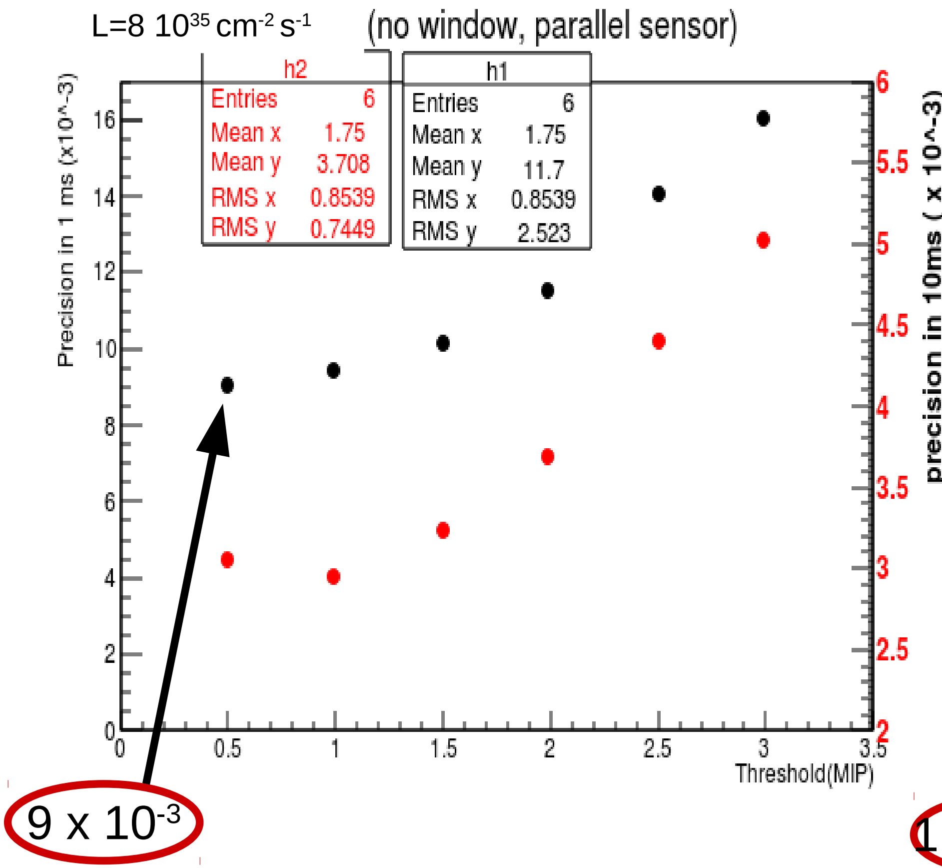
GEANT4 Simulation Results

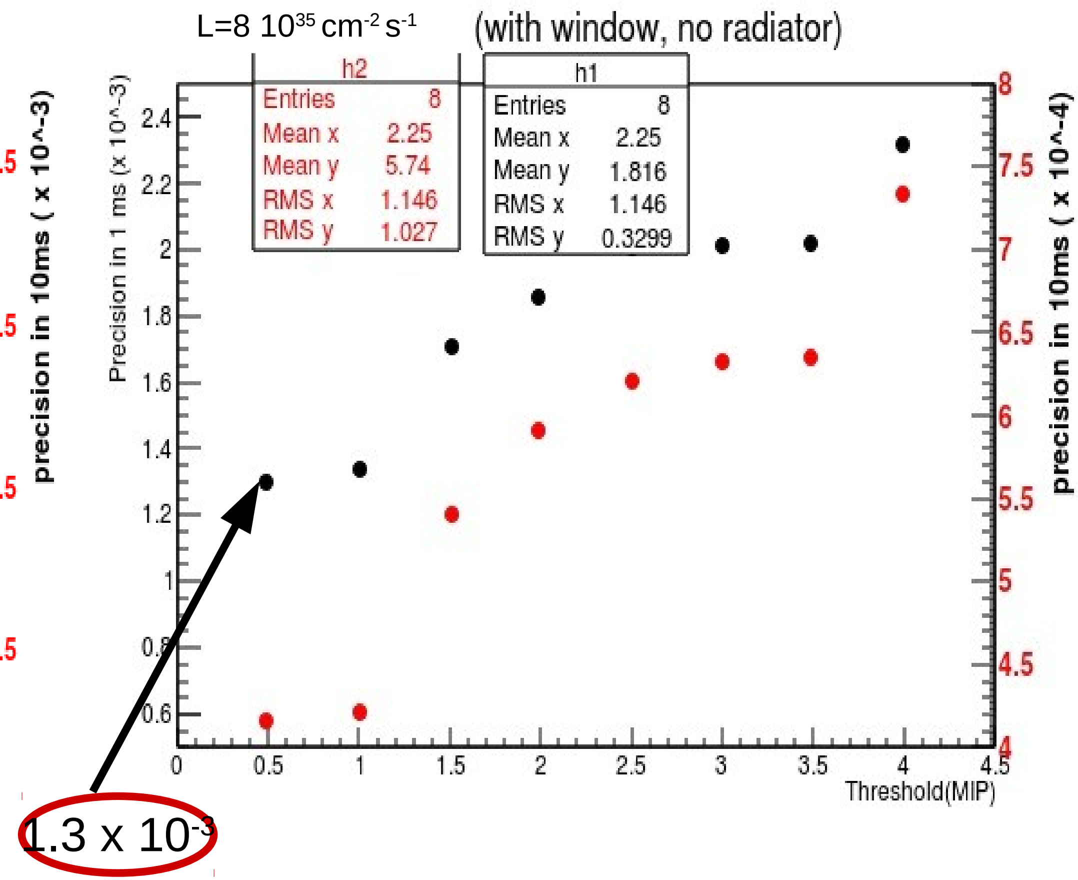
- Geant4 simulations were performed, considering the material and the beam pipe geometry, to estimate the actual signals in the sensors
- Precision= 1/sqrt(N), where N is the number of incident particles in a given interval of time with signals in the diamond
- N= 4.7 % x $\mathcal{L}$ x σ x ($N_{diamond}$ / $N_{exiting}$) ; $\mathcal{L}$ = Luminosity , σ = cross-section, $N_{diamond}$= number of incident particles in the diamond per b.c , $N_{exiting}$= total number of exiting particles over 3 m
- Threshold represents the energy deposited in the diamond per incident particle, 0.5 MIP= 26 KeV
- For L= 10^{34} cm^{-2} s^{-1}, the window improves the precision by a factor of 10 (100μm diamond)





At Nominal Luminosity L= 8 10^{35} cm^{-2}



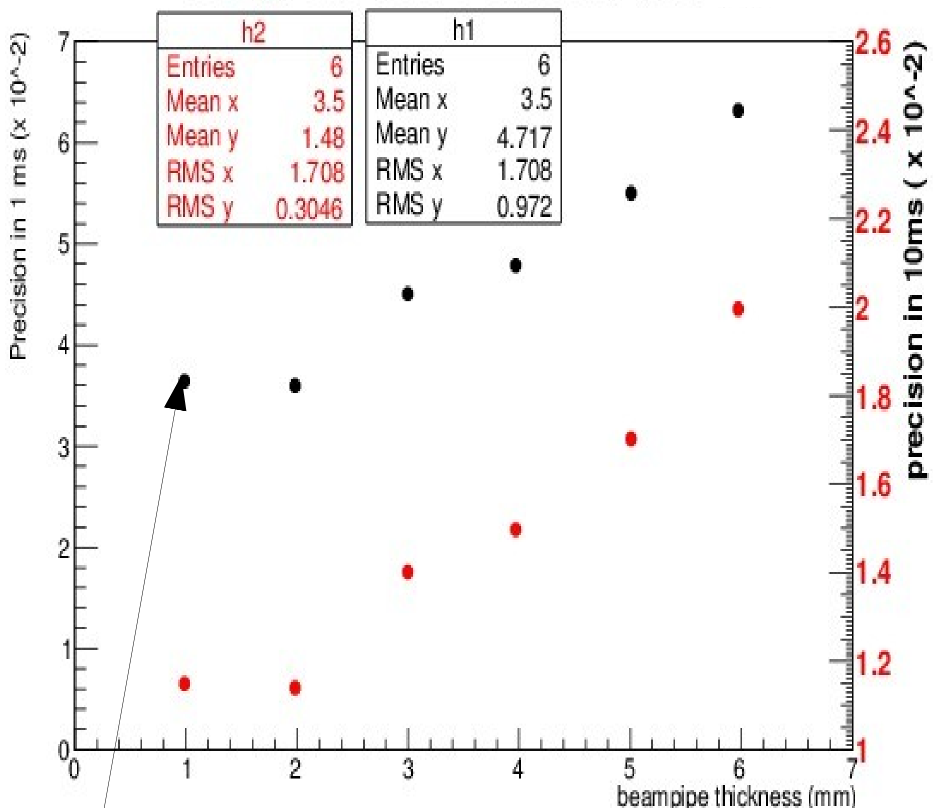


- Presence of a window at 45 degrees improves the precision by a factor of 7 , thus a window is necessary to attain the specified precision
- Such a window may cause the impedance of the beam pipe thus introducing wakefields and thus beam instabilities ..

A Thinner Beam Pipe??

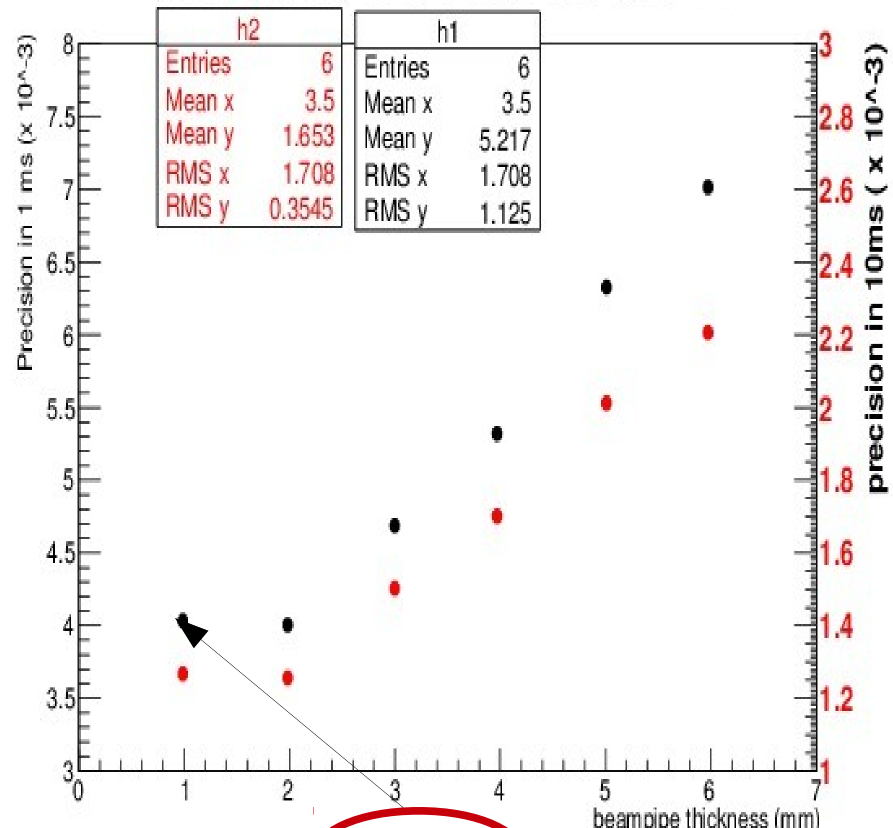
- Simulations of a thinner copper beam pipe was done by Geant4 (500 µm diamond)

Precision as a function of the thickness of the beam pipe for $L=10^{34}$ cm^{-2} s^{-1}



3.5 10^{-2}

Precision as a function of the thickness of the beam pipe for $L=8\ 10^{35}$ cm^{-2} s^{-1}

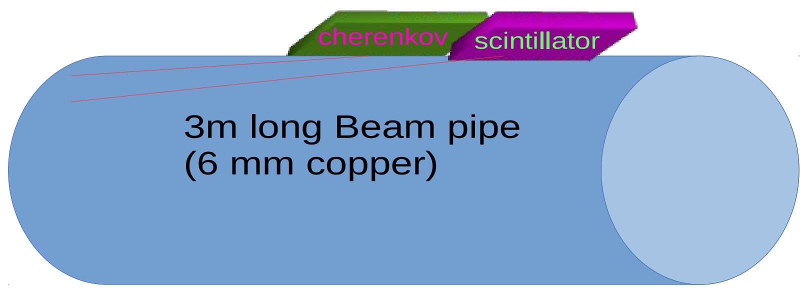


4 10^{-3}

- A thinner beam pipe improves the precision by a factor of 2 BUT the aimed precision not reached yet
- Other materials (Be, Ti, Al) could give better precisions ????!!!   ==> To be simulated and defined

Preliminary Results on Cherenkov And Scintillator Detectors

- 15 mm x 15 mm x 50 mm
- Charged particles of path length λ >15 mm are considered
- Cherenkov : Pure Quartz SiO_2 , density= 2.7 g/cm^3
- Scintillator: LGSO : $Lu_{1.8}Gd_{0.2}SiO_5$, density= 7.3 g/cm^3



- Detectors are simulated in two manners

  1) Independently (events in each detector separately)

  2) In coincidence (Poisson distribution)

Preliminary Results

Independently

Luminosity ($cm^{-2} s^{-1}$)	Precision in 1 ms	Precision in 10 ms
10^{34}	2×10^{-2}	6.5×10^{-3}
10^{35}	6.5×10^{-3}	2.04×10^{-3}

In coincidence

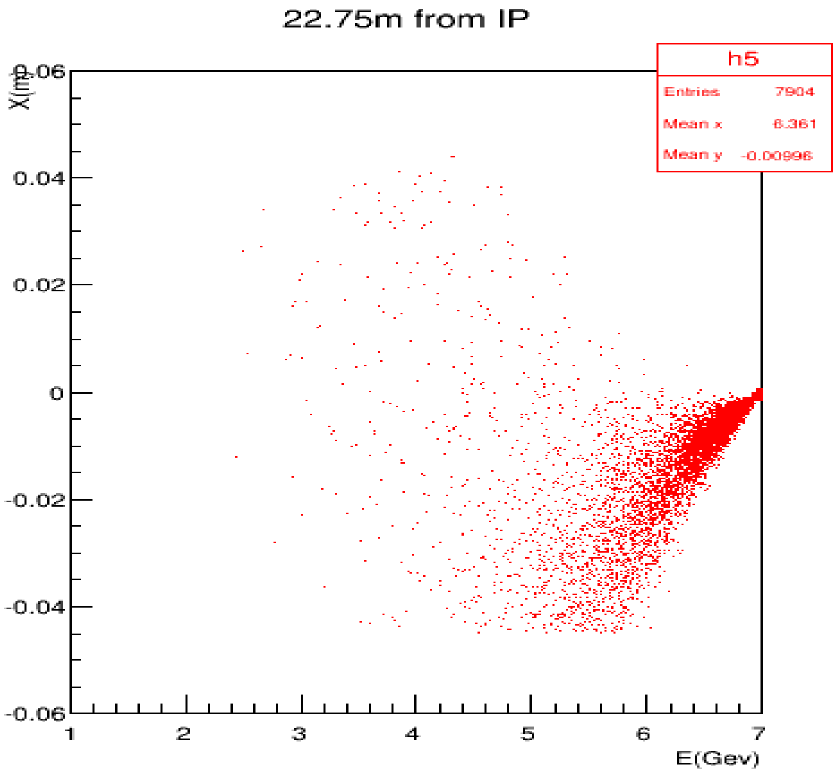
Luminosity ($cm^{-2} s^{-1}$)	Precision in 1 ms	Precision in 10 ms
10^{34}	0.2	6.3×10^{-2}
10^{35}	2.2×10^{-2}	6.9×10^{-3}

→ Precisions are 4 times better than the case of 5x5 mm^2 diamond for independent detectors

→ Precisions are 2.5 times worse than the case of 5x5 mm^2 diamond for coincidence case

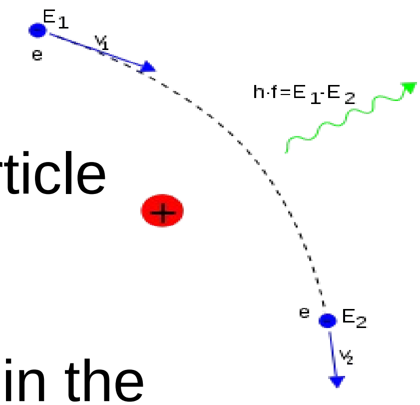
Study Of HER

- Unlike LER, the HER showed non-linear distributions in the x-E plane, mainly due to chromaticity corrections, in addition to very low Bhabha rates
- No candidate place for our sensor is yet considered
- Search for a candidate places was started again with an internship student … but results are yet preliminary and no good candidates for the moment ….



Preliminary Analysis of Backgrounds From Single Beam Losses

- How much is the drift at 13.9 m contaminated by single beam losses??
- Backgrounds considered are :



1) Nuclear Bremsstrahlung: Deceleration of a charged particle

in the field of an atomic nucleus

2) Touschek effect: Coulomb scattering between particles in the

same bunch, resulting in energy transfer from the transverse plane to the longitudinal plane due to relativistic effects, and thus the loss of the particles ..

3) Coulomb scattering: scattering of the bunch particles on the atomic electrons . (Similar as Touschek)

Table of comparison

- Developing collaboration with Ohnishi san on background simulation and analysis
- Preliminary analysis of the files was done in the 3 meters drift , at the diamond position

Process	Bremsstrahlung	Touschek	Coulomb	Bhabha@phase2
N (PPS)	1.815×10^5	1.44×10^5	4.6×10^5	14.1×10^6

- $N_{\text{total backgrounds}} = 7.855 \times 10^5$ (PPS) < losses from Bhabha
- For $L=10^{34}$ cm^{-2} s^{-1} @phase2, vacuum is much better and thus backgrounds from Bremsstrahlung and Coulomb are less ..
- Geant4 simulations should be considered as well to study the signal of the backgrounds in the sensors ..

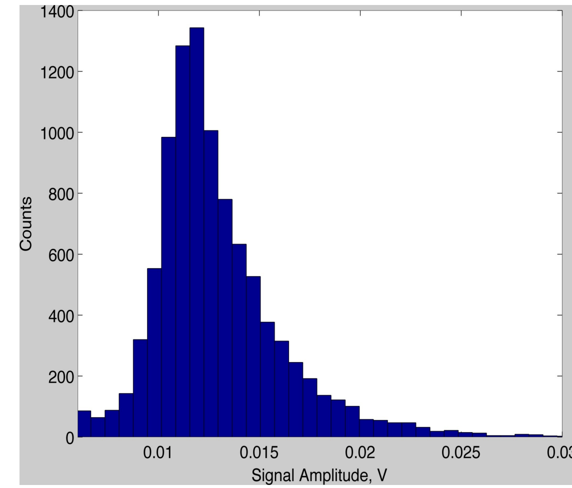
Diamond Sensors

- Diamond sensor technology already exists at LAL since 2012 for Beam-halo study at ATF2 (prototype of ILC final focus)
- For SuperKEKB @ L= 8 x 10^{35} cm^{-2} s^{-1} : signal width <1-2 ns,

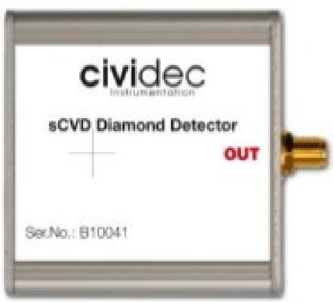
  since bunch spacing is 4 ns
- Charge amplifier : $\sigma = 10$ ns (shaping time)

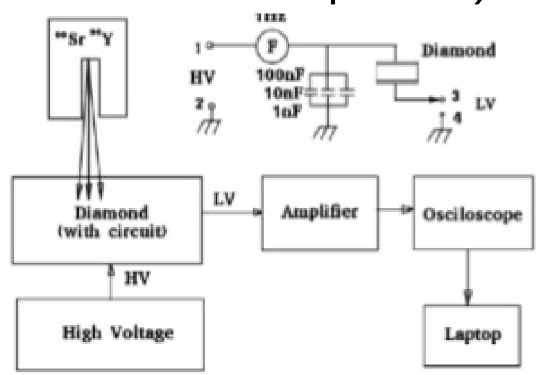
  → enough for phase 2 (L=10^{34} cm^{-2} s^{-1})

  (average signal rate < 1 Bhabha per b.c)



ATF2 Group at LAL (500µm diamond)





Characteristics of the cividec charge amplifier

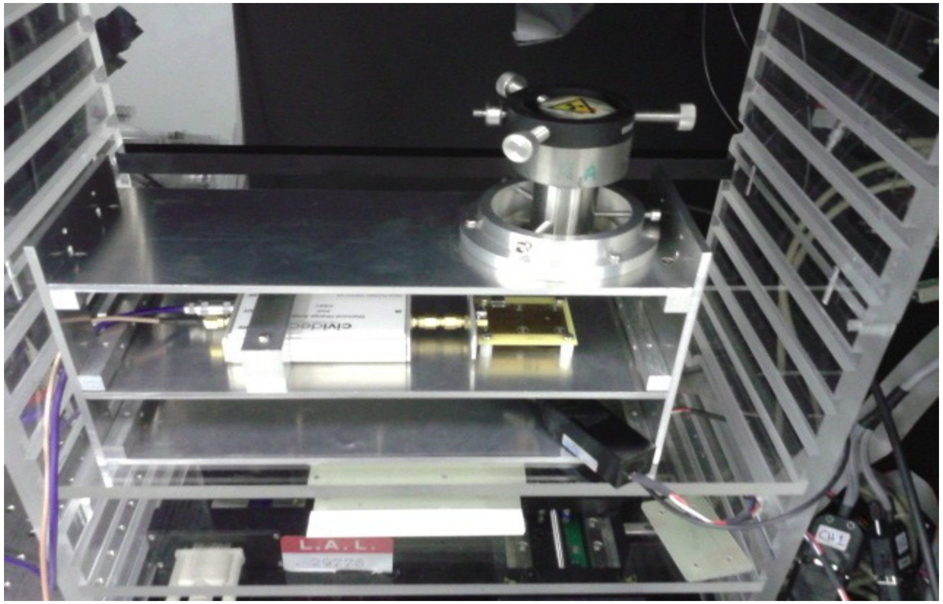
Type:	Charge amplifier
Input coupling:	AC coupled
Input protection:	IEC61000-4-2 (±8 kV, 2 A for 1 µs)
Input polarity:	Negative, unipolar
Output polarity:	Inverting, positive
Linear output voltage:	+1 V
Output impedance:	50 Ω
Impulse response:	
Pulse shape:	Gaussian
Rise time:	3.5 ns
Pulse width at FHWM:	10 ns
Performance (4.3 pF load):	
ENC noise:	1000 electrons
Gain:	4 mV/fC
SNR:	6/fC

Geometry	No window	Window	Window + Radiator	No window	Window	Window + Radiator
N^0 of Bhabha particles per b.c	0.00056	0.0176	0.06	0.052	1.4	4.8
	L = 10^{34} cm^{-2} s^{-1}			L = 8 10^{35} cm^{-2} s^{-1}		

Diamond sensor tests in the clean room at LAL

Landau reconstruction of the MIP(s) of the new 140 μm diamond (cividec):

- Beta source ^{90}Sr
- Charge amplifier (signal width ~ 10 ns)
- Scintillator (Trigger)
- High voltage
- Oscilloscope

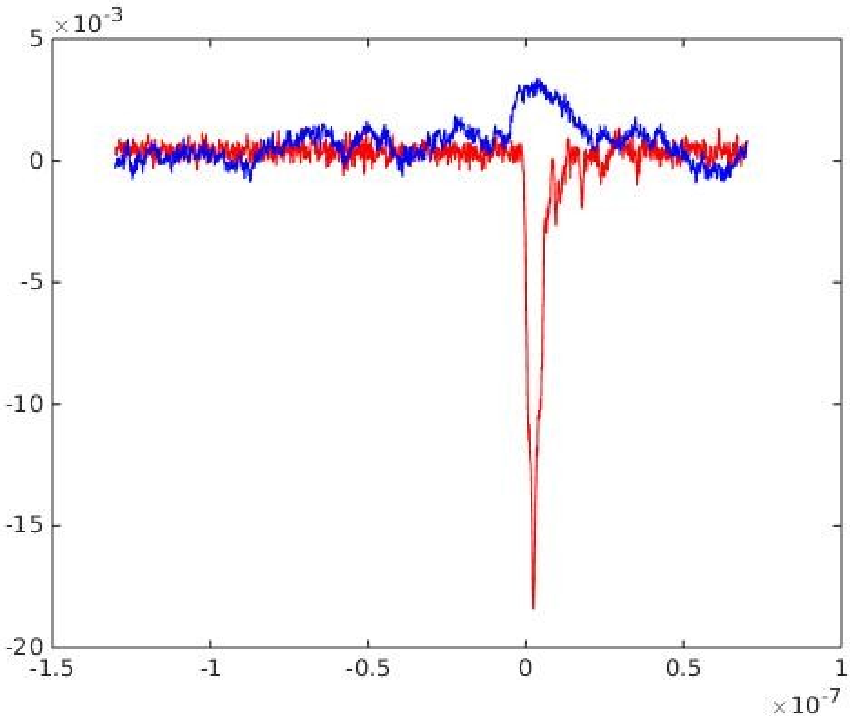


Experimental setup @ clean room @ LAL

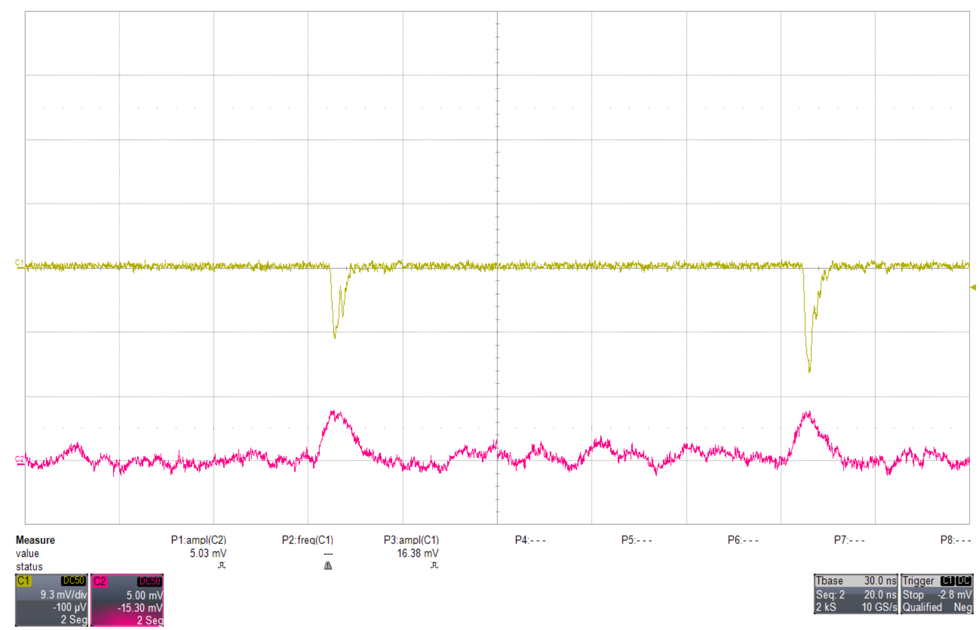
Charge amplifier

- High voltage applied : V = -100 Volts
- In a diamond, 1 MIP creates 36 e-/h pairs per µm
- For 140 µm diamond , the charge produced per 1 MIP is :

  Q~0.8 fC
- Gain of charge amplifier is G= 4 mV/fC ==> 1 MIP = 3.2 mV

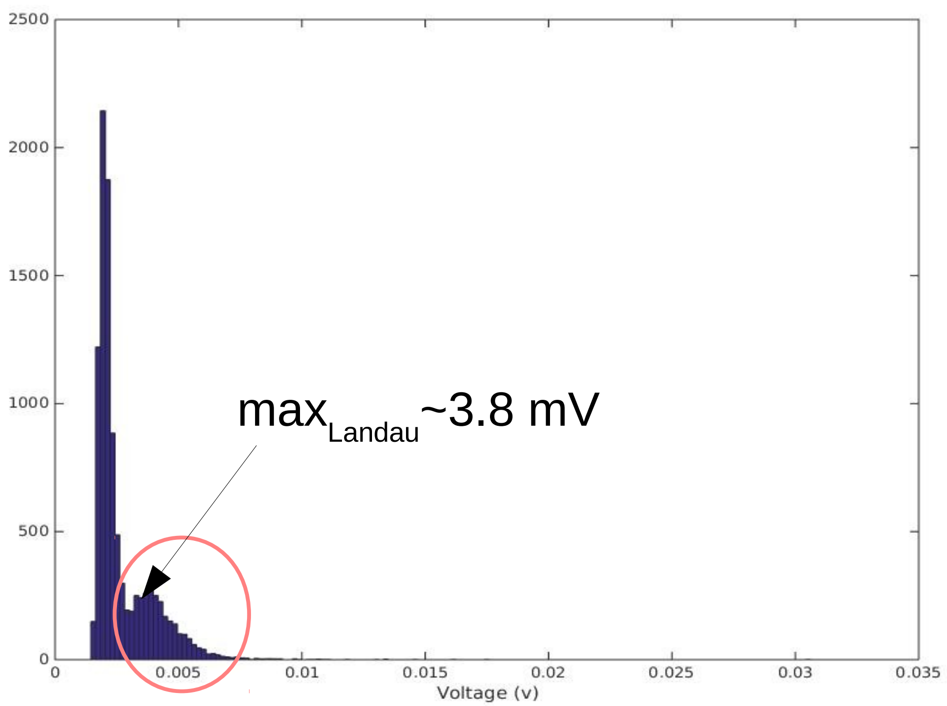


Blue signal (diamond) , Red signal (scintillator)

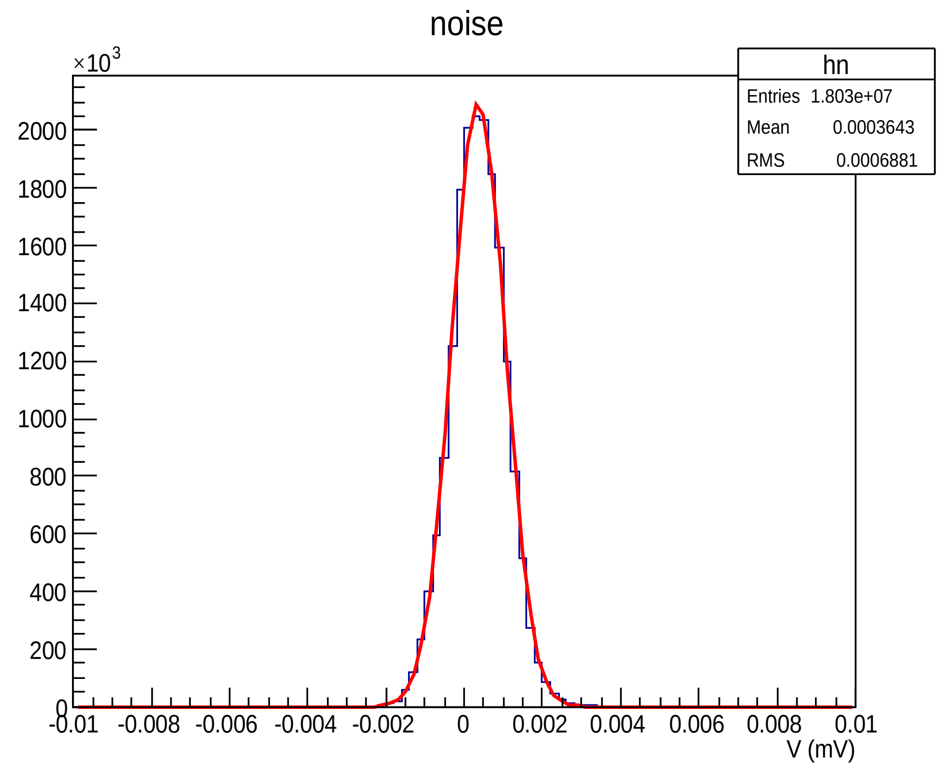


Screen shot from the oscilloscope: signal from scintillator , signal from diamond

Preliminary Data Analysis



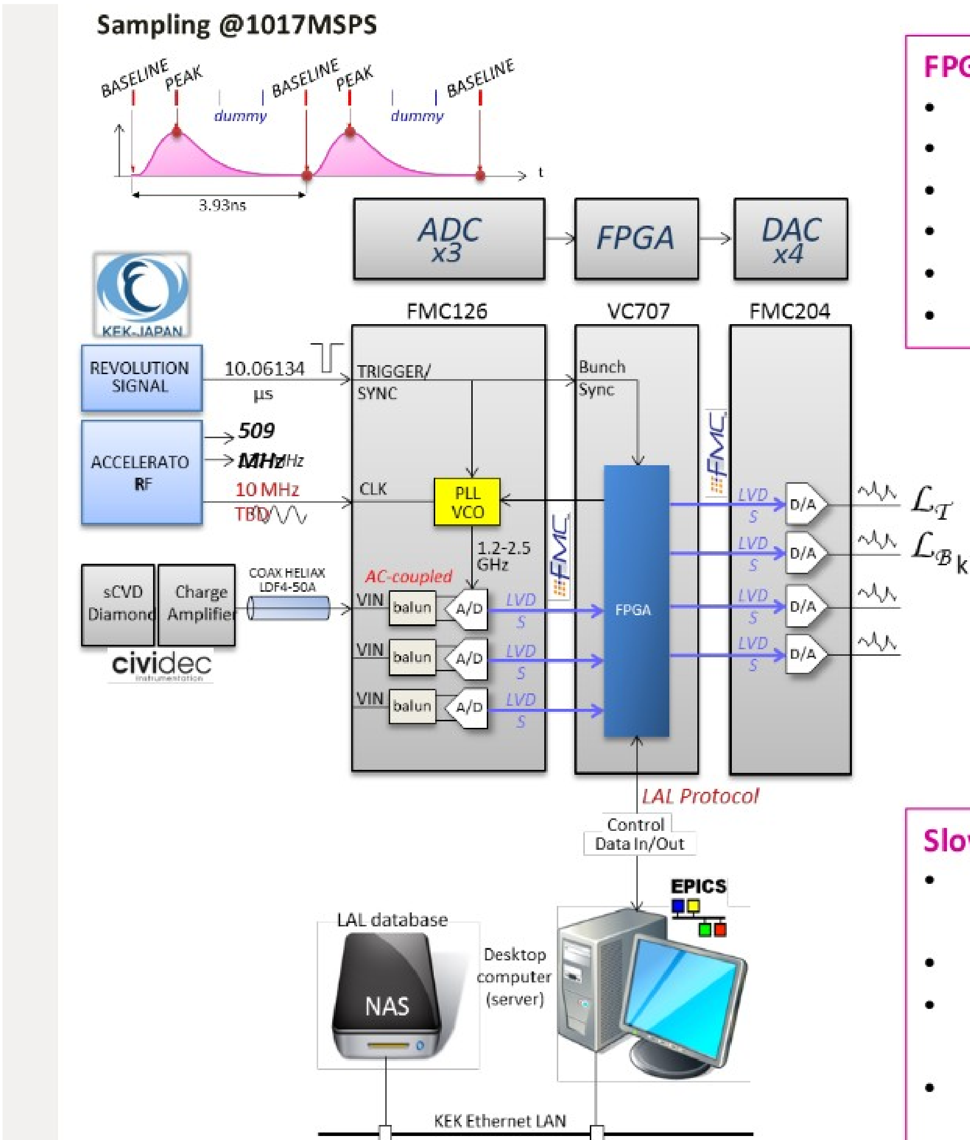
Histogram of maximum of signals in the diamond



Gaussian fit of the noise from the amplifier

- 1 MIP creates a 5040 e^-/h pairs ~ 3.2 mV
- Noise from the amplifier is 1000 electrons = 0.16 fC= 0.64 mV
- For a 140 µm diamond, noise is not well separated from the signal ..
- For a 500 µm diamond, 1 MIP creates an 18000 e^-/h pairs ~11.5 mV , thus signal and noise are well separated ...

Readout (Didier's Presentation)



FPGA-based digital acquisition

- Synchronized to acc. RF Clock @ 10MHz
- Sampling every 1ns
- Phase adjustment by the ADC board
- Peak value acquisition : determines Bhabha events nb
- 2015 : signal FWHM 10ns (140µm diamond thickness)
- 2016 : signal FWHM ~2ns (100µm diamond thickness)

Outputs

- Train Integrated Luminosity over 1ms
- Bunch Integrated Lumi over 1ms : 2500 values @254 MHz

Slow Control / Interface

- Sampling controlled by local Linux machine (LM) connected to FPGA board
- TIL and BIL directly computed by FPGA and read by LM
- EPICS protocol installed on LM and provides TIL + BIL to EPICS users in real time (1ms)
- DAQ also comes with 4 Analog outputs
  Controlled by EPICS users
  Used for tests, debug and orbit feedback

Conclusions & Next Plans

- Fast Luminosity monitoring is very important for a feedback system and for optimization
- Optimal position of the sensor is to be at 13.9 meters from the IP in the LER …. For the HER, candidate places are not yet found ...
- Simulations in Geant4 considering different geometries (normal beam pipe, window (radiator), thin beam pipe) were established … Further simulations to be done to define the best material of the beam pipe (by April 2015)
- Fast readout and electronics are always under development to be able to monitor bunch by bunch luminosity
- Primary tests and data analysis on the 140 μm diamond sensor were performed using a β source in the clean room @LAL …. Further characterization tests will take place in the coming weeks
- Preliminary simulation analysis of backgrounds from single beam losses is done … Further analysis will be considered and new simulation of the backgrounds will take place using SAD by the end of the coming month
- Installation of the whole set-up will take place at KEK with the start of single beam commissioning at the end of 2015

THANK YOU !!!

Backgrounds vs Bhabha

- Simulations of backgrounds (Bremsstrahlung, Touschek and Coulomb) were performed by Ohnishi san using SAD for phase 1 (one beam run commissioning)
- Data files are as follows :

  $s_{scatter}$ s_{loss} x_{pos} x_{ang} y_{pos} y_{ang} dp/p_0 rate turn L_{obs} $l_c = L_{scatt}/L_{circ}$ p_1 p_2

- $I = 1A$ ($n_b = 1000$)
- In the given data files, we have:
  - $N_B = 14107$ macro p. , $N_T = 20274$ macro p. , $N_C = 14846$ macro p.

Table of comparison

Process	Bremsstrahlung	Touschek	Coulomb	Bhabha
N (PPS)	1.815×10^5	1.44×10^5	4.6×10^5	14.1×10^6

- $N_{total\ backgrounds} = 7.855 \times 10^5$ (PPS)
- Rates are added in the drift (between 10.7 m and 14 m)

  Sum= $(\text{rate} \times l_c)/L_{obs}$

  N(PPS) = Sum x 1000 x (N_m / N_T) , N_m = number of macro particles lost in the drift , N_T = total number of simulated macro particles
- For Bhabhas, we have 4.7 % lost in the 3 meters drift , for L= 10^{34} $cm^{-2}\,s^{-1}$, we have 3 Bhabhas produced per bunch crossing (4 ns , 2500 bunches)

Explanations & precisions

- Total number of positrons that exit the beam-pipe over 3 m is 971 $\longrightarrow$

  4.7% of the total cross-section

- Average number of positrons is 75.4 $\xrightarrow{\text{Averaging}}$ 75.4 / 971 = 0.078
- Number of signals per b.c is ν = 3 x 0.078 x 4.7% = 0.01 (each 4 ns)
- Number of signals in the sensor in 1 ms is N= 2500
- Precision is 1/sqrt(N)

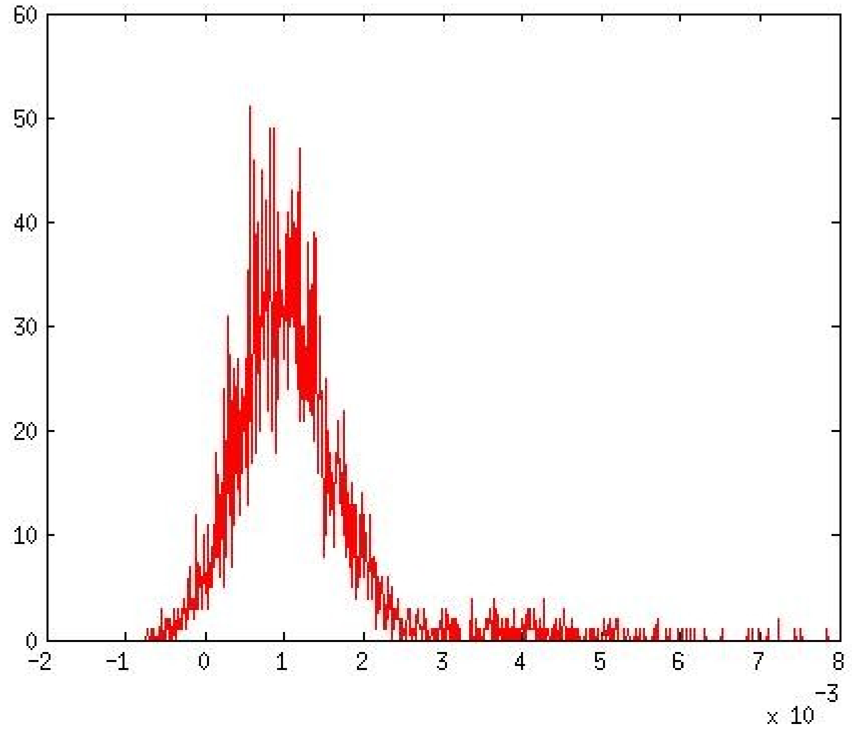
➢ Detectors in coincidence implies to have at least one signal in both at the same time from the same bunch crossing

➢ Poisson distribution is given as $P(n,\nu)=\frac{\nu^n e^{-\nu}}{n!}$, probability to get n signals in the sensors for the case of an average of ν signals

➢ $P_1=P_2= P(0,0.01)= 0.99$; $P'_1=P'_2= 1- P_1=0.01$ (is the probability to have at least one signal in one of the two counters)

➢ $P_1' \times P_2' = 1- P(0,\nu)$, $\boxed{\nu=??}$ $\longrightarrow$ Obtain precision from by calculating an effective number of signals corresponding to the coincidence

Tests and Analysis on the diamond



Trigger on all the signals on the scintillator (max of signal in the diamond)