Occupancy Tolerances for VTX

ILD Technical Task Forces Meeting, LAL November 7-8 2016

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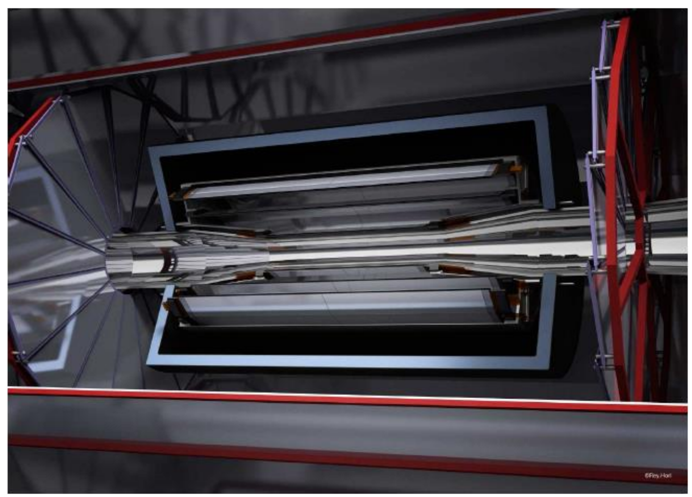
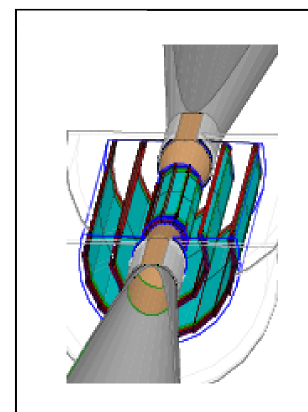
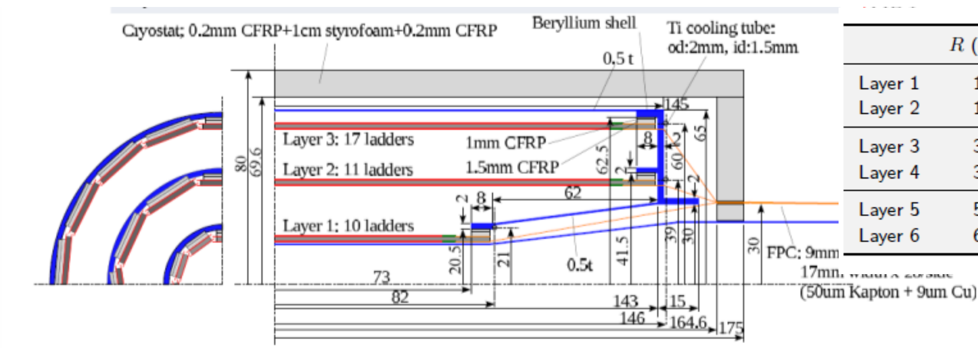




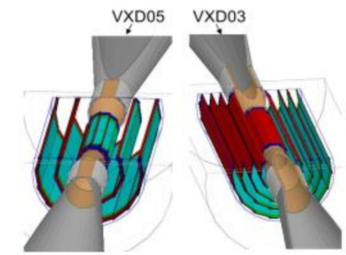
Introduction

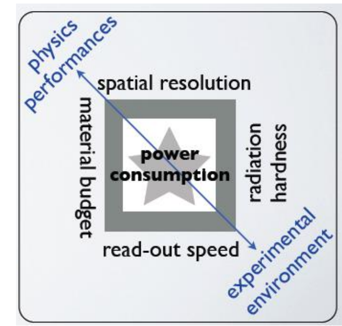
- Main question: which maximum occupancy can the VTX stand ?
  - Defeatist answer: impossible to answer today ⇨ should one surrender ?
  - Typical answer: ~1% occupancy max is mainly an educated guess
- Why ?
  - The expected rate depends on the accelerator/beam configuration and the geometry
    - Expected rate: #hits/cm^2/BX for a given layer (R, ϕ, Z)
    - Beam: (time between bunch, Energy, luminosity, IR geom, antiDID option, etc.)
    - Large uncertainties on beam background simulations
  - The occupancy depends on the detector design:
    - #hits/cm^2/BX needs to be translated into a % of the pixels per read-out.
    - Fast read-out in conflict with resolution & power consumption
    - Technology (sensitive thickness, depletion)
    - Read-out time & strategy, pitch, geometry
  - Estimate effects on detector performances:
    - tracking efficiency, IP resolution, b/c/τ tagging performances
    - Depends on a combination of the above + algorithms (which are themselves strongly correlated to the detector design)
  - Finally estimate the effects on the physics measurement
- How to answer to this question without ambiguity ?
  - Define completely Red + Orange + Purple + Pink ⇨
- Still: what do we know today ?
  - We can explore the parameter space and the different options

Reminder: ILD Vertex Detector requirements (DBD @ 500 GeV)



	R (mm)	$\lvert z\rvert$ (mm)	$\lvert\cos\theta\rvert$	σ (μm)	Readout time (μs)
Layer 1	16	62.5	0.97	2.8	50
Layer 2	18	62.5	0.96	6	10
Layer 3	37	125	0.96	4	100
Layer 4	39	125	0.95	4	100
Layer 5	58	125	0.91	4	100
Layer 6	60	125	0.9	4	100





- Physics: Mat. budget and granularity

  $\sigma_b < 5 \oplus 10/p\beta \sin^{3/2}\theta \ \mu m.$ (a & b parameters)

  - $\sigma_{R\phi}$ ~ 3 μm (pitch ~ 17 μm)
  - O(0.15%X_0/layer)
- Experimental constraints
  - Radiation hardness :
    O(100 kRad) & O(1x10^{11} n$_{eq\ (1MeV)}$) /yr
  - Occupancy (Beam background)
    ~ 5 part/cm²/BX ⇨ few % occupancy max ?
  - Power dissipation : (Cooling)
    ~ 50 mW/cm² ⇨Power cycling, ~3% duty cycle
  - EM compliance and (μ)electronic safety
    Single Event Effect safety
    higher mode beam wake field disturbance, etc.
- Layout (DBD geometry):
  - Long Barrel approach (R ~16 mm – 60mm)
  - 3 x double sided layers OR 5 layers

- Others constraints
  - Read-out & electronics
    - highly integrated read-out microcircuits
    - high data transfer rate (no trigger)
  - Costs !
  - Large B field
    - Large Lorentz angle
  - Integration
    - Routing for services
    - Fabrication reliability and flexibility
    - Mechanical integration: low mass, rigidity, heat conductive
    - Geometry: short or long barrel ?
    - Alignment: micron level capabilities needed

⇨ reaching the specifications all together is the real challenge

Reminder: DBD requirements and beyond

- Beam background (DBD) #Hits/cm^2/BX with anti-DID

Layer	1	2	3	4	5	6
0.5 TeV	6.3±1.8	4.0±1.2	0.25±0.11	0.21±0.09	0.05±0.03	0.04±0.03
1 TeV	11.8±1.0	7.5±0.7	0.43±0.13	0.36±0.11	0.09±0.04	0.08±0.04

- Occupancy
  - e.g. 17x17 μm^2 pitch, cluster mult. ~5, 50 μs read-out time @ 0.5TeV & @550ns Bunch sep.
    - ➢ on Layer 1 ⇨ ~ 1 % ⇨ easy to reach with no safety factor !
- Large potential variations (beyond B field and Radius)
  - No anti-DID option ⇨ x ~O(50%) ? + L* configuration (beamcal+forward masks)
  - Inhomogeneity in z and ϕ ?
  - 1 TeV ⇨ +50% higher occupancy ?
  - Luminosity upgrades ⇨ ~ x2 higher occupancy ?
  - Large uncertainties on M.C. simulations ⇨ Safety factors needed (> x5)

cf. Christopher Milke @ LCWS 2015

- Reconstruction will benefit from lower occupancies
  - ➢ Reduced combinatorial to reduce fake tracks
  - ➢ Stand alone tracking capabilities
  - ➢ Low momentum tracks, VTX/Jet charge determination, c-tagging, etc.

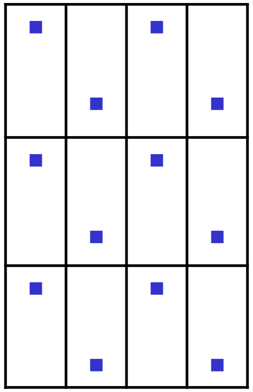
⇨ Strong motivations to get reduced occupancy / faster read-out

The occupancy : squaring the circle

- How to decrease occupancy if needed ?

$$\sigma_b < 5 \oplus 10/p\beta \sin^{3/2}\theta \ \mu m.$$

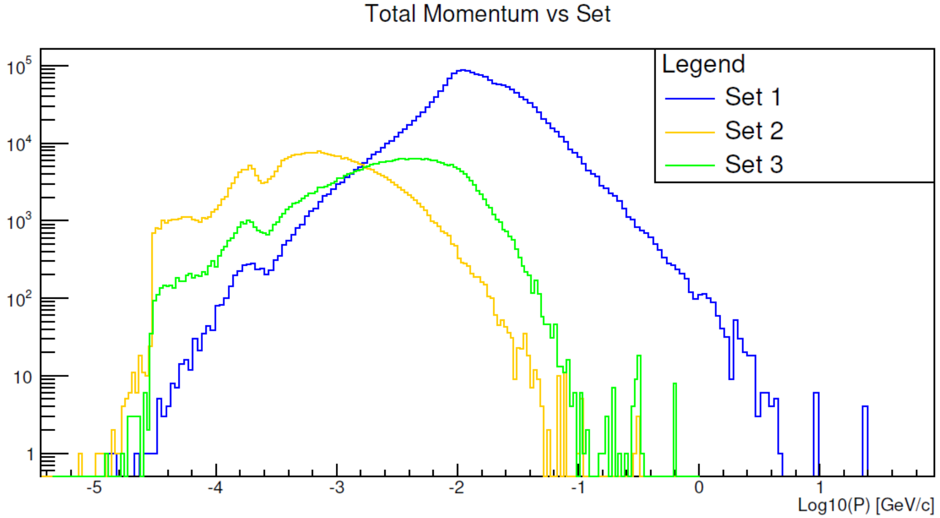
  - Increase read-out speed ?
    - Enlarge pixel pitch ⇨ deteriorate spatial resolution (⇨ 2-3 bits instead of 1 bit output ?)
    - Elongated pixels ⇨ improved read-out speed while keeping resolution not degraded too much
    - Increase power consumption
  - Smaller pitch ?
    - More pixel to read ⇨ decrease read-out speed ⇨less bunch time stamping
    - Effective if it compensates the number of superimposed BXs in one read-out

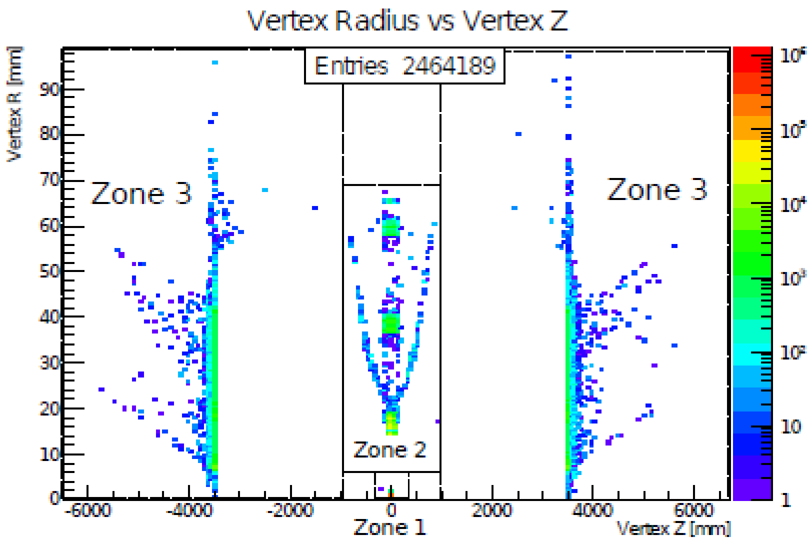


  - Decrease cluster multiplicity ? (BB tends to have large incident angles)
    - Full depletion: helps a bit (marginal effect)
    - Decrease sensitive thickness ⇨ deteriorates S/N for a marginal effect.
    - Suppress any chance to identify background with cluster shapes
    - Increase S/N threshold ⇨ mitigate efficiency/resolution ⇨ marginal effect
    - Multiplicity – pitch – depletion – angle relation ⇨ multi-parameter space
  - Increase inner radius ?
    - Not really an option: Deteriorate σ_{IP} ⇨ $\sigma_{d_0}^2 = \dfrac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$
  - Increase B field ?
    - Not really a free parameter
  - Technology progress : the way to go ?
    - e.g. smaller feature size ⇨ less power consumption, more memories in pixels, etc.
    - Go lower than ~100 ns/row read-out time ? (more parallelism, asynchronous read-out, etc.)

L.Cousin PhD

Beam background features.

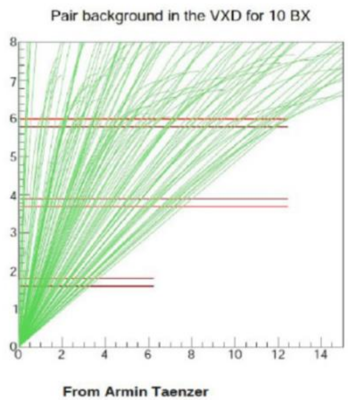




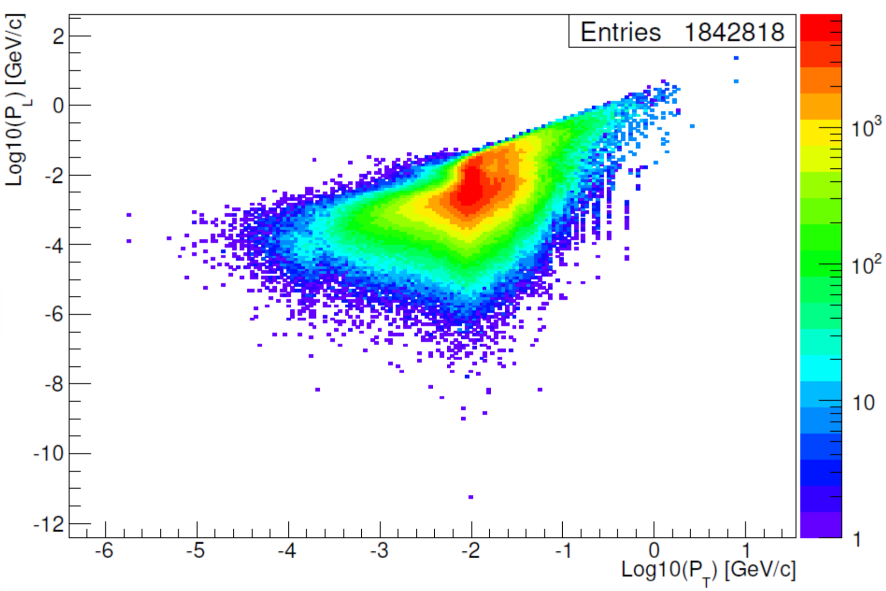
- Origin of background:

Zone 1 = interaction region
Zone 2 = detector region
Zone 3 = backscattered particles
⇨ Most background is coming from IR
⇨ Typical pT ~10-100 MeV
⇨ They are real tracks !

(pT ~8 MeV to reach Layer 1)
(pT ~30 MeV to reach Layer 6)



Longitudinal vs Transverse Momentum, Set1



Sustainable occupancy rate ?

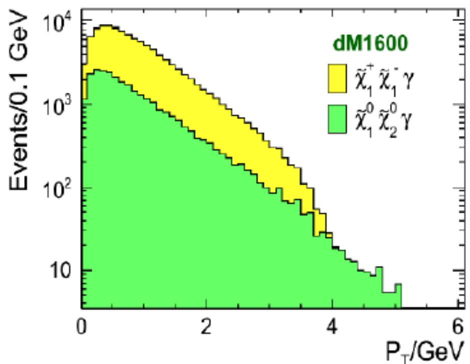
- Study by G.Voutsinas (DESY) cf. 31.05.2016 **ECFA 2016**

Chargino cross-section study

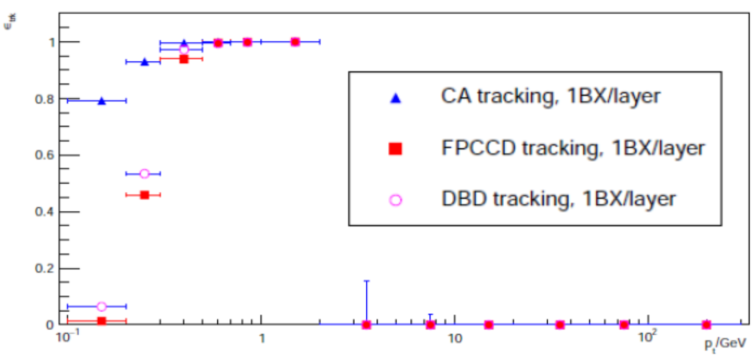
⇨ ≠r.o. time configurations tested

	DBD VXD		Ideal VXD		Conservative VXD		Ambitious VXD	
layer	σ_{sp} (μm)	σ_{time} (μs)	σ_{sp} (μm)	σ_{time} (BXs)	σ_{sp} (μm)	σ_{time} (μs)	σ_{sp} (μm)	σ_{time} (μs)
L1 / L2	3 / 6	50 / 10	3/ 3	1 / 1	4 / 4	4 / 4	3 / 3	1 / 1
L3 / L4	4 / 4	100 / 100	3 / 3	1 / 1	4 / 4	8 / 8	3 / 3	2 / 2
L5 / L6	4 / 4	100 / 100	3 / 3	1 / 1	4 / 4	8 / 8	3 / 3	2 / 2

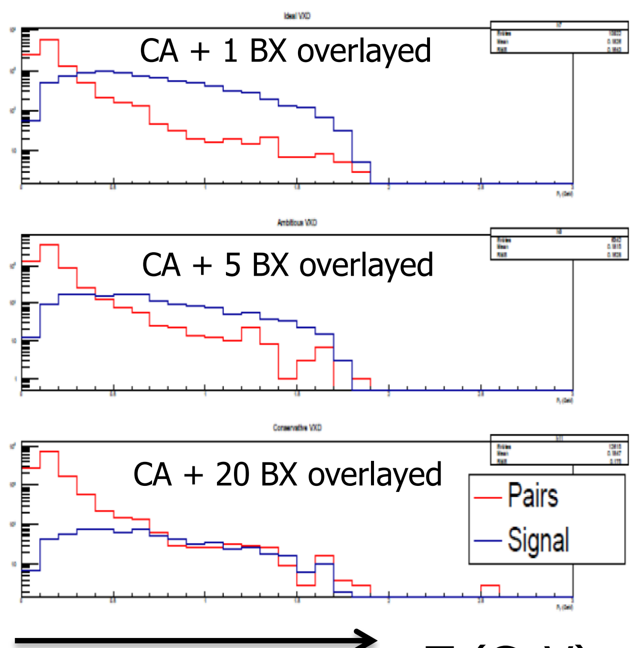
M_h=124 GeV
δm(chargino – neutralino) 1.59GeV



$P_T < 5$ GeV



⇨ Track seeding in the VTX helps low momentum track efficiency



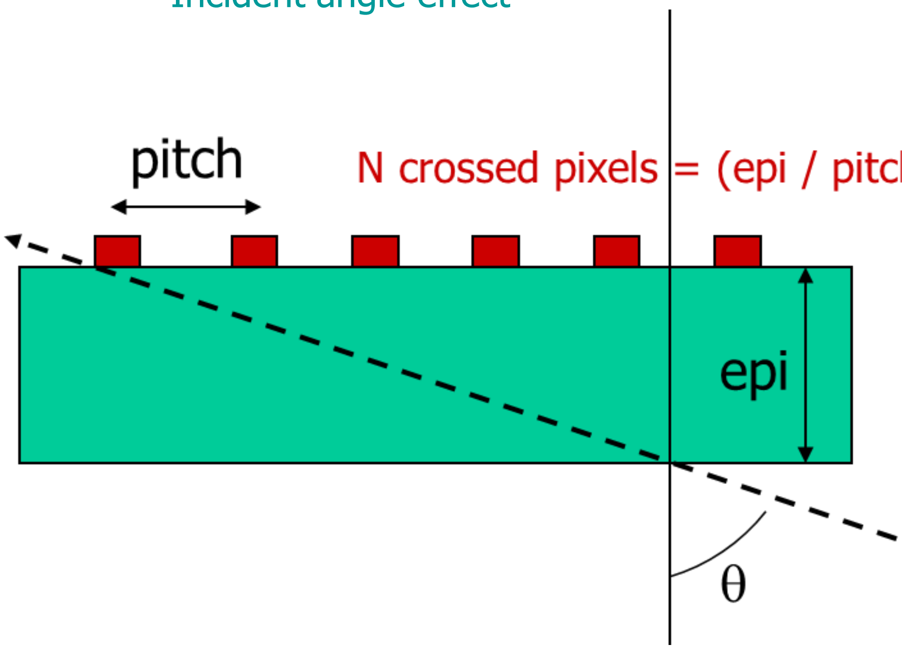
pT (GeV)

⇨Faster read-out do help to disentangle “Tracks signal” from tracks coming from BB

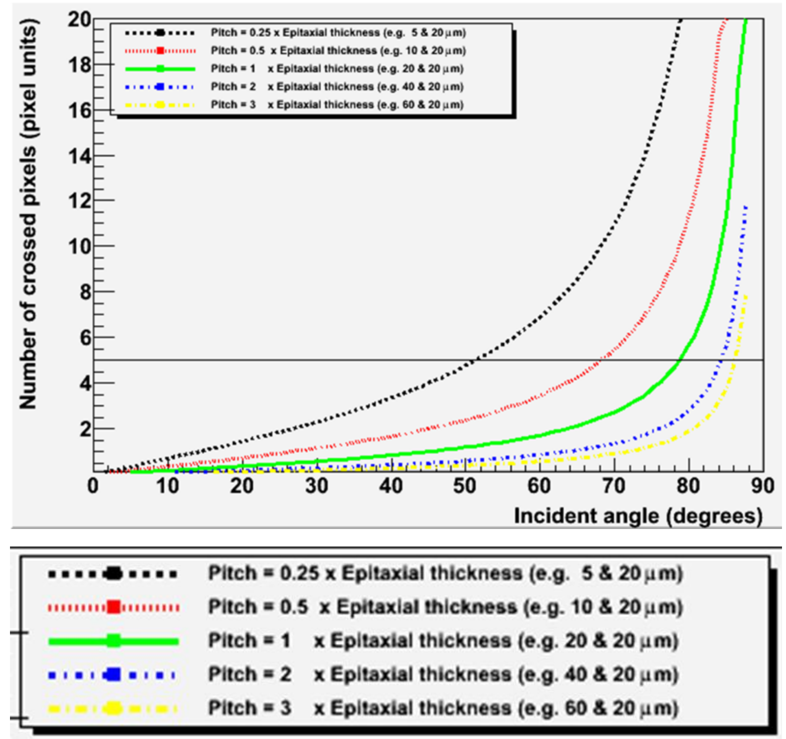
Multiplicity discussion

- 1 hit ≠ 1 pixel fired
  - Typically 1-4 for perpendicular particles
- ⇨ Depends on:
  - Threshold applied on discriminators
  - Charge sharing
    - Smaller for fully depleted technologies
    - Increases with sensitive thickness
  - Incident angle effect

N crossed pixels = (epi / pitch) x tan(θ)

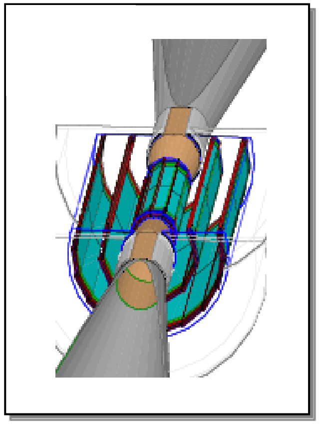


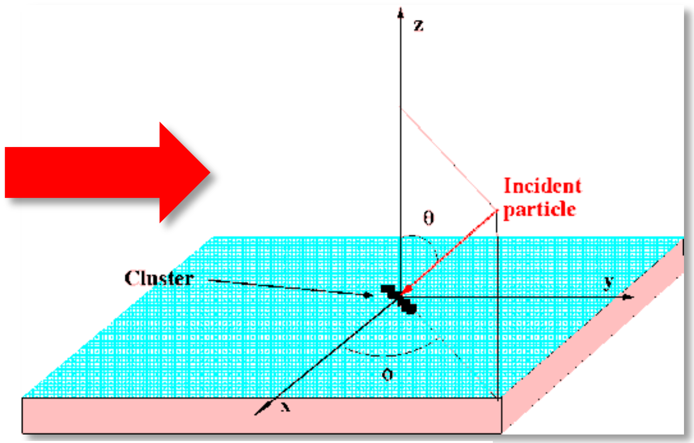
Crucial parameter: pitch / epitaxial layer thickness



e.g. :
20 μm pitch, 20 μm thickness, θ= 70º
⇨ 3 crossed pixels ⇨ ~ x3 occupancy

Beam background properties in the local frame of the sensors

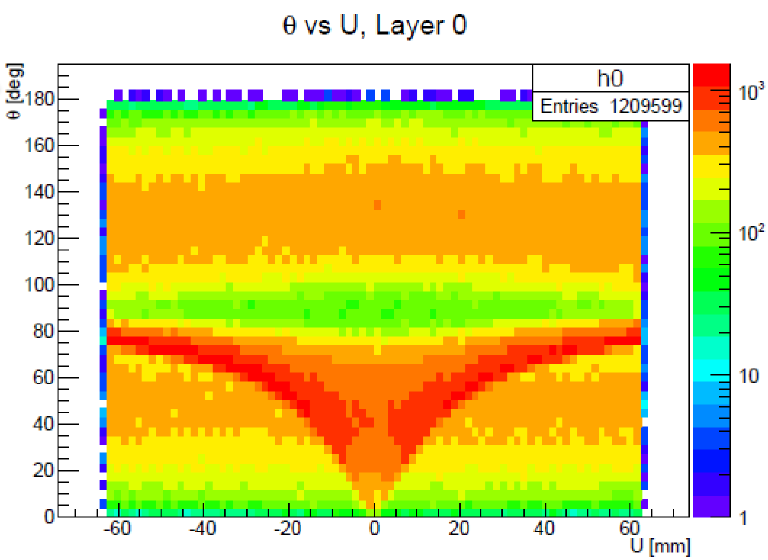




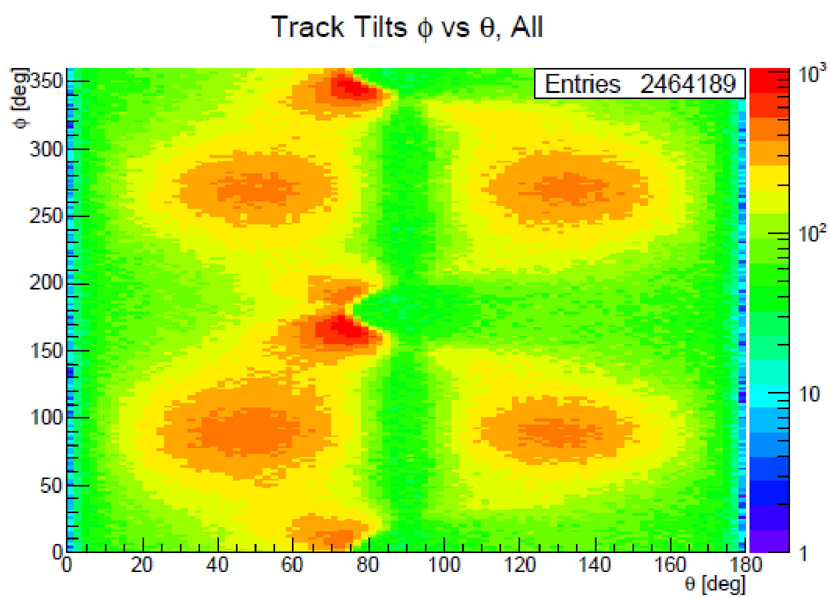
- Background properties:
  - z-φ-θ correlations ⇨ Elongated clusters
  - Use cluster shape to tag/reject beam background ?
  - easier for small pitch & large sensitive thickness

Beam background simulation
(with anti DID)

θ



φ

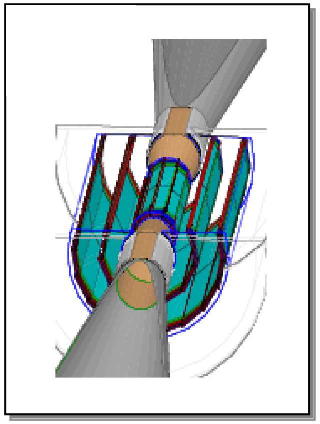


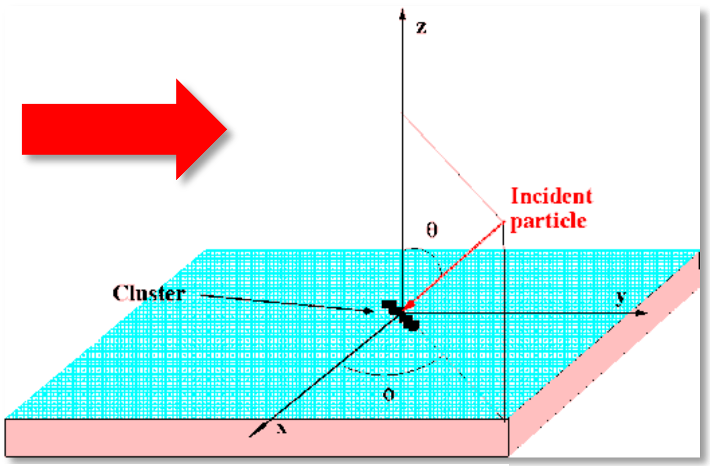
(L.Cousin PhD, IPHC)

Beam axis

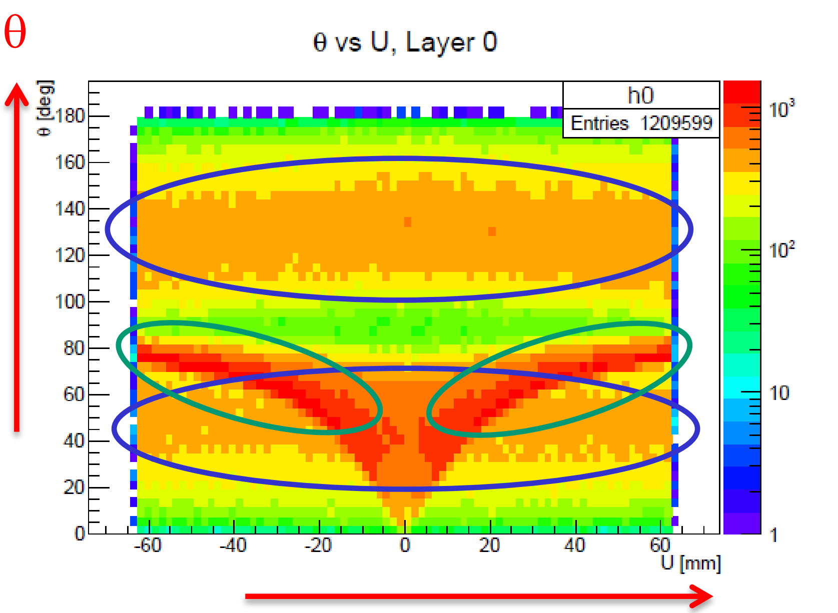
θ

Beam background properties in the local frame of the sensors

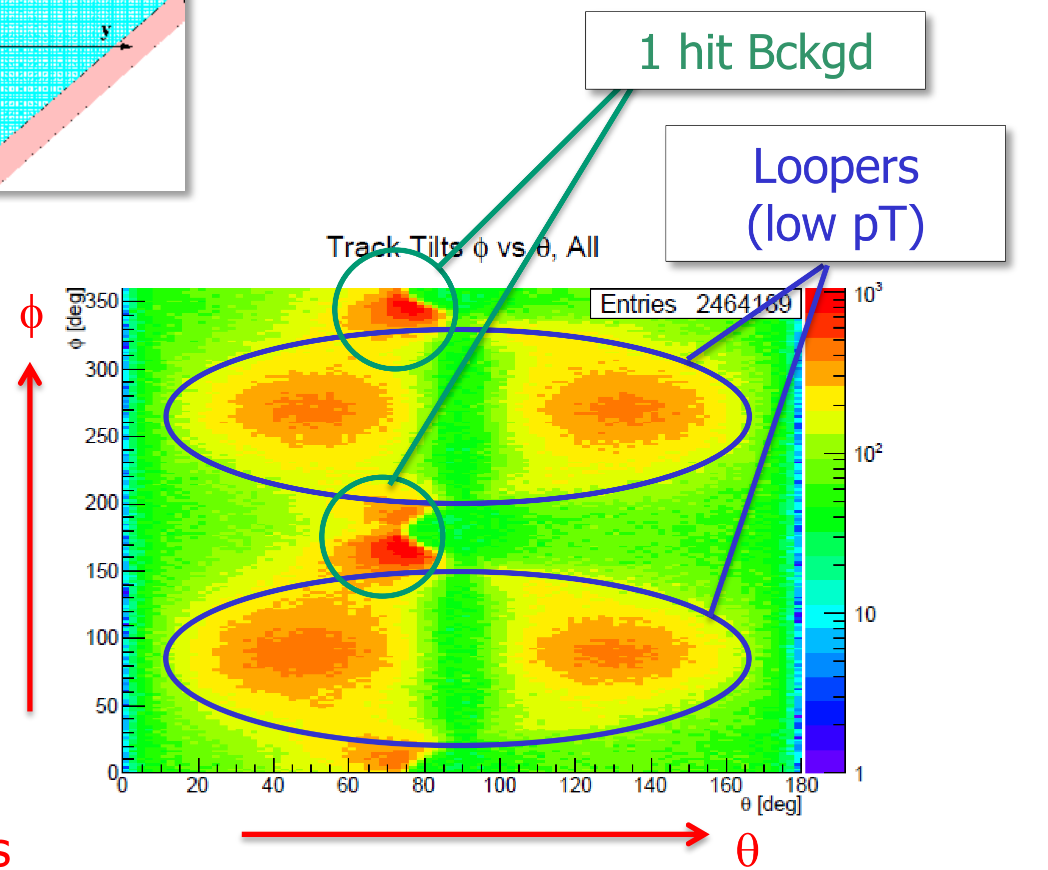




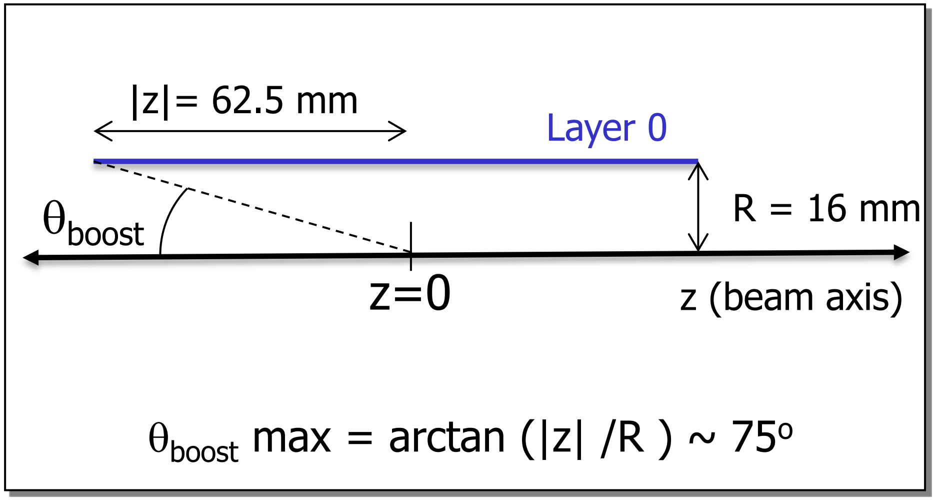
- Background properties:
  - z-ϕ-θ correlations ⇨ Elongated clusters
  - Use cluster shape to tag/reject beam background
  - old idea for small pitch

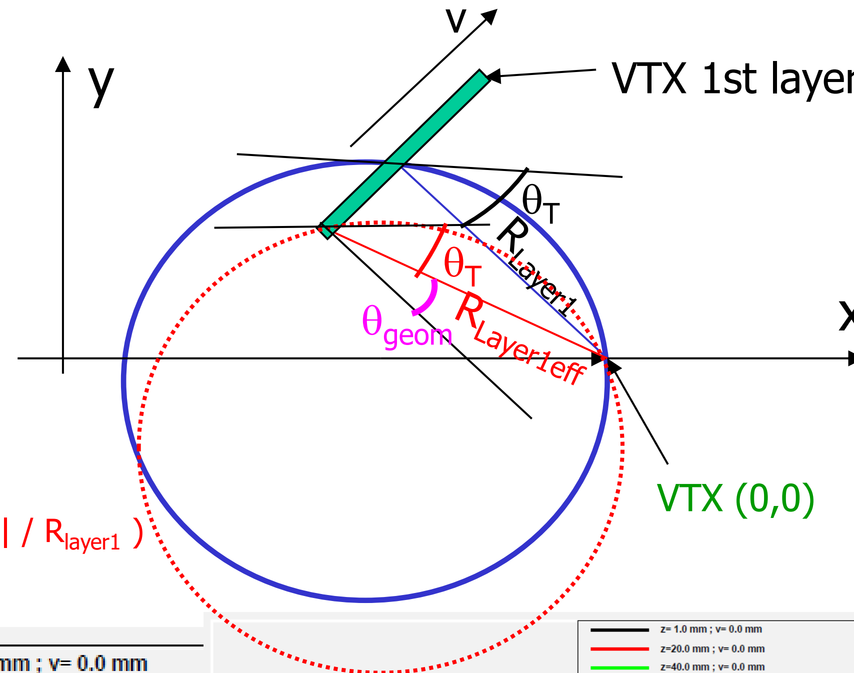


Beam axis

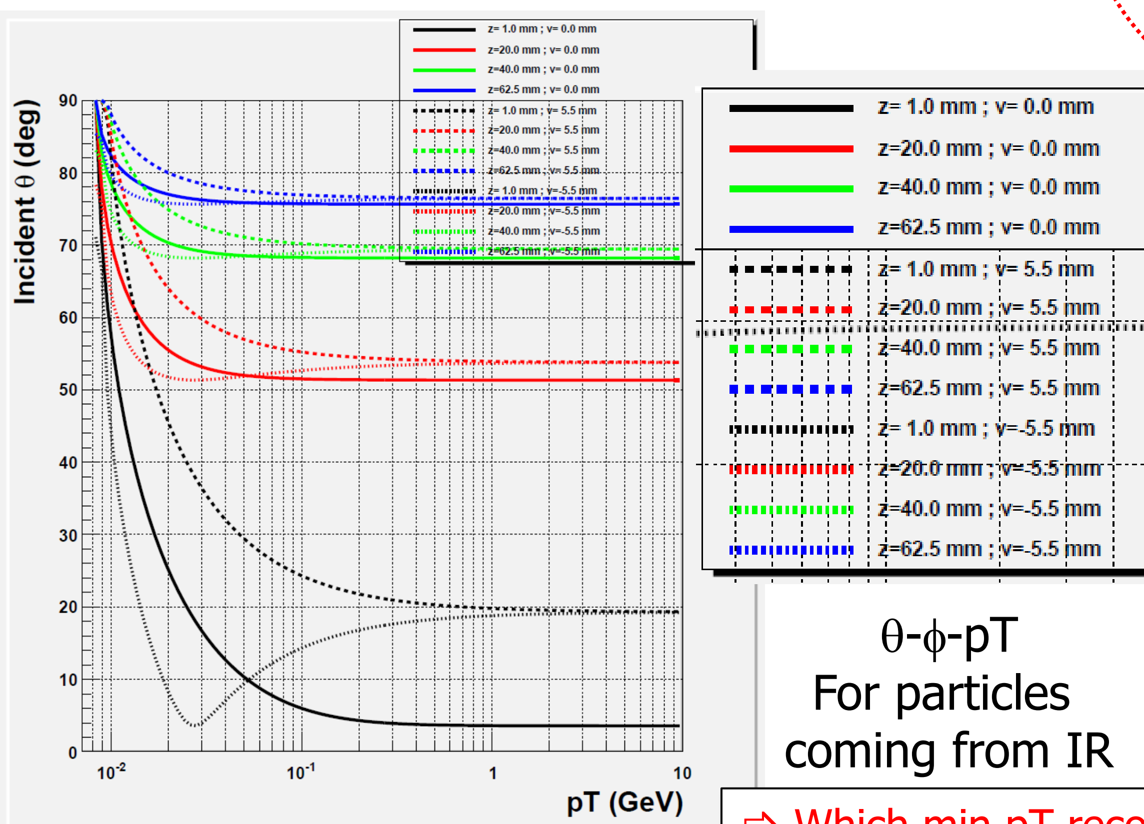


(L.Cousin PhD, IPHC)

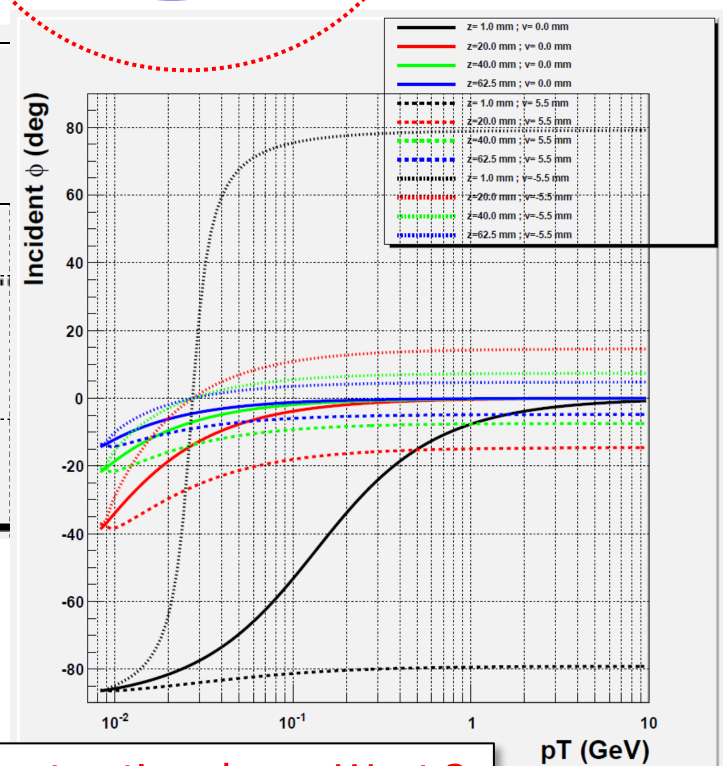




θ_T effective = $(\pi/2)$ - Arccos $(0.3.\times B\times R_{layer1eff}/(2\times pT))$ $\pm$ arctan ($|v|$ / R_{layer1})

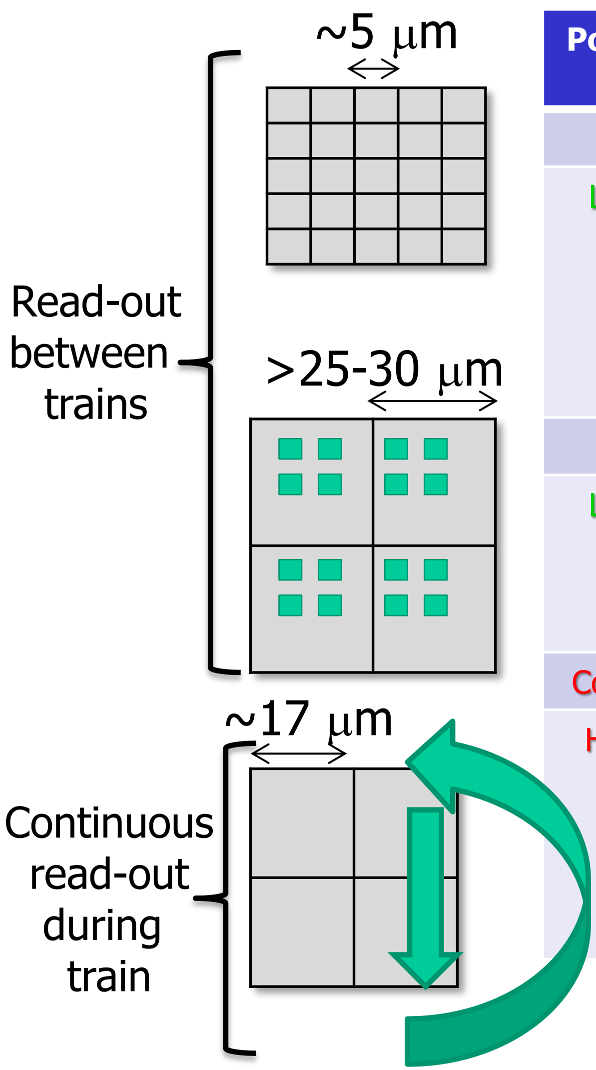


θ-φ-pT
For particles coming from IR



⇨ Which min pT reconstruction do we Want ?

Read-out strategies vs resolution/occupancy



Power	Time resolution	Spatial resolution	Advantages	Caveats
Fine pixels (e.g. FPCCD)				
Low	1 complete train	~ 1 μm	Spatial Resolution Hit separation Beam background tagging capabilities ? (cluster shapes)	⇨x16 #pixels to read-out in 200ms ⇨No time stamping ⇨Occupancy issues ?
In pixel circuitry to store hits with time stamping (e.g. chronopixels, SOI)				
Low	Single or few bunches (>~ 0.5 μs)	>~ 5 μm	Hit time stamping Well suited to outer layers	⇨BX time stamping storage in conflict with granularity
Continuous read-out during train (e.g. DEPFET, CMOS): rolling shutter or priority encoding.				
High	Few to 10s bunches (5-50 μs)	~ 3 μm	Time & spatial resolution compromise	Power cycling mandatory ? ⇨F(Lorentz) ~ 10^s grams ⇨Distribute 100s Amps shortly before train ⇨heat cycles the ladders.

⇨ Figures may evolve significantly with R&D and access to new technologies
e.g. feature size ⇨Power, read-out speed, granularity, etc.

⇨Different options / room for mixed strategies ?
e.g. double sided ladders: 1-fast / 1-precise

Typical occupancy rate (layer 1, with DBD rates)

Pixel pitch	σ_{sp}	Read-out Time / time resolution	Assumed average cluster multiplicity	Lumi Mode (bunch Per train)	BX time spacing	$\sqrt{s}$	Assumed Expected Background	Expected background with safety factor 5	Occupancy	remarks
(μmxμm)	μm	(μs)	# pixels	B/train	ns	GeV	$\#hits/cm^2/BX$		w.o./w safety	
17x17	~3	50	5	Baseline (1312)	554	500	6	30	$8x10^{-3}$ / $4x10^{-2}$	DBD
17x17	~3	50	5	Upgrade (2625)	**366**	500	6	30	$1x10^{-2}$ / $6x10^{-2}$	Lumi upgrade
17x17	~3	50	5	1312	554	**250**	3	15	$4x10^{-3}$ / $2x10^{-2}$	250 GeV
17x17	~3	50	5	2500	366	**1000**	10	50	$2x10^{-2}$ / $1x10^{-1}$	1 TeV
17x17	~3	**25**	5	Baseline (1312)	554	500	6	30	$4x10^{-3}$ / $2x10^{-2}$	DBD X 2 faster
22 x 22	**~4**	4	5	Baseline (1312)	554	500	6	30	$1.5x10^{-3}$ / $8x10^{-3}$	Async. Read-out
25 x 25	**~5**	**1BX**	**3**	Baseline (1312)	554	500	6	30	$1x10^{-4}$ / $5x10^{-4}$	Bunch stamping
5 x 5	**~1**	**1 train**	**6**	Baseline (1312)	554	500	6	30	$1x10^{-2}$ / $6x10^{-2}$	Fine pixel BB tagging

$$Occupancy = (\#hits/cm^2/BX) \times \langle mult \rangle \times (pitch)^2 \times (r.o.time) / (BXtime) \times safety$$

Conclusion

- Maximum occupancy
  - Large uncertainties on the background rate
  - A large safety margin is needed (x5-10 ?)
    - ➢ Anti-DID should help but is a factor 2 reduction significant enough ?
  - R&D: push the read-out speed as high as possible while keeping the other parameters (cf SiD Strategy)
    - ➢ mat.budget, σ_{sp}, power consumption
  - Room for new ideas: (technology combinations, background tagging, etc.)
- The 1% occupancy target
  - Based on educated guess and experience
  - needs to be assessed much more carefully ⇨ may turn to $10^{-3} - 10^{-4}$ range
  - What is the lowest momentum tracking capabilities we want ?
- What should be done
  - Perform complete physics analysis
    - ➢ with different superimposed background rates AND ≠ σ_{IP}
    - ➢ Background with correlated hits on the different layers mandatory
    - ➢ Ideally with different VTX configurations (read-out, resolution, geometry, etc.)
    - ➢ Ideally with different tracking/vertexing algorithms
  - Need to test different kind of final states:
    - ➢ high multiplicity final states (e.g. t-t-H)
    - ➢ Final states with forward tracks
    - ➢ Final states with b/c/τ (e.g. Higgs coupling)
    - ➢ Final states with low momentum tracks (e.g. light higgsino)
  - Put occupancy requirements in balance with a & b parameters requirements

$$\sigma_b < 5 \oplus 10/p\beta \sin^{3/2}\theta \ \mu m.$$

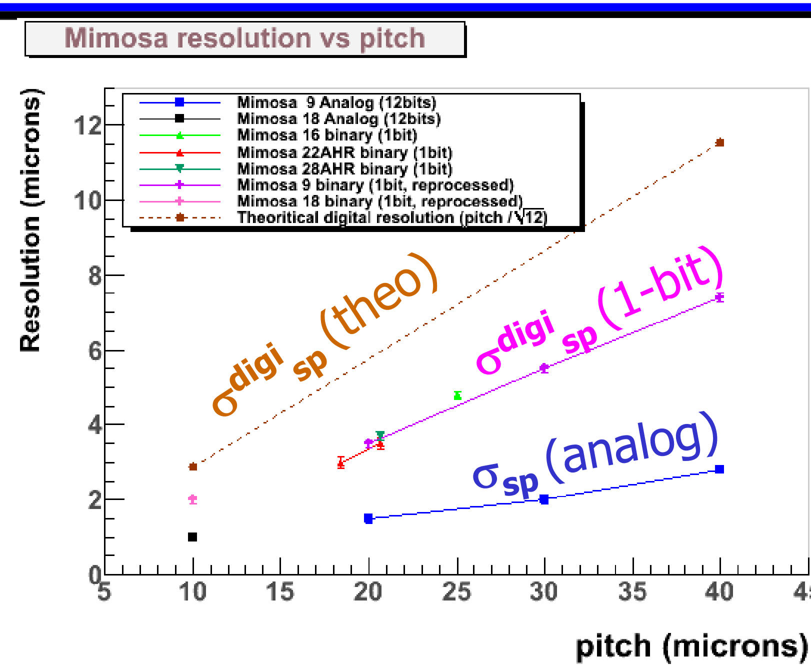
(a & b parameters)

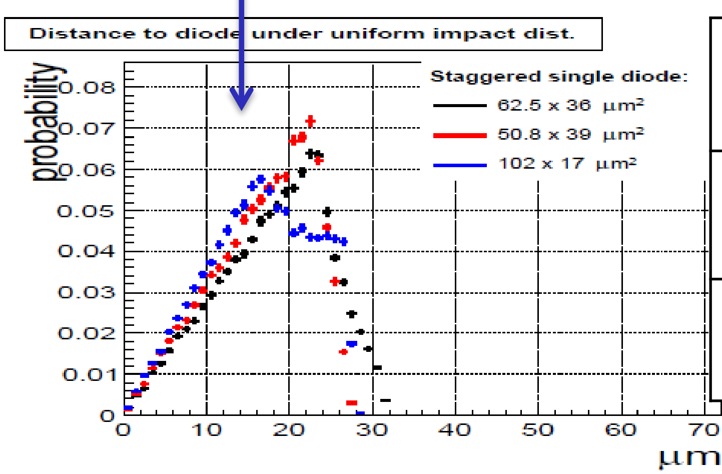
⇨ The final answer might take years from now

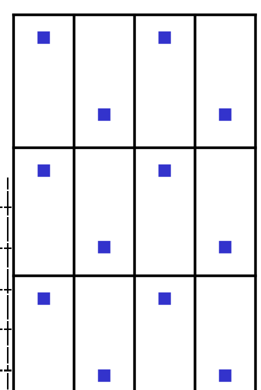
Backup for discussion

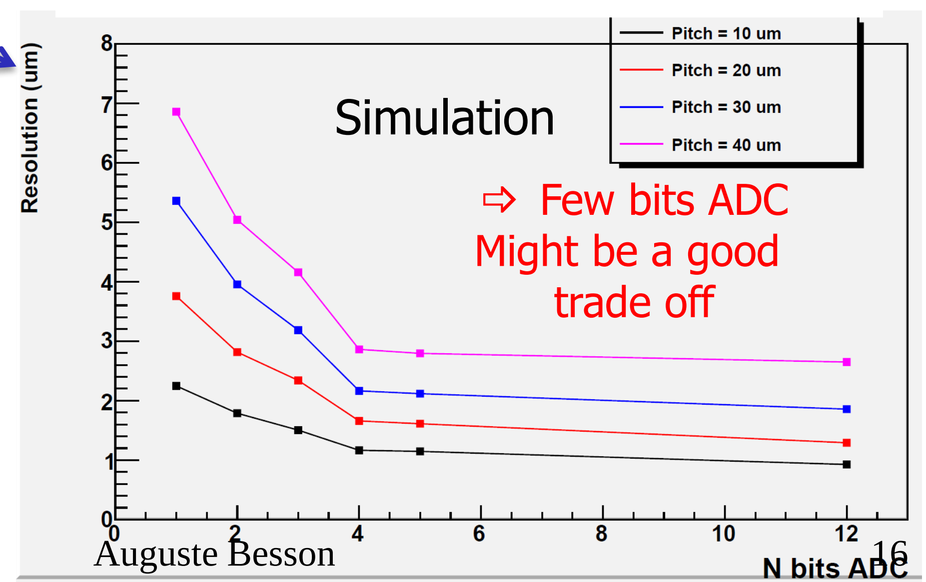
Resolution and pitch discussion

- Resolution governed by
  - Pitch
  - S/N & Collecting diode
    - ➢ Charge sharing
    - ➢ epi. thickness, resistivity, etc.
  - Signal encoding (binary or ADC)
- Pitch impact
  - $\sigma_{sp} \propto$ pitch (~linear)
- Signal encoding
  - e.g. σ_{sp}(1bit, ~17 μm) ~ σ_{sp}(2bits, ~23 μm) ~ 3 μm
- Staggered pixels
  - Preserve resolution in both direction



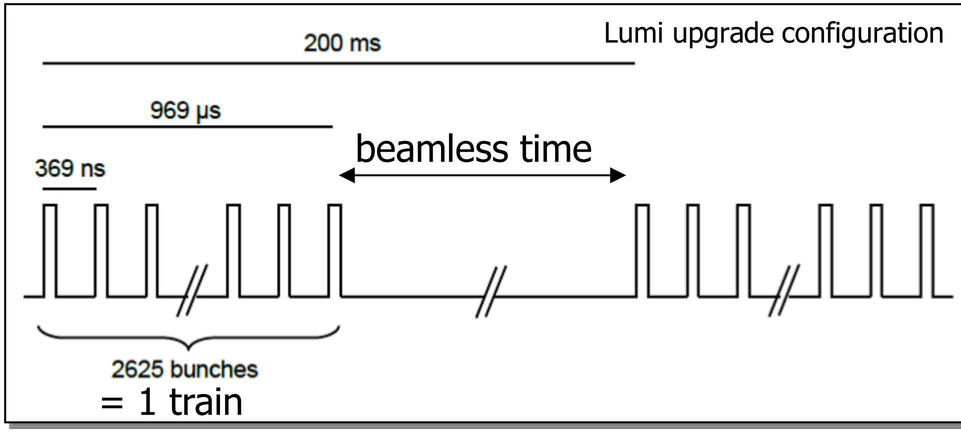






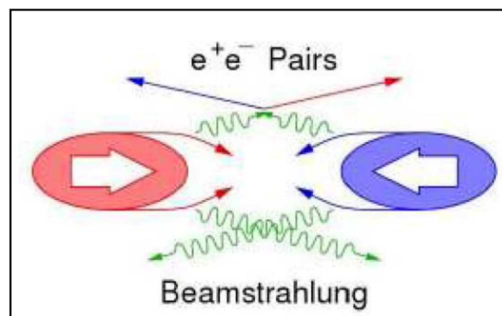
ILC experimental conditions

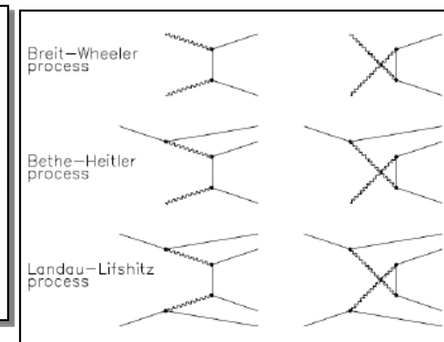
- Beam structure
  - 5 trains/s of ~1300/2600 bunches
  - 1 bunch every ~ 550/360 ns
  - « Quiet time » of ~ 200 ms (between each train)
  - Consequences on read-out
    - ➢ No trigger, power pulsing, cooling
    - ➢ Possible read-out during beamless time



- Beam background :
  - Beamstrahlung: RMS energy loss:
    - ➢ δ_{BS} ~ 1% @ $\sqrt{s}$ = 250 GeV
  - Drives occupancy :
    - ➢ Read-out speed, Inner radius
    - ➢ Physics cross section: ~ 1 evt/s ⇨ negligible
  - Drives radiation level
    - ➢ Moderate (compared to LHC)
    - ➢ Vertex detector 1st layer: O(100) kRad/yr & O(10^{11}) n_{eq}(1MeV)/cm^2/yr
  - Required tiny flat bunches
    - ➢ σ_x~500 nm, σ_y~5 nm

Bunches have electric space charge
⇨particles deflected
⇨photons emissions
⇨ e^+e^- pairs ("beamstrahlung")





$$BS \propto \frac{1}{\sigma_x + \sigma_y}$$

$$\mathcal{L} \propto \frac{1}{\sigma_x \sigma_y}$$

ILC parameters (DBD)

			Baseline 500 GeV Machine			1st Stage	L Upgrade	E_{CM} Upgrade	
								A	B
Centre-of-mass energy	E_{CM}	GeV	250	350	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	10	5	5	10	5	4	4
Number of bunches	n_b		1312	1312	1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	554	554	366	366	366
Pulse current	I_{beam}	mA	5.8	5.8	5.8	5.8	8.8	7.6	7.6
Main linac average gradient	G_a	MV m^{-1}	14.7	21.4	31.5	31.5	31.5	38.2	39.2
Average total beam power	P_{beam}	MW	5.9	7.3	10.5	5.9	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	122	121	163	129	204	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.190	0.158	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.152	0.100	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	µm	10	10	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	13.0	16.0	11.0	13.0	11.0	22.6	11.0
IP vertical beta function	β_y^*	mm	0.41	0.34	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	729.0	683.5	474	729	474	481	335
IP RMS veritcal beam size	σ_y^*	nm	7.7	5.9	5.9	7.7	5.9	2.8	2.7
Luminosity	L	$\times 10^{34}$ cm^{-2}s^{-1}	0.75	1.0	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		0.97%	1.9%	4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	62.4	93.6	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	46.5	115.0	344.1	46.5	344.1	1338.0	3441.0

½ gradient
Initial Higgs factory

Baseline

½ length
(Option 1e phase)

Lumi
upgrade

1TeV upgrade

Luminosity options

Luminosity Upgrades for ILC

Mike Harrison (Brookhaven), Marc Ross (SLAC), Nicholas Walker (DESY)

August 15, 2013

		TDR reference				Further options	
		baseline			upgrade		
Ecm	**GeV**	**250**	**350**	**500**	**500**	**250**	**350**
Rep. rate	Hz	5	5	5	5	10	8
Bunches/pulse		1312	1312	1312	2625	2625	2625
Total beam power	MW	5.3	7.4	10.5	21.0	21.0	23.5
AC power	**MW**	**122**[a]	**121**	**163**	**204**	**187**	**204**
Luminosity	**$\times 10^{34}$ cm^{-2}s^{-1}**	**0.75**	**1.0**	**1.8**	**3.2**	**3.0**	**3.2**

a) TDR baseline assumes 10-Hz mode for e+ production

ILC Operating Scenarios

ILC Parameters Joint Working Group

T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker, K. Yokoya

ILC-NOTE-2015-068
DESY 15-102
IHEP-AC-2015-002
KEK Preprint 2015-17
SLAC-PUB-16309
June 25, 2015

	$\sqrt{s}$	$\int \mathscr{L} dt$	L_{peak}	Ramp				T	T_{tot}	Comment
	[GeV]	[fb^{-1}]	[fb^{-1}/a]	1	2	3	4	[a]	[a]	
Physics run	500	500	288	0.1	0.3	0.6	1.0	3.7	3.7	TDR nominal at 5 Hz
Physics run	350	200	160	1.0	1.0	1.0	1.0	1.3	5.0	TDR nominal at 5 Hz
Physics run	250	500	240	0.25	0.75	1.0	1.0	3.1	8.1	operation at 10 Hz
Shutdown								1.5	9.6	Luminosity upgrade
Physics run	500	3500	576	0.1	0.5	1.0	1.0	7.4	17.0	TDR lumi-up at 5 Hz
Physics run	250	1500	480	1.0	1.0	1.0	1.0	3.2	20.2	lumi-up operation at 10 Hz

Table 7: Scenario H-20: Sequence of energy stages and their real-time conditions.

Beam background in various detectors (ILD)

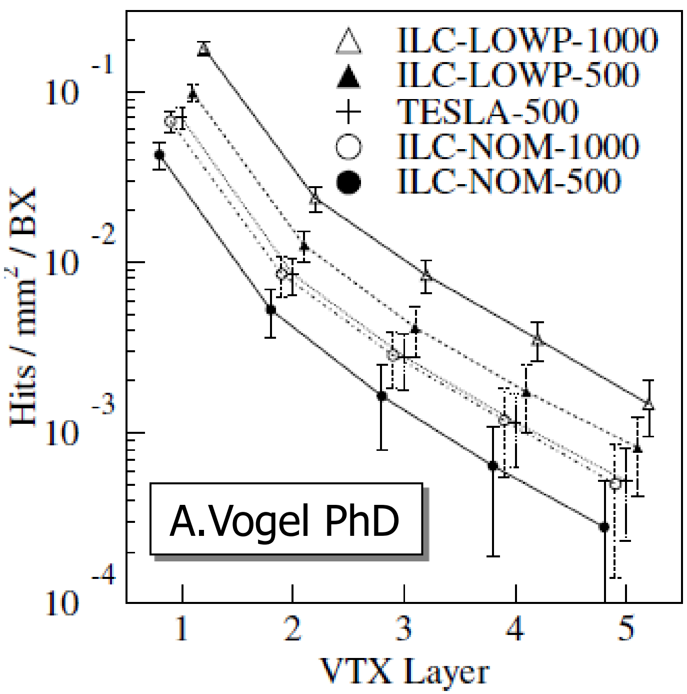
- Beam Background simulation
  (Guinea Pig)
  - Pair induced background
  - Depends on $\sqrt{s}$
  - 20 % due to back scatterers
  - Statistical error only
    - ➢ systematics much higher

Subdetector	Units	Layer	Nom-500	Low-P-500	Nom-1000
VTX-DL	hits/cm^2/BX	1	3.214±0.601	7.065±0.818	7.124±1.162
		2	1.988±0.464	4.314±0.604	4.516±0.780
		3	0.144±0.080	0.332±0.107	0.340±0.152
		4	0.118±0.074	0.255±0.095	0.248±0.101
		5	0.027±0.026	0.055±0.037	0.046±0.036
		6	0.024±0.022	0.046±0.030	0.049±0.044
SIT	hits/cm^2/BX	1	0.017±0.001	0.031±0.007	0.032±0.012
		2	0.004±0.003	0.016±0.005	0.008±0.002
FTD	hits/cm^2/BX	1	0.013±0.005	0.031±0.007	0.019±0.006
		2	0.008±0.003	0.023±0.007	0.013±0.005
		3	0.002±0.001	0.005±0.002	0.003±0.001
		4	0.002±0.001	0.007±0.002	0.004±0.001
		5	0.001±0.001	0.006±0.002	0.002±0.001
		6	0.001±0.001	0.005±0.002	0.002±0.001
		7	0.001±0.001	0.007±0.002	0.001±0.001
SET	hits/BX	1	5.642±2.480	57.507±10.686	13.022±7.338
		2	5.978±2.360	59.775±8.479	13.711±7.606
TPC	hits/BX	-	408±292	3621±709	803±356
ECAL	hits/BX	-	155±50	1176±105	274±76
HCAL	hits/BX	-	8419±649	24222±744	19905±650

R = 16mm

R = 60mm

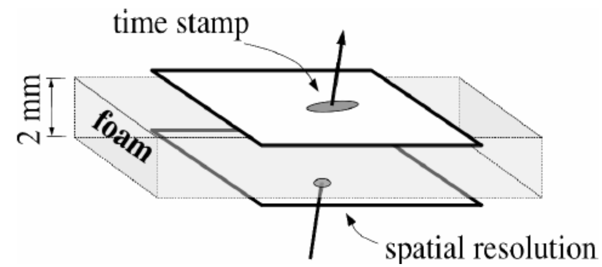
Table 3.5.1: Pair induced backgrounds in the subdetectors for nominal (500 GeV and 1 TeV) and Low-P (500 GeV) beam parameters. The numbers for the ECAL and the HCAL are summed over barrel and endcaps. For the vertex detecor, the double-layer option has been chosen for this simulation, the numbers for the single-layer option differ. The errors represent the RMS of the hit distributions of the simulation of ≈ 100 bunch crossings (BX).



- typical value (layer 1)
  - ➢ ~ 5 hits/cm^2/BX
- Very sensitive to IR geometry
- Safety factor needed !
  - ➢ at least x 5 !

ILD-VXD design options

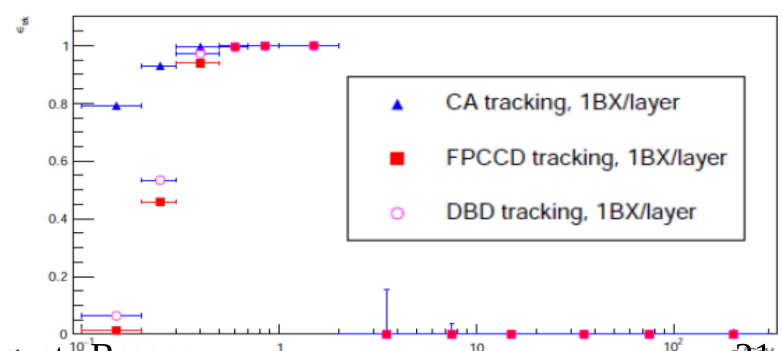
- ILD-VXD Options
  - Achievable with our present knowledge
    - ➢ L1 17x17 μm² ⇨ σ~<3μm & 32-64 μs
    - ➢ L2 17x102 μm² ⇨ σ~<5μm & 2-5 μs
    - ➢ L3-L6 25x51 μm² ⇨ σ~3.5 μm & 40 μs AND 27x29 μm² ⇨ σ~5 μm & 4 μs
  - A la ALPIDE option
    - ➢ 6 Layers with 22x22 μm² ⇨ σ~<4 μm & 5 μs
  - Others
    - ➢ Outer layers with a la ALPIDE read-out (reduce power cons.)
    - ➢ Fine pixels (4μmx4μm) with delayed read-out



- cf. Y.Voutsinas studies (e.g. ILD optimization workshop)
  - Standalone tracking efficiency

⇨ Stay open to new ideas

	DBD VXD		Ideal VXD		Conservative VXD		Ambitious VXD	
layer	σ_{sp} (μm)	σ_{time} (μs)	σ_{sp} (μm)	σ_{time} (BXs)	σ_{sp} (μm)	σ_{time} (μs)	σ_{sp} (μm)	σ_{time} (μs)
L1 / L2	3 / 6	50 / 10	3/ 3	1 / 1	4 / 4	4 / 4	3 / 3	1 / 1
L3 / L4	4 / 4	100 / 100	3 / 3	1 / 1	4 / 4	8 / 8	3 / 3	2 / 2
L5 / L6	4 / 4	100 / 100	3 / 3	1 / 1	4 / 4	8 / 8	3 / 3	2 / 2



Resolution (simulation model based on data)