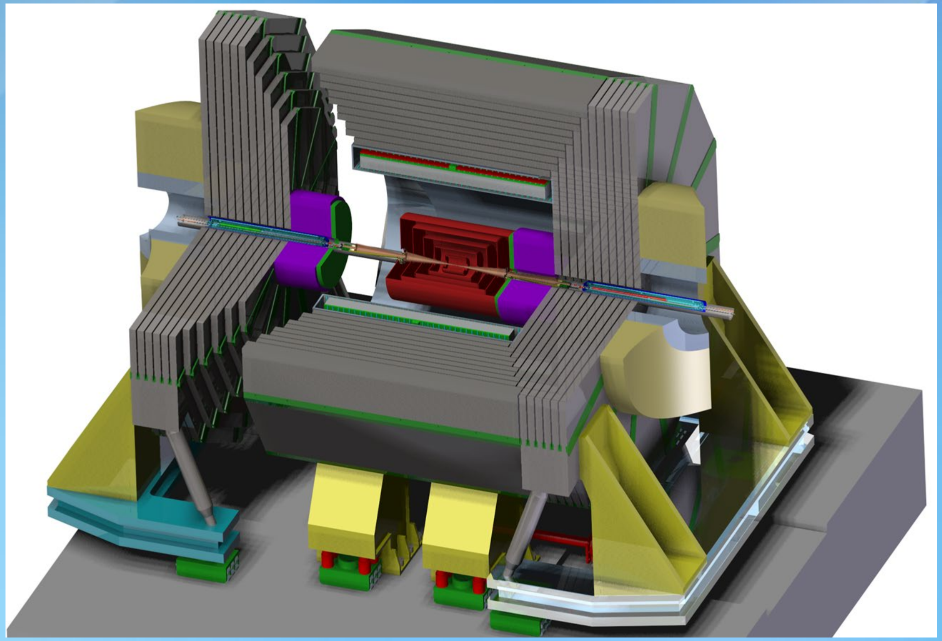
The SiD Detector – design considerations for C^3

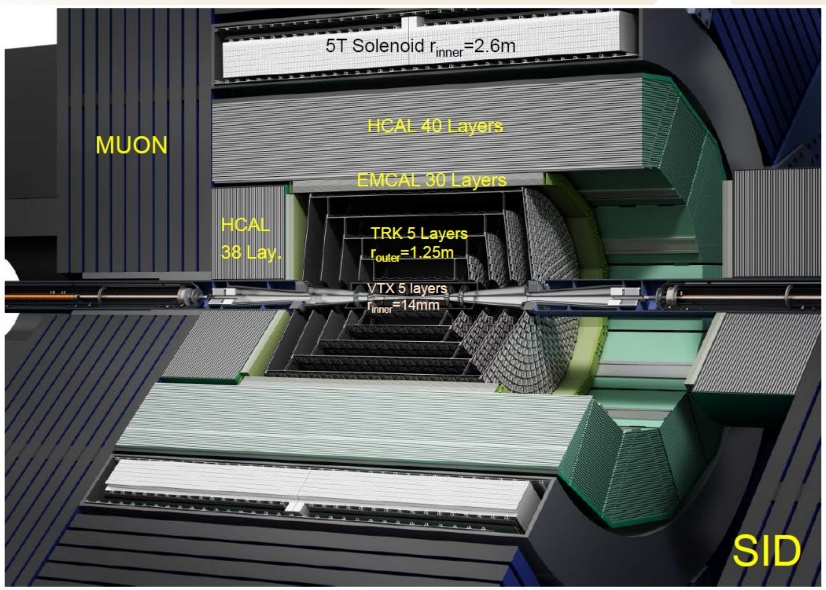


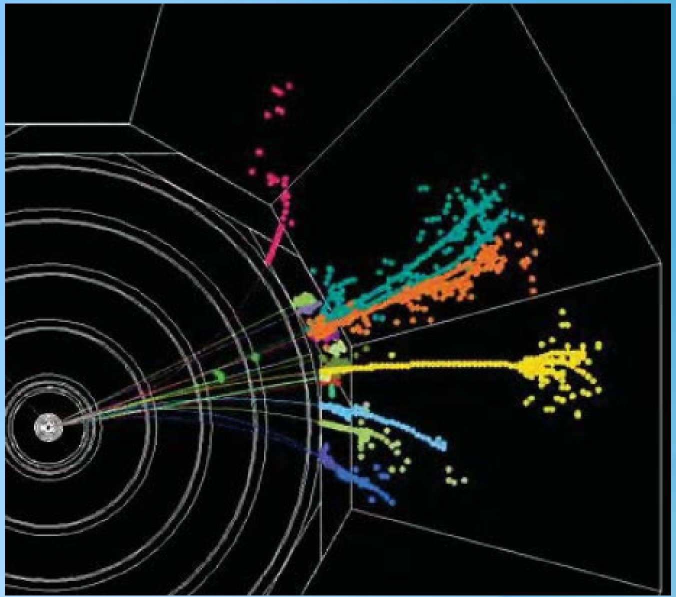
Andy White

UNIVERSITY OF TEXAS ARLINGTON

On behalf of the
SiD Consortium
(M. Stanitzki, A.White
Spokespersons)

With thanks to SiD colleagues
for materials provided!





The SiD Detector and the SiD Consortium

SiD Detector

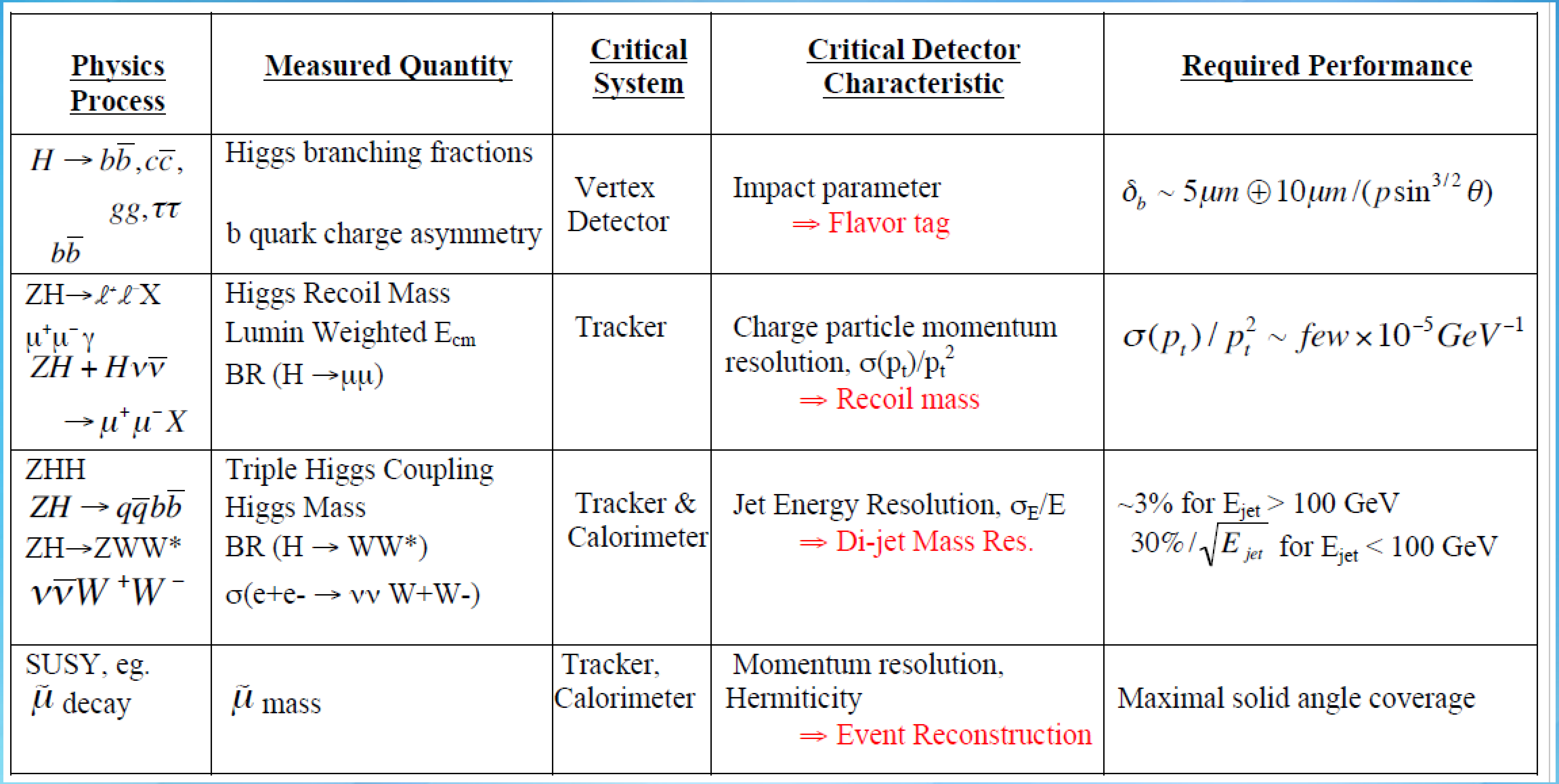
SiD Design Study started 2004 (Victoria ALCPG)
Validated by International Detector Advisory Group
Can deliver for the ILC Physics Program as configured

SiD Consortium

- since 2013
- Byelaws
- Individual and institutional memberships (Guest membership available for Snowmass studies!
- IB Chair – Phil Burrows (U. Oxford)

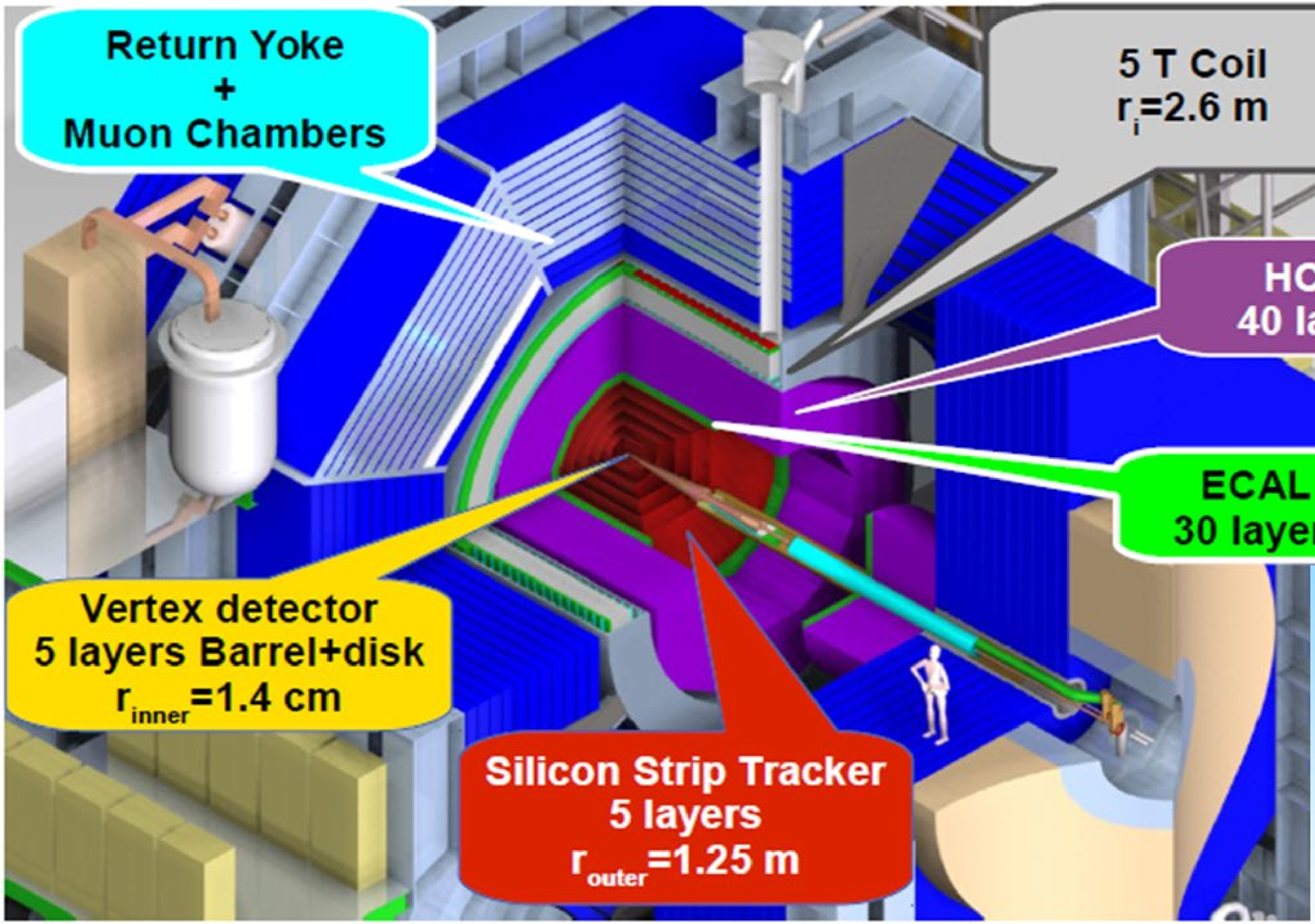
Very open and welcoming of new colleagues to join SiD to make it better by contributing new ideas, upgrades/alternatives– particularly by the younger generation!

SiD – Required Physics Performance



Physics Process	**Measured Quantity**	**Critical System**	**Critical Detector Characteristic**	**Required Performance**
$H \to b\bar{b}, c\bar{c},$ $gg, \tau\tau$ $b\bar{b}$	Higgs branching fractions b quark charge asymmetry	Vertex Detector	Impact parameter ⇒ Flavor tag	$\delta_b \sim 5\mu m \oplus 10\mu m/(p\sin^{3/2}\theta)$
ZH→$\ell^+\ell^-$X $\mu^+\mu^-\gamma$ $ZH + H\nu\bar{\nu}$ $\to \mu^+\mu^- X$	Higgs Recoil Mass Lumin Weighted E_{cm} BR (H →μμ)	Tracker	Charge particle momentum resolution, $\sigma(p_t)/p_t^2$ ⇒ Recoil mass	$\sigma(p_t)/p_t^2 \sim few \times 10^{-5} GeV^{-1}$
ZHH $ZH \to q\bar{q}b\bar{b}$ ZH→ZWW* $\nu\bar{\nu}W^+W^-$	Triple Higgs Coupling Higgs Mass BR (H → WW*) σ(e+e- → νν W+W-)	Tracker & Calorimeter	Jet Energy Resolution, σ_E/E ⇒ Di-jet Mass Res.	~3% for E_{jet} > 100 GeV $30\%/\sqrt{E_{jet}}$ for E_{jet} < 100 GeV
SUSY, eg. $\tilde{\mu}$ decay	$\tilde{\mu}$ mass	Tracker, Calorimeter	Momentum resolution, Hermiticity ⇒ Event Reconstruction	Maximal solid angle coverage

SiD Detector Baseline



Return Yoke
+
Muon Chambers

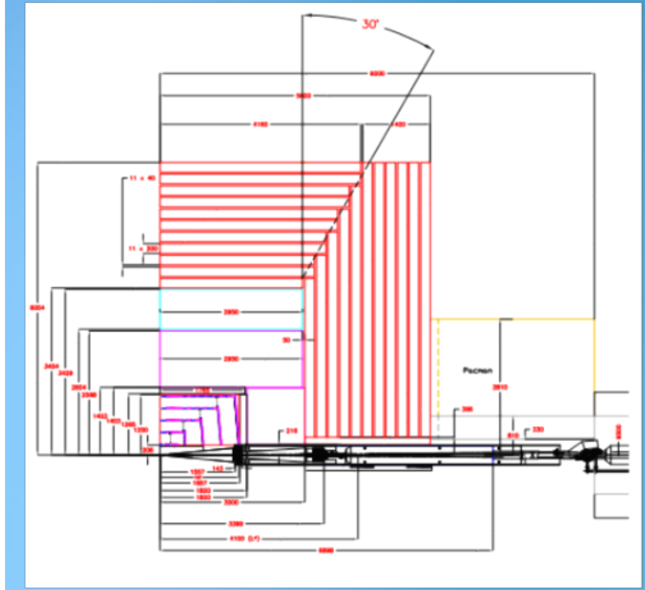
5 T Coil
r_i=2.6 m

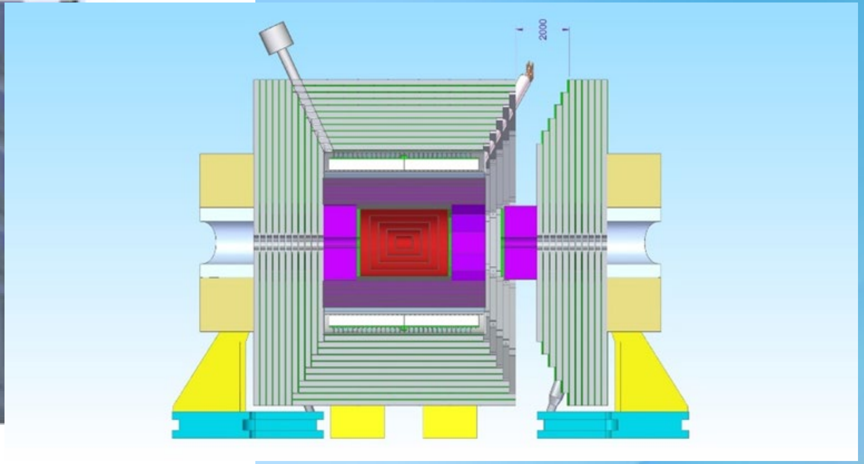
HCAL
40 layers

ECAL
30 layers

Vertex detector
5 layers Barrel+disk
r_{inner}=1.4 cm

Silicon Strip Tracker
5 layers
r_{outer}=1.25 m





The SiD Design Rationale

A compact, cost-constrained detector designed to make precision measurements and be sensitive to a wide range of new phenomena.

Design basics:

Robust silicon vertexing and tracking system – excellent momentum resolution, live for single bunch crossings.

Highly segmented “tracking” calorimeters optimized for Particle Flow.

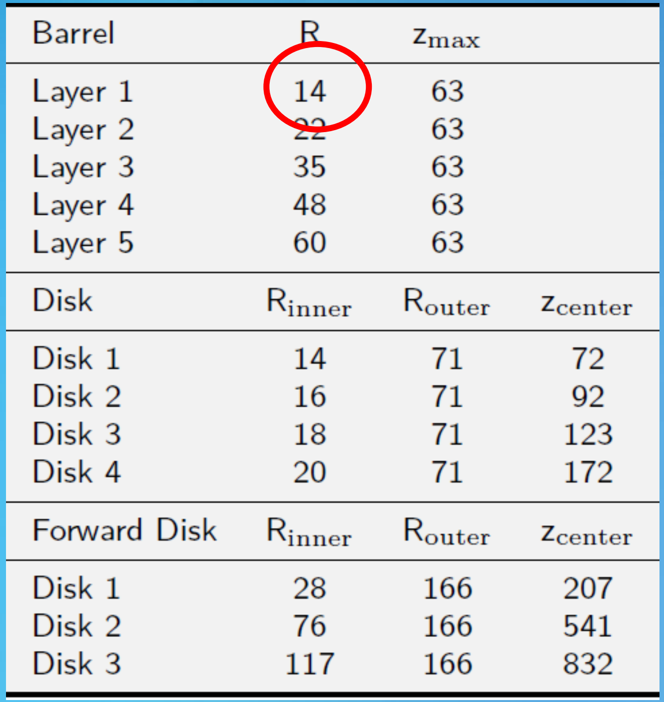
Compact design with 5T field.

Iron flux return/muon identifier – component of SiD self-shielding.

Detector is designed for rapid push-pull operation.

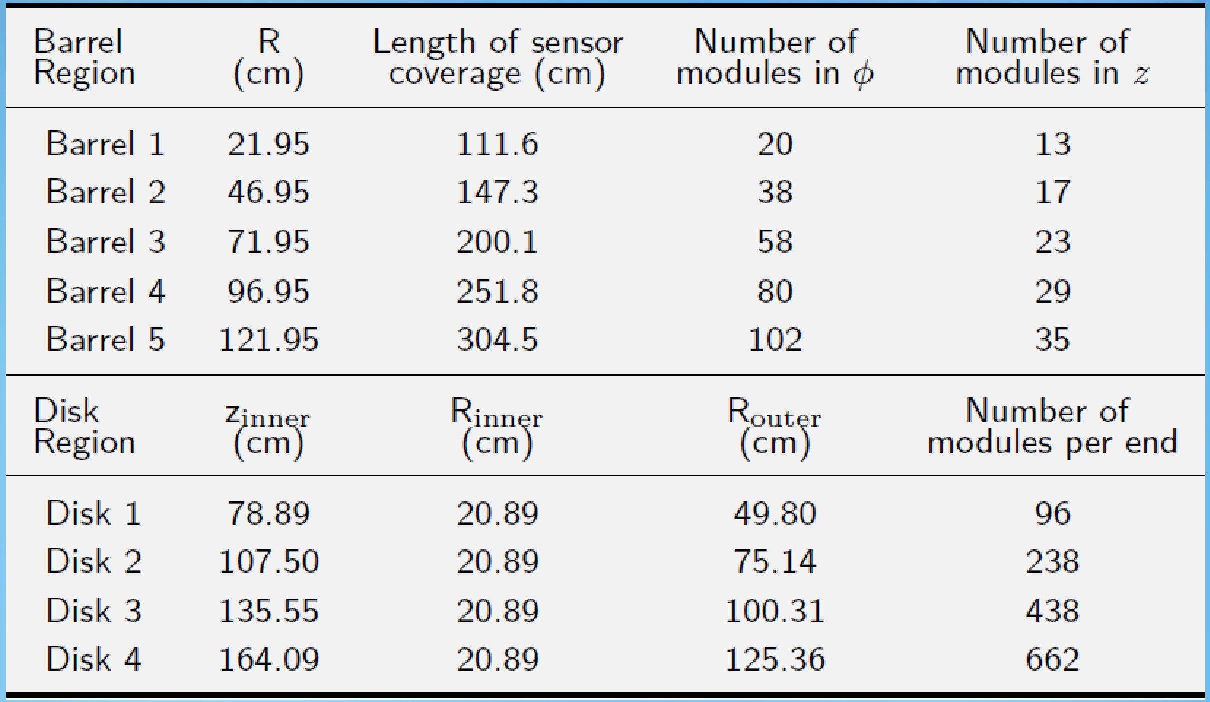
SiD Detector Parameters

Vertex Detector



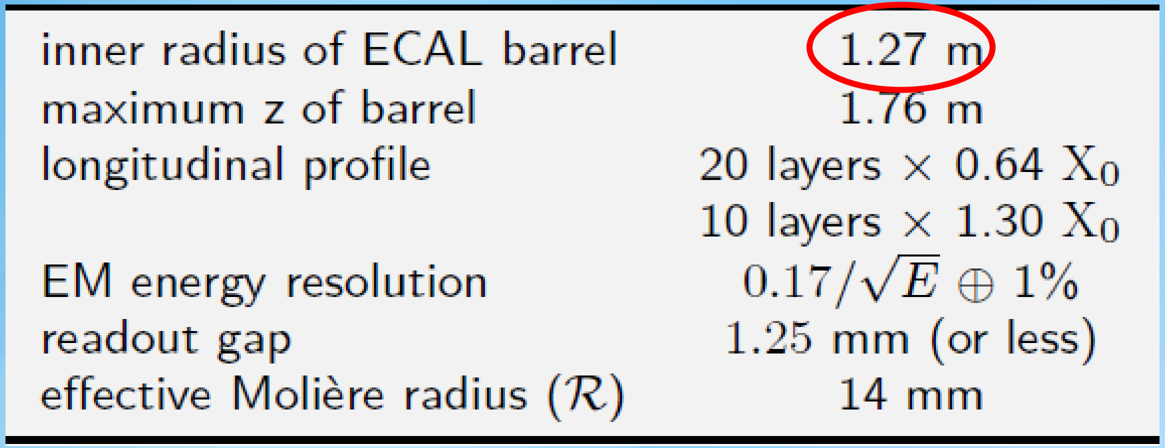
Barrel	R	z_{max}	
Layer 1	14	63	
Layer 2	22	63	
Layer 3	35	63	
Layer 4	48	63	
Layer 5	60	63	
Disk	**R_{inner}**	**R_{outer}**	**z_{center}**
Disk 1	14	71	72
Disk 2	16	71	92
Disk 3	18	71	123
Disk 4	20	71	172
Forward Disk	**R_{inner}**	**R_{outer}**	**z_{center}**
Disk 1	28	166	207
Disk 2	76	166	541
Disk 3	117	166	832

Main tracker

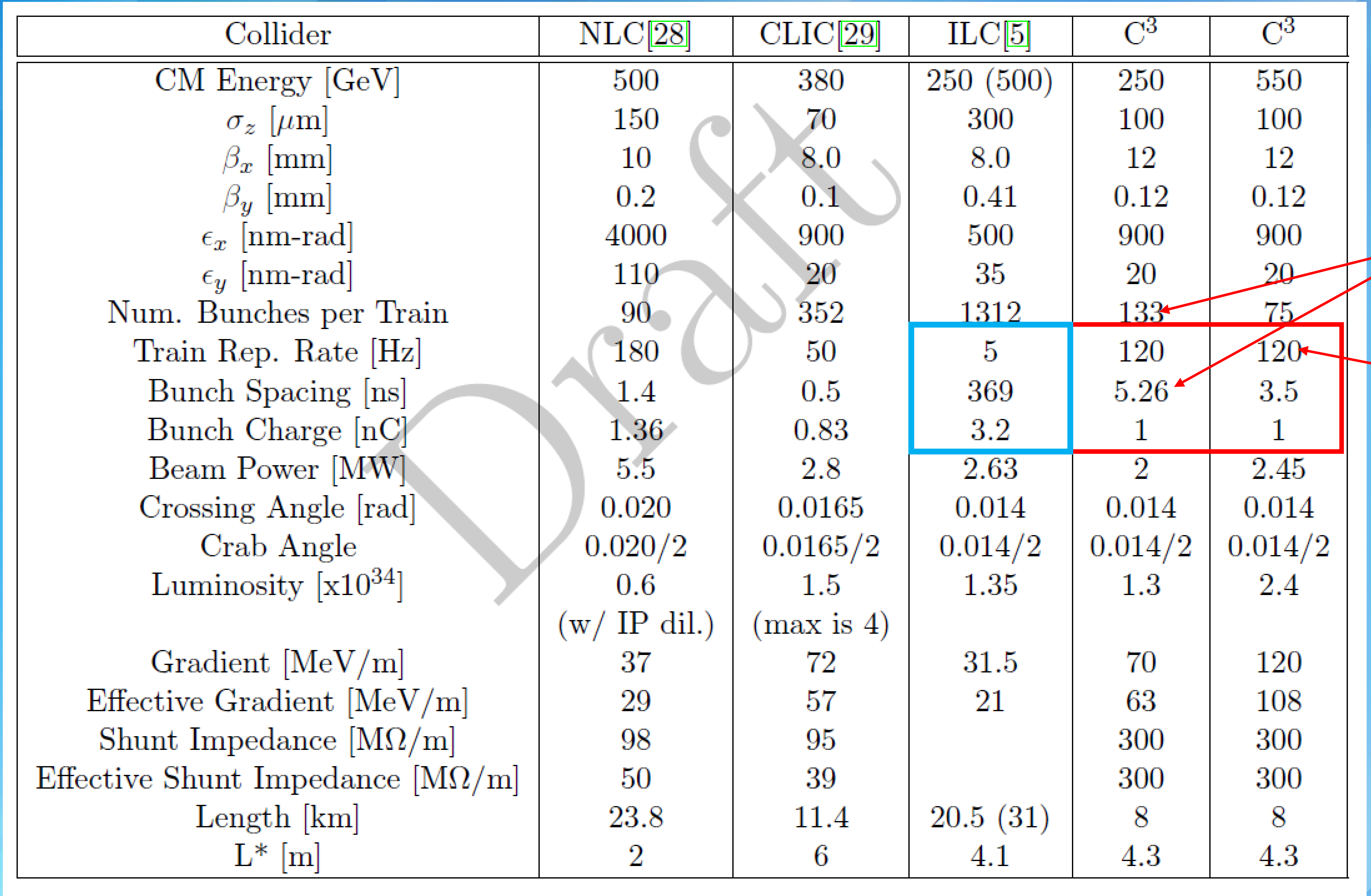


Barrel Region	R (cm)	Length of sensor coverage (cm)	Number of modules in ϕ	Number of modules in z
Barrel 1	21.95	111.6	20	13
Barrel 2	46.95	147.3	38	17
Barrel 3	71.95	200.1	58	23
Barrel 4	96.95	251.8	80	29
Barrel 5	121.95	304.5	102	35
Disk Region	**z_{inner} (cm)**	**R_{inner} (cm)**	**R_{outer} (cm)**	**Number of modules per end**
Disk 1	78.89	20.89	49.80	96
Disk 2	107.50	20.89	75.14	238
Disk 3	135.55	20.89	100.31	438
Disk 4	164.09	20.89	125.36	662

Electromagnetic Calorimeter



inner radius of ECAL barrel	1.27 m
maximum z of barrel	1.76 m
longitudinal profile	20 layers × 0.64 X_0
	10 layers × 1.30 X_0
EM energy resolution	$0.17/\sqrt{E} \oplus 1\%$
readout gap	1.25 mm (or less)
effective Molière radius ($\mathcal{R}$)	14 mm



Collider	NLC[28]	CLIC[29]	ILC[5]	C^3	C^3
CM Energy [GeV]	500	380	250 (500)	250	550
σ_z [μm]	150	70	300	100	100
β_x [mm]	10	8.0	8.0	12	12
β_y [mm]	0.2	0.1	0.41	0.12	0.12
ϵ_x [nm-rad]	4000	900	500	900	900
ϵ_y [nm-rad]	110	20	35	20	20
Num. Bunches per Train	90	352	1312	133	75
Train Rep. Rate [Hz]	180	50	5	120	120
Bunch Spacing [ns]	1.4	0.5	369	5.26	3.5
Bunch Charge [nC]	1.36	0.83	3.2	1	1
Beam Power [MW]	5.5	2.8	2.63	2	2.45
Crossing Angle [rad]	0.020	0.0165	0.014	0.014	0.014
Crab Angle	0.020/2	0.0165/2	0.014/2	0.014/2	0.014/2
Luminosity [x10^{34}]	0.6 (w/ IP dil.)	1.5 (max is 4)	1.35	1.3	2.4
Gradient [MeV/m]	37	72	31.5	70	120
Effective Gradient [MeV/m]	29	57	21	63	108
Shunt Impedance [MΩ/m]	98	95		300	300
Effective Shunt Impedance [MΩ/m]	50	39		300	300
Length [km]	23.8	11.4	20.5 (31)	8	8
L* [m]	2	6	4.1	4.3	4.3

700 ns
Flat top

every

8.3 ms

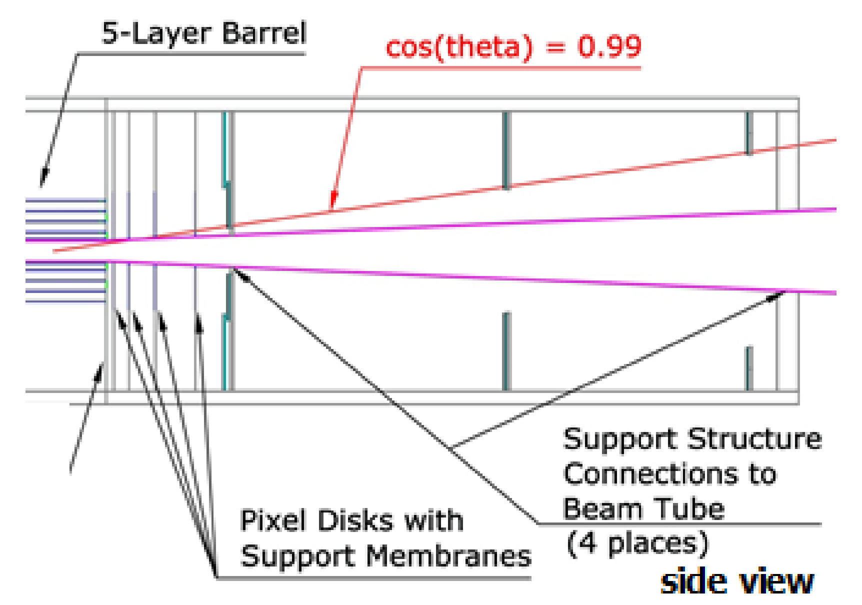
SiD Design Considerations for C^3

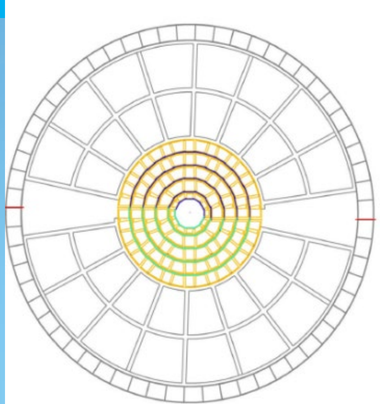
- Beam time structure – effects for each subsystem/bunch tagging
- Beam profile at IP – VTX inner layer
- Beam pipe
- Beam exit profile for BeamCal
- Pair background (also vs Ecm), beamstrahlung
- Muon background – mitigation
- L* - IR layout
- QD0/detector
- Event overlap in calorimeters
- LumiCal
- Rep. rate – power pulsing
- P(e+) = 0
- 250/550 running – multi-TeV?
- One or two detectors?

In general we expect the effects of using SiD at C3 vs. ILC to be relatively moderate with no show stoppers.

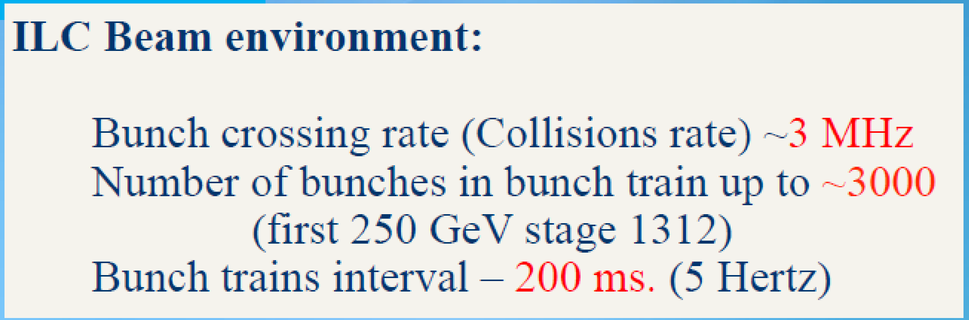
This talk will consider these issues for the subsystems of SiD.

SiD Tracking: A Robust, Low Material, High Precision Silicon System Vertex Detector





Preliminary ideas for mechanical design.
Power pulsing, forced air cooling



ILC Beam environment:

Bunch crossing rate (Collisions rate) ~3 MHz
Number of bunches in bunch train up to ~3000
(first 250 GeV stage 1312)
Bunch trains interval – 200 ms. (5 Hertz)

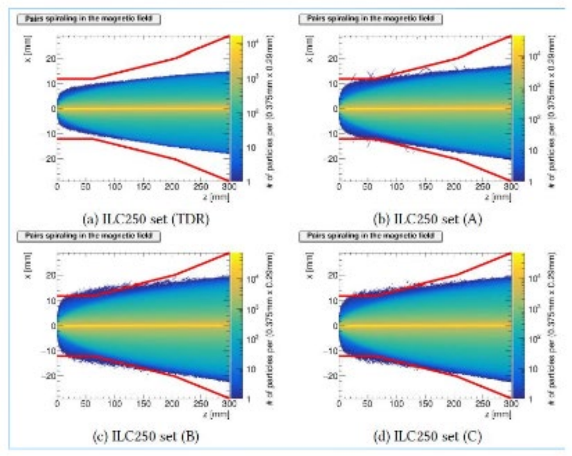
5T field allows first layer to be very close to the beam.

R_{min} = 14mm.

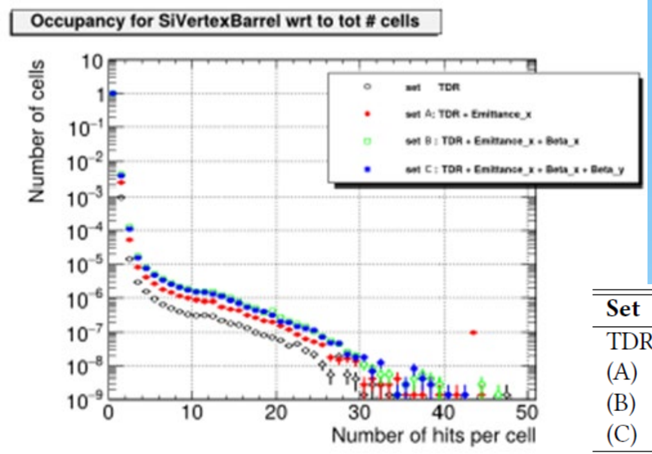
Pair background/Occupancy study

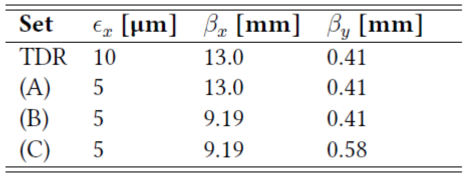
Very challenging requirements

- < 3 μm hit resolution
- Feature size ~20 μm
- ~0.1% X_0 per layer material budget
- < 130 μW / mm^2
- Single bunch time resolution



(a) ILC250 set (TDR)
(b) ILC250 set (A)
(c) ILC250 set (B)
(d) ILC250 set (C)





Set	ϵ_x [μm]	β_x [mm]	β_y [mm]
TDR	10	13.0	0.41
(A)	5	13.0	0.41
(B)	5	9.19	0.41
(C)	5	9.19	0.58

Anne Schuetz
(DESY)

SiD Tracking: A Robust, Low Material, High Precision Silicon System Vertex Detector

Three prototypes studied

Chronopixel - Oregon, Yale

Chronopixel prototype 3 development board

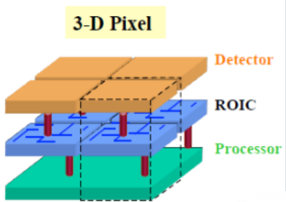
Chronopixel PIC 16F1527 microcontroller

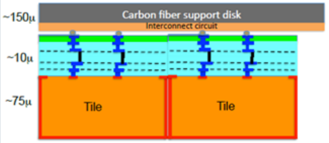
- monolithic CMOS design
  90 nm feature size,
  7 µm epitaxial layer
  280 µm thick chip
  10 ohm·cm
  manufactured by TSMC
- store up to 2 hits per pixel, 12 bit per timestamps
- 25 µm pixel pitch
- implements 6 sensor diode options

Following a multi-year R&D effort, Chronopixel prototype 3 demonstrated a working ILC CMOS vertex sensor that satisfies the ILC design requirements.

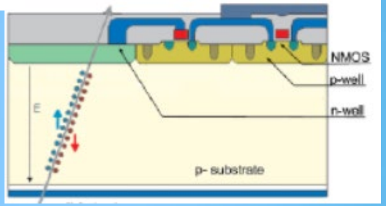
Possible alternatives

Vertically Integrated ("3D")

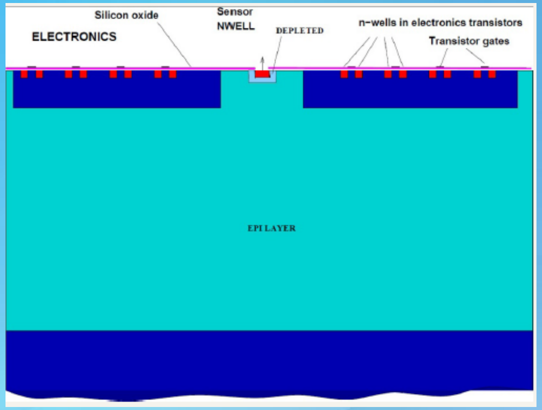




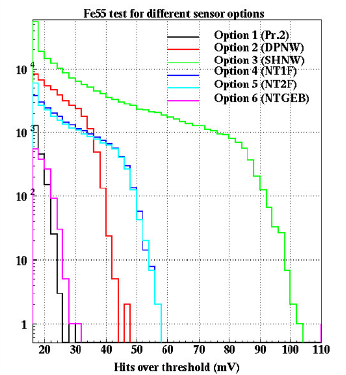
HV
CMOS



Option 3 – shallow N-WELL



Best option, but more studies needed



diode option	Capacitance (fF)	µV/e
1	9.0	18
2	6.2	26
3	2.7	59
4	4.9	33
5	4.9	33
6	8.9	18

Option #	Noise r.m.s (mV)	Noise r.m.s (# electrons)
1	1.12	63
2	1.08	42
3	1.7	29
4	1.21	37
5	1.23	38
6	0.98	54

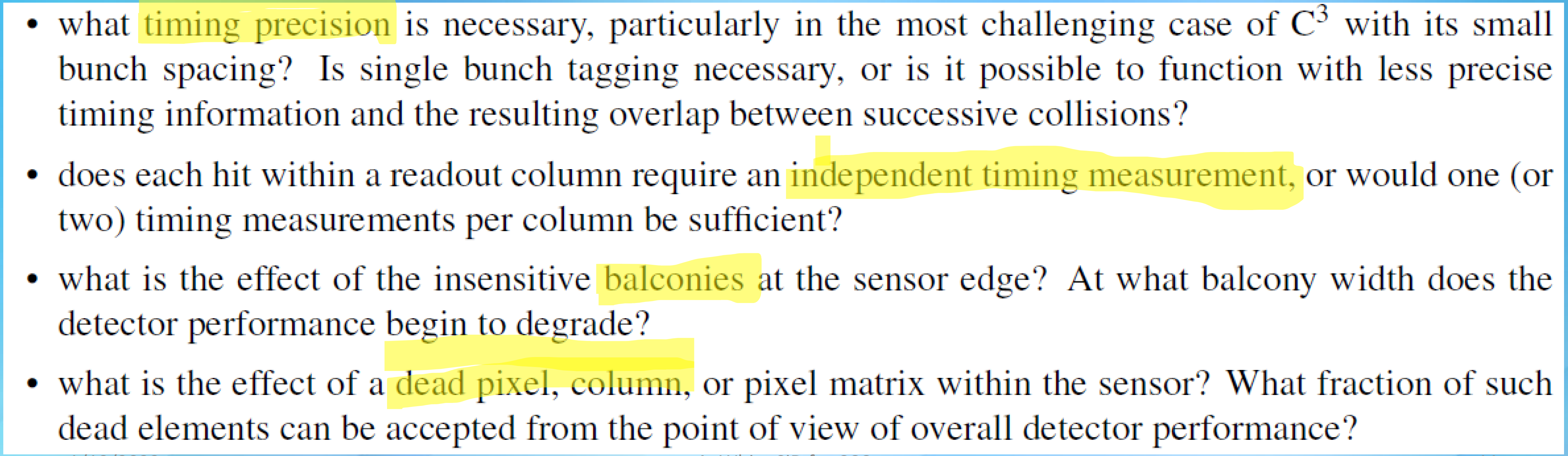
Parameter	ILC Requirement	Prototype Tests
Detector Sensitivity	10 µV/electron	59 µV/electron
Detector Noise	25 electrons	29 electrons
Comparator Accuracy	0.2 mV RMS	0.2 mV RMS
Sensor Capacitance	10 fF	2.7 fF
Clocking Speed	3.3 MHz	7.3 MHz
Charge collection time	300 nsec	20 nsec
Readout Rate	25 Mbits/sec	25 Mbits/sec
Power Consumption	0.13 mW/mm^2	OK by estimate
Radiation Hardness	10^{11} neutrons/cm^2/yr	10^{13}neutrons/cm^2 or 110 Mrad

J. Brau – CPAD Workshop Dec '19

SiD design update: MAPS

- MAPS for Vertex, Main Tracker, E.M. Calorimeter (65 nm)
- Stitching – large scale sensors, reduced dead areas
- 25 x 100 μm^2 pixels(25μm in bend plane)
- Lower power, lower cost, less material.
- Fully-depleted MAPS/CMOS: faster charge collection, higher efficiency, less cross-pixel charge sharing

US-Japan Proposal – R&D questions

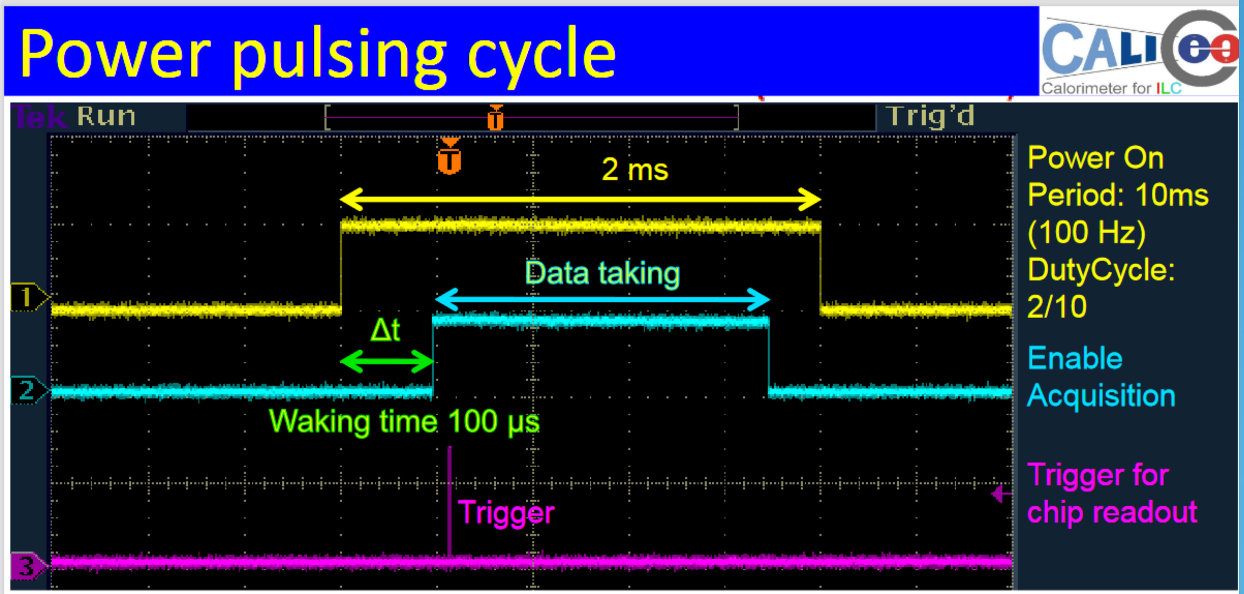


- what timing precision is necessary, particularly in the most challenging case of C^3 with its small bunch spacing? Is single bunch tagging necessary, or is it possible to function with less precise timing information and the resulting overlap between successive collisions?
- does each hit within a readout column require an independent timing measurement, or would one (or two) timing measurements per column be sufficient?
- what is the effect of the insensitive balconies at the sensor edge? At what balcony width does the detector performance begin to degrade?
- what is the effect of a dead pixel, column, or pixel matrix within the sensor? What fraction of such dead elements can be accepted from the point of view of overall detector performance?

Power Pulsing

ILC – 5 Hz. “On” for ~1ms , “off” for 199ms

ILC – allow few ms for acquisition



Power pulsing cycle

C^3 – 120 Hz -> bunch train (133 bunches x 5.26ns = 700 ns) every 8.3ms

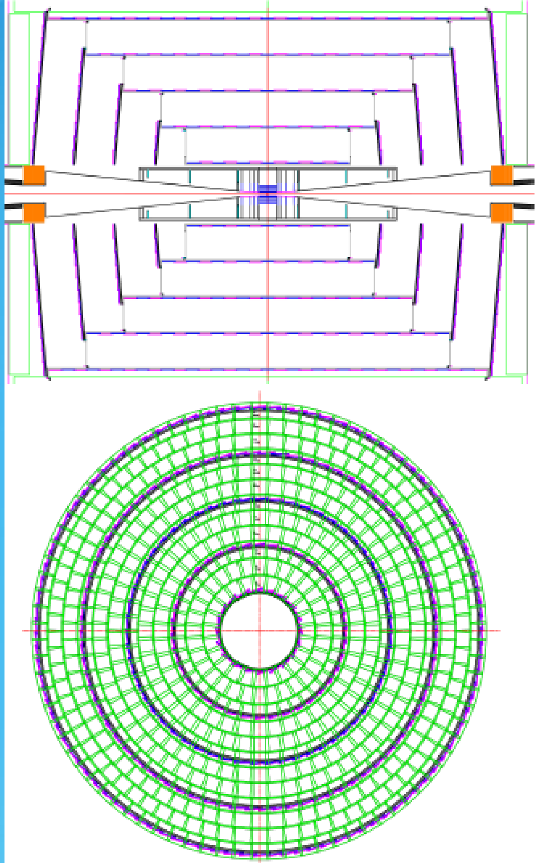
C^3 – few µs for power on/off. EMI effects? Pulsing in 5T field?

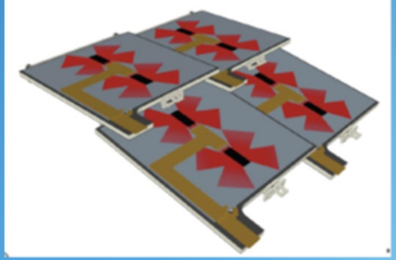
MAPS – “lower power” -> needed reduction factor from power pulsing?
(1/100) for ILC – similar for C^3

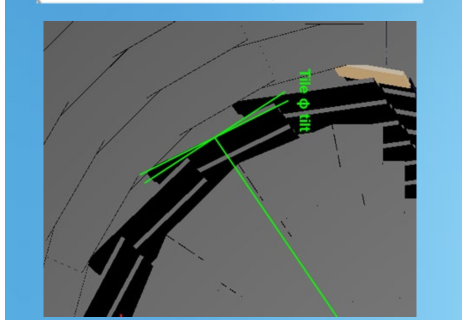
SiD VTX for C^3

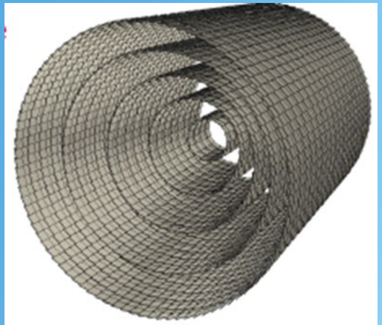
- Required time resolution? MAPS initial goal ~3 ns (power limited)
- SiD is following ALICE/ALPIDE (MAPS for ITS) developments
- Do we need single bunch tagging?
- Need new study/simulation (train) of pair background
- Reduced bunch charge C^3 vs ILC -> smaller pair background
- Pair envelope – stay-clear region?
- Occupancy per layer
- Beam pipe design – same a for ILC?
- Beam profile – radius of inner layer?
- Is 5T optimal?
- Power pulsing – cooling/material

SiD Silicon (Strip) Tracker





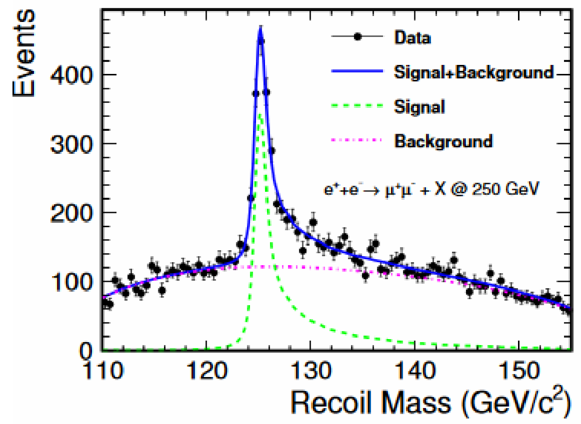




Baseline

- All Silicon Tracker
  - Using Silicon micro-strips
    - 25 µm pitch / 50 µm readout
    - v2 sensor prototype July 2017*
- 5 barrel layers / 4 disks
- Tracking unified with vertex detector
  - 10 layers in barrel
- Gas-cooled
- Material budget < 20% X_0 in the active region
- Readout using KPiX ASIC
  - Same readout as ECAL
  - Bump-bonded directly to the module

Physics goal

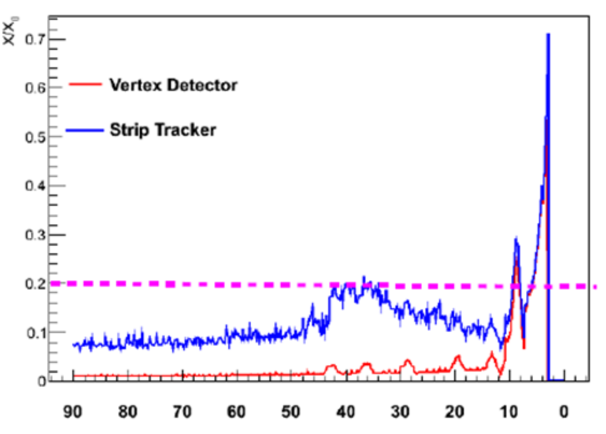


Excellent momentum resolution to obtain the best possible recoil mass measurement

MAPS/Pixel tracker option

kPixM – optimized for tracker, 25µm x 500µm pixels. Position resn. < 10µm, S/N >20

Future initiative: SLAC/DESY for MAPS tracker development.



Goal – full prototype test: sensor + kPix + cables

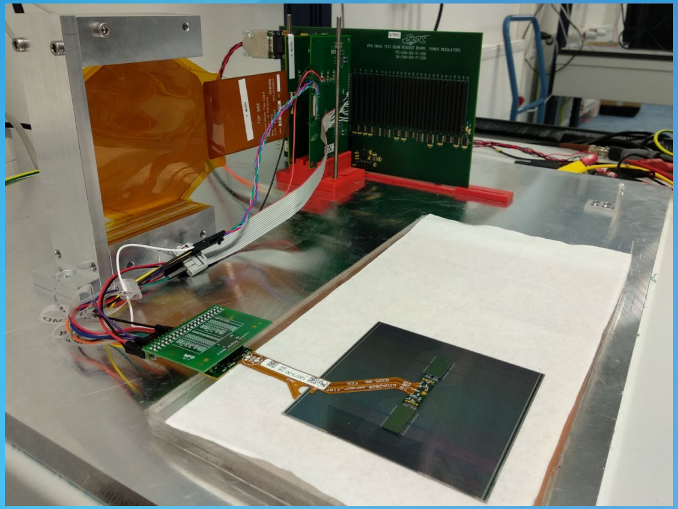
Pixel tracker option and alignment methods (Bristol)

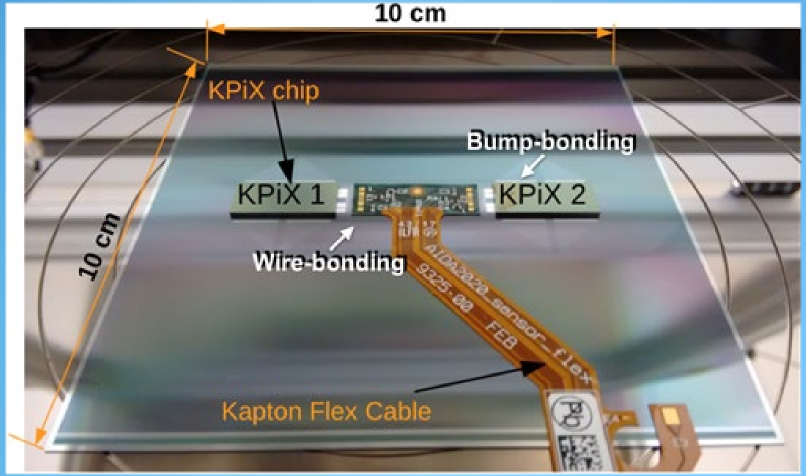
Carbon fiber structures for low material, integrated services (Oxford, Lancaster, Liverpool)

SiD Silicon (Strip) Tracker

DESY Test Beam results

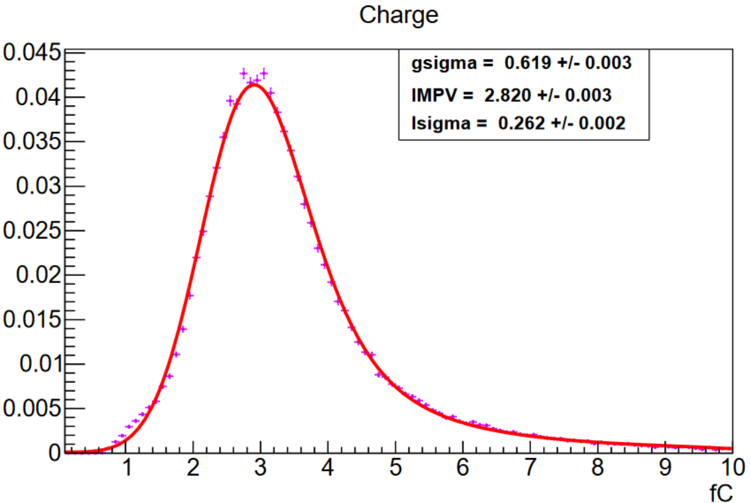
M. Stanitzki, U. Kraemer DESY
M. Breidenbach SLAC



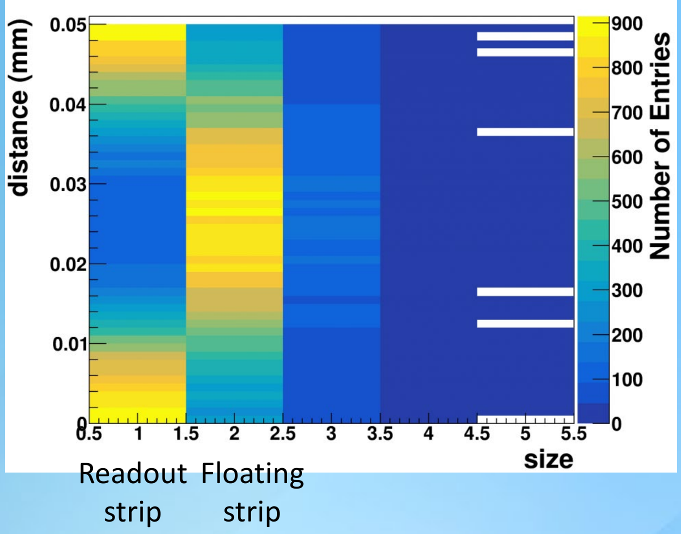


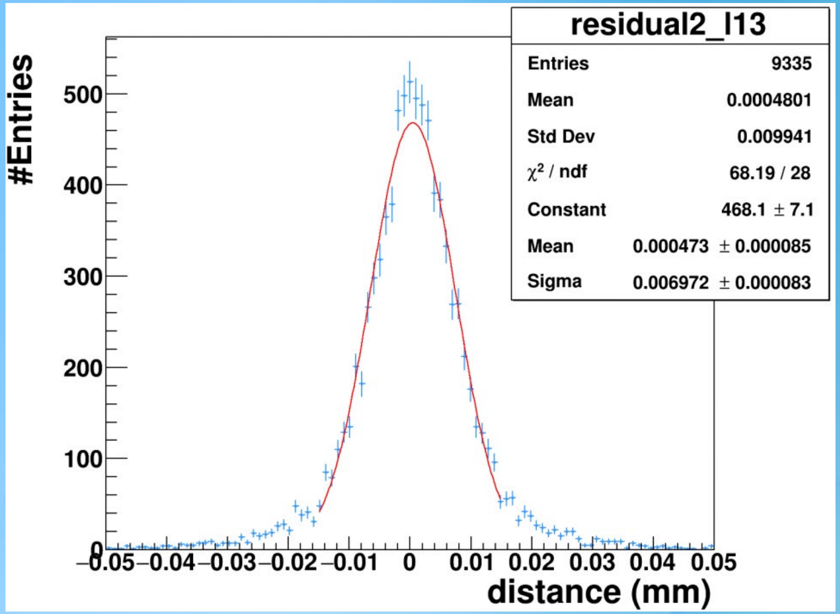
Residuals of sensor measurement
External telescope

Single point resolution 7µm



Charge distribution – hits on track
MPV of charge of 2.8 fC

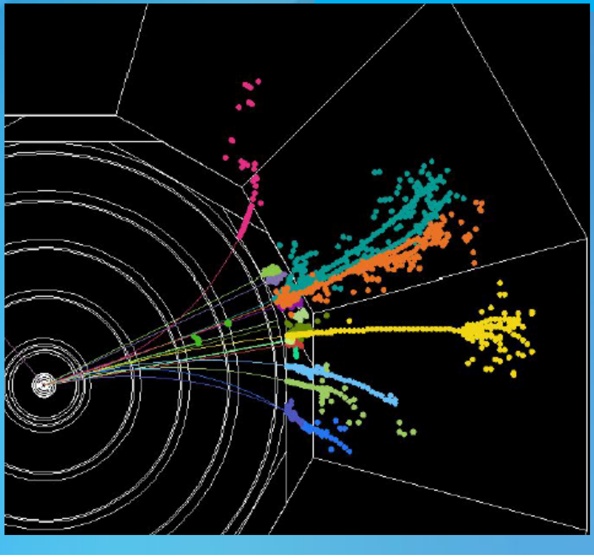




SiD Main Tracker for C^3

- Required time resolution? MAPS initial goal ~3 ns
- Do we need single bunch tagging?
- Develop new layout for VTX + TRK system using MAPS
- New material profile
- Study:
    - tracking efficiency/dead pixels/lost hits
    - fake rates
    - use of fast timing/4-D tracking
    - issues (material?) from including fast timing?
    - pattern recognition
    - momentum resolution
    - effects of beam backgrounds

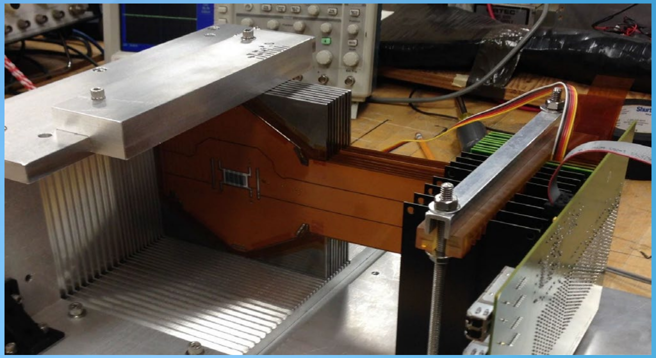
SiD Electromagnetic Calorimeter

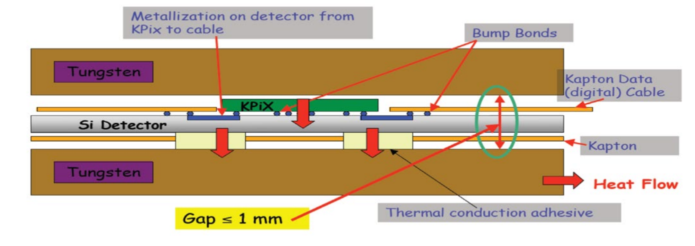


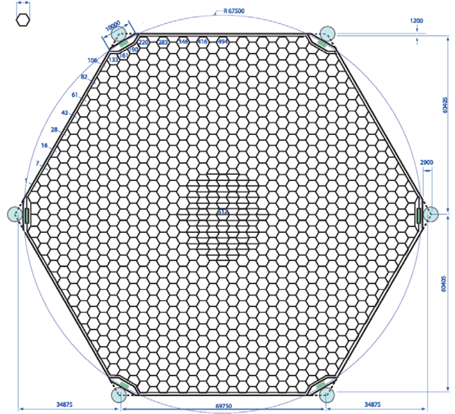
Highly granular “imaging” calorimetry essential for ILC physics program:

- Particle id/reconstruction
- Tracking charged particles
- Integral part of Particle Flow detector design

Beam tests,9-layers, SLAC

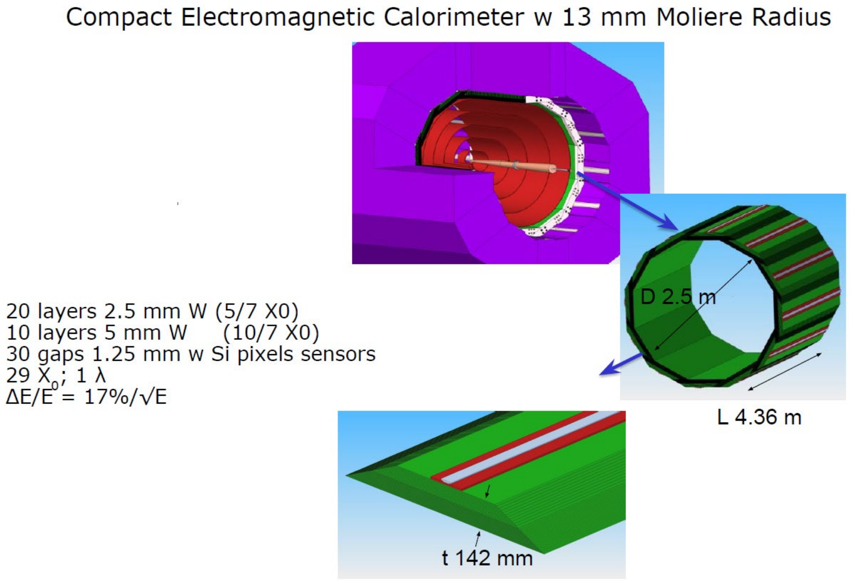






1024 pixels
13 mm^2

Baseline design: Silicon/Tungsten

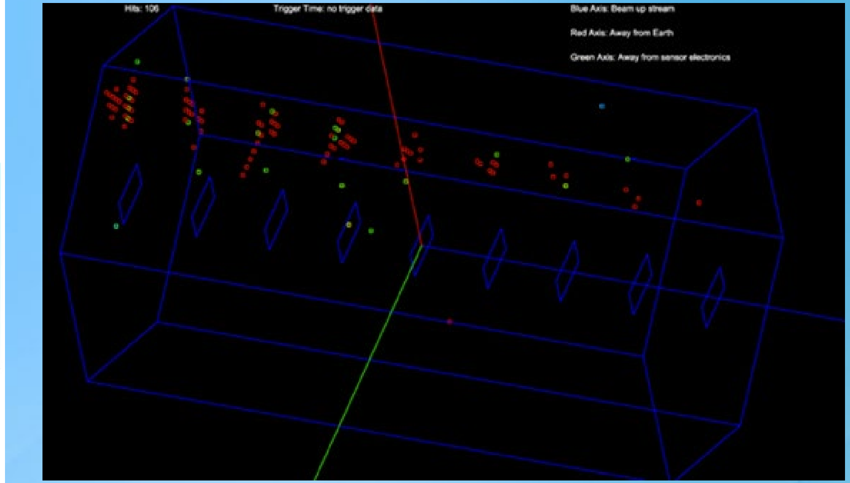


Compact Electromagnetic Calorimeter w 13 mm Moliere Radius

20 layers 2.5 mm W (5/7 X0)
10 layers 5 mm W (10/7 X0)
30 gaps 1.25 mm w Si pixels sensors
29 X_0 ; 1 λ
$\Delta E/E = 17\%/\sqrt{E}$

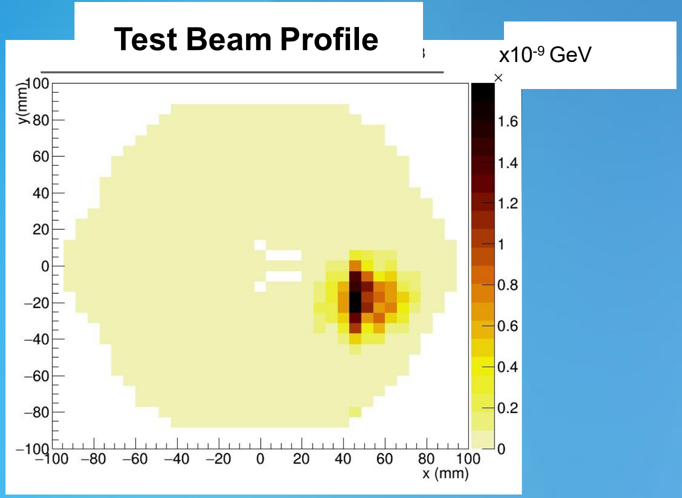
Oregon, SLAC, UC Davis

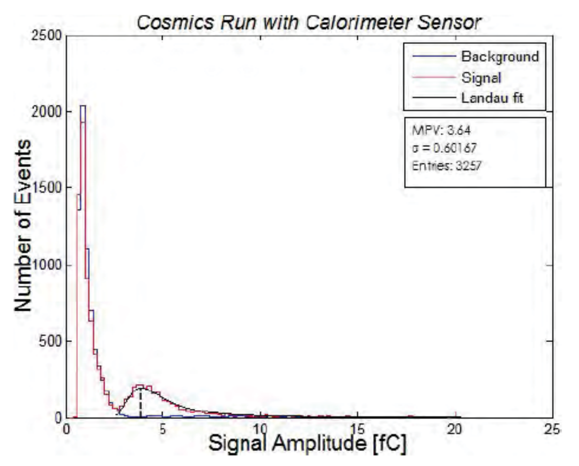
Single electron event

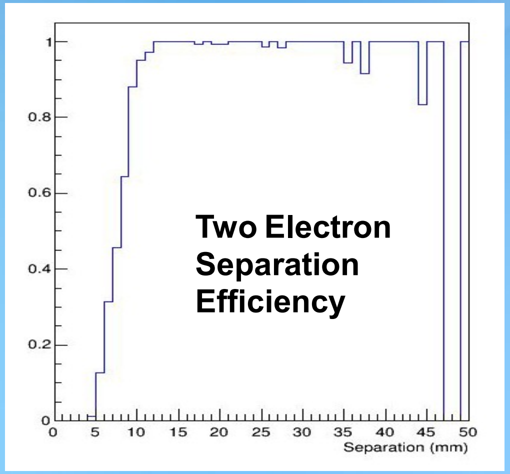


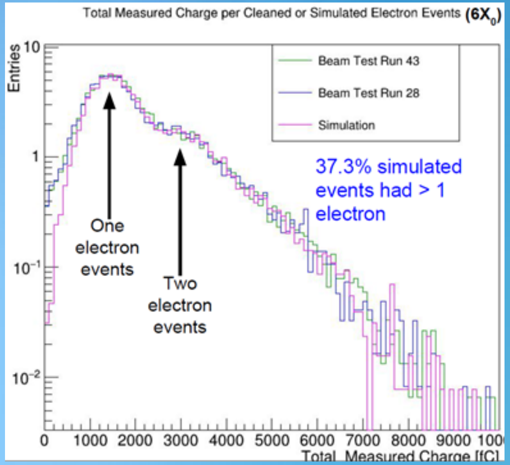
SiD Electromagnetic Calorimeter

J Barkeloo et al 2019 J. Phys.: Conf. Ser. 1162 012016

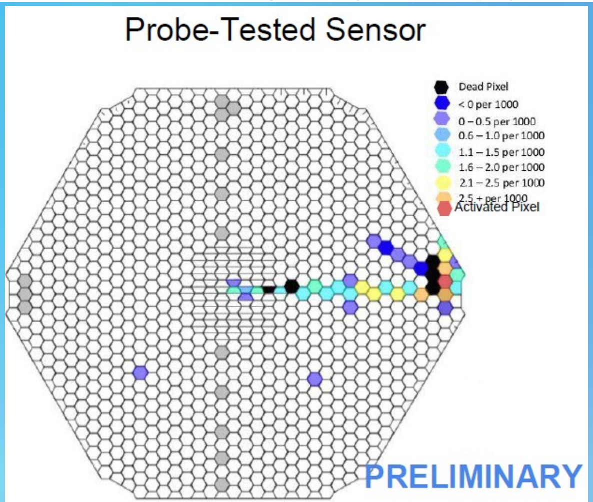

Test Beam Profile



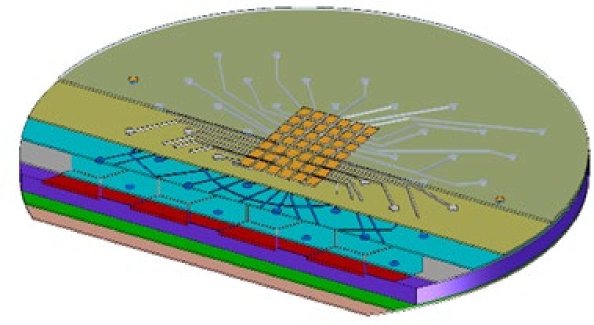




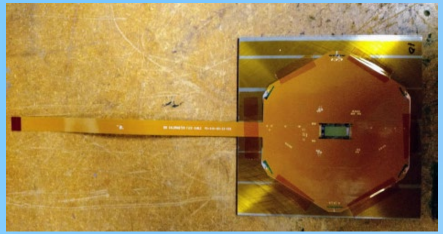
Additional signal detected in pixels along trace of activated pixel (cross talk)

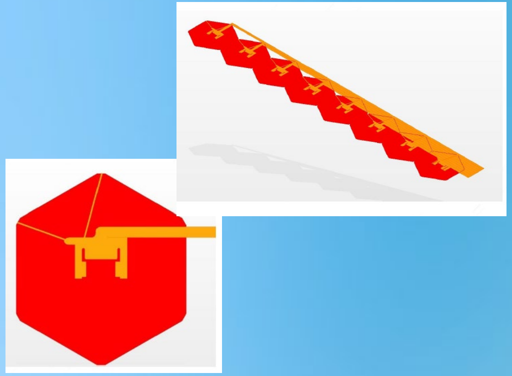

Probe-Tested Sensor

New sensor design – added shield layer



New cable design: one cable/sensor, wire bonded





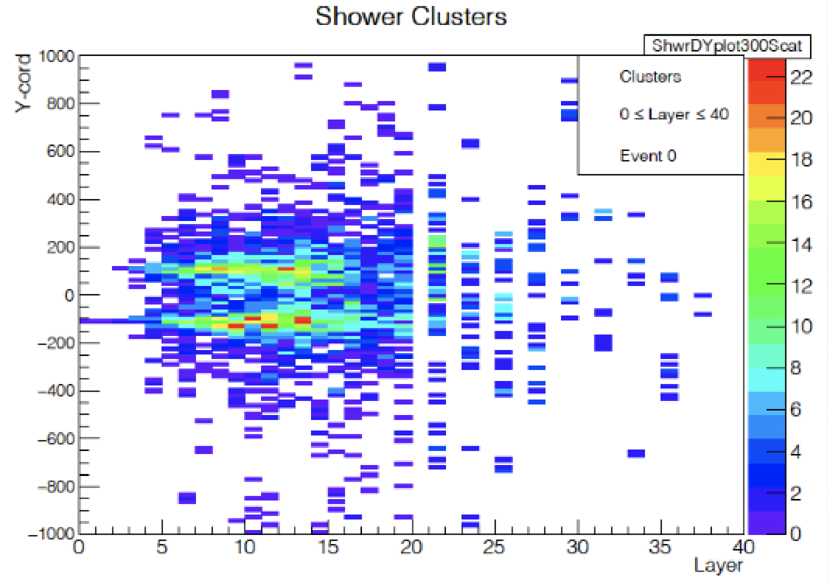
Status: testing beginning of *new* sensor bump-bonded to KPiX, new cable wire-bonded. Sensor and KPiX calibrate – all connections are good.

MAPS for SiD ECal

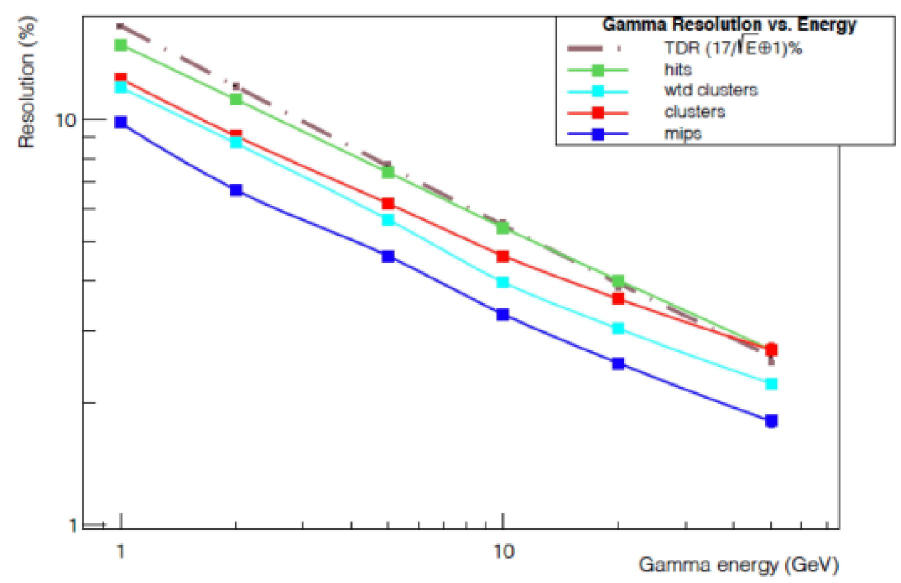
Jim Brau – detailed simulation of digital Si/W ECal using MAPS approach

- 20 thin W layers (0.64 X_0), 10 Thick W layers.
- Pixels 25μm x 100 μm (25μm in bend plane)
- MIP counting
- Examples of excellent results – very significant advance on SiD TDR ECal.
- Results are guiding the design of the MAPS sensor
- Benefits of including fast timing? (See HCal timing discussion later)

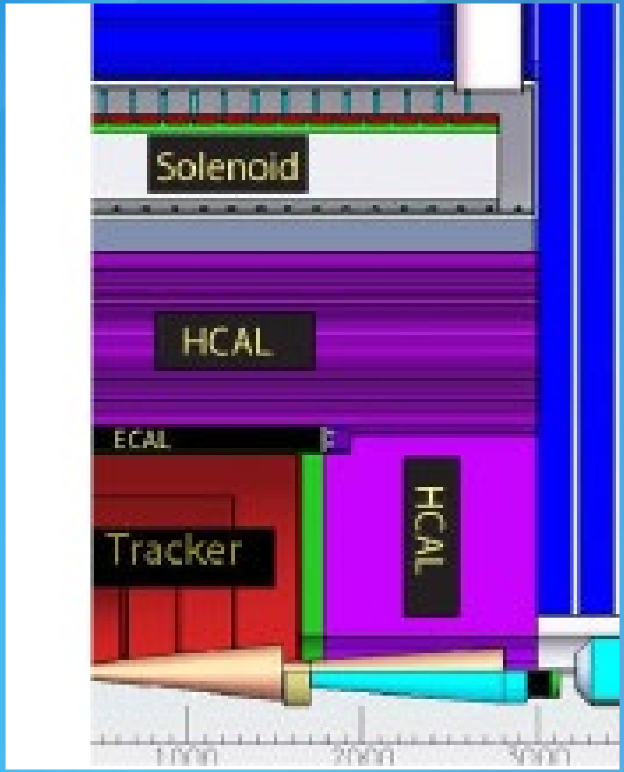
Pixel clusters – 40 GeV π^0 -> two 20 GeV γ

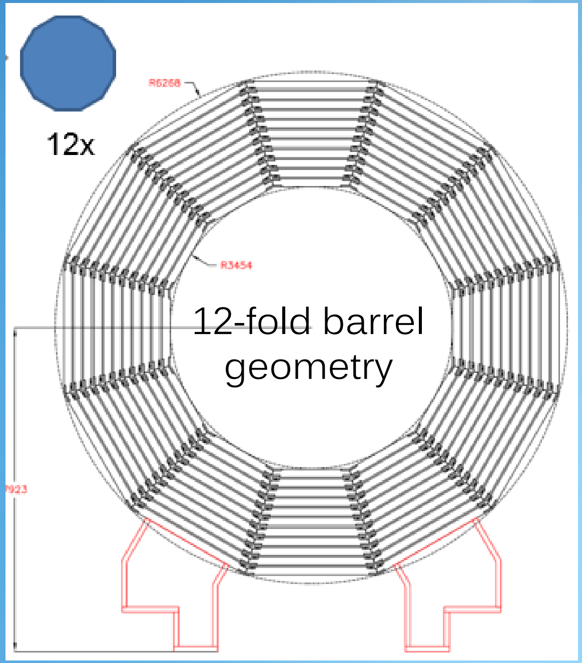


Energy resolution of γ showers

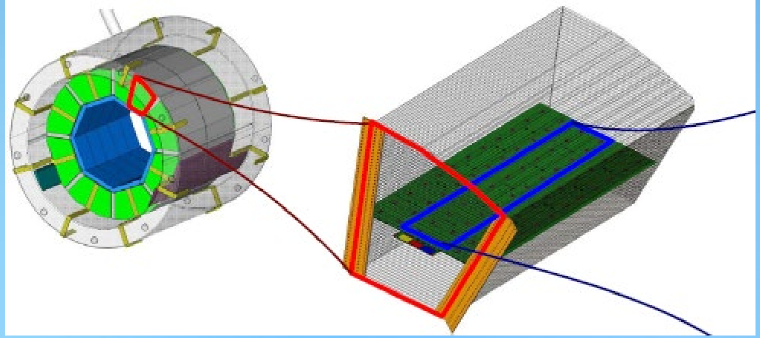


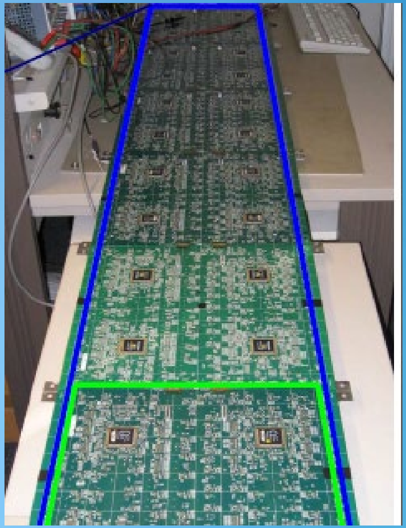
SiD Hadron Calorimeter

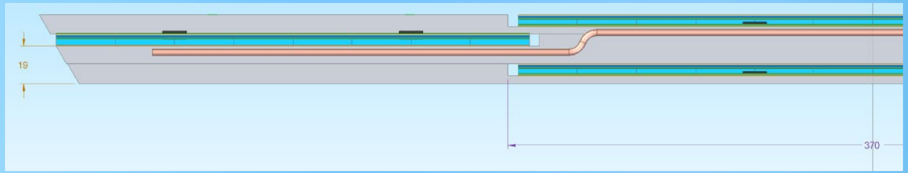




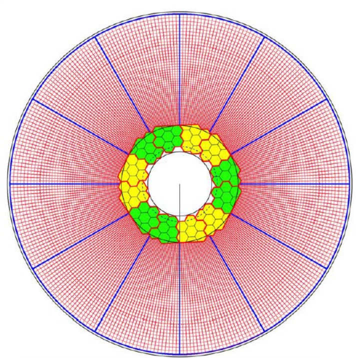
Marco Oriunno
(SLAC)



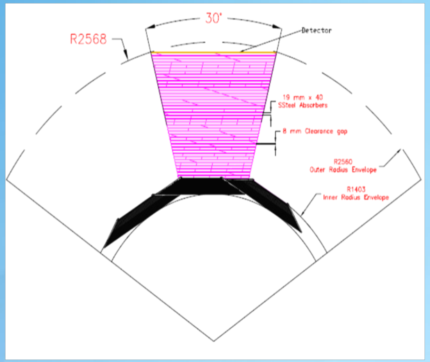


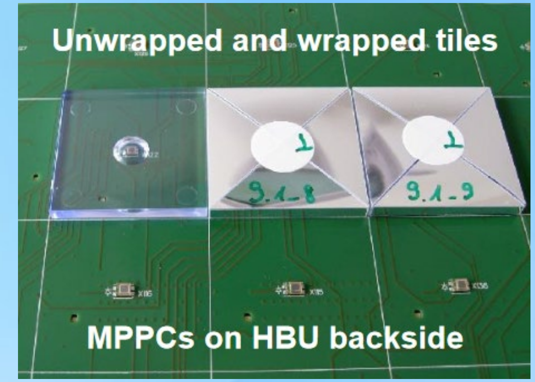


Same issues for CMS HGCAL



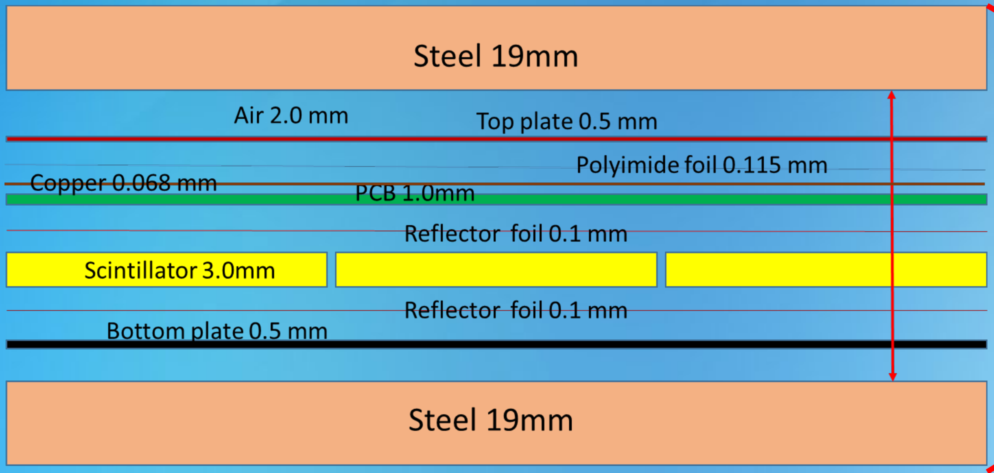
Baseline technology for the SiD HCal is Scintillator/SiPM/Steel





UTA, SLAC, NIU

SiD Hadron Calorimeter


Steel 19mm

Air 2.0 mm

Top plate 0.5 mm

Polyimide foil 0.115 mm

Copper 0.068 mm

PCB 1.0mm

Reflector foil 0.1 mm

Scintillator 3.0mm

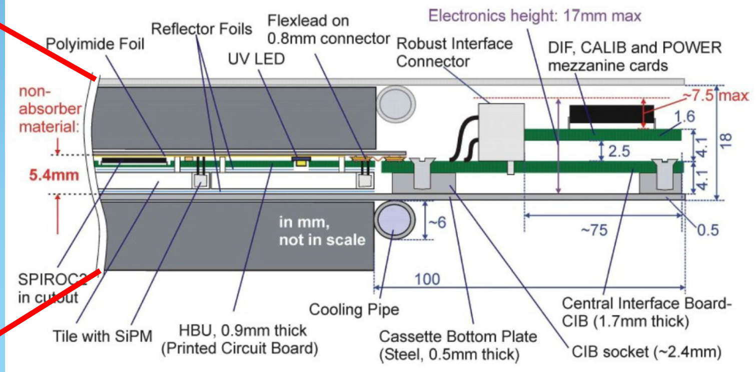
Reflector foil 0.1 mm

Bottom plate 0.5 mm

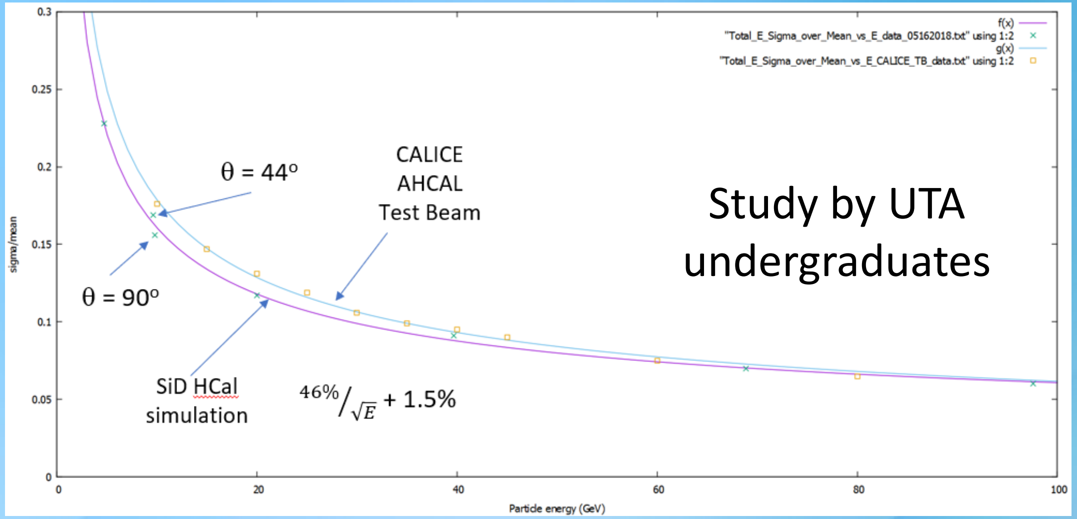
Steel 19mm

Active layer thickness = 7.383 mm

CALICE design



Checking new SiD simulation: compare simulated single particle energy resolution with actual CALICE test beam results



θ = 44°

θ = 90°

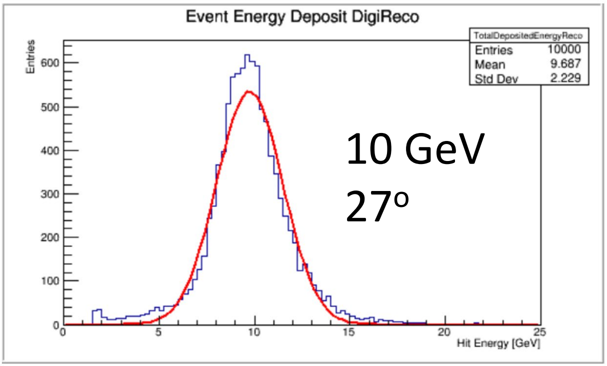
CALICE AHCAL Test Beam

SiD HCal simulation

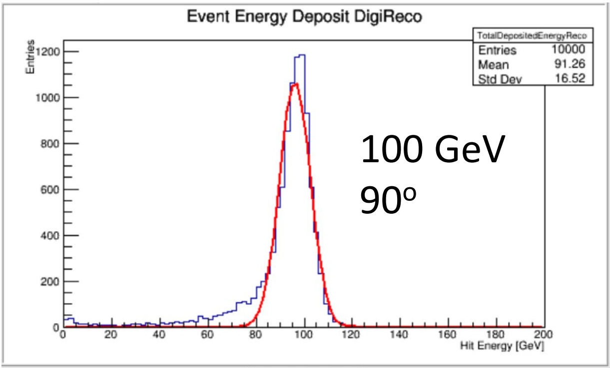
$46\%/\sqrt{E} + 1.5\%$

Study by UTA undergraduates

Ongoing: single particle studies.
Next: full event studies with PANDORA as prelude to next round of physics studies



10 GeV
27°



100 GeV
90°

UTA, SLAC

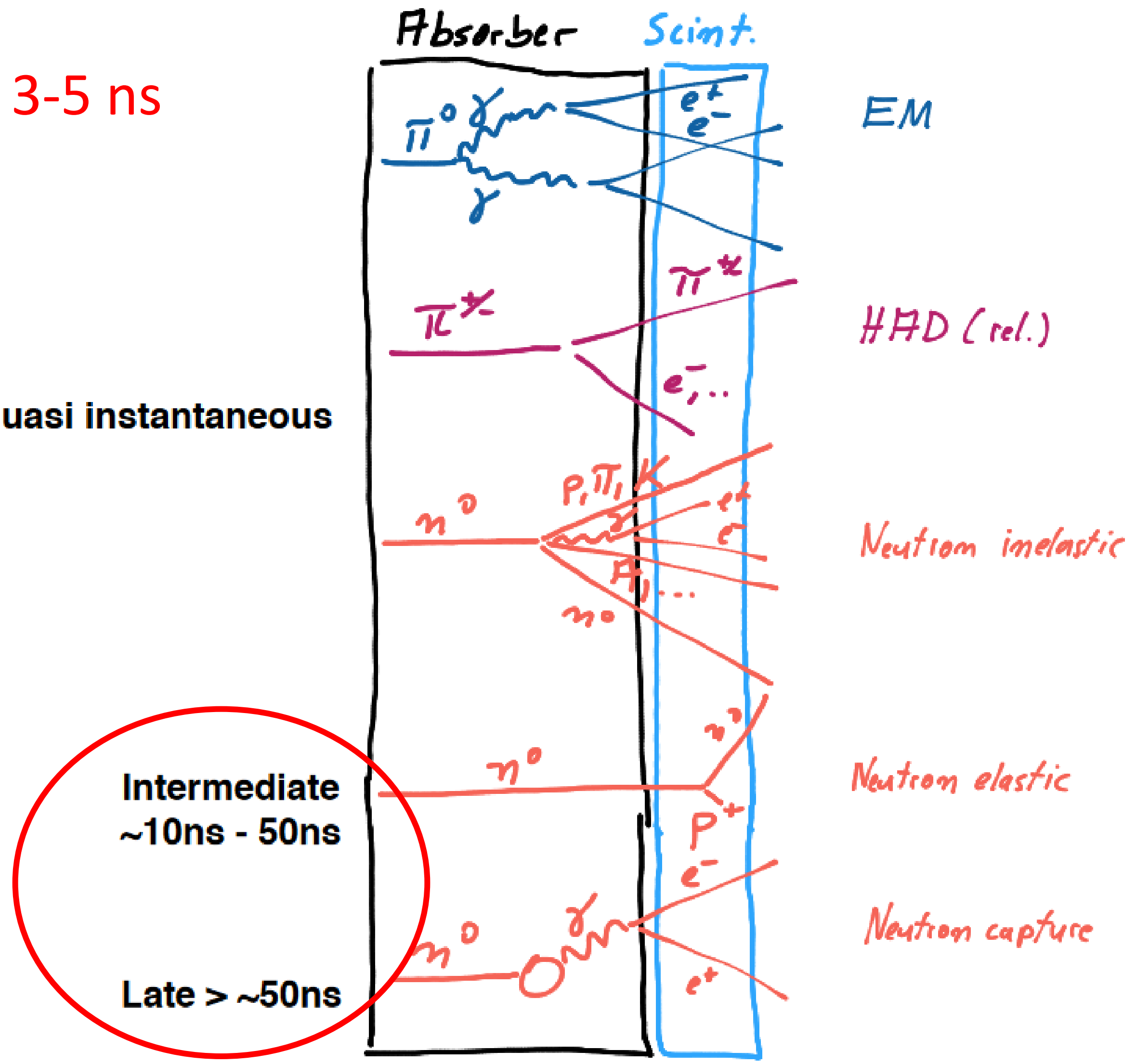
Note: C^3 bunch spacing 3-5 ns

- Three time regimes:
  - Quasi instantaneous
  - Intermediate 10-50ns
  - Late > 50ns

- Late energy deposition are due to slow neutrons

- Study time evolution in steel and tungsten absorbers

- Compare to monte carlo



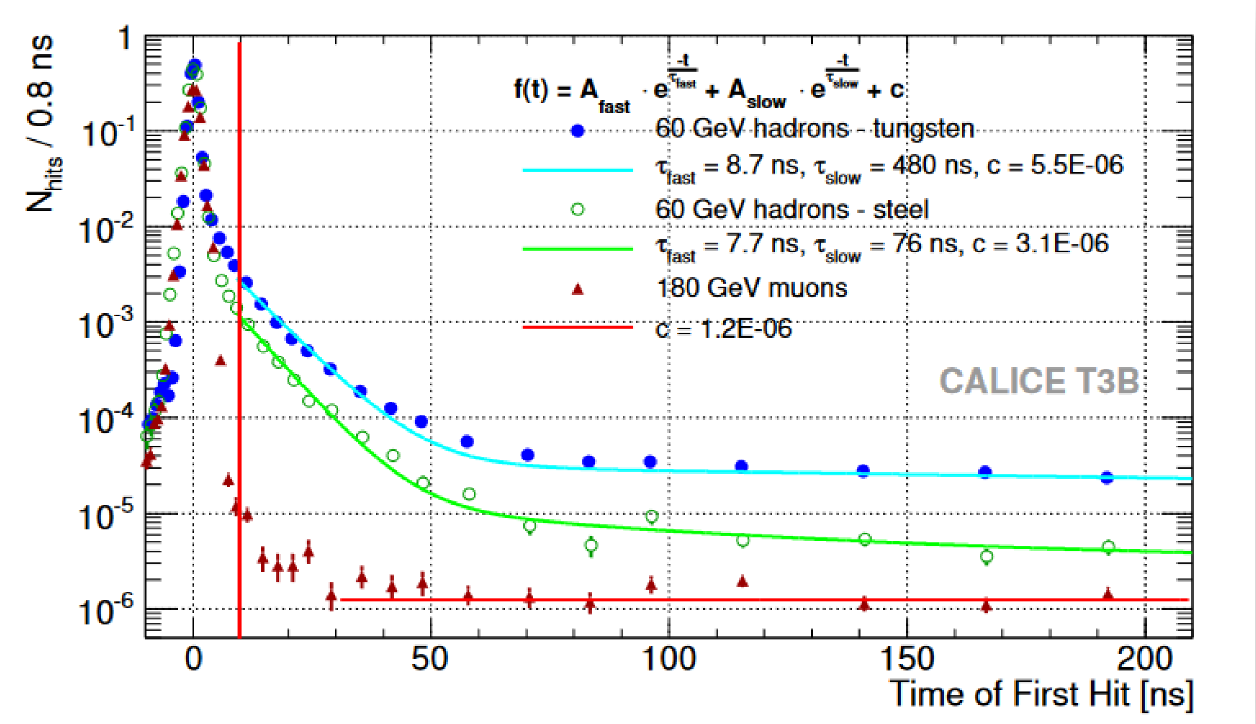
Quasi instantaneous

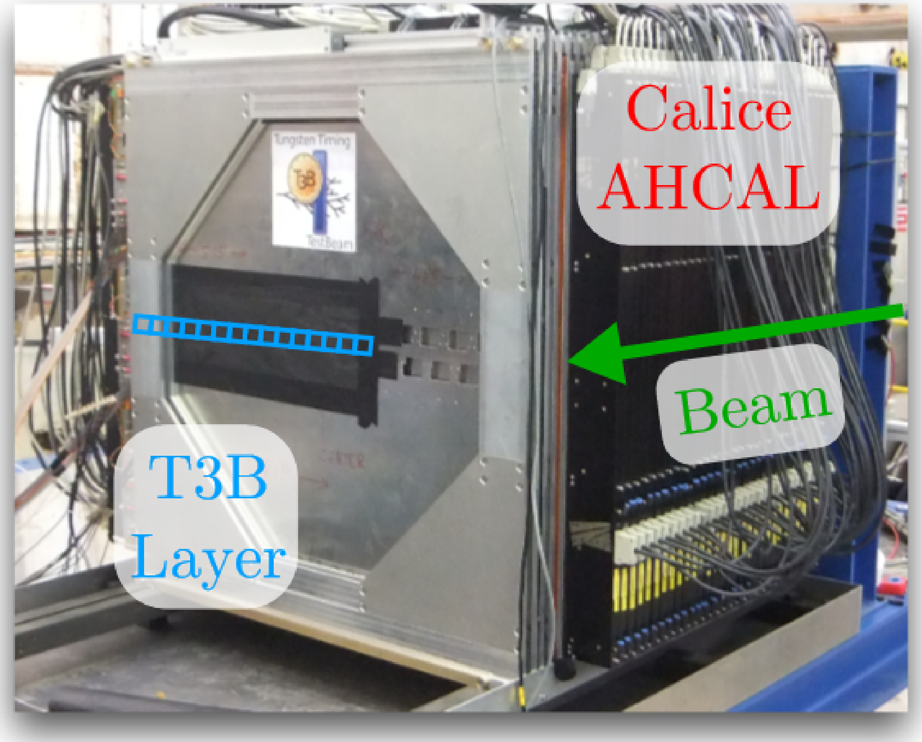
Intermediate ~10ns - 50ns

Late > ~50ns

Small part of deposited energy

Christian Graf – CLICdp Workshop '19 CERN





- T3B: Timing measurements parasitic to the CALICE AHCAL
- Complex time structure of hadronic showers visible
- Steel / tungsten absorber

Frank Simon et al./CALICE

Timing layers for SiD HCal

CALICE test beam prototypes (SiPM/Tile – based) have achieved O(1ns) timing accuracy.

LHC experiments are including LGADs with timing resolution of 30ps.

For C^3 with 3-5ns bunch spacing, would few x100ps resolution contribute usefully to a Particle Flow Algorithm?

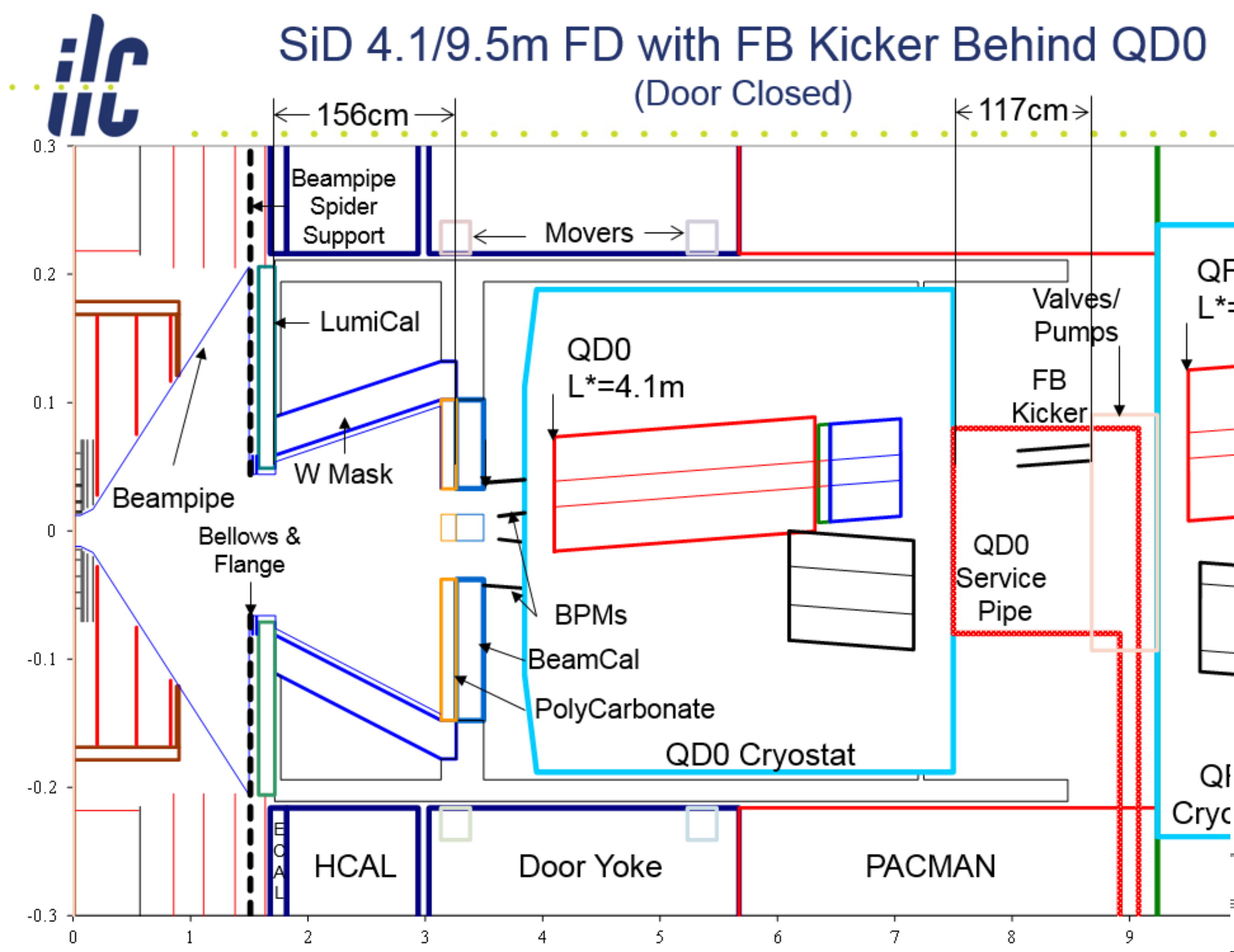
e+e- - Low cross-sections – low overlap probabilities

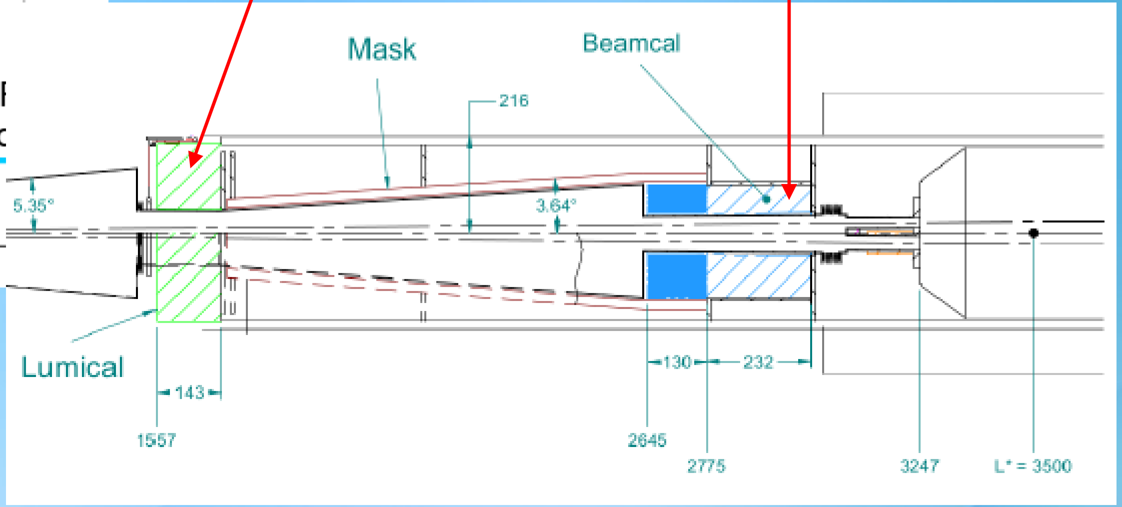
Can the few x100ps resolution be achieved for readout of the cells in the HCal?

Is there a downside to adding timing layers to the HCal?

Are there integration problems arising from inclusion of timing layers?

Forward calorimetry



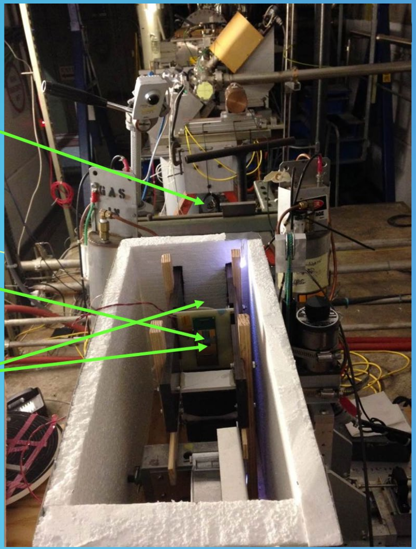


Lumi Cal

Beam Cal

Forward calorimetry

- **Sensor irradiation studies for Forward Calorimetry**
  (B. Schumm et al. UCSC – SLAC Expt. T-506)
  Cal radiation dose at inner radius ~100 Mrad/year

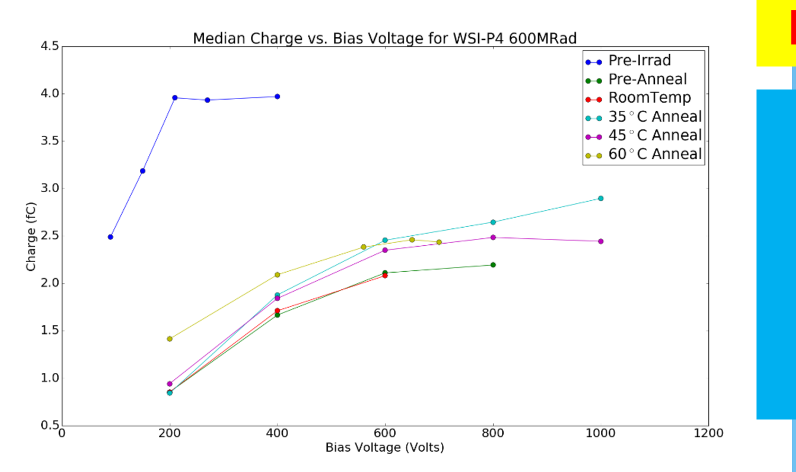


2 X_0 pre-radiator; introduces a little divergence in shower

Sensor sample

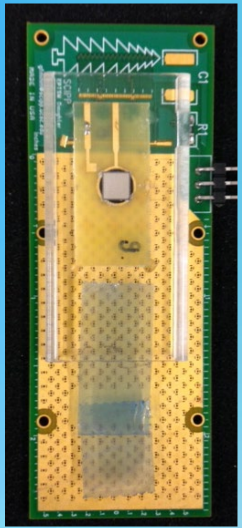
Not shown: 4 X_0 "post radiator" and 8 X_0 "backstop"

Ongoing electromagnetic radiation damage studies (Si diode, GaAs…) within FCAL Collaboration umbrella

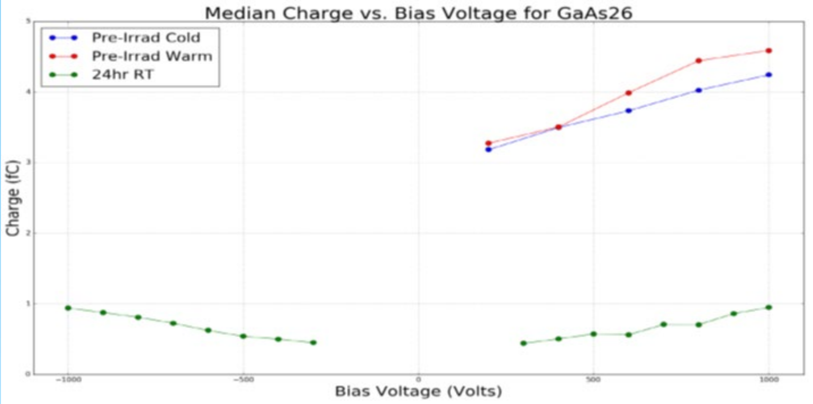


570 Mrad Exposure

PF Si Diode Sensor
300μm
Area 0.025 cm^2



- Gallium Arsenide sensor provided by Georgy Shelkov, JINR
- Sn-doped Liquid-Encapsulated Czochralski fabrication
- 300 μm thick
- 0.16 cm^2 area



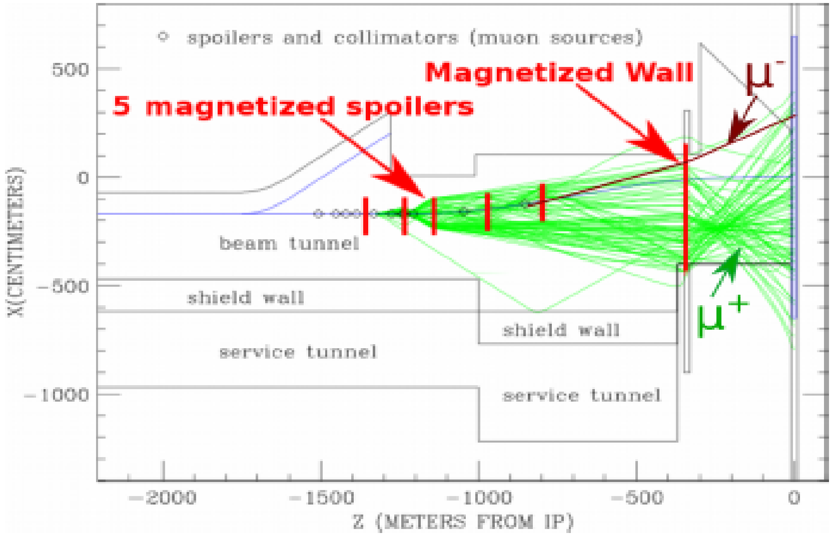
Expect integrated radiation dose to be similar to ILC

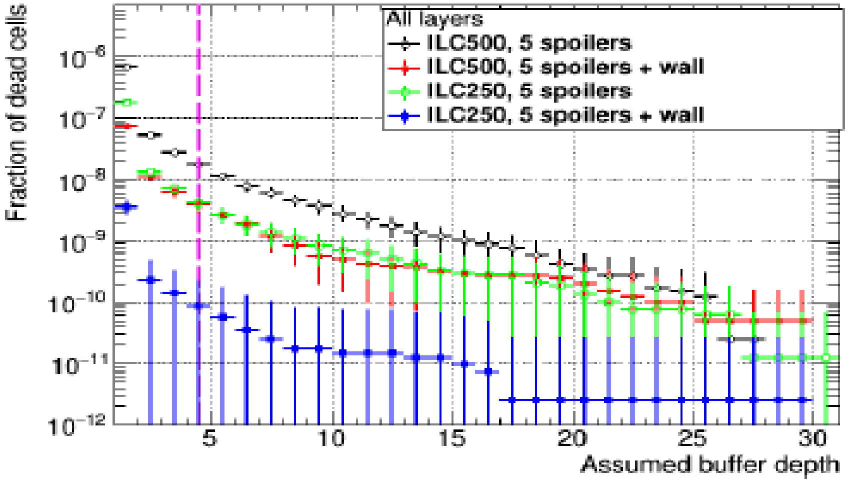
GaAs Charge Collection after 100 Mrad Exposure
(previously only for 21 Mrad)

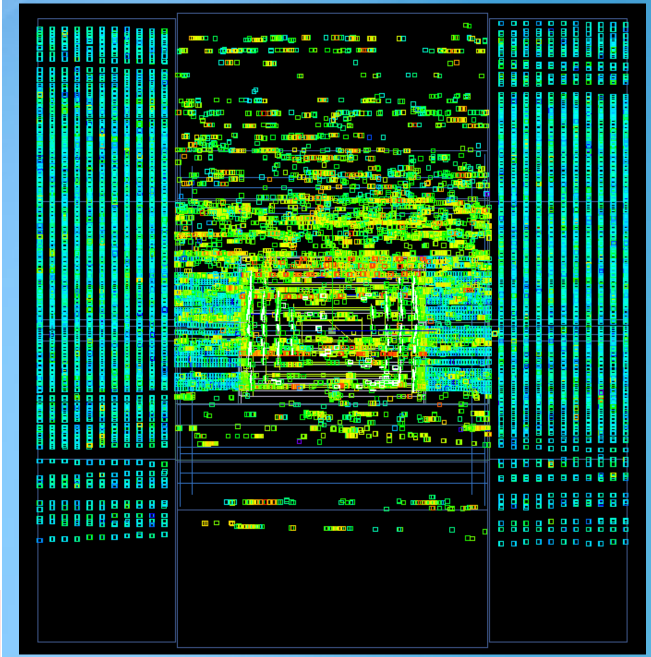
Sean Hyslop

MDI Studies

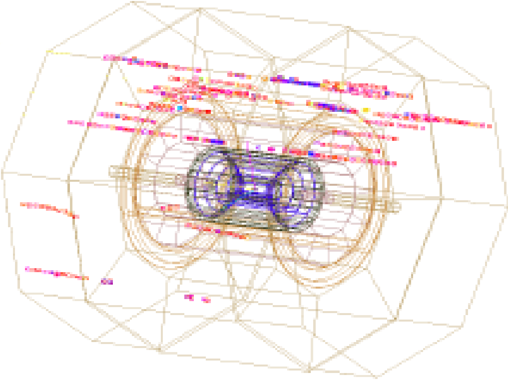
BDS muon study







#muons / bunch crossing	ILC250	ILC500
No shielding	39.3	130.1
Magnetized spoilers	1.3	4.3
Magnetized spoilers + wall	0.03	0.6



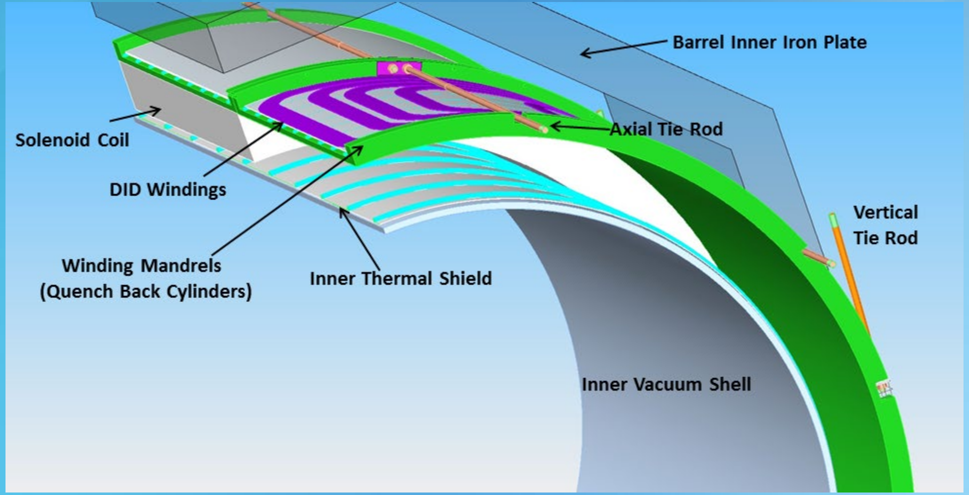
At ILC250, magnetized spoilers without wall are sufficient for occupancy mitigation.

Wall might me neccessary at higher stages, and as a tertiary containment device.

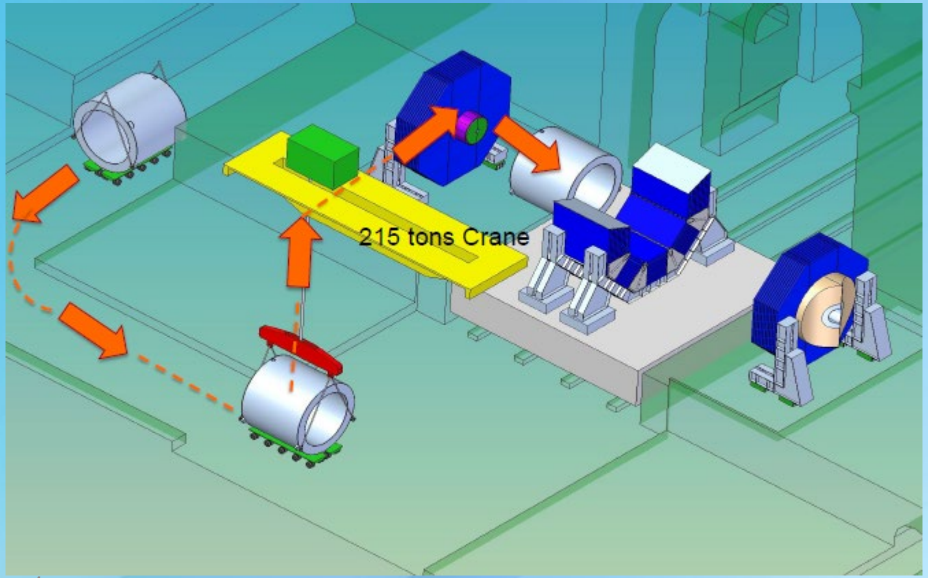
Anne Schuetz
(DESY)

Expect for C^3 muon background similar to ILC – but need to simulate.

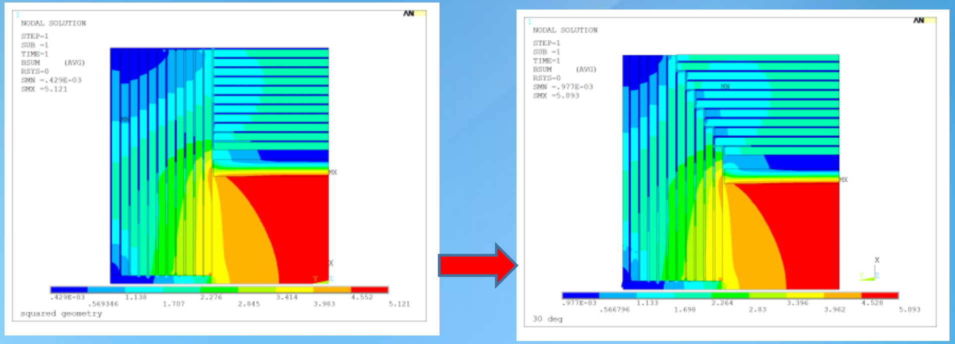
SiD Solenoid



Baseline CMS conductor – investigating **CICC** (Cable in Conduit Conductor)

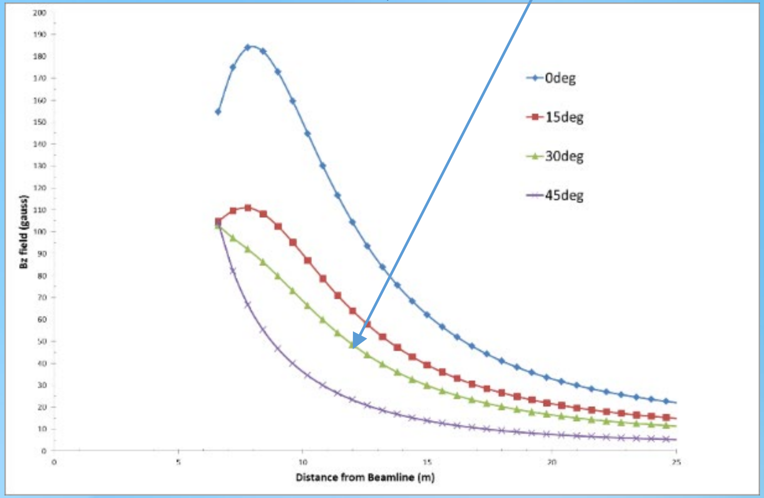


30° design



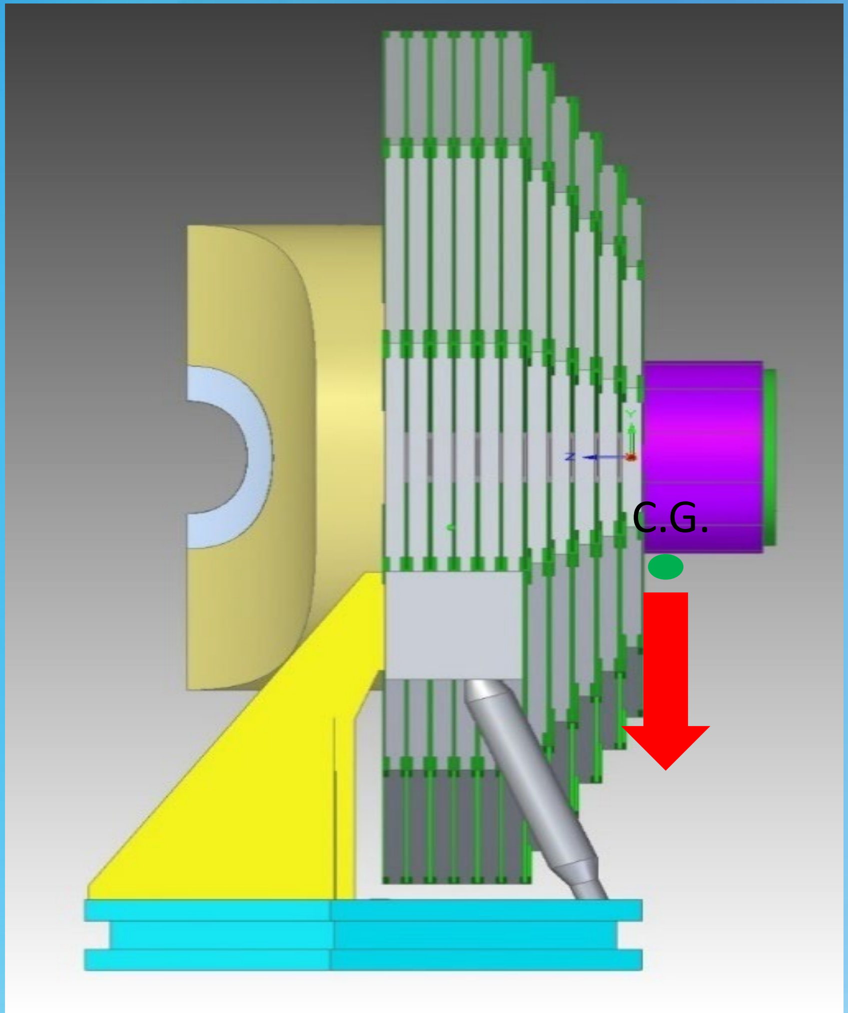
Redesign of barrel/door junction
More efficient flux return
Easier transport/handling

< 50 Gauss at 15m/30 deg cut

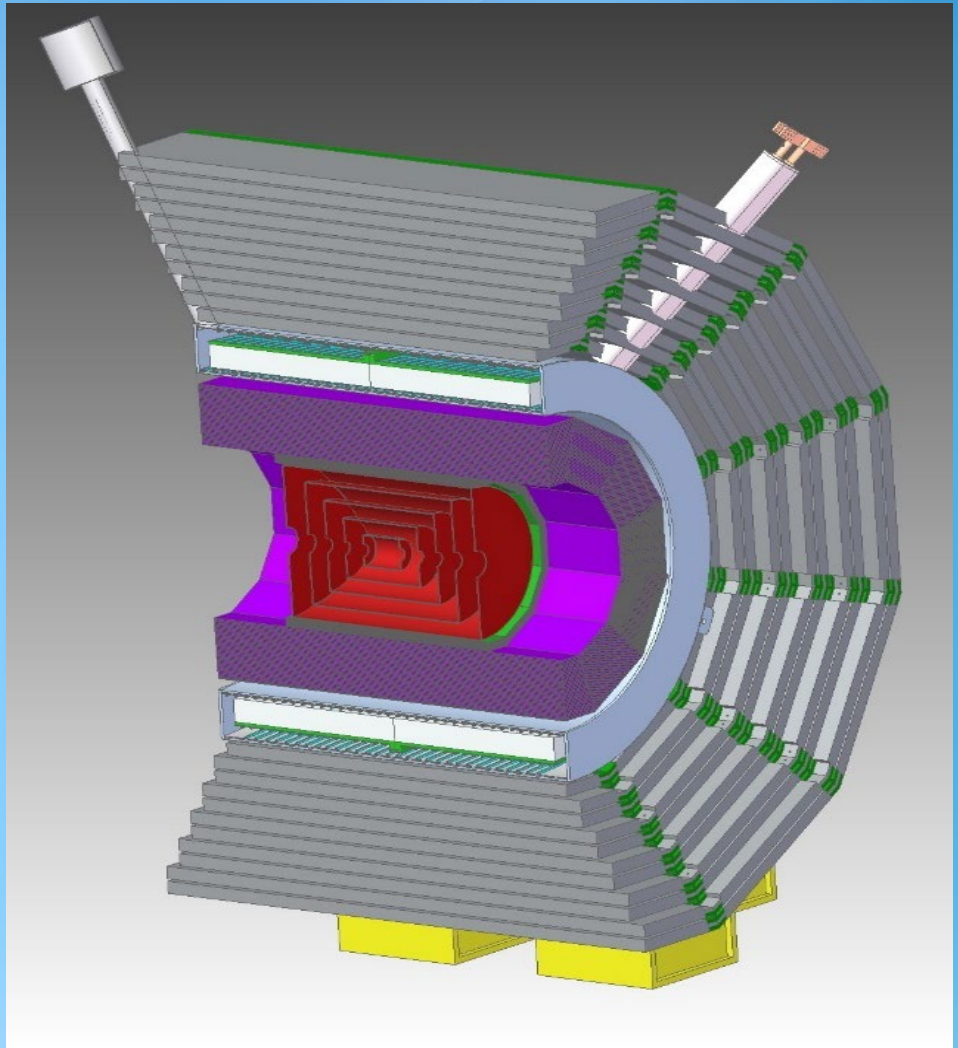


M. Oriunno (SLAC)

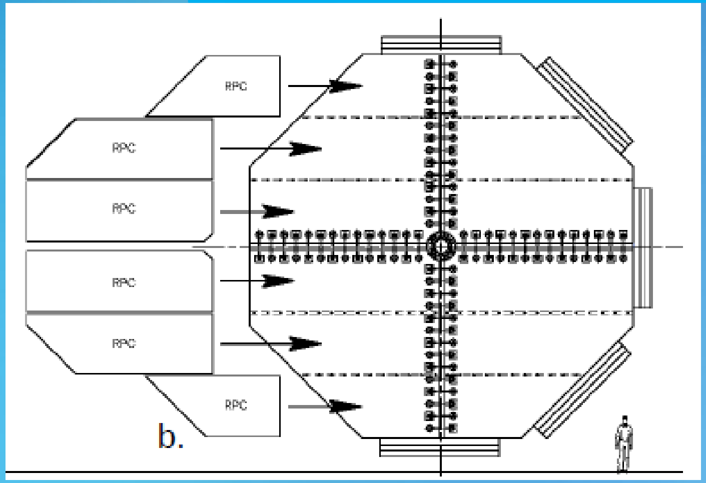
Muon identifier/Calorimeter Tail Catcher

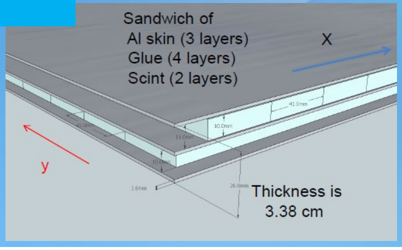


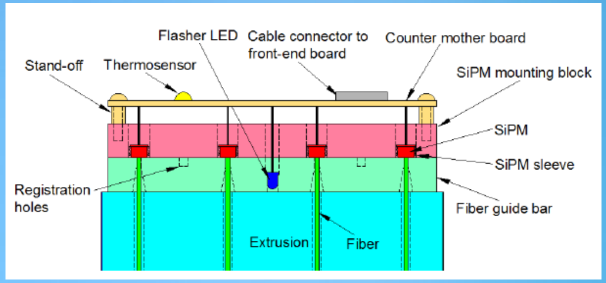
Marco Oriunno
(SLAC)



Muon identifier/Calorimeter Tail Catcher



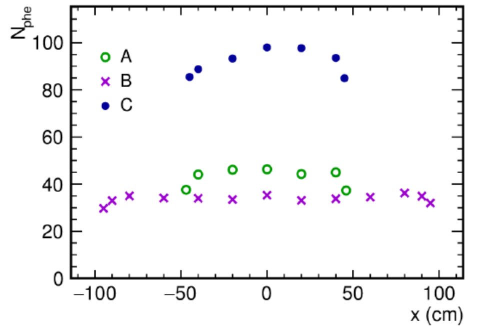




SiD Baseline – long scintillator strips with WLS fiber and SiPM readout

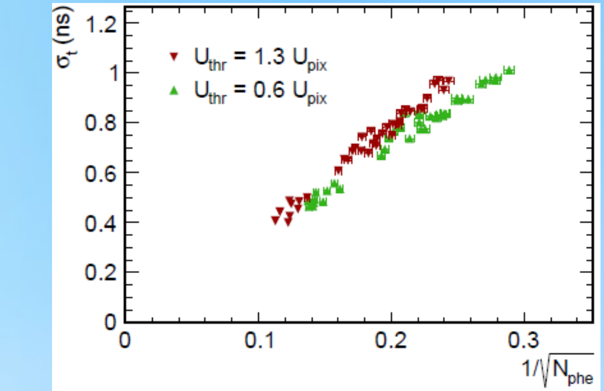
- Consistent extension of the baseline HCal scintillator technology
- Need to optimize number of layers, strip dimensions.

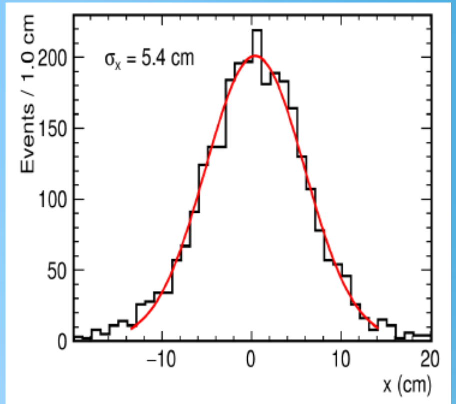
Development work at Fermilab:



Paper published:
NIMA, **848**, 54-59, 2017

Time resolution





Position resolution

Muon identifier/Calorimeter Tail Catcher

Scintillator strip/SiPM system shows O(1ns) time resolution
Should be good for C^3?

How many layers to instrument for SiD?

? Use muon layer(s) to time end of hadron showers?

Global/programmatic issues

C^3 – path to 550 GeV running built in from start (RF upgrade)

1 or 2 Detectors – risk, redundancy, cost,…

Multi-TeV running – 3 TeV? Increase gradient, extend accelerator

> 3 TeV? Re-design SiD – no VTX,…

P(e+) = 0, strong push for P(e+) at ILC (systematics)

SiD Consortium

SiD Consortium

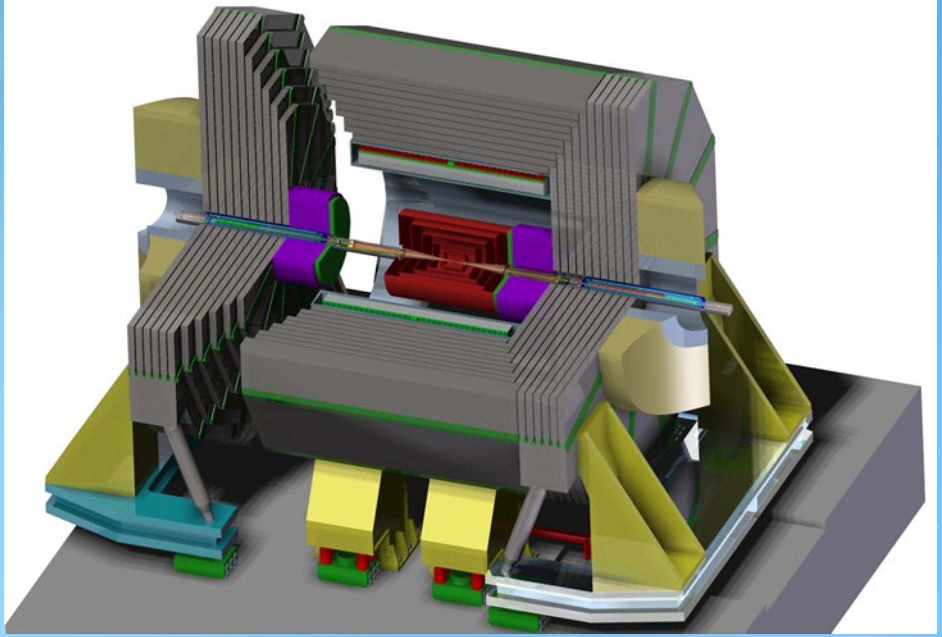
- since 2013
- Byelaws
- Individual and institutional memberships (Guest membership available for Snowmass studies!)
- IB Chair – Phil Burrows (U. Oxford)

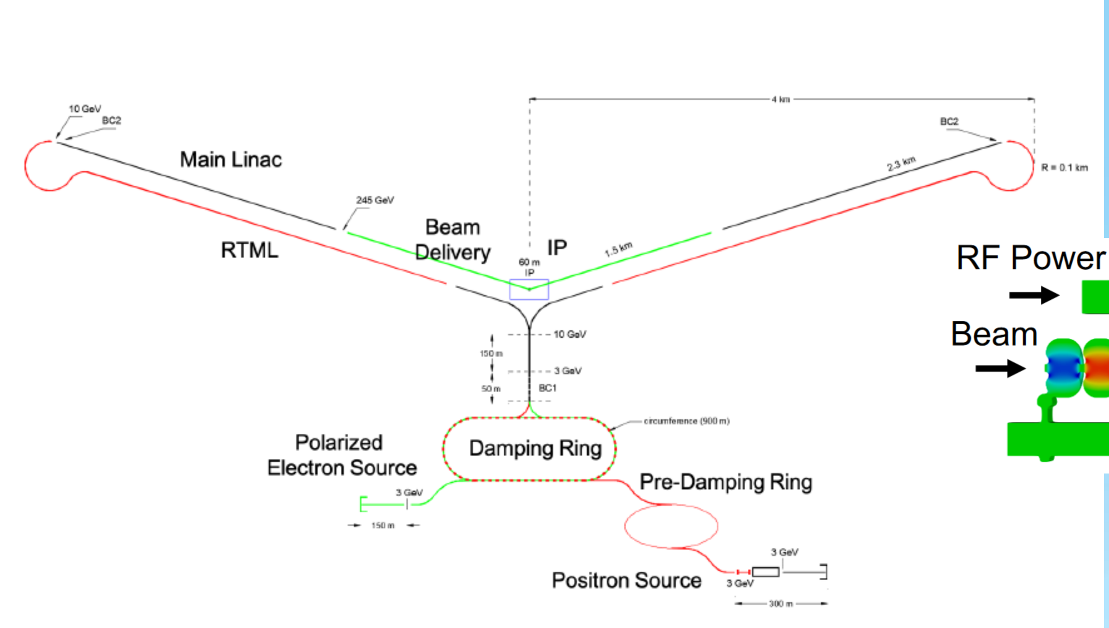
Very open and welcoming of new colleagues to join SiD to make it better by contributing new ideas, upgrades/alternatives– particularly by the younger generation!

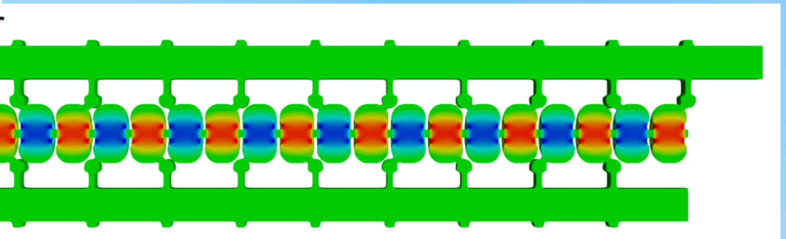
SiD Detector for C^3

- SiD would work with C^3 to deliver Higgs and complete physics program
- Mainly minor issues center on C^3 timing
- Potential solutions with precision timing – need studies
- Also need to study/check: pair envelope/backgrounds, muon background/mitigation.
- Upgrade of SiD design (MAPS, timing layers,…) gives opportunity to consider needs for C^3
- Open invitation to join SiD – new colleagues are very welcome!

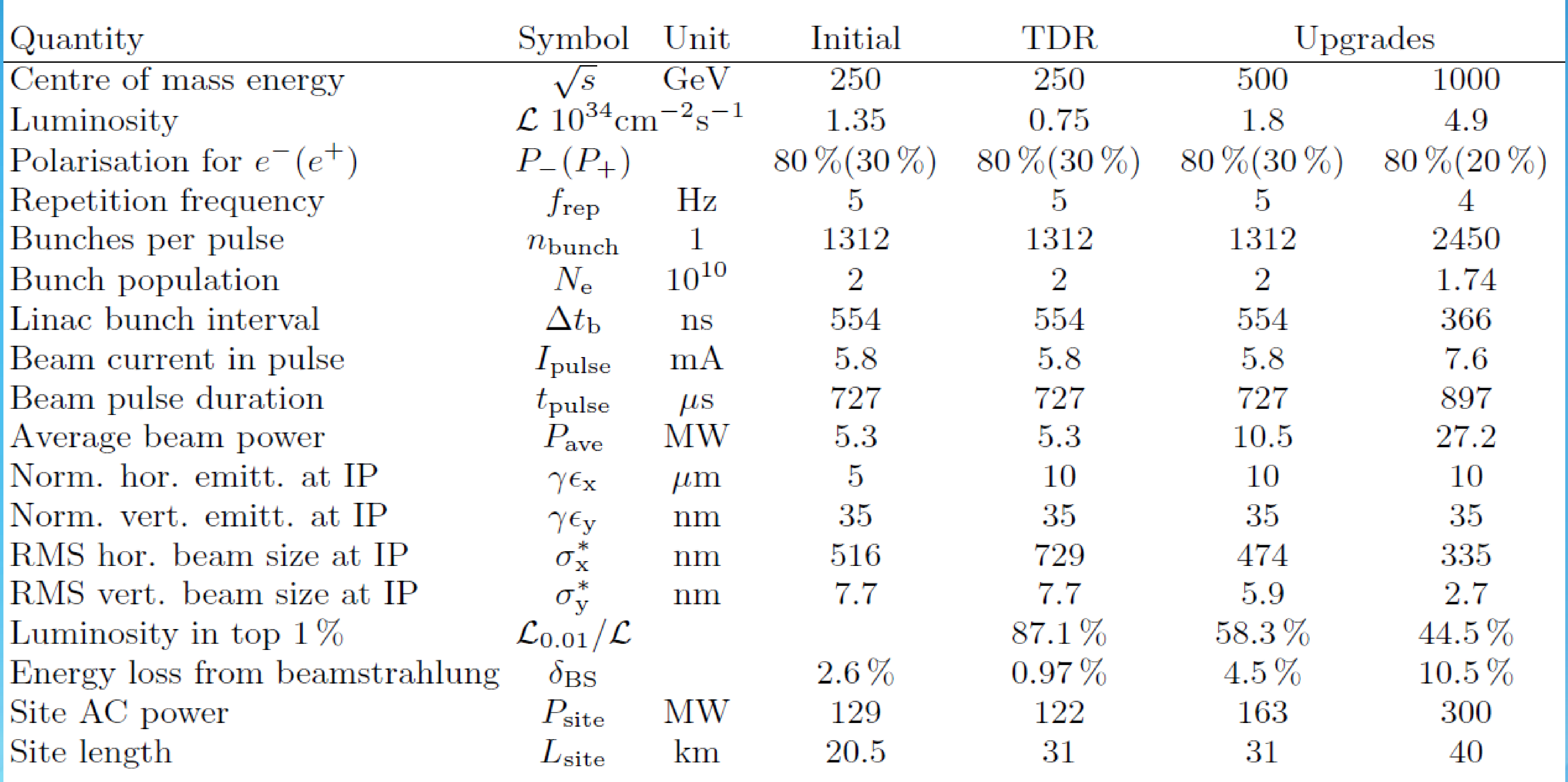
Thank you




10 GeV
BC2
Main Linac
245 GeV
RTML
Beam Delivery
IP
60 m
IP
1.5 km
2.3 km
4 km
BC2
R = 0.1 km
10 GeV
150 m
3 GeV
50 m
BC1
circumference (900 m)
Polarized Electron Source
Damping Ring
Pre-Damping Ring
3 GeV
150 m
Positron Source
3 GeV
3 GeV
300 m


RF Power
Beam

ILC Parameters



Quantity	Symbol	Unit	Initial	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	0.75	1.8	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	1312	1312	2450
Bunch population	N_{e}	10^{10}	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	554	554	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	727	727	897
Average beam power	P_{ave}	MW	5.3	5.3	10.5	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35
RMS hor. beam size at IP	σ^*_{x}	nm	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$			87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	0.97 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	129	122	163	300
Site length	L_{site}	km	20.5	31	31	40

THE INTERNATIONAL LINEAR COLLIDER

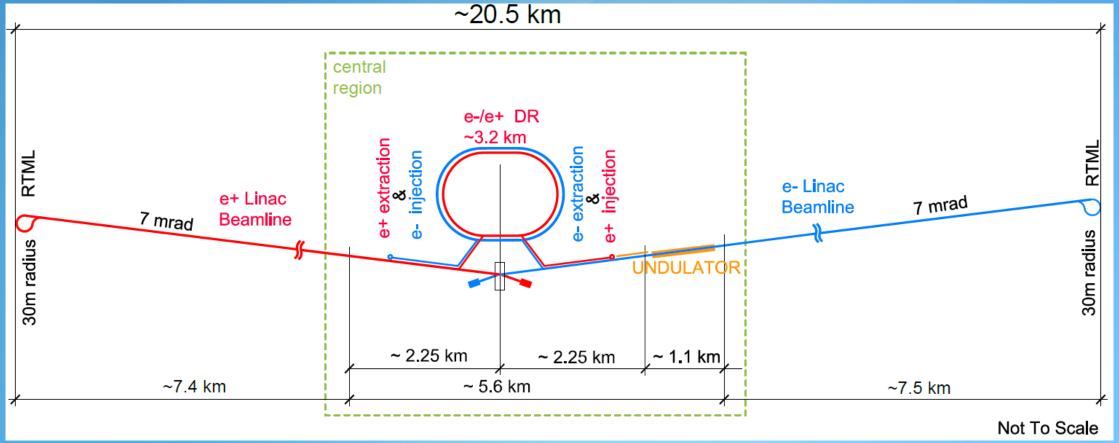

Transition (Development Team)

~1 year

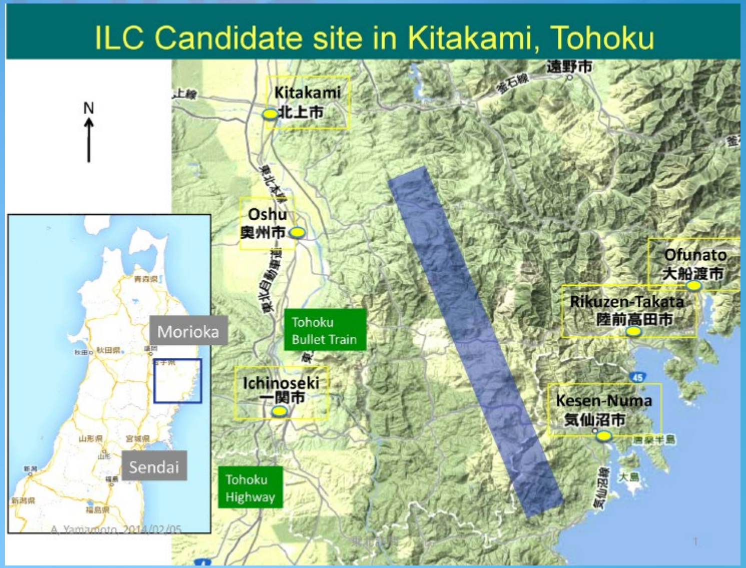
Preparatory Phase (Pre-Lab)

~4 year

ILC Lab



ILC Schematic for 250 GeV staged configuration



Parameter	Initial stage	TDR
C.M. Energy (GeV)	250	500
Length (km)	20	31
Luminosity (x10^{34})	1.35 (2.7, 5.4)	1.8
Repetition (Hz)	5 (10)	5
Beam Pulse Period (ms)	0.73	0.73
Beam Current (mA in pulse)	5.8	5.8
Beam size (y) at FF (nm)	7.7	5.9
SRF Cavity Gr (MV/m), Q_0	31.5, 1x10^{10}	31.5, 1x10^{10}
Site Power (MW)	129	163