The ILD concept from linear to circular colliders

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On behalf of
the ILD Collaboration and
ILC IDT Detector and Physics Working Group

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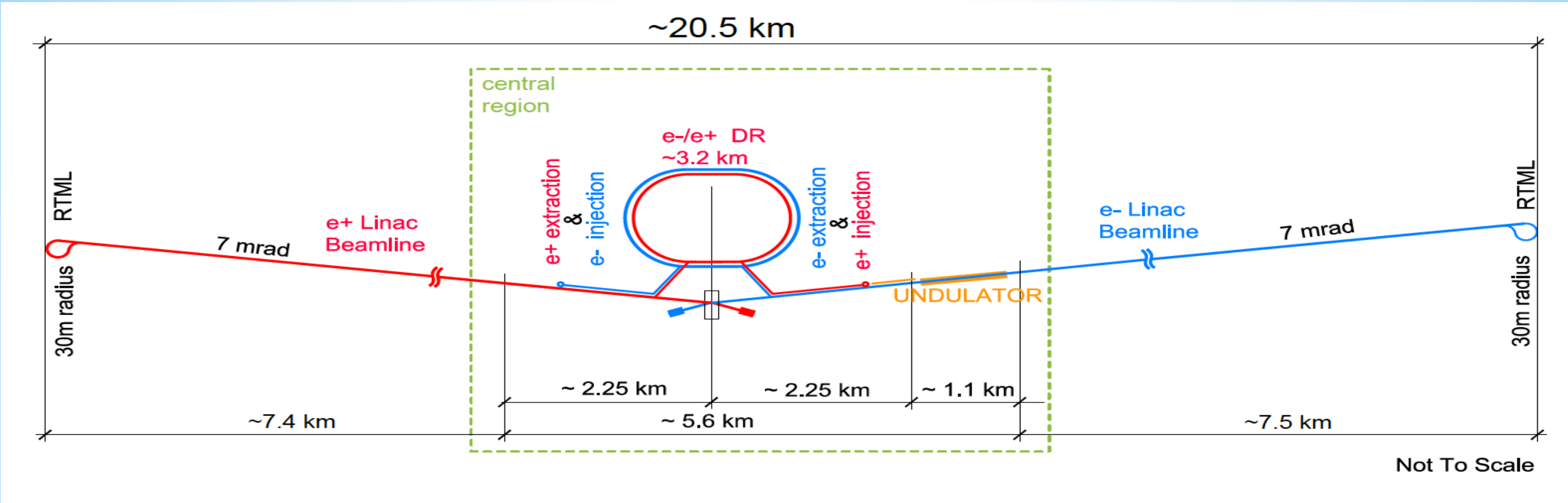
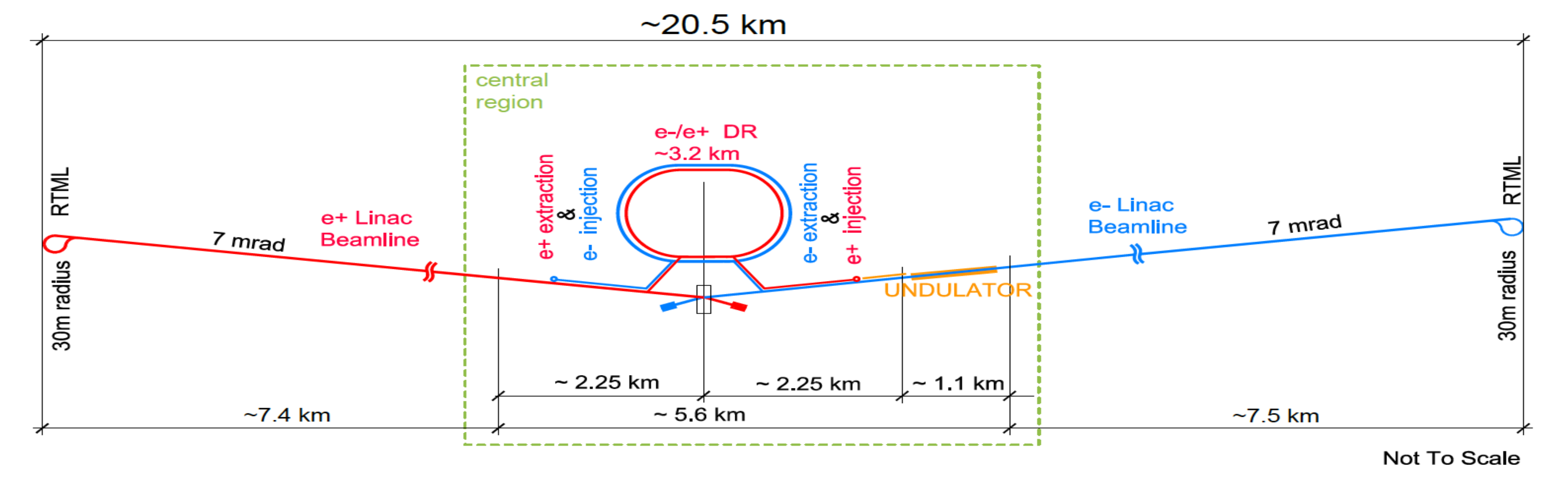
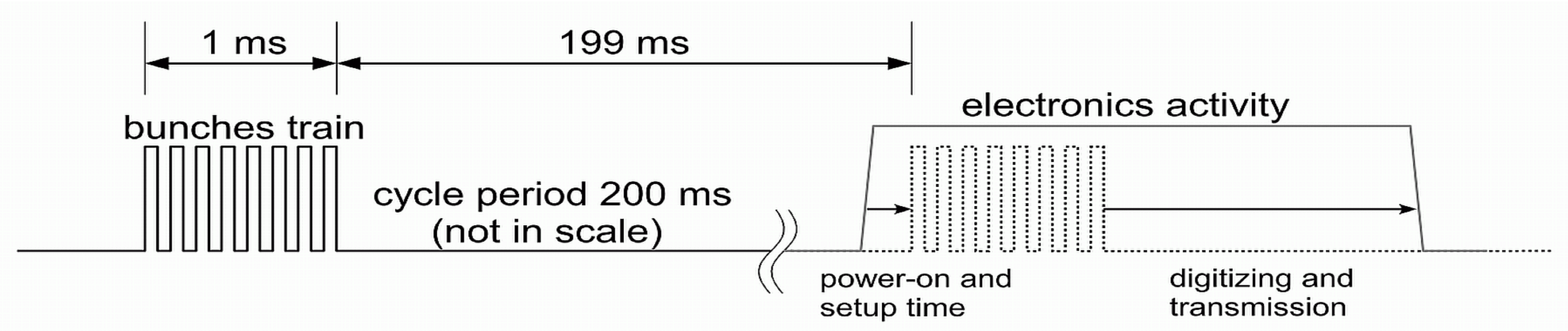
Prelude

- International Large Collider (ILD) was born within the ILC project
- ILD was optimized for ILC duty cycle mode and for the different expected CM energies of ILC (250, 500 and 1000 GeV)
- ILD was used as the starting point for the first CEPC baseline detector
- Last year ILD collaboration decided to study the possibility to propose ILD for other colliders, namely the FCCee with the main challenges coming form the Tera-Z run scenario.



Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 % (30 %)	80 % (30 %)	80 % (30 %)	80 % (30 %)	80 % (20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\text{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\text{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	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	20.5	31	31	40





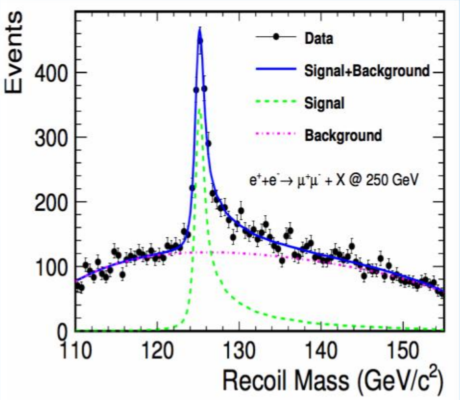
Train of 1ms duration every 200 ms (5 Hz), **1312 BC/train**

- Readout electronics is conceived to read out all the events (triggerless mode) during the bunch crossings, store them and then transfer them just after.
- Electronics is switched off after data transfer until a new train (a factor 100 of power reduction)

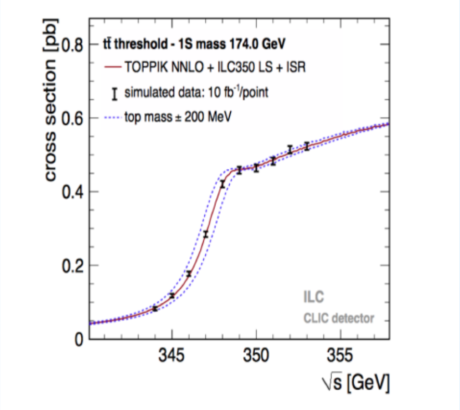
→ almost no cooling →low material budget

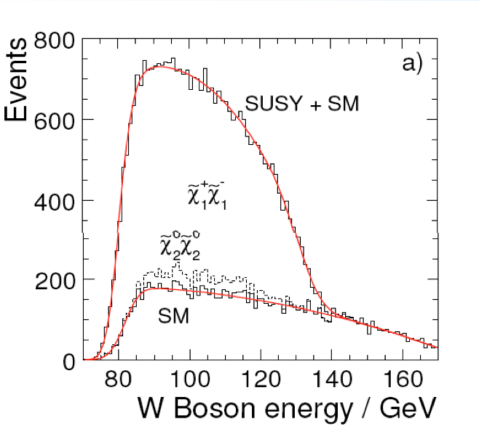
Philosophy of ILD

- ❑ Detectors should be a **precision** and **discovery** tool beyond the LHC scope.
- ❑ Relevant Physics phenomena in the TeV energy range are associated to multi jet final states
  → **Jet energy measurement** is the most important item.



Energy	Reaction	Physics Goal
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry



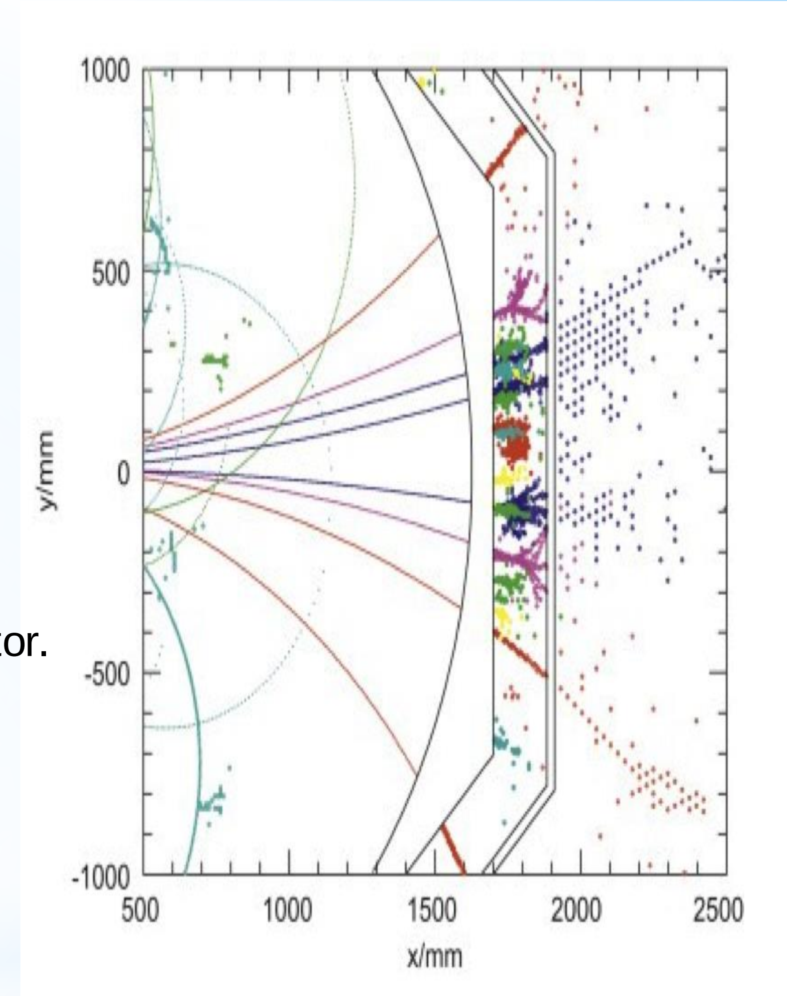


Philosophy of the ILD detectors

- Detectors should be **precision** and **discovery** tools beyond the LHC scope.
- Relevant Physics phenomena in the TeV energy range are associated to multi jet final states → **Jet energy measurement** is the most important item.

- **Particle Flow Algorithm PFA**: Construction of individual particles and estimation of their energy/momentum n the most appropriate sub-detector.

PFA can be used in any kind of colliders



PFA requires the different sub-detectors including calorimeters to be highly granular.
PFA uses their granularity to separate **neutral** from **charged** contributions and exploits the **tracking system** to measure with precision the energy/momentum of charged particles.

Philosophy of ILD : Requirements

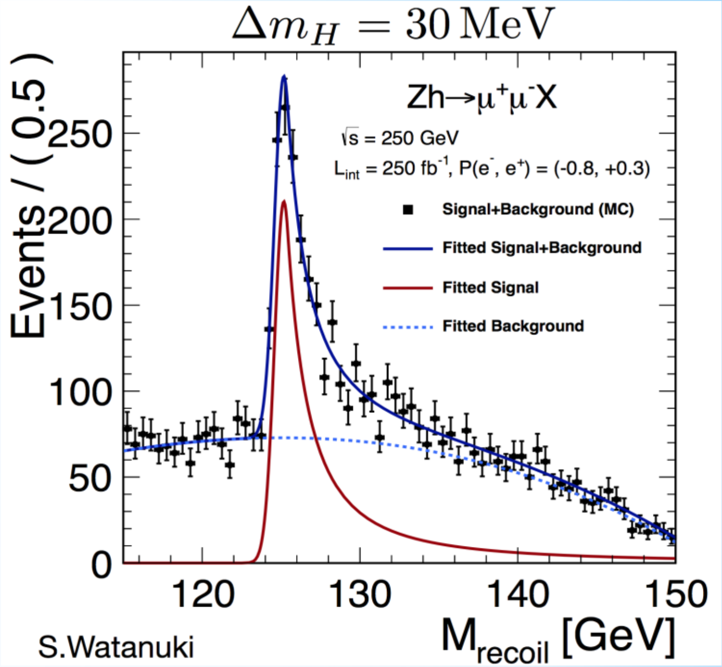
- Vertex detector : **excellent resolution**
  $\sigma_{IP}(r\phi) = 5 \square 10/(p \sin^{2/3}(\theta))$ μm
  b-tag, c-tag,… for H → bb, cc, ττ studies

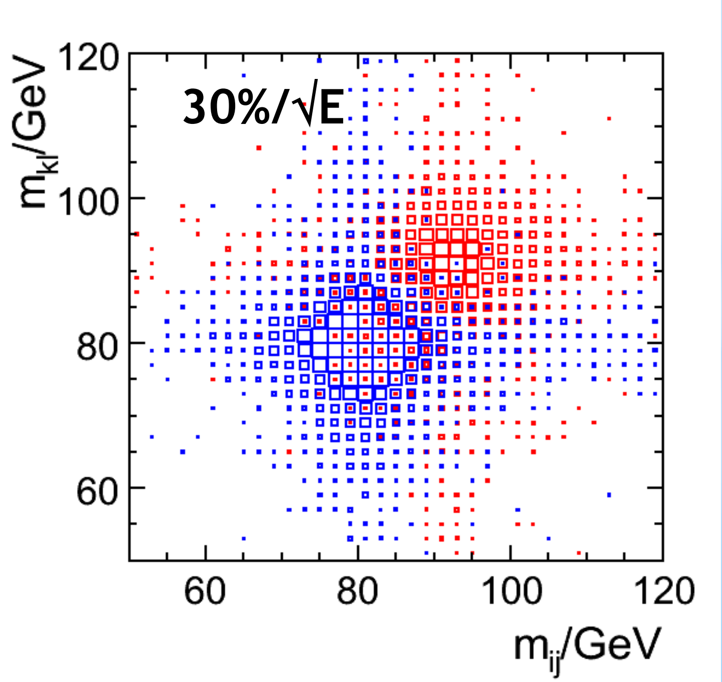
- Tracker : **excellent precision** measurement of p_t
  asympt: $\sigma(1/p_t) = 2\ 10^{-5}\ \mathrm{GeV}^{-1}$
  H mass recoil, $e^+ e^- \rightarrow HZ \rightarrow \mu^+ \mu^-$ + anything

- Calorimeters : **highly granular** but still providing good measurement of jets

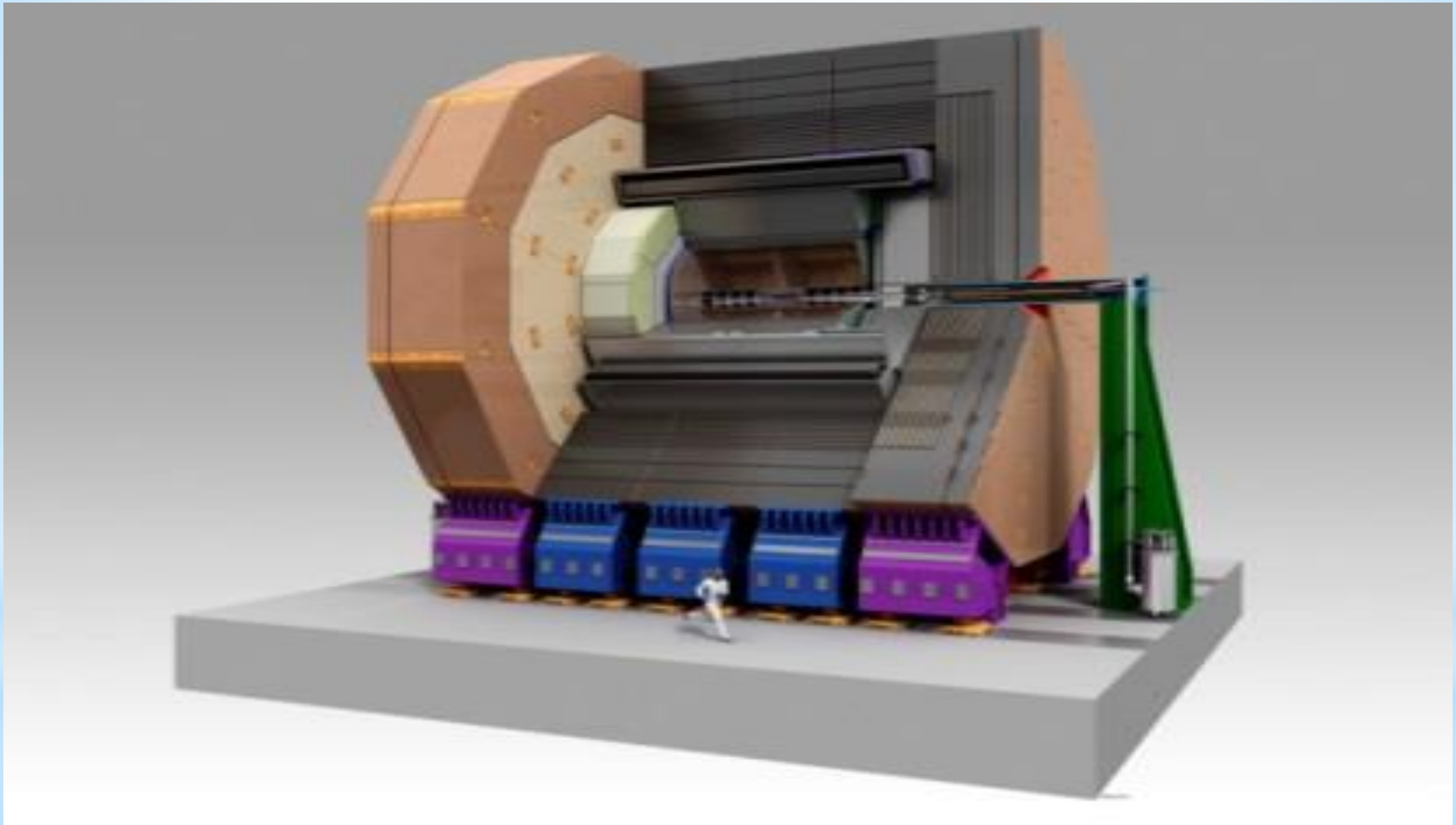
  $\sigma_E/E = 30\%/\sqrt{E}$. E in GeV

The whole detector should be hermetic, compact with moderate power consumption

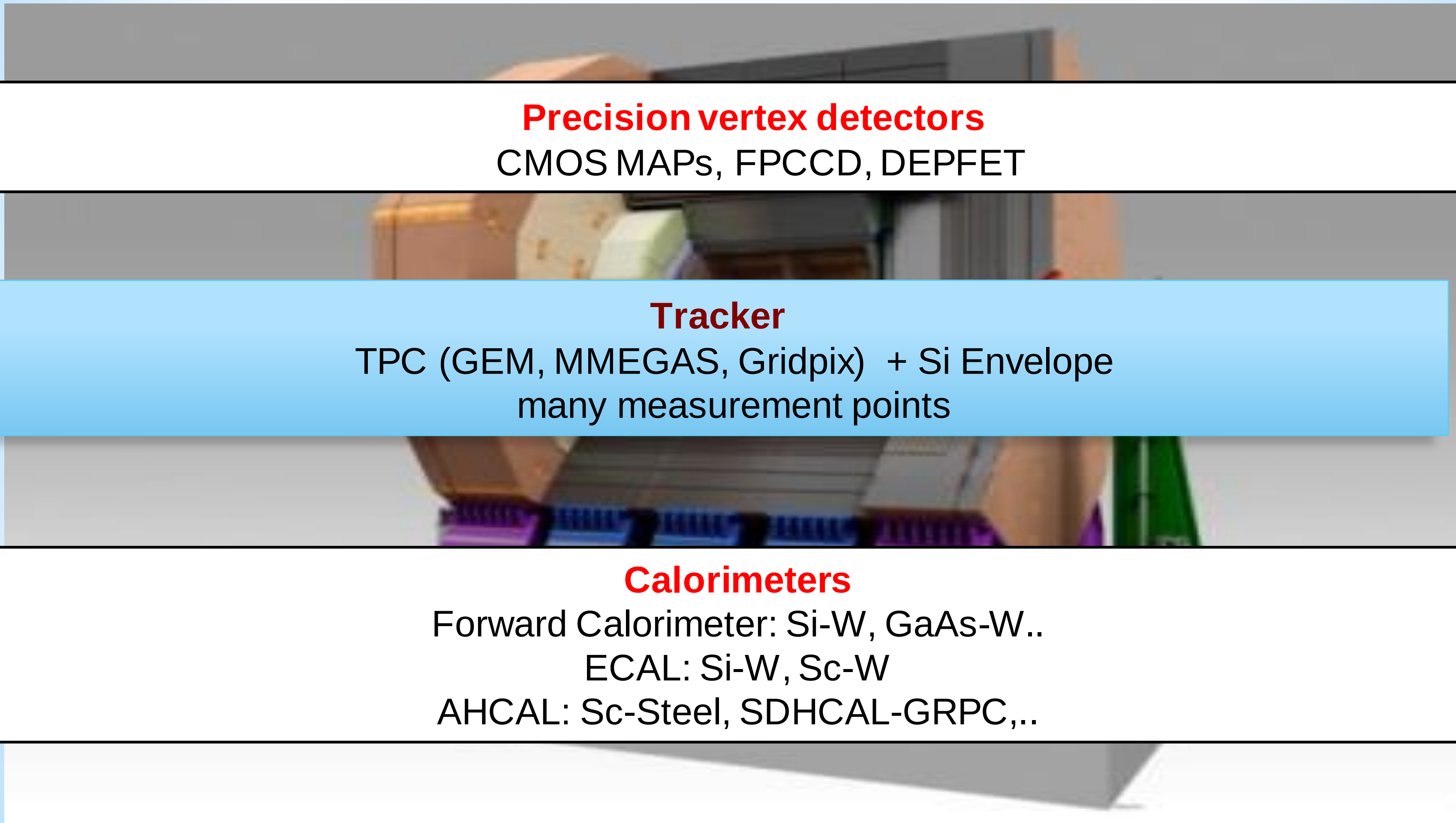




ILD



ILD



Precision vertex detectors
CMOS MAPs, FPCCD, DEPFET

Tracker
TPC (GEM, MMEGAS, Gridpix) + Si Envelope
many measurement points

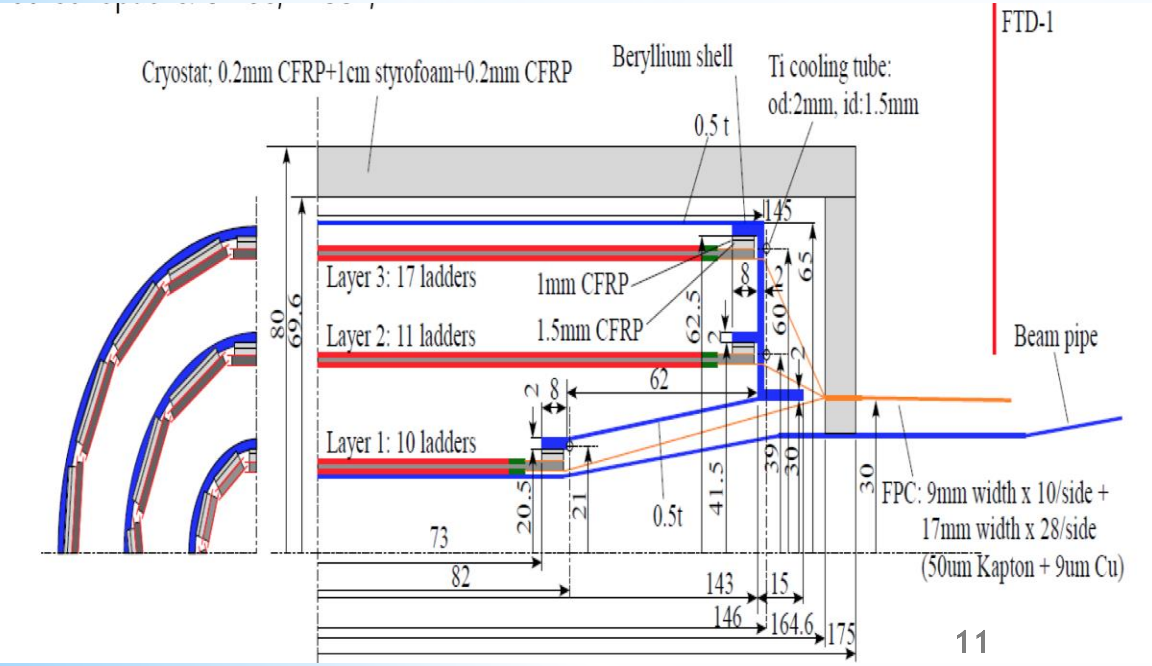
Calorimeters
Forward Calorimeter: Si-W, GaAs-W..
ECAL: Si-W, Sc-W
AHCAL: Sc-Steel, SDHCAL-GRPC,..

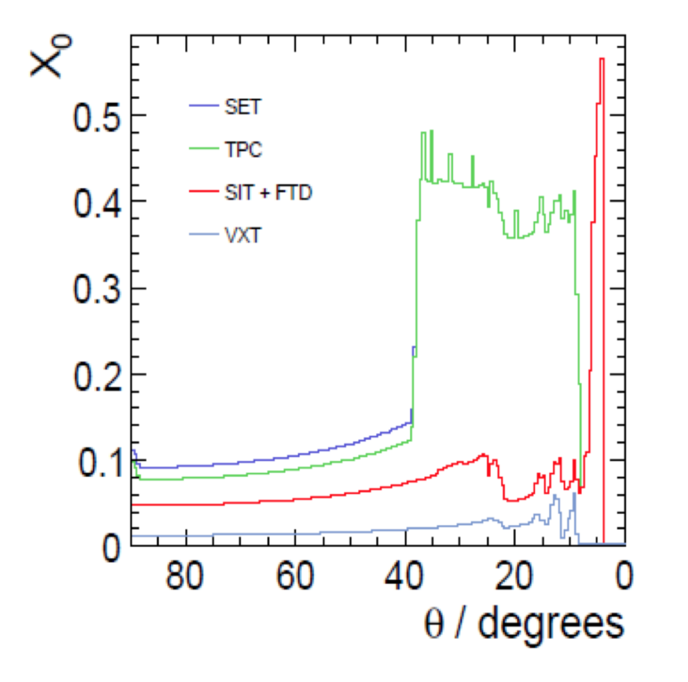
Size/Magnet
Large/3.5 Tesla

	ILD
R(in) Vertex	16 mm
R(out) tracker	1808 mm
N(tracker hits)	<228>
X(0) until ECAL	12% (barrel), 42% (EC)
R(out) HCAL	3973 mm
Λ (until end of HCAL)	7 (min), 8.5 (max)
Coil inner radius	3440 mm
B(coil)	3.5 T
Outer Radius	7755 mm
Total length	6620 mm

Vertex detector

- 3 ladders of double layers (6 pixel layers)
- $|\cos(\theta)| < .97$ for inner layer, $|\cos(\theta)| < .9$ for outer layer
- Inner radius ~1.6 cm, outer radius ~ 6 cm
- **3μm** resolution in the inner layer
- Material budget **~ 0.3% X_0/ladder layer** : light support and air-based cooling system.
- **A pixel occupancy not exceeding a few %**

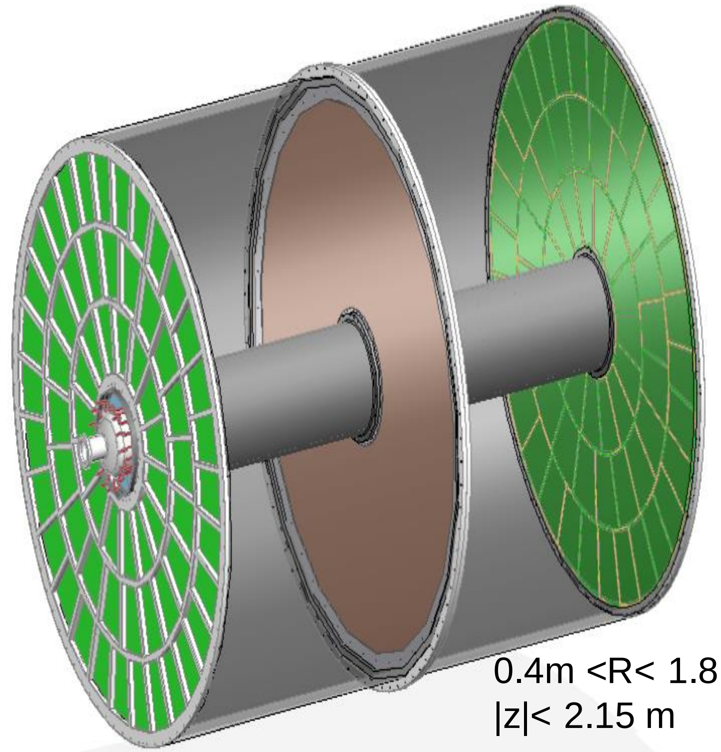




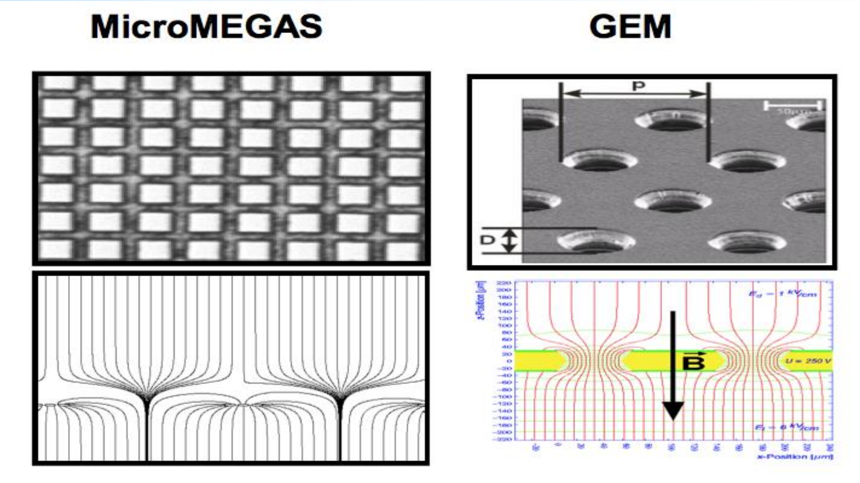
ILD TPC tracker

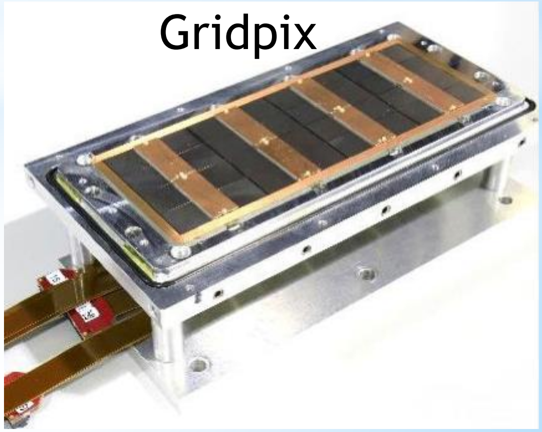
Time Projection Chamber (TPC) is chosen as the central tracker of ILD

- 3D tracks (rϕz) can be built thanks to many **hits (~200/Track) and 10e4/track if pixels**
- **σ(rϕ) of 100 μm** (60 μm at z=0) is expected
- **σ(z) of 1400 μm** (400 μm at z=0) is expected
- **$\sigma(1/p_t) \sim 10^{-4}$ GeV^{-1}**
- dE/dx information is provided (particle identification)
- Readout pad size ~ 1x6 mm^2 → 10^6 pads/side
- Material budget : 5%X_0 in central region and less than **0.25 X_0** in the endplate region
- Cooling is needed: two-phase CO_2 is a possibility.
- Two main options for gas amplification are considered : GEM, Micromegas and more granular one (GridPix)



0.4m <R< 1.8m
|z|< 2.15 m

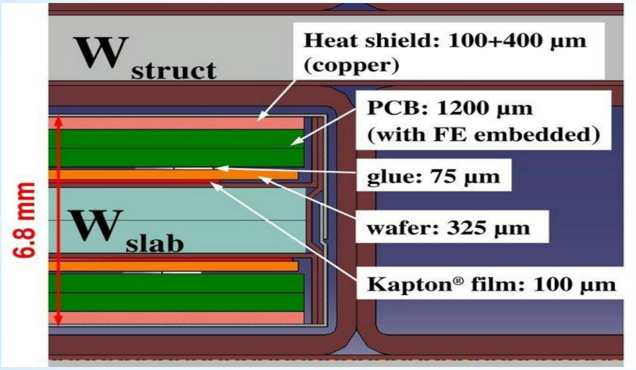


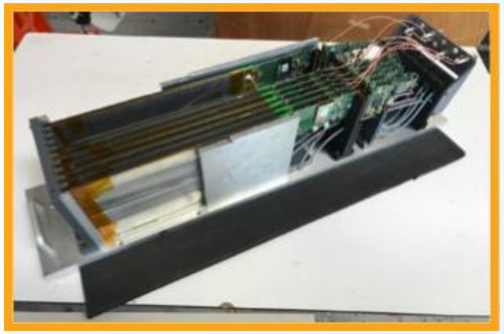


ECAL for ILD

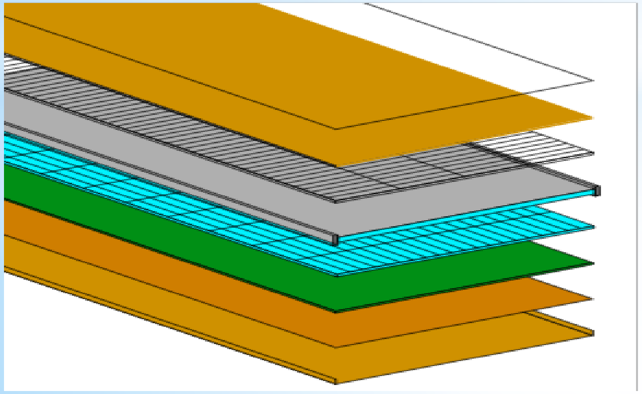
Two technologies are proposed. For both 30 layers of tungsten with three different thickness representing (**$24X_0$**) interleaved with:

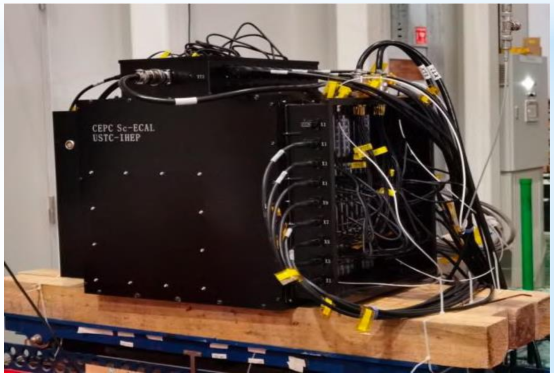
- Pixellated Silicon of **5x5 mm^2** with silicon wafer thickness (300-500 µm)





- Doublets each made of two layers of scintillator bars of **45x5x2 mm^3** with in horizontal position for one and vertical position for the other

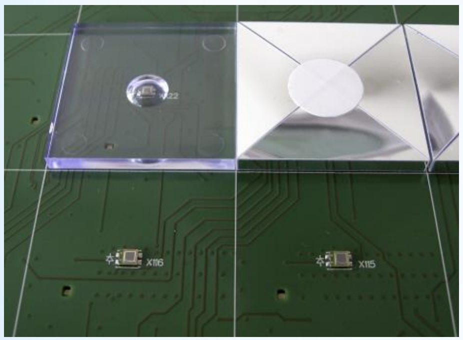




HCAL for ILD

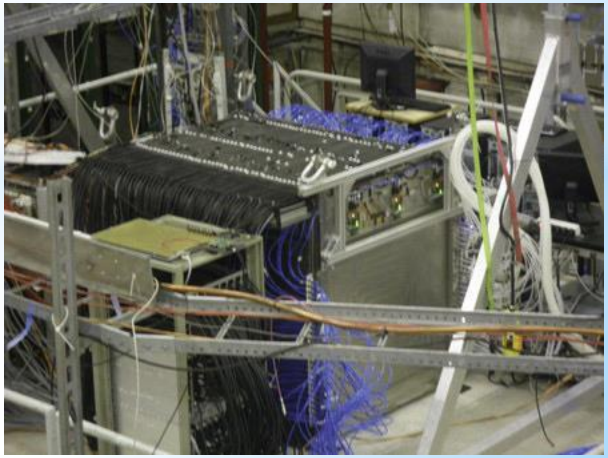
Two technologies are proposed. For both, 48 layers of 2 cm stainless steel (**6 λ_I**) interleaved with planes made of:

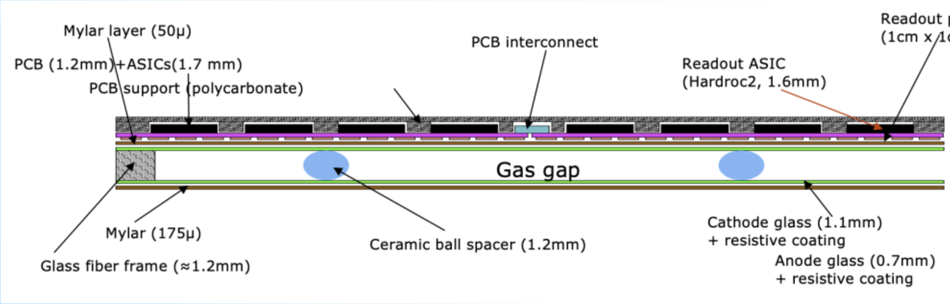
- 3 x 3 x .3 cm^3 tiles read out with SiPM



or

- Glass RPC and their embedded readout 2-bit electronics allowing a lateral segmentation of **1 cm^2**





Forward calorimeters

Lumical

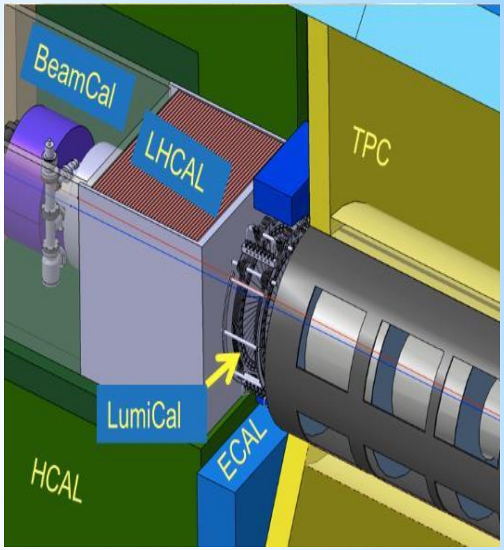
– Precise integrated luminosity measurements (Bhabha events)
– Extend calorimetric coverage to small polar angles.
  Important for physics analysis
  Si-W

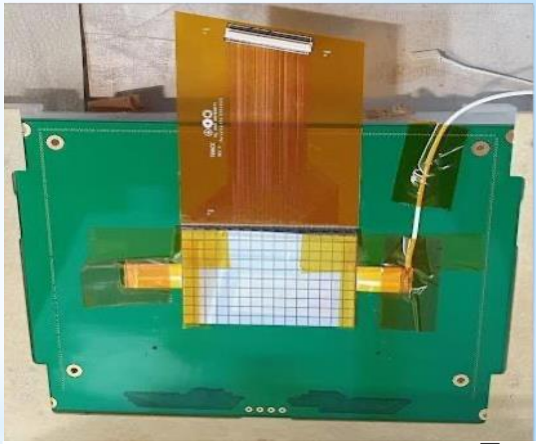
Beamcal

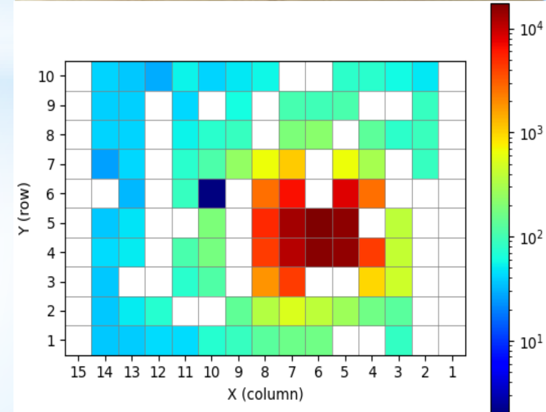
- Measure instant Luminosity. Feedback for beam tuning
– Tagging of high energy electrons to suppress backgrounds to potential BSM process
  GaAS, CVD Dimond, Sapphire

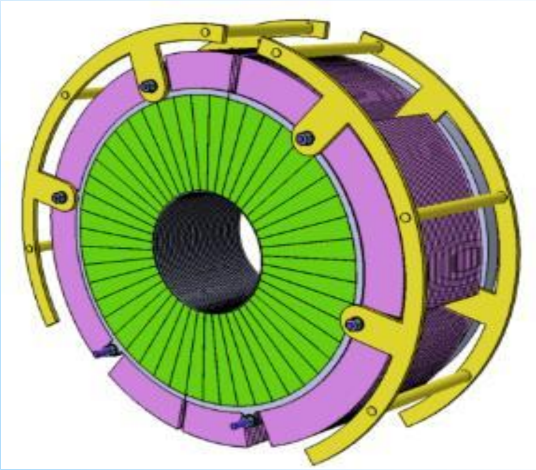
LHCAL

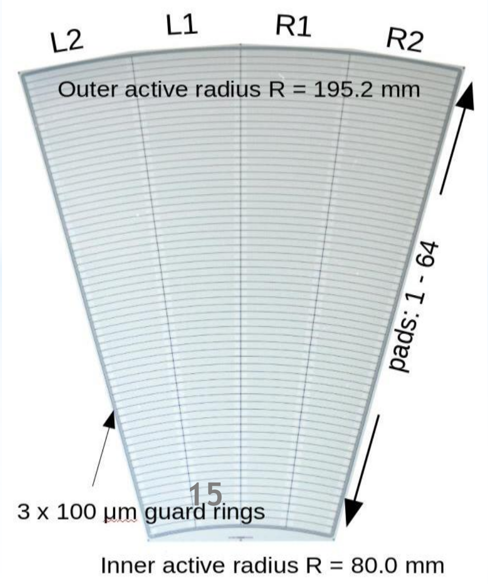
- Extends the coverage of HCAL
  Si-W or Fe







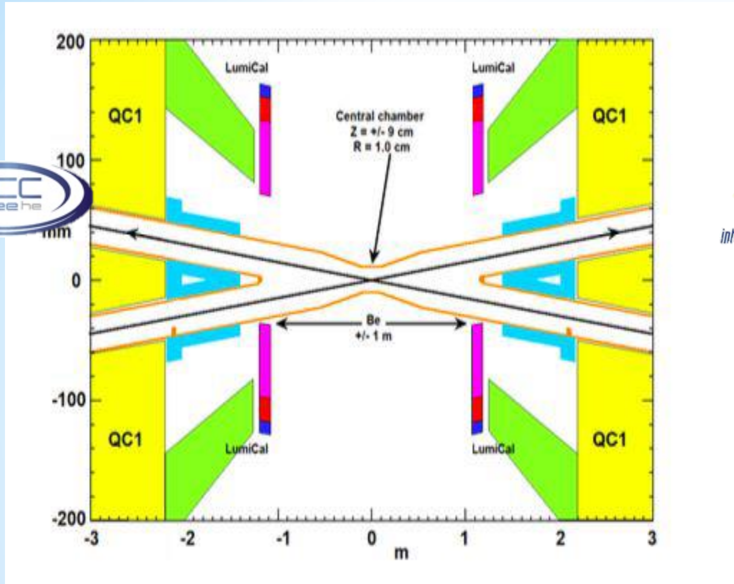


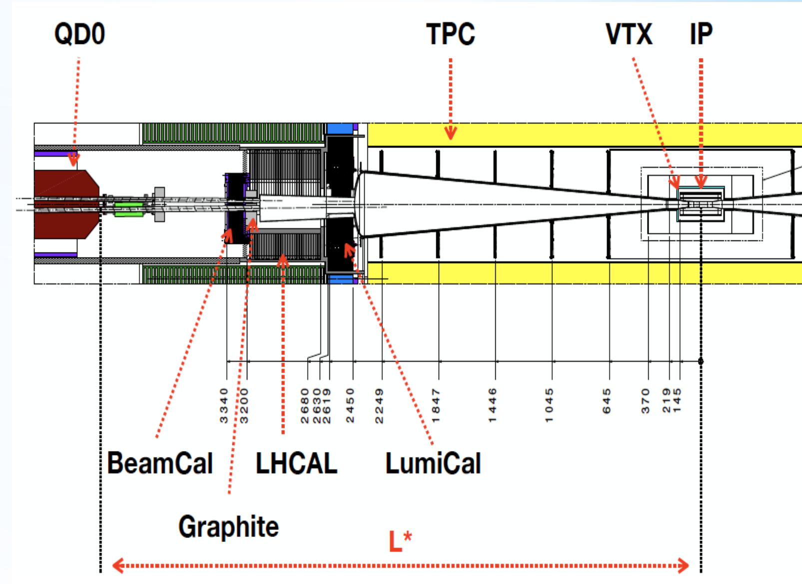


What one should do to adapt ILD detectors to circular colliders

- Vertex Detector
- Central tracker
- Calorimeters

FCCee vs ILC MDI





Crossing angle 30mrad
L* 2m: Final Quadrupole inside the detector
Solenoid magnetic field restricted to 2T maximum
Lumical at ~1m from IP
➔ Tracker acceptance: cosθ ~ 0.984
Inner beam pipe radius 10mm

Crossing angle 14 mrad
L* 4.1 m: Final Quadrupole outside the detector
Solenoid magnetic field 3.5 - 4 T
Lumical at ~2.5m from IP
Conical ➔ Tracker acceptance: cosθ ~ 0.996
Inner beam pipe radius 16 mm

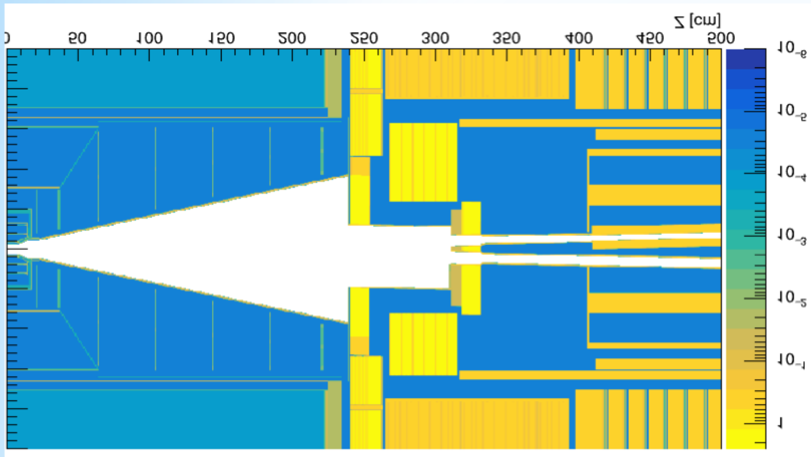
Vertex detectors &Tracker

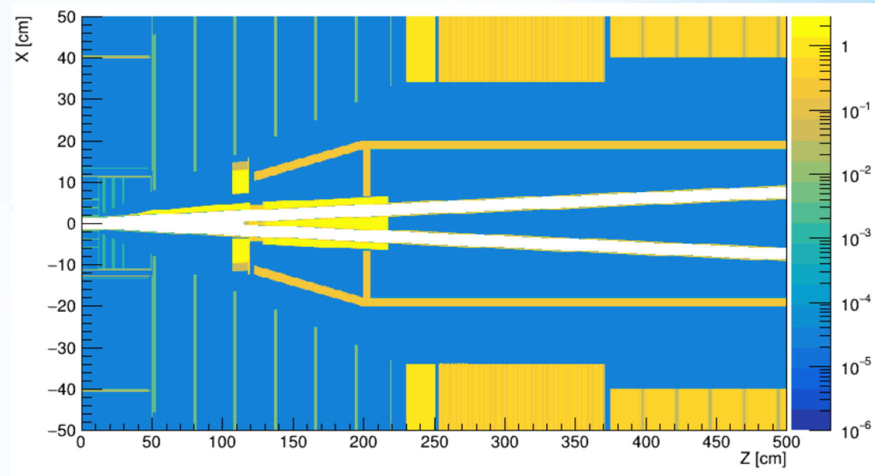
Collider	ILC		CLIC	FCCee			CEPC	
Bunch separation (ns)	330/550		0.5	20/990/3000			25/680	
Power Pulsing	yes		yes	no			no	
beamstrahlung	high		high	low			low	
Detector concept	SiD	ILC	CLICdet	CLD	IDEA	Lar	Baseline	IDEA
B Field (T)	5	3.5	4	2	2	2	3	2
Vertex	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel	Si-Pixel
Vertex Rmin (mm)	16	16	31	12	12	12	16	16
Tracker	Si-strips	TPC	Si-Pixel	Si-Pixel	DC/Si-strips	DC/Si-strips or Si-Pixels	TPC or Strips	DC/Si-strips
Tracker Rmax (m)	1.25	1.8	1.5	2.2	2.0	2.0	1.8	2.1
Disks layers	4 + 4	2 + 5	6 + 7	3 + 7	3 (150 mrad)		2+6	

Why ILD Vertex detector and tracker need to be adapted?

Structure:

The space available to vertex and inner trackers are not the same due to different L*





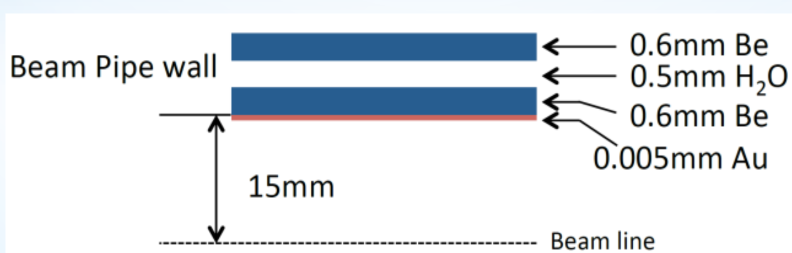
Beam pipe in FCCee is thicker than that of ILC with additional Au coating

ILC: 500 μm → 0.15% X_0

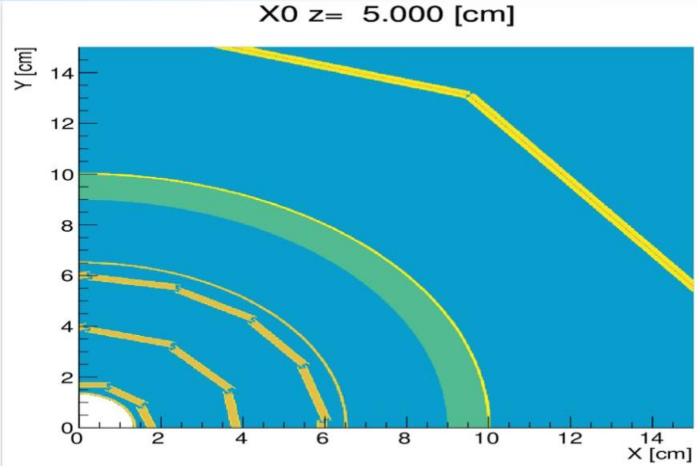
FCCee: 2x400 μm (2 pipes) + 400 μm (water) + 5 μm Au → 0.4% X_0

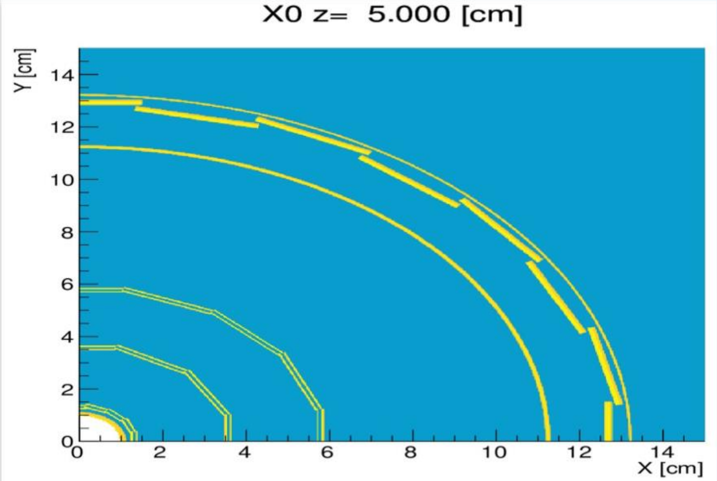
-The increase in material budget will result in a degradation of the spatial resolution. Reducing the inner radius of the vertex detector could reduce the deterioration.

-Forward calo need to be rad-hard since they come much closer to the beam pipe

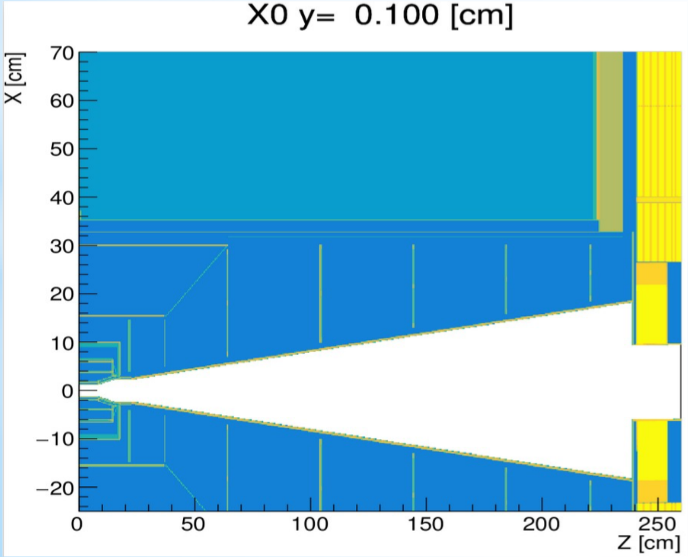


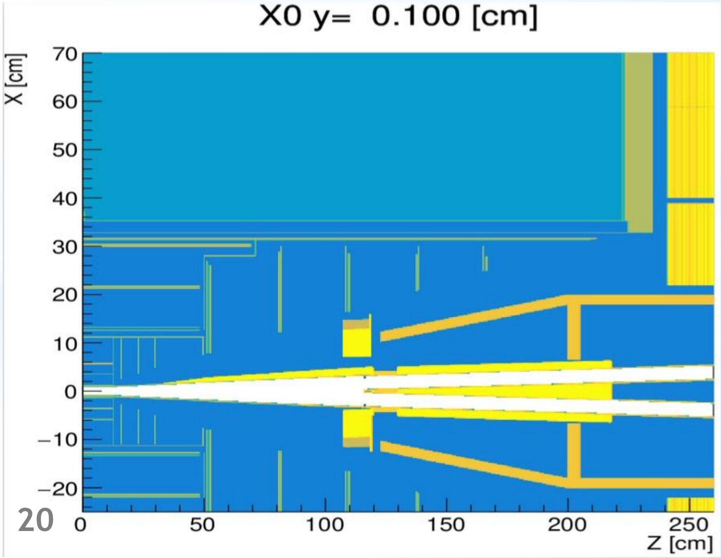
Why ILD Vertex detector and inner trackers need to be adapted?





The silicon inner tracker should be compressed if one decides to keep the same dimension of the TPC-→ smaller pitch is probably needed





Why ILD Vertex detector and inner trackers need to be adapted?

Backgrounds:

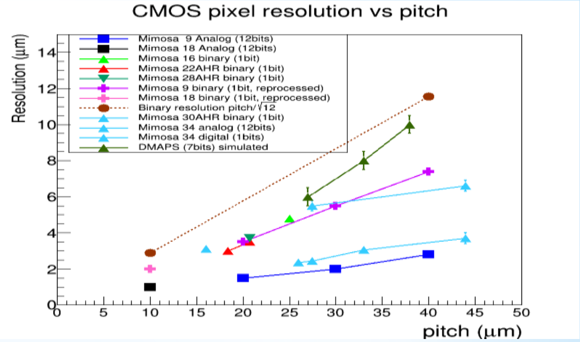
-Less bremsstrahlung in circular than in linear (reduced beampipe radius)
-More synchrotron background in circular than in linear (increased beampipe thickness)
-Backscattered background is different due to difference in L*
Time resolution (< 10 ns) could reject much of the background but the price should be paid in terms of power consumption

Power:
The duty cycle of FCCee results in continuous data taking

-Power depends on # channels, data flux and time information
-Air cooling is ok up to 20mW/cm^2 but more complex structure renders such solution more difficult.
-For power consumption > 20 mW/cm^2 active cooling may be needed resulting in more material budget and less precision

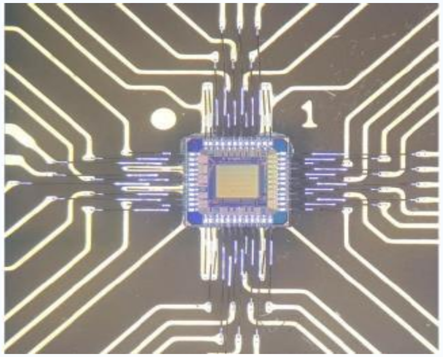
A compromise should be found

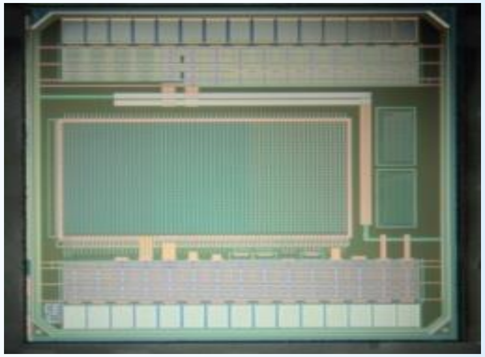
The silicon-based technologies proposed for ILC can be adapted for CC



-Reduced pitch to improve on spatial resolution:
possible with finer technologies which also gives
better charge collection efficiency).
and/or
use analog readout and shared charge

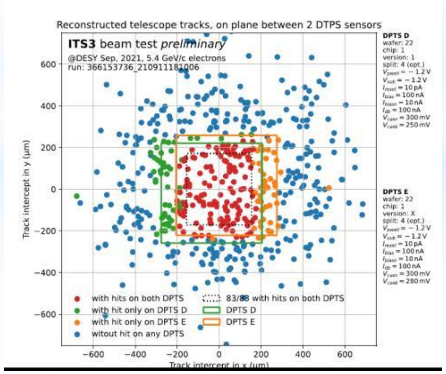
-Reduced power consumption: about 50% less when going from 180 to 65 nm

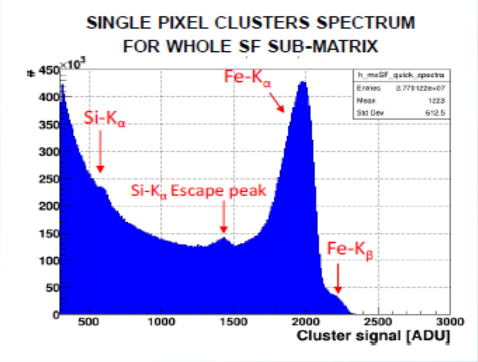




65 nm MLR1

Pitch: 15-25 microm, different EPI
Very encouraging results





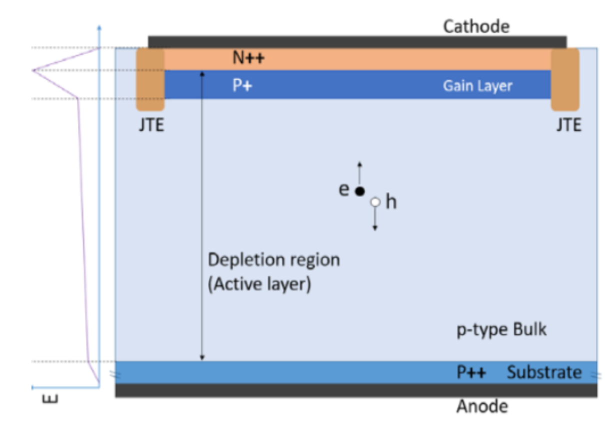
Other technologies with precise time information (4D) are also being investigated

-One can have excellent spatial resolution O(1 μm)
-One can have excellent timing O(10 ps)

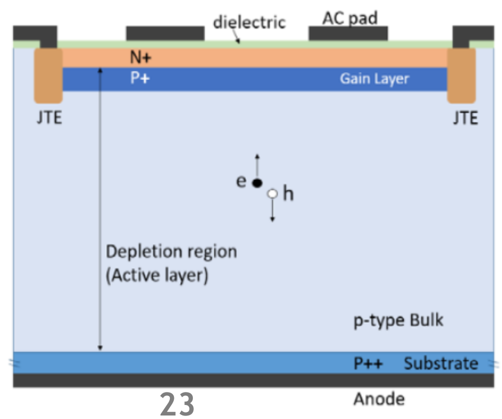
Timing requires complex circuitry and thus large pitch
Timing increases power consumption necessitating more complex cooling system and thus high material budget
Both lead to spatial resolution degradation.

Timing layers (1-2) could be used but more in the external part

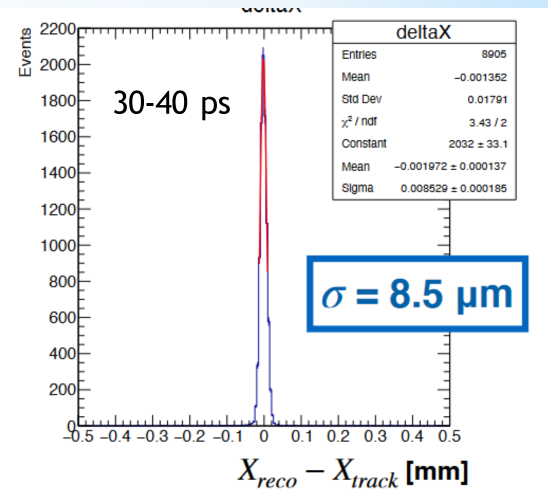
One of the most attractive technology that is under study is the 2D AC-LGAD where a better spatial resolution can be obtained by charge sharing. M. Mandurrino et al., IEEE Electron Device Lett. 40(11) (2019) pp.1780-1783



LGAD (Low-Gain Avalanche Diode)

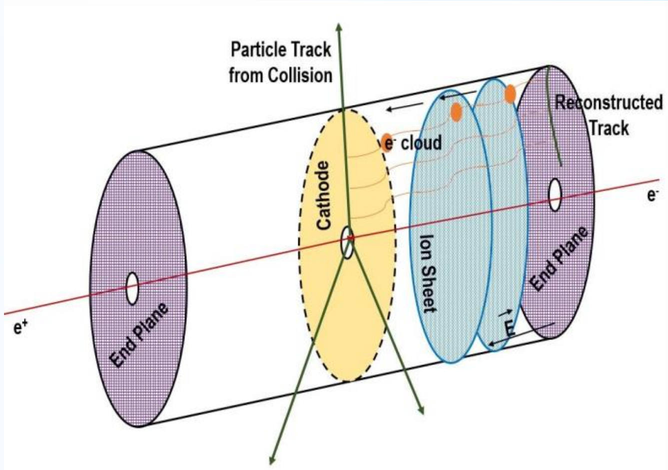


AC-LGAD (AC-coupled LGAD)



TPC

TPC is an important sub-detector of ILD:
- ➢ 220 hits → momentum measurement
  continuous tracking (V0)
- ➢ dE/dX → PID
- ➢ Low material budget



TPC is impacted by two sorts of ions
-Primary ions
-Flow Back ions

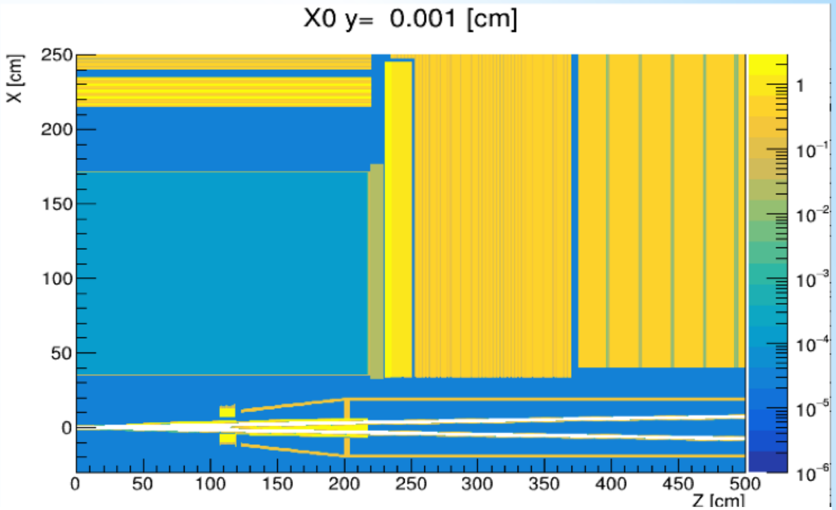
The ions produced in the TPC gas amplification drift through the gas volume for ~0.44 s

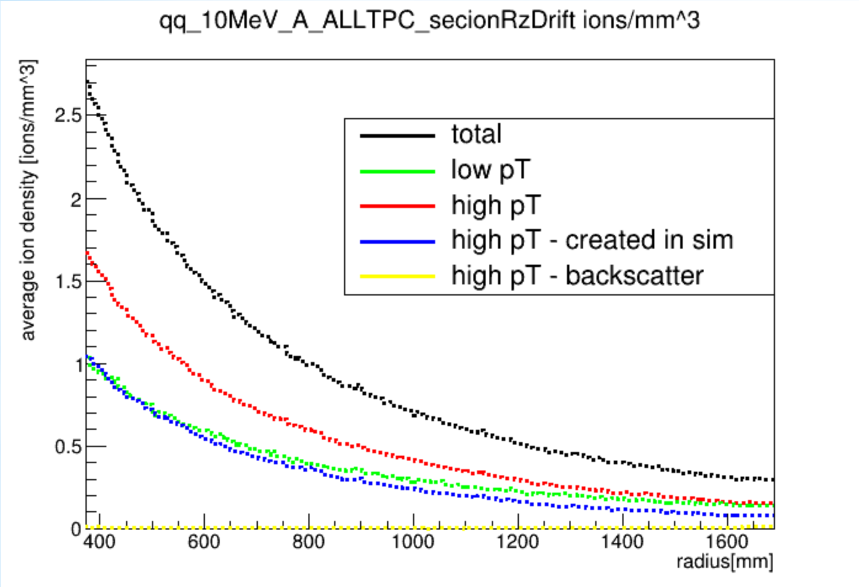
In case of ILC this results in 3 localized disks of ions drifting through the TPC each made from ions produced by a train of **1.3k BX→ we have a solution**

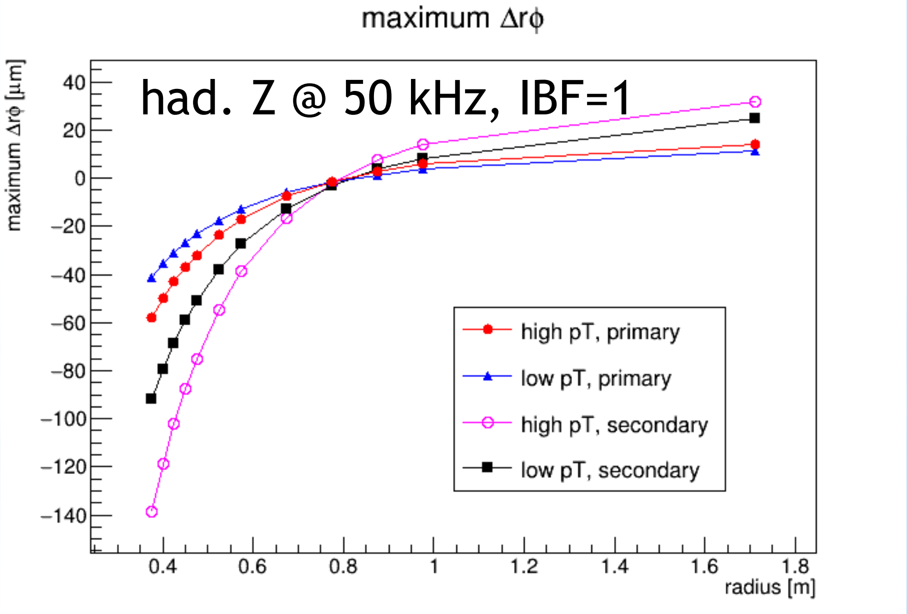
In the case of FCCee-pole (~33 MHz) it is **14 M BX** producing a cloud of ions that introduces a big distortion of the electric field of the TPC

TPC

By placing ILD TPC within FCCee MDI structure and a 2T magnetic field the impact of ions produced by the tracks of the 22 kHz hadronic Z decays that take place during the TPC clearing time (0.44 s) was studied and their impact on the field distortion Is found to be quite important (up to 1 mm).







~1.3 M primary ions / event

maximum distortion~ (100 + 230*IBF) μm
IBF=1-5

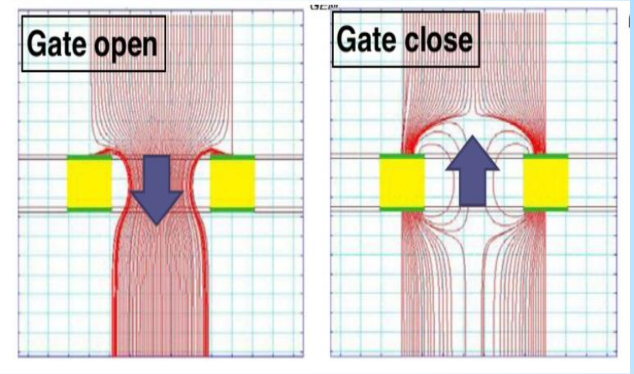
TPC

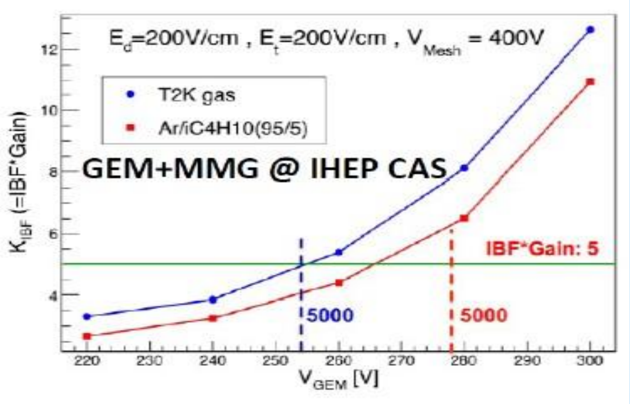
Reducing IBF is rather mandatory to be able to reduce the distortion and then to correct for.

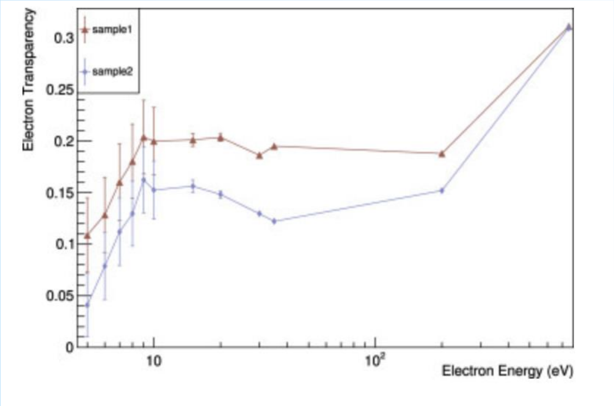
Several methods are proposed to reduce the IBF:
-Active gating proposed for ILC seems not possible in CC but passive gating (E field configurations) could help.

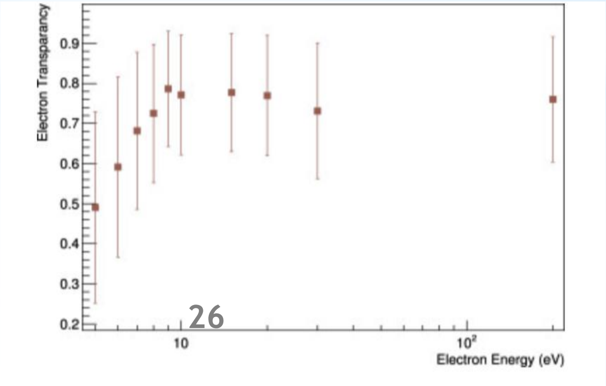
-Using a combination of MPGD can reduce the IBF.

-Most promising solution is to use graphene to stop IBF since graphene allows the passing of electrons but not ion.



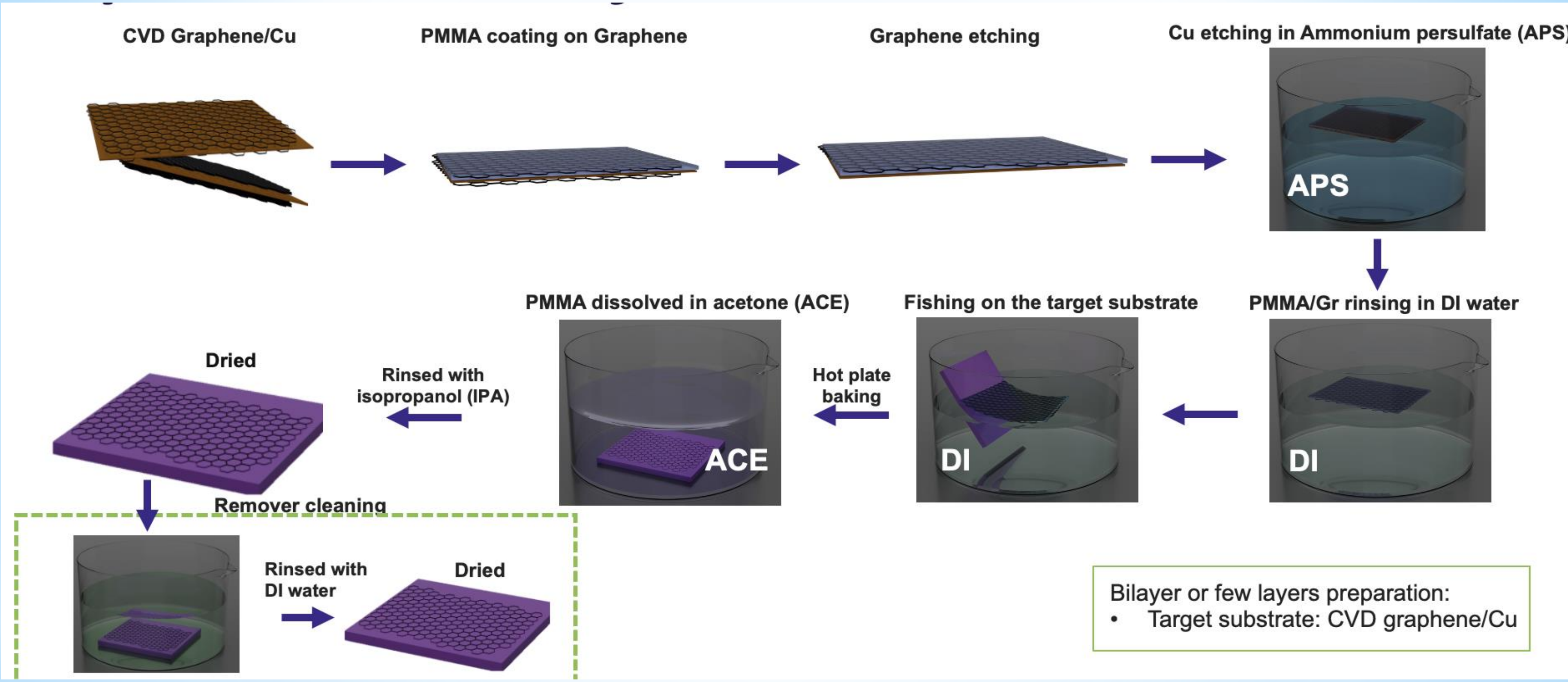




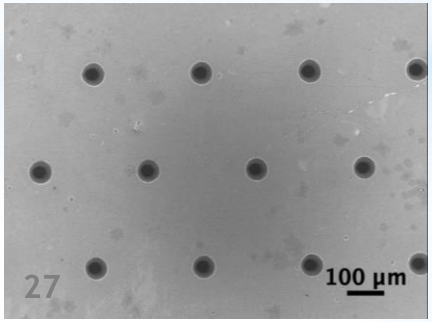


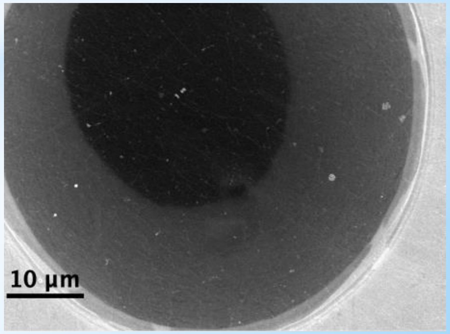
J. Kang et al
NIMA 1031 (2022) 166521

Graphene deposition on GEM foil is being developed by CERN group using a wet transfer procedure



Coverage estimation with bilayer: ~90% after the first cleaning in ACE
Coverage estimation: ~30% after the second cleaning w/ Remover





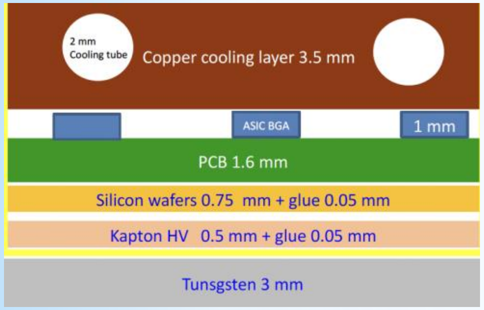
Calorimeters

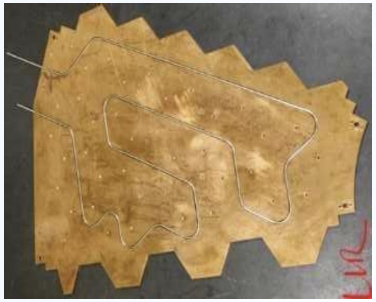
The most important issue to face when proposing PFA calorimeters for future CC is the power consumption in the absence of LC power-pulsing scheme. This represents 100 more power consumption that needs to be addressed. Several solutions are under scrutiny:

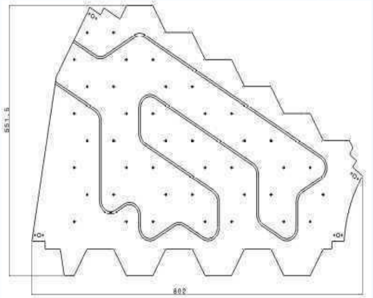
-Active cooling:

Similar in spirit to the one proposed for HGCAL for SiW ECAL

By adding a Cu plate containing hollow tubes in which 2-phase CO_2 circulates



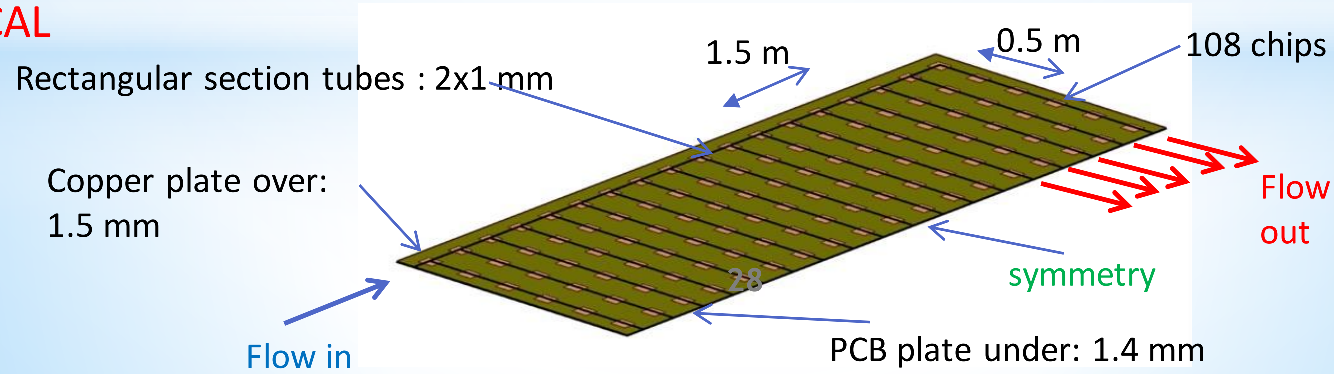




Or by adding a thin copper plate in thermal contact with the electronics and a water cooling circuit that could be cast in the absorber layer

water circulation in copper pipes

SDHCAL



Calorimeters

The most important issue to face when proposing PFA calorimeters for future CC is the power consumption in the absence of LC power-pulsing scheme. This represents 100 more power consumption that needs to be addressed. Several solutions are under scrutiny:

-Electronics with less power consumption and/or less granularity:

First option

-Use finer technologies → less power consumption (**factor of 2 or more**)
350 nm → 130nm → 65 nm →
-Work out the ASIC design and optimize the power consumption of each component

Second option

Reduce the granularity
Going from pads of 5 mm x 5 mm to 1 cm x 1 cm reduced the ASIC related power consumption by a **factor of 4**.
here the consequence on performances needs to be carefully studied

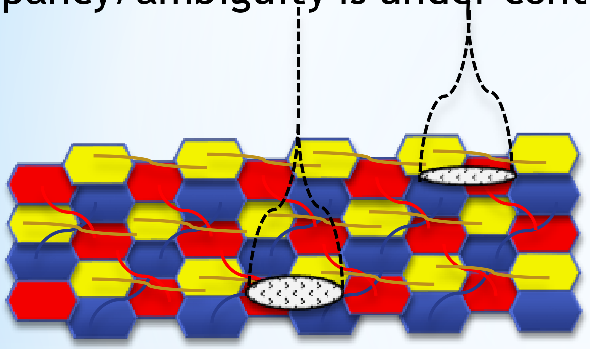
Probably combining both and compare with realistic performance obtained with active cooling to decide for the future

Calorimeters

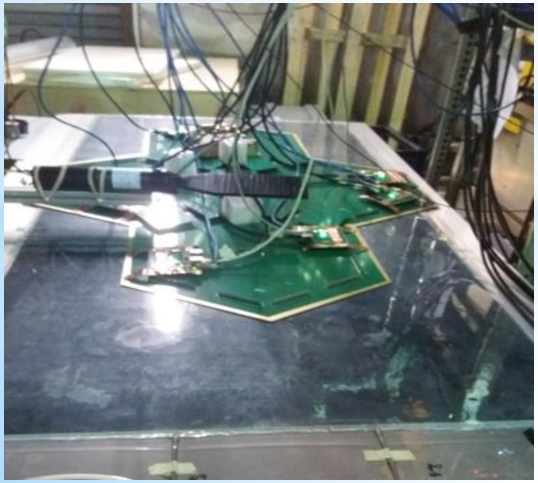
The most important issue to face when proposing PFA calorimeters for future CC is the power consumption in the absence of LC power-pulsing scheme. This represents 100 more power consumption that needs to be addressed. Several solutions are under scrutiny:

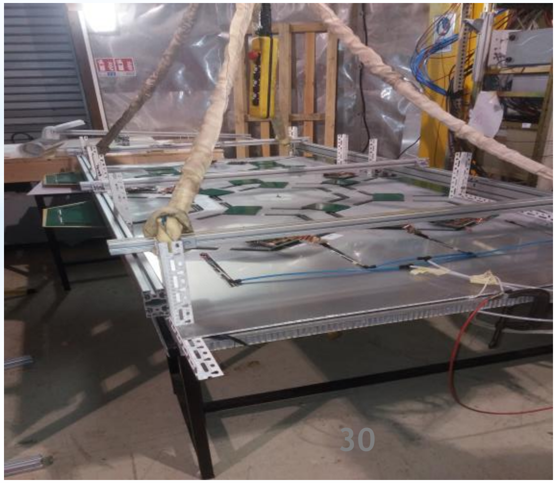
-New ideas:

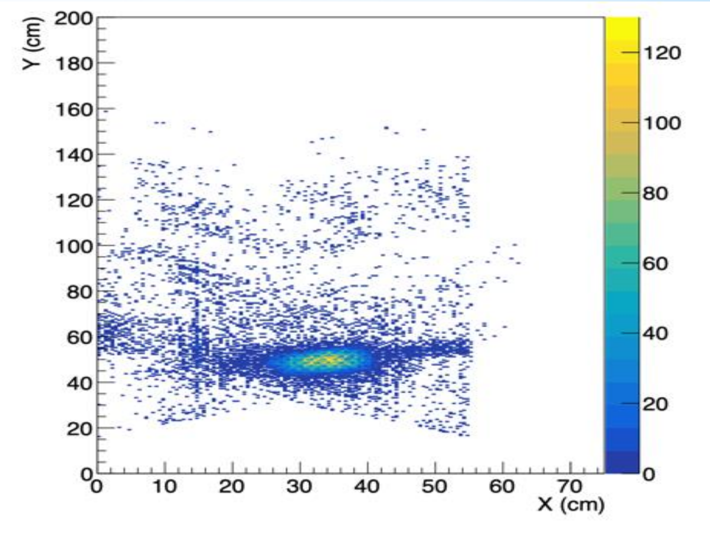
Reduction of number of channels by interconnecting pads/pixels as far as the occupancy/ambiguity is under control



NxN→ 3N reduction
For large area detectors like calorimeters this may as efficient as PP reduction





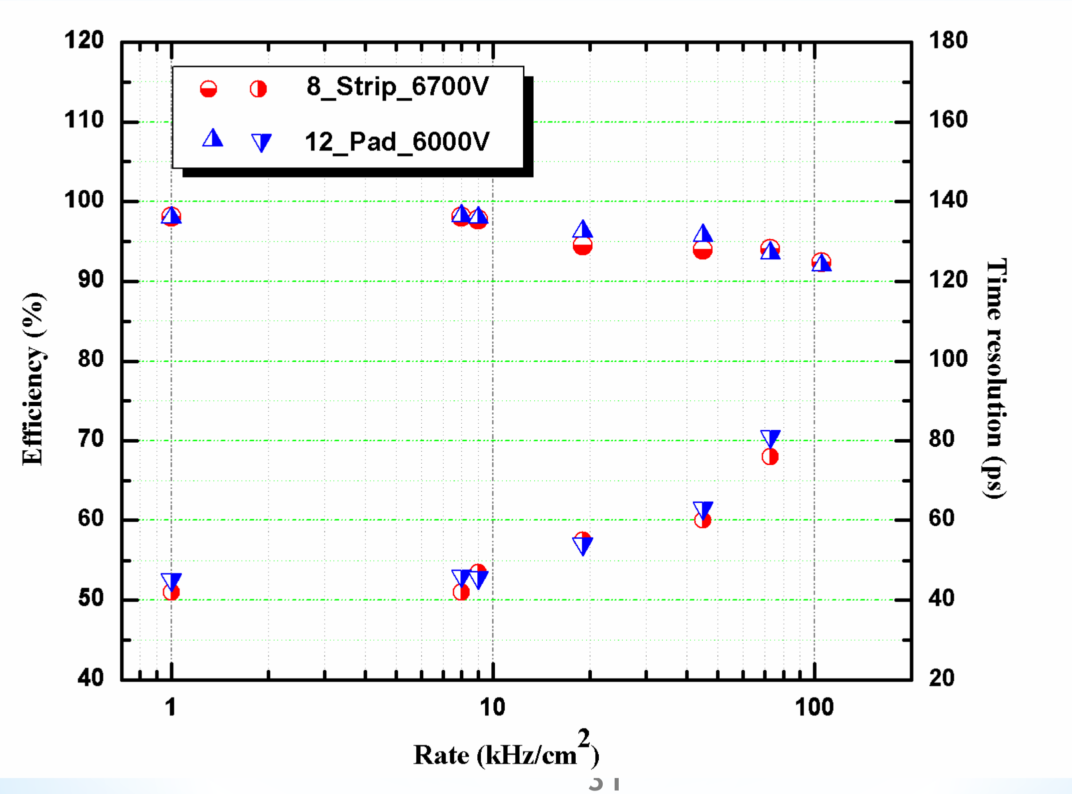


Calorimeters

High rate capability of some technologies is questioned in particular at FCCee@Zpole

For instance, GRPC-based SDHCAL in its present status could not be efficiently used

Hopefully, development of new low resistive materials such as the low-resistivity glass (Tsinghua) and low-resistivity thermoplastic (Lyon) will allow to increase the rate capability from $O(10^2)$ Hz/cm2 to a $O(10^4)$ Hz/cm2



Timing@ILD

Adding time information to ILD detectors will provide them with additional tools to to reject background and also to improve on PID and jet reconstruction

A few points that need to be considered before to switch for T-detectors:

-Time information comes however with a price, namely increasing power consumption that we are trying to reduce

-Trackers equipped with time information could not compete with detectors like TPC for PID but could provide valuable information on low momenta in particular @ Z-pole

-Calorimeters with time information could be very useful for PID and PFA but this should be in balance with the degradation of energy resolution due to active cooling

Conclusion

- ILD collaboration intends to play a major role in any future $e^+ e^-$ collider

- ILD@ILC has reached the required maturity even though improvements could always be brought in

- ILD@CC studies have started

  - Adaptation of ILD detector within the constraints of CC
  - Adequacy of some sub-detectors with CC conditions and solutions
  - Physics performance study (not shown in this talk)

- ILD collaboration is eager to build bridges with other collaborations to face the challenges the CC environments pose