* ILC Calorimeters →FCCee Calorimeters

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Outline

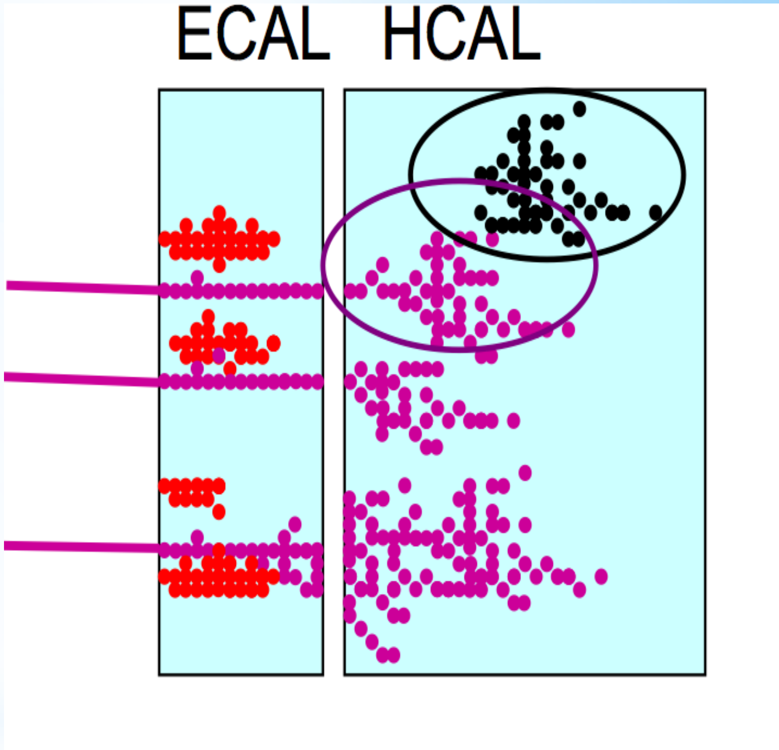
→ILC detectors philosophy
→ILC calorimeters options :
SiD, ILD
→ ILC calorimeters for FCCee
Examples: SDHCAL, Si-W ECAL

Philosophy of the ILC 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** is adopted in both SiD and ILD concepts. **PFA**: Construction of individual particles and estimation of their energy/momentum in the most appropriate sub-detector.



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.

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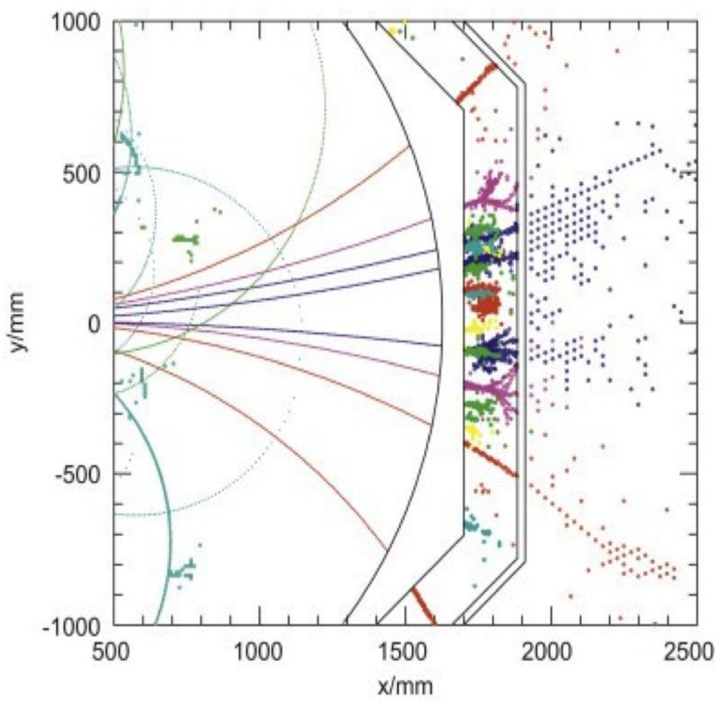

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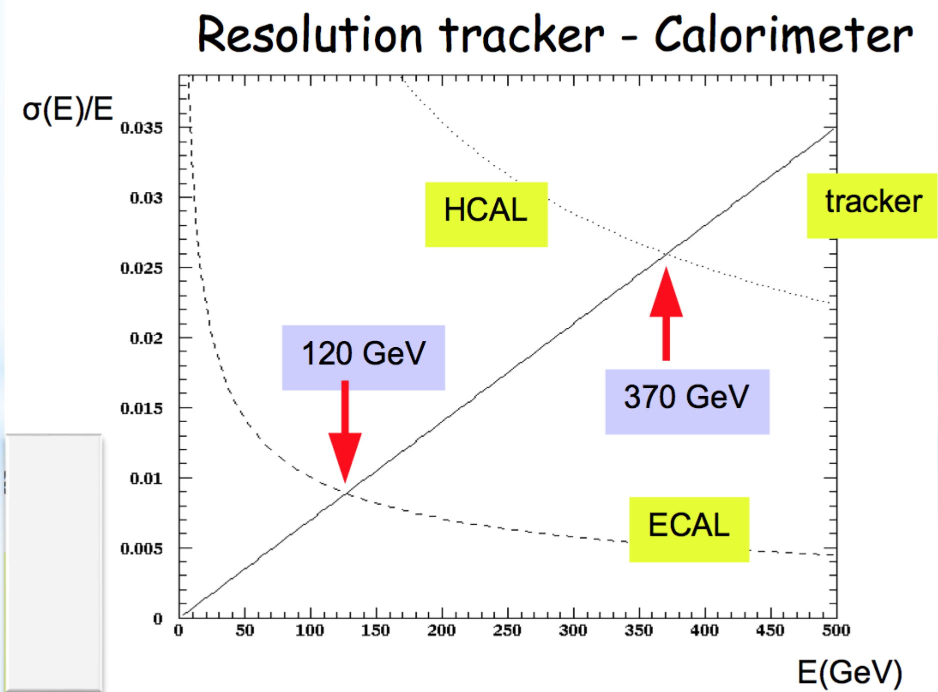
Why tracking is so important?

E_{jet} =	$E_{charged\ t}$ +	E_{γ} +	E_{h0}
fraction	65%	26%	9%

Charged tracks resolution	$\Delta p/p \sim$ few10^{-5}
Photon(s) energy resolution	$\Delta E/E \sim 12\% / \sqrt{E}$
Neutral hadrons energy resolution	$\Delta E/E \sim 45\% / \sqrt{E}$



Philosophy of the ILC detectors : Requirements

- Vertex detector : **excellent resolution**

  $\sigma_{IP}(r\phi) = 5 + 10/(p \sin^{2/3}(\theta))\ \mu m$

  b-tag, c-tag,… for H → bb, cc, $\tau\tau$ studies

- Tracker : **excellent precision** measurement of p_t

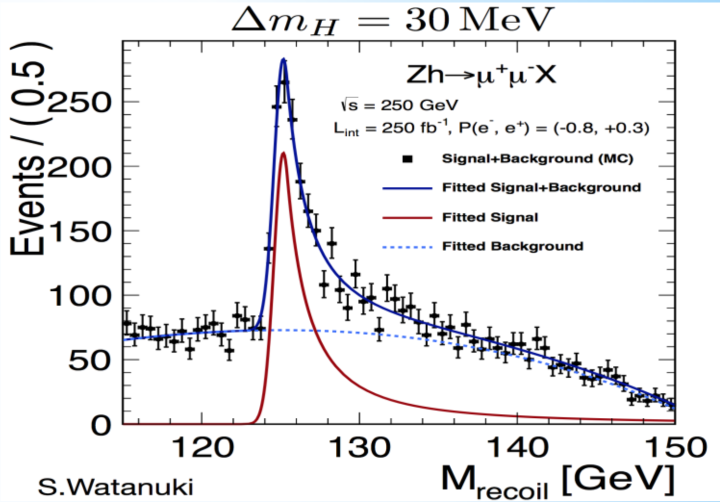
  $\sigma(1/p_t) = 10^{-5}\ GeV^{-1}$

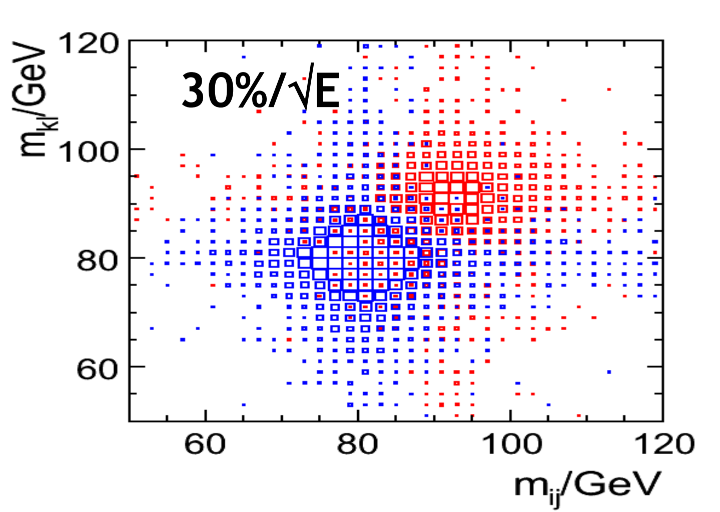
  H mass recoil, $e^+ e^-$ → H Z→ $\mu^+ \mu^-$ + anything

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

  $\sigma_E/E = 30\%/\sqrt{E}$

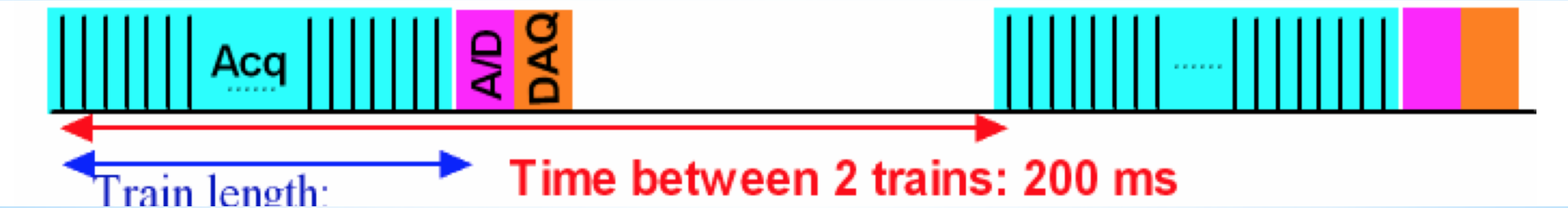
The whole detector should be hermitic, compact with moderate power consumption





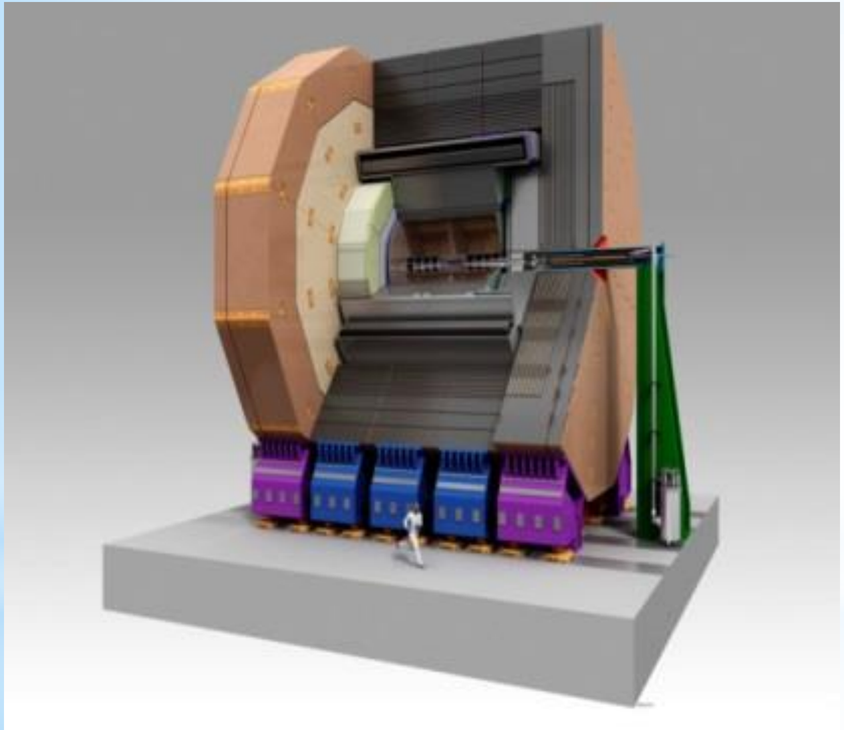
Power-Pulsing

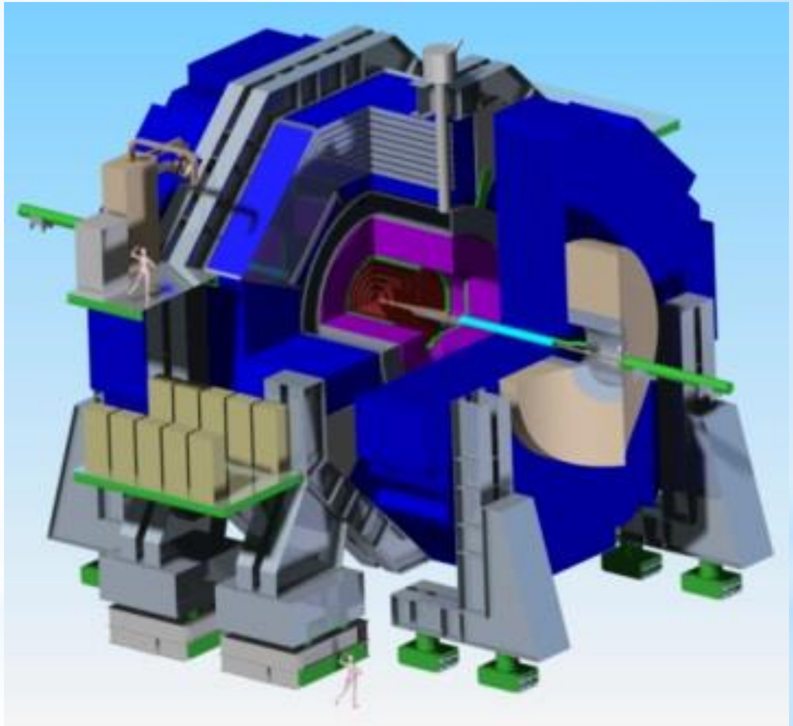
Important feature of ILC detectors to reduce power consumption and heating for highly-granular detectors
Electronics switched on just before the bunches train and off after
A factor 100-200 power reduction could be achieved.



→ 2820 bc by train
→ 337 ns separating two bc.

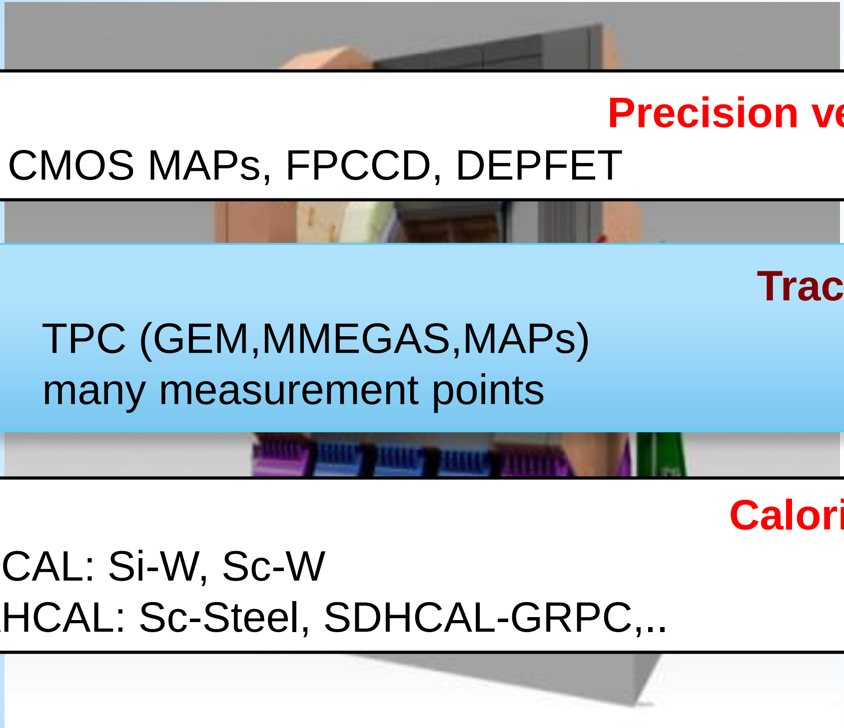
ILD SiD

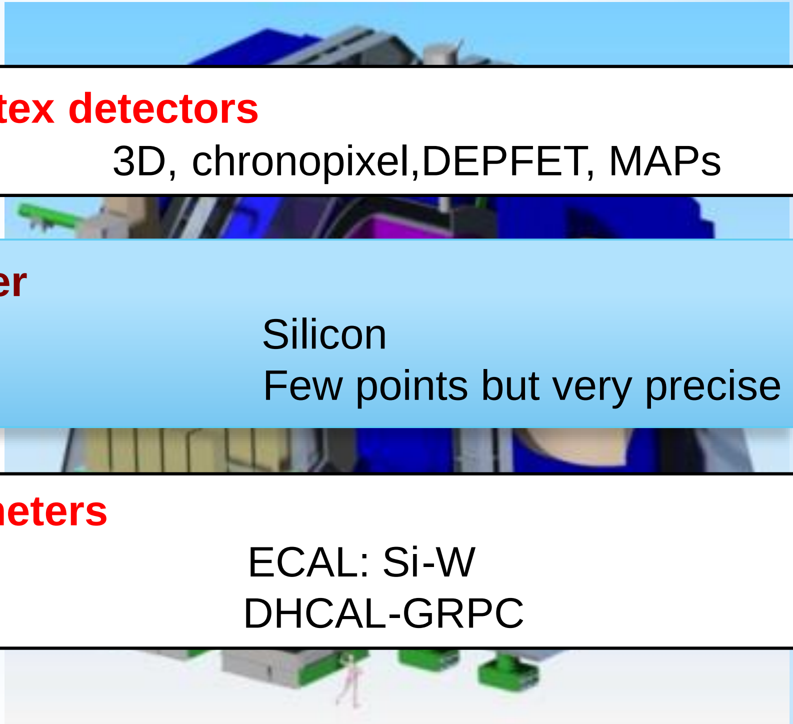




	SiD	ILD
R(in) Vertex	14 mm	16 mm
R(out) tracker	1221 mm	1808 mm
N(tracker hits)	<12>	<228>
X(0) until ECAL	12% (barrel), 20% (EC)	12% (barrel), 42% (EC)
R(out) HCAL	2493 mm	3973 mm
Λ (until end of HCAL)	4.5	7 (min), 8.5 (max)
Coil inner radius	2591 mm	3440 mm
B(coil)	5 T	3.5 T
Outer Radius	6042 mm	7755 mm
Total length	5673 mm	6620 mm

ILD	SiD





Precision vertex detectors

ILD	SiD
CMOS MAPs, FPCCD, DEPFET	3D, chronopixel,DEPFET, MAPs

Tracker

ILD	SiD
TPC (GEM,MMEGAS,MAPs) many measurement points	Silicon Few points but very precise

Calorimeters

ILD	SiD
ECAL: Si-W, Sc-W AHCAL: Sc-Steel, SDHCAL-GRPC,..	ECAL: Si-W DHCAL-GRPC

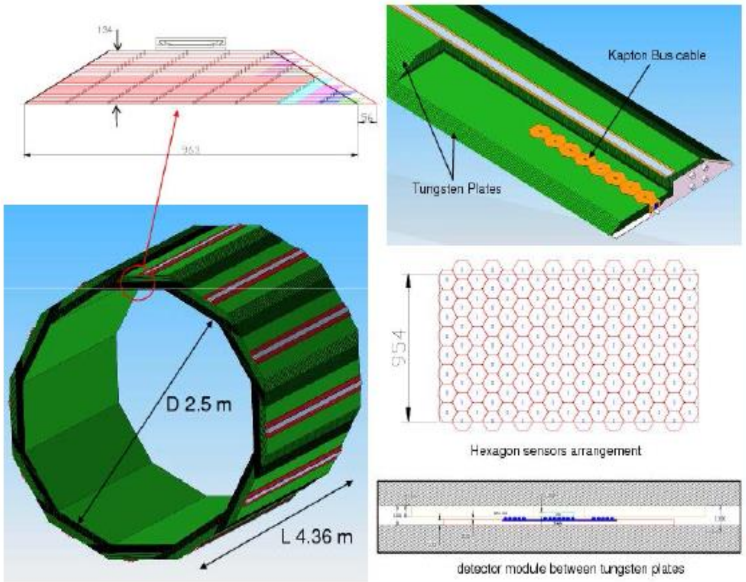
Size&Magnet

ILD	SiD
Large size, 3.5 Tesla	Compact, 5 tesla

Technologies proposed for ILD&SiD calorimeters

ECAL for SiD

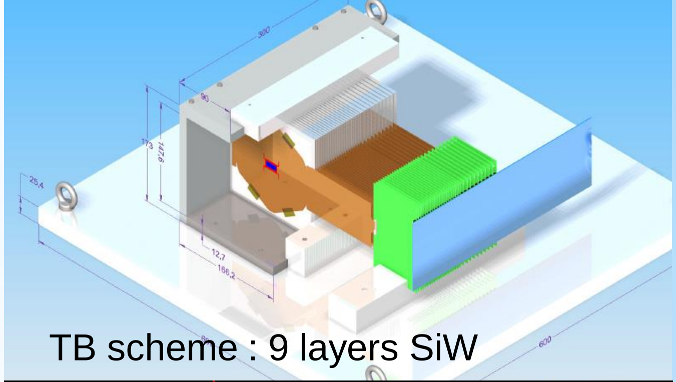
An imaging calorimeter: 30 layers tungsten interleaved with 30 layers pixellated silicon



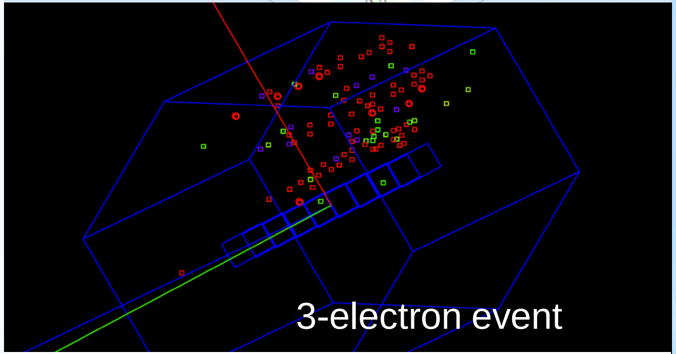
Baseline configuration:

- transverse: 12 mm^2 pixels
- longitudinal: $(20 \times 5/7\ X_0)$ + $(10 \times 10/7\ X_0)$ $\Rightarrow$ 17%/sqrt(E)
- 1 mm readout gaps $\Rightarrow$ 13 mm effective Moliere radius

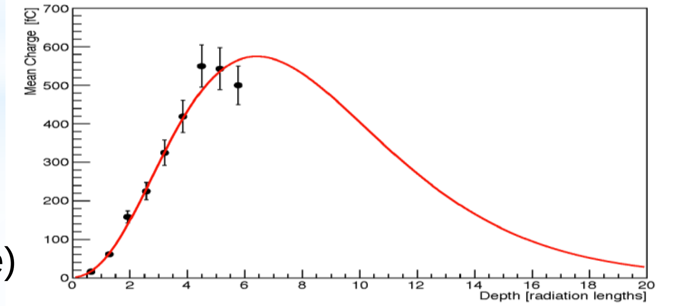
1024 KPiX ASIC
Power-pulsed



TB scheme : 9 layers SiW



3-electron event



- ➢ X-talk to be reduced by better shielding
- ➢ New scheme to have rectangular sensor (modified cells on the edge)
- ➢ Mechanical structure study needed

Technologies proposed for ILD&SiD calorimeters

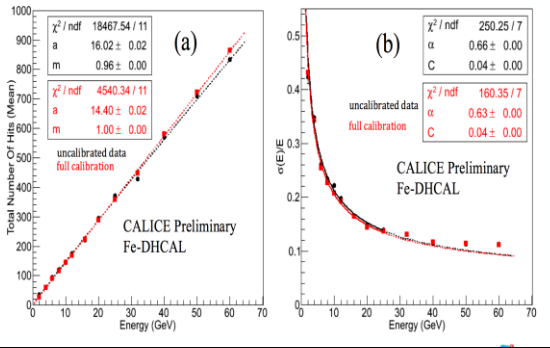
HCAL for SiD

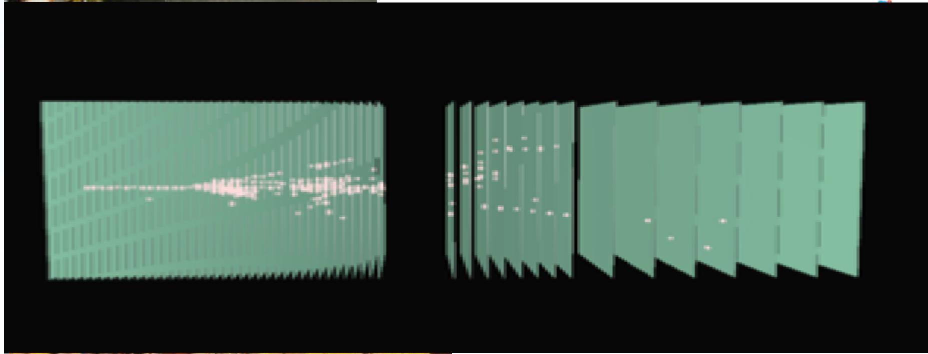
40 layers of 2 cm stainless steel interleaved with planes made of Glass RPC and their embedded readout 1-bit electronics allowing a lateral segmentation of 1 cm^2

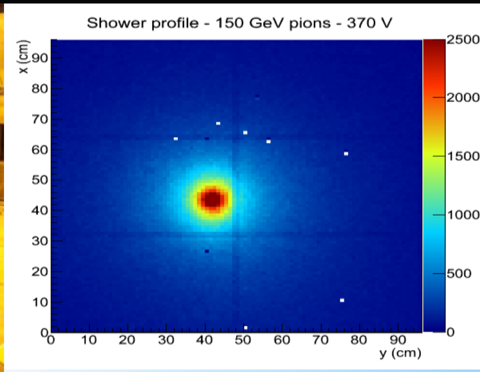
An advanced physical (embedded electronics) prototype of 54 was built and successfully run.

Other options with GEM and micromegas detectors are also proposed as active layers for the SiD HCAL Several layers of mm were built and tested using 2-bit readout electronics. Few GEM planes are also in preparation.

Scintillator tiles is an option.
Dual readout is also an option for both ECAL&HCAL







Technologies proposed for ILD&SiD calorimeters

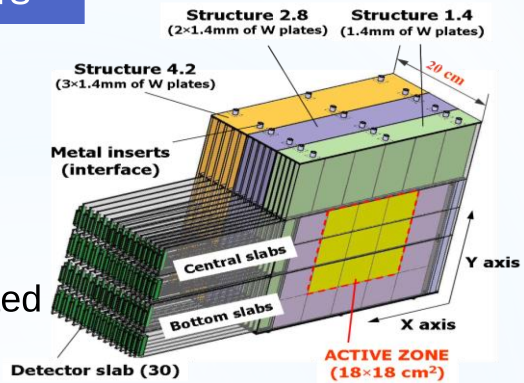
ECAL for ILD

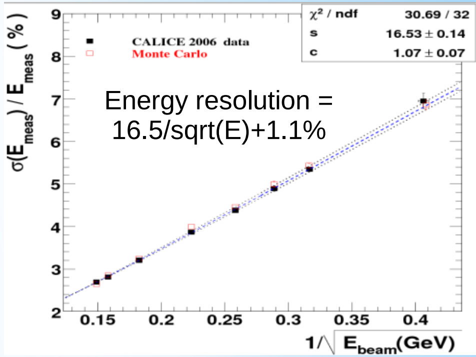
30 layers of tungsten ($24X_0$) interleaved with
-Pixellated Silicon of 5x5 mm^2,

A physics prototype (1x1 mm^2 cell size) with a deported electronics was built and successfully tested.

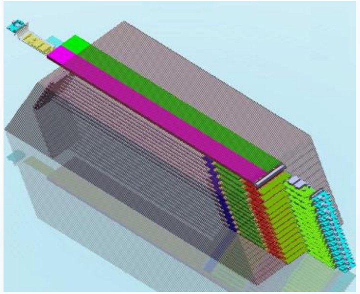
A technological prototype fulfilling the ILD DBD requirement is being developed :

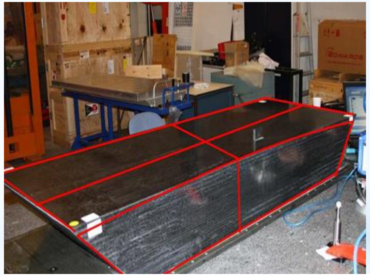
- ➢ Self-supporting structure (alveolar)
- ➢ Embedded power-pulsed electronics
- ➢ Large surface detector

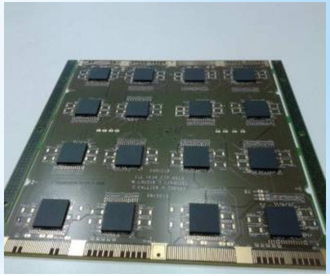


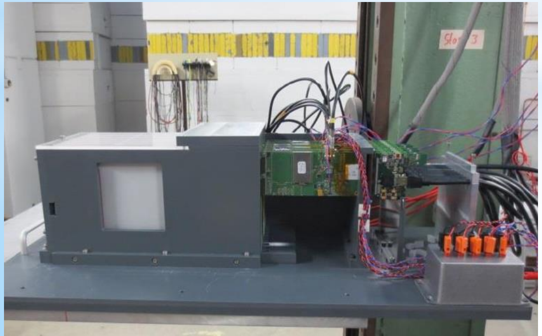


Linearity <1%

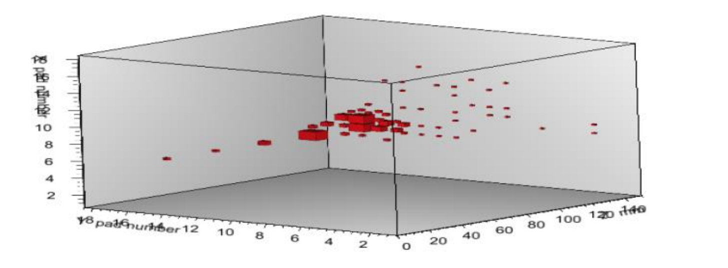








Several TB took place at DESY



Technologies proposed for ILD&SiD calorimeters

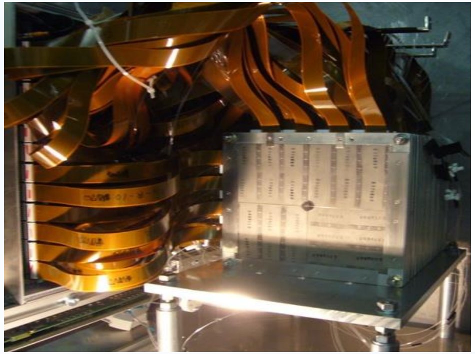
ECAL for ILD

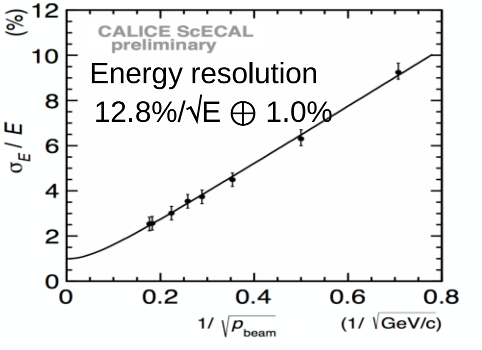
30 layers of tungsten ($24X_0$) interleaved with of 5x45 mm^2 scintillator strip with alternating direction layers (X&Y) → equivalent of 5x5 mm^2 (SSA)
Read out by SiPM
A physics prototype with a deported electronics was built and successfully tested

A technological prototype is being developed with

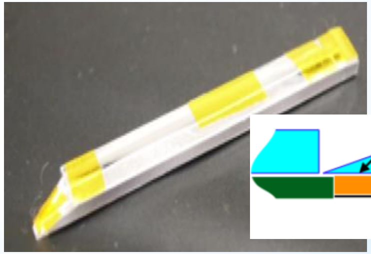
- Scintillator shape that optimizes light collection and reduces dead zones : rectangular, wedge, tapered..
- SiPM more compact with higher linearity range and less noise (MPPC 10000 ch in 1x1mm^2)
- Electronic board to host ASIC on one side and scintillator plane on the other.

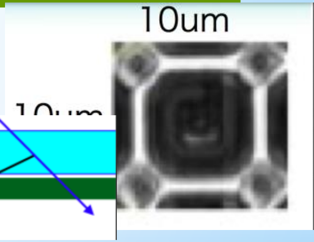
A first plane with the new technology was tested in 2014.

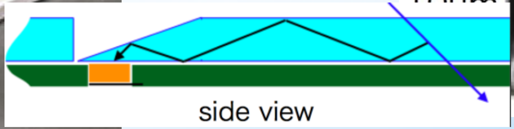


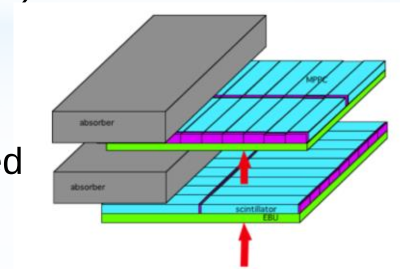


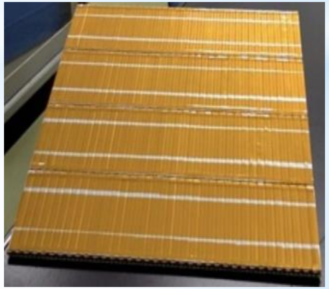
Linearity <1.5%

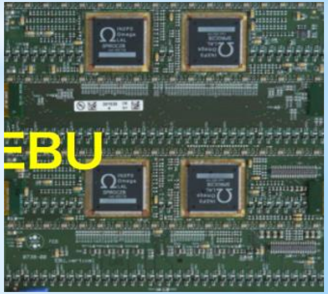




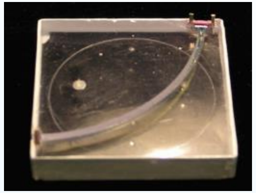


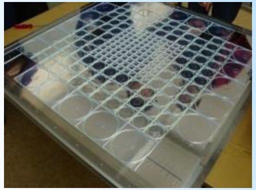






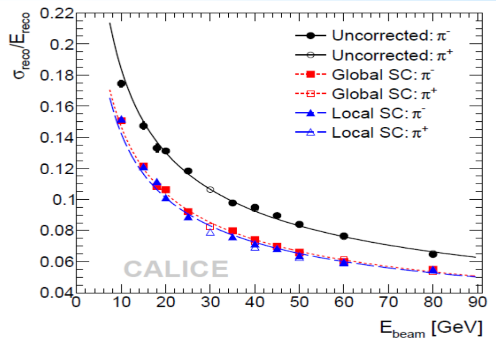
Technologies proposed for ILD&SiD calorimeters





HCAL for ILD

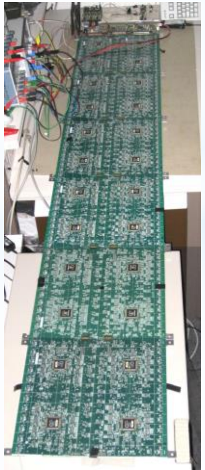
48 layers of 2 cm stainless steel interleaved with planes made of 3x3 cm^2 tiles, read out directly by SiPM and embedded electronics.

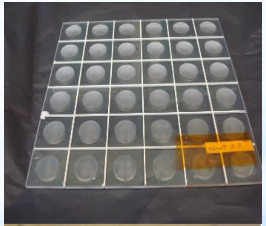


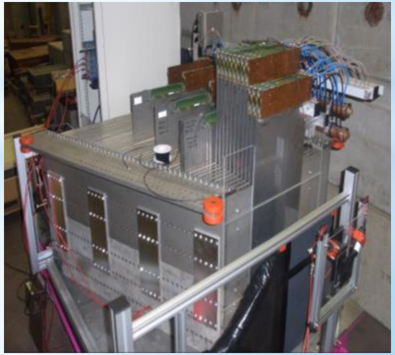
A physical prototype of 38 layers of 1 m^2, totalizing (5.3 λ_I) accompanied by a tail catcher (6 λ_I) with deported electronics was built and successfully tested

A technological prototype fulfilling the ILD requirements is being developed :

- Optimized tile shape for direct readout
- Embedded, power-pulsed readout electronics
- Large plane with tiles assembled in a way to reduce dead zones
- Self-supporting mechanical structure







Several planes of different sizes were made

and successfully tested in 2014

Technologies proposed for ILD&SiD calorimeters

HCAL for ILD

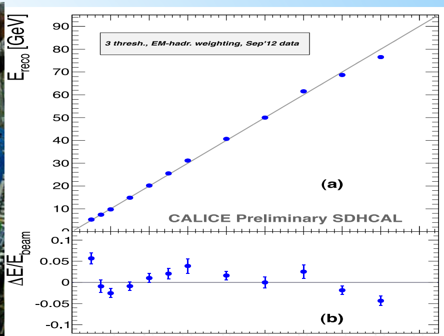
48 layers of 2 cm stainless steel interleaved with planes made of Glass RPC and their embedded readout 2-bit electronics allowing a lateral segmentation of 1 cm^2

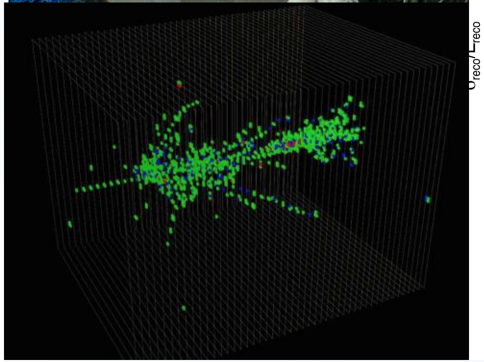
A technological prototype of 48 fulfilling almost all the ILD requirements of compactness and power consumption was built with a self-supporting mechanical structure. It ws successfully tested with

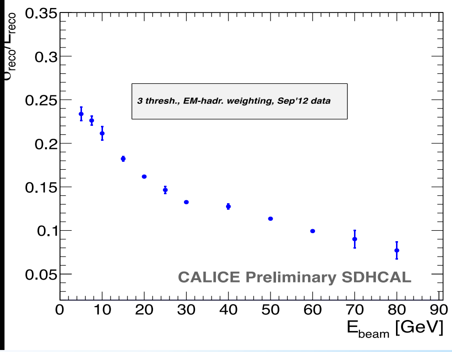
- Triggerless mode
- Power-pulsing mode

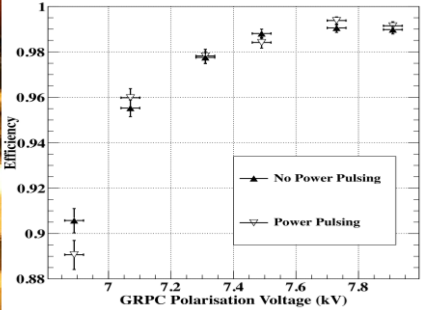
Last step is to build very large GRPC and equip them with the last generation of the readout electronics

The GRPC was also successfully tested in a magnetic field of 3 T using the power-pulsing mode

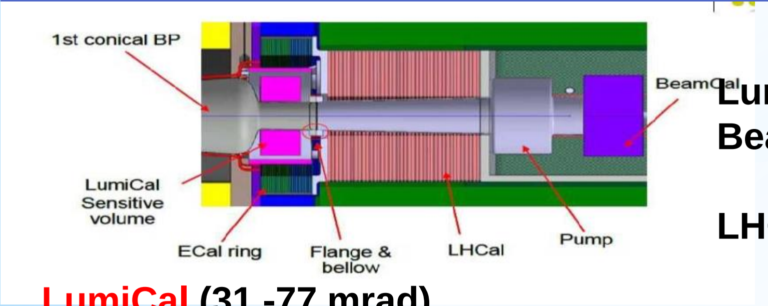




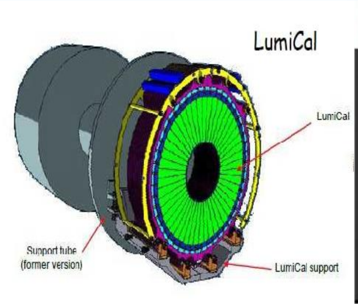


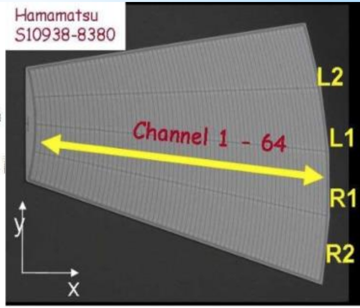


Technologies proposed for ILD&SiD forward calorimeters



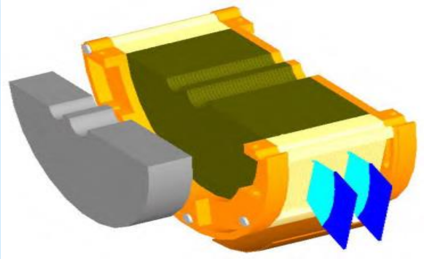
LumiCal: Precise luminosity measurement (10^{-3}) at 500 GeV.
BeamCal : Instantaneous luminosity measurement, beam diagnostics but very high radiation load (up to 1MGy/ year)
LHCaL: Extends the calorimeter measurements to small polar angles

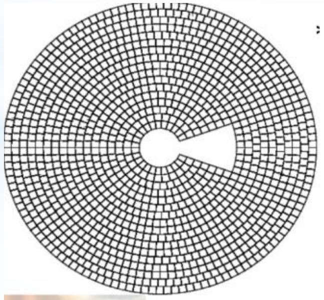


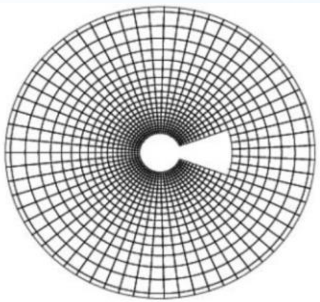


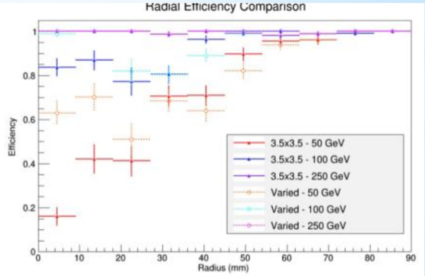
LumiCal (31 -77 mrad)
- Two Si-W sandwich EM calo at ~ 2.5 m from the IP (both sides).
- 30 tungsten disks of 3.5 mm thickness. Si sensor pitch of 1.8 mm
- Two tracking layers in front are envisaged to improve angle measurement and separate e/γ.

BeamCal (5 – 40 mrad)
- similar W-absorber as for the LumiCal but radiation hard sensors (GaAs, CV Diamond, Sapphire, Si).
- Segmentation is being worked out, new ideas on the sensor orientation

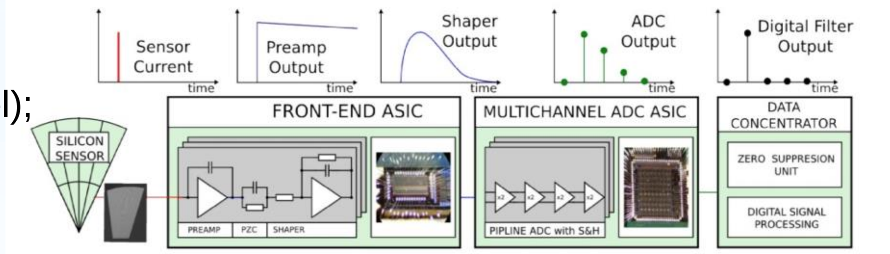



roportional Segment.


Uniform Segment.

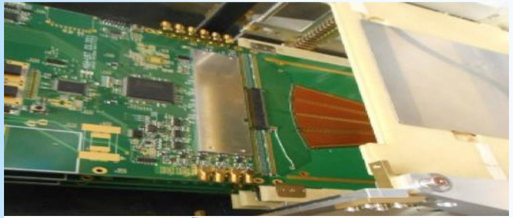


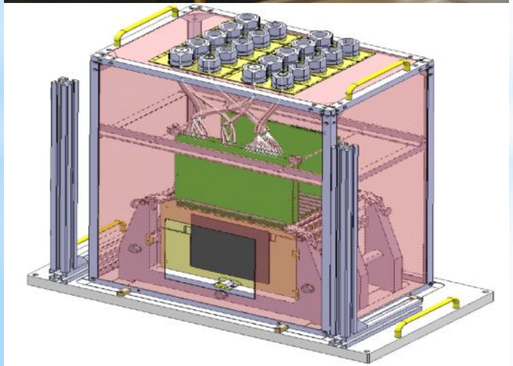
Technologies proposed for ILD&SiD forward calorimeters

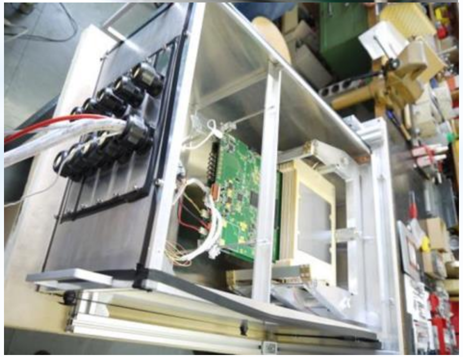


- ✓ LumiCal chip in 130 nm.
- ● 8 channel (preamp, shaper Tpeak ~ 60 ns,~9 mW channel);
- ● 8 channel pipeline ADC, ~1.2 mW/MHz;
- ● FPGA based data concentrator and further readout.

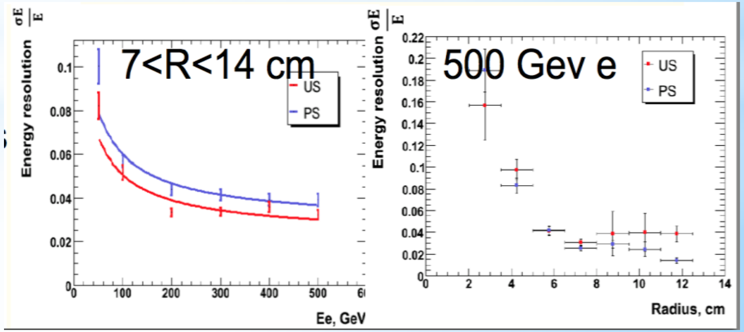
- ✓ 4 layers are realized and tested in TB
- ✓ Mechanical structure studied and prototyped







- ✓ BeamCal
- • Choice of the sensor will depend on the T-506 studies at SLAC
- • BeamCal is sensitive above 50 GeV. At 50 GeV the fake rate due to beamshtrahlung is 0.5% for R>7 cm, energy resolution = 10%, at 200, 4% at 500 GeV 4%



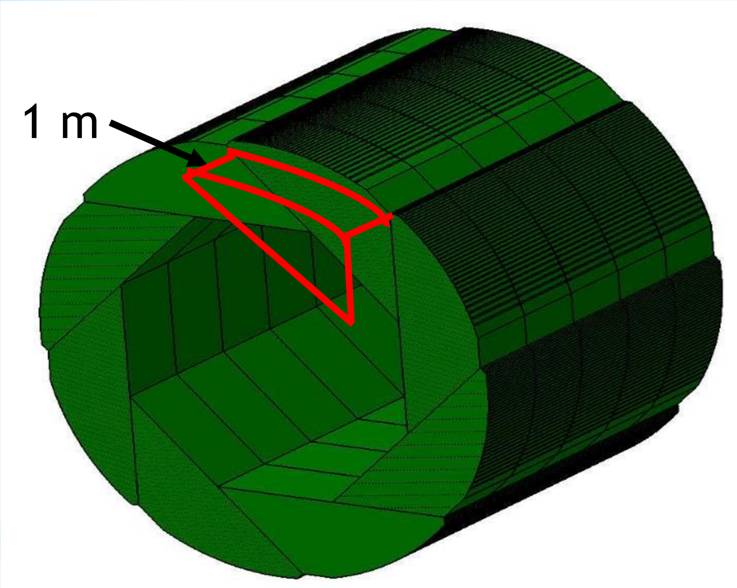
From ILC to FCCee

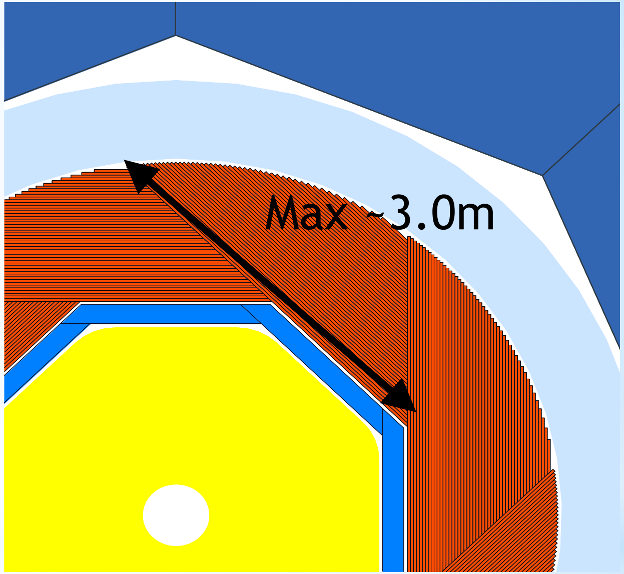
For ILC the high-granularity calorimeters concept is possible thanks to the power-pulsing mode. This mode allows a reduction of power consumption of a factor of 100-200. Cooling is still needed but is limited to the outer surface.

For FCCee and similar accelerators (CEPC) the power-pulsing is not possible and one should extract the heat produced by the embedded electronics in efficient way.

Some studies have been initiated in the case of SDHCAL and SiW ECAL.

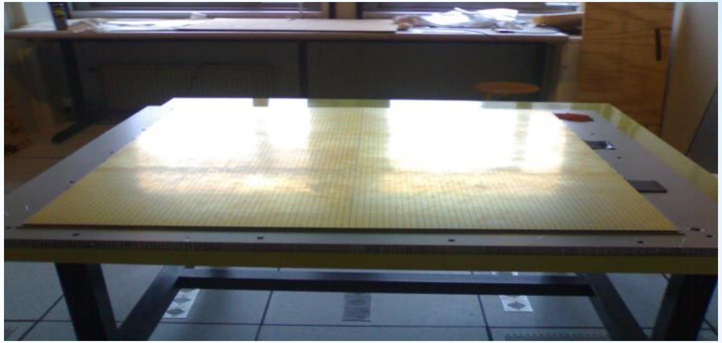
Example1: ILD SDHCAL

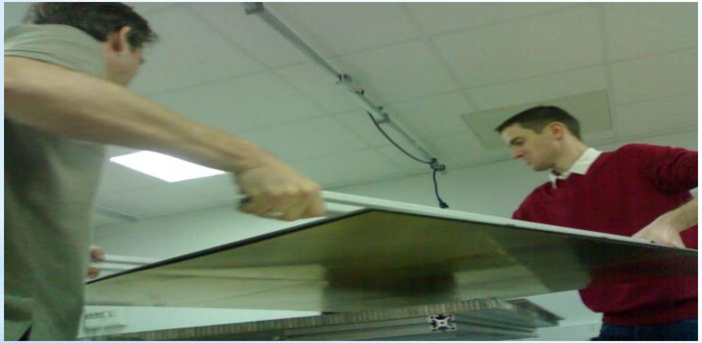


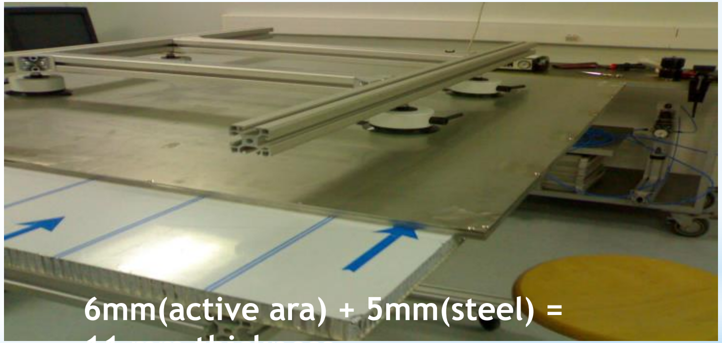


- Chambers are 91.6 cm in width, maximum length 290 cm
- Embedded front-end Hardroc electronics cover the whole area
- Active cooling essential if no power-pulsing : 70 10^6 channels
- Power of each channel : 1 mW

SDHCAL technological prototype







- 12 x 12 matrix for SDHCAL prototype → 144 Hardroc / m2
- For longest chambers in ILD design: 1m x 3m → 432 hardroc
- Power (no power-pulsing): ~10 W / m2 (1 mW/chan, 64 chans / Hardroc)
- ILD-SDHCAL : 70 kW

Active cooling scenarios

→ ‘In-chamber’ routing

-Attempt to make thermal contact between cooling pipes and all Hardrocs (not easy)

-Embed pipes in cassette cover (cover thickness 2mm: very small pipe diameters)

→ ‘In-absorber’ routing

-Embed pipes in absorber

-Convective heat transfer in air gaps between Hardrocs and cassette, and cassette and absorbers

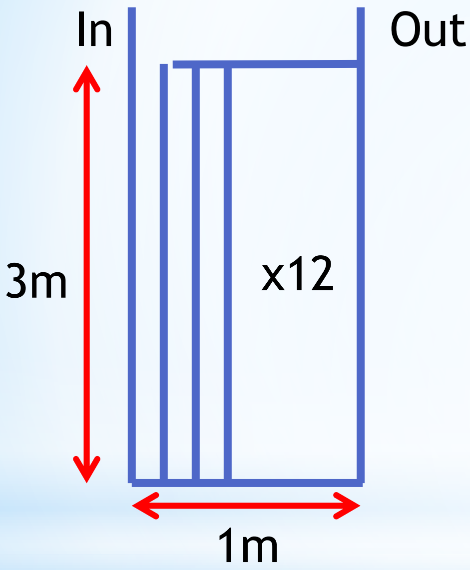
-Larger pipe diameters possible

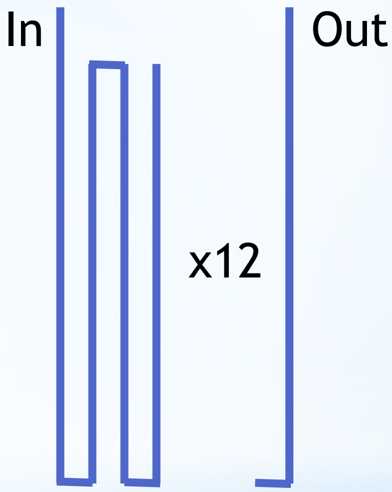
-Caveat: degradation of physics performance as diameters increase!

→ Outside edge of absorber (between HCAL and cryostat) or full circumference of absorber

-As for ‘in-absorber’ routing, but much longer heat transfer paths through absorber to cooling pipe.

In-chamber' cooling: possible pipe configurations





Longest pipe ~3m
Disadvantage: many joints/welds

Length ~36m
Disadvantage: high Δp

Pressure drops for water and 2-phase CO_2

Global assumptions:

- Pipe length = 36 m (single pipe option)
- Power to evacuate = 30 W

Water (single phase)

* Heat capacity: 4.18 J/g/K
* Kinematic viscosity: 1.0 * 10-6 m2/s
* Assume ΔT of 2°C
* Then needed mass flow = 11 kg/hr
* ΔP for 1 mm pipe ~175 bar
* For L = 3m, ΔP = 15 bar

CO_2 (two phase)

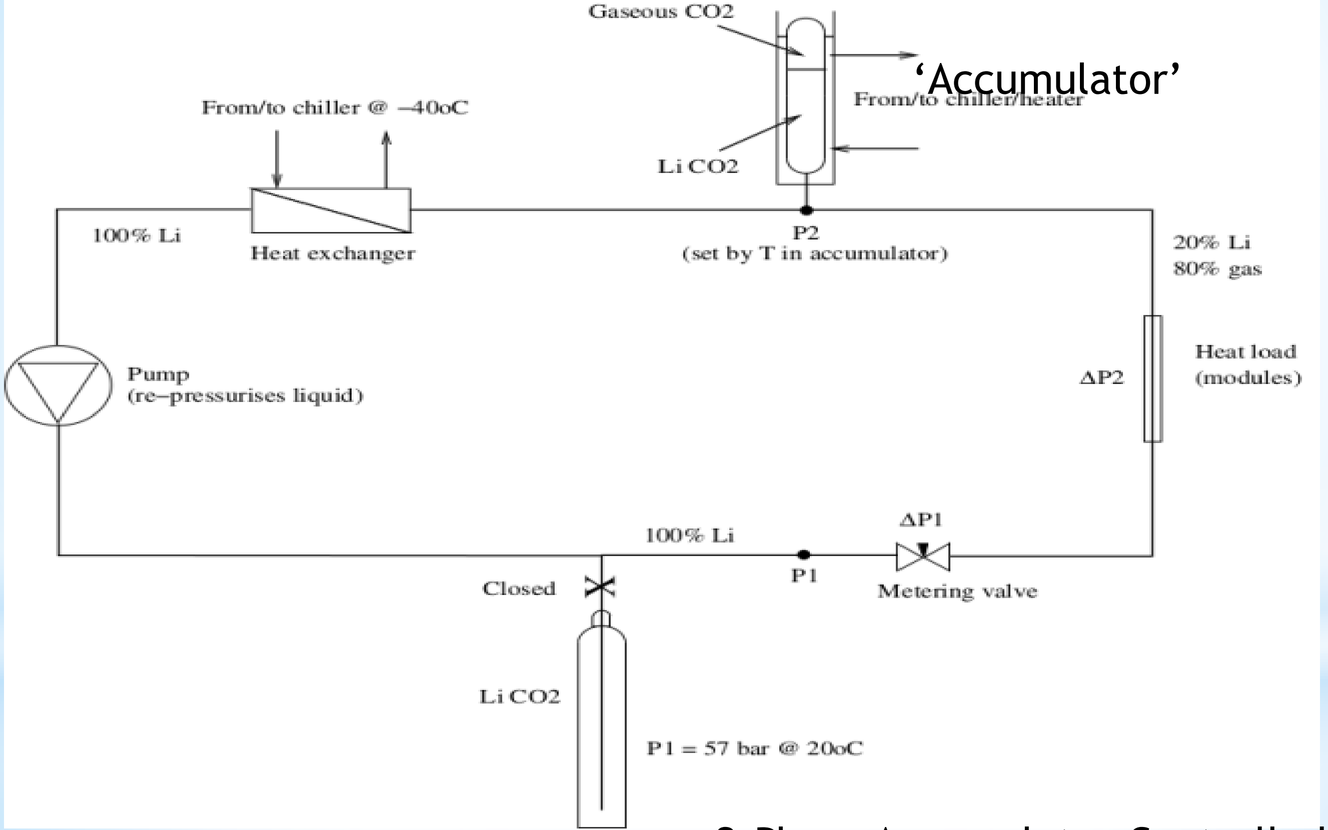
- Heat of evaporation: 574 J/g
- Kinematic viscosity: 0.1 * 10-6 m2/s

- Needed mass flow = 0.25 kg/hr
- ΔP for 1 mm pipe ~0.2 bar*

*Friedel method

Conclude: single pipe OK for CO_2, water needs parallel pipes

Two-phase CO2 cooling



2-Phase Accumulator Controlled Loop (2PACL) (NIKHEF)

CO_2 cooling - Background in HEP

Attractions:

-High latent heat (low flow) + low viscosity → Small Δp

-Small Δp → small pipe sizes

-Small pipe sizes → low mass

-High heat transfer coefficient

-Radiation hard

-Low global warming potential

Disadvantage: High pressures (60 bar at room temp), components expensive

Running systems:

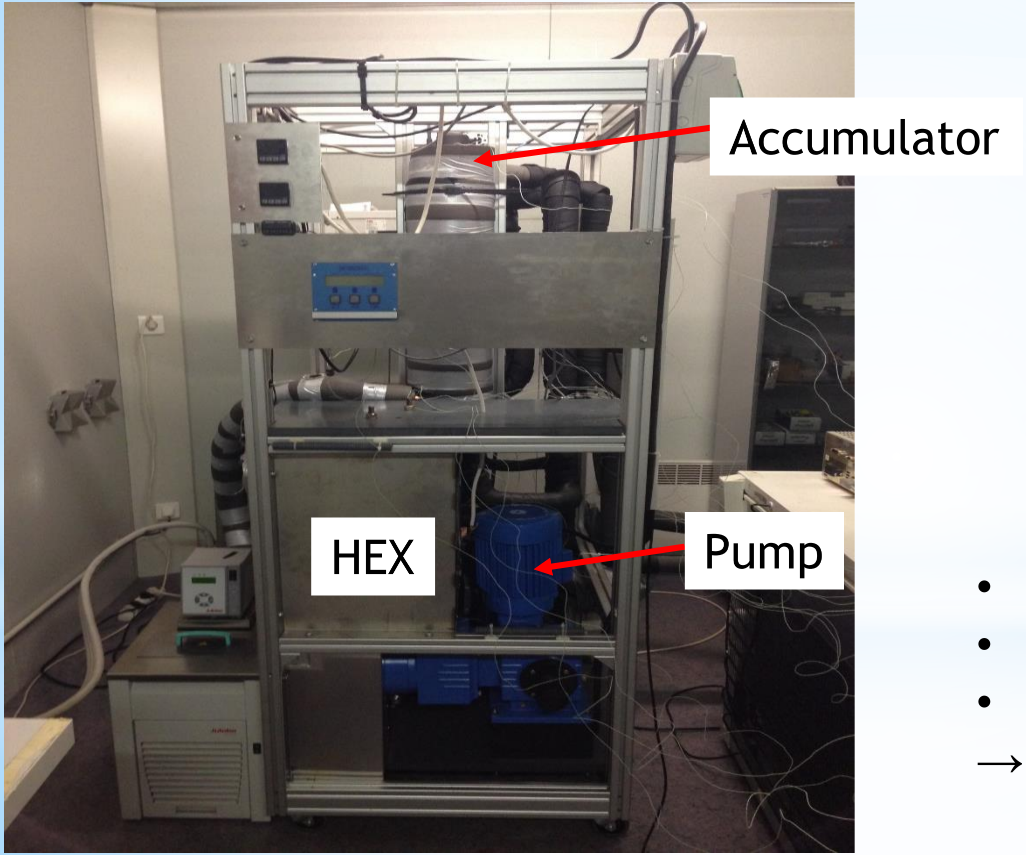
-AMS tracker (150 W)

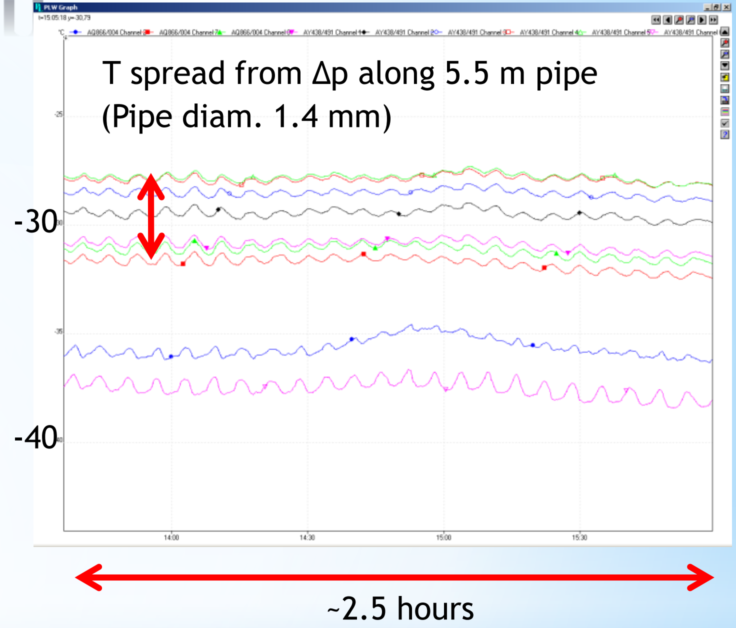
-LHC-b VELO vertex detector (2x 750W)

-CMS pixel Phase 1 upgrade (2x 15 kW, system fully tested)

Proposed for: CMS and ATLAS silicon trackers

1 kW Test system at IPN-Lyon

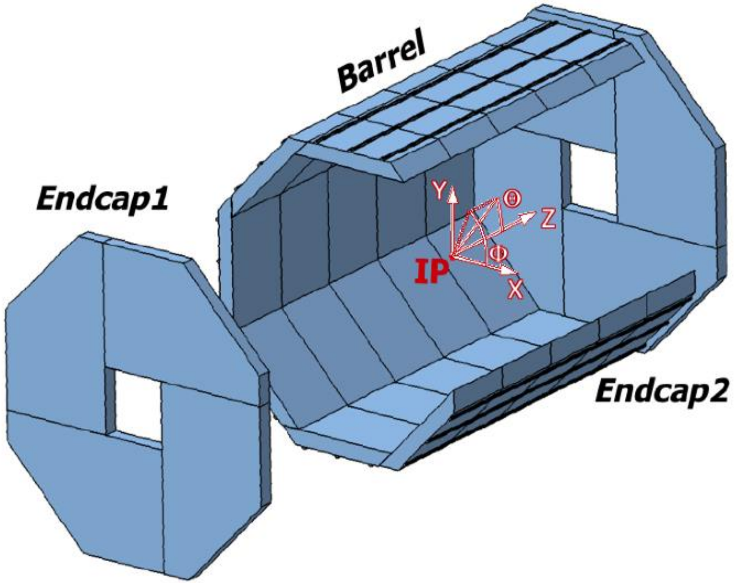


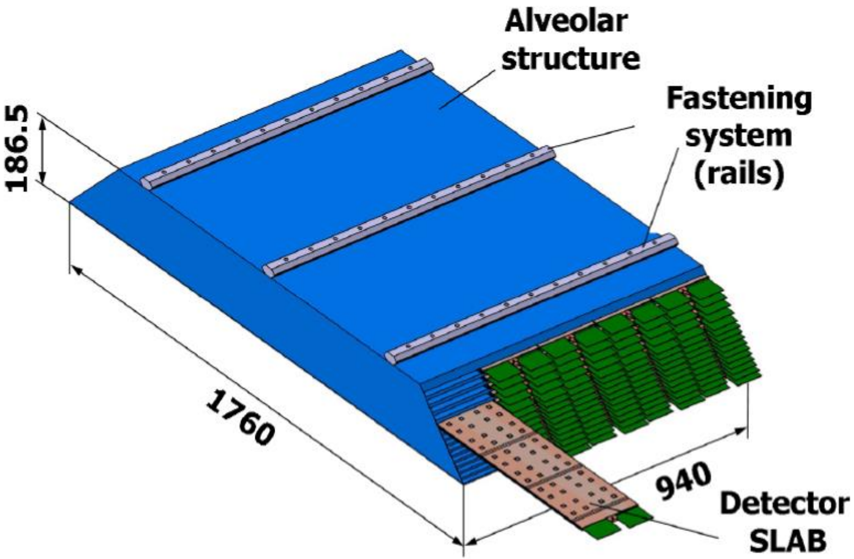


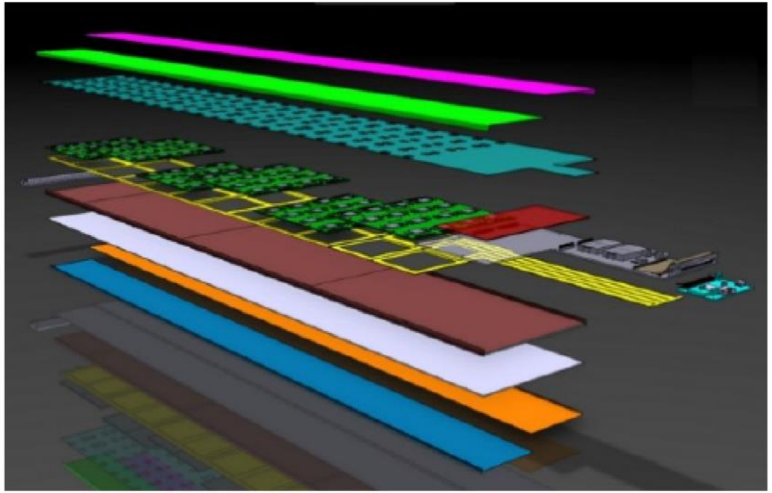
- Developed for CMS Phase-2 TK testing
- Operation at -30°C
- Could also operate at, say, 20°C

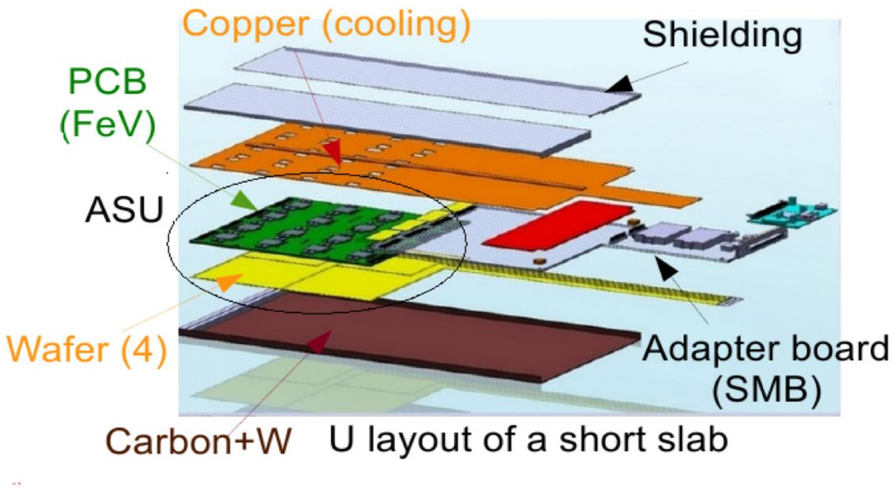
→ Test-bed for SDHCAL system?

Example2: ILD Si-W ECAL



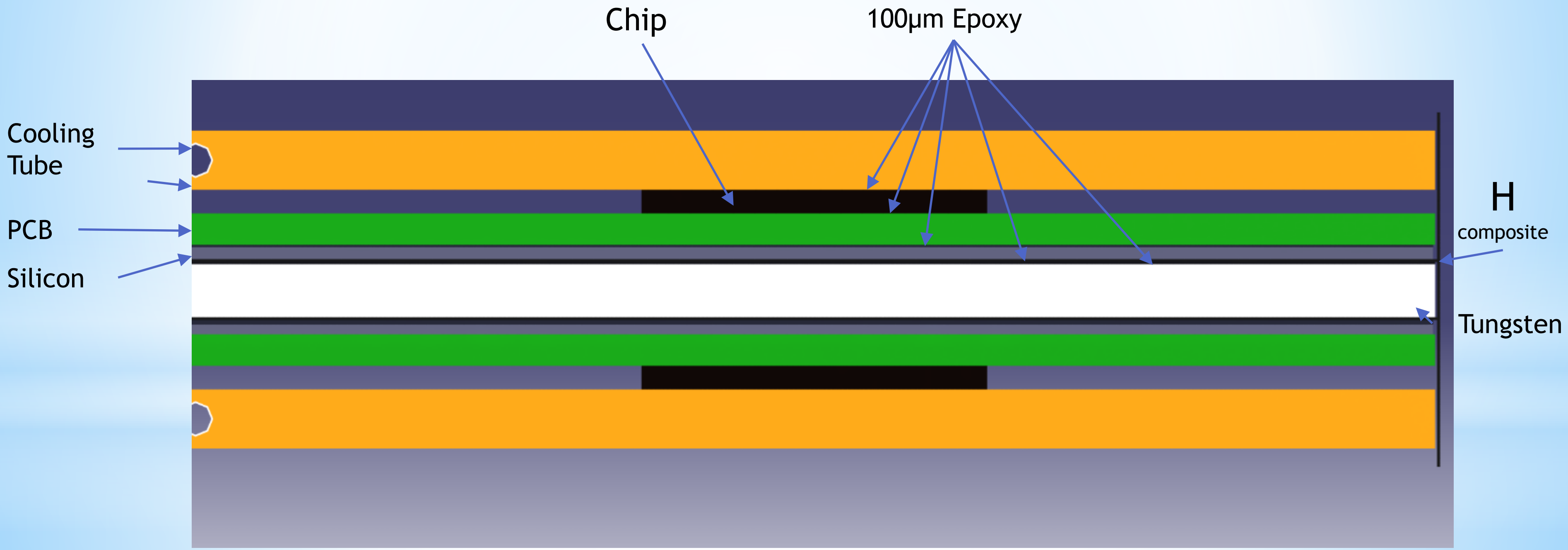


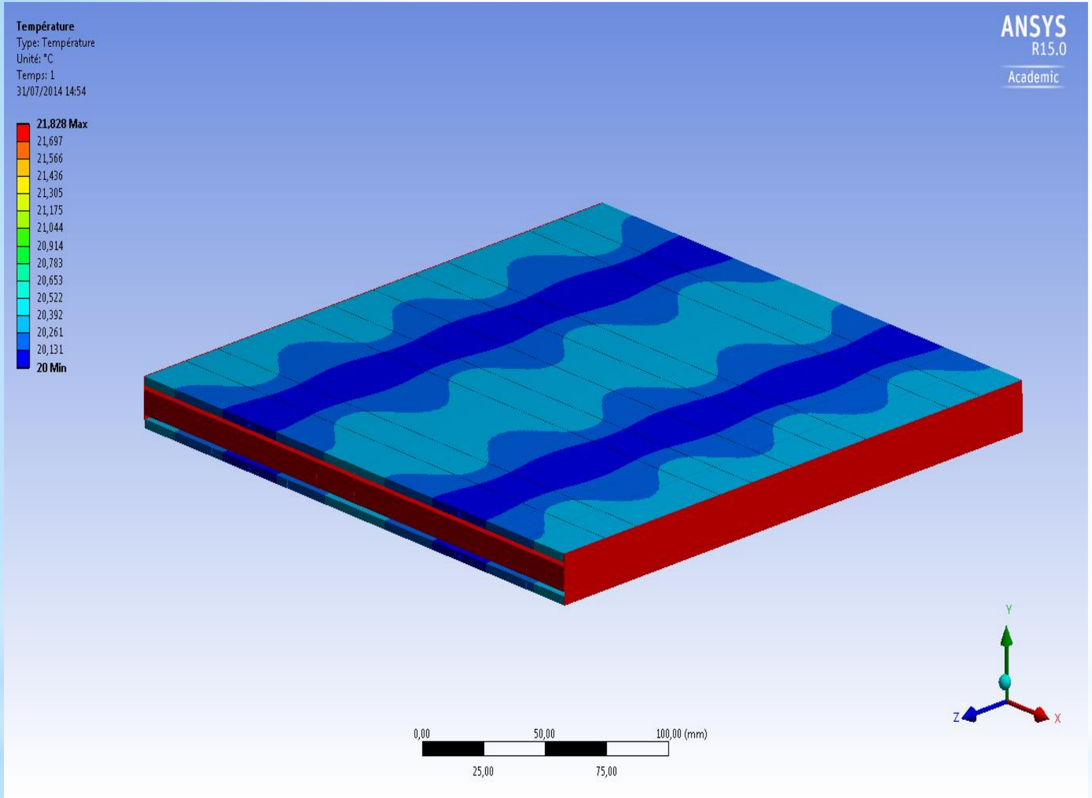




Average surface of one active layer 1.5 m2, pixels of 0.5x0.5 cm^2
SKYROC ASIC is used (64 channels)
Power : 10 mW/ch if no power-pulsing
For one layer 60000 x 10 mW = 600 W
ILD-SiW ECAL 1400 kW

Two-Phase CO_2 cooling for Si-W ECAL active layer





Ideal case:

By requiring a temperature of 20°c at in the heat exchanger tube, the temperature map of one active layer shows that variation is 2°c

A demonstrator for the HGCAL is being built to confirm the simulation results.

Rate &Timing

Time information could be a big asset for FCCee calorimeters when contamination by delayed neutron and pile-up become an issue.

Some ILC calorimeters like SDHCAL could achieve excellent time resolution by replacing single gap RPC by multigap RPC to reach resolution better than 100 ps. Their rate capability could also be enhanced using new low-resistivity material (rate capability of 100 kHz/cm2). Calorimeters become not only trackers but also TOF.

FCCee groups interested to work on these topics are welcome to join the efforts initiated by IPN-Lyon and recently joined by GWNU.

Conclusion

ILC Calorimeters are PFA-based detectors that could be used in other projects (CLIC, FCCee, CEPC,…).

Technical issues related to power consumption and consequently heating and cooling problems are being addressed. Demonstrators are to be built soon.

Timing in FCCee calorimeters could be an asset that needs to be carefully investigated.

Collaboration on $e^+ e^-$ is always welcome.

ILD PFA performance

Jet energy	σ_E/E
45 GeV	3.66%
100 GeV	2.83%
180 GeV	2.86%
250 GeV	2.95%

Z→u,d,s events
|cosθ|<0.7