New Ideas on ILC Detector Technologies & Sustainability Studies for Linear Colliders

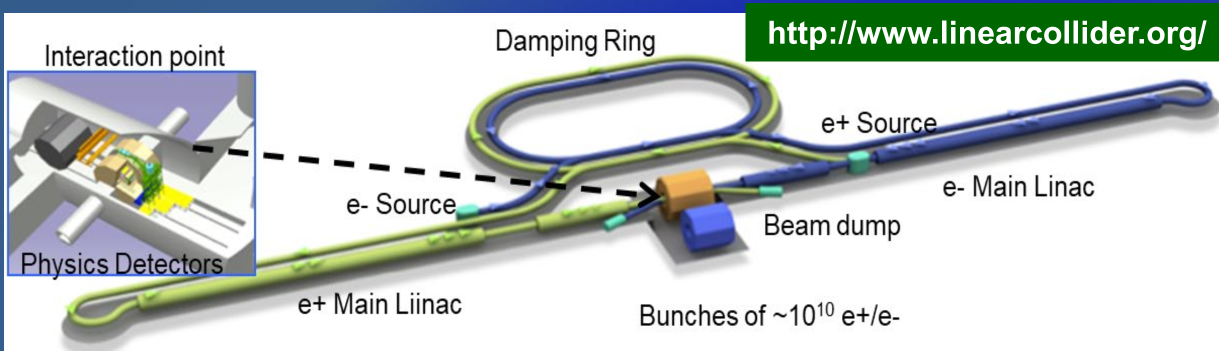
Maxim Titov

CEA Saclay, Irfu, France / CERN

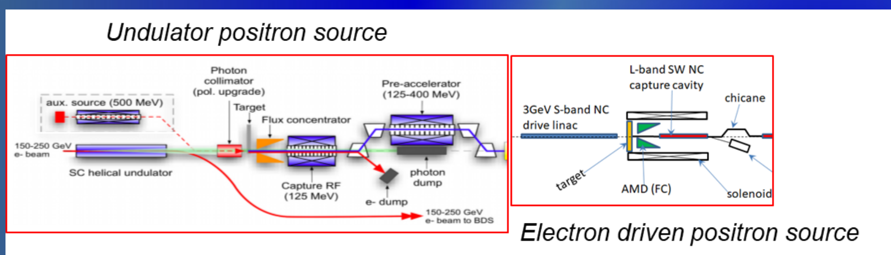
on behalf of the ILC International Development Team Detector and Physics Group

6th Technology and Instrumentation in Particle Physics (TIPP 2023) Conference, Cape Town, South Africa, September 4-8, 2023

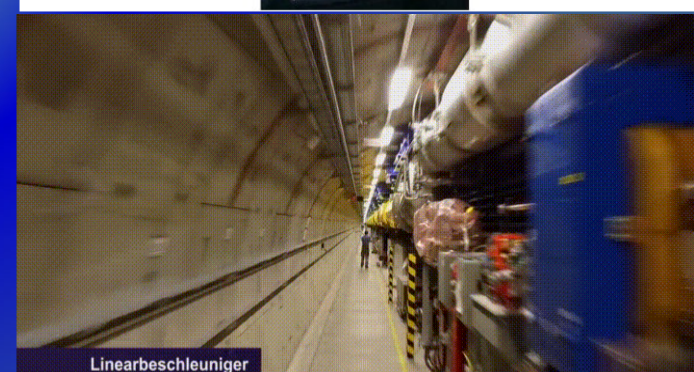
The ILC (250 GeV) Accelerator:



- *Creating particles* ***ITN focus areas (>2023):***
  - *→ polarized elections/positrons* ***Sources***



- *High quality beam* ***Damping ring***
  - *→ low emittance beams*
- *Acceleration* ***Main linac***
  - *→ superconducting radio frequency (SRF)*
- *Collide them* ***Final focus***
  - *→ nano-meter beams*
- *Go to* ***Beam dumps***



Recent talks (2022 eeFACT Symposium): https://agenda.infn.it/event/21199/

International Development Team (IDT) to Prepare ILC Pre-Lab

Established in August 2020

ICFA

ilc international development team

ILC International Development Team

Executive Board

Americas Liaison	Andrew Lankford (UC Irvine)
Working Group 2 Chair	Shinichiro Michizono (KEK)
Working Group 3 Chair	Jenny List (DESY)
Executive Board Chair and Working Group 1 Chair	Tatsuya Nakada (EPFL)
KEK Liaison	Yasuhiro Okada (KEK)
Europe Liaison	Steinar Stapnes (CERN)
Asia-Pacific Liaison	Geoffrey Taylor (U. Melbourne)

Working Group 1 Pre-Lab Setup

Working Group 2 Accelerator

Working Group 3 Physics & Detectors

The original timescale to start the ILC Pre-lab in 2022 was too optimistic:

- → *there was no progress in the "top-down" political-governmental approach (> 2021)*
- → *The IDT Pre-lab plan was reviewed by a MEXT appointed panel and deemed premature, referring to that the prospects for ILC international cost sharing are not clear.*
- → *increased support for technical developments & accelerator R&D was recommended (these plans were included MEXT budget request and has been approved by the JP Finance Ministry in FY2023 → double KEK resources for ILC preparation for the ILC ITN)*

Proposal for the ILC Preparatory Laboratory (Pre-lab)

International Linear Collider
International Development Team

1 June 2021

arXiv:2106.00602v1 [physics.acc-ph] 1 Jun 2021

ILC Pre-lab proposal developed by IDT-WG1 and submitted to MEXT on Jun. 2, 2021:

Abstract

During the preparatory phase of the International Linear Collider (ILC) project, all technical development and engineering design needed for the start of ILC construction must be completed, in parallel with intergovernmental discussion of governance and sharing of responsibilities and cost. The ILC Preparatory Laboratory (Pre-lab) is conceived to execute the technical and engineering work and to assist the intergovernmental discussion by providing relevant information upon request. It will be based on a worldwide partnership among laboratories with a headquarters hosted in Japan. This proposal, prepared by the ILC International Development Team and endorsed by the International Committee for Future Accelerators, describes an organisational framework and work plan for the Pre-lab. Elaboration, modification and adjustment should be introduced for its implementation, in order to incorporate requirements arising from the physics community, laboratories, and governmental authorities interested in the ILC.

arXiv: 2106.00602

IDT-WG2 TP document:

ILC Pre-lab

Actual cavity /CM manufacturing

SRF ~41MILCU 285 FTE-yr
- WP-1 Cavity production
- WP-2 Cryomodule assembly
- WP-3 Crab cavity

e- source ~2.5MILCU, 6 FTE-yr
- WP-4 Electron source

e+ source ~6MILCU, 15FTE-yr

Undulator scheme
- WP-5 Undulator
- WP-6 Rotating target
- WP-7 Magnetic focusing

e-Driven scheme
- WP-8 Rotating target
- WP-9 Magnetic focusing
- WP-10 Capture cavity
- WP-11 Target replacement

DR ~2.5MILCU, 30FTE-yr
- WP-12 System design
- WP-13 Collective effect
- WP-14 Injection/extraction

BDS ~2MILCU, 16FTE-yr
- WP-15 Final focus
- WP-16 Final doublet

Dump ~3MILCU, 12FTE-yr
- WP-17 Main dump
- WP-18 Photon dump

For detail, http://doi.org/10.5281/ zenodo.4742018

http://doi.org/10.5281/ zenodo.4742018

SRF technology is energy-efficient, and its applications are increasing around the world.
These WPs will contribute to the promotion of SRF accelerators in each region.

- The technical preparation document was reviewed by the international review committee (chair:Tor Raubenheimer (SLAC)).
- The total global cost of the project is about 60 MILCU and about 360 FTE-year. (This does not include the cost of the infrastructure for the WPs.)
- The cost will be shared internationally as in-kind contribution.

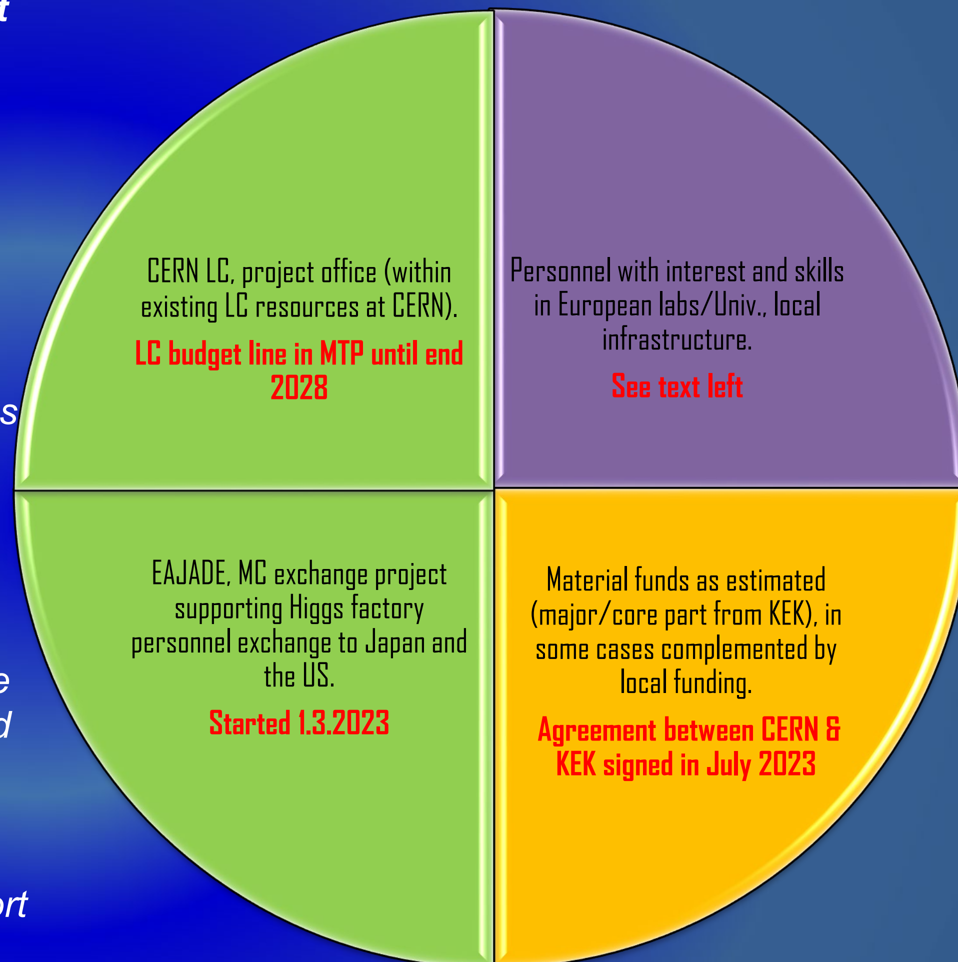
IDT - WG2 summarized the technical preparation as Work Packages (WPs) for the Pre-Lab stage in the Technical Preparation (TP) Document

ILC Technology Network (ITN) – European Focus Areas

A subset of the initial plan for the ILC preparation phase activities ("Pre-lab") have been identified at the most critical, and the priorities emphasized in the ITN:

→ European Preparation for the ITN (2023 ->) distributed on five main activity areas, and foreseen to concentrate for the accelerator part (ILD-WG2) & technical activities :

- *A1 SC RF related: Cavities, Module, Crab-cavities*
- *A2 Sources: Concentrate on undulator positron scheme – fast pulses magnet, consult on conventual one (used by CLIC and FCC-ee)*
- *A3 Damping Ring including kickers: low Emittance Ring community, and also kicker work in CLIC and FCC*
- *A4 ATF activities for final focus and nanobeams: many European groups active in ATF, more support for its operation expected using the fresh funding*
- *A5 Implementation including Project Office: Dump, CE, Cryo, Sustainability, MDI, others (many of these are continuations of on-going collaborative activities)*



S. Stapnes: https://indico.cern.ch/event/1297278/contributions/5453722/attachments/2675796/4641399/linear-colliders.pptx

Many Forms of Linear Collider Detector R&D Efforts

RPC DHCAL Silicon ECAL LCTPC

KPIX SDHCAL (ILD) RPC Muon

GEM DHCAL CMOS MAPS

Silicon ECAL (SiD) VIP FPCCD Scintillator HCAL

TPAC DEPFET SOI Scintillator ECAL

FCAL Dual Readout

ChronoPixel CLICPix

Linear Collider Collaboration

DOI 10.5281/zenodo.4496000

Detector R&D Report

https://doi.org/10.5281/zenodo.3749461

doi:10.5281/zenodo.3749461

Editors

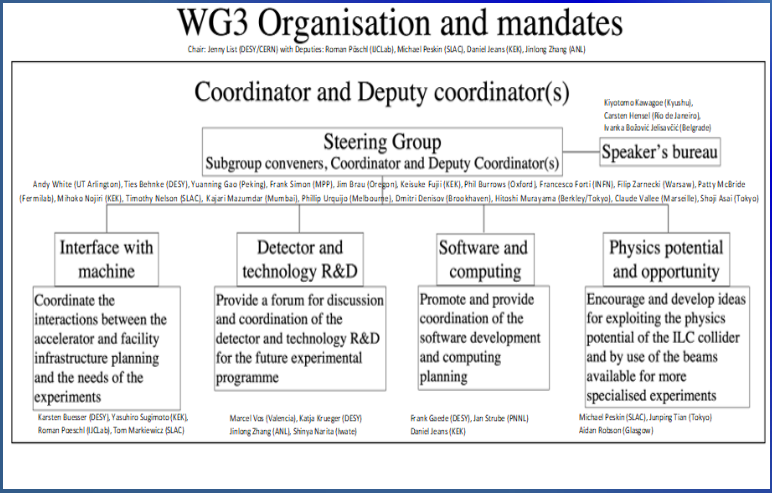
Detector R&D Liaison
Maxim Titov
Institut de Recherche sur les lois Fondamentales de l'Univers (IRFU)
CEA - Saclay, F-91191 Gif-sur-Yvette Cedex, France
maxim.titov@cea.fr

Detector R&D Liaison
Jan F Strube
Pacific Northwest National Laboratory
902 Battelle Boulevard
Richland, WA 99352, USA
University of Oregon
Institute for Fundamental Science
Eugene, OR 97403, USA
jstrube@uoregon.edu

February 2, 2021

Linear Collider Collaboration

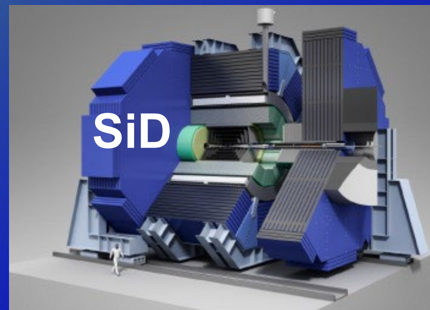
IDT-WG3: ensure interplay between detector concepts (ILD, SiD, Clicdp) & more generic R&D



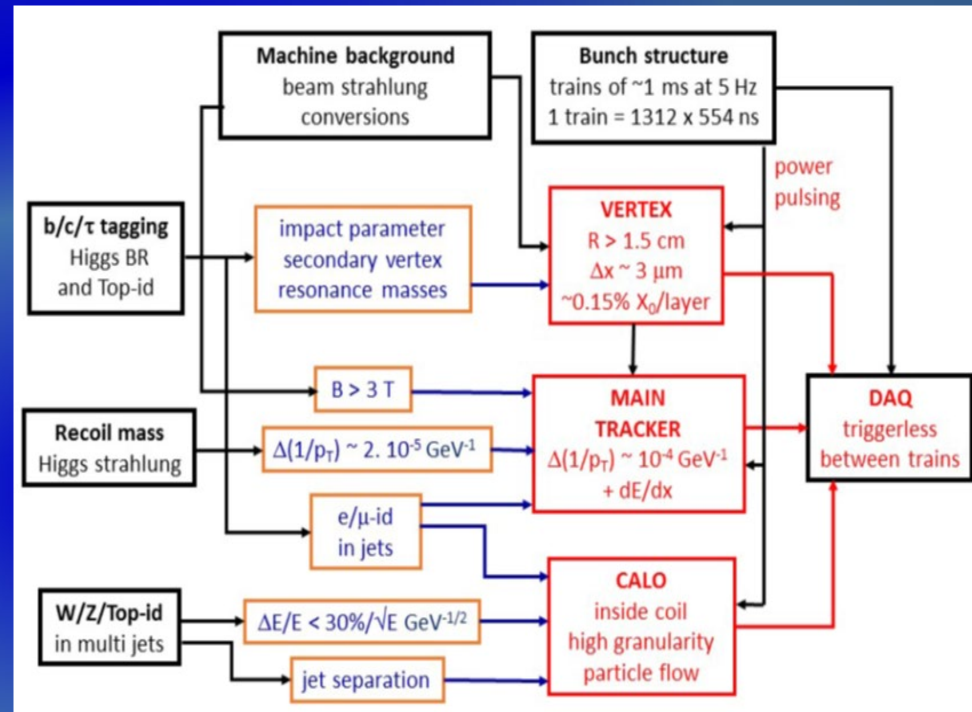
- ✓ *Keep various detector technology options and <u>do not prioritize</u>. This has the advantage that the technologies can be further developed until specific choices have to made once future Higgs Factory is approved.*

- ✓ *Furthermore — and as important — this keeps a broad community of detector research groups at universities and laboratories involved and increases the chance to arrive at the best technically possible detector solution when it has to be built.*

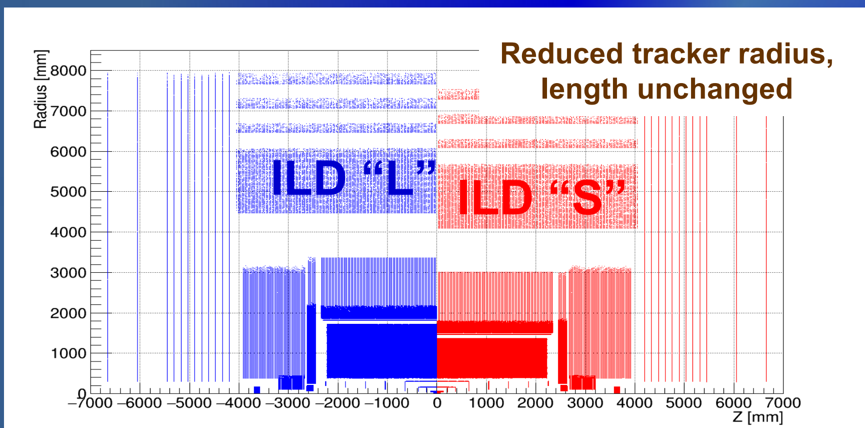
ILC Detector Concept Groups: ILD and SiD



- ✓ **ILD: International Large Detector**
- ✓ **SiD: Silicon Detector**



ILD Re-optimisation: Large (L) & small (S) options



ILD ("L" & "S") — ILD Interim Design Report: arXiv: 2003.01116	SiD — SiD Design Update: arXiv: 2110.09965
Both optimized for PFA Performance: ~ $B \cdot R_{ECAL,inner}^2$ (two-track separation @ ECAL)	
B = 3.5 T / 4 T	B = 5 T
$R_{ECAL,inner}$ = 1.8 / 1.46 m	$R_{ECAL,inner}$ = 1.27 m
Si + TPC tracking Outer radius: 1.77 / 1.43 m	Silicon Tracking only Outer radius: 1.22 m

ILC Tracking (ILD vs SiD): Two Complementary Approaches

ILD: Silicon + Gaseous Tracking

SiD: All-Silicon Tracking

VERTEXING:

- long barrel of 3 double layers of Si-pixels

  0.3% X_0 / layer, $\sigma_{sp} \lesssim 3\ \mu m$

- short barrel of 5 single layers of Si-pixels

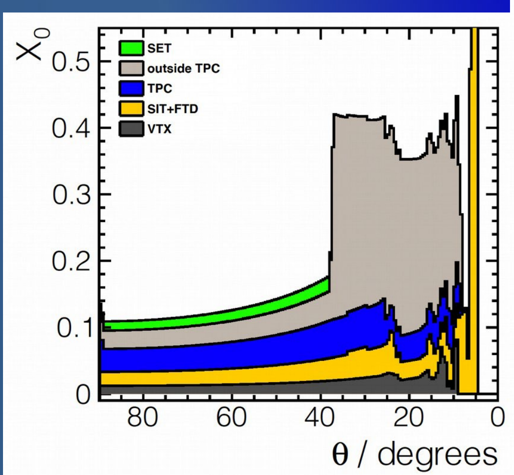
  0.15% X_0 / layer, $\sigma_{sp} \lesssim$ 3-5 μm

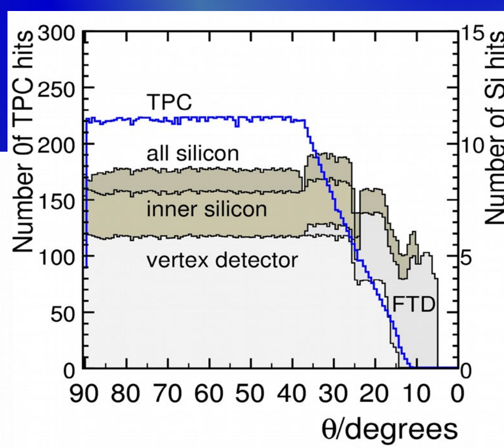
TRACKING:

- Intermediate Si-tracker (SIT, SET, FTD)
  - SIT/FTD: silicon pixel sensors (e.g. CMOS)
  - SET: silicon strip sensors
- Time Projection Chamber with MPGDs
  - High hit redundancy (200 hits / track)
    - → 3D tracking / pattern recognition;
    - → dE/dx information for PID

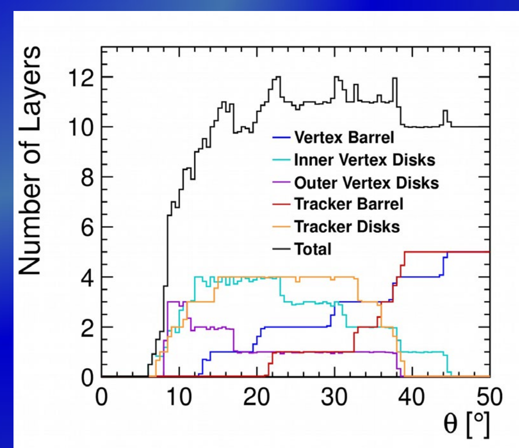
- 5 layers Silicon-strip tracker
  (25um strips, 50 um readout pitch)
- Fewer highly precise hits (max. 12)
- Robustness, single bunch time stamping

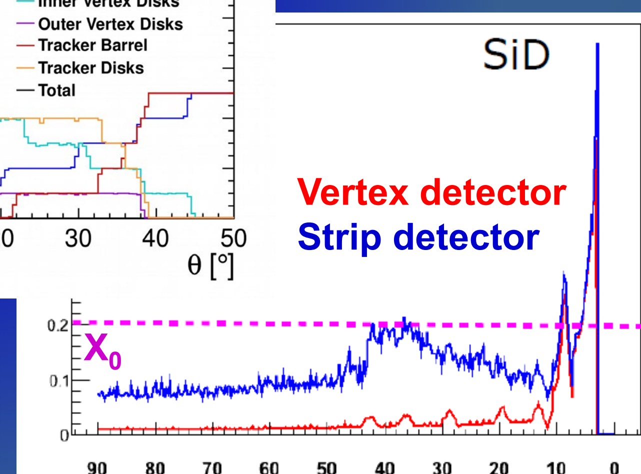
ILD:





SiD:





Still a lot of opportunities in ILD/SiD optimization : physics goals, software developments and technology options

Vertex Technologies for Future Linear Colliders (ILC)

- **Sensor's contribution to the total X_0 is 15-30% (majority cables + cooling + support)**
- **Readout strategies exploiting the ILC low duty cycle 0(10^{-3}): triggerless readout, power-pulsing**
  - → continuous during the train with power cycling → mechanic. stress from Lorentz forces in B-field
  - → delayed after the train → either ~5µm pitch for occupancy or in-pixel time-stamping

Physics driven requirements — **Running constraints** — **Sensor specifications**

$\sigma_{s.p.}$ 2.8um → Small pixel ~16 μm

Material budget 0.15% X_0/layer → Thinning to 50 μm

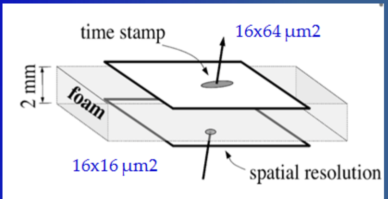
→ Air cooling → low power 50 mW/cm^2

r of Inner most layer 16mm → beam-related background → fast readout ~1 μs

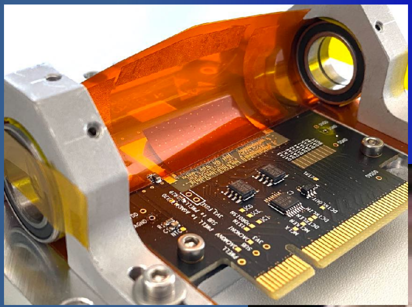
→ radiation damage → radiation tolerance ≤ 3.4 $Mrad/year$, $\leq 6.2 \times 10^{12} n_{eq}/(cm^2 year)$

Technology	FPCCD	DEPFET	SOI	CMOS	iLGAD
Added value (example)	Very granular	Low material budget	2 tier process (high density µcircuits)	Industry evolution	PID

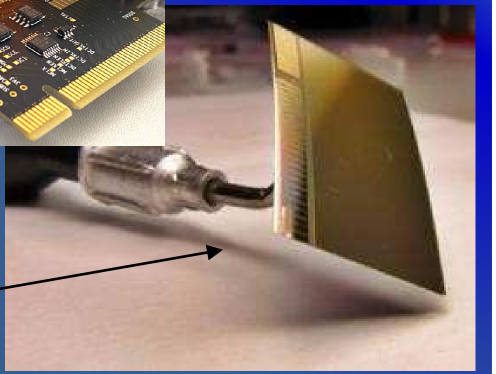
CMOS (MAPS): 2-sided ladders:
« mini-vectors » concept for ILC with high spatial resolution & time stamping



180 nm CMOS technology: VALIDATED



ALPIDE@ ALICE ITS-3 (bending 50 um sensor)



MIMOSIS @ CBM-MVD

ALICE-ITS3 upgrade drives the R&D:

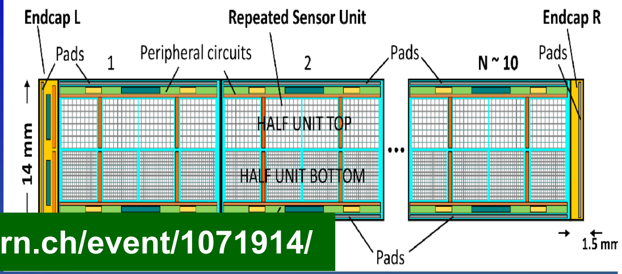
Bending thin Si-layers (MAPS):

Truly cylindrical, supportless CPS for ALICE-ITS3 upgrade (65 nm)

Industrial stitching & large surfaces for low-mass detect.:

using several reticles from the same wafer (possible with both 180 and 65 nm)

arXiv: 2105.13000



https://indico.cern.ch/event/1071914/

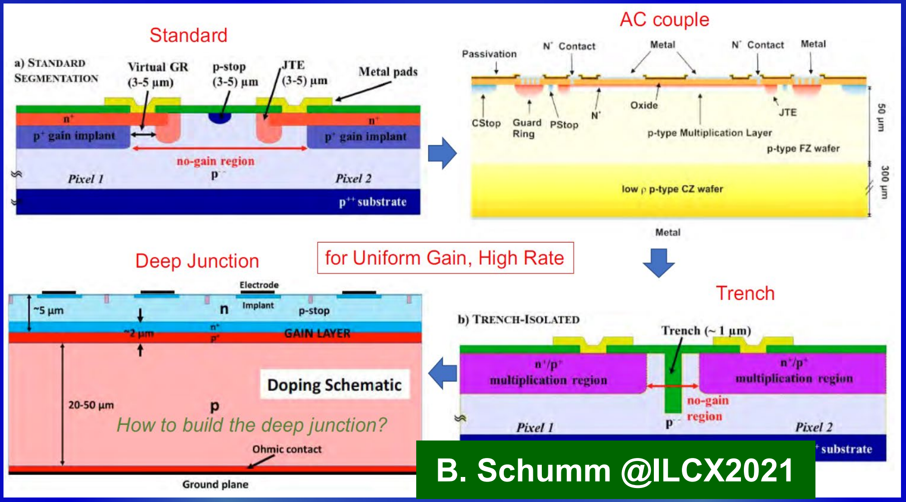
Silicon Tracking Conceptual Studies for ILC

Not much dedicated development work recently on Silicon tracking technologies

→ Baseline solution: silicon-microstrip tracker; also some enabling technologies (e.g. based on LGAD concept)

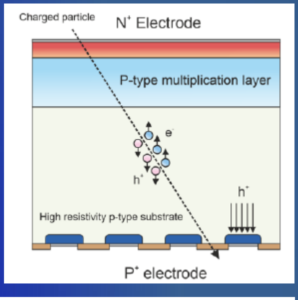
Timing Detectors open up 4D (and 5D) tracking → ATLAS/CMS upgrades include several m^2 of LGADs:

- ✓ Large area detectors
- ✓ High-precision tracking → a few um per layer
- ✓ High-precision timing → tens of ps per layer
- ✓ Optimal geometrical acc. (large fill-factor).
- ✓ Low material (50 μm thickness per plane).

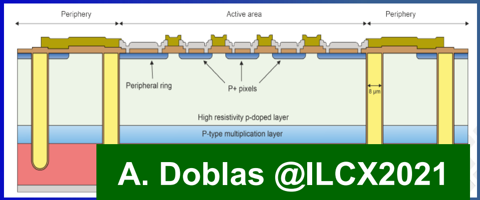


B. Schumm @ILCX2021

iLGAD:



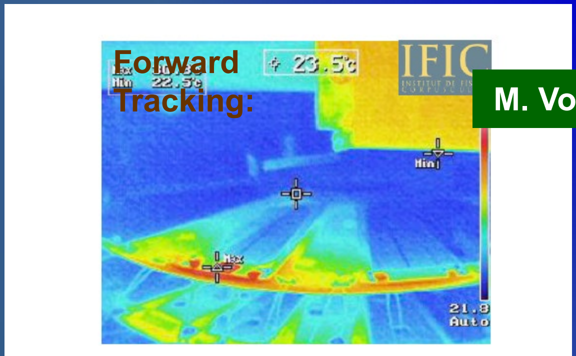
Trench iLGAD:



A. Doblas @ILCX2021

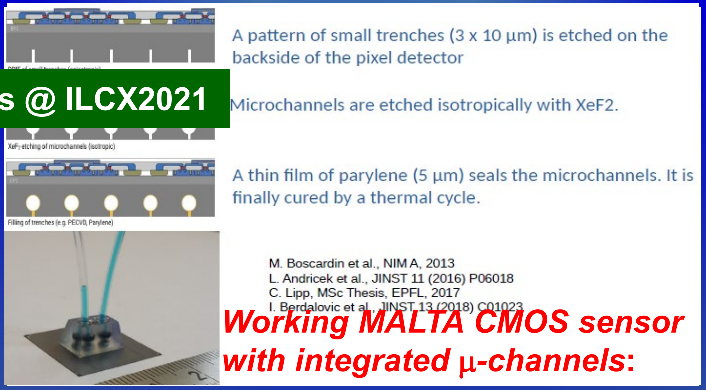
Readout ASICs (power dissipation) may limit the intrinsic sensor performance

→ power pulsing to reduce energy consumprion or the use of microchannnels to complement air cooling



Thermal management optimization strongly linked with supporting structure desing

M. Vos @ ILCX2021



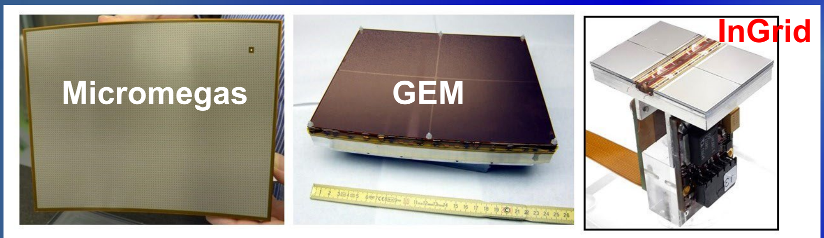
Working MALTA CMOS sensor with integrated μ-channels:

Ultra-light microchannel cooiling:

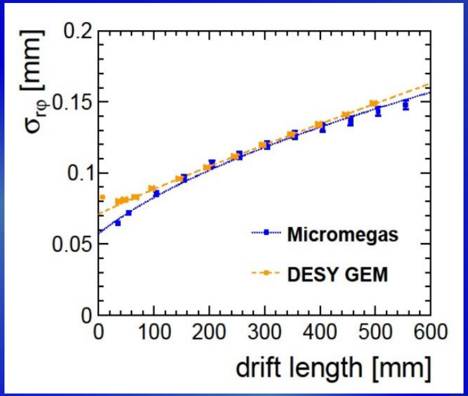
LHCb VELO: P. Collins; arXiv: 2112.12763

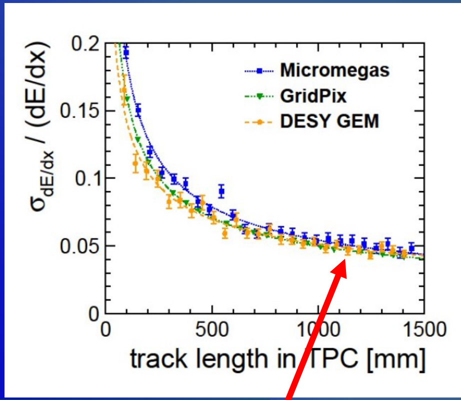
Gaseous Tracking: TPC with MPGD-based Readout

Three MPGD options are foreseen for the ILC-TPC:
- → Wet-etched / Laser-etched GEMs
- → Resistive Micromegas with dispersive anode
- → GEM + CMOS ASICs, « GridPix » concept (integrated Micromegas grid with Timepix chip)



Spatial resolution of σ_T ~ 100 um and dE/dx res. < 5% have been reached with GEM, MM and InGrid)

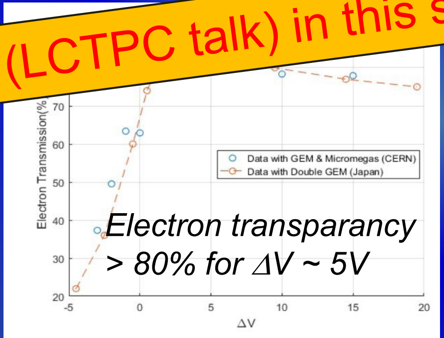




arXiv: 2003.01116

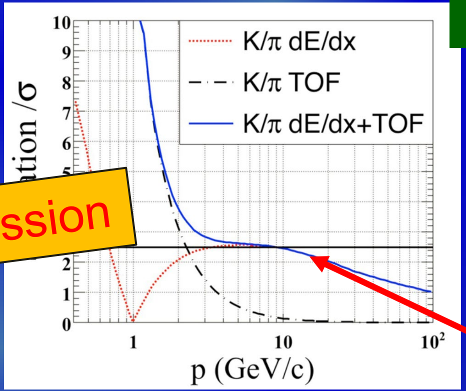
dE/dx ~ <4 % can be achieved with Gridpix (cluster-counting)

ILC: gating scheme, based on large-aperture GEM
- → Machine-induced background and ions from gas amplific.
- → Exploit ILC bunch structure (gate opens 50 us before the first bunch and closes 50 us after the last bunch)

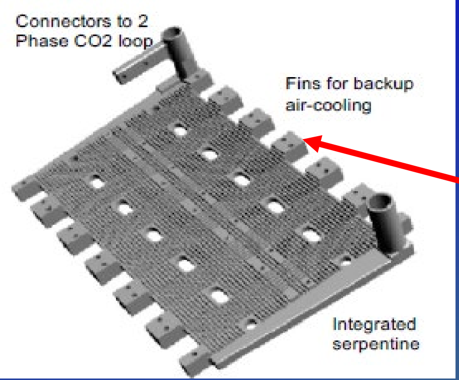


Electron transparancy > 80% for ΔV ~ 5V

→ See Huirong Qi (LCTPC talk) in this session



Added value of TIME information for ILC: dE/dx combined with ToF (SiW-ECAL) for K-PID



3D-printed monolithic cooling plate for a TPC using 2-phase CO2

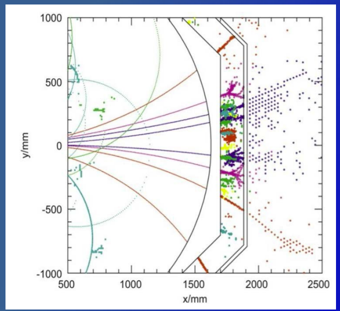
CHALLENGES / FUTURE PLANS:
- ✓ Common modules with a final design (with gating)
- ✓ Optimization of cooling & material budget
- ✓ GridPix development (dN/dx cluster counting)

P. Colas @ ILCX2021

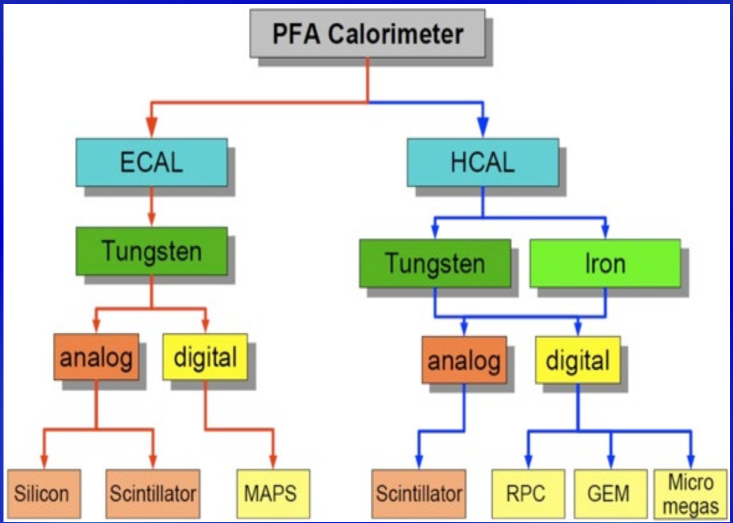
Particle Flow Calorimeters: CALICE Collaboration

Development and study of finely segmented / imaging calorimeters: initially focused on the ILC, now widening to include developments of all imaging calorimeters, e.g. CMS HGCAL for Phase II):

Imaging Calorimetry → high granularity (in 4D), efficient software (PFA).



Issues: overlap between showers, complicated topology, sep. "physics event" from beam-induced bkg.



Mixture of matured concepts and advanced ideas:

MATURED (CALICE):

- **SiW-ECAL**
- **SciW-ECAL**
- **AHCAL**
- **DHCAL (sDHCAL)**

→ (Almost) ready for large-scale prototype
→ Prepare for quick realization of 4-5 years to real detector

Example: **ILD detector for ILC**, proposing **CALICE** collaboration tech.

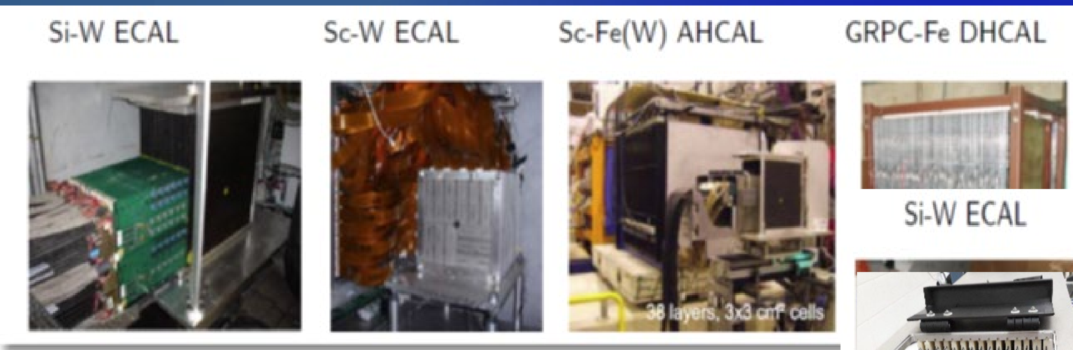
	ECAL option	ECAL option	HCAL option	HCAL option
Active layer	silicon	scint+SiPM	scint+SiPM	glass RPC
Absorber	tungsten	tungsten	steel	steel
Cell size (cm×cm)	0.5×0.5	0.5×4.5	3×3	1×1
# layers	30	30	48	48
Readout	analog	analog	analog	Semi-dig (2 bits)
Depth # (X_0/Λ_{int})	24 X_0	24 X_0	5.5 Λ_{int}	5.5 Λ_{int}
# channels [10^6]	100	10	8	70
Total surface	2500	2500	7000	7000

ADVANCED (beyond CALICE):

- **MAPS ECAL**
- **Dual-readout ECAL**
- **LGAD ECAL (CALICE)**

→ Evaluate additional physics impact to ILC experiment
→ Needs intensive R&D effort to realize as real detector

Particle Flow Calorimeters: CALICE Collaboration

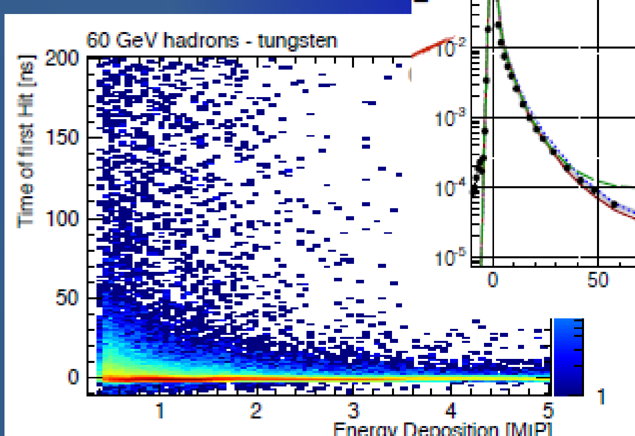


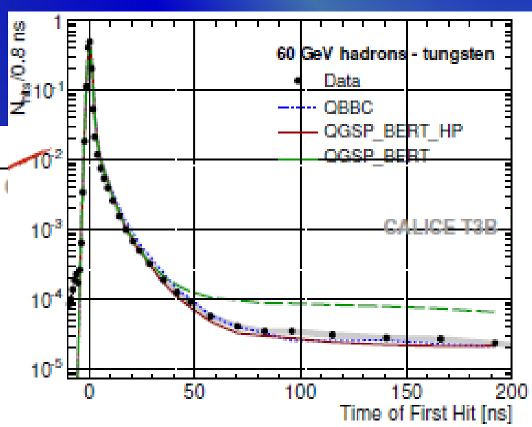
Proof-of-principle with first generation physics prototypes (2003-2012)

Scalability tests with 2nd generation (>2010) technological prototypes (power pulsing, compact mechanical design, embedded electronics, assembly, calibration approaches)

- **Timing measurement for shower development (from 4D to 5D):**
  Today's CALICE prototypes (SiW ECAL, AHCAL) provides unprecedented granularity and cell-by-cell ns-level timing for validation hadronic models on different readout technologies (gas, silicon, schint.)

JINST9 (2014) P07022





→ **improve GEANT simulation models**

ILC AHCAL & CMS HGCAL common test-beam

CMS HGCAL has measured **evoluton of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)

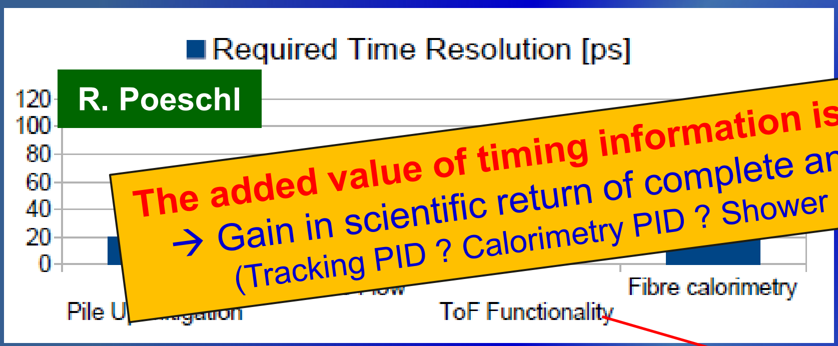
Particle Flow (Imaging) Calorimeters: The 5th Dimension ?

Impact of 5D calorimetry (x,y,z, energy, time) needs to be evaluated more deeply to undertand optimal time acc.

What are the real goals (physics wise)?

- Mitigation of pile-up (basically all high rates)
- Support for full 5D PFA → unchartered territory
- Calorimeters with ToF functionality in first layers?
- Longitudinally unsegmented fibre calorimeters

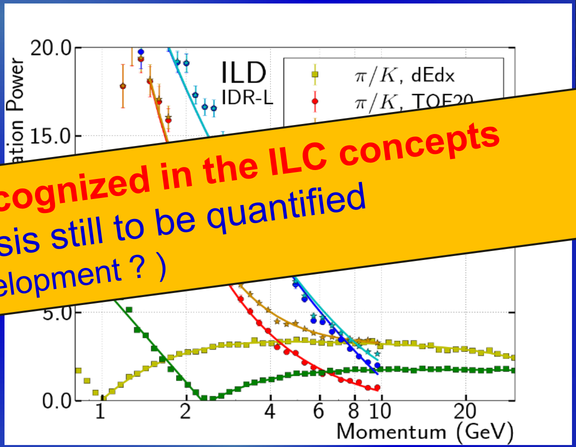
R. Poeschl



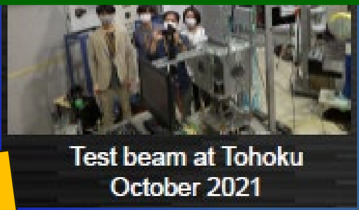
The added value of timing information is recognized in the ILC concepts
→ Gain in scientific return of complete analysis still to be quantified
(Tracking PID ? Calorimetry PID ? Shower development ?)

Replace (part of) ECAL with LGAD for O(10 ps) timing measurement

20 ps TOF per hit can separate π/k/p up to 5-10 GeV



T. Suehara @ILCX2021

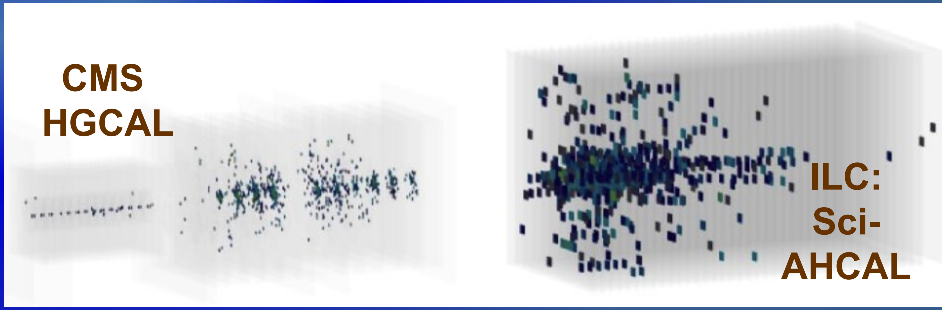

Test beam at Tohoku October 2021

Timing resolution Is affected by noise

Sensor	Amp. th.	Time reso.
S8664-50K (inverse)	20 mV	123 psec
	40 mV	63 psec
S2385 (normal)	20 mV	178 psec
	40 mV	89 psec

✓ **Trade-off between power consumption & timing capabilities (maybe higher noise level)**

ILC AHCAL & CMS HGCAL common test-beam



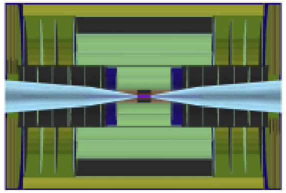
✓ Timing in calorimeters / energetic showers?

→ intelligent reconstruction using O(100) hits & NN can improve “poor” single cell timing

→ can help to distinguish particle types:
usable for flavour tagging (b/c/s),
long-lived searches (decaying to neutrals) ,
enhance $\sigma(E)$ / E

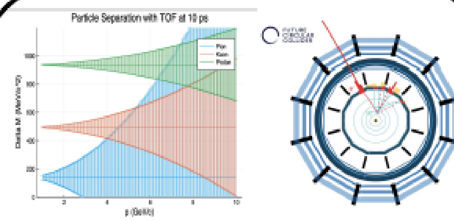
CMS HGCAL has measured **evoluton of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)

Fast Timing in Higgs Factory Detectors



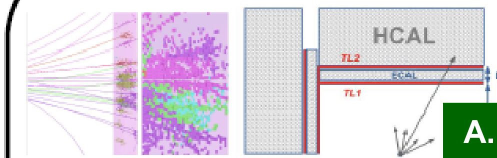
Suppression of beam induced backgrounds at muon colliders

Full 4D tracking



Time of Flight for Particle ID at low momentum and Long Lived particles

Timing layers



Exploit the time structure of hadronic showers to enhance PFA and improve jet energy resolution

5D Calorimetry

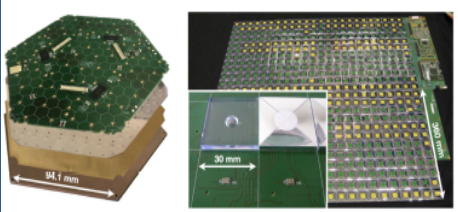
Timing layers or volumetric timing

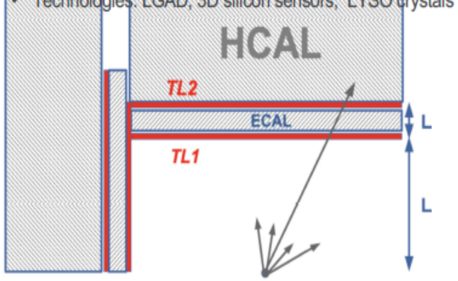
A. Schwartzman @LCWS2023

Z. Zhang @LCWS2023

Precision timing at the level of 10-30ps is a new capability to enhance PID and calorimeter measurements

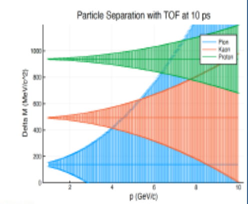
- **Large-radius Timing Layers in the in front of the calorimeter can provide Time-of-Flight (ToF) for PID**
- ***Volume timing***: good time resolution on the cell level in highly granular calorimeters
  - requires technologies that can provide this timing; significant implications for electronics
  - potential compromises in timing for objects
  - Technologies: LGAD or silicon tiles
- ***Timing layers***: extreme timing in a few selected layers inside of the calorimeter system
  - can be combined with a wide range of technologies
  - excludes applications that require timing in the full shower volume, rather than on object level
  - Technologies: LGAD, 3D silicon sensors, LYSO crystals





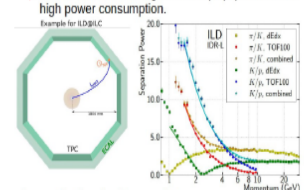
Precision Timing @ ILC

- Integrated time-stamping in the trackers
  - e.g. Background rejection in the Vertex Detector
    - Requiring ns-level resolution (intra-bunching timing)
    - Doable already today
- Timing measurements for shower development in calorimeters
  - Neutral and slow components
    - Requiring ~ns precision
    - Reachable today by reading out the cells
- Dedicated Timing Layers
  - Full 4D Tracking in the ILC environment
    - Nothing like the LHC
  - What about 5D calorimetry
    - How can precision timing be best used in PFA
    - What level of precision timing can make a real difference of calorimeter performance
  - Time-of-Flight systems for PID
    - 10 ps resolution as a goal to be competitive
  - What kind of physics does this enable and what are the Instrumentation implications
    - For a detector designed for 250-1000 GeV



TOF in the ECAL – Particle ID

- "Standard" silicon sensors could reach O(100-300ps)
- LGAD sensors could get us to O(10ps) Drawback: high power consumption.



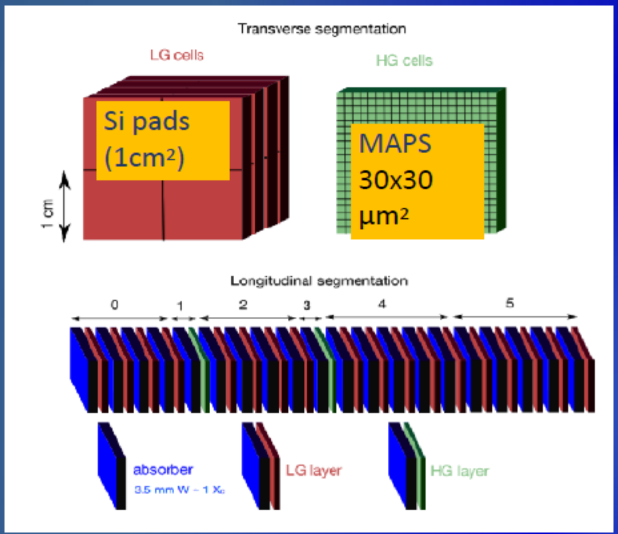
Impact in the physics reach?

- Could be a game changer for s-quark measurements

New Trends: Ultra-High Granularity (MAPS ECAL)

CMOS Sensors for calorimetry → Synergies between LC Detector R&D and ALICE FoCAL

ALICE FoCAL: 24 layer MIMOSA CMOS sensor calorimeter Si-W stack



Forward electromagnetic and **hadronic calorimeters;**

- ✓ FoCal-E: high-granularity Si-W sampling calorimeter → direct γ, $\pi0$
- ✓ FoCal-H: Pb-Sc sampling calorimeter for photon isolation and jets

Digital ECAL prototype:

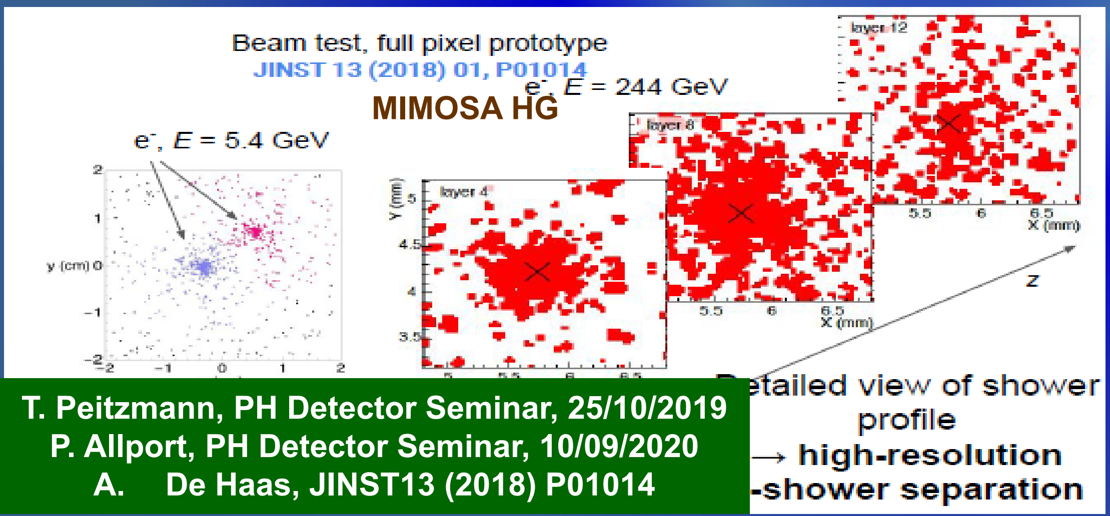
- number of pixels above threshol ~ deposited energy
- Monolithic Active Pixel Sensors (MAPS) PHASE2/MIMOSA23 wit a pixel size: 30x30 µm2
- 24 layers of 4 sensors each: activ area 4x4 cm2 , 39 M pixels
- 3 mm W absorber for 0.97 X0 pe layer R_M ~ 11 mm

FoCAL: assuming ≈ 1m^2 detector surface

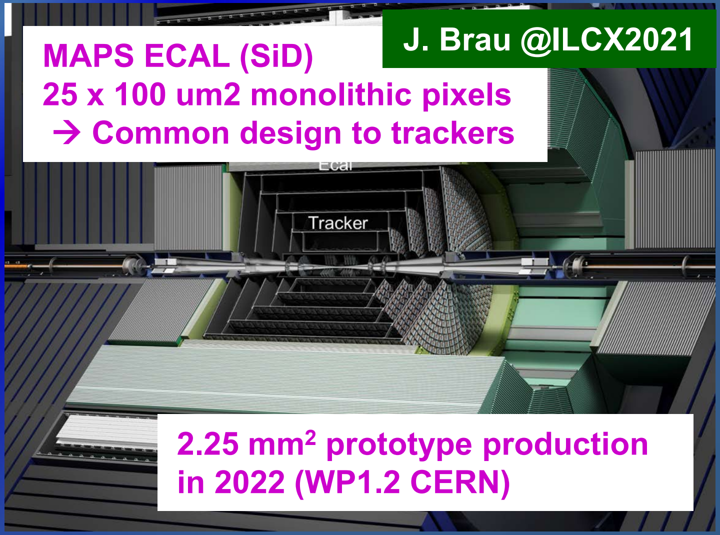
A. Rossi @ ICHEP2020

	LG	HG
pixel/pad size	≈ 1 cm^2	**≈ 30x30 µm^2**
total # pixels/pads	≈ 2.5 x 10^5	**≈ 2.5 x 10^9**
readout channels	≈ 5 x 10^4	**≈ 2 x 10^6**

Could be a unique tool to improve shower simulation …



T. Peitzmann, PH Detector Seminar, 25/10/2019
P. Allport, PH Detector Seminar, 10/09/2020
A. De Haas, JINST13 (2018) P01014

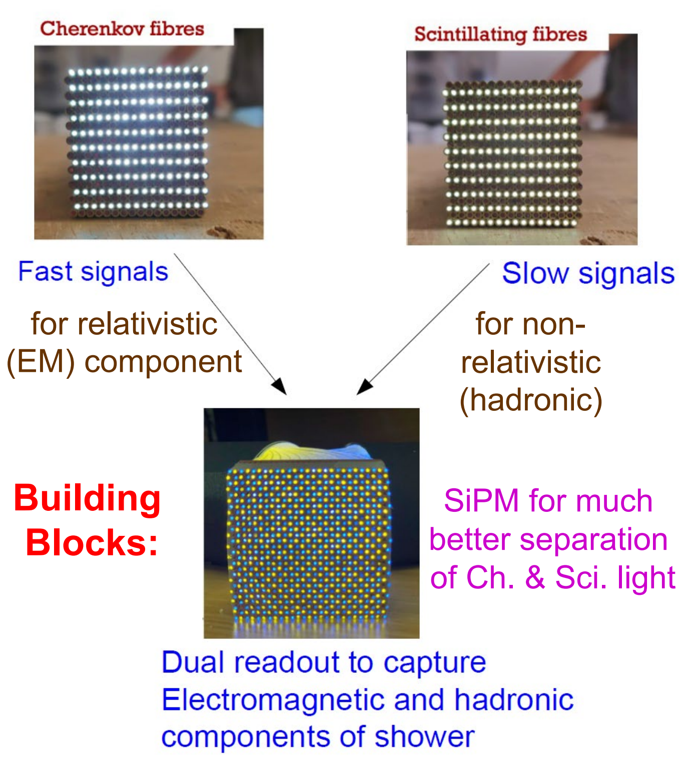


J. Brau @ILCX2021

MAPS ECAL (SiD)
25 x 100 um2 monolithic pixels
→ Common design to trackers

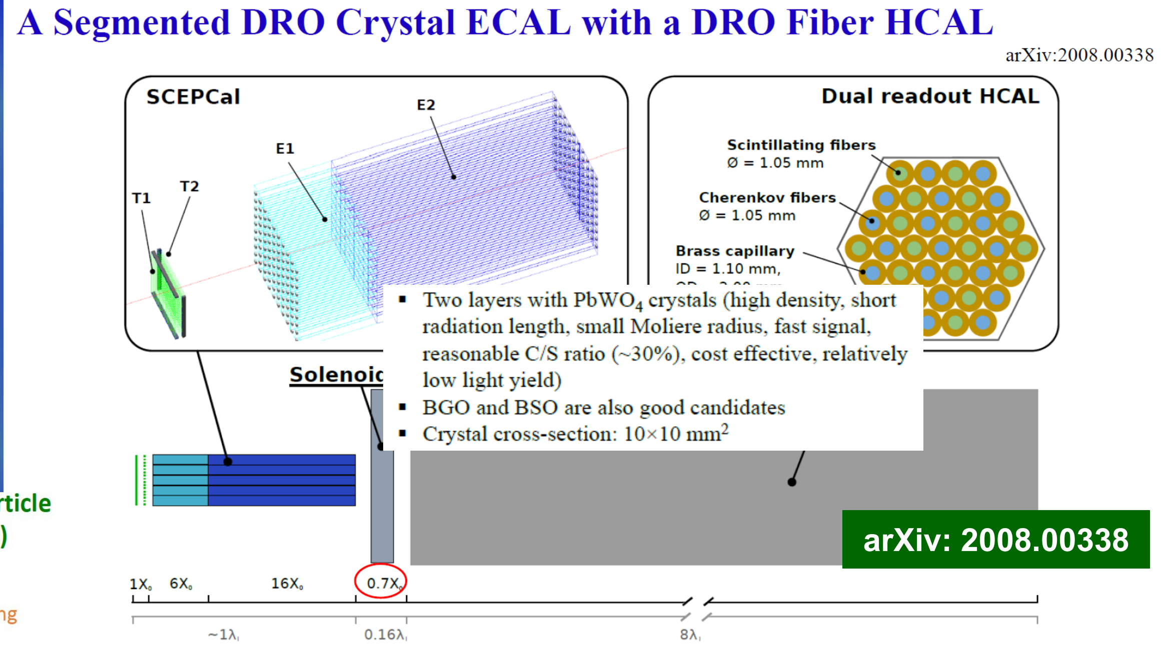
2.25 mm² prototype production in 2022 (WP1.2 CERN)

New Ideas: Dual-Readout Calorimetry + High Granularity

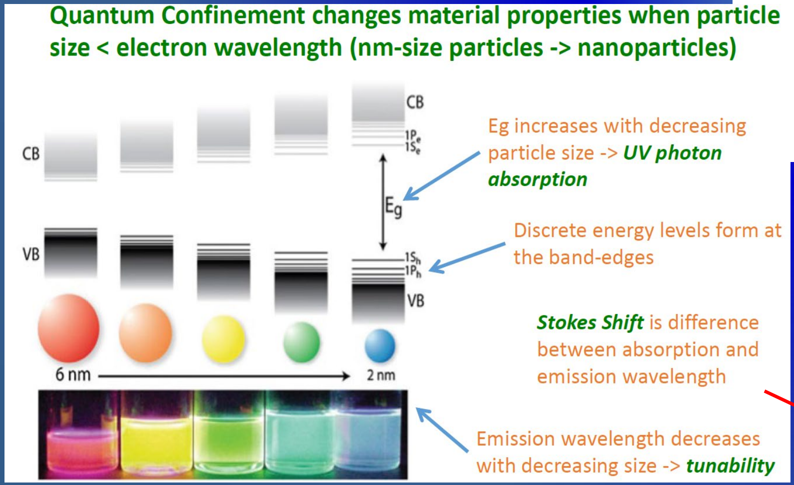


Extensive R&D by the DREAM/RD52/IDEA collaborations
(Rev. Mod. Phys. 90, 025002, 2018): an old idea in 4th ILC concept
→ Recent technological progress (SiPM, 3D-printed absorber material) enables highly granular DREAM calorimetry

✓ **Dual-readout (DRO) crystal ECAL:** **J. Zhu @ILCX2021**



arXiv: 2008.00338

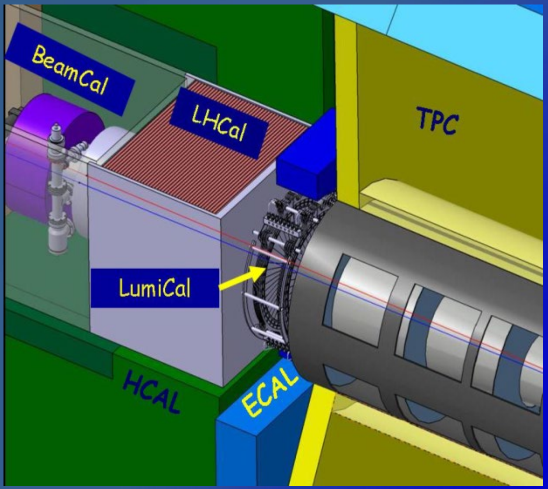


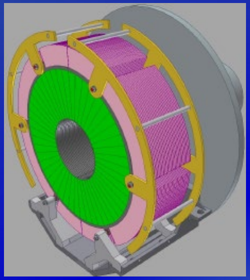
Readout Detector Development R&D: **S. Magill @ILCX2021**

R&D Focus : Optimal readout technologies for scintillation and Cherenkov signals – includes minimization of material between crystals to maximize sampling *(-> homogeneous calorimeter)*

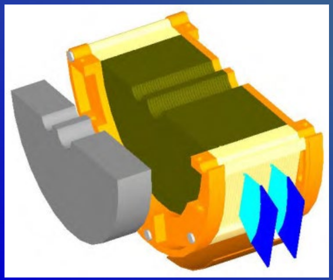
Wavelength conversion by nanoparticles discussed for detection of Cherenkov light

Forward Calorimetry R&D: FCAL Collaboration





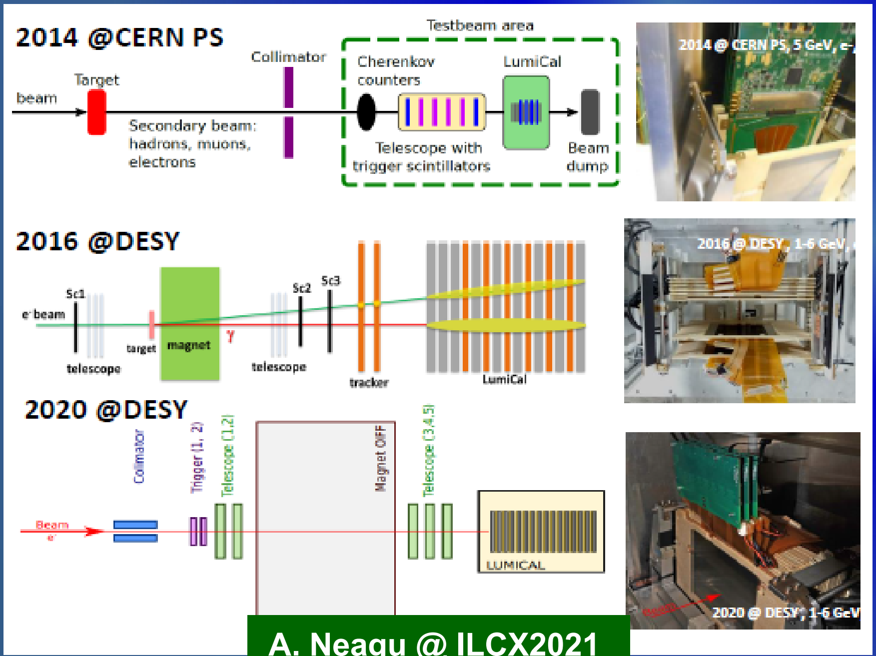
LumiCal:
→ precise luminosity measurement
10^{-3} - 500 GeV @ ILC



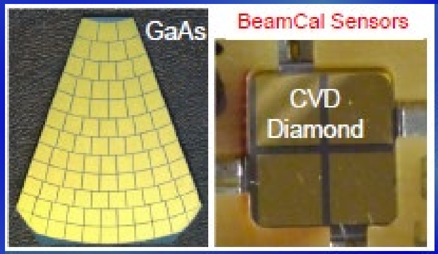
BeamCal:
→ inst. lumi measurement / beam tuning, beam diagnostics

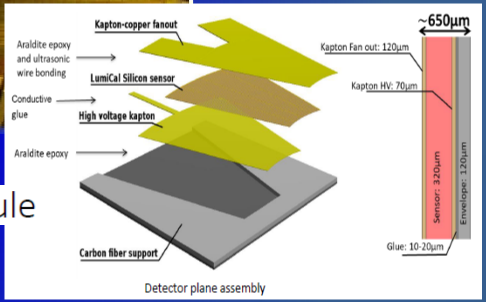
LumiCal: Two Si-W sandwich EM calo at a ~ 2.5 m from the IP (both sides)
BeamCal: very high radiation load (up to 1MGy/ year) → similar W-absorber, but radiation hard sensors (GaAs, CVD diamond, sapphire)
LHCAL: sampling calo (tungsten or iron with SI) → extend HCAL coverage

Beam-test campaings:
LumiCal prototypes multi-plane operation:



A. Neagu @ ILCX2021





LumiCal thin prototype module

LumiCal Challenges:

- ✓ Build a ultra compact LumiCal (alignment, deformation);
- ✓ Edgeless sensors (to avoid dead areas)
- ✓ Milti-layer LumiCal prototype with new (FLAME) ASIC;

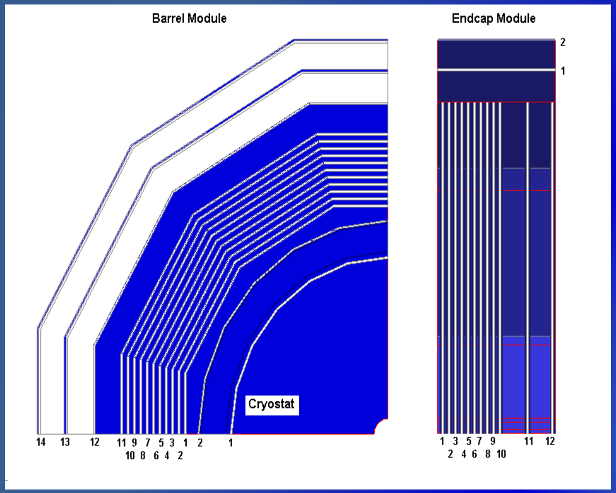
BeamCal Challenges:

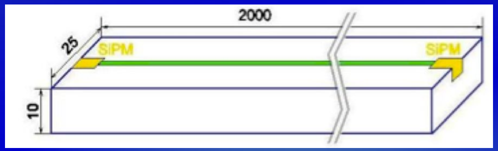
- ✓ Development of sapphire sensors with dedicated ASIC;
- ✓ Ongoing radiation damage studies (GaAs, Si diode, CVD diamond, sapphire …)

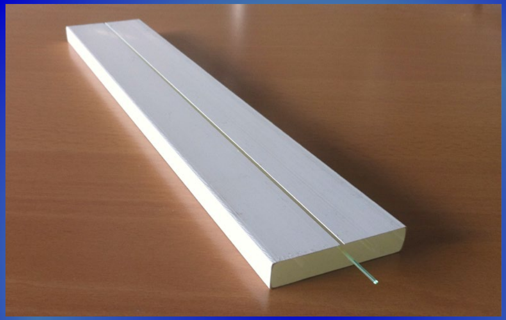
Muon System / York Instrumentation

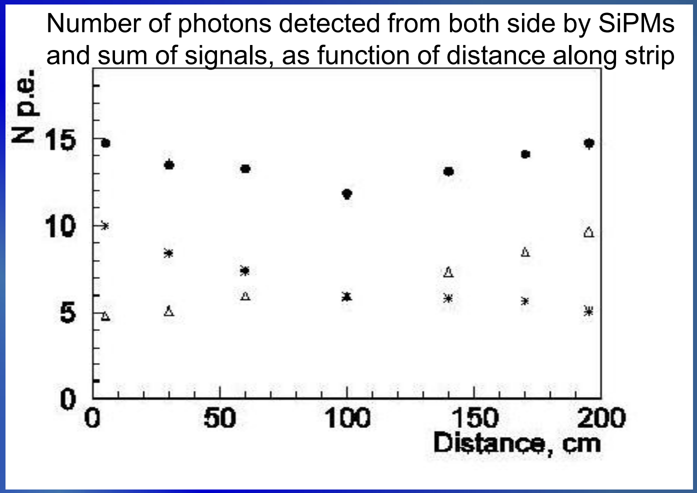
Efficient Muon Identification & Measurement of the Energy Leakage from Hadron Calorimeter

Main technology (compatible with HCAL) – Scintillation strips with WLS and SiPM readout

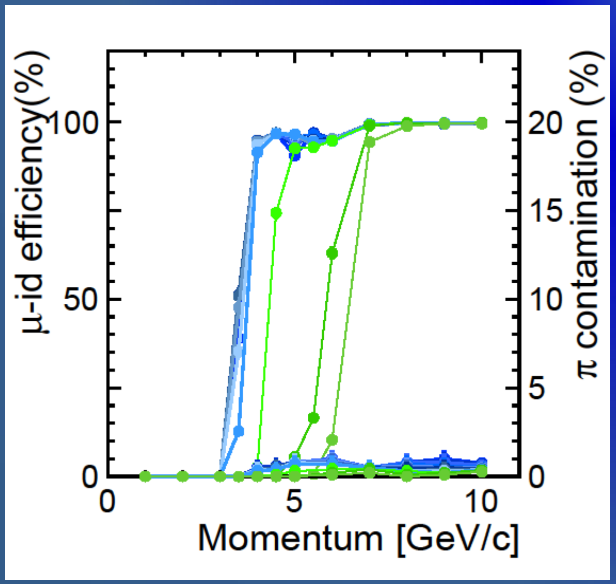






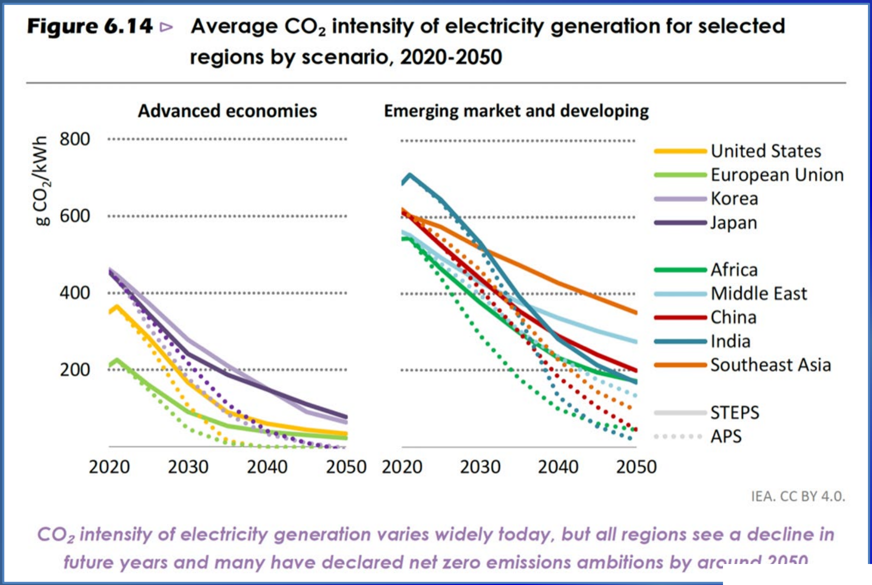


Muon efficiency & Pion contamination:



- ✓ Baseline option under development:
  → Scintillator + WaveLengthShifter + SiPM;
- ✓ Development of the Key Elements Sc/WLS/SiPM – Digital Silicon Photomultiplier in CMOS technology is in progress;
- ✓ Gas Detector - RPC (high coordinate resolution, excellent granularity up to 1 x 1 cm^2 pads) → not active for now;
- ✓ Not many groups are participating in the Muon System Study
- ✓ No significant challenges in terms of particle fluxes and radiation environment → many technologies feasible

Sustainable Linear Collider Operation



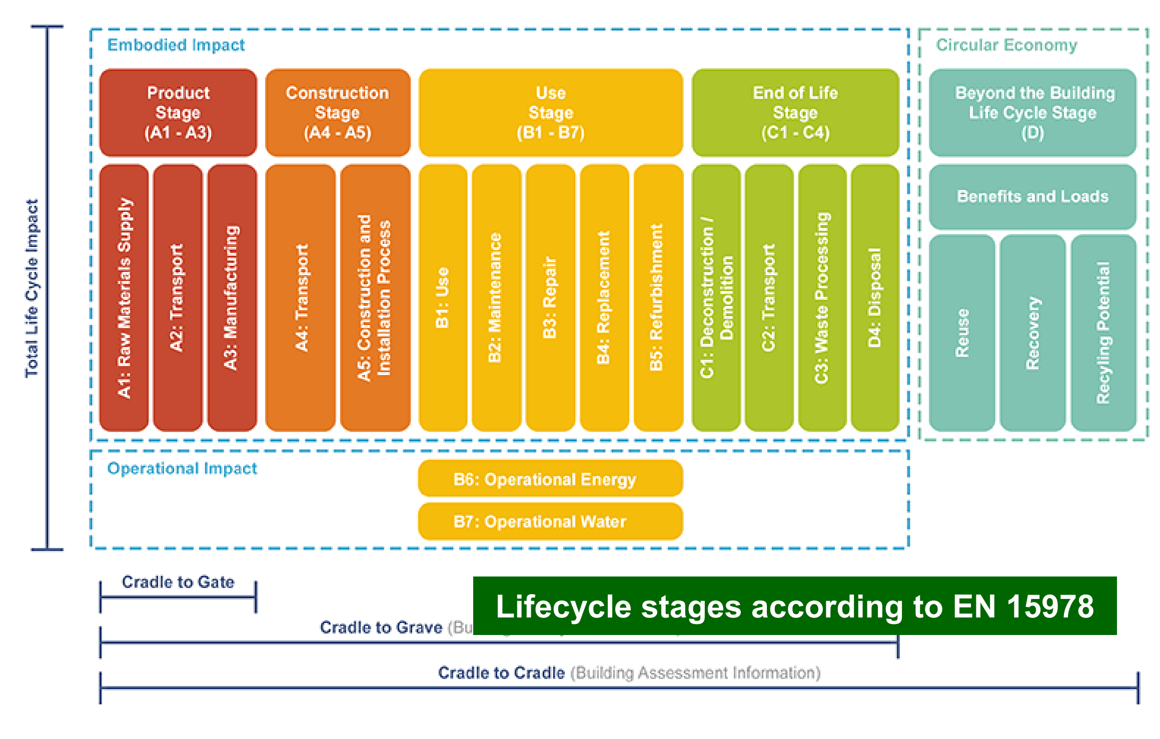
Data of carbon intensity of electric power
(Nuclear energy remains very important, on the timescale of a future CERN facility):

Power Projections Europe (2040):
- 50% nuclear at 5g CO_2/kWh;
- 50% renewables at 20g CO_2/kWh (mix sun, wind, hydro,…)

IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)

Whole Lifecycle is Important – Lifecyle Assessment (LCA):

- ✓ ***Ultimate Goal:***
  - Quantify the environmental impact of a whole accelerator project, i.e., CLIC / ILC
- ✓ ***Accepted method:***
  - LCA = Life Cycle Assessment
- ✓ ***Define Scope:***
  - System Boundaries
  - Lifecycle Stages



Lifecycle stages according to EN 15978

Sustainable Construction: Life-Cycle Assessment

ARUP

Full ARUP report is now available and public:
https://edms.cern.ch/document/2917948/1

Life Cycle Assessment

Comparative environmental footprint for future linear colliders CLIC and ILC

Final Report
July 2023

Inherent tension between invest and operation requires a quantitative approach:

Lifecycle Assessment

CERN KEK-JAPAN

Life Cycle Assessment

Comparative environmental footprint for future linear colliders CLIC and ILC

LCWS 2023 - SLAC | 16/05/2023

LCWS2023: ARUP talk –
https://indico.slac.stanford.edu/event/7467/contributions/5902/attachments/2851/7968/ARUP_CERN_LCA_LCWS_-_2023.pdf

ARUP: *Suzanne Evans, Ben Castle, Yung Loo, Heleni Pantelidou, Jin Sasaki
CERN: John Osborne, Steinar Stapnes, Benno List, Liam Bromiley
KEK: Nobuhiro Terunuma, Akira Yamamoto, Tomoyuki Sanuki

(*presenter: suzanne.evans@arup.com)

LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

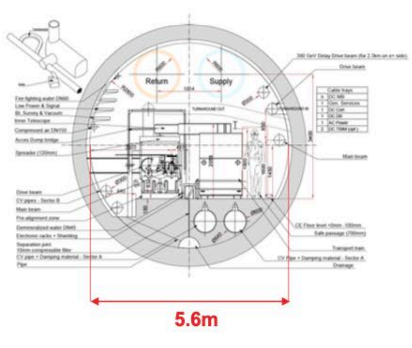
Sustainable Construction: Life-Cycle Assessment

Ref: ISO 14040:2006

Linear Collider Options

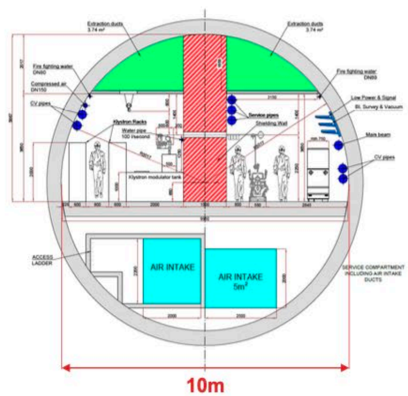
Full ARUP report:
https://edms.cern.ch/document/2917948/1

1. CLIC Drive Beam
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)



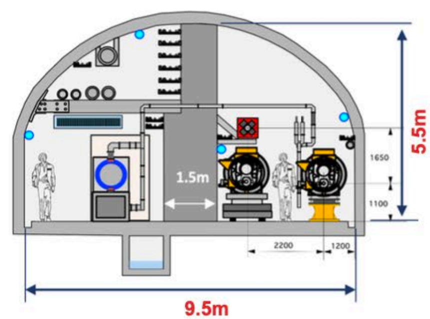
Reference: CLIC Drive Beam tunnel cross section, 2018

2. CLIC Klystron
10m internal dia. Geneva.
(380GeV)



Reference: CLIC Klystron tunnel cross section, 2018

3. ILC
Arched 9.5m span. Japan.
(250GeV)



Reference: Tohoku ILC Civil Engineering Plan, 2020

System	Sub-system	Components	Sub-components
CLIC Drive Beam & Klystron			
	Tunnels		
		Main accelerator tunnel and turnarounds	
			Primary Lining Permanent Lining Invert/shielding wall
	Shafts		
		9-18m dia.	
			Primary Lining Permanent Lining
	Caverns		
		BDS, UTRC, UTRA, BC2, DBD, service cavern, IR cavern, detector and service hall	
			Primary Lining Permanent Lining
ILC 250GeV			
	Tunnels		
		Main accelerator tunnel, loop sections at both ends, damping ring tunnel, access tunnels, BDS beam tunnels, widening sections, reversal pits, peripheral tunnels, RTML tunnels, AT-DR and AT-DH tunnels	
			Primary Lining Permanent Lining Invert/shielding wall
	Shafts		
		Main (18m dia. 70m depth) and utility (10m dia. 70m depth)	
			Primary Lining Permanent Lining
	Caverns		
		Access Hall S/E/M Dome, HE Dome, Detector Hall	
			Primary Lining Permanent Lining

ARUP

2030 Baseline assumptions

LCA Modules		CLIC Drive Beam	CLIC Klystron	ILC
A1-A3	Materials	Concrete (CEMI) & Steel (80% recycled)		
A4	Transport of materials to site	Concrete: Local by road (50km) Steel: European by road (1500km)		Concrete: Local by road (50km) Steel: National by road (300km)
A5	Material wasted in construction	Concrete insitu: 5% Precast concrete: 1% Steel reinforcement: 5%		
A5	Transport of disposal materials off site	Concrete and steel recycling: 30km by road Concrete and steel landfill: 30km by road Spoil: 20km by road *Assumed that 90% of EoL construction materials are recycled or repurposed and 10% is in landfill.*		
A5	Construction process	Tunnel Boring Machine (TBM)		Drill & Blast
A5	Electricity mix 2021/2022	Fossil: 12% Non-fossil: 88%		Fossil: 71% Non-fossil: 29%

Methodology

CA follows the ISO 14040/44 methodology.

CA has been carried out using the LCA tool
pro 9.4.0.2 which uses Ecoinvent 3.8 database. The ReCiPe Midpoint (H) 2016 method has been used to estimate the environmental impacts across 18 impact categories – see table to the right.

Data for the CLIC and ILC LCA has been gathered from CERN and KEK respectively through drawings and reports, which feeds directly into the Life Cycle Inventory (LCI).

Data quality

Simapro 9.4.0.2 uses Ecoinvent 3.8 database, released in September 2021. Ecoinvent is widely recognised as the largest and most consistent LCI database. Ecoinvent validates the LCI data through ecoEditor software. Ecoinvent reviews the data through manual inspection from at least 3 experts prior to the storage of data in Ecoinvent database (Data quality guideline for the ecoinvent database version 3, 2013).

ReCiPe Midpoint (H) 2016 Impact Categories

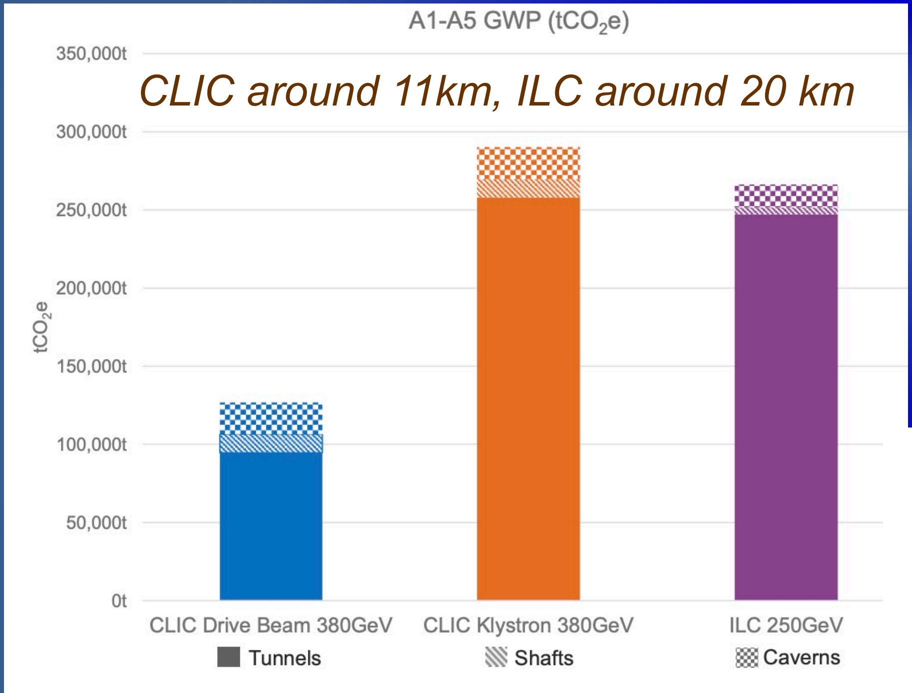
Midpoint Impact Categories	Abbr.	Unit
Global warming	GWP	kg CO_2 eq
Stratospheric ozone depletion	ODP	kg CFC-11 eq
Ionizing radiation	IRP	kBq Co-60 eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Ozone formation, Human health	HOFP	kg NOx eq
Ozone formation, Terrestrial ecosystems	EOFP	kg NOx eq
Terrestrial acidification	TAP	kg SO_2 eq
Freshwater eutrophication	FEP	kg P eq
Marine eutrophication	MEP	kg N eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Marine ecotoxicity	METP	kg 1,4-DCB
Human carcinogenic toxicity	HTPc	kg 1,4-DCB
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB
Land use	LOP	m^2a crop eq
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq
Water consumption	WCP	m^3

Reference: ReCiPe Midpoint (H) 2016

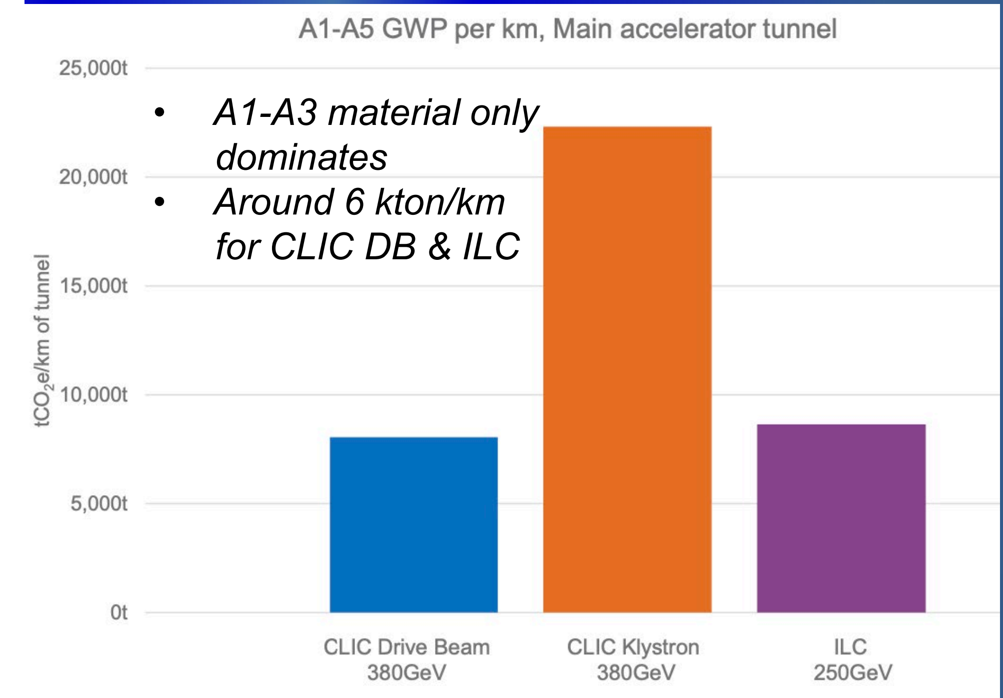
Sustainable Construction: Life-Cycle Assessment

Full ARUP report: https://edms.cern.ch/document/2917948/1

Comparative environmental footprint for future linear colliders CLIC & ILC



Assuming a small CLIC tunnel (~5.6m diameter) ***and*** *that the* *<u>equipment has the same carbon footprint as the tunnel</u> itself,* *20 km accelerator (tunnel plus components) correspond to 240 kton CO_2 equivalent*

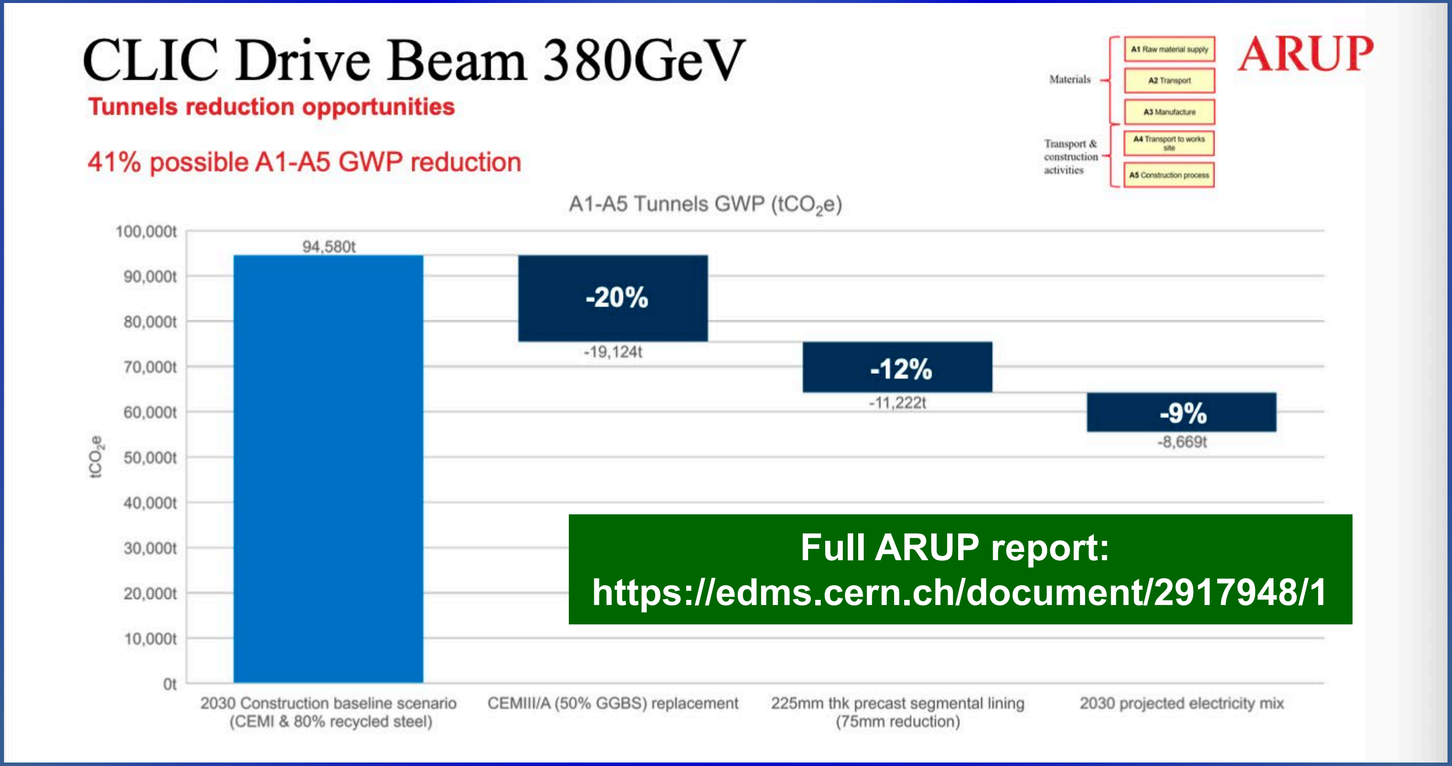


- ✓ *Include all tunnels (access, transfer, damping rings), shafts and caverns. A1-A5*
- ✓ *Scaling to main linac tunnel lengths we are now at 11-14 kton/km for the CLIC DB and ILC*

Sustainable Construction: Life-Cycle Assessment

Many caveats, first of all this is a very first indication of the scale:

- \+ *many more components in tunnel (also infrastructure), injectors, shafts, detectors, construction, spoils, etc …*
- \+ *upgrades and decommissioning, this is not only an initial important contribution*
- \- *improvement and optimisations (e.g. less and/or better concrete mixes, support structures, steel in tunnels)*
- \- *responsible purchasing (understanding the impact of supply chain, costs and potential for changes – will be essential for future projects – CERN implementation information from E. Cennini)*



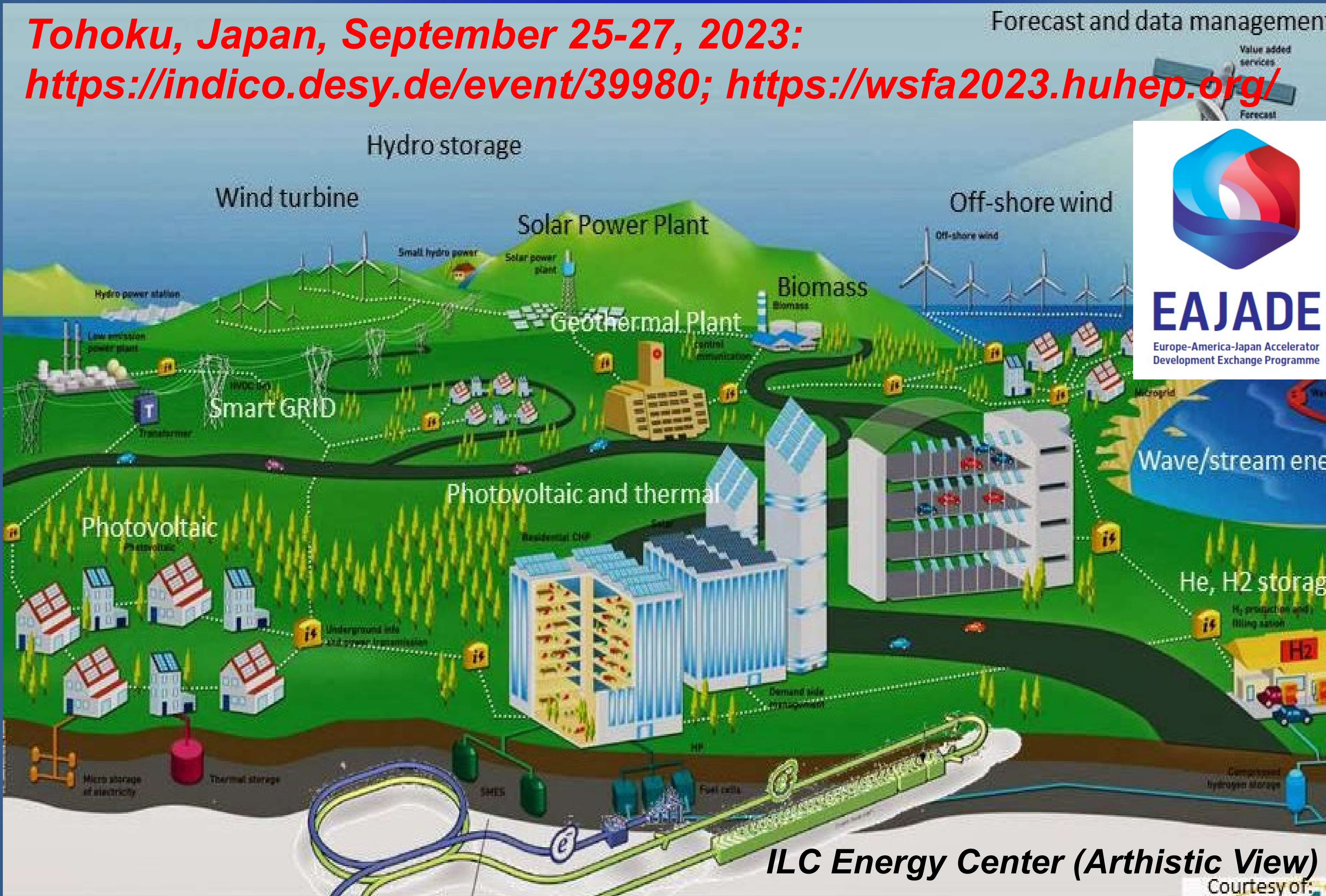
If we have energy available at 12.5 g CO_2/kWh = 12.5 kton CO_2/TWh (not unlikely in 2050):

- ***20km accelerator construction ~ 20 years of operation.***
- ***1 km accelerator construction ~ 1 TWh annual electricity (annual LC operation 0.6 TWh)***

EAJADE Workshop on Sustainability in Future Accelerators

Tohoku, Japan, September 25-27, 2023:

https://indico.desy.de/event/39980; https://wsfa2023.huhep.org/



ILC Energy Center (Arthistic View)