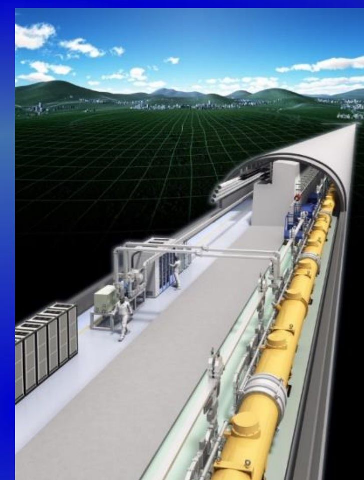
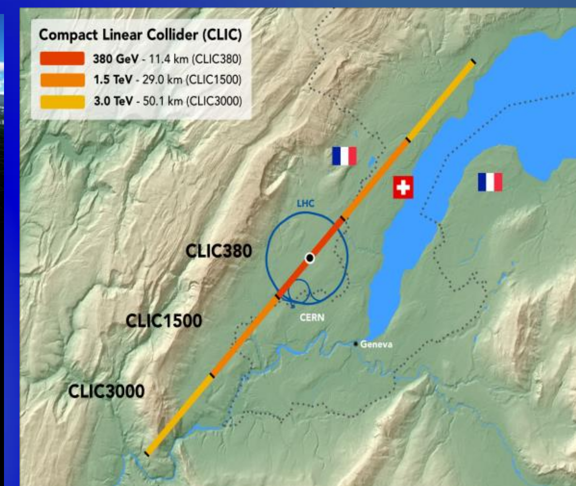
Challenges of Future Linear Colliders (ILC / CLIC)

Maxim Titov, CEA Saclay / CERN





40th Conference on Recent Developments in High Energy Physics and Cosmology (HEP2023), Ioannina, Greece, April 5 -7, 2023

Linear Collider Challenges

Critical aspects: Physics, Gradient and Power Efficiency, Cost

Construction cost
$ ~ L

Energy

$$E_{CM} = L \cdot g$$

Luminosity

$$\mathcal{L} = \frac{\eta P_{AC}}{E_{CM}} \cdot \frac{N_e}{4\pi \sigma_x^* \sigma_y^*} H_D$$

Operation cost
$ ~ P_{AC}

High Gradient g

High Efficiency η

Small Beamspot $\sigma_x \sigma_y$

$$\sigma^* = \sqrt{\beta^* \varepsilon}$$

Main Linac Technology

Losses in cavity walls $\frac{P_{wall}}{L} \propto \frac{g^2 R_s}{\omega}$

Low resistivity

Small duty cycle:
Pulsed operation

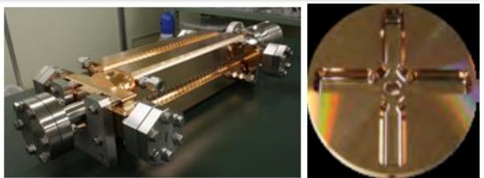
High frequency &
Ultra-short pulses

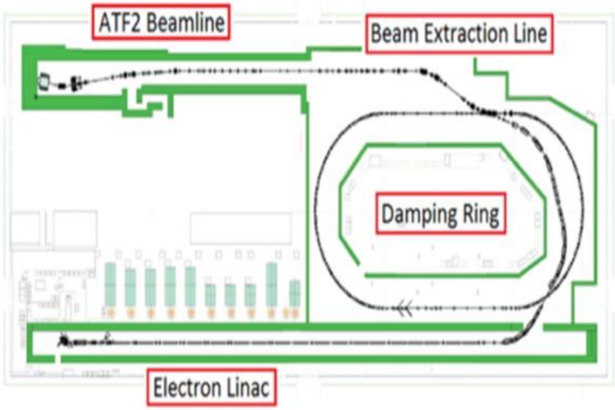
Nanobeam Technology

- Damping ring (ε)
- Final focus (β^*)

ILC
Superconducting RF

CLIC
2 beam acceleration





B. List: https://indico.ihep.ac.cn/event/17020/

Two e+e- linear collider designs, starting as a Higgs factory

International Linear Collider (ILC):

- 250 GeV CME, upgradeable to 500, 1000 GeV
- L = 1.35E34 $cm^{-2}s^{-1}$, 20km length, in Tohoku / Japan

- SRF Cavities, 31.5 MV/m, 1.3 GHz

  → relaxed tolerances & smaller emittance dilution
- High-Q (Q_0 =10^{10}):
- Larger apertur
- Long beam pul
- Cryogenics

Compact Linear Collider (CLIC):

Two-beam acceleration (or klystron driven initially)

- 380GeV CME, upgradeable to 1500, 3000 GeV
- L = 2.3E34 $cm^{-2}s^{-1}$, 11.4km long, at CERN

- NC Copper Cavities, 72 MV/m, 11.4 GHz
-
- Smaller aperture / better accuracy
- Ultra-short beam pulses (μs pulse)
- Water cooling

General consensus: next "big collider" should be e+e- collider to scrutinize Higgs boson characteristics

DESY-22-045, IFT–UAM/CSIC–22-028,
KEK Preprint 2021-61, PNNL-SA-160884,
SLAC-PUB-17662
January 2023

The International Linear Collider: Report to Snowmass 2021

THE ILC INTERNATIONAL DEVELOPMENT TEAM AND THE ILC COMMUNITY

ABSTRACT

ILC Snowmass White paper: arXiv: 2203.07622

and will provide a new window to look beyond it. This document brings the story of the ILC up to date, emphasizing its strong physics motivation, its readiness for construction, and the opportunity it presents to the US and the global particle physics community.

The CLIC project

O. Brunner[a], P. N. Burrows[b], S. Calatroni[a], N. Catalan Lasheras[a], R. Corsini[a], G. D'Auria[c], S. Doebert[a], A. Faus-Golfe[d], A. Grudiev[a], A. Latina[a], T. Lefevre[a], G. Mcmonagle[a], J. Osborne[a], Y. Papaphilippou[a], A. Robson[e], C. Rossi[a], R. Ruber[f], D. Schulte[a], S. Stapnes[a]*, I. Syratchev[a], W. Wuensch[a]

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April 19, 2022

Abstract

CLIC Snowmass White paper: arXiv: 2203.09186

The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development by the CLIC accelerator collaboration, hosted by CERN. The CLIC accelerator has been optimised for three energy stages at centre-of-mass energies 380 GeV, 1.5 TeV and 3 TeV [1]. CLIC uses a novel two-beam acceleration technique, with normal-conducting accelerating structures operating in the range of 70 MV/m to 100 MV/m.

Report of the Snowmass'21
Collider Implementation Task Force

Thomas Roser (chair)[1], Reinhard Brinkmann[2], Sarah Cousineau[3], Dmitri Denisov[1], Spencer Gessner[4], Steve Gourlay[5], Philippe Lebrun[6], Meenakshi Narain[7], Katsunobu Oide[8], Tor Raubenheimer[4], John Seeman[4], Vladimir Shiltsev[9], Jim Strait[9], Marlene Turner[5], and Lian-Tao Wang[10]

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[6]ESI Archamps, 74160 Archamps, France

Snowmass Implementation TF Report, arXiv: 2208.06030

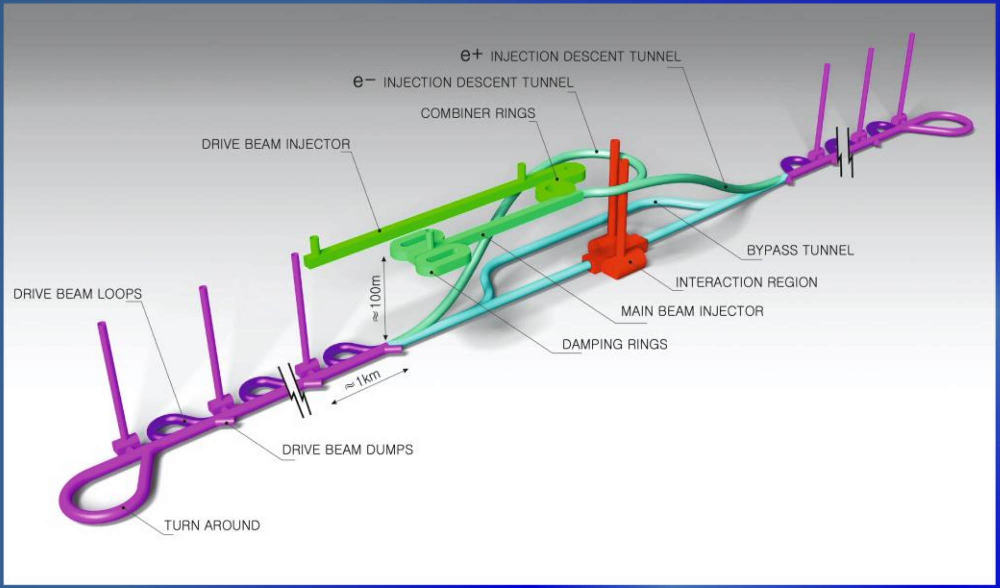
August 15, 2022

Abstract

The Snowmass'21 Implementation Task Force has been established to evaluate the proposed future accelerator projects for performance, technology readiness, schedule, cost, and environmental impact. Corresponding metrics has been developed for uniform comparison of the proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron and *ep* collider facilities, based on traditional and advanced acceleration technologies. This report documents the metrics and processes, and presents evaluations of future colliders performed by Implementation Task Force.

Snowmass Implementation TF Report: provided an opportunity for formulating new ideas, overviews – for the US and worldwide

The Compact Linear Collider (CLIC)

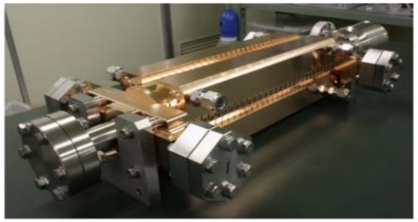


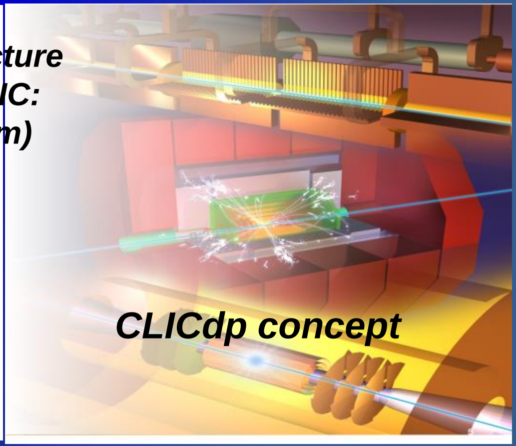
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV
- CDR in 2012 with focus on 3 TeV. Updated project overview in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs & top factory.

The CLIC accelerator studies are mature:

- ***Optimised design for cost and power***
- ***Many technical tests in CTF3*** (drive-beam production issues), FELs, light-sources, and test-systems (alignment, damping rings, beam delivery, etc.)
- Technical developments of "all" key elements; ***C-band XFELS (SACLA and SwissFEL) now operational:*** large-scale demonstrations of normal- conducting, high-frequency, low-emittance linacs

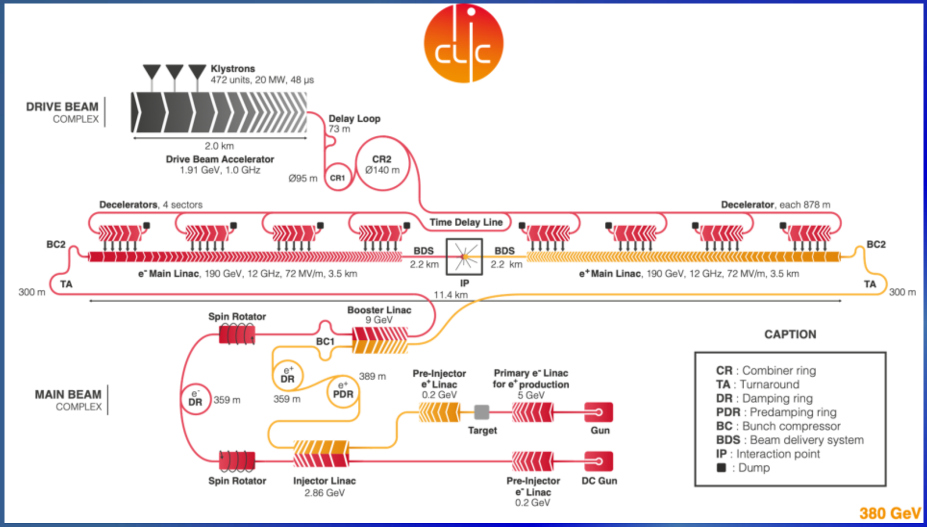
Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)





- **Accelerator Cost:** 5.9 BCHF for 380 GeV
- **Power/Energy:** 110 MW at 380 GeV (~0.6 TWh annually), corresponding to 50% of CERN's energy consumpt. today
- Comprehensive **Detector and Physics** studies

CLIC Baseline (380 GeV initial) - Drive-beam Based Machine



Concept:

1. *Drive beam accelerated to ~2 GeV using conventional klystrons*
2. *Intensity increased using a series of delay loops and combiner rings*
3. *Drive beam decelerated and produces high-RF*
4. *Feed high-RF to the less intense main beam using waveguides*

Four main technology challenges:

- ***High-current drive beam bunched at 12 GHz***
- ***Power transfer and main-beam acceleration, efficient RF power***
- ***Towards 100 MV/m gradient in main-beam X-band cavities***
- ***Alignment and stability ("nano-beams")***

Some (key improvements) study goals by ~ 2025:

- Luminosity numbers, covering beam-dynamics, nanobeam, and positrons - at all energies. Performance risk reduction, system level studies
- Energy/power: 380 GeV well underway, 3 TeV to be done, L-band klystron efficiency
- Sustainability issues, more work on running/energy models and carbon footprint
- X-band progress – for CLIC, smaller machines, industry availability, including RF network
- R&D for higher energies, gradient, power, prospects beyond 3 TeV
- Cost update, only discuss changes wrt Project Implementation Plan in 2018
- Low cost klystron version – reoptimize for power, cost and fewer klystrons

B. List: https://indico.ihep.ac.cn/event/17020/

On-going CLIC Studies Towards next European Strategy Update

Project Readiness Report as a step toward a TDR

Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030

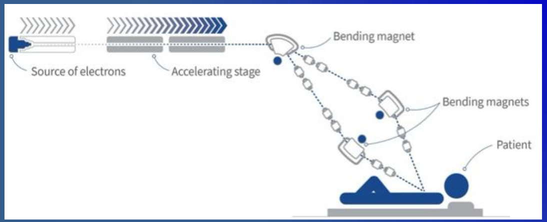
The X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators

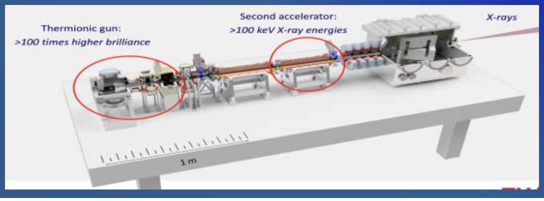

CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

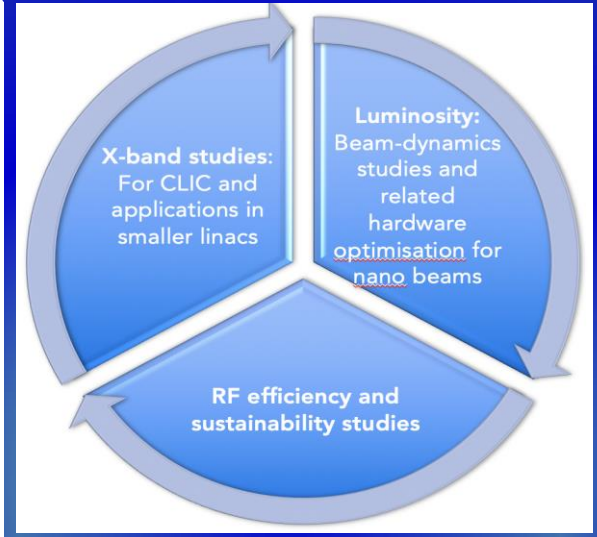
CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020

Close-up of the Compact Linear Collider prototype, on which the electron FLASH design is based (Image: CERN)







S. Stapnes: https://indico.cern.ch/event/1260648/

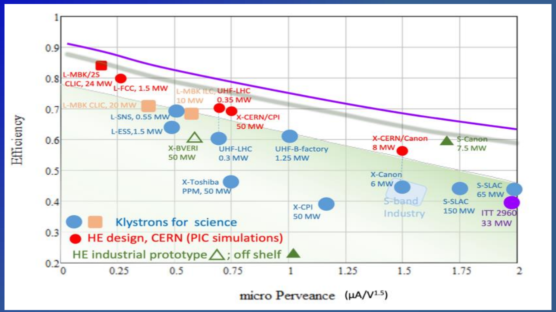
Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue:

Luminosity margins and increases:

- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 1034 cm-2 s-1
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above 2.3 x 1034 cm-2 s-1 (this is the value currently used)

Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies:

Very large reductions in power estimate (380 GeV) since the CDR: better estimates of nominal settings, much more optimised drive-beam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies

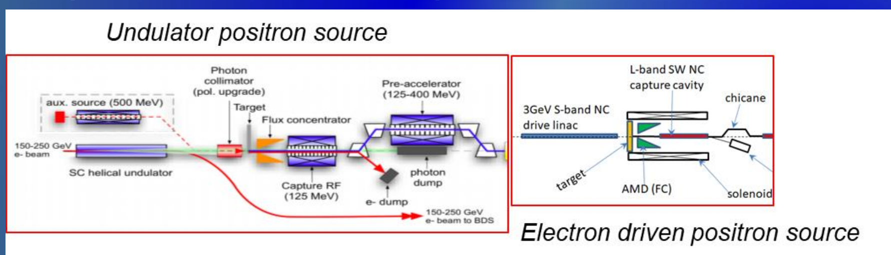


The ILC (250 GeV) Accelerator:

http://www.linearcollider.org/

Global Context → ILC (Japan) has to be Coexisting and Synergistic with CERN future

- *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***

Worldwide SRF Collaboration:
International partner labs lend their expertize

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

ILC Baseline (250 GeV initial) – Recent Key Technology Updates

- ✓ ***Mature technology** → R&D is ongoing to mitigate the identified risks*
  *→ ready to be built, once **diplomatic decisions have been reached***
- ✓ ***Positron source** remains THE biggest challenge*
- ✓ ***Priority work packages** have been identified for the next (4-5) years*

ILC Technology Level:

Since the publication of the conceptual design report (RDR) in 2007 and the Technical Design Report (TDR) in 2013, the technical development has been progressing steadily toward the start of construction.

Status	(RDR) (TDR) ~2017	2021 2018~2021	(EDR)* Pre-lab
SRF cavity, CM	Technology development ->Model work-> Prototype	High performance and cost reduction of cavities	International mass production, and transfer demonstration
SRF Linac	Model work: small-scale models, partial/component models.	European XFEL user operation	
e- source	Tech. Design->Tech. Development->Tech. Demonstration		Tech. confirmation
e+ source Undulator scheme	Tech. Design->Tech. Development	Tech. Demonstration	Target and magnetic focusing
e+ source e-driven scheme	Tech. Design->Tech. Developmen	Tech. Demonstration	Target and capture cavity
DR	Design->Tech. Development-> Tech. demonstration achieved at KEK ATF		Kicker
Final focus	Design->Tech. Development->Tech. demonstration achieved at KEK ATF		Stable op.
Dump	Tech. Design->Tech. Development	Facility design	Remote handling

ILC construction

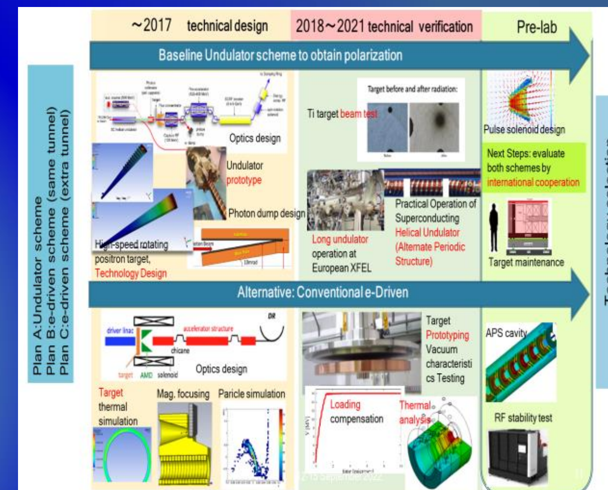
: ~2017
: 2018~2021
: Pre-lab

*EDR:Detailed Engineering Design Report required to start construction.

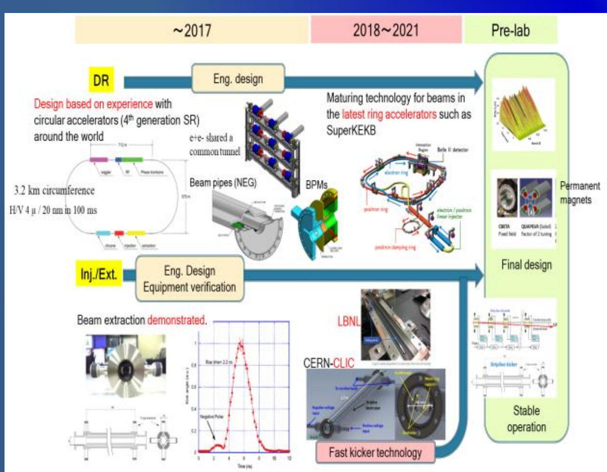
6

International Cooperation in SRF:

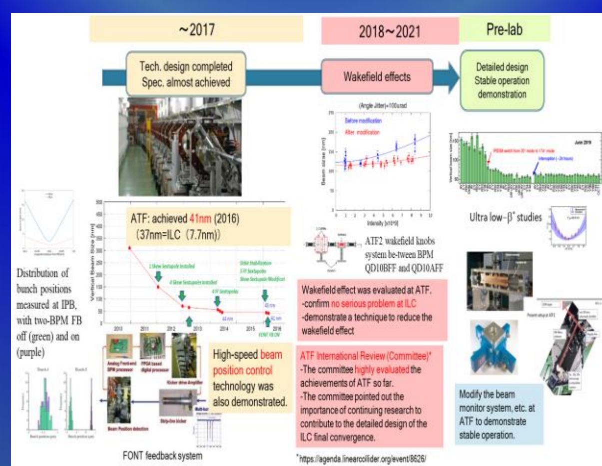
Progress in Positron Sources:



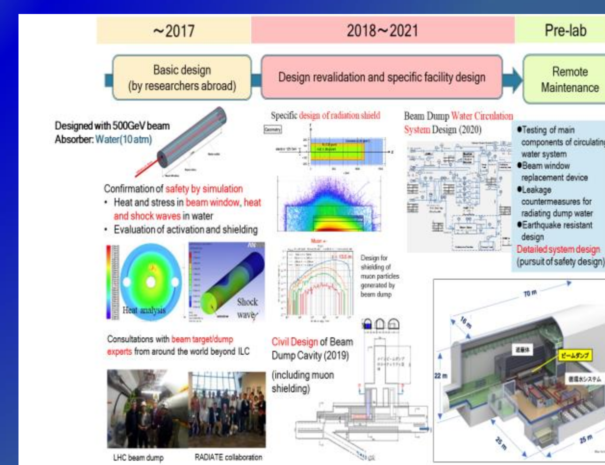
Progress in Damping Rings:



Progress in Final Focus:



Progress in Beam Dump:



Examples of Worldwide Efforts on ILC (2017-2021)

	～2017	2018～2021
CERN	Cooperation on nano-beam at ATF, study on industrialization of cavity and cryomodule for SRF, cooperation on design of cryogenics, beam dump, and civil engineering	Nanobeam collaboration at ATF, SRF cavity fabrication technology, cryogenics, beam dump and civil design collaboration. Overall coordination of ILC R&D in Europe.
Americas (USA+Canada)	Start of construction of LCLS-II; development of a new SRF cavity treatment method for LCLS-II; development of a crab cavity for HL-LHC.	US-Japan collaboration on SRF cavity performance improvement and cost reduction, assembly and installation of cryomodules for LCLS-II.Production began for in-kind contributions of the RFD crab cavities and cryomodules to the HL-LHC by the US & Canada
France	Experience in assembly of SRF input couplers and cryomodule assembly at XFEL in Europe, cooperation with Nanobeam at ATF	In-kind contributions to the European Neutron Source (ESS), the US PIP-II project, cavity performance improvement at SRF, nanobeam collaboration at ATF.
Germany	TESLA (preliminary stage of ILC) planning study, XFEL construction started in 2007, SRF cost estimate for TDR.	Demonstration of large SRF accelerator with stable operation of XFEL, and improvement of SRF cavity performance
Italy	Contribution to ILC-TDR for cryomodules, cavities and reference Blade tuners, in-kind contribution to half of the cavities and cryomodules at XFEL in Europe.	In-kind contributions to the European Neutron Source (ESS), the US PIP-II project, cavity tuner design at the VSR Upgrade of BESSY storage ring HZB
Spain	Nanobeam collaboration at ATF, in-kind contributions such as superconducting magnets at European XFEL, in-kind contributions to IFMIF in Japan	In-Kind contribution to the European Neutron Source (ESS), CIEMAT was awarded a budget for the R&D of the ILC superconducting magnet.
UK	Nanobeam collaboration at ATF. Contributions to TDR for damping rings, positron sources, beam delivery system, RF sources, and beam dump.	In-kind contributions to the European Neutron Source (ESS) and the US PIP-II projects, design of the LHC crab cavity.

S. Michizono @ILCX2021: https://doi.org/10.5281/zenodo.5535621

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

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

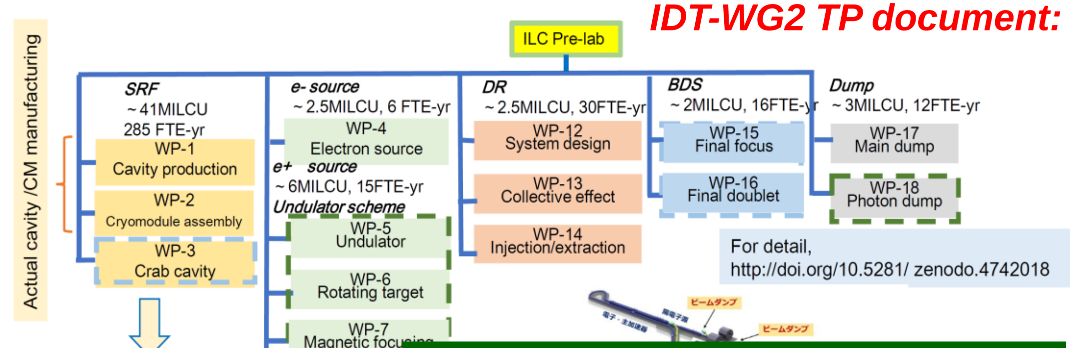
ILC Pre-lab proposal developed by IDT-WG1 and submitted to MEXT on Jun. 2, 2021:

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:



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.

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

- 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

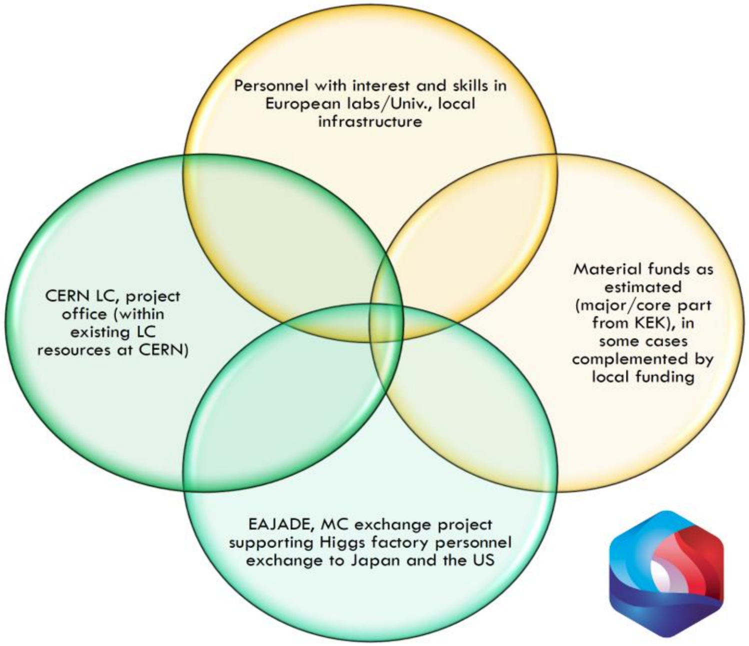
ILC Technology Network (ITN) – European Focus Areas

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:

→ Some funding can be used to foster international collaboration and efforts (budget needs to be approved yearly, but the programme is set up for 5 years)

→ 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)*



EAJADE

Europe-America-Japan Accelerator Development Exchange Programme

EAJADE EU Program (2023-2027):

Table 1 – Work Package (WP) List

Work package no.	Work package title	Activity type	Number of person-months involved per secondment	Lead benefi-ciary	Start month	End month
1	R&D&I at currently operating state-of-the-art facilities	Research, training	143	CNRS	1	48
2	State-of-the-art high-gradient, high-efficiency, reduced-cost radio-frequency structures and power sources	Research, training	68	INFN	1	48
3	Special technologies, devices and systems performance	Research, training	74	CERN	1	48
4	Sustainable technologies for scientific facilities	Research, Training	12	CEA	1	48
5	Investigation of potential early applications of novel and advanced technologies for colliders	Research, training	52	DESY	1	48
6	Management, dissemination, training, knowledge transfer, and communication	Management, training, dissemination,	4	DESY	1	48

EAJADE Exchange program: https://www.e-jade.eu/

Many Forms of Linear Collider Detector R&D Efforts

RPC DHCAL Silicon ECAL (ILD) LCTPC

KPIX SDHCAL 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

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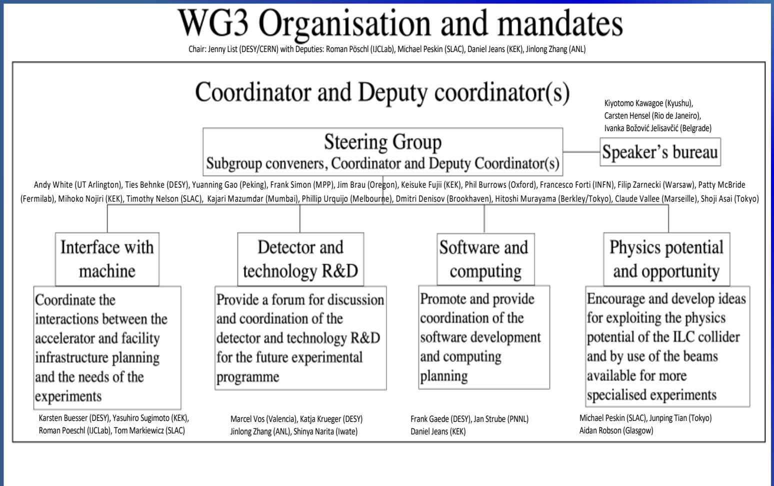
February 2, 2021

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 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

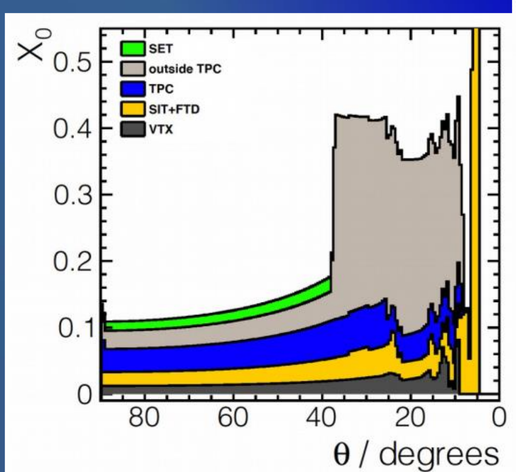
  0.15% X_0 / layer, $\sigma_{sp} \lesssim$ 3-5 μm

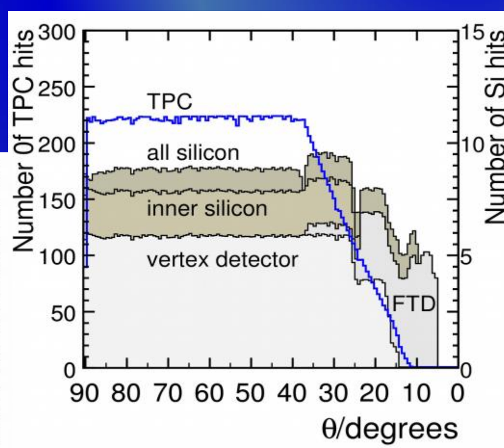
TRACKING:

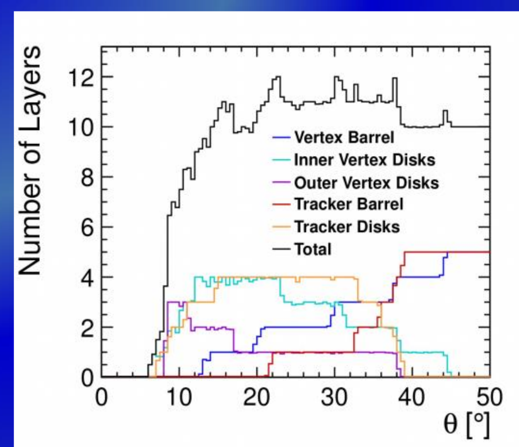
- Intermediate Si-tracker (SIT, SET, FTD)
  - SIT/FTD: silicon pixel sensors (e.g. CMOS)
  - SET: silicon strip sensors
- Time Projection Chamber with MPGDs
  - High hit redundancy (200 hits / track)
    - → 3D tracking / pattern recognition;
    - → dE/dx information for PID

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

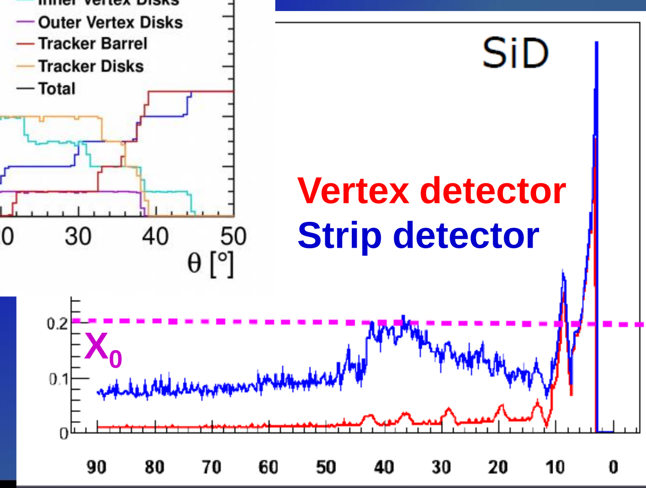
ILD:







SiD:



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

Vertex Technologies for Future Linear Colliders (ILC)

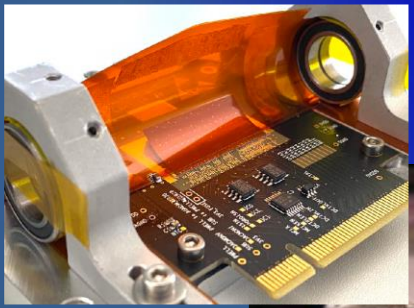
- **Sensor's contribution to the total X_0 is 15-30% (majority cables + cooling + support)**
- **Readout strategies exploiting the ILC low duty cycle 0(10^{-3}): triggerless readout, power-pulsing**
  - → continuous during the train with power cycling → mechanic. stress from Lorentz forces in B-field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

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

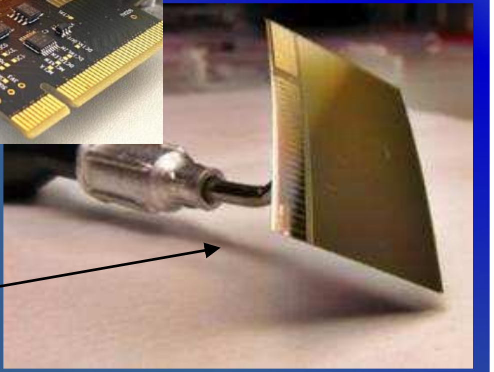
- $\sigma_{s.p.}$ 2.8um → Small pixel ~16 µm
- Material budget 0.15% X_0/layer → Thinning to 50 µm
- → Air cooling → low power 50 mW/cm²
- r of Inner most layer 16mm → beam-related background → fast readout ~1 µs
- → radiation damage → radiation tolerance ≤3.4 Mrad/ year, ≤$6.2\times10^{12} n_{eq}/(cm^2 year)$

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

180 nm CMOS technology: VALIDATED

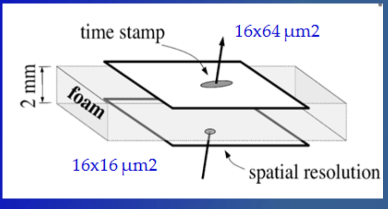


ALPIDE@ ALICE ITS-3 (bending 50 um sensor)



MIMOSIS @ CBM-MVD

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



ALICE-ITS3 upgrade drives the R&D:

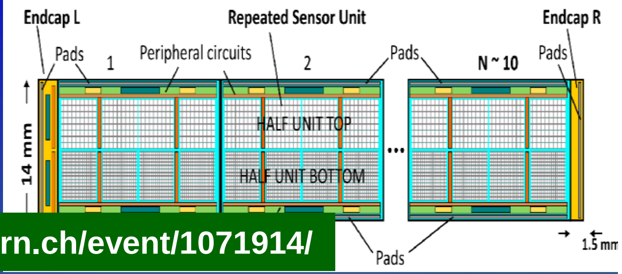
Bending thin Si-layers (MAPS):

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

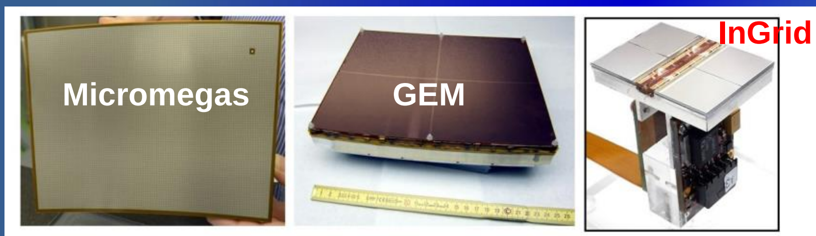


https://indico.cern.ch/event/1071914/

Gaseous Tracking: TPC with MPGD-based Readout

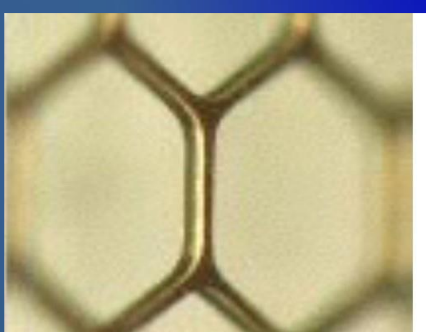
Three MPGD options are foreseen for the ILC-TPC:

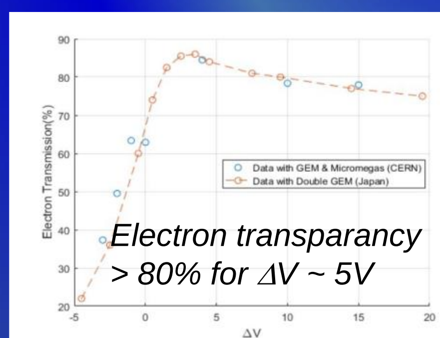
→ Wet-etched / Laser-etched GEMs
→ Resistive Micromegas with dispersive anode
→ GEM + CMOS ASICs, « GridPix » concept
(integrated Micromegas grid with Timepix chip)



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)

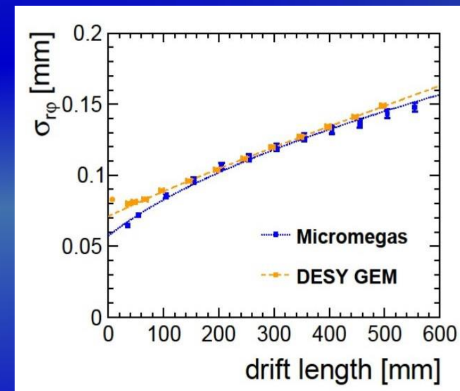


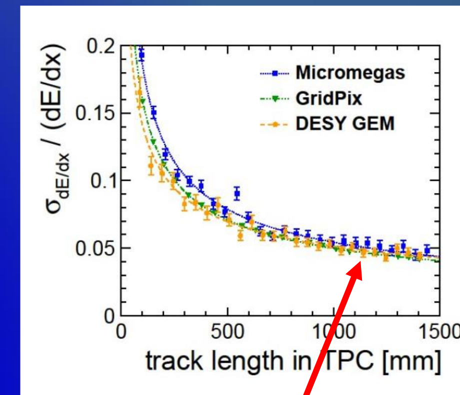


CHALLENGES / FUTURE PLANS:

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

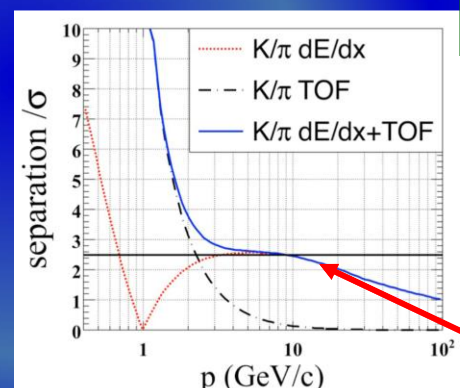
Spatial resolution of σ_T ~ 100 um and dE/dx res. < 5% have been reached with GEM, MM and InGrid)



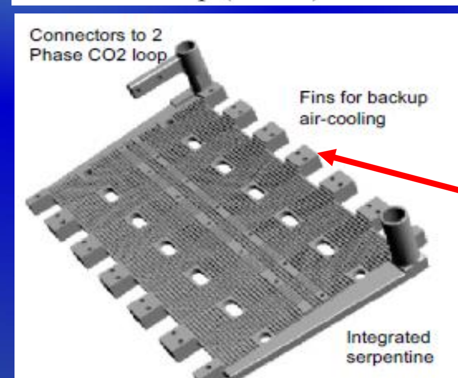


arXiv: 2003.01116

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



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 CO_2

P. Colas @ ILCX2021

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)?

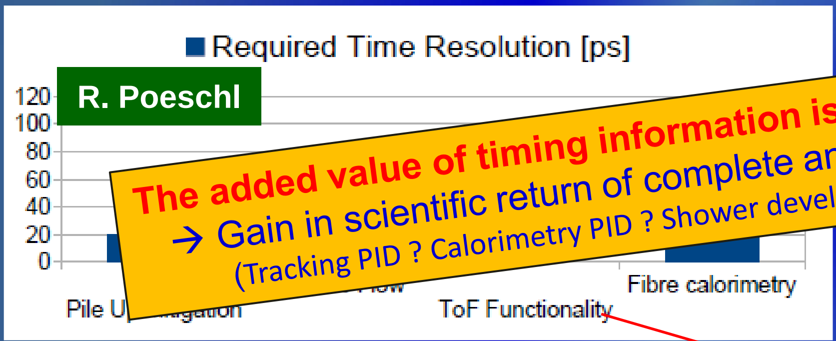
- Mitigation of pile-up (basically all high rates)
- Support for full 5D PFA → unchartered territory
- Calorimeters with ToF functionality in first layers?
- Longitudinally unsegmented fibre calorimeters

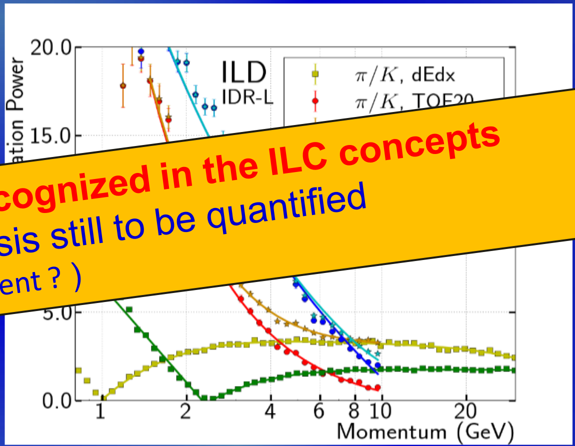
Replace (part of) ECAL with LGAD for O(10 ps) timing measurement

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

T. Suehara @ILCX2021

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 ?)

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?

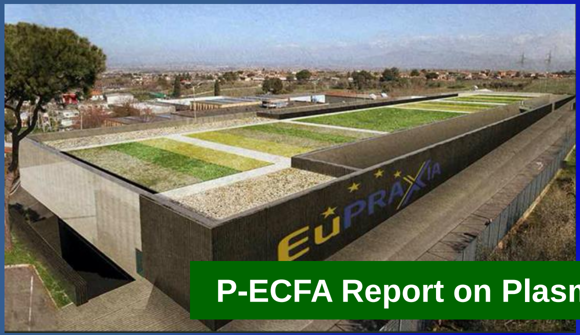
→ intelligent reconstruction using O(100) hits & NN can improve "poor" single cell timing

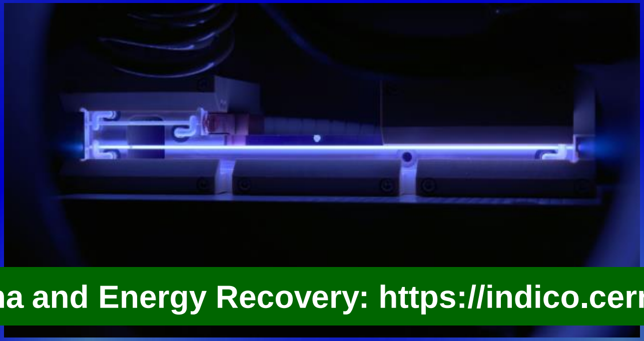
→ can help to distinguish particle types:
usable for flavour tagging (b/c/s),
long-lived searches (decaying to neutrals) ,
enhance σ(E) / E

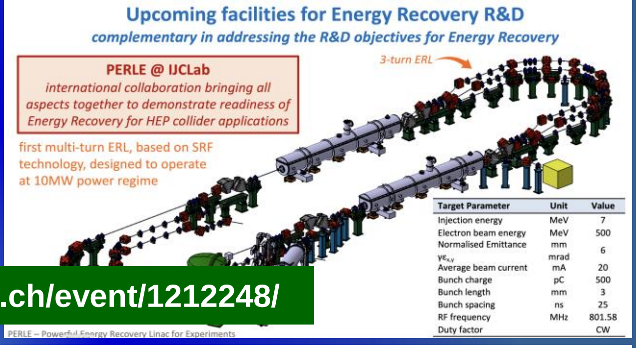
CMS HGCAL has measured **evoluton of hadronic showers in the time domain** with ~80ps accuracy (50ps TDC binning)

Energy Recovery and Plasma Acceleration

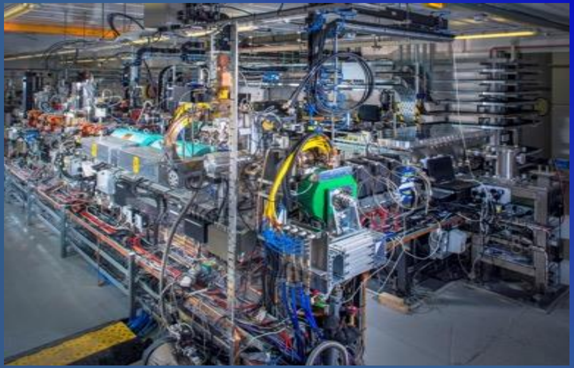
Project concepts exists and need to be further advanced. Practical work concentrated on smaller facilities (e.g. PEARL, bERLinPro, EUPRAXIA and many others (Flashforward, CLARA, AWAKE, etc), use of plasma acceleration for injectors, in many cases outside particle physics).







P-ECFA Report on Plasma and Energy Recovery: https://indico.cern.ch/event/1212248/



A Hybrid Asymmetic Linear Higgs Factory (HALHF)

arXiv: 2303.10150

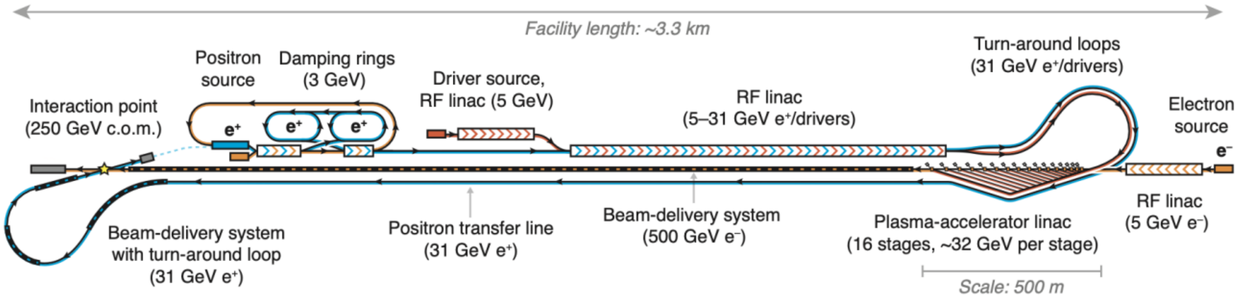
A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration

B. Foster,[1,*] R. D'Arcy,[2] and C. A. Lindstrøm[3]

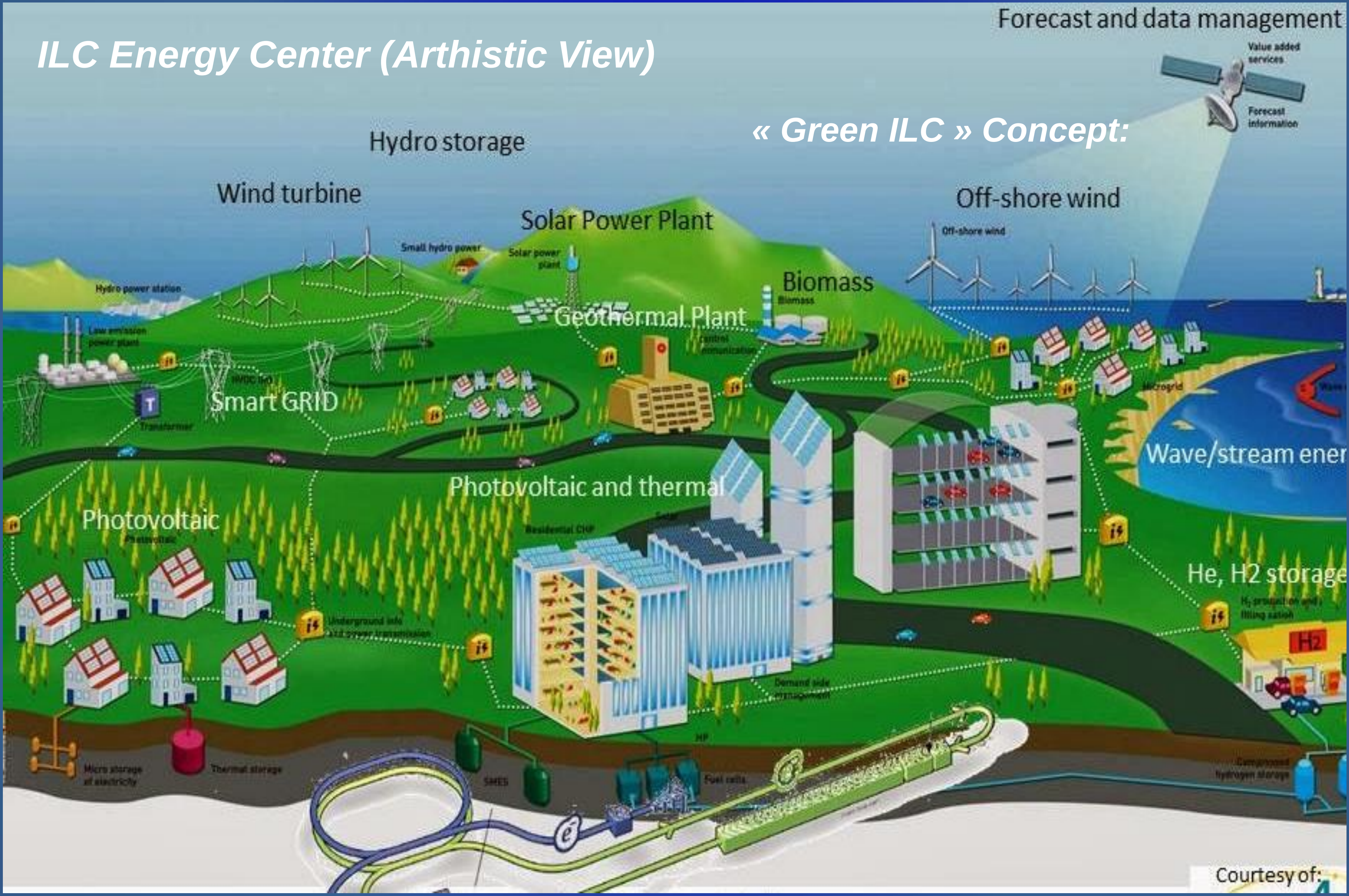
[1] *John Adams Institute for Accelerator Science at University of Oxford, Oxford, UK*
[2] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*
[3] *Department of Physics, University of Oslo, Oslo, Norway*

(Dated: March 17, 2023)

The construction of an electron–positron collider "Higgs factory" has been stalled for a decade, not because of feasibility but because of the cost of conventional radio-frequency (RF) acceleration. Plasma-wakefield acceleration promises to alleviate this problem via significant cost reduction based on its orders-of-magnitude higher accelerating gradients. However, plasma-based acceleration of positrons is much more difficult than for electrons. We propose a collider scheme that avoids positron acceleration in plasma, using a mixture of beam-driven plasma-wakefield acceleration to high energy for the electrons and conventional RF acceleration to low energy for the positrons. We emphasise the benefits of asymmetric energies, asymmetric bunch charges and asymmetric transverse emittances. The implications for luminosity and experimentation at such an asymmetric facility are explored and found to be comparable to conventional facilities; the cost is found to be much lower.



ILC / CLIC Accelerators – Power, Energy and Sustainability



Power and Energy

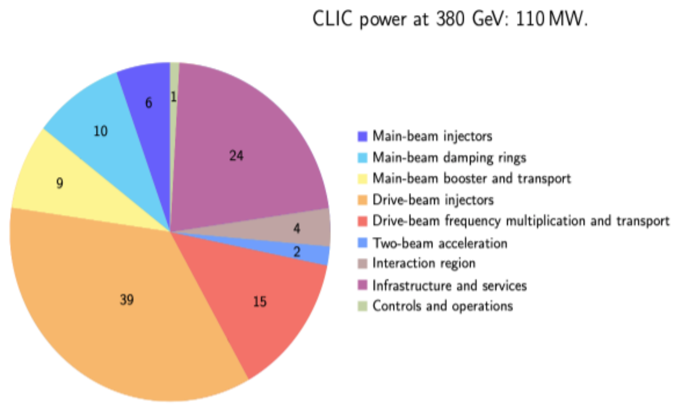


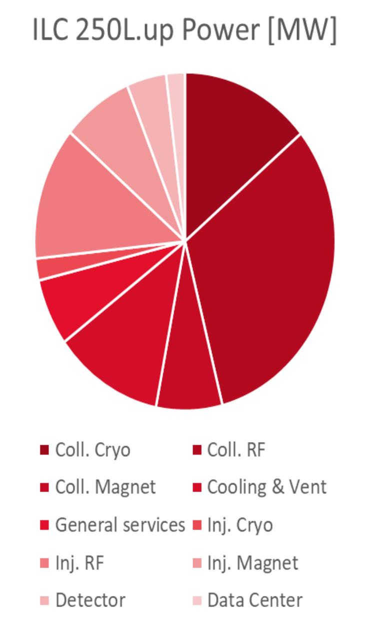
Fig. 4.8: Breakdown of power consumption between different domains of the CLIC accelerator in MW at a centre-of-mass energy of 380 GeV. The contributions add up to a total of 110 MW. (image credit: CLIC)

Table 4.2: Estimated power consumption of CLIC at the three centre-of-mass energy stages and for different operation modes. The 380 GeV numbers are for the drive-beam option and have been updated as described in Section 4.4, whereas the estimates for the higher energy stages are from [57].

Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	110	25	9
1500	364	38	13
3000	589	46	17

ILC (250 GeV) and Lumi Upgrade

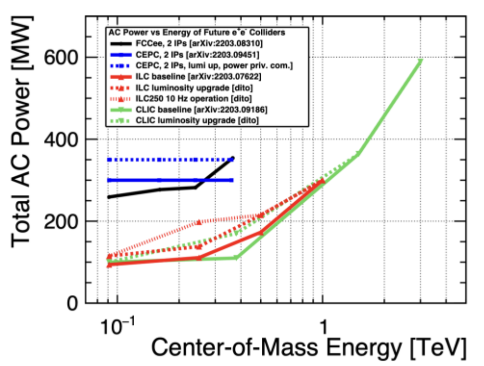
	ILC 250L.up	(ILC250)	(TDR)
Coll. Cryo	**18.7**	17.8	32.4
Coll. RF	**42.8**	29.2	56.9
Coll. Magnet	**9.5**	9.5	12.6
Cooling & Vent	**15.7**	13.1	19.9
General services	**8.6**	8.8	13.4
Inj. Cryo	**2.8**	2.8	2.8
Inj. RF	**17.1**	10.0	11.3
Inj. Magnet	**10.1**	8.6	8.6
Detector	**5.7**	5.7	5.7
Data Center	**2.7**	2.7	-
Margin (3%)	**4.0**	3.3	-
Total [MW]	**138**	111	164

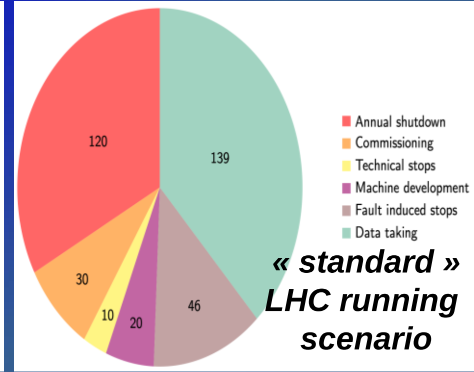


Power estimate bottom up (concentrating on CLIC (380 GeV):

- *Very large reductions since the CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies*
- *1.5 TeV and 3 TeV numbers still from the CDR (but included in the reports), to be re-done the next ~2 years*
- *Savings of high efficiency klystrons, DR RF redesign or permanent magnets not included at this stage, so numbers will be reduced*

With standard running scenario every 100MW corresponds to ~ 0.6 TWh annually; corresponding to ~85 MCHF annually





« standard » LHC running scenario

S. Stapnes

Power Optimization – CLIC Example

- ***Design Optimisation:***

All projects aim to optimize – most often energy reach, luminosities and cost. Power is becoming at least as important, maybe even compromising ultimate performance for power saving

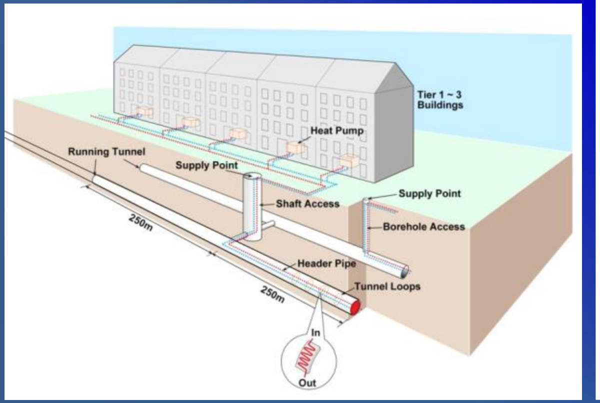
- ***Technical Developments:***

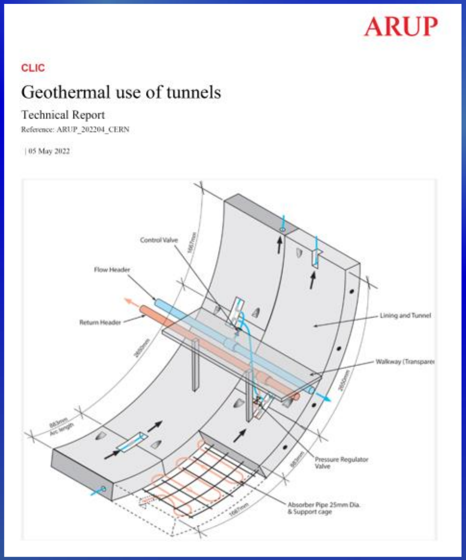
Technical developments targeting reduced power consumptions at system level high efficiency klystrons and RF systems generally, RF cavity design and optimisation (treatment of bulk Nb, thin film SRF, beyond bulk niobium), magnets (traditional SC and HTS including cryo, and also permanents magnets):

- ***Heat recovery:***

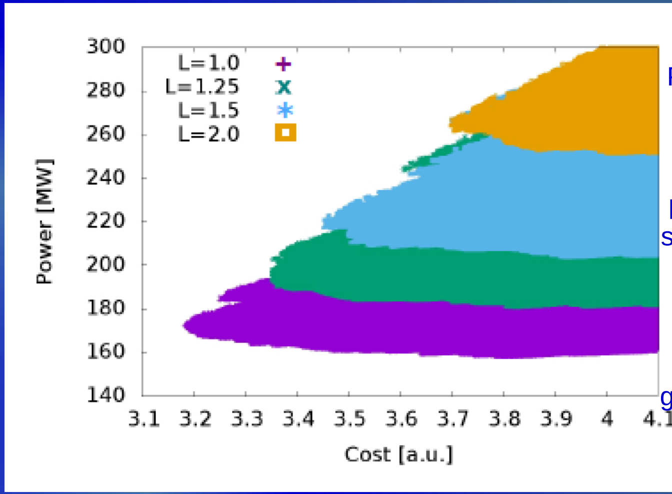
- Already implemented & LHC P8

- Tunnel hear recovery study by ARUP in 2022



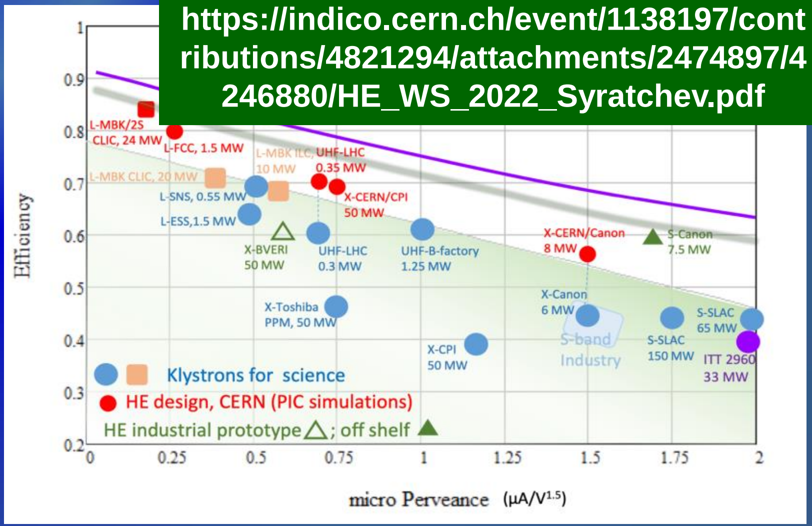


The designs of CLIC (drive-beam), including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost and power



Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum

Efficiency performance of the selected commercial klystrons and the new HE klystrons.

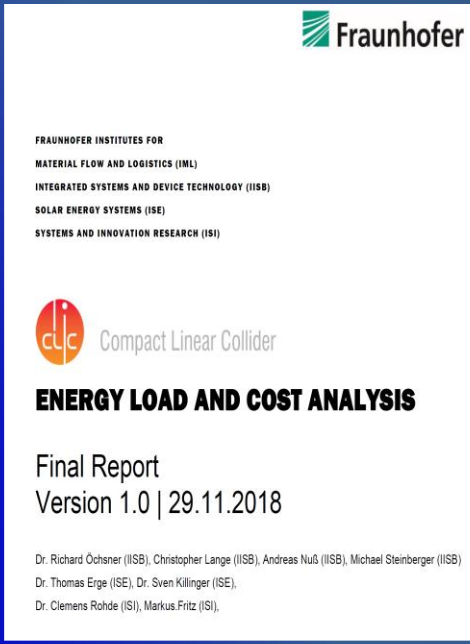


https://indico.cern.ch/event/1138197/contributions/4821294/attachments/2474897/4246880/HE_WS_2022_Syratchev.pdf

Power Modulation - Running on Renewables

Studies in 2017:

- *Supply the annual electricity demand of CLIC (380Gev) by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators) at a cost of slightly more than 10% of the CLIC*
- *Study done for 200 MW, in reality only ~110 MW are needed*
- *Self-sufficiency during all times can not be reached but 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.*
- *Can one run an accelerator as CLIC in a mode where one turn “on” and “off” depending prices (fluctuating with weather?)*
- *Flexibility to adjust the power demand is expected to become increasingly important and in demand by energy companies*


Fraunhofer

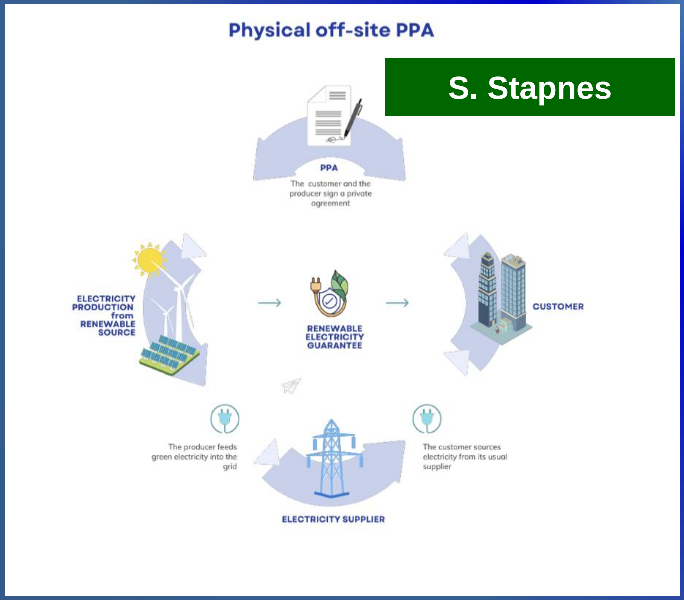
FRAUNHOFER INSTITUTES FOR
MATERIAL FLOW AND LOGISTICS (IML)
INTEGRATED SYSTEMS AND DEVICE TECHNOLOGY (IISB)
SOLAR ENERGY SYSTEMS (ISE)
SYSTEMS AND INNOVATION RESEARCH (ISI)

Compact Linear Collider

ENERGY LOAD AND COST ANALYSIS

Final Report
Version 1.0 | 29.11.2018

Dr. Richard Öchsner (IISB), Christopher Lange (IISB), Andreas Nuß (IISB), Michael Steinberger (IISB)
Dr. Thomas Erge (ISE), Dr. Sven Killinger (ISE),
Dr. Clemens Rohde (ISI), Markus Fritz (ISI),



A real implementation of renewable energy supply:

- ✓ A physical power purchase agreement (PPA) is a long-term contract for the supply of electricity at a defined, fixed price at the start and then indexed every year, and a consumer for a defined period (generally 20 years). Being considered for CERN, initially at limited scale. Advantages: price, price stability, green, renewable.
- ✓ Nuclear energy remains very important, on the timescale of a future CERN facility
- ✓ *Must be a goal to run future accelerator at CERN primarily on green and more renewable energy with very low carbon footprint. However, energy costs will remain a concern (two slides back).*

"Green ILC" and Carbon Neutrality

Although SRF has been adopted, the AC power consumption of ILC Main Linac is < 50%, of the total of 110 MW (250 GeV ILC)

- ***"Green ILC":* Past efforts include increasing the efficiency of accelerators (SC, klystron) https://green-ilc.in2p3.fr/documents/**
- ***Carbon neutrality:* Common challenge for all future HEP accelerators.**

Proceedings of the 17th Annual Meeting of Particle Accelerator Society of Japan
September 2 - 4, 2020, Online

PASJ2020 WEPP57

STUDY ON A SUSTAINABLE ENERGY MANAGEMENT SYSTEM FOR THE ILC

Masakazu Yoshioka [#, A, B, C], Tohru Kano[B], Shinya Narita[C], Hisashi Odaira[D], Sadayoshi Hirai[E], Yasuo Kawabata[F], Junji Sawai[G]
[A] Tohoku University
[B] Iwate Prefectural University
[C] Iwate University
[D] Iwate Prefectural Office
[E] NTT FACILITIES, INC., Solution Business Department, Tohoku Branch,
[F] TOBISHIMA CORPORATION, Civil Engineering Division
[G] Sumitomo Mitsu Construction Co.,Ltd. Civil Engineering Division

Masakazu Yoshioka

Proceedings of the 19th Annual Meeting of Particle Accelerator Society of Japan
October 18 - 21, 2022, Online (Kyushu University)

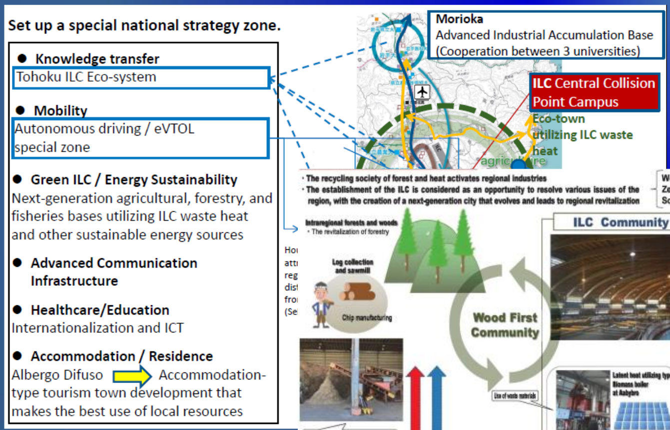
PASJ2022 WEOB05

STUDY ON SUSTAINABLE ENERGY MANAGEMENT SYSTEM IN ILC, PART-II

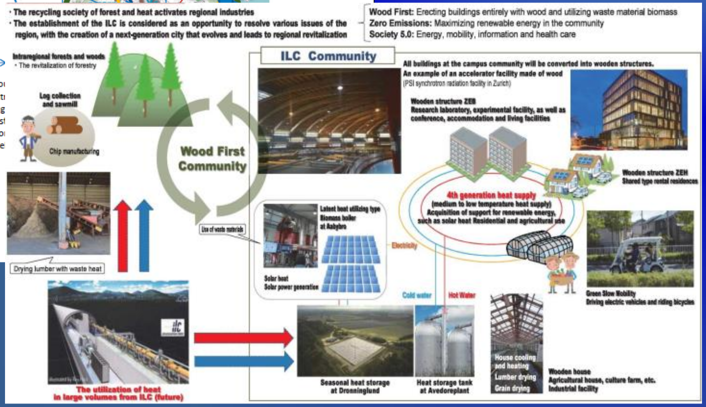
M. Yoshioka†, Iwate University, Morioka, Japan and Iwate Prefectural University, Takizawa, Japan
T. Kano, Iwate Prefectural University, Takizawa, Japan
S. Narita, Iwate University, Morioka, Japan
H. Odaira, Iwate Prefectural Office
S. Hirai and R. Ueda, NTT FACILITIES, INC., Solution Business Department, Tohoku Branch
Y. Kawabata, TOBISHIMA CORPORATION, Civil Engineering Division
J. Sawai, Sumitomo Mitsu Construction Co., Ltd. Civil Engineering Division

Next generation town development for ILC operation

ILC Central Collision Point → Eco-Campus Concept



ILC Link with Region → Wood first, Zero emissions, …



ILC Workshop on Potential Experiments (ILCX2021)

ILCX2021 ILC Workshop on Potential Experiments

Basic policy of Green ILC activities at Kitakami ILC candidate site

Masakazu Yoshioka (Iwate/Iwate Prefectural/Tohoku University)
Green ILC Session, Oct. 28, 2021

Content

Carbon neutrality by 2050 is one of the most urgent issues in the world, and the ILC aiming to start operation in 2035 should be in line with this global policy. The basic policy of Green ILC activities is not to achieve carbon neutrality within the ILC facility, but to achieve carbon neutrality in the region where the ILC is located. The key to achieving this goal is to cooperate with local companies and municipalities in three areas: (1) developing energy-saving technologies, (2) increasing the ratio of renewable energy, and (3) improving the CO2 absorption rate. The industrial aspect will prevail in (1) and (2), but there is no choice but to rely on forests for (3). The area of the candidate site has a high percentage of forest, and therefore high potential, so the construction of ILC-related facilities should be in line with forest industry management that maximizes CO2 absorption.

AAA talk @ ILCX2021

LCWS2023 @SLAC: International Workshop Future Linear Colliders (May 15-19, 2023)

INDUSTRY PLENARY SESSION (May 16, afternoon):

- Introduction to Industry/Sustainability Session – Session Conveners
- Japan - AAA activity - Takahashi Tohru (Hiroshima Univ./AAA, Japan)
- US Office of accelerator R&D and Production (ARDAP) – Ginsburg Camille (Deputy Director of ARDAP, USA)
- Advances in Spanish Science Industry – Fernandez Erik (INEUSTAR, Spain)
- RadiaBeam experience of supporting the accelerator community - speaker tbd (Radiabeam, USA)
- Experience in parti[illegible] [illegible]ment of an [illegible] source as a company in the [illegible]hoku region - KONDO, Masahiko (Kondo Equipment Corporation, Japan)
- Development of Nb3Sn SRF cavity using electroplating method - TAKAHASHI, Ryo (Akita Chemical Industry Co., Ltd, Japan)

SUSTAINABILITY PLENARY SESSION (May 16, afternoon):

- Sustainability Studies for Future Linear Collider – Benno List (DESY, Germany)
- LC related high efficiency RF systems, status and prospects – Syratchev Igor (CERN)
- Green ILC Concept – Yoshioka Masakazu (Iwate University/KEK, Japan)
- Sustainability: Permanent Magnets – Shepherd Ben (STFC, UK)
- ARUP Study Report (Carbon Cost/ Life Cycle Assessment)
- [illegible] high power klystron development - Zusheng Zhou (IHEP, China)
- Basic research using synchrotron radiation and commercialization of waste heat recovery technology from ILC - Mitoya Goh (Higashi Nihon Kidenkaihatsu Co., Ltd., Japan)
- Town planning in the vicinity of ILC candidate site as a regional company - Kondo Masahiko (Kondo Equipment Corporation, Japan)

Linear Colliders «ENERGY and SUSTAINABILITY» Workshop in Tohoku /Japan will take place in Fall 2023

Sustainable Construction – Life-Cycle Assessment

For carbon mission, the construction impact will be much earlier and might be more significant (rare earths and many other issues)

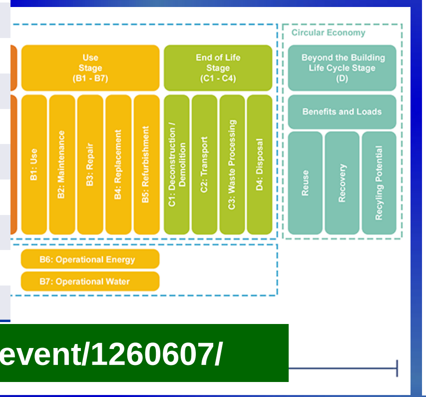
- *Construction: CE, materials, processing and assembly – not easy to calculate*
- *Markets will push for reduced carbon, responsible purchasing crucial (see right) – construction costs likely to increase*

Decommissioning – how do we estimate impacts ?

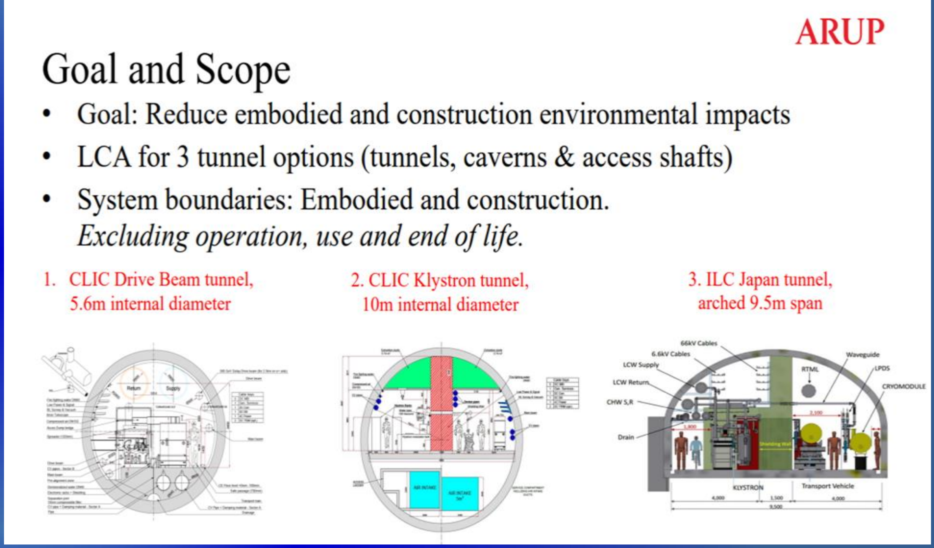
Responsable purchasing – and understnding the impact of supply chain, costs and potential for changes – will be essential for future projects

Carbon Cost/Life Cycle Assessment (ARUP study 2023)

Quantity	DB	Klys.
Inner Diameter [m]	5.6	10
Tunnel Cross Section [m^2]	25	79
Lining / Grouting [cm]	30 / 10	45 / 15
Concrete Area [m^2]	12.4	44.8
Lining & Floor Area [m^2]	8.2	19.7
Concrete per m [t/m]	31	129
Steel per m [t/m]	0.95	2.3
Concrete GWP [t CO2-eq/m]	3.1	12.9
Steel GWP [t CO2-eq/m]	1.6	3.8
Material GWP [t CO2-eq/m]	**5**	**17**
Total GWP (25% overhead)	**6**	**21**



B. List: https://indico.cern.ch/event/1260607/



Assume a small tunnel (~5.6m diameter) ***and*** *that the equipment in the tunnel has the same carbon footprint as the tunnel itself, a 20km accelerator (tunnel plus components) correspond to 240 kton CO2 equivalent*

S. Stapnes

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, etc etc*

Summary and Outlook

- ***CLIC and ILC are two mature designs for an e+e- Higgs Factory based on Linear Collider technology***
- ***Both concepts can be extended in energy to study tth production and the Higgs self coupling in double Higgs production at energies of 500 GeV and beyond***:

  → *CLIC energy upgrades to 1.5 and 3 TeV*

  → *ILC upgrades to 500 GeV and 1TeV*
- ***In baseline configuration, both use 110MW electric power (similar to LHC)***

  → *Flexible operation (power modulation) is a strength of linear colliders*
- ***R&D programs for the next 3-4 years are defined***

  → *CLIC: focus on X-band and nanobeam technology, prepare for next European Strategy update*

  → *ILC: focus on time critical items (esp. SRF, positron source concept) parallel to inter-governmental discussions towards an international project*

  → *Both: continue luminosity optimisation: ATF3*
- ***Sustainability studies are important and will be extended***

Special thanks to:

Benno List, Steinar Stapnes

and all the colleagues from the CLIC and ILC collaborations