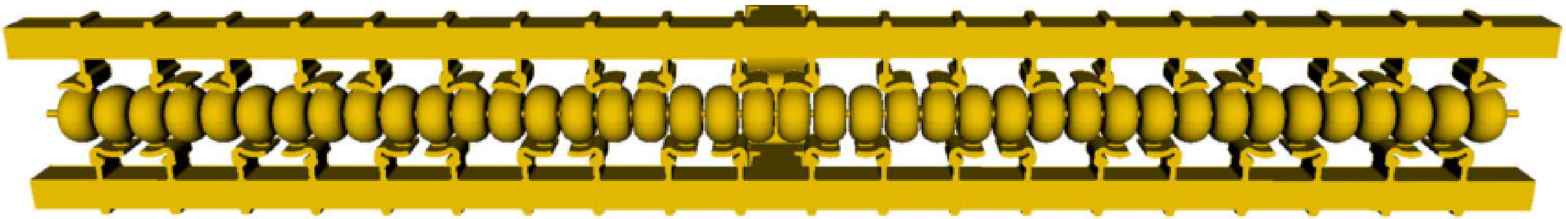
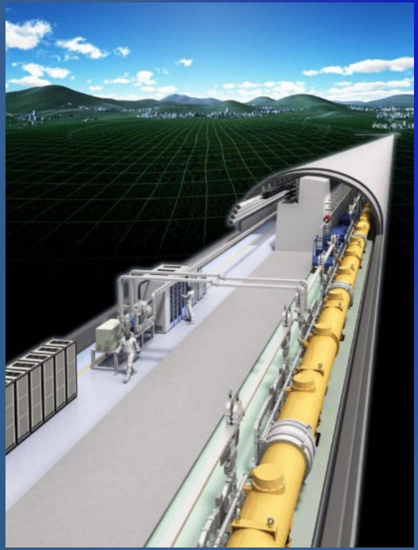
Cold Copper Accelerator Technology and Applications Workshop

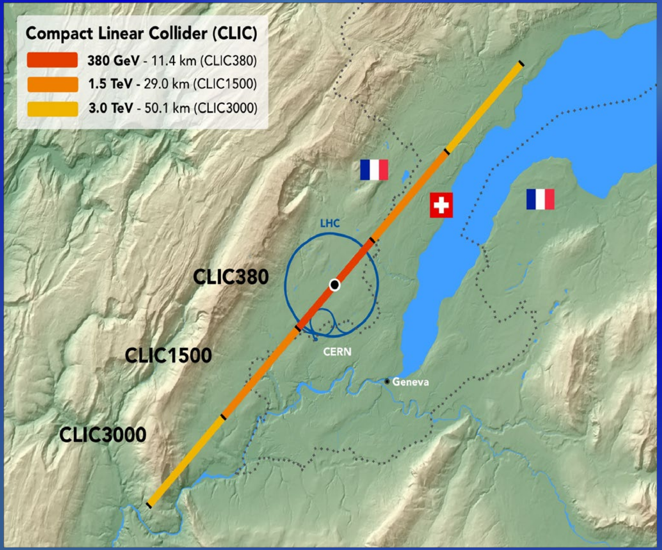


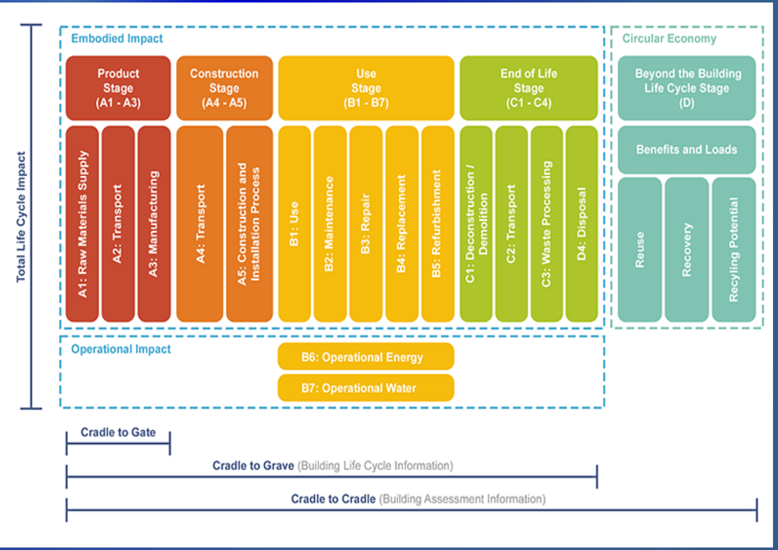
Cornell University, August 31 – September 1, 2023

Sustainability Studies for Future Linear Colliders & Life-Cycle Assessment

Maxim Titov, CEA Saclay / CERN







ILC / CLIC: Approaches to Increase Sustainability

✓ **Resource optimization traditionally done for accelerators:**

- *Length/complexity -> construction cost*
- *Power/energy consumption -> operating costs*

Traditionally we optimize for energy reach and luminosity wrt to cost and power

✓ **Sustainability in a wider sense adds new construction and operation optimization criteria:**

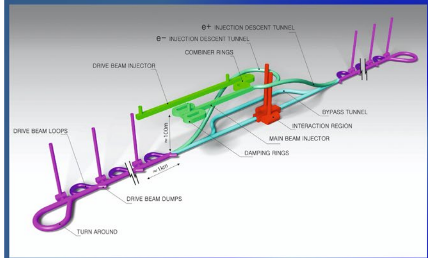
- *Energy use not only costs but also embedded CO_2 in construction materials and components, rare earth usage → responsible sourcing in general for all parts, landscaping, integration in local communities, life cycle assessments including decommission and many more issues*

- ***Overall system design***
  - ***Compact accelerator***
    → high gradient; high field magnets
  - ***Energy efficient***
    → low losses (wall-plug to beam)
  - ***Effective***
    → nm-beam sizes to maximize luminosity
  - ***Energy recovery concepts***
  - ***Civil engineering including landscaping and « community » integration***
- ***Subsystem and component design, e.g.***
  - ***High-efficiency cavities and klystrons***
  - ***Permanent magnets, HTS magnets***
  - ***Heat-recovery. e.g. in tunnel linings***
  - ***Responsible sourcing and material choices***
- ***Sustainable operation concepts***
  - ***Renewables***
  - ***Adapt to regenerative power availability***
  - ***Exploit energy buffering potential***
  - ***Recover energy (heat recovery)***

Good progress on the green points (was also part of the our radiational approach), initial progress/focus on the yellow / black ones

ILC / CLIC: Overall Resource Efficiency Considerations

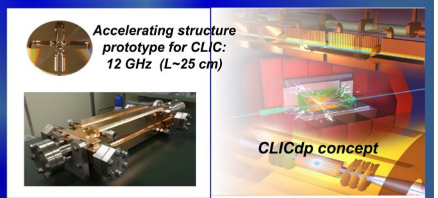
The Compact Linear Collider (CLIC)



- **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

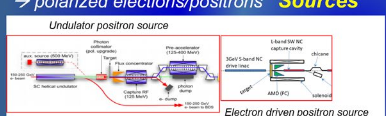


- **Accelerator Cost:** 5.9 BCHF for 380 GeV
- **Power/Energy:** 110 MW at 380 GeV (~0.6 TWh annually), corresponding to 50% of CERN's energy consumpt. today
- Comprehensive **Detector and Physics** studies

The ILC (250 GeV) Accelerator:

ITN focus areas (>2023):

- *Creating particles* → *polarized elections/positrons* — ***Sources***



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

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

Challenge: Achieve target **energy** and **luminosity** with least possible amount of **resources**

✓ ***Optimize resources for construction/operation:***

- Compact: high acceleration gradient
- Energy-efficiency: RF efficiency becomes increasingly important for higher energies
  - ILC: superconducting RF
  - CLIC: high frequency & ultra-short pulses
- Effectiveness: maximize luminosity / beam power → nanobeams technology

✓ ***ILC (250 GeV) and CLIC (380 GeV):***

- Different solutions to the efficiency problem → final power consumption similar (~100 MW)

✓ ***Embodied CO_2: proportional to facility length***

- Efficient RF systems, luminosities optimization vs. beam power for stability, alignment, instrumentation for nano-beams, etc …
- Embodied carbon addressed by reducing length of installation and tunnel diameter

On-going CLIC Studies Towards next European Strategy Update

Project Readiness Report as a step toward a TDR

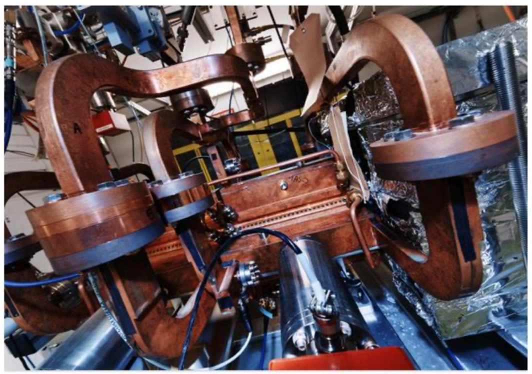
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030

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

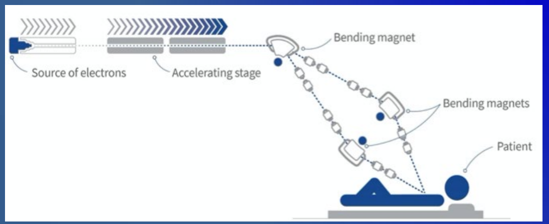
CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

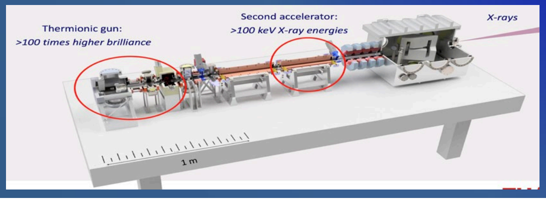
CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

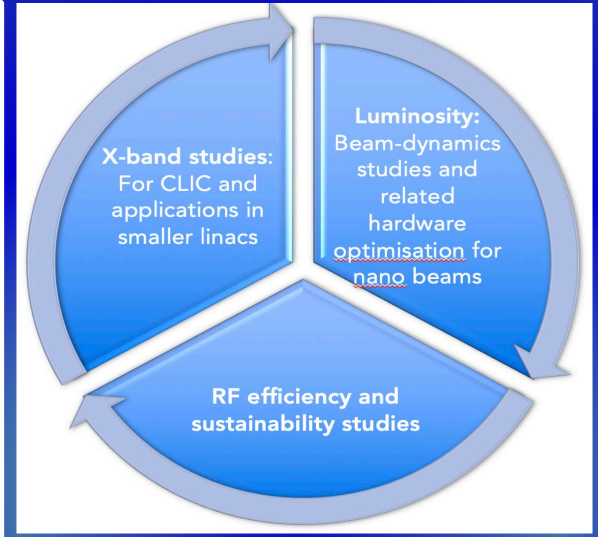
15 SEPTEMBER, 2020



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/

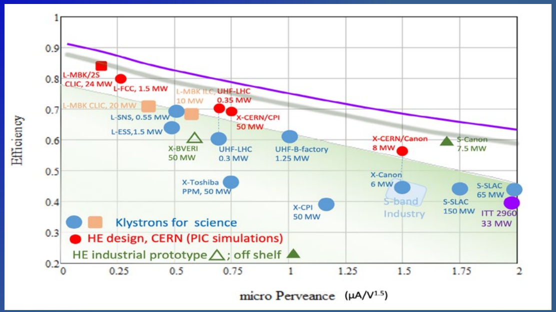
Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue:

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

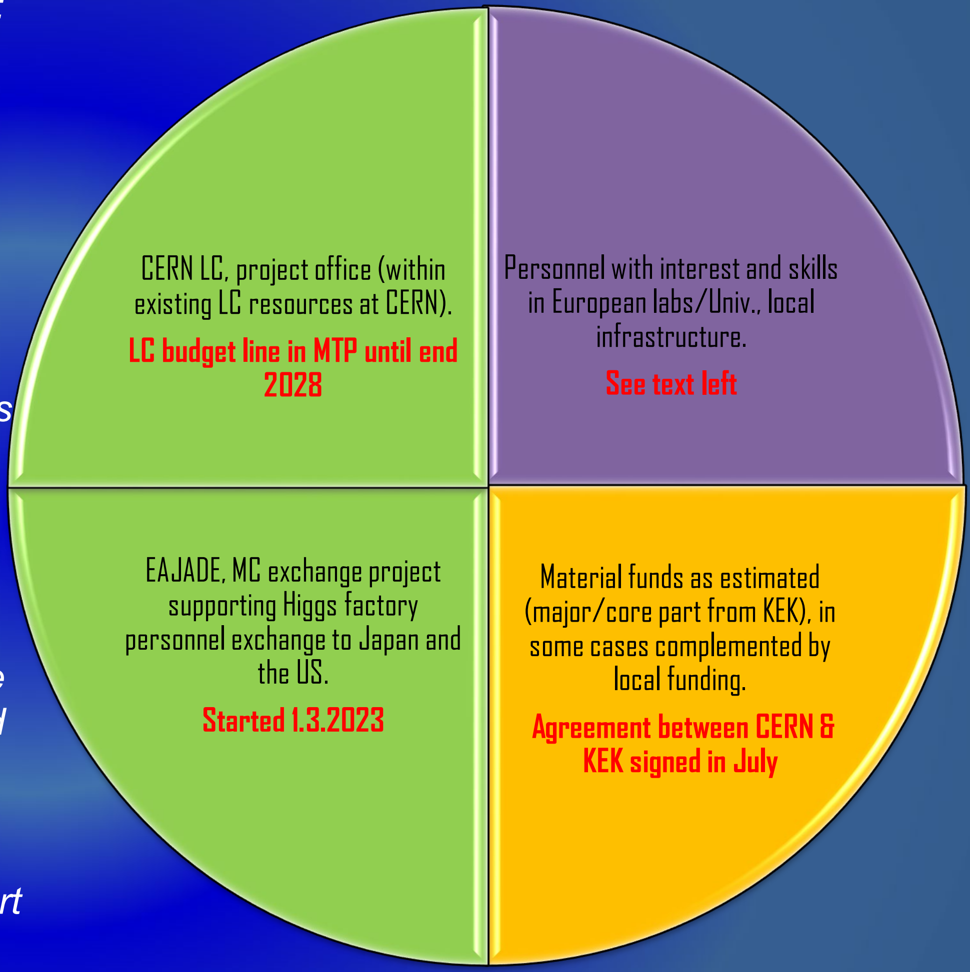


ILC Technology Network (ITN) – European Focus Areas

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

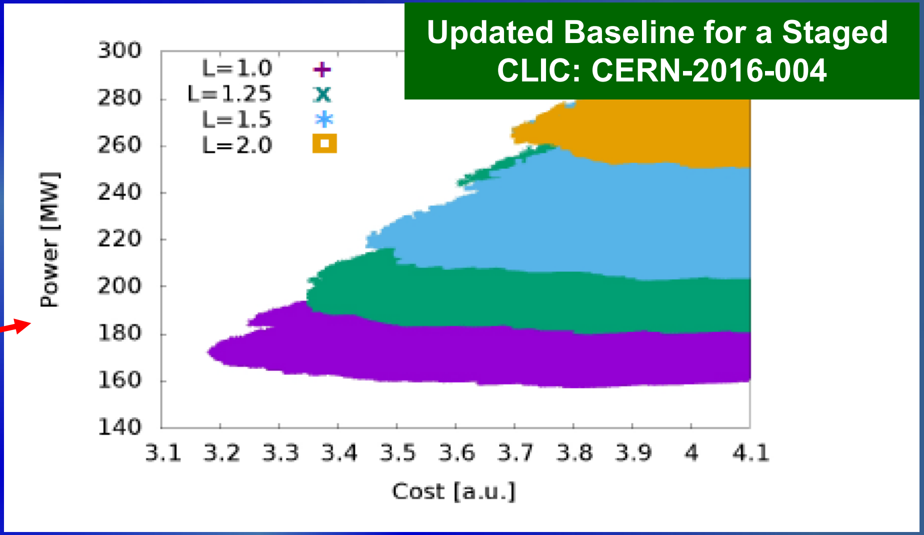
ILC / CLIC: Overall System Design & Optimization

Usually, projects optimize – energy reach, luminosity and cost. Power becomes increasingly important; solutions exist compromising ultimate performance for power consumption & savings

- ***Design Optimization for CLIC:***

CLIC designs (drive-beam), including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost, but also focusing on power consumption (in parallel: re-design and optimisation of RF systems, e.g. damping rings and drive-beam)

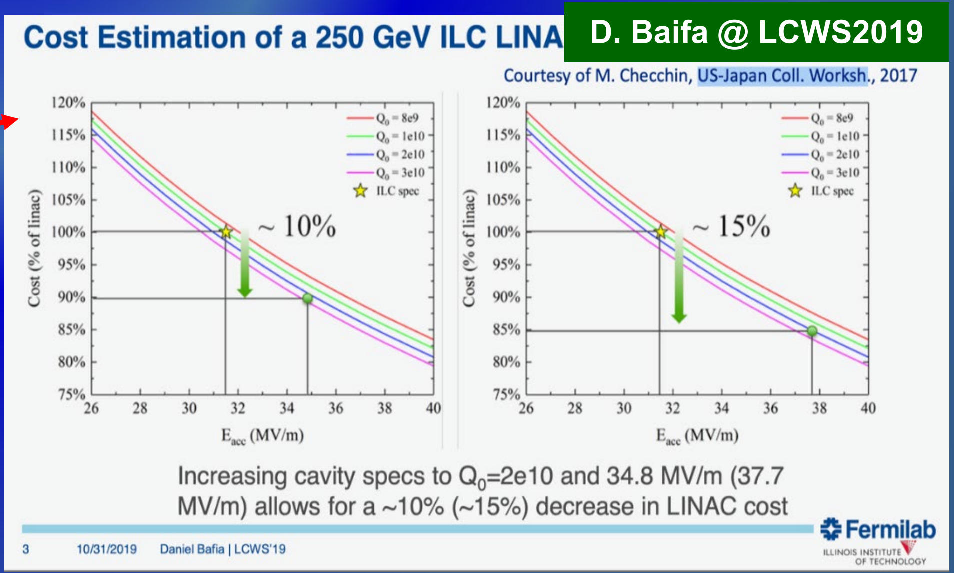
E.g. Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum (2015)



- ***Design Optimization for ILC:***

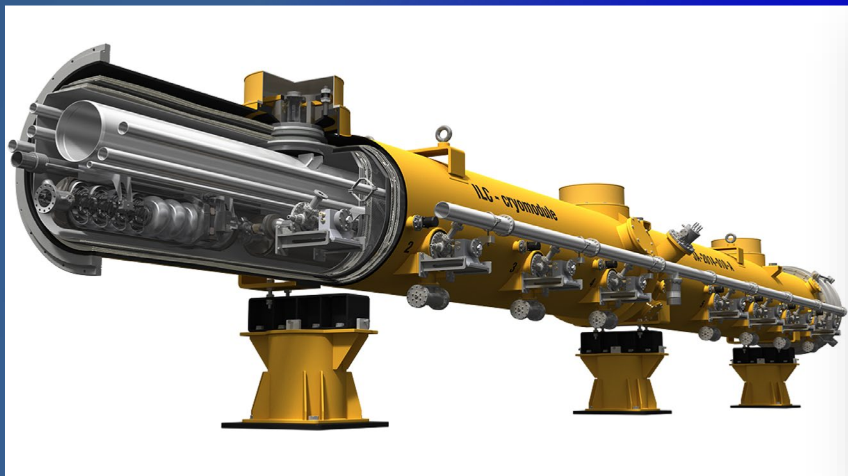
ILC design optimization have been, focusing on parameters choices, for example repetition rates, pulse-lengths, cryo and RF systems for various luminosity choices

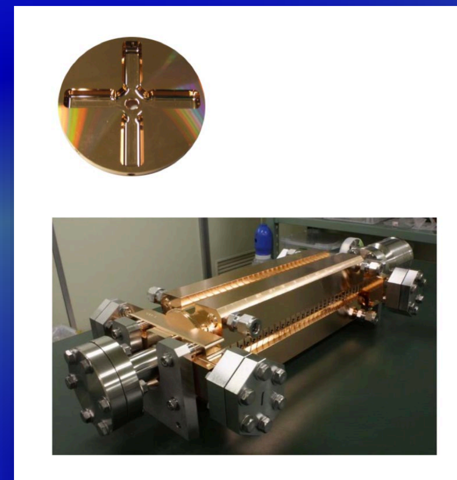
E.g. higher E_{acc} means lower invest in cavities/cryomodules, but larger invest in RF/cryogenics (losses per length scale as E_{acc}^2)



***For both ILC / CLIC,** it would be interesting to repeat studies, focusing more strongly on power consumption, and including exercise with CO_2 (e.g. weigh the savings in embodied CO_2 vs the expense of CO_2 through operation…)*

Approaches to Increase Sustainability: Optimization of Subsystems and Components





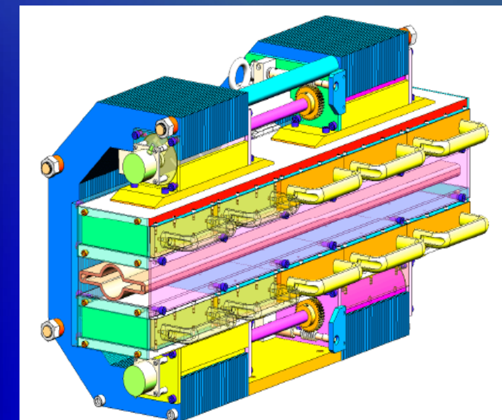
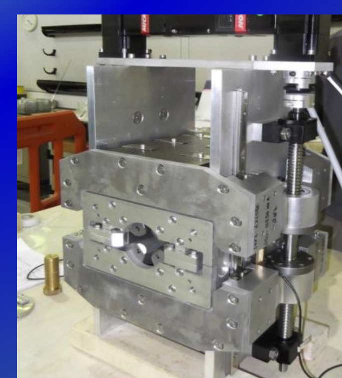
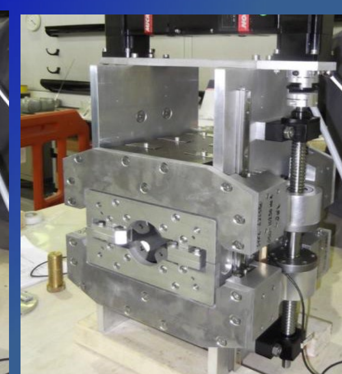


Figure 3: Overview of possible design of PM dipole for ILC damping ring.





R&D for Improved ILC SRF Performance & Sustainability

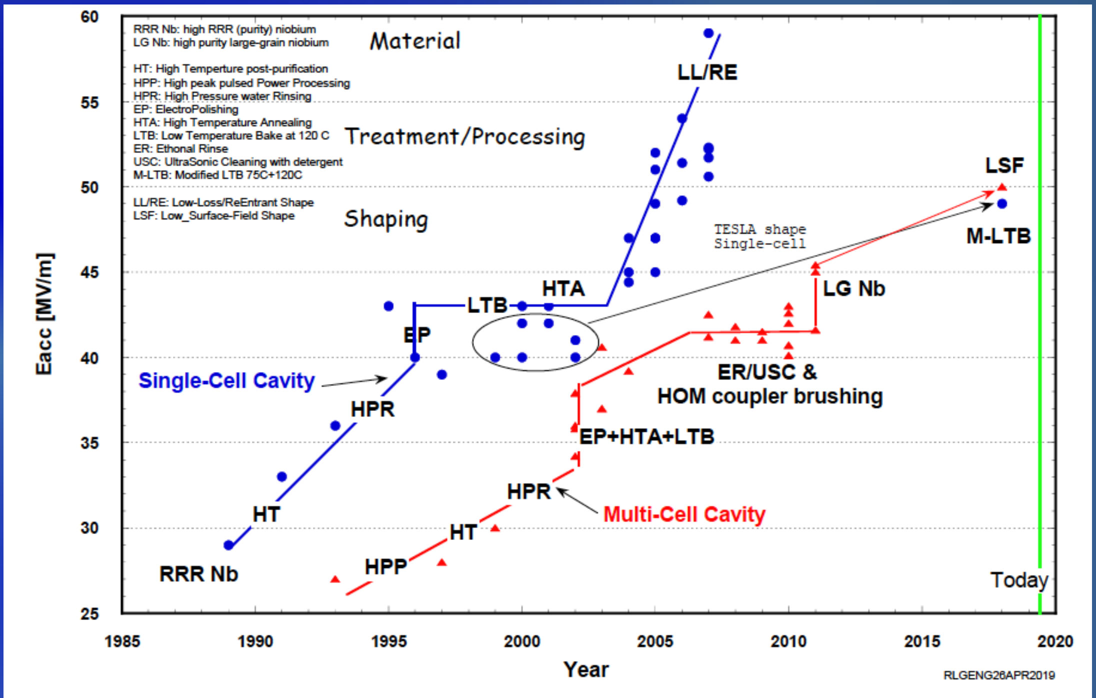
Major progress during past 10 years:

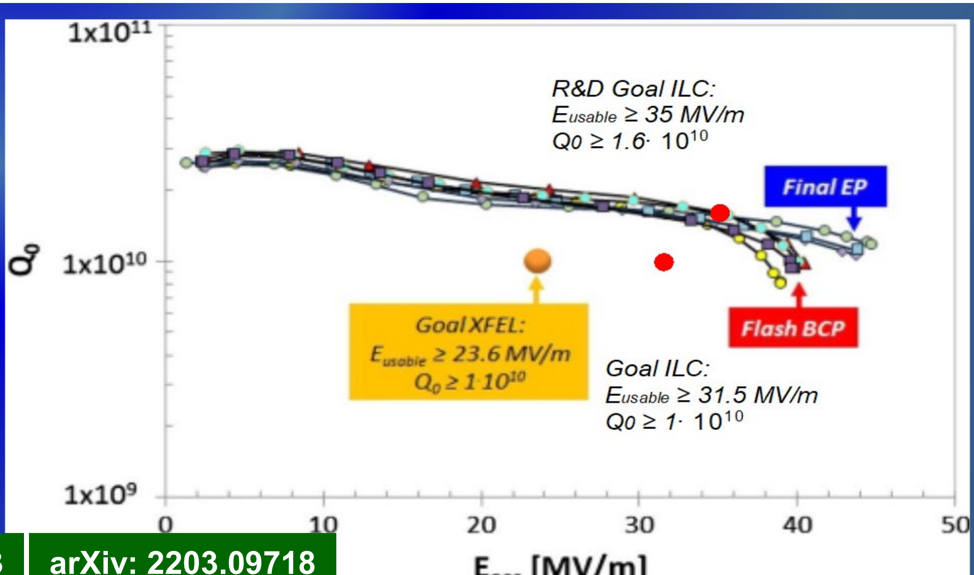
- *bulk niobium (1.3 GHz as ILC & FEL linacs), improvements in gradient, processing steps; surface treatment, cavity shapes; power efficiency (Q_0) always an integrated part of studies*

  - *Raise Gradient:*
    Short term goal: 31.5MV/m -> 35MV/m
    Medium term goal: 45MV/m
    Lab record: 59MV/m
  - *Improve Q_0: reduce cryogenic losses*
    (1W @ 2K requires ~750W AC power!)
    Short term goal: 1E10 -> 2E10

- *State-of-the-art surface treatment of bulk Nb: baking/annealing/doping, plasma processing (possibly reducing aggressive chemicals, required for electropolishing)*

- *R&D into replacement of bulk niobium cavities with Nb or Nb3Sn coated copper (beyond bulk Nb – thin-film SRF): reduce Nb consumption, increase performance*





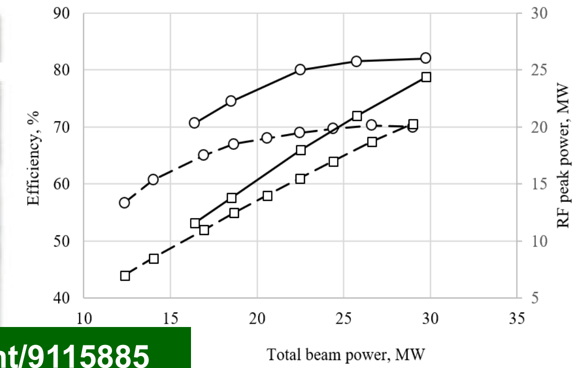
C. Antoine talk @IPAC2023 | arXiv: 2203.09718

High Efficiency (L-Band, X-Band) Klystron Project at CERN

Accelerators technology could require RF signals in a wide range of the frequencies (few 100 MHz – 12 GHz), peak power levels (few 100 kW – 100 MW) and pulse lengths (CW -100ns). The klystron amplifiers technology is the one that covers almost all RF frequency/power demands of the modern accelerators.

High Efficiency implementations:

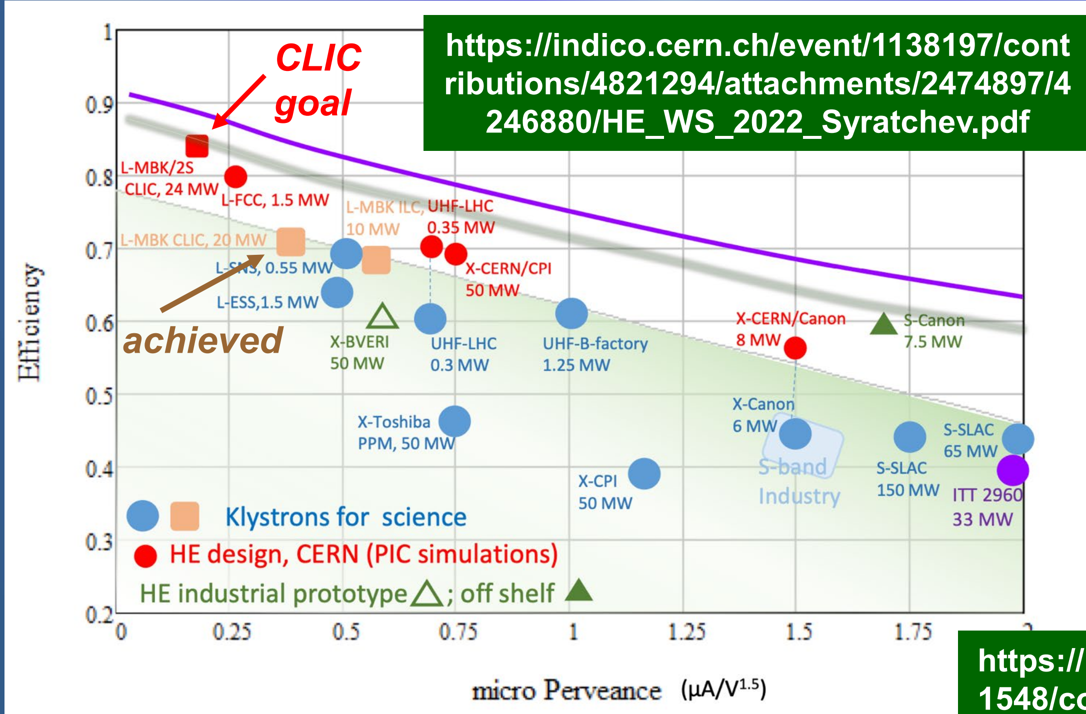
- New small X-band klystron – recent successful prototype
- Large X-band with CPI
- L-band two stage, design done, prototype desirable



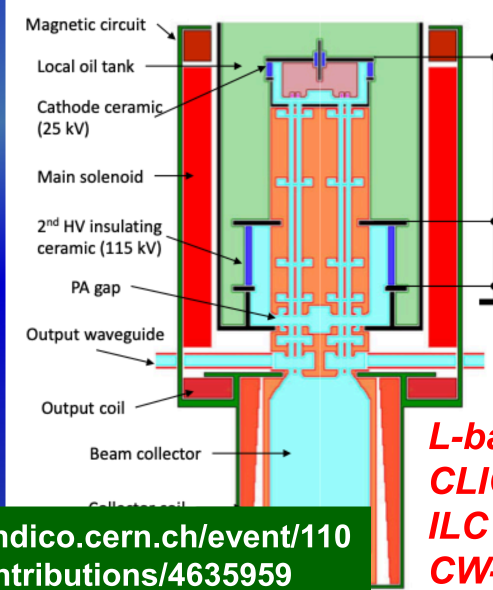
https://ieeexplore.ieee.org/document/9115885

Drivebeam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs beam power.

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



High efficiency: 24MW, CLIC TS MBK

L-band klystron CLIC (1 GHz), ILC (1.3 GHz) CW-FCC (600 MHz)

https://indico.cern.ch/event/1101548/contributions/4635959

R&D for Permanent Magnets (also important for Higgs Factories)

1.5 TeV CLIC power
Magnets second largest

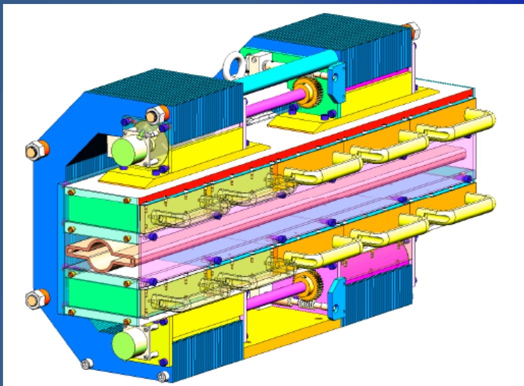
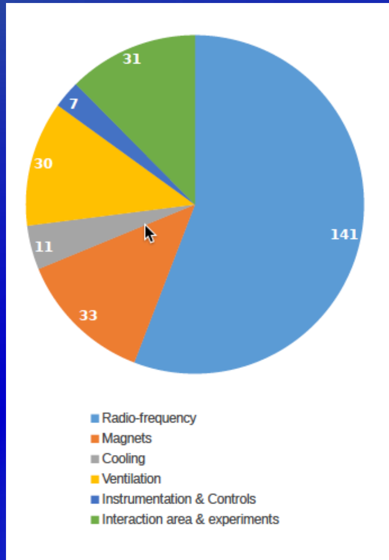
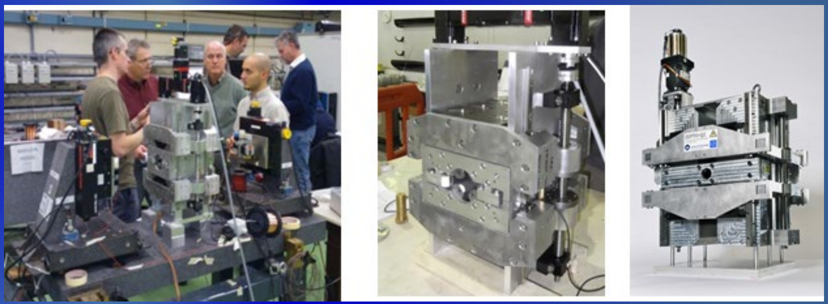


Figure 3: Overview of possible design of PM dipole for ILC damping ring.



- ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory to save power and costs by switching from resistive electromagnets to permanent magnets
- For CLIC the dominant power is in the drive-beam quadrupoles, successfully prototyped & tested as permanent (two different strengths) magnets, and also dipoles (in drivebeam turn arounds)

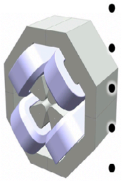


ZEPTO: comparing carbon footprints

- Electromagnetic quadrupole
- Main materials: steel, copper
- Manufacture impacts

CO_2 | steel 201kg | copper 52kg

- Operation costs
  - 856W at 100% excitation
  - Another 250W for cooling
  - Assume 251 days / year operation
  - 6.7 MWh / year
  - EU avg intensity 225 gCO2e/kWh



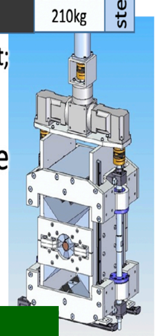
CO_2 | electricity 1160 $kgCO_2e$ / year | cooling 340 $kgCO_2e$ / year

- Permanent magnet quadrupole
- Main materials: steel, NdFeB, aluminium
- Manufacture impacts ($kgCO_2e$)

CO_2 | NdFeB 1097kg | aluminium 210kg | steel 91kg

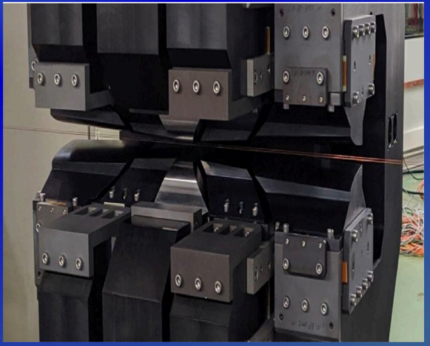
(big uncertainties in NdFeB footprint; using recycled magnets could significantly reduce it)

- Operation costs: negligible
- “Carbon payback”: 1 year



Ben Shepherd, ESSRI Workshop 2022, https://indico.esrf.fr/event/2/contributions/108/

- **Longitudinal gradient dipole magnet for the CLIC DR (CIEMAT)**



HTS magnets might be of interest in Higgs factories to reduce power consumption (CIEAMT/ILC: HTS; N3Ti magnets for ILC main quadrupoles for)

Power and Energy

Focus on CLIC (380 GeV) *← Power Estimate →* *ILC (250 GeV) & Lumi Upgrade*

CLIC power at 380 GeV: 110 MW.

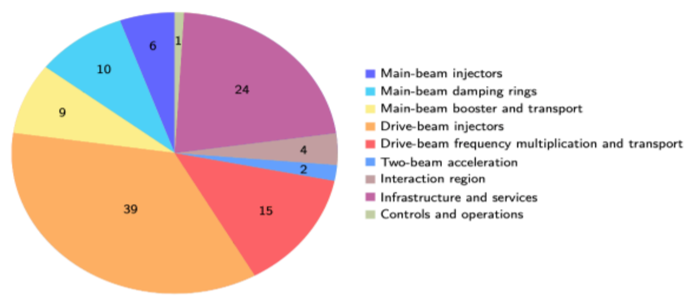
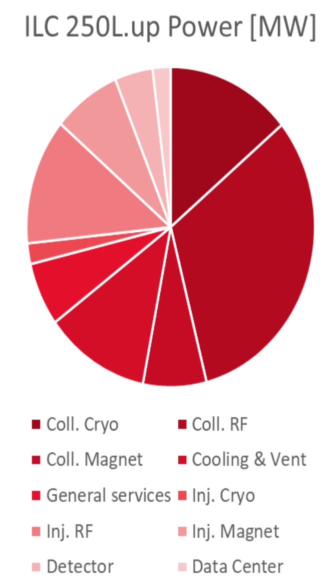


Fig. 4.8: Breakdown of power consumption between different domains of the CLIC accelerator in MW at a centre-of-mass energy of 380 GeV. The contributions add up to a total of 110 MW. (image credit: CLIC)

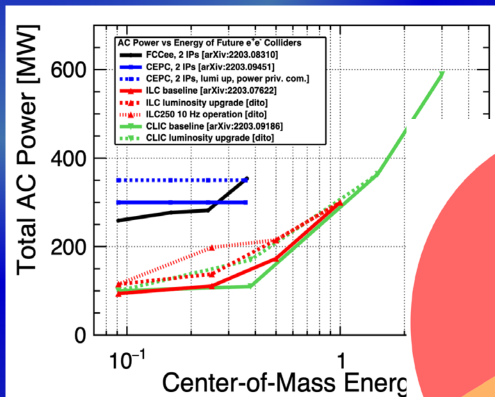
Table 4.2: Estimated power consumption of CLIC at the three centre-of-mass energy stages and for different operation modes. The 380 GeV numbers are for the drive-beam option and have been updated as described in Section 4.4, whereas the estimates for the higher energy stages are from [57].

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

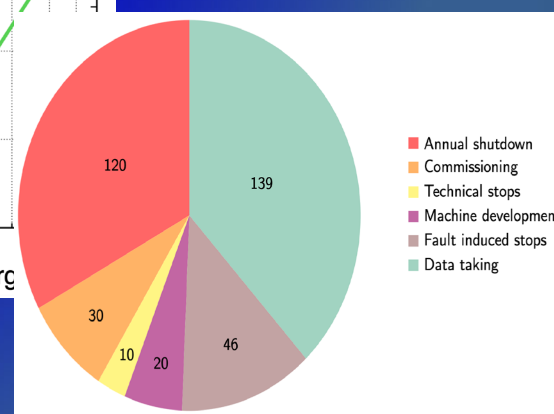
	ILC 250L.up	(ILC250)	(TDR)
Coll. Cryo	**18.7**	17.8	32.4
Coll. RF	**42.8**	29.2	56.9
Coll. Magnet	**9.5**	9.5	12.6
Cooling & Vent	**15.7**	13.1	19.9
General services	**8.6**	8.8	13.4
Inj. Cryo	**2.8**	2.8	2.8
Inj. RF	**17.1**	10.0	11.3
Inj. Magnet	**10.1**	8.6	8.6
Detector	**5.7**	5.7	5.7
Data Center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



- *Very large reductions in power estimate (380 GeV) 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*



«Standard» LHC running scenario



With standard running scenario every 100MW corresponds to ~ 0.6 TWh (~85 MCHF) annually → CERN MTP assumes 140 MCHF/TWh beyond 2026

Green ILC and Carbon Neutrality - Regional Revitalization

CO2-neutrality by 2050 is a goal for Tohoku region → next generation town development when ILC is operational (Green ILC Concept):

- *Exhaust heat recovery from the ILC and the creation of business derived from it*
- *Connecting the ILC with agriculture, forestry, fisheries industries to reduce CO_2 emissions and offset by increasing CO_2 absorption*
- *Building an energy recycling society based on the Global Village Vision*
- *23% regenerative electricity today – sufficient for ILC operation (ILC is < 1%)*


ILC Workshop on Potential Experiments (ILCX2021)

ILCX2021 ILC Workshop on Potential Experiments

Basic policy of Green ILC activities at Kitakami ILC candidate site

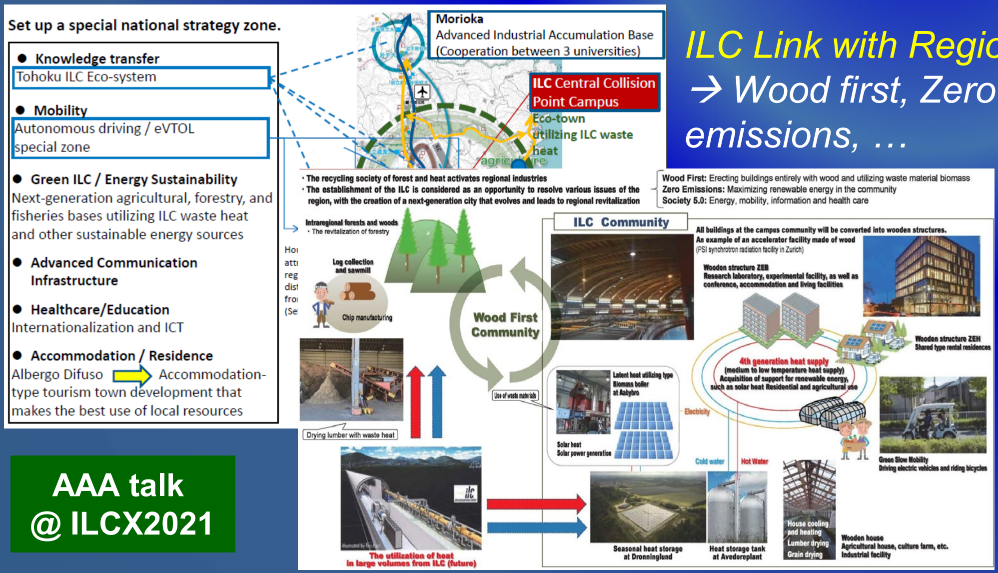
Masakazu Yoshioka (Iwate/Iwate Prefectural/Tohoku University)
Green ILC Session, Oct. 28, 2021

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 ne[...] located. T[...] (1) develo[...] the CO2 a[...] 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.

M. Yoshioka; PASJ2020 & PASJ2022 Proceedings

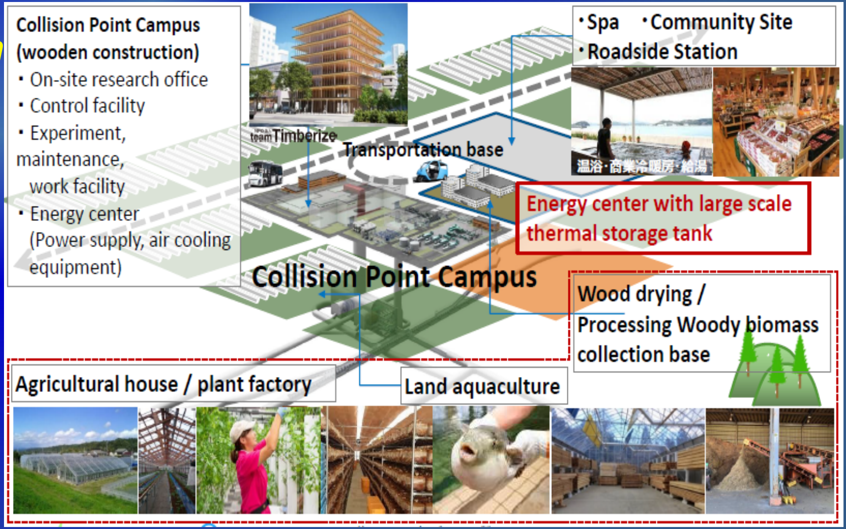
Next generation town development for ILC operation



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

AAA talk @ ILCX2021

ILC Central Collision Point → Eco-Campus Concept

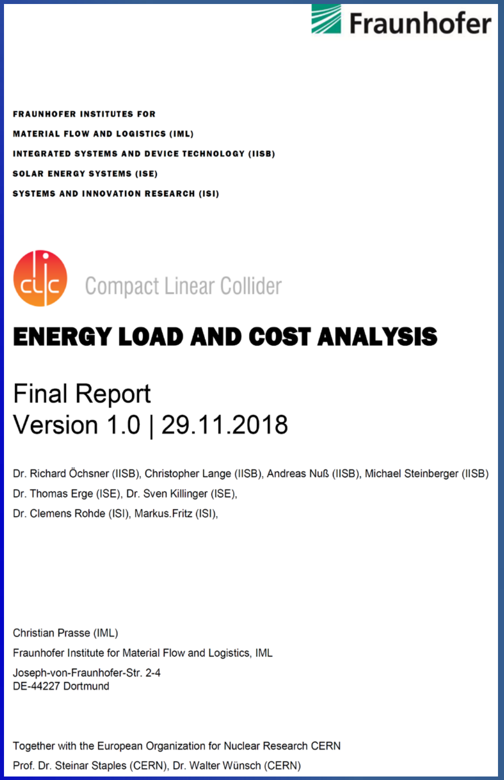


"Green ILC": https://green-ilc.in2p3.fr/documents/

Power Modulation - Running on Renewables

Different approaches to reduce impact of large electric power consumption (single pass colliders are wel suited):

- ***Reduce power (by higher efficiency)***
- ***Re-use waste energy (heat)***
- ***Modulate power according to availability (price)***
- ***Use regenerative power***


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

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Prof. Dr. Steinar Staples (CERN), Dr. Walter Wünsch (CERN)

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.

✓ *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.*

https://edms.cern.ch/document/2065162/1

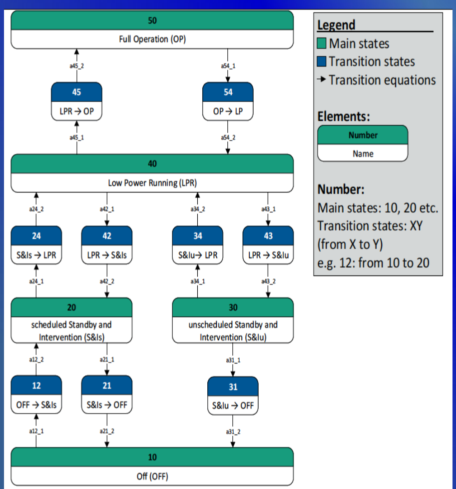


Figure 1-1: Schematic representation of the finite state machine

FRAUNHOFER STUDY:

- *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.*
- *Flexibility to adjust the power demand is expected to become increasingly important and in demand by energy companies*

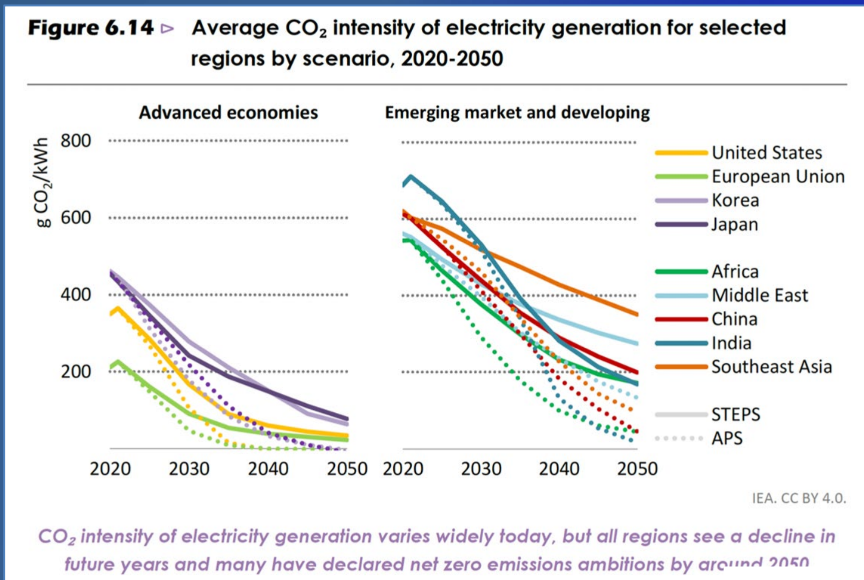
Sustainable Construction: Proactivity

- ***Operation costs dominated by energy (and personnel)***
  - Reducing power use, and costs of power, will be crucial → huge uncertainty in how the energy market, prices and price variations will be in ~2040 (ILC), ~2050 (CERN projects)
  - Carbon footprint related to energy source, relatively low already for CERN (helped by nuclear power), expected to become significantly lower towards 2050 when future accelerators are foreseen to become operational (in Europe, US and Japan).
  - Align to future energy markets, green and more renewables, make sure we can be flexible customer and deal with grid stability/quality
  - Other consumables (gas, liquids, travels, computing …) during operation need to be justified (and estimated)

- ***For carbon the construction impact might be (more) significant (also rare earths etc) than operational footprint***
  - *Construction: CE, materials, processing and assembly – not easy to calculate, very likely a/the dominating carbon source*
  - *Markets will push for reduced carbon, "responsible purchasing" crucial – construction costs likely to increase*
  - *Many other factors than a carbon life cycle assessment, rare earths, toxicity, acidity ..*
  - *Environmental studies, integration in local environment/power grids, very important (CERN generally, Green ILC)*

- ***Decommissioning – how do we estimate impacts ?***

Sustainable Linear Collider Operation



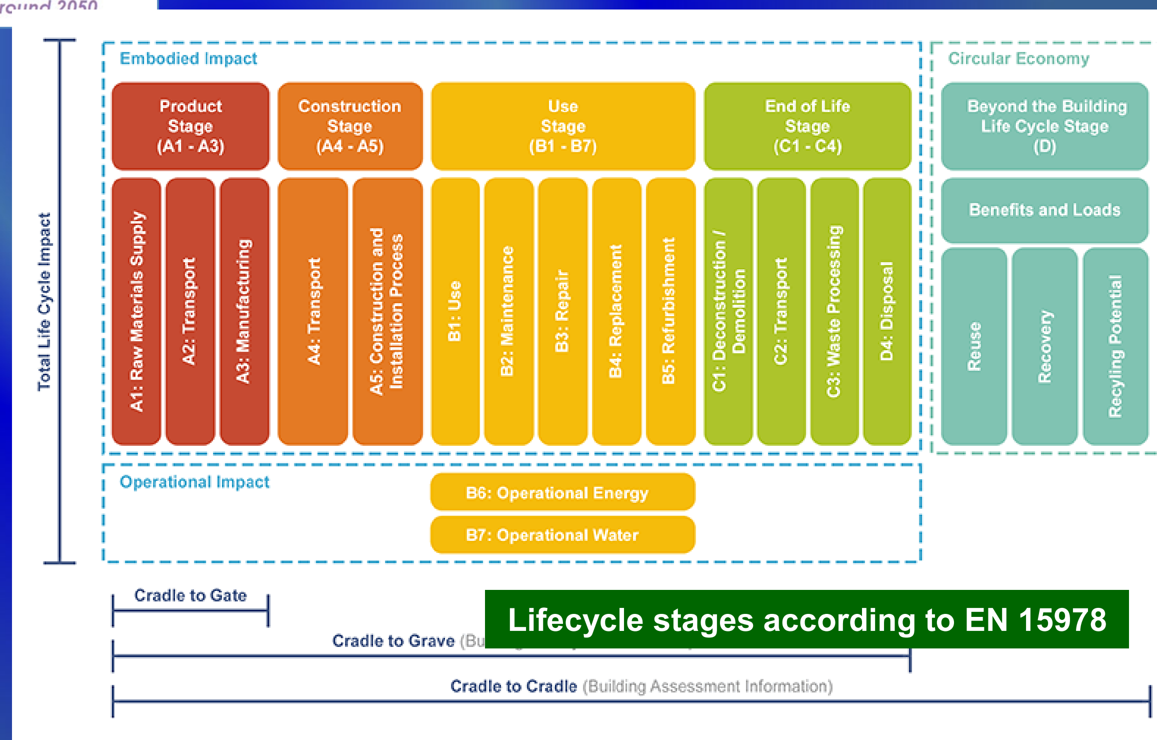
Data of carbon intensity of electric power
(Nuclear energy remains very important, on the timescale of a future CERN facility):

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):

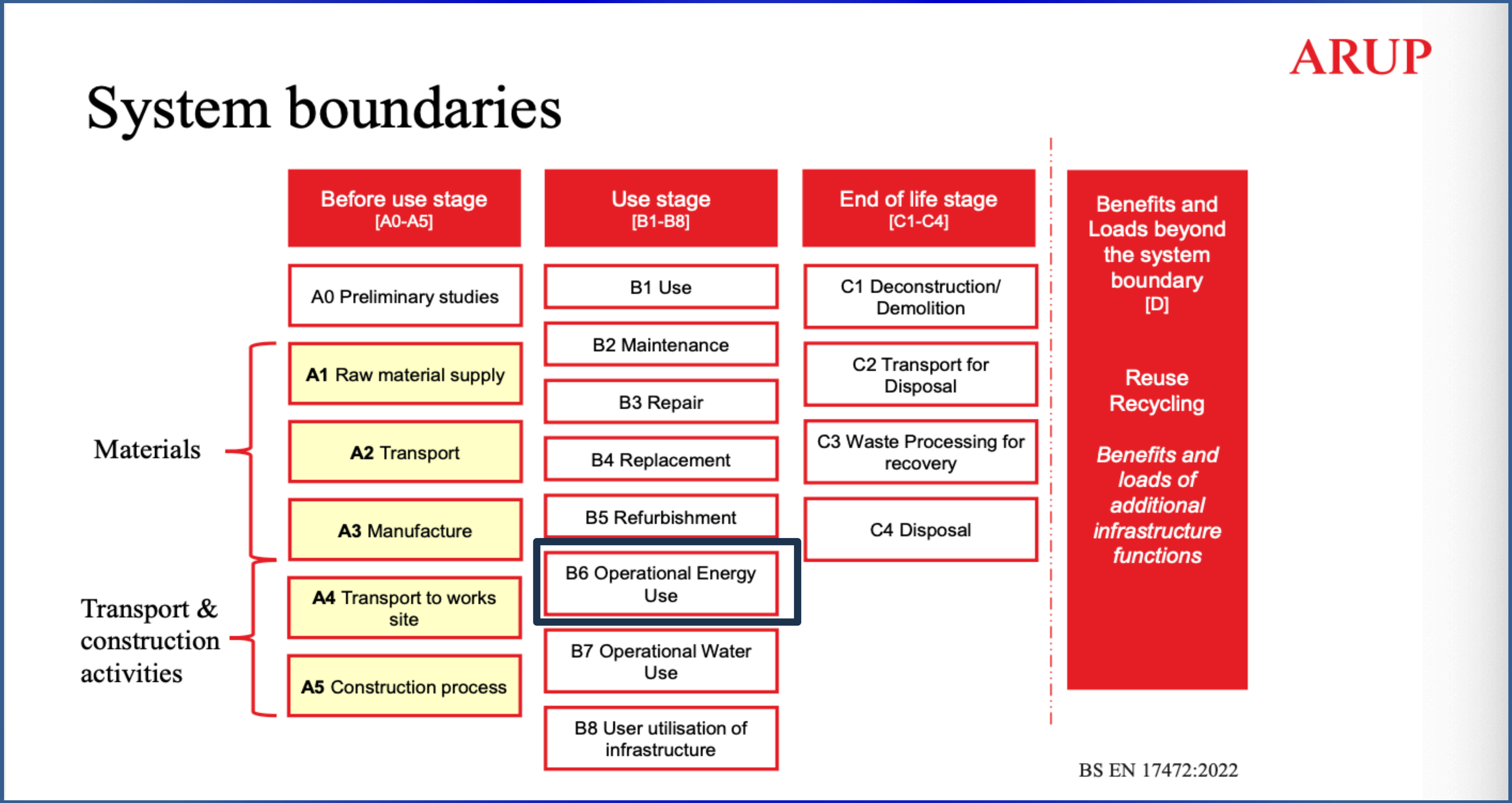
- ✓ ***Ultimate Goal:***
  - *Quantify the environmental impact of a whole accelerator project, i.e., CLIC / ILC*
- ✓ ***Accepted method:***
  - *LCA = Life Cycle Assessment*
- ✓ ***Define Scope:***
  - *System Boundaries*
  - *Lifecycle Stages*



Lifecycle stages according to EN 15978

Sustainable Construction: Life-Cycle Assessment

LCA starting point: Determine the embodied and construction environmental impact of tunnel, caverns and shafts
→ perform a LCA (Lifecycle Assessment) for the construction stage (A1-A5)



- ✓ ***Only B6 discussed in all the slides above, now discuss A1-A5 for the CE***
- ✓ ***Missing A1-A5 for accelerator, some surface installations, all maintenance and upgrades, all EoL activities***

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

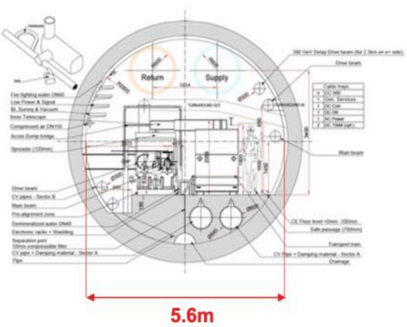
Sustainable Construction: Life-Cycle Assessment

Ref: ISO 14040:2006

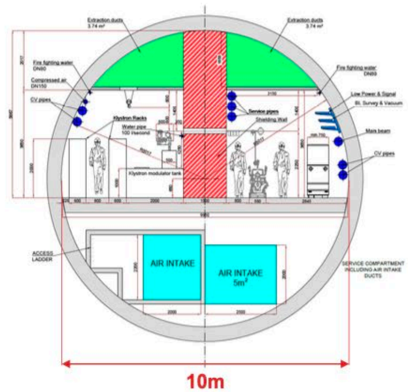
Full ARUP report:
https://edms.cern.ch/document/2917948/1

Linear Collider Options

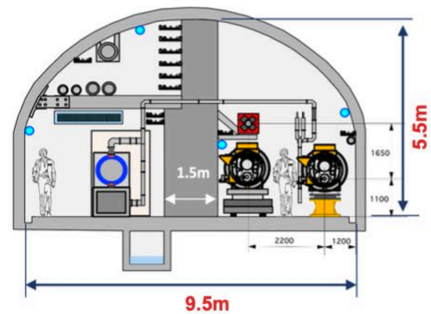
1. CLIC Drive Beam	2. CLIC Klystron	3. ILC
5.6m internal dia. Geneva. (380GeV, 1.5TeV, 3TeV)	10m internal dia. Geneva. (380GeV)	Arched 9.5m span. Japan. (250GeV)



Reference: CLIC Drive Beam tunnel cross section, 2018



Reference: CLIC Klystron tunnel cross section, 2018



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 …apro 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

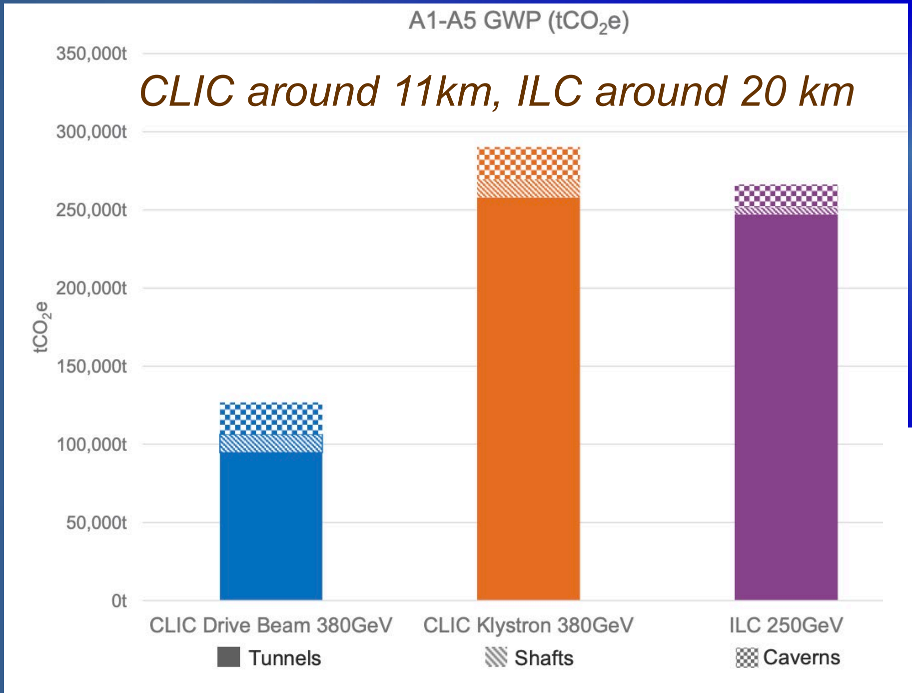
Midpoint Impact Categories	Abbr.	Unit
Global warming	GWP	kg CO_2 eq
Stratospheric ozone depletion	ODP	kg CFC-11 eq
Ionizing radiation	IRP	kBq Co-60 eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Ozone formation, Human health	HOFP	kg NOx eq
Ozone formation, Terrestrial ecosystems	EOFP	kg NOx eq
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

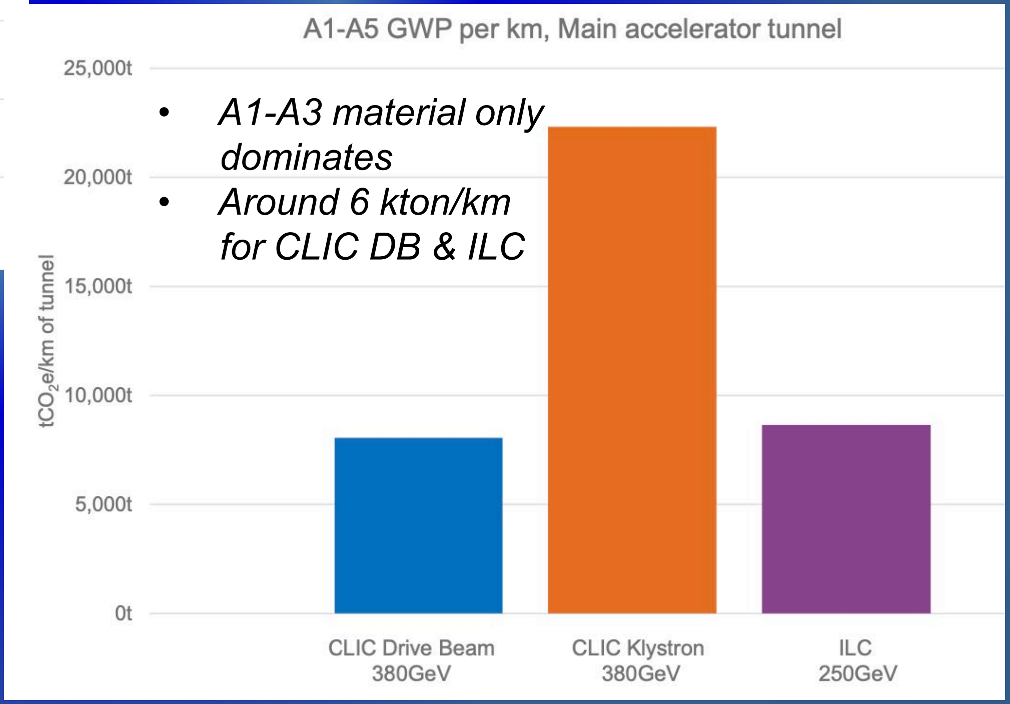
Full ARUP report: https://edms.cern.ch/document/2917948/1

Comparative environmental footprint for future linear colliders CLIC & ILC

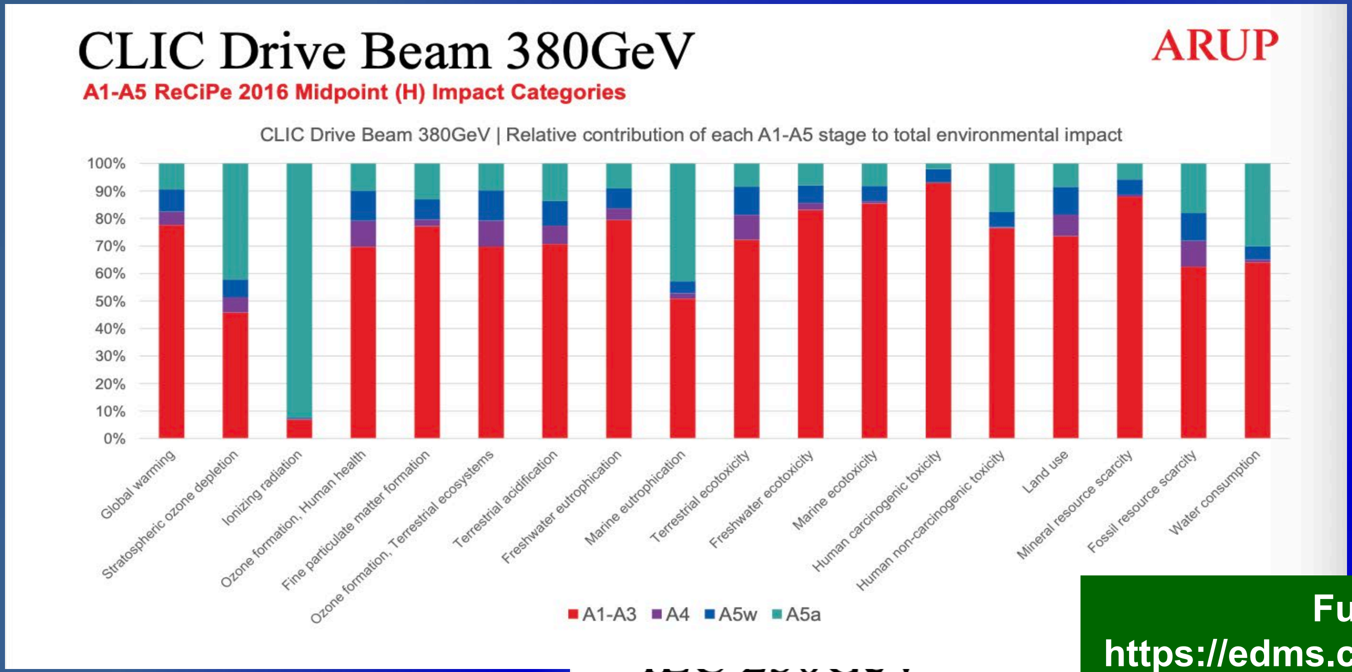


Assuming a small CLIC tunnel (~5.6m diameter) ***and*** *that the <u>equipment has the same carbon footprint as the tunnel</u> itself,*
20 km accelerator (tunnel plus components) correspond to 240 kton CO_2 equivalent

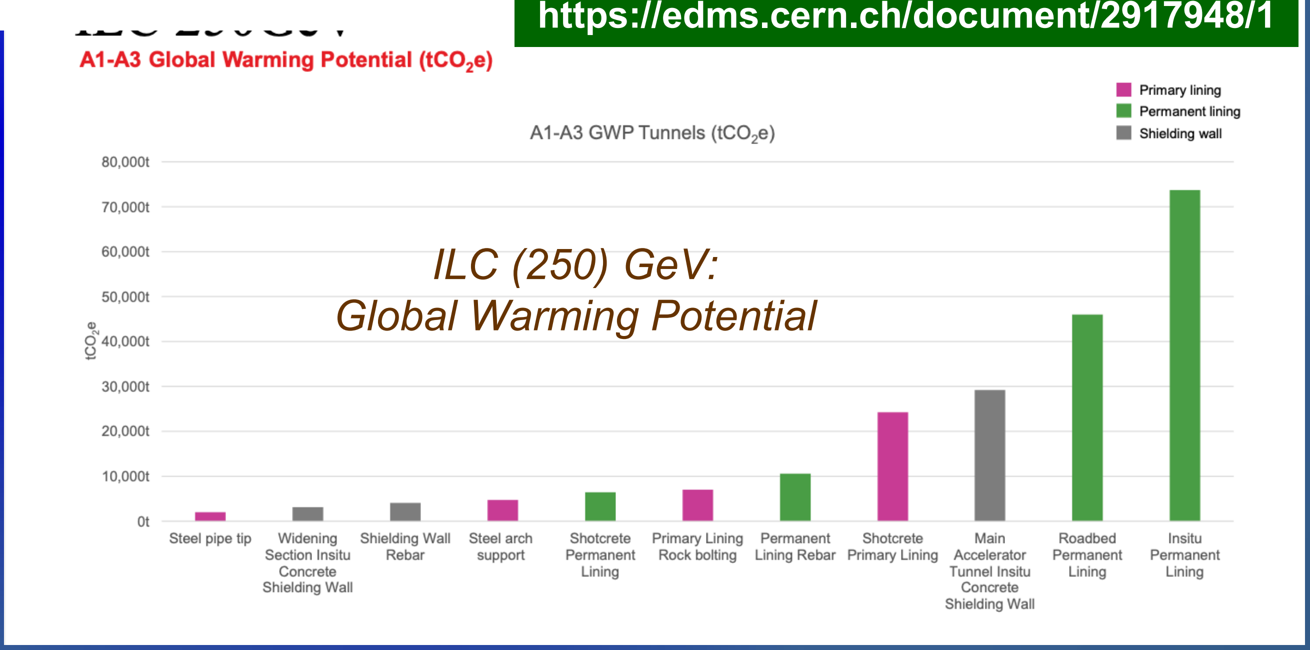
- ✓ *Include all tunnels (access, transfer, damping rings), shafts and caverns. A1-A5*
- ✓ *Scaling to main linac tunnel lengths we are now at 11-14 kton/km for the CLIC DB and ILC*



Sustainable Construction: Life-Cycle Assessment



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

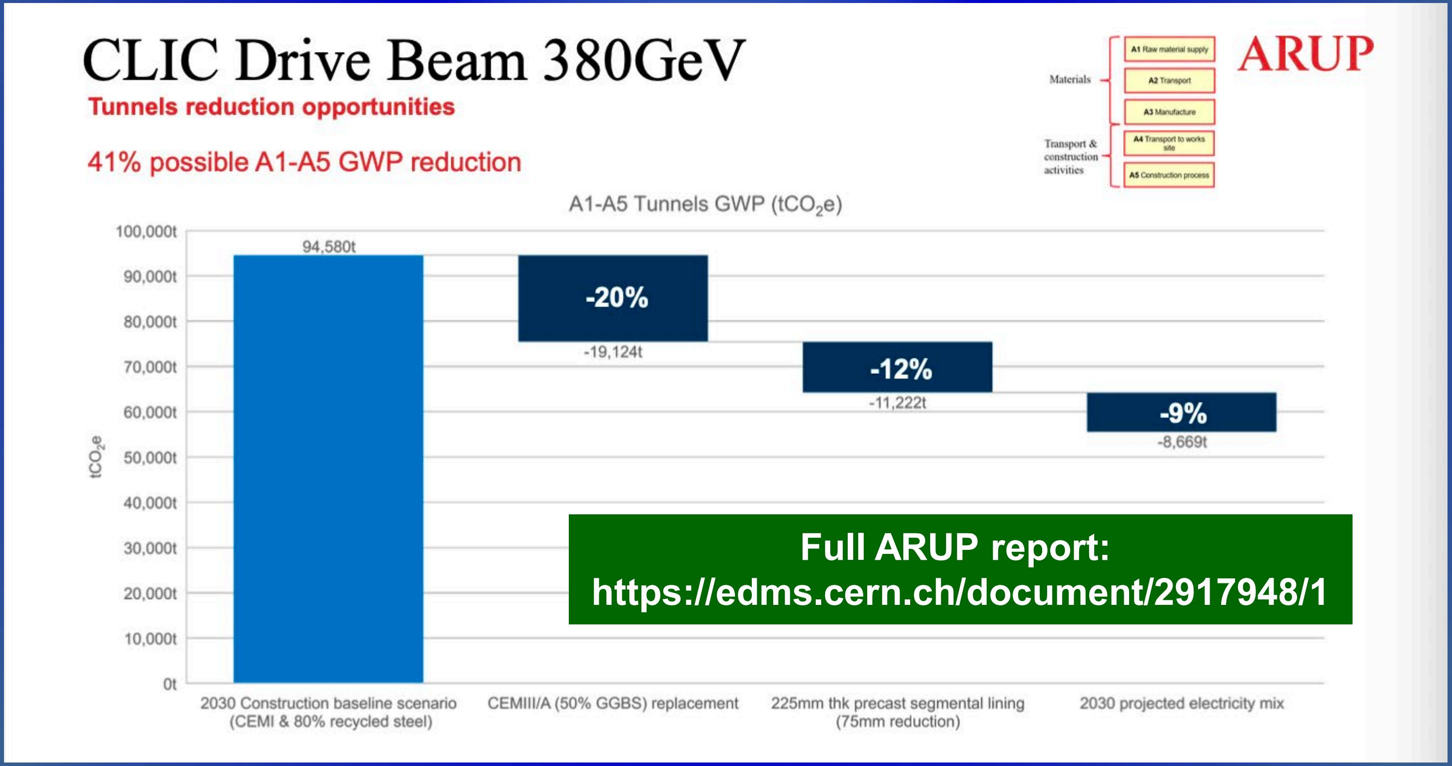


The embedded carbon due to civil engineering work and material (concrete for example) is a very important contribution, on a level comparable to many years of carbon emission due to energy use during the operational phase

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)***

Europe – America – Japan (EAJADE) Program (2023-2027)

European Union's Horizon Europe Marie Sklodowska-Curie Staff Exchanges programme under grant agreement no. 101086276

2014 → 2023

http://www.eajade.eu/

E-JADE
Europe -Japan Accelerator Development Exchange Programme

EAJADE
Europe-America-Japan Accelerator Development Exchange Programme

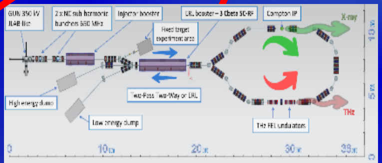
Work package no.	Work package title	Activity type	Number of person-months involved per secondment	Lead benefi-ciary	Start month	End month
1	R&D&I at currently operating state-of-the-art facilities	Research, training	143	CNRS	1	48
2	State-of-the-art high-gradient, high-efficiency, reduced-cost radio-frequency 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, communication	4	DESY	1	48

WP4: Sustainable Technologies for Scientific Facilities

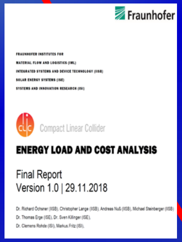
WP4

***Task 4.1:* High Efficiency & Sustainable SC cavities**

***Task 4.2:* High efficiency RF power amplifiers**



***Task 4.3:* Energy Recovery Linacs**


Fraunhofer

Compact Linear Collider

ENERGY LOAD AND COST ANALYSIS

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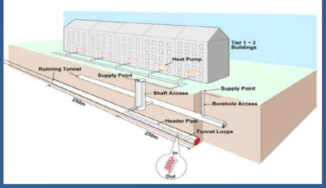
Version 1.0 | 29.11.2018

***Task 4.4:* Power Modulation**

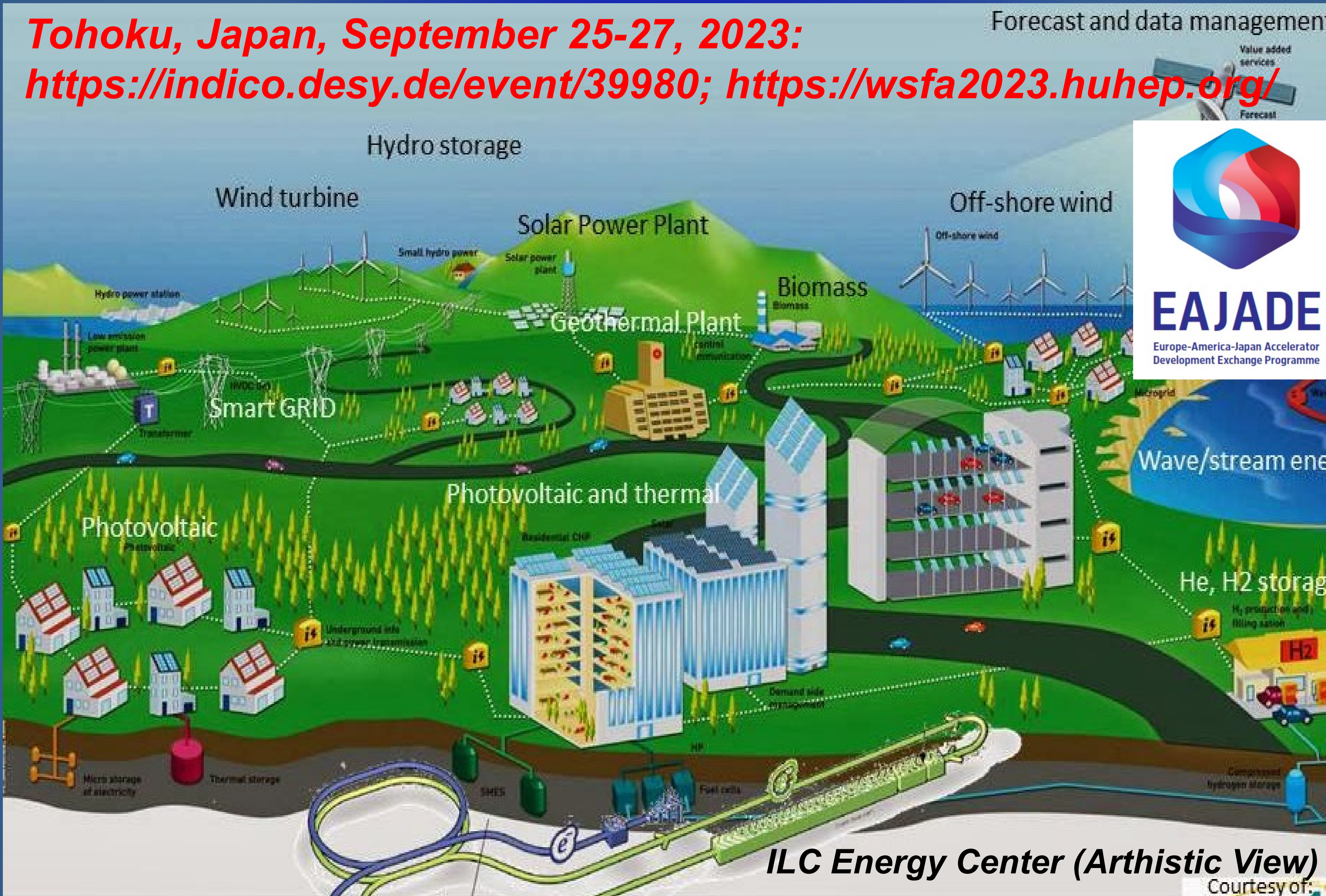
***Task 4.6:* "Green ILC"**

***Task 4.5:* Smart Tunneling**



EAJADE Workshop on Sustainability in Future Accelerators

Tohoku, Japan, September 25-27, 2023:
https://indico.desy.de/event/39980; https://wsfa2023.huhep.org/



EAJADE
Europe-America-Japan Accelerator Development Exchange Programme

Summary and Outlook

- ✓ ***Power efficiency, energy consumption* and also *carbon emission* and other sustainability targets are today important drivers of accelerator development and R&D:**

  - Related to designs, new concepts and many technical developments
  - Very large synergy across the entire field of accelerator science (small and large installations)
  - Funding in many cases "encourages" this R&D

- ✓ ***Optimisation* of subsystems and components *for energy efficiency*, e.g.:**

  - Better accelerator cavities (optimize design for more gradient, reduced losses, etc …)
  - Efficient klystrons
  - Permanent magnets

- ✓ ***Important to be pro-active, anticipating the changes happening in the energy markets and society with respect to sustainability driven changes:***

  - Power, energy efficiency at all levels
  - Adapting to and using more renewables (increased availability of it, can be increased by contracts)
  - Reducing carbon in construction from civil engineering to technical components
  - Making use of materials, technologies and working with suppliers that are invested in these changes
  - Integration in/with local areas, their infrastructure and development plans (e.g. Green ILC)

Special thanks to:

Benno List, Steinar Stapnes,

Shin Michizono, Takayuki Saeki, John Osborne, Liam Bromiley, Suzanne Evans, Yung Loo, Igor Syratchev, Ben Shepherd, Caterina Vernieri, Emilio Nanni, Sergey Belomestnykh, Masakasu Yoshioka

and many colleagues from the CLIC and ILC collaborations