Sustainability Studies for ILC and CLIC

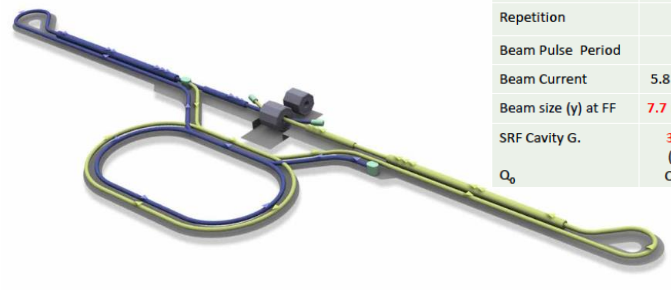
Benno List,

IFAST, 4th Annual Meeting

April 8, 2025

ILC and CLIC

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

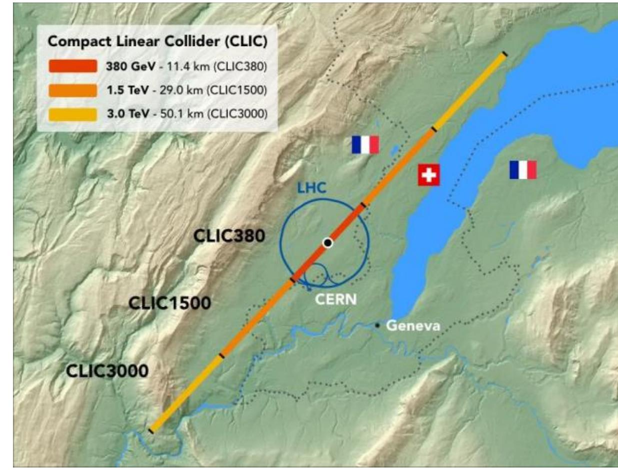


Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 $\times 10^{34}$ $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1 \times 10^{10}$

International Linear Collider ILC

- Superconducting Cavities, 1.3GHz, 31.5MV/m
- 250GeV CME, upgradeable to 500, 1000 GeV
- L = 1.35E34 $cm^{-2}s^{-1}$
- 20km length, in Tohoku / Japan

ESPPU submission #275
https://indico.cern.ch/event/1439855/contributions/6461661/



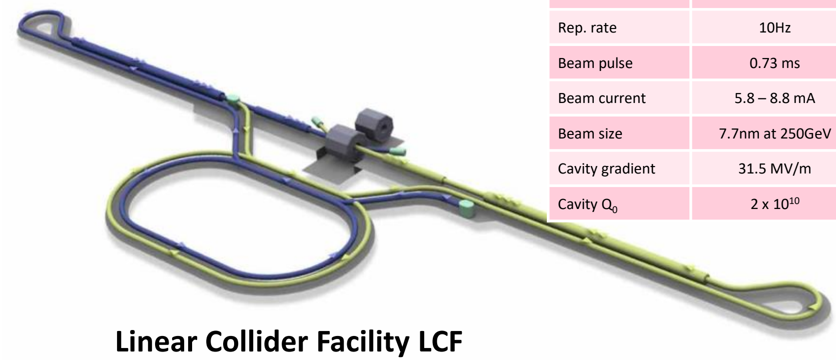
Compact Linear Collider CLIC

- NC Copper Cavities, 11.4GHz, 72MV/m
- 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 / France & Switzerland

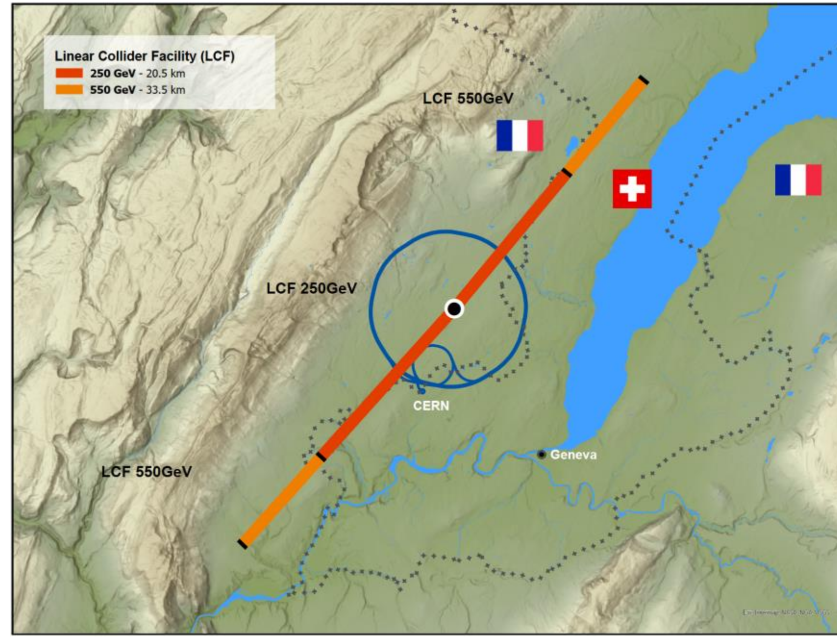
ESPPU submission #78
https://indico.cern.ch/event/1439855/contributions/6461475/
arXiv:2503.24168

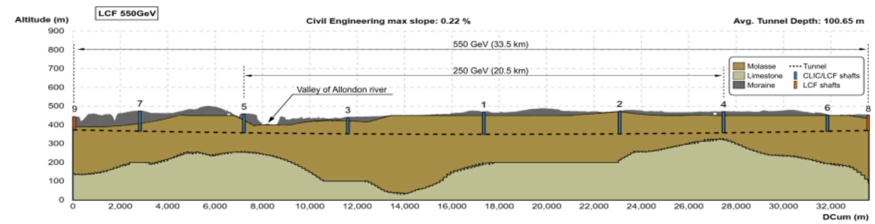
A new project: Linear Collider Facility LCF at CERN

A linear collider based on ILC technology for CERN, with technology upgrade options



Parameter	Value
CM Energy	250 – 550 GeV
Length	33.5 km
Luminosity	2.7 – 7.7 x 10^{34} $cm^{-2}s^{-1}$
Rep. rate	10Hz
Beam pulse	0.73 ms
Beam current	5.8 – 8.8 mA
Beam size	7.7nm at 250GeV
Cavity gradient	31.5 MV/m
Cavity Q_0	2 x 10^{10}





Linear Collider Facility LCF

- Superconducting Cavities, 1.3GHz, 31.5MV/m
- 250GeV CME, upgradeable to 550 GeV
- L = 2.7 E34 $cm^{-2}s^{-1}$ initial
- 33.5km length, at CERN
- Upgradeable with C3 or CLIC technology

ESPPU submission #40
https://indico.cern.ch/event/1439855/contributions/6461433/
arXiv:2503.24049

Approaches to Improve Sustainability

- Accelerators for High Energy Physics are at the leading edge of technology: beam energy, intensity, luminosity…
- Ressource conservation is paramount:
- Sustainability adds new cost measures: e.g. CO_2, rare earth usage -> Lifecycle Assessment!

Overall System Design

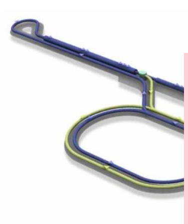
- Compact (short) accelerator -> high gradient
- Energy efficient -> low losses
- Effective -> small beam sizes

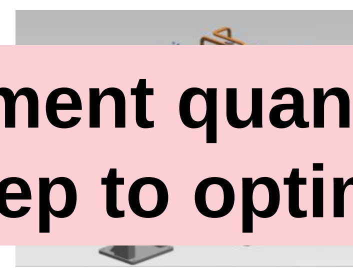
Subsystem and Component Optimisation

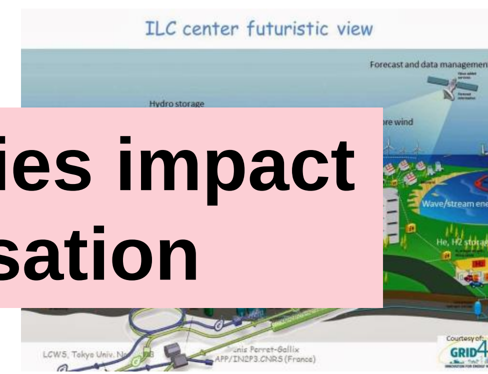
- High-efficiency cavities and klystrons
- Permanent magnets
- Heat-recovery in tunnel linings

Operation

- Recycle energy (heat recovery)
- Adapt to regenerative power availability
- Exploit energy buffering potential







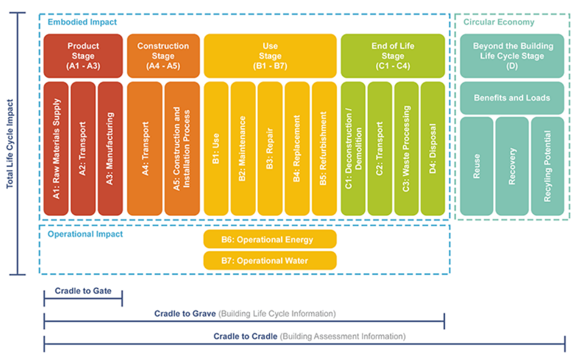
Lifecycle assessment quantifies impact -> the first step to optimisation

Lifecycle Thinking and Lifecycle Assessment (LCA)

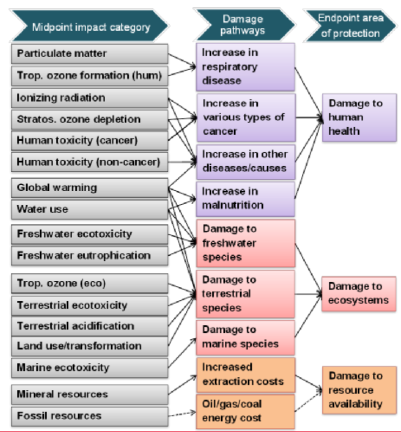
- Consider the **whole lifecycle** and its impact
- Avoid **burden shifting**, i.e. moving problems elsewhere: consider diverse impact categories
- Lifecycle Assessment (LCA)
  - Standardized approach to evaluate impact
  - Quantifying total damage by **endpoint** indicators difficult
  - ”**Midpoint** indicators” asses impact on environment in a quantitative way
- **Measure** in order to **improve:**
  - **Identify hot spots**
  - **Evaluate and choose alternatives**

https://www.nist.gov/el/systems-integration-division-73400/lifecycle-graphic

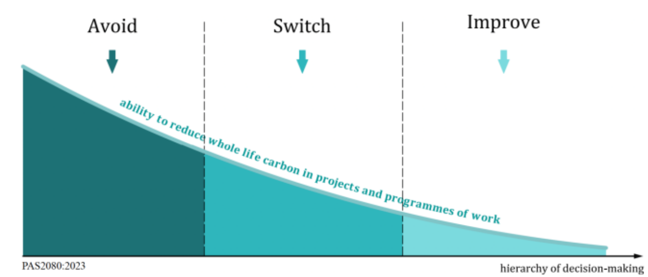
https://browningday.com/news/lca-stages-matter-when-tracking-embodied-carbon/
https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/89547-lca-stages-matter-when-tracking-embodied-carbon



Lifecycle stages according to EN 15978

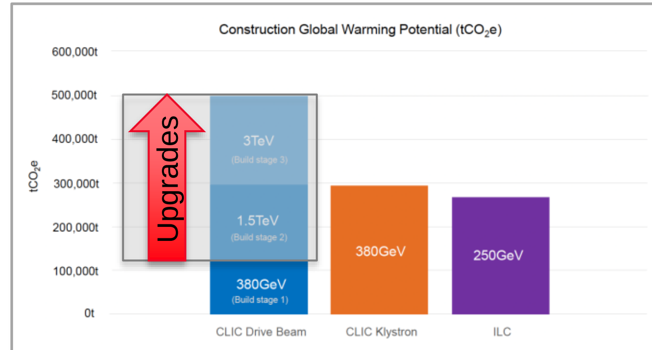


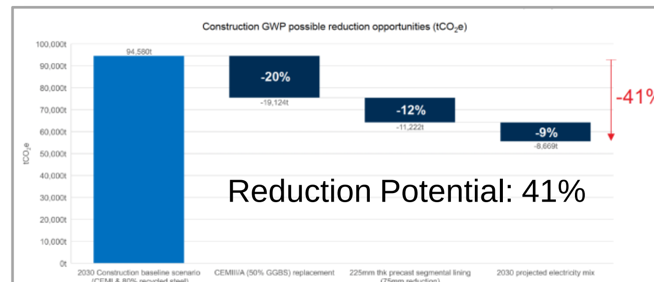
M.A.J. Huijbregts et al., Int. J. Life CycleAss. **22** (2017) 138, DOI:10.1007/s11367-016-1246-y

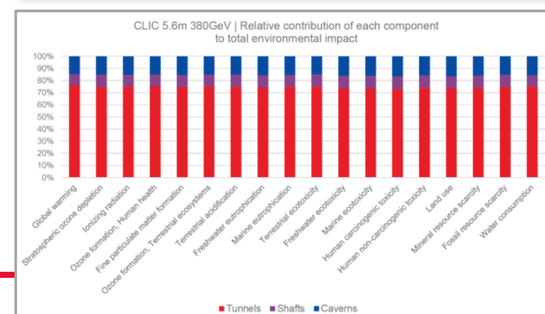


LCA of Civil Engineering Infrastructure

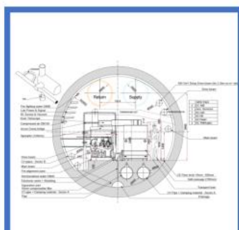
- LCA study of tunnels, shafts and caverns:
  - Common study for ILC and CLIC (link)
  - Professional consultant company: ARUP
  - Include two design alternatives for CLIC: Two-beam acceleration or klystron driven
- Results:
  - CLIC 2-beam design: 127 kton CO2-e
  - CLIC klystron: 290 kton CO2-e
  - ILC (250GeV CoM): 266 kton CO2-e
- LCA helps to compare design alternatives
- LCA identifies reduction potential:
  - 20% from using low carbon cement (CEM III/A)
  - 12% from thinner lining
  - (9% from future electricity mix -> not a project decision)

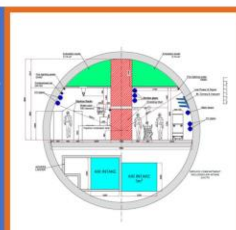


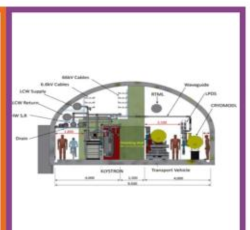




Further Impact categories


CLIC Drive beam, 5.6m dia.

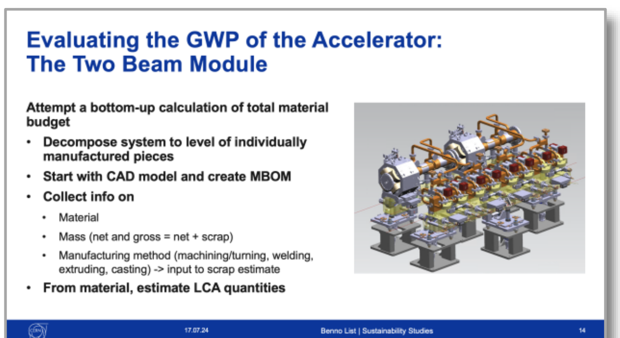

CLIC Klystron, 10m dia.

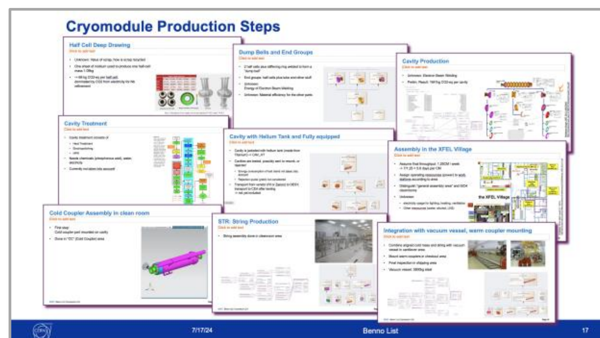

ILC, 9.5m span

Full study: https://edms.cern.ch/document/2917948/1

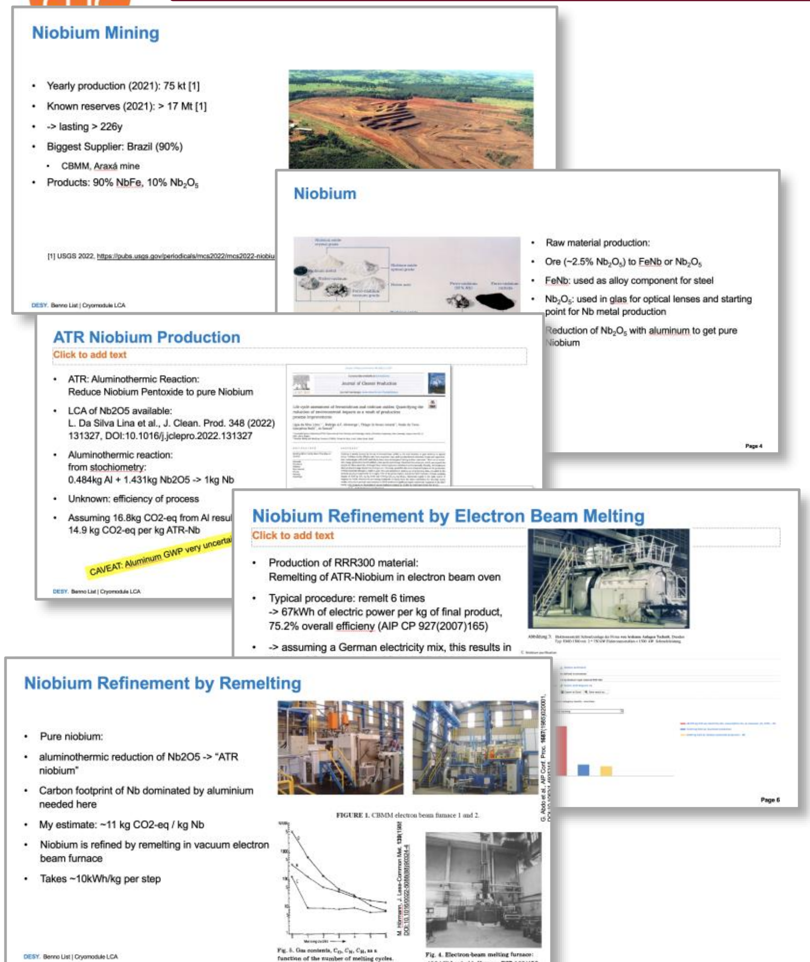
New Study: LCA of Accelerator

- LCA of accelerator and detectors much more demanding than civil infrastructure:
  - Many different components
  - Many materials, also unusual materials
- ILC and CLIC performed LCA effort with ARUP
- Study almost concluded,
  looking in detail on Main Linac building blocks:
  - ILC Cryomodule
  - CLIC two beam module
- Finished study will be available at
  https://edms.cern.ch/document/3283864/1



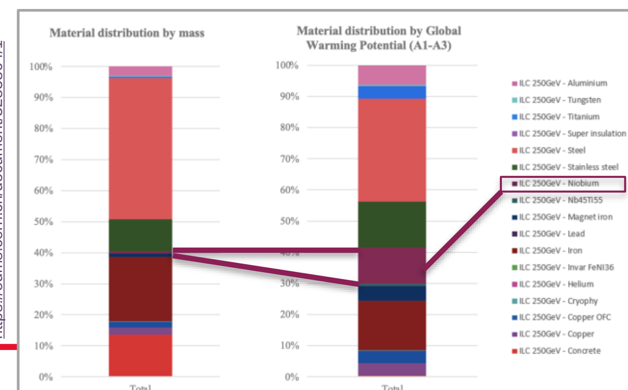


Special Materials – Example: Niobium Material

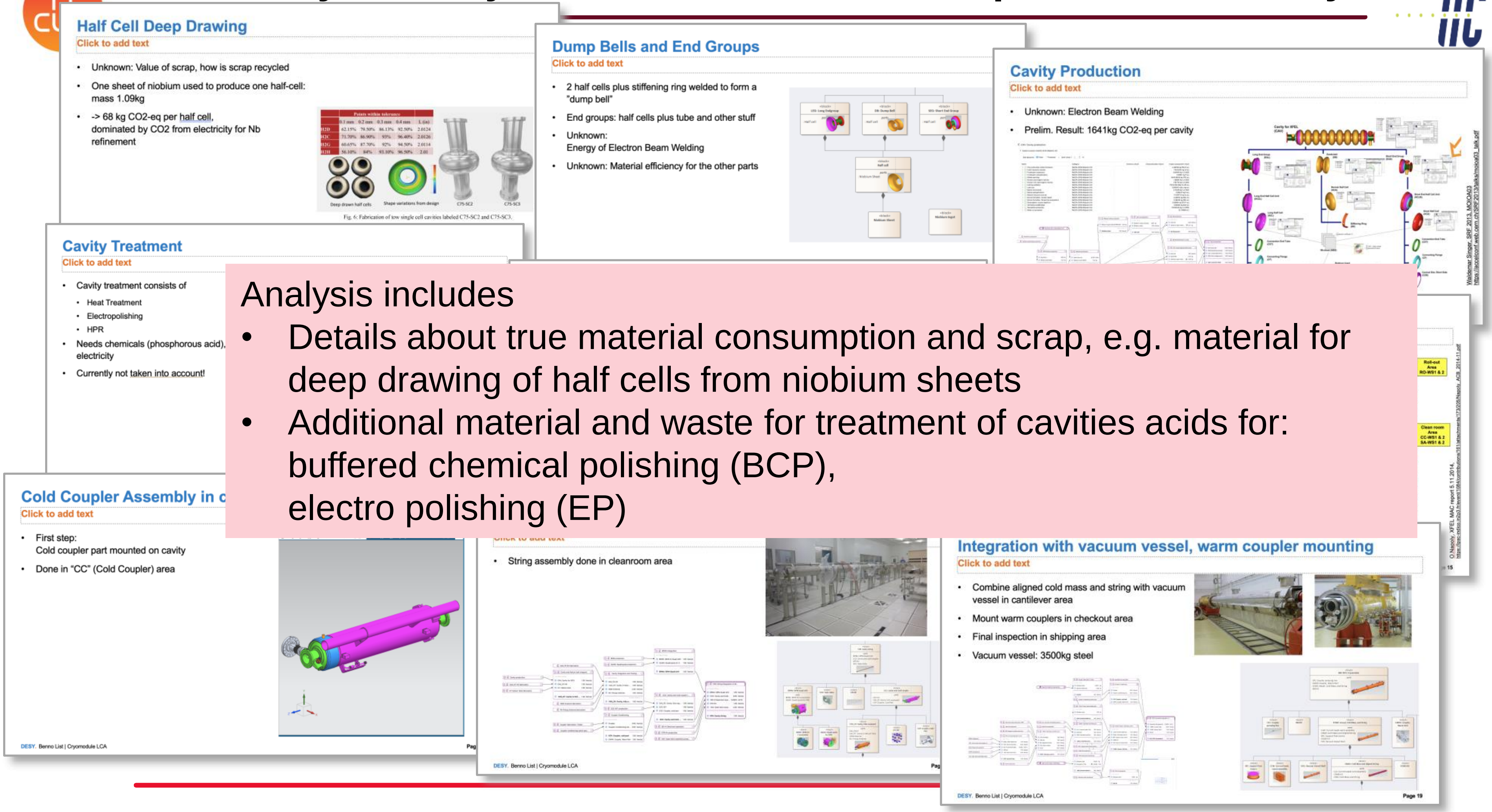


- Problem for this work:
  LCA data for some materials does not exist
  -> here: **niobium and ultra-pure niobium**
- No data for high-purity ("RRR300") niobium available
- Not even for 99% pure ATR (aluminothermic reduction) niobium (processed from Nb2O5, LCA data available)
- Research of niobium processing -> implementation
- Dominant factor for RRR>300 niobium: electricity for electron beam remelting -> depends on local conditions (**assume: China**)
- Results
  - Niobium RRR>300, from China: 98kg CO2-e / kg
    -> 10% of total GHG for ILC250 accelerator!
    -> large impact reduction potential

https://edms.cern.ch/document/3283864/1



ILC Cavity and Cryomodule Production Steps: Detailed analysis



Analysis includes

- Details about true material consumption and scrap, e.g. material for deep drawing of half cells from niobium sheets
- Additional material and waste for treatment of cavities acids for:
  buffered chemical polishing (BCP),
  electro polishing (EP)

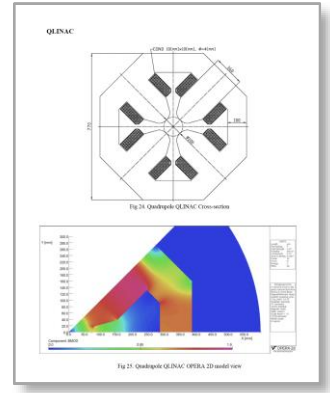
Magnets

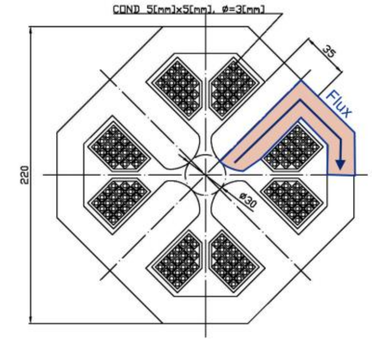
- Resistive Electromagnets are a big contributor to LCA, because of large mass
- Many different types: dipoles, quadrupoles, sextupoles …
- 2 Parts:
  - Yoke: Iron / magnetic steel, often made from stamped laminations
  - Coil: Copper conductor, extruded, insulation: epoxy resin
- Not to be forgotten: Stands! Here, data is often scarce…

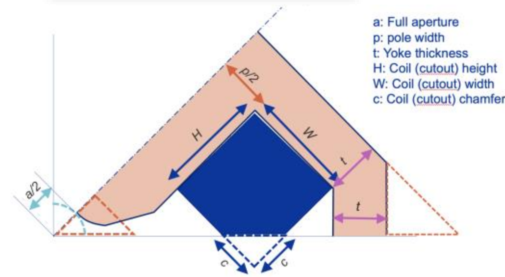
Magnets in an accelerator

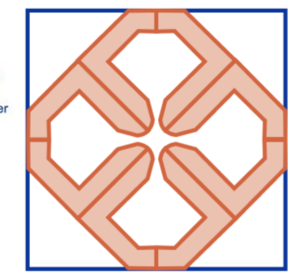
Input for magnets and stands

- Start from a catalogue of magnets
  - CLIC: dimensions known for all magnet types
  - ILC: Main design parameters known (aperture, strength coil cross section), use parametric model to determine size
- Main Components considered:
  - Yoke: from iron – consider scrap!
  - Copper, extruded: 8.5 kg kg CO2-e / kg
- Yoke materials
  - Soft iron: ~3.8 kg CO2-e / kg
  - For high field magnets: assume Vacoflux
    - 49% Fe, 49% Co, 2% V -> 22.3 kg CO2-e / kg
- Conclusion:
  - Yoke material dominates over copper from coils
  - High field magnets with **cobalt rich material** have a much larger impact
- Stands: assume reinforced concrete pillars steel frames, or girders on racks (ILC damping rings)



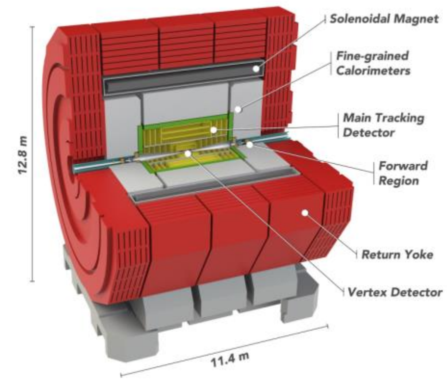




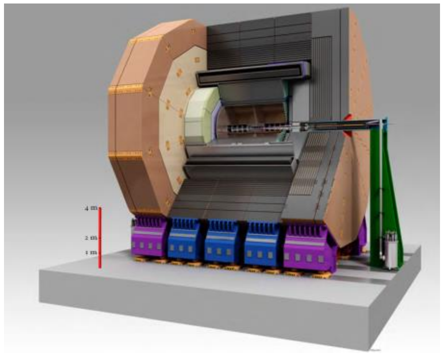


Detectors

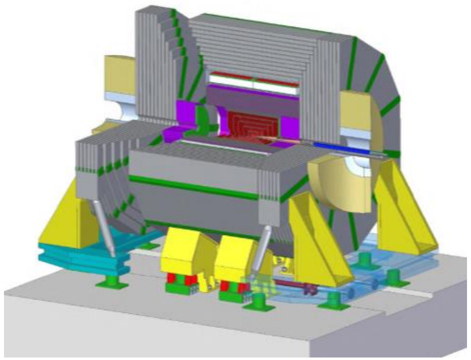
- Detectors were modelled in a simplified way: Use net weight of most heavy components
  - Yoke: Iron / Steel
  - Calorimeters: Steel, Tungsten
  - Reinforced concrete for support platforms
- Impact is by far dominated by the huge amount of iron in return yokes:
  ILD 13400t, SiD 6810t
  -> huge reduction opportunities
  (e.g. H1 used steel from ship scrap from Russia)
- Important assumption (requirement):
  No significant direct GHG emissions during operation:
  - Avoid usage of CFC coolants
  - And/or build gas tight system



Detector. Source: CERN (2018)The Compact Linear e+ e− Collider (CLIC): Accelerator and Detector



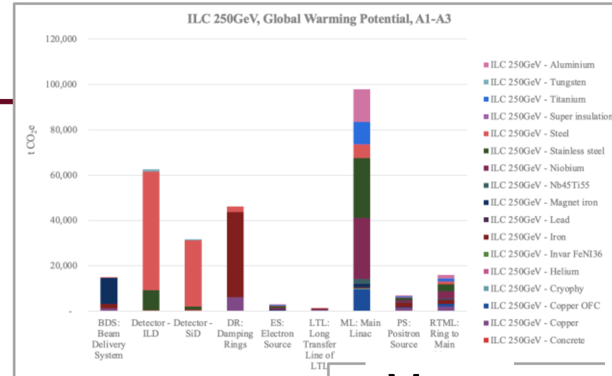
ILD Detector. Source: ILC TDR, volume 4

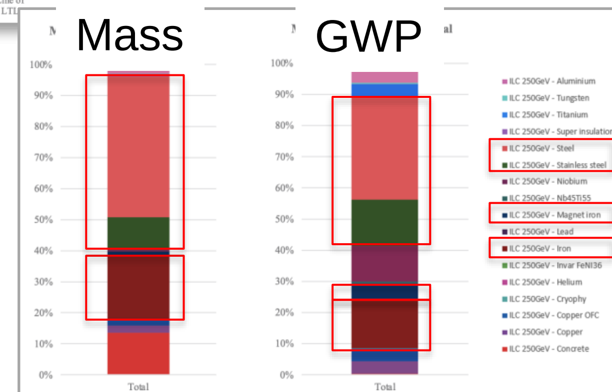


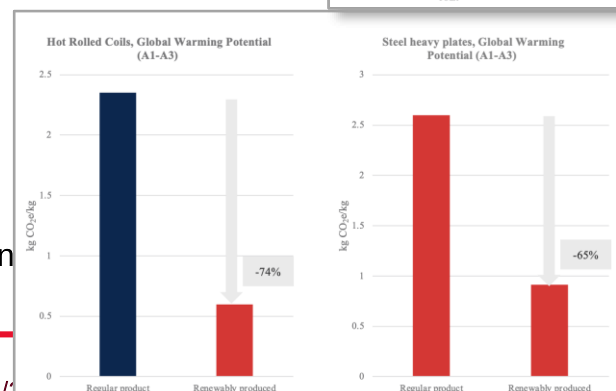
SiD Detector. Source: ILC TDR, volume 4

Main Results for ILC

- Accelerator & detector GWP hotspots:
  - Main linac: dominated by stainless steel, niobium, aluminium in cryo modules
  - Damping rings:
    dominated by **iron for magnet yokes**
  - Detectors ILC & SiD:
    Dominated by **steel for magnet yokes**
- Iron and steel is the by far dominant source of GHG emissions! Huge impact reduction opportunity
  - Note: “magnet iron” for some high field magnets assumed to be 49% Fe, 49% Co, 2% V
    -> GHG is 23 kg CO2-e / kg,
    10 times higher than mild steel (1.9 kg CO2-e / kg)
  - Dominated by iron in magnet yokes, especially **detectors**
- Other important materials:
  - Niobium ~11%
  - Copper: ~10%
  - Aluminium ~ 6%
  - -> have a high dependency on electricity in country of origin
    -> procurement policy important



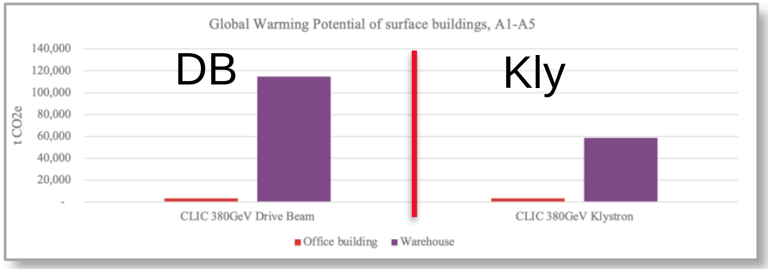


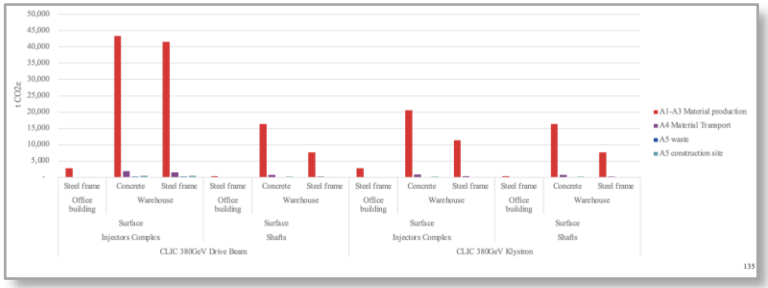


https://edms.cern.ch/document/3283864/1

CLIC: Surface Buildings

- Phase I Lifecycle Assessment: Underground construction – tunnels, caverns, shafts
- Phase II: Include also surface buildings and shallow (cut & cover) tunnels
- Particularly relevant for CLIC with large injector complex above ground
- Surface buildings: Office and “warehouse” buildings – described with 8 arche types
- “Warehouse” = accelerator buildings by far dominant, impact quite significant w.r.t. underground structures
  -> especially **injector complex buildings**





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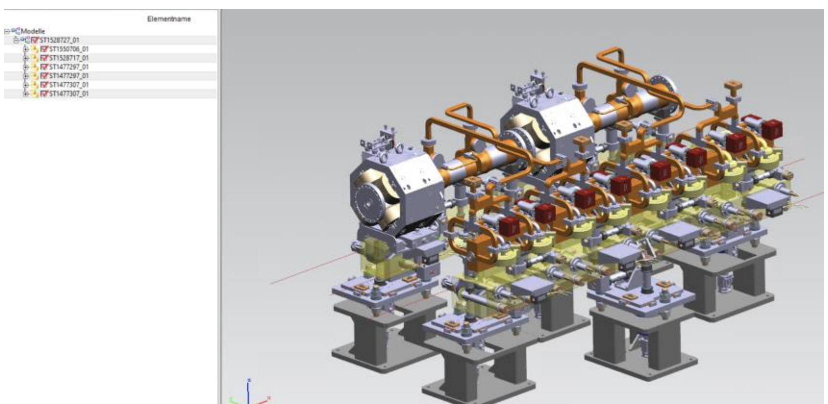
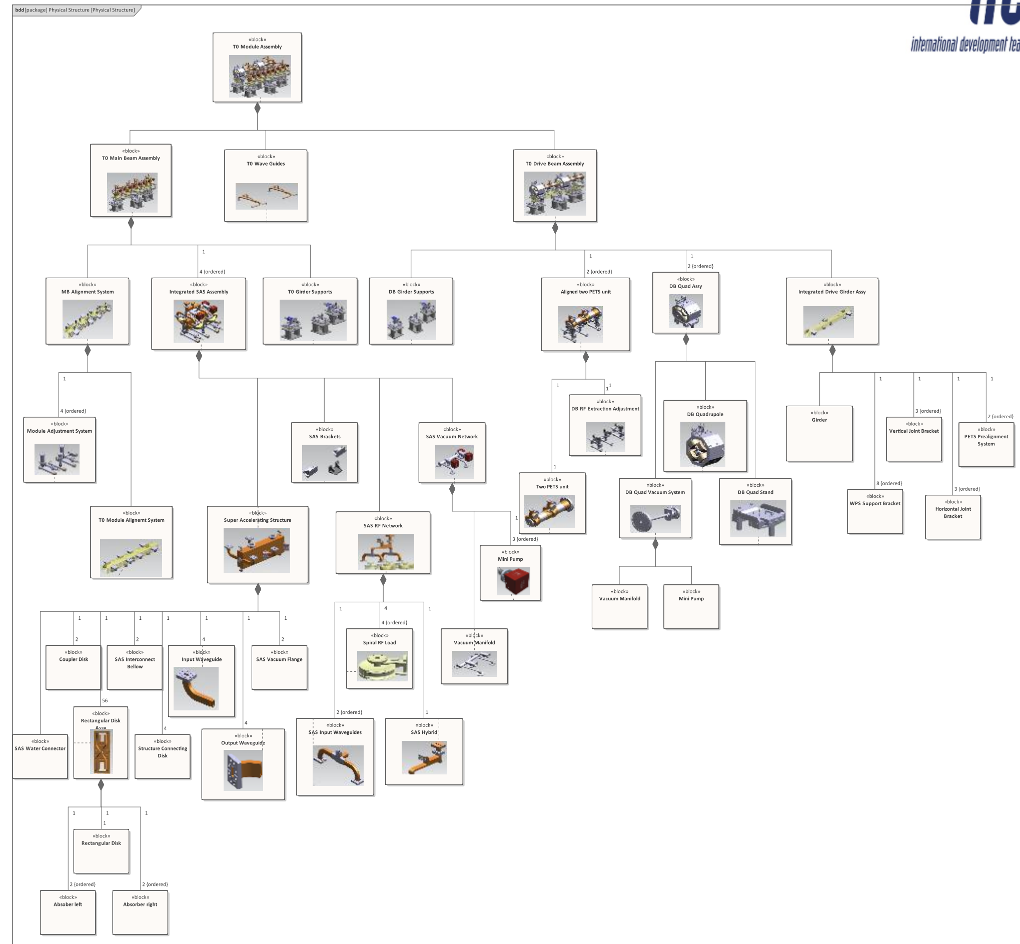
CLIC: 2-Beam Module

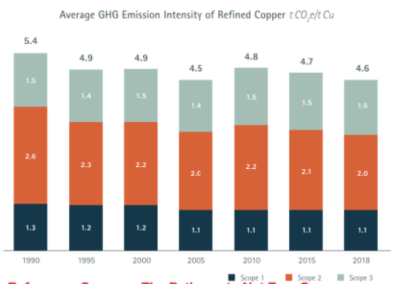
- CLIC 2-beam module: The fundamental building block of the CLIC main linac
- Collect material data on existing CAD model
- Special material: OFC (oxygen free) copper 9.7 kg CO2-e / kg





CLIC Accelerator: GHG Main Results

- Main Linac dominates GHG emissions in construction
- Dominant materials
  - Steel: ~70%
  - Copper: ~25%
- -> Explore reduction opportunities for copper



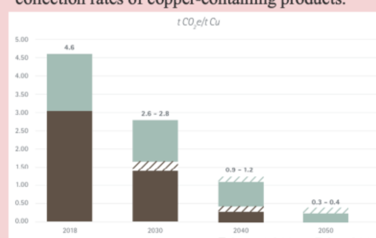
Reference: Copper – The Pathway to Net Zero Summary, ICA, March 2023

The ICA identify abatement opportunities which include decarbonised electricity, alternative fuels, equipment electrification and energy efficiency in the copper production process.

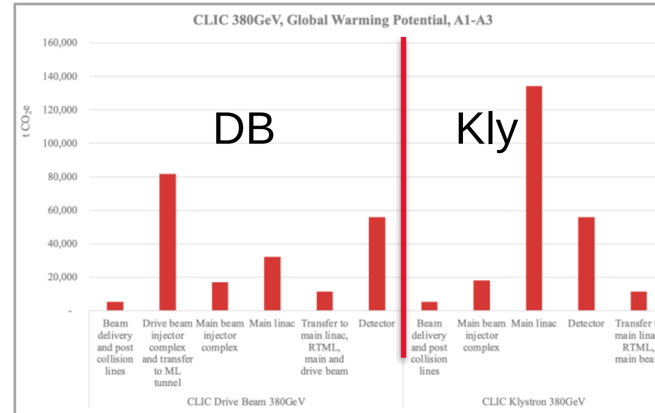
CLIC & ILC machine componentry utilise a significant amount of copper and therefore have a large control and influence over the scope 3 emissions of copper production. This requires partnership between the value chain to maximise potential abatements.

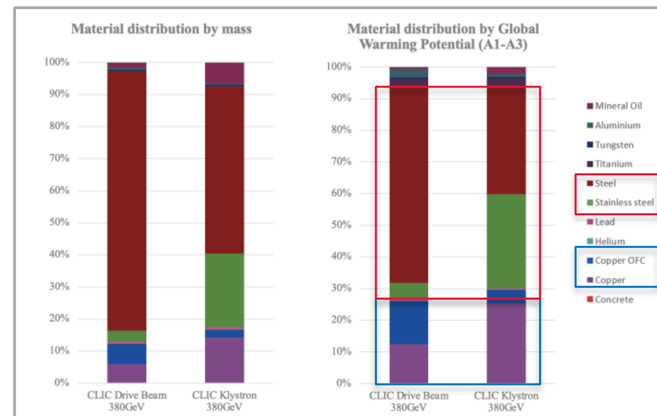
CLIC and ILC copper reduction opportunities

- Design optimisation of machine componentry to reduce quantity of copper material required.
- Partner with copper suppliers that are committed to The Copper Mark, to increase the quantity of responsibly sourced, produced and recycled copper across the value chain.
- Recycle as much copper in maintenance and end of life as possible to contribute to the International Copper Association aim of increasing the end-of-life collection rates of copper-containing products.



Reference: Forecasted Evolution of carbon intensity of Copper Cathode (McKinsey Asset Decarbonization tool; Team Analysis) 39





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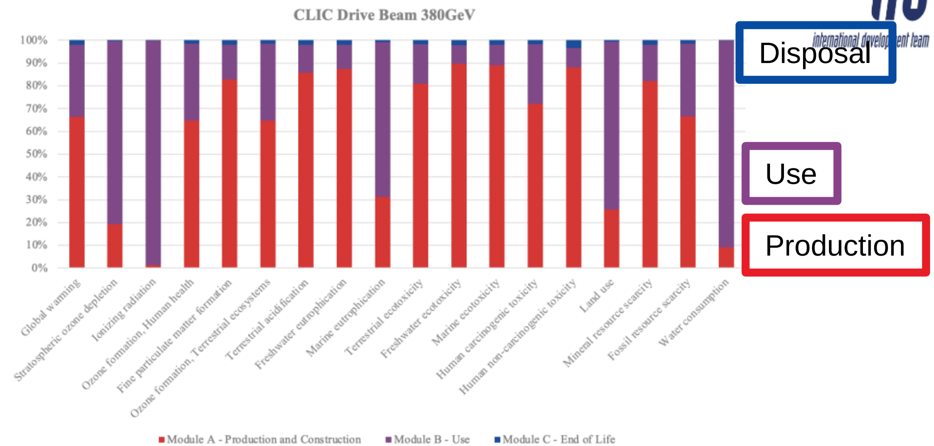
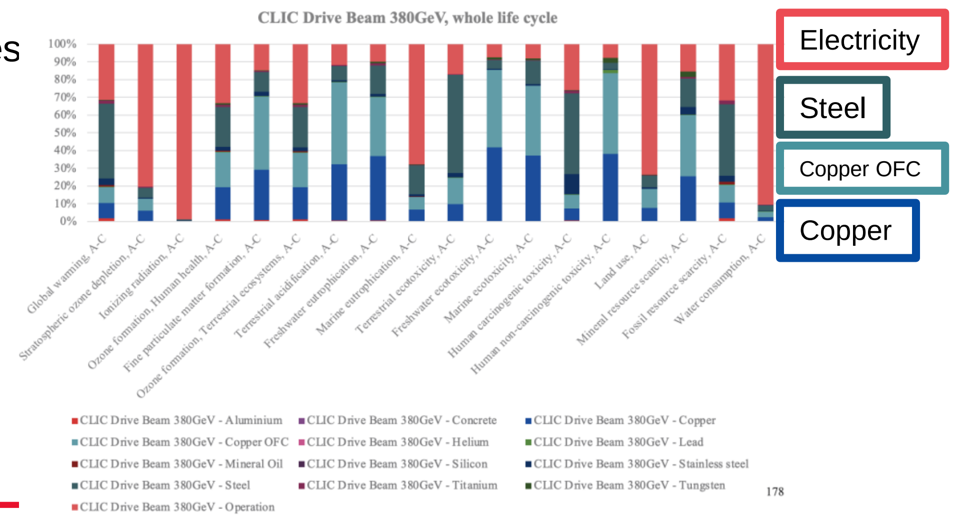
Whole lifecycle results for all ReCiPe 2016 indicators

- Example: **CLIC (drive beam option)**
- All 16 ReCiPe 2016 mid point indicators were evaluated
- Which lifecycle phase dominates the impact? –
  A: production and construction
  - result depends on emission factor for electricity!
- Which material dominates the impact?
  - Steel and copper
  - Operation (i.e. electricity) prominent for some categories
- Results vary significantly between impact categories – **which categories are the most important**?

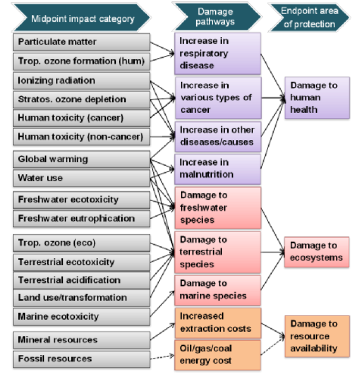


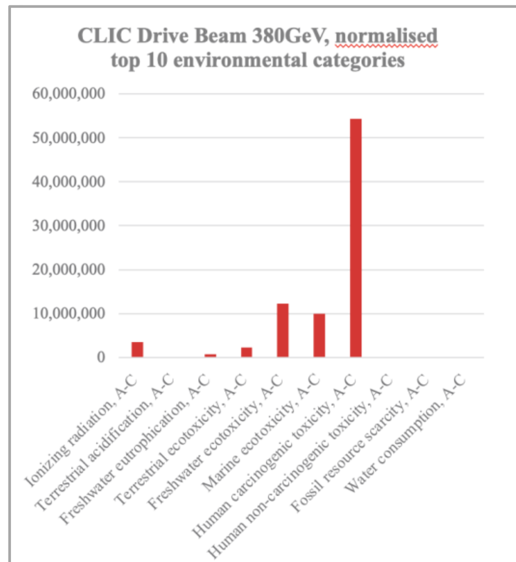


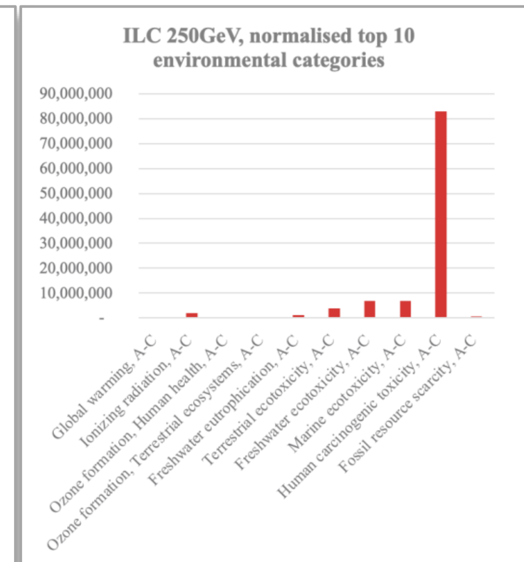
Weighting Impact Categories - Normalisation

- One approach: endpoint categories
  -> consider damage to
  - Human health
  - Eco systems
  - Resource availability
- Alternative approach:
  weight with global impact (per person)
  -> approach chosen here
- **Use ReCiPe World (2010) normalisation set**

- Human carcicogenic toxicity sticks out, followed by marine ecotoxicity and freshwater ecotoxicity
  -> **where does that come from?**

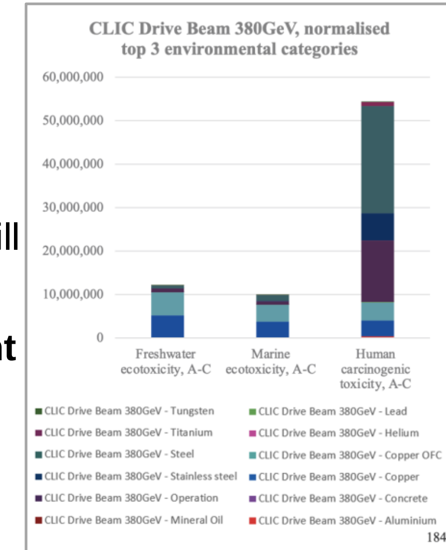


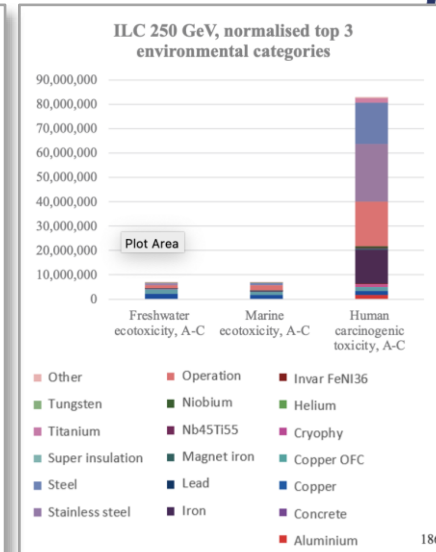




Hotspot analysis: Toxicity

- Toxicity dominated by **steel (incl. stainless steel),** followed by operation (i.e., electricity)
- Toxicity impact of steel dominated by **electric arc furnace slag**, which is deposited as landfill
- Hard to control in procurement process
- Choose suppliers with an **environmental commitment** and an **environmental management strategy**
- **Reduction potential is 90%**





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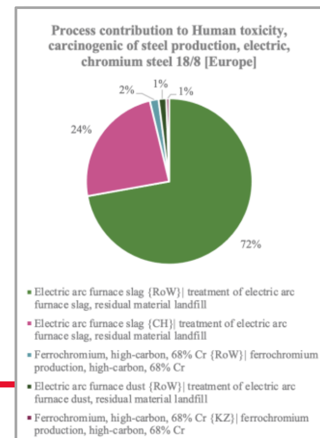
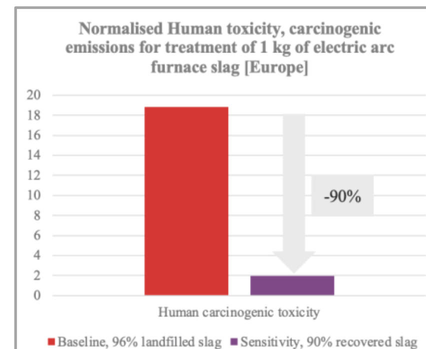
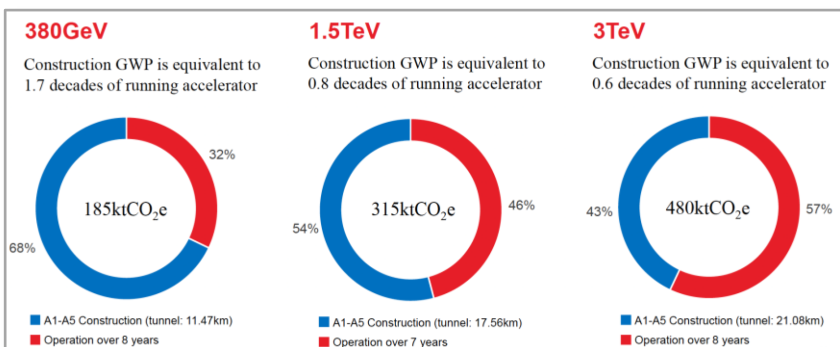
CC-BY-4.0 J.M. Terrones-Saeta et al.,
http://dx.doi.org/10.3390/ma14040782



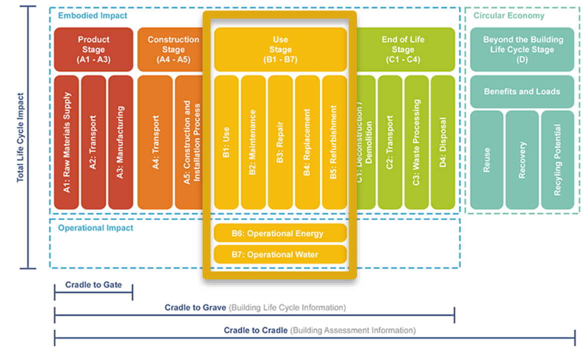


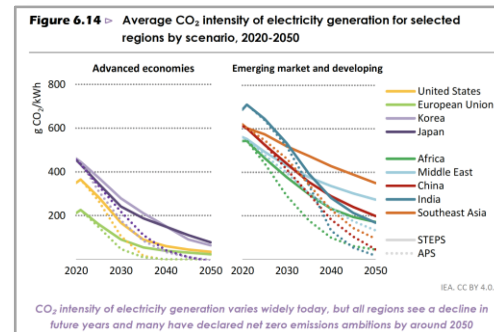
Operation

- Operation stage very important:
  Large CO2 emissions from electricity production
- Impact assessment depends on assumptions of future (reduction of) carbon intensity of electricity
  → common numbers would be helpful
- CLIC study indicates that 6 – 17 year of electricity cause as much CO2 as all tunnels/shafts/caverns
  - even at very low carbon intensity in France
- CLIC study in 2020 about running only on renewables (link):
  Energy can be provided, fluctuations require grid as buffer
  → **modulate operation (demand side flexibility)**
  → rapidly falling battery prices change the field,
  GWh size storage will be possible in 2030

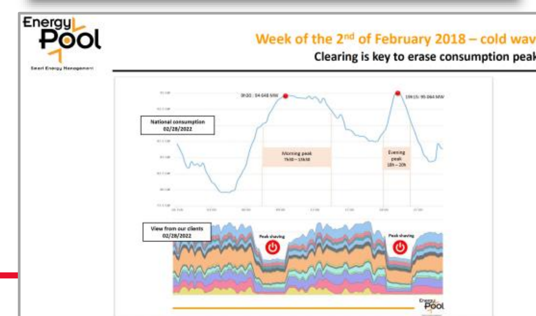


S. Evans, LCWS 2024





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



C. Gaunand, B. Remenyi: ESSRI 2022

Results: Scope 2 Emissions from Operation

- Define operational phases:
  - Shutdown – only static cryo load and HVAC, lighting etc
  - Downtime and technical stops: RF power off
  - Data taking: full power
  - Commissioning and machine development: 50% “data taking” and 50% downtime
- Use mixture of these modes to calculate overall energy consumption over the year
- Emission factors were updated:
  16 g CO_2-e / kWh for CERN in 2050
  81 CO_2-e / g/kWh for ILC in Japan in 2040:
  - 20% nuclear
  - 70% renewables (dedicated contracts)
  - 10% LNG

		Fraction of peak power			
Operational phase	days/year	LCF 250 LP	250 FP	550 LP	550 FP
Annual shutdown	120	28 %	18 %	28 %	25 %
Commissioning	30	77 %	72 %	75 %	72 %
Technical stops	10	54 %	45 %	50 %	44 %
Machine development	20	77 %	72 %	75 %	72 %
Downtime (faults)	46	54 %	45 %	50 %	44 %
Data taking	139	100 %	100 %	100 %	100 %

Table 4: Operational phase definition, with relative power consumption for each operation phase in relation to the nominal operating power assumed in the electricity consumption calculation.

arXiv:2503.24049

Overall result for ILC and LCF at CERN, and CLIC

- A comprehensive overview of GHG emissions from construction and operation
- Available for ILC in Japan
- Scaled / adapted for an LCF at CERN
  - Tunnels: emission factors for tunnels in Japan and CLIC tunnel in Geneva almost identical – keep
  - Scale up main linac and damping ring componentry for longer main linac and 3rd damping ring
- Reporting in the common format proposed by the LDG sustainability working group

	ILC 250	ILC 500	LCF 250 LP	LCF 550 FP
CoM energy [GeV]	250	500	250	550
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	1.35 / 2.7	3.6	2.7	7.7
Number of IPs	1		2	
Operation time for physics/yr [10^7 s/yr]	1.6		1.2	
Integrated luminosity/ yr [1/fb/ yr]	215 / 430	580	320	920
Host countries	Japan		France / Switzerland	
GHG emissions from construction, stages A1-A5				
Subsurface tunnels, caverns, shafts [kt CO_2e]	282	402	305	411
Accelerator (coll.) [kt CO_2e]	151	273	166	313
Accelerator (inj.) [kt CO_2e]	82	82	59	82
Detectors [kt CO_2e]	94		94	
Total [kt CO_2e]	609	851	624	900
Collider tunnel length [km]	21.5	33.5	33.5	
Collider tunnel diameter [m]	9.5		5.6	
Collider tunnel GHG / m [t CO_2e/ m]	8.6		8.5	
Concrete GHG [kg CO_2e/ kg] / [kg CO_2e/ m^3]	0.16 / 400 (C25/30)		0.16 / 400 (C25/30)	
Main Linac accelerator GHG / m [t CO_2e/ m]	5.3		5.3	
GHG emissions from operation				
Maximum power in operation [MW]	111 / 138	164	143	322
Annual electricity consumption [TWh/ yr]	0.7 / 0.9	1.1	0.8	1.8
Reference year of operation	2040	2040	2050	2050
Carbon intensity of electricity [g CO_2e/ kWh]	81	81	16	16
Average Scope 2 emissions / yr [kt CO_2e]	59 / 74	87	13	28

Table 6: Data on GHG emissions for the ILC project in Japan and the Linear Collider Facility proposal for CERN. These are baseline numbers, before application of possible CO_2 reduction measures.

arXiv:2503.24049

CLIC	Stage 1	Stage 2	Reduce by 2040-50
CoM energy [GeV]	380	1500	
Luminosity/IP [10^{34}cm^{-2}s^{-1}]	4.5	3.7	%
Number of IPs	2	1	
Operation time for physics/yr [10^7s/yr]	1.2		
Integrated luminosity/ yr [1/fb/ yr]	540	444	
Host countries	France and Switzerland		
GHG emissions from construction, stage A1-A5			
Subsurface structures incl. tunnel services [kt CO2 eq.]	152	199	40-50
Surface sites and constructions [kt CO2 eq.]	in progress	NC	40-50
Accelerator (coll.) [kt CO2 eq.]	56	NA	in progress
Accelerator (drivebeam and inj.) [kt CO2 eq.]	118	NC	in progress
Two detectors [kt CO2 eq.]	90-120		NA
Total [kt CO2 eq.]			
Collider tunnel length [km]	11.5	29.1	
Collider tunnel diameter [m]	5.6		
Collider tunnel GWP /mt CO2 eq/m]	8.1		
Concrete GWP [kg CO2 eq./kg]	0.16		
Accelerator GWP / mt CO2 eq./m]	Not estimated		
GHG emissions from operation			
Maximum power in operation [MW]	166	287	
Average power in operation [MW]			
Electricity consumption / yr [TWh/ yr]	0.82	1.40	
Years of operation	10	10	
Carbon intensity of electricity [g CO2 eq./ kWh]	16		Estimate for 2050
Average Scope 2 emissions / yr [kt CO2 eq.]	13	22	Estimate for 2050

Table 8: Data on GWP for the CLIC project. These numbers are are based on the reports (one still in draft) mentioned above and will be further developed. NC means No (or small) Changes. NA refers to Not Available (outside the scope of present studies).

arXiv:2503.24168

Some conclusions

Accelerators are generally optimised for physics performance, costs, schedule and power consumption

Sustainability goals suggest the lifecycle approach, addressing for example carbon footprint and material use from construction to decommission, and integration in the local communities (water, landscaping, traffic, waste, etc)

- Changes the optimisation and also provides new opportunities

A recipe for a sustainable facility:

- Reduce size
- Reduce power consumption, understand/selects all materials being used carefully
- Integrate within local communities
- Use low carbon and renewable power, CO2 compensate
- Use the facility for a long time and understand its life cycle

Thank you

Many thanks to
Steffen Doebert, Steinar Stapnes, Thomas Schörner-Sadenius, Maxim Titov, Shin Michizono, Takayuki Saeki, Nobuhiro Terunuma, Tomoyuki Sanuki, John Osborne, Liam Bromiley, Suzanne Evans, Yung Loo, Igor Syratchev, Ben Shepherd, Caterina Vernieri, Sergey Belomestnykh, Masakasu Yoshioka, and many others

Sustainability: What It Is…

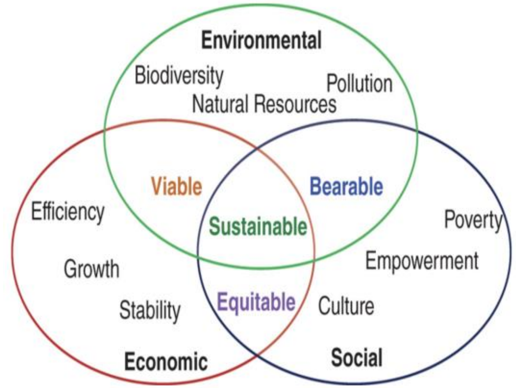
Cover of the “Brundtland Report” 1987

Gro Harlem Brundlandt at WEF 1989

*Development that meets the **needs of current generations without compromising the ability of future generations** to meet their needs and aspirations*. (WCED, 1987)

WCED (World Commission for Environment and Development) (1987) *Our Common Future*, Oxford University Press, Oxford.

https://sdgs.un.org



R.Y. Surampalli et al. (eds), Sustainability. Wiley 2020.

Three aspects:

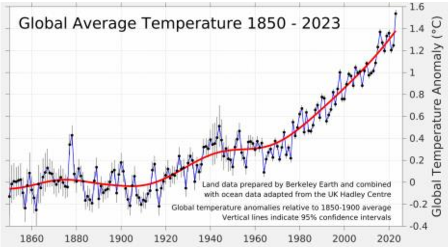
- environmental
- economical
- social

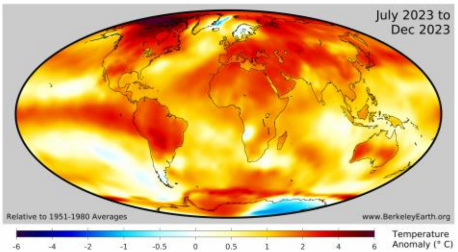
… and Why It Matters

Climate is Warming

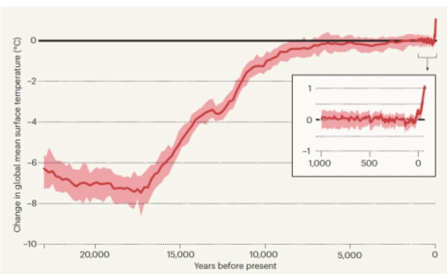
Faster than ever, leading to the highest temperatures in the last 125000 years

https://berkeleyearth.org/global-temperature-report-for-2023/





Nature **599**(2021)208.

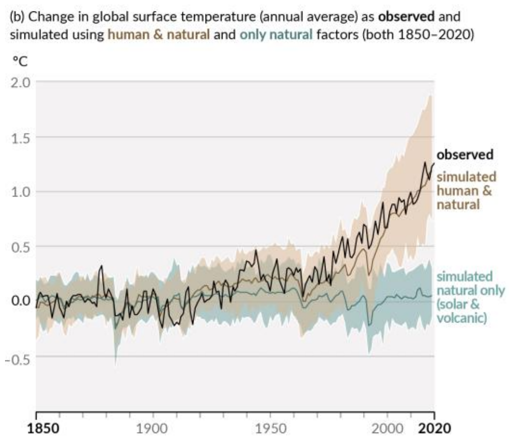


Due to Anthropogenic Greenhouse Gas Emissions

In particular CO_2 and methane

*It is **unequivocal** that **human influence** has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.*

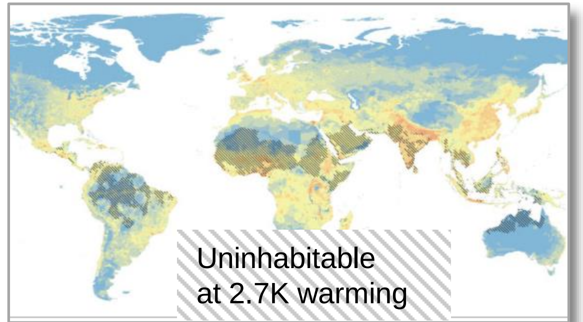
IPCC AR6

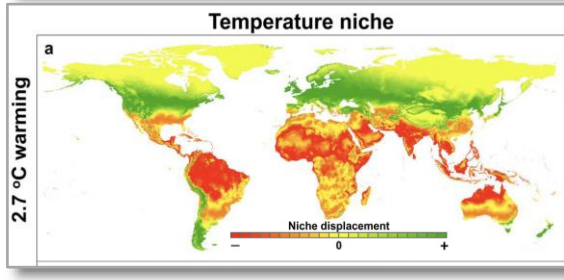


IPCC AR6 WG1 SPM, Fig SPM 1
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf

With Negative Consequences

Making habitable regions uninhabitable, leading to famine, heat deaths and causing mass migration



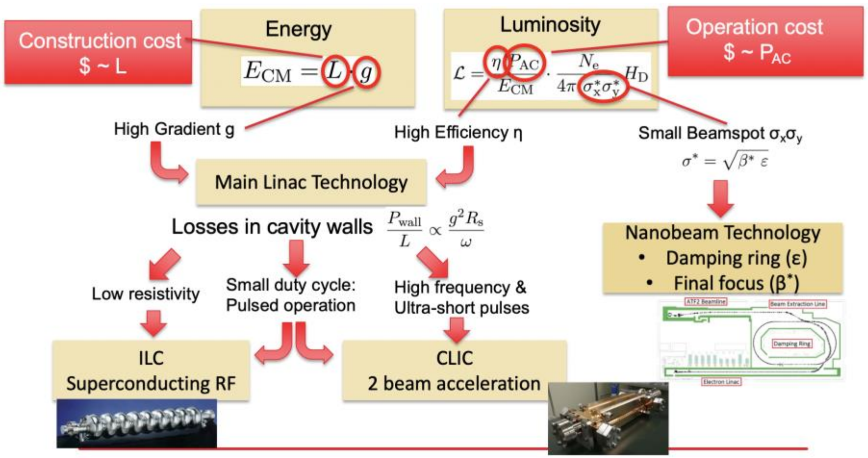


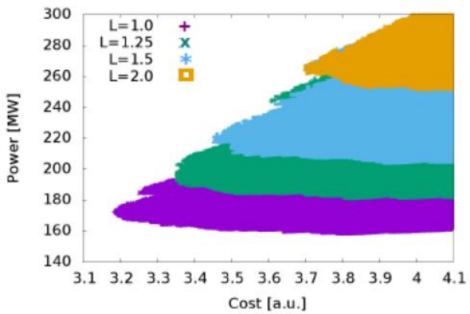
Nat. Sust. **6** (2023) 1237.

Extreme heat killing more than 100 people in Mexico hotter and much more likely due to climate change

worldweatherattribution.org/

Overall System Design





Optimisation at CLIC: Parameter scan

- Challenge: Achieve target **energy** and **luminosity** with least possible amount of **resources**
- Conserve resources for construction:
  - compact -> high acceleration gradient
- Conserve ressources in operation:
  - Energy-efficiency (limit losses in cavity walls): superconducting RF – ILC high frequency & ultra-short pulses: CLIC
  - Effectiveness: maximum luminosity per charge -> nanobeam technology
- ILC and CLIC:
  - different solutions to the efficiency problem
  - Final power consumption similar

Inherent tension between invest and operation requires a quantitative approach:

Lifecycle Assessment

Optimisation of Components and Subsystems

Win-Win:

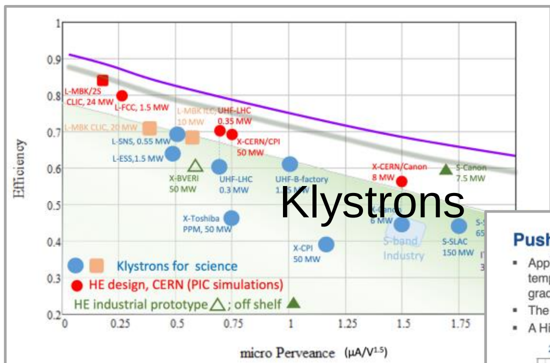
Better performance through better technology at same or lower cost

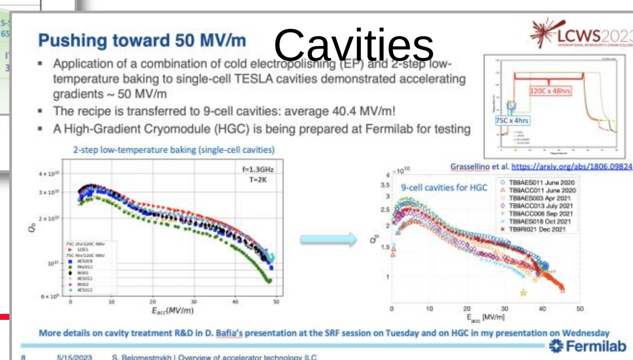
- High efficiency klystrons through better electron optics → pushing to 85% efficiency
- Cavities with higher gradient and lower losses → pushing for >45MV/m (ILC baseline: 35MV/m)

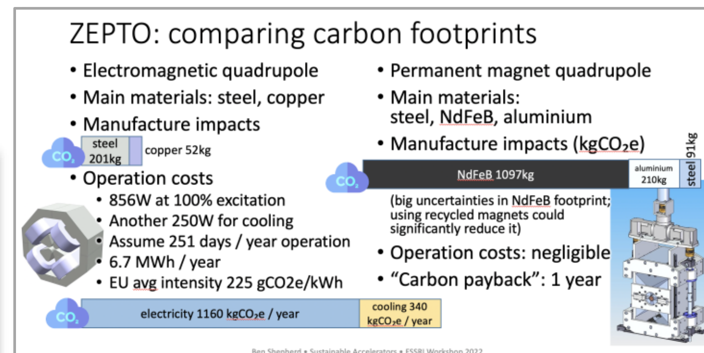
Trade-off:

Difficult: lower operating cost through higher invest / higher initial impact: needs trade off studies → LCA

- Example permanent magnets:
  - Save CO2 from electricity during operation
  - Materials used in production, esp. rare earths, have high impact
  - ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory, made an analysis:
    in case considered, production CO2 is amortized in 1 year







B. Shepherd, LCWS 2023

Greenhouse Gas Emissions over the Full Lifecycle

Towards Carbon Accounting with LCA

This is for 11 km of tunnel, scales with length