Sustainability for future colliders

TopLHCFrance
30/04/25

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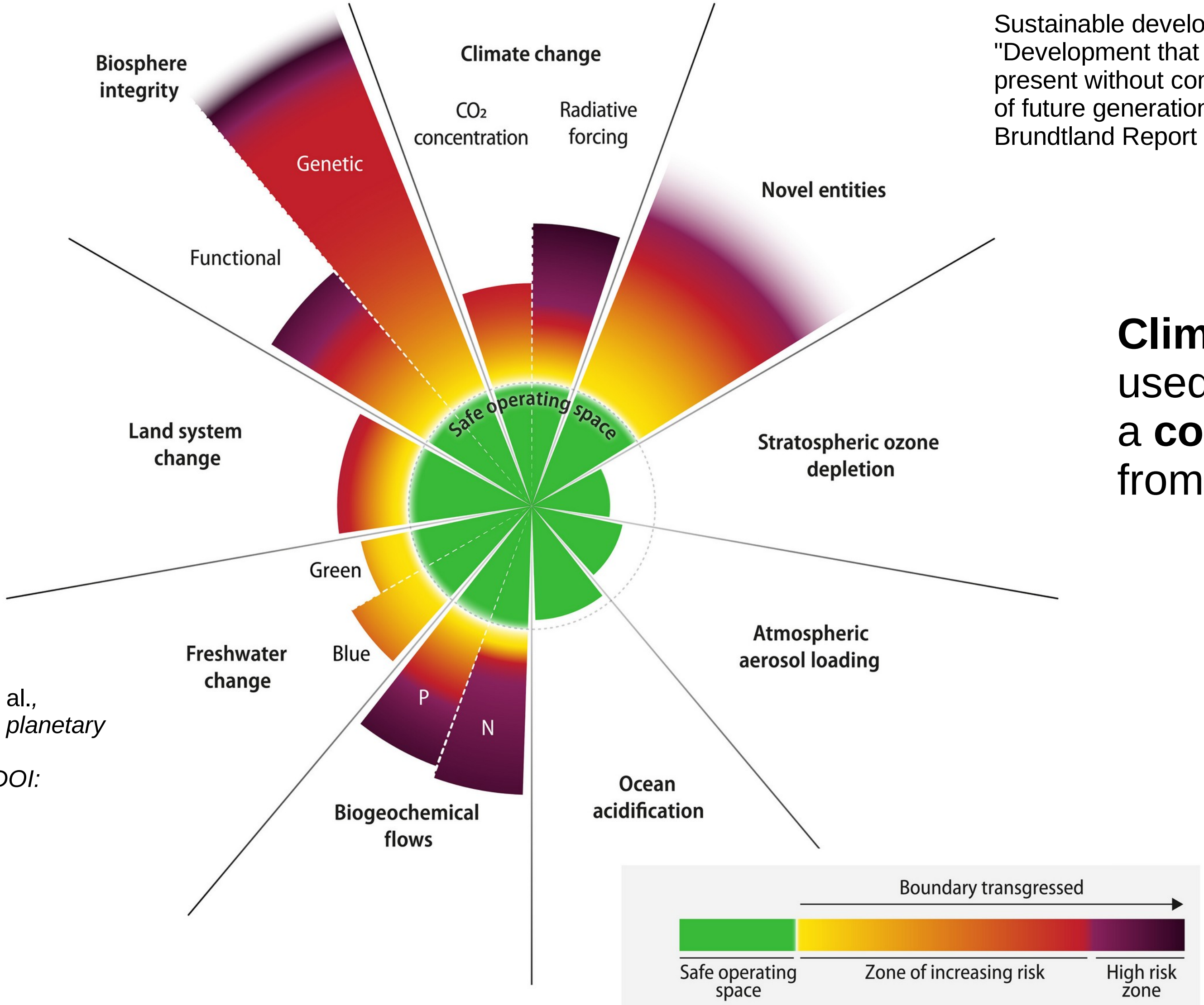
CNRS NUCLÉAIRE & PARTICULES

LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

Sustainability = be within planetary boundaries

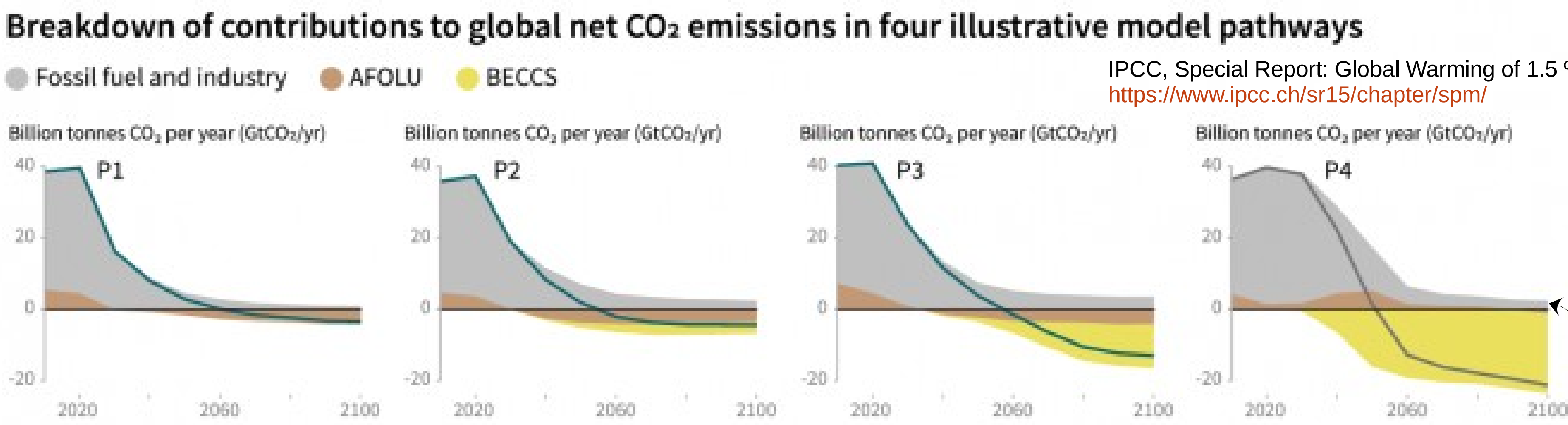


Sustainable development:
"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs"
Brundtland Report (1987) for UN

Climate change
used as
a **convenient proxy**
from now on...

Katherine Richardson et al., *Earth beyond six of nine planetary boundaries.Sci. Adv.9,eadh2458(2023).DOI:* *10.1126/sciadv.adh2458*

Climate change & society – in 1 slide



IPCC, Special Report: Global Warming of 1.5 ºC, 2018
https://www.ipcc.ch/sr15/chapter/spm/

=2t/pers

- The longer we wait to reduce our CO2 emissions, the more carbon capture (CC) technology will be needed

- Neutrality needed by ~2050

- CC techs are not yet ready or are expensive

- Carbon budget (to stay <2°C, with 50% chance) : 200GtCO_2eq (starting from early 2023)

Forster et al., 2024, Earth System Science Data

Life Cycle Assessment/Analysis

- LCA very useful to reduce env. footprint of project during R&D
  - Estimate impacts in terms of C, water consumption, ozone, ...
- New CERN course:
  https://lms.cern.ch/ekp/servlet/ekp?PX=N&TEACHREVIEW=N&CID=EKP000044552&TX=FORMAT1&LA

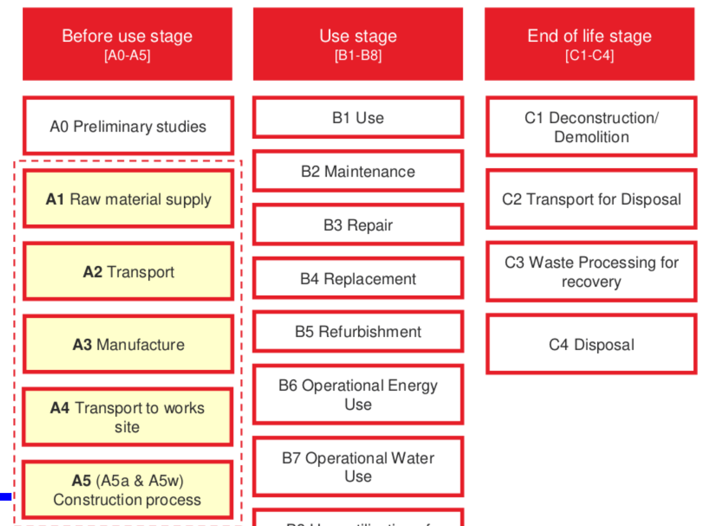
Introduction to Environmental Life Cycle Assessment (LCA) for Engineers (e-learning)

Accéder à la session

This e-learning provides an **introduction to Life Cycle Assessment (LCA)**, a detailed method for evaluating the environmental impacts of products throughout their entire life cycle, from raw material extraction to disposal. The primary objective of this course is to build your knowledge and skills in the Life Cycle Assessment, enrich the theoretical part of LCA, and understand how to use this in your work.

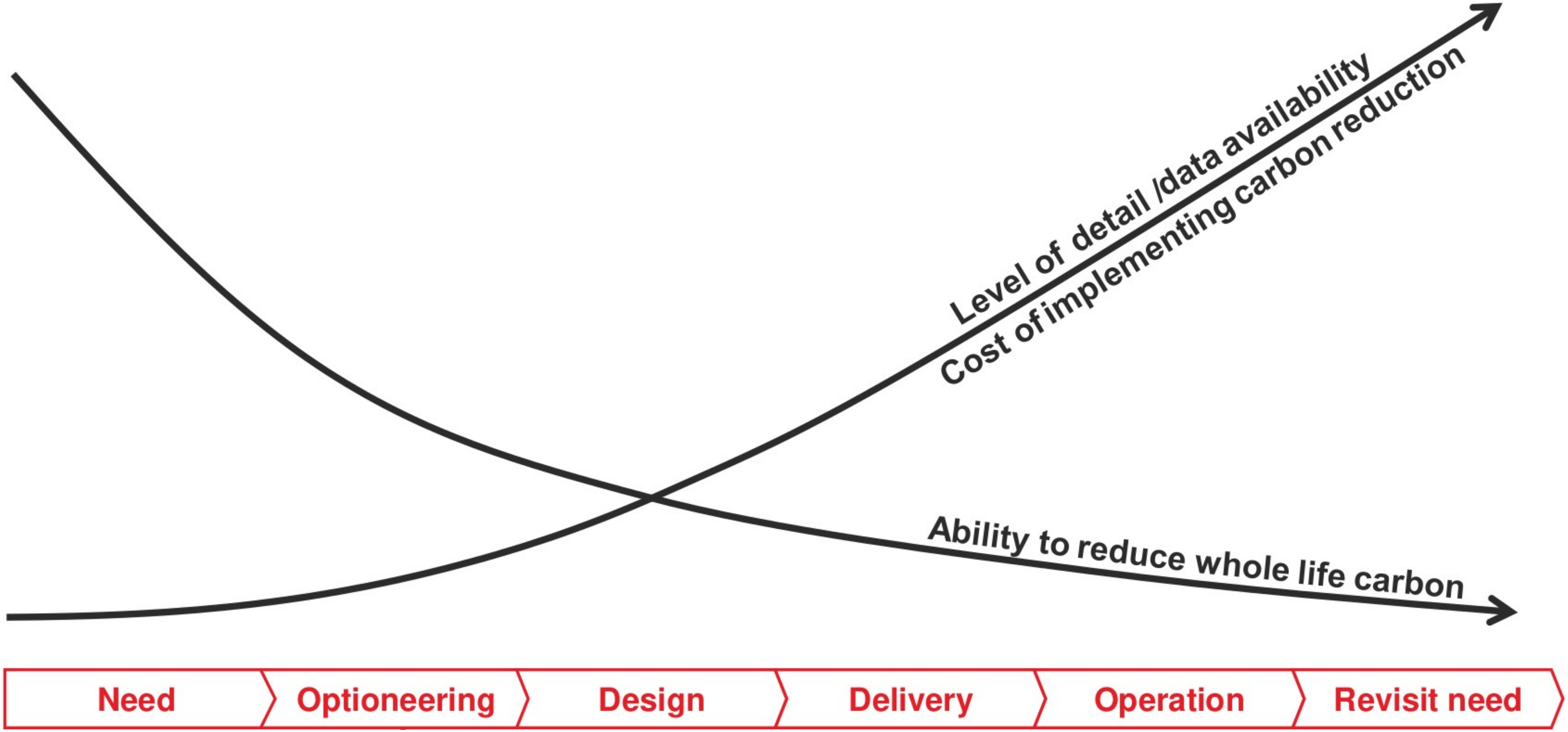
- ActionNationaleFormation "eco-conception" (CNRS)
  - IN2P3/INSIS
  - 12-17/10/2025
  - For engineers/physicists
  - Registration will open in May

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



Scope of LCA

The key plot



You are here

From CLIC&ILC ***Life Cycle Assessment (LCA)***

What are the main ingredients for a collider ?

Environnemental footprint = tunnel

+ accelerator construction
+ accelerator operation

$$\left.\begin{array}{l} + \text{ detector construction} \\ + \text{ detector operation} \\ + \text{ computing} \\ + \text{ collaboration life} \end{array}\right\} \text{x } N_{\text{experiments}}$$

What are the main ingredients for a collider ?

Environnemental footprint = tunnel
+ accelerator construction
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+ detector construction
+ detector operation
+ computing
+ collaboration life

$\left.\begin{array}{l}\text{+ detector construction} \\ \text{+ detector operation} \\ \text{+ computing} \\ \text{+ collaboration life}\end{array}\right\} \times N_{experiments}$

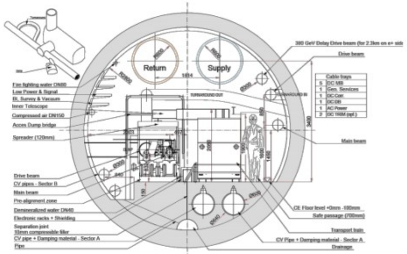
Today: 35tCO_2eq/year/LHC physicist when LHC is running
(not accounting for travels, WLCG, ...)

Tunnel (@LO)

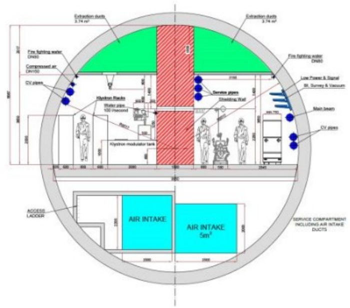
Main parameters:

length, profile : amount of concrete and steel

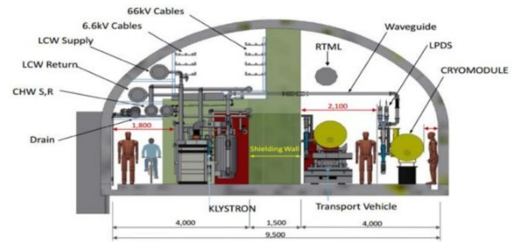
11-50km



CLIC Drive beam, 5.6m dia.
Geneva
Energies: 380GeV, 1.5TeV, 3TeV.



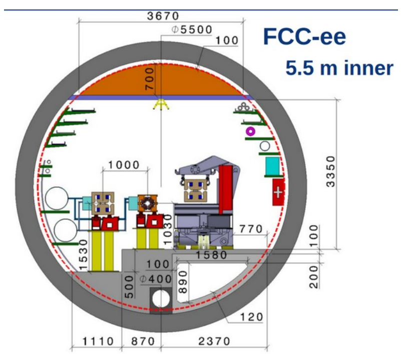
CLIC Klystron, 10m dia.
Geneva
Energies: 380GeV



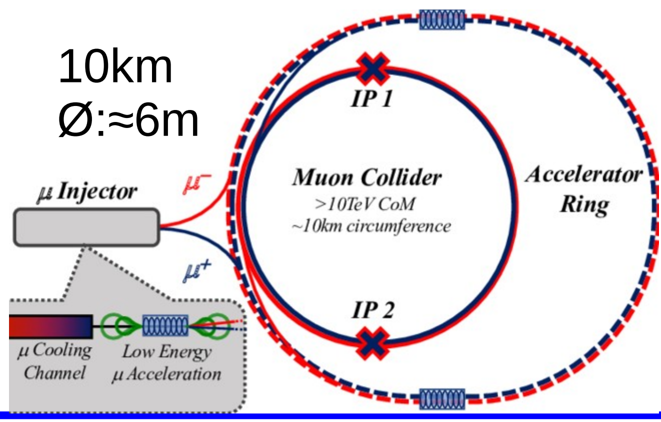
ILC, 9.5m span
Tohoku Region, Japan
Energies: 250GeV

33km

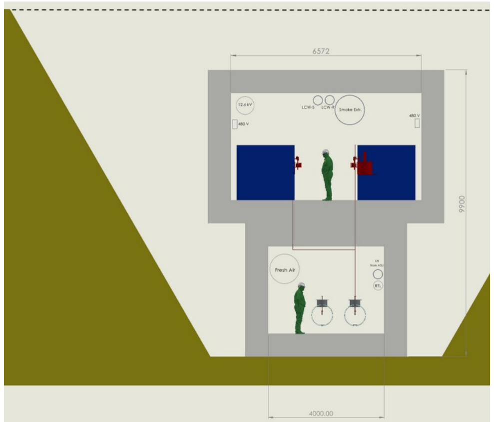
90km



10km
Ø:≈6m

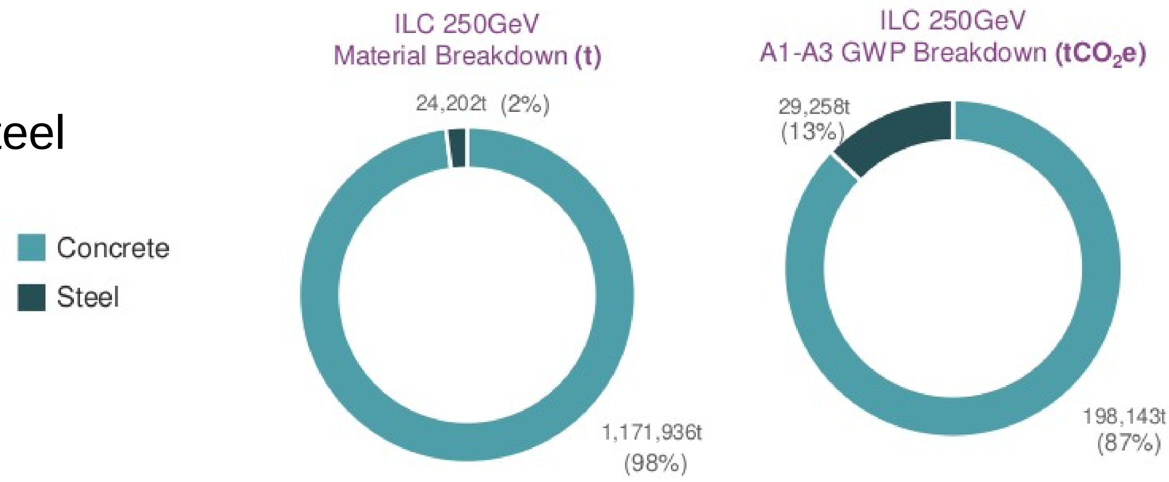


CCC
8km
T=80K



Tunnel (LO) + everything related to it (NLO)

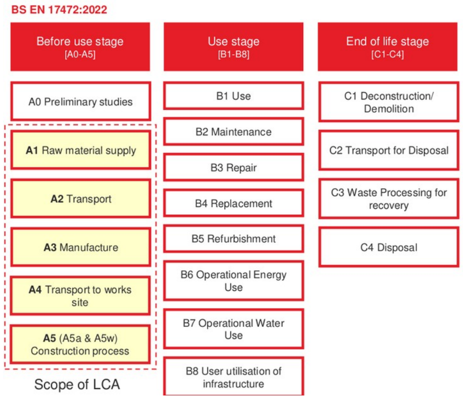
Ex: ILC
- CEMI concrete
- 80% recycled steel



Project	Main tunnel length (km)	GWP (kton CO_2e) Main tunnel	+ other structures	+ A4-A5	
FCC	90.6	578	751	939	+60%
CEPC	100	638	829	1040	
ILC	13.3	97.6	227	266	+170%
CLIC	11.5	73.4	98	127	+70%
C^3	8.0	133	133	146	+10%

From https://arxiv.org/abs/2307.04084
FCC&CEPC: rough estimates from CLIC LCA!

A4-A5: transport + construction process

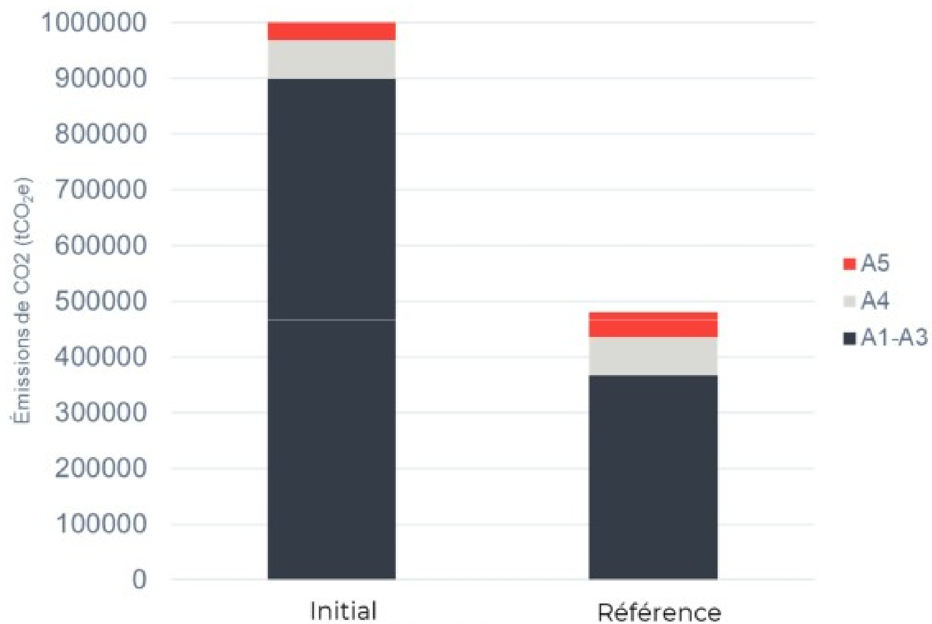


Tunnel @NLO

- FCC LifeCycleAnalysis:
  big impact of concrete and steel types

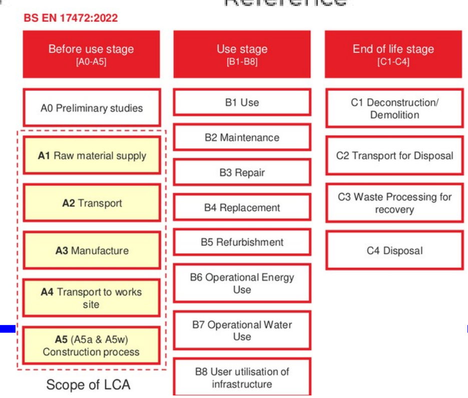
Matériaux de référence dans l'outil OneClickLCA	Émission CO_2	Fournisseurs locaux avec une proposition équivalente	Réduction par rapport au matériau initial
Steel sheets, generic, 100% recycled content, S235, S275 and S355	0.87 $kgCO_2e/kg$	Sottas Morand	77%
Steel fibre for concrete reinforcement, 100% recycled content	0.51 $kgCO_2e/kg$	Sottas	75%
Reinforcement steel (rebar), generic, 100% recycled content, A615	0.42 $kgCO_2e/kg$	Stahl Sottas	70%
Ready-mix concrete, normal strength, generic, C35/45 (5000/6500 PSI) with CEM III/A (340 kg/m^3)	170.36 $kgCO_2e/m^3$	Probéton Vigier Holcim	48%
Ready-mix concrete, low-strength, generic, C12/15 (1700/2200 PSI) (220 kg/m^3)	149.41 $kgCO_2e/m^3$	Probéton Vigier Holcim	31%
Ready-mix concrete, normal-strength, generic, C40/50 (5800/7300 PSI) with CEM III/B,	173.00 $kgCO_2e/m^3$	Probéton Vigier Holcim	39%

Calcul initial	Scénario de référence
999 780 tCO_2(eq)	477 390 tCO_2(eq)
Réduction	52%



Possible k-factor of 0.5

But need to check ...
- the scaling up with industry
- the cost
- the timescale

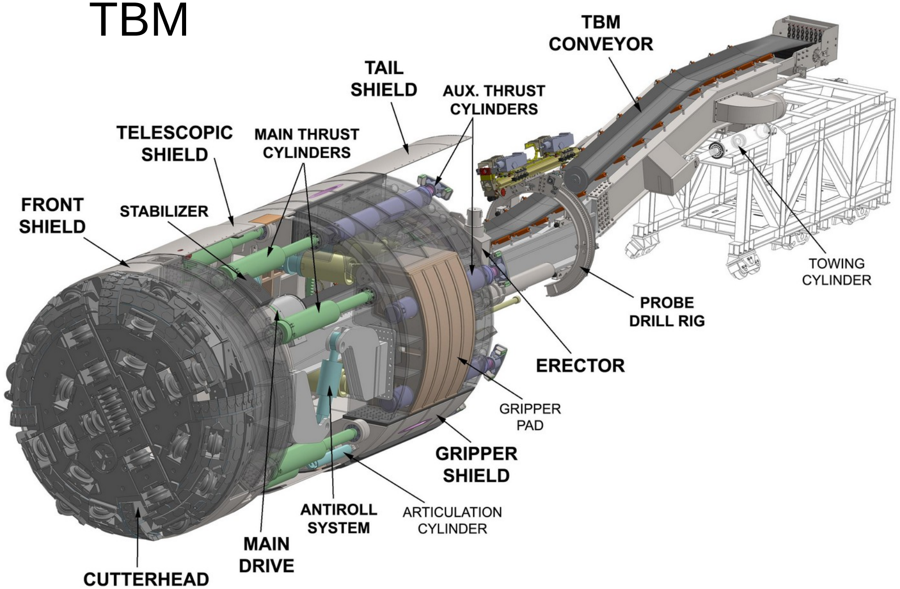


Tunnel @NLO

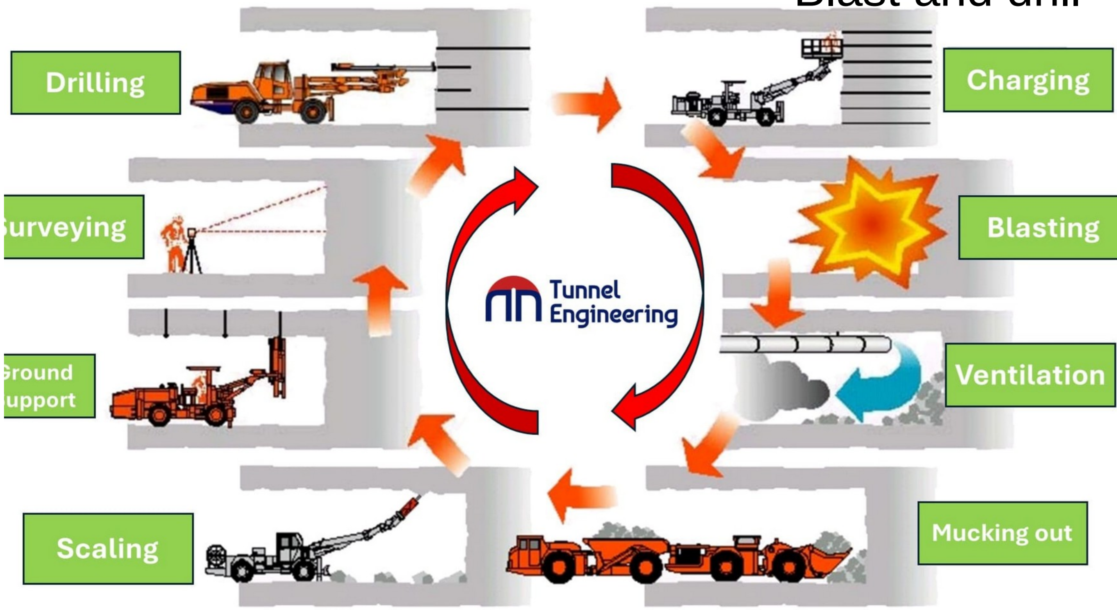
Main parameters:

length, profile : amount of concrete and steel, **technology**

TBM



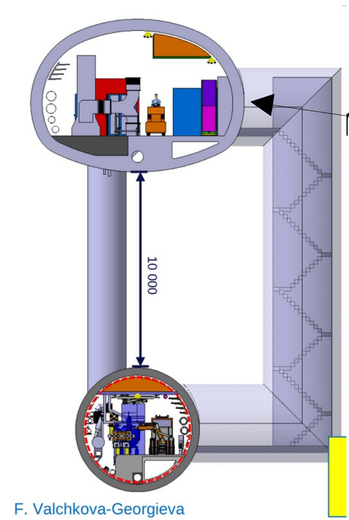
Blast and drill



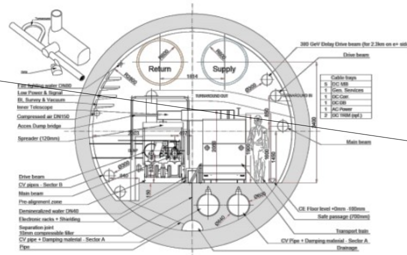
Tunnel @NLO

Main parameters:

- length, profile : amount of concrete and steel, technology
- Klystron isolation, number of shafts, caverns



F. Valchkova-Georgieva



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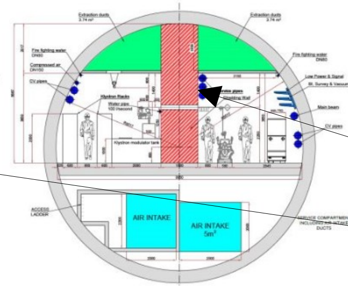

CLIC Klystron, 10m dia.

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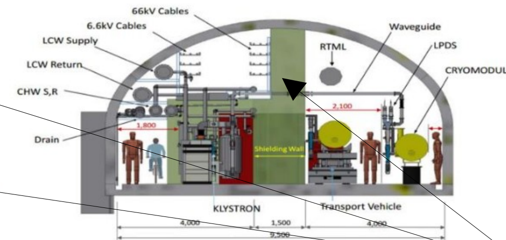
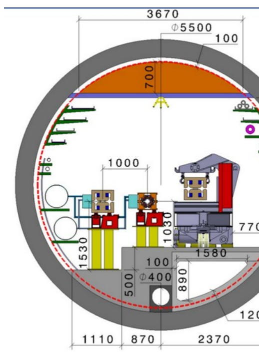


ILC, 9.5m span

Tohoku Region, Japan

Energies: 250GeV

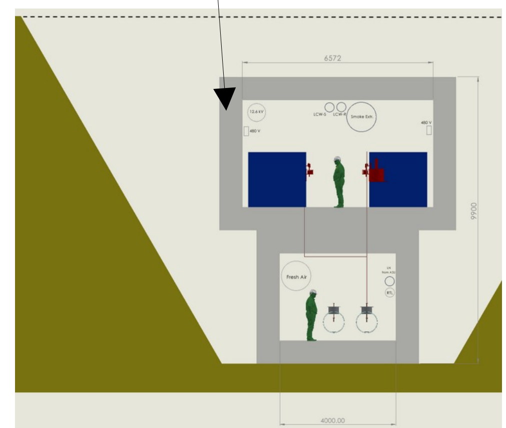
Isolate the beams from klystron's heat and electromagnetic noise



FCC-ee

5.5 m inner

CCC
8km
T=80K



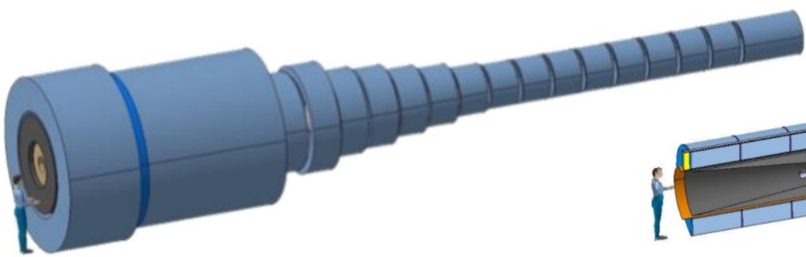
Accelerator construction

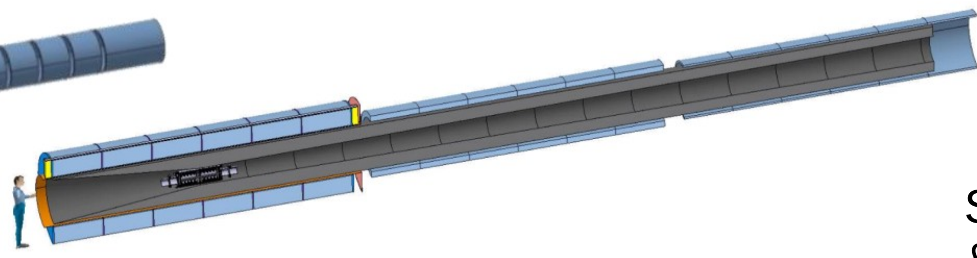
- Could not not find a lot of evaluations...
- Interesting one: muon collider

Future accelerator technologies?
High Temperature Superconductors

International MUON Collider Collaboration

Target & Capture Solenoids for the Muon Collider





Save energy
& materials

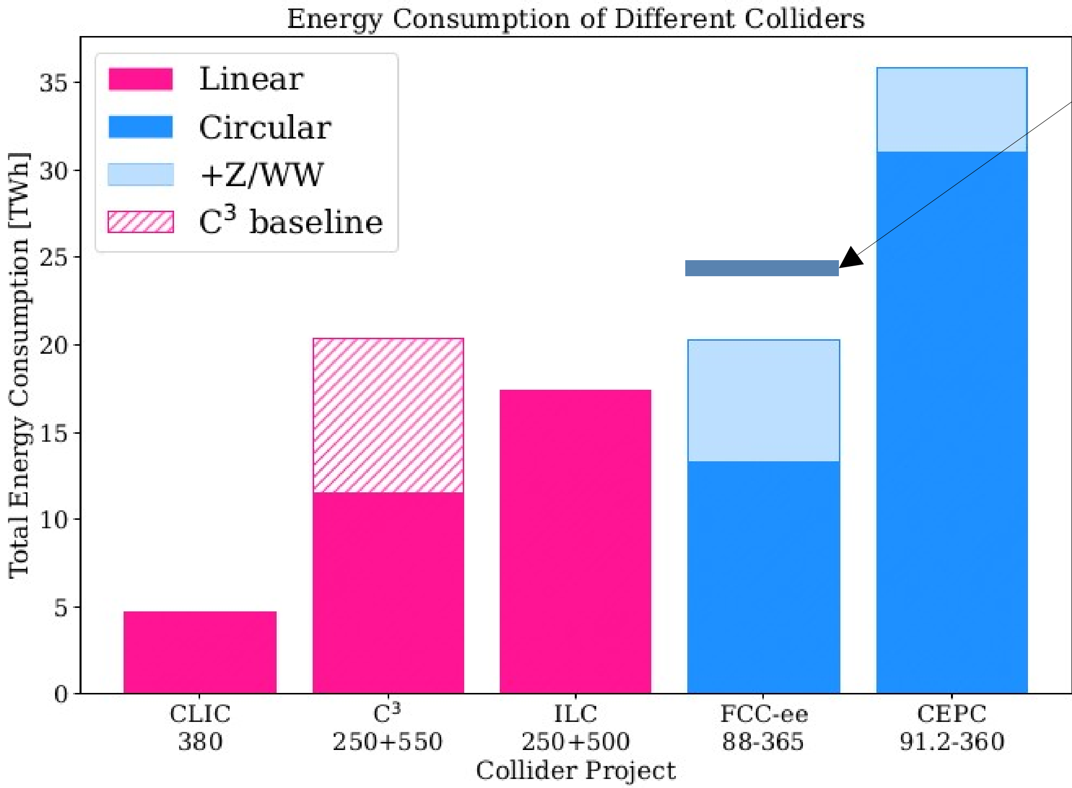
US-MAP
Proposal
(<2016)

E_M = 2.9 GJ
T_{op} = 4.2 K
M_{coils} = 200 tons
M_{shield} = 300 tons
P = 12 MW

EM = 1 GJ
Top = 10…20 K
Mcoils = 110 tons
Mshield = 196 tons
P = 1 MW

IMCC
Proposal
(2023)

Accelerator operations

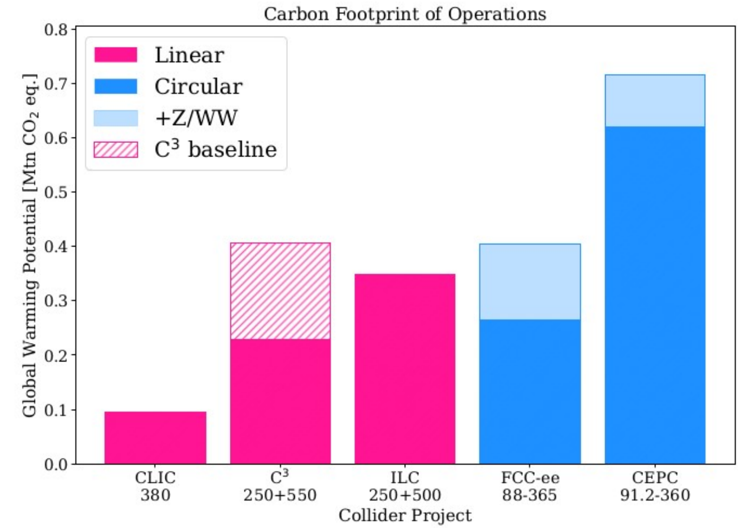


From J.P Burnet (sept 2024)

https://agenda.ciemat.es/event/4431/timetable/#20240926.detailed

To compare with 1.2TWh/year of present total CERN consumption

From https://arxiv.org/abs/2307.04084



Higgs factory	CLIC [40]	ILC [12]		C^3 [11]		CEPC [53], [54]				FCC [20], [55], [56]					
$\sqrt{s}$ (GeV)	380	250	500	250	550	91.2	160	240	360	88,91,94		157,163	240	340-350	365
P (MW)	110	111	173	150 (87)	175 (96)	283	300	340	430	222		247	273	357	
$T_{\text{collisions}}$ (10^7 s/year)	1.20	1.60		1.60		1.30				1.08					
T_{run} (years)	8	11	9	10	10	2	1	10	5	2	2	2	3	1	4
$\mathcal{L}_{\text{inst}}$/IP ($\cdot 10^{34}$ cm^{-2} s^{-1})	2.3	1.35	1.8	1.3	2.4	191.7	26.6	8.3	0.83	115	230	28	8.5	0.95	1.55
$\mathcal{L}_{\text{int}}$ (ab^{-1})	1.5	2	4	2	4	100	6	20	1	50	100	10	5	0.2	1.5

Accelerator operations

- Lots of developments on going. For example, a French one:

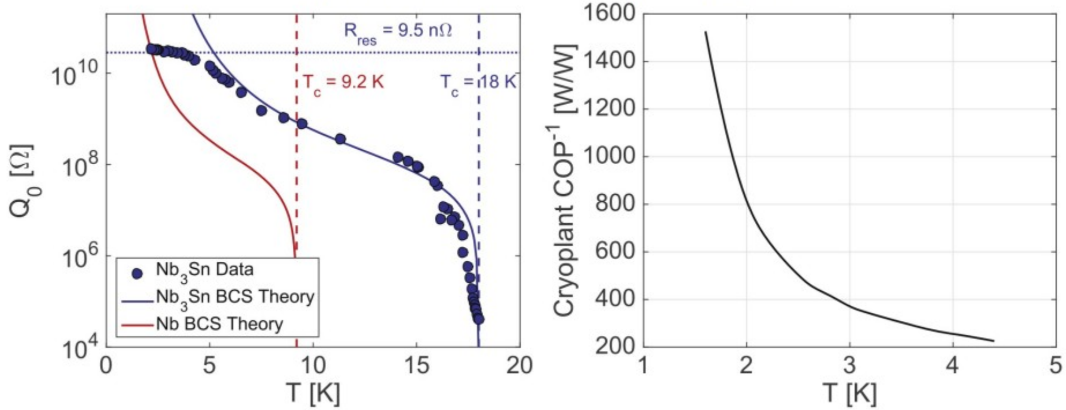
iSAS *develops, prototypes & validates SRF energy-saving technologies*

TA#2: energy-savings from cryogenics

The objective is focused on the development of thin-film cavities and aims to transform conventional superconducting radio-frequency technology based on off-shelf bulk niobium operating at 2 K, into a technology operating at 4.2 K using a highly functionalized material, where individual functions are addressed by different layers.

iSAS will optimize the coating recipe for Nb_3Sn on copper to optimize tunability and flux trapping of thin-film superconducting cavities and to validate a prototype beyond the achievements of the ongoing Horizon Europe I.FAST project, and the various US-based achievements (e.g., GARD).

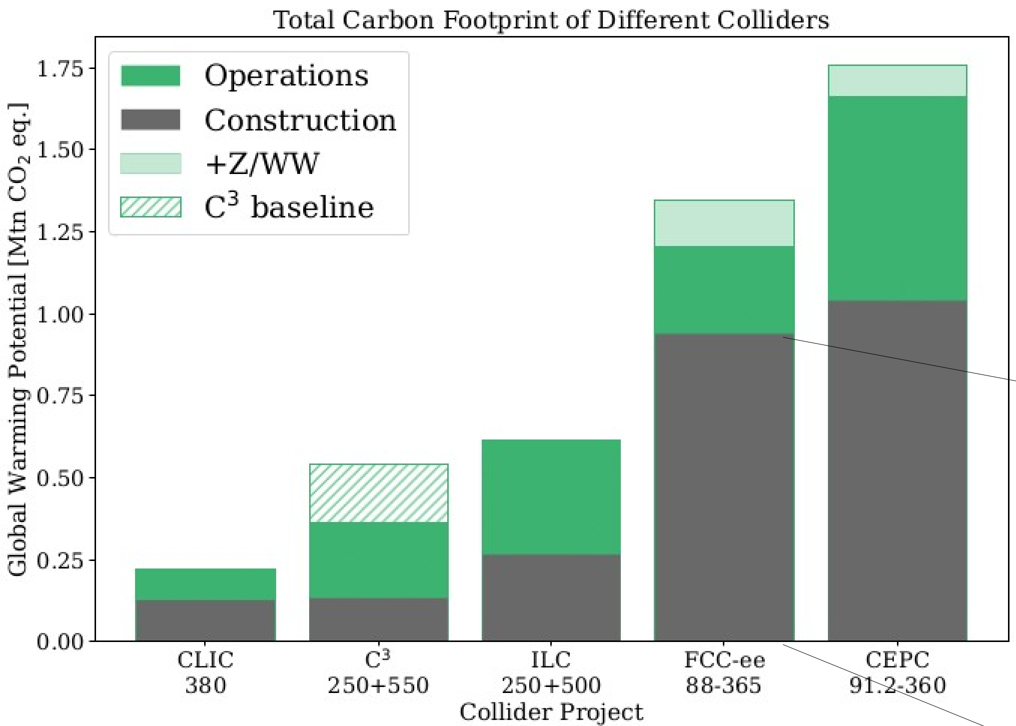
Supercond. Sci. Technol. 30 (2017) 033004



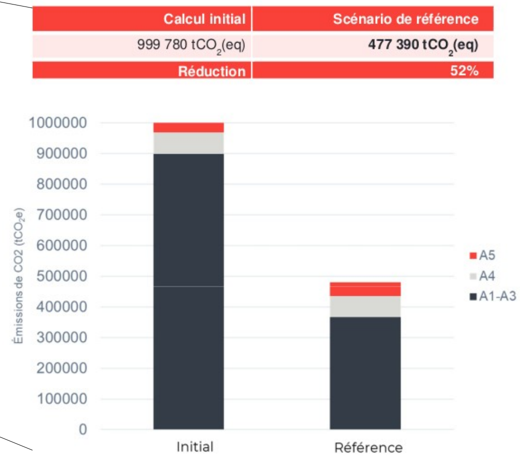
The higher critical temperature (T_c) of Nb_3Sn allows for the maximum value of quality factor Q_0 for 1.3 GHz cavities to be achieved at operating temperatures of about 4 K compared to 2 K for Nb (left figure). The graph on the right shows the efficiency of a cryogenic plant (COP) as a function of temperature achieving about 3 times higher COP efficiency when operating at a temperature of 4.2 K than at 2 K. This suggests that operating a cryogenic plant at 4.2 K with Nb_3Sn SRF cavities, can lead to significant better performances and energy savings.

https://agenda.ciemat.es/event/4431/contributions/5058/

Tunnel + accelerator operation (wo/ building accelerator!)



Present estimates give similar order of magnitude between these 2 items
Sum = O(0.5-1)MtCo2eq



Detector construction

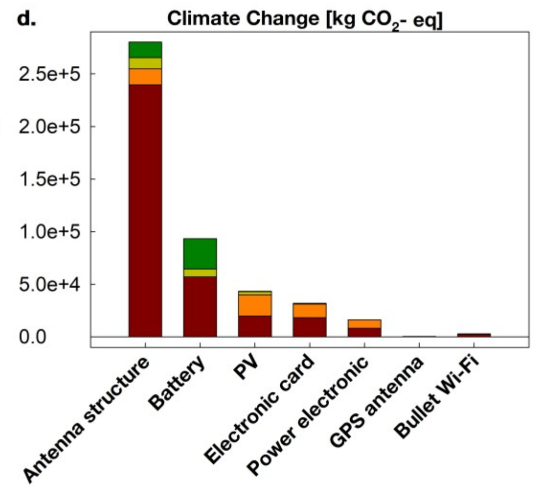
Radiotelescope array

- **No data yet !**
- Nice example of LCA :

Life Cycle Analysis of the GRAND Experiment

Leidy T. Vargas-Ibáñez[a,b], Kumiko Kotera[c,d], Odile Blanchard[e], Peggy Zwolinski[a], Alexis Cheffer[f], Mathieu Collilieux[f], Paul Lambert[f], Quentin Lefèbvre[f], Thomas Protois[f]

https://arxiv.org/abs/2309.12282



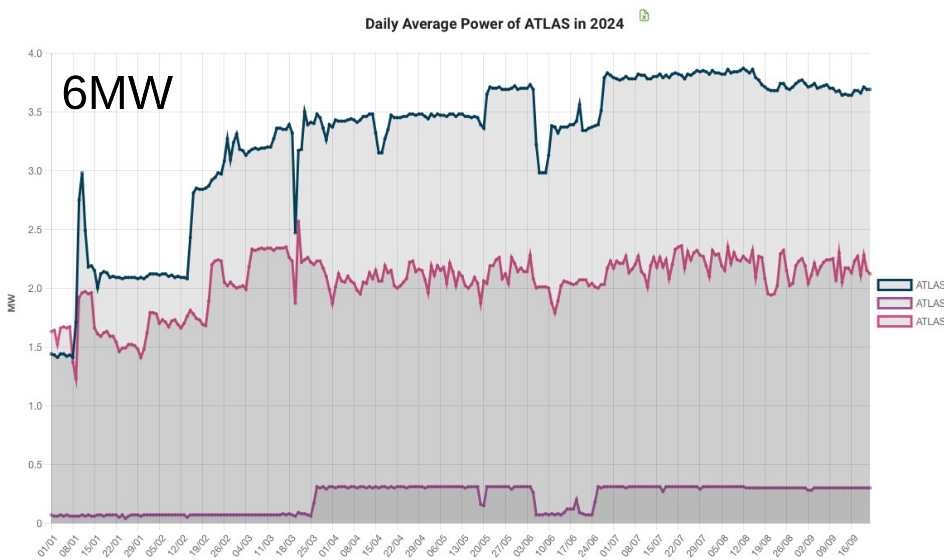
Antenna structure	Raw material production (extraction)	Total/net (including all components and processes)	AAPD* (%)
	Climate Change [kg CO2eq]		
Base case X5CrNiMo18 (316)	239649.43	282015.80	
Alloy 1 X5CrNi18 (304)	229170.75	268695.30	4.72
Alloy 2 X20Cr13 (420)	146834.08	186358.63	33.92
Stainless Steel (secondary)	56667.74	91552.11	67.54
	Ressource use, fossils [MJ]		
Base case X5CrNiMo18 (316)	3290049.95	3678502.85	
Alloy 1 X5CrNi18 (304)	3146177.23	3493535.40	5.03
Alloy 2 X20Cr13 (420)	1999582.65	2346940.82	36.20
Stainless Steel (secondary)	908311.97	1385277.37	62.34
	Ressource use, minerals and metals [kg Sb eq]		
Base case X5CrNiMo18 (316)	11.60	11.60	
Alloy 1 X5CrNi18 (304)	1.94	1.94	83.30
Alloy 2 X20Cr13 (420)	3.98	3.97	65.78
Stainless Steel (secondary)	0.01	0.01	99.91
	Acidification [mol H+ eq]		
Base case X5CrNiMo18 (316)	841.15	936.53	
Alloy 1 X5CrNi18 (304)	675.27	763.35	18.49
Alloy 2 X20Cr13 (420)	642.97	731.05	21.94
Stainless Steel (secondary)	98.85	210.65	77.51
	Ionizing radiation, human health [kBq U235 eq]		
Base case X5CrNiMo18 (316)	106.47	4019.62	
Alloy 1 X5CrNi18 (304)	109.43	4013.06	0.16
Alloy 2 X20Cr13 (420)	156.69	4060.33	-1.01
Stainless Steel (secondary)	156.73	3111.96	22.58

Optimize the alloy of antenna, battery/Photovoltaic panel/PCB

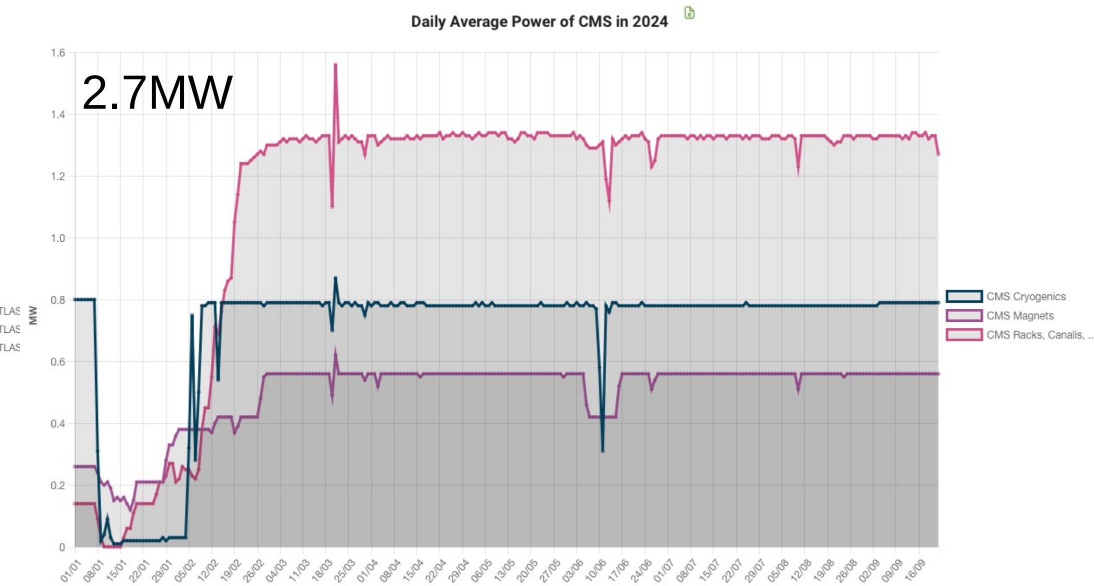
Impact categories	Base case	Battery weight -10% mass	AAPD (%)	PV size -10% size	AAPD (%)	Printed circuit board weight -10% mass	AAPD (%)
Climate Change [kg CO2eq]	471460	461999	2,01	467383	0,86	468860	0,55
Ressource use, fossils [MJ]	6220747	6099235	1,95	6171177	0,80	6176872	0,71
Ressource use, minerals and metals [kg Sb eq]	28	27	3,48	28	0,52	28	1,20
Acidification [mol H+ eq]	1709	1682	1,55	1687	1,29	1697	0,68
Ionizing radiation, human health [kBq U235 eq]	15565	15512	0,34	15343	1,43	15074	3,16

Detectors: Power consumption

- W. Riegler (sept 2024) https://agenda.ciemat.es/event/4431/contributions/5081/
  - For the LHC, ~5% of the PC is from the experiments
  - **O(5MW)/experiment**, but depend a lot of the deseign !
  - Same consomption is expected for FCCee
    - **Cryogeny is the key !**



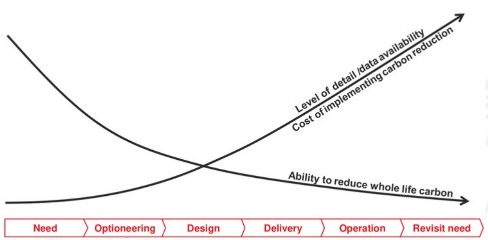
ATLAS

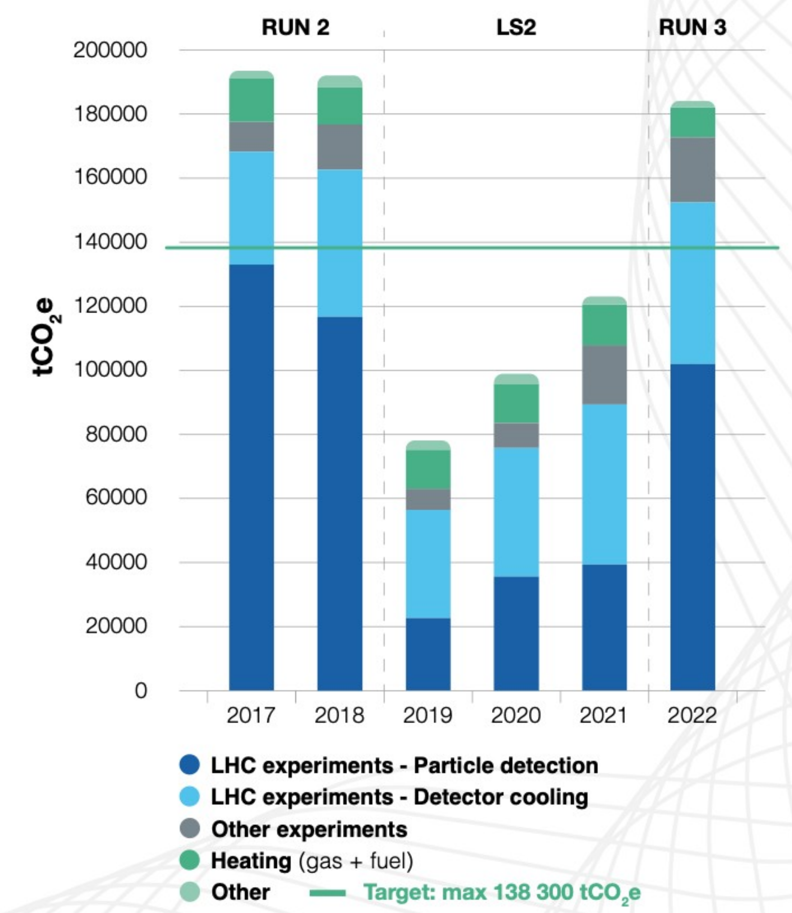


CMS

Detectors: Direct emissions

- Presently, the **main contributor** of CERN GHG
  - Cooling, RPC, RICH
  - HFCs, PFCs and SF_6
  - **O(0.2)MtCO2eq/year**
  - **Future detectors are expected to drastically reduce such usages**
- **Warning**: detector complexity may have strong impact on the cpu/gpu needed for **simulation/reconstruction** !
- No LCA yet
  - The sooner the better





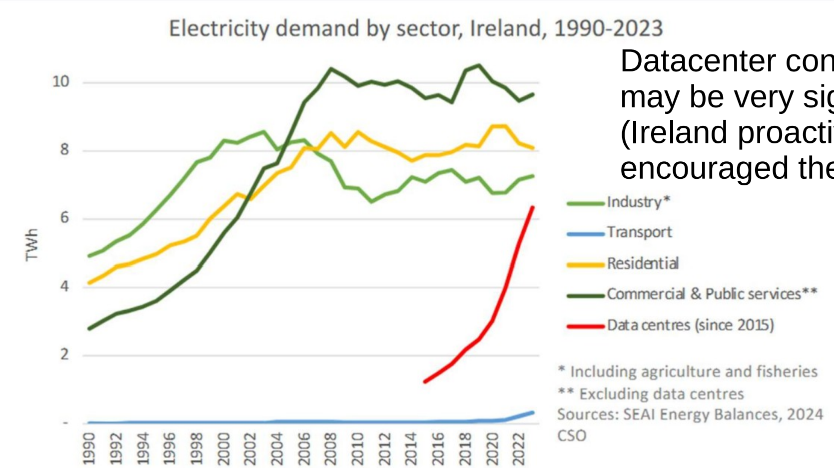
CERN SCOPE 1 EMISSIONS FOR 2017–2022 BY CATEGORY
"Other" includes air conditioning, electrical insulation, emergency generators and the fuel consumption of the CERN vehicle fleet.

Computing

- Usually done on World wide grid → strongly depends on the electricity mix
  - So will assume a low-C electricity production in the future…
    → Likely more intermittent
- Some ways to save energy:
  - Use the heat from datacenter for heating other buildings
  - Use different chips, with lower consumption (ARM)

    But most of the gains have already be made

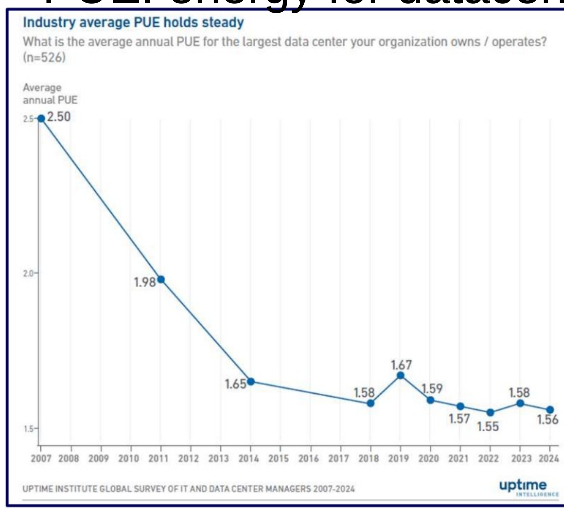
  - Vary the cpu frequency
    – Decrease/increase the frequency when little/a lot of low-C electricity is produced

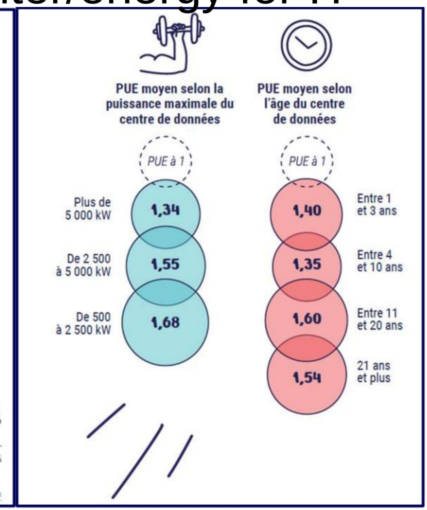


Datacenter consumption may be very significant (Ireland proactively encouraged them)

https://theshiftproject.org/wp-content/uploads/2025/03/Rapport-intermedaire-IA-VF.pdf

PUE: energy for datacenter/energy for IT





Collaboration structure/life

- Still assuming a world that has achieved its transition in 2050…

- Amount of fly should have been drastically reduced
  - Producing enough C-free fuel is challenging (O(25%) of today electricity to replace kerosene with e-fuel)
  - How can we organize ourself to reduce the distance and the number of flies ?

    Example (crazy idea nowadays, but in 2050…?):
    organizing the detector-collaborations by continent

  - How many collaborations/detectors do we really need ?

- It would be interesting to have an estimate of this item ? Bigger than acc.?

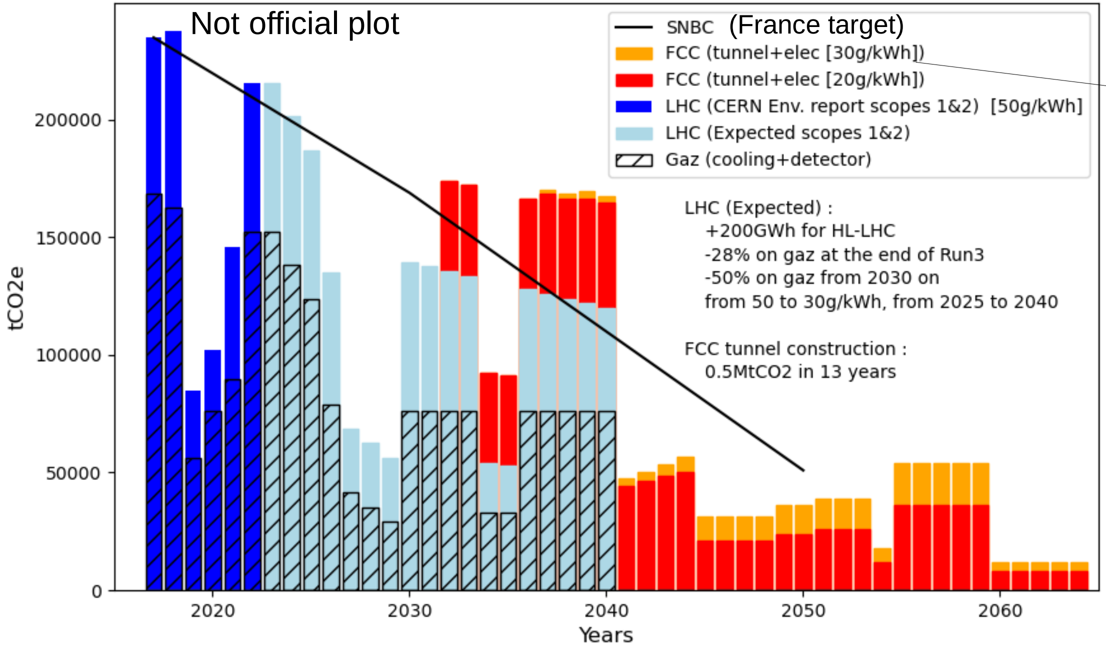
  Back to the envelop calculation:
  9k physicists x 14years x 2t/fly x 2 flies/year = 0.5MtCO2

  Geneva-NY

Summary

Environnemental footprint = tunnel ✓
+ accelerator construction ??
+ accelerator operation ✓
+ detector construction ??
+ detector operation Gaz ?
+ collaboration life O(0.5)Mt ?

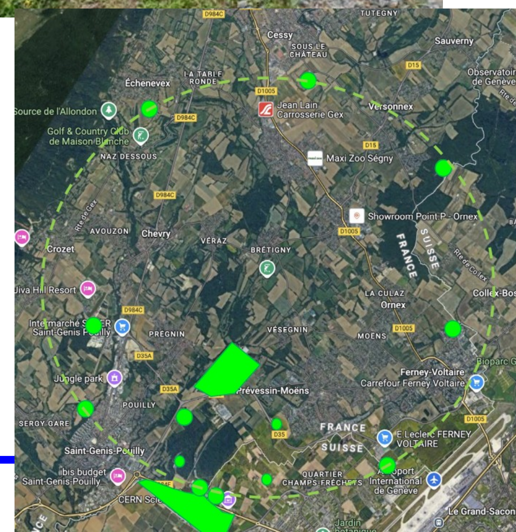
O(0.5-1)MtCo2eq



Biodiversity

- Reduce the impact during construction
  example at GANIL, with Semi-permeable barriers around the site:

- Plan constructions that are biodiversity friendly
  - Isolated areas for technical building can be biodiversity refuges
  - Avoid barrier, create corridors btw/ sites



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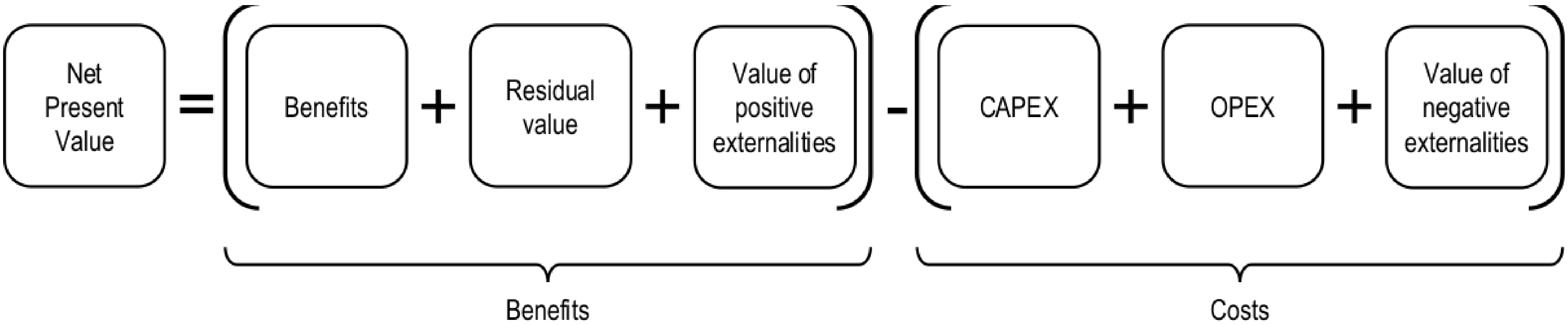
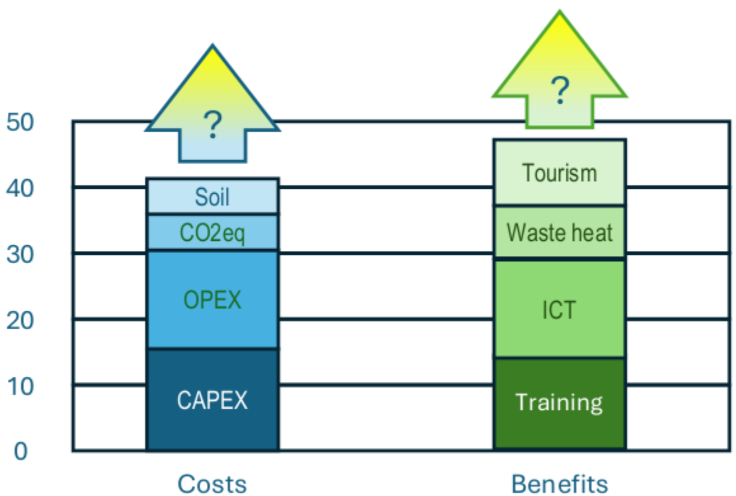
How do we decide whether a collider is “sustainable” ?

FCC Feasibility Study Report Vol 3 : Civil Engineering, Implementation and Sustainability
https://cds.cern.ch/record/2928194



Estimations with best estimates
and unknowns...



Economic formula to actualize the benefits/costs:

$$\text{Present\_Value} = \frac{\text{Future\_Value}}{(1+\text{SDR})^{\text{year}-\text{base\_year}}}$$

SDR: Social Discount Rate
- debate on the right value:
(0 means future generations
are equally important as present one)
- set it to 2.8%

Institution	SDR for Carbon
US EPA (old)	3%
US EPA (new)	2%
Stern Review	1.4%
EIB	~1–2%

How do we decide whether a collider is “sustainable” ?

→ : Effect of SDR

Cost/Benefit	Undiscounted	Discounted
(A) Costs		**19 666 MCHF**
Investment costs (for 4 experiments, injector and $t\bar{t}$ stage)	16 215 MCHF	10 171 MCHF
Personnel costs	16 802 MCHF	7544 MCHF
Operation costs (materials, consumables, services)	4410 MCHF	1879 MCHF
Dismantling costs	228 MCHF	72 MCHF
(B) Negative externalities		**354 MCHF**
Shadow cost of carbon	634 MCHF	342 MCHF
Loss of agricultural income, biodiversity & habitat	7.6 MCHF	4.1 MCHF
Social cost of project-related, induced noise	0.02 MCHF	0.02 MCHF
Social cost of project-related, traffic-induced air pollution	0.9 MCHF	0.6 MCHF
Social cost of project-related, traffic-induced GHG externalities	9.8 MCHF	7 MCHF
Social cost of ionising radiation	1.3 MCHF	0.6 MCHF
(C) Core benefits		**23 974 MCHF**
Scientific production	6507 MCHF	2813 MCHF
Early career researcher training	20 687 MCHF	4986 MCHF
Industrial benefits for suppliers	17 577 MCHF	9569 MCHF
Onsite visitors	4538 MCHF	2129 MCHF
Online and social media	229 MCHF	102 MCHF
Open software (experiments and detectors)	7428 MCHF	4375 MCHF
Total costs including negative externalities	**(A + B)**	**20 020 MCHF**
Total core benefits	**(C)**	**23 974 MCHF**
Reference net present value (NPV)	**(C) - (A + B)**	**3954 MCHF**
Reference Benefit Cost Ratio (BCR)		**1.20**

Cost due to C-emission for tunnel construction and operations w/ 4 interaction points *(no detector, nor computing, nor collaboration life)*

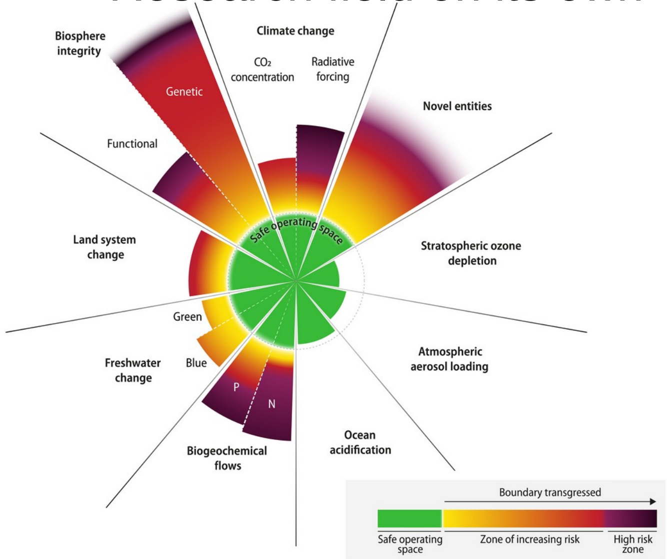
>0 :FCC feasibility study concludes it is worth to make it

Conclusions

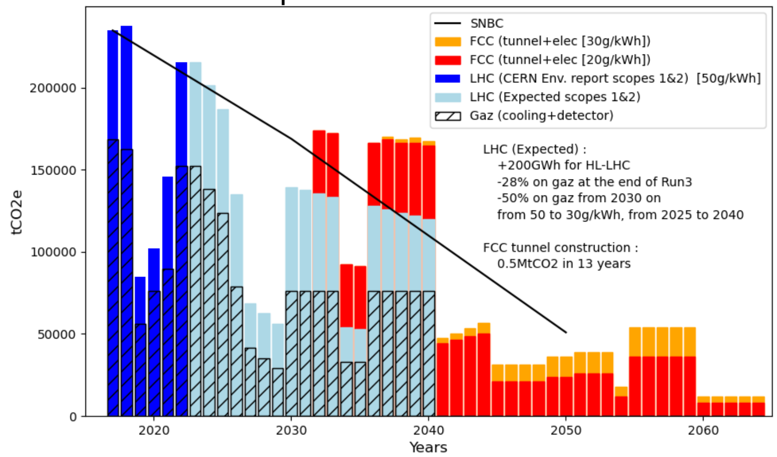
- Humanity is facing huge challenges

- How could HEP be part of the solution ?
  - innovations (tech, but also social ?)
  - be patient ? (tech readiness)
  - biodiversity harvest ?

- LCA is a crucial tool, to evaluate & to plan how to reduce the impacts
  - Research field on its own



Not official plot



Backup

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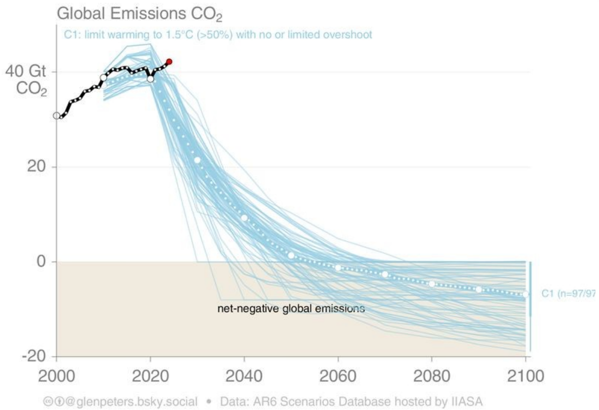
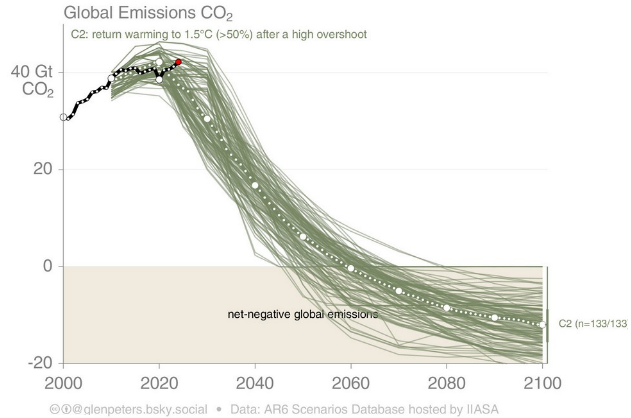
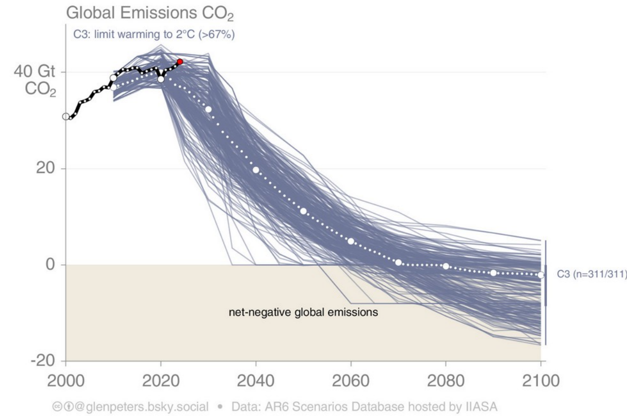
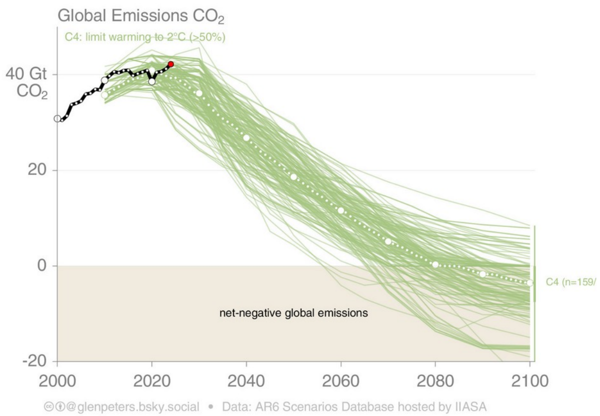
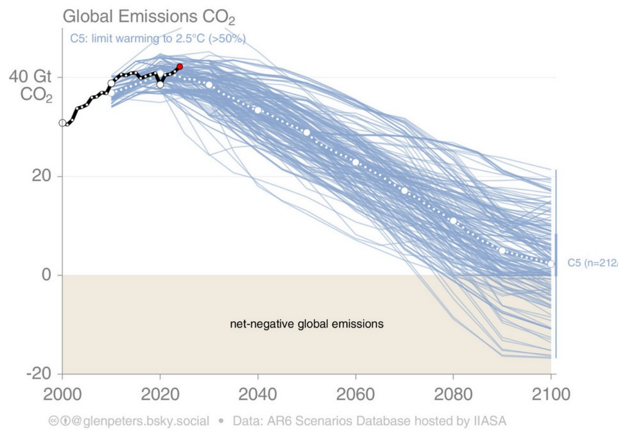
- FCC LCA (oct 2024) https://zenodo.org/records/13899160
- Energy for Sust. Sc. At Research Infra (sept 2024) https://agenda.ciemat.es/event/4431/
- Interim report for the International Muon Collider Collaboration (IMCC) (July 2024) https://arxiv.org/abs/2407.12450
- Know your footprint (for HEP physicists) (mar 2024) https://arxiv.org/abs/2403.03308
- Sustainability Strategy for the Cool Copper Collider (nov 2023) https://arxiv.org/abs/2307.04084
- LCA of CLIC&ILC (July 2023) https://edms.cern.ch/ui/#!master/navigator/document?D:101320218:101320218:subDocs
- The carbon footprint of proposed e+e− Higgs factories (sept 2022) https://arxiv.org/abs/2208.10466

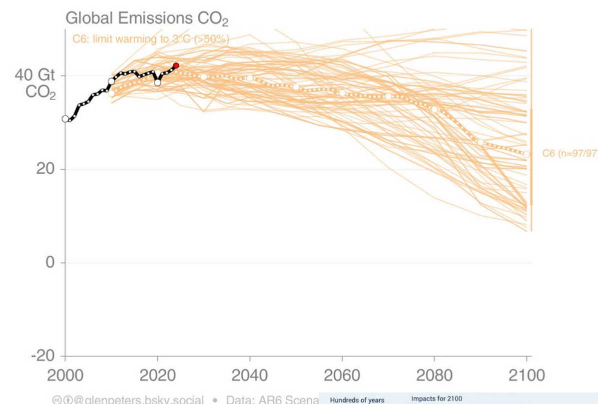


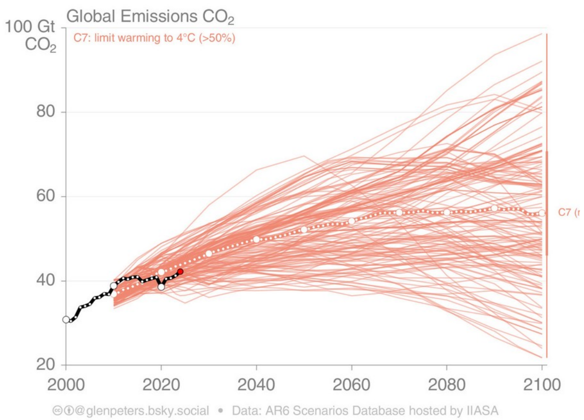


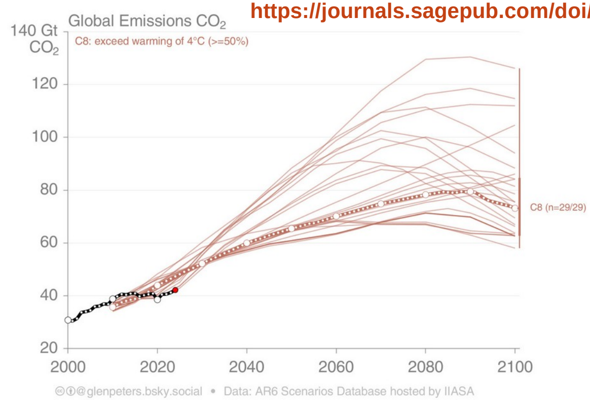




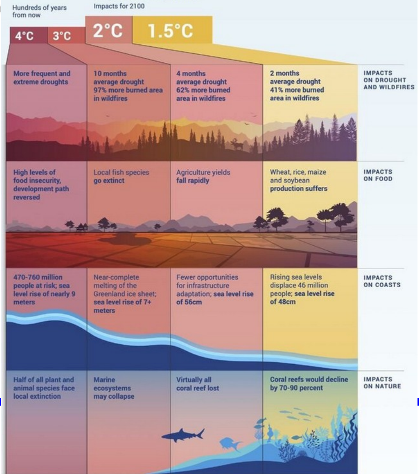








Is limiting the temperature increase to 1.5°C still possible?, G. Peters
https://journals.sagepub.com/doi/full/10.1177/29768659241293218



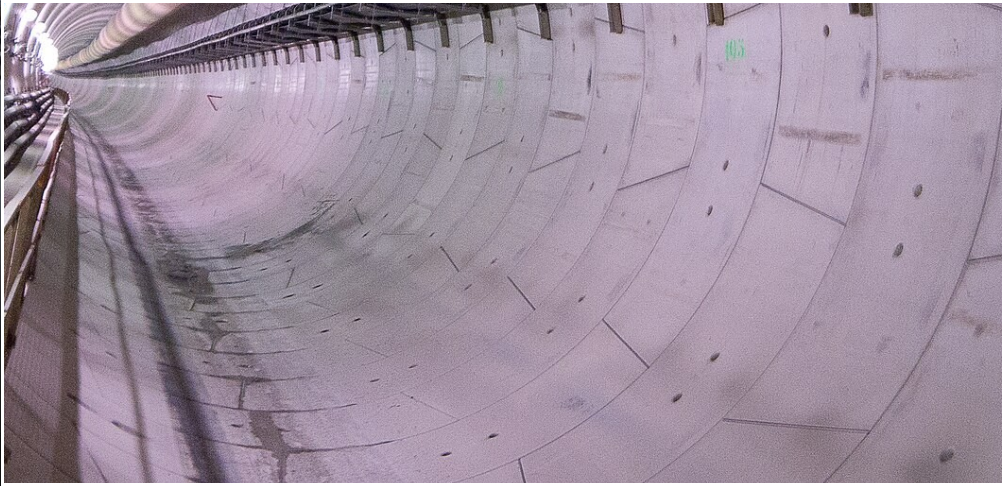
Toward a 0-net CO_2 emission tunnel ?

Industry is elaborating cement free concrete
- cement fully replaced by steel slag
- $C0_2$ captured from a plant
- CO_2 injected into the slag+gravel to produce concrete

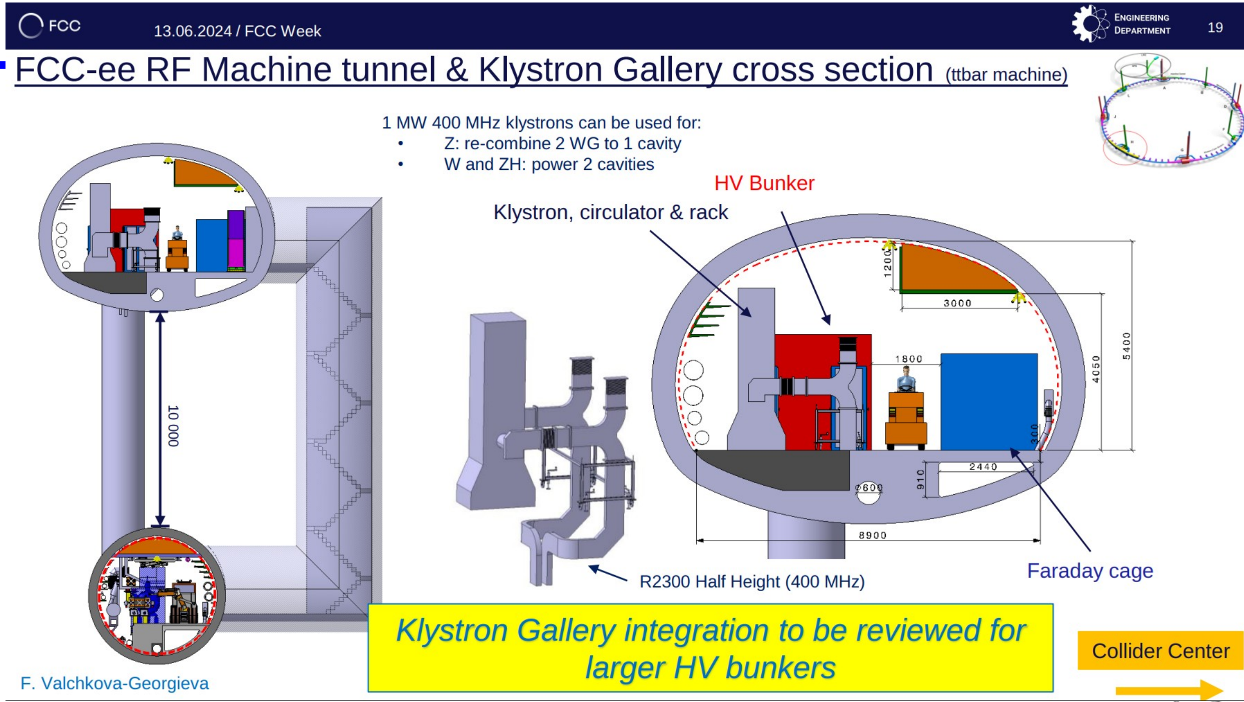
→ **negative CO_2eq concrete** ! (but only prefab)

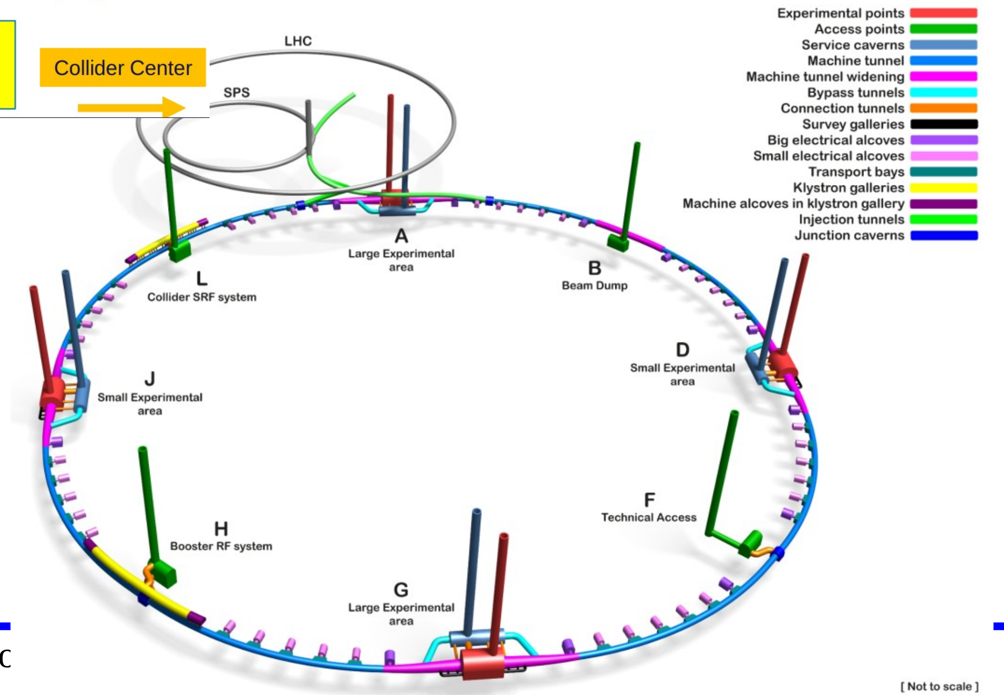
https://carbicrete.com/specify-carbicrete/

Needs to certify the concrete for tunnel usage
Usual scaling-up issue, but would help the civil society



Idea submitted to CERN

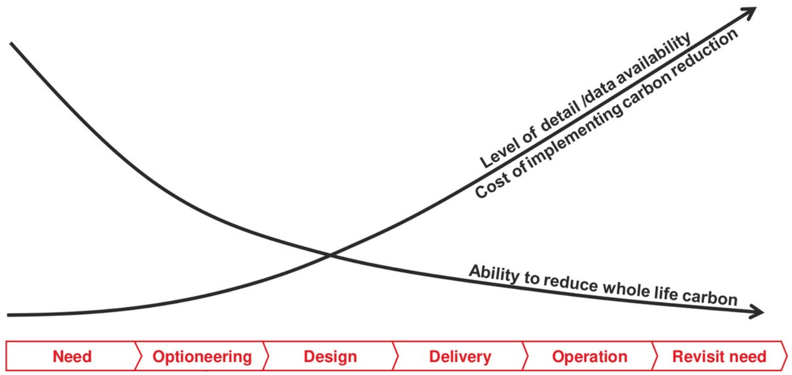


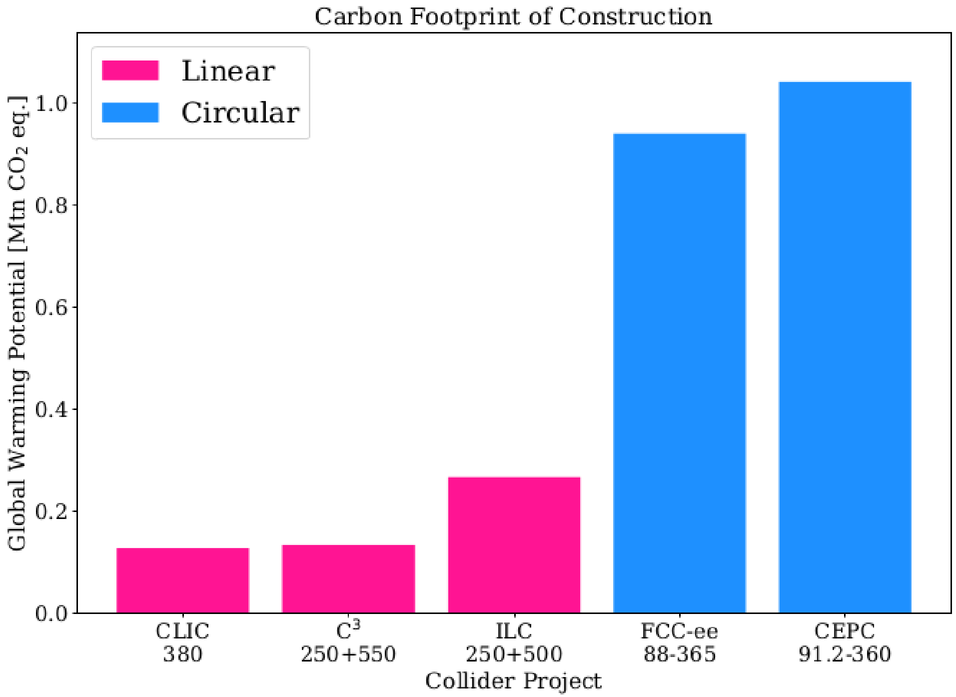


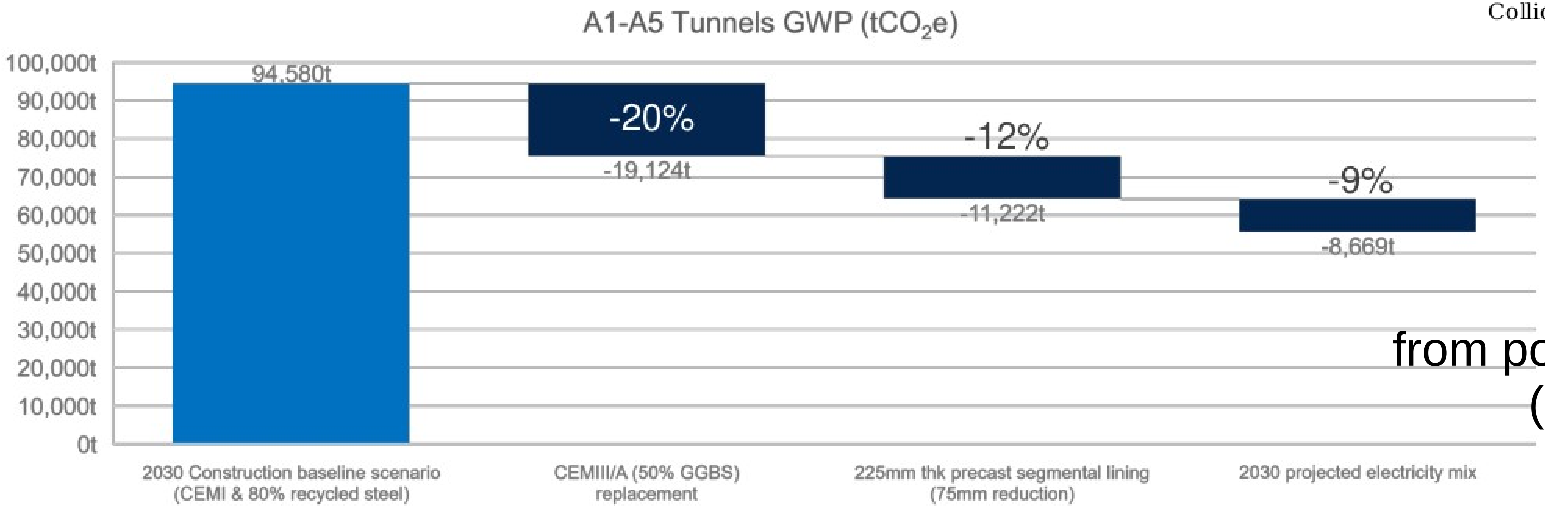
Sustainability fc

Tunnel @NLO

From https://arxiv.org/abs/2307.04084
FCC&CEPC: rough estimates
from CLIC LCA!



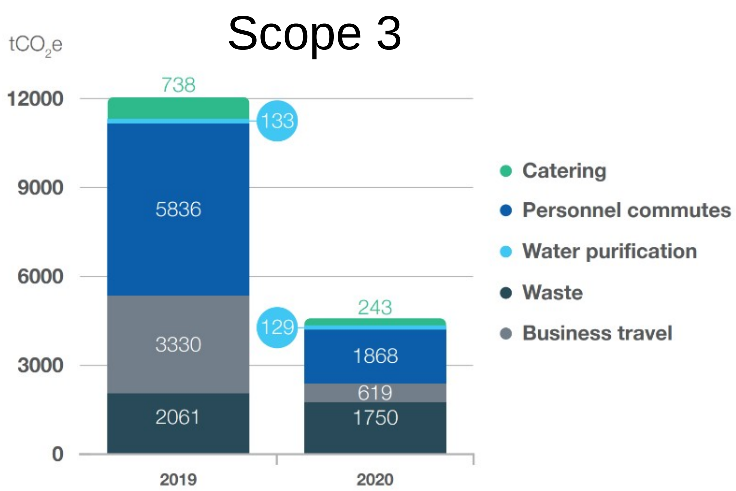


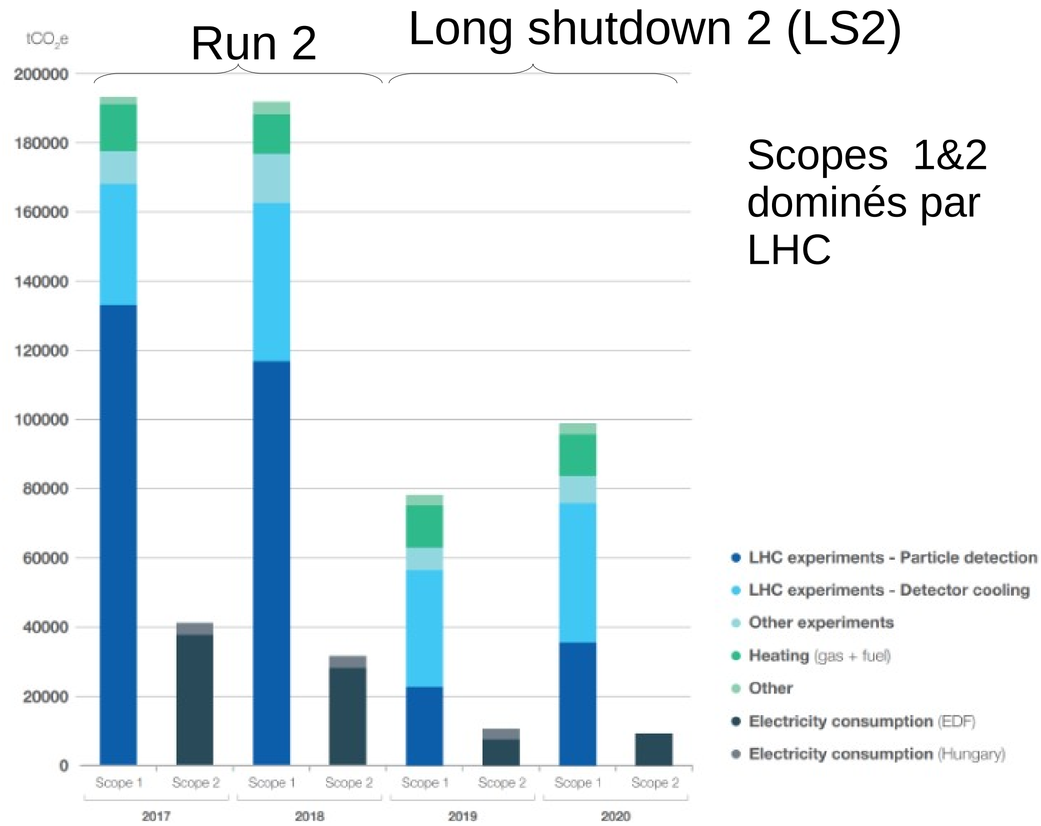


NLO corrections…
from possible improvements
(ex CLIC Drive beam):

Inputs

- CERN environment report 2019-2020
  https://hse.cern/environment-report-2019-2020





- CERN Annual Personnel Statistics
  https://cds.cern.ch/collection/CERN%20Annual%20Personnel%20Statistics

Construction du LHC

- Pas clair comment amortir
  - Tunnel déjà existant (accélérateur LEP)
  - Temps d'amortissement ?
  - Prise en compte des upgrades ?

- Ordre de grandeur

	A	B	C	D	E	F
1	cout:	4,50E+09	euros	LHC+4 experiences (CHF=euros)		
2	annees:	2008	2040	32	ans	
3				1,41E+08	euros/an	
4	FE:	0,3	kg/euros			
5	Co2eq:	4,22E+04	tonnes			
6	physiciens:	8600				
7		4,91	t/phys			

→ Pas pris en compte