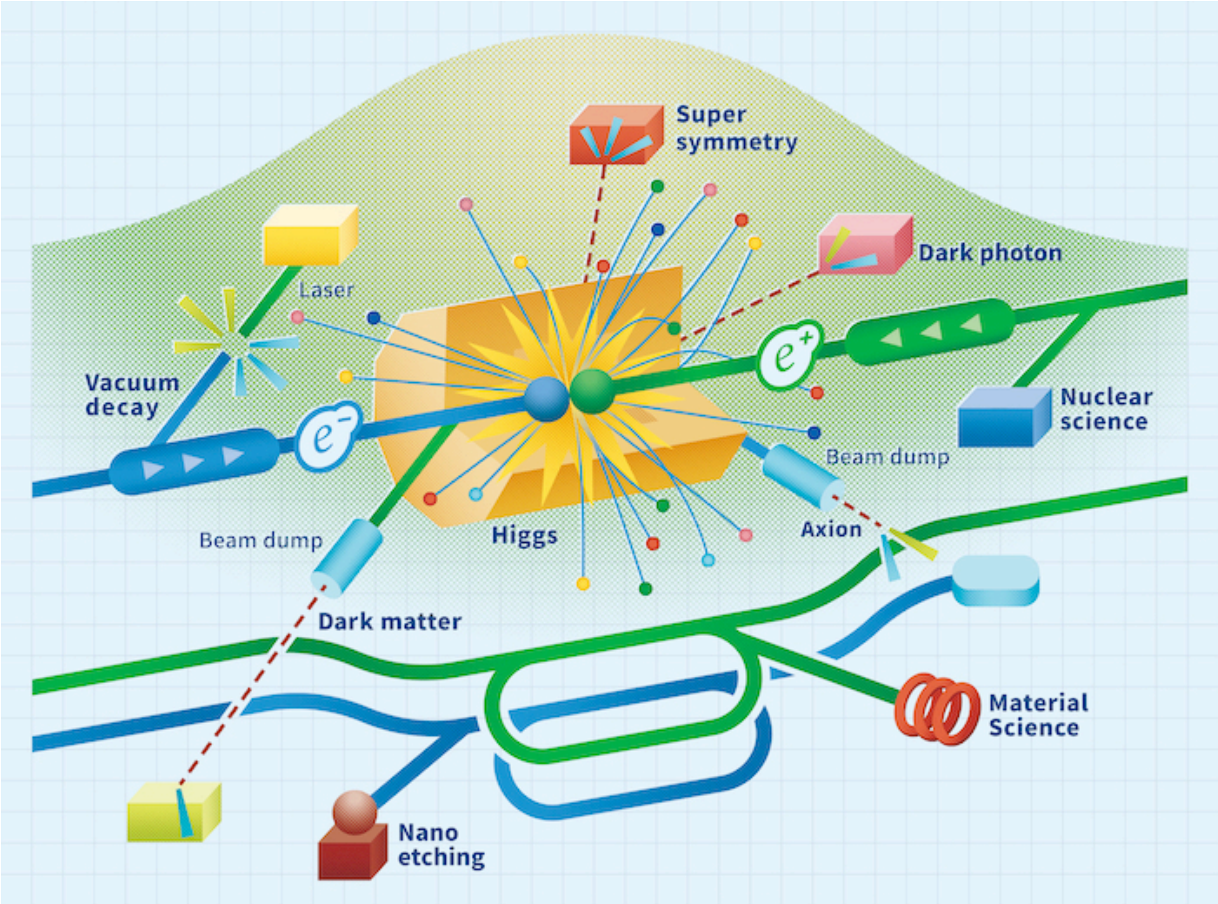
ILC and CLIC — Project Status and Plans

Physics, Technologies, Resources, Open Questions & Challenges



Jenny List (DESY)

ICHEP
18-25 July 2024
Prague

HELMHOLTZ

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

FTX DESY.

Outline

Today's menu

- **Project Overview & Updates**
  - a tour across ILC, CLIC
- **Plans towards the EPPSU**

- **Linear Collider Workshop 2024**
  - 8-11 July 2024, U Tokyo, Japan
  - https://agenda.linearcollider.org/event/10134

Many thanks to all who contributed material!
(with and without being asked ;)

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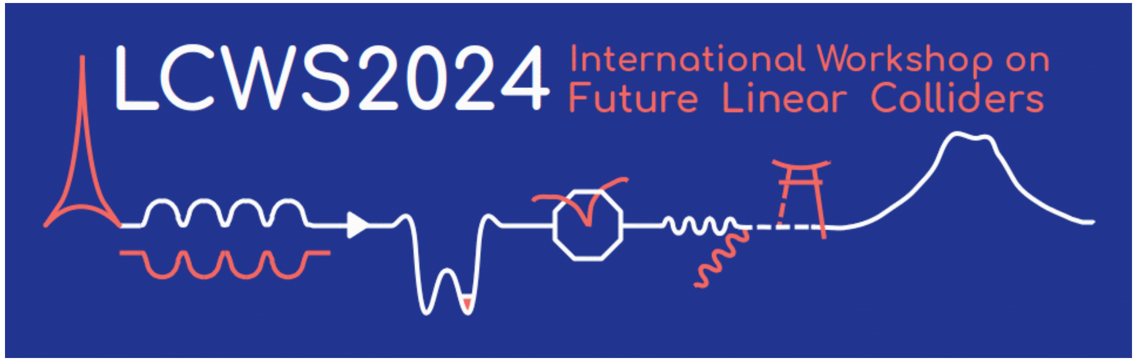

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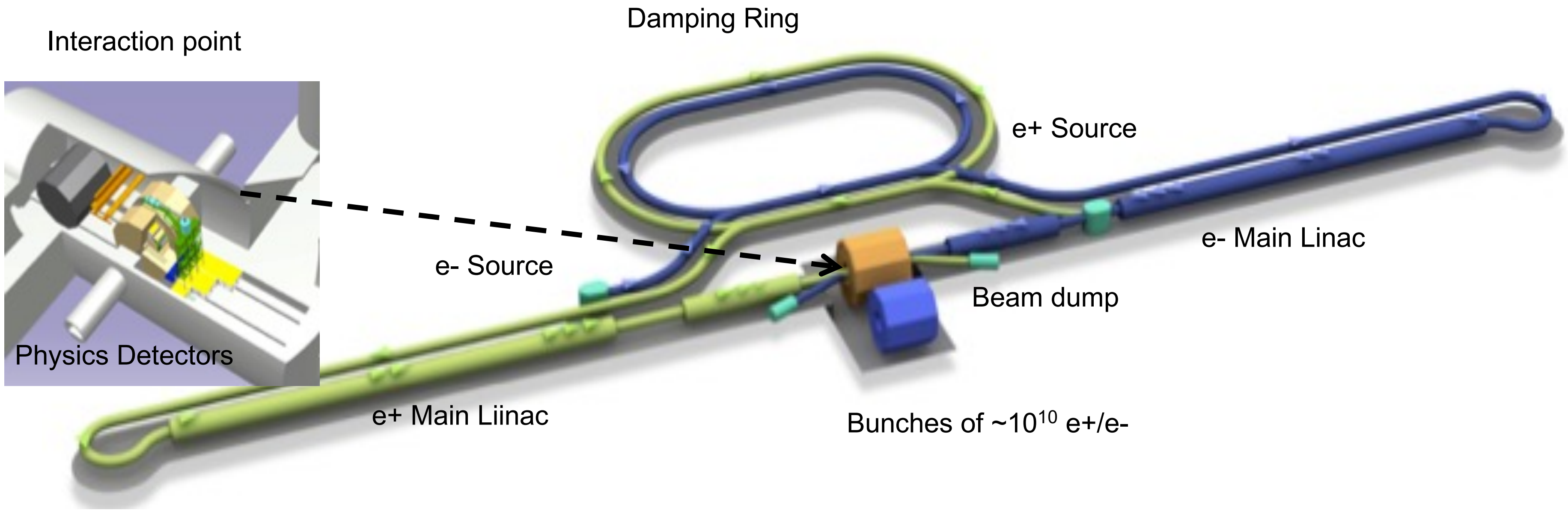
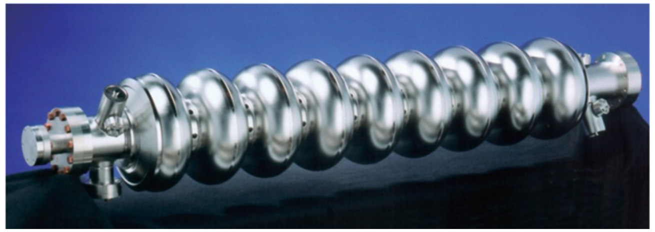
Project Overview & Updates

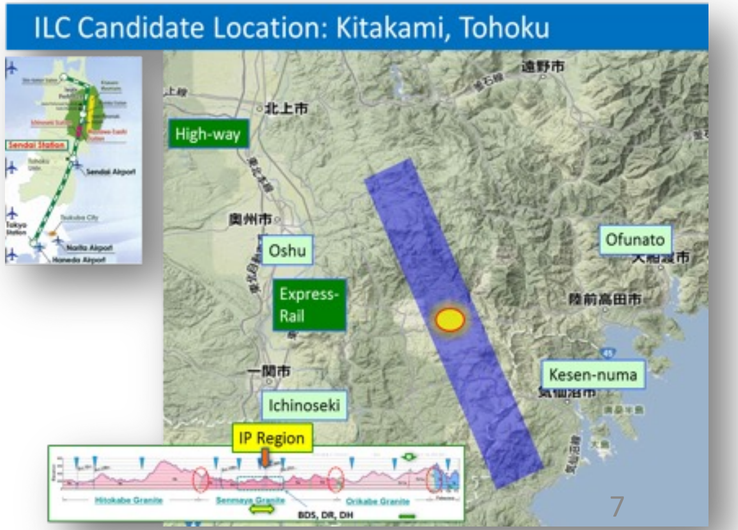
The ILC250 accelerator facility



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{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 = 1x10^{10}



Parameters and plans for luminosity and energy upgrades are available, interesting and relevant SCRF R&D also for such upgrades (Snowmass input)



Key systems and challenges

The ILC is a very mature design, with a comprehensive TDR

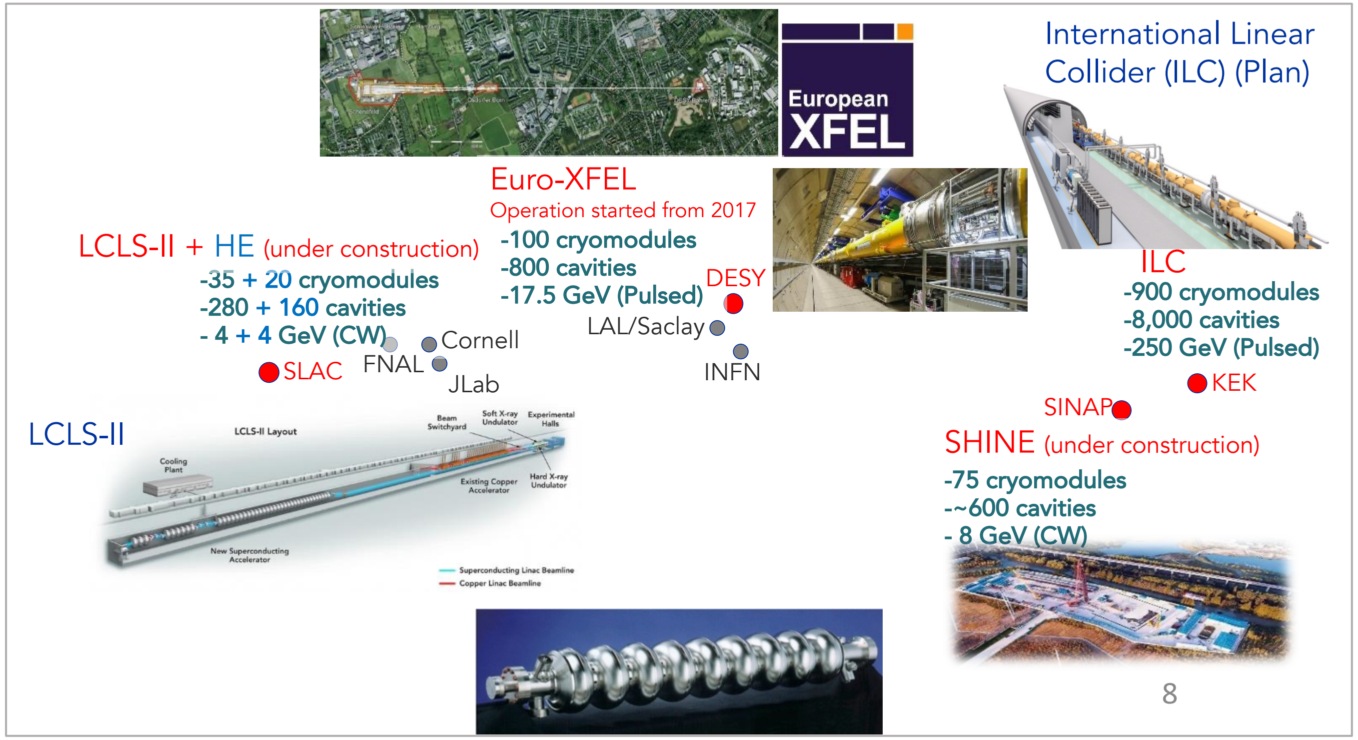
Next steps involve technical developments and industrial prototyping with final specs as needed for an Engineering Design and in preparation of pre-series and construction

- Creating particles — Sources
  - polarized elections/positrons
- High quality beam — Damping ring
  - low emittance beams
- Acceleration — Main linac
  - superconducting radio frequency (SRF)
- Collide them — Final focus
  - nano-meter beams
- Go to — Beam dumps

EU.XFEL:

Largest deployment of SCRF technology

- **100 cryomodules**
- **800 cavities**
- **17.5 GeV**
- **First beams 2016**



The ILC IDT organization – initiated at the ICFA meeting at SLAC February 2020

2020-21: The IDT – created by ICFA and hosted by KEK – was set up to move ILC towards construction. The worldwide structure of the WGs: https://linearcollider.org/team/
A set of key activities were identified in a Preparation Phase Programme.

2022-23: A subset of the technical activities of the full ILC preparation phase programme have been identified as critical (next slide). These are being addresses by a ~4 year programme called ITN – the ILC Technology Network. Moving forward with this work is being supported by the MEXT (ministry) providing crucial increased funding.

As of today: With funding from 1.4.2023 ITN is now starting. An agreement KEK and CERN and several European lab activities have been/are being set up. In the US the P5 process is ongoing, the hope is that ITN planning and interests can turn into important ITN involvements in due time.

The ITN

Promoting the technological development of the International Linear Collider:
Twenty-eight research institutes participated in the ITN Information Meeting

WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

Building the ITN activities:

- Planning in the IDT WG2 – significant interests and expertise already represented
- Information meeting at CERN 16-17.10 jointly organized by KEK and the IDT
- Interest matrix for the ITN work-packages, being consolidated
- The next step: Further technical discussion to define deliverables, followed by agreement who among the laboratories will deliver what

SRF	WPP	1	Cavity production	✓		✓	✓	✓			✓	✓	✓				✓	✓	✓		✓	✓		✓	✓	
	WPP	2	CM design	✓				✓				✓			✓	✓	✓	✓	✓			✓		✓	✓	
	WPP	3	Crab cavity			✓	✓							✓					✓			✓	✓		✓	✓
Sources	WPP	4	E-source			✓						✓							✓		✓			✓		
	WPP	6	Undulator target				✓												✓	✓			✓			
	WPP	7	Undulator focusing				✓												✓	✓			✓			
	WPP	8	E-driven target	✓		✓												✓	✓							
	WPP	9	E-driven focusing	✓														✓	✓							
	WPP	10	E-driven capture	✓															✓					✓		
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	WPP	14	DR Injection/extraction	✓					✓										✓				✓	✓		
	WPP	15	Final focus	✓			✓		✓		✓							✓			✓			✓		
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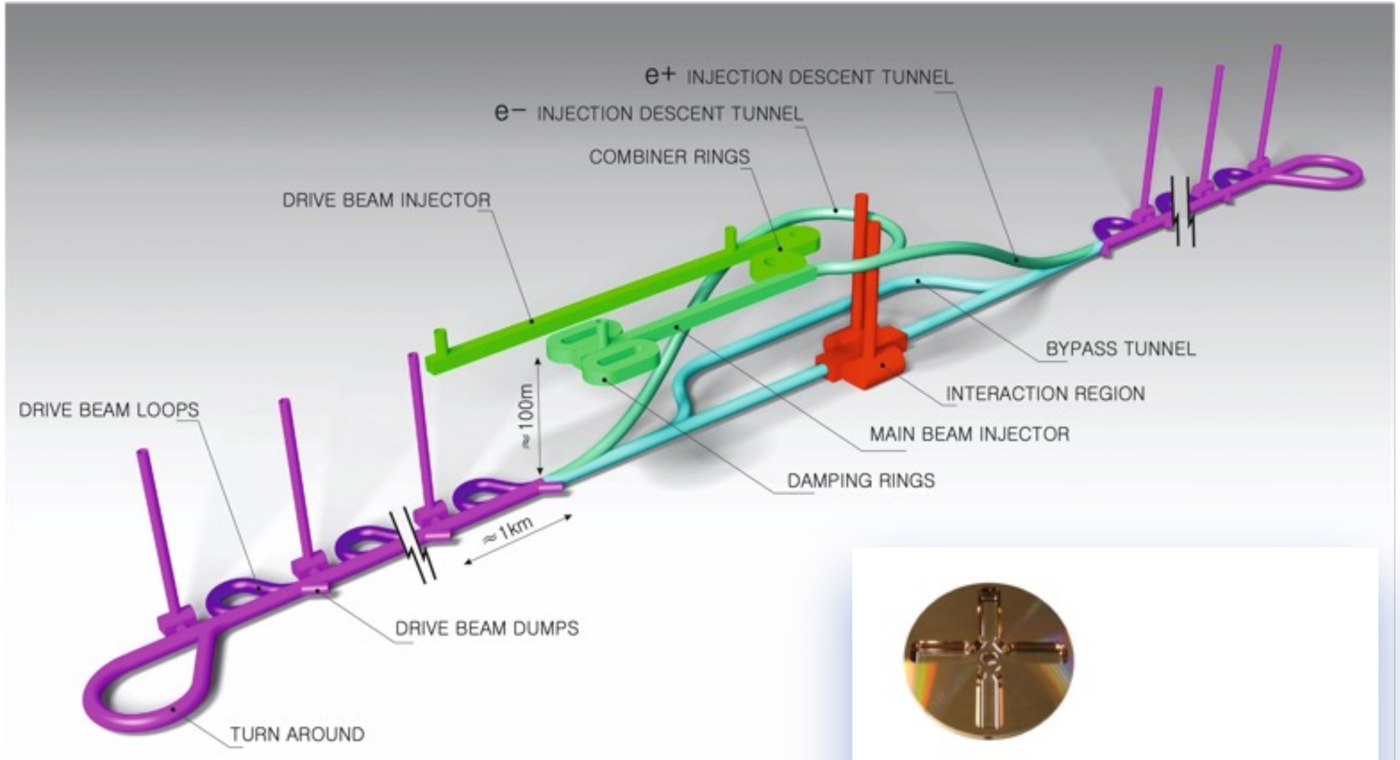
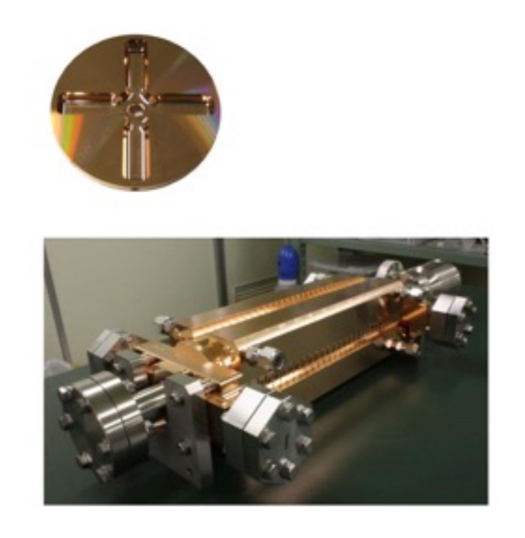
The Compact Linear Collider (CLIC)





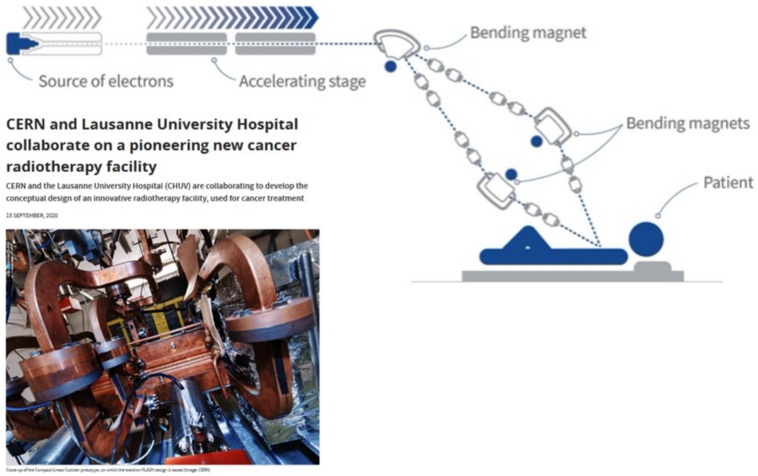
Accelerating structure prototype for CLIC: 12 GHz (L~25 cm), 100 MV/m

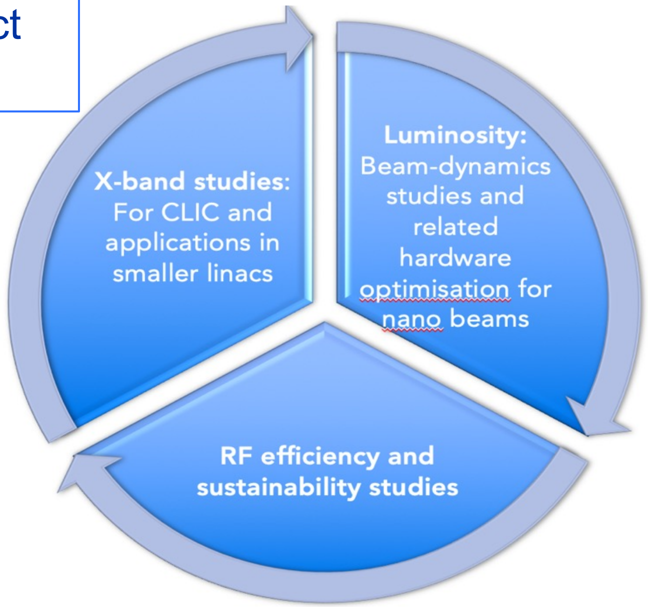
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision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

On-going CLIC studies towards next ESPP update

Project Readiness Report as a step toward a TDR
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

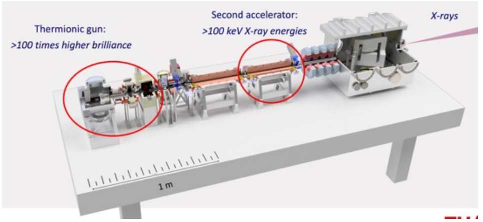
The X-band technology readiness for the 380 GeV CLIC initial phase - manufacturability and developments driven by use in small compact accelerators for industrial experience



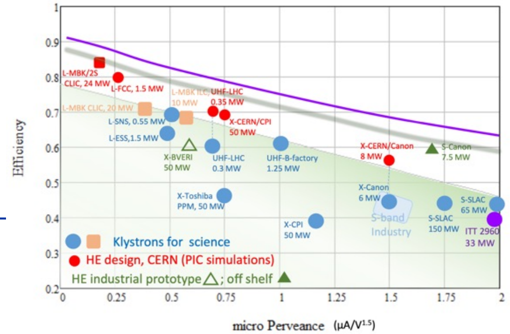


Optimizing the luminosity at 380 GeV at 2.3 x 10^{34} cm^{-2} s^{-1}– already implemented for Snowmass paper, further work to provide margins will continue (HW and SW)

Project summary for Snowmass:
https://arxiv.org/pdf/2203.09186.pdf



Improving the **power efficiency** for both the initial phase (already in Snowmass report) and at high energies, including more **general sustainability studies** (in many cases done together with ILC – see later)



Plans for the EPPSU — towards a global LC vision

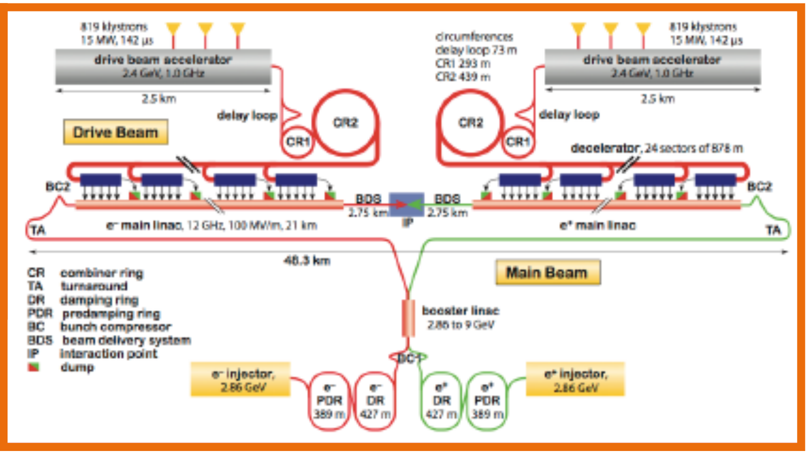
See Linear Collider Workshop 2024 for more information

- https://agenda.linearcollider.org/event/10134

A Linear Collider Facility — at CERN or in Japan

- **What could be the initial technology for an LCF at CERN? (Japan=ILC)**
  - For many years, CERN pioneered CLIC — from 380 GeV to 3 TeV
    - drive beam technology demonstrated
    - detailed design and costing **=> first stage can be built within CERN budget** (shown in CLIC Project Implementation Plan, 2018)

CLIC: e^+e^- @ 0.38, 1.5, 3 TeV
Conceptual Design **2012**
Updated Baseline in **2017 & 2021** for Snowmass
2-beam acceleration



- **However could also consider to start out with a linear collider based superconducting RF**
  - proven and *industrialised* technology
  - strong general interest in technology around the world
  - significant industrial production capacities in Europe (and elsewhere)
  - strong lab expertise *outside* of CERN => could take significant load off CERNs shoulders while still busy with / paying off HL-LHC
  - CERN site actually been studied for ILC TDR…

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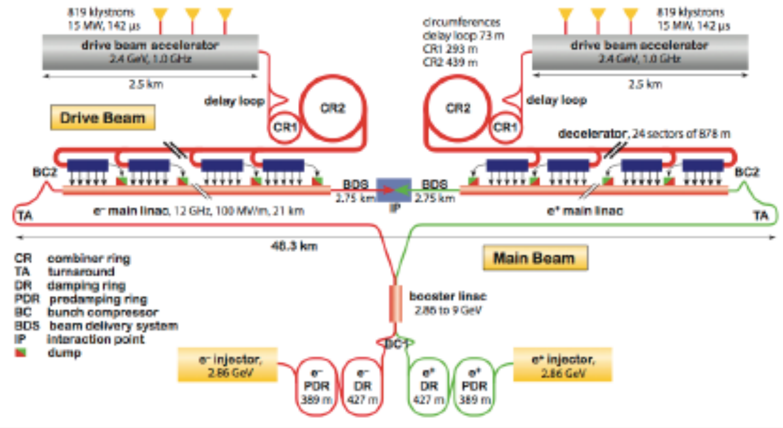

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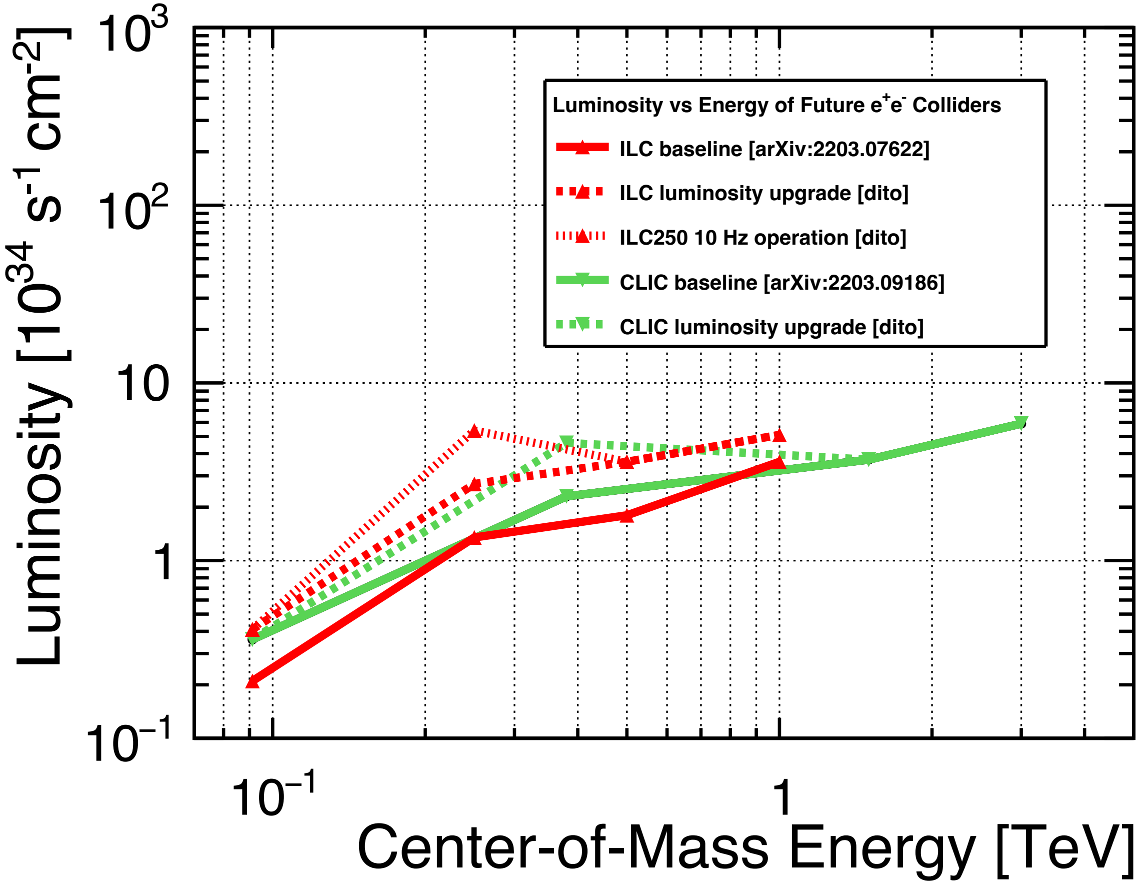
ILC in Japan — or LCF@CERN starting with ILC technology — minimize time til next project
=> crucial for next generation of our community!

A physics-driven, polarised operating scenario for a Linear Collider

- **250 GeV, ~2ab-1:**
  - precision Higgs mass and total ZH cross-section
  - Higgs -> invisible (Dark Sector portal)
  - basic ffbar and WW program
  - optional: WW threshold scan
- **Z pole, few billion Z's: EWPOs 10-100x better than today**
- **350 GeV, 200 fb-1:**
  - precision top mass from threshold scan
- **500…600 GeV, 4 ab-1:**
  - **Higgs self-coupling in ZHH**
  - **top quark ew couplings**
  - **top Yukawa coupling incl CP structure**
  - improved Higgs, WW and ffbar
  - probe Higgsinos up to ~300 GeV
  - probe Heavy Neutral Leptons up to ~600 GeV
- **800…1000 GeV, 8 ab-1:**
  - Higgs self-coupling in VBF
  - further improvements in tt, ff, WW, ….
  - probe Higgsinos up to ~500 GeV
  - **probe Heavy Neutral Leptons up to ~1000 GeV**
  - searches, searches, searches, …

Based on classic ILC/CLIC luminosity assumptions limited by self-allowed power budget



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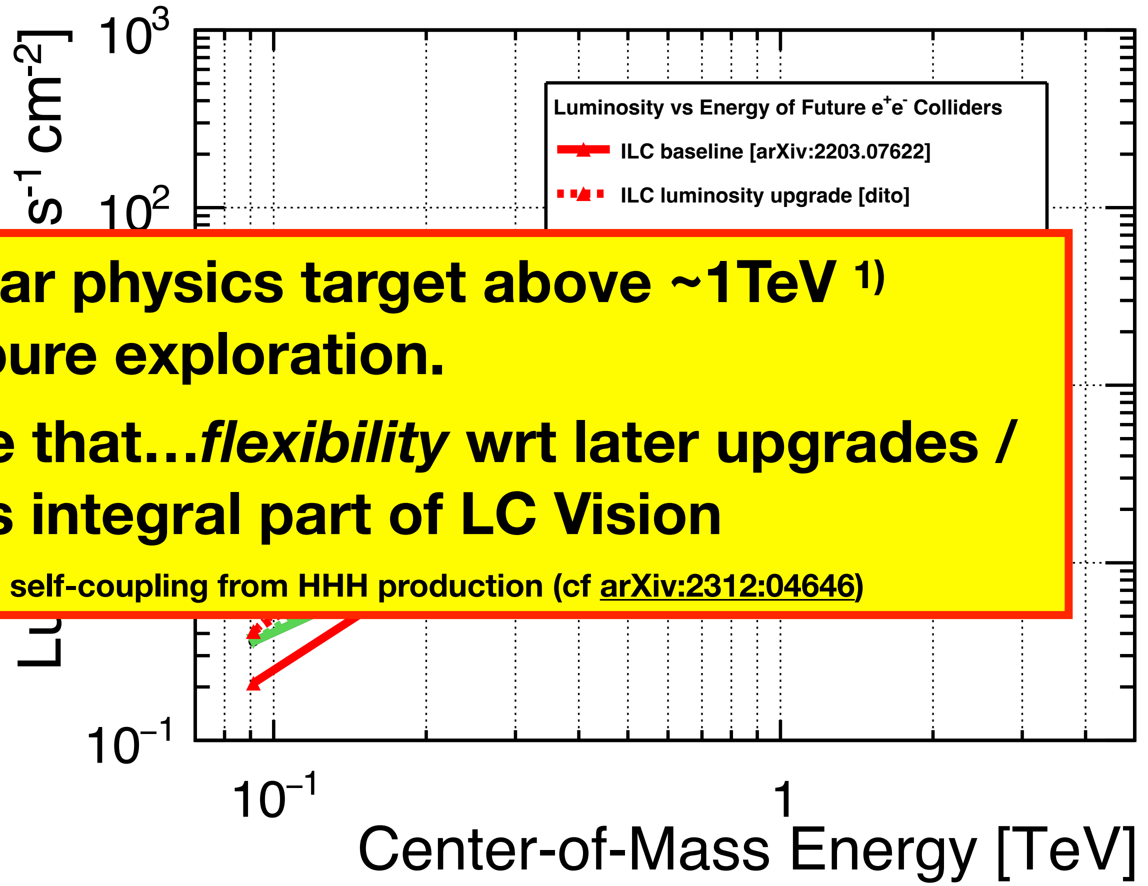


As of today, there's no very clear physics target above ~1TeV [1)] — apart from pure exploration.

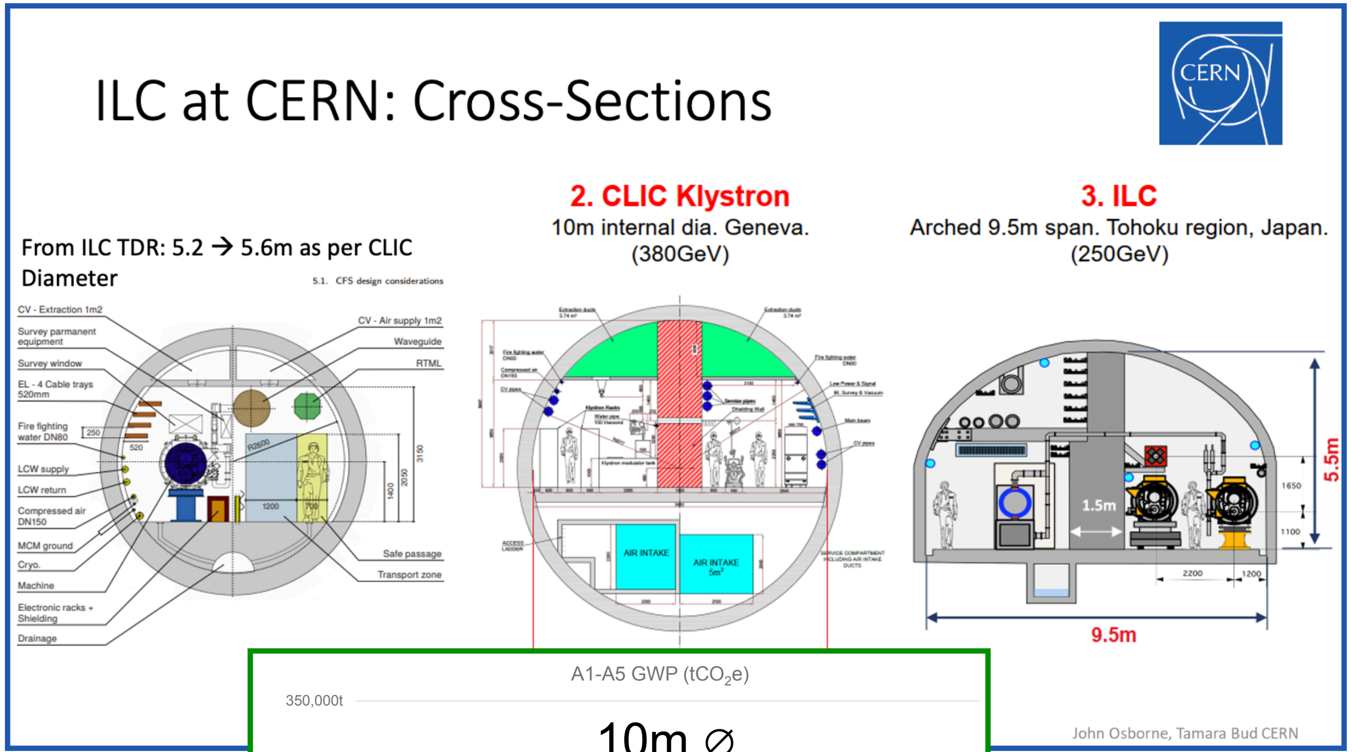
However HL-LHC might still change that…*flexibility* wrt later upgrades / choice of 10 TeV pCoM is integral part of LC Vision

1) 3-10 TeV with 5-10 ab-1 might give access to quartic self-coupling from HHH production (cf arXiv:2312:04646)

Tunnel Geometry and Global Warming Potential

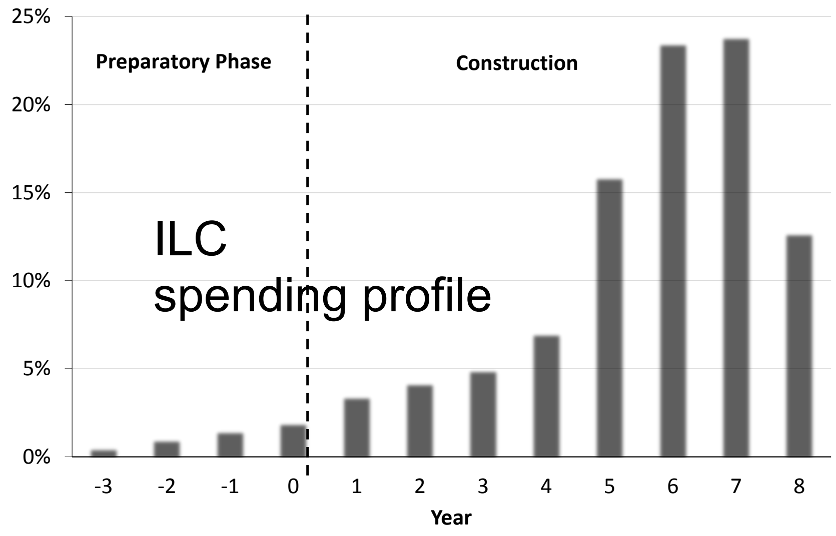
- Linear Collider Facility at CERN:
  - **round tunnel like for XFEL (5.2m) or CLIC (5.6m)**
  - diameter, wall thinkness to be optimised
- ARUP study for CLIC/ILC tunnels:
  - **full life-cycle assessment according to ISO standards by consultancy company (ARUP)**
  - green house gas emission plus 13 more impact categories
  - showed room for 40% reduction of GWP
  - **new**: being extended to "content" of tunnels & halls

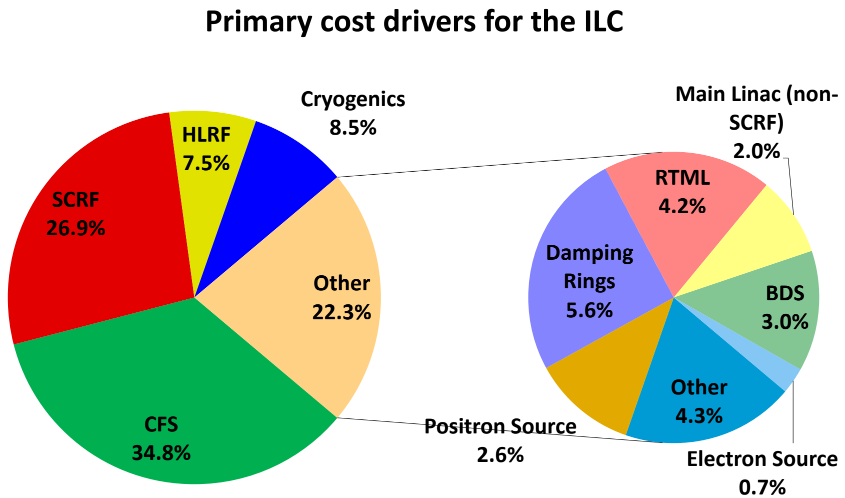
https://edms.cern.ch/document/2917948/1

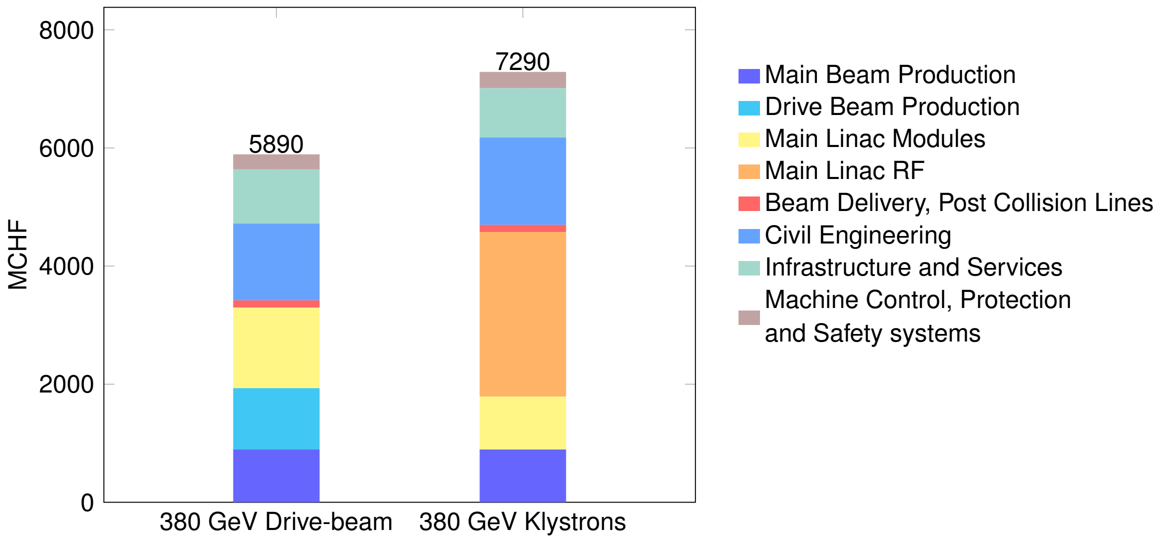


Cost estimates…

- **Cost estimates are being updated - stay tuned….**
- **old (!)** existing costings (European accounting):
  - CLIC500 (CDR, 2010): **7.4 BCHF**
  - ILC500 (TDR, 2012): **8 BILCU** (ILCU = US$ in 2012)
  - CLIC380 (drive-beam / klystron, EPPSU 2018): **5.9 / 7.3 BCHF**
  - ILC250 (EPPSU 2018): **5 BILCU**
- **CLIC380 has been shown to be financiable from CERN budget over construction time** (CLIC Project Implementation Plan 2018)







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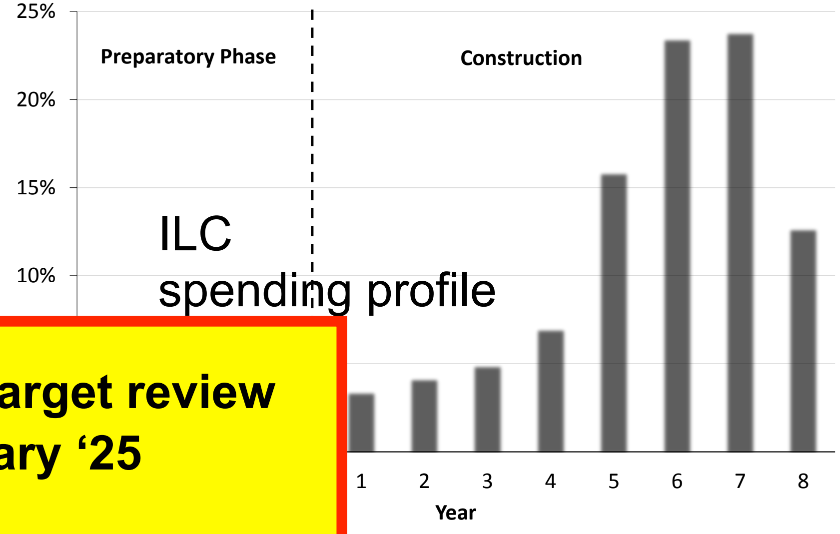
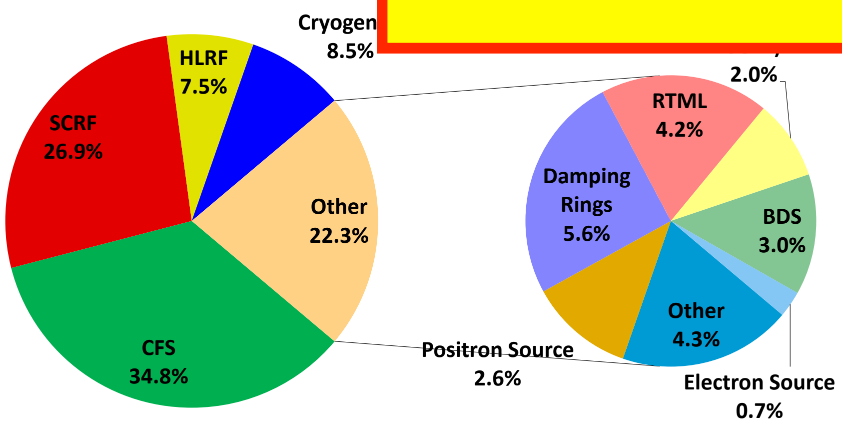
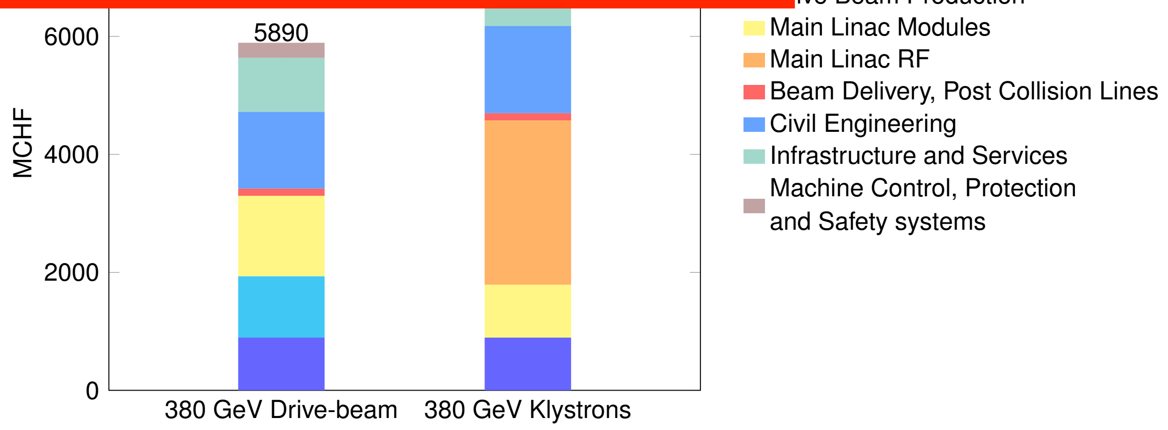


ILC (in Japan) cost update underway by IDT, target review in December '24, public release in January '25

Will estimate ILC@CERN based on CLIC and ILC in Japan costings





Beyond e+e- Collisions - Test and R&D Facilities

ILCX workshop

- **low-emittance, mono-energetic beams ideal for**
  - high-rate detector and beam instrumentation tests
  - creating **low-emittance beams of photons / muons / neutrons** for various applications (hadron spectroscopy, material science, irradiation, tomography, radioactive isotope production, …
  - **accelerator development:**
    - high-gradient accelerating structures, new final focus schemes, deceleration (for ERLs), beam and laser driven plasma, …
    - from extracted beam to test small setups - **to large-scale demonstrators for upgrades of the main facility**
- **impact on e+e- luminosity?**
  - ILC: ~1300 / ~2600 bunches per train
  - **extracting 10 bunches per train is few-permille loss in luminosity**

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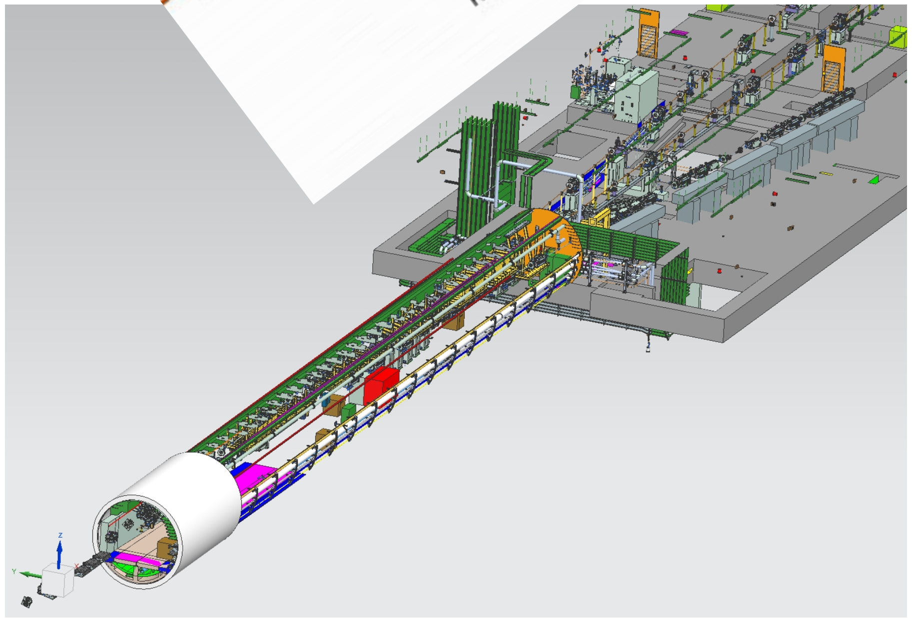


Pioneering this *now* at DESY / Eu.XFEL with ELBEX facility (beam extraction for LUXE & other applications)

Upgrade Options - Higher Energy "conventional"

Chap 15 of arXiv:2203.07622

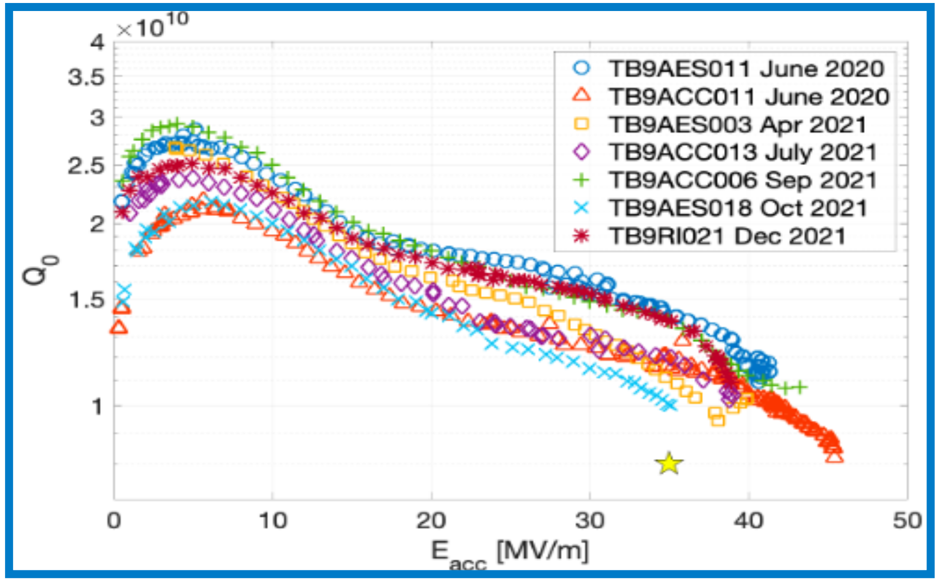
- **ILC TDR: upgrade of SCRF machine up to ~1 TeV**
  - extend tunnel to ~50 km, upgrade power to 300 MW

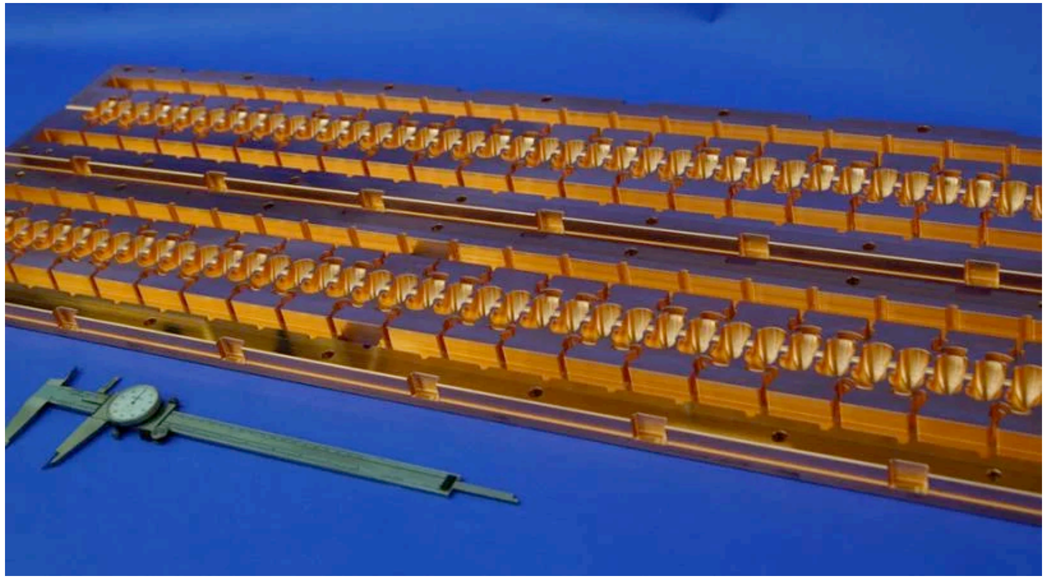
  => huge but unsexy? Still: guaranteed fall-back…

- **Advanced SCRF**
  - higher gradient cavities exist in the lab (45 MV/m vs 31.5 MV/m ILC design), though not yet industrially available

  => upgrade to > 1 TeV — or less new tunnel

- **rip out SCRF and replace by X-band copper cavities (à la CLIC or C3)**
  - 70-150 MV / m **=> double (3x, 4x …?) energy without tunnel extension**
  - sell / donate SCRF modules to build XFELs, irradiation facilities, … all around the world





Upgrade Options - Double ECM by “HALHFing” LCF

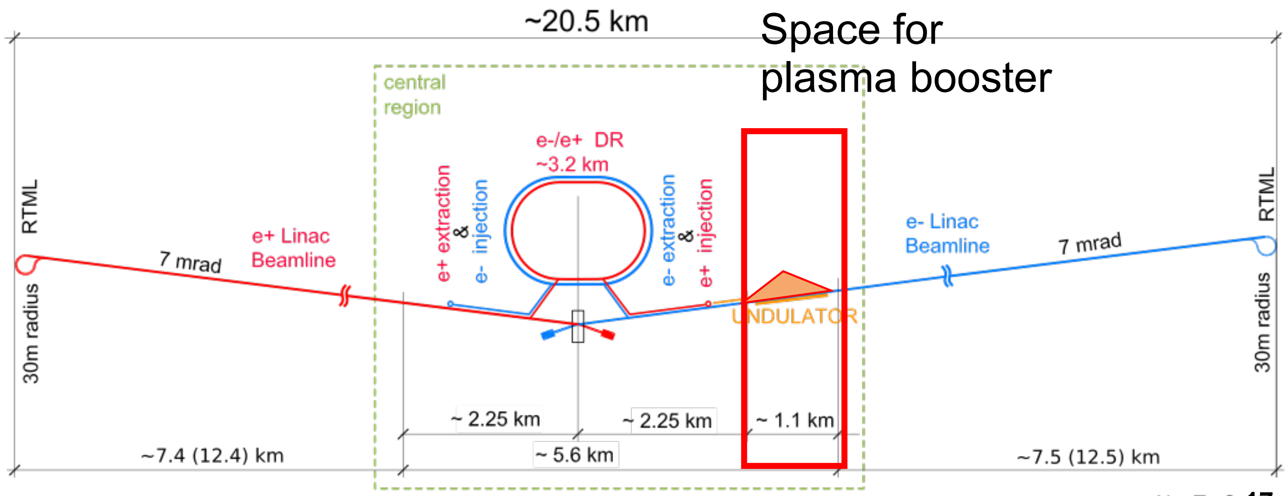
- **Apply HALHF concept to eg 250 GeV ILC:**
  - plasma-accelerate e- to 550 GeV
  - keep e+ linac
    (small upgrade 125 -> 137.5 GeV)

⇒ 137.5 GeV on 550GeV ⇒ ECM = 550 GeV

⇒ **upgrade Higgs Factory to tt / tth / Zhh factory**

- How?
  - Reduce e- linac energy by 4 to 34.4GeV
  - Drive 16 stage plasma accelerator
- Use space between electron ML and BDS to install plasma booster
- Feed boosted electrons into existing BDS (already laid out for E_{beam} ≈ 500 GeV)

		E- (drive)	E- (Collide)	E+
Beam energy	GeV	34.4	34.4 → 550	137.5
Linac Gradient	MV/m	8.7		35
CoM energy	GeV	550		
Bunch charge	nC	4.3	1.6	6.4
Bunches/pulse		10496	656	656
Rep rate	Hz	5		
Beam power	MW	8.0	0.18 → 2.9	2.9
Lumi (approx.)	$cm^{-2}s^{-1}$	$\sim 1 \cdot 10^{34}$		



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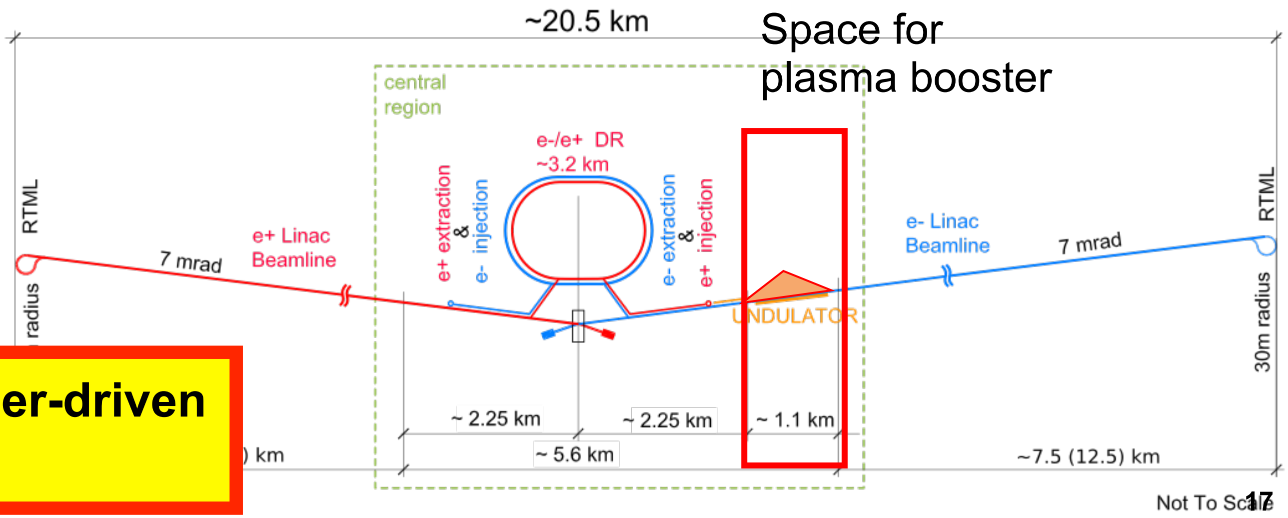

Can we work out a corresponding scheme for laser-driven plasma / ALEGRO-style upgrade?

A Linear Collider Facility and the Energy Frontier

Eventually, we want to explore the O(10 TeV)-parton-ECM scale:

- **a Linear Collider Facility does not restrict the choice of how to explore the energy frontier**
  => can choose independently based on scientific and technological developments
- **nor is it coupled to the site:**
  => if technology ready fast, could start building energy frontier machine without stopping e+e- program

A Linear Collider Facility and the Energy Frontier

Eventually, we want to explore the O(10 TeV)-parton-ECM scale:

- **a Linear Collider Facility does not restrict the choice of how to explore the energy frontier**
  => can choose independently based on scientific and technological developments
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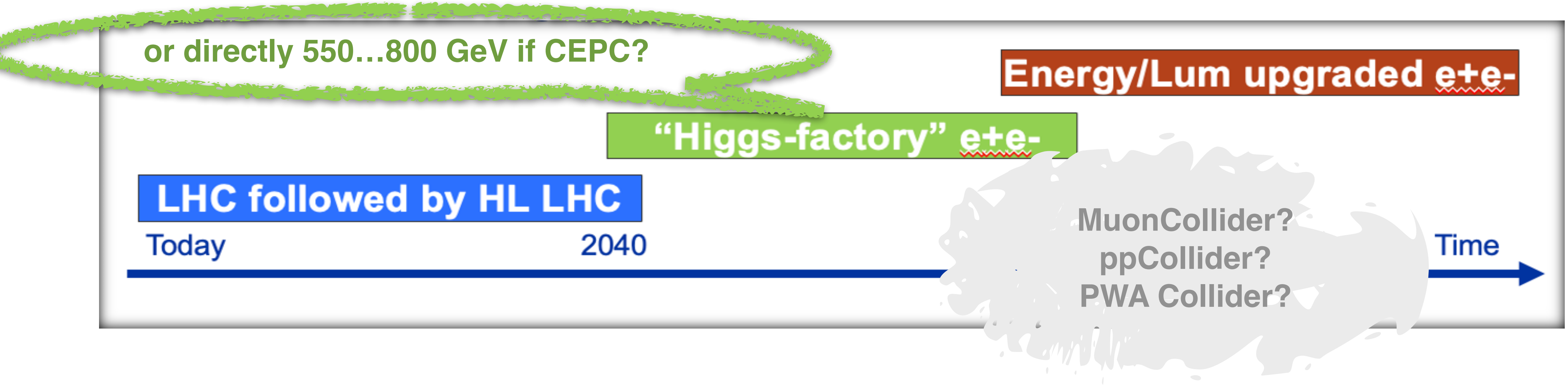

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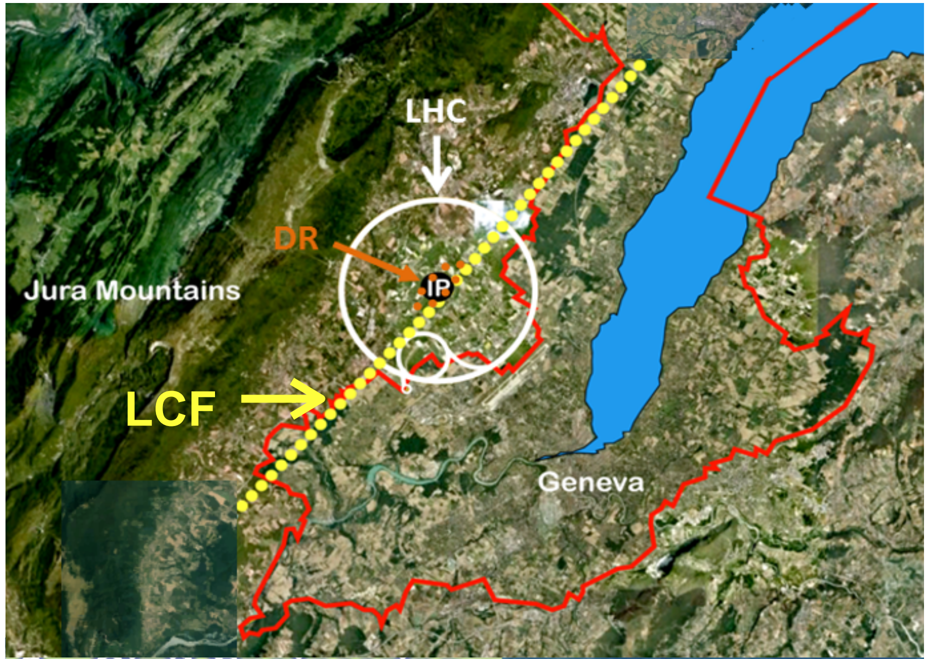
Important: need significant R&D program and demonstrators to bring advanced accelerators to construction readiness - must be part of the over all picture (funding, people, facilities…)

Conclusions

A Linear Collider Facility in Japan, at CERN or whereever

- offers
  - the **full Higgs/top/EW e+e- physics program** from 91 to (at least) 1000 GeV with polarised beams
  - and a rich program of **other collision modes and beyond-collider / R&D opportunities**
- can be built
  - at CERN:
    - ~within the CERN budget (ref CLIC PIP), leaving resources for scientific diversity and investment in R&D / demonstrators
    - **early:** industrialised SCRF production & expertise in other labs minimizes interference with HL-LHC
  - in Japan: **even earlier** if we could overcome political obstacles for funding…
- can be **upgraded** with same - or **advanced accelerator technology** (CLIC, C3, Plasma, ERL, …)
- leaves time to decide on target energy and best technology for exploring the energy frontier based on
  - scientific progress from HL-LHC *and* Higgs Factory
  - technology development



Thank you

Backup

Snowmass Implementation Task Force

arXiv:2208.06030

Consistent assessment of readiness, risks, costs etc - not always identical to projects self-assessment

Proposal Name	c.m. energy [TeV]	Luminosity/IP [10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Yrs. pre-project R&D	Yrs. to 1st physics
FCC-ee[1,2]	0.24	7.7 (28.9)	0-2	13-18
CEPC[1,2]	0.24	8.3 (16.6)	0-2	13-18
ILC[3]-0.25	0.25	2.7	0-2	$<$12
CLIC[3]-0.38	0.38	2.3	0-2	13-18
CCC[3]	0.25	1.3	3-5	13-18

all rather similar in time for R&D and (technically needed) time to physics

Circular colliders larger and more power hungry - but more lumi as well
CLIC more complex

Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
CCC (0.25 TeV)	150	3.7 km	I	I

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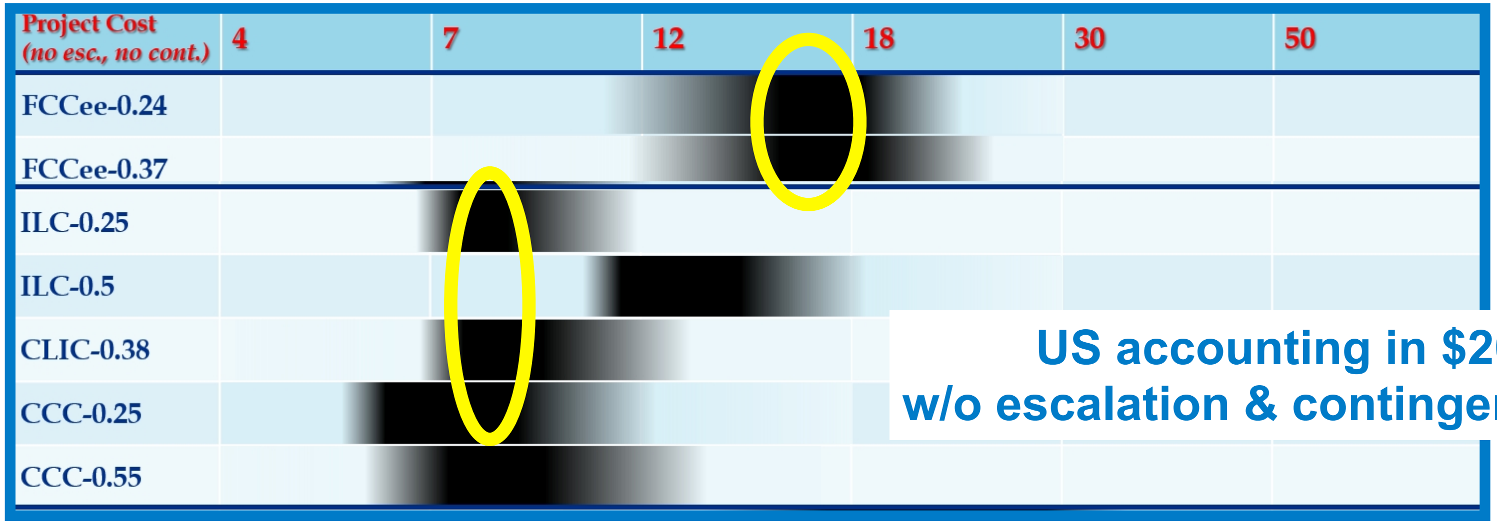


US accounting in $2021
w/o escalation & contingency

Linear Higgs Factory ~7-8B$
Circular Higgs Factory ~15B$

Lowest Technology Readiness Levels
- RF systems
- e+ source

=> let's take a closer look at relevant R&D!

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier
FCCee-0.24	II	RF sys,. e+ src, arc & booster magnets				1
CEPC-0.24	II					1
ILC-0.25	I	pol. e+ src				1
CCC-0.25	III	cryomodules, HOM detuning				2
CLIC-0.38	II	RF sys, 2-beam acc, emm. pres., spot size IP, stability				1

Sustainability

Gro Harlem Brundlandt at WEF 1989

Cover of the "Brundtland Report" 1987

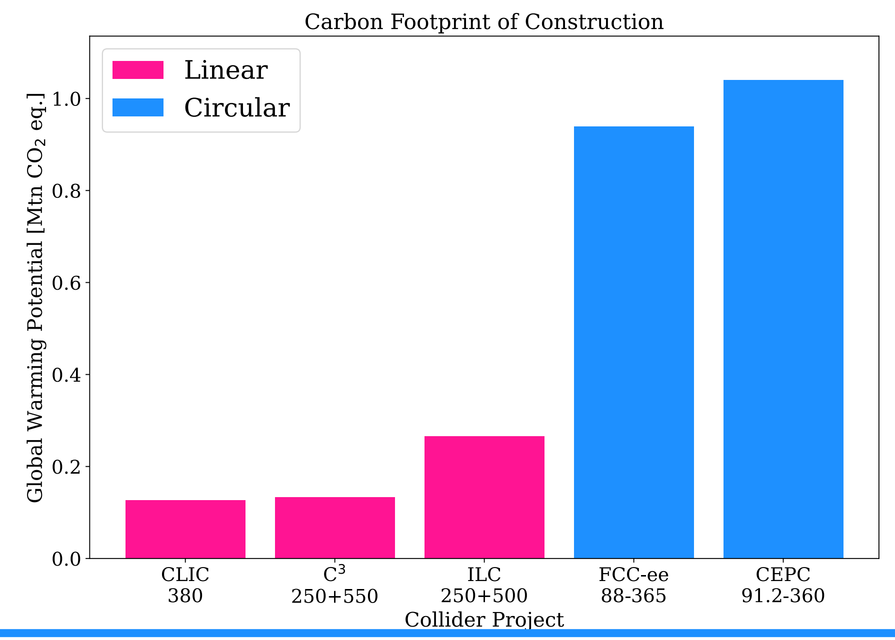
Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations. (WCED, 1987)

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

Global Warming Potential

Study by C3

GWP of construction dominated by CO2 emission from the required concrete & steel => tunnel length (diameter, tunneling technique)



arXiv:2307.04084

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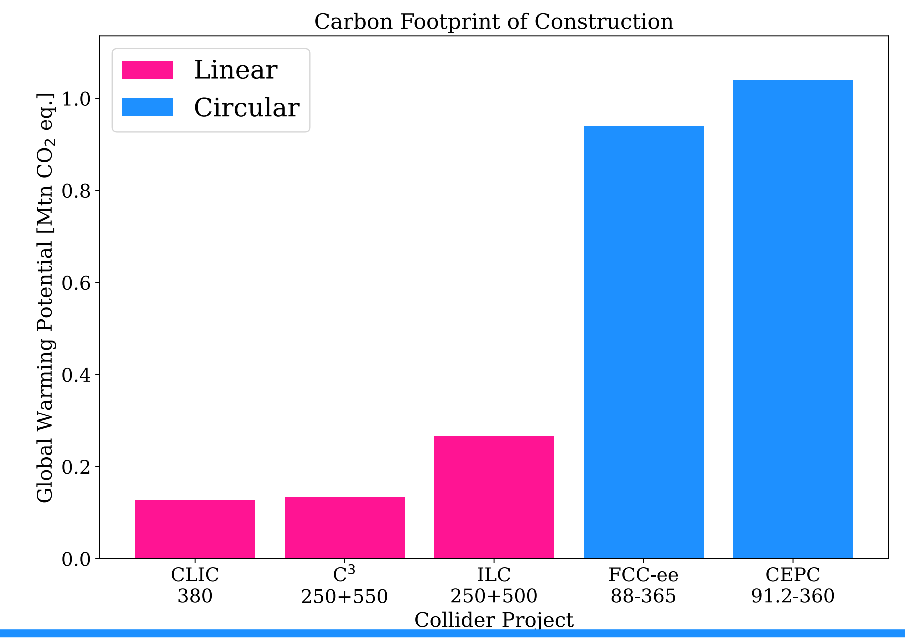

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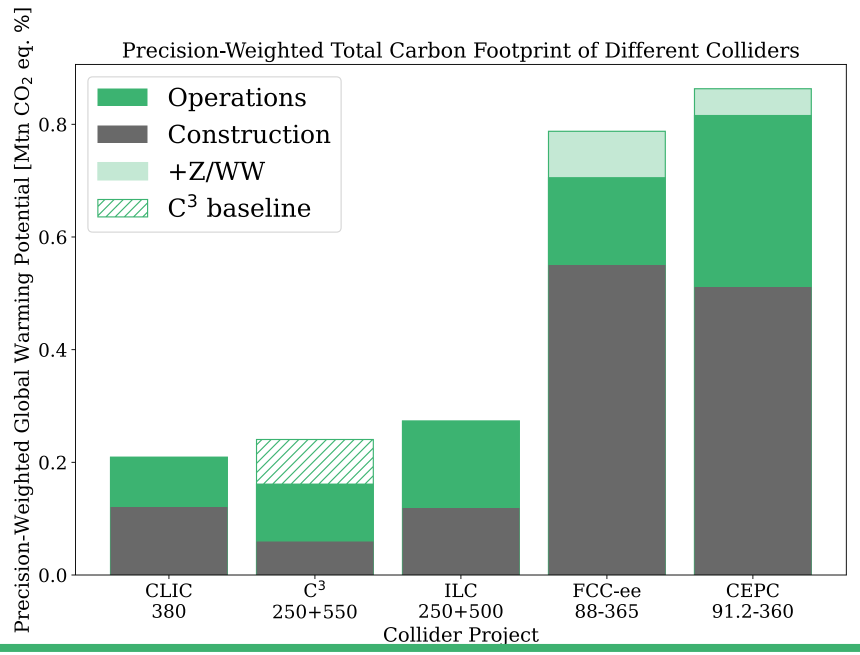


Adding operation GWP

(here weighted by improvement of Higgs couplings over HL-LHC, and with power mix predictions for CERN, US, Japan, China):

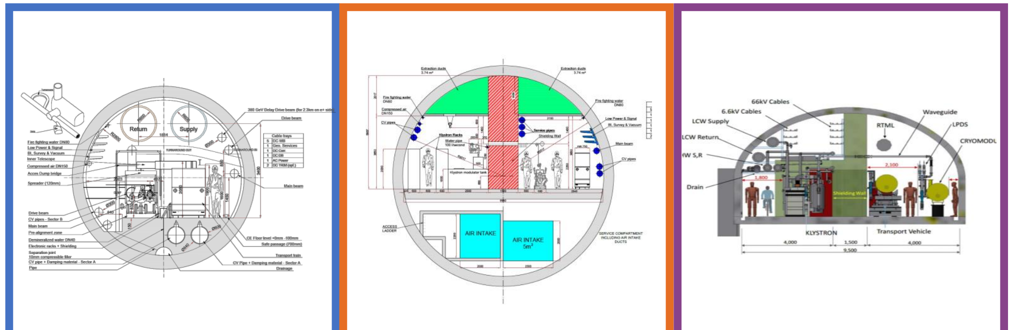
- **Operation dominates for LCs**
- **Construction dominates for CCs**

arXiv:2307.04084

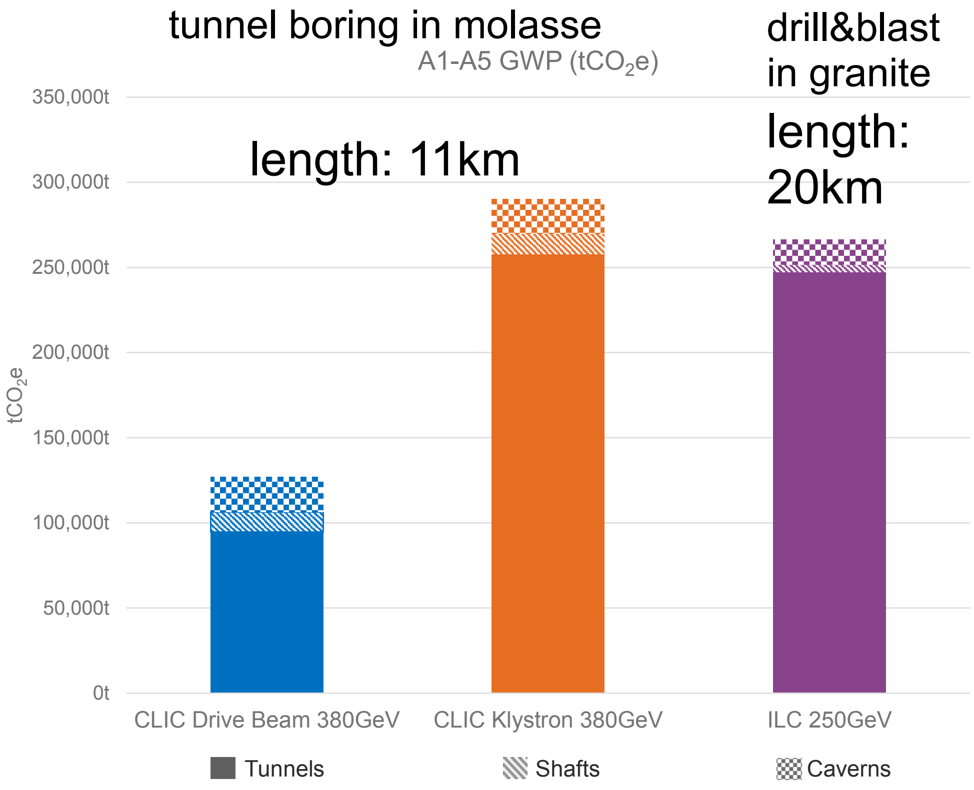
GWP of tunnel construction

Study by CLIC and ILC

- **full life-cycle assessment according to ISO standards by consultancy company (ARUP)**
- **green house gas emission plus 13 more impact categorie**
- roughly confirms C3 estimates (prev. slide)



CLIC Drive beam, 5.6m dia.
CLIC Klystron, 10m dia.
ILC, 9.5m span



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

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  - usage of low-CO2 materials (concrete, steel)
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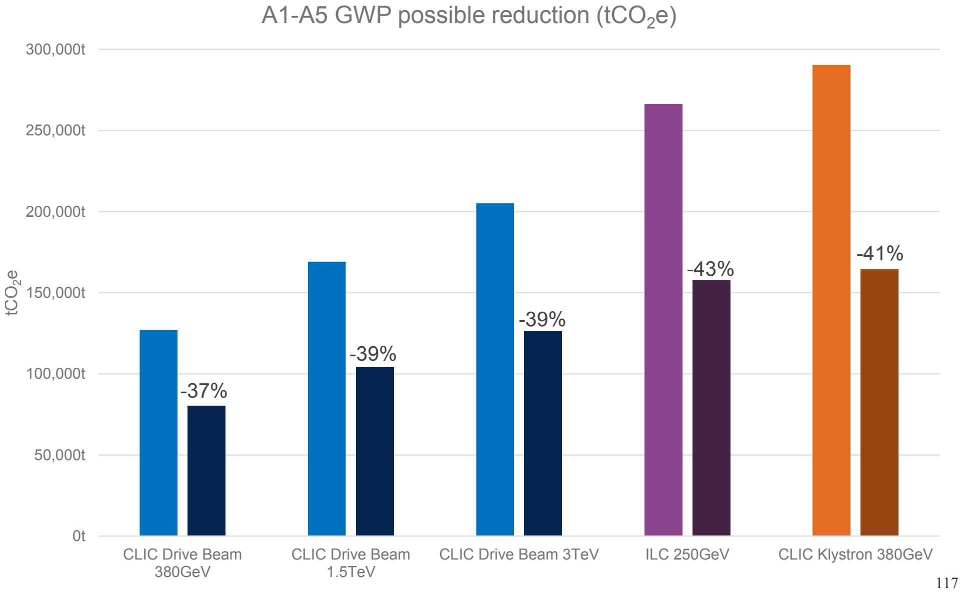

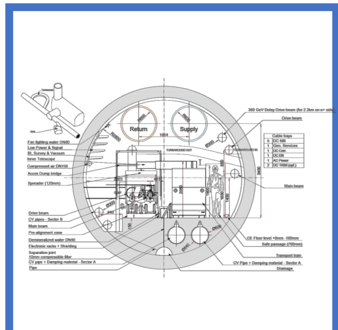

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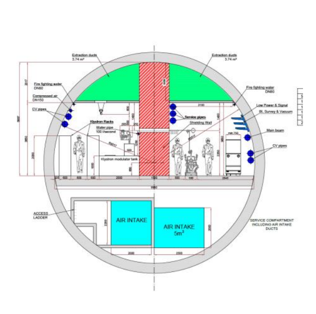

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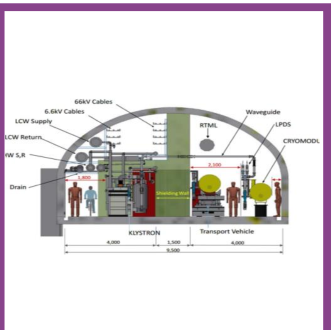
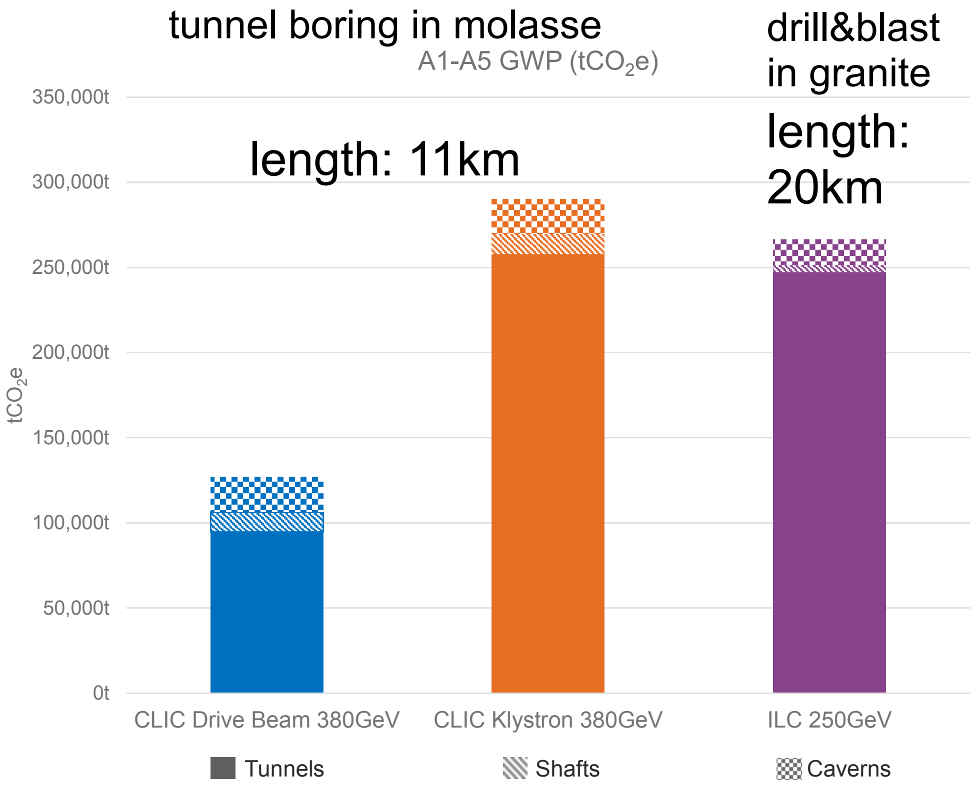


ILC, 9.5m span



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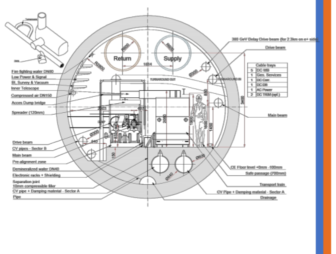

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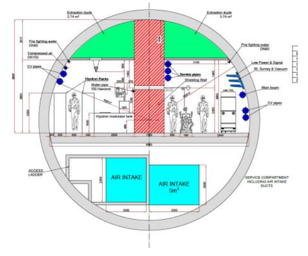

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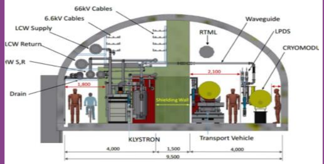
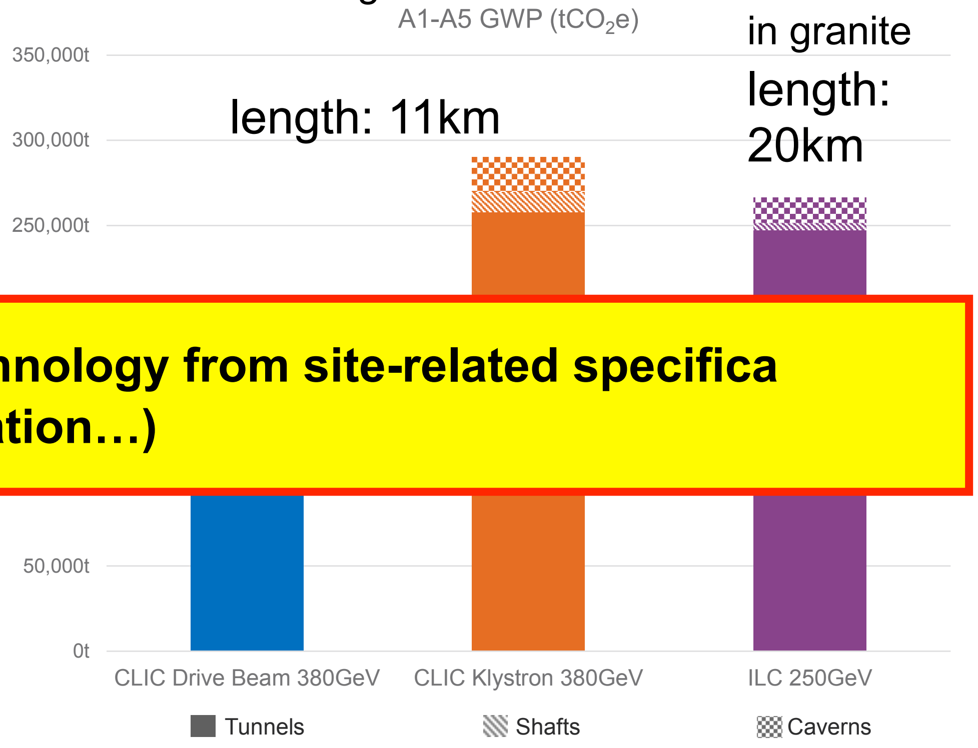
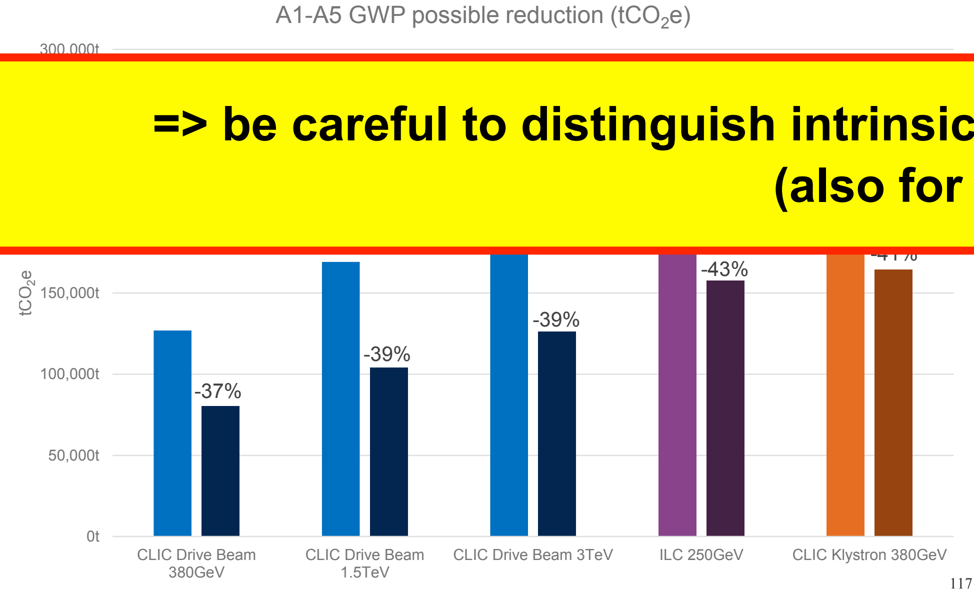


ILC, 9.5m span

tunnel boring in molasse

drill&blast in granite





=> be careful to distinguish intrinsic needs of technology from site-related specifica (also for GWP of operation…)

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Contact

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