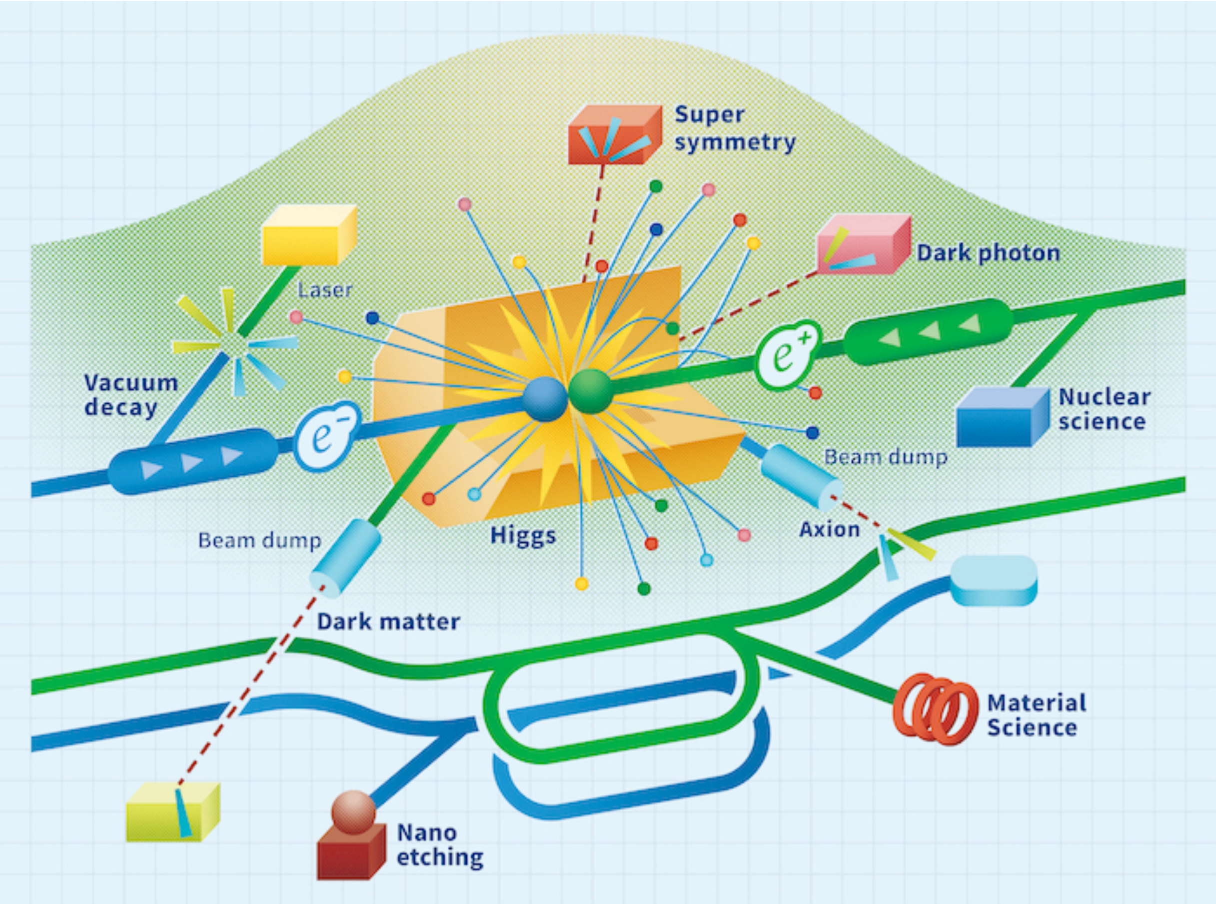
ILC and CLIC — Project Status and Plans

Physics, Technologies, Resources, Open Questions & Challenges



Jenny List (DESY) on behalf of CLIC and the ILC IDT

ICHEP
18-25 July 2024
Prague

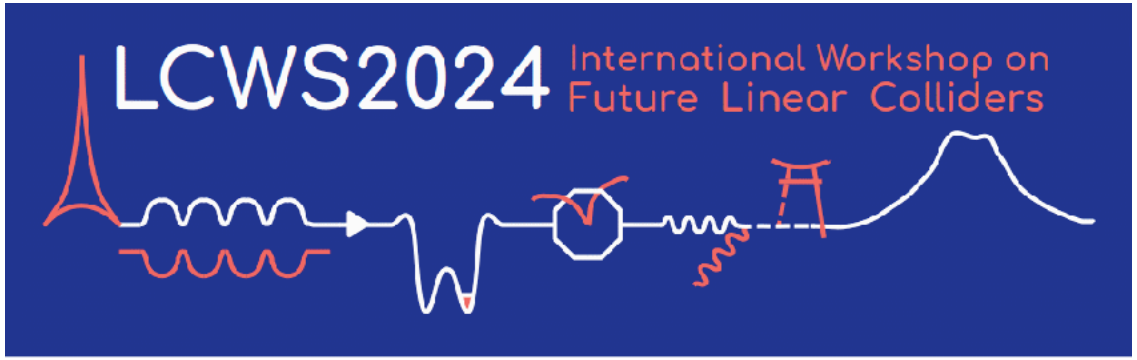
HELMHOLTZ
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
FTX
DESY.

Outline

Today's menu

- **Project Overviews & Updates**
  - **ILC**
  - **CLIC**
- **Plans towards the EPPSU**
  - **a global Linear Collider Facility**

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

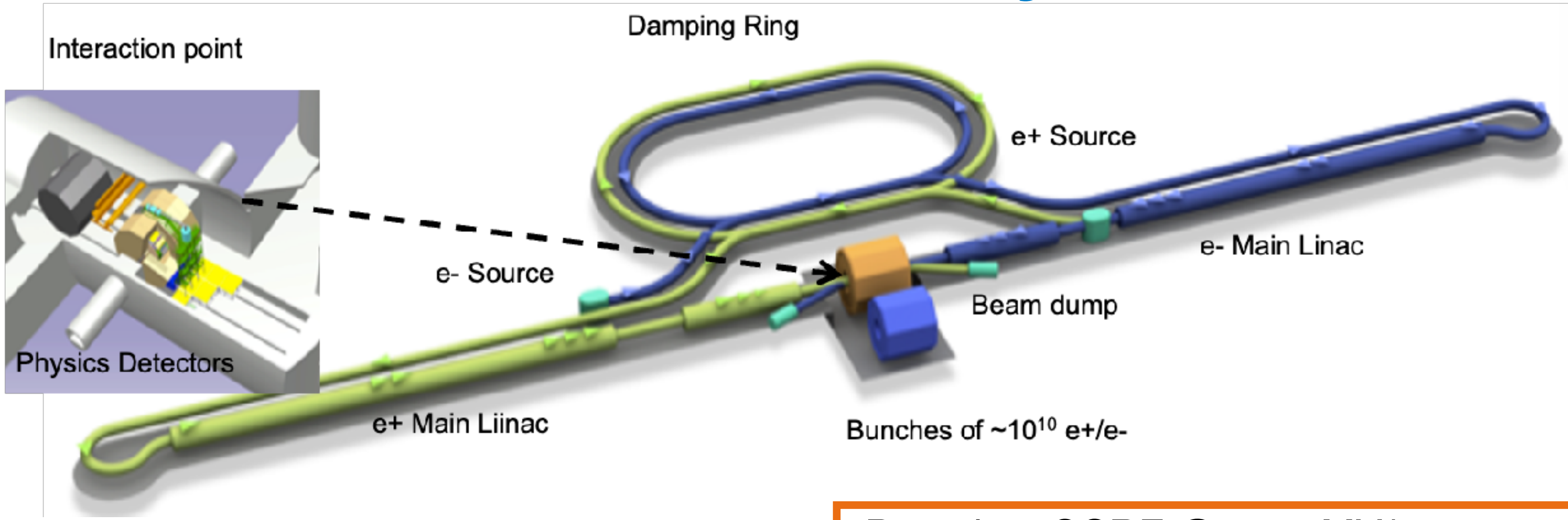


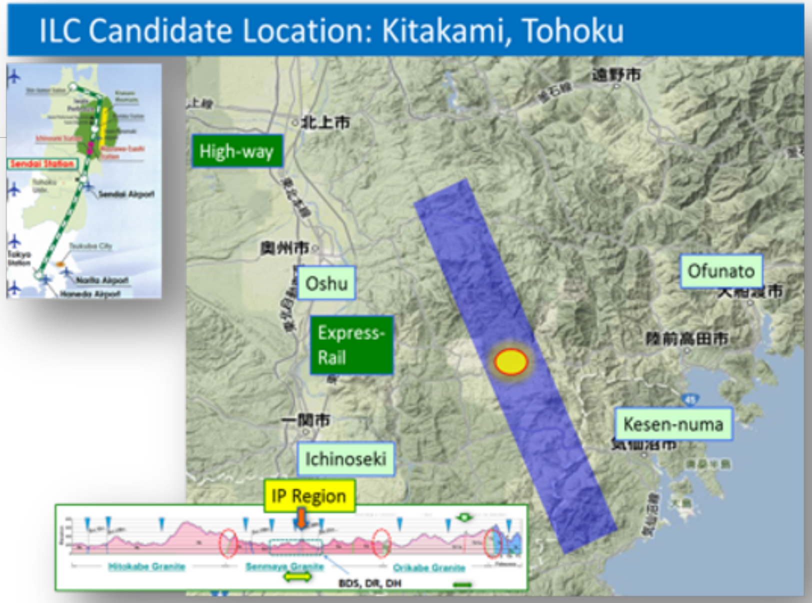
Linear Collider Workshop 2024

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

Project Overview & Updates

The ILC250 Baseline 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}

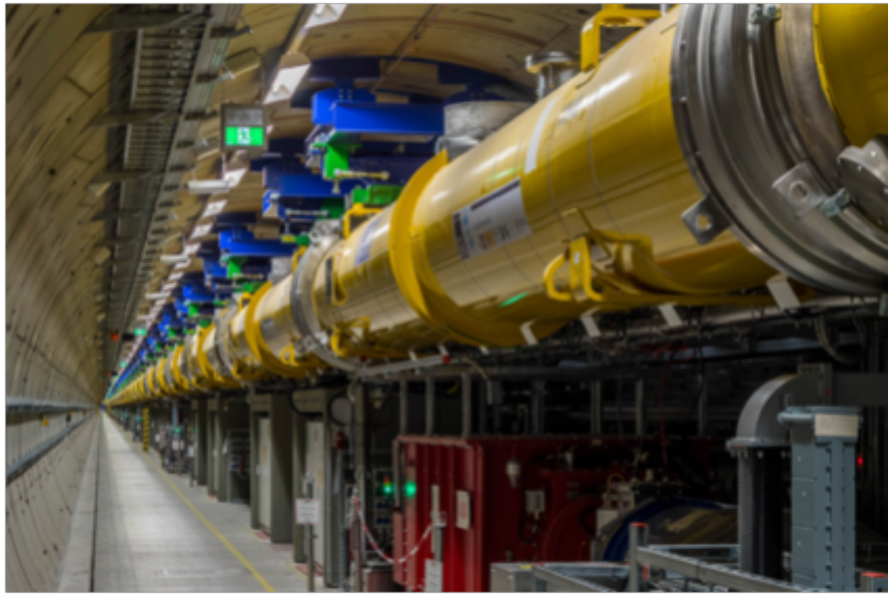
- Based on SCRF @ 31.5 MV/m
- Very mature technology and system design
- Comprehensive TDR in 2012 for 500 GeV (30km, 160-200 MW, 8 BILCU), upgradable to 1 TeV (50km, 300 MW)
- **since 2018 focus on 250 GeV (20 km, 110-140 MW, 5 BILCU) as a first stage**

Key Systems and Challenges

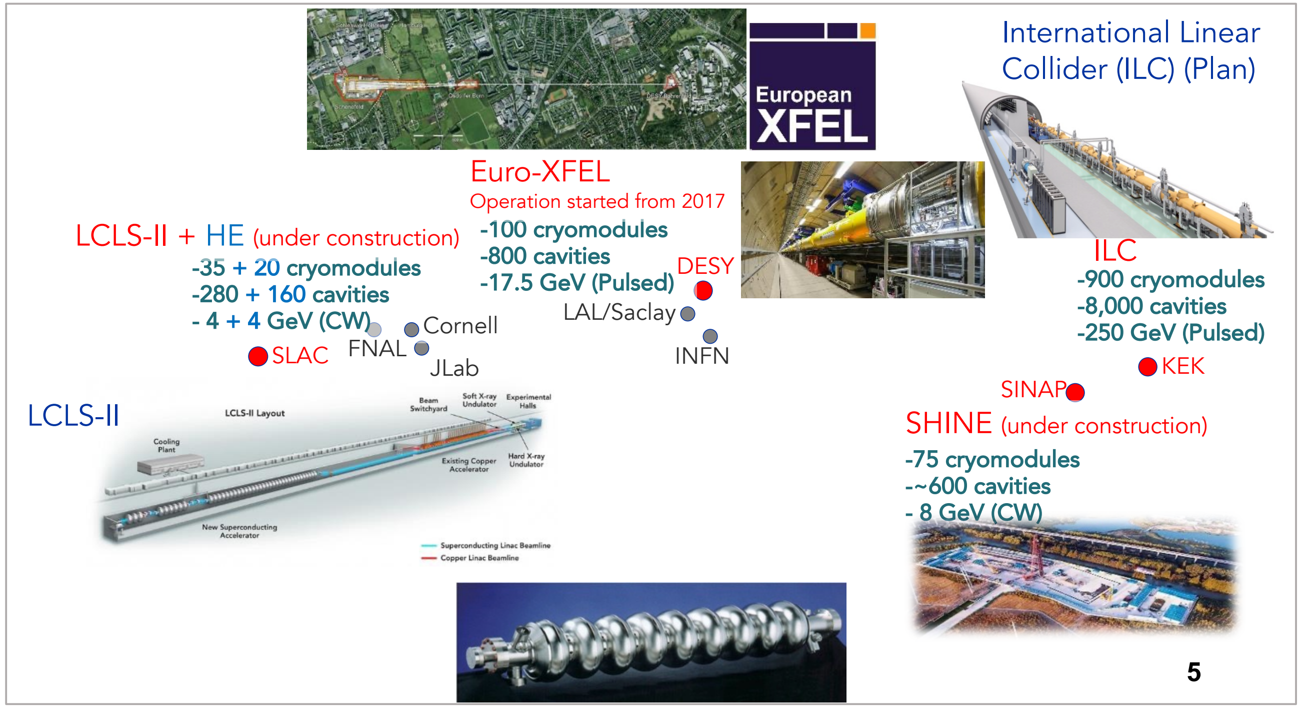
Very mature design

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

=> ILC Technology Network => Preparation Phase => 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



The ILC IDT Organisation - initiated by ICFA in 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.

2023/24: ITN started. An agreement KEK and CERN and several European lab activities have been/are being set up. US participating as observer while P5 recommendations are being implemented with DoE labs.

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

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The ILC Technology Network ITN

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

Topics

2023/11/16

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

- "Interest matrix" matching institutes and work packages well filled
- definition of detailed deliverables
- work started in many WPs

	Work packages			Participating institutes (confidential)																						
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	✓															✓					✓		
	WPP	11	Target replacement	✓																						
Nano-beams	WPP	12	DR System design	✓	✓				✓	✓		✓							✓				✓	✓		
	WPP	14	DR Injection/extraction	✓					✓										✓				✓	✓		
	WPP	15	Final focus	✓			✓		✓		✓							✓			✓			✓		
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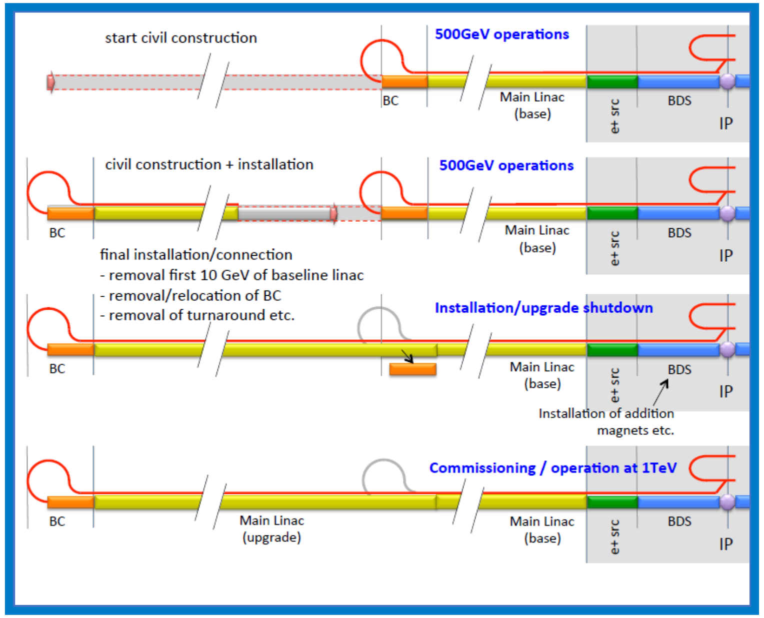
	WPP	17	Main dump	✓			✓					✓														

Beyond Baseline — Leverage Today's R&D



- ILC TDR offers **guaranteed upgrade path up to ~1 TeV**: extend tunnel to ~50 km, upgrade power to 300 MW
- **Higher gradients through treatments:** higher gradient niobium cavities exist in the lab (45 MV/m vs 31.5 MV/m ILC design), though not yet industrially available
- **Nb3Sn or multi-layer** — potential of up to 80 MV/m
- **Traveling-wave SCRF —** potentially double gradient wrt standing wave due to lower peak fields

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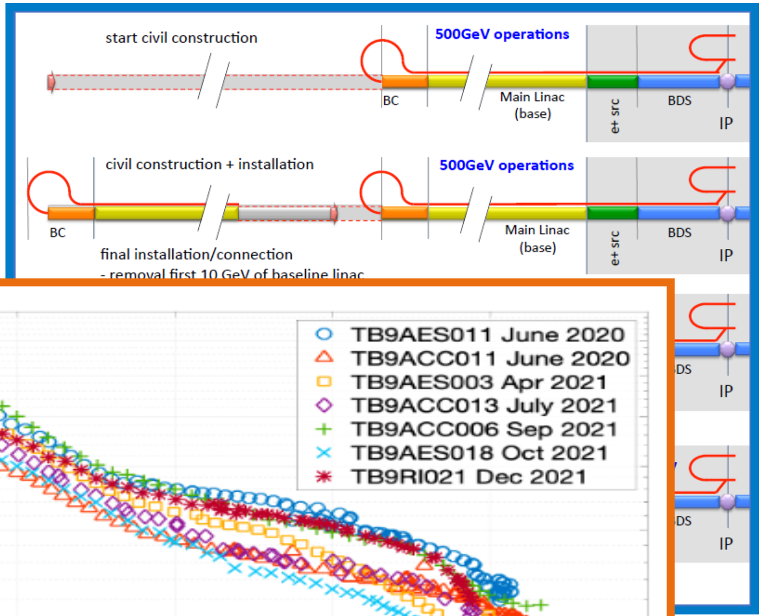

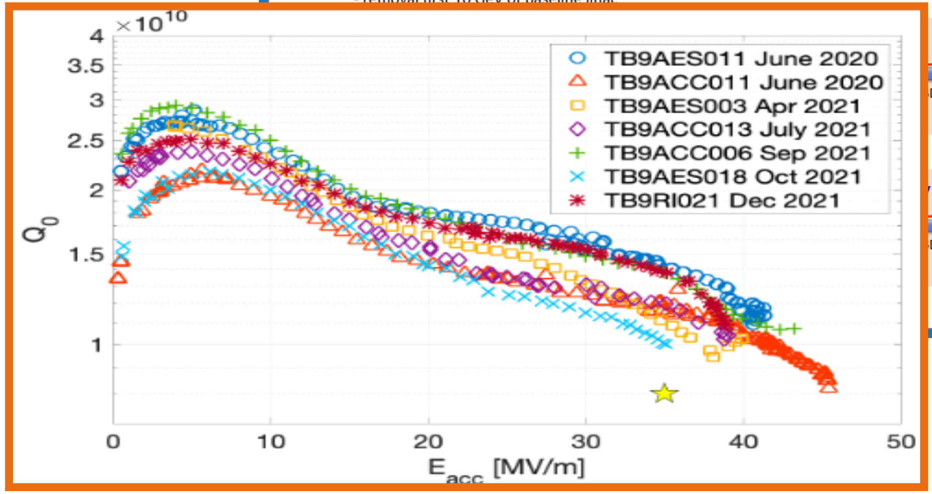

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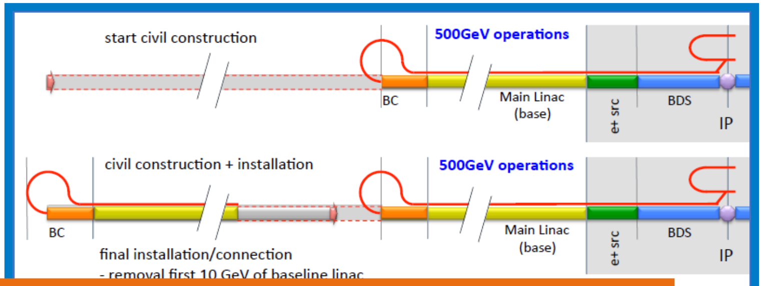

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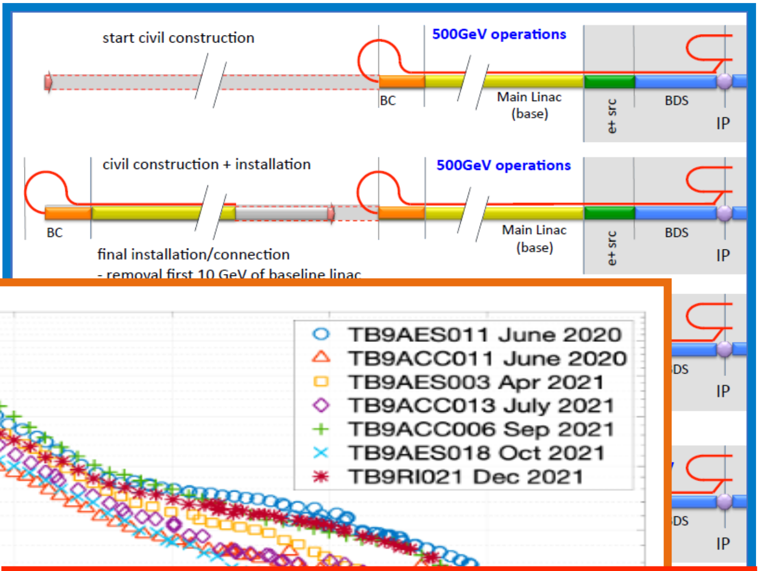
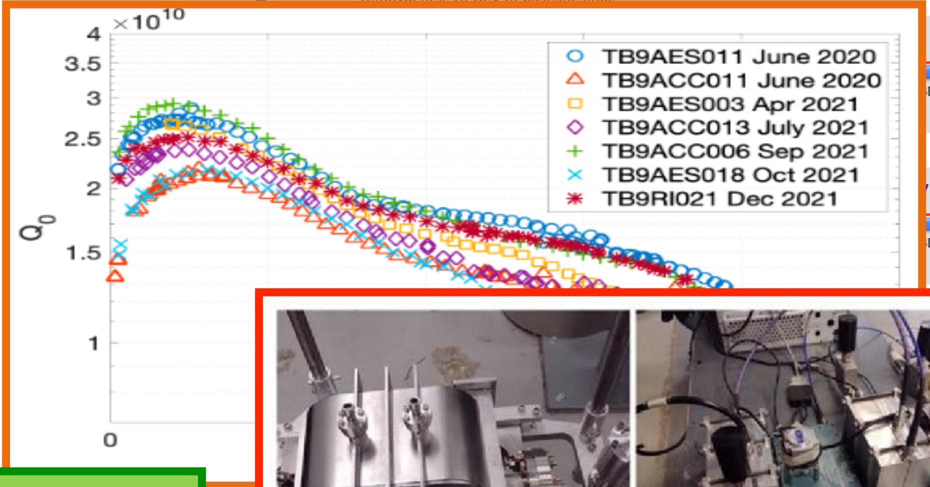




Summary of future upgrade using SRF

	ECM [GeV]	Gradient [MV/m]	Length [km]	#of cavities	AC power [MW] *5	Additional material cost [MILCU*1]	Technology ready
TDR	250	31.5	20.5	~8,000	~110	(~5,000 MILCU)	---
TDR	500	31.5	33.5	~16,000	~170	+3,000 MILCU	---
TDR	1,000	45	44.5	~23,000	~300	+3,000+7,100 MILCU	In 10 years
Nb3Sn/multilayer or TW	500	63	20.5	~8,000 *2	~180 *6	?	In 20 years
NB3Sn/multilayer & TW	1,000	126 *3	20.5	~8,000 *4	~260 *7	?	In >20 years

*1 based on the ILC TDR and referring the ILC unit as of 2012.
*2 Requires RF source upgrade (x2) + Cryogenic upgrade (~x2)
*3 Surface discharge etc. can happen at such a high gradient operation
*4 Requires RF source upgrade (x4) + Cryogenic upgrade (~x4)
*5 further reduction will be done by higher efficiency of cryogenics and RF (65%->80%?), etc.
*6 Q0=3e10, 4.5K operation (1/3.5 cryo-power)
*7 Q0=3e10, 4.5K operation (1/3.5 cryo-power) and 1ms filling for TW

Beyond Baseline - Double E_{CM} by "HALHFing" ILC

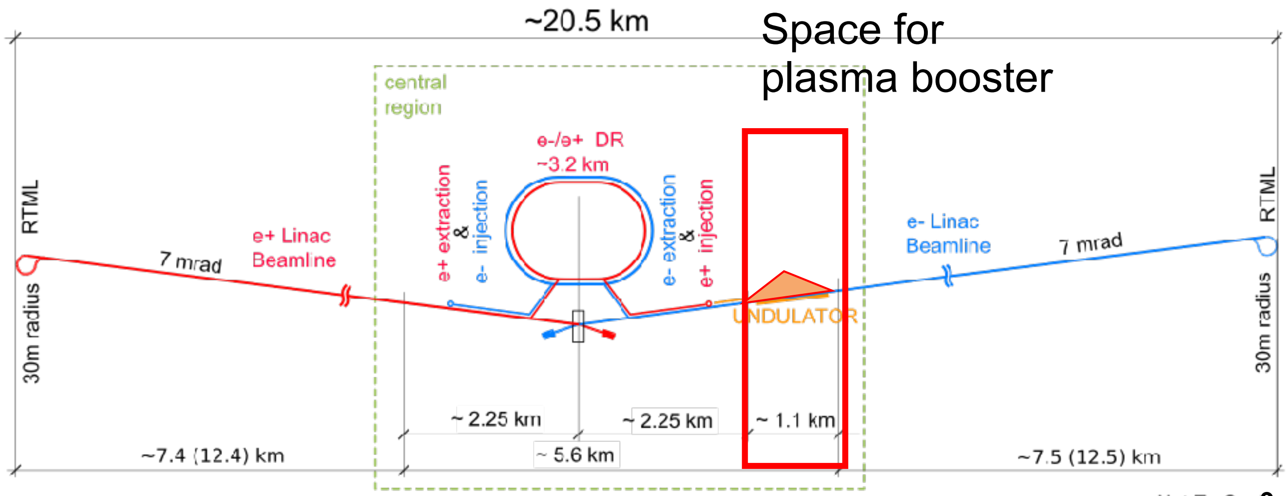
- **Apply HALHF concept to eg 250 GeV ILC:**
  - **plasma-accelerate** e- to 550 GeV
  - keep e+ linac
    (small upgrade 125 -> 137.5 GeV)

⇒ 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.)	$cm^{-2}s^{-1}$	~ $1 \cdot 10^{34}$		



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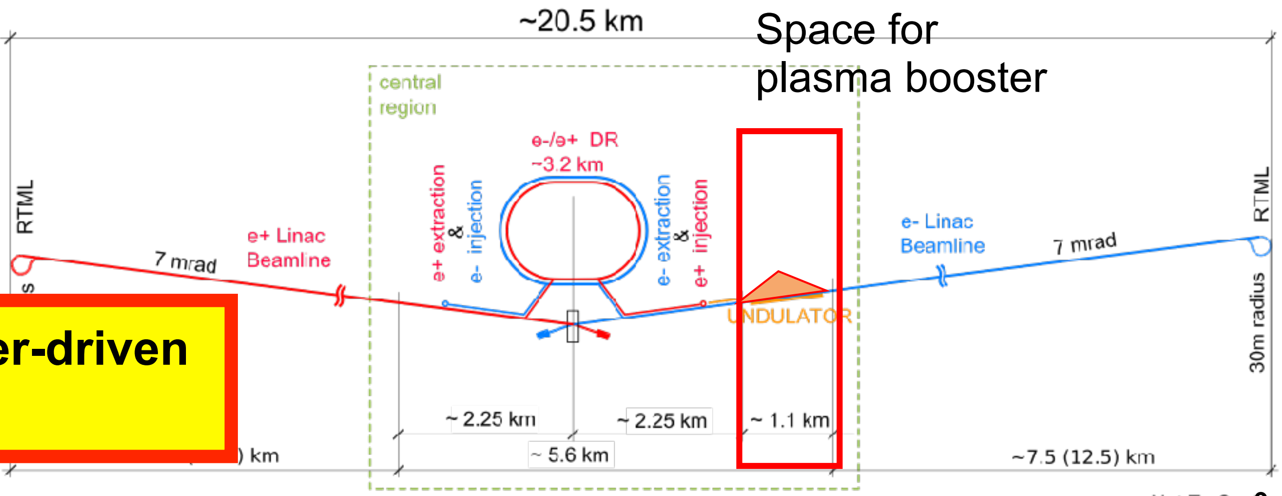
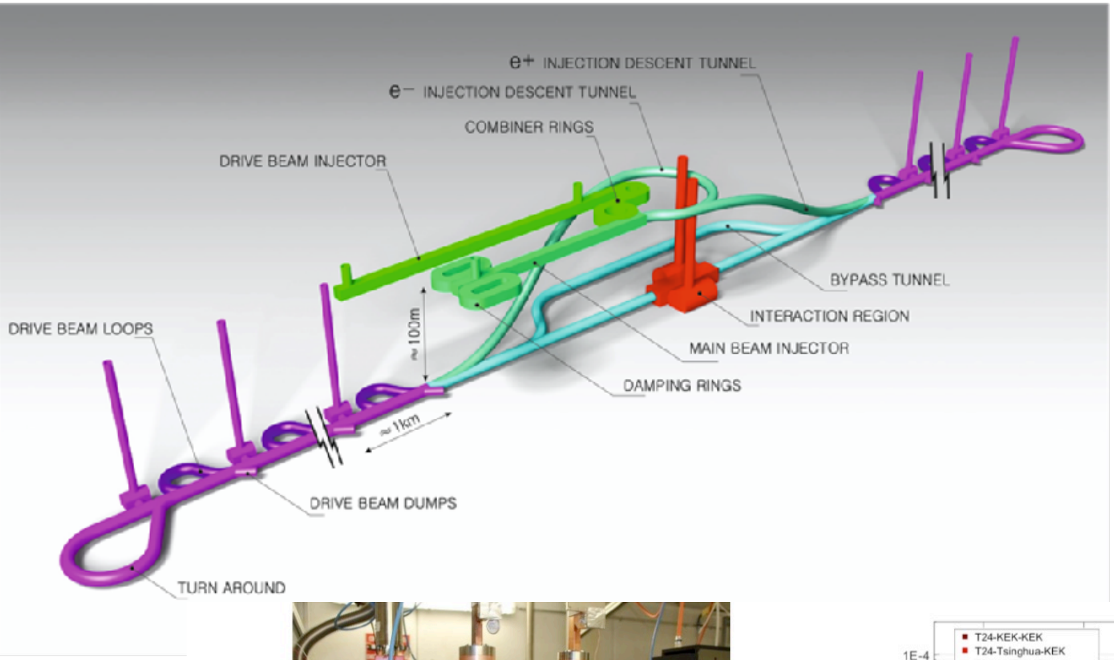
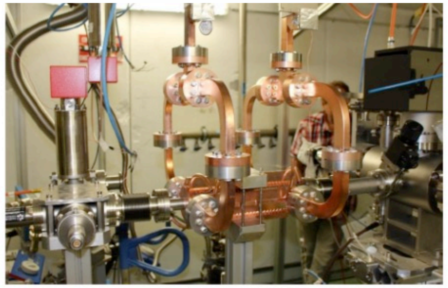


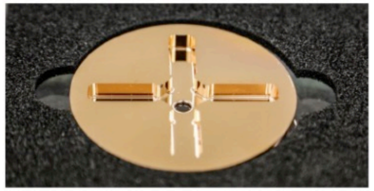
To do: work out a corresponding scheme for laser-driven plasma / ALEGRO-style upgrade!

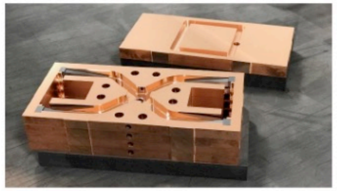
The Compact Linear Collider CLIC

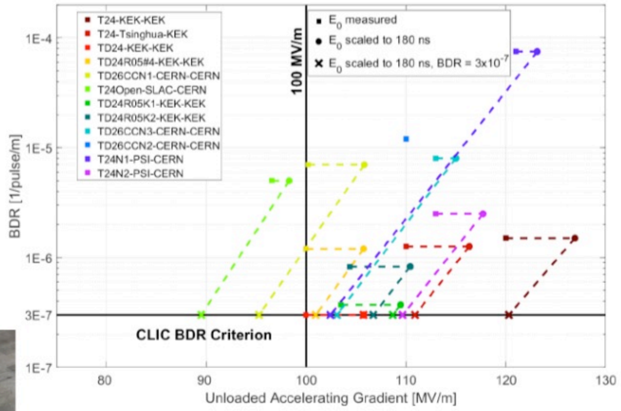




Test structure





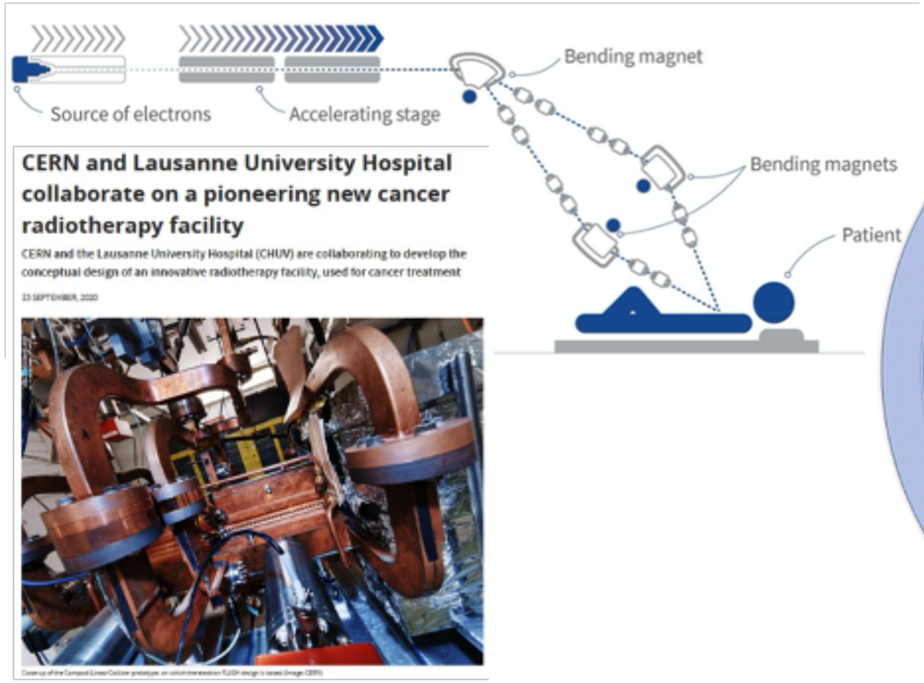


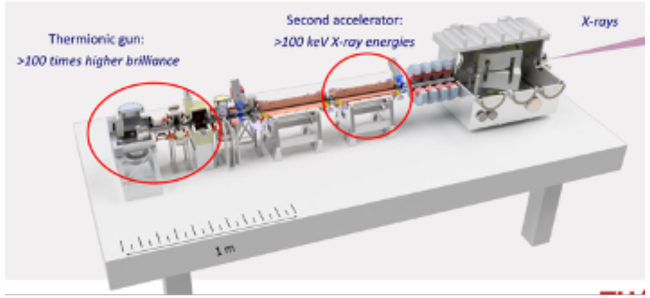
Achieved accelerating gradients in tests

- **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
- **Energy frontier:** upgradable up to 3 TeV
- **CDR in 2012:** focus on 3 TeV.
- **Project Implementation Plan 2018:** Updated project overview documents with focus on 380 GeV for Higgs and top.
  - costs drive-beam / clystron: **5.9 / 7.3 BCHF**
  - **found to be affordable within CERN budget (PIP)**

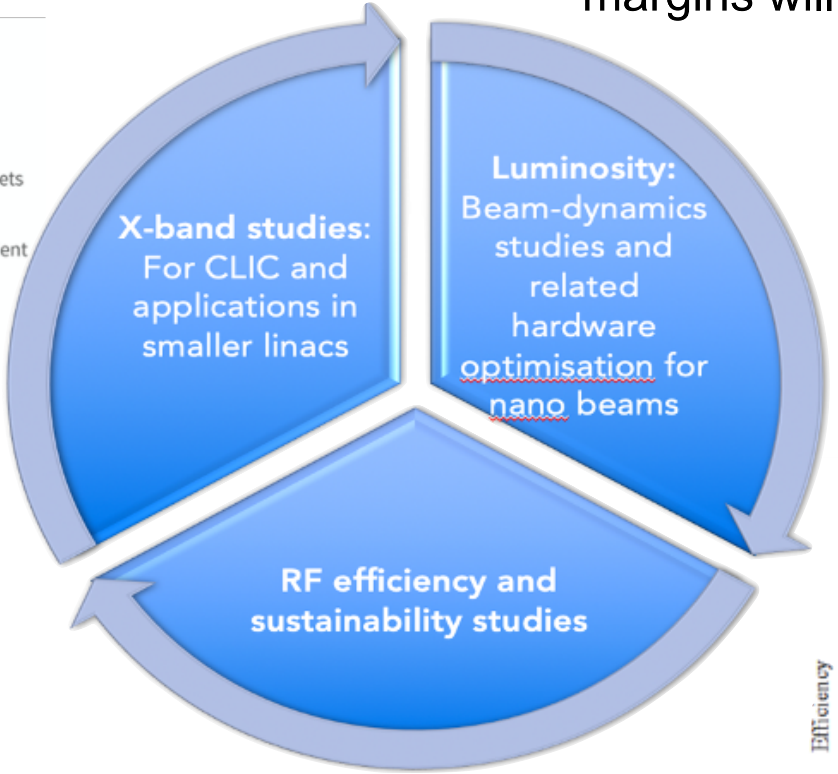
Ongoing CLIC Studies

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

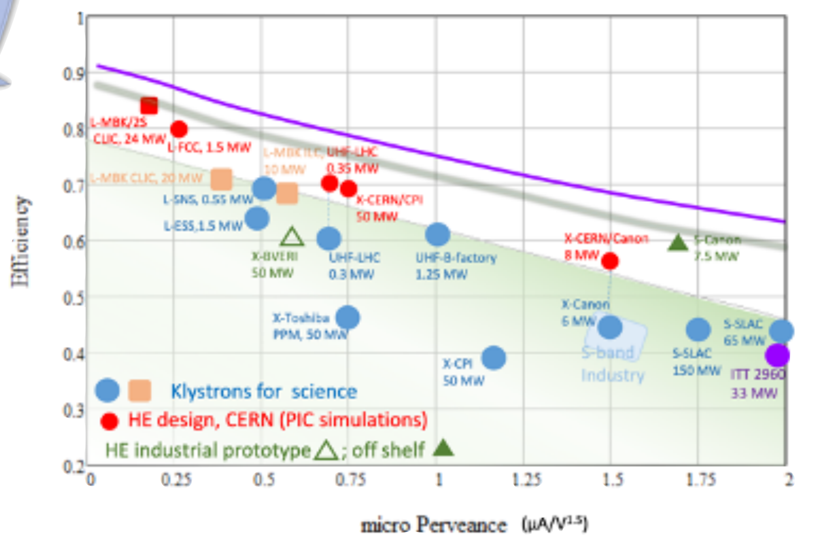




Optimizing the luminosity at 380 GeV at 2.3 x 10^{34} cm^{-2} s^{-1}– already implemented for Snowmass paper, further work to provide margins will continue (HW and SW)



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

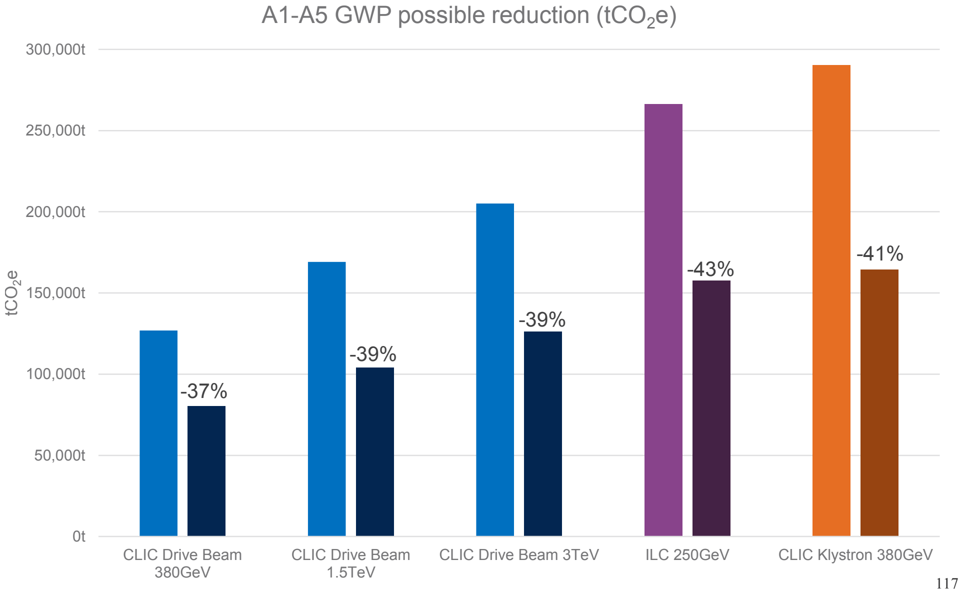


Improving the **power efficiency** for both the initial phase (already in Snowmass report) and at high energies, including more **general sustainability studies**

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 categories**
- roughly confirms C3 estimates (prev. slide)
- **~40% of reduction potential by**
    - usage of low-CO2 materials (concrete, steel)
    - reduction of tunnel wall thickness



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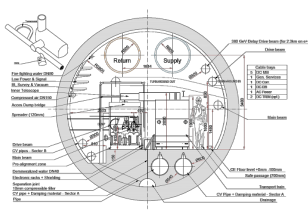
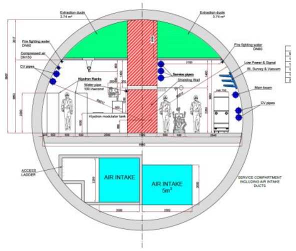
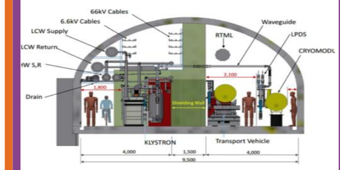


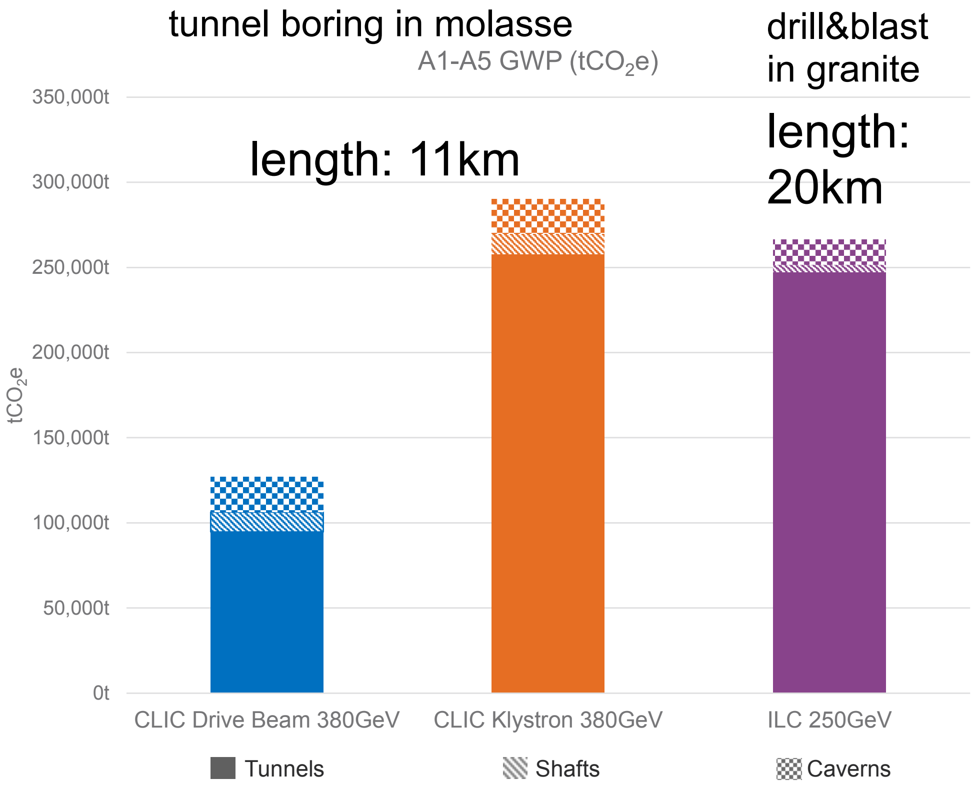
CLIC Drive beam, 5.6m dia.



CLIC Klystron, 10m dia.



ILC, 9.5m span



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

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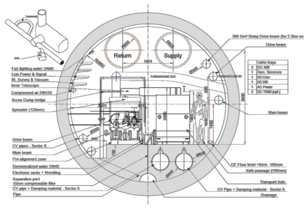
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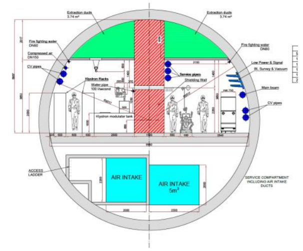
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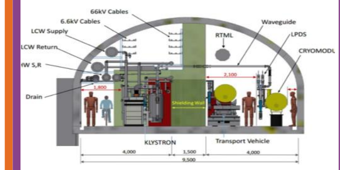
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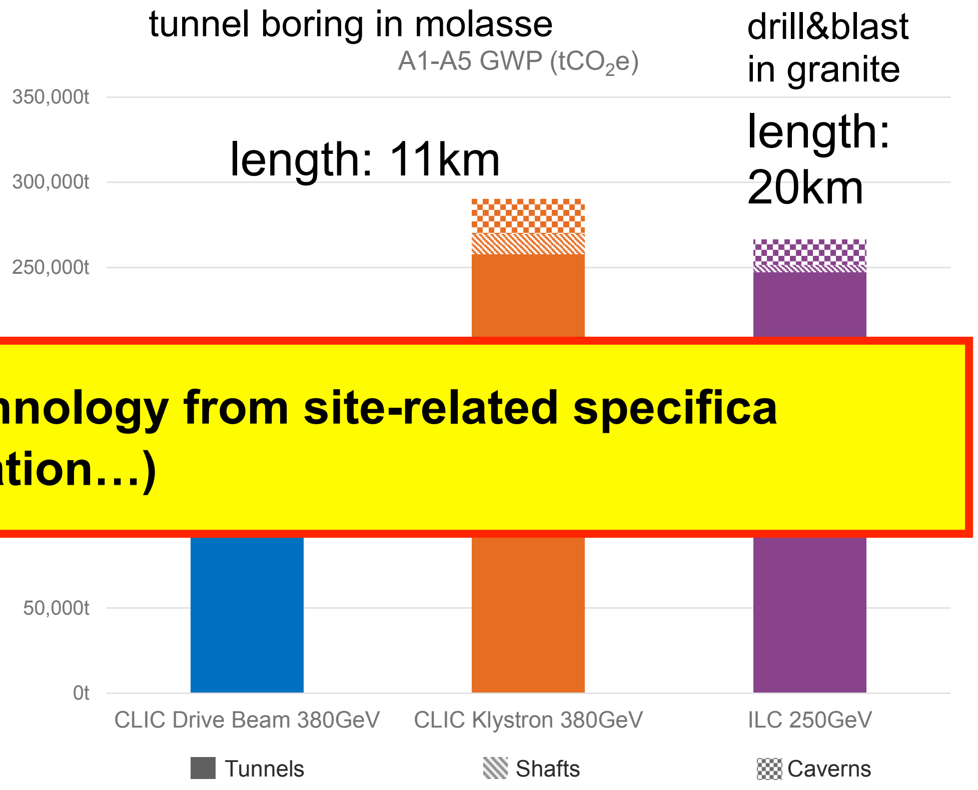

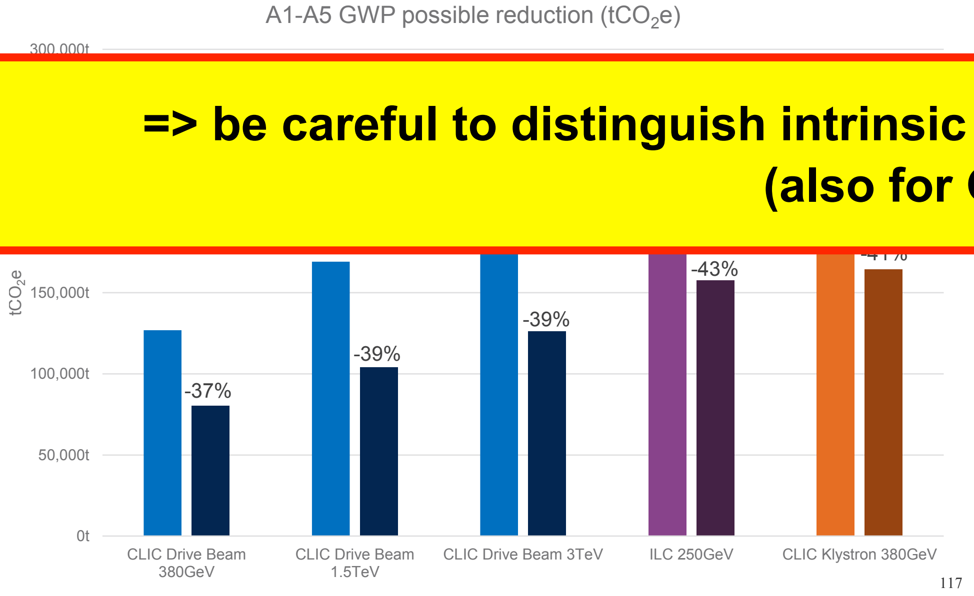

=> be careful to distinguish intrinsic needs of technology from site-related specifica (also for GWP of operation…)

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

Plans for the EPPSU — towards a global Linear Collider Vision

See Linear Collider Workshop 2024 for more information

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

A Linear Collider Facility — somewhere in the world…

- **Technologies not a priori coupled to regions** => widen perspective beyond "CLIC=CERN, ILC=Japan, C3=FNAL I …" logic
- **Linear Collider Community started to discuss a *common* vision —** including **CLIC, ILC**, C3, plasma acceleration, energy recovery, and representatives of many more ideas
- **Which key physics measurements should be performed, and what is the *best* energy for each of them?** => energy steps / running scenario
- **Which technology is most promising for early start?**
- **Consider all other technologies as upgrade candidates:**
  - available when?
  - which requirements need to be fulfilled by initial facility?

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SCRF is proven and *industrialised* technology:
- strong general interest around the world
- significant industrial production capacities

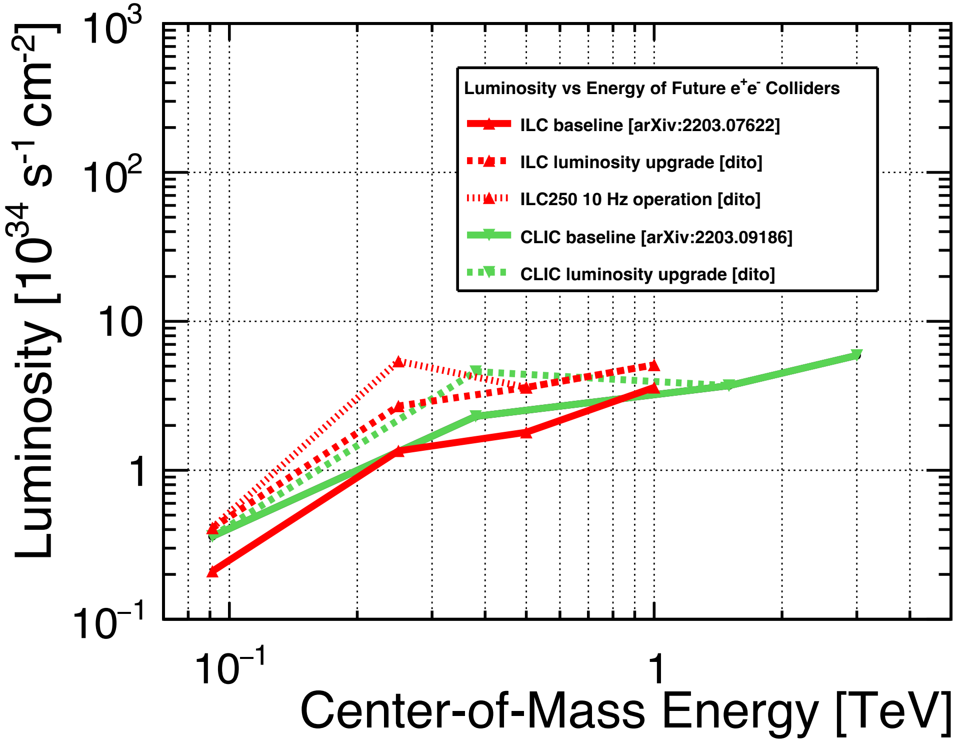
=> ILC technology minimizes time to realisation

=> 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



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-coup**
  - **top quark ew co**
  - **top Yukawa cou**
  - improved Higgs, \
  - probe Higgsinos \
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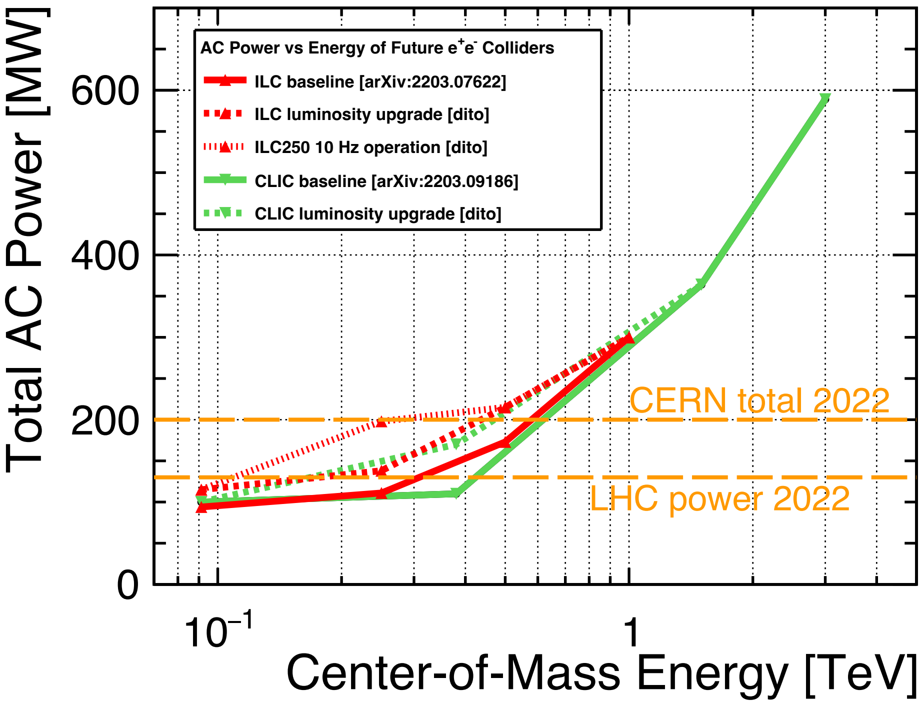

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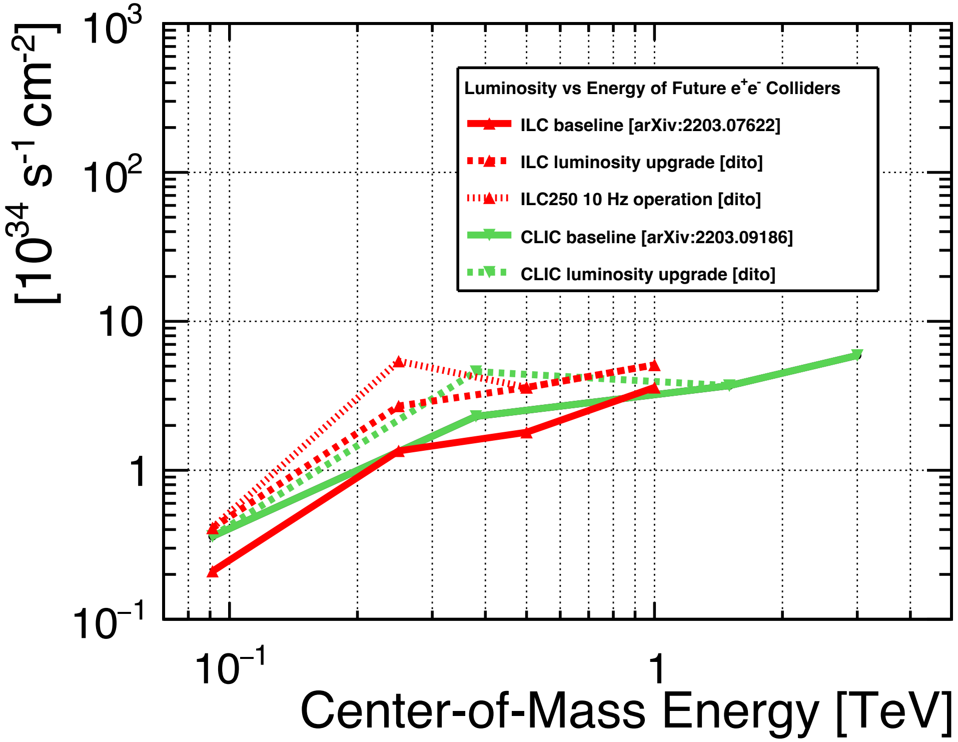

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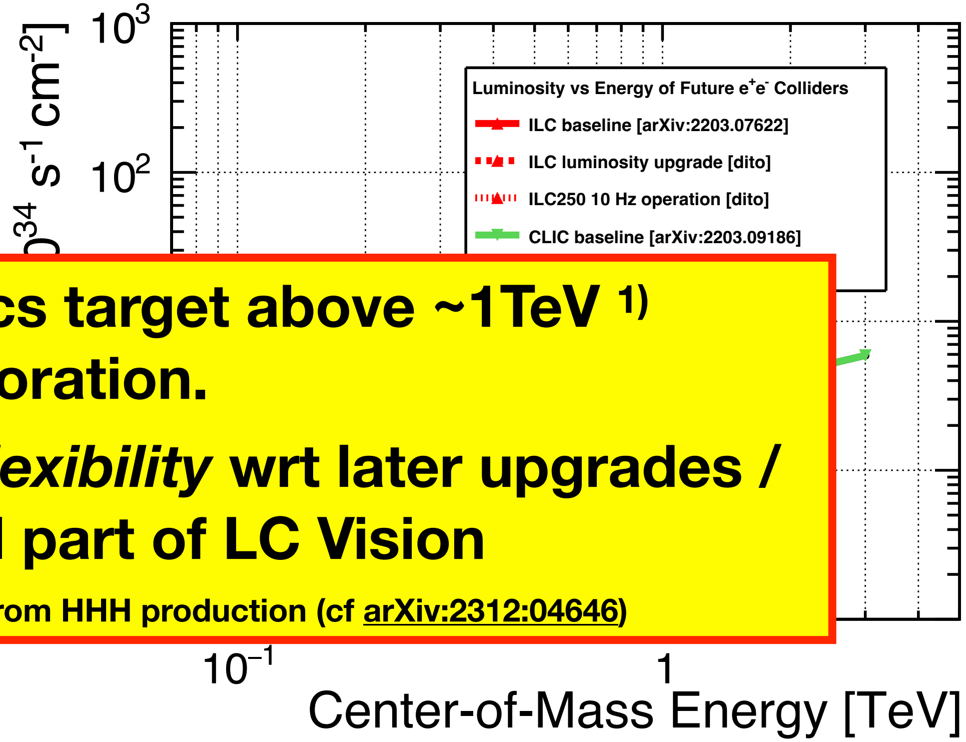
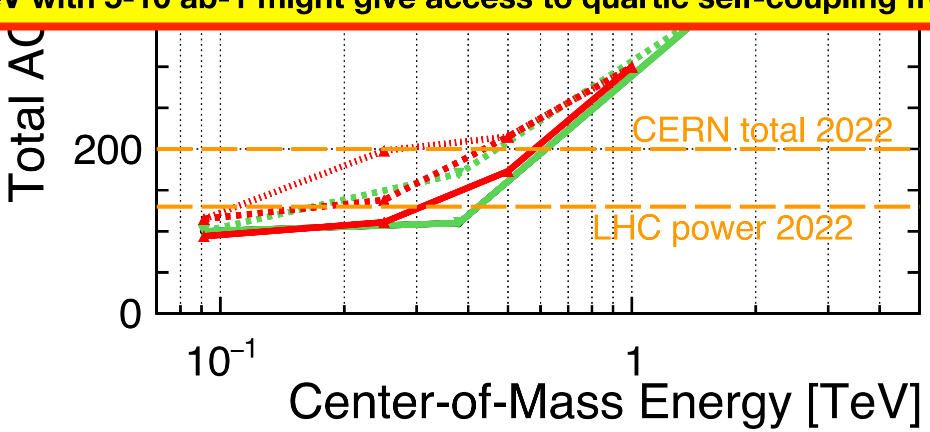




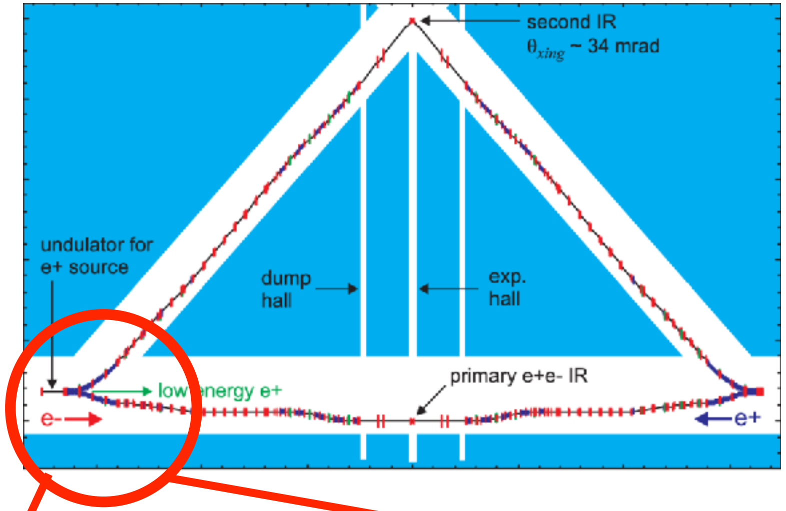
As of today, there's no very clear physics target above ~1TeV [1)] — apart from pure exploration.

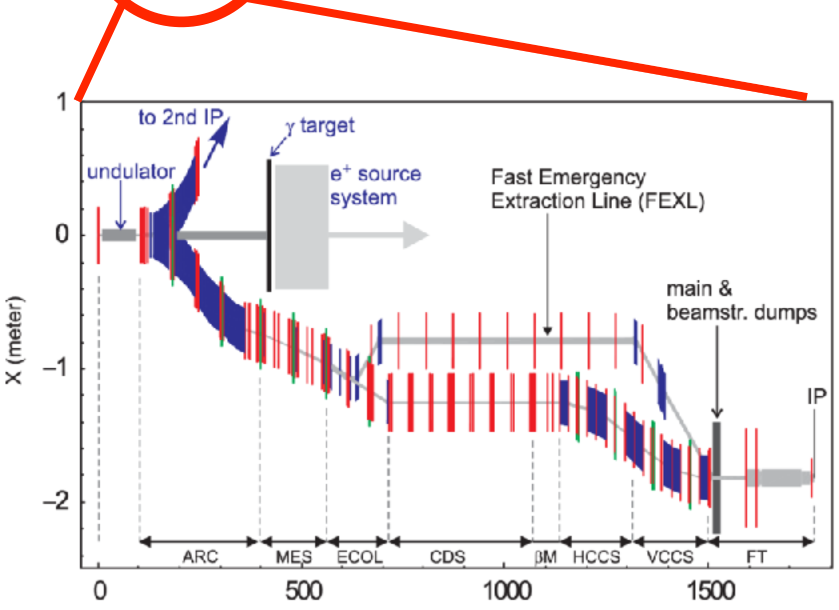
However HL-LHC might still change that…*flexibility* wrt later upgrades / choice of 10 TeV pCoM is integral part of LC Vision

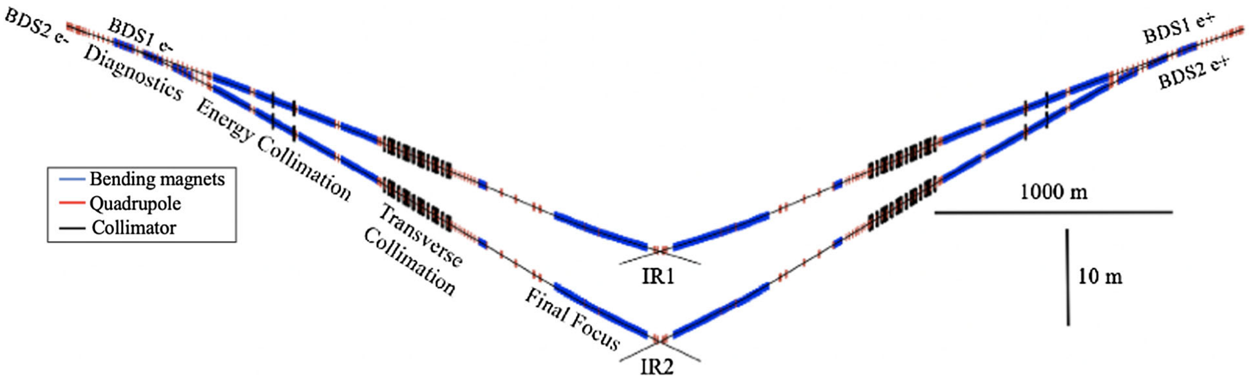
1) 3-10 TeV with 5-10 ab-1 might give access to quartic self-coupling from HHH production (cf arXiv:2312:04646)

2nd Interaction Region — for 2nd e+e- detector — or γγ / eγ / e-e- ?

- **2nd Beam Delivery System (BDS) to 2nd Interaction Region,** served "quasi-concurrently", by switching on train-by-train basis have been **designed for ILC & CLIC**
- eliminating it from ILC baseline "saved" **O(0.5) BILCU — could reinstantiate for a Linear Collider Facility**
- **2 IRs are important for**
  - 2 detectors for redundancy, technological complementarity, systematic cross-checks, competition
  - special collision modes: e-e- / γe / $\gamma\gamma$, each adding specialized, unique physics opportunities
  - …but do of course *not* double the e+e- luminosity







Beyond e+e- Collisions - Beam Dump / Fixed Target Experiments

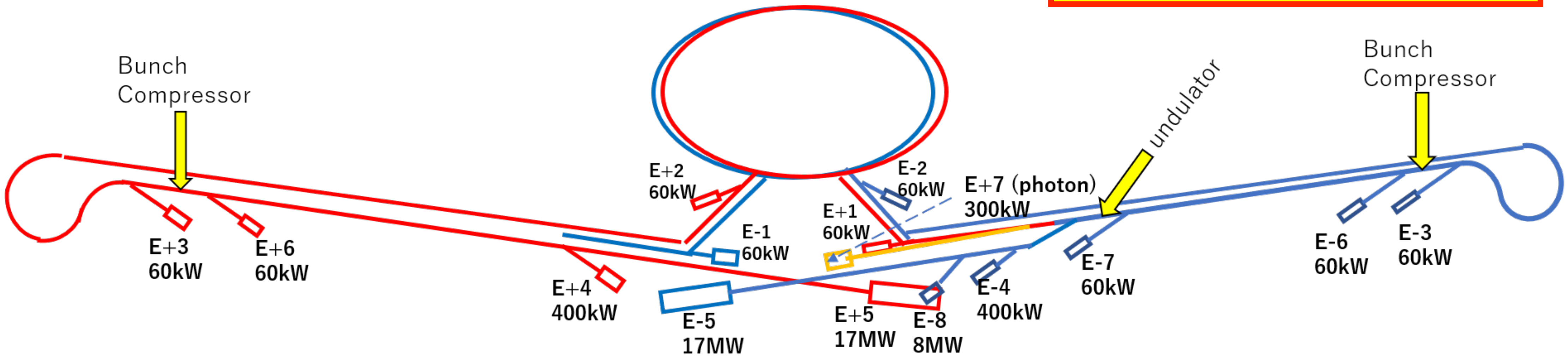
- **Ample opportunities to foresee beam extraction / dump instrumentation / far detectors at a LCF**
  - extraction of bunches before IP -> mono-energetic, extremely stable, few 10^{10} @ 1-10 Hz
    - **super-LUXE (SF-QED χ = O(few hundred) & BSM search)**
    - **super-LDMX, …**
  - disrupted beam after IP -> broad energy and highly divergent, **up to 4×10^{21} eot/a** (SHIP: 10^{20} pot in 5 years)
    - **super-SHIP, generic dark photon and ALP searches**

      => together with e+e- cover all Dark Sector portals
- **Studied for ILC around 2021**
- **Revisit for LCF — estimate size of user community?**

ILCX workshop

Chap 11 of arXiv:2203.07622

and talks at LCWS 2024



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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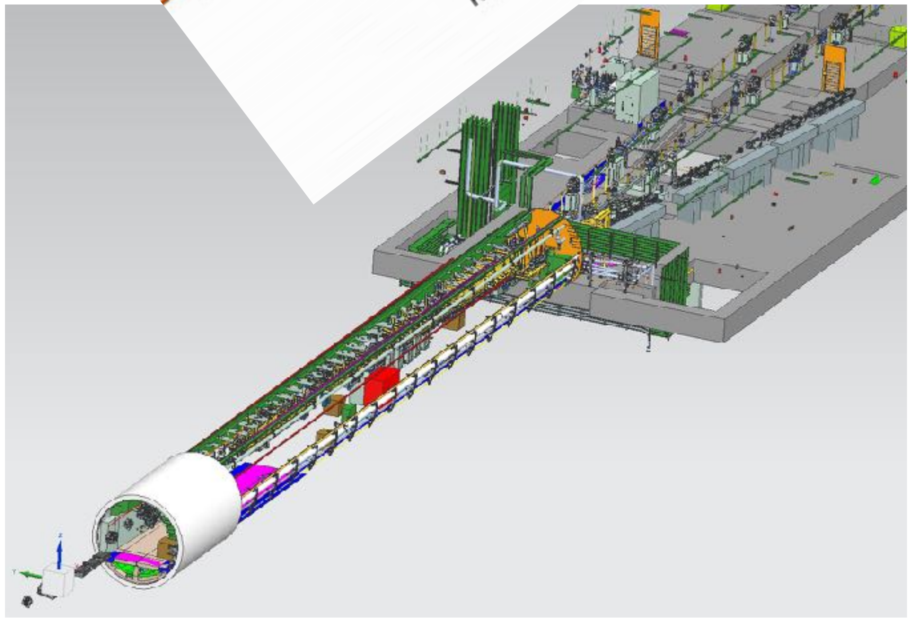

Pioneering this *now* at DESY / Eu.XFEL with ELBEX facility (beam extraction for LUXE & other applications)

A Linear Collider Facility and the Energy Frontier

Start with an affordable, technologically-ready initial e+e- collider "Higgs Factory"

Upgrade to higher energy / luminosity as technologies become ready and affordable

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

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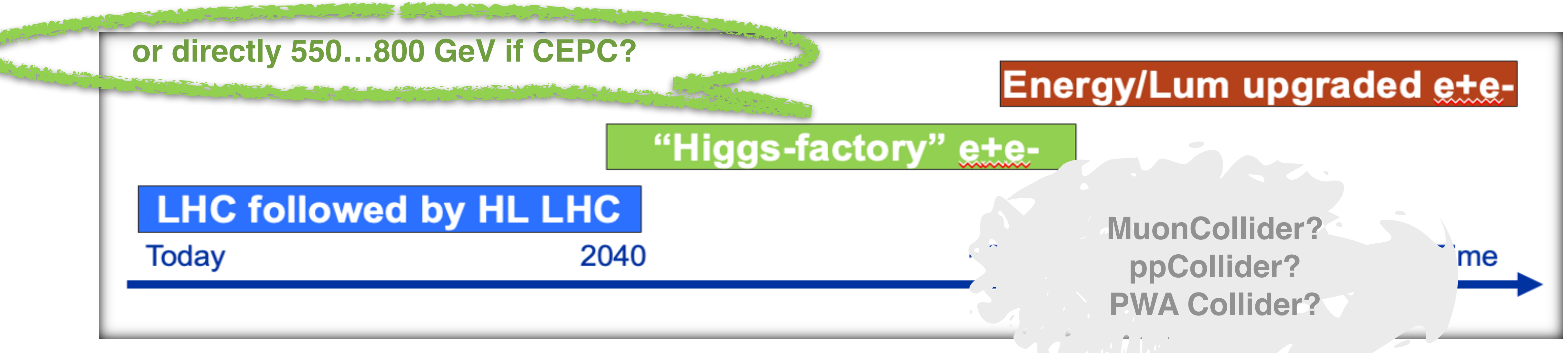


Important: need significant R&D program and demonstrators to bring advanced accelerators to construction readiness - must be part of the over all picture (funding, people, facilities…)

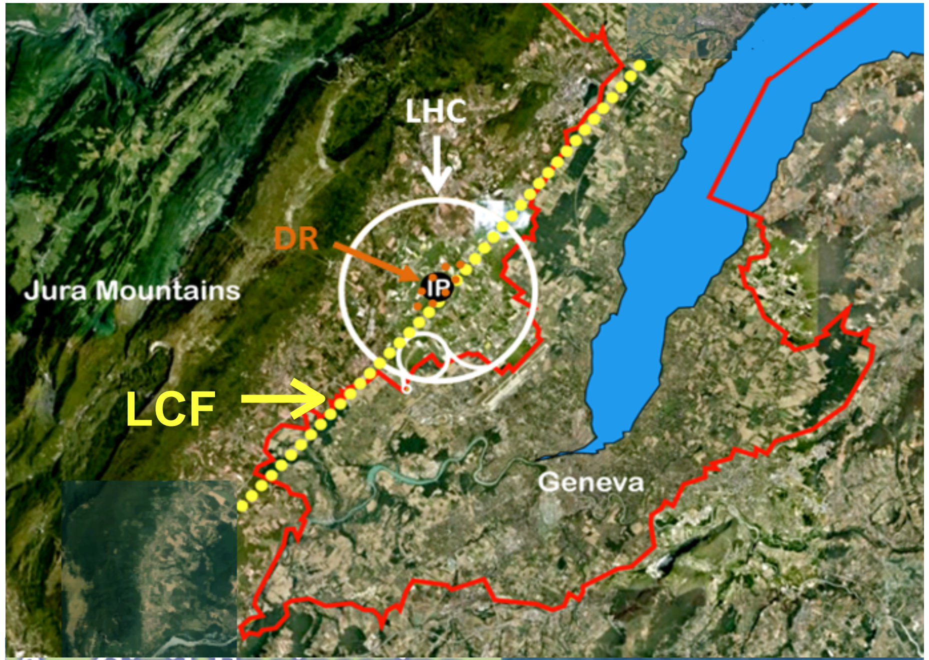
Conclusions

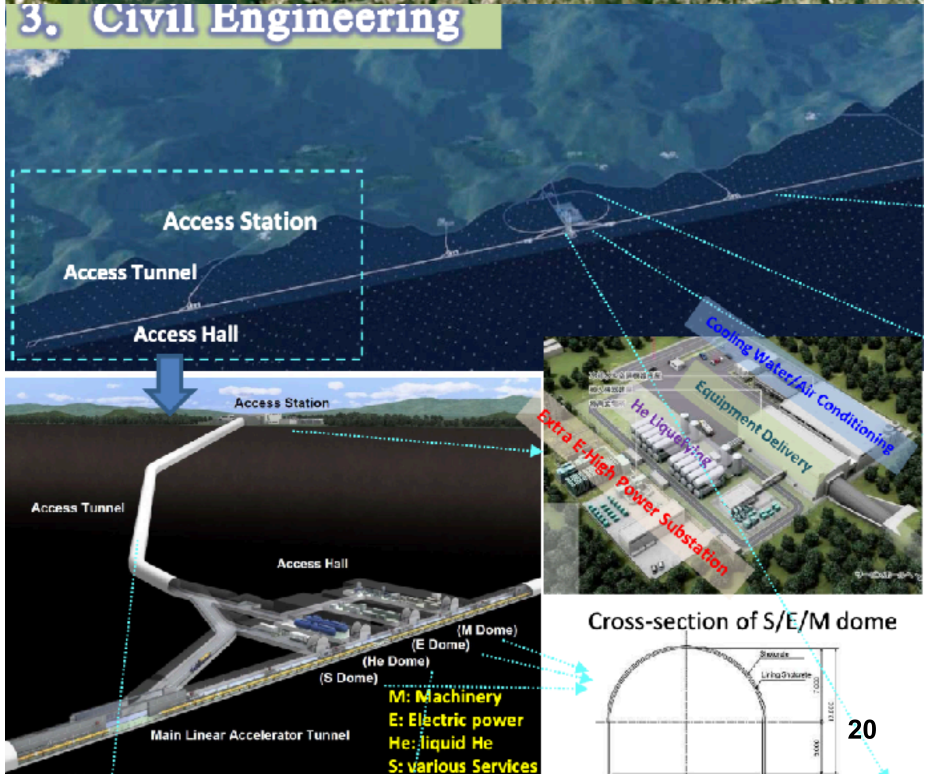
ILC and CLIC actively pursue key topics:

- ILC Technology Network started work on high-priority items
- full Life-cycle Assessment including accelerator components
- optimisations for more efficiency - system and components
- upgrade options with advanced technologies
- cost updates

The Linear Collider Community started discussions towards a global Linear Collider Vision:

- 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**
- starting with **cost-conscious first stage based on SCRF**
- **upgrades** with same - or **advanced accelerator technology** (CLIC, C3, Plasma, ERL, …)
- prepare 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} cm^{-2}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

Snowmass Implementation Task Force

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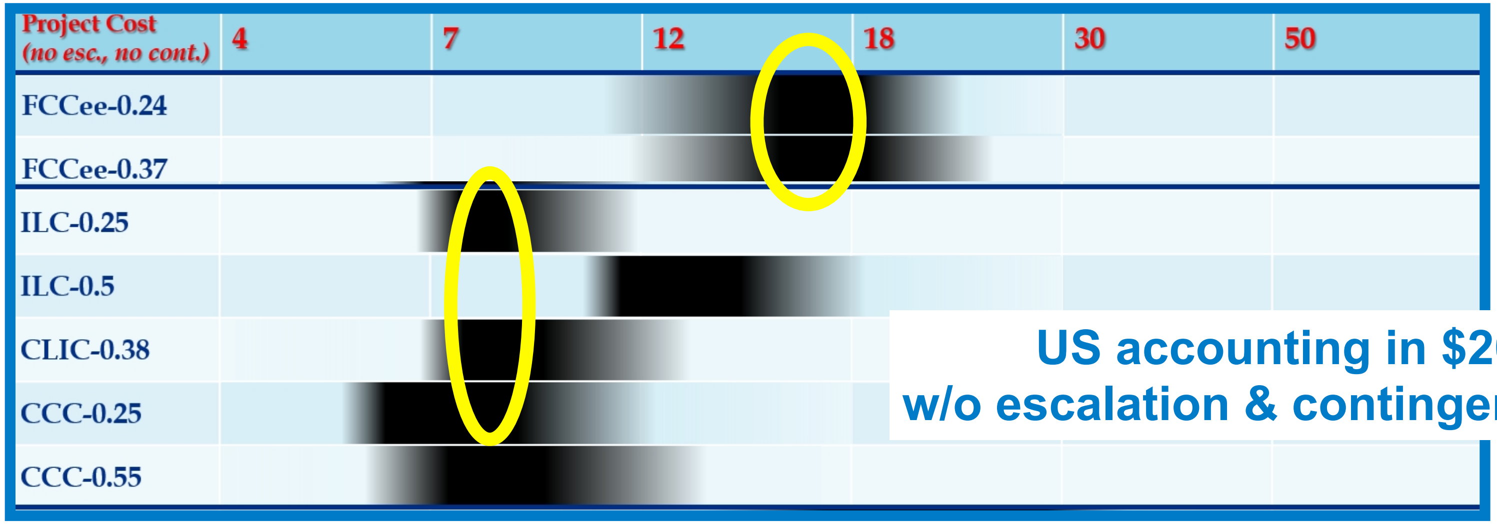


US accounting in \$2021
w/o escalation & contingency

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

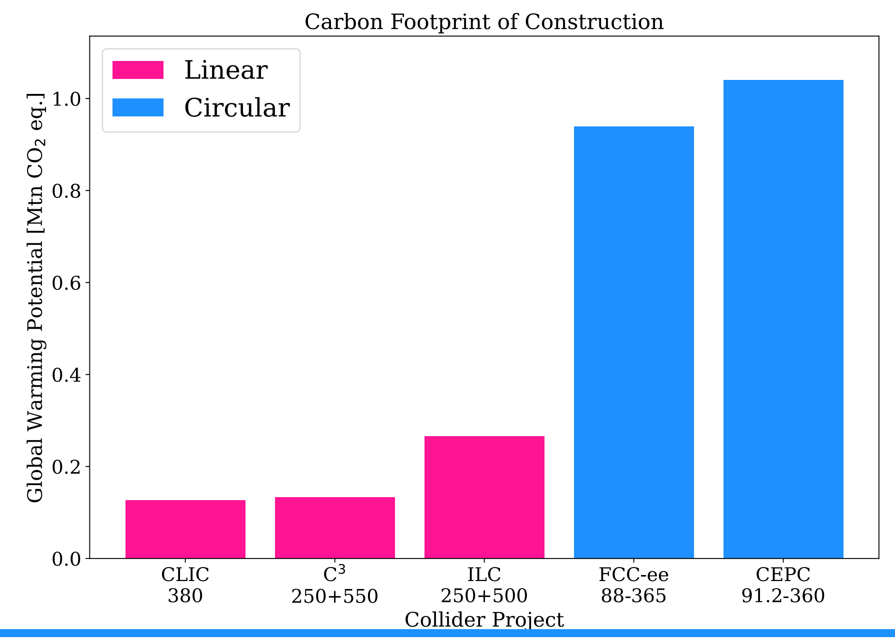
Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations. (WCED, 1987)

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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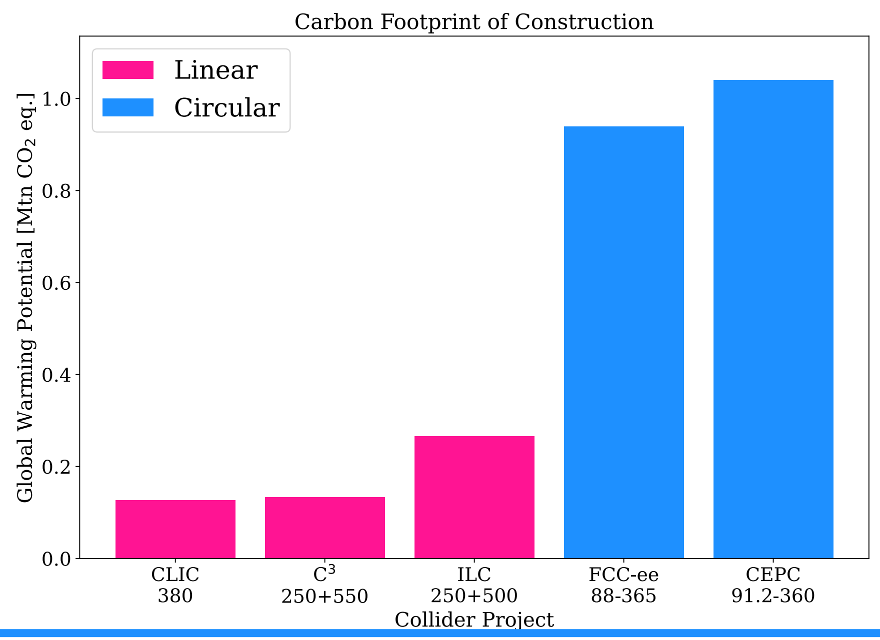
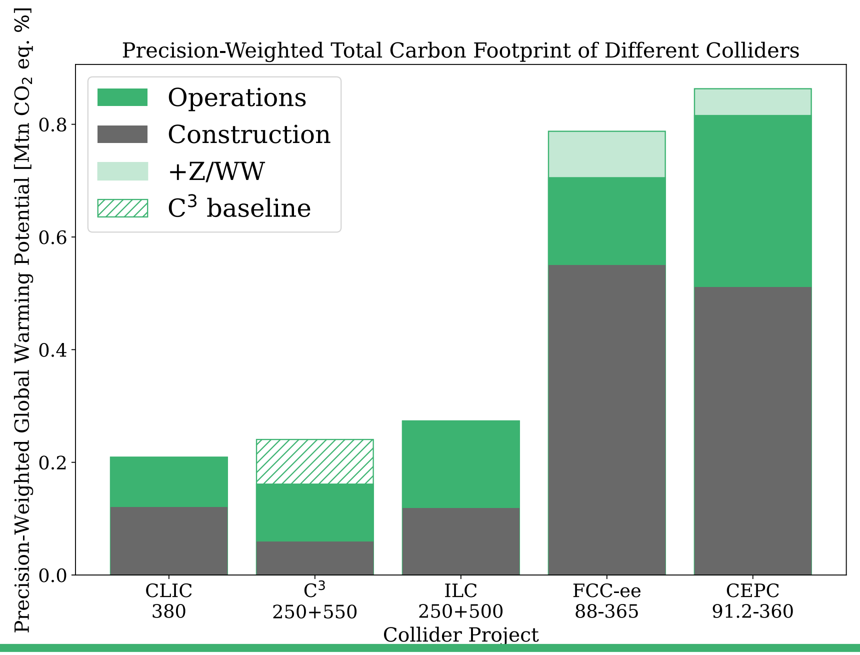




Adding operation GWP

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

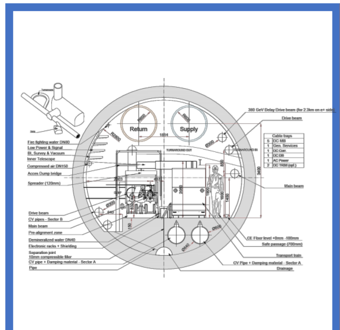
- **Operation dominates for LCs**
- **Construction dominates for CCs**

arXiv:2307.04084

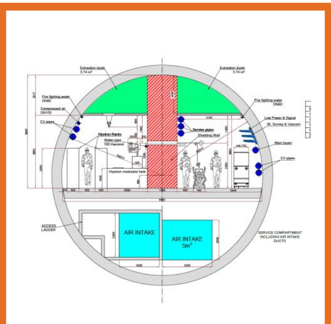
GWP of tunnel construction

Study by CLIC and ILC

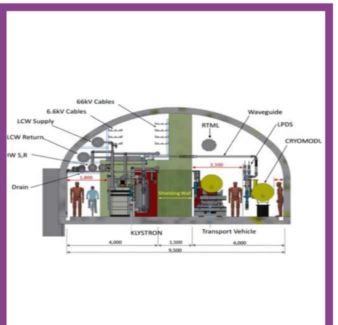
- **full life-cycle assessment according to ISO standards by consultancy company (ARUP)**
- **green house gas emission plus 13 more impact categorie**
- roughly confirms C3 estimates (prev. slide)



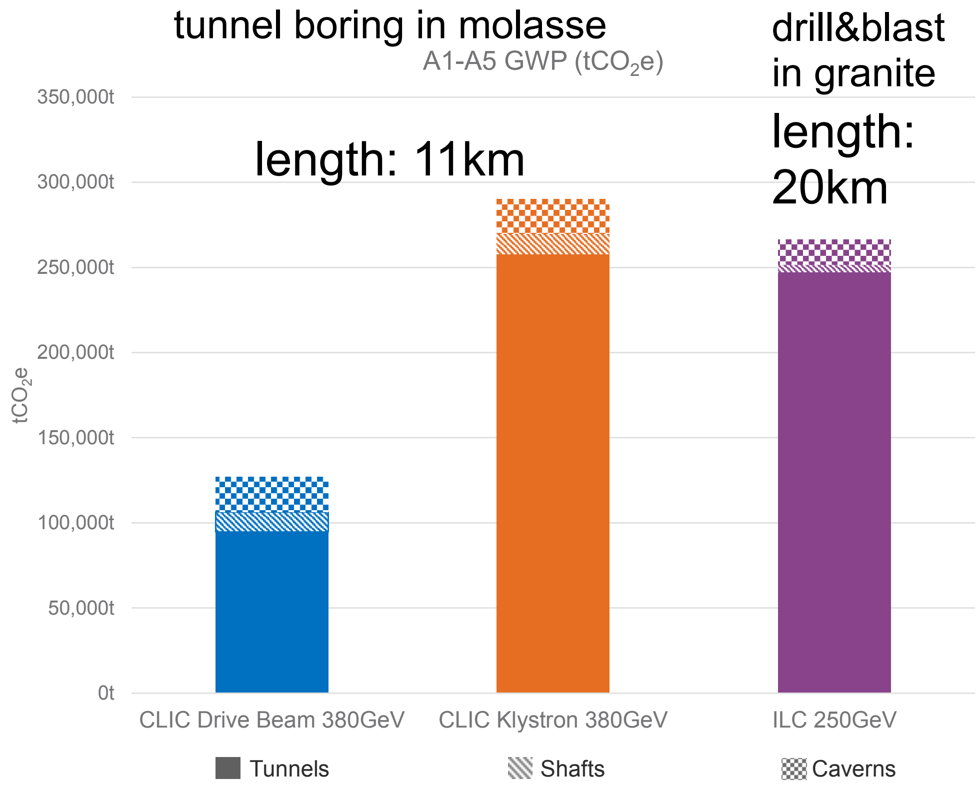
CLIC Drive beam, 5.6m dia.



CLIC Klystron, 10m dia.



ILC, 9.5m span



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

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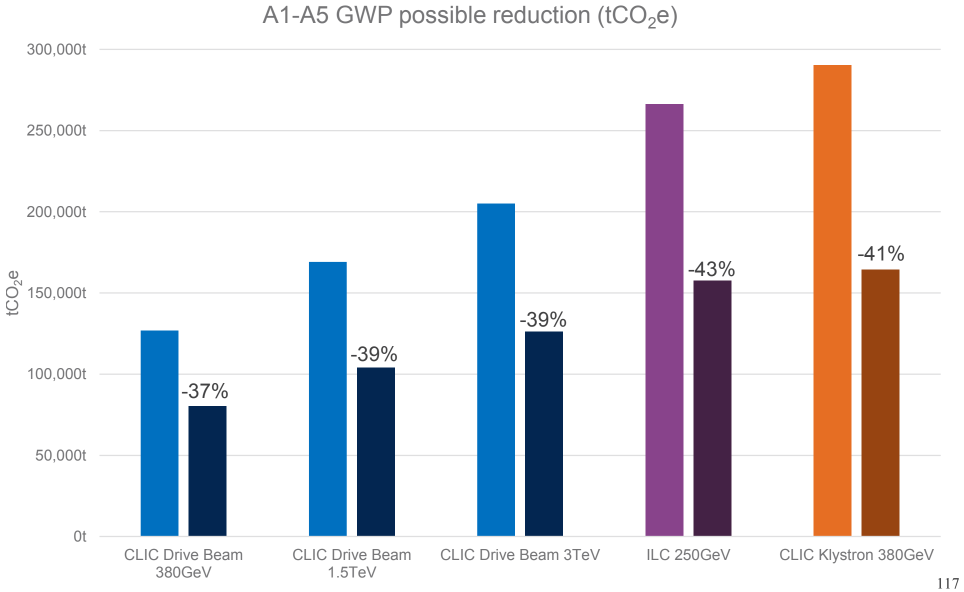
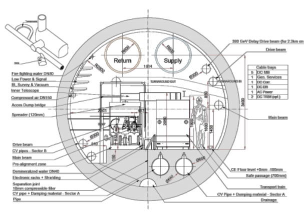
  - reduction of tunnel wall thickness





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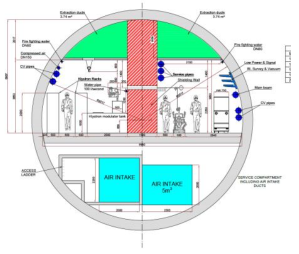

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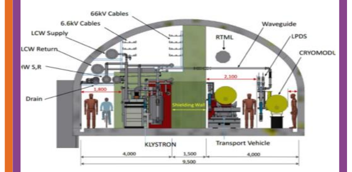

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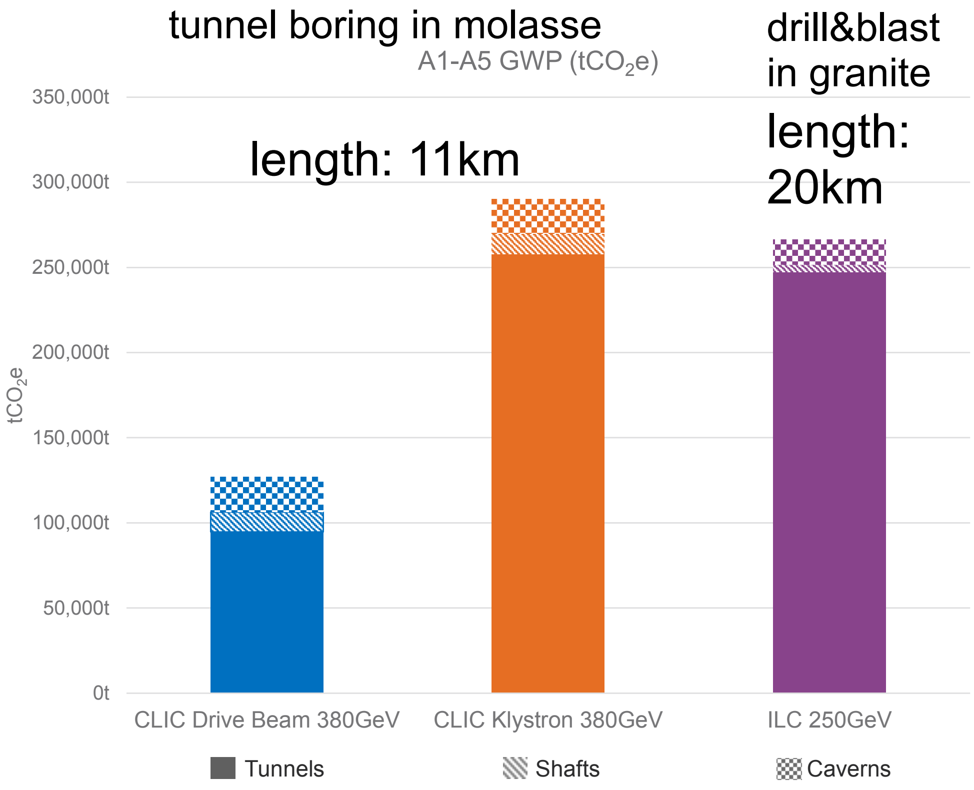

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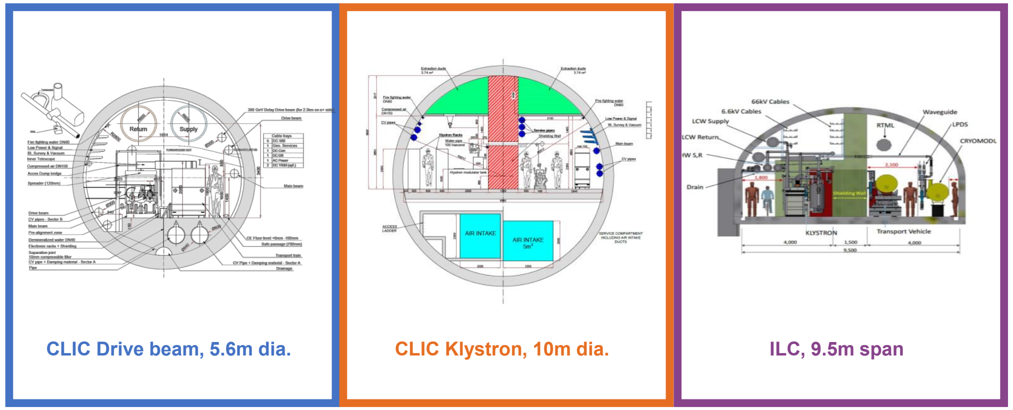

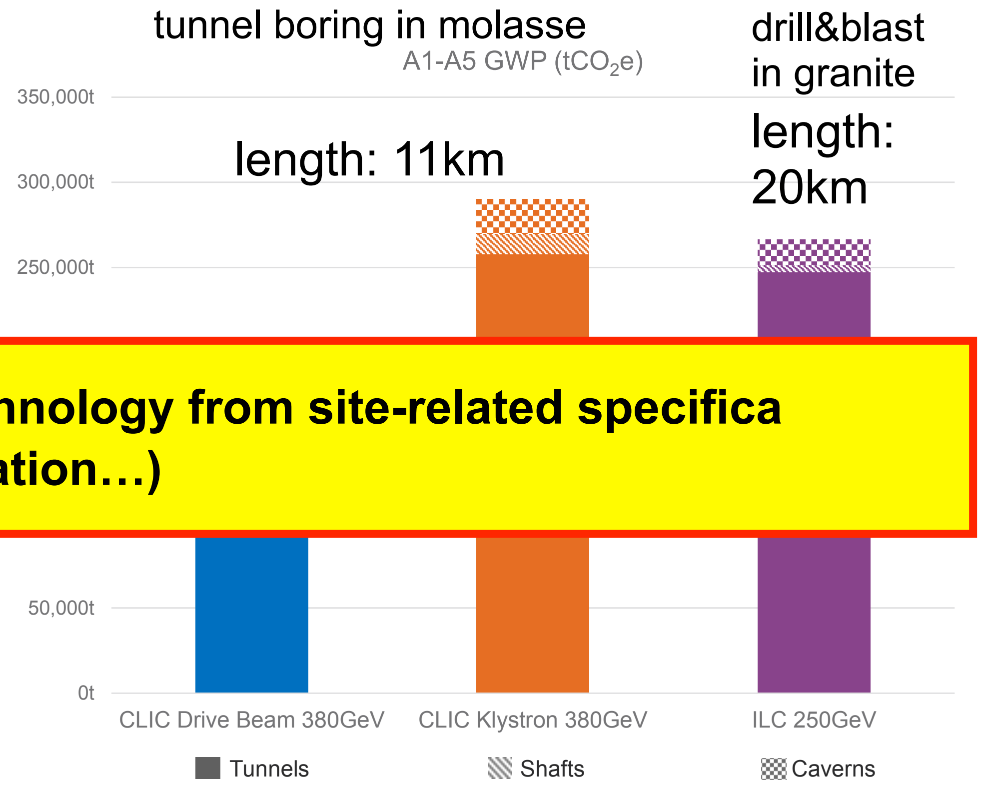

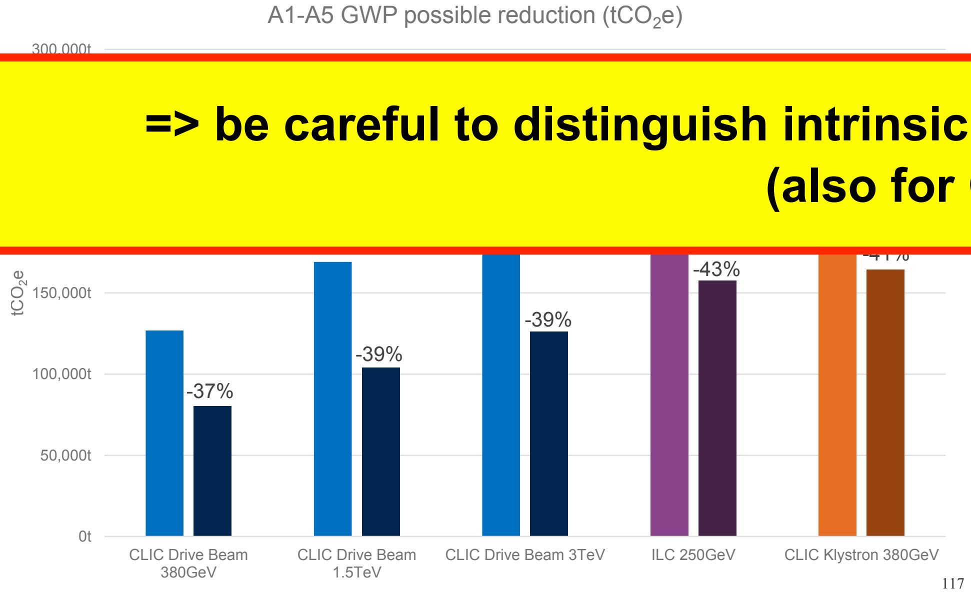

=> be careful to distinguish intrinsic needs of technology from site-related specifica (also for GWP of operation…)

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Contact

Deutsches Elektronen-
Synchrotron DESY

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