Linear Colliders.

A Vision of a Linear Collider at CERN for the European Strategy

Benno List
KET workshop “The future of collider physics”, DESY, Hamburg, Nov 28, 2024

Plan of the Talk

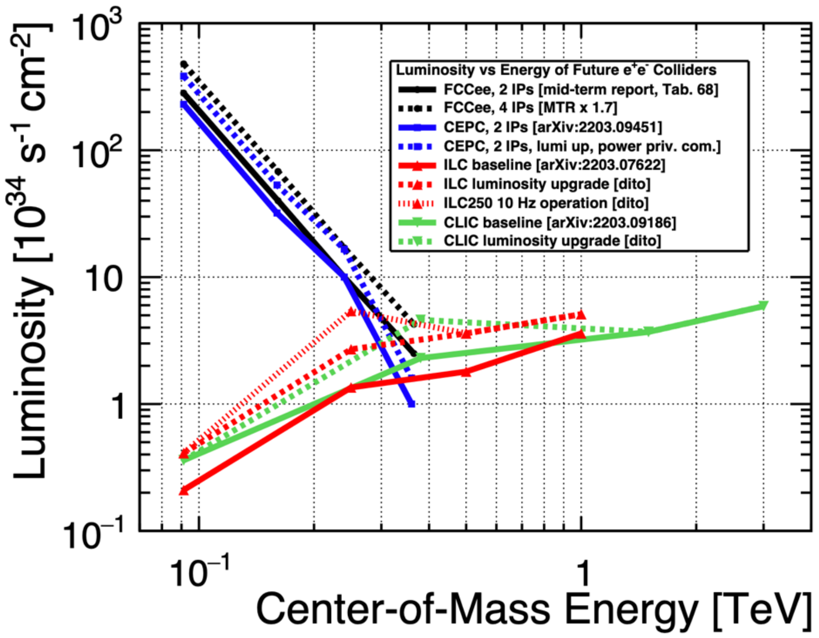
- Linear Colliders – Introduction
- The Projects – ILC, CLIC, C3, HALHF
- LCVision: A Vision for a Linear Collider Facility at CERN
- Schedule, Costs, Organisation, and Risks
- Sustainability
- Conclusions and Outlook

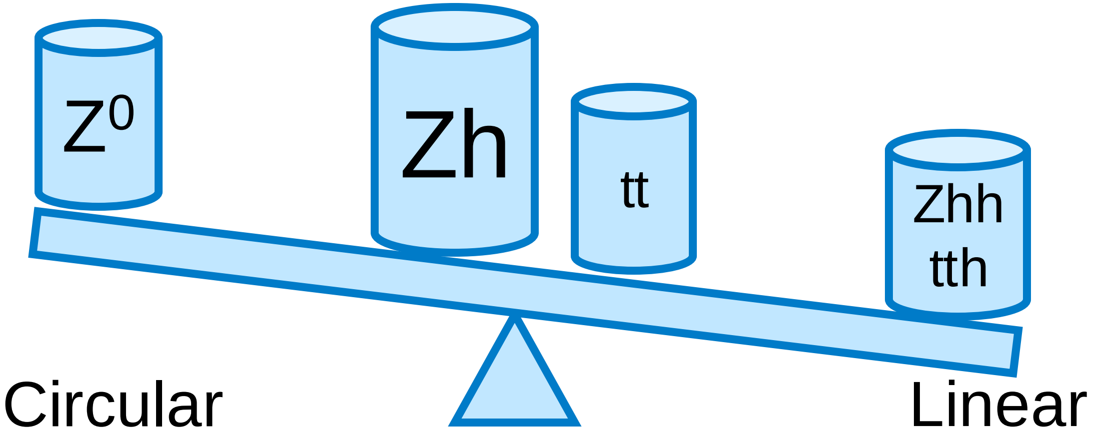
Linear Colliders – Introduction.

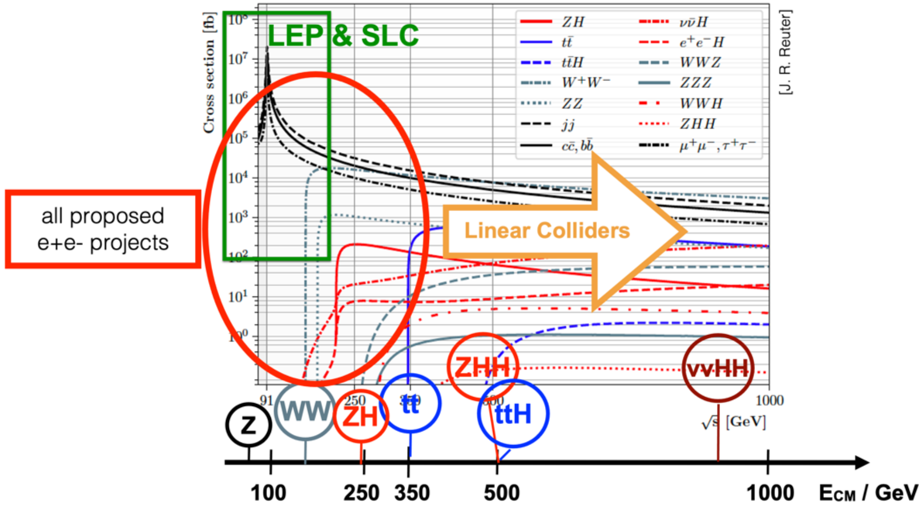
Linear Colliders

The path to the energy frontier in e+e- collisions

- Linear colliders are the e+e- energy frontier machines
- Linear colliders have **increasing** luminosity with energy, luminosity/power approx. constant
- Energy frontier facility has a rich, guaranteed physics program at 250, 350, 550 GeV up to 1TeV
- Z^0 running at 100x LEP luminosity (3×10^{33})
- Polarisation
- CLIC technology can reach 2 TeV
- **Complementarity** between circular and linear colliders







Linear Accelerator Design Challenges

Construction cost
$ ~ L

Energy

$$E_{\mathrm{CM}} = L \cdot g$$

Luminosity

$$\mathcal{L} = \frac{\eta P_{\mathrm{AC}}}{E_{\mathrm{CM}}} \cdot \frac{N_{\mathrm{e}}}{4\pi \sigma_{\mathrm{x}}^{*} \sigma_{\mathrm{y}}^{*}} H_{\mathrm{D}}$$

Operation cost
$ ~ P_{AC}

High Gradient g

High Efficiency η

Small Beamspot $\sigma_x \sigma_y$

$$\sigma^{*} = \sqrt{\beta^{*}\ \varepsilon}$$

Main Linac
Technology

Losses in cavity walls $\frac{P_{\mathrm{wall}}}{L} \propto \frac{g^2 R_{\mathrm{s}}}{\omega}$

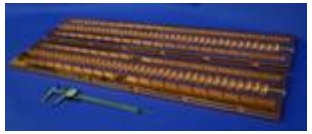
Low resistivity

Small duty cycle:
Pulsed operation

High frequency &
Ultra-short pulses

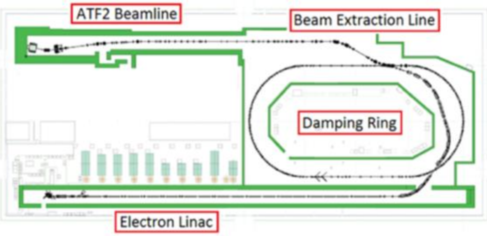
ILC
Superconducting RF

C3



CLIC
2 beam acceleration

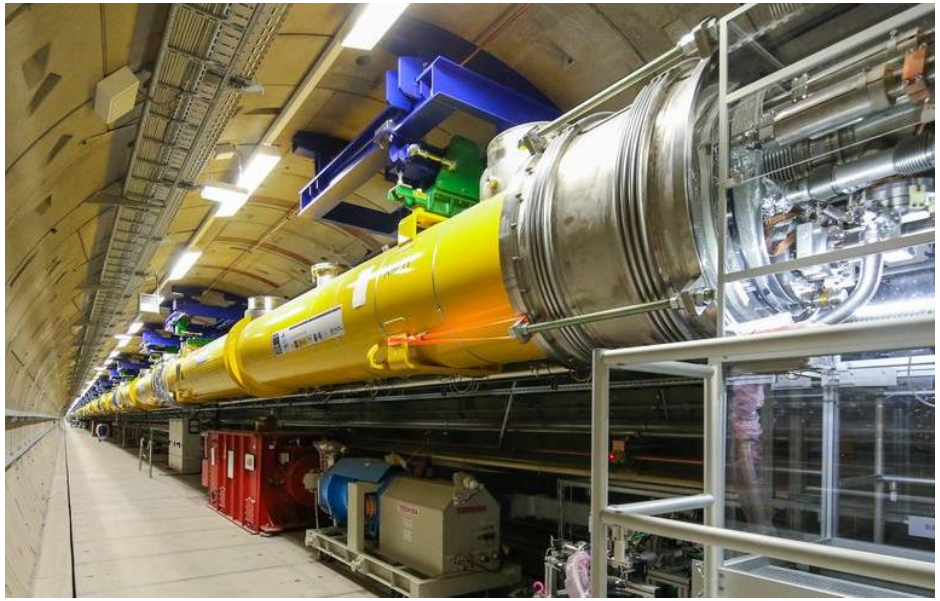
Nanobeam Technology
- Damping ring (ε)
- Final focus (β^*)



Linear Collider Project Properties

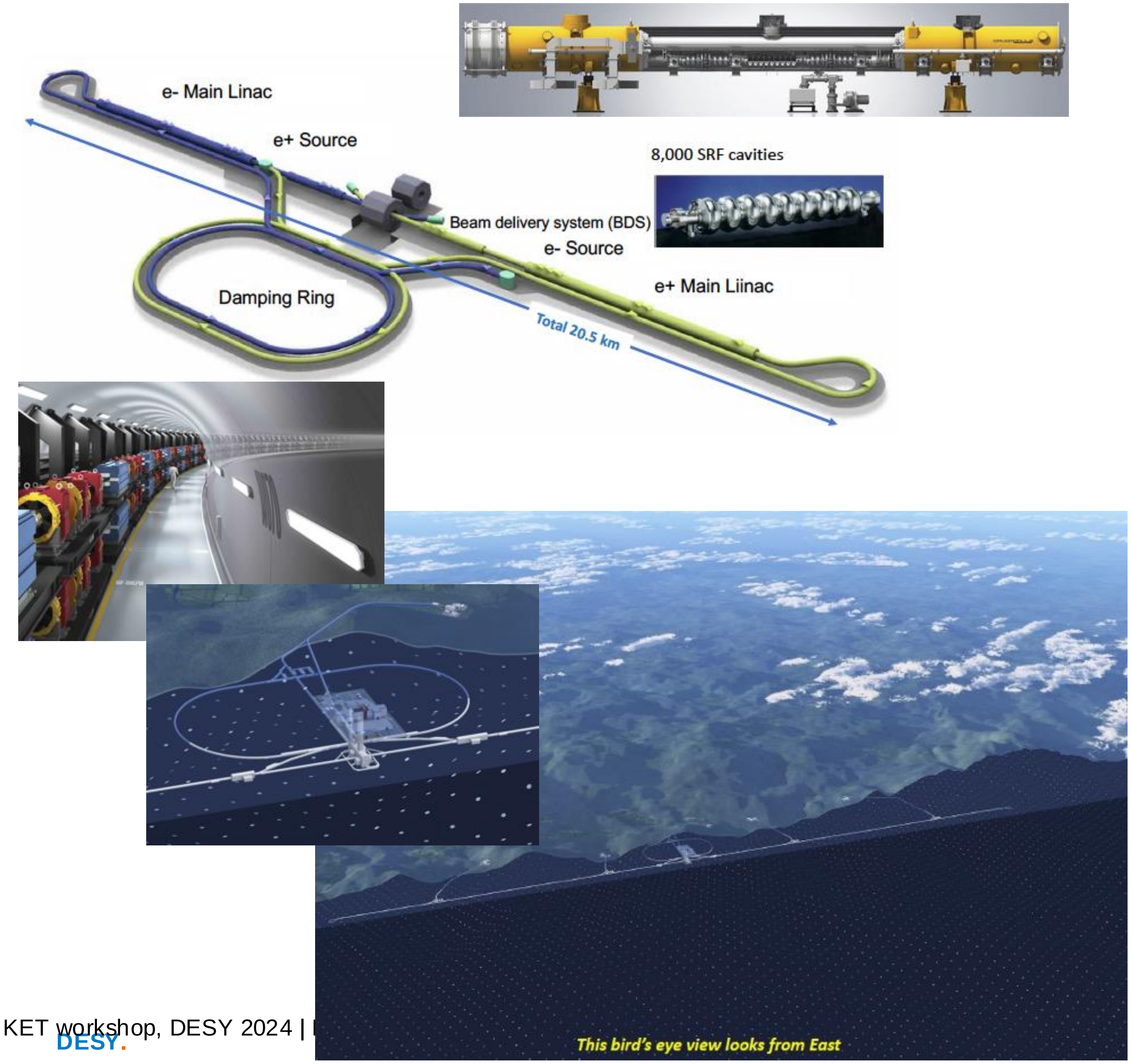
What makes a linear collider an attractive project in uncertain times

- Expandable – make them longer for more beam energy
  - Cost of initial configuration can be kept reasonable (staging)
  - Additional contributions from outside partners directly increase beam energy or luminosity
  - Upgrade with future, improved accelerator technologies
- Flexible
  - Project can be adjusted to changes in physics knowledge, competition, or funding
- Highly modular
  - Much of project value is in acceleration modules with industrial production basis in several regions
  - Performance is given by **sum** of all modules
    -> lower performance of individual modules can be compensated -> easier ramp-up
    -> reduces risk: financial and technological



The Projects.

ILC in a nutshell

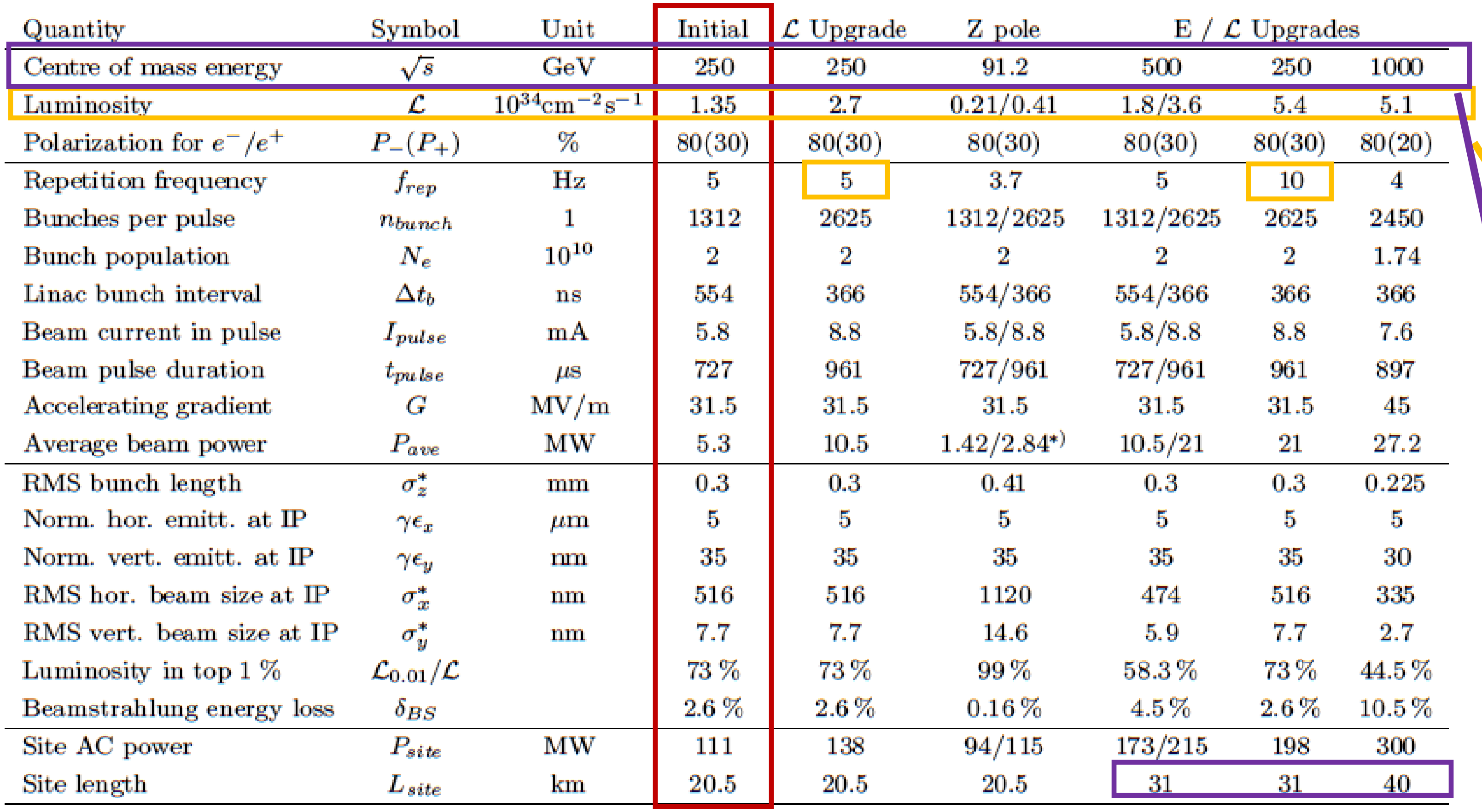


International Linear Collider ILC

- Superconducting Cavities, Nb 1.3GHz, 31.5 (35) MV/m
- Klystrons
- 250GeV CME, upgradeable to 500, 1000 GeV
- L = 1.35 x 10^{34} $cm^{-2}s^{-1}$ (at initial 250GeV)
- 20km length, site proposal: Tohoku / Japan
- Polarisation 80%(e-), 30%(e+)
- Based on proven technology (European XFEL)

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}

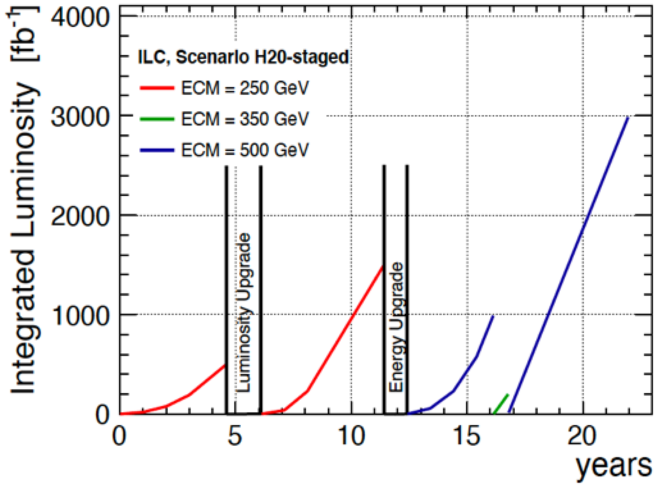
ILC Baseline, extension and upgrades



Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	µs	727	961	727/961	727/961	961	897
Accelerating gradient	G	MV/m	31.5	31.5	31.5	31.5	31.5	45
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ_z^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	µm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ_x^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

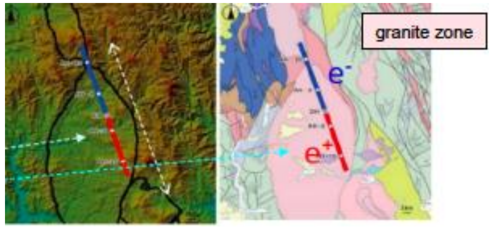
Luminosity upgrades:

- 2 x bunches, 1.5 x RF (1.35 -> 2.7×10^{34})
- Run 500GeV machine at 250GeV, 10Hz: factor 2 (2.7×10^{34} -> 5.4×10^{34})
- Improves power efficiency

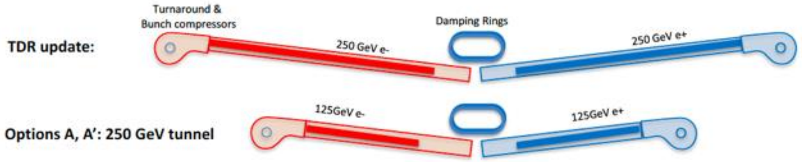


Energy upgrades:

- 500GeV (31.5 MV/m $Q_0=1 \times 10^{10}$)
- 1TeV (45 MV/m $Q_0=2 \times 10^{10}$, 300 MW) more SCRF, tunnel extension
- Kitakami site: 50km long, sufficient for 1TeV

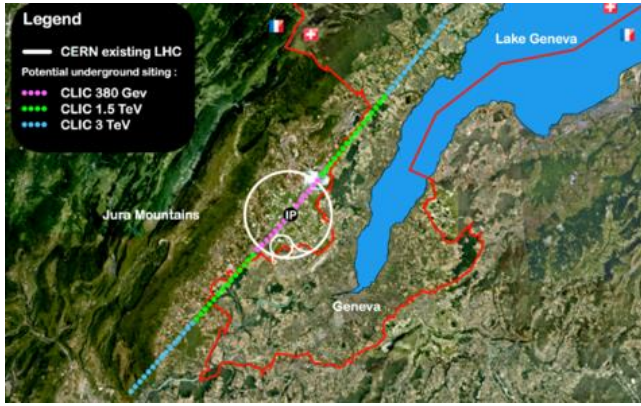


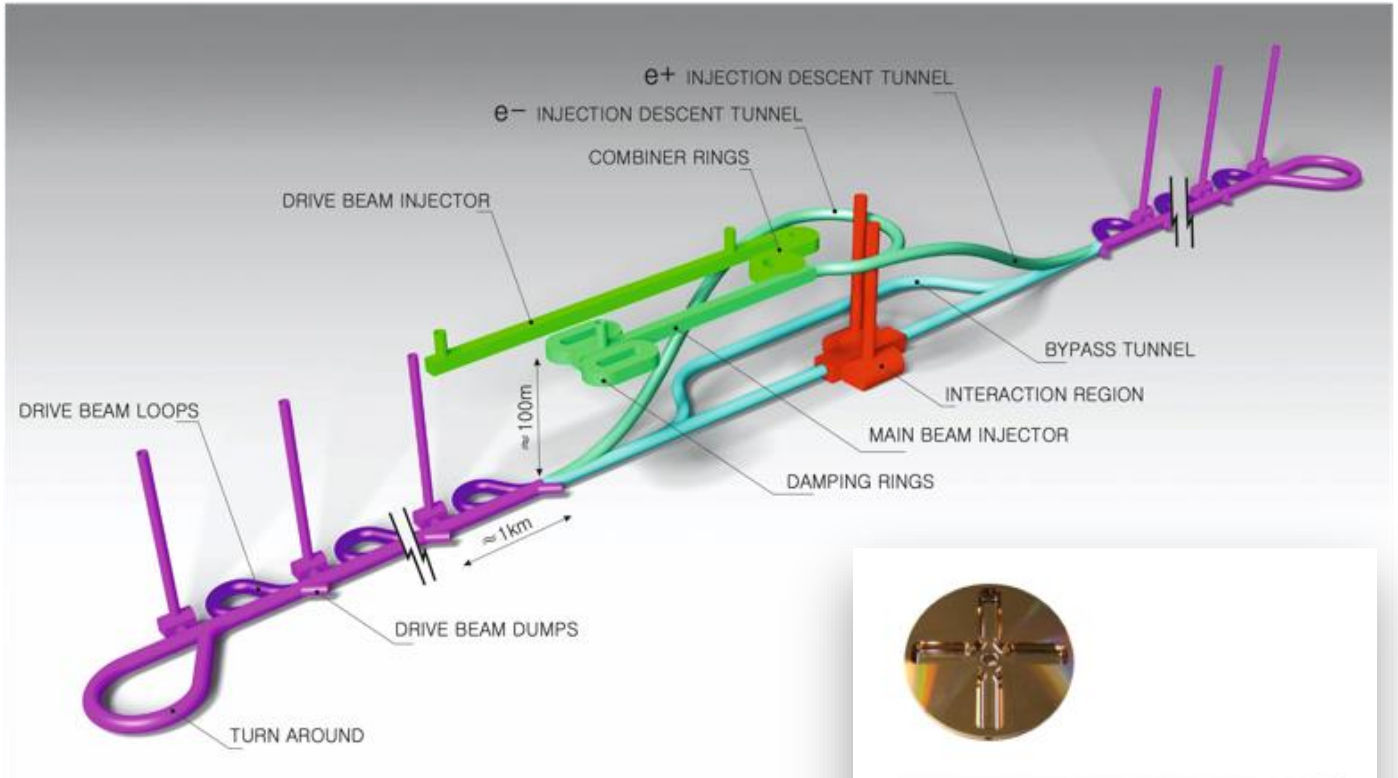
Kitakami mountains

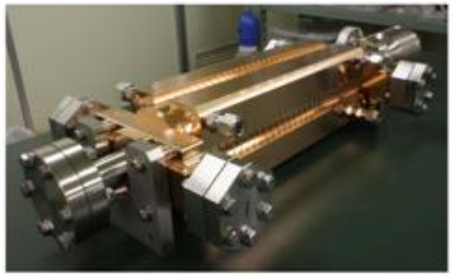


References: arXiv:1903.01629 (EPSUU), 2203.07622 (Snowmass)

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) presented in previous ESPP updates
- 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.

The CLIC ESPP Update

Guidelines:
Preparing “**Project Readiness Report**” as a step toward a TDR
Assuming ESPP in ~ 2025-6, Project Approval ~ 2028,
Project (tunnel) construction can start in ~ 2030.

However, several important changes:

- Energy scales: 380 GeV and 1.5 TeV with one drivebeam
- Consider also 100 Hz running at 250 GeV (i.e. two parallel experiments, two BDSs)
- Several updates on parameters (injectors, damping rings, drive-beam) based on new designs, results and prototyping (e.g. klystrons, magnets) - however no fundamental changes beyond staying at one drivebeam
- **Technology results updates**, including more on use of them in other projects (e.g. alignment, instrumentation, X-band RF is small linacs)
- **Update costing and power – interplay between inflation and CHF**
- **Life Cycle Assessments**
- More detailed prep phase planning (next 5-7 years)

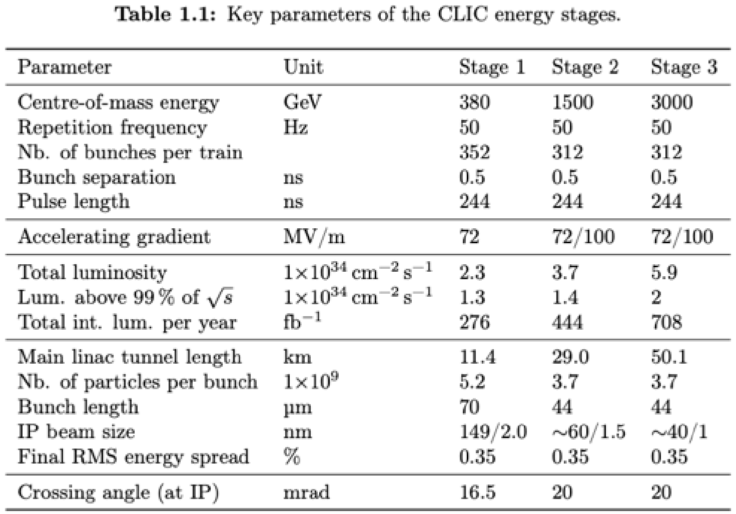
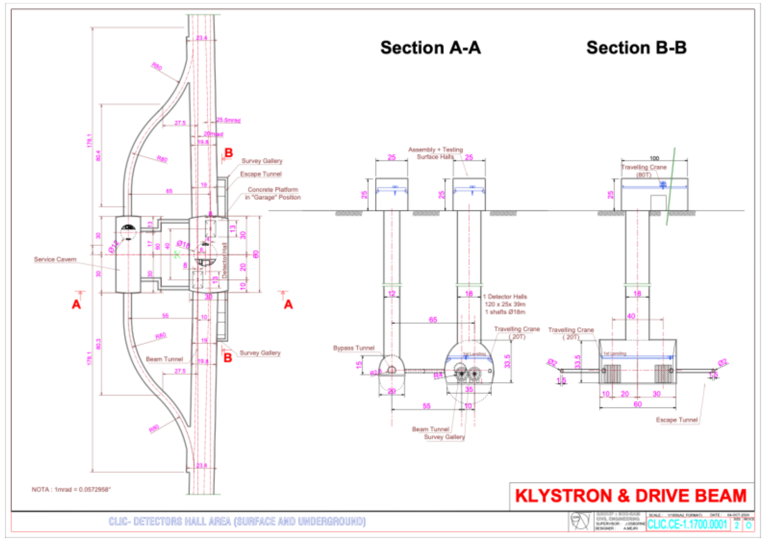


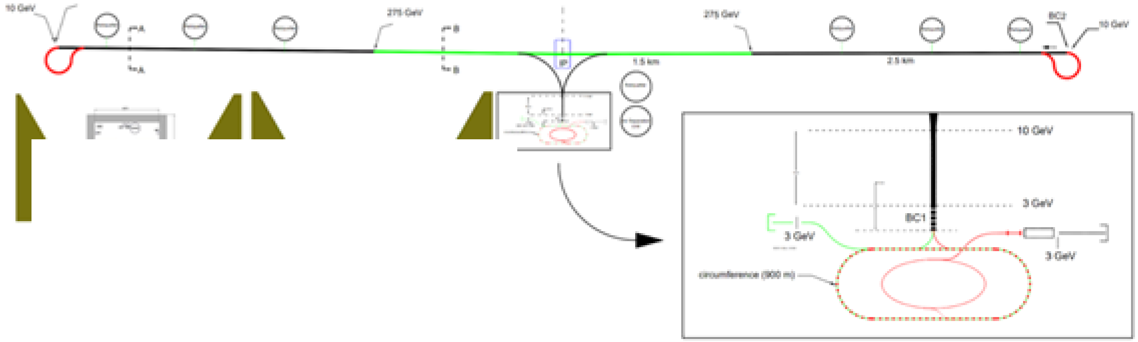
Table 1.1: Key parameters of the CLIC energy stages.

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20



Project summary for Snowmass already include some of these changes, i.e. luminosity improvements, 100 Hz study, power update for 380 GeV: LINK

Accelerator Complex

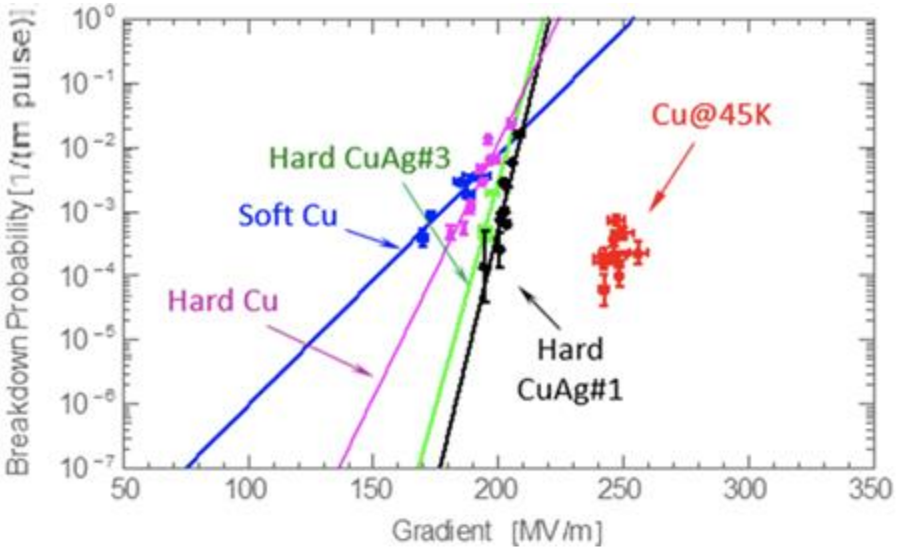


8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m

Large portions of accelerator complex compatible between LC technologies

- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline

- Snowmass paper: https://arxiv.org/pdf/2203.07646.pdf

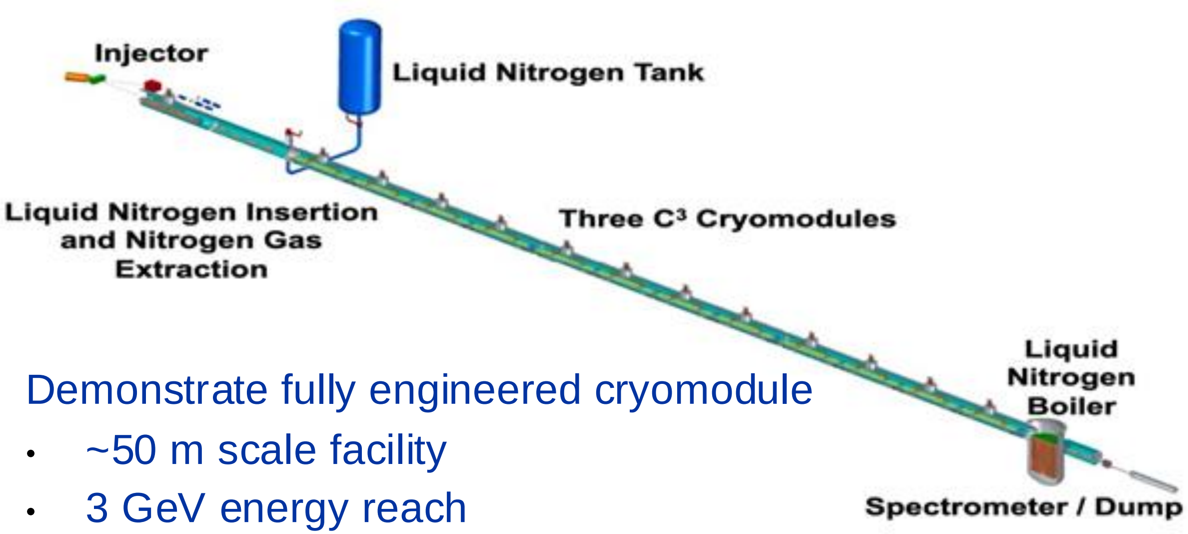


Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	$\sim$150	$\sim$175	$\sim$110	$\sim$125

C3 Recent Developments and Immediate Plans

Towards a technology demonstrator

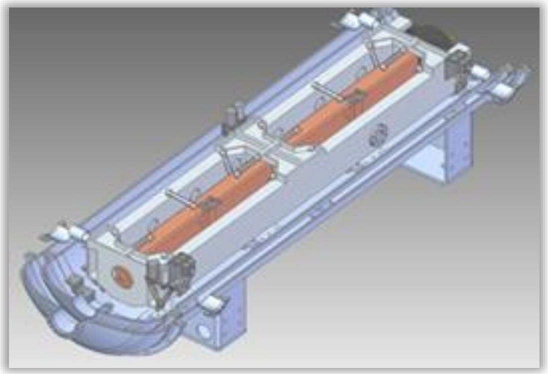


Demonstrate fully engineered cryomodule

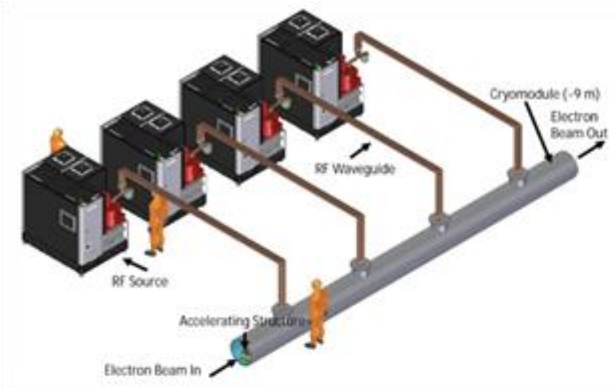
- ~50 m scale facility
- 3 GeV energy reach

QCM:

- Delivery of prototype quarter cryomodule (QCM) expected Fall 2024
- Address Gradient, Vibrations, Damping, Alignment, Cryo, etc

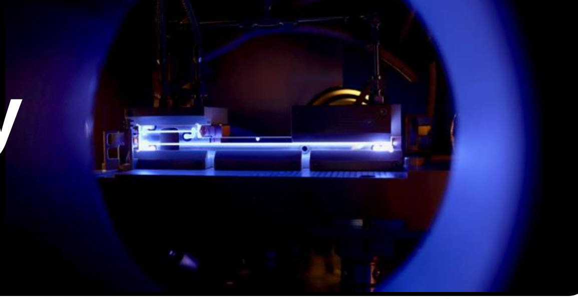


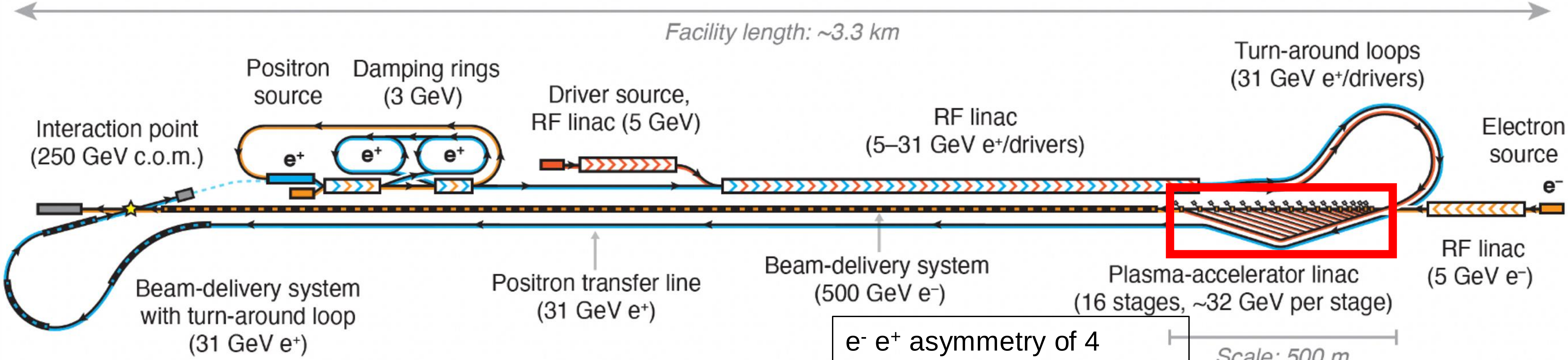
C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



C^3 Prototype One Meter Structure

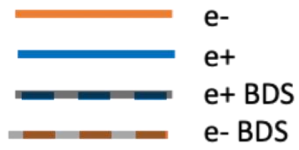
HALHF: A hybrid, asymmetric, linear Higgs factory





[Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)](#)
[Lindstrøm, D'Arcy and Foster, arXiv:2312.04975](#)

e$^-$ e$^+$ asymmetry of 4
IP boost of 2.13 (HERA 3)
e$^-$ ε_{ny} of 0.56 μm
$\mathcal{L} \sim 1\times10^{34}$/cm^2/s

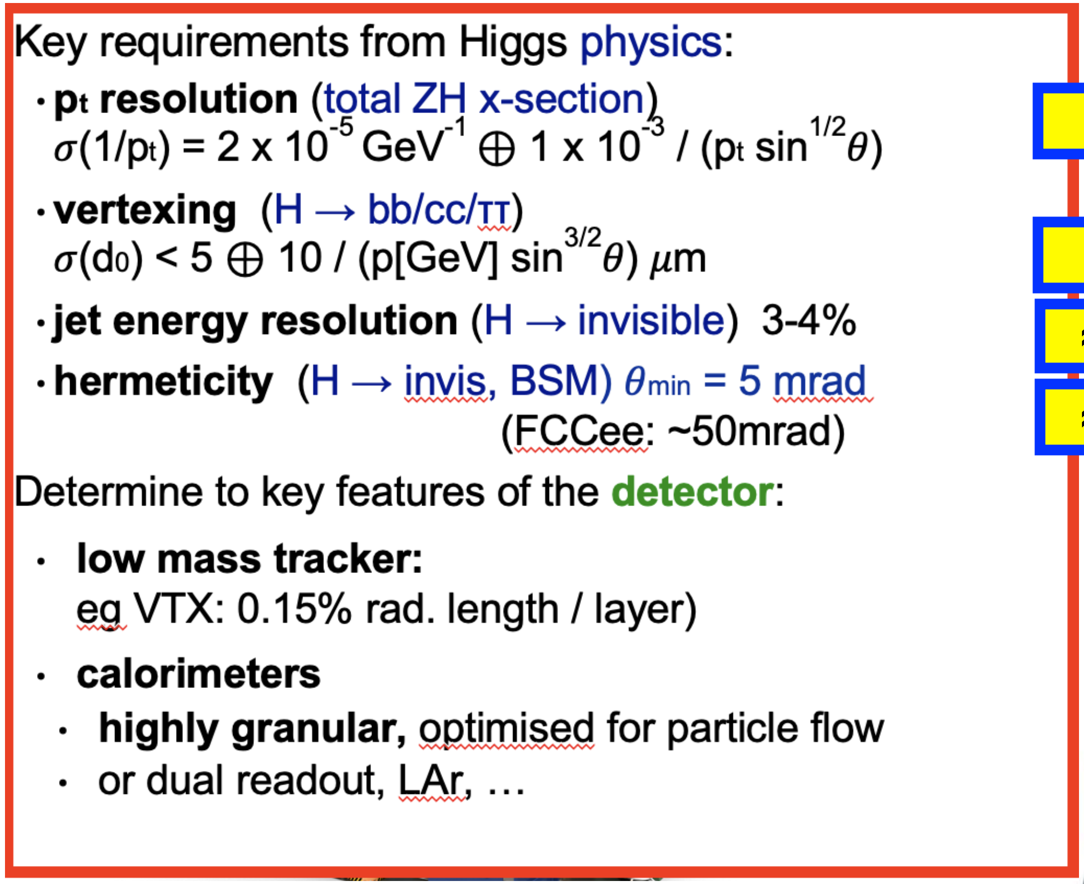


The concept enables us to work towards :

- Performance of the plasma linac? (Emittance, efficiency, effective gradient, tolerances, polarization...)
- How to integrate a plasma linac in a collider? (linac technology, time structure, drive-beam scheme..)
- Requirements of the plasma source? (Rep. rate, time structure, heating..)
- Asymmetric collisions? (Specific to HALHF)

E. Adli, EFCA seminar, https://indico.cern.ch/event/1361604/contributions/6190120/

Higgs Factory Detector Concepts



Key requirements from Higgs physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad
  (FCCee: ~50mrad)

Determine to key features of the **detector**:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **calorimeters**
  - **highly granular,** optimised for particle flow
  - or dual readout, LAr, …

≈ CMS / 40

≈ CMS / 4

≈ ATLAS / 2

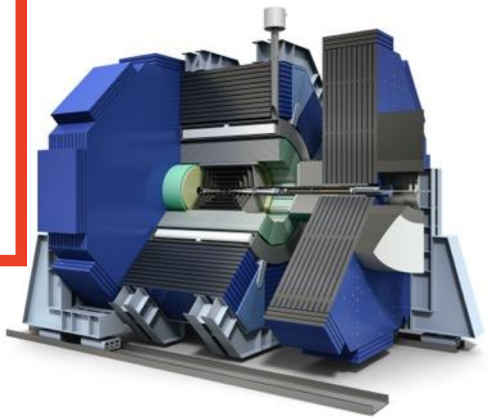
≈ ATLAS / 3

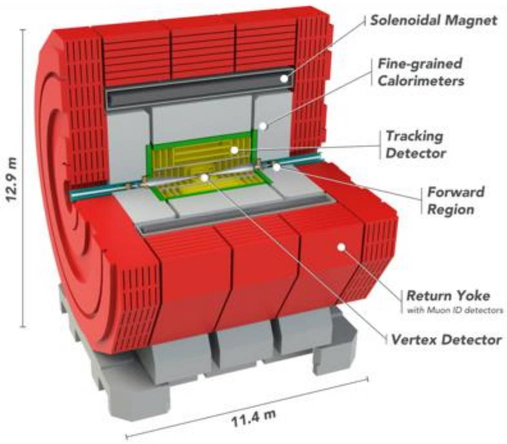
For LCs, bunches inside trains

- at ILC: Δt_b = 554 ns; f_{rep} = 5 -10 Hz
- at CLIC: Δt_b = 0.5 ns; f_{rep} = 50-100 Hz

The lower collision rate enables

- passive cooling only => low material budget
- triggerless operation



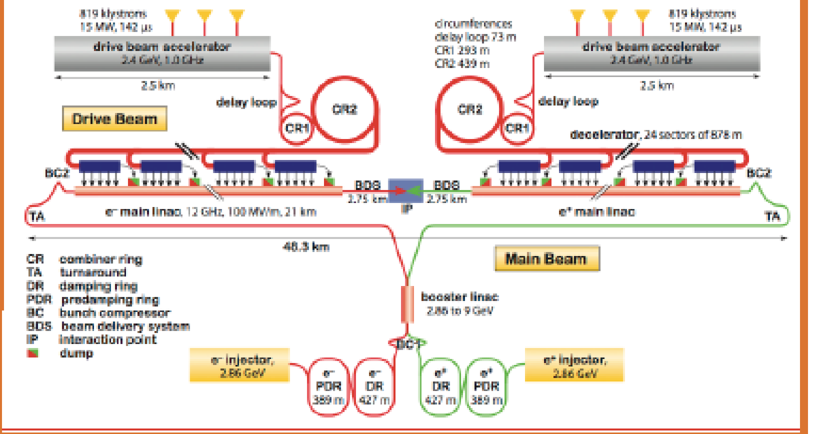


LCVision: a Vision for a Linear Collider Facility at CERN.

A Linear Collider Facility at CERN

A Linear Collider Vision

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



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

Opportunity to minimize time until next project
=> crucial for next generation of our community!

LC Vision: Preparing EPPSU inputs

A forum to make the physics case and develop a proposal for a linear collider facility at CERN

LC Vision Overview

Chairs: J. List, S. Stapnes

Coordination Group

Halina Abrahmovic, Erik Adli, Ties Behnke, Ivanka Bosovic, Phil Burrows, Marcel Demarteau, Yuanning Gao, Carsten Hensel, Mark Hogan, Masaya Ishino, Daniel Jeans, Imad Laktineh, Andy Lankford, Benno List, Kajari Mazumar, Shin Michizono, Emmanuela Musumeci, Tatsuya Nakada, Mihoko Nojiri, Dimitris Ntounis, Jens Osterhoff, Ritchie Patterson, Aidan Robson, Daniel Schulte, Taikan Suehara, Geoffrey Taylor, Caterina Vernieri, Marcel Vos, Georg Weiglein, Filip Zarnecki, Jinlong Zhang, Laura Monaco, Patrick Koppenburg, Hitoshi Murayama, Jochen Schieck

Expert Team 1
"Physics-driven run plan and EPPSU documents"
Roman Poeschl, Michael Peskin

Expert Team 3
"SCRF upgrades"
Sergey Belomestnykh, Hiroshi Sakai, Marc Wenskat

Expert Team 5
"ERL upgrades"
Walid Kaabi, Vladimir Litvinenko, Kaoru Yokoya

Expert Team 7
"Beyond Collider"
Yasuhito Sakaki, Ivo Schulthess

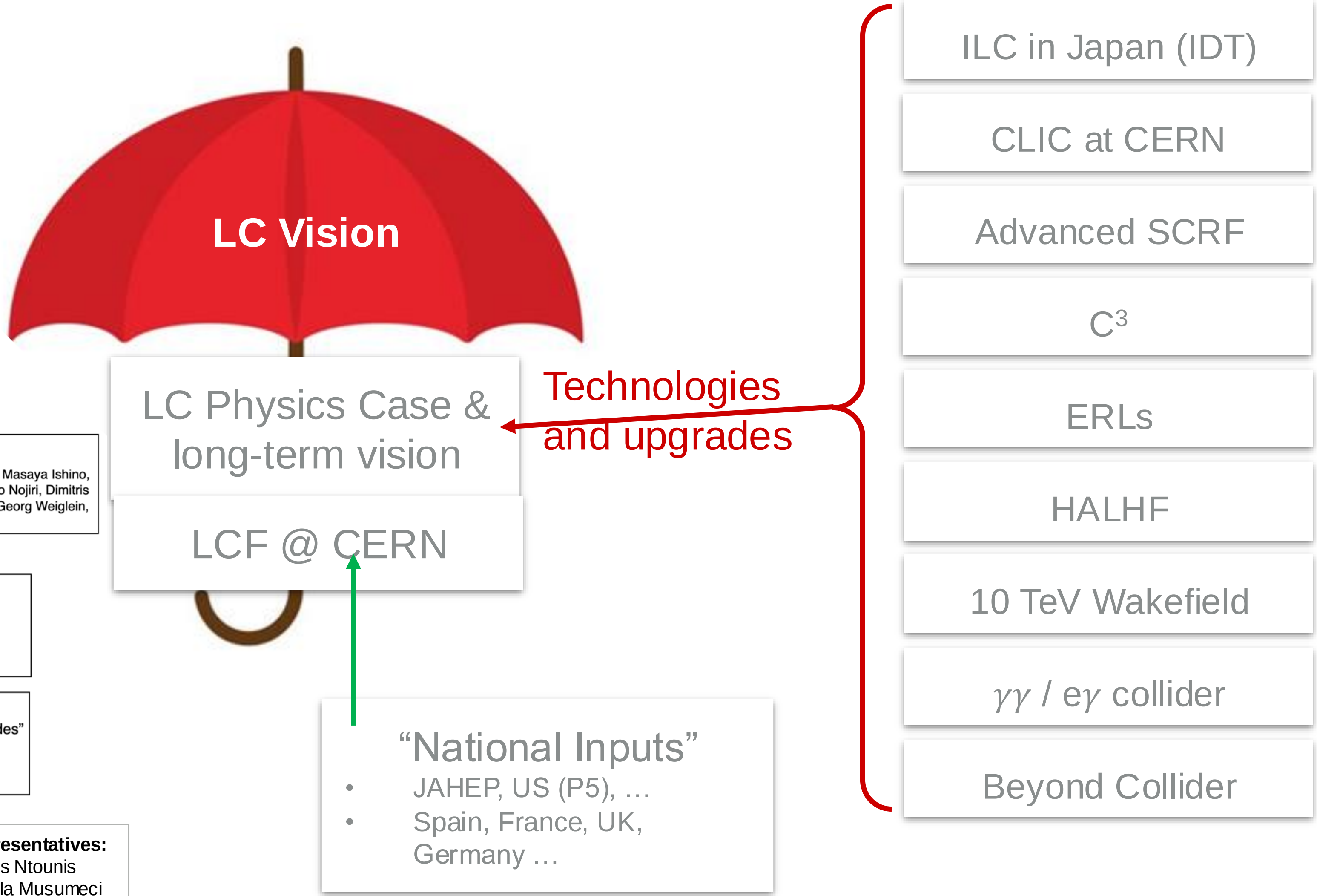
Expert Team 2
"LCF@CERN"
Steinar Stapnes, Thomas Schörner

Expert Team 4
"C3/CLIC upgrades"
Angeles Faus-Golfe, Enrico Nanni

Expert Team 6
"Plasma upgrades"
Brian Foster, Spencer Gessner

Expert Team 8
"Alternative Collider Modes"
Tim Barklow, Gudi Moortgat-Pick

ECR representatives:
Dmitris Ntounis
Emanuela Musumeci



LC Vision

LC Physics Case & long-term vision

LCF @ CERN

Technologies and upgrades

- ILC in Japan (IDT)
- CLIC at CERN
- Advanced SCRF
- C^3
- ERLs
- HALHF
- 10 TeV Wakefield
- $\gamma\gamma$ / eγ collider
- Beyond Collider

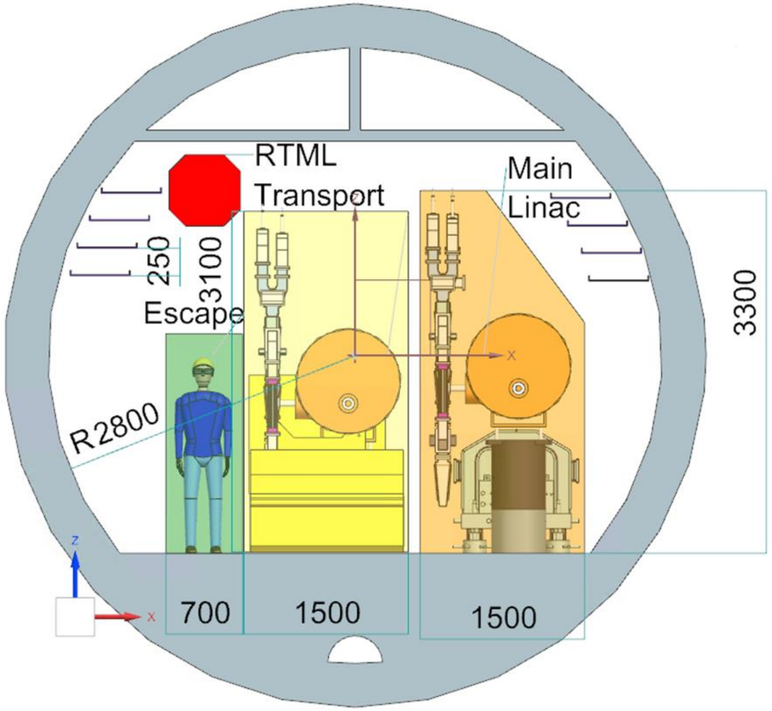
"National Inputs"

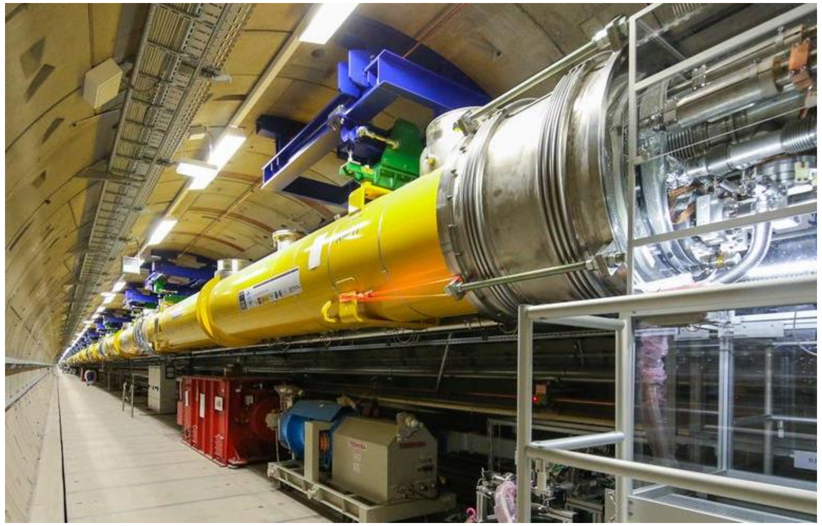
- JAHEP, US (P5), …
- Spain, France, UK, Germany …

A Linear Collider Facility at CERN

Concept under discussion in LCVision team

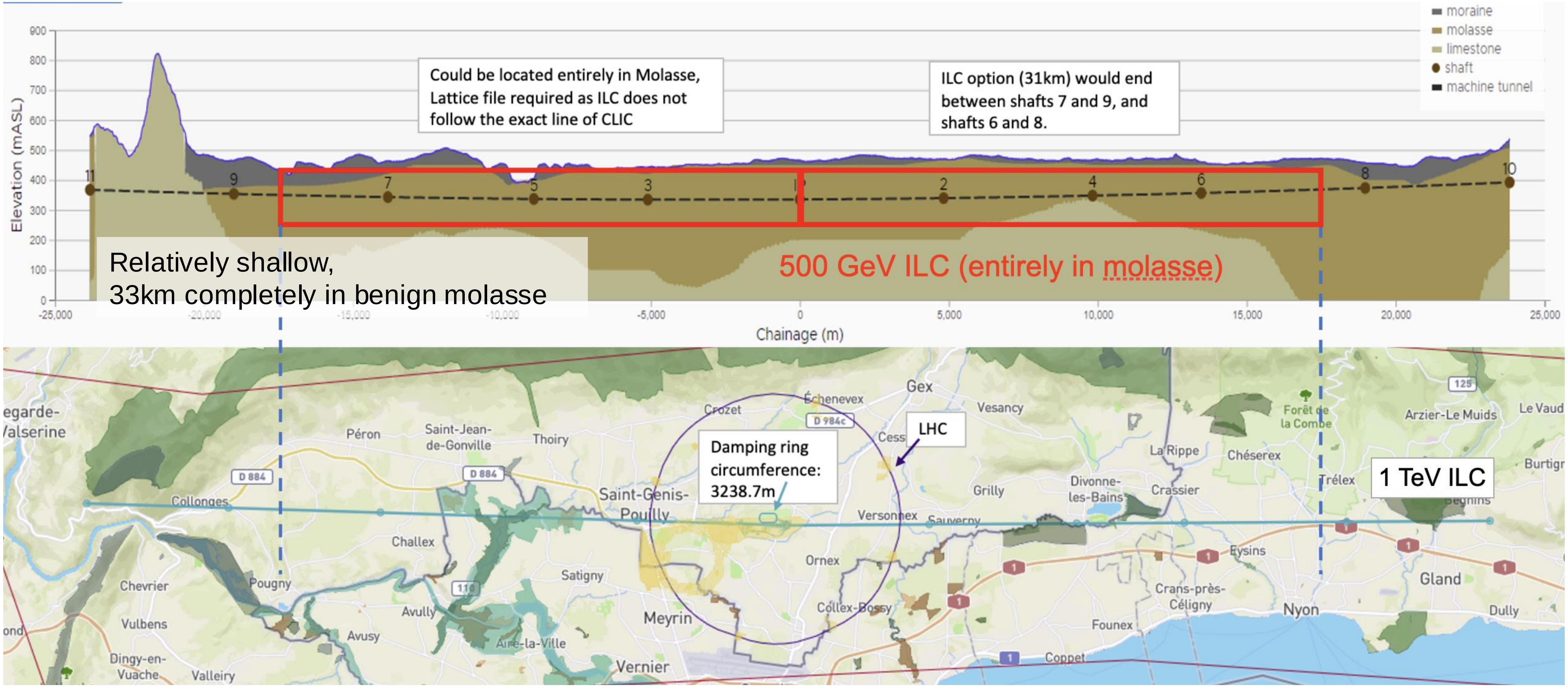
- Initially facility
  - Based on superconducting (ILC) technology
  - Higgs factory with **250 GeV (length: 20.5km)** alternative 550 GeV (33.5km)
  - Luminosity 2.7·10^{34} at 250GeV, alternative 5.4·10^{34}
  - Two interaction points (sharing luminosity)
  - Single tunnel, TBM (tunnel boring machine), 5.6m diameter -> suitable for Geneva area
  - Space for extracted beam facilities for non-colliding experiments and R&D
  - Compatible with upgrades to 1 … 1.5TeV
- Upgrade paths
  - Luminosity (more power, energy/particle recovery)
  - Energy (new technology or extended tunnel)
  - Possible technologies: CLIC, C^3, plasma, ERL…





Siting Study at CERN

Siting study (including cost estimate) for CERN in preparation, based on CLIC siting



Could be located entirely in Molasse, Lattice file required as ILC does not follow the exact line of CLIC

ILC option (31km) would end between shafts 7 and 9, and shafts 6 and 8.

Relatively shallow,
33km completely in benign molasse

500 GeV ILC (entirely in molasse)

Damping ring circumference: 3238.7m

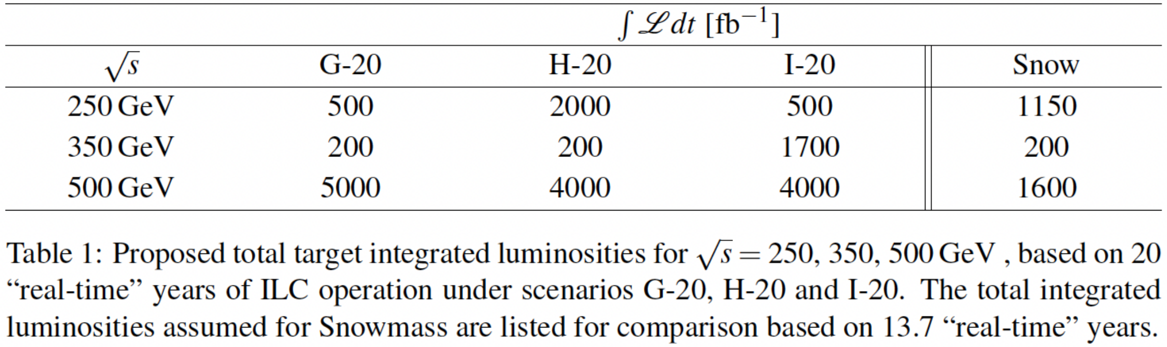
LHC

1 TeV ILC

Running Scenarios

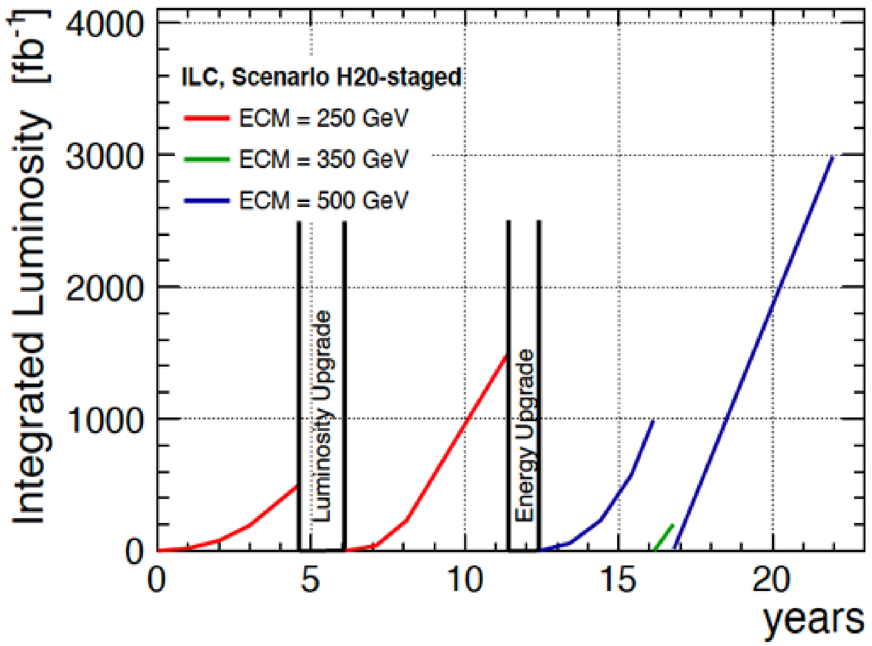
A flexible, 20 years+ program

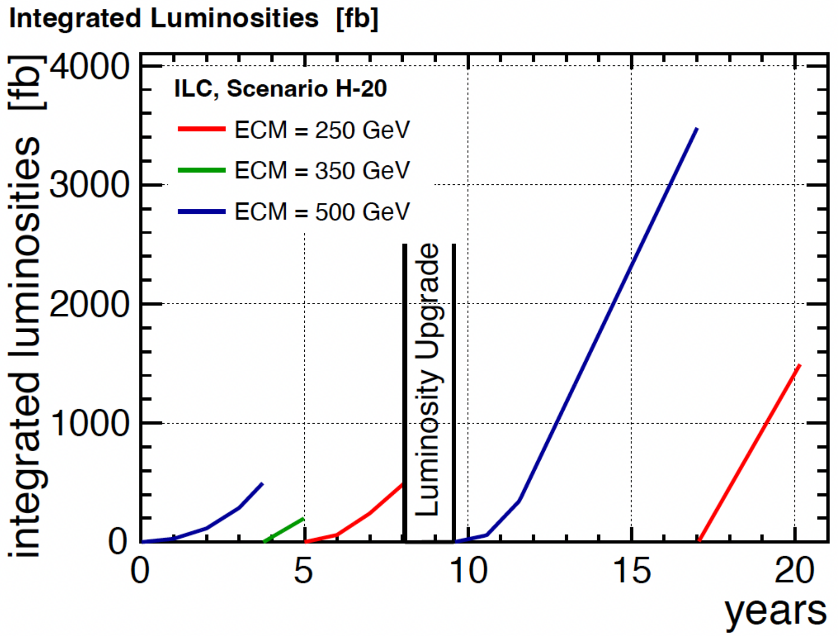
- Different scenarios:
    - Start with a minimal machine at 250 GeV, upgrade later
    - Or, exploit highest energies first, if full 550GeV available
- All scenarios take into account ramp up time (10%/30%/60% lumi in first 3 years)
- Assumption: 75% availability, 8 months running -> 1.6E7 seconds / year



	$\int \mathscr{L} dt$ [fb^{-1}]			
$\sqrt{s}$	G-20	H-20	I-20	Snow
250 GeV	500	2000	500	1150
350 GeV	200	200	1700	200
500 GeV	5000	4000	4000	1600

Table 1: Proposed total target integrated luminosities for $\sqrt{s} = 250, 350, 500$ GeV, based on 20 "real-time" years of ILC operation under scenarios G-20, H-20 and I-20. The total integrated luminosities assumed for Snowmass are listed for comparison based on 13.7 "real-time" years.



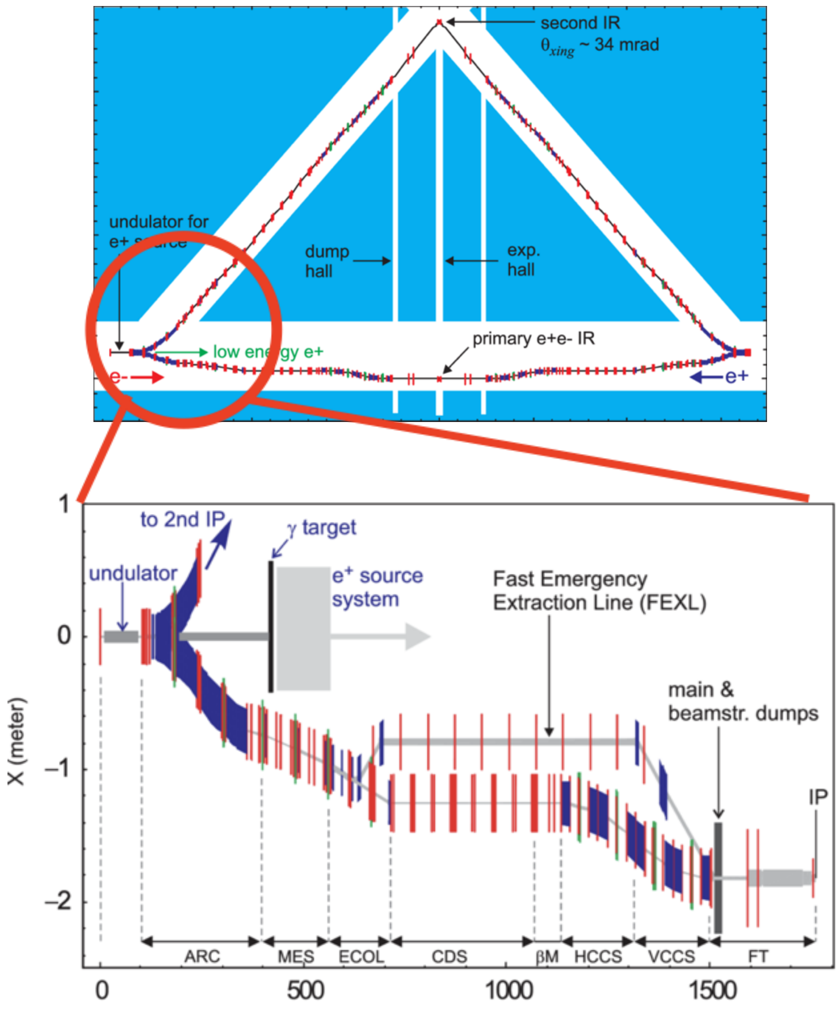


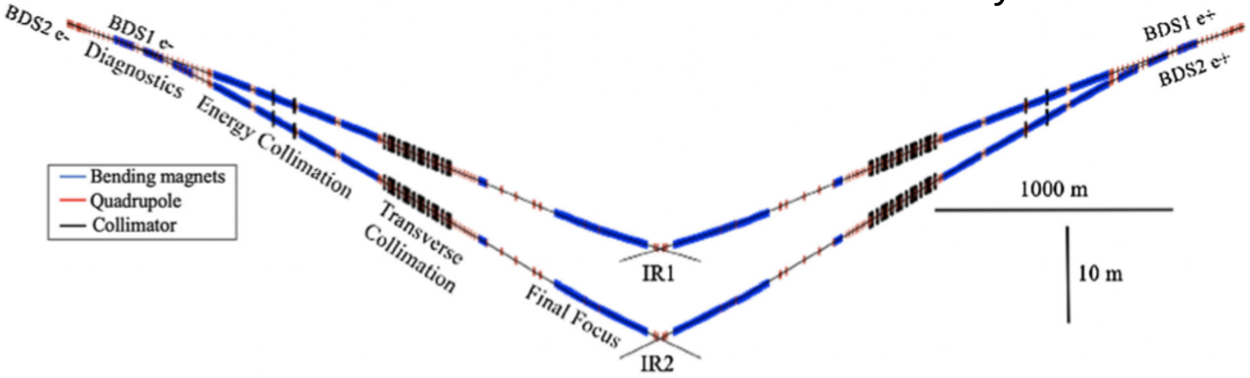
Ref: arXiv:1506.07830, arXiv:1710.07621

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

2 different interaction regions for additional physics opportunities

- 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(0.250) BILCU — has been reinstantiated 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



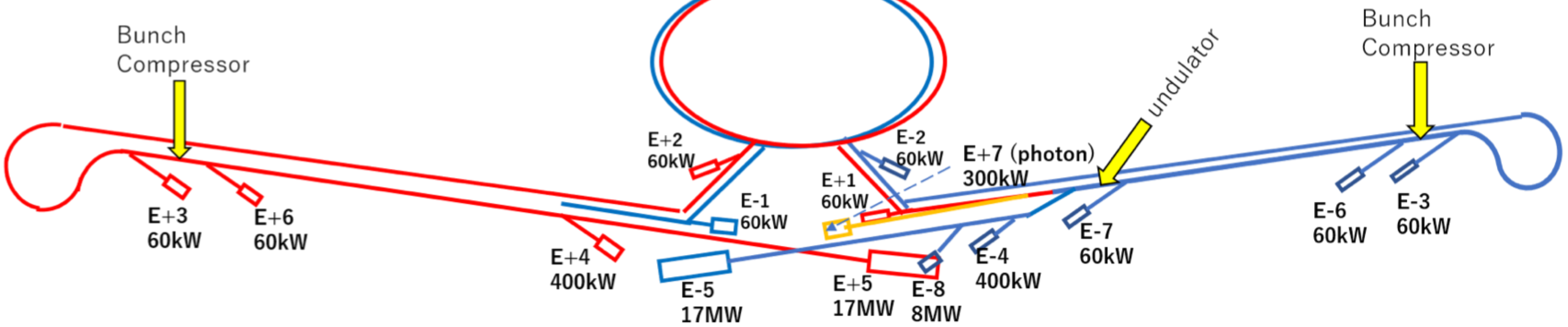


Beyond e+e- Collisions: Beam Dump & Fixed Target Experiments

Broadening the user base

- **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, but up to 10^{15} eot / s
    - 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?

References:
ILCX workshop
Chap 11 of arXiv:2203.07622

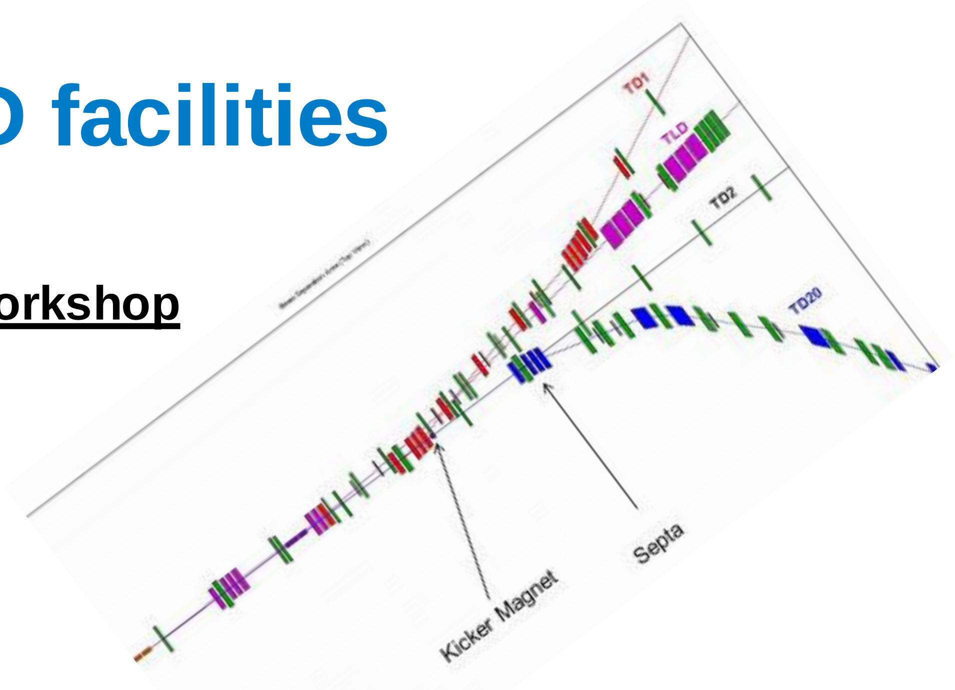


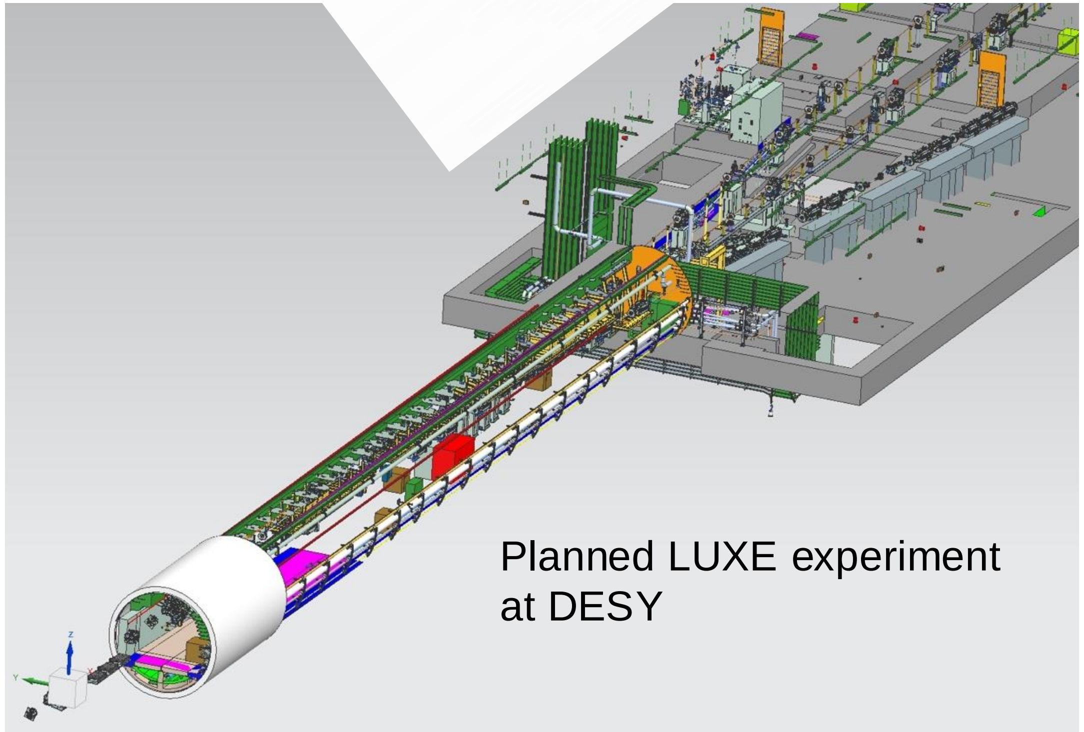
Beyond e+e- Collisions: Test and R&D facilities

- **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

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

ILCX workshop





Planned LUXE experiment at DESY

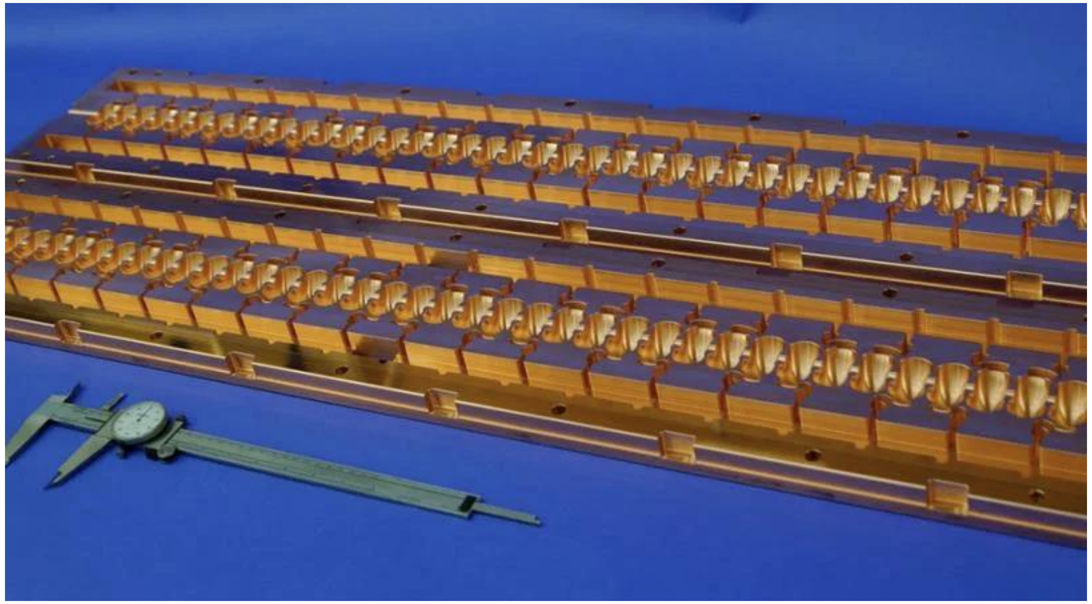
Upgrade option: Higher Energy

Increasing the energy by conventional accelerator technology

- 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 (> 60 MV/m vs 31.5 MV/m ILC design), though ~10..20 years until industrialisation
    => upgrade to ~ 1 TeV or less new tunnel
- rip out SCRF and replace by X-band copper cavities (à la CLIC or C^3)
  - Raise gradient to 70-150 MV / m
    => double (3x, 4x …?) energy without tunnel extension
  - sell / donate SCRF modules to build XFELs, irradiation facilities, … all around the world

	ECM [GeV]	Gradient [MV/m]	Length [km]	#of cavities	AC power [MW] [*5]
TDR	250	31.5	20.5	~8,000	~110
TDR	500	31.5	33.5	~16,000	~170
TDR	1,000	45	44.5	~23,000	~300
Nb3Sn/multilayer or TW	500	63	20.5	~8,000[*2]	~180[*6]
NB3Sn/multilayer & TW	1,000	126[*3]	20.5	~8,000[*4]	~260[*7]

Ref: **Chap 15 of arXiv:2203.07622**



LC Vision Baseline: higher energy by advanced technology, tunnel extension fall-back

Upgrade Options - Double E_{CM} by “HALHFing” LCF

Employing novel accelerator technologies

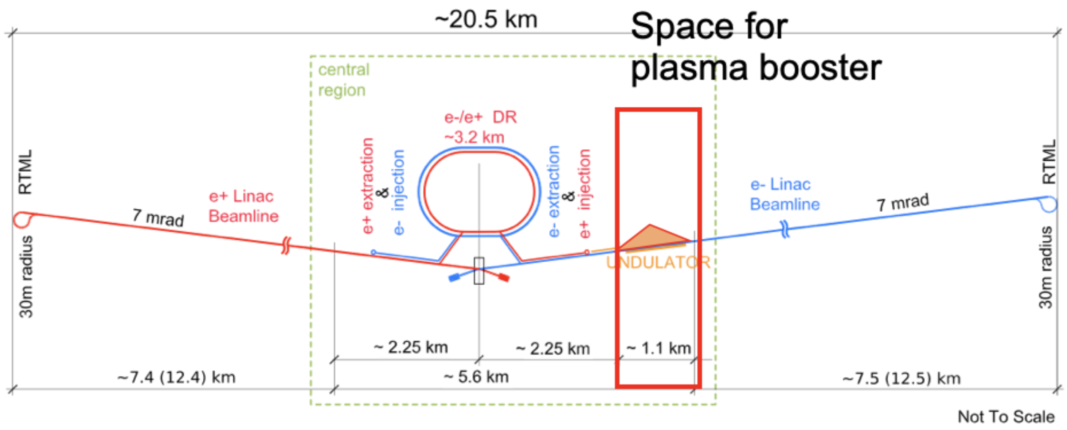
- **Apply HALHF concept to eg 250 GeV ILC:**
  - plasma-accelerate e- to 550 GeV
  - keep e+ linac (small upgrade 125 -> 137.5 GeV)

⇒ 137.5 GeV × 550GeV ⇒ E_{CM} = 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.)	$cm^{-2}s^{-1}$	~ $1 \cdot 10^{34}$		


Space for plasma booster

Ref: BL, HALHF workshop Erice

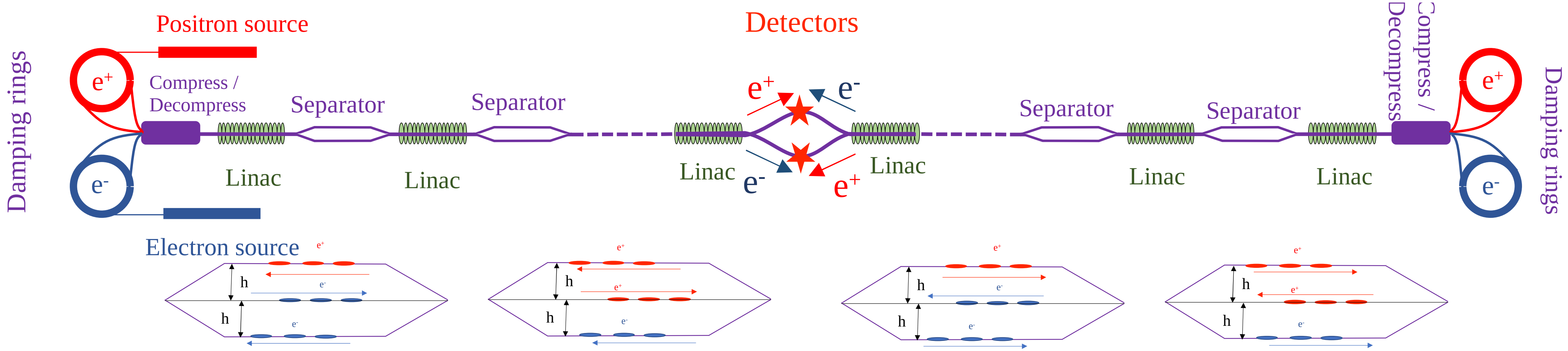
Upgrade Options - Higher Luminosity à la “ReLiC”

Energy recovery: gateway to the highest luminosities

- Energy and particle recovery by de-celaration and re-cooling
- Conceptual study indicates up to O(100) higher luminosity than ILC / CLIC conceivable
- Effectively no beamstrahlung => even Higgs resonance operation not fundamentally excluded (conceptual idea exists but needs verification by beam optics study)

Integrate R&D and demonstrator into initial LCF, upgrade option if successful?

arXiv:2203.06476 [hep-ex]



A Linear Collider Facility and the Energy Frontier

Complementarity to a O(10 TeV)-parton-E_{CM} scale facility

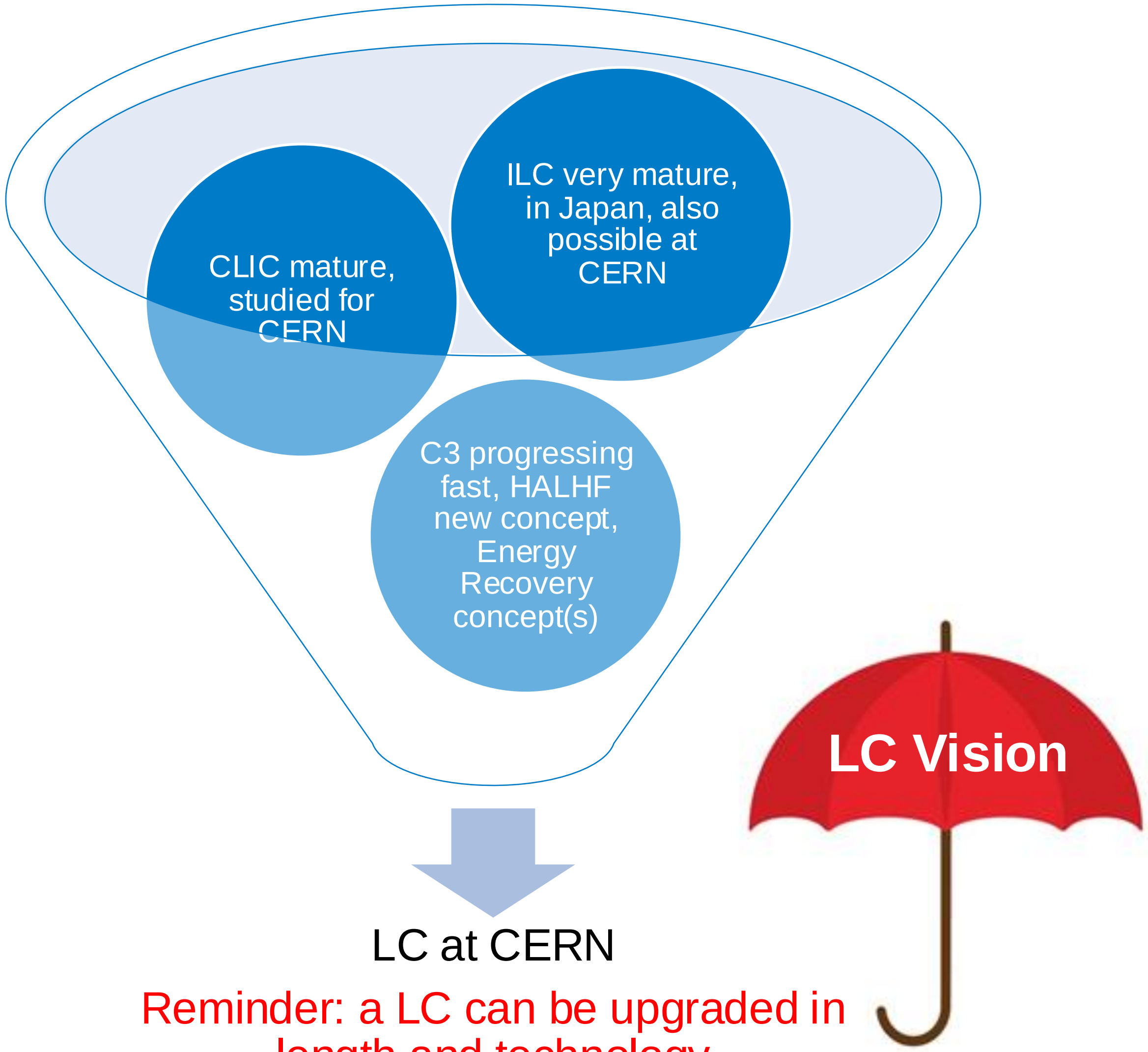
- An e+e- Linear Collider Facility does not pre-emt the choice of how to explore the energy frontier
  => can choose independently based on scientific and technological developments
- nor is it coupled to the site:
  => if technology ready fast, could start building energy frontier machine without stopping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

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

The LCVision Plan

From existing international projects to a new vision for a CERN facility

- Evaluate cost, schedule etc based on existing projects
- Transfer / adapt to CERN
- Input to the European Strategy:
  - Linear Collider physics case (site independent)
  - Linear Collider Facility at CERN proposal
- Will be based on
  - Updated 2024 ILC costs
  - CLIC project implementation plan
  - CERN site study, updated and costed
  - Design adaptions for CERN site
- -> based on data presented in the following



CLIC mature, studied for CERN

ILC very mature, in Japan, also possible at CERN

C3 progressing fast, HALHF new concept, Energy Recovery concept(s)

LC at CERN

Reminder: a LC can be upgraded in length and technology

Costs, Schedule, Organisation, and Risks.

ILC International Development Team IDT and ILC Technology Network ITN

From IDT and ITN to LCVision

ICFA

ILC International Development Team

Executive Board

Americas Liaison	Andrew Lankford (UC Irvine)
Working Group 2 Chair	Shinichiro Michizono (KEK)
Working Group 3 Chair	Jenny List (DESY)
Executive Board Chair and Working Group 1 Chair	Tatsuya Nakada (EPFL)
KEK Liaison	Yasuhiro Okada (KEK)
Europe Liaison	Steinar Stapnes (CERN)
Asia-Pacific Liaison	Geoffrey Taylor (U. Melbourne)

Working Group 1
Pre-Lab Setup

Working Group 2
Accelerator

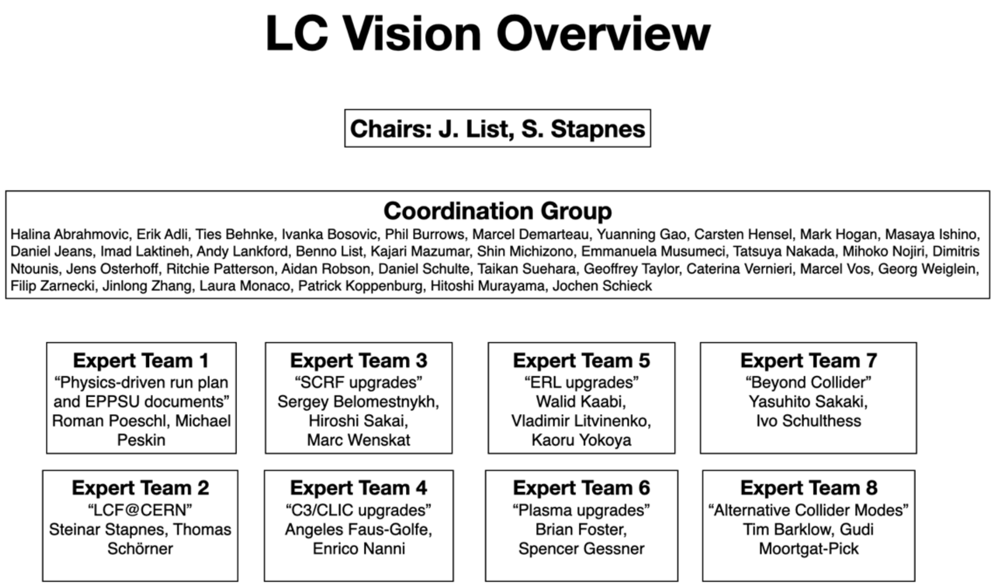
Working Group 3
Physics & Detectors

IDT-WG2 has about 50 accelerator researchers from around the world participating in discussions on ILC accelerator development research.

2020/21: International Development Team IDT:
mandated by ICFA, hosted by KEK, to move ILC towards construction

2022/23: ILC Technology Network: Addresses critical technical developments; based on bilateral agreements with KEK, supported by MEXT

2024: LCVision: Group of interested people to formulate a linear collider vision for CERN to be submitted to the EPPSU



LC Vision Overview

Chairs: J. List, S. Stapnes

Coordination Group
Halina Abrahmovic, Erik Adli, Ties Behnke, Ivanka Bosovic, Phil Burrows, Marcel Demarteau, Yuanning Gao, Carsten Hensel, Mark Hogan, Masaya Ishino, Daniel Jeans, Imad Laktineh, Andy Lankford, Benno List, Kajari Mazumar, Shin Michizono, Emmanuela Musumeci, Tatsuya Nakada, Mihoko Nojiri, Dimitris Ntounis, Jens Osterhoff, Ritchie Patterson, Aidan Robson, Daniel Schulte, Taikan Suehara, Geoffrey Taylor, Caterina Vernieri, Marcel Vos, Georg Weiglein, Filip Zarnecki, Jinlong Zhang, Laura Monaco, Patrick Koppenburg, Hitoshi Murayama, Jochen Schieck

Expert Team 1
"Physics-driven run plan and EPPSU documents"
Roman Poeschl, Michael Peskin

Expert Team 2
"LCF@CERN"
Steinar Stapnes, Thomas Schörner

Expert Team 3
"SCRF upgrades"
Sergey Belomestnykh, Hiroshi Sakai, Marc Wenskat

Expert Team 4
"C3/CLIC upgrades"
Angeles Faus-Golfe, Enrico Nanni

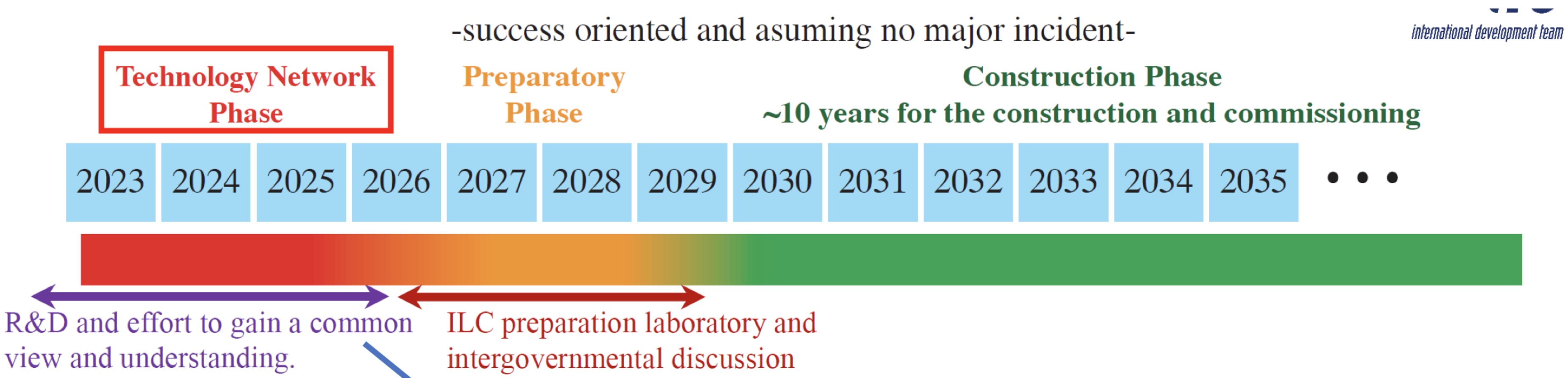
Expert Team 5
"ERL upgrades"
Walid Kaabi, Vladimir Litvinenko, Kaoru Yokoya

Expert Team 6
"Plasma upgrades"
Brian Foster, Spencer Gessner

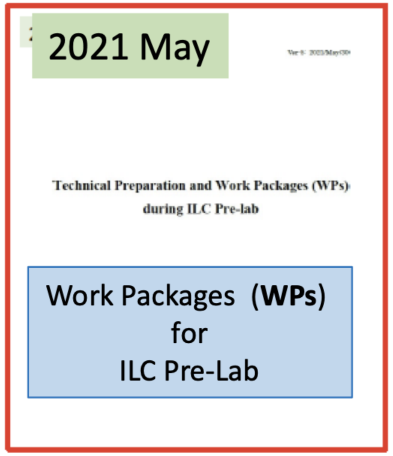
Expert Team 7
"Beyond Collider"
Yasuhito Sakaki, Ivo Schulthess

Expert Team 8
"Alternative Collider Modes"
Tim Barklow, Gudi Moortgat-Pick

ILC Timeline



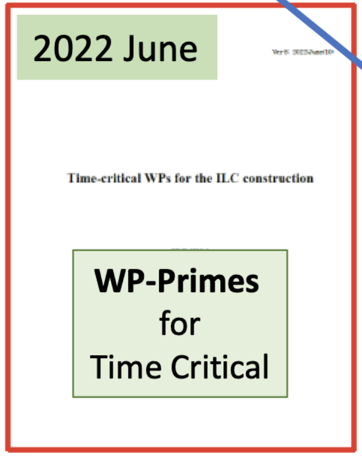
S. Michizono, LCWS 20223



2021 May

Technical Preparation and Work Packages (WPs) during ILC Pre-lab

Work Packages (**WPs**) for ILC Pre-Lab



2022 June

Time-critical WPs for the ILC construction

WP-Primes for Time Critical

http://doi.org/10.5281/zenodo.4742018

https://agenda.linearcollider.org/event/9735/contributions/50816/attachments/38190/59968/Time-Critical_WPsV8b.pdf

ILC Technology Network (ITN)

-- global collaboration program---

- **Acc. R&Ds** focusing on
  - SRF
  - e- & e+ Sources
  - Nano-beam

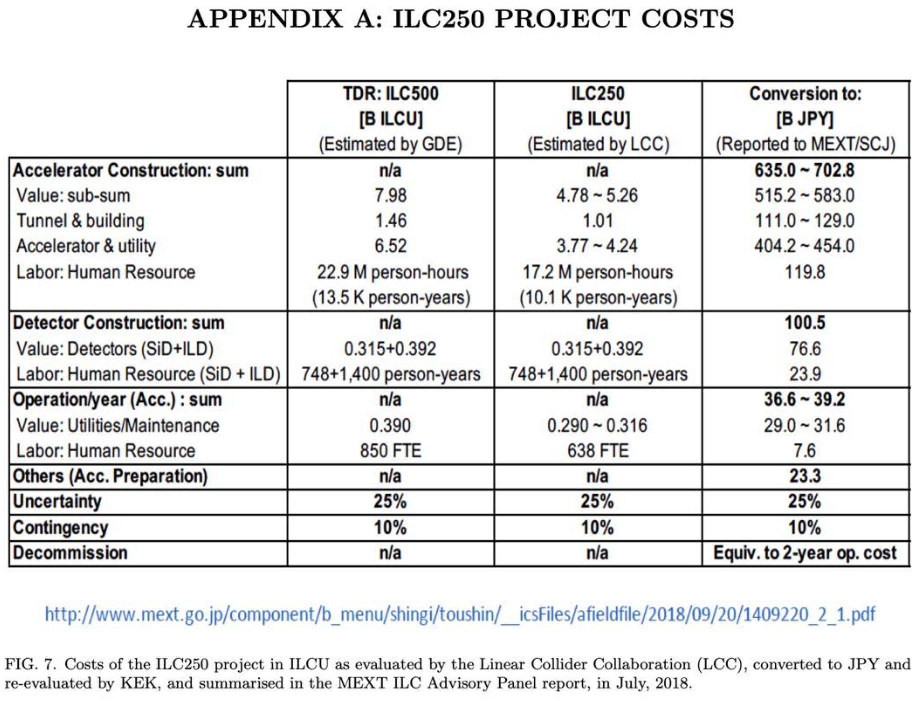
} Synergy with other colliders

KEK obtained a budget for these R&Ds and started the activity from this April.

4-year preparation phase to produce an Engineering Design Report and Project Implementation Plan
After project approval and construction start: 10 years of construction
=> A linear collider facility at CERN would be ready for construction in time for next project

Cost Estimates - ILC

- Cost estimates for ILC in 2012 US$ (today: US$ ≃ CHF) (ILC Currency Unit ILCU), for the Japanese site:
  - TDR: **500GeV, 31.5km tunnel: 7.98 BILCU** + 13.5 kFTE-y, operation 390 MILCU/y + 850 FTE
  - Higgs factory: **250GeV, 20.5km tunnel**: **5.26 BILCU** + 10.1 kFTE-y, operation 316 MILCU + 638 FTE
  - + 2 detectors: 0.71 BILCU + 2.1 kFTE-y
  - Costs include accelerator and civil construction, exclude site activation (roads, power lines) and land acquisition
  - **Substantial inflation since 2021**
  - **Updated cost estimate being prepared for input to European Strategy update, in 2024 prices**
    - New estimates for main cost drivers (75% of cost): civil construction and SRF
    - Other items scaled up for inflation



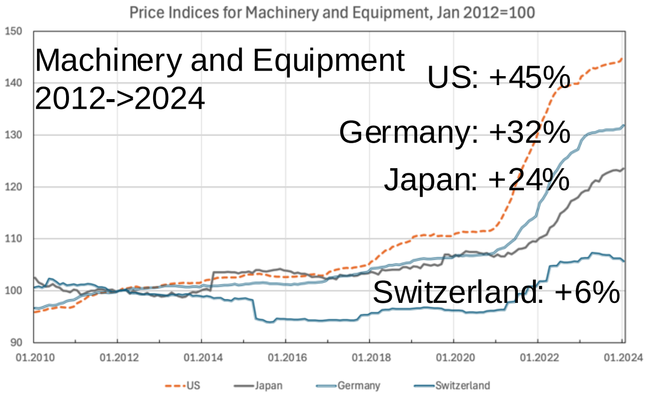
APPENDIX A: ILC250 PROJECT COSTS

	TDR: ILC500 [B ILCU] (Estimated by GDE)	ILC250 [B ILCU] (Estimated by LCC)	Conversion to: [B JPY] (Reported to MEXT/SCJ)
Accelerator Construction: sum	n/a	n/a	**635.0 ~ 702.8**
Value: sub-sum	7.98	4.78 ~ 5.26	515.2 ~ 583.0
Tunnel & building	1.46	1.01	111.0 ~ 129.0
Accelerator & utility	6.52	3.77 ~ 4.24	404.2 ~ 454.0
Labor: Human Resource	22.9 M person-hours (13.5 K person-years)	17.2 M person-hours (10.1 K person-years)	119.8
Detector Construction: sum	n/a	n/a	**100.5**
Value: Detectors (SiD+ILD)	0.315+0.392	0.315+0.392	76.6
Labor: Human Resource (SiD + ILD)	748+1,400 person-years	748+1,400 person-years	23.9
Operation/year (Acc.) : sum	n/a	n/a	**36.6 ~ 39.2**
Value: Utilities/Maintenance	0.390	0.290 ~ 0.316	29.0 ~ 31.6
Labor: Human Resource	850 FTE	638 FTE	7.6
Others (Acc. Preparation)	n/a	n/a	**23.3**
Uncertainty	**25%**	**25%**	**25%**
Contingency	**10%**	**10%**	**10%**
Decommission	n/a	n/a	**Equiv. to 2-year op. cost**

http://www.mext.go.jp/component/b_menu/shingi/toushin/__icsFiles/afieldfile/2018/09/20/1409220_2_1.pdf

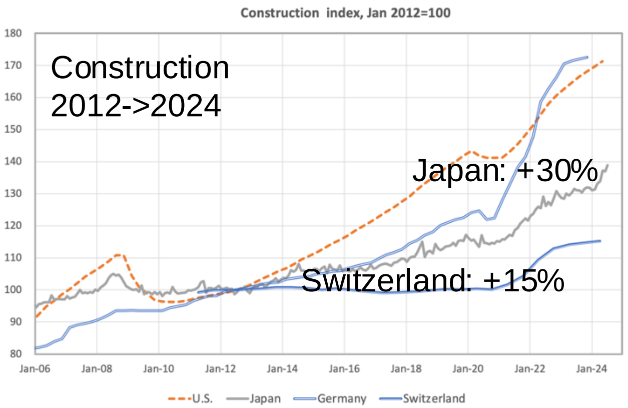
FIG. 7. Costs of the ILC250 project in ILCU as evaluated by the Linear Collider Collaboration (LCC), converted to JPY and re-evaluated by KEK, and summarised in the MEXT ILC Advisory Panel report, in July, 2018.

ILC 250 cost estimate



Price Indices for Machinery and Equipment, Jan 2012=100

Machinery and Equipment 2012->2024



Construction index, Jan 2012=100

Construction 2012->2024

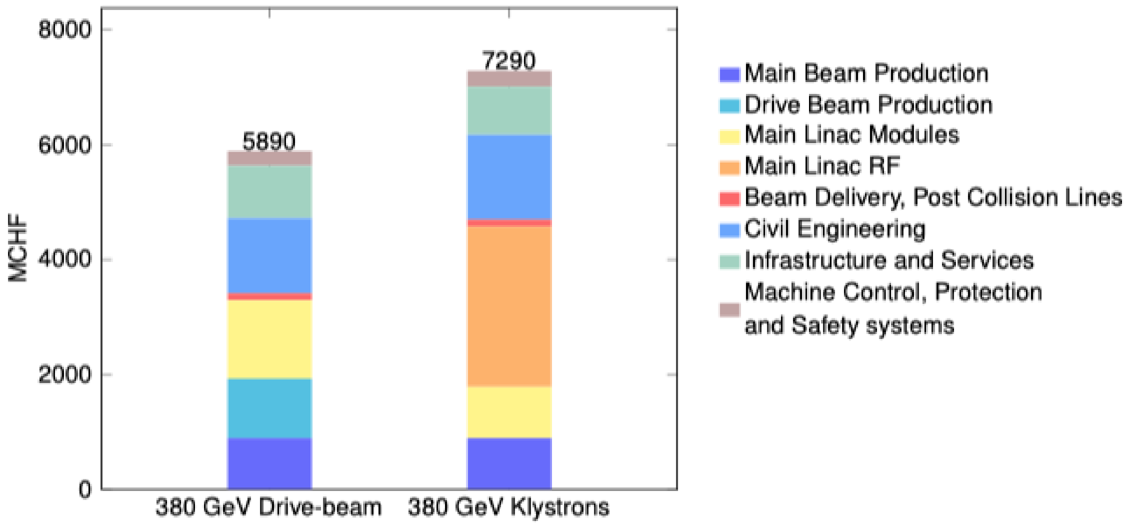
CLIC Cost

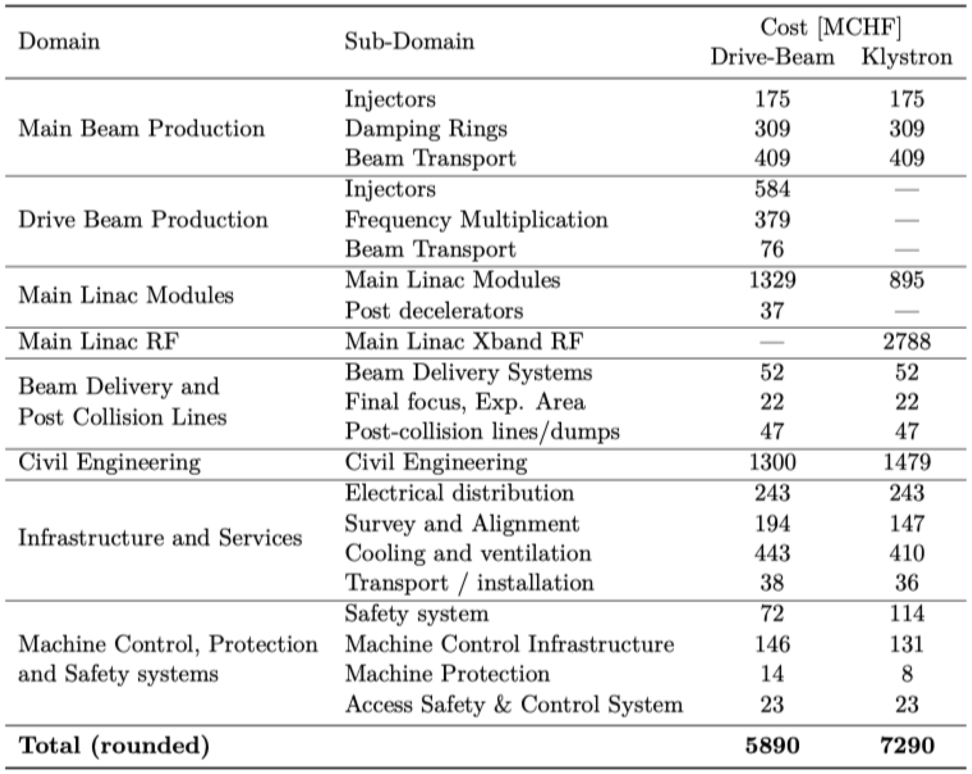
Machine has been re-costed bottom-up in 2017-18 (LINK)

- Methods and costings validated at review on 7 November 2018 – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated

- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

- **Updated cost in preparation**





Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

$$\text{CLIC 380 GeV Drive-Beam based:} \quad 5890^{+1470}_{-1270}\,\text{MCHF};$$

$$\text{CLIC 380 GeV Klystron based:} \quad 7290^{+1800}_{-1540}\,\text{MCHF}.$$

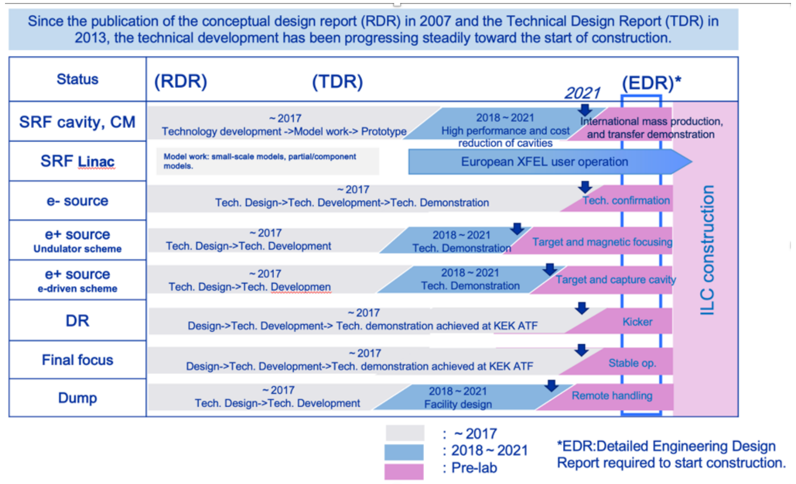
Technological Readiness and Risk

ILC can be built

- Technological readiness of subsystems and key components was evaluated in preparation of ILC technology network and in Snowmass process

- No show stoppers found,
  - positron source is technologically most challenging (TRL 5-6, score 2 from Snowmass implementation task force (arXiv:2208.06030))

- SRF technology fully industrialised (E-XFEL, LCLS-II) -> low technology and cost risk



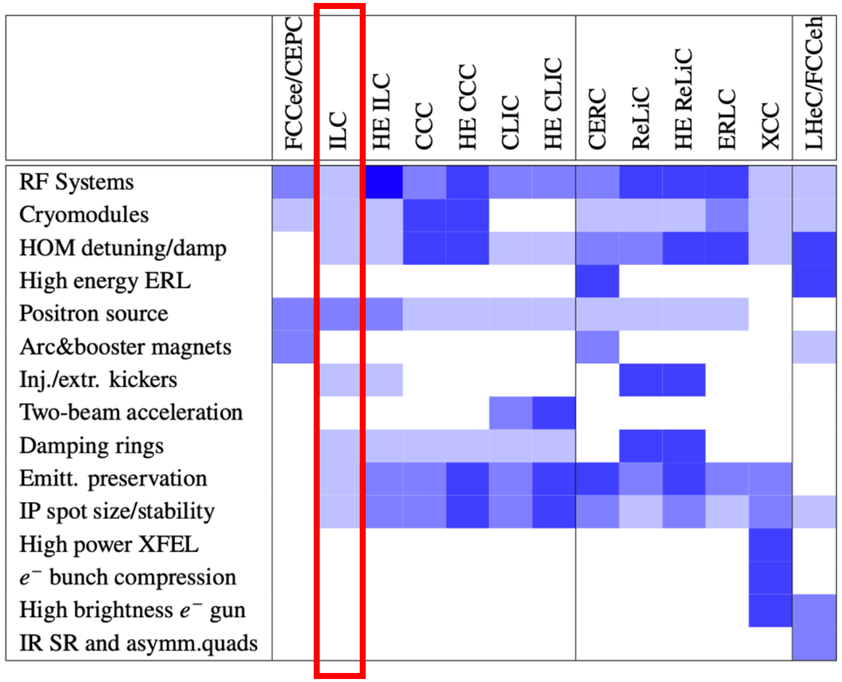
Since the publication of the conceptual design report (RDR) in 2007 and the Technical Design Report (TDR) in 2013, the technical development has been progressing steadily toward the start of construction.

Status	(RDR) (TDR) 2021 (EDR)*
SRF cavity, CM	~2017 Technology development ->Model work-> Prototype; 2018~2021 High performance and cost reduction of cavities; International mass production, and transfer demonstration
SRF Linac	Model work: small-scale models, partial/component models.; European XFEL user operation
e- source	~2017 Tech. Design->Tech. Development->Tech. Demonstration; Tech. confirmation
e+ source Undulator scheme	~2017 Tech. Design->Tech. Development; 2018~2021 Tech. Demonstration; Target and magnetic focusing
e+ source e-driven scheme	~2017 Tech. Design->Tech. Developmen; 2018~2021 Tech. Demonstration; Target and capture cavity
DR	~2017 Design->Tech. Development-> Tech. demonstration achieved at KEK ATF; Kicker
Final focus	~2017 Design->Tech. Development->Tech. demonstration achieved at KEK ATF; Stable op.
Dump	~2017 Tech. Design->Tech. Development; 2018~2021 Facility design; Remote handling

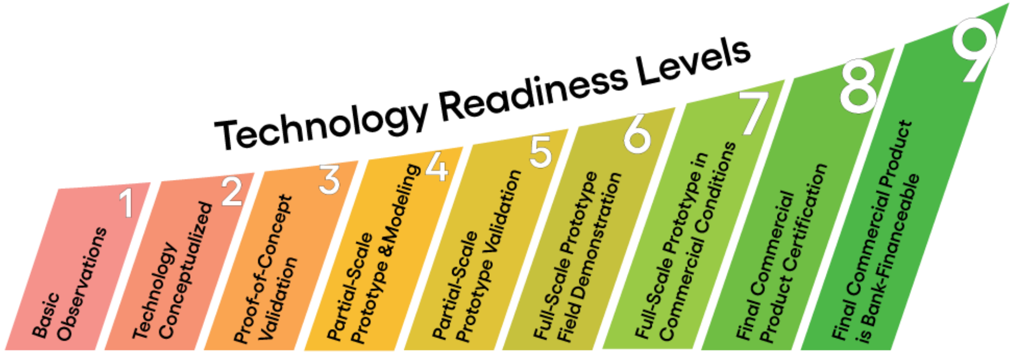
: ~2017
: 2018~2021
: Pre-lab

*EDR:Detailed Engineering Design Report required to start construction.

Table 2. Technical risk registry of accelerator components and systems for future e^+e^- and ep colliders: lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.



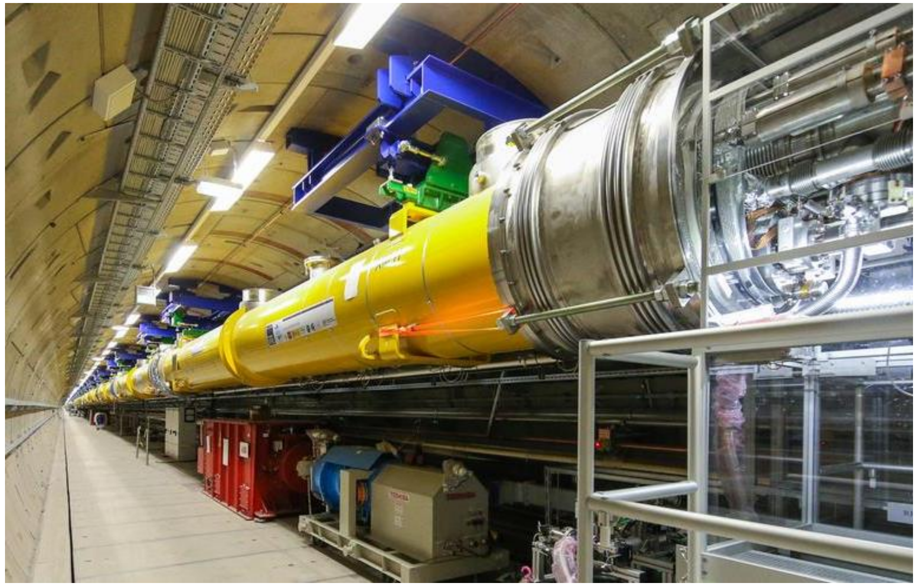
	FCCee/CEPC	ILC	HE ILC	CCC	HE CCC	CLIC	HE CLIC	CERC	ReLiC	HE ReLiC	ERLC	XCC	LHeC/FCCeh
RF Systems	▒	░	█	▒	▓	▒	▒	▒	▓	▓	▓	░	░
Cryomodules	░	░	░	▓	▓			░	░	░	▒	░	░
HOM detuning/damp		░	░	▓	▓	░	░	▒	▒	▓	▓	░	▓
High energy ERL								▓					▓
Positron source	▒	▒	▒	░	░	░	░	░	░	░	░		
Arc&booster magnets	▒							▒					░
Inj./extr. kickers		░	░						▓	▓			
Two-beam acceleration						▒	▓						
Damping rings		░	░	░	░	░	░		▓	▓			
Emitt. preservation		░	▒	▒	▓	▒	▓	▓	▒	▓	▒	▒	
IP spot size/stability		░	▒	▒	▓	▒	▓	▒	░	▒	░	▒	░
High power XFEL												▓	
e^- bunch compression												▓	
High brightness e^- gun												▓	▒
IR SR and asymm.quads													▒



German Perspective

Germany has a long tradition and strong leadership position in linear accelerators

- Strong participation and leadership in
  - Physics studies for e+e-
  - Detector development for ILC, CLIC
  - Accelerator technology
- Strong industrial base for superconducting technology in Germany and Europe
- Lots of experience at DESY
  - SC technology know how
  - Construction and operation experience of E-XFEL
  - Test facilities for material, cavities, cryo modules
- German labs, universities and industry are strong participants for LC projects

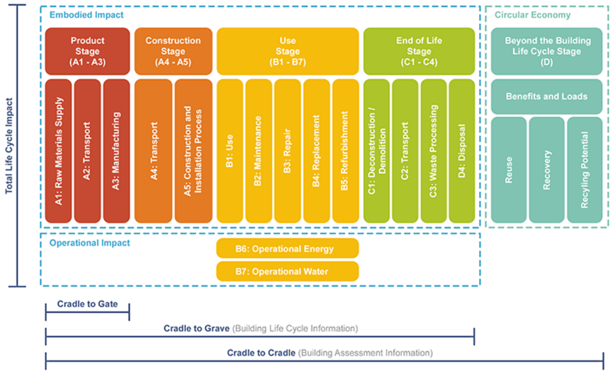


Sustainability.

Sustainability Approach

A high priority for all planned projects

- Close collaboration between ILC and CLIC on sustainability aspects, similar efforts by C3
- Common lifecycle assessment (LCA) studies on
  - Civil construction (finished)
  - Accelerator & detectors (ongoing)
- Overarching concepts for sustainable accelerator projects (“Green ILC”)
- Address whole lifecycle and all aspects: overall system design, components, operation models



Total Life Cycle Impact

Embodied Impact

Product Stage (A1 - A3)
- A1: Raw Materials Supply
- A2: Transport
- A3: Manufacturing

Construction Stage (A4 - A5)
- A4: Transport
- A5: Construction and Installation Process

Use Stage (B1 - B7)
- B1: Use
- B2: Maintenance
- B3: Repair
- B4: Replacement
- B5: Refurbishment

End of Life Stage (C1 - C4)
- C1: Deconstruction / Demolition
- C2: Transport
- C3: Waste Processing
- D4: Disposal

Circular Economy

Beyond the Building Life Cycle Stage (D)

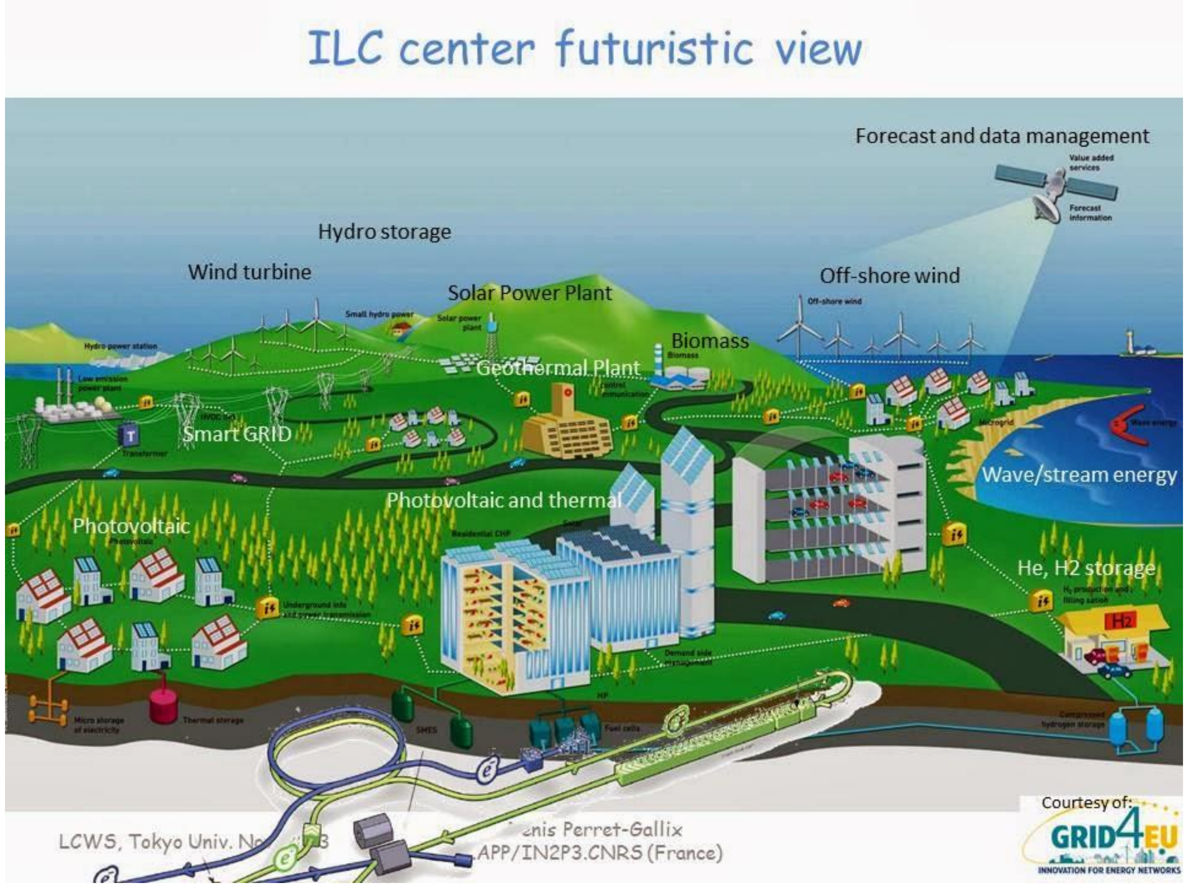
Benefits and Loads
- Reuse
- Recovery
- Recyling Potential

Operational Impact
- B6: Operational Energy
- B7: Operational Water

Cradle to Gate

Cradle to Grave (Building Life Cycle Information)

Cradle to Cradle (Building Assessment Information)



ILC center futuristic view

LCWS, Tokyo Univ. No... 3

...enis Perret-Gallix APP/IN2P3.CNRS (France)

Courtesy of: GRID4EU INNOVATION FOR ENERGY NETWORKS

LCA of Civil Engineering Infrastructure

Evaluate the impact to improve it

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

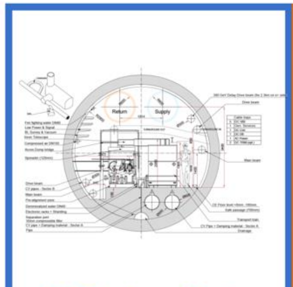
Results:

CLIC 2-beam design:	127 kton CO2-e (+ surface bldgs.)
CLIC klystron:	290 kton CO2-e
ILC (250GeV CoM):	266 kton CO2-e

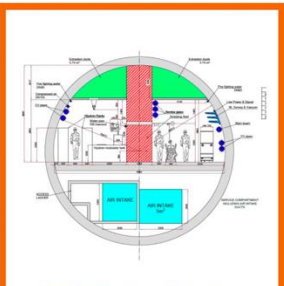
LCA helps to compare design alternatives

LCA identifies reduction potential:

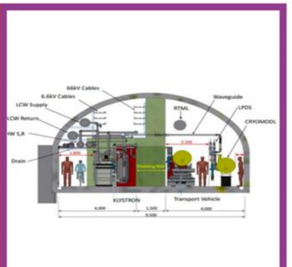
- 20% from using low carbon cement (CEM III/A)
- 12% from thinner lining
- (9% from future electricity mix -> not a project decision)



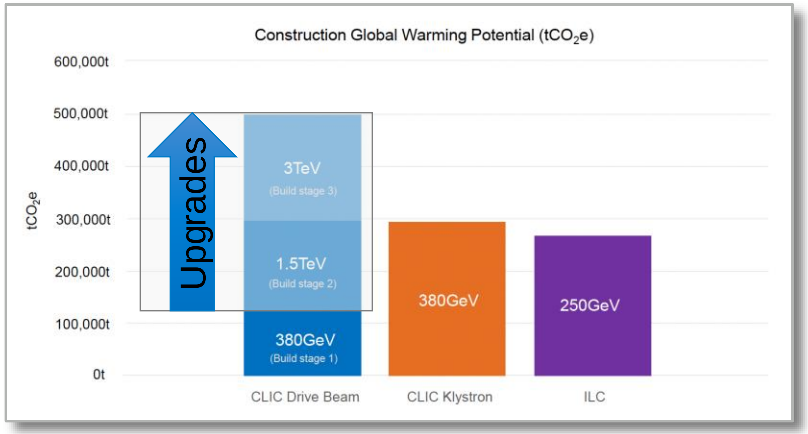
CLIC Drive beam, 5.6m dia.

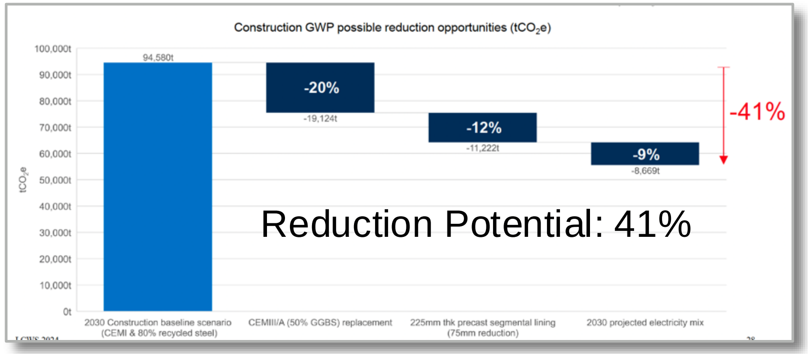


CLIC Klystron, 10m dia.

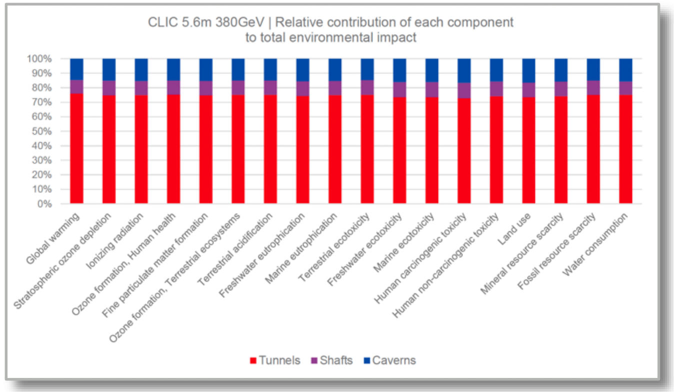


ILC, 9.5m span





Reduction Potential: 41%

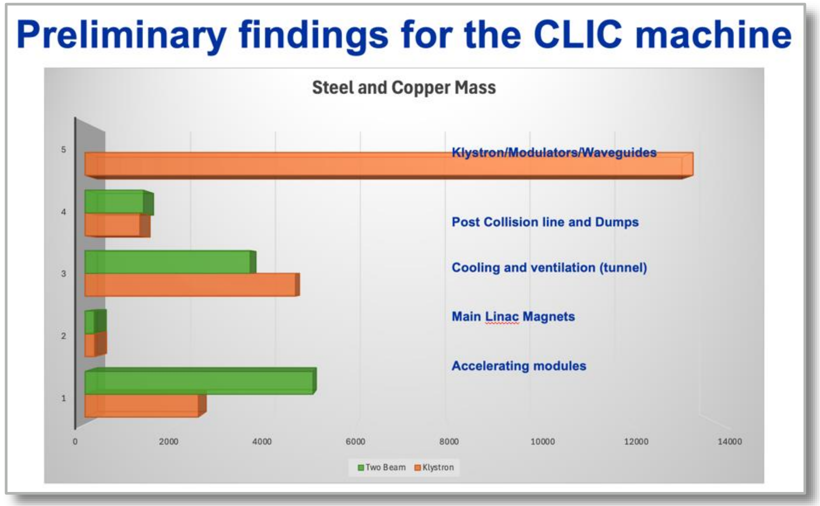


Further Impact categories

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

LCA of Accelerator

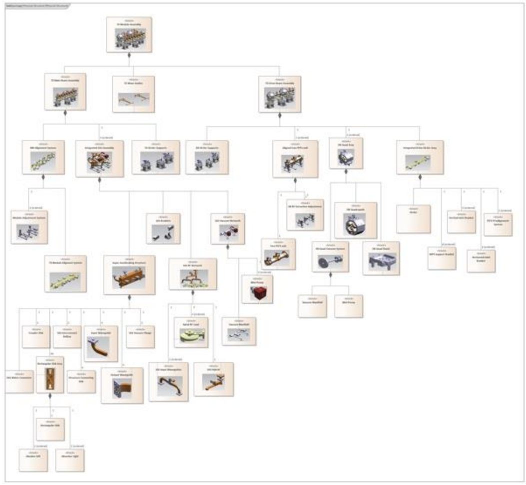
- LCA of accelerator and detectors much more demanding than civil infrastructure:
  - Many different components
  - Many materials, also unusual materials
- ILC and CLIC started LCA effort with ARUP
- Study still ongoing, looking in detail on Main Linac building blocks:
  - ILC Cryomodule
  - CLIC two beam module
- Main Linac components add several tons of CO2 per meter compared to Main Linac tunnels at 6-7 tons/m

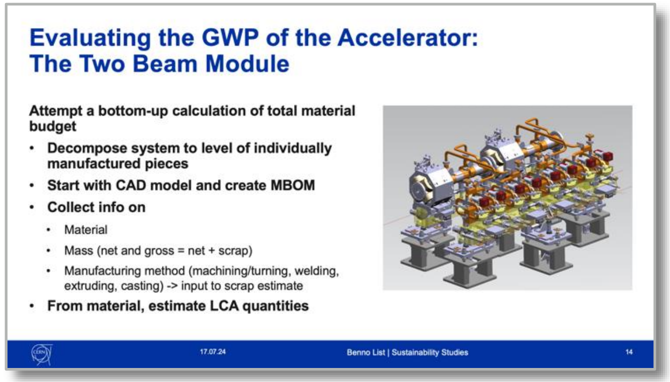


Preliminary findings for the CLIC machine

S. Doebert, LCWS 2024

Comparison of CLIC Main Linac for 2-beam and klystron options



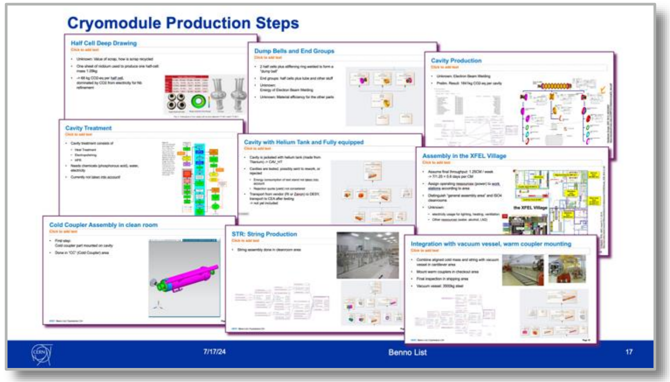


Evaluating the GWP of the Accelerator: The Two Beam Module

Attempt a bottom-up calculation of total material budget

- **Decompose system to level of individually manufactured pieces**
- **Start with CAD model and create MBOM**
- **Collect info on**
  - Material
  - Mass (net and gross = net + scrap)
  - Manufacturing method (machining/turning, welding, extruding, casting) -> input to scrap estimate
- **From material, estimate LCA quantities**

17.07.24 Benno List | Sustainability Studies 14



Cryomodule Production Steps

Half Cell Deep Drawing

Dump Bells and End Groups

Cavity Production

Cavity Treatment

Cavity with Helium Tank and Fully equipped

Assembly in the XFEL Village

Cold Coupler Assembly in clean room

STR: String Production

Integration with vacuum vessel, warm coupler mounting

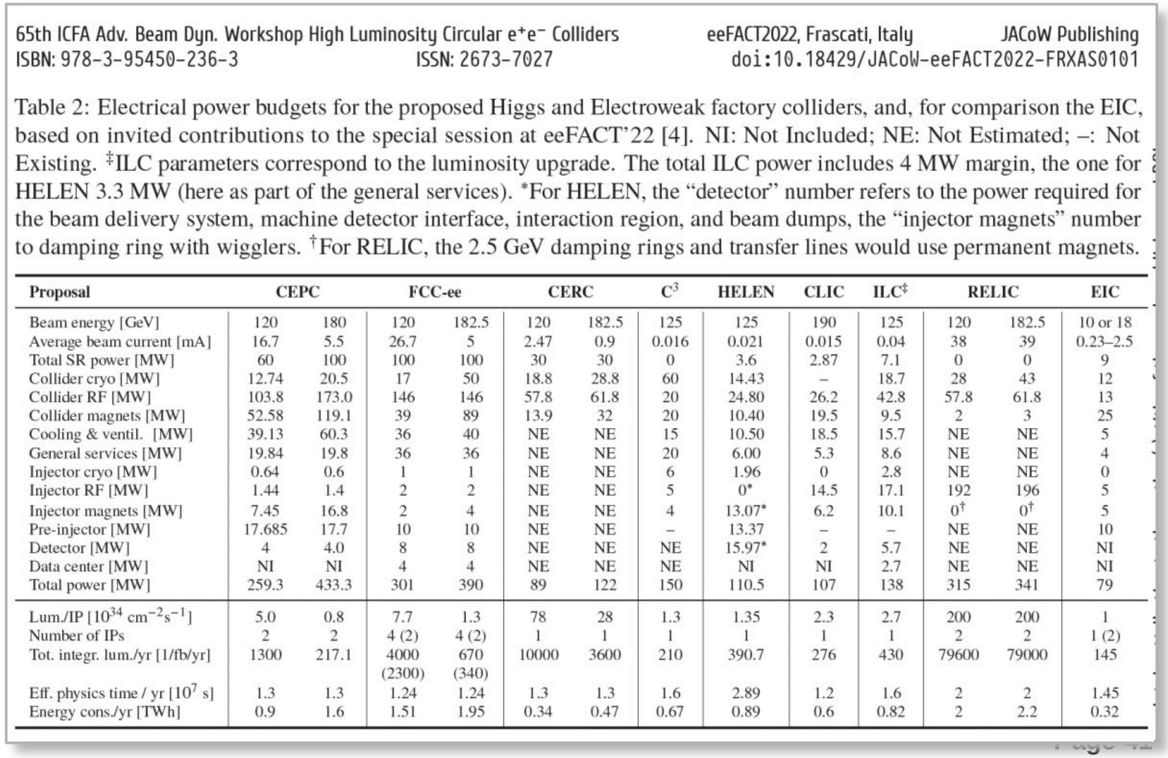
7/17/24 Benno List 17

Power Consumption: ILC and CLIC

- Power consumption of ILC and CLIC:
  - ILC 250: 111 / 138 MW baseline / luminosity upgrade
  - ILC 500: 164 MW
  - CLIC 380: 107 MW
- For CERN in 2040, assume 12.5g CO_2-e/kWh (today: ~50)
- Yearly energy consumption: 0.6 – 1.0 TWh
  -> CERN today: 1.2TWh (LHC: ~0.6 TWh)

Power consumption of a linear collider facility is comparable to LHC power consumption today

	ILC 250		ILC 500	CLIC 380
	baseline	upgrade		
Power (MW)	111	138	164	107
Electricity (TWh/y)	0.66	0.82	0.97	0.6
CO2 at CERN (kton/y)	8	10	12	7



65th ICFA Adv. Beam Dyn. Workshop High Luminosity Circular e⁺e⁻ Colliders eeFACT2022, Frascati, Italy JACoW Publishing
ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-FRXAS0101

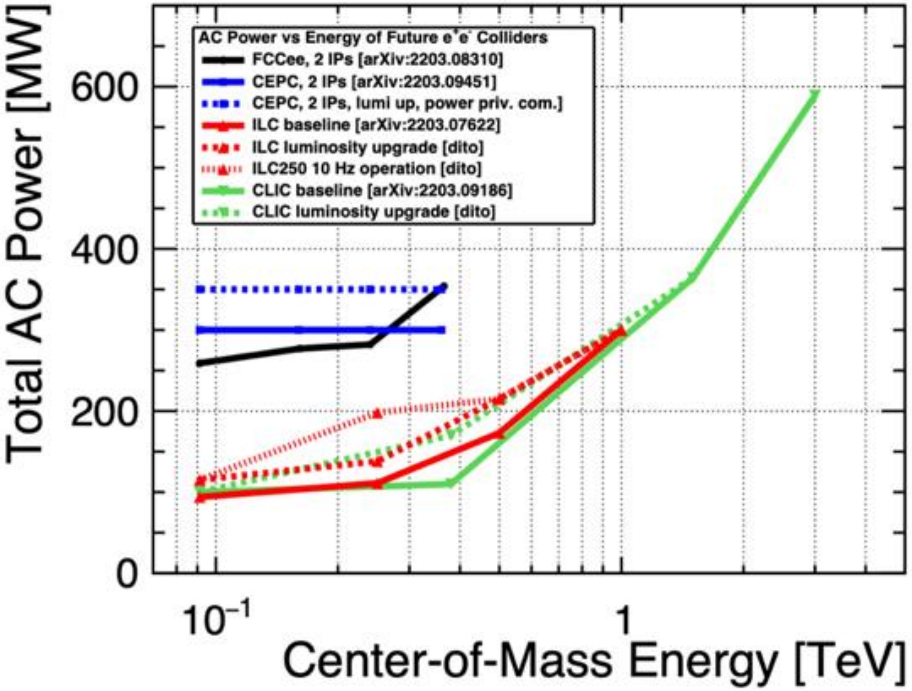
Table 2: Electrical power budgets for the proposed Higgs and Electroweak factory colliders, and, for comparison the EIC, based on invited contributions to the special session at eeFACT'22 [4]. NI: Not Included; NE: Not Estimated; –: Not Existing. ‡ILC parameters correspond to the luminosity upgrade. The total ILC power includes 4 MW margin, the one for HELEN 3.3 MW (here as part of the general services). *For HELEN, the "detector" number refers to the power required for the beam delivery system, machine detector interface, interaction region, and beam dumps, the "injector magnets" number to damping ring with wigglers. †For RELIC, the 2.5 GeV damping rings and transfer lines would use permanent magnets.

Proposal	**CEPC**		**FCC-ee**		**CERC**		**C^3**	**HELEN**	**CLIC**	**ILC‡**	**RELIC**		**EIC**
Beam energy [GeV]	120	180	120	182.5	120	182.5	125	125	190	125	120	182.5	10 or 18
Average beam current [mA]	16.7	5.5	26.7	5	2.47	0.9	0.016	0.021	0.015	0.04	38	39	0.23–2.5
Total SR power [MW]	60	100	100	100	30	30	0	3.6	2.87	7.1	0	0	9
Collider cryo [MW]	12.74	20.5	17	50	18.8	28.8	60	14.43	–	18.7	28	43	12
Collider RF [MW]	103.8	173.0	146	146	57.8	61.8	20	24.80	26.2	42.8	57.8	61.8	13
Collider magnets [MW]	52.58	119.1	39	89	13.9	32	20	10.40	19.5	9.5	2	3	25
Cooling & ventil. [MW]	39.13	60.3	36	40	NE	NE	15	10.50	18.5	15.7	NE	NE	5
General services [MW]	19.84	19.8	36	36	NE	NE	20	6.00	5.3	8.6	NE	NE	4
Injector cryo [MW]	0.64	0.6	1	1	NE	NE	6	1.96	0	2.8	NE	NE	0
Injector RF [MW]	1.44	1.4	2	2	NE	NE	5	0*	14.5	17.1	192	196	5
Injector magnets [MW]	7.45	16.8	2	4	NE	NE	4	13.07*	6.2	10.1	0†	0†	5
Pre-injector [MW]	17.685	17.7	10	10	NE	NE	–	13.37	–	–	NE	NE	10
Detector [MW]	4	4.0	8	8	NE	NE	NE	15.97*	2	5.7	NE	NE	NI
Data center [MW]	NI	NI	4	4	NE	NE	NE	NI	NI	2.7	NE	NE	NI
Total power [MW]	259.3	433.3	301	390	89	122	150	110.5	107	138	315	341	79
Lum./IP [10^{34} $cm^{-2}s^{-1}$]	5.0	0.8	7.7	1.3	78	28	1.3	1.35	2.3	2.7	200	200	1
Number of IPs	2	2	4 (2)	4 (2)	1	1	1	1	1	1	2	2	1 (2)
Tot. integr. lum./yr [1/fb/yr]	1300	217.1	4000 (2300)	670 (340)	10000	3600	210	390.7	276	430	79600	79000	145
Eff. physics time / yr [10^7 s]	1.3	1.3	1.24	1.24	1.3	1.3	1.6	2.89	1.2	1.6	2	2	1.45
Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.34	0.47	0.67	0.89	0.6	0.82	2	2.2	0.32

https://accelconf.web.cern.ch/eefact2022/papers/frxas0101.pdf

Power and Energy

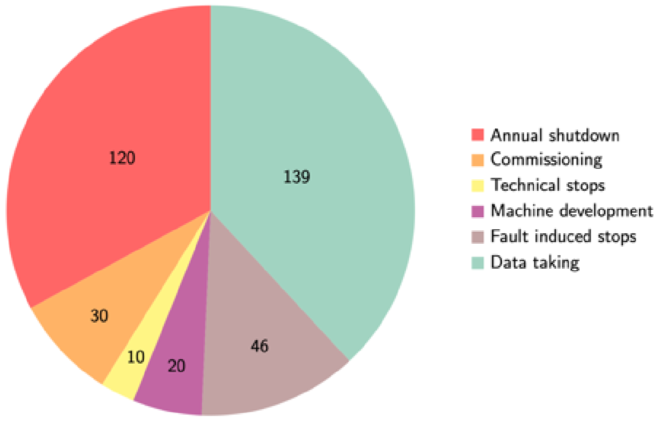
Energy Consumption beyond a Higgs factory



To set a scale, 100 MW with the running scenario on the right this corresponds to ~0.6 TWh annually

CERN is currently consuming 1.2 – 1.3 TWh annually

CERN "standard" running scenario used to convert to annual energy use



Includes studies of overall designs optimisation to reduce power, SRF cavities (grad,Q), cryo efficiency, RF power system (klystrons, modulators, components), RF to beam efficiencies, permanent magnets, operation when power is abundant, heat recovery, nanobeam and more.

Recent overview for linear colliders (LINK)

Running on renewables and when electricity is cheap


Victor Gleim CC-BY-SA-4.0


Asurnipal CC-BY-SA-4.0

Two studies in 2017 for CERN / CLIC (Fraunhofer institute):

- Supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators) at a cost of slightly more than 10% of the CLIC 380 GeV cost.
  - Study done for 200 MW, in reality only ~110 MW are needed
- Self-sufficiency during all times can not be reached but 54% of the time
  - Can one run an accelerator as CLIC in a mode where one turn “on” and “off” depending prices (fluctuating with weather, demand, availability etc) ? **Demand side flexibility***.
  - Specify transition times (relatively fast for a LC) and the annual luminosity goal
  - Significant savings – but the largest saving is the obvious one, not running in the winter.
  - Flexibility to adjust the power demand is expected to become increasingly important and in demand by energy companies.
  - Future availability of affordable 100MWh-size batteries will improve prospects
- More information (link)

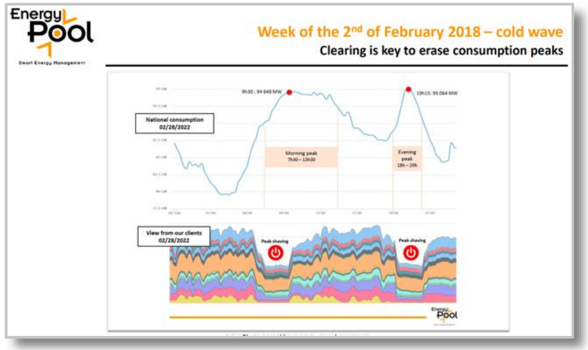
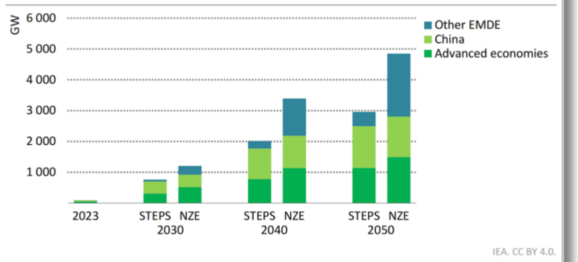


Figure 2.14 ▻ Global installed battery storage capacity by scenario, 2023-2050

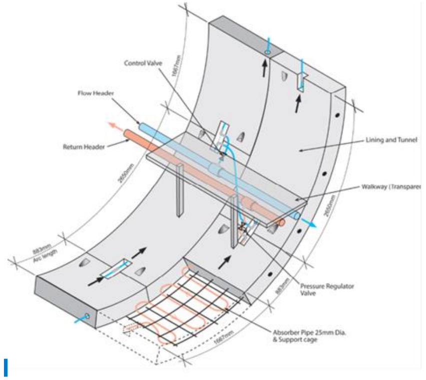


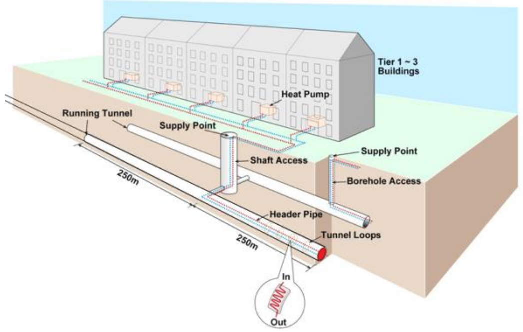
IEA. CC BY 4.0.

Total installed battery storage capacity rises significantly in both scenarios, with strong growth in emerging market and developing economies outside China in the NZE Scenario

Note: GW = gigawatts; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; Other EMDE = Emerging market and developing economies other than China.

Prospects to run fully on renewables are good
Operational flexibility of linear accelerators is an advantage
Less energy is always better





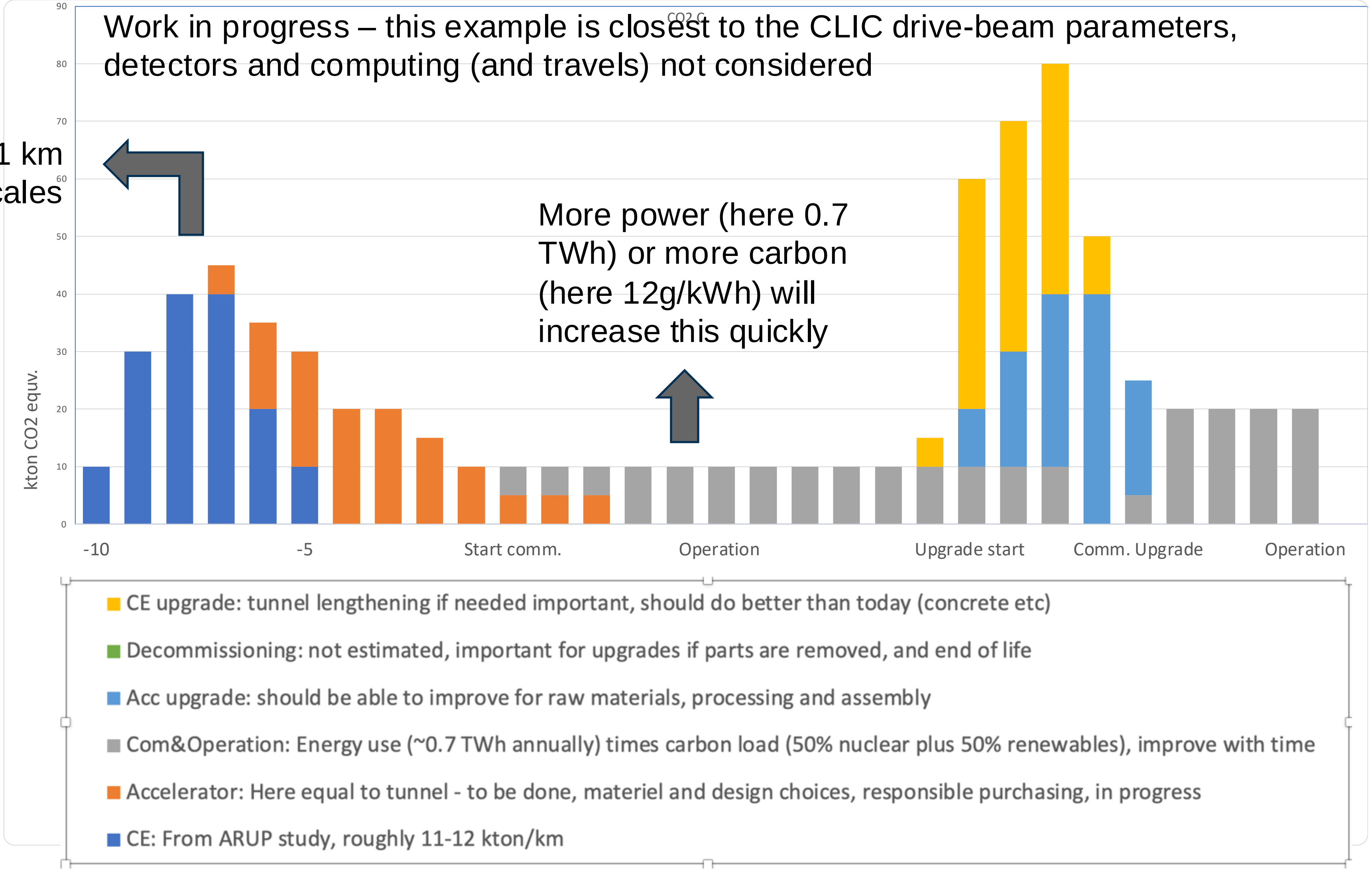
Heat recovery:
Already implemented in point 8 for LHC
Another approach to increase sustainability

*C. Gaunand, B. Remenyi: *Introduction to Demand Side Flexibility*
ESSRI Workshop 2022 https://indico.esrf.fr/event/2/contributions/94/

CC-BY-4.0 I IEA, batteries and secure energy transition,
https://www.iea.org/reports/batteries-and-secure-energy-transitions

Greenhouse Gas Emissions over the Full Lifecycle

Consider construction, operation, and upgrades



Work in progress – this example is closest to the CLIC drive-beam parameters, detectors and computing (and travels) not considered

This is for 11 km of tunnel, scales with length

More power (here 0.7 TWh) or more carbon (here 12g/kWh) will increase this quickly

🟨 CE upgrade: tunnel lengthening if needed important, should do better than today (concrete etc)

🟩 Decommissioning: not estimated, important for upgrades if parts are removed, and end of life

🟦 Acc upgrade: should be able to improve for raw materials, processing and assembly

⬜ Com&Operation: Energy use (~0.7 TWh annually) times carbon load (50% nuclear plus 50% renewables), improve with time

🟧 Accelerator: Here equal to tunnel - to be done, materiel and design choices, responsible purchasing, in progress

🟦 CE: From ARUP study, roughly 11-12 kton/km

CO_2 of Accelerator Projects in Perspective

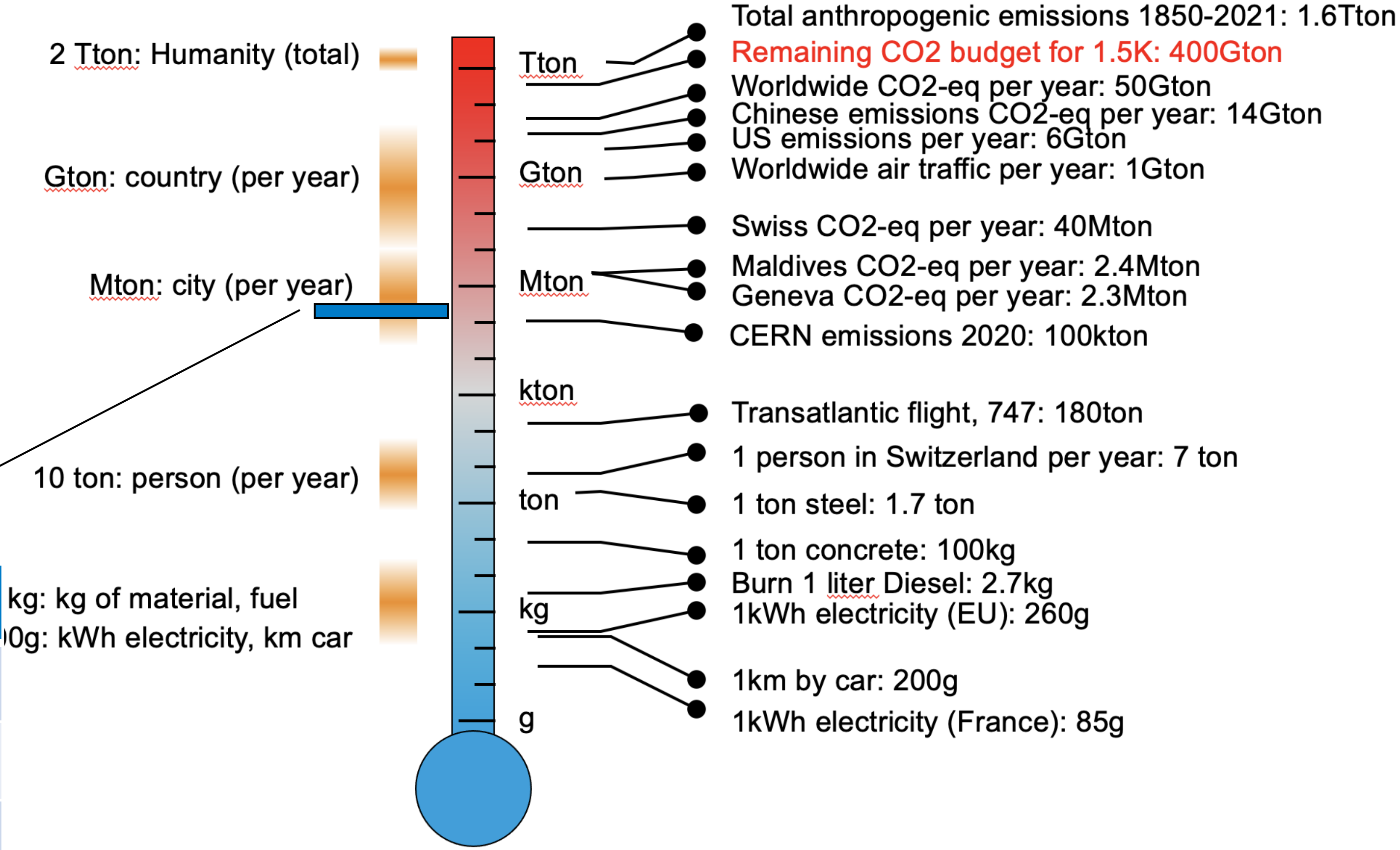
How does an accelerator compare to other human activities

- CO2 emissions of accelerator projects:
  - 100s of kton CO2 for construction
    100kton is yearly CO2 emission of CERN
  - Civil construction: 250 kton
  - Yearly operation in 2040 (est):
    7-10 kton (at CERN)

A linear collider facility has a sizeable CO2 impact, dominated by civil construction

Shorter tunnel and lower power consumption are strong sustainability arguments

CO2 footprint (kton)	LC 250	CLIC 380
Civil construction	266	127 / 290
Accelerator	tbd	tbd
Yearly operation	10	7



2 Tton: Humanity (total)

Gton: country (per year)

Mton: city (per year)

10 ton: person (per year)

kg: kg of material, fuel

0g: kWh electricity, km car

Tton

Gton

Mton

kton

ton

kg

g

Total anthropogenic emissions 1850-2021: 1.6Tton

Remaining CO2 budget for 1.5K: 400Gton

Worldwide CO2-eq per year: 50Gton

Chinese emissions CO2-eq per year: 14Gton

US emissions per year: 6Gton

Worldwide air traffic per year: 1Gton

Swiss CO2-eq per year: 40Mton

Maldives CO2-eq per year: 2.4Mton

Geneva CO2-eq per year: 2.3Mton

CERN emissions 2020: 100kton

Transatlantic flight, 747: 180ton

1 person in Switzerland per year: 7 ton

1 ton steel: 1.7 ton

1 ton concrete: 100kg

Burn 1 liter Diesel: 2.7kg

1kWh electricity (EU): 260g

1km by car: 200g

1kWh electricity (France): 85g

Conclusions and Outlook.

Conclusions

- A linear collider facility for CERN, based on superconducting ILC technology
- Offers a Higgs factory at at a reasonable cost and time scale, with upgrade options
- Profits from a large international experience and interest – good opportunities for in-kind contributions
- Offers a rich long-term physics programme with guaranteed results, and a long-term perspective through future upgrades
  - Including rich opportunities for diverse non-collider experiments and R&D facilities
- Can be expanded for more energy or luminosity, as needs arise and funds are available
- Is a sustainable solution, with respect to embodied carbon from construction and energy usage in operation
- Keeps Europe at the forefront of particle physics

Outlook

LCVision inputs for the EPPSU

- Umbrella document of physics case & upgrade options
- Proposal for Linear Collider Facility at CERN
  - ILC like initial facility adapted to CERN
  - Civil engineering study, based on CLIC design study plus ILC at CERN siting study of TDR
  - Cost estimate based on
    - Updated 2024 ILC costs
    - Translated into CHF and CERN procurement model
    - CERN civil engineering costs

As part of the new Strategy:

- Pursue Linear Collider Facility project at CERN up to decision readiness
- Engineering Design Study for a CERN based project
  - Based on the ILC and CLIC designs and R&D plans
  - Together with the existing ILC, CLIC and wider Linear Collider communities
  - Including a specific siting proposal

Thank you.

Thanks to

Steinar Stapnes, Jenny List, Emilio Nanni, Brian Foster, Erik Adli, Ties Behnke, Shin Michizono, Nobuhiro Terunuma, Phil Burrows, Suzanne Evans, Maxim Titov and many others for their material and support

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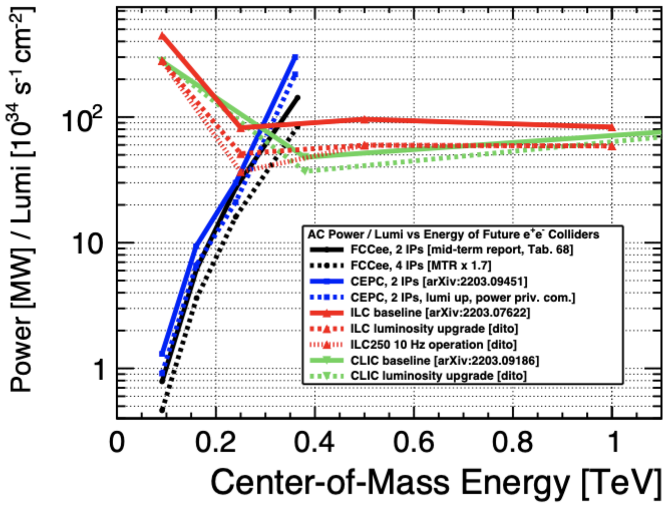
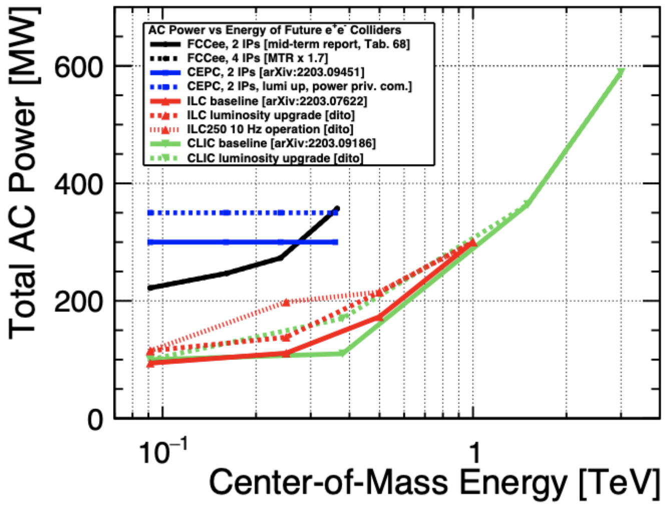
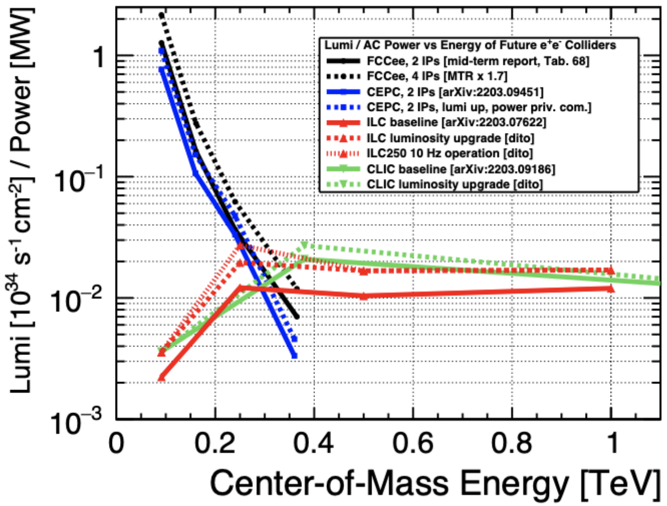
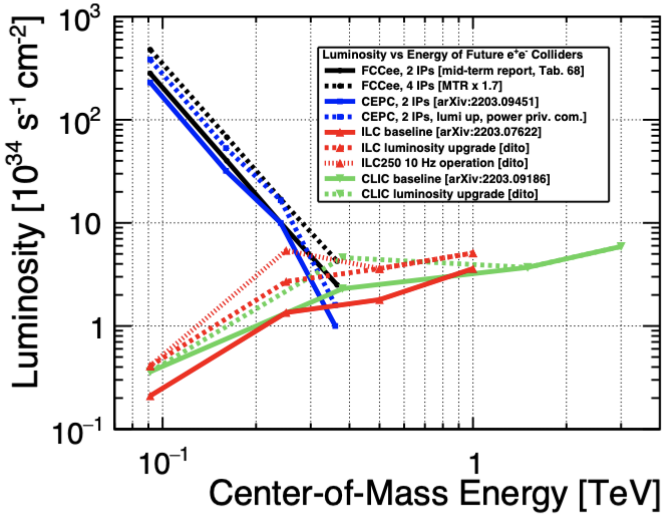
Luminosity and Power



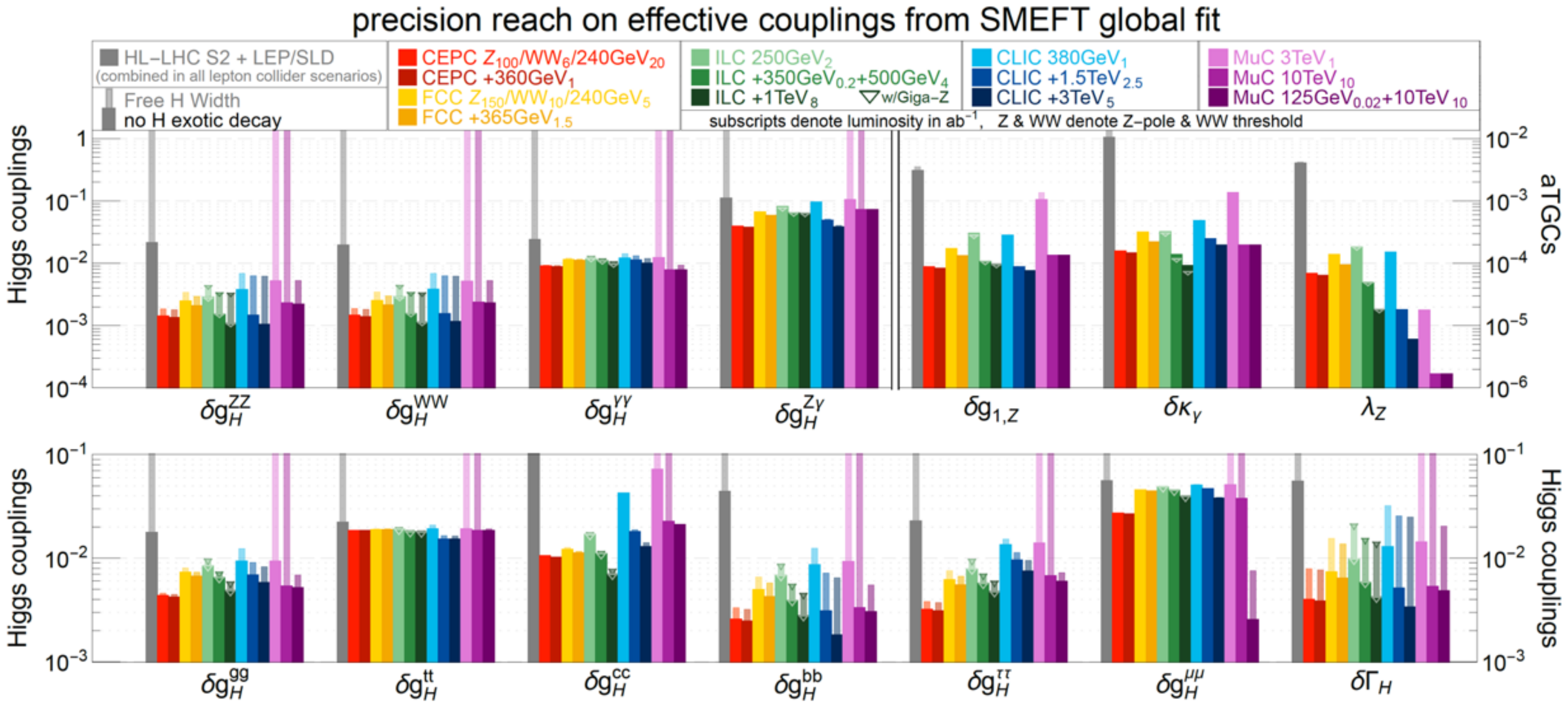






LC physics opportunities - reminder

arXiv:2206.08326

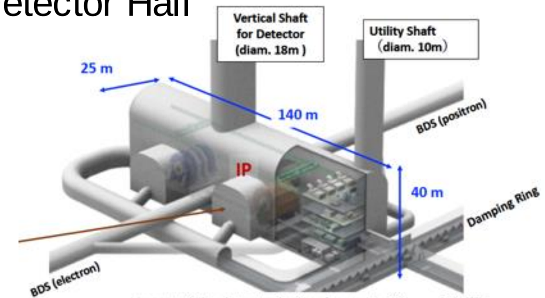


e+e- colliders show very comparable performance for standard Higgs program, despite quite different assumed integrated luminosities => longitudinal beam polarization an important factor for LCs

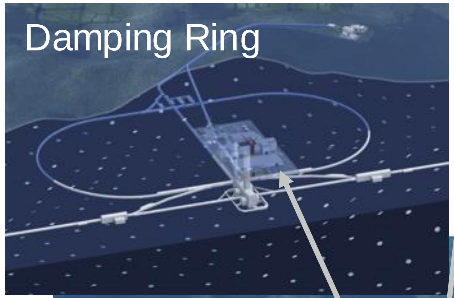
- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

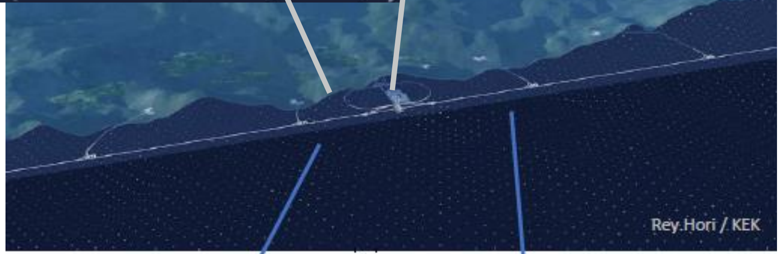
ILC Site Selection and Civil Engineering

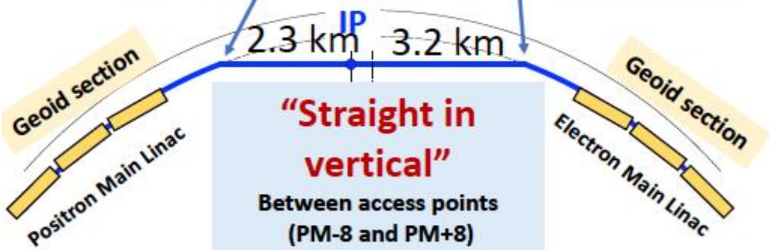
Detector Hall



Layout of the detector hall and around will be optimized with detector groups.



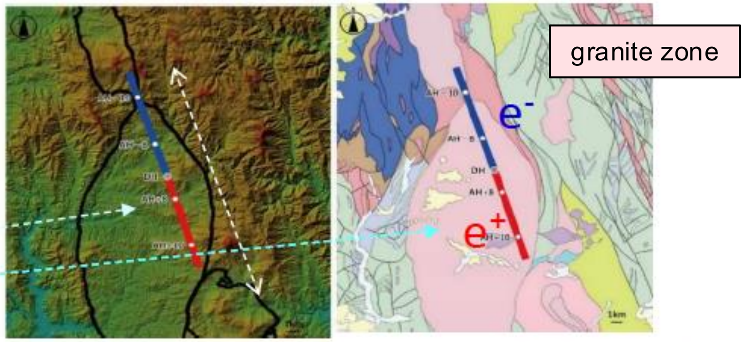




“Straight in vertical”

Between access points (PM-8 and PM+8)

Kitakami mountains



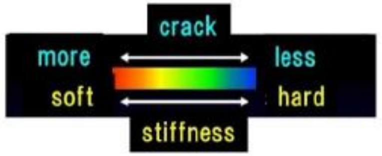
① ILC Location

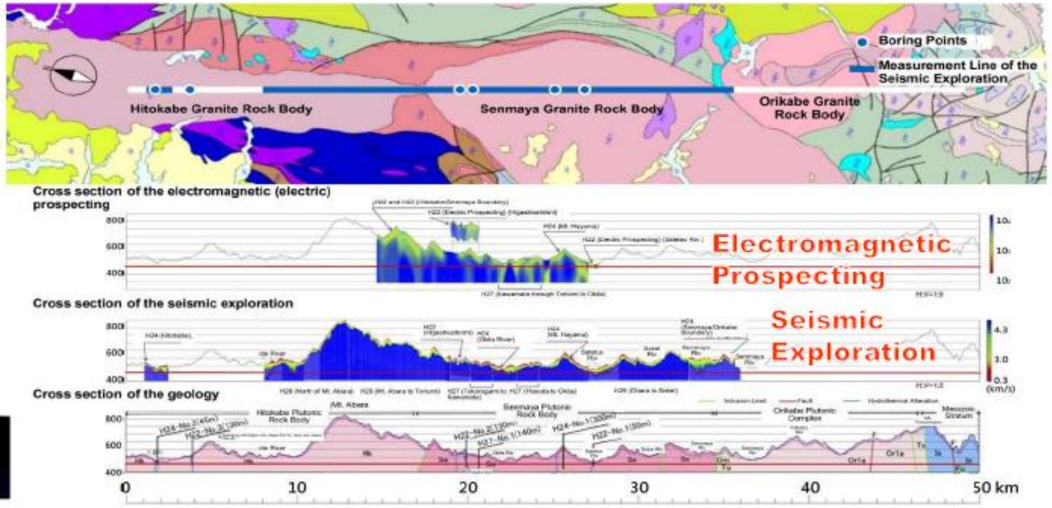
ILC accelerator area : inside the granite rock bodies
→ inside black curves (left)
→ in the pink color (right)
→ possible up to 50 km

→ On-going jobs : Optimal accelerator placement, considering surface environment, land-use and land-acquisition

② Geological Surveys

- Electric Prospecting (crack)
- Seismic Exploration (stiffness)
- Boring Survey
- Borehole Camera
- Measurement of Initial Stress of the Ground

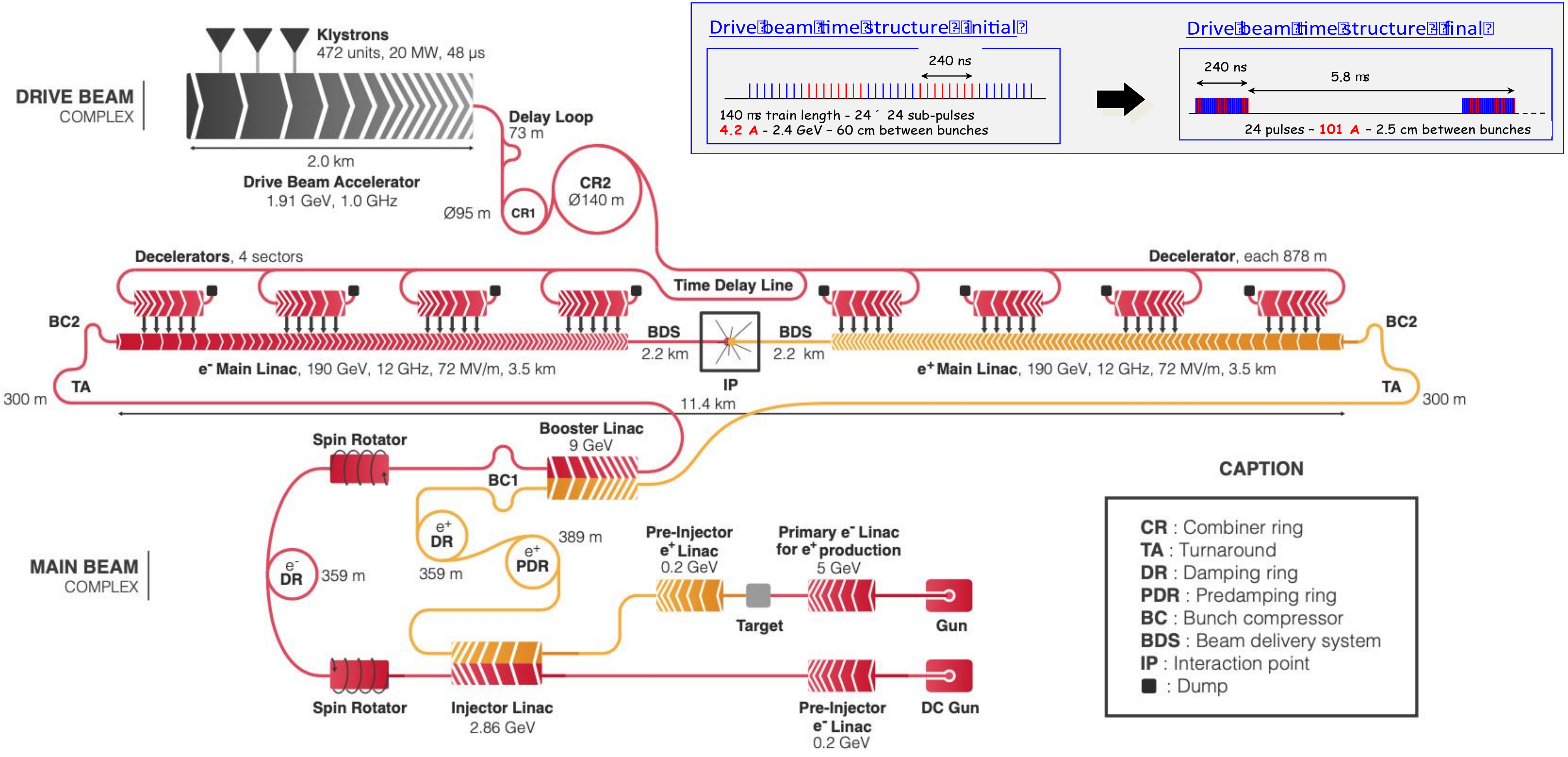




→ no issues from previous surveys

→ requiring : additional surveys around access tunnel head and access tunnel inside for detailed designing

CLIC 380GeV Layout



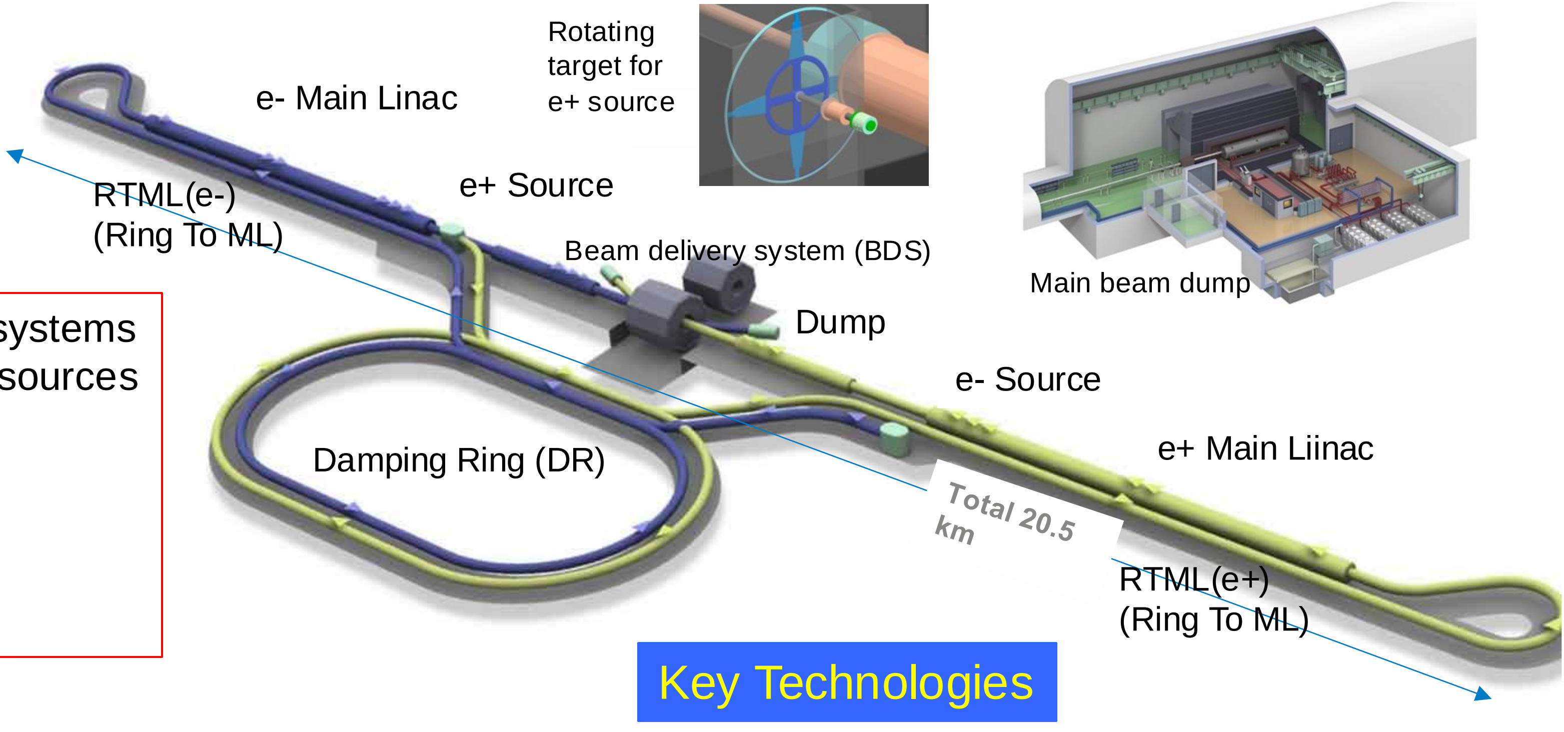
CAPTION

- **CR** : Combiner ring
- **TA** : Turnaround
- **DR** : Damping ring
- **PDR** : Predamping ring
- **BC** : Bunch compressor
- **BDS** : Beam delivery system
- **IP** : Interaction point
- ■ : Dump

Baseline electron polarisation ±80%

P. Burrows, EPS 2019, https://indico.cern.ch/event/577856/contributions/3420379/

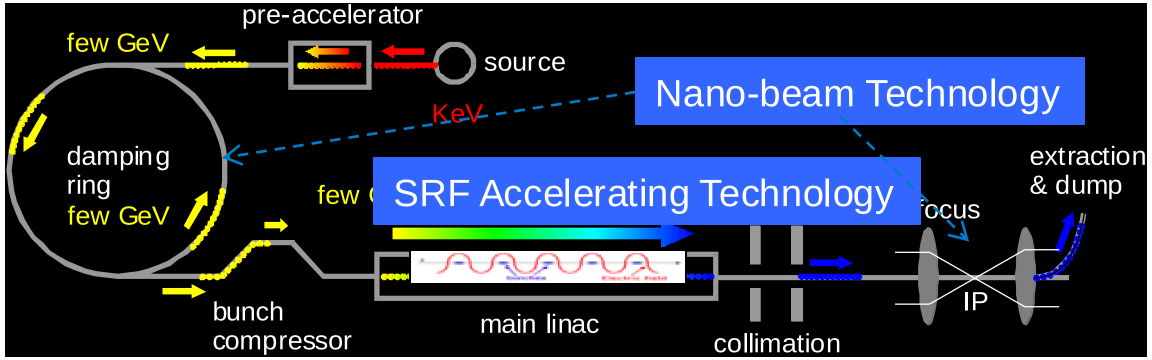
ILC250 accelerator facility



Area systems
e-/e+ sources
DR
RTML
ML
BDS
Dump

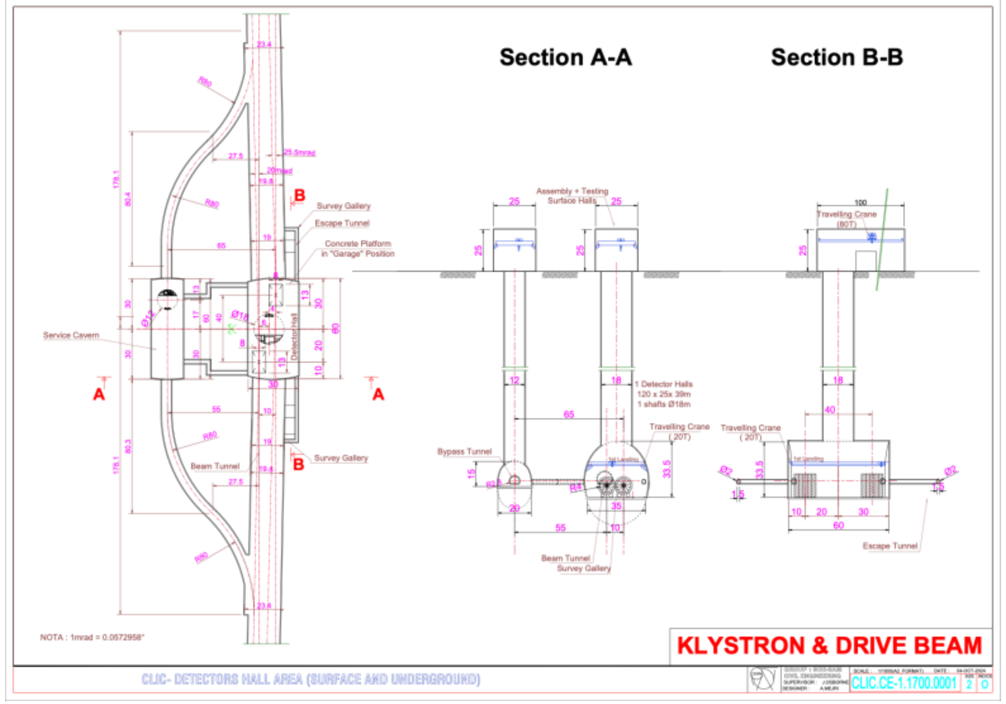
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 $\times 10^{34}$ $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) $Q_0 = 1 \times 10^{10}$

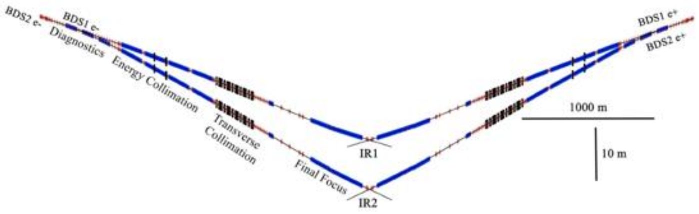
Key Technologies



8,000 SRF cavities will be used.

The CLIC ESPP update – II





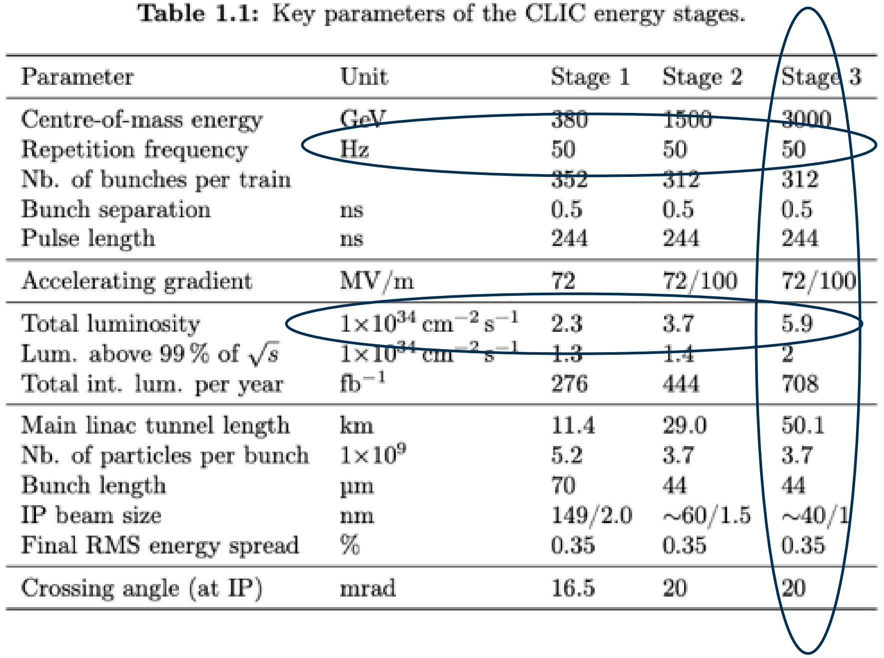
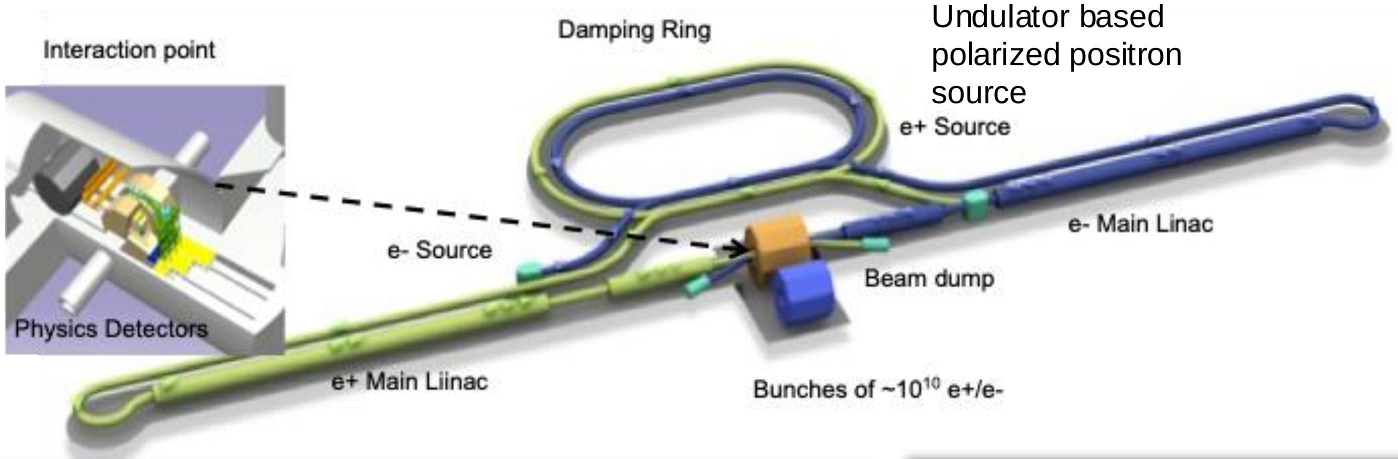


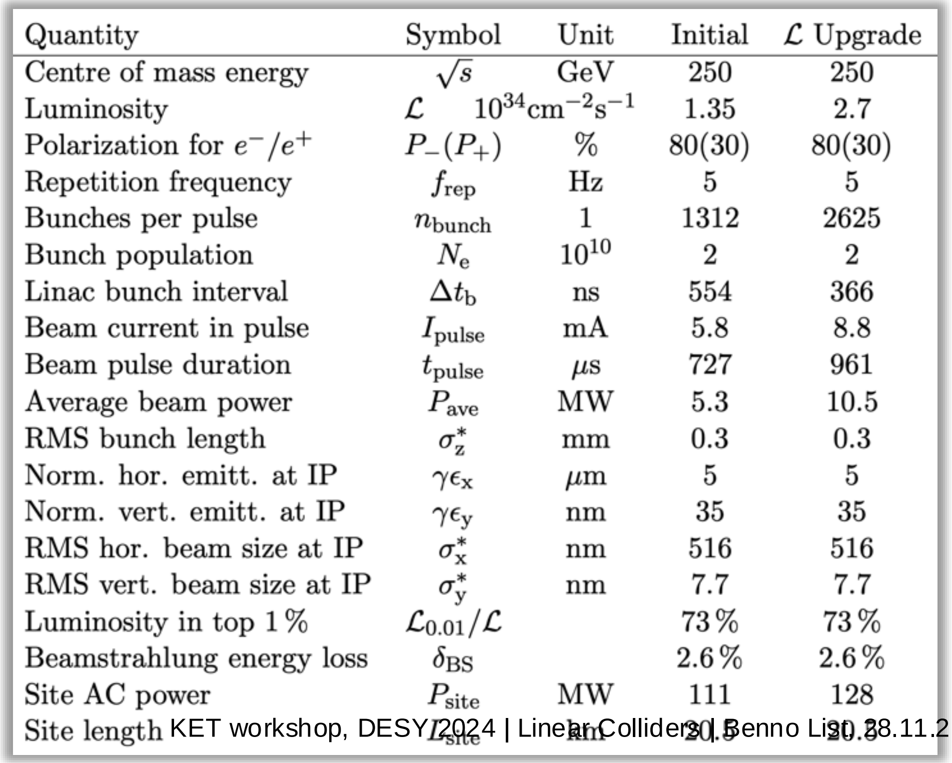
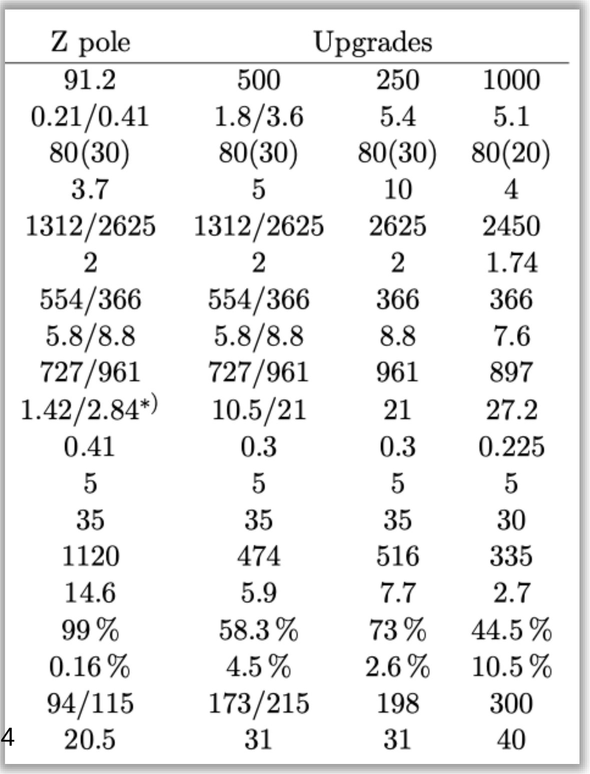
Table 1.1: Key parameters of the CLIC energy stages.

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

The ILC250 accelerator facility



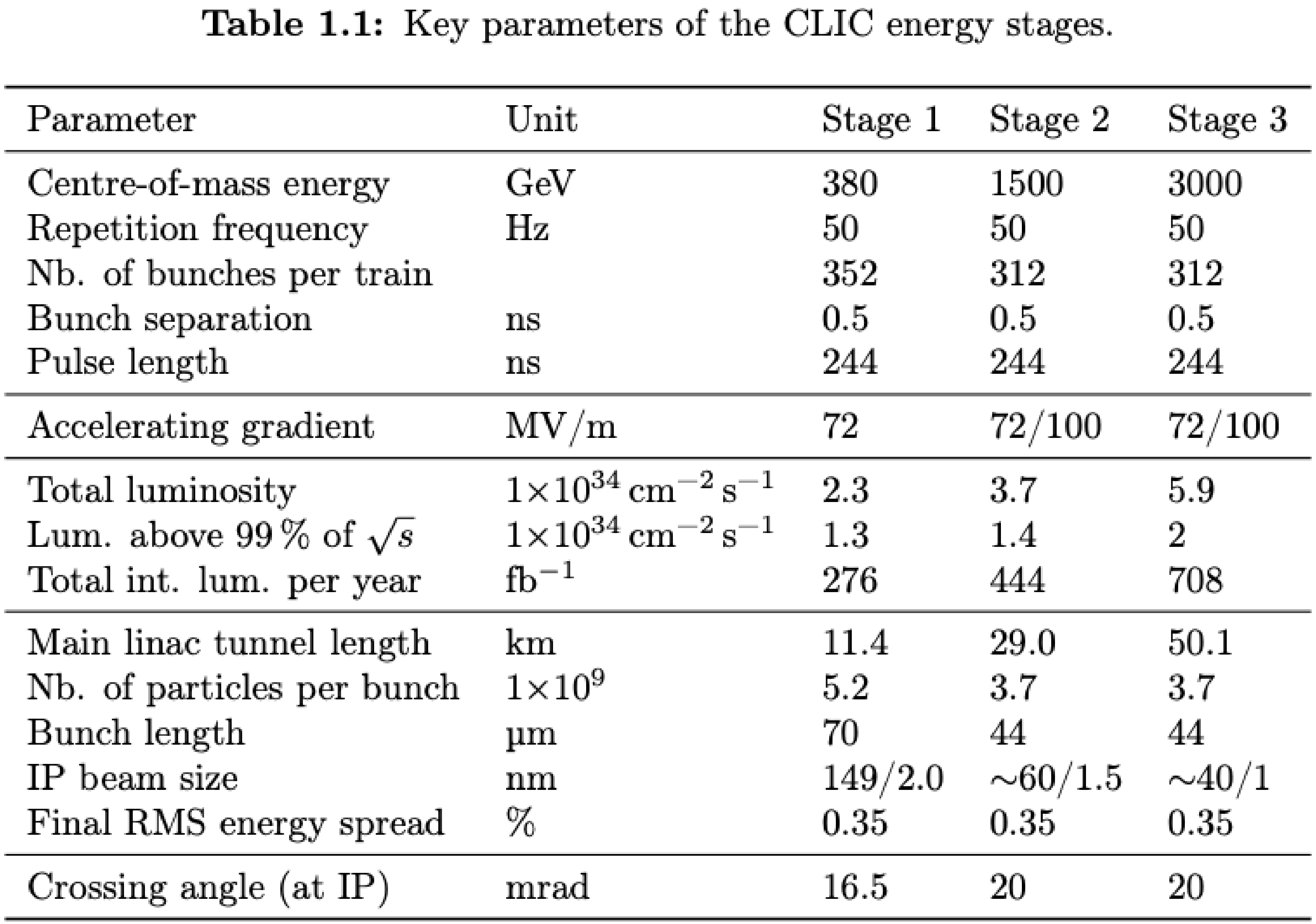
Undulator based polarized positron source

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_rep	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_bunch	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_pulse	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_pulse	µs	727	961	727/961	727/961	961	897
Average beam power	P_ave	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ^*_z	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_\mathrm{x}$	µm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_\mathrm{y}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_x	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_y	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_BS		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_site	MW	111	128	94/115	173/215	198	300
Site length	L_site	km	20.5	20.5	20.5	31	31	40

Parameters and plans for luminosity and energy upgrades are available, including information about relevant SCRF R&D for such upgrades at (Snowmass input)

CLIC parameters (Snowmass)



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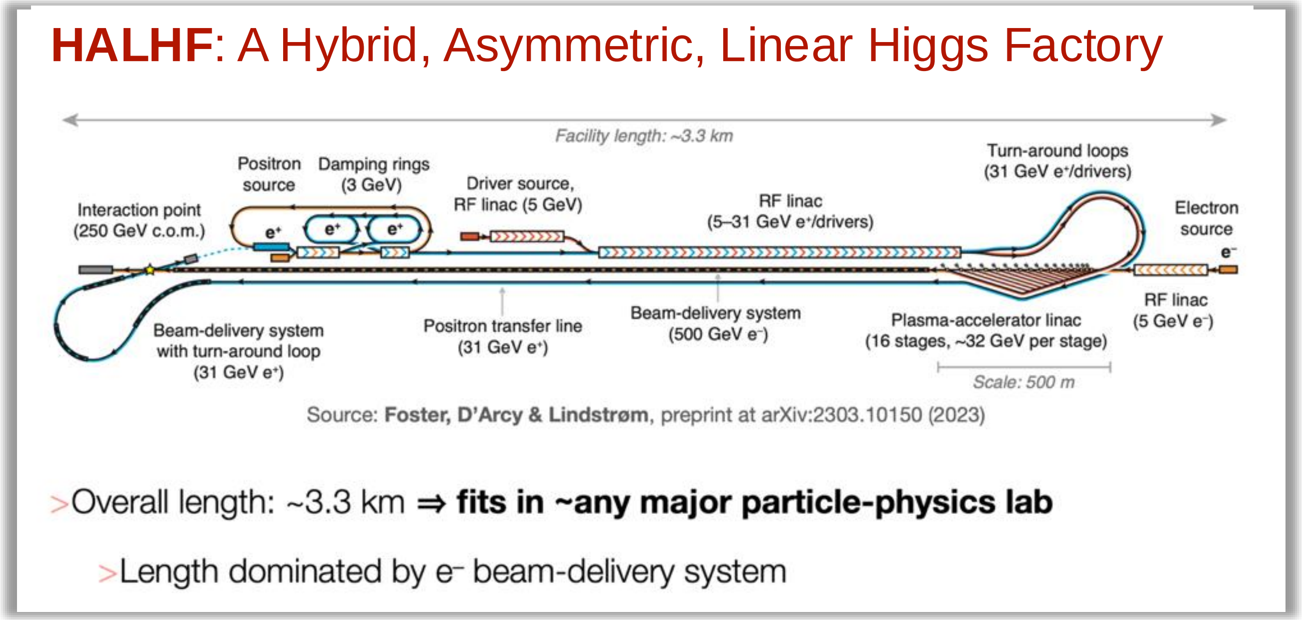


HALHF: A Hybrid, Asymmetric, Linear Higgs Factory

Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

>Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**

>Length dominated by e− beam-delivery system

New concept, aiming for pre-CDR (LINK)

- 500 GeV for electrons with plasma acceleration
- 31 GeV positrons with RF based linac, used also to provide electron drivebeam for the plasma acceleration
- Reach 250 GeV collision energy, luminosity 10^{34}

Asymmetric technologies, energies and bunch charges

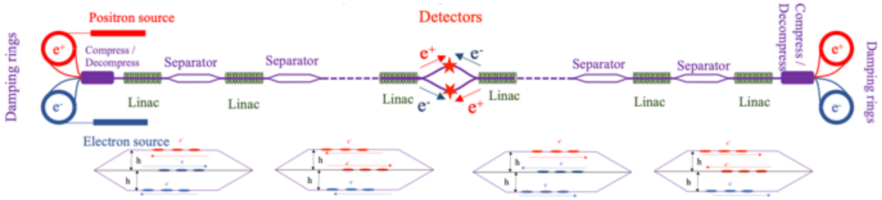
Small footprint, lower cost

Several key plasma acc. challenges:
Multi-staging, emittances, energy spread, stabilities, spin polarisation preservation, efficiencies, rep rate, plasma cell cooling and more

Conventional beam(s) challenges:
Positron production, damping rings, RF linac, beam delivery system

Experimental challenges with asymmetric beams

Energy recovery options, potentially very large luminosities but early stage of development



Twin LC with energy recovery

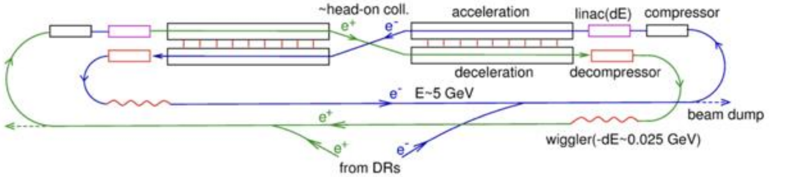
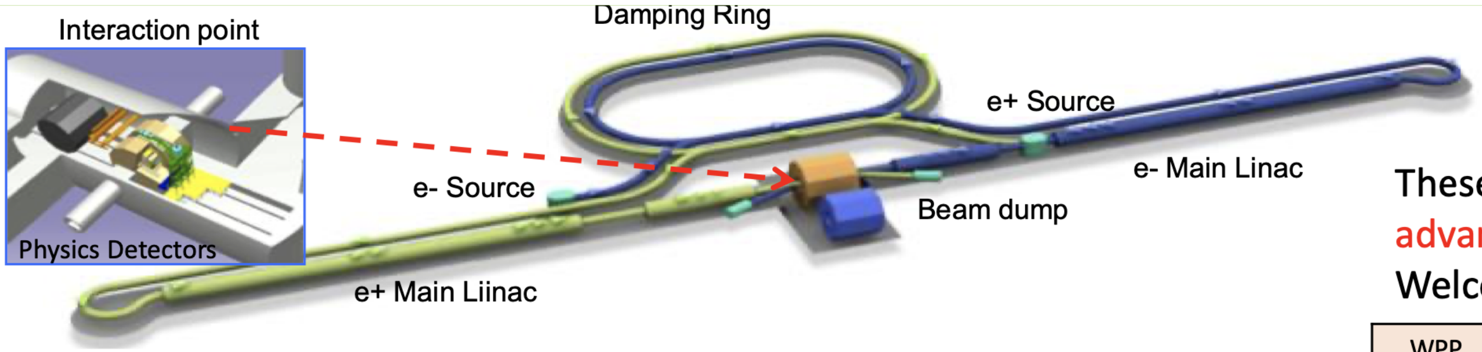
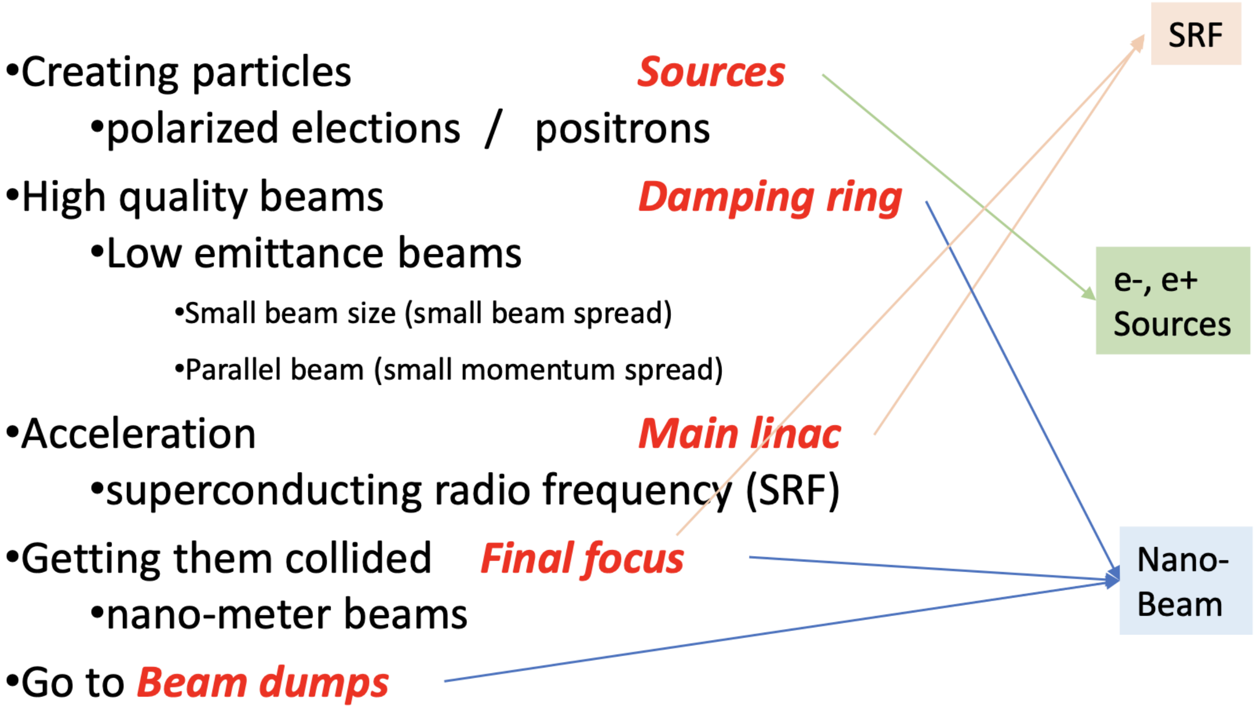


Figure 3-10. *Conceptual layout of the ERLC.*

The updated Priority Work Packages (WP')



These WPs can be applied to various **advanced accelerators**.
Welcome to join!



- Creating particles ***Sources***
  - polarized elections / positrons
- High quality beams ***Damping ring***
  - Low emittance beams
    - Small beam size (small beam spread)
    - Parallel beam (small momentum spread)
- Acceleration ***Main linac***
  - superconducting radio frequency (SRF)
- Getting them collided ***Final focus***
  - nano-meter beams
- Go to ***Beam dumps***

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

S. Michizono, LCWS 20223

Some recent ILC developments - I

ICFA

ILC International Development Team

Executive Board

Americas Liaison Andrew Lankford (UC Irvine)
Working Group 2 Chair Shinichiro Michizono (KEK)
Working Group 3 Chair Jenny List (DESY)
Executive Board Chair and Working Group 1 Chair Tatsuya Nakada (EPFL)
KEK Liaison Yasuhiro Okada (KEK)
Europe Liaison Steinar Stapnes (CERN)
Asia-Pacific Liaison Geoffrey Taylor (U. Melbourne)

Working Group 1
Pre-Lab Setup

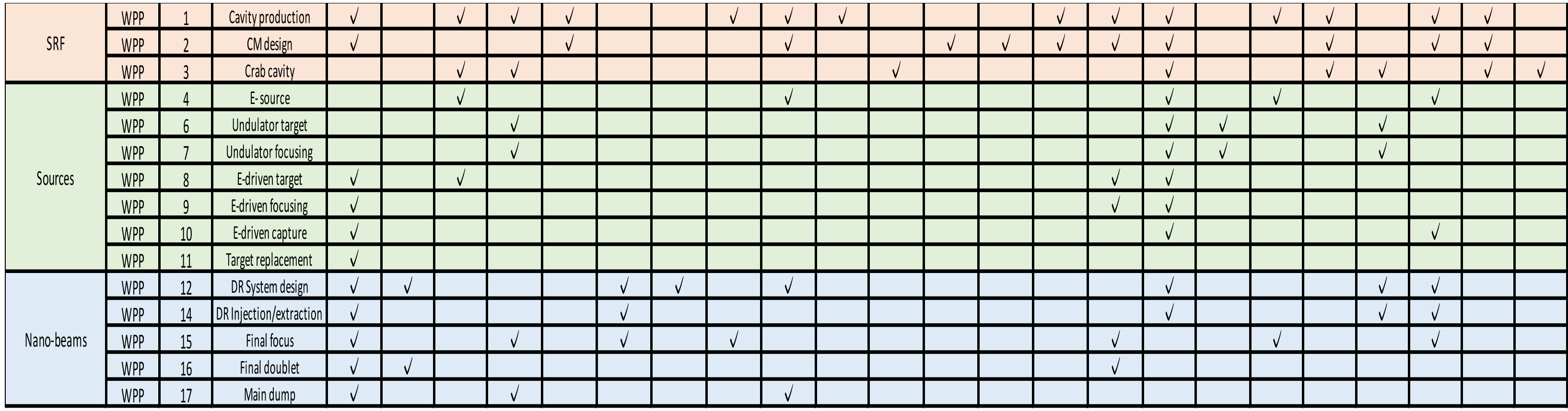
Working Group 2
Accelerator

Working Group 3
Physics & Detectors

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

Topics

2023/11/16



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	√			√		√		√							√			√			√		
	WPP	16	Final doublet	√	√													√								
	WPP	17	Main dump	√			√					√														

Above: ILC Technology Network (ITN), interest/capability matrix from 28 labs/universities

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

European ITN studies are distributed over five main activity areas:

ML related tasks

- SRF and ML elements: Cavities and Cryo Module, Crab-cavities, ML quads and cold BPMs (INFN, CEA, DESY, CERN, IJCLAB, UK, CIEMAT, IFIC)

Sources

- Pulsed magnet and wheel/target (Uni.H, DESY, CERN)

Damping Ring including kickers

- Low Emittance Rings (UK)

ATF activities, final focus and nanobeams

- ATS and MDI (UK, DESY, IJCLAB, CERN, IFIC)

Implementation

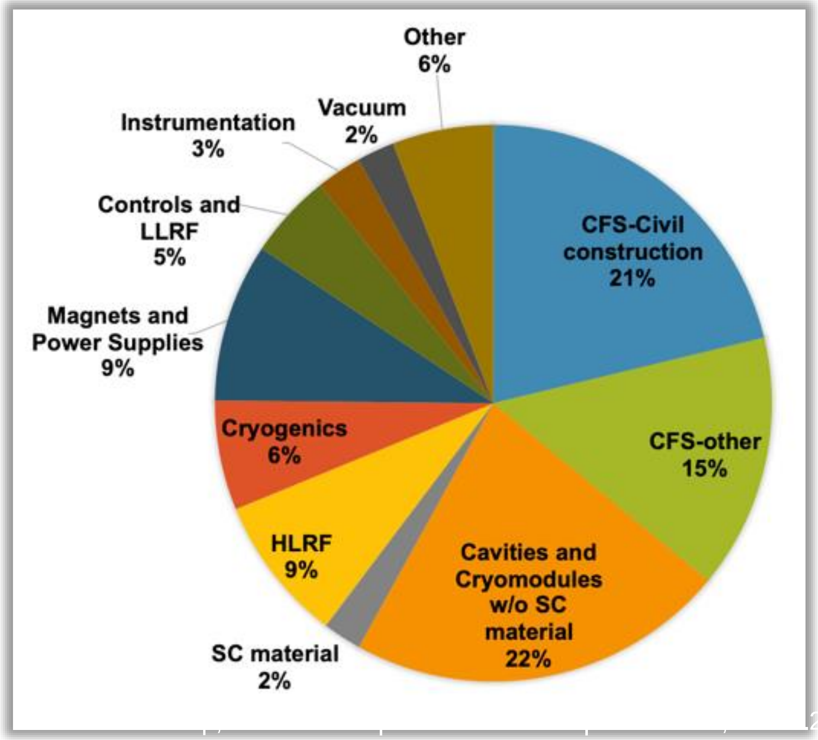
- Dump, CE, Cryo – follow up efforts at CERN
- Sustainability, Life Cycle Assessment (CERN, DESY, CEA, UK groups)
- EAJADE started (EU funding) (DESY, UK, CEA, CNRS, IFIC, INFN, UHH, CERN)

Costs

Cost exercises and international reviews:

- ILC TDR 2012-13, 500 GeV primarily (LINK)
- CLIC CDR 2012-13, 3 TeV primarily and 500 GeV (LINK)
- ILC in Japan 2017-18, 250 GeV, reviewed within LCC (LINK)
- CLIC PiP 2018, 380 GeV primarily (LINK)

Updates and reviews underway (e.g. scheduled in December for ILC costs)



For the ESPP – concerning starting with ILC at CERN:

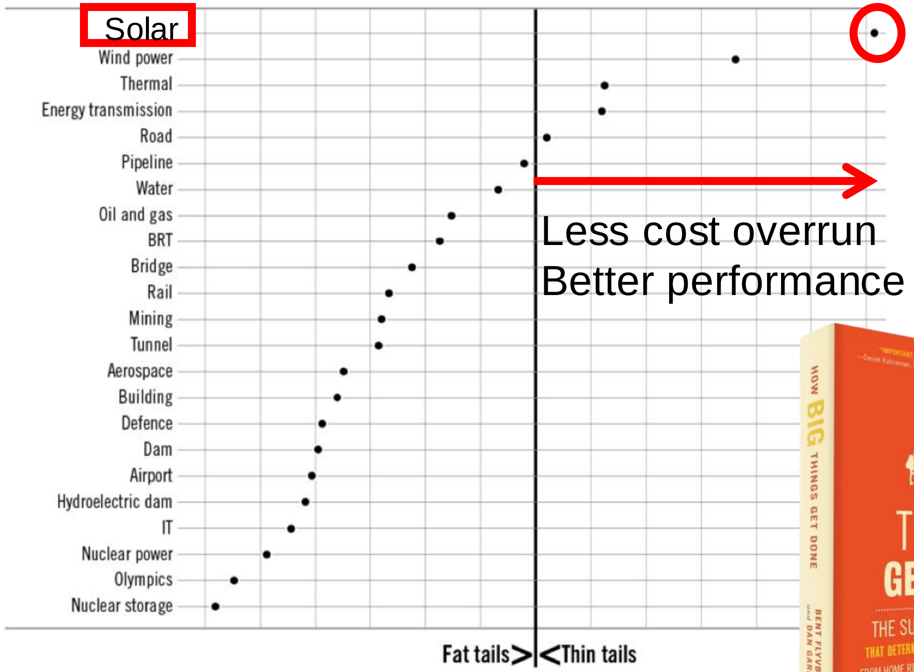
- Updated: ILC in Japan with updated technology results, updated CFS (CE and conv. systems, SCRF) – discussed on slide 10
- CERN implementation: CE costs based on CLIC and other CERN projects, same main linac footprint, change in number of shafts, add larger underground DR, remove drivebeam CE and turn arounds, slightly different BDS dimensions and cavern sizes

Modularity as success concept

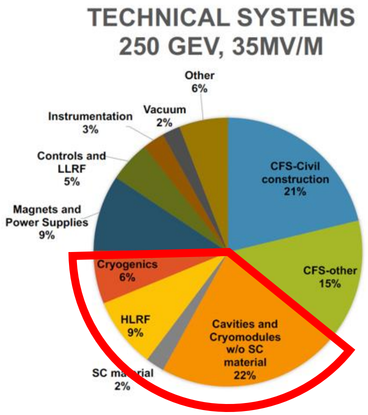
- Study by B. Flyvbjerg and D. Gardner identifies modularity as key factor to success of mega projects
  - **“What is your lego?”**
  - Evidence: Most successful mega project type are solar power plants owing to inherent modularity
- Cryomodules are the central building block of a superconducting accelerator, large fraction of value
  - Get them right, get the project right

> *“Get a small thing, a basic building block. Combine it with another and another until you have what you need. … Modularity delivers faster, cheaper and better … for building at a truly huge scale … modularity is not just valuable, it’s indispensable.”*
>
> Flyvbjerg, Gardner “How big things get done”

Study: performance of 16000 mega projects according to project type



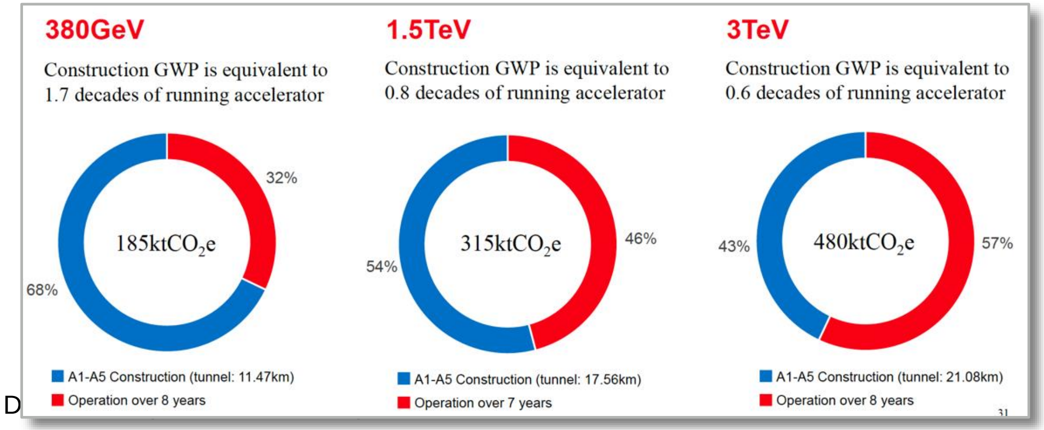
Less cost overrun
Better performance



Flyvbjer, Gardner: How big things get done.
https://sites.prh.com/how-big-things-get-done-book

Operation

- Operation stage very important:
  Large CO2 emissions from electricity production
- Impact assessment depends on assumptions of future (reduction of) carbon inten of electricity → assumptions still under debate
- 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):
  Total energy is sufficient, **fluctuations** require grid as buffer
  → **modulate operation (demand side flexibility) -> strength of linear accelerators**
  → rapidly falling battery prices change the field,
  GWh size storage will be affordable in 2030s



380GeV

Construction GWP is equivalent to 1.7 decades of running accelerator

1.5TeV

Construction GWP is equivalent to 0.8 decades of running accelerator

3TeV

Construction GWP is equivalent to 0.6 decades of running accelerator

S. Evans, LCWS 2024

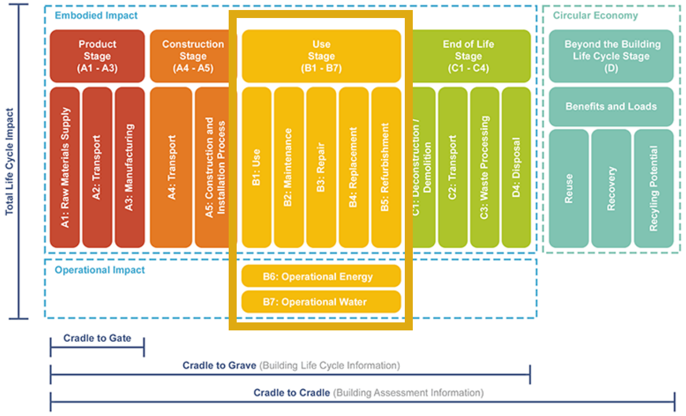
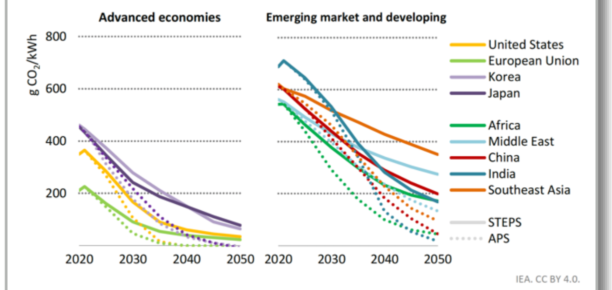


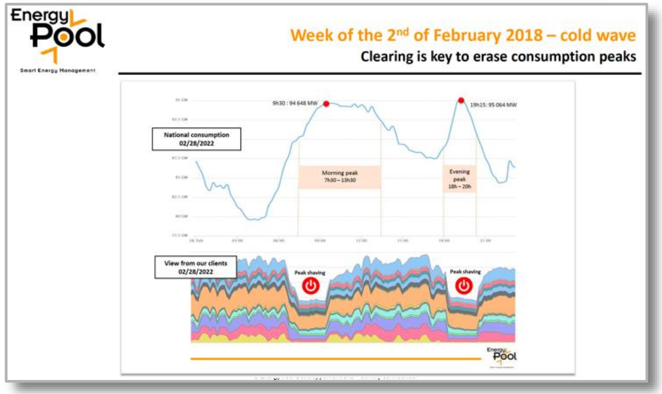
Figure 6.14 ▷ Average CO$_2$ intensity of electricity generation for selected regions by scenario, 2020-2050



IEA. CC BY 4.0.

CO$_2$ intensity of electricity generation varies widely today, but all regions see a decline in future years and many have declared net zero emissions ambitions by around 2050

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



Week of the 2nd of February 2018 – cold wave

Clearing is key to erase consumption peaks

C. Gaunand, B. Remenyi: ESSRI 2022