Accelerator Landscape

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Outline

- Introduction + context
- e+e- colliders
- Hadron and electron-hadron colliders
- Muon collider
- Observations

HL-LHC

I assume it is given that HL-LHC remains the highest-priority collider project

The current CERN schedule foresees HL-LHC operations starting in 2030 and running thru 2041

Hence I will not say any more about it!

Collider inputs

- **Linear Colliders: ILC, CLIC, C^3, HALHF** (Aidan Robson)
- **FCCee** (Guy Wilkinson)
- **FCChh** (Andy Pilkington)
- **FCCeh** (Monica D'Onofrio, Uta Klein, Paul Newman, Claire Gwenlan)
- **LHeC** (Paul Newman)
- **Muon Collider** (Chris Rogers, Karol Krizka)

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Collider options (2020)

John Adams Institute for Accelerator Science

Collider	Type	$\sqrt{s}$	$\mathcal{P}$ [%] $[e^-/e^+]$	N_{Det}	$\mathcal{L}_{\mathrm{inst}}$/Det. $[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	$\mathcal{L}$ $[\mathrm{ab}^{-1}]$	Time [years]	Ref.
HL-LHC	pp	14 TeV	–	2	5	6.0	12	[23]
HE-LHC	pp	27 TeV	–	2	16	15.0	20	[23]
FCC-hh	pp	100 TeV	–	2	30	30.0	25	[637]
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[637]
		$2M_W$	0/0	2	25	10	1-2	
		240 GeV	0/0	2	7	5	3	
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5	
		(1y SD before $2m_{top}$ run)					(+1)	
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[342]
		350 GeV	±80/±30	1	1.6	0.2	1	[346]
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5	
		(1y SD after 250 GeV run)					(+1)	
CEPC	ee	M_Z	0/0	2	17/32	16	2	[509]
		$2M_W$	0/0	2	10	2.6	1	
		240 GeV	0/0	2	3	5.6	7	
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[638]
		1.5 TeV	±80/0	1	3.7	2.5	7	
		3.0 TeV	±80/0	1	6.0	5.0	8	
		(2y SDs between energy stages)					(+4)	
LHeC	ep	1.3 TeV	–	1	0.8	1.0	15	[636]
HE-LHeC	ep	1.8 TeV	–	1	1.5	2.0	20	[637]
FCC-eh	ep	3.5 TeV	–	1	1.5	2.0	25	[637]

EPPSU 2020 Briefing Book
https://arxiv.org/abs/1910.11775

Collider options (2020)

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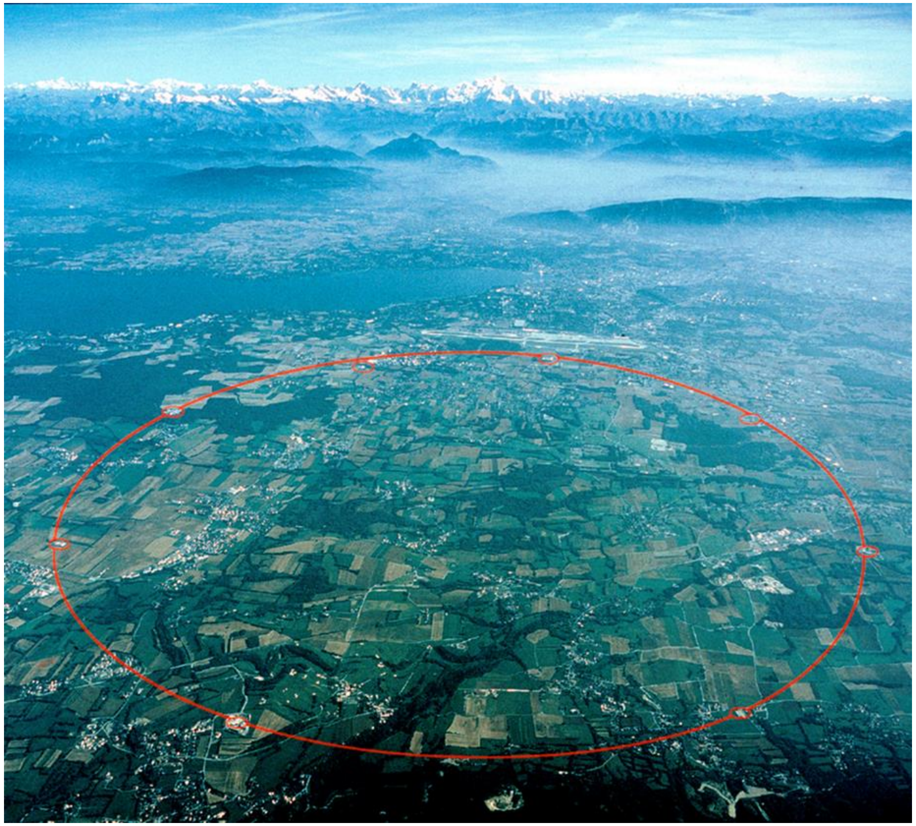
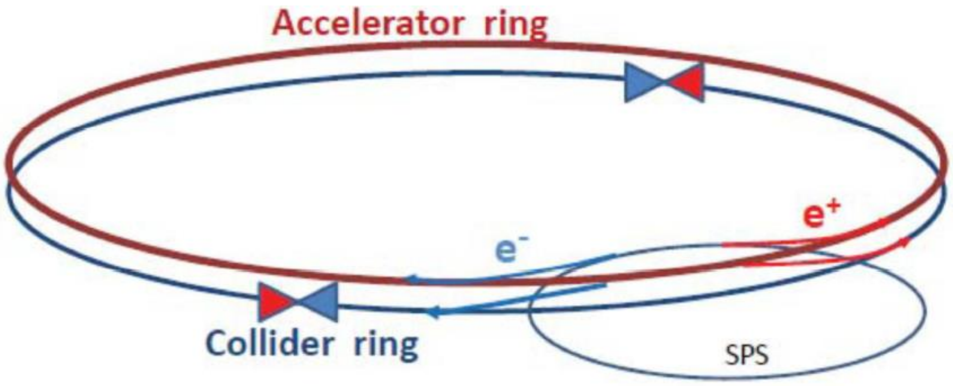
LEP3?





240 GeV: 10^34 luminosity for 100MW of synchrotron radiation

https://www.researchgate.net/publication/230610106_LEP3_A_High_Luminosity_ee-_Collider_to_study_the_Higgs_Boson

Collider options (2020)

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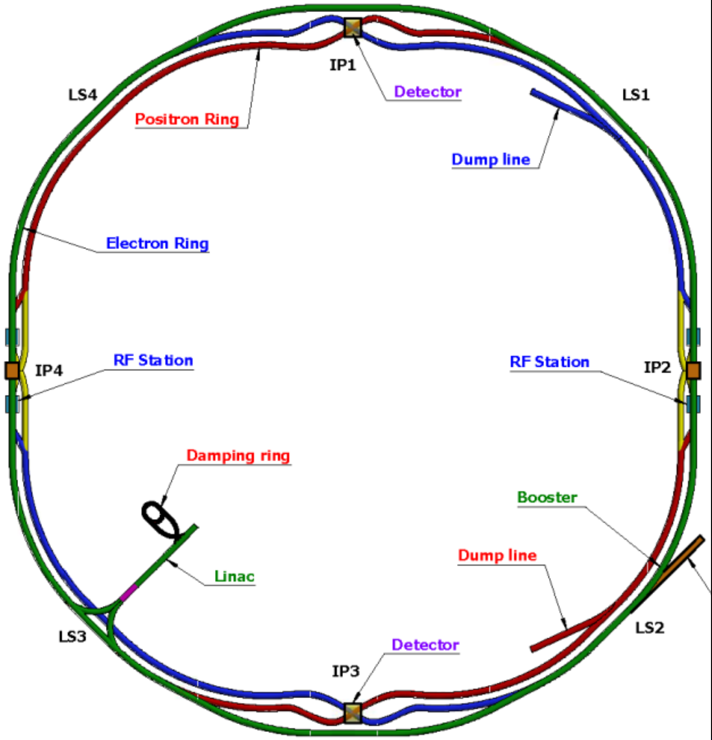
CEPC



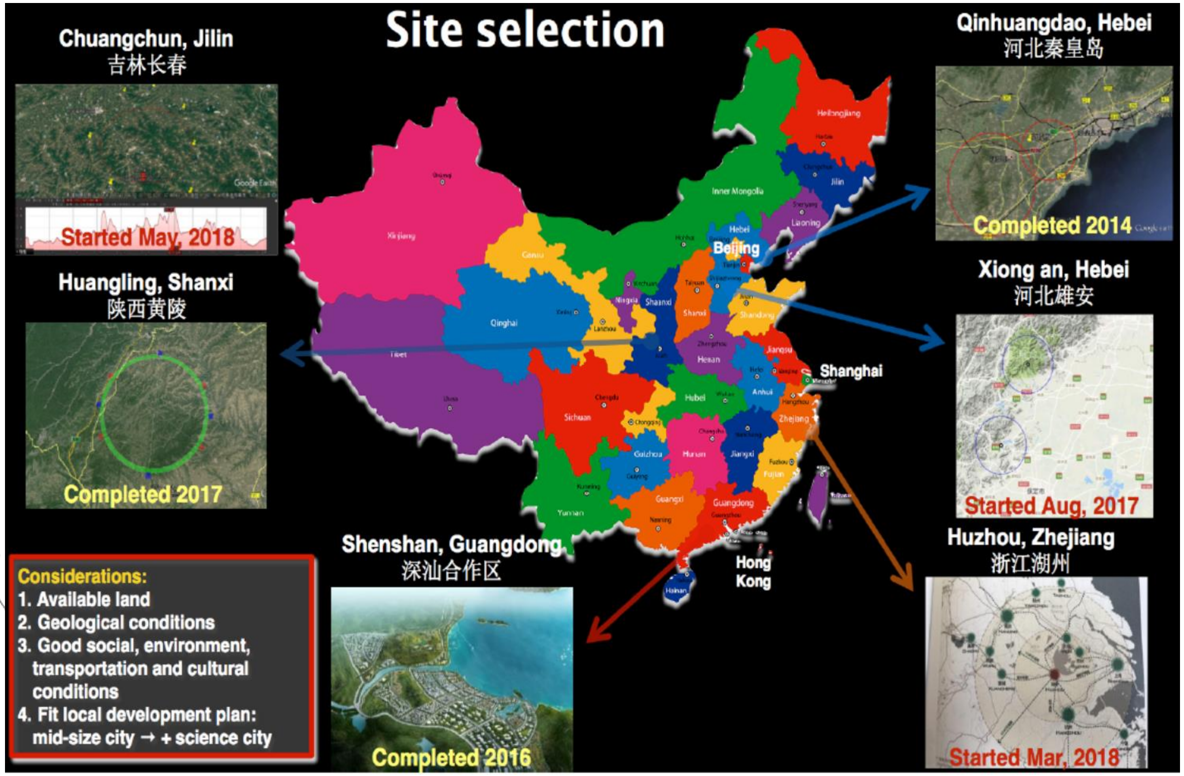


Table 3.2: CEPC operation plan (@ 50 MW)

Particle	$E_{c.m.}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H	240	8.3	2.2	10	21.6	4.3×10^6
Z	91	192*	50	2	100	4.1×10^{12}
W	160	26.7	6.9	1	6.9	2.1×10^8
$t\bar{t}$**	360	0.8	0.2	5	1.0	0.6×10^6

TDR completed (Dec 2023)
Awaiting decision on inclusion in next 5-year plan 2026-2030
Could be operational mid 2030s

Key parameters requested

- Environmental cost of construction (in units of tonnes of CO2 equivalent)
- Environmental cost of operation per year (in units of tonnes of CO2 equivalent)
- Estimate of financial costs (provide separate numbers for R+D phase, construction phase and operations phase)

For each energy stage:

- centre-of-mass energy
- integrated luminosity
- number of interaction points
- time running at stage
- wall power
- accelerator length
- estimated year for first collisions
- future upgrade paths

Disclaimer

The compilation that follows is based on the input provided - any errors in reporting or interpretation are mine!

Number of IPs

Linear colliders:

- **Current baseline is 1 IP: 2 detectors are still possible in 'push-pull' mode**
- **2 IPs also possible @ cost of extra beam delivery system: being studied for ILC/CLIC**
- **Luminosity would be shared between 2 detectors**

Circular colliders:

- **2 or 4 IPs possible for circular machines (FCC baseline now 4)**

e-p colliders:

- **1 IP**

Muon collider

- **2 IPs**

Linear e+e- colliders

	ILC 250	ILC 350	ILC 500	CLIC 380	CLIC 1.5 TeV	CLIC 3 TeV	C^3 250	C^3 550	HALHF 250
Site	Japan			CERN			FNAL		CERN?
Time till start (yrs)	>5+9	+ >11	+ >1	>5+8	+ >8	+ >7	4+4?	?	10+5?
Run time (yrs)	11	1	9	8	7	8	?	?	?
Lumi (ab-1)	2	0.2	4	1.5	2.5	5	2	4	?
Length (km)	20.5	31	31	11	29	50	8	8	3.3
CO2 civil construction (ktonCO2eq)	266	?	?	127	169	205	146	146	49
CO2 accelerator (ktonCO2eq)	?	?	?	?	?	?	?	?	?
Wall power (MW)	111/138	?	173/215	110	?	*550*	150	175	80
Lifetime CO2 operations (ktonCO2eq)	?	?	?	59	145	*274*	?	?	?
Cost: construction	635-703 GY (2017) Incl labour	?	6.7B$ (2010) + 13ky labour	5.9BChF (2018) + 11ky labour	+5.1BChF (2018) + labour	+7.3BChF (2018) + labour	4B$ (2021) + labour	?	1.9B$ (2023) + labour
Cost: operations/yr	37-39 GY (2017)	?	?	116MChF (2018) + 640y	?	?	?	?	?

Linear e+e- colliders

	ILC 250	ILC 350	ILC 500	CLIC 380	CLIC 1.5 TeV	CLIC 3 TeV	C^3 250	C^3 550	HALHF 250
Site	Japan			CERN			FNAL		CERN?
Time till start (yrs)	>5+9	+ >11	+ >1	>5+8	+ >8	+ >7	4+4?	?	10+5?
Run time (yrs)	11	1	9	8	7	8	?	?	?
Lumi (ab-1)	2	0.2	4	1.5	2.5	5	2	4	?
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CO2 accelerator (ktonCO2eq)	?	?	?	?	?	?	?	?	?
Wall power (MW)	111/138	?	173/215	110	?	*550*	150	175	80
Lifetime CO2 operations (ktonCO2eq)	?	?	?	59	145	*274*	?	?	?
Cost: construction	635-703 GY (2017) Incl labour	?	6.7B$ (2010) + 13ky labour	5.9BChF (2018) + 11ky labour	+5.1BChF (2018) + labour	+7.3BChF (2018) + labour	4B$ (2021) + labour	?	1.9B$ (2023) + labour
Cost: operations/yr	37-39 GY (2017)	?	?	116MChF (2018) + 640y	?	?	?	?	?

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Run time (yrs)	11	1	9	8	7	8	?	?	?
Lumi (ab-1)	2	0.2	4	1.5	2.5	5	2	4	?
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CO2 accelerator (ktonCO2eq)	?	?	?	?	?	?	?	?	?
Wall power (MW)	111/138	?	173/215	110	?	*550*	150	175	80
Lifetime CO2 operations (ktonCO2eq)	?	?	?	59	145	*274*	?	?	?
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Cost: operations/yr	37-39 GY (2017)	?	?	116MChF (2018) + 640y	?	?	?	?	?

Linear e+e- colliders

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Time till start (yrs)	>5+9	+ >11	+ >1	>5+8	+ >8	+ >7	4+4?	?	10+5?
Run time (yrs)	11	1	9	8	7	8	?	?	?
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Cost: operations/yr	37-39 GY (2017)	?	?	116MChF (2018) + 640y	?	?	?	?	?

Observations

Luminosity range:	1 (250 GeV) → 6 (3 TeV) x 10**34	
Cost:		
ILC250	~ 6-7B$	(2017) incl. labour
ILC500	~ 8B$	(2010) incl. labour
CLIC380	~ 5.9BChF	(2018) core
C^3 250	~4B$	(2021) capital
HALHF250	~2B$	(2023) capital
Wall-plug power range:	80 → 215 MW for energies up to 550 GeV	
Civil construction:	49 → 266 kton CO2-eq	

Other remarks

ILC: Also looking at 550 GeV (modest scaling from 500 GeV design)
Costs being updated by international expert panel → early 2025
Design + costs for CERN site in progress

CLIC: Power savings implemented for 380 GeV to be done for 1.5 TeV and 3 TeV
Design/costs for 250 GeV expected

C^3: Borrows from ILC + CLIC for everything except linac
Linac test facility proposed to validate the 'cool Cu' linac concept

HALHF: Requires investment in R&D to validate concept
Parameter sets + costs for 380 GeV and 550 GeV as well as 250 GeV

All could be run at lower energies (Z, WW …) with lower luminosity: GigaZ sample @ 91 GeV
Polarised electrons baseline; polarised positrons also (ILC baseline)

FCCee

	FCCee:	Z 91+-3	WW 160+-2.5	ZH 240	tt 340-360	FCChh	FCCeh	LHeC
Site	CERN							CERN
Start date	2048					2074/2054	>2054	late 2030s
Run time (yrs)	15 total	4	2	3	5	~25	ditto	few years
Lumi (ab-1)		205	19	11	3.1	30	1-2	< 1
Length (km)	91						+6	5.4
CO2 civil construction (ktonCO2eq)	1170					1170 +?	+?	?
CO2 accelerator (ktonCO2eq)	?	?	?	?	?	?	?	?
Wall power (MW)	222-357					550-580	+100	100
Lifetime CO2 operations (ktonCO2eq)	?	?	?	?	?	?	?	?
Cost: construction	15BChF core (2023) +30% -20%					+17BChF core (2018)/ 24BChF (no FCCee)	+?	1.4BChF core (2018)
Cost: operations/yr		?	?	?	?	180MChF electricity (2015)	?	?

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FCChh

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	FCCee:	Z 91+-3	WW 160+-2.5	ZH 240	tt 340-360	FCChh	FCCeh	LHeC
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CO2 accelerator (ktonCO2eq)	?	?	?	?	?	?	?	?
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Cost: construction	15BChF core (2023) +30% -20%					+17BChF core (2018)/ 24BChF (no FCCee)	+?	1.4BChF core (2018)
Cost: operations/yr		?	?	?	?	180MChF electricity (2015)	?	?

FCCeh + LHeC

	FCCee:	Z 91+-3	WW 160+-2.5	ZH 240	tt 340-360	FCChh	FCCeh	LHeC
Site	CERN							CERN
Start date	2048					2074/2054	>2054	late 2030s
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Cost: construction	15BChF core (2023) +30% -20%					+17BChF core (2018)/ 24BChF (no FCCee)	+?	1.4BChF core (2018)
Cost: operations/yr		?	?	?	?	180MChF electricity (2015)	?	?

Observations

Feasibility study report due end March 2025 → updated design + costs

Luminosity higher than LCs up to 240 GeV

FCCee:

15BChF core cost (2023) → 360 GeV, 4 IPs, CERN contribution to 2 detectors

FCChh:

+17BChF core cost (2018) from FCCee → FCChh

24BChF FCChh standalone

Luminosity vs c.m. energy

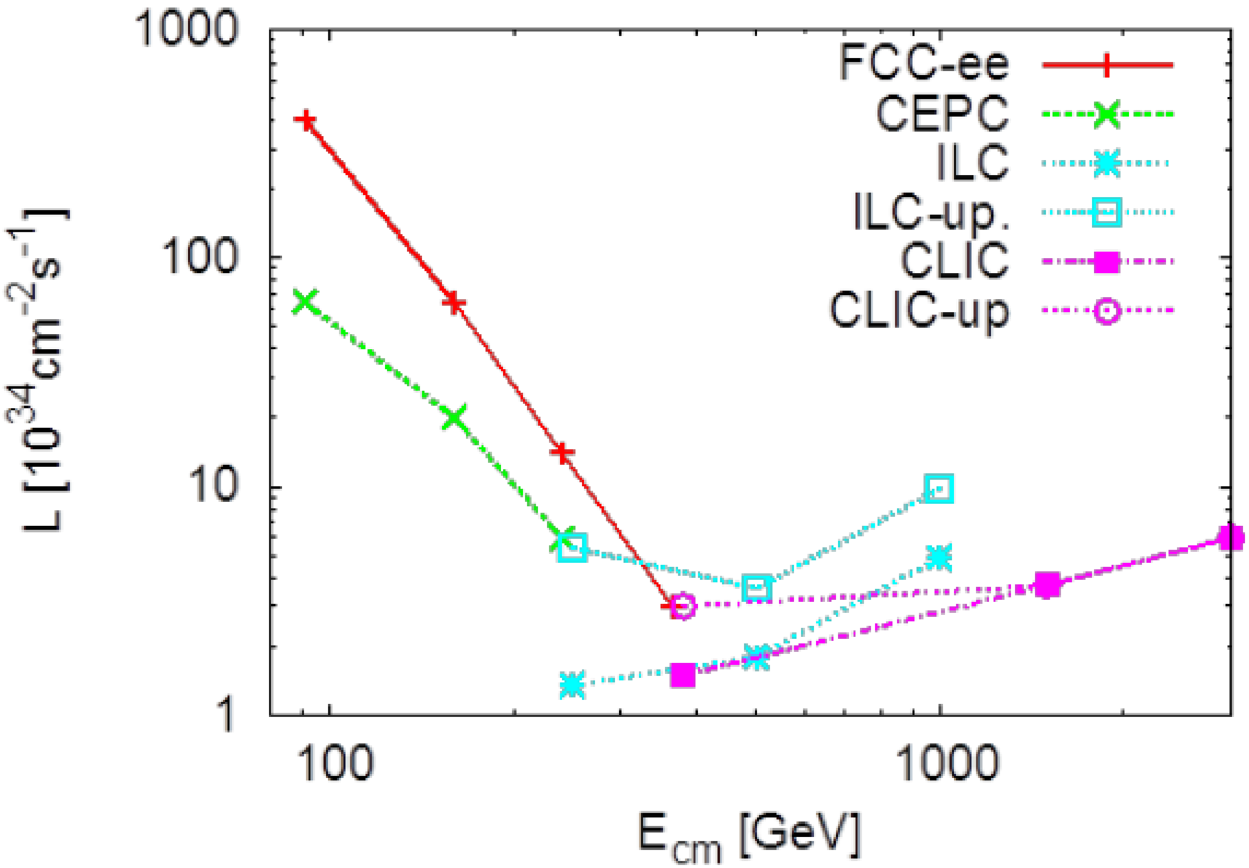

Fig. 10.2: Luminosity versus c.m. energy for e^+e^- Higgs Factories. Two IPs are assumed for the circular colliders FCC-ee and CEPC.

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Higgs/top factories

	ILC 250	C^3 250	HALHF 250	FCCee 240	FCCee 340-365	ILC 350	CLIC 380
Site	Japan	FNAL	CERN?	CERN	CERN	Japan	CERN
Time till start (yrs)	>5+9	4+4?	10+5?	24	33	>25	>5+8 <24
Run time (yrs)	11	?	?	3	5	1	8
Lumi (ab-1)	2	2	?	10.8	3.1	0.2	1.5
Length (km)	20.5	8	3.3	91	91	31	11
CO2 civil construction (ktonCO2eq)	266	146	49	1170	1170	?	127
CO2 accelerator (ktonCO2eq)	?	?	?	?	?	?	?
Wall power (MW)	111/138	150	80	~300	357	?	110
Lifetime CO2 operations (ktonCO2eq)	?	?	?	?	?	?	59
Cost: construction	635-703 GY (2017) Incl labour	4B$ (2021) + labour	1.9B$ (2023) + labour	13.5BChF (2023) + labour	15BChF (2023) + labour	?	5.9BChF (2018) + 11ky labour
Cost: operations/yr	37-39 GY (2017)	?	?	?	?	?	116MChF (2018) + 640y

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Higgs/top factories

	ILC 250	C^3 250	HALHF 250	FCCee 240	FCCee 340-365	ILC 350	CLIC 380
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Time till start (yrs)	>5+9	4+4?	10+5?	24	33	>25	>5+8 <24
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Lifetime CO2 operations (ktonCO2eq)	?	?	?	?	?	?	59
Cost: construction	635-703 GY (2017) Incl labour	4B$ (2021) + labour	1.9B$ (2023) + labour	13.5BChF (2023) + labour	15BChF (2023) + labour	?	5.9BChF (2018) + 11ky labour
Cost: operations/yr	37-39 GY (2017)	?	?	?	?	?	116MChF (2018) + 640y

Higgs/top factories

	ILC 250	C^3 250	HALHF 250	FCCee 240	FCCee 340-365	ILC 350	CLIC 380
Site	Japan	FNAL	CERN?	CERN	CERN	Japan	CERN
Time till start (yrs)	>5+9	4+4?	10+5?	24	33	>25	>5+8 <24
Run time (yrs)	11	?	?	3	5	1	8
Lumi (ab-1)	2	2	?	10.8	3.1	0.2	1.5
Length (km)	20.5	8	3.3	91	91	31	11
CO2 civil construction (ktonCO2eq)	266	146	49	1170	1170	?	127
CO2 accelerator (ktonCO2eq)	?	?	?	?	?	?	?
Wall power (MW)	111/138	150	80	~300	357	?	110
Lifetime CO2 operations (ktonCO2eq)	?	?	?	?	?	?	59
Cost: construction	635-703 GY (2017) Incl labour	4B$ (2021) + labour	1.9B$ (2023) + labour	13.5BChF (2023) + labour	15BChF (2023) + labour	?	5.9BChF (2018) + 11ky labour
Cost: operations/yr	37-39 GY (2017)	?	?	?	?	?	116MChF (2018) + 640y

‘Energy frontier’

	CLIC 3 TeV	Muon 3 TeV	Muon 10 TeV	FCChh 100 TeV
Site	CERN	CERN/ FNAL	CERN/ FNAL	CERN
Start date	>2052 <2063	2049?	>2049 <2056	>2054 <2074
Run time (yrs)	8	5	5	~25
Lumi (ab-1)	5	1	10	30
Length (km)	50	26.5	72	91
CO2 civil construction (ktonCO2eq)	205	?	?	1170 +?
CO2 accelerator (ktonCO2eq)	?	?	?	?
Wall power (MW)	*550*	?	?	550-580
Lifetime CO2 operations (ktonCO2eq)	*274*	?	?	?
Cost: construction	18.3BChF core (2018) + labour	?	?	32BChF core (2018)/ 24BChF (no FCCee) + labour
Cost: operations/yr	?	?	?	180MChF electricity (2015)

‘Energy frontier’

	CLIC 3 TeV	Muon 3 TeV	Muon 10 TeV	FCChh 100 TeV
Site	CERN	CERN/ FNAL	CERN/ FNAL	CERN
Start date	>2052 <2063	2049?	>2049 <2056	>2054 <2074
[illegible] (yrs)	[illegible]	[illegible]	[illegible]	[illegible]
Lumi (ab-1)	5	1	10	30
Length (km)	50	26.5	72	91
CO_2 civil construction (ktonCO_2eq)	205	?	?	1170 +?
CO_2 accelerator (ktonCO_2eq)	?	?	?	?
Wall power (MW)	*550*	?	?	550-580
Lifetime CO_2 operations (ktonCO_2eq)	*274*	?	?	?
Cost: construction	18.3BChF core (2018) + labour	?	?	32BChF core (2018)/ 24BChF (no FCCee) + labour
Cost: operations/yr	?	?	?	180MChF electricity (2015)

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Cost: operations/yr	?	?	?	180MChF electricity (2015)

'Energy frontier'

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CO_2 accelerator (ktonCO2eq)	?	?	?	?
Wall power (MW)	*550*	?	?	550-580
Lifetime CO_2 operations (ktonCO2eq)	*274*	?	?	?
Cost: construction	18.3BChF core (2018) + labour	?	?	32BChF core (2018)/ 24BChF (no FCCee) + labour
Cost: operations/yr	?	?	?	[illegible] electricity (2015)

General observations

Costs:

Some estimates are several years old, and in various cost bases

- **Materials costs have generally increased → higher construction costs**
- **Electricity cost has increased → higher operating costs**
- **Exchange rates have fluctuated (eg. $/Yen) → eg. benefits ILC in Japan**

Expect updates by March 2025

Sustainability:

- **Some projects have made estimates for CO2-eq for construction (+ operation)**
- **Needs to be evaluated with industry standards: materials vs. cost**
- **Operation costs need to be estimated using future power generation models**
- **CO2-eq for accelerator components needs to be evaluated**

Expect updates by March 2025

Thanks to many colleagues

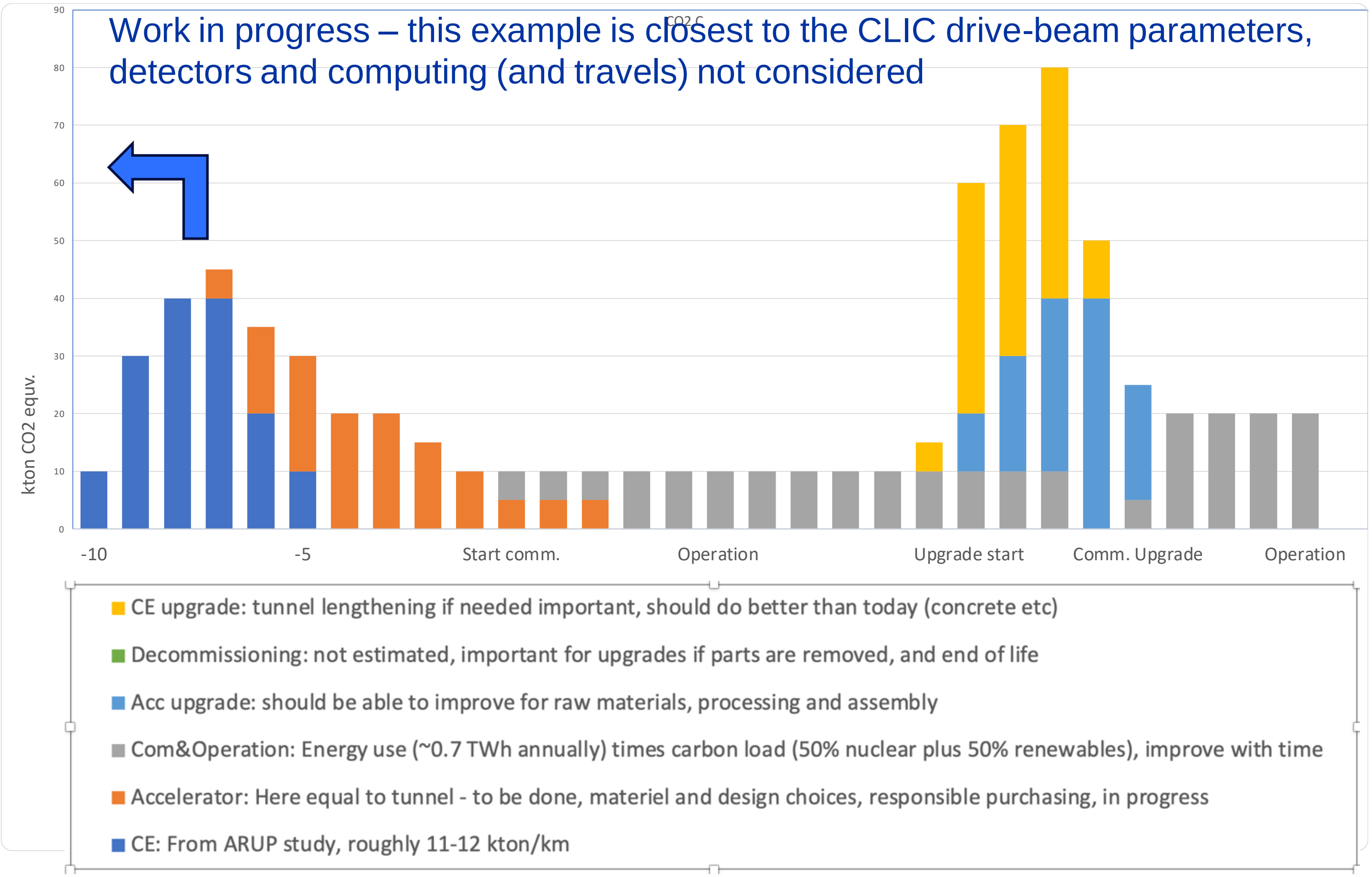
Extra material

Towards CLIC Carbon Accounting via Life Cycle Assessment

This plot (blue part) is for 11 km of tunnel, scales with length

Now working on machine parts (orange), here assumed hardware = civil engineering impact

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

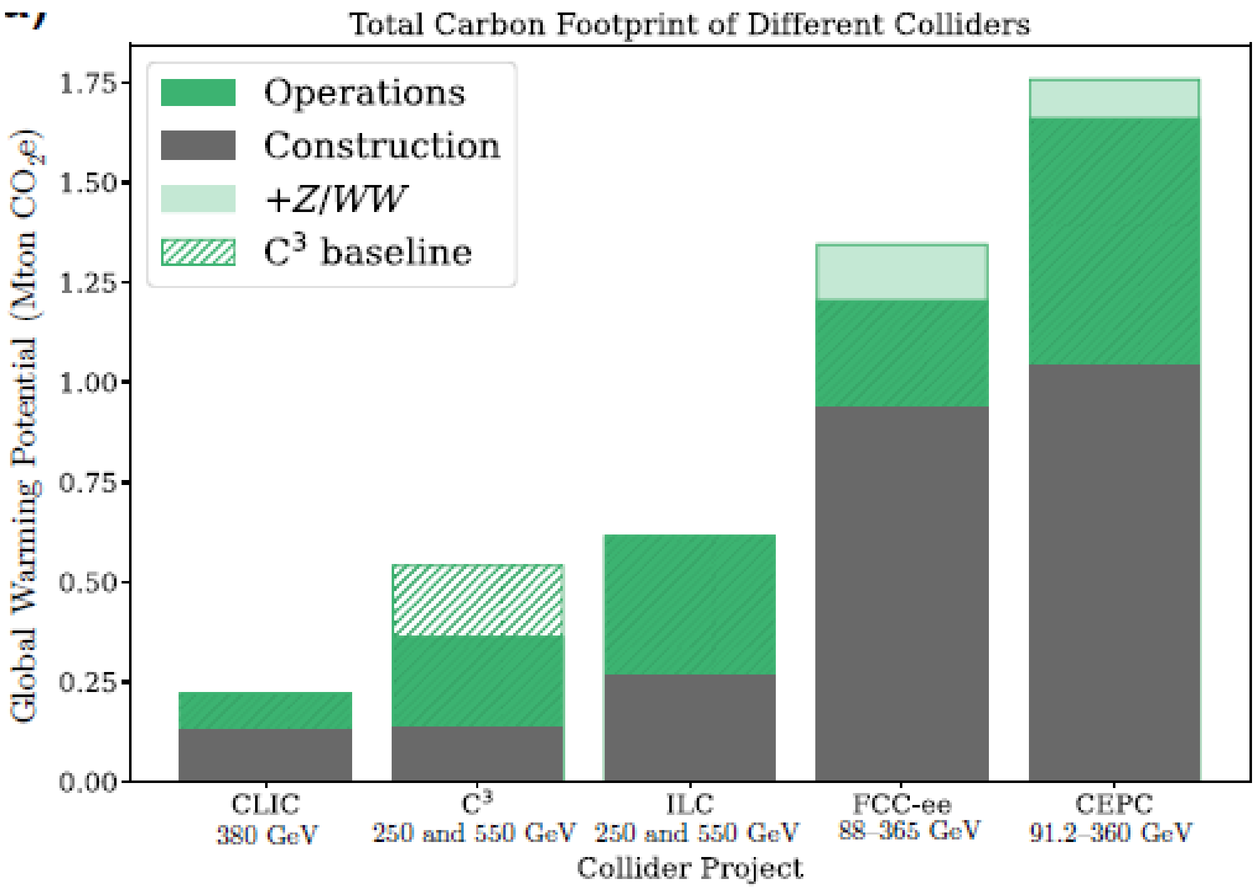


Steinar Stapnes

Environmental impact

Will be a major consideration for any new facility

Eg. Study by Breidenbach et al, PRX Energy 2 047001 (Oct 2023):



Detailed life-cycle assessment (LCA)

Consistent basis

Using industry standards for CO2eq costs for construction, operation + decommissioning

LCA in progress for ILC, CLIC, FCCee

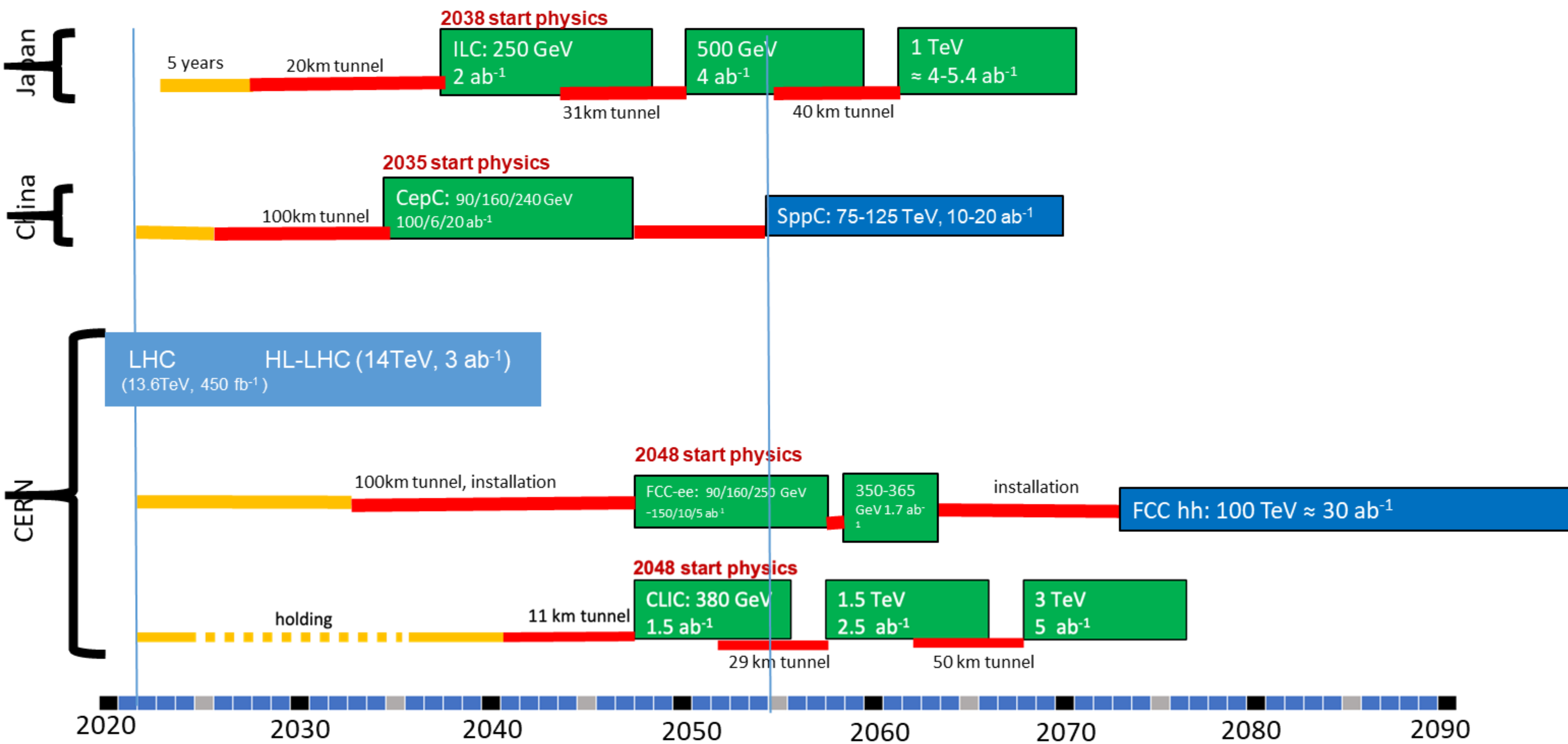
Schedules?

Indicative scenarios of future colliders [considered by ESG]

Proton collider
Electron collider
Muon collider

Construction/Transformation
Preparation / R&D

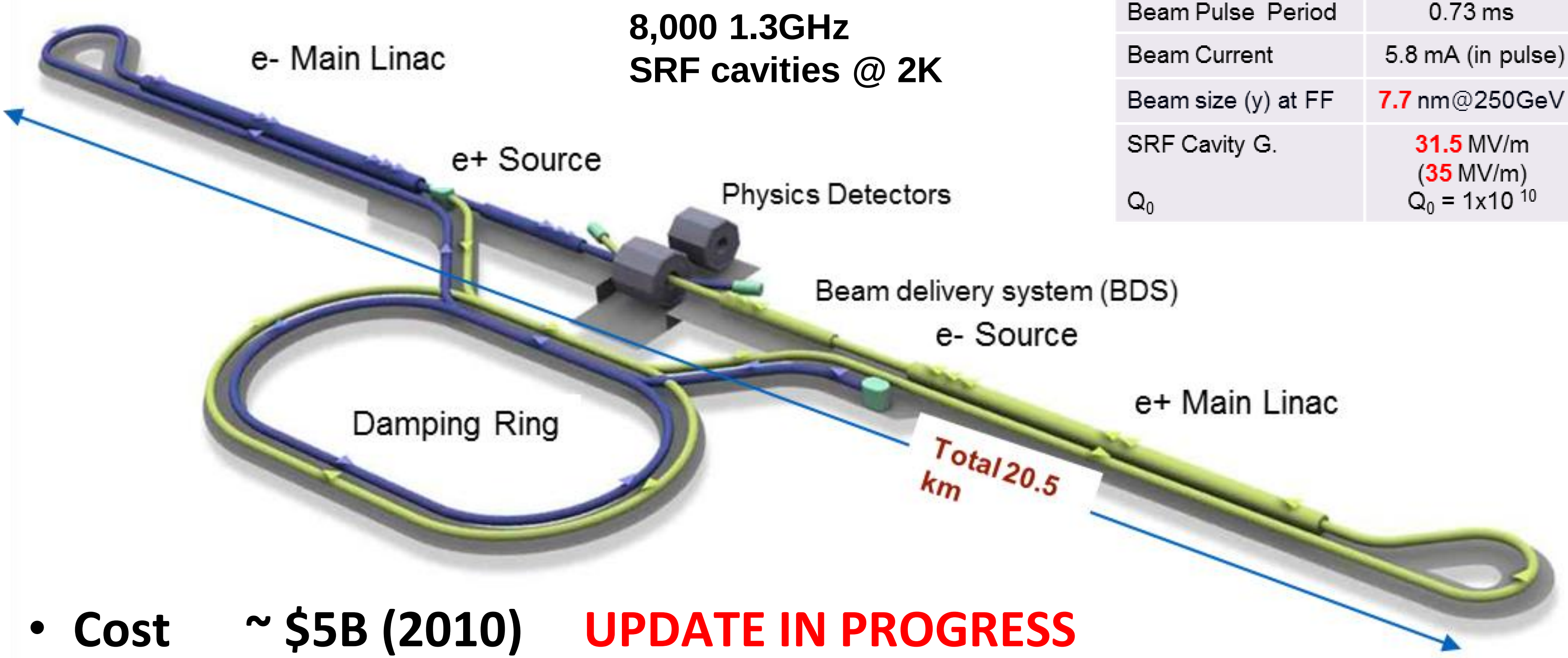
Original from ESG by UB
Updated July 25, 2022 by
M.Narain (Snowmass summary)



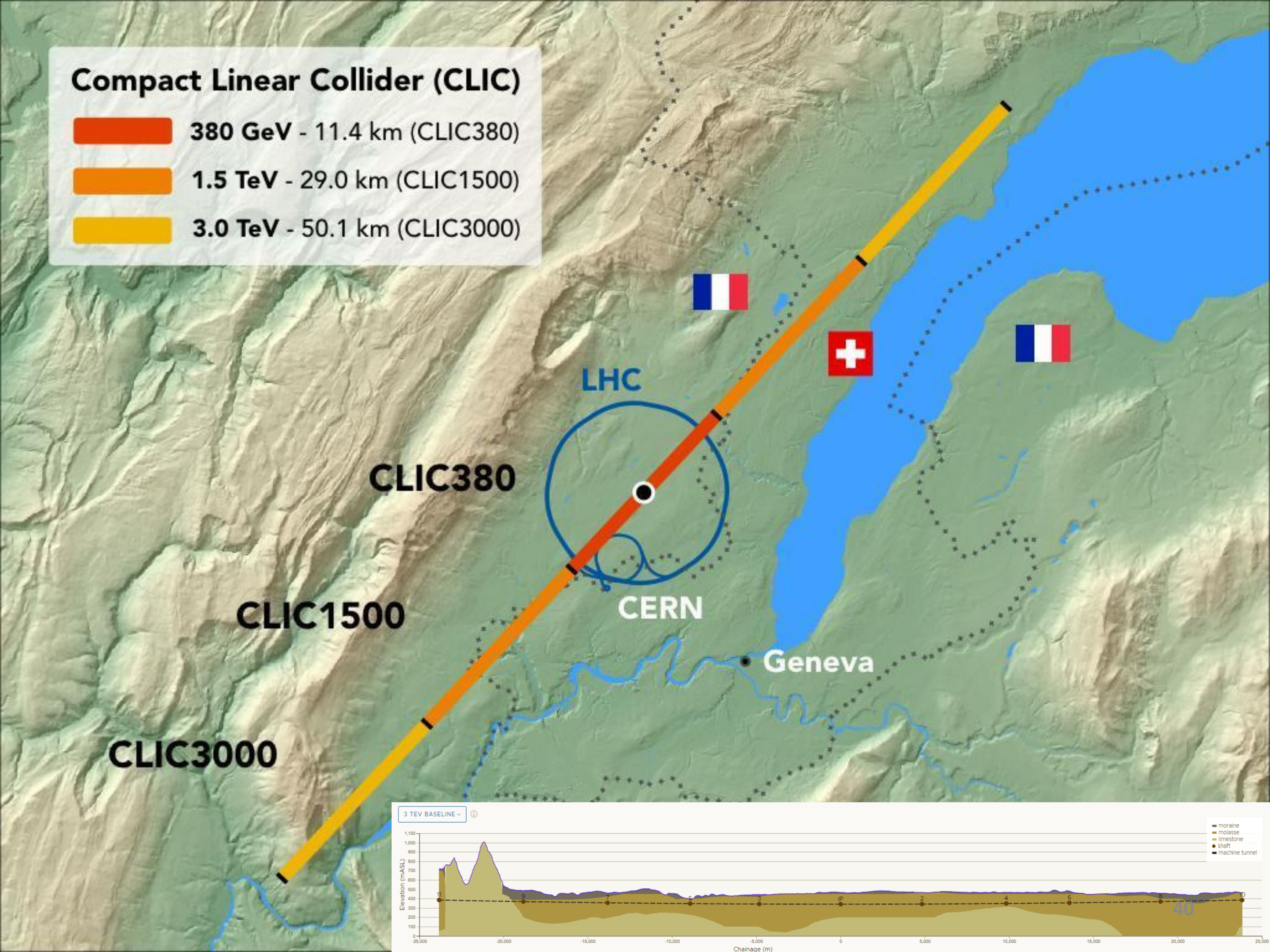
ILC 2017/8

8,000 1.3GHz
SRF cavities @ 2K

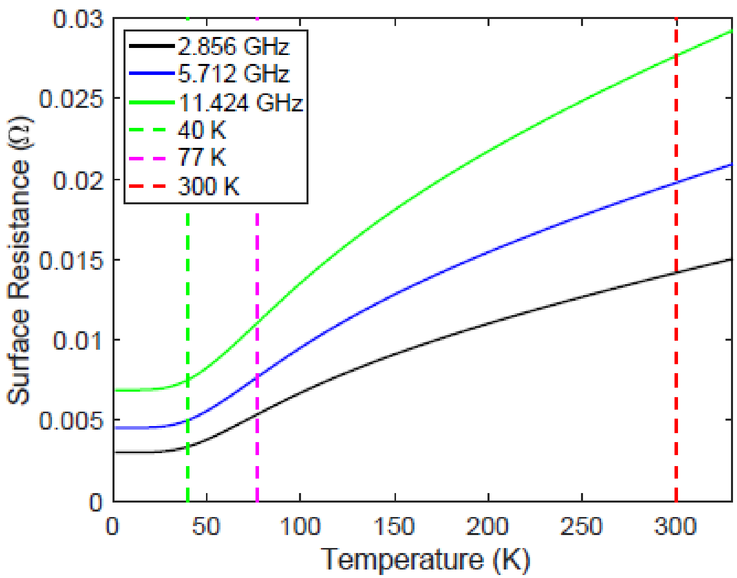
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}



- **Cost** ~ $5B (2010) **UPDATE IN PROGRESS**
- **Power** ~ 111 MW **FOR EPPSU MARCH 25**


Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva
3 TEV BASELINE
moraine
molasse
limestone
shaft
machine tunnel
Elevation (mASL)
Chainage (m)

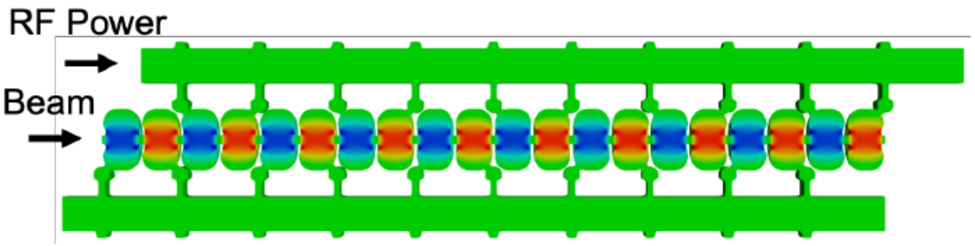
Cool Copper Collider (C^3)



Design choice: C-band Cu RF cavities @ 77K (LN2)

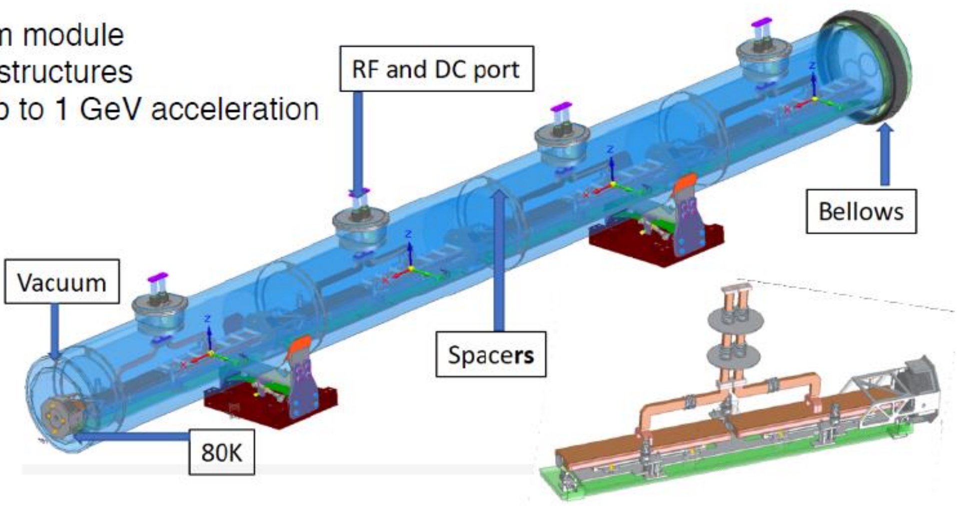
higher gradients ←→ lower RF power

higher RF → beam efficiency



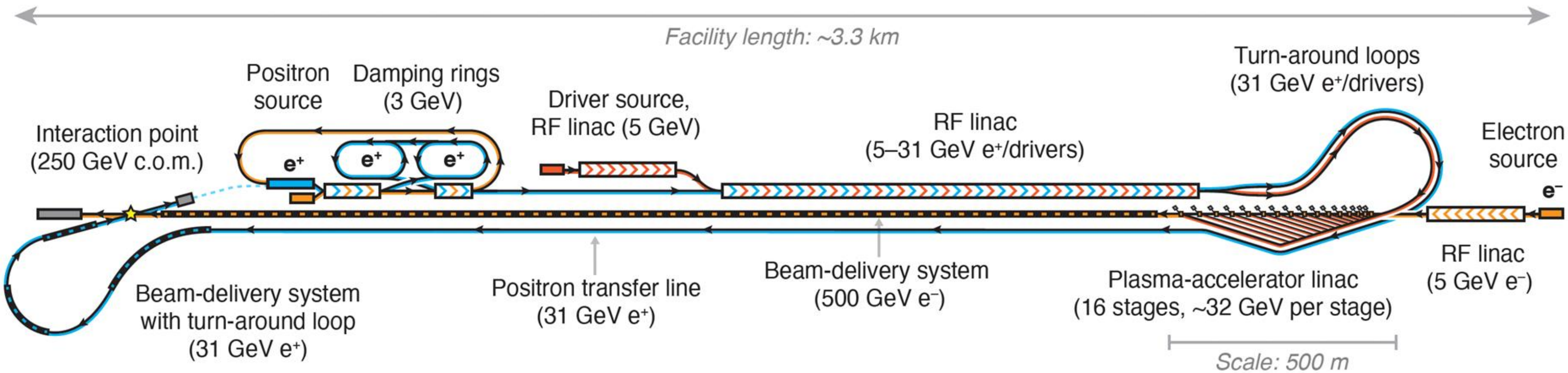
Electric field magnitude for equal power from RF manifold

9m module
8 structures
Up to 1 GeV acceleration



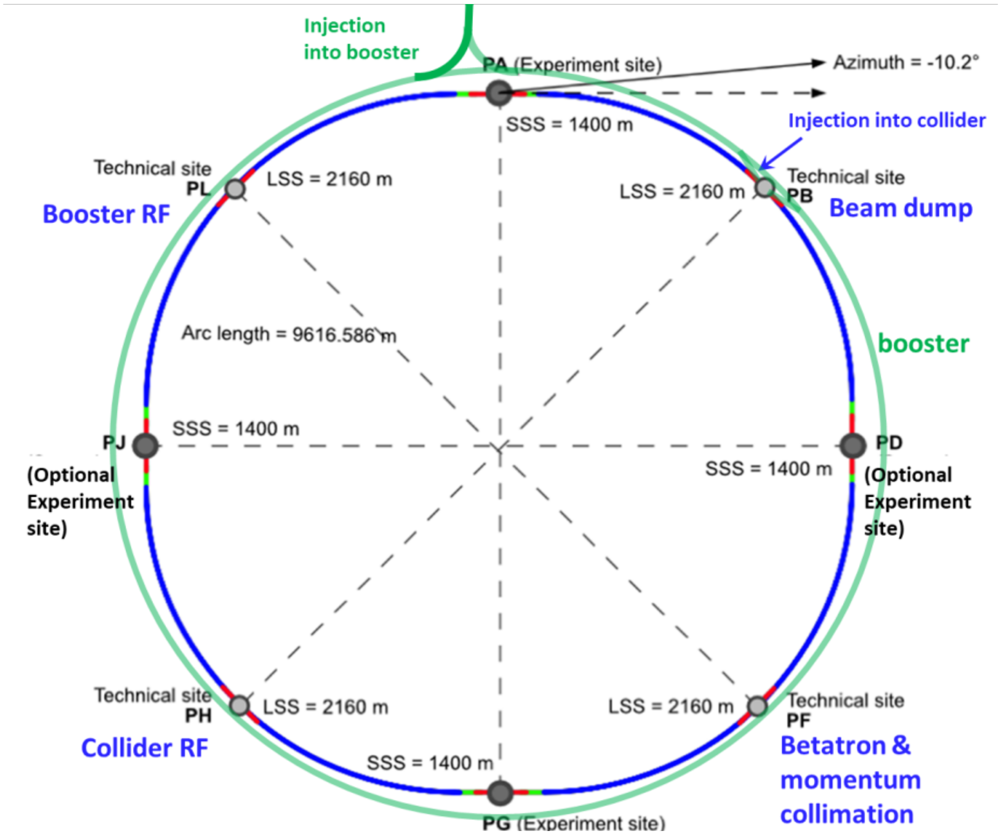
Hybrid Asymmetric Linear Higgs Factory (HALHF)

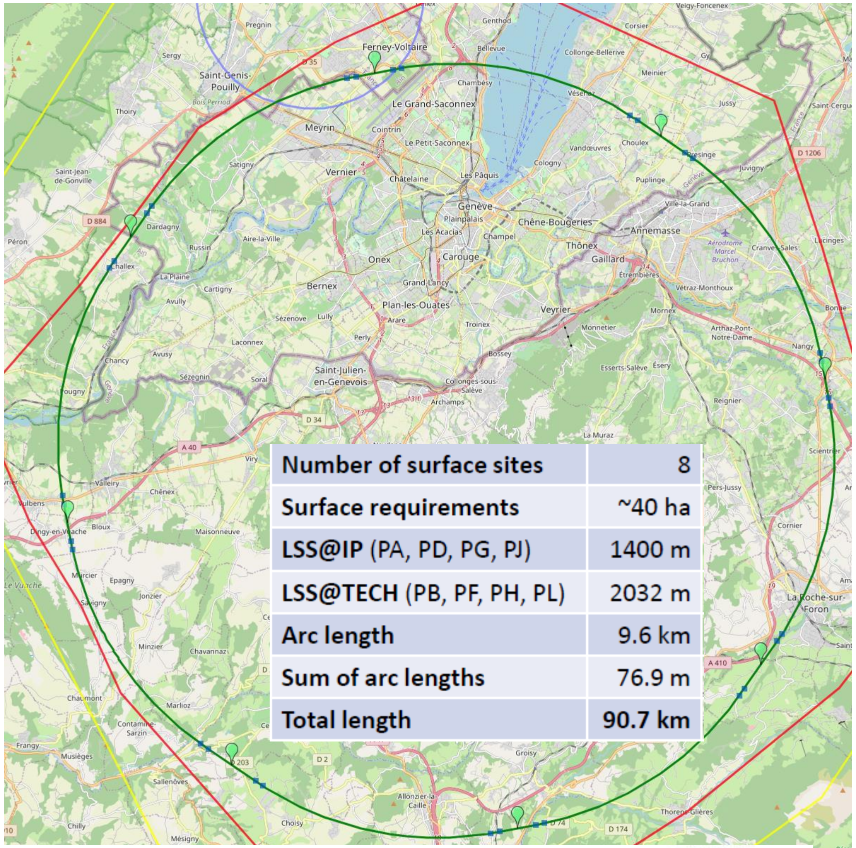
Foster, D’Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)
Lindstrøm, D’Arcy and Foster, arXiv:2312.04975



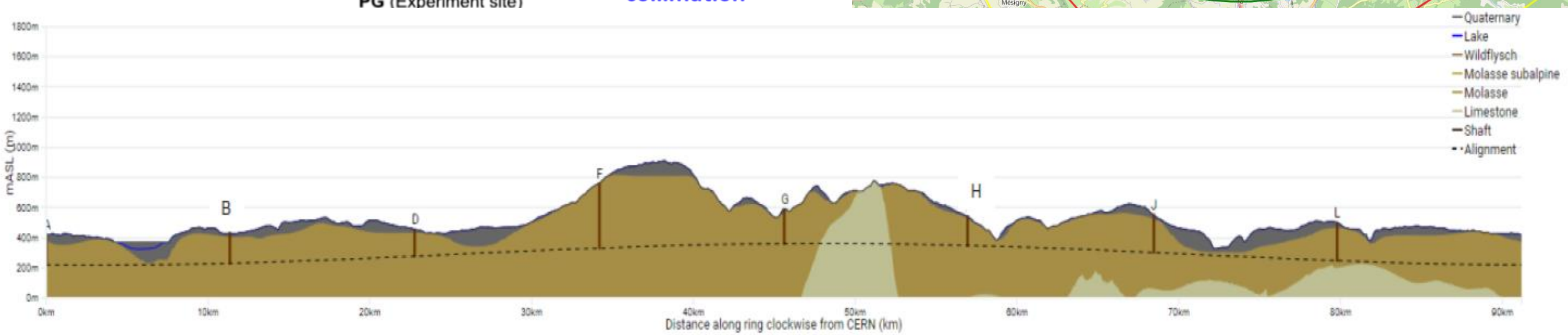
Future Circular Collider ee

Feasibility Study due to report March 2025



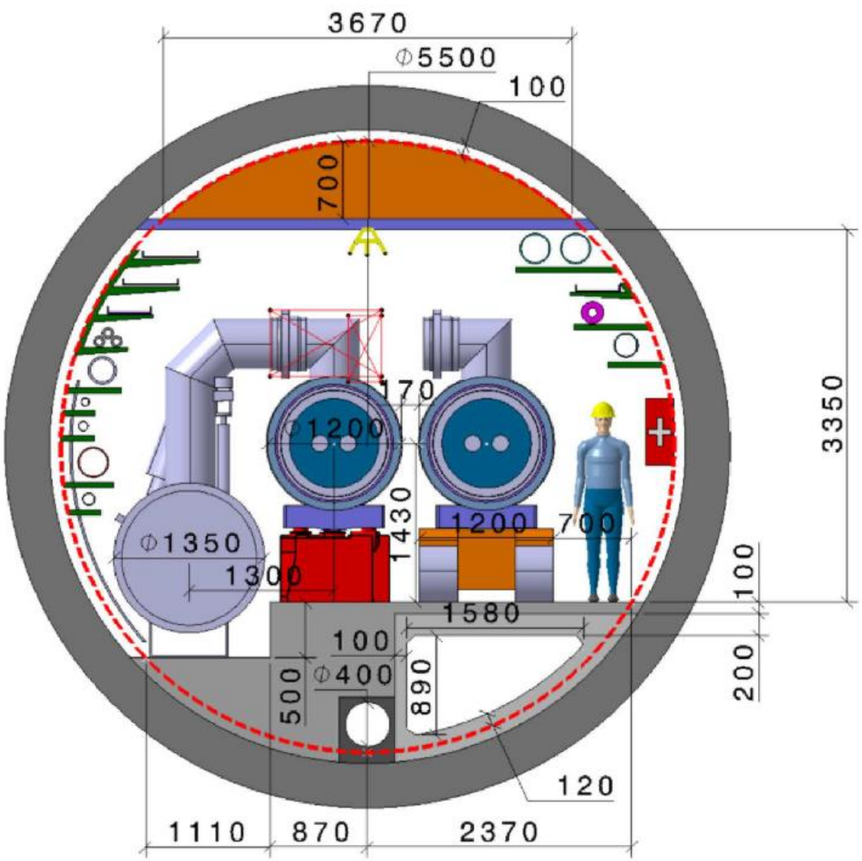


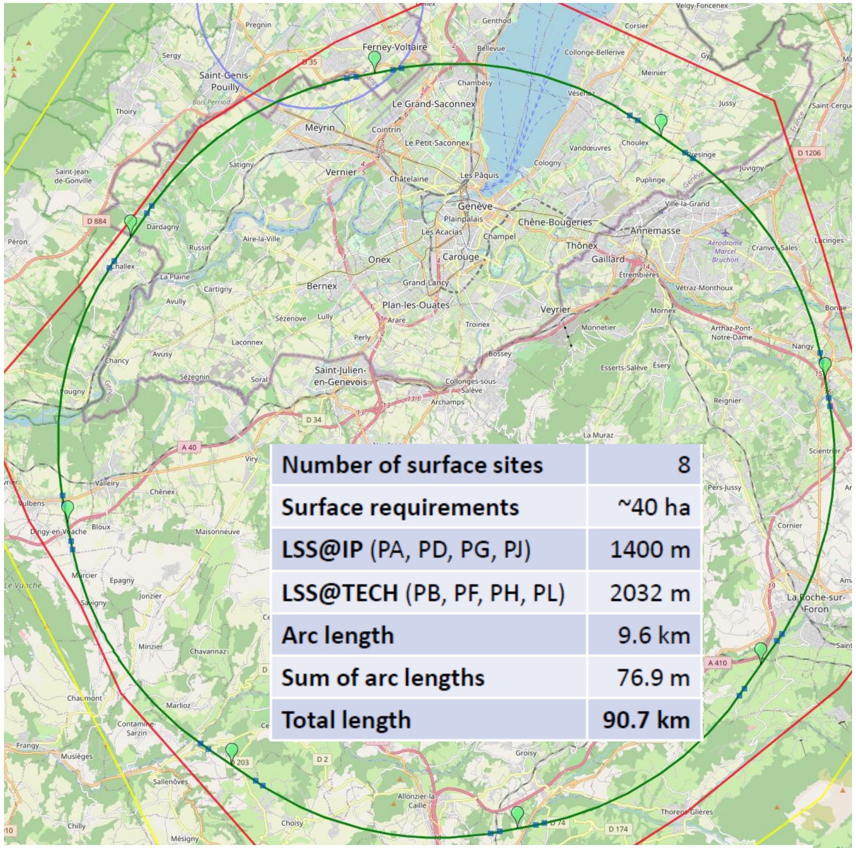
Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	90.7 km



Future Circular Collider hh

Feasibility Study due to report March 2025





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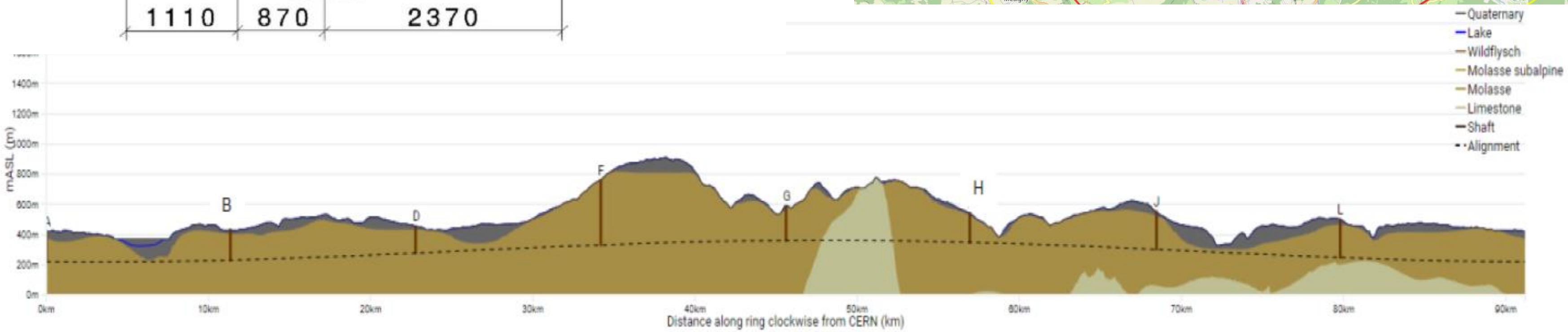
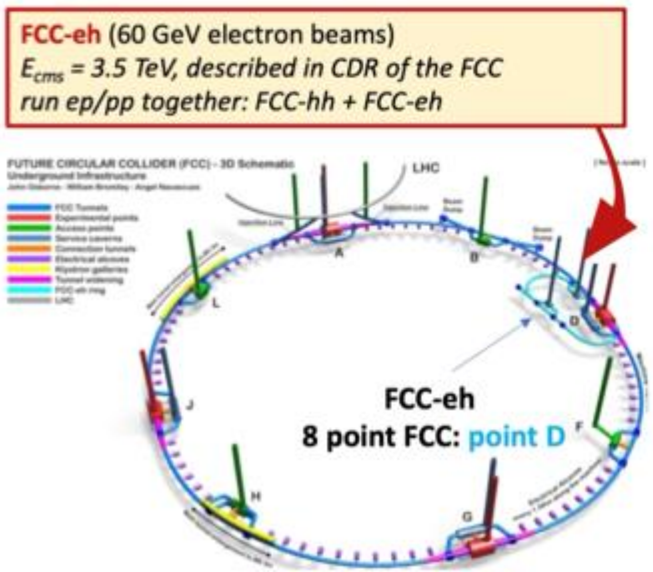
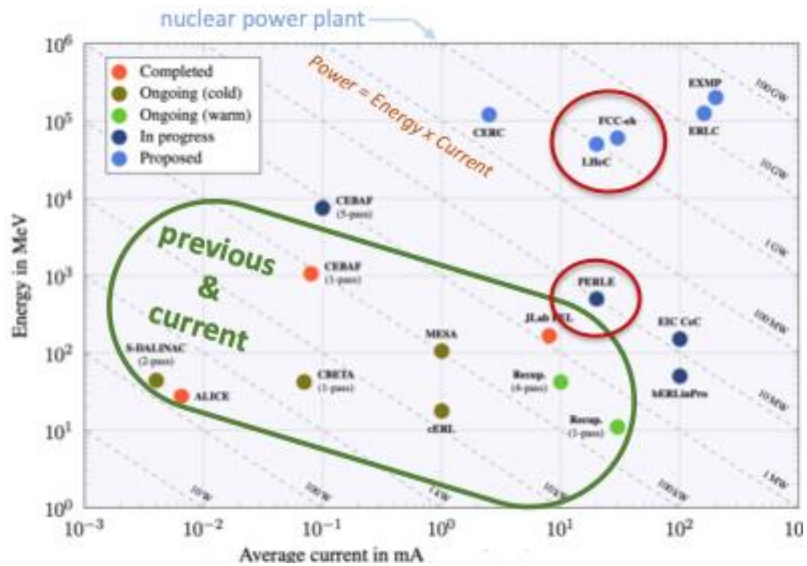


The FCC-eh complex

- centre-of-mass energy: 3.5 TeV (assuming 60 GeV electron beam, 50 TeV proton beam)
- integrated luminosity: 1 or 2 /ab
- number of interaction points: 1
- time running at stage: 10-20 years (as many as FCC-hh)
- wall power: 100 MW for ERL?
- accelerator length: same as FCC-hh for proton beam, ERL: 2 km arc, 1 km straight-length, 3 turns
- estimated year for first collisions: 2050+
- future upgrade paths: none at the moment



ERL development in progress



Monica D'Onofrio et al

Muon Collider

Comprehensive References:

- [The Muon Smasher's Guide]
- [Towards a Muon Collider]

Collider Specifications

Source: Interim report for the International Muon Collider Collaboration (IMCC)

Parameter	Units	Energy Staging		Luminosity Staging	
		Stage 1	Stage 2	Stage 1	Stage 2
Center-of-mass energy	TeV	3	10	10	
Integrated Luminosity	ab^{-1}	1	10	10	
Number of Interaction Points		2		2	
Estimated Year for First Collisions		2049	2056	2049	2058
Time Running at Stage	years	5	5	8	4+
Wall Power	MW				
Accelerator Length*	km	26.5	Stage 1 + 45	72	
Future Upgrade Paths		N/A, upgrade would be far away in 2060+.			

* Sum of all accelerator components. Numbers from WIP Parameters Report.