Possible Realizations of Future Colliders

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References at the end

Projects and Rationales

CLIC:
Go for highest lepton energies
From 0.38 to 3 TeV electron-positron collisions
- Linear collider with high gradient normal-conducting acceleration
- Overcome the challenges with technologies
- Now: do it in stages for physics and funding

FCC-hh + FCC-ee + FCC-eh
Push the energy frontier with protons / hadrons
- Large ring (100 km) with high field magnets
- 100 TeV

Use the FCC-hh tunnel for an electron-positron collider
- The layout and cost is not optimised for FCC-ee proper, but now being explored

HE-LHC
Expand hadron physics with limited cost

LHeC:
Expand the LHC programme with limited cost

ILC:
0.25 TeV electron positron linear collider with potential upgrades
- Use high gradient superconducting technology
- minimum cost to obtain funding in Japan

CEPC / SppC:
Build a higgs factory (CEPC) with limited energy with a tunnel that could house a hadron collider (SppC) afterwards

Plasma collider:
Expand linear colliders with novel technology to reach highest energies

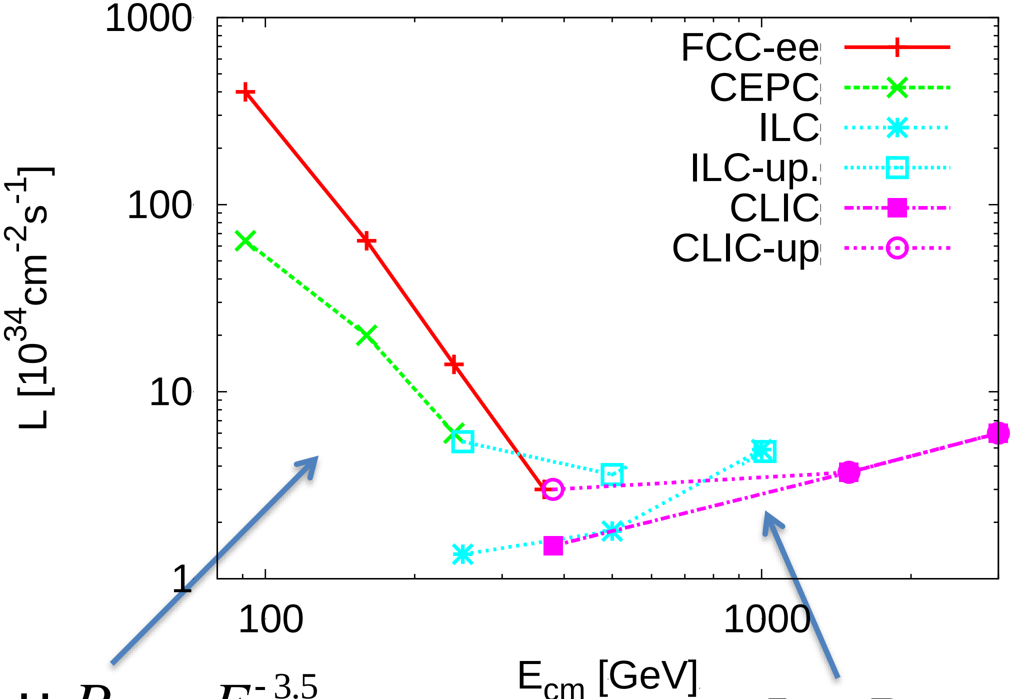
Muon collider:
Use muons to reach highest lepton energies

Overview Table

Project	Type	CM Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6	2+1	149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	0.060 e / 7 p	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Lepton Collider Luminosity

Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF}$

Energy dependence:

At low energies circular colliders shine

- Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel

- Luminosity per beam power roughly constant

High-energy frontier for hadrons is FCC-hh and SppC

Note: Cross over is at typical higgs factory energies

Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung

- All included in the physics studies

The picture is much clearer at lower or higher energies

FCC-ee / CEPC

Parameter	Z	W	H	t
Cm E [GeV]	91.2	160	240	350
FCC-ee				
L [10^{34} cm^{-2}s^{-1}]	200	28	8.5	1.8
Years op.	4	2	3	5
Int. L / 2 IP [ab^{-1}]	150	10	5	1.5
CEPC				
L [10^{34} cm^{-2}s^{-1}]	32	10	3	
Years op.	2	1	7	
Int. L / 2 IP [ab^{-1}]	16	2.6	5.6	

Based on

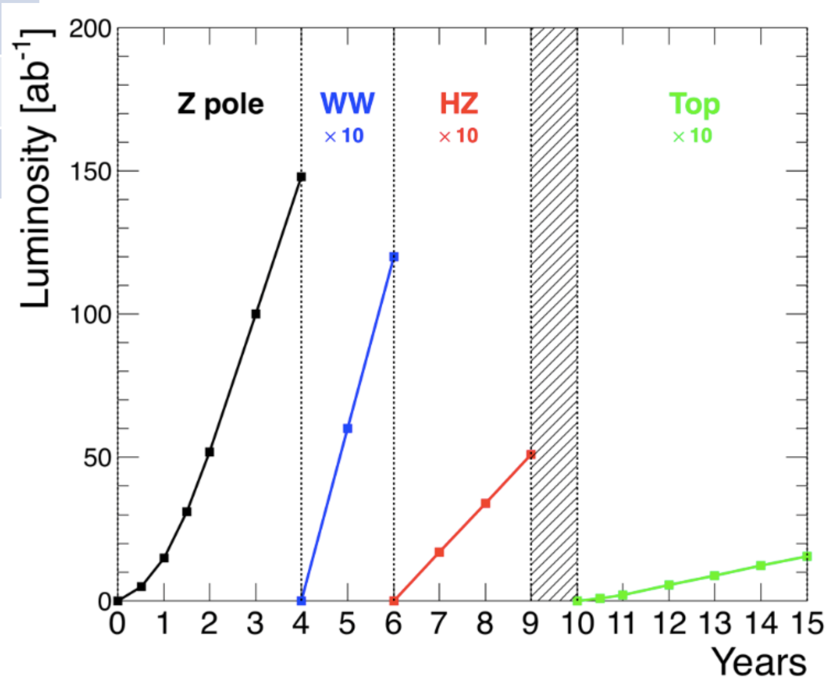
- Combining concepts of previous projects, e.g. top-up scheme
- Further developing existing technologies

Significant luminosity increase compared to LEP (0.01 x 10^{34} cm^{-2} s^{-1} @ 208 GeV)

Smaller emittances, beta-functions, larger power consumption

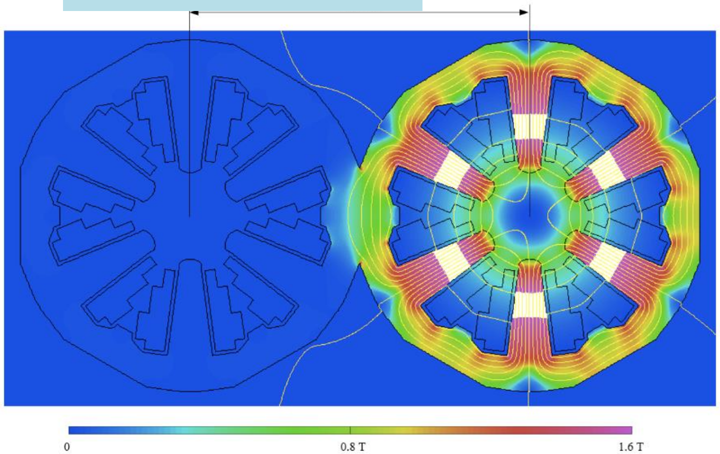
FCC-ee limit 100MW of synchrotron radiation (both beams)

$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$



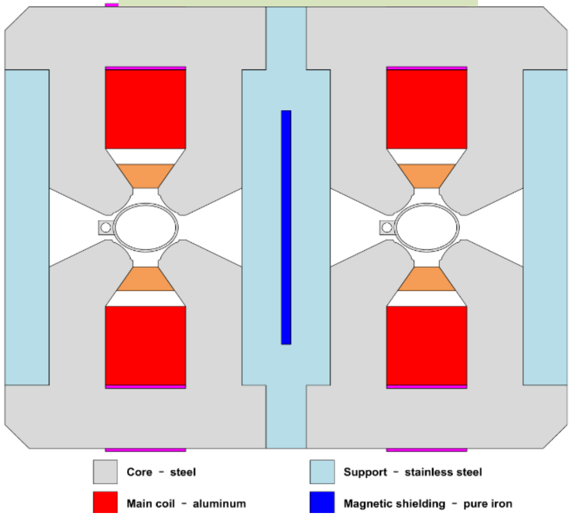
FCC-ee / CEPC Technologies

FCC-ee arc sextupole



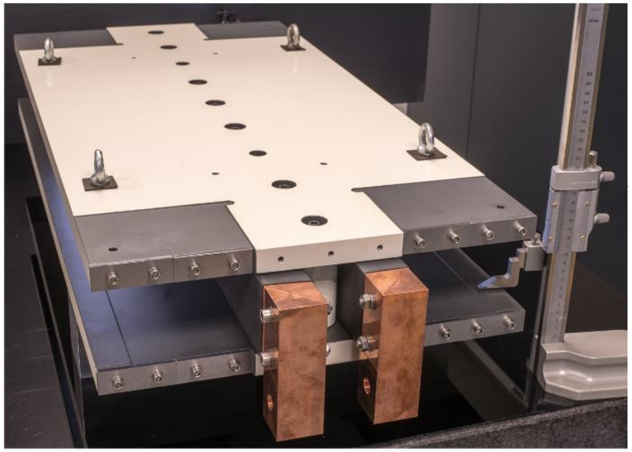
FCC-ee 800 MHz cavity

CEPC arc quadrupole

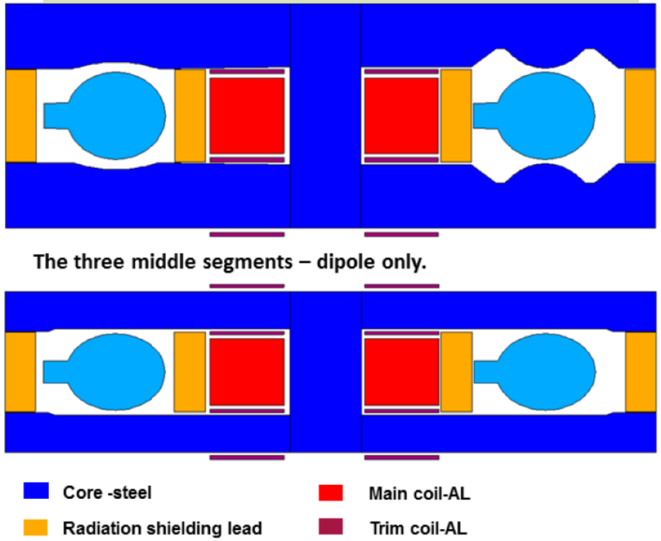


FCC-ee arc quadrupole

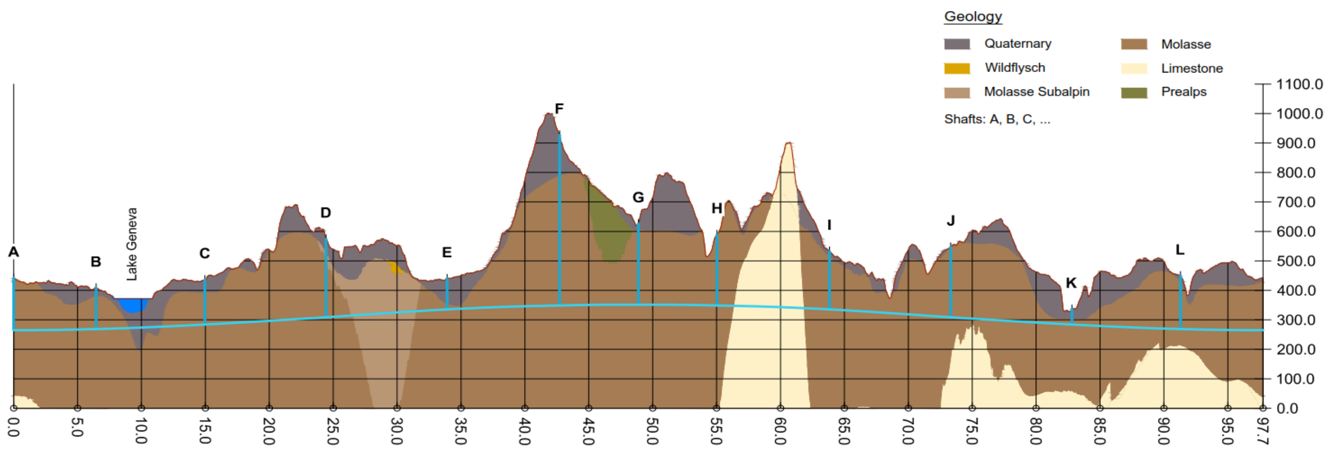
FCC-ee arc dipole

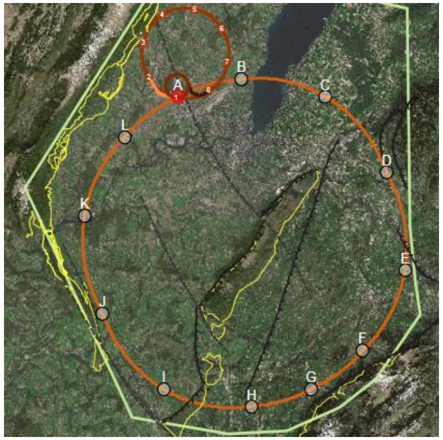


CEPC arc combined function magnet



Site and Infrastructure Planning





Site planning has been developed for FCC-hh:

- Injection from LHC or SPS possible

FCC-ee can be implemented with small additional effort (e.g. some modifications in interaction region)

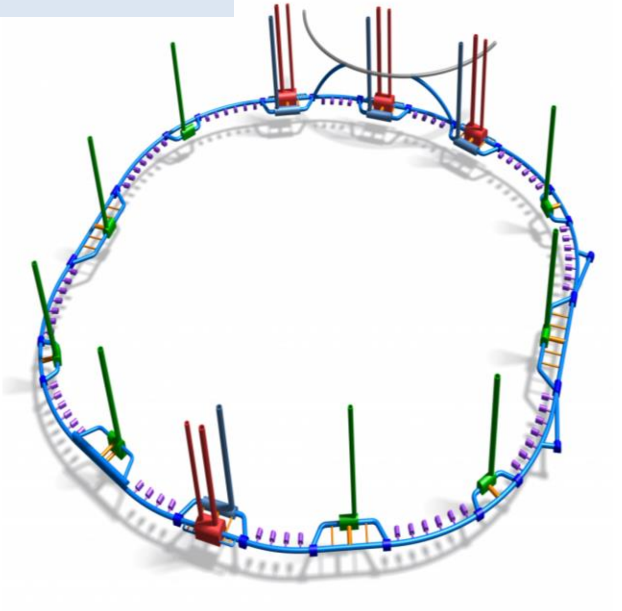
Main issue for FCC-ee is cost of tunnel and infrastructure

- could be reused for FCC-hh

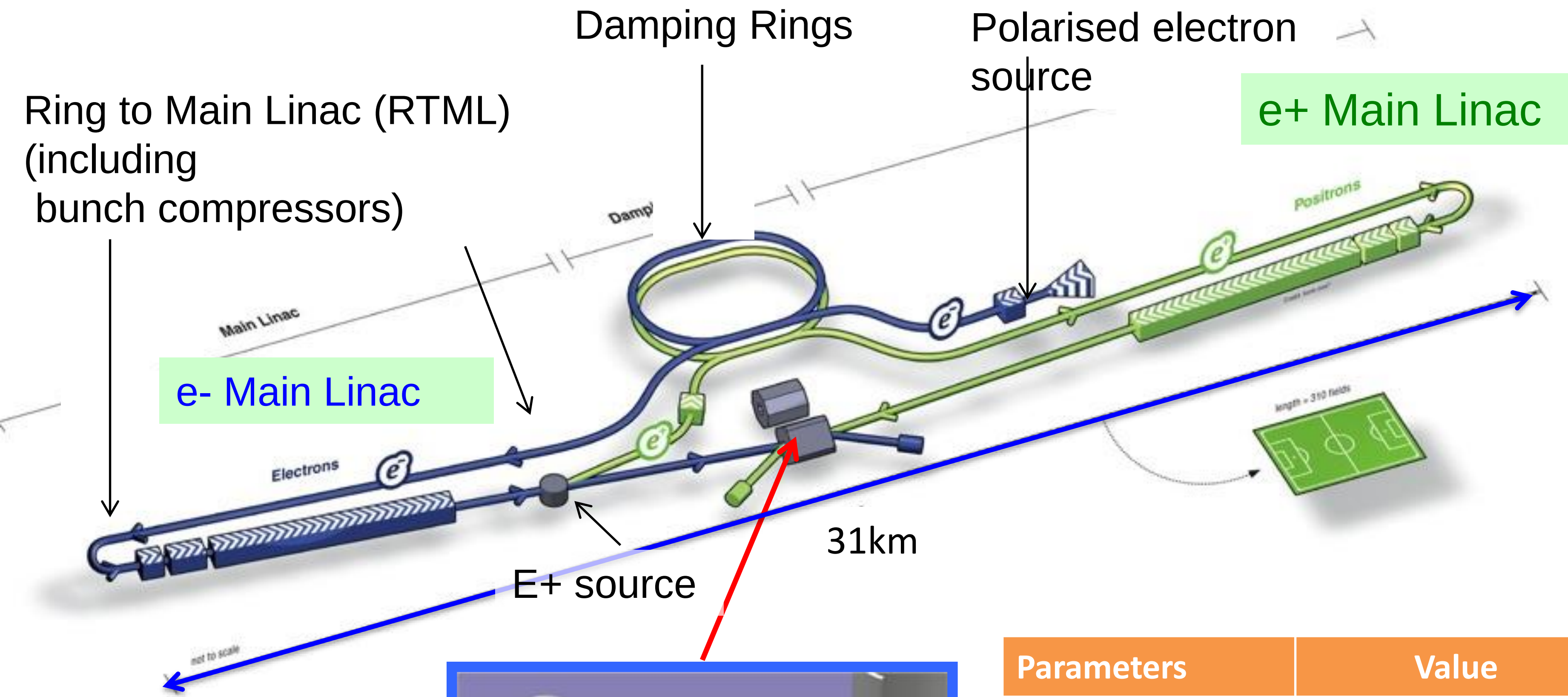
CEPC (SppC) also is studying sites

HE-LHC has a known site, challenge is to fit everything in it

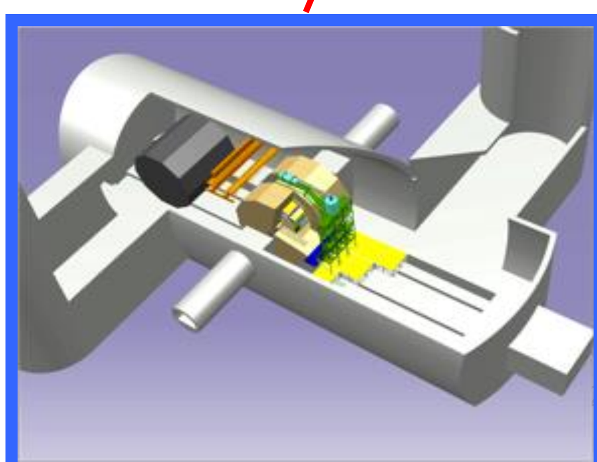
FCC at CERN



ILC



ILC Scheme | © www.form-one.de

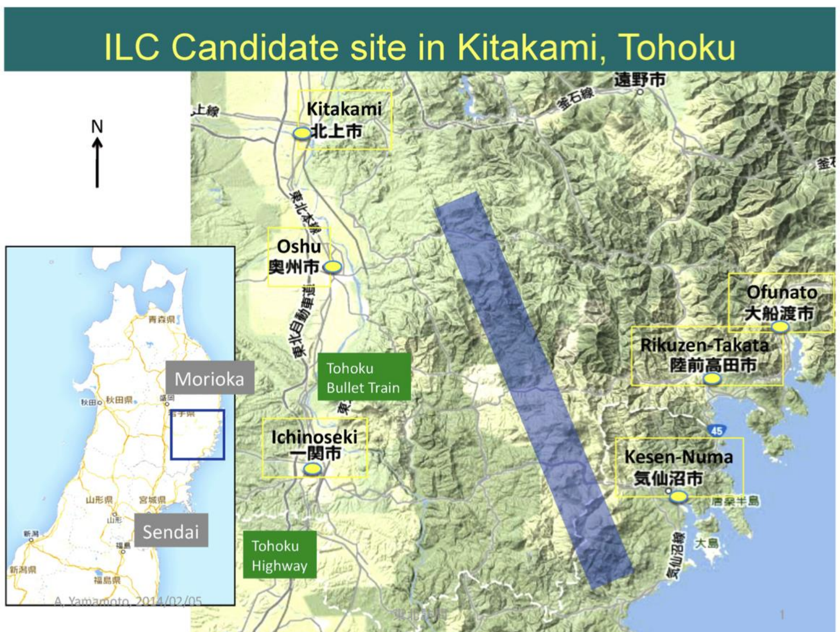


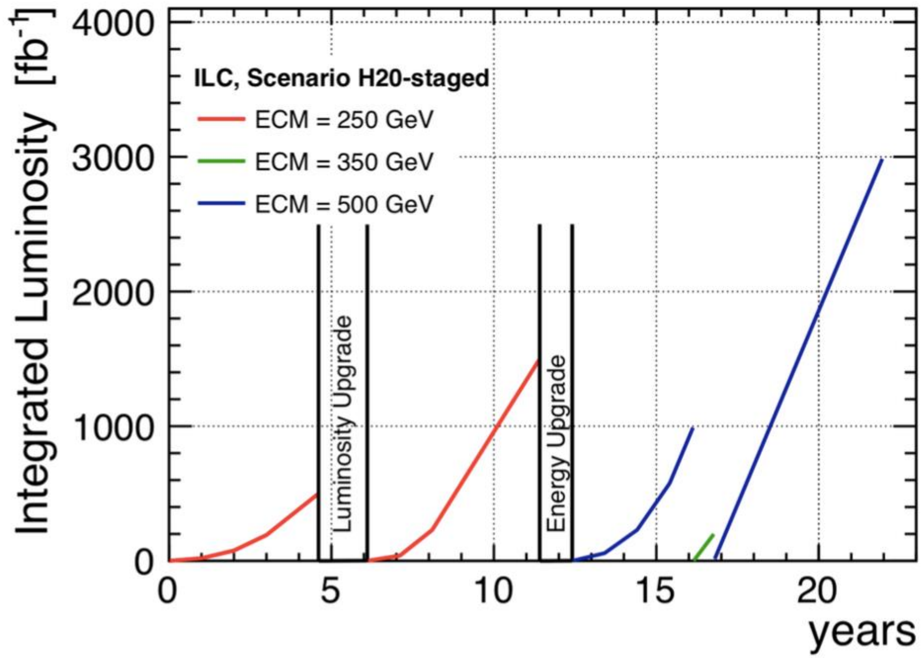
Parameters	Value
C.M. Energy	250 GeV
Peak luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Beam power	5 MW
Beam Rep. rate	5 Hz
E gradient	31.5 MV/m +/-20%

ILC Implementation

Very mature technology
800 cavities installed in XFEL in Hamburg

Detailed site studies in Japan





80% electron polarisation, 30% for positrons

Initial machine with 250 GeV is being discussed with officials
Upgrades to 500 GeV or more are technically possible

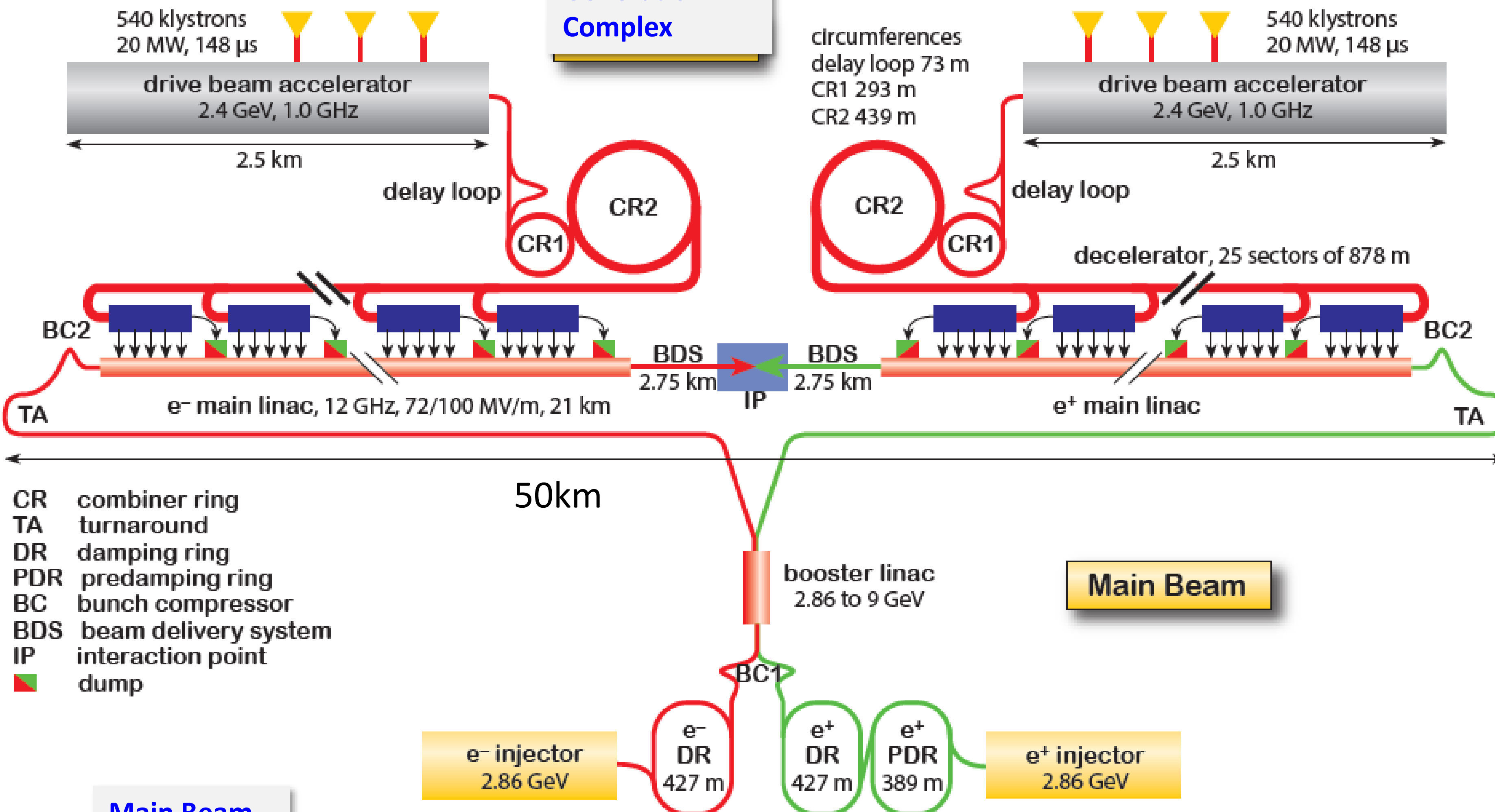
Mainly waiting for Japan to make decisions

CLIC

Goal: Lepton energy frontier

Drive Beam Generation Complex

CLIC at 3TeV shown



Main Beam

Main Beam Generation Complex

Stages at E_{cms}=0.38, 1.5 and 3TeV

L=6×10^{34}cm^{-2}s^{-1} at 3TeV

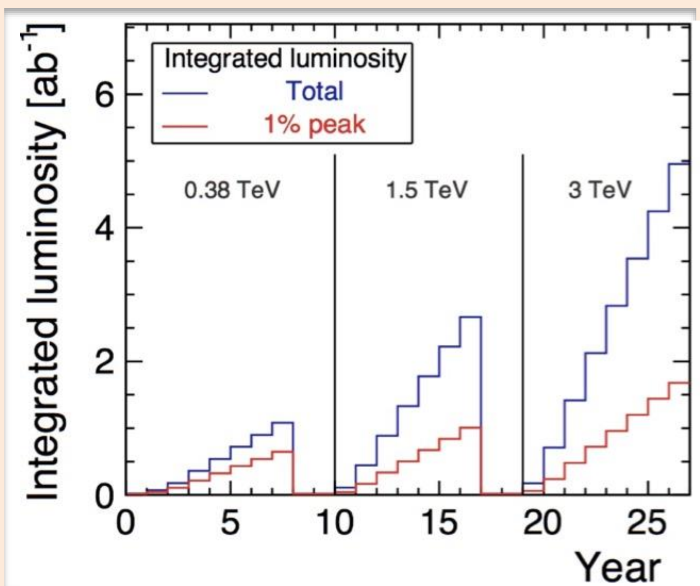
Beam power 30MW at 3TeV

CLIC Implementation Scenario

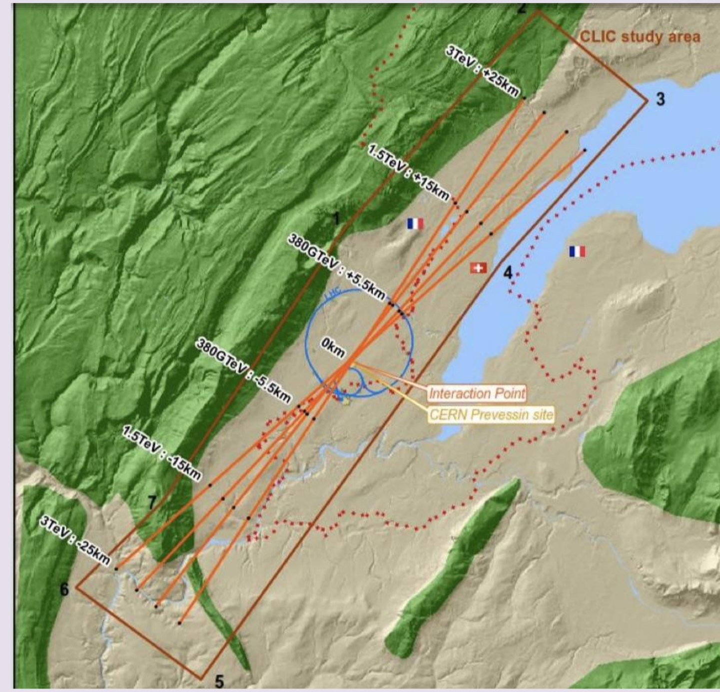
Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

80% e^- polarisation

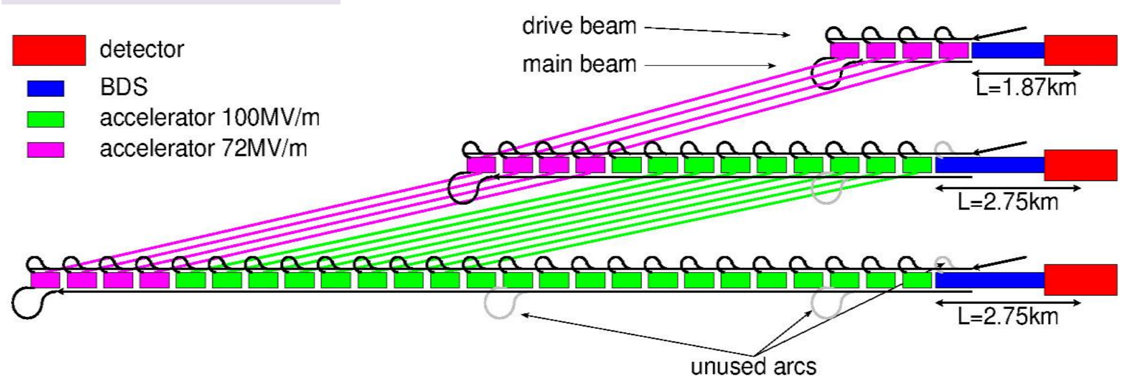
Luminosity targets from Physics Study group
Hopefully input from LHC



Luminosity evolution



Central complex on Prevessin site

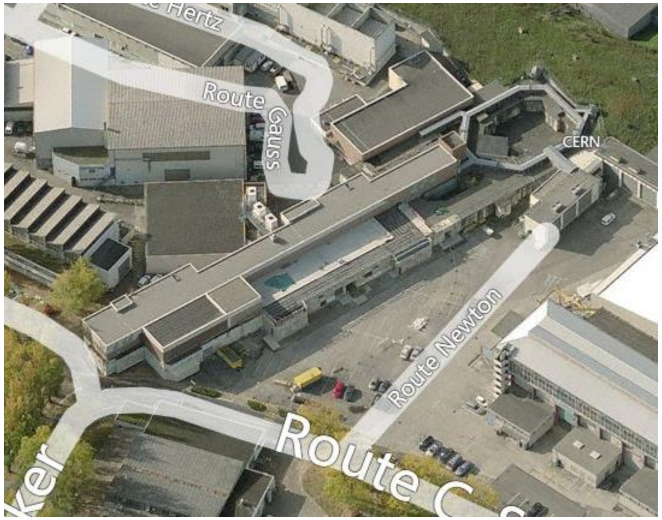


Lower gradient optimum for lower energy

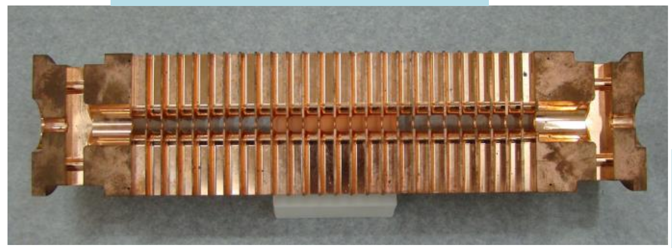
CLIC Technologies

Key technologies have been developed
Transfer to other facilities ongoing
Preparation for mass production required

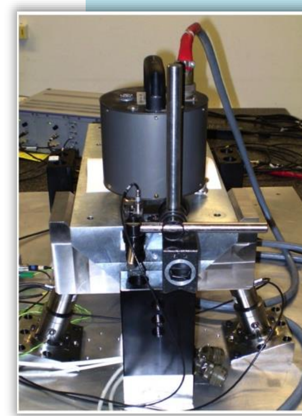
Drive beam tests in CTF3 completed



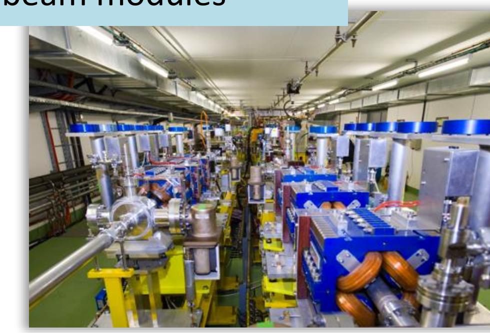
Accelerating structure



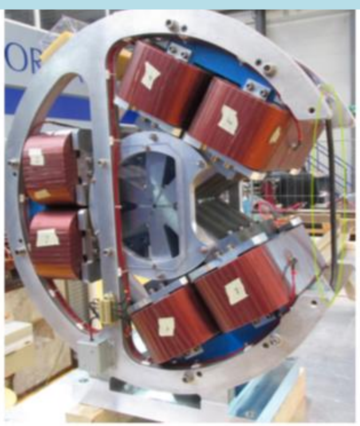
Magnet stabilisation



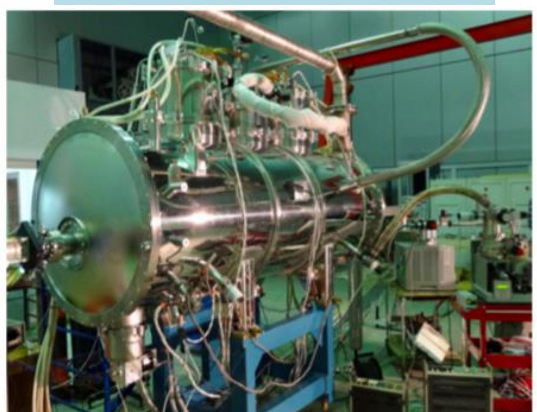
Drive beam and main beam modules



Short BDS sextupole prototype



NbTi damping ring wiggler



Short final quadrupole prototype

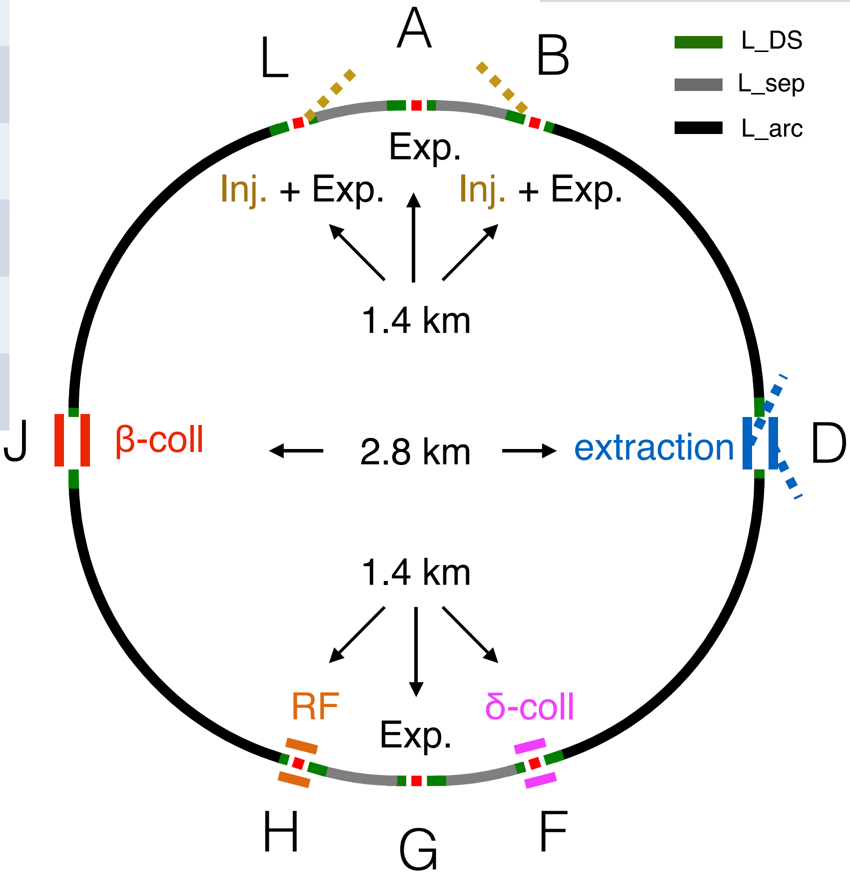
High efficiency klystrons, Instrumentation, kickers, …

FCC-hh / SppC / HE-LHC

	HL-LHC	HE-LHC	FCC-hh	SppC
Cms energy [TeV]	14	27	100	75
Int. L., 2 det. [ab^{-1}]	6	15	30	
Operation [years]	12	20	25	
L [$10^{34}cm^{-2}s^{-1}$]	5	16	20-30	10
Circumference	26.7	26.7	97.75	100
Arc dipole field [T]	8	16	16	12
Bunch dist. [ns]	25	25	25	25
Backgr. events/bx	135	440	<1020	
Bunch length [cm]	7.5	7.5	8	7.55

CDRs exist
Full FCC-hh lattice and many component conceptual designs, addressing the key challenges

FCC-hh layout



HE-LHC is not cheap and has similar challenges than FCC-hh
Physics case appears less interesting
Note: “low”-field NbTi magnets in FCC tunnel were looked at, but cost saving is limited, and energy compromised significantly (< 40 TeV)

Challenges and Status

Successfully addressed the key challenges:

High total beam energy (8 GJ = 2t TNT) and potentially high loss rate

- beam transfer systems, collimation system, machine protection, focusing triplet protection

Synchrotron radiation (total 5 MW, 30 W/m/beam):

- novel beamscreen design
- more efficient cooling design

Collective effects:

- electron cloud suppression by beamscreen design and coating
- fast feedback to suppress impedance effects
- …

Magnet concept (but prototypes are still to come)

- high field
- field quality

Injector concept

…

Profited from all the LHC expertise

In regard to accelerator community preparedness the most advanced of all projects

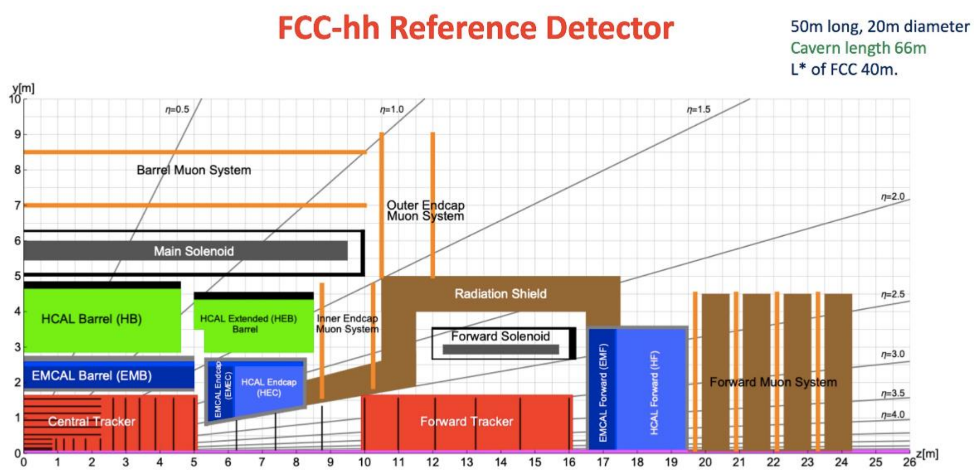
MDI

Particular challenge 1000 events per bunch crossing

500 kW power into detector and machine

Efforts to distribute luminosity over more crossings, e.g. 12.5 and 5 ns
But have to work on electron cloud suppression

Radiation in magnets requires some improvements of radiation hardness, which is considered feasible with improved raisin



Tunnel
(transverse not to scale)

Add. protection

TAS

Triplet

Hall half length: 33m

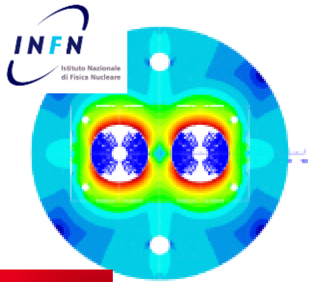
Tunnel before triplet: 7m

L^*=40 m

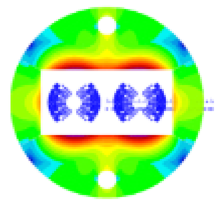
Detector half length 23.5m

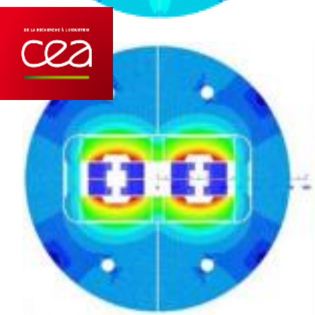
Space to open 9.5m

Magnets

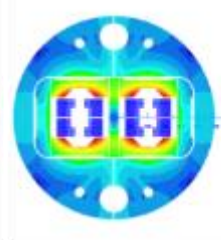


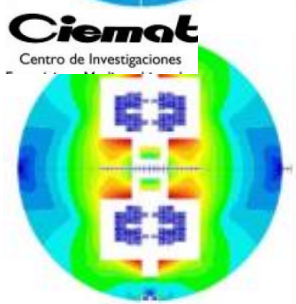
Cosine theta



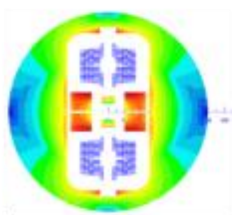


Block design

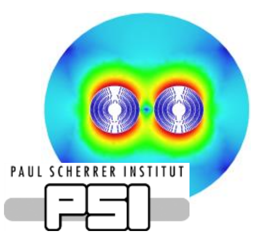




Common coils



Canted coils



Need 16 T to reach 50 TeV /beam

⇒ Move from NbTi (LHC technology) to Nb_3Sn

⇒ same as for HL-LHC

⇒ 14.5 T achieved in test coil (Fermilab)

⇒ Can explore HTS if FCC-hh to be realised after FCC-ee

Development time for magnets is long

Magnet development time the key technical limitation of the schedule

Starting with FCC-hh requires very strong development programme

Five year programme

For LTS:

Conductor R&D, cost reduction approaching FCC-hh requirements

Insulating materials

Magnet technology, to take critical designs on margins etc.

Accelerator magnet engineering R&D, e.g. mass production

Test infrastructure

For HTS:

Conductor targets and alternatives

Magnet technology R&D: design concepts, fabrication technology, …

Demonstrator undulator

Higher Energy Lepton Collider Options

CLIC is probably limited by cost and power consumption to O(3 TeV)
- Total cost is 5.9 + 5.1 + 7.9 = 18 GCHF
- Power consumption is 590 MW

Higher energy increases cost about linearly
Also need higher luminosity at higher energy this increases power consumption
- power roughly proportional to luminosity in linear colliders with given technology

Plasma acceleration can achieve very high gradients (> GV/m)
- could be used for main linac
- and maybe reduces collider cost

But have to still find solutions for the power consumption
- would have to push beyond performance limits that have been established in decades of R&D

Muon colliders
- can be circular since much less synchrotron radiation
- might be cheaper since less voltage required
- Might have better luminosity to power ratio
- But muons are hard to produce and do not live long (2.2 μs)

Luminosity Comparison

Luminosity goal (Muon Collider WG)

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Muon collider:

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

at 14 TeV: P_{beam}= O(20 MW)

But need to establish feasibility

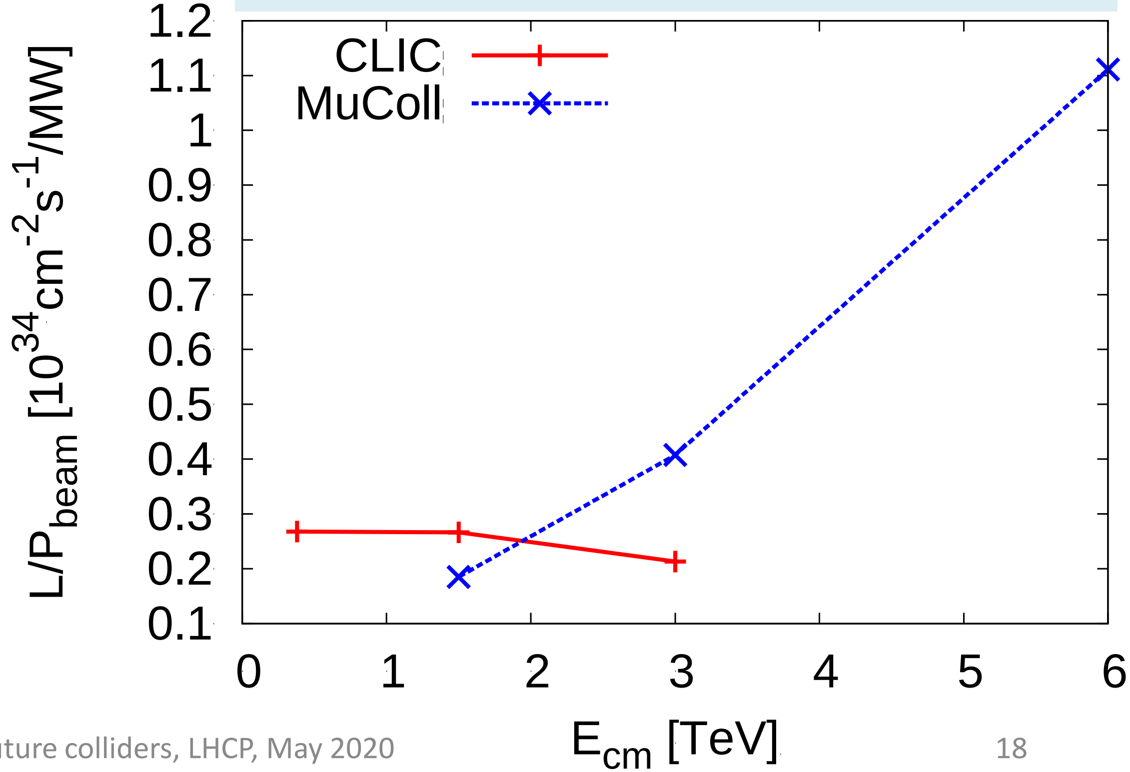
Linear plasma colliders:

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

CLIC to 14 TeV: P_{beam}= O(200 MW)
P_{total} = O(2-4 GW)

Need to establish feasibility

So plasma colliders would have to do much better than CLIC, which has been optimised for decades

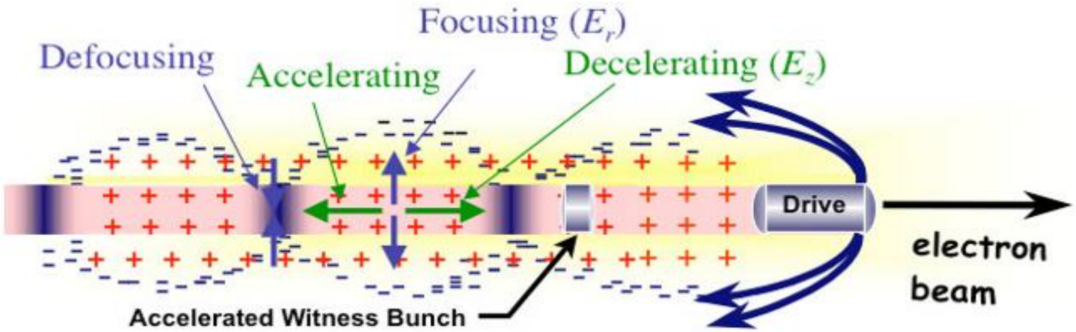


Plasma Acceleration

Use novel technology in main linac

Plasma acceleration achieves very high gradients (> GV/m)

- Powered with beam or laser
- different regimes (bubble, quasi-linear, hollow, …)



ALEGRO (Advanced LinEar collider study GROup) plans to have CDR/TDR in 20 years

No collider parameter set developed for ESU

- issues had been found with first tentative sets
- technology still quite in flux
- need to better understand all boundaries

Different test facilities exist or are planned

AWAKE, FACET, EUPRAXIA …

Mostly aimed to make technology useful in view of FELs

Many technology specific issues have to be solved

- staging of cells
- beam quality preservation
- …

More for collider applications

- orders of magnitude better beam quality
- high efficiency
- acceleration of positrons
- power handling in cells
- …

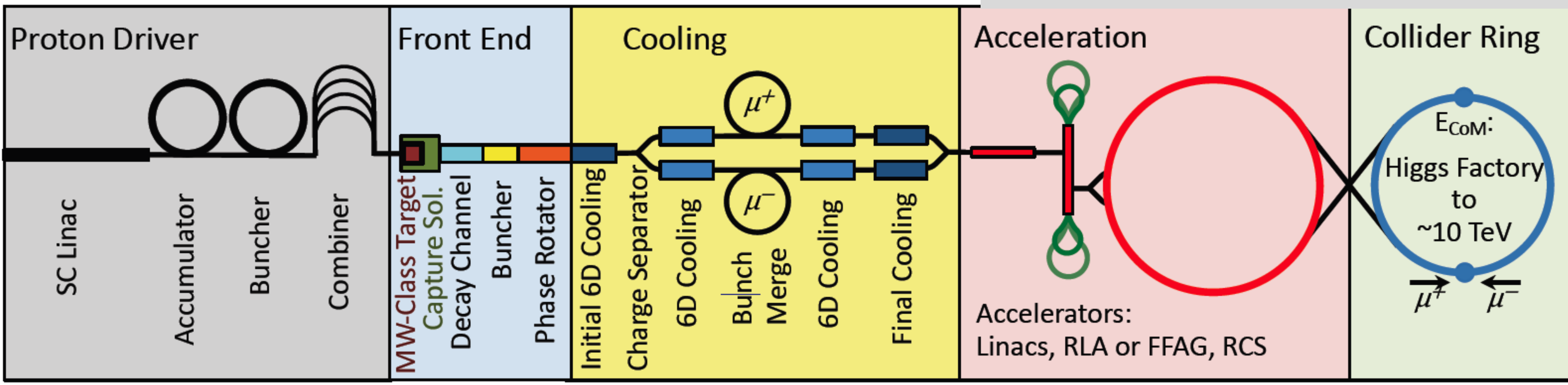
And for highest energies

- further improvement of beam quality in all collider parts beyond current linear colliders
- invent novel and better beam focusing

Proton-driven Muon Collider Concept

Muon collider study group using input from MAP and LEMMA collaborations

MAP collaboration M. Palmer et al.



Short, intense proton bunches to produce hadronic showers

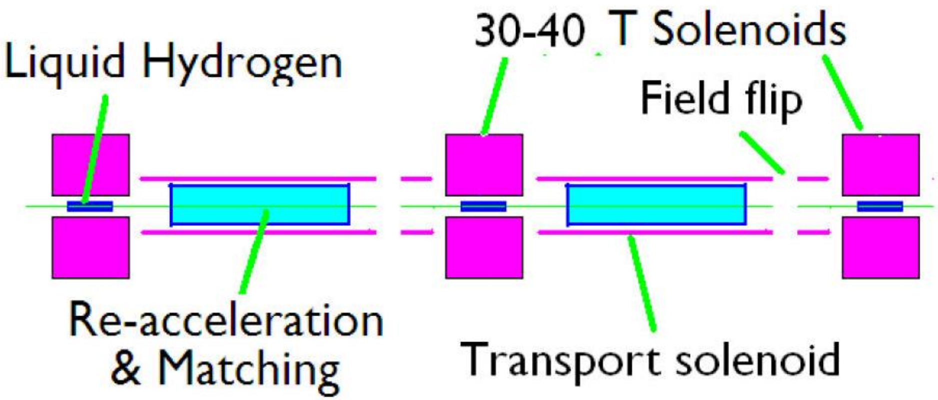
Pions decay into muons that can be captured

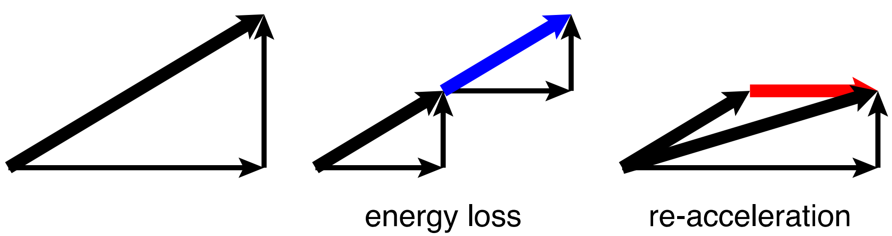
Muons are captured, bunched and then cooled

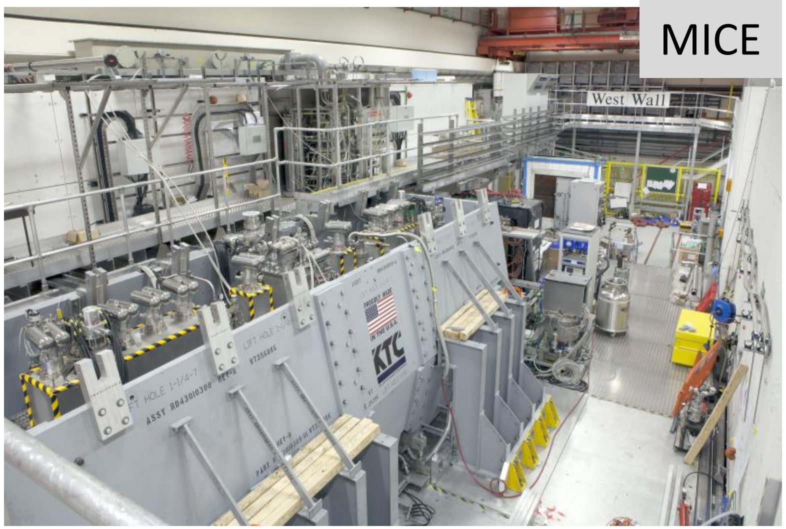
Acceleration to collision energy

Collision O(1000)

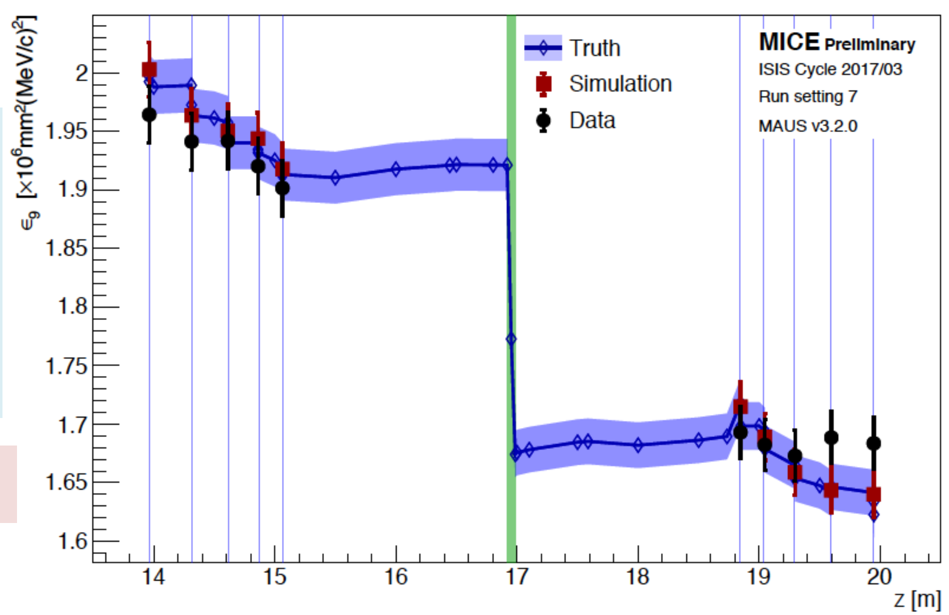
Transverse Cooling and Technology







Noticeable reduction of 9% emittance



Principle of ionisation cooling has been demonstrated

Several key components have been demonstrated

But important work left to establish feasibility

Tentative Target Parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.8	12.8	17.9
C	km	4.5	10	14
$\langle B \rangle$	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Scaled from MAP parameters

Meets luminosity goal

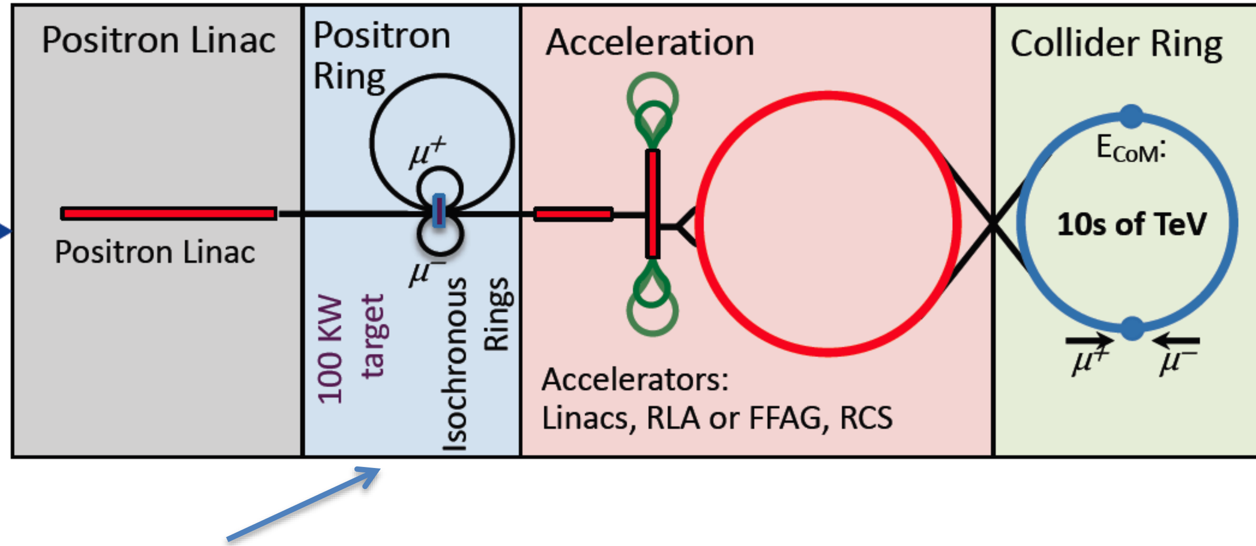
Beam power < 20 MW
CLIC would expect 200 MW

Feasibility remains to be demonstrated

Could expect 4 years to establish baseline + 6 years to CDR (technically limited)

The LEMMA Scheme

Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.



Key concept:
Produce muon beam with low emittance using a positron beam
No cooling required

But need large flux of positrons
An important challenge

Could maybe use plasma acceleration

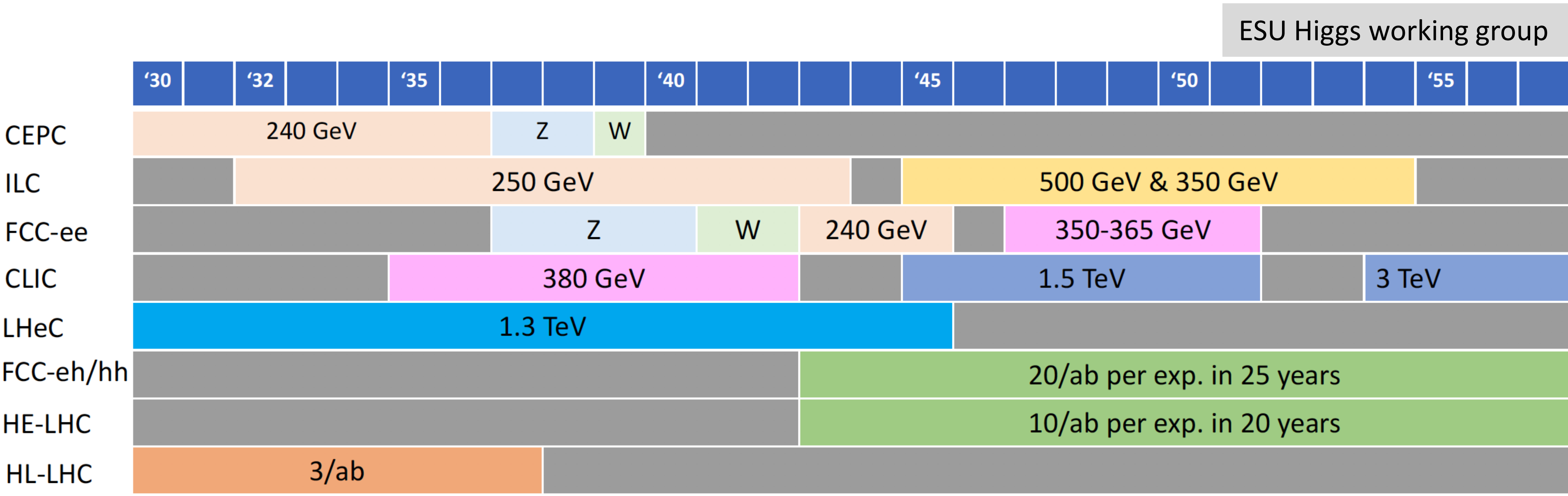
More work and innovations required to achieve high luminosities

Conclusion

- Several proposals for higgs factories exist
  - ILC is waiting for political decisions
  - CEPC depends on China
  - FCC-ee and CLIC appear feasible and need technical design, which can be ready for next strategy (waiting for current strategy to decide which options)
- For highest energies proposals exist
  - FCC-hh (and SPPC) to push the proton frontier is feasible, mainly the magnet development defines the critical path, should know by next strategy
  - CLIC to push the lepton frontier is feasible, with a similar status than for the CLIC higgs factory
- Other lepton energy frontier options are being thought about
  - plasma acceleration is in an early stage for the technology and its use in a collider
  - Muon collider is a unique concept using pushed proton and lepton collider technologies and concepts, goal to know by next strategy if feasible

For discussion: https://vidyoportal.cern.ch/join/GxHvDjPMz5

Proposed Schedules



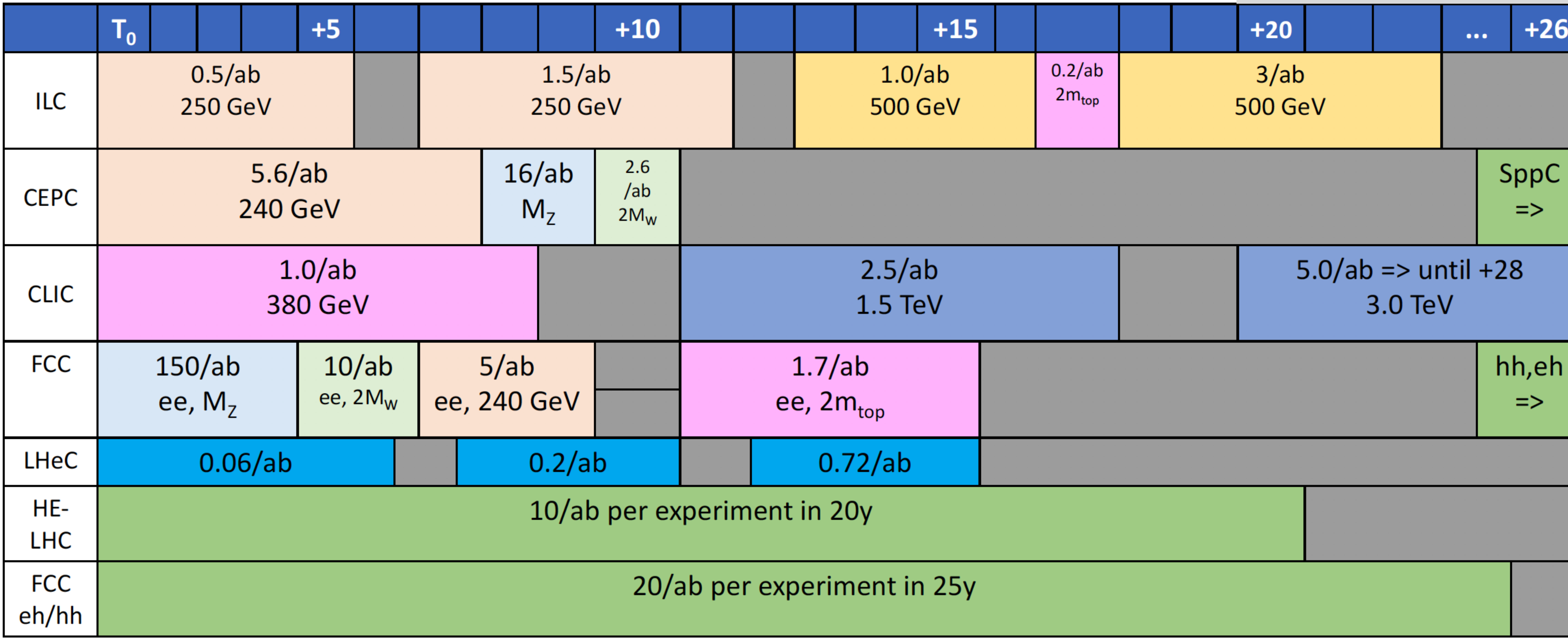
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)

Proposed dates from projects

Would expect that technically required time to start construction is O(5-10 years) for prototyping etc.

Proposed Schedules

ESU Higgs working group



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Proposed dates from projects

Would expect that technically required time to start construction of higgs factories is O(5-10 years) for prototyping etc.

Some References

B. Cros, Advanced LinEar collider study GROup (ALEGRO) Input
A. Caldwell, AWAKE: On the path to Particle Physics Applications

N. Pastrone, Muon Colliders
C. Rubbia, Further searches of the Higgs scalar sector
Many individual papers

J. Gao, CEPC Input to the ESPP 2018 –Accelerator
Y. Wang

M. Benedikt, Future Circular Collider - The Lepton Collider (FCC-ee)
M. Benedikt, Future Circular Collider – The Hadron Collider (FCC-hh)
M. Benedikt, Future Circular Collider – The Integrated Programme (FCC-int)
M. Benedikt, Future Circular Collider – The High-Energy LHC (HE-LHC)
The FCC CDRs

J. Fuster, The International Linear Collider. A European Perspective
J. Fuster, The International Linear Collider. A Global Project
arXiv:1903.01629

A. Robson, The Compact Linear e+e- Collider (CLIC): Accelerator and Detector
The Project Implementation Plan

M. Klein, PERLE : A High Power Energy Recovery Facility for Europe
M. Klein, Exploring the Energy Frontier with Deep Inelastic Scattering at the LHC
LHeC CDR

Several others, e.g. input from member states, R. Poeschl, Future colliders - Linear and circular, …

Reserve

Plasma Collider

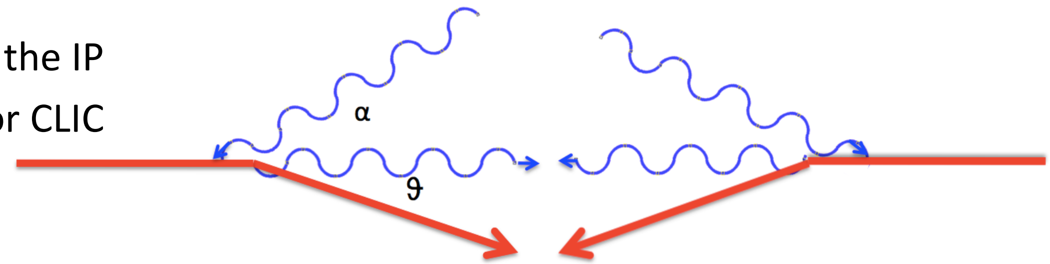
Gamma-gamma Collider Concept

Based on e^-e^- collider

Collide electron beam with laser beam before the IP

Additional options that could be considered for CLIC and ILC

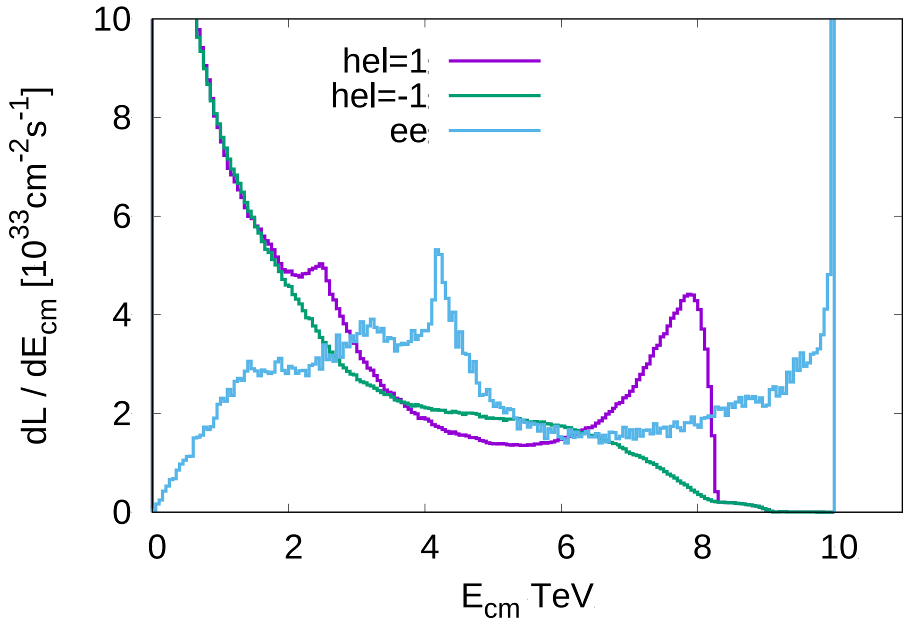
Could be **the** option for plasma colliders



Backscattered photons form a spectrum

Practical maximum energy is 83% of electron energy

Luminosity for 30 MW beam power at 10 TeV



$\beta_{x,y}$ = 8 mm / 0.1 mm

total 7×10^{34} $m^{-2}s^{-1}$

above 60% 0.9×10^{34} $m^{-2}s^{-1}$

$\beta_{x,y}$ = 5 μm (insanely small)

total 1×10^{36} $m^{-2}s^{-1}$

above 60% 0.14×10^{36} $m^{-2}s^{-1}$

How far can we push the beam parameters?
Need an important effort

Beam Size Limits

Studied in detail for CLIC

- Very difficult to reduce emittances for given bunch charge
  - Could gain some in the vertical plane if we improved the beam transport imperfections and their mitigation
- Difficult to reduce beta-functions
  - See non-linear and radiation effects
  - Actual beam size is larger than linear estimate
  - Ideal case would have 50% more luminosity
- Realistically already challenging to main scaling of beam sizes with sqrt(1/E)

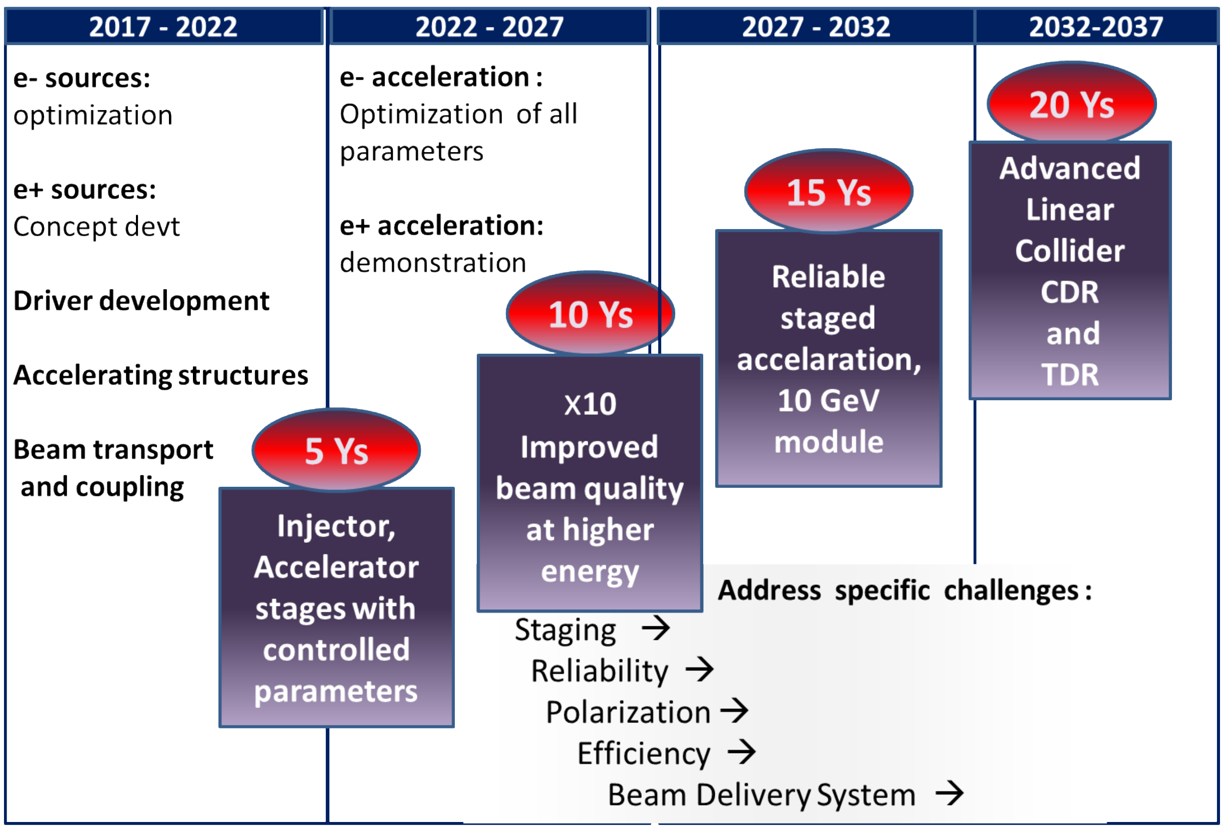
- Consequence for CLIC design
  - Cannot profit from very short bunch lengths very much

- For plasma technology this is even more important
  - Currently find larger energy spread in beam, i.e. harder to focus
  - Bunches are shorter so could profit more from better focusing

ALIC: Proposed Schedule

Path to ALIC (Advanced Lineat Collider)
proposed by ALEGRO (Advanced LinEar collider study GROup)

- Physics Case (PC); WG1: M. Peskin (SLAC), Junping Tian (U. Tokyo)
- Collider machine design/definitions (CMD) ; WG2: D. Schulte (CERN), A. Seryi (JAI), Hitoshi Yamamoto (Tohoku Uni)
- Theory, Modeling, Simulations (TMS); WG3: J.-L. Vay (LBNL), J. Vieira (IST)
- LWFA; WG4: C. Schroeder (LBNL), S. Hooker (JAI/Oxford), B. Cros (CNRS/U. Paris Sud)
- PWFA; WG5: J. Osterhoff (DESY), E. Gschwendtner (CERN), P. Muggli (MPP)
- SWFA; WG6: P. Piot (NIU), J. Power (ANL)
- DLA; WG7: J. England (SLAC), B. Cowan (Tech-X)
- Positron acceleration (PAC); WG8: S. Corde (LOA), S. Gessner (CERN)



No parameters yet
Need more work before we can produce a good target set

Ultimate goal: enable modeling of 100s-1000s stages by 2025-2035 for 1-30 TeV collider design!

Muon Collider

Muon Collider Working Group

Jean Pierre Delahaye, CERN, Marcella Diemoz, INFN, Italy,
Ken Long, Imperial College, UK, Bruno Mansoulie, IRFU, France,
Nadia Pastrone, INFN, Italy (chair), Lenny Rivkin, EPFL and PSI, Switzerland,
Daniel Schulte, CERN, Alexander Skrinsky, BINP, Russia, Andrea Wulzer, EPFL and CERN

appointed by CERN Laboratory Directors Group in September 2017

to prepare the Input Document to the European Strategy Update

"Muon Colliders," arXiv:1901.06150

de facto it is the seed for a renewed international effort

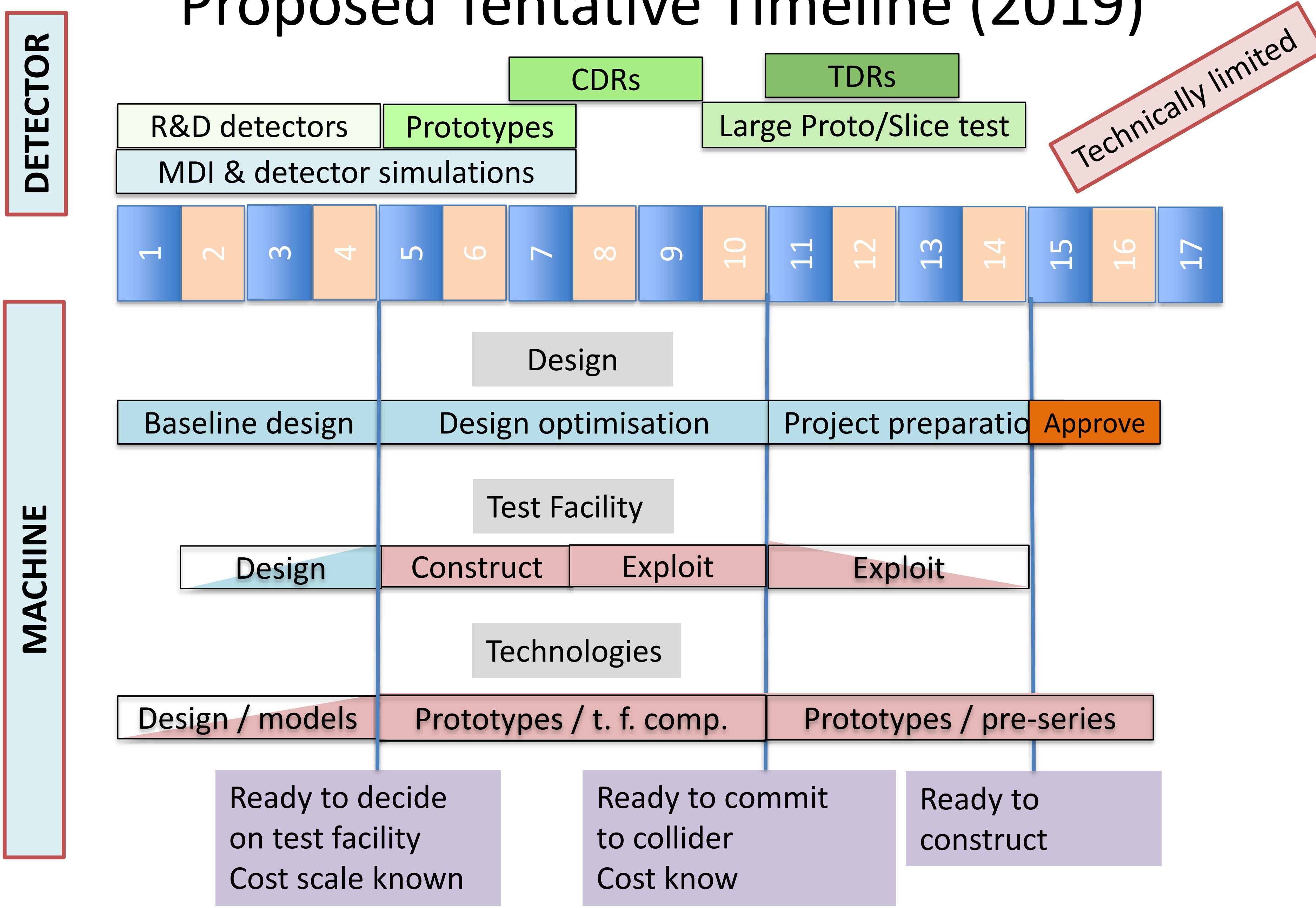
Past experiences and new ideas discussed at the joint ARIES Workshop

July 2-3, 2018
Università di Padova - Orto Botanico
https://indico.cern.ch/event/719240/overview

Preparatory meeting to review progress for the ESPPU Symposium

April 10-11, 2019
CERN – Council Room
https://indico.cern.ch/event/801616

Proposed Tentative Timeline (2019)



Proposed Tentative Timeline (2019)

DETECTOR

CDRs

TDRs

R&D detectors

Prototypes

Large Proto/Slice test

MDI & detector simulations

Technically limited

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

MACHINE

Limited Cost

Mainly paper design

And some hardware component R&D

Higher cost for test facility

Specific prototypes

Significant resources

Higher cost for technical design

Significant resources

Higher cost for preparation

Full project

Design / models

Prototypes / t. f. comp.

Prototypes / pre-series

Ready to decide on test facility
Cost scale known

Ready to commit to collider
Cost know

Ready to construct

Electron-Positron Colliders

Energy Challenge

The energy of the collider is the most costly part
Energy can be predicted somewhat reliably based on prototypes e.g. performance of accelerating structures or dipole magnets
CLIC drive beam is special case

ILC

Cavities have already been mass-produced
Not quite the gradient for ILC but better than what has been required for X-FEL
Advances in cavity gradients with nitrogen infusion

⇒ Very mature
⇒ Next step: Industrialisation of full-gradient ILC structures

FCC-ee

800 MHz prototype
Expect that the gradient should be well in hands, based on LHC

⇒ Improving existing technology

CLIC

The limits of normal-conducting are quite well understood and experimentally verified
Several prototypes exist
The normal-conducting acceleration technology has been used in many projects
Applications of X-band frequency is increasing

⇒ Mature
⇒ Next (ongoing) step: industrialisation of CLIC structures

Power source (drive beam) has been tested

FCC-hh / HE-LHC

The main challenge are the arc dipoles
No short models yet

⇒ The technology needs to be developed and one has to produce prototypes

LHeC

Aim to build a test facility PERLE

Physics and Luminosity Goal

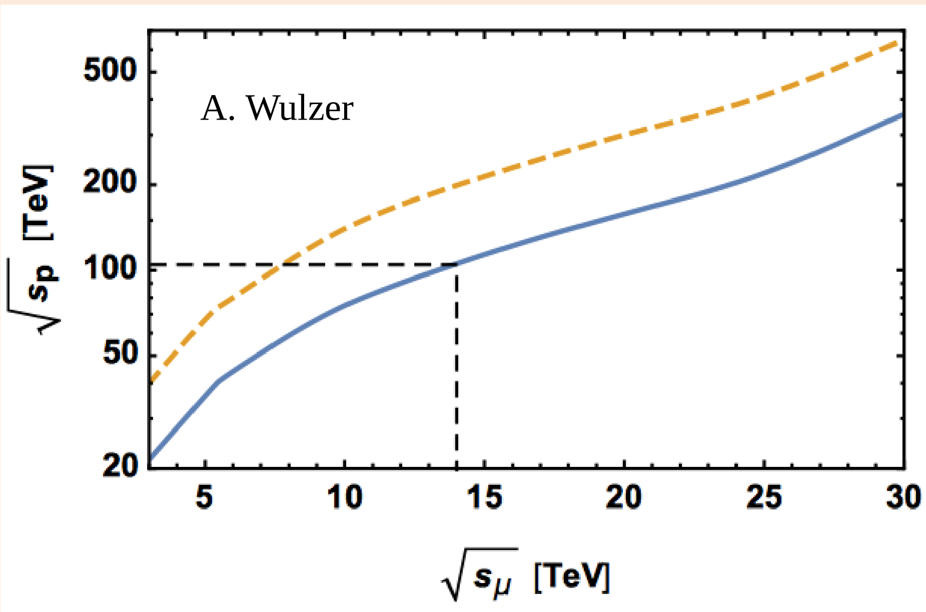
High energy lepton colliders are **precision** and **discovery** machines

$$V = \frac{1}{2} m_h^2 h^2 + (1 + k_3)\lambda_{hhh}^{SM} v h^3 + (1 + k_4)\lambda_{hhhh}^{SM} h^4$$

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao
[Muon Collider - Preparatory Meeting]

Precision potential

Measure k_4 to some 10%
With 14 TeV, 20 ab^{-1}



Discovery reach

14 TeV lepton collisions are comparable to 100 TeV proton collisions

For s-channel physics target

Luminosity goal

(Factor O(3) less than CLIC at 3 TeV)
4×10^{35} $cm^{-2}s^{-1}$ at 14 TeV

$$\boxed{L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}}$$

Key Parameters

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	$10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

Schedule

Technically limited schedule

2013 – 2019

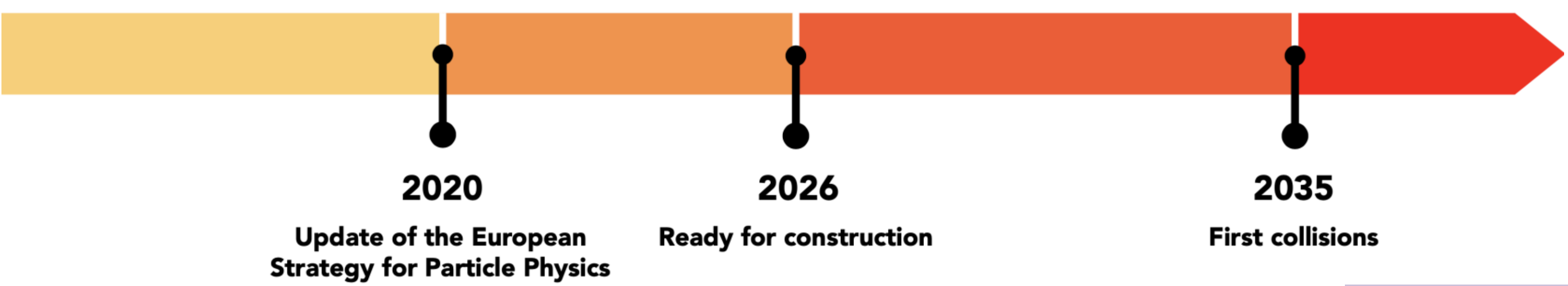
Development Phase
Development of a project plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

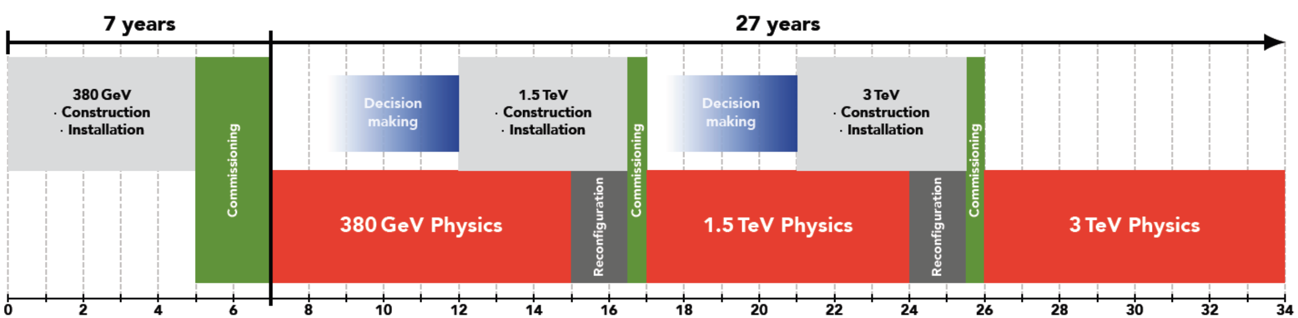
2020 – 2025

Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, pre-series and system optimisation studies, technical proposal of the experiment, site authorisation

2026 – 2034

Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning





Costs 5.9 GCHF (380 GeV)
+ 5.1 GCHF (1.5 TeV)
+ 7.3 GCHF (3 TeV)

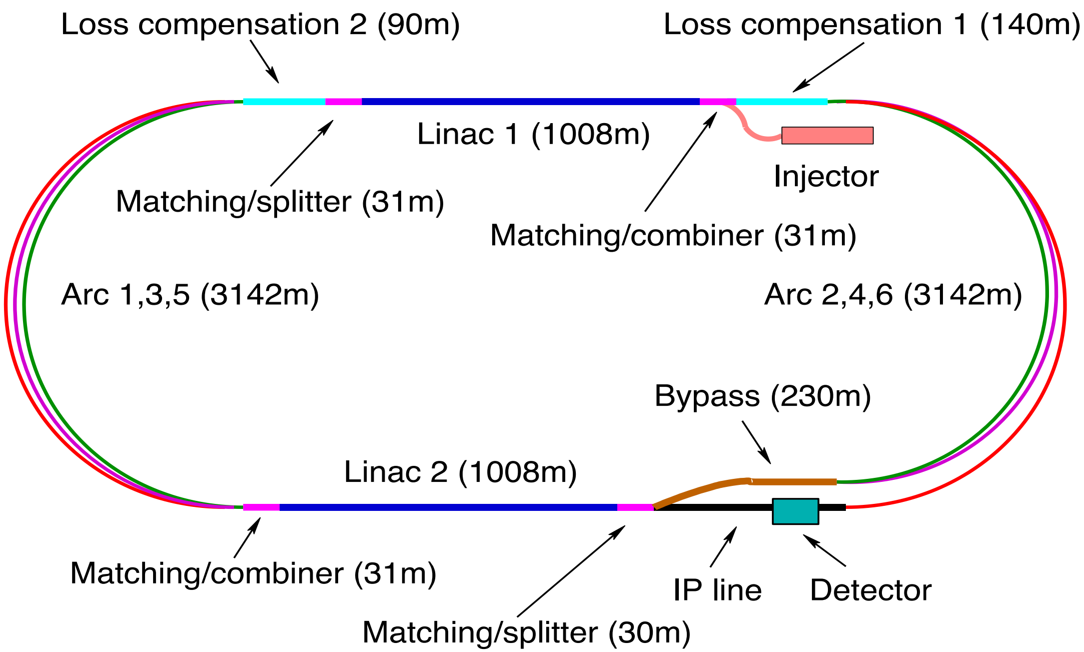
0.4 GCHF for the detector

First collisions in 2035

Ready for construction in 2026
Time for R&D until then could be sufficient

Electron-Hadron Colliders

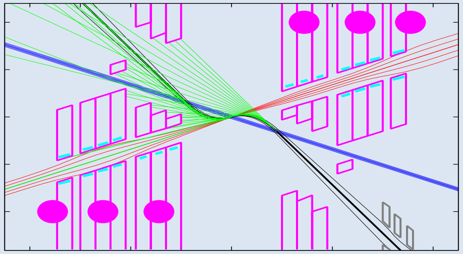
Lepton-Proton Collider Opportunities and Challenges



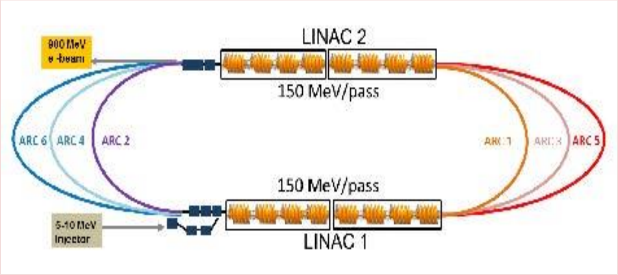
Integrated luminosity goal
LHC run 5+6 and dedicated run O(1 ab^{-1})

	LHeC CDR	HL-LHeC	HE-LHeC	FCC-he
E_p [TeV]	7	7	13.5	50
E_e [GeV]	60	60	60	60
L [10^{33} $cm^{-2}s^{-1}$]	1	8	12	15

Interaction region
design ongoing



Development of accelerator technology
E.g. RF power required to control cavities
Test facility (PERLE) planned in Orsay



CDR in 2012, update being finalised right now
- Do need important increase in resources for detailed studies
- Are not aware of any show-stopper