Technical Overview and Challenges of Proposed Higgs Factories

D. Schulte

Many thanks to

M. Benedikt, A. Blondel, O. Brunner, J. Gao, A. Grudiev, B. Heinemann, E. Jensen, P. Janot, M. Klein, B. List, M. Mangano, S. Michizono, K. Oide, T. Okugi, M. Palmer, L. Rivkin, V. Shiltsev, S. Stapnes, D. Tommasini, J. Wenninger, G. White, W. Wuensch, A. Yamamoto, F. Zimmermann

And all the people that did the work in the different studies

Submissions and Papers

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, …

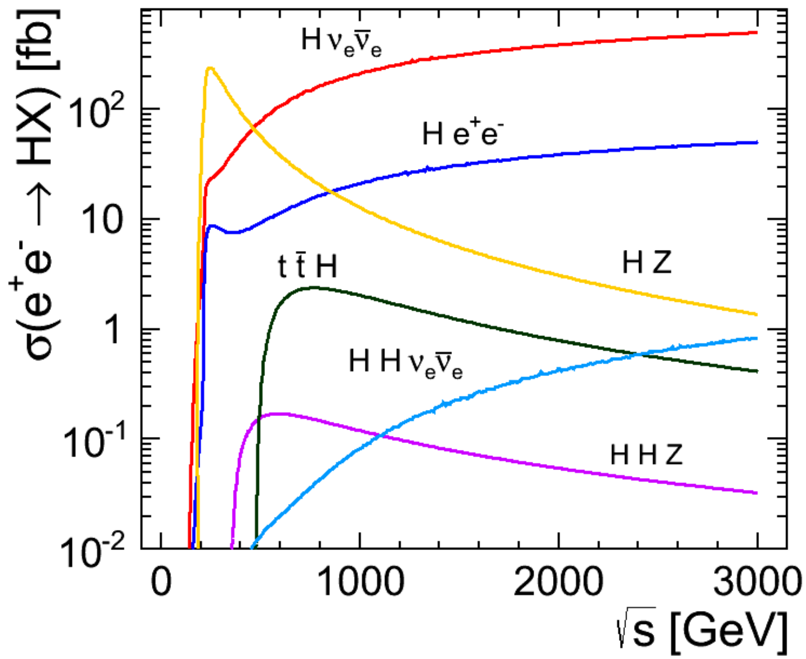
Higgs Factories

All new high-energy colliders are also higgs factories

- Cannot cover them all in detail, so focus on some

- Electron-positron colliders
  - Linear colliders
    - ILC and CLIC
  - Circular colliders
    - FCC-ee and CepC
    - (LEP 3)

One in Europe, one in Asia



- Hadron colliders
  - LHC, HL-LHC, HE-LHC, FCC-hh and SppC

Happens in any case

- Lepton-hadron colliders
  - LHeC and FCC-eh

- Muon colliders
- Plasma colliders
- LEP3 and "Low-field" magnets in FCC tunnel

Not mature enough at this moment
More R&D needed
Muon colliders could come in if we fail to have another higgs factory

Rationales

CLIC:
Ultimate goal: Achieve multi-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

ILC:
Ultimate goal: Reach energies of originally 0.5-1 TeV
- Use high gradient superconducting technology
- Now reduce cost to obtain funding

FCC-hh + FCC-ee
Push the energy frontier with protons
- Large ring with high field magnets

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

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

LHeC:
Expand the LHC programme with limited cost

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

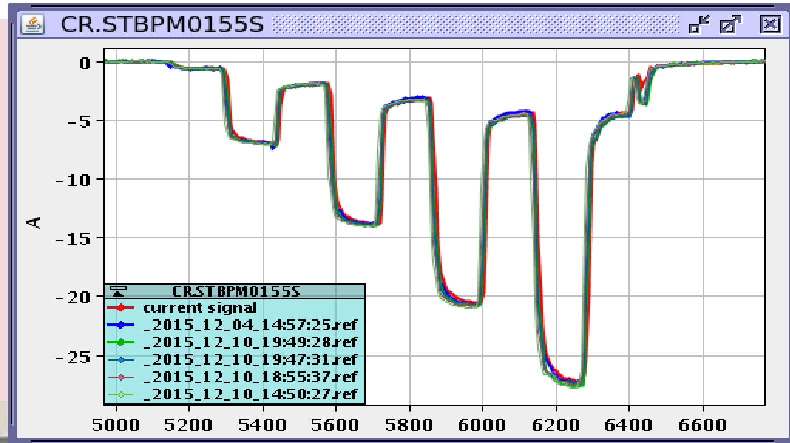
FCC-hh / HE-LHC
The main challenge are the arc dipoles
No short models yet
⇒ The technology needs to be developed and one has to produce prototypes

LHeC
Aim to build a test facility PERLE

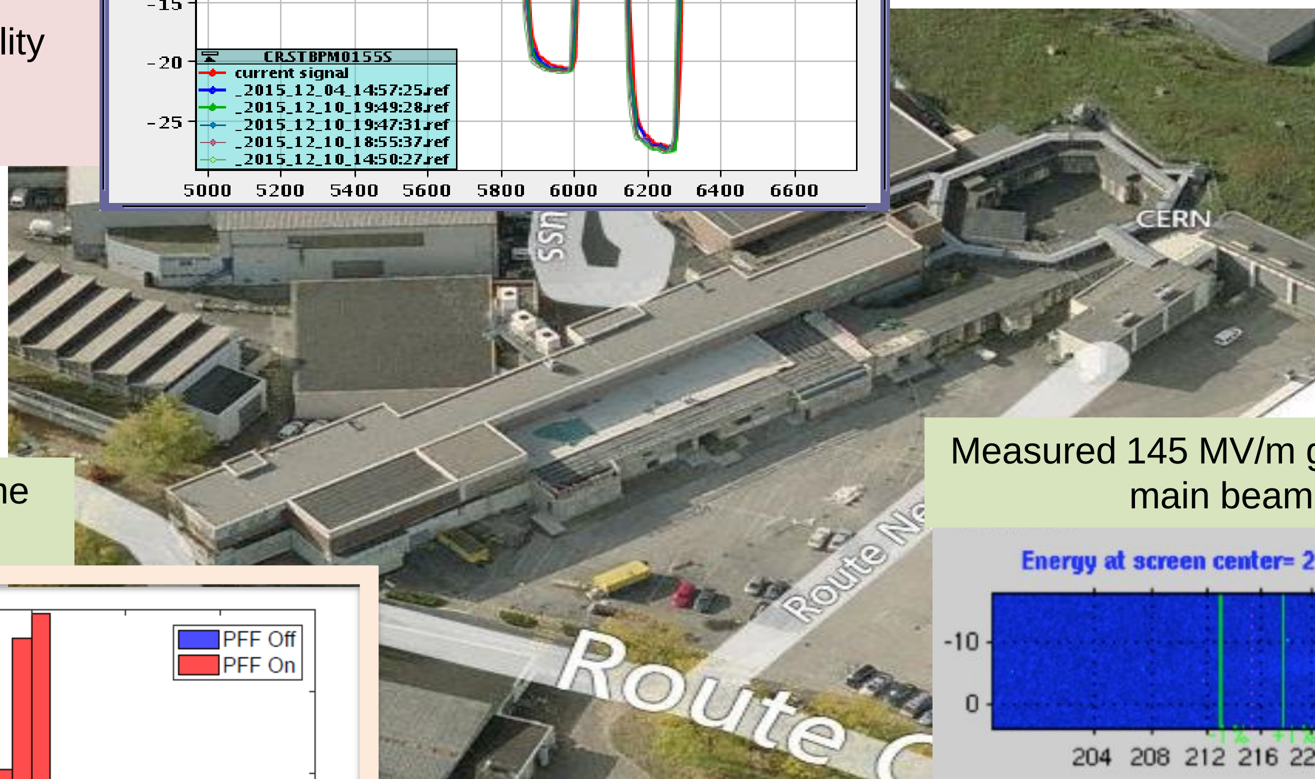
⇒ Akira Yamamoto, this morning

Drive Beam Results

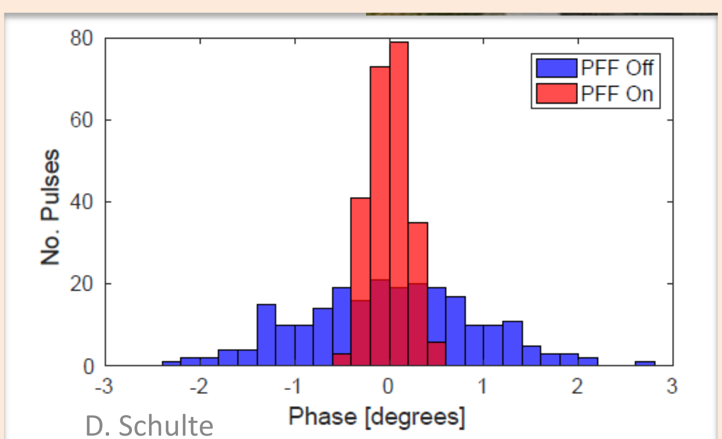
CTF3 measurements:
- RF to drive beam efficiency > 95%
- Current multiplication factor 8
- Most of beam quality
- 145 MV/m X-band acceleration



Detailed simulations of drive beam performance in CLIC



Drive beam arrival time with feedback



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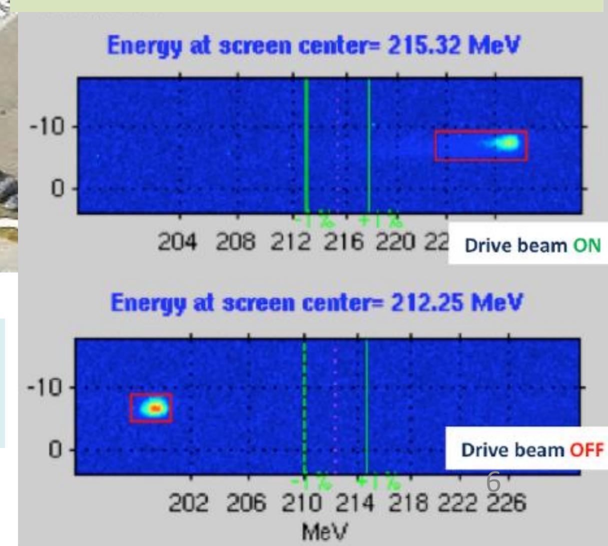
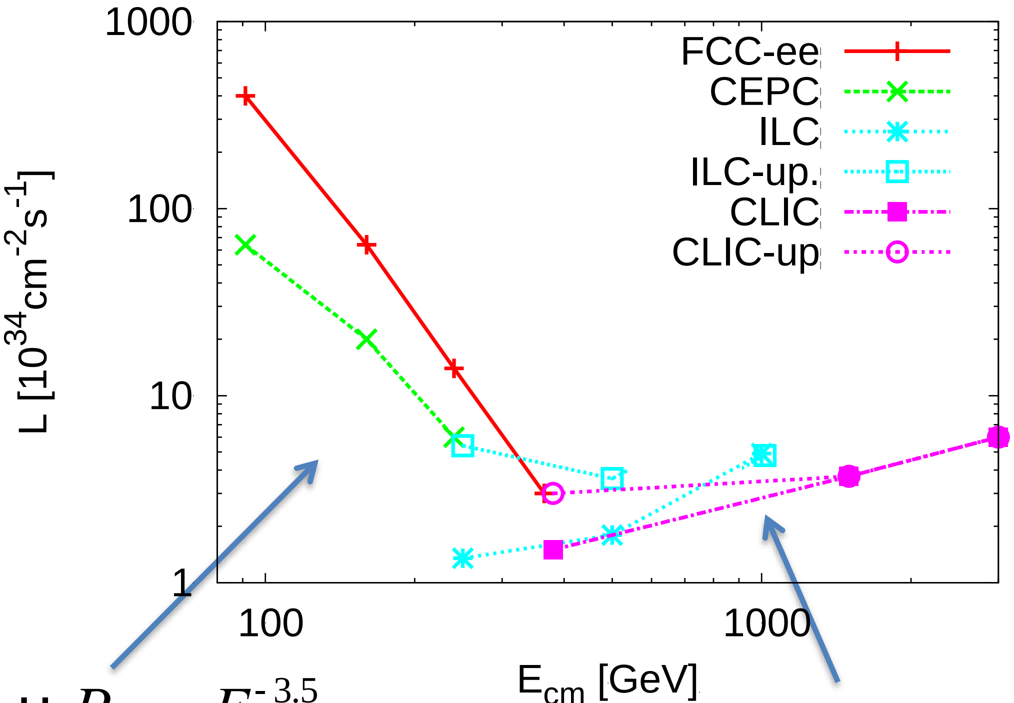
Measured 145 MV/m gradient on main beam



New facility: CLEAR
Focus on main beam

Luminosity

Luminosity per facility



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

$$L \propto P_{RF} E_{cm}$$

Energy dependence:

At low energies circular colliders trump

- Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel

- Luminosity per beam power roughly constant

Note: The typical higgs factory energies are close to the cross over in luminosity

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

Luminosity Goals

Goals are based on technologies but also judgement of the supporters

Could be higher at some cost

- FCC-ee could consider more experiments or running longer
    - Higher total luminosity
    - Some cost increase
    - Maybe can also push performance limits
- ILC considers more bunches per pulse and doubling the repetition rate
    - Each would double the luminosity
    - More bunches requires more main linac RF
    - Higher repetition rate requires undulator-based source to work
    - More power consumption and somewhat higher cost
- CLIC discusses doubling the repetition rate at 380 GeV
    - Luminosity would double
    - Expect increase of power from 170 MW to 220 MW and slight cost increase

All projects could run longer to have more integrated luminosity

All projects should have margins on luminosity to ensure that gaol is met

Be careful with strong conclusions based limited differences of these numbers

Luminosity Challenge

Luminosity cannot be fully demonstrated before the project implementation
- Luminosity is a feature of the facility not the individual technologies
- Have to rely on experiences, theory and simulations
- Foresee margins

FCC-ee and CEPC are based on experience from LEP, DAPHNE, KEKB, PEP II, superKEKB, …
- Gives confidence that we understand performance challenges
- New beam physics occurs in the designs,
    - e.g. beamstrahlung is unique feature of FCC-ee and CEPC
        - Identified and anticipated in the design, should be able to trust simulations
- The technologies required are improved versions of those from other facilities

Linear colliders are based on experiences from SLC, FELs, light sources, …
- Gives confidence that we understand the performance challenges
- Gives us confidence that we can do better than SLC
- Still performance goal more ambitious, e.g. beam size of nm scale
    - Creates additional challenges and requires additional technologies, e.g. stabilisation
- A part of the technologies are improved versions of those from other facilities
- Some had to be purpose-developed for linear colliders

All studies prioritised their work because of limited resources
- Depending on your preference you will see holes in any of them that you find are unacceptable
- Or you will be convinced that this very issue is a mere detail …

Luminosity

Luminosity depends on

- Beam current
- Beam quality
- Focusing ability (small β_y^*)

- Beamstrahlung
- Beam-beam stability

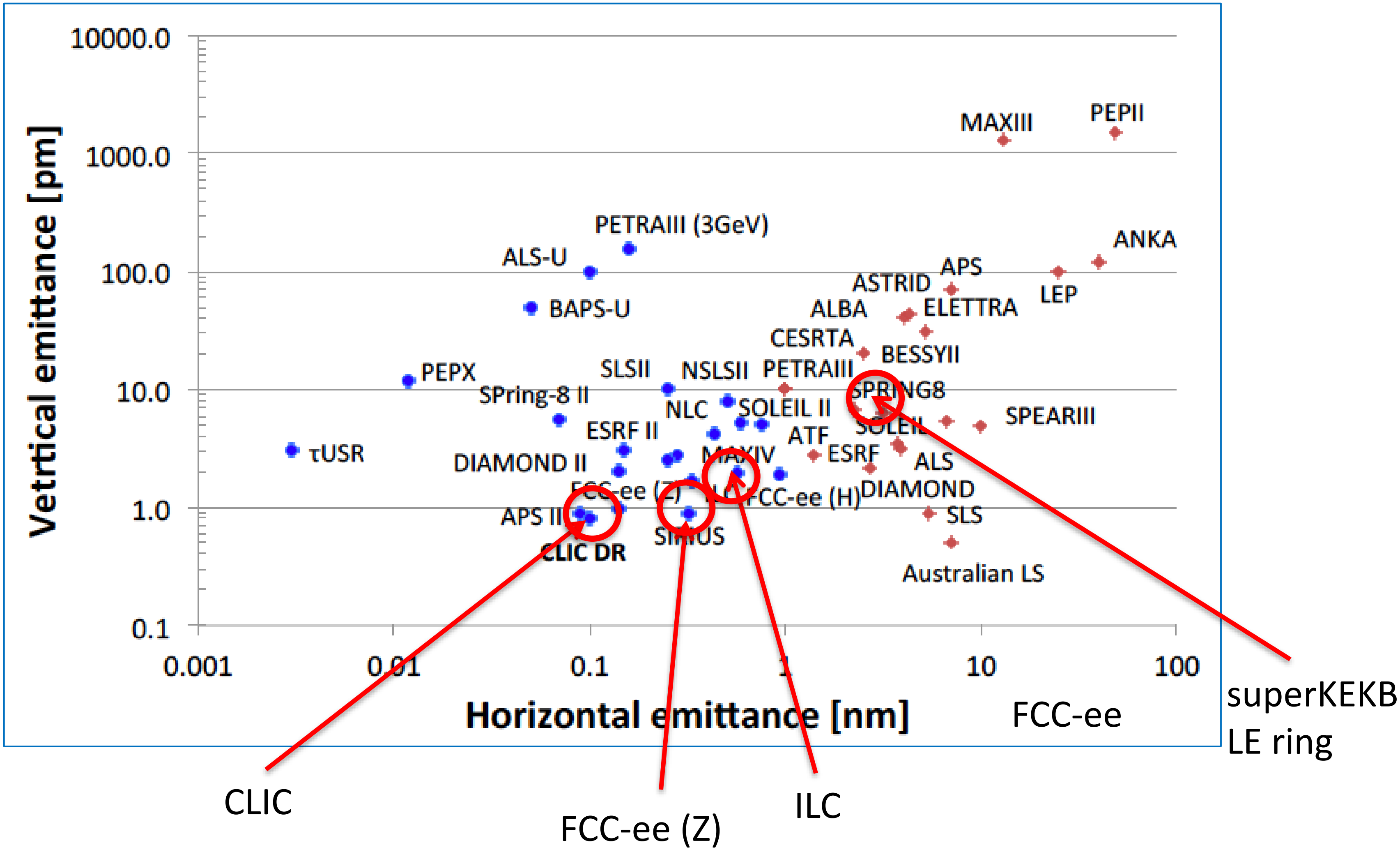
Circular collider

$$L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta_y^*} \cdot R_{\mathrm{HG}}$$

Linear collider

$$\mathcal{L} \propto H_D \quad \frac{N}{\sigma_x} \quad N n_b f_r \quad \frac{1}{\sigma_y}$$

Low Emittance Generation



Small emittance is generated in collider ring for FCC-ee
Small emittance is generated in damping ring for linear colliders

Emittance Preservation in FCC-ee

Emittance in FCC-ee are better than superKEKB due to interaction region design

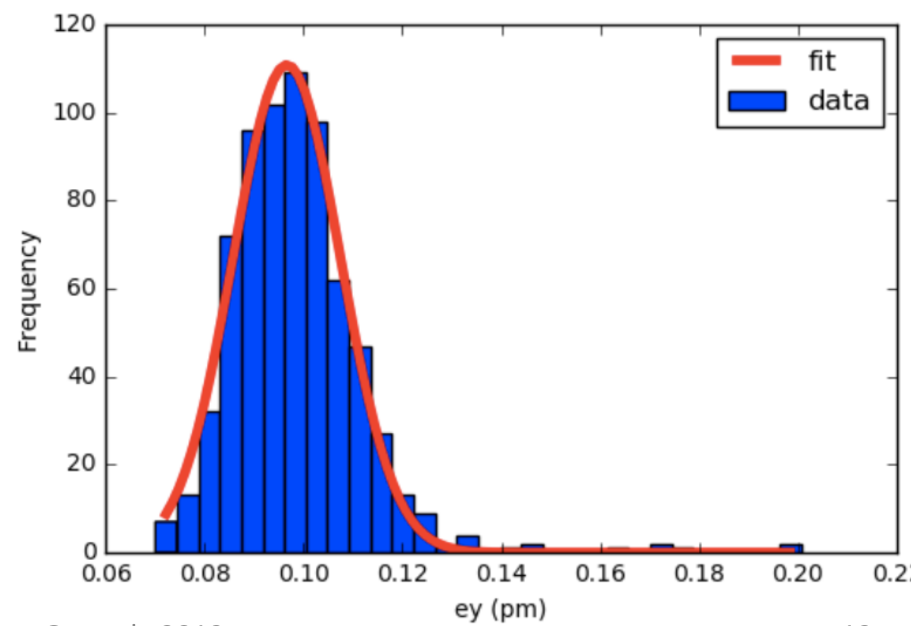
Critical effects have been simulated

- Beam lifetime
- beam-beam effects
- Impedance
- Electron cloud
- …

E.g. Simulation of component misalignment shows acceptable vertical emittance

Some reserve for other effects

	E_{beam} [GeV]	ε_x [nm]	ε_y [pm]
FCC-ee	45.6	0.27	1.0
	120	0.63	1.3
	182.5	1.46	2.9
LEP	45.6	19.3	230
SuperKEKB	4	3.2 (1.9)	8.6 (2.8)
	7	4.6 (4.4)	11.5 (1.5)



We are not aware of any feasibility issue

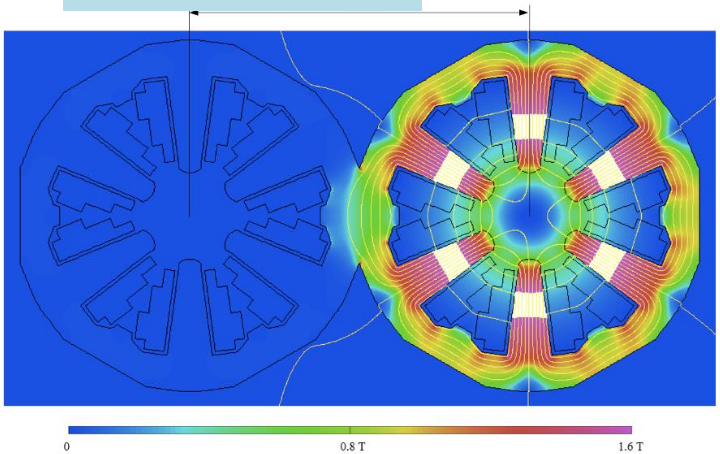
- But some issues still have to be addressed
  - E.g. strong-strong beam-beam with full lattice errors
- superKeKB, DAPHNE, … are test facilities

Technology risks to achieve luminosity are probably limited

- prototypes are essential to confirm this

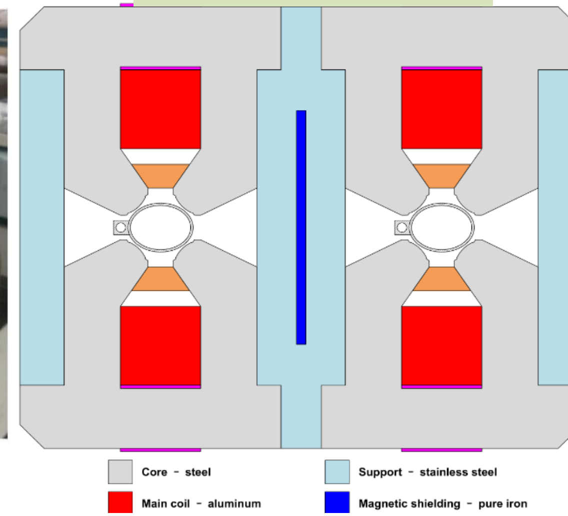
FCC-ee / CEPC Technologies

FCC-ee arc sextupole



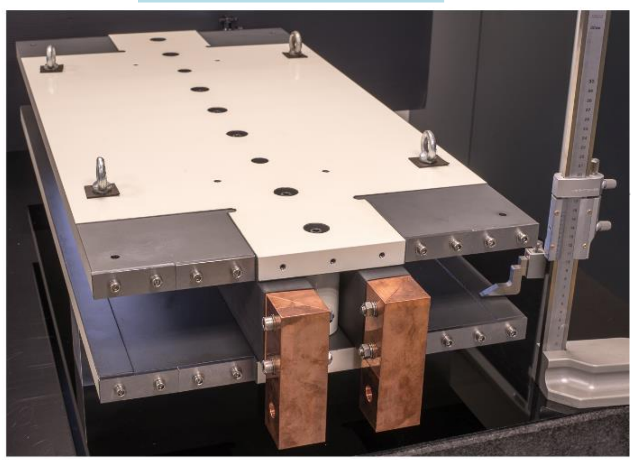
FCC-ee 800 MHz cavity

CEPC arc quadrupole

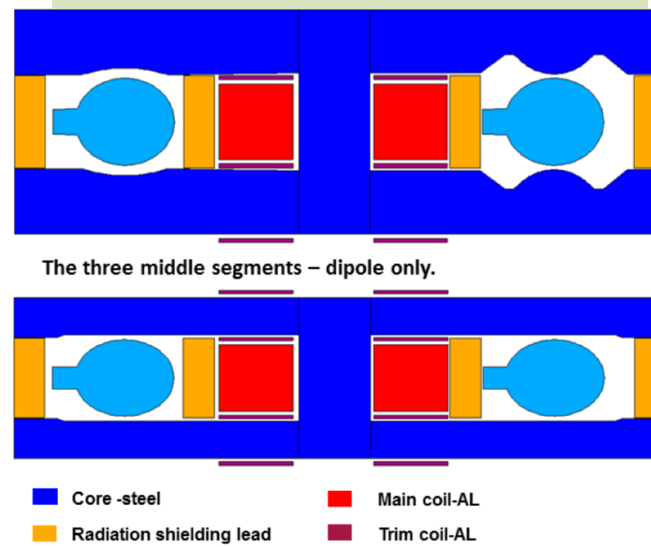


FCC-ee arc quadrupole

FCC-ee arc dipole



CEPC arc combined function magnet



Emittance Preservation (CLIC)

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y} \qquad \sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Damping ring main source of horizontal emittance

Imperfections are main source of final vertical emittance
Otherwise would have L = 4.3×10^{34} $cm^{-2}s^{-1}$

Require 90% likelihood to meet static emittance growth target

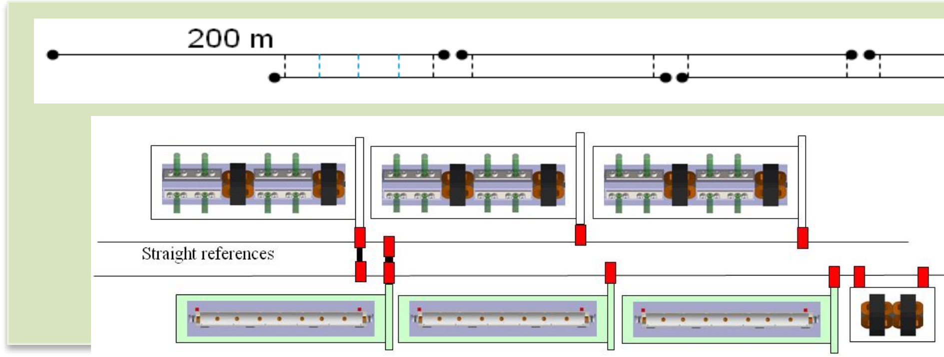
	Norm $\Delta\epsilon_x$ [nm]	$\Delta\epsilon_y$ [nm]		
	Total contribution	Design limits	Static imperf.	Dynamic imperf.
Damping ring exit	700	5	0	0
End of RTML	150	1	2	2
End of main linac	50	0	5	5
Interaction point	50	0	5	5
sum	950	6	12	12

Similar approach in ILC

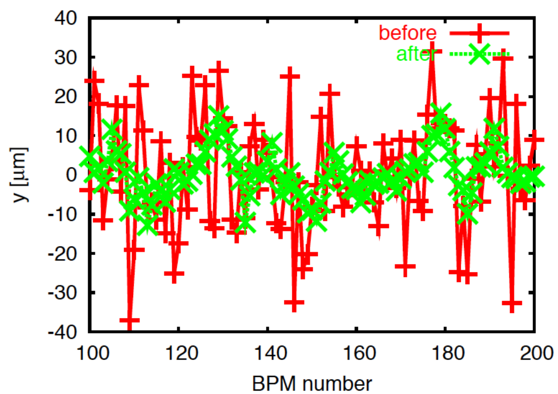
Example: Main Linac

Goal 90% less than 5 nm emittance growth

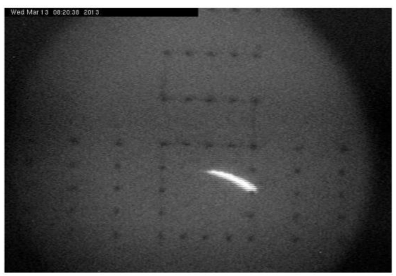
- Optimised design for stability
- Developed prototype alignment system
- Model system with codes
- Apply beam-based methods
- Tested methods at SLAC



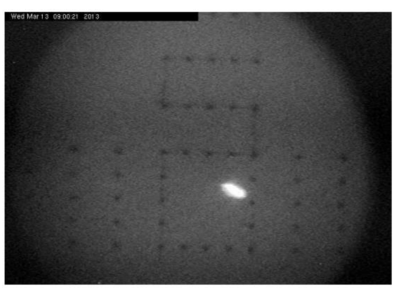
Alignment accuracy, O(10µm)
Further improvement with beam



Before correction



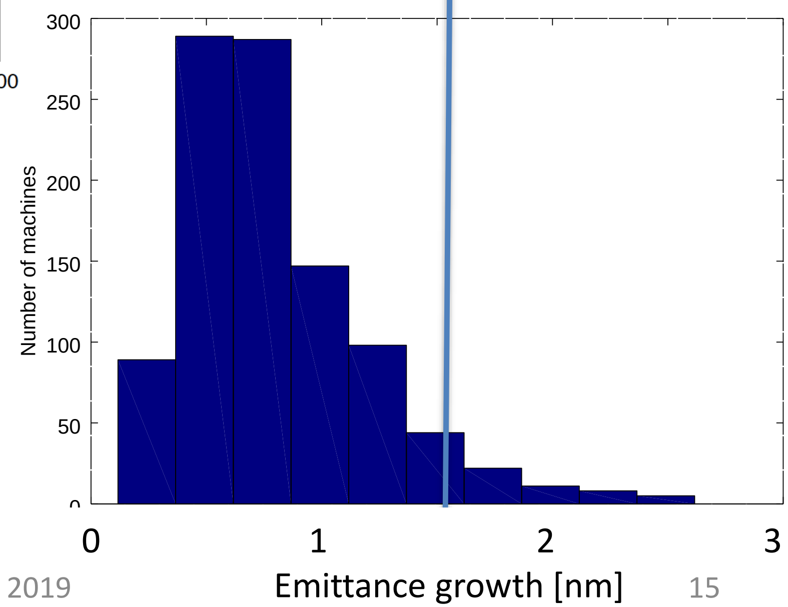
After 3 iterations



90% likelihood to stay below 1.5 nm
Expectation value: less than 1 nm

Luminosity expectation value including also RTML and BDS
3 x 10^{34} $cm^{-2}s^{-1}$, i.e. twice the target

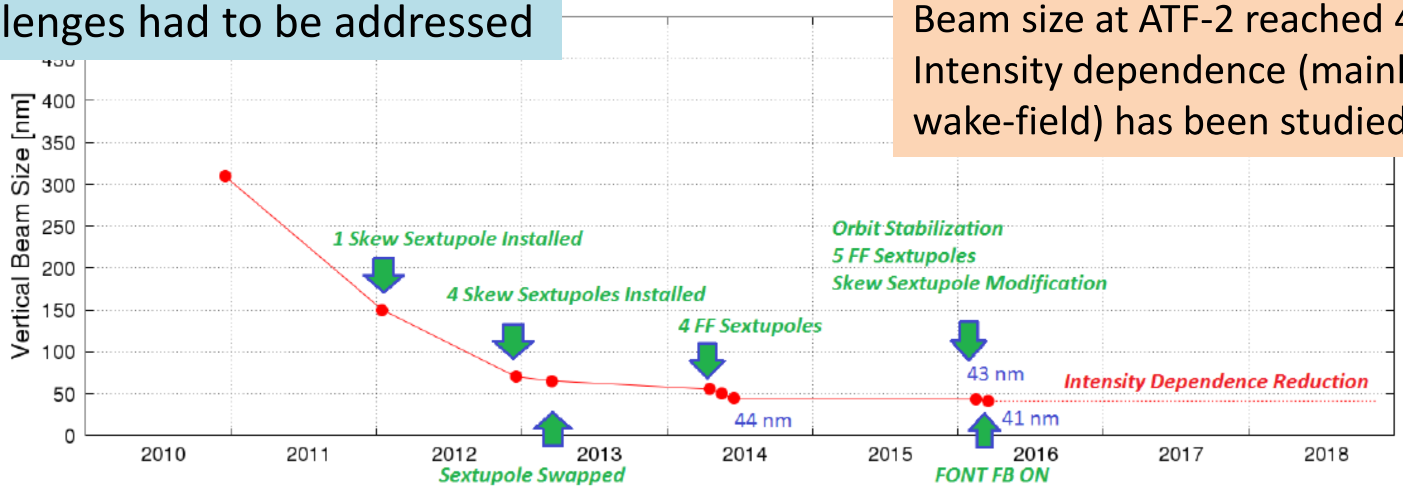
Important margin is kept
Studies show also margin for 3 TeV

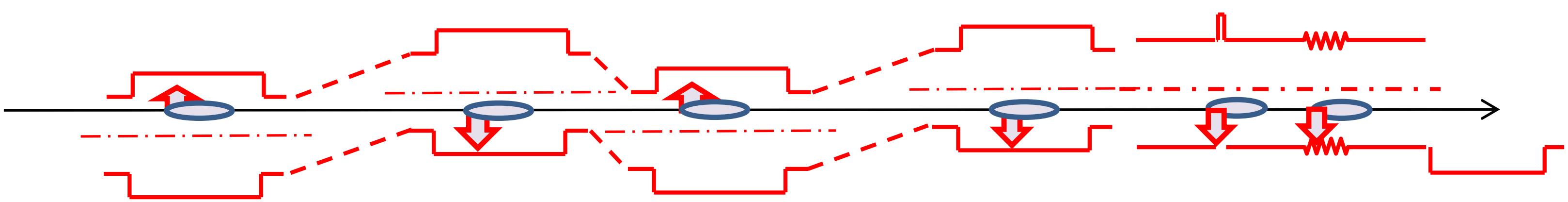


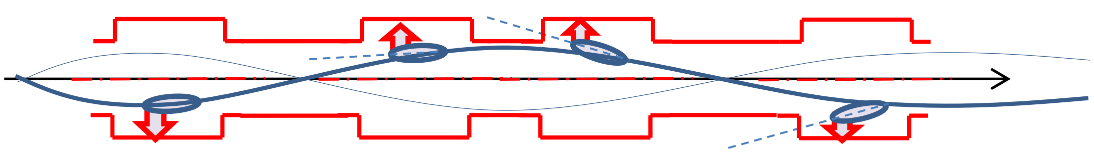
Example: Beamsize at ATF2

Many challenges had to be addressed

Beam size at ATF-2 reached 41 nm. Intensity dependence (mainly by wake-field) has been studied.







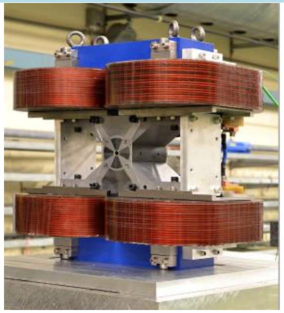
Seem to understand wakefield effects, would not be sever in colliders

ILC / CLIC Technologies

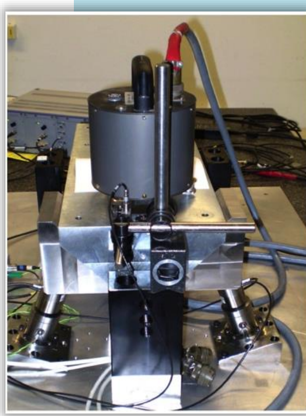
Cavity

High efficiency klystrons,
Instrumentation, kickers, …

Short final quadrupole prototype

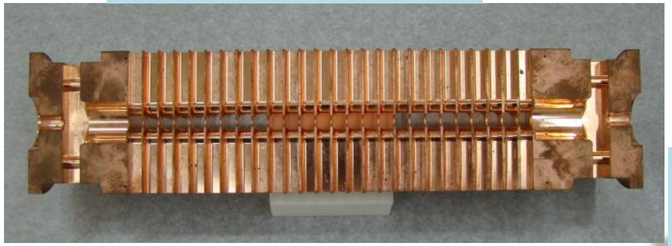


Magnet stabilisation



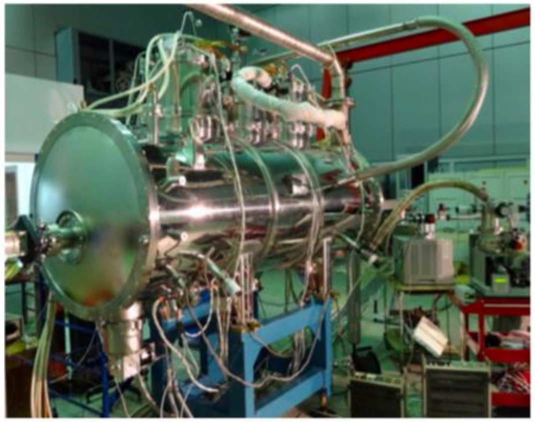
Kryomodules

Accelerating structure

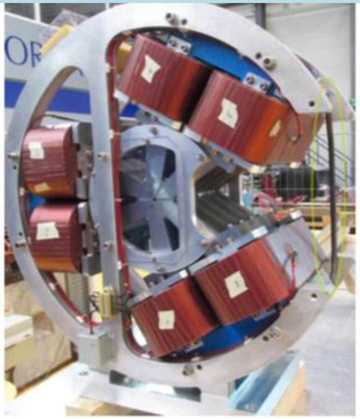


Drive beam and main beam modules

NbTi damping ring wiggler



Short BDS sextupole prototype



ILC / CLIC Technologies

Technologies are used in a number of facilities
- e.g. LCLS / LCLS 2 at SLAC
- European X-FEL
- SACLA, SPRING 8, Swiss FEL, …

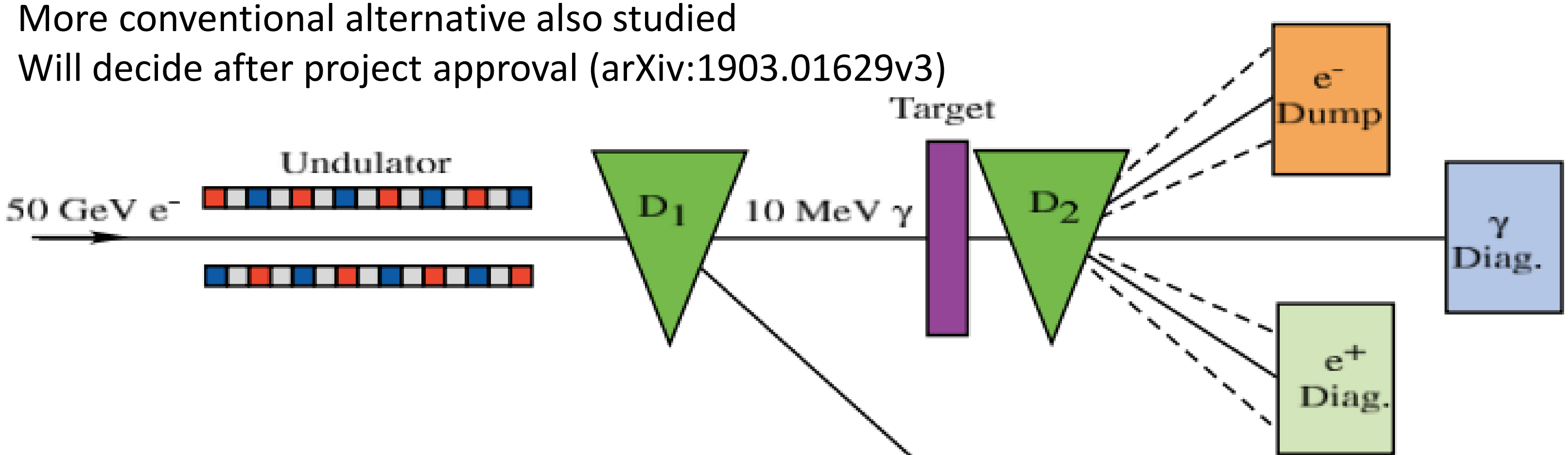
More to come
- European Commission supported X-band FEL design study
- SPARC
- SHINE
- …

Polarisation

Electron polarisation only in linear colliders
- 80%, SLC had 78% under difficult conditions
- Non-colliding bunches use transverse polarisation for energy measurements in FCC-ee

Positron polarisation of 30% in ILC
- not foreseen in CLIC, since not demanded by the physics study

ILC considers undulator-based positron source
- More conventional alternative also studied
- Will decide after project approval (arXiv:1903.01629v3)



At lower collision energy need longer undulator to produce positrons
- More heat on the target
- More tails mitigated by thinner target
- Slightly reduced positron yield (1.36, goal has been 1.5), i.e. reduced margin
- Worst score in review: “Calculation study only. But no show stopper seen yet.“
- Conventional source should be fine
- Risk for luminosuty upgrades

It appears OK
But if it is essential
it has to be checked

Operation Time

Effective operation time per year
We do not see a reason to assume this would differ much between CLIC and FCC-ee, i.e. 1.2×10^7 s/year
ILC assumes 1.6×10^7 s/year

- No longer stop in the year, similar to FCC-hh

Calculation for CLIC: 1.2×10^7 s/year
17 weeks winter shutdown
30 days commissioning
20 days machine development
10 days technical stops
75% efficiency on other days

Calculation for FCC-ee: 1.2×10^7 s/year
17 weeks end-of-the-year technical stop
30 days commissioning
20 days machine development
10 days technical stops
Availability 80%-5% for recovery

Calculation for ILC: 1.6×10^7 s/year
8 months of luminosity runs with 75% efficiency
4 months for stops, commissioning and machine development

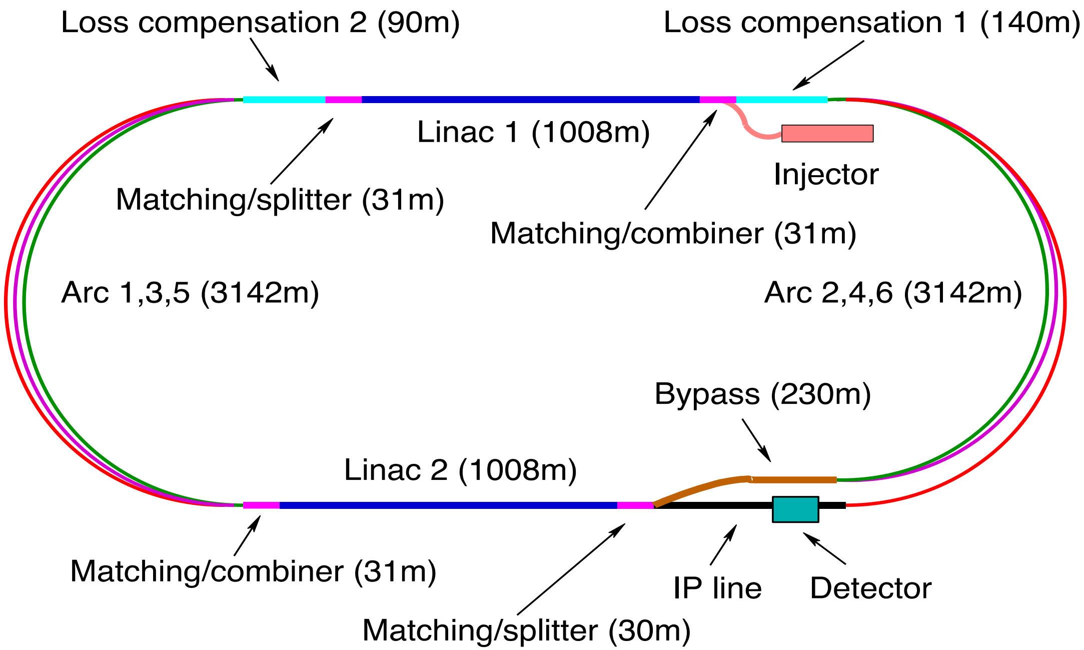
Availability / Efficiency
Challenging to meet in all cases
But goal of 75% is good

- Better cost more
- Worse makes it hard to achieve performance

Studies performed for CLIC indicates this appears realistic

- Defines the overheads

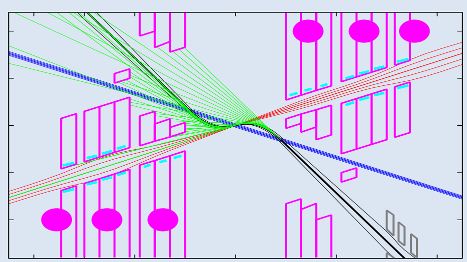
Lepton-Proton Collider Opportunities and Challenges



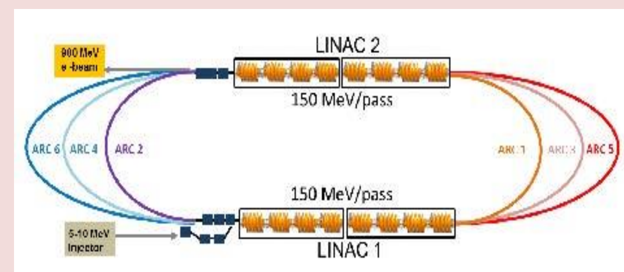
Integrated luminosity goal
LHC run 5+6 and dedicated run O(1 ab^{-1})

	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



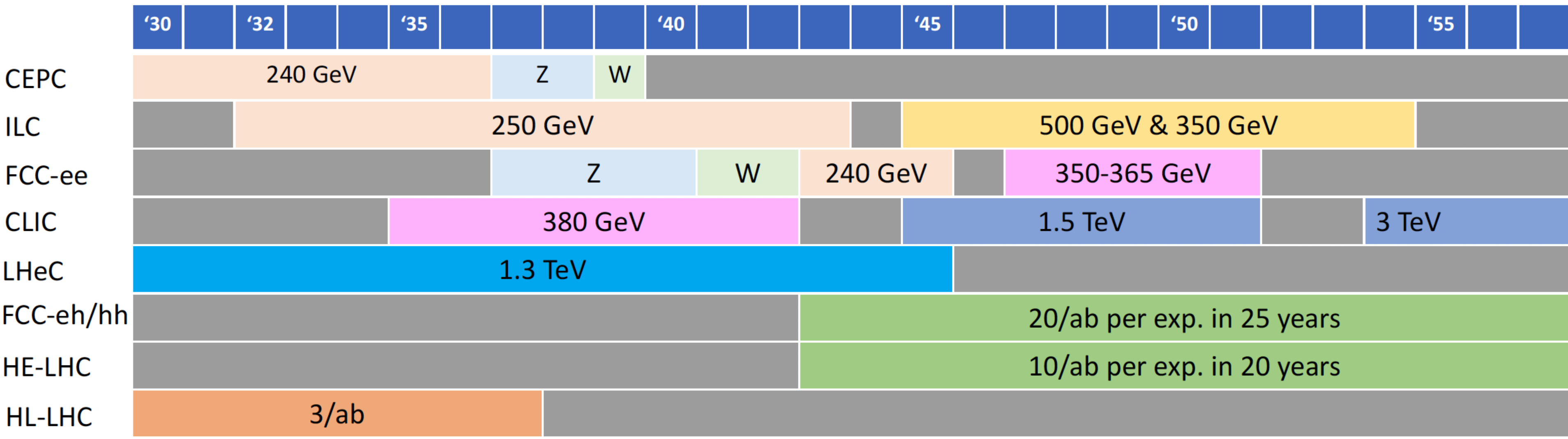
Development of accelerator technology
E.g. RF power required to control cavities
Test facility (PERLE) planned in Orsay



CDR in 2012, update planned for this autumn

- Do need important increase in resources for detailed studies
- Are not aware of any show-stopper

Proposed Schedules

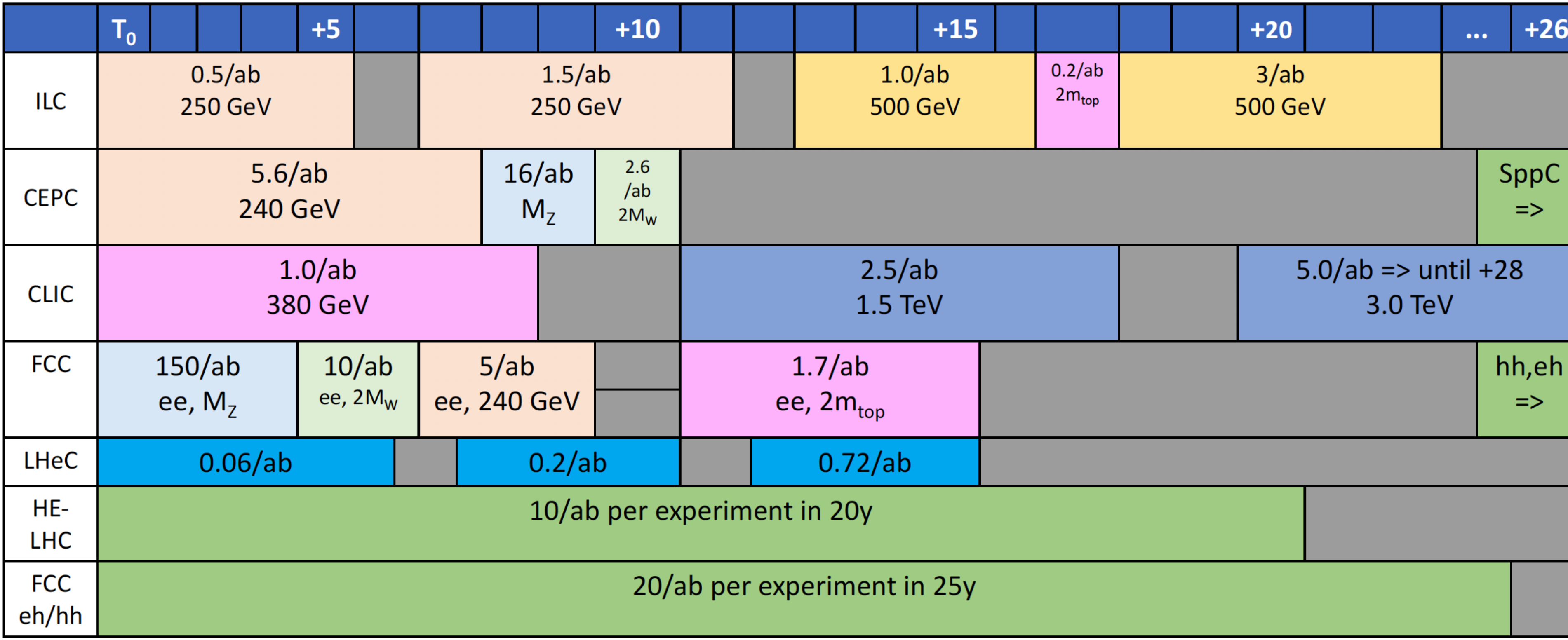


Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC		

Proposed dates from projects

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

Proposed Schedules



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Comparisons

Project	Type	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		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	60 / 7000	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

Maturity (Personal View)

- CEPC and FCC-ee
  - Do not see a feasibility issue with technologies or overall design
  - But more hardware development and studies essential to ensure that the performance goal can be fully met
    - E.g. high power klystrons, strong-strong beam-beam studies with lattice with field errors, …

- ILC and CLIC
  - Do not see a feasibility issue with technology or overall design
  - Cutting edge technologies developed for linear colliders
    - ILC technology already used at large scale
    - CLIC technology in the process of industrialisation
  - More hardware development and studies required to ensure that the performance goal can be full met
    - e.g. undulator-based positron source, BDS tuning, …

- Do not anticipate obstacle to commit to either CEPC, FCC-ee, ILC or CLIC
  - But a review is required of the chosen candidate
  - More effort required before any of the projects can start construction

- Guidance on project choice is necessary
  - Physics potential
  - Political considerations
  - Otherwise should review all projects

Important Note

- Here, I give my understanding and appreciation of the maturity and technical risk of the projects
- There is a large error bar
  - I do not have all the information and even if, I could not review it in detail
  - The projects probably do not have all the information yet
  - You only get my opinion
- To commit to a project would require an in-depth review process
  - To make sure that all critical issues are identified
  - To assess the quality of the proposed solutions and related technology
  - To identify and prioritise remaining work and to help to ask for the resources
- To me this seems like a process that will take time
  - Gather experts, review what exists
  - Potentially do more work to have sufficient answers
- I think we are ready to launch such a process
  - On our preferred solution(s)

Conclusion

- Four main proposals for higgs factories exist
  - ILC, CLIC, FCC-ee and CEPC
  - FCC-hh and HE-LHC need time for technology development
  - LHeC would also produce some higgs
  - No clear proposal for options like LEP3 or low field magnets in FCC-tunnel
  - Muon and plasma-based colliders will need more time to become realistic alternatives

- No feasibility issue is known for any of the proposed higgs factories CLIC, ILC, FCC-ee and CEPC
  - More work has to be done for each of them to ensure performance goal is met
  - Should review in detail them before commitment is made
  - In all cases need several years before construction could start
  - Currently, technology can not help with the choice of the next project

- Cost are high in all
  - 5.9 GCHF for 380 GeV CLIC, 5.3 GILCU for ILC, 11.6 GCHF for FCC-ee, 5 G$ for CEPC

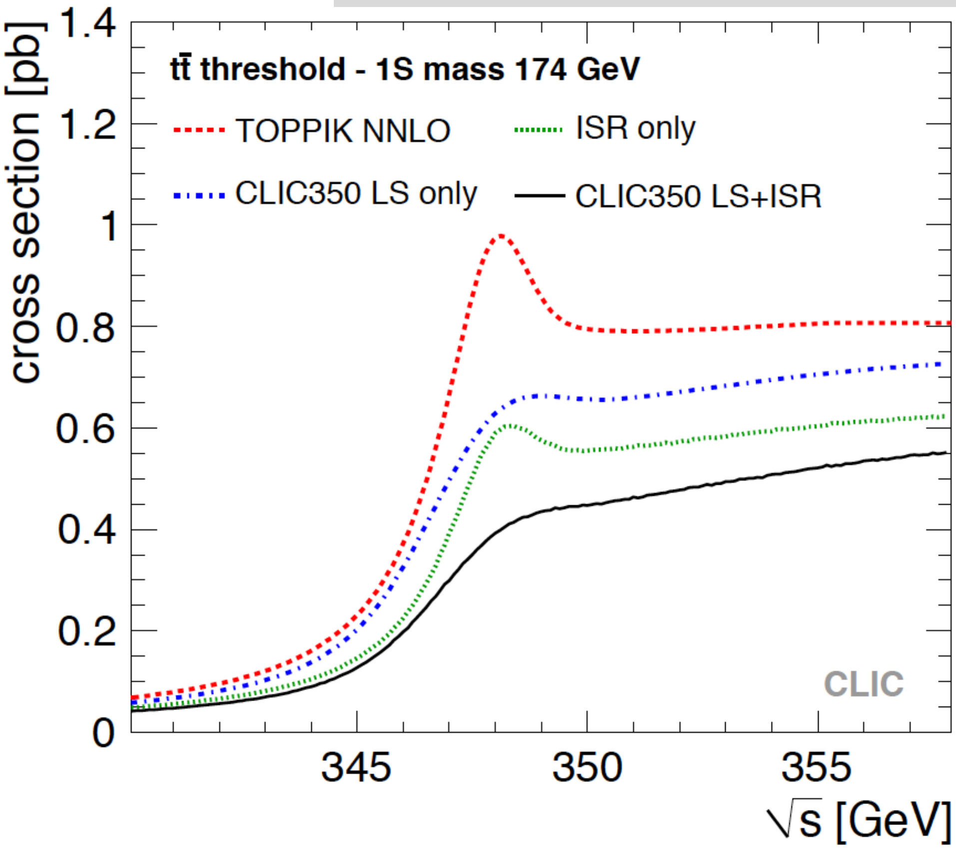
- Physics potential and strategy should be the governing principles

Reserve

Beamstrahlung

K. Seidel et al. **arXiv:1303.3758**

Linear colliders emit beamstrahlung in the collision
The level depends on the luminosity



Beamstrahlung is comparable to initial state radiation

- At low energies tuned to have a similar size effect
    - Actually beamstrahlung increases higgs production cross section at 380 GeV
- At high energy tuned for more luminosity
    - Mainly t-channel physics
    - Can always reduce beamstrahlung at cost of luminosity

Lessons from SLC

SLC allowed to identify and solve many issues

- Finally 50 feedback loops existed
  - Now foreseen from the beginning
- Muon background mitigated by spoilers
  - Space for muon protection foreseen
- Charge limitation due to instability in damping ring and linac
  - Fully understood and taken into account in ILC and CLIC designs

SLC also demonstrated the concept

- Luminosity enhancement by beam-beam effects
- Polarisation of 78%
- Exceeded the planned beam parameters except for charge and repetition rate

SLC paved the way by making sure we do not overlook potential issues

FCC-hh / SppC

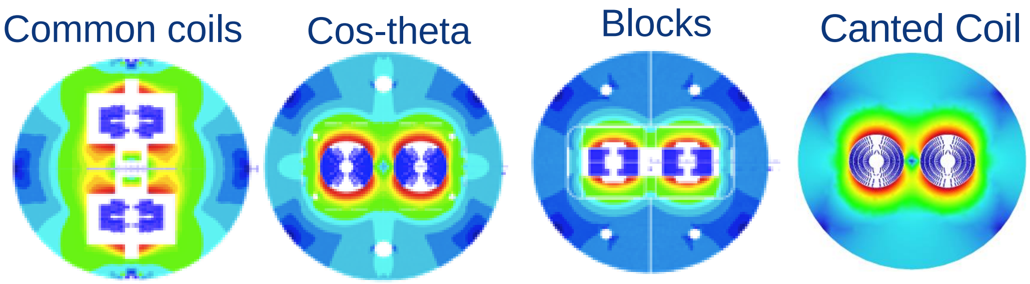
Core challenges are the magnets

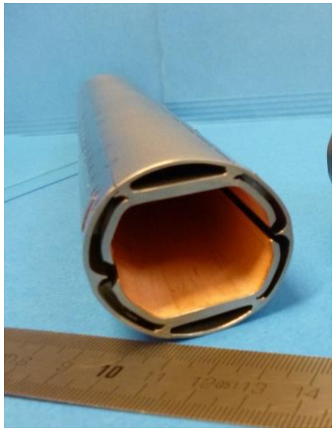
- High-field Nb_3 or HTS cables (FCC-hh)
- Iron-based HTS (SppC)
- Need to increase performance and reduce cost

Also beam energy and synchrotron radiation pose challenges

Profit very much from LHC experience

- All the expertise is available



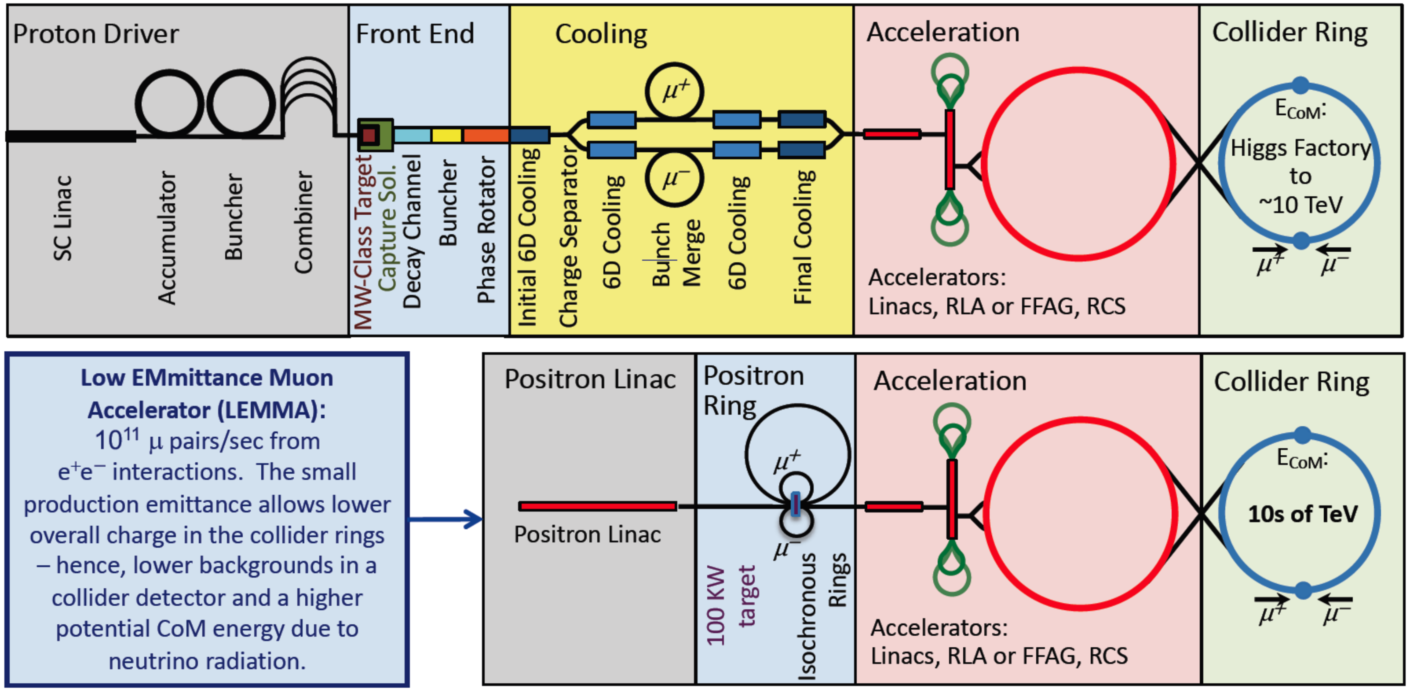


FCC-hh as standalone project
Costs 24 GCHF
First collisions in 2044

After FCC-ee
Cost 17 GCHF
First collisions in 2064

More time is required to develop the magnets
Otherwise FCC-hh seems feasible
Note: Some people suggest use of low-field magnets, but what about upgrade scenarios?

Note: Muon Colliders



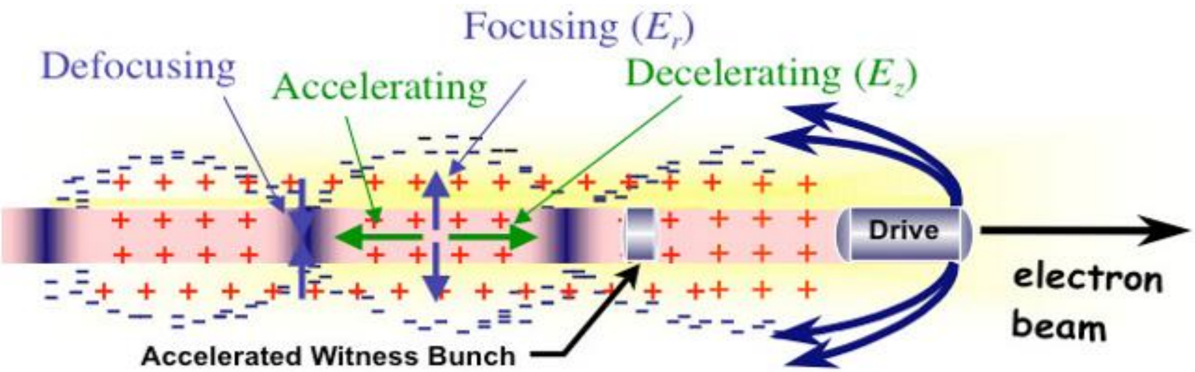
Not mature enough for the next project
But might have potential for very high energies
R&D should be supported
So see it as higgs factory at high energies
At threshold only if we fail to get a project in due time

Note: Novel Acceleration Technologies

Mainly replace the main linac of linear colliders with novel technology acceleration

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

- Powered with beam or laser



But are only now starting to consider beam quality

- There are good reasons to worry about beam quality, so need to wait for R&D results

Dielectric accelerating structures promise more modest increase in gradient

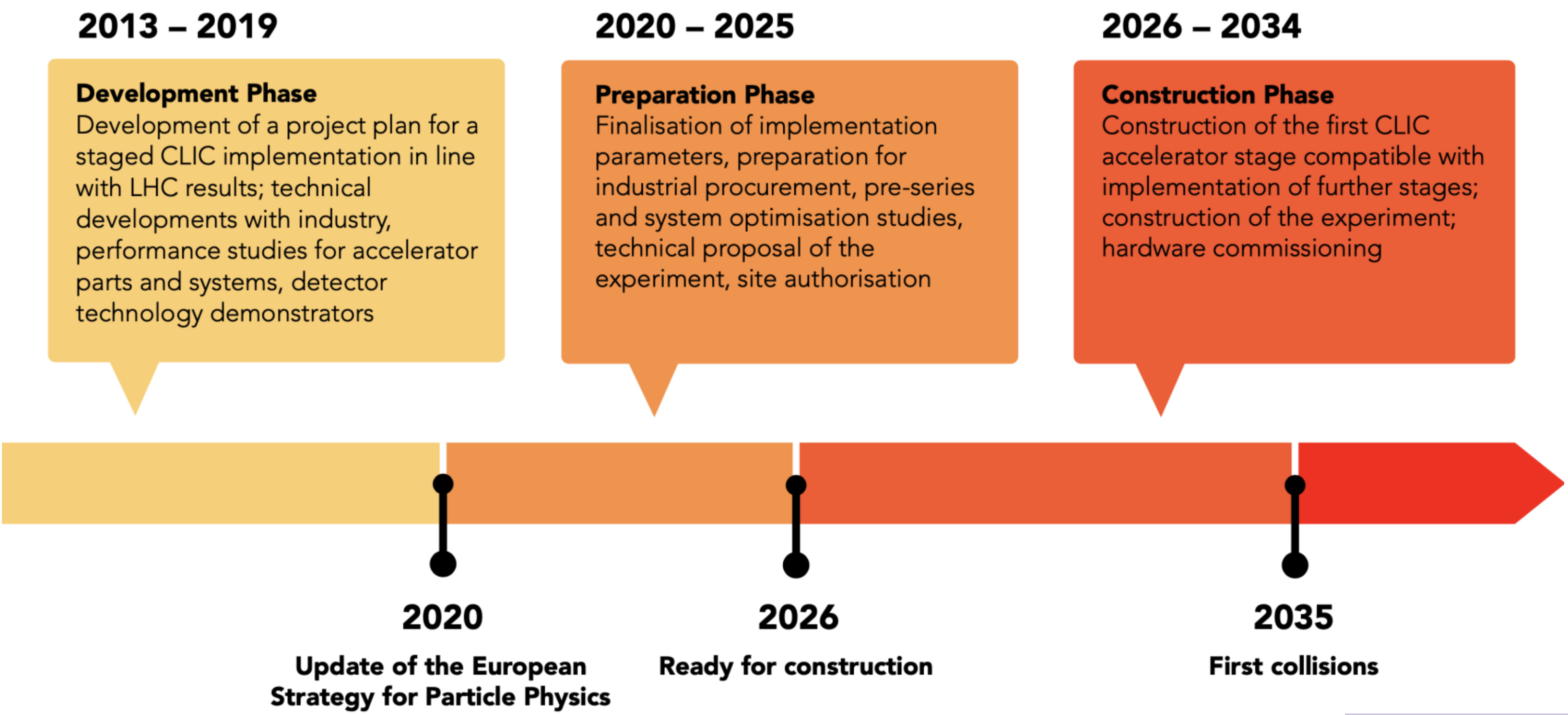
Might become interesting in the longer run but not right now

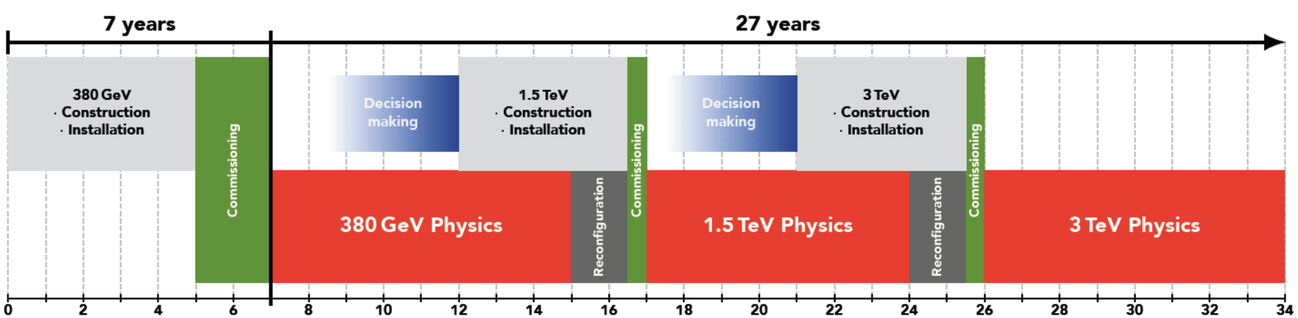
- R&D should be supported if possible

Might become interesting in the longer run

- but not right now
- R&D is interesting

CLIC





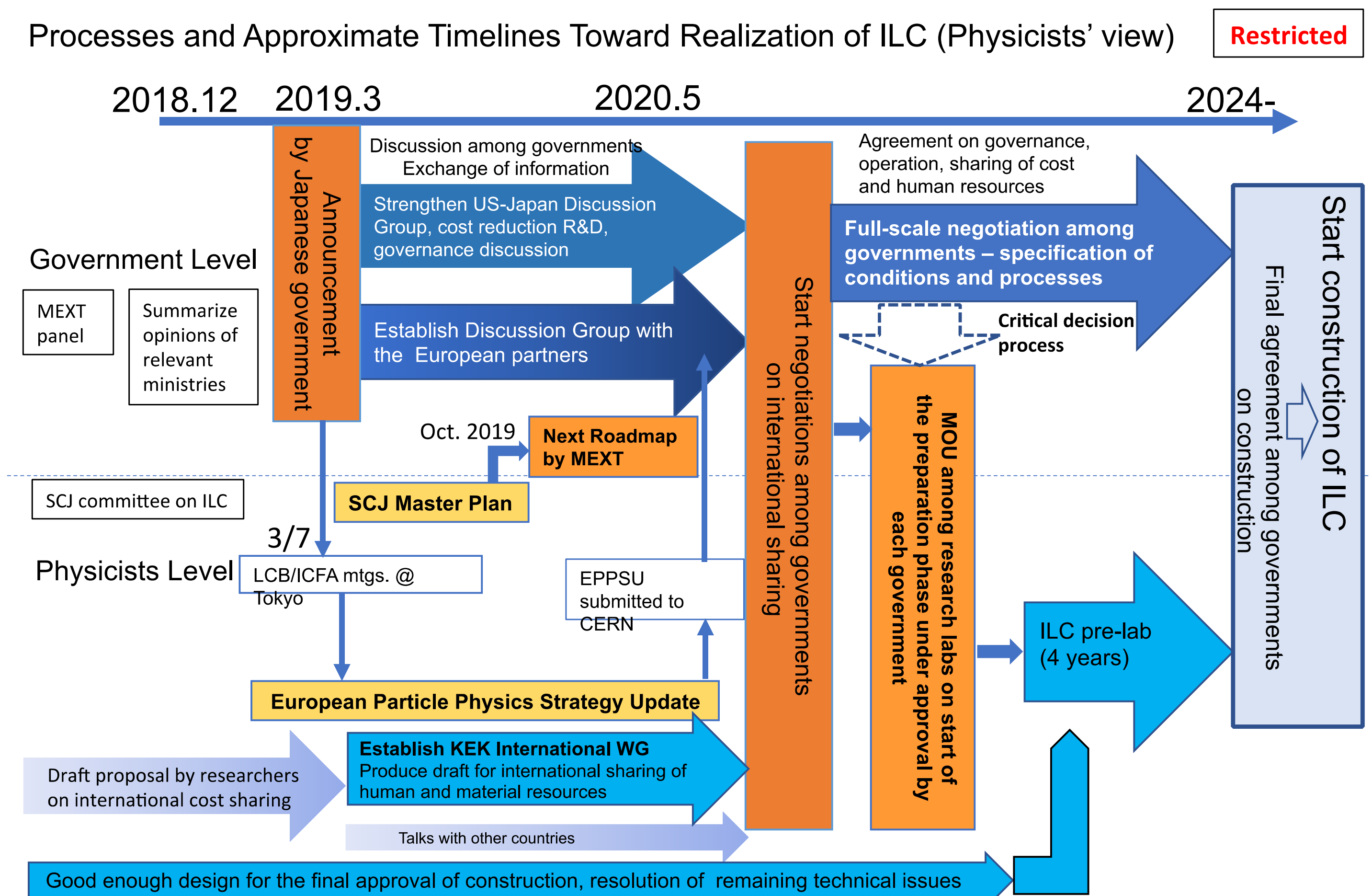
Costs 5.9 GCHF (380 GeV)
+ 5.1 GCHF (1.5 TeV)
+ 7.3 GCHF (3 TeV)

0.4 GCHF for the detector

First collisions in 2035

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

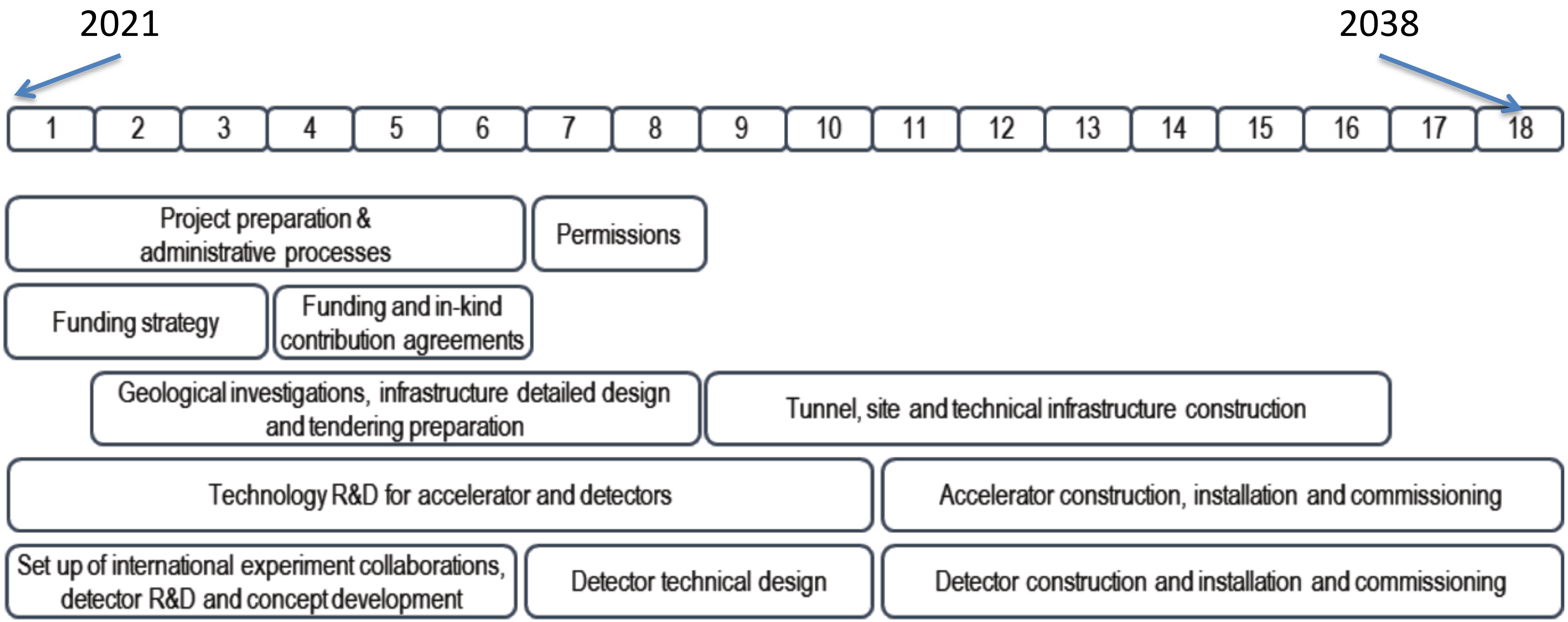
ILC



* ICFA: international organization of researchers consisting of directors of world's major accelerator labs and representatives of researchers
* ILC pre-lab: International research organization for the preparation of ILC based on agreements among world's major accelerator labs such as KEK, CERN, FNAL, DESY etc.

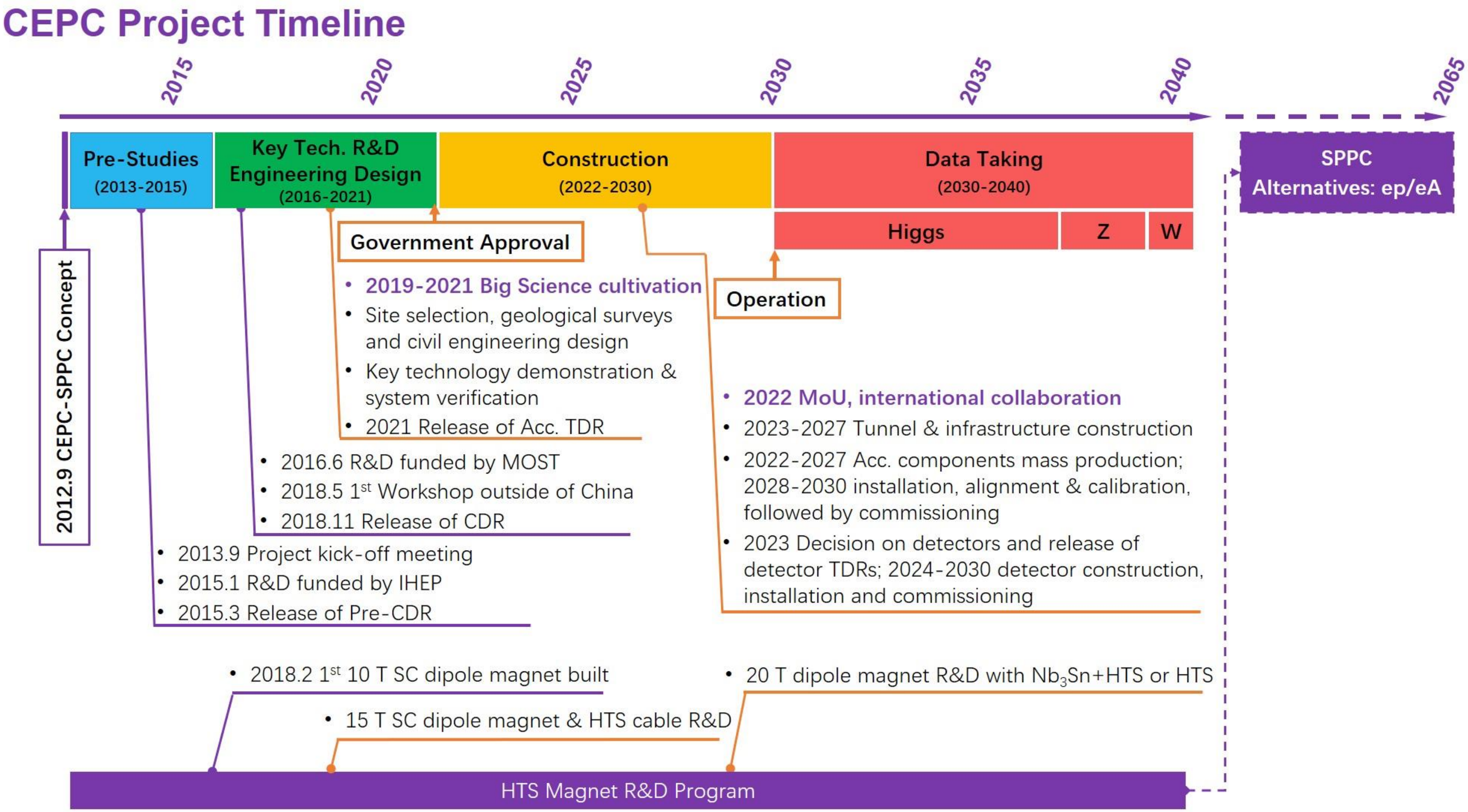
Time to start of construction in 2024 is short, mainly political process

FCC-ee



Time for R&D until start of construction in 2028 and a bit beyond could be adequate

CEPC



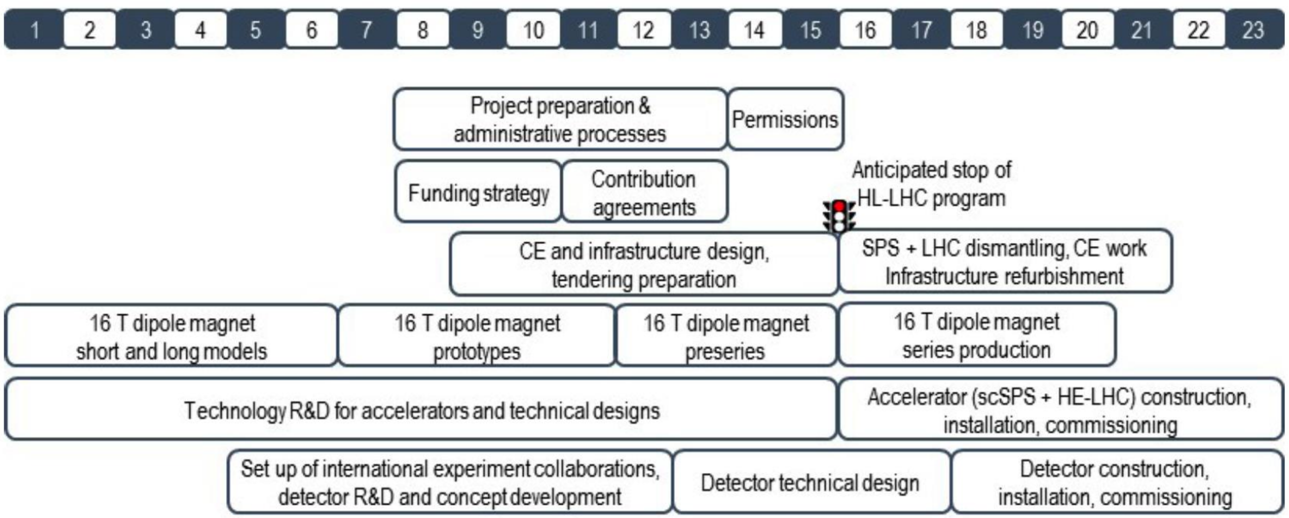
Impressively short time from now to start of construction in 2022

HE-LHC

HE-LHC aims to increase LHC energy to 27 TeV and to triple integrated luminosity

Main challenges

- Requires magnets similar to FCC-hh
- Needs to be integrated into existing tunnel
- Upgrade of existing injector complex (superconducting SPS)



Costs 7.2 GCHF
First collisions in 2044

More time is required to develop the magnets
Is it worth the additional cost or is it better to do a larger step?

ILC and CLIC

CLIC is proposal for project at CERN

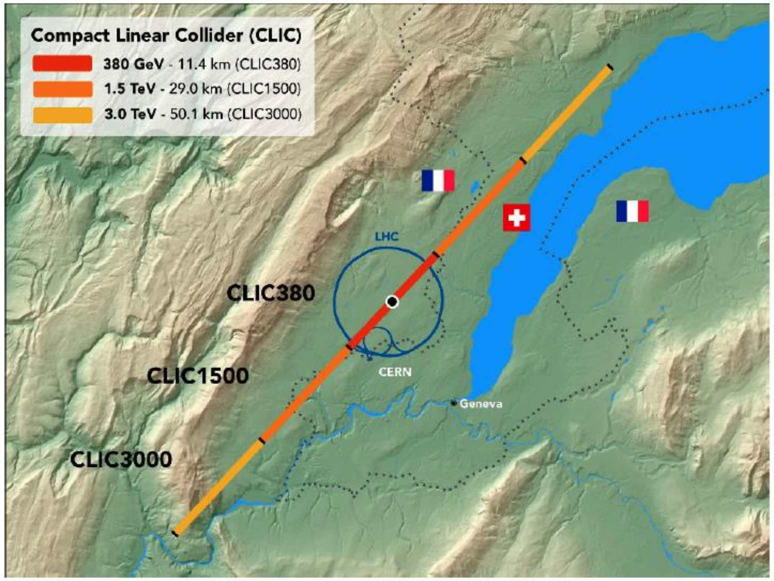
- Provided Project Implementation Plan to EU strategy in 2018 (CDR in 2012)

Staged approach

- 380 GeV for higgs and top
- 1.5 TeV
- 3 TeV

Basic goal is high energy

- Use of normal conducting technology
- Special drive beam scheme reduces peak RF power needs



ILC is proposal for project in Japan

- Provided TDR in 2012

Reduced scope to 250 GeV

- Higher luminosity and energy can be considered as upgrades

Use of superconducting technology

- reduces peak RF power needs

FCC / CepC+SppC

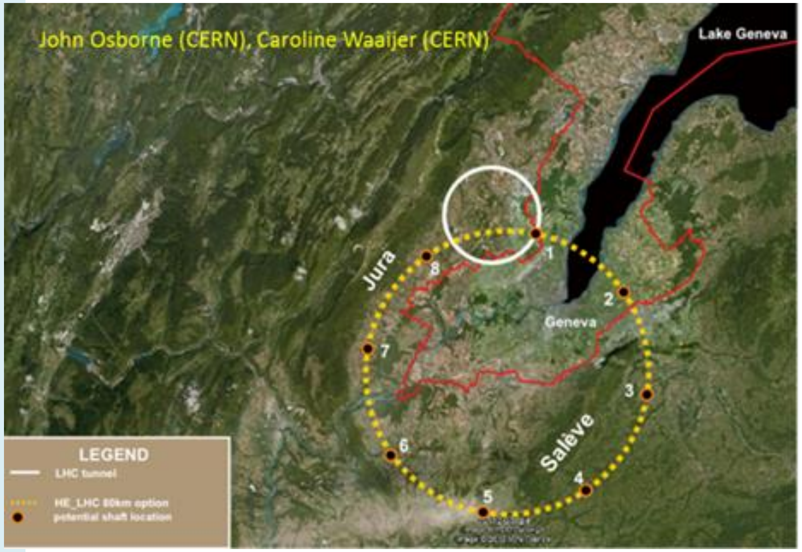
Proposal for project at CERN
- Provided CDR to EU strategy in 2018

FCC-hh
- pp collider with E_{cm}= 100 TeV
- Ion option
- Defines infrastructure
- Focus of past years

FCC-ee
- Potential e^+e^- first stage
- Now this seems more likely

FCC-eh
- additional option

HE-LHC
- LHC with high field magnets

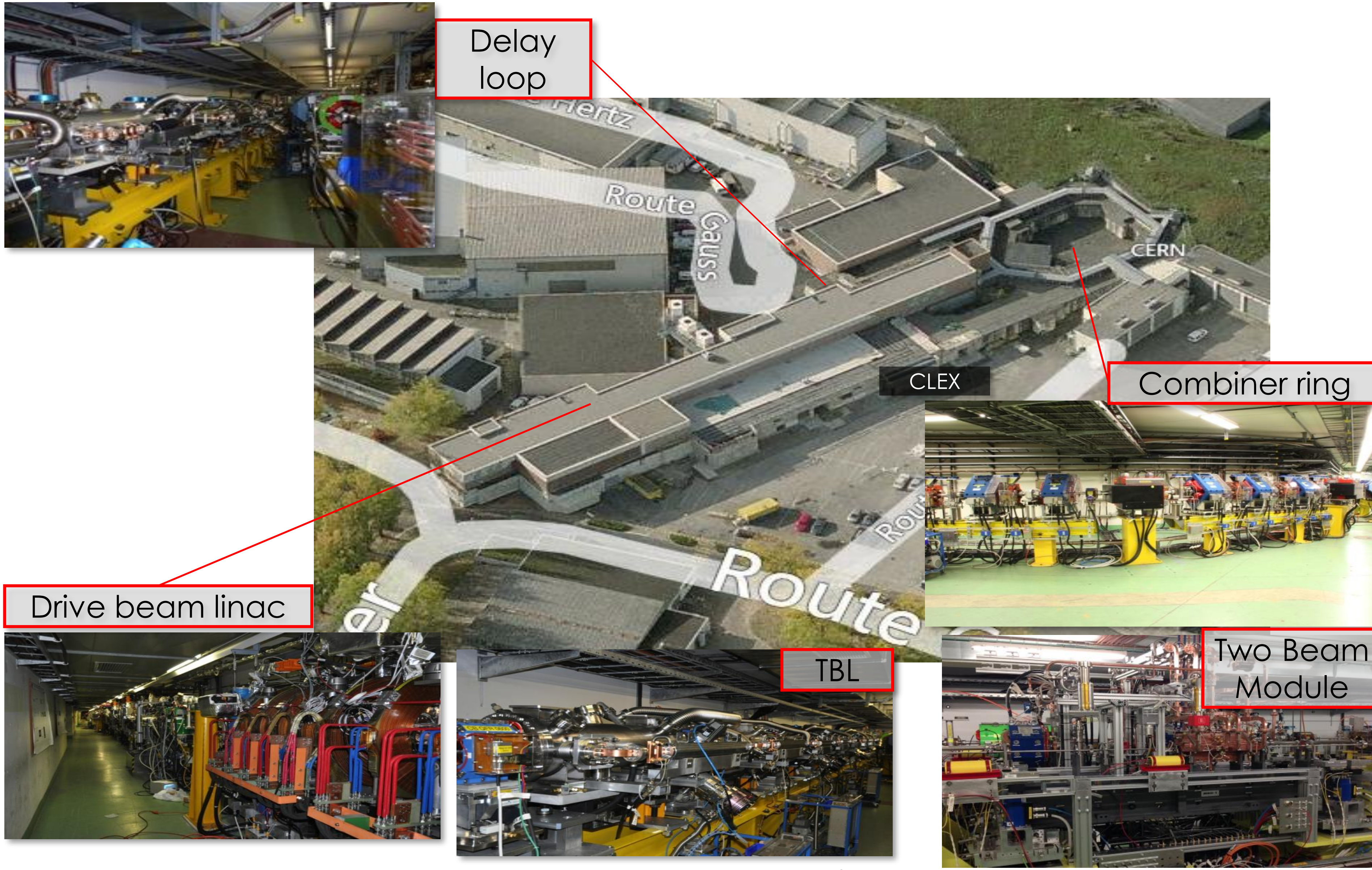


Proposal for project in China
- CDRs exist but changes since

CEPC
- e^+e^- collider 90-240 GeV
- focus on higgs

SppC
- Hadron collider to later be installed in the same tunnel
- 75 to O(150) TeV

Drive Beam Demonstration (CTF3)



Expertise

Number of experts is an important factor in maturity

FCC-hh is most ready

- Scaled up LHC
- All hardware components are covered
- All beam physics is covered

ILC, CLIC, FCC-ee, CEPC and LHeC need more experts

- For linear colliders much hardware and design expertise exists now scattered on other projects
  - Detailed competitive studies performed
  - Many components developed and prototyped
  - Different test facilities, e.g. CTF3
- Need to further build expert community
- Example: in all cases the RF becomes significantly more important than now
- Civil engineering, in particular for FCC-ee and CEPC

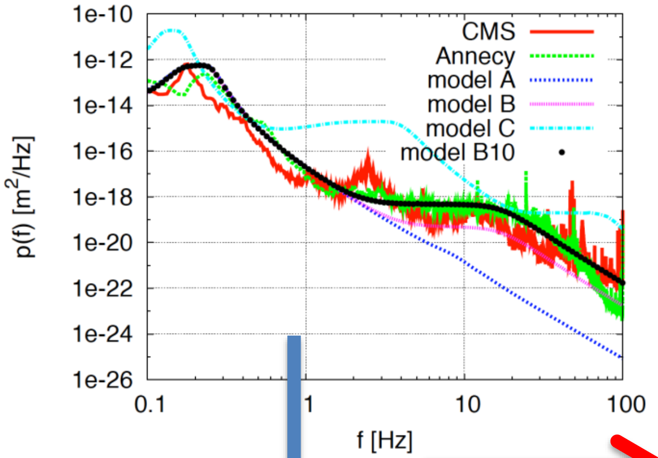
For all projects, need to spent more money and convince people that this is likely going to happen

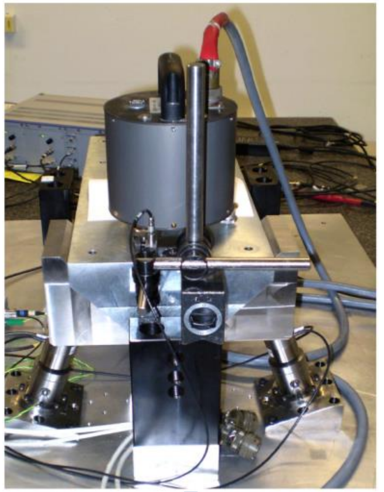
- This will draw in more people
- In particular the engineering experts

Example: Ground Motion and Active Stabilisation

Ground motion can reduce CLIC luminosity

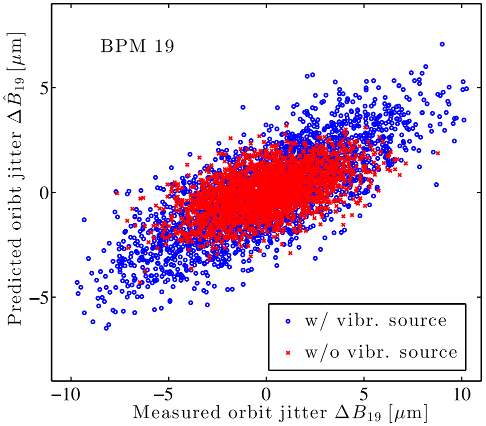
Mixed approach to address issue
- Measurements
- Hardware development
- Simulations
- Experiments



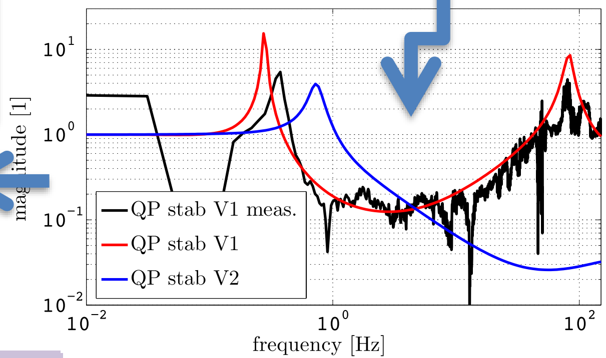


Beam-based Feedback design

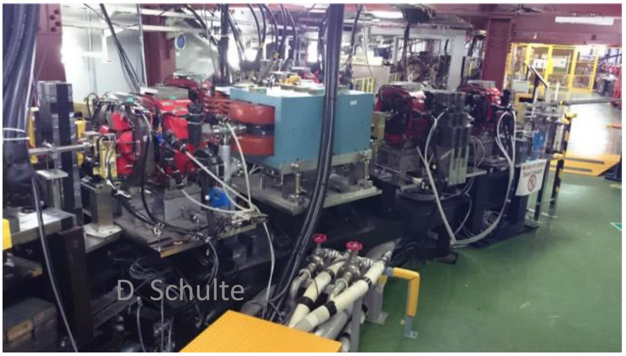
PLACET GUINEA-PIG



Feed-forward



Conclusion: Performance target met with stabilisation



Performance is OK for 3 TeV
Even better at 380 GeV

Note: Simulations

All projects rely on simulation tools to predict the luminosity performance

- Benchmarking is critical
  - Code vs. code, code vs. experiment, code vs. brain
- But keep some skepticism
  - That a code works in one case does not mean that is is certain to work in another case
- There might be surprises
  - FCC-ee novel beam-beam instability found in 2016
  - Seems now understood and well in hands
- Start-to-end and integrated simulations are important
  - Linear colliders have a longer history here
  - But should be able to catch up with circular colliders with enough resources

Simulations of specific linear colliders is most mature due to work of decades

- But need to regain enough resources

Circular colliders need to and can catch up

- Can be based on other collider experience
- Need also more resources

LHeC is least advanced and would need significant ramp-up

CLIC 3TeV Beamstrahlung

Goal is to maximise $L_{0.01}$
And $L_{0.01}/L > 0.3$

$$\Upsilon \gg 1$$

$$n_\gamma \propto \left(\frac{\sigma_z}{\gamma}\right)^{\frac{1}{3}} \left(\frac{N}{\sigma_x + \sigma_y}\right)^{\frac{2}{3}}$$

$$\mathcal{L} \propto \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}} \eta P_{wall} \frac{1}{\sigma_y} H_D$$