ESPPU 2019 Granada

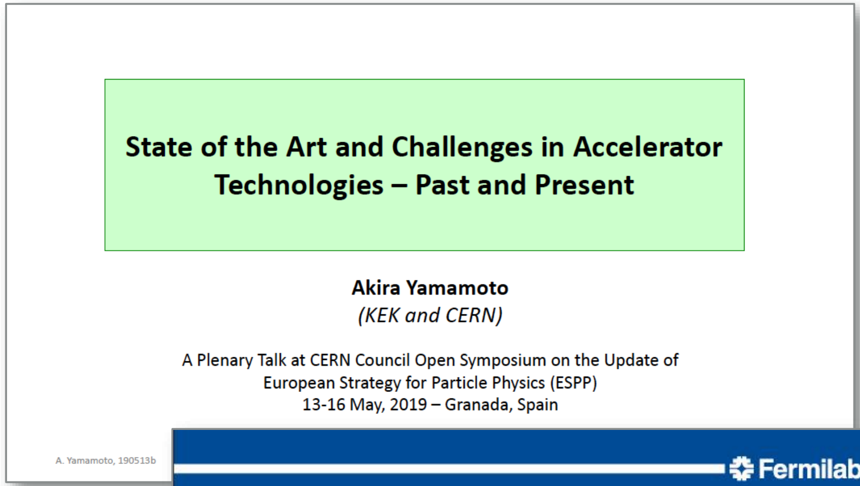
Accelerator Session

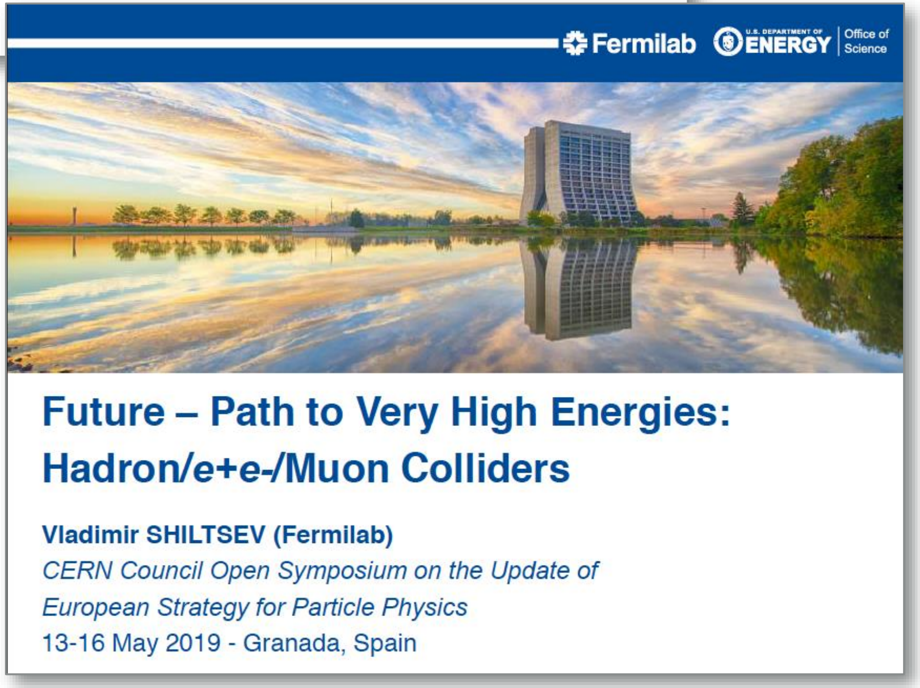
Benno List

(I)LC Project Meeting 24.5.2019

Accelerator related plenary talks

- Monday:
  - Akira Yamamoto (KEK/CERN): State of the art and challenges in accelerator technology - Past and present
  - Vladimir Shiltsev (Fermilab): Future – Path to very high energies
- Friday: Lenny Rivkin (PSI): Accelerator Science and Technology [Accelerator Summary]





Accelerators related inputs

About 60 different inputs + national inputs which include accelerators

- e+e- colliders
- hh colliders
- ep colliders
- FCC
- Gamma factories
- Plasma acceleration
- Muon colliders
- Beyond colliders
- Technological developments

Input to speakers:

- Contributions of the community
- Coherent parameters (Integrated luminosity, duty cycle, readiness definition, …)
- What about costs and time schedule?

Output from speakers

- comprehensive summary of 2-3 slides, including open questions, challenges, opportunities and objectives.

Big Questions

In particular for the Accelerator Science and Technology

- What is the best implementation for a Higgs factory?
  Choice and challenges for accelerator technology: linear vs. circular?
- Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?
- How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?
- Energy management in the age of high-power accelerators?

The Themes

The questions in the focus

- e+e-: Linear vs Circular
  - Technological maturity
  - Performance: Luminosity and Power (Energy reach not so much, but obvious)
- FCC-hh (and SPPC)
  - State of high field (16T) magnets
- Muon Collider
  - Back from the dead??? (not discussed here)
- Plasma Wakefield Acceleration
  - Very convincing presentations (not discussed here)

Big Questions

In particular for the Accelerator Science and Technology

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- How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?
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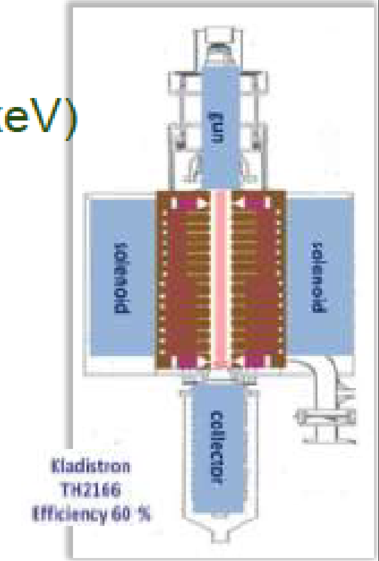
Linear vs Circular

Linear Colliders e+e- Higgs Factories

- *Advantages:*
  - Based on mature technology (Normal Conducting RF, SRF)
  - Mature designs: ILC TDR, CLIC CDR and test facilities
  - Polarization (ILC: 80%-30% ; CLIC 80% - 0%)
  - Expandable to higher energies (ILC to 0.5 and 1 TeV, CLIC to 3 TeV)
  - Well-organized international collaboration (LCC) → "we're ready"
  - Wall plug power ~130-170 MW (i.e. <= LHC)
- *Pay attention to:*
  - Cost more than LHC ~(1-1.5) LHC
  - LC luminosity < ring (e.g., FCC-ee), upgrades at the cost:
    - e.g. factor of 4 for ILC: *x2* $N_{bunches}$ and *5 Hz → 10 Hz*
  - Limited LC experience (SLC), two-beam scheme (CLIC) is novel, klystron option as backup
  - Wall plug power may grow >LHC for *lumi* / E upgrades

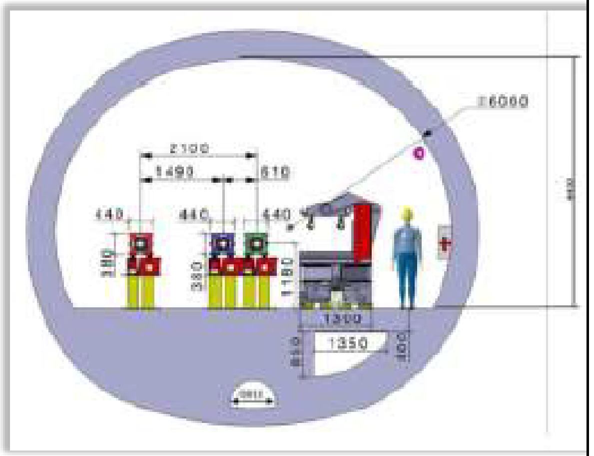
e+e- Ring Higgs Factories

- ***Advantages:***
  - Based on mature technology (SRF) and rich experience → lower risk
  - High(er) luminosity and ratio luminosity/cost; upto 4 IPs, EW factories
  - 100 km tunnel can be reused for a *pp collider* in the future
  - Transverse polarization (τ~ 18 min at *tt*) for ***E*** calibration *O*(100keV)
  - CDRs addressed key design points, mb ready for ca 2039 start
  - Very strong and broad *Global FCC Collaboration*



Strategic R&D ahead :

- High efficient RF sources:
  - Klystron 400/800 MHz η from 65% to >85%
- High efficiency SRF cavities:
  - 10-20 MV/m and high Q_0; Nb-on-Cu, Nb_3Sn
- Crab-waist collision scheme:
  - *Super KEK-B* nanobeams experience will help
- Energy Storage and Release R&D:
  - Magnet energy re-use > 20,000 cycles
- Efficient Use of Excavated Materials:
  - 10 million cu.m. out of 100 km tunnel



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

Conclusion

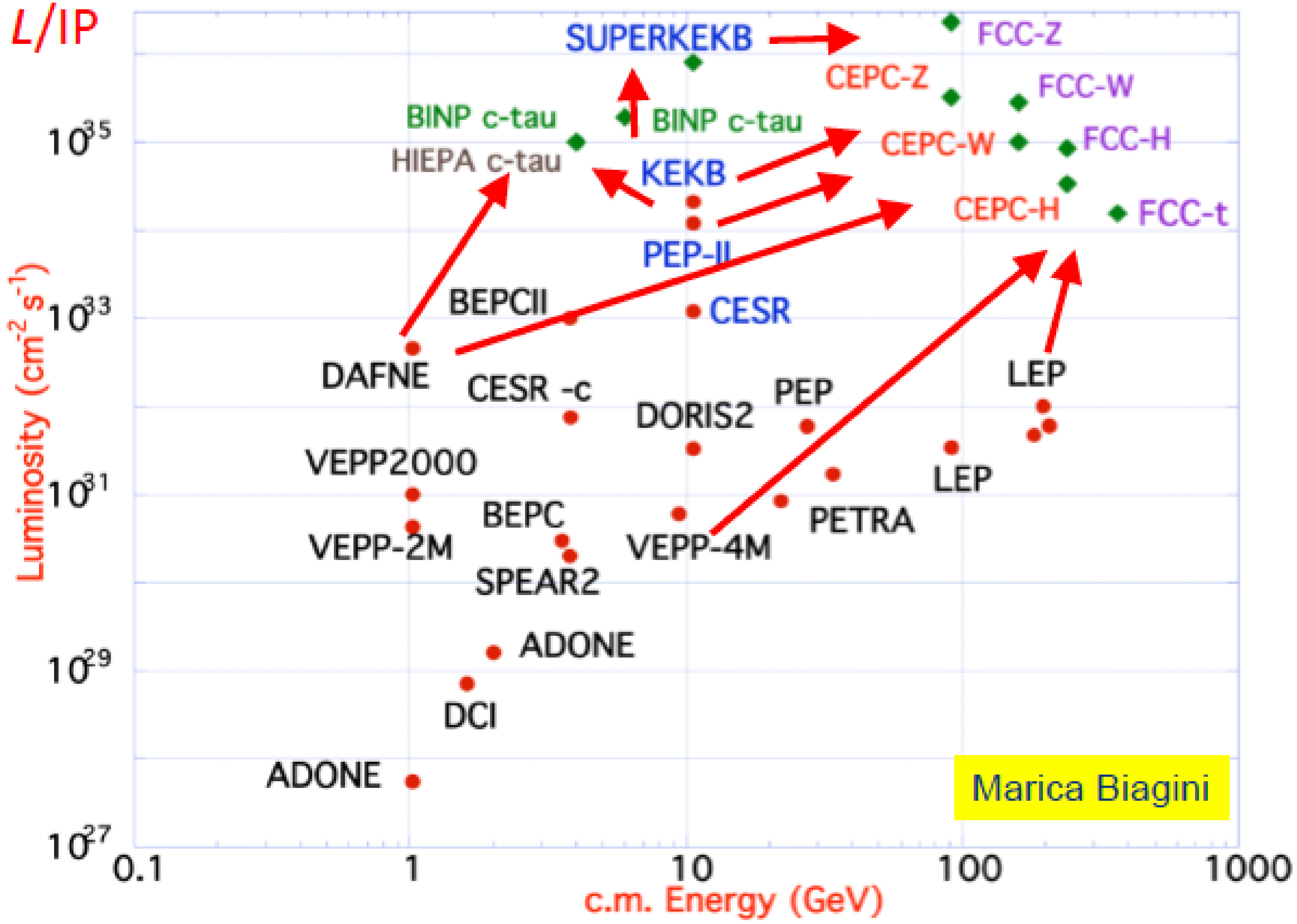
- Four main proposals for higgs factories exist
  - ILC, CLIC, FCC-ee and CEPC
  - FCC-hh and HE-LHC need time for technology development
  - LHeC would also produce some higgs
  - No clear proposal for options like LEP3 or low field magnets in FCC-tunnel
  - Muon and plasma-based colliders will need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

future circular lepton factories based on proven concepts and techniques from past colliders and light sources



B-factories: **KEKB & PEP-II:**
- double-ring lepton colliders,
- high beam currents,
- top-up injection

DAFNE: crab waist, double ring

Super B-factories, **S-KEKB:** low β_y^*

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

General Summary: Personal Prospect (1/2)

- Accelerator Technologies are ready to go forward for **lepton colliders** (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory **construction to begin in > ~5 years.**
- SRF accelerating technology is well **matured** for the realization including cooperation with industry.

- Continuing R&D effort for higher performance is very important for future project upgrades.
  - **Nb-bulk, 40 – 50 MV/m**: ~ 5 years for single-cell R&D and the following 5 – 10 years for 9cell cavities statistics to be integrated. Ready **for the upgrade**, **10 ~ 15 years.**

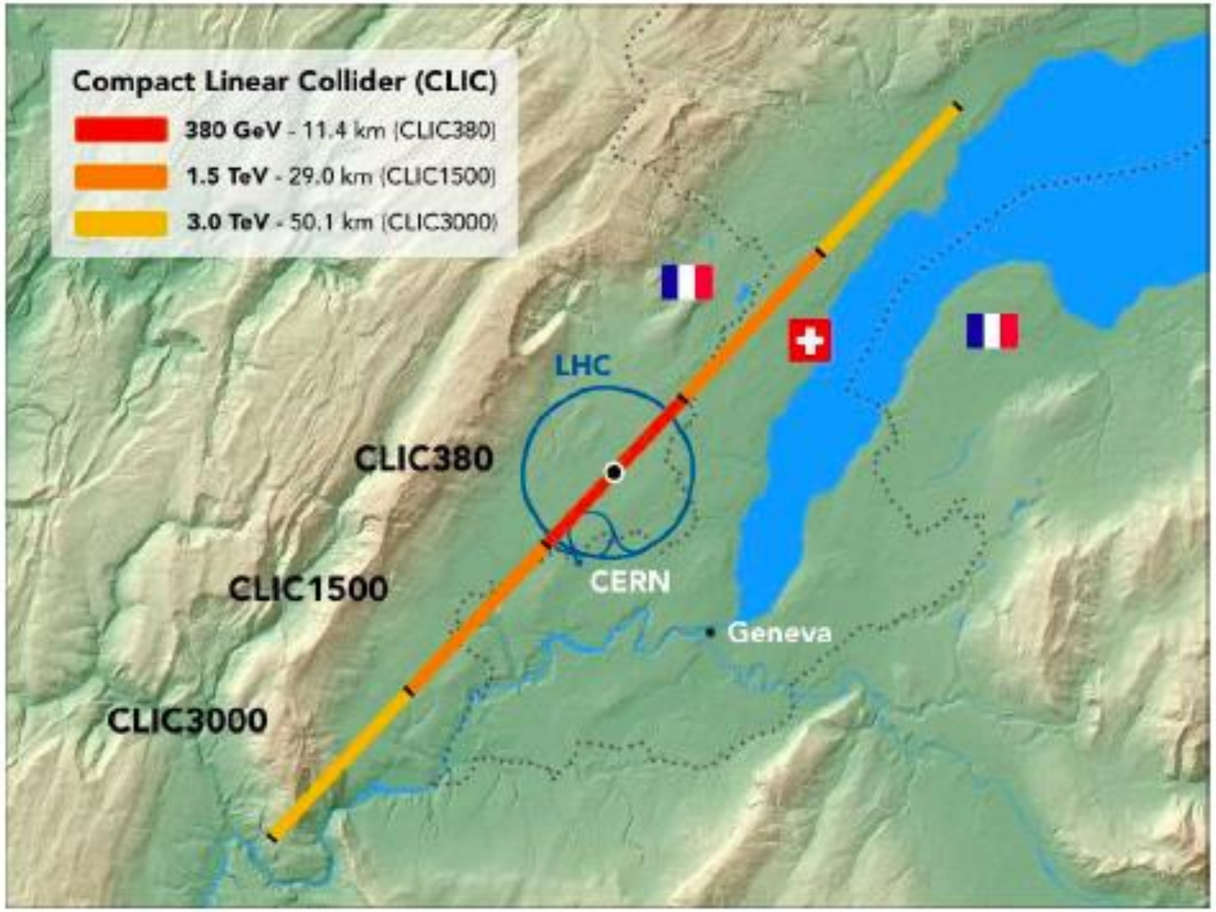
Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear *250 GeV*			
ee Rings *240GeV/tt*			
μμ Collider *125 GeV*			*
Highest Energy			
ee Linear *1-3TeV*			
pp Rings *HE-LHC*			
FCC-hh/SppC			
μμ Coll. *3-14 TeV*			*

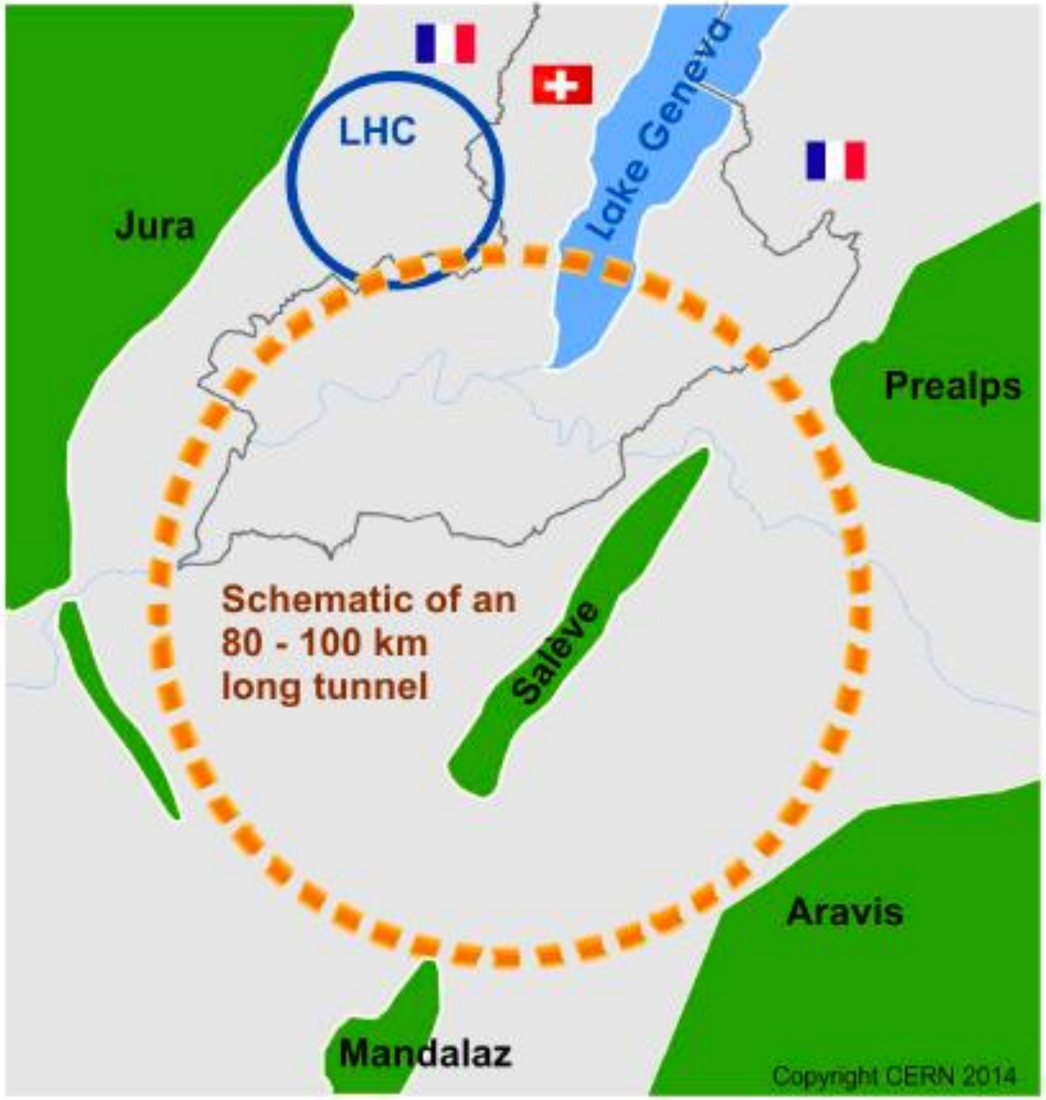
Accelerators summary

Caterina Biscari and Lenny Rivkin, Phil Burrows, Frank Zimmermann

Open Symposium towards updating the European Strategy for Particle Physics
May 13-16, 2019, Granada, Spain

Q1: What is the best implementation for a Higgs factory?
Choice and challenges for accelerator technology: linear vs. circular?

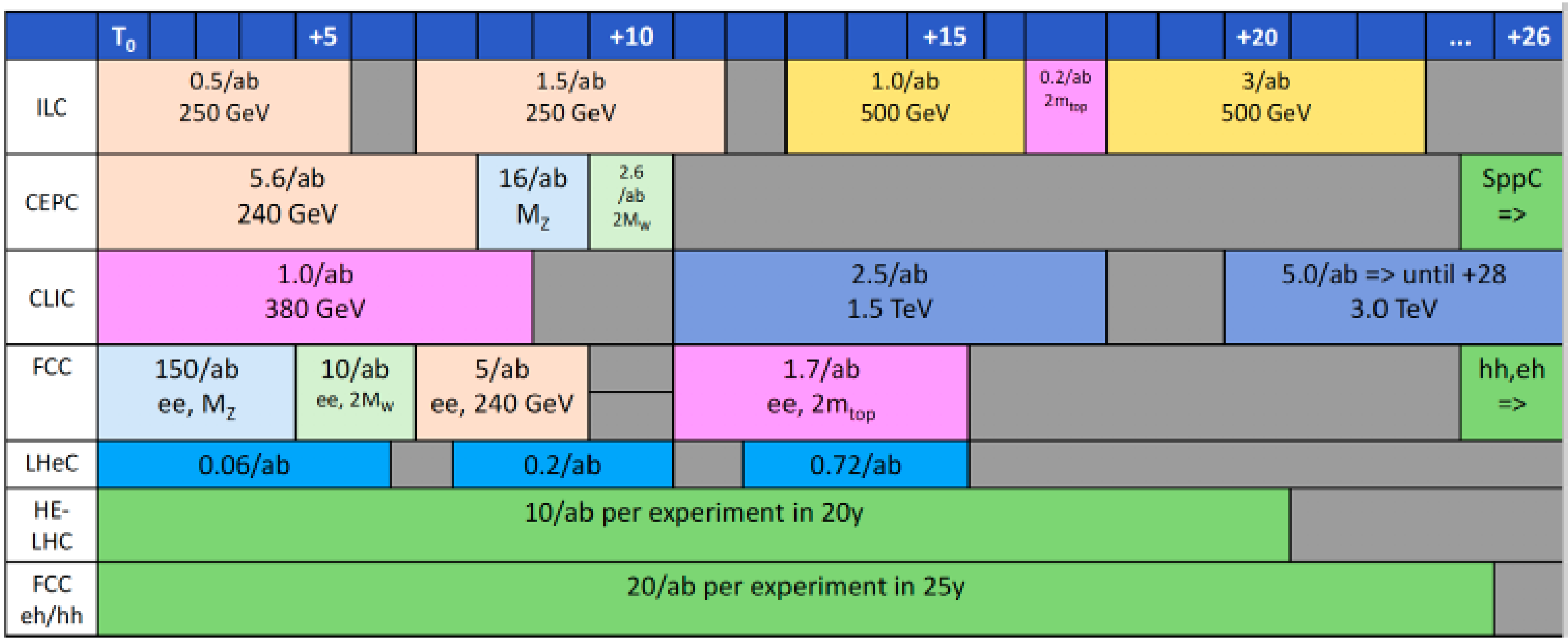




Comparisons

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)	7.98 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

Proposed Schedules and Evolution



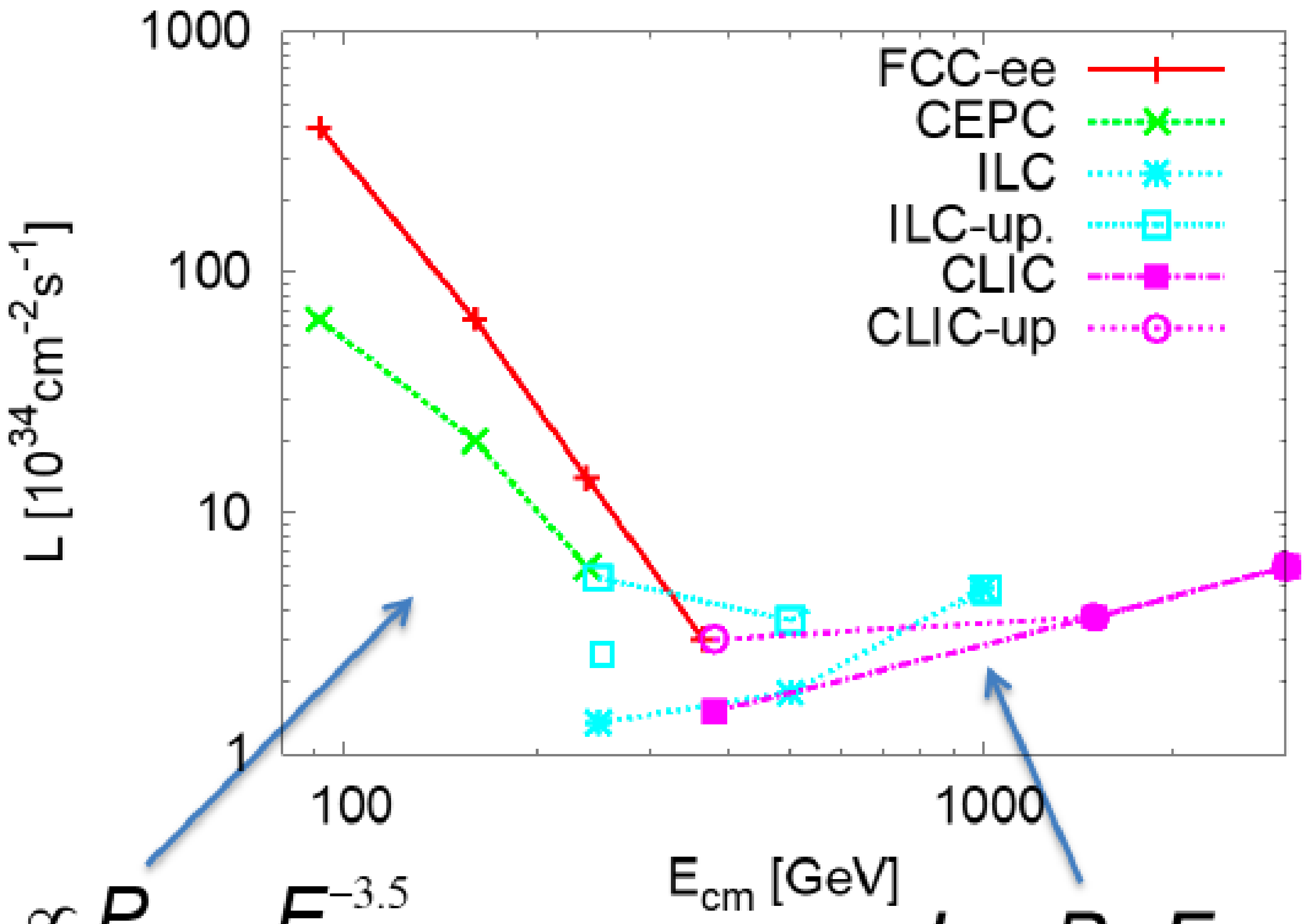
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

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

Ours is a very dynamic field!
(Luminosity upgrades for ILC, CLIC)

Luminosity per facility



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

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

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 …

Maturity

- CEPC and FCC-ee, LHeC
  - 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(s)
  - More effort required before any of the projects can start construction

- Guidance on project choice is necessary
  - Physics potential
  - Strategic considerations

Q4: Energy management in the age of high-power accelerators?

Energy Efficiency

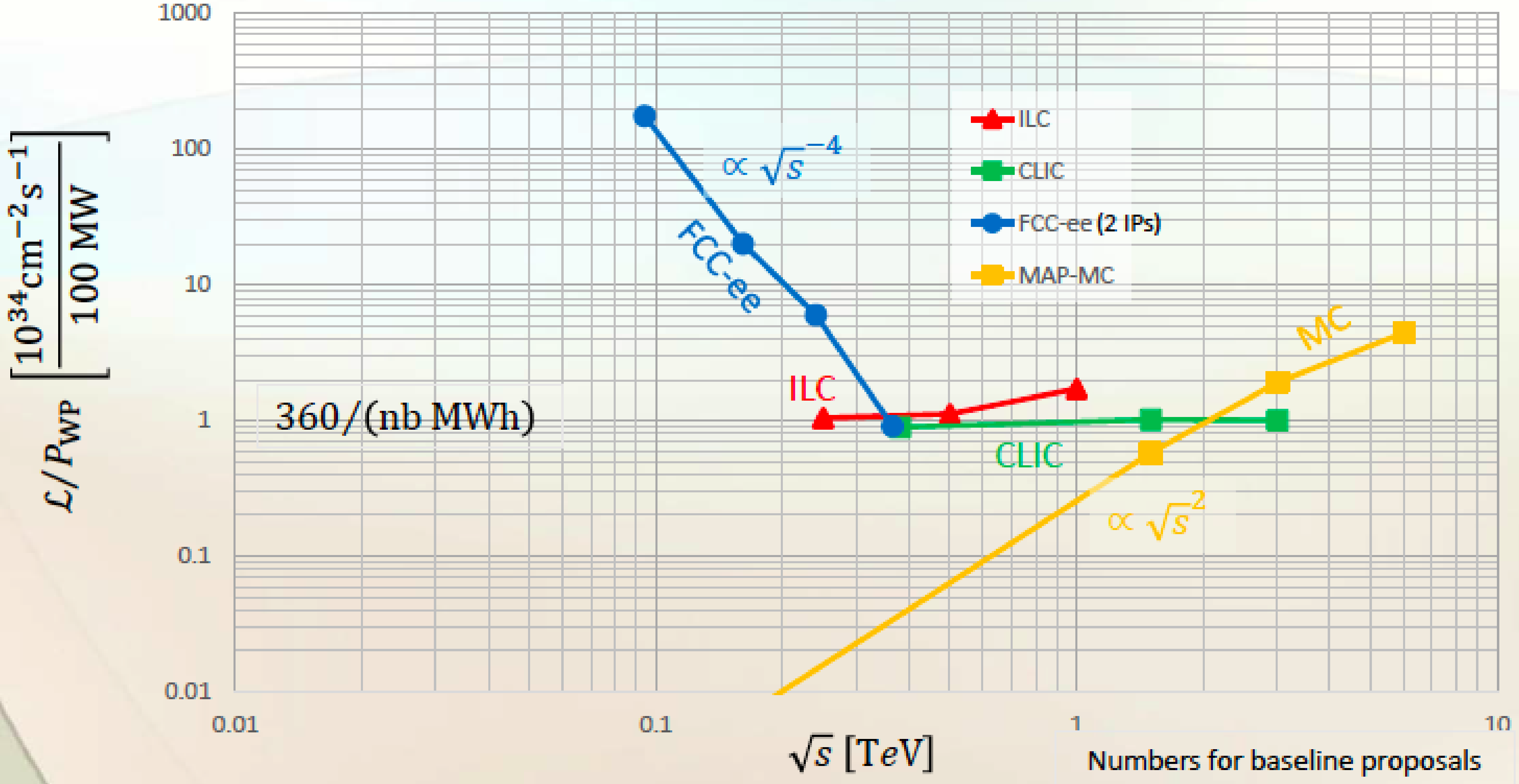
- Energy efficiency is not an option, it is a must!
- Proposed HEP projects are using $\mathcal{O}(\mathrm{TWh/y})$, where energy efficiency and energy management must be addressed.
- Investing in dedicated R&D to improve energy efficiency pays off since savings can be significant.
- This R&D leads to technologies which serve the society at large.
- District heating, energy storage, magnet design, RF power generation, cryogenics, SRF cavity technology, beam energy recovery are areas where energy efficiency can be significantly be improved.

Figure of merit for proposed lepton colliders

European Strategy Update

Disclaimers:

1. This is not the only possible figure of merit
2. The presented numbers have different levels of confidence/optimism; they are still subject to optimisations



Numbers for baseline proposals

Getting Our Message Across

Many variants of the same plot

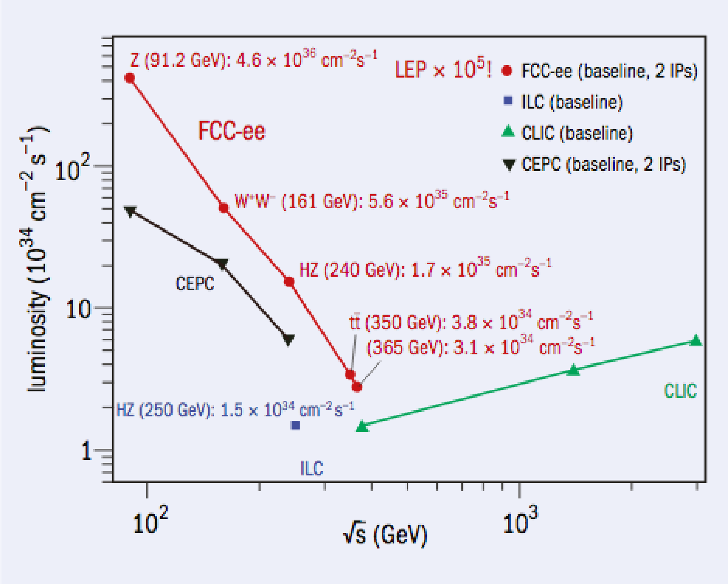
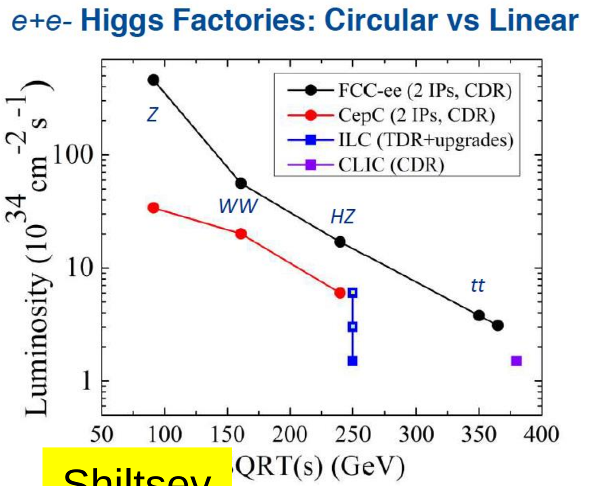
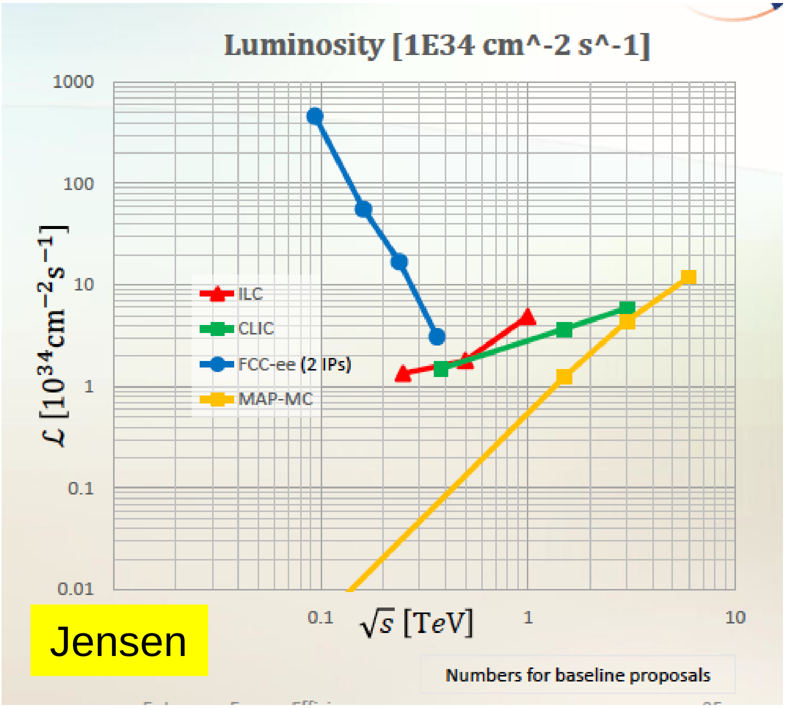


Fig. 1. *Lepton-collider luminosity as a function of centre-of-mass energy for different accelerator baseline projects and technologies, showing FCC-ee, the Circular Electron Positron Collider (CEPC), the Compact Linear Collider (CLIC) and the International Linear Collider (ILC).*

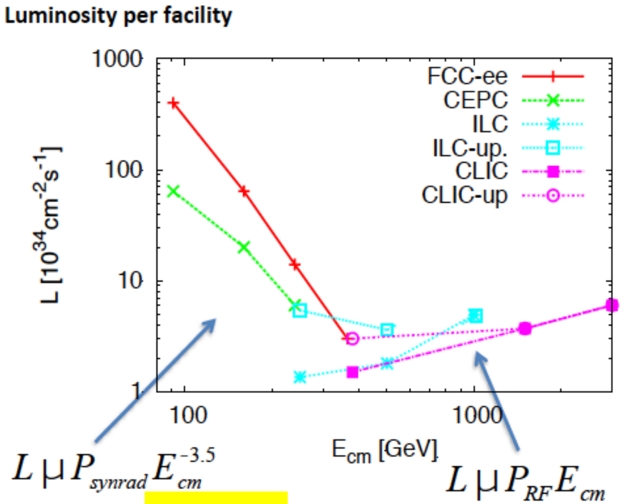
CERN Courier / FCC



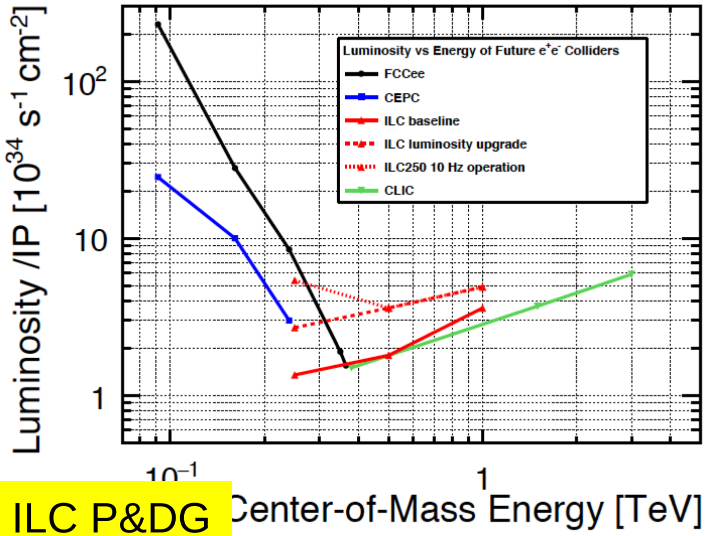
Shiltsev



Jensen



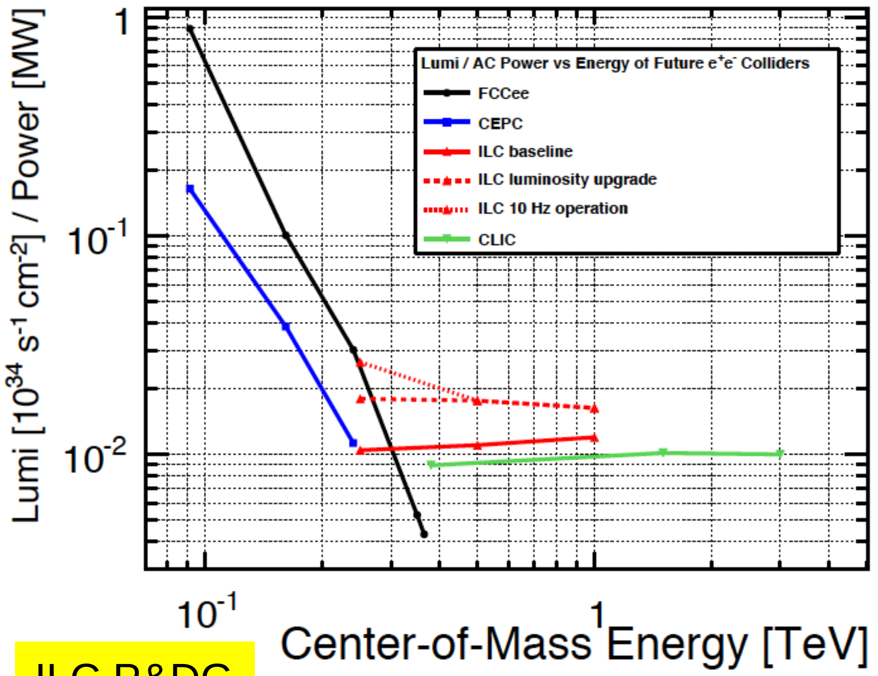
Schulte



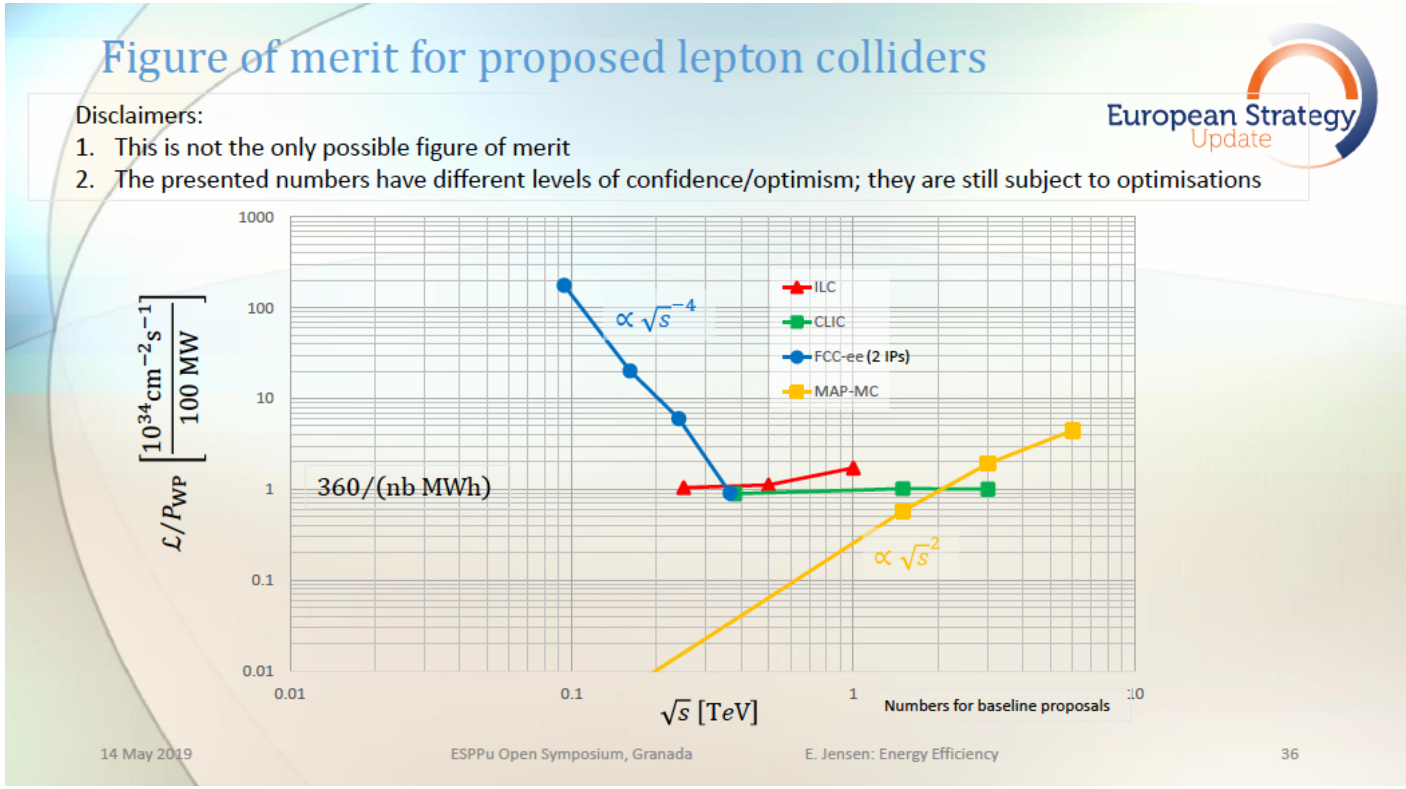
ILC P&DG

Luminosity / Power

The new figure of merit



ILC P&DG



Last Minute Efforts

Heroic Efforts to control the message – not fully successful

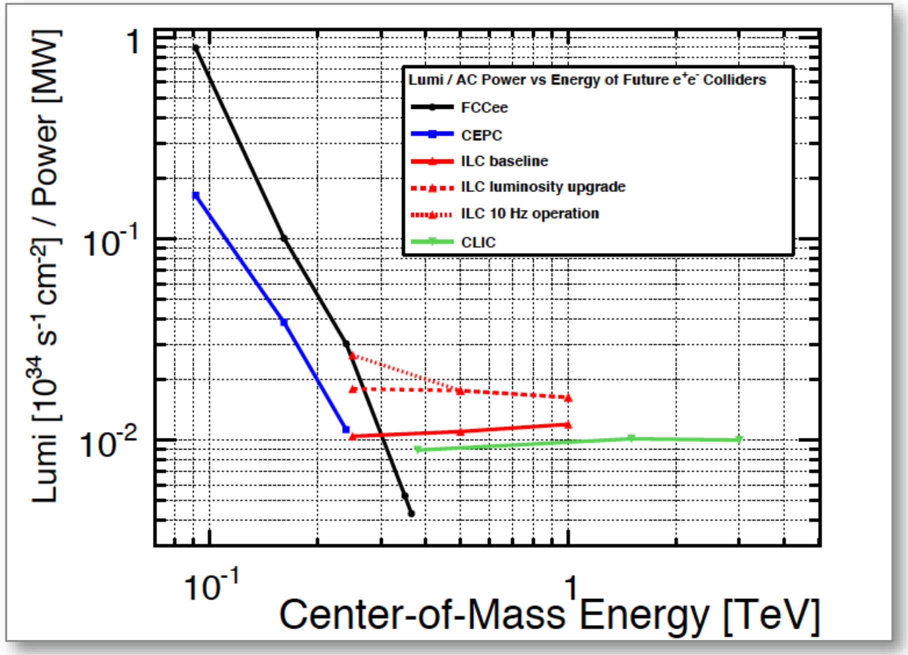
Luminosity and Site AC Power of the ILC

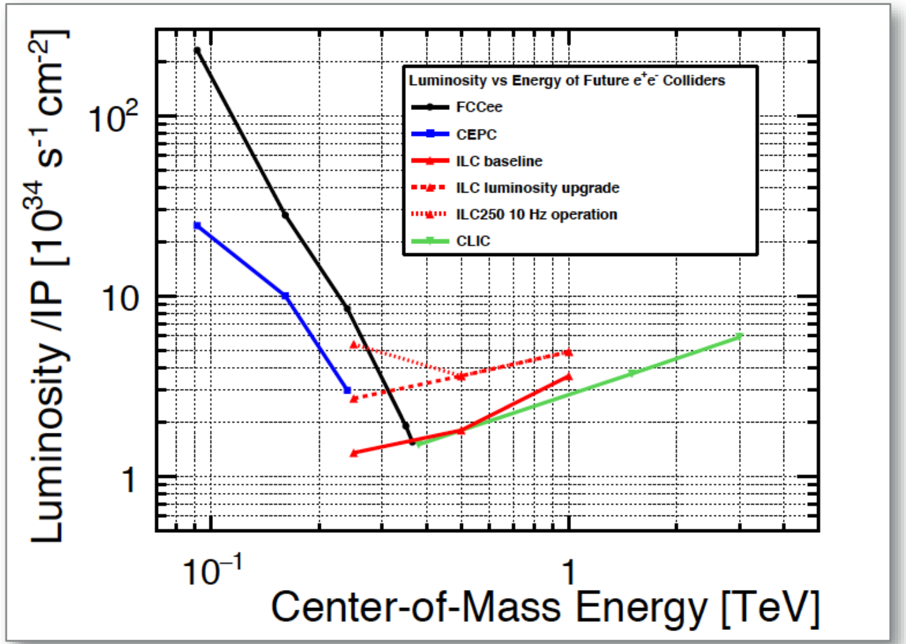
May 9, 2019

Table 1 summarizes the ILC luminosities and relevant accelerator parameters. It is assumed that the baseline (namely, undulator-based) positron source is used. The numbers are taken from documents submitted to the European Particle Physics Strategy Update 2018-2020[1], its supplementary document[2] as well as the ILC technical design report[3].

Collision energy(GeV)	Lum.(/cm^{2}s)	Pol.(P^-/P^+)	Nbunch×freq.	power(MW)
250 (baseline)	1.35	$\pm0.8/\pm0.3$	1312×5	129
250 (Nbunchx2)	2.7	$\pm0.8/\pm0.3$	2625×5	~150
250 (above + 10 Hz)	5.4	$\pm0.8/\pm0.3$	2625×10	~200
500 (baseline)	1.8	$\pm0.8/\pm0.3$	1312×5	163
500 (Nbunchx2)	3.6	$\pm0.8/\pm0.3$	2625×5	204
1000 (baseline)	3.6	$\pm0.8/\pm0.2$	2450×4	300
1000 (high L)	4.9	$\pm0.8/\pm0.2$	2450×4	300

Table 1: Summary of ILC accelerator parameters. For each operation mode, luminosity, polarizations of electron and positron, number of bunch per pulse and pulse frequency (Hz), and site AC power are shown. For the power requirements of the upgraded 250 GeV operations, see the descriptions in text.



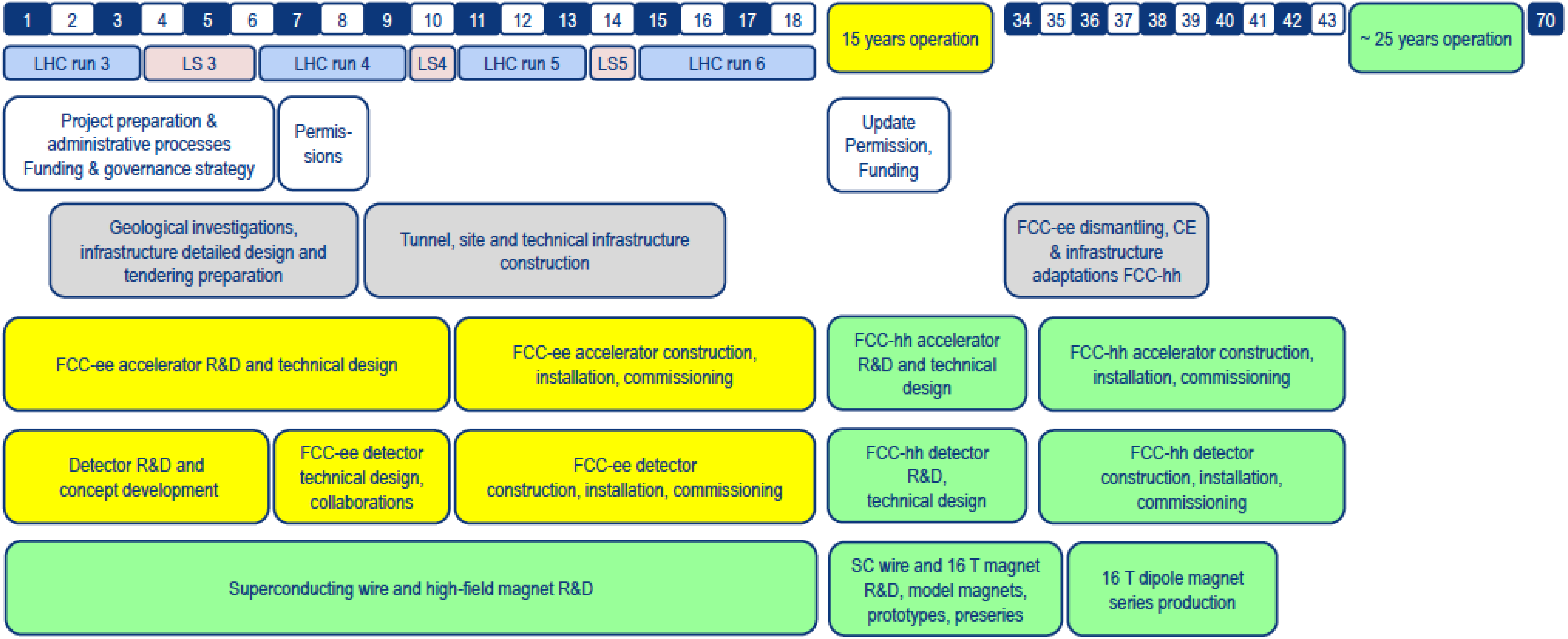


FCC-hh

FCC-hh and SppC collider parameters

parameter	FCC-hh		SppC	HL-LHC	LHC
collision energy cms [TeV]	100		75	14	14
dipole field [T]	16		12	8.33	8.33
circumference [km]	97.75		100	26.7	26.7
beam current [A]	0.5		0.73	1.1	0.58
bunch intensity [10^{11}]	1	1	1.5	2.2	1.15
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		1100	7.3	3.6
SR power / length [W/m/ap.]	28.4		12.8	0.33	0.17
long. emit. damping time [h]	0.54		1.17	12.9	12.9
beta* [m]	1.1	0.3	0.75	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.4	2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	10	5 (lev.)	1
events/bunch crossing	170	1000	~300	132	27
stored energy/beam [GJ]	8.4		9.1	0.7	0.36

FCC integrated project technical schedule

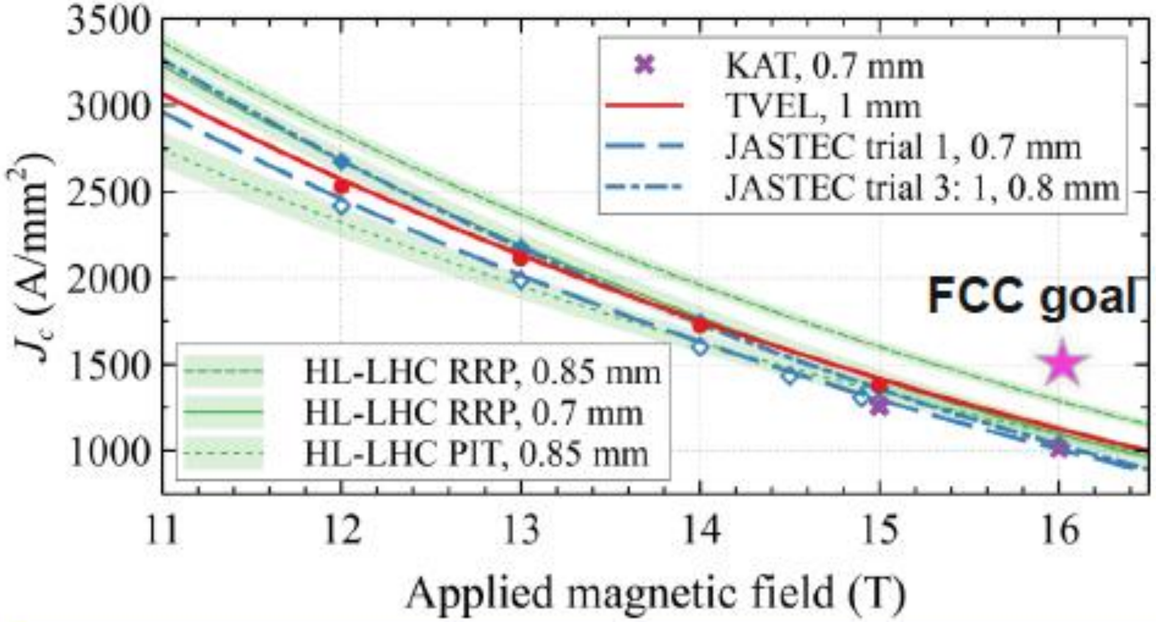


FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

high-field magnet R&D for FCC-hh

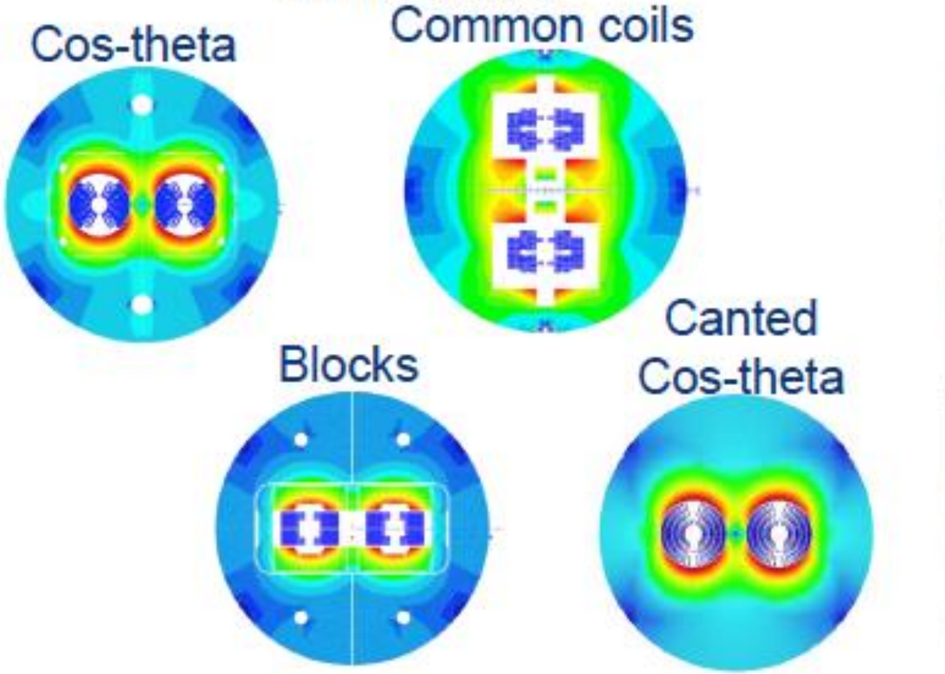
FCC baseline: 16 T magnets, Nb_3Sn, exploiting experience of LHC and HL-LHC
In parallel, HTS magnets (special magnets, hybrid configurations)

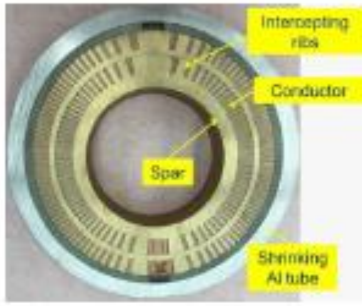
- **Worldwide wire R&D towards J_c (16T, 4.2K) > 1500 A/mm²**

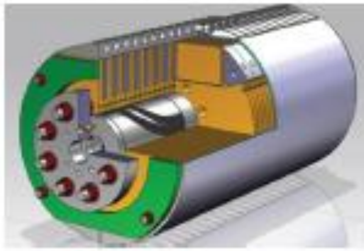


After ~2 years development, **prototype Nb_3Sn wires from several R&D partners already achieve HL-LHC J_c performance**

- **Worldwide short model magnet R&D → various coil geometries**
- **2018 – 2025**





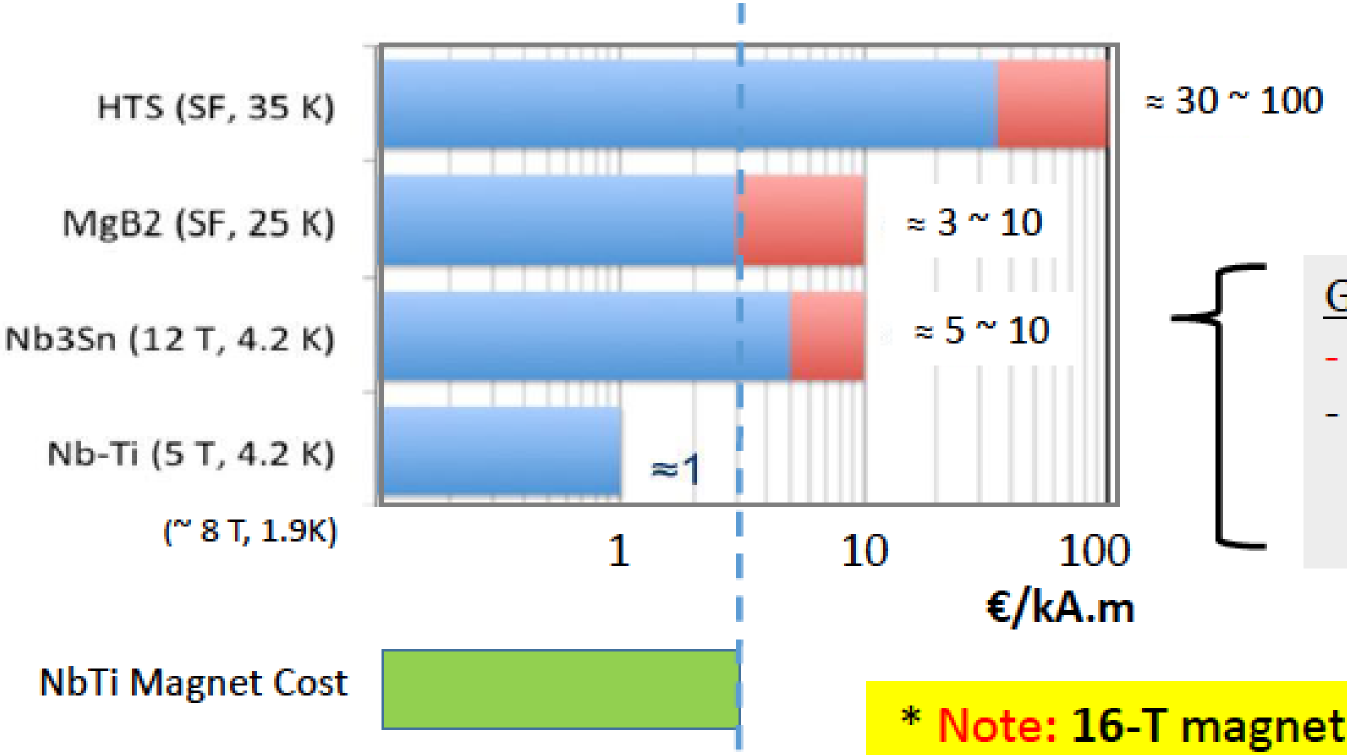


CEA, CIEMAT, INFN, PSI, US-MDP (FNAL, LBNL), BINP

Courtesy: F. Bordry, L. Bottura, A. Devred

Relative Cost Comparison for High-field SC and Magnet

- An approach for cost consideration:
  - Superconductor cost to be 30 % of the total cost for the LHC NbTi dipole magnet assembled.
  - It gives a general guideline for acceptable superconductor cost.
  - The currently available HTS cost is still too far, exept for Iron-based-SC (IBS) potential



Goal for Nb_3Sn for FCC or HE-LHC:

- **3.5 €/kA.m at 16 T and 1.9 K**
- Corresponding to 500…600 €/kg,
  - a factor 2.5 ~ 3 lower than the present cost 1300 ~ 1500 EUR/kg for HL-LHC (RRP)

*** Note: 16-T magnet requires x 2 conductor to that of 14 T.**

Personal View on Relative Timelines

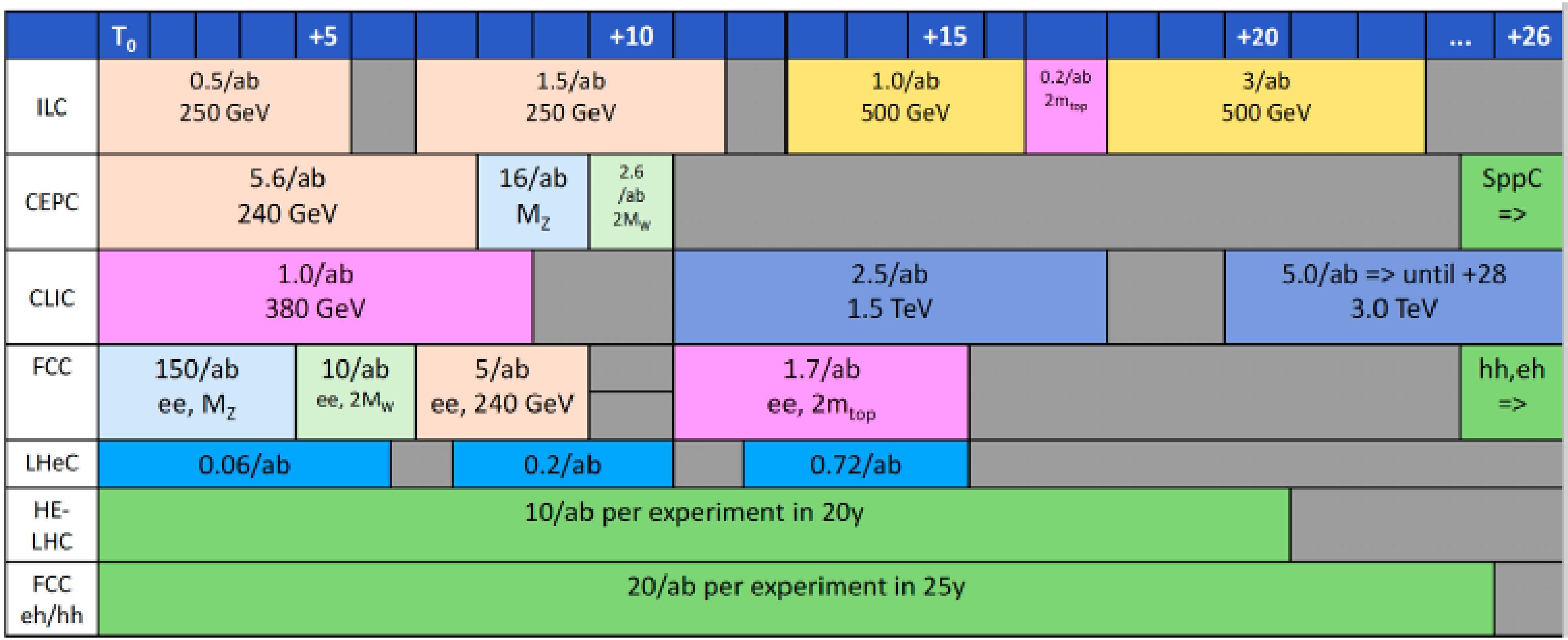
Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

Note: **LHC experience**: **NbTi (10 T)** R&D started in 1980's --> **(8.3 T)** Production started in late 1990's, in **~ 15 years**

Personal Prospect (2/2)

- Nb_3Sn superconducting magnet technology for hadron colliders, still requires **step-by-step** development to reach **14, 15, and 16 T**.
- It would require the following **time-line** (in my personal view):
  - Nb_3Sn, 12~14 T: 5~10 years for short-model R&D, and the following 5~10 years for prototype/pre-series with industry. It will result in 10 – 20 yrs for the construction to start,
  - Nb_3Sn, 14~16 T: 10-15 years for short-model R&D, and the following 10 ~ 15 years for protype/pre-series with industry. It will result in 20 – 30 yrs for the construction to start, (consistently to the FCC-integral time line).
  - NbTi , 8~9 T: proven by LHC and Nb_3Sn, 10 ~ 11 T being demonstrated. It may be feasible for the construction to begin in > ~ 5 years.
- **Continuing R&D effort** for high-field magnet, present to future, should be critically **important**, to realize highest energy frontier hadron accelerators in future.

Proposed Schedules and Evolution



Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

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

A linear collider as part of an overall strategy?

2020 to ~2045	Goal	Status ~2035-45	Options open ~2040-50 →
2020 - 2038 LHC/HL-LHC	- on-going -	Programme completed	Could be extended
2020 - ~2035 construction 2035-2045 operation • CLIC or ILC	Fast access to a high quality e+e- data, at the lowest possible cost (at ~LHC scale). The scientific case is well established. Build in capabilities for higher energies and new technologies.	Physics guidance from HL, LC stage 1 and PBC (and others) Technical experience for LC stage 1	Possibilities: continue running at same or increased energy, use same/improved technology or introduce NAT
Develop hadron and muon machines towards construction readiness in 2030-2040 range	R&D for future machine with a timeline 10-20 years (mainly HF magnets and pp designs, and muon machine studies and designs)	Physics guidance from HL, LC stage 1 and PBC (and others) HF magnet R&D progress, hadron machine design options, muon TDR	Aim to put proton (FCC type or more modest) and/or muon machines into operation
Develop NAT technologies for LC colliders	R&D for much higher energy LCs (and linear accelerators in general), similar timeline	Possibly TDR for use in a LC facility	Around 2040-50: Introduce these technologies – if available – in LC facility (line above)
"Physics Beyond Collider" (PBC) projects	Cover (among others) light dark matter searches		Continue ?
Other projects – CEPC among them	...	Progress	...

Operational physics facilities

Blue: Ring based facility, Red: Linear facility

My Impression how it went

- Linear vs Circular higgs factory:
  - Call it a draw. Could not counter notion „circular is just a bigger LEP“ completely. But (I)LC still standing.
  - Power consumption an issue, but stellar performance claims by FCC et al counter this
  - CLIC was considered doable (but little to no enthusiasm from CERN)
  - Main argument against CLIC from CERN: Cannot keep 10000 experimentalists busy (not messy enough?)
  - „Tera-Z“ is a powerful argument. LC cannot really compete, but Giga-Z is back!
- FCC-hh:
  - Magnet development still needs a lot of R&D. Cost goals (~2x cost of a LHC magnet?) nowhere explicitly given
  - Possibility to equip 100km tunnel with LHC-type 8T magnets mentioned, but no input paper to ESPPU
  - Timelines, cost etc are being discussed with no regard to financial constraints or need to show a convincing physics case, enourmous sense of entitlement – „bigger has always been better, and we deserve it“
- FCC-ee less popular than FCC-hh. A sense of „get this off our back“ makes ILC popular
  - Most powerful statement from Lyn Evans:
    „Refurbishing tunnel from FCC-ee to FCC-hh will take you 20 years – I know, I did it!“
- No general feeling that „ILC is dead“

Outlook from ILC perspective

- Power consumption: A big strength of ILC
  - Problem: No reliable numbers for many configurations we propose
  - I think we need a Change Request for that
- Luminosity: The other battlefield
  - Suddenly: 10Hz for physics is back in Japan – another CR? But increased cost...
- Giga-Z: Back on the table
  - FCC-ee makes a lot of noise about their Tera-Z capability
  - Some sort of Z program needed at ILC to cover everything FCC-ee would offer
- Personal view: ILC could stress more the **possibilities** of ongoing / future R&D work (in addition to ist solid baseline)