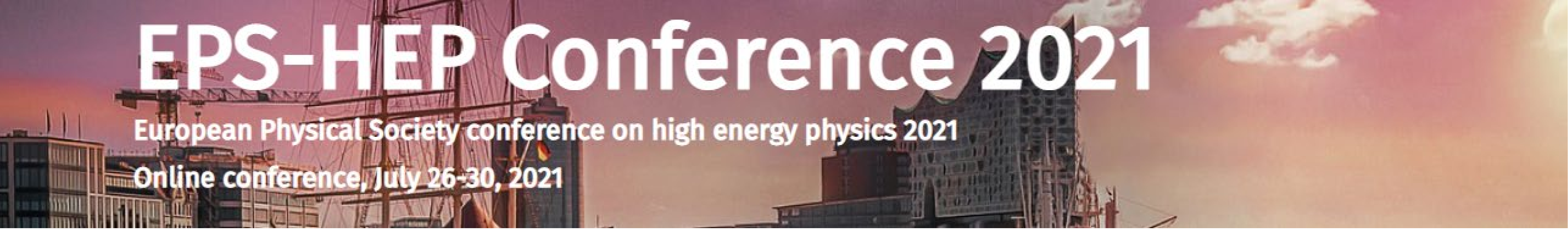


Future Collider Projects

Lenny Rivkin

Paul Scherrer Institute (PSI) & École Polytechnique Fédérale de Lausanne (EPFL)

30 June, 2021

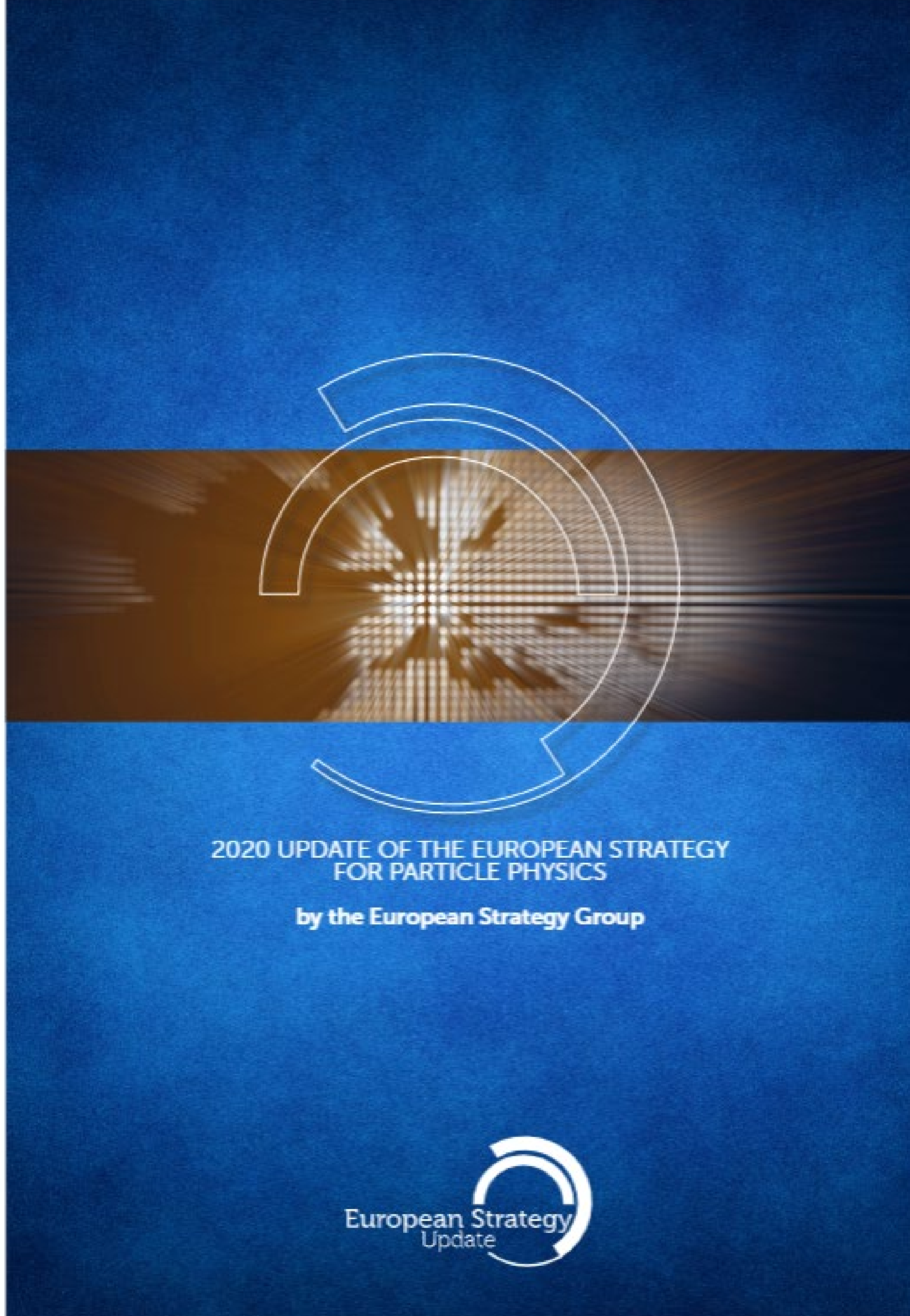
EPFL PAUL SCHERRER INSTITUT PSI UNIVERSITÉ DE GENÈVE

2020 ESPP Update, Preamble

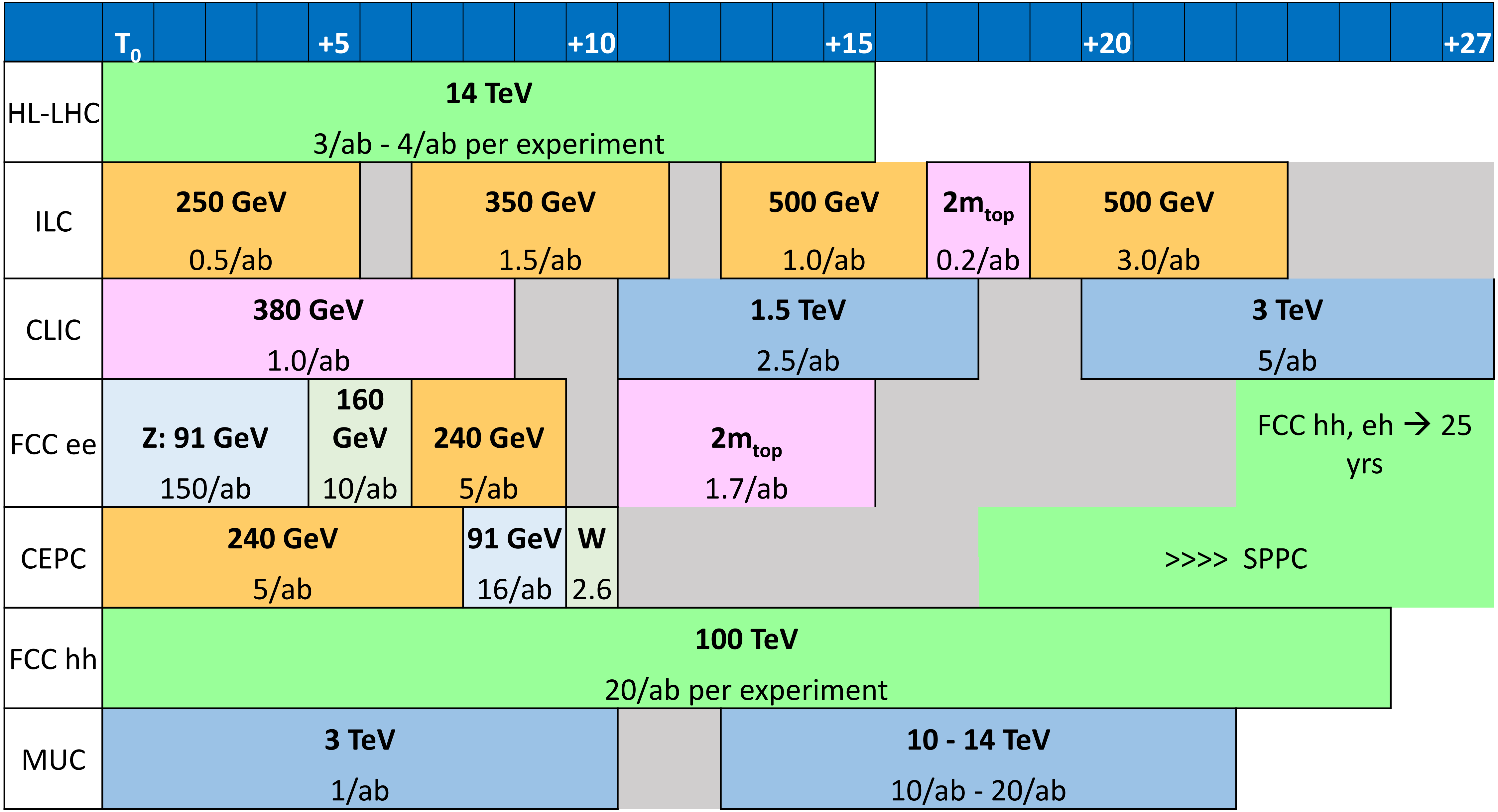
Nature hides the secrets of the fundamental physical laws in the **tiniest nooks of space and time**.

By developing technologies to probe ever-higher energy and thus smaller distance scales, particle physics has made discoveries that have transformed the scientific understanding of the world.

Nevertheless, many of the mysteries about the universe, such as the nature of dark matter, and the preponderance of matter over antimatter, are still to be explored.



Proposed Energy and Luminosity Evolution



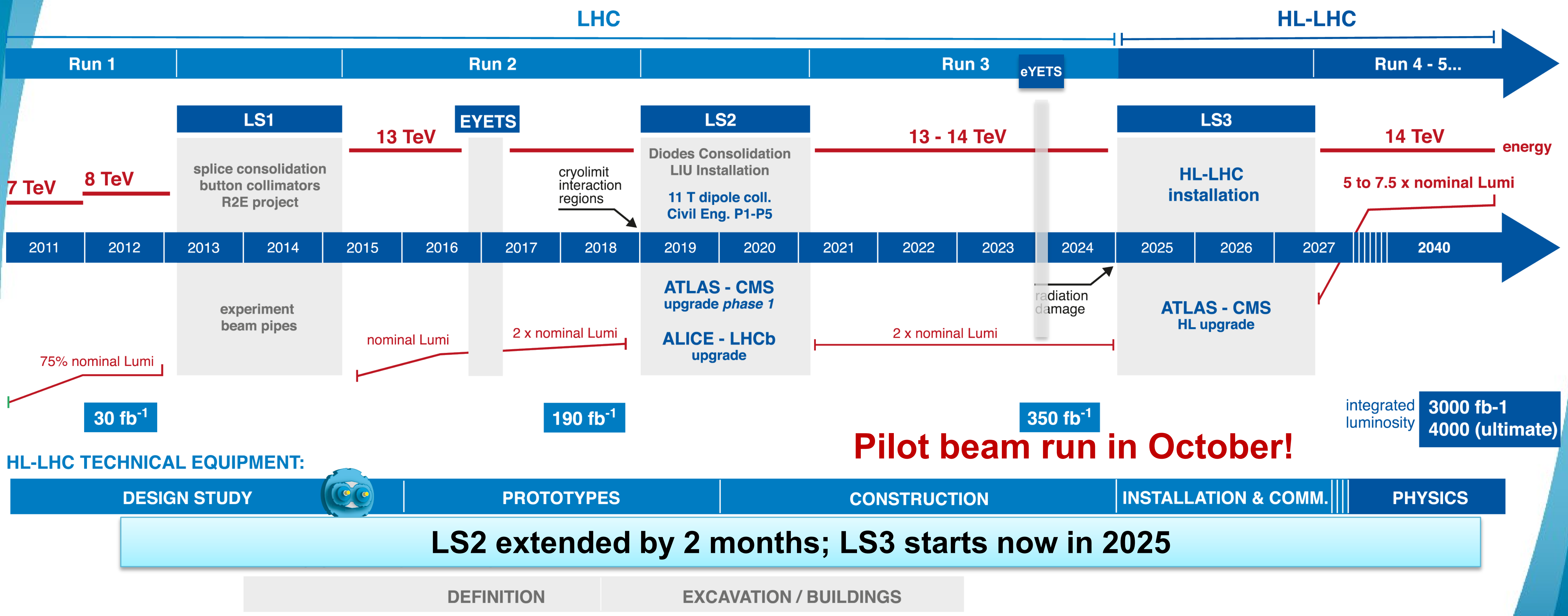
After B. Heinemann

LHC and High-Lumi LHC

Highest priority in short and medium term

J. Wenninger
O. Brüning
presentations on Tuesday

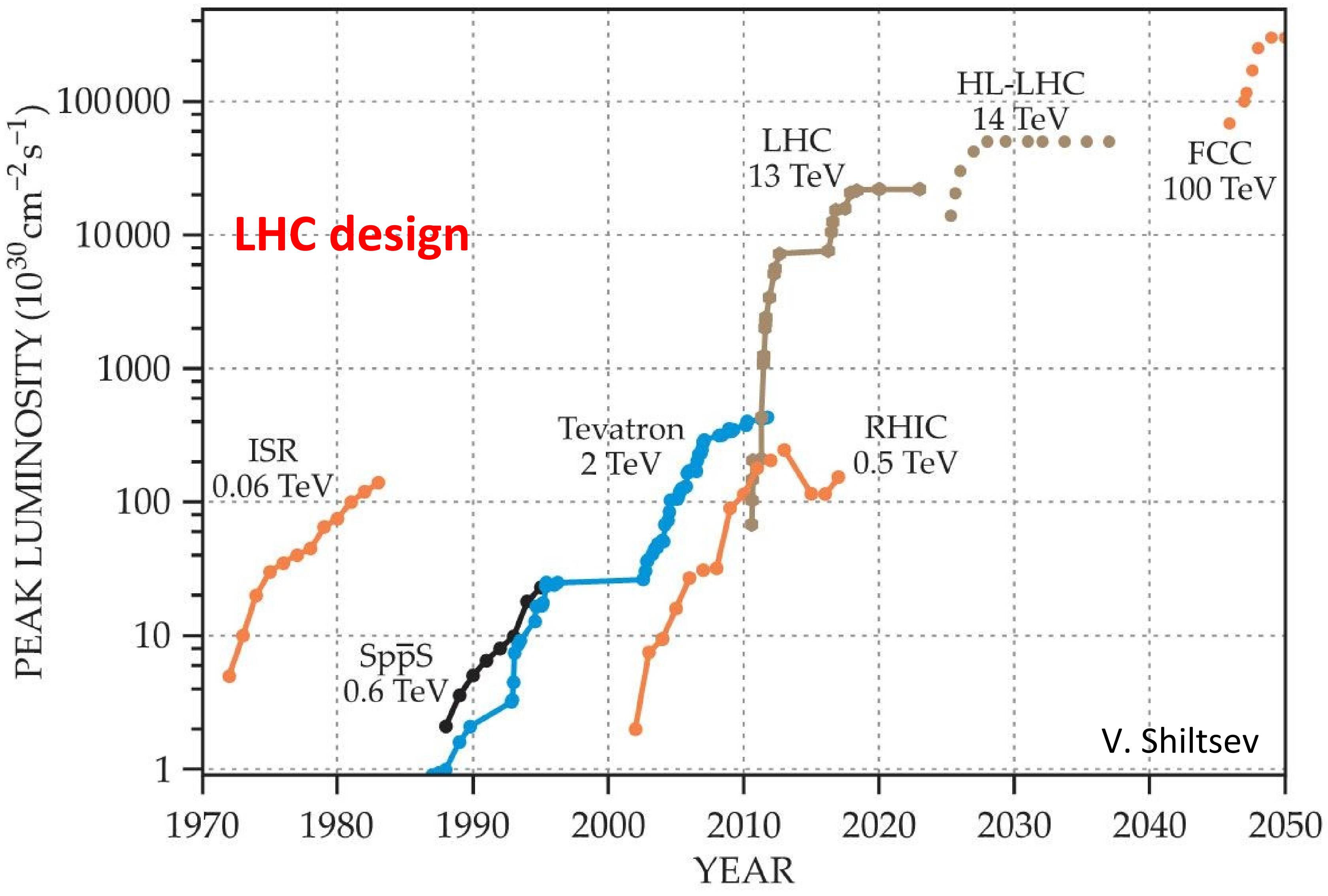
LHC / HL-LHC Plan



Pilot beam run in October!

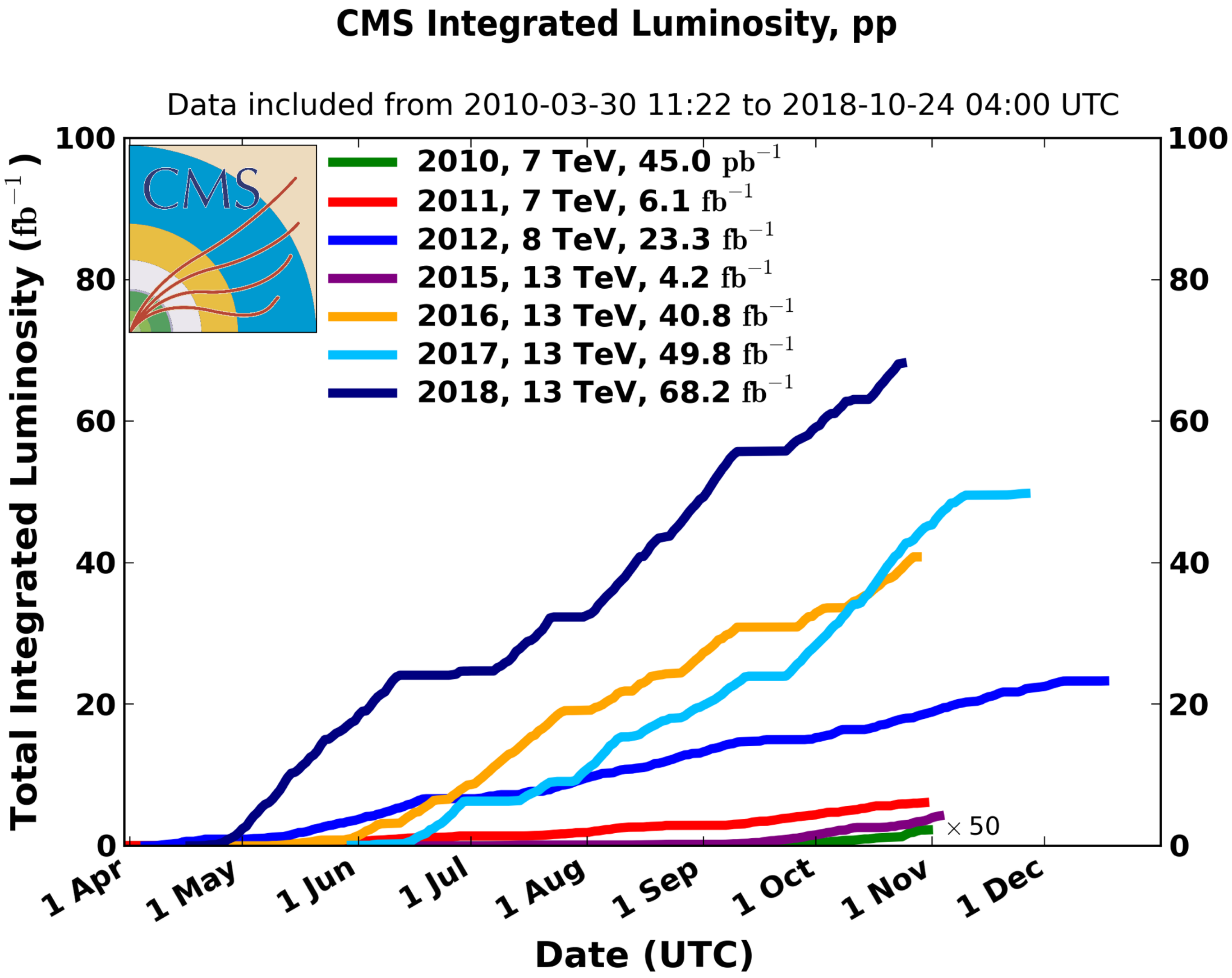
LS2 extended by 2 months; LS3 starts now in 2025

Hadron colliders peak luminosity



LHC integrated luminosity

- Peak luminosity
- Availability
- Luminosity leveling to control pile-up
- Ultimate **4000 fb^{-1}**



e+e- Higgs Factory

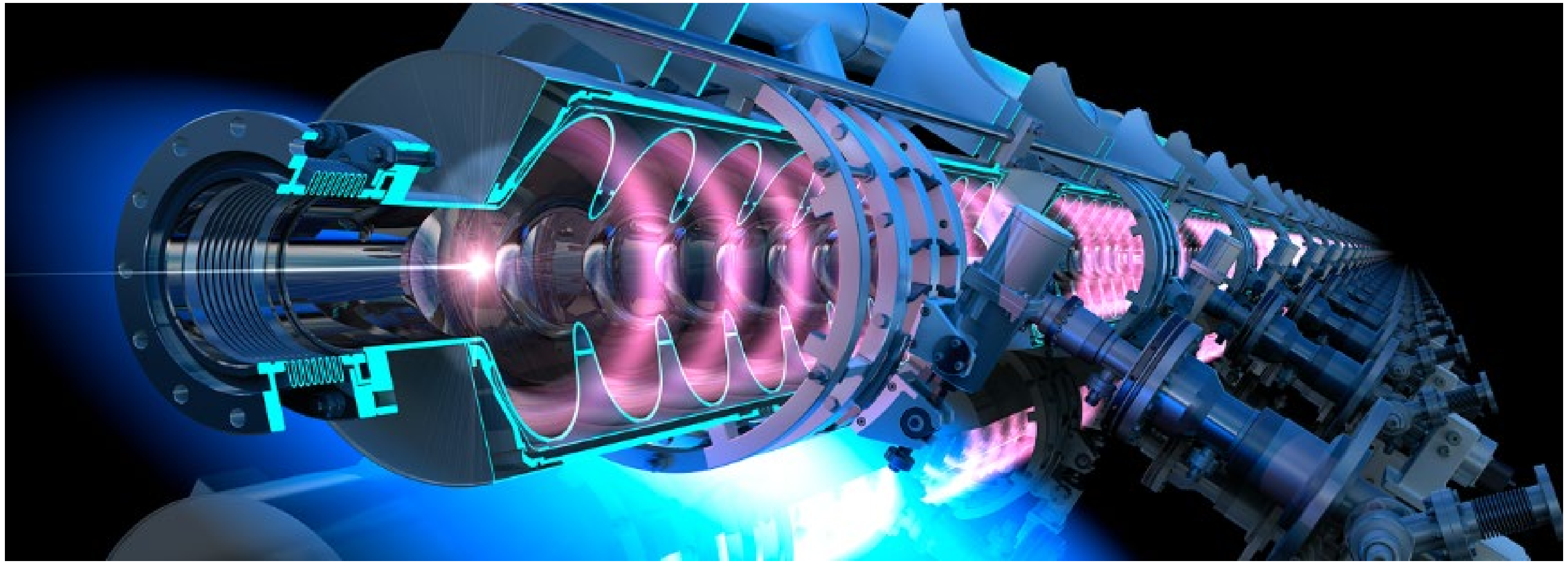
Highest priority next future collider

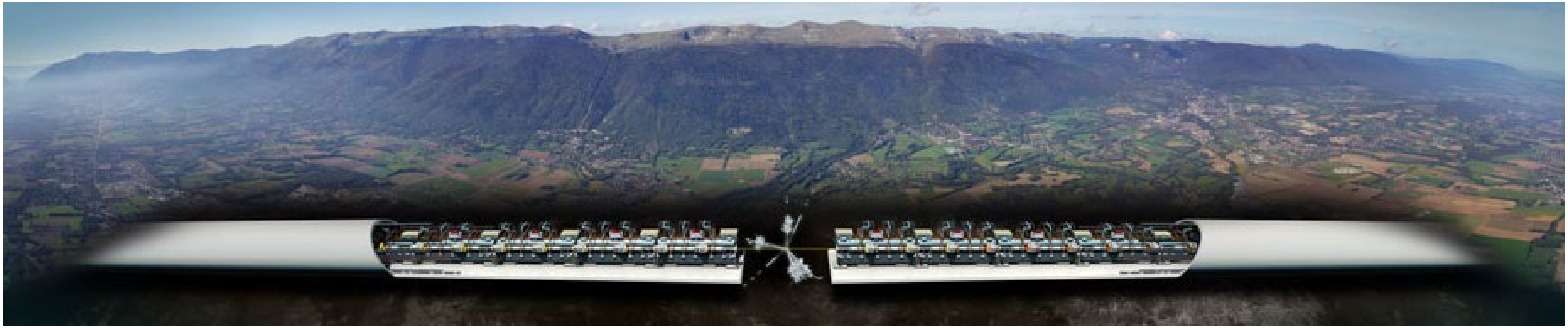
- Circular CEPC, FCC-ee
- Linear CLIC, ILC

A. Faus-Golfe
B. List
F. Zimmermann

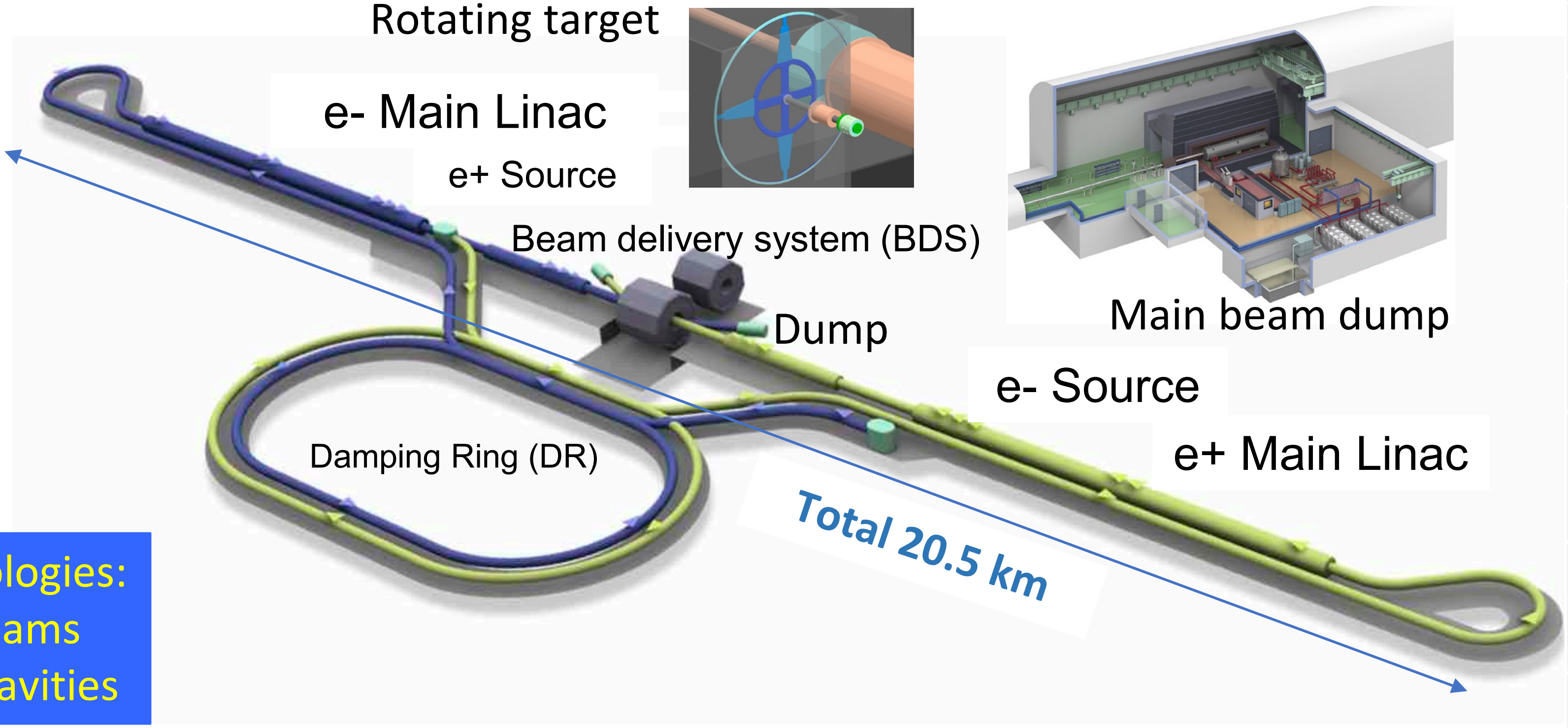
Linear colliders proposed

- ILC
- CLIC





ILC250 accelerator facility



Key Technologies:
- nano-beams
- S.c. RF cavities

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


ILC: artistic view

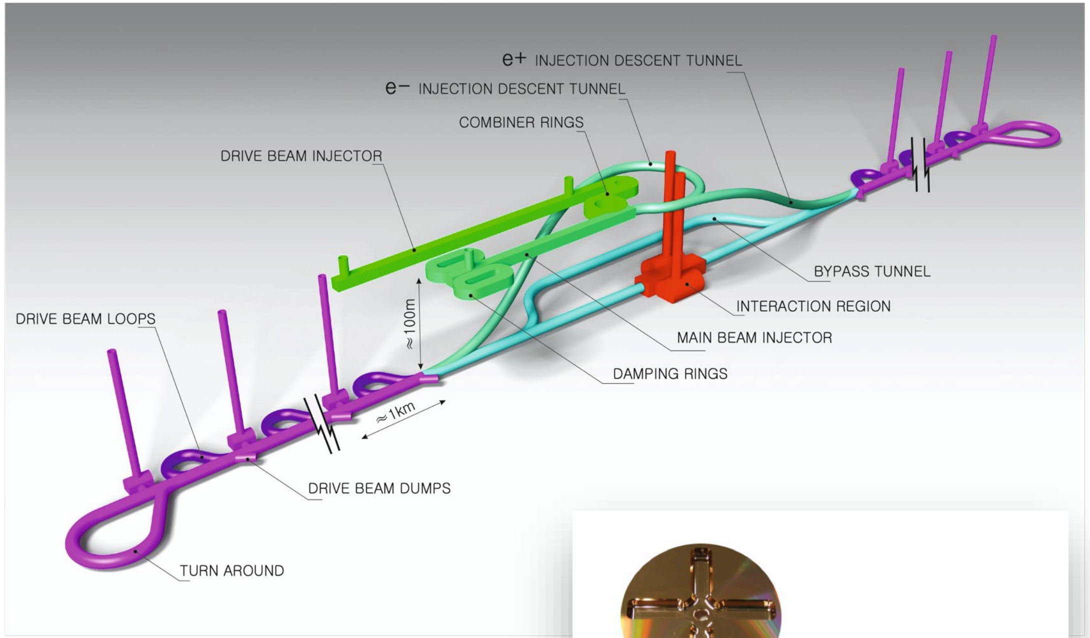

E-XFEL: Reality

10% of ILC

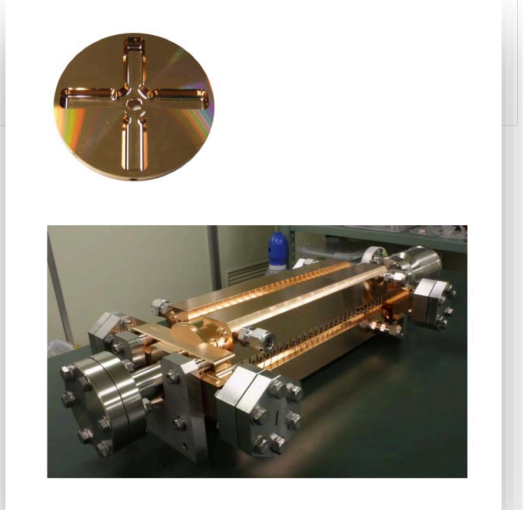

8,000 SRF cavities will be used.

Benno List

Proposed e^+e^- linear colliders – CLIC



Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)



The Compact Linear Collider (CLIC)

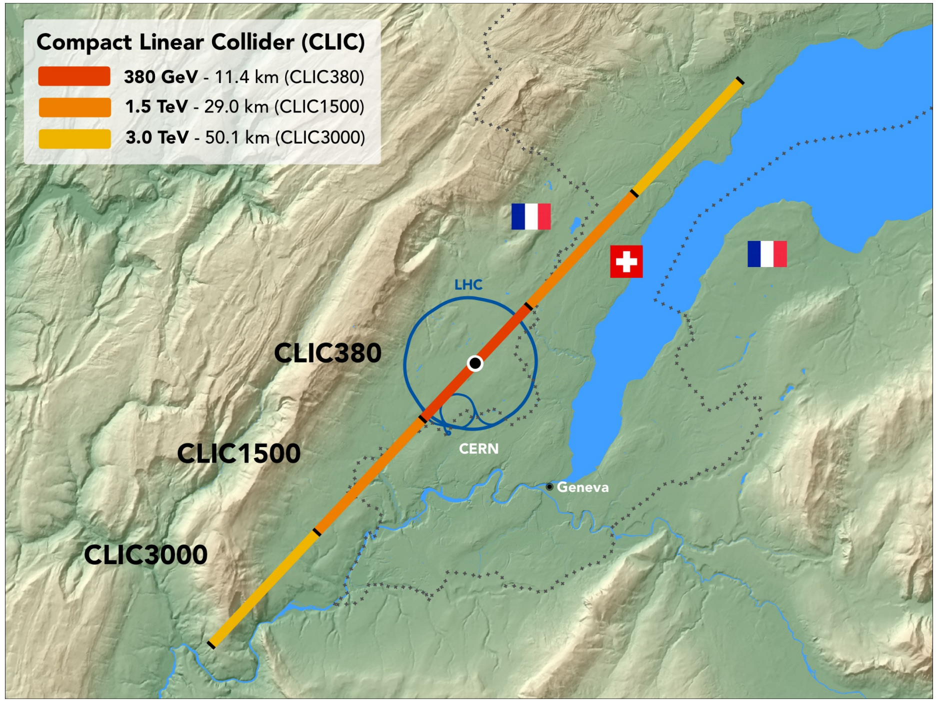
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20'500 cavities at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

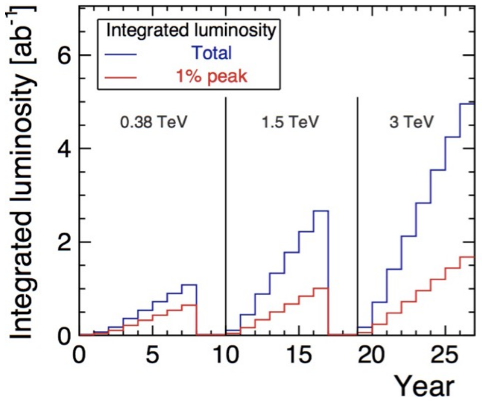
- CDR in 2012. Updated project overview documents in 2018 (Project Implementation Plan).

- **Cost:** 5.9 BCHF for 380 GeV (stable wrt 2012)
- **Power:** 168 MW at 380 GeV (reduced wrt 2012), some further reductions possible

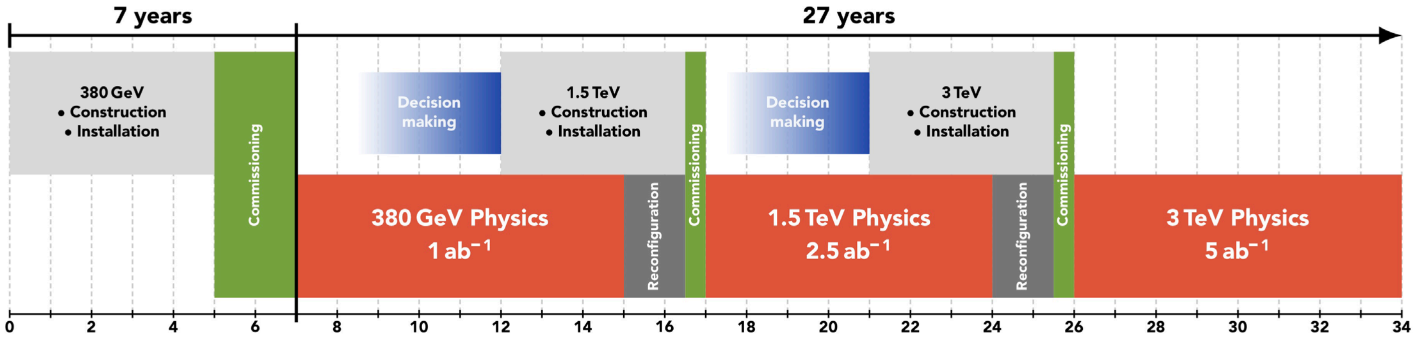
- Comprehensive **Detector and Physics** studies

CLIC timeline





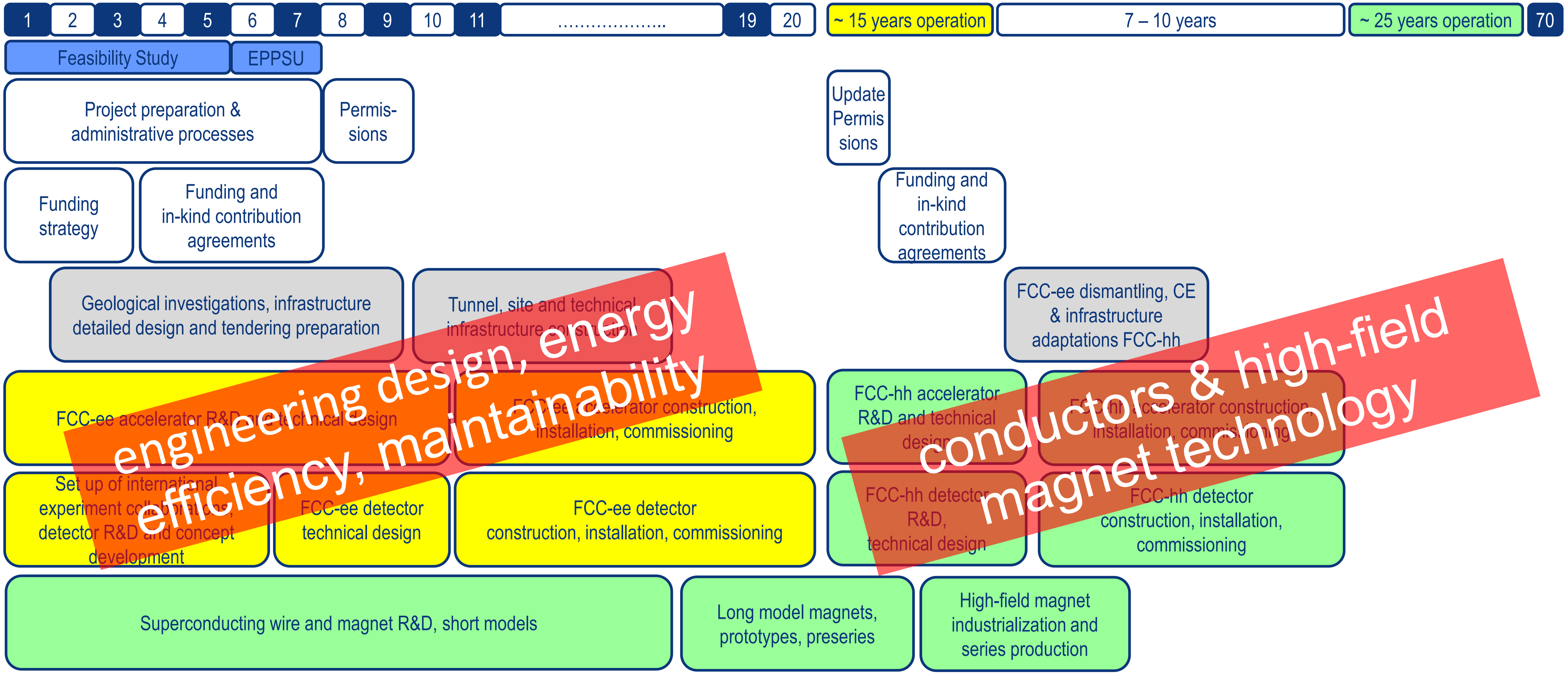
Ramp-up and up-time assumptions: arXiv:1810.13022, Bordry et al.



Technology Driven Schedule from start of construction shown above.

A preparation phase of ~5 years is needed before (estimated resource need for this phase is ~4% of overall project costs)

FCC integrated project technical schedule



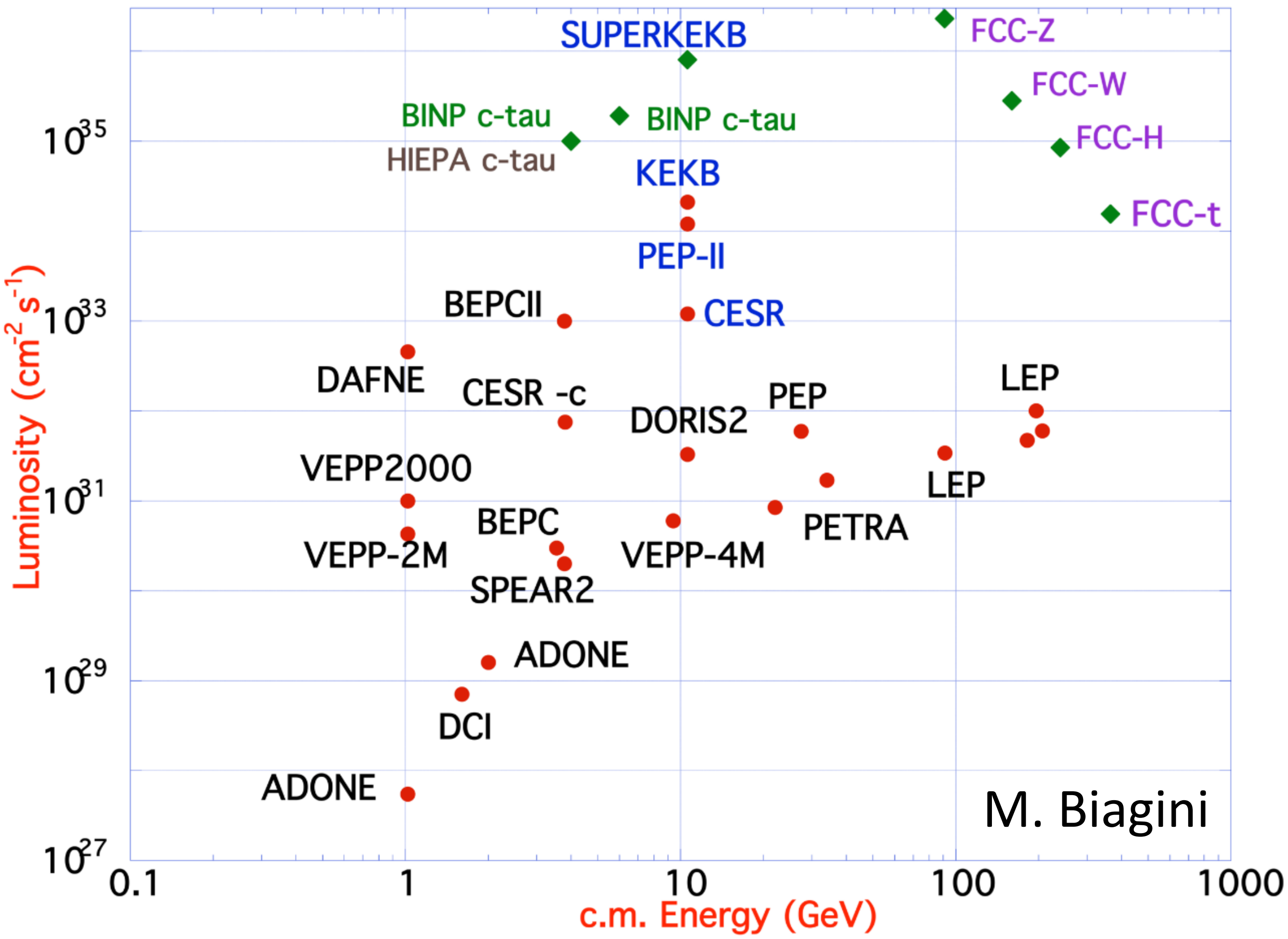
SuperKEKB at KEK

Design luminosity $8 \cdot 10^{35}$

Testing grounds for FCCee:

In several aspects more challenging than FCC-Z!

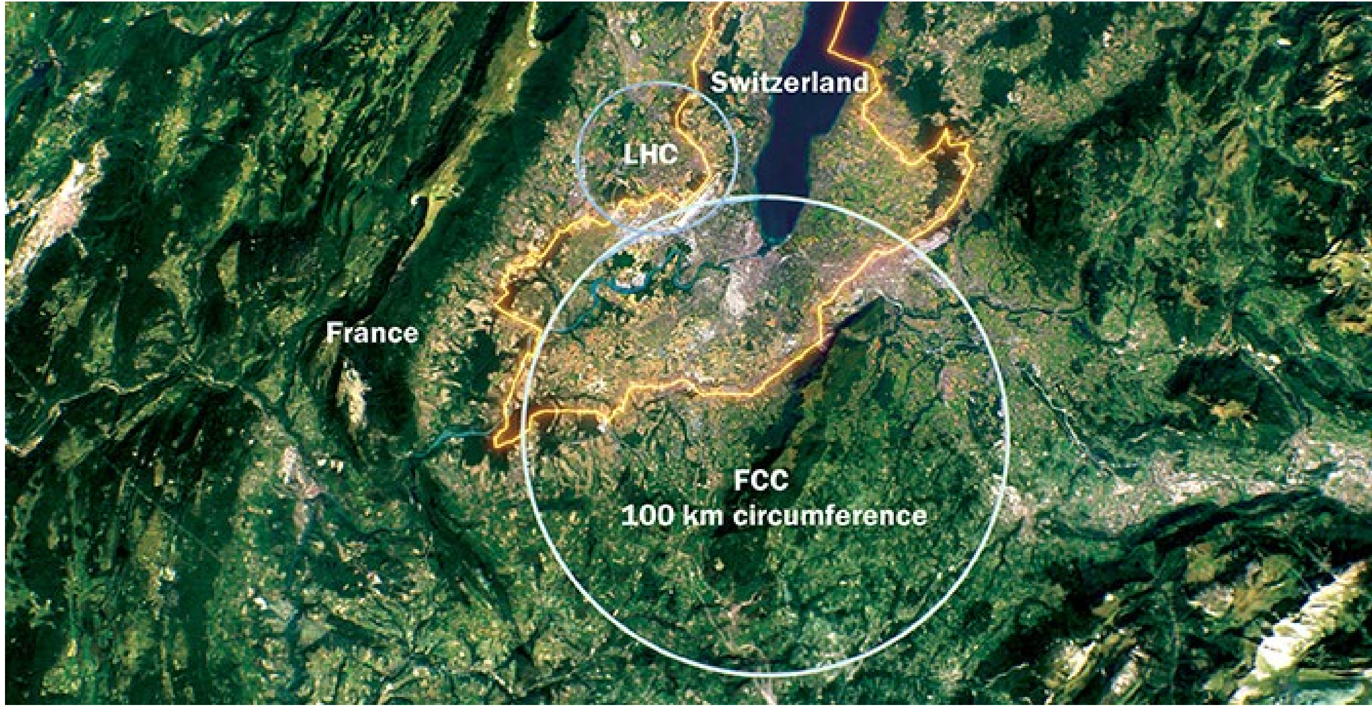
- *quads inside solenoid*
- *asymmetric collider*
- *strong focusing at IP*
- *top-up operation*
- *crab-waist scheme*

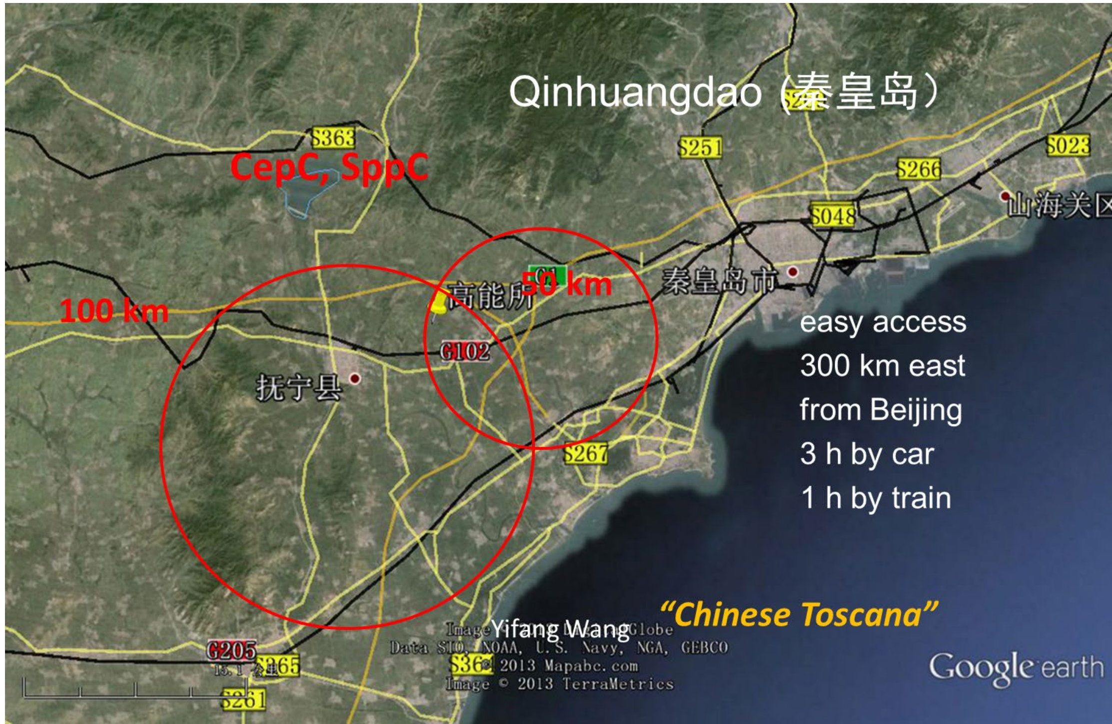


Hadron colliders

Future hadron colliders

- FCC-hh preceded by FCC-ee
- SPPC preceded by CEPC





FCC-hh: future hadron collider

FUTURE CIRCULAR COLLIDER

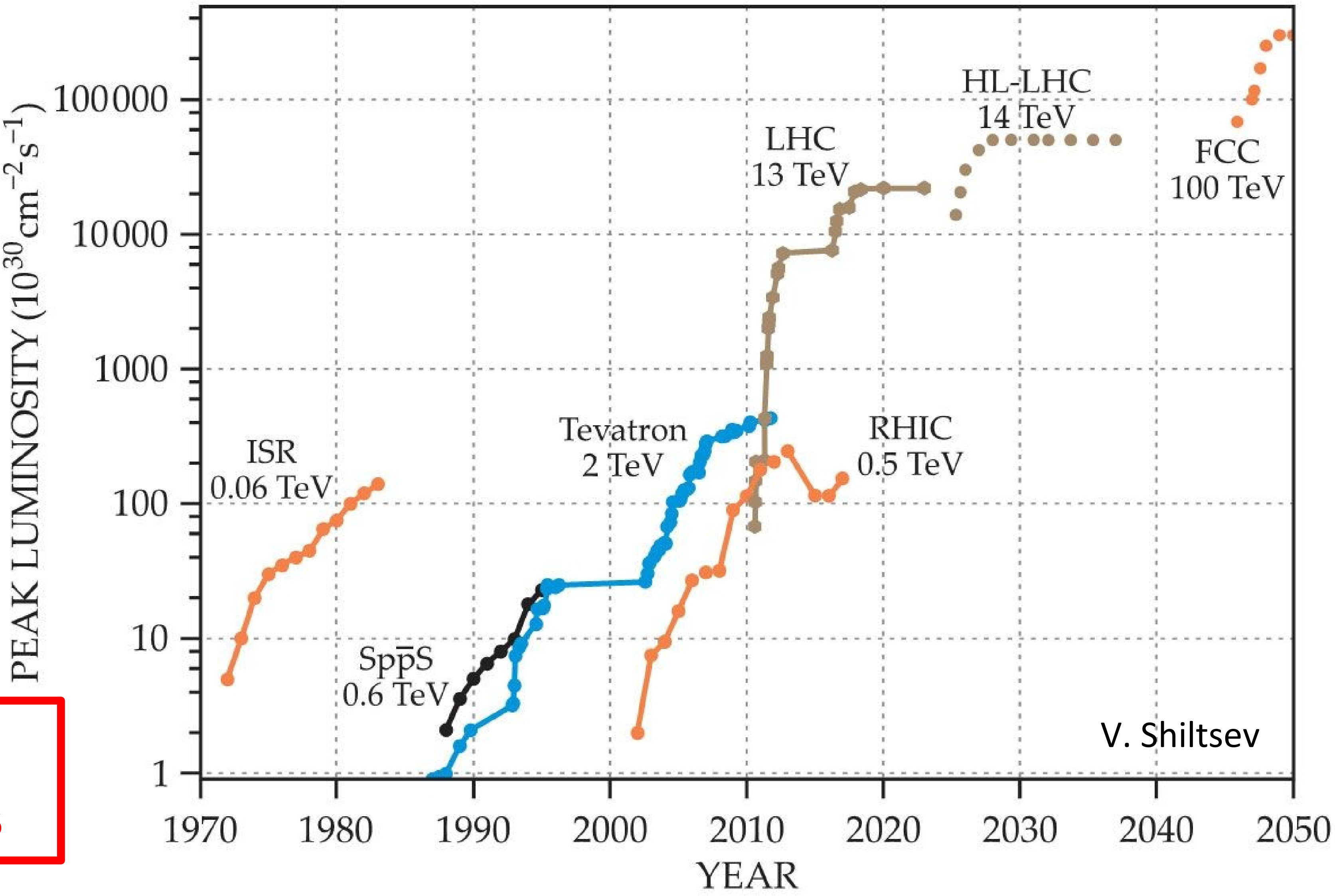
Factor 10 performance increase in energy & luminosity

100 TeV cm collision energy

20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

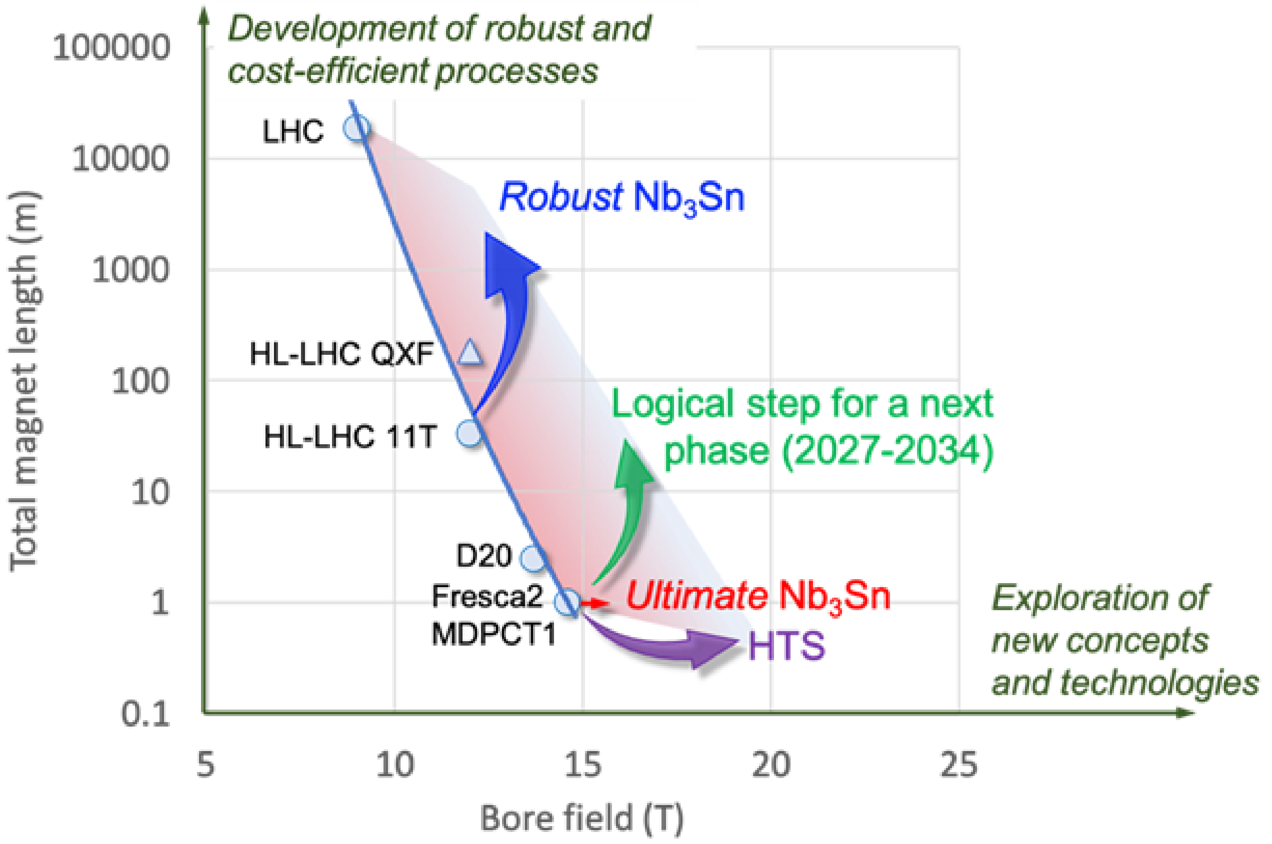
similar performance increase as from Tevatron to LHC

key technology: high-field magnets



GOALS OF A HIGH FIELD MAGNETS R&D PROGRAM

- **Demonstrate Nb_3Sn magnet technology for large scale deployment, pushing it to its practical limits, both in terms of maximum performance as well as production scale**
  - Demonstrate Nb_3Sn full potential in terms of **ultimate performance** (**towards 16 T**)
  - Develop Nb_3Sn magnet technology for collider-scale production, through **robust design**, industrial manufacturing processes and cost reduction (benchmark 12 T)
- **Demonstrate suitability of HTS for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the reach of Nb_3Sn (towards 20 T)**



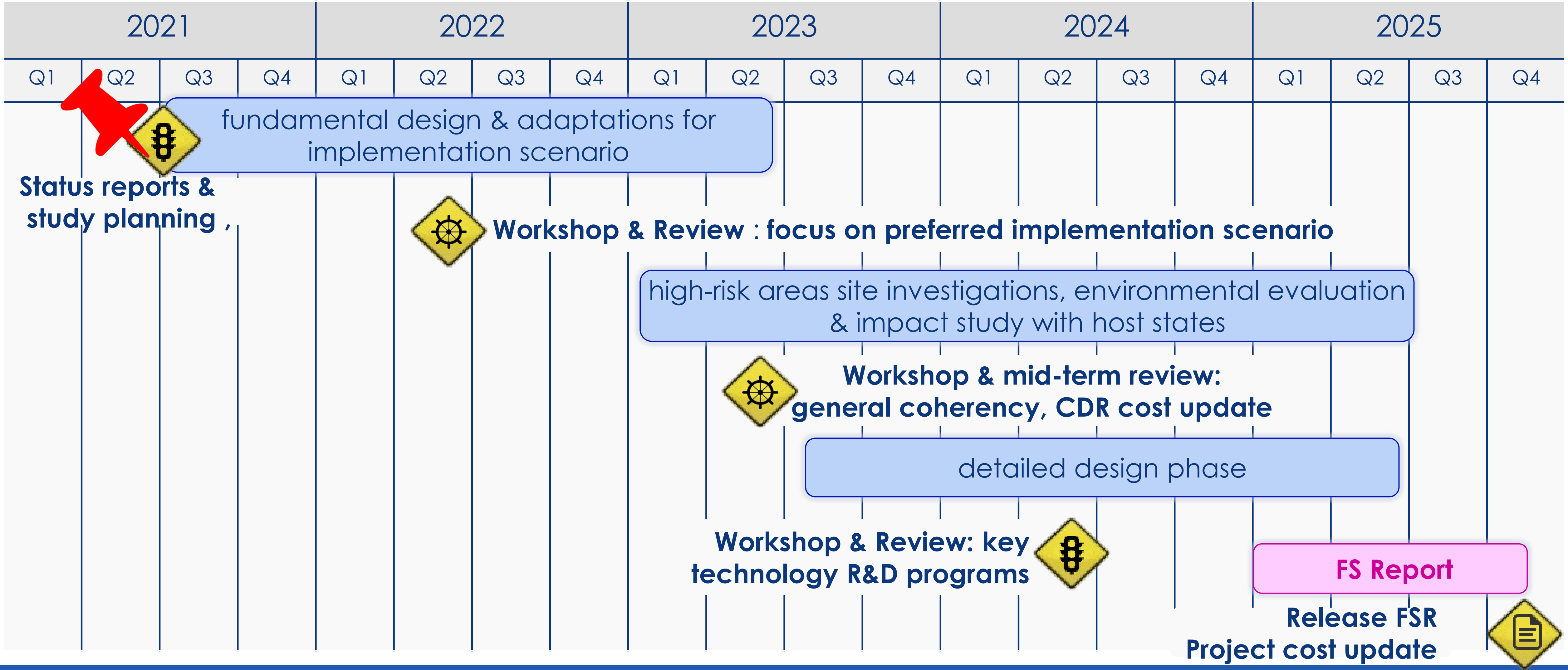
- **Other key parameters:**
  - Cost of Magnets & R&D
  - Timeline of a realistic development

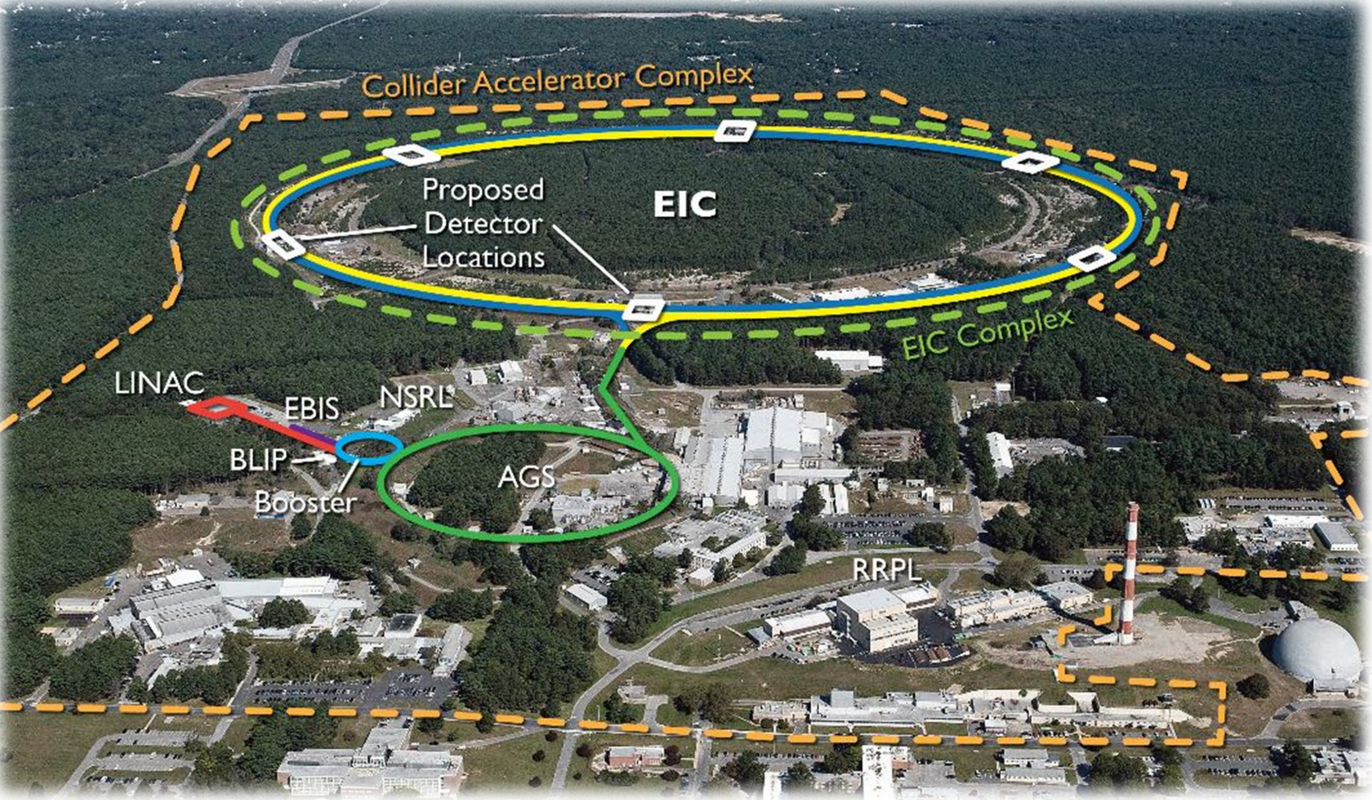
FCC Feasibility Study

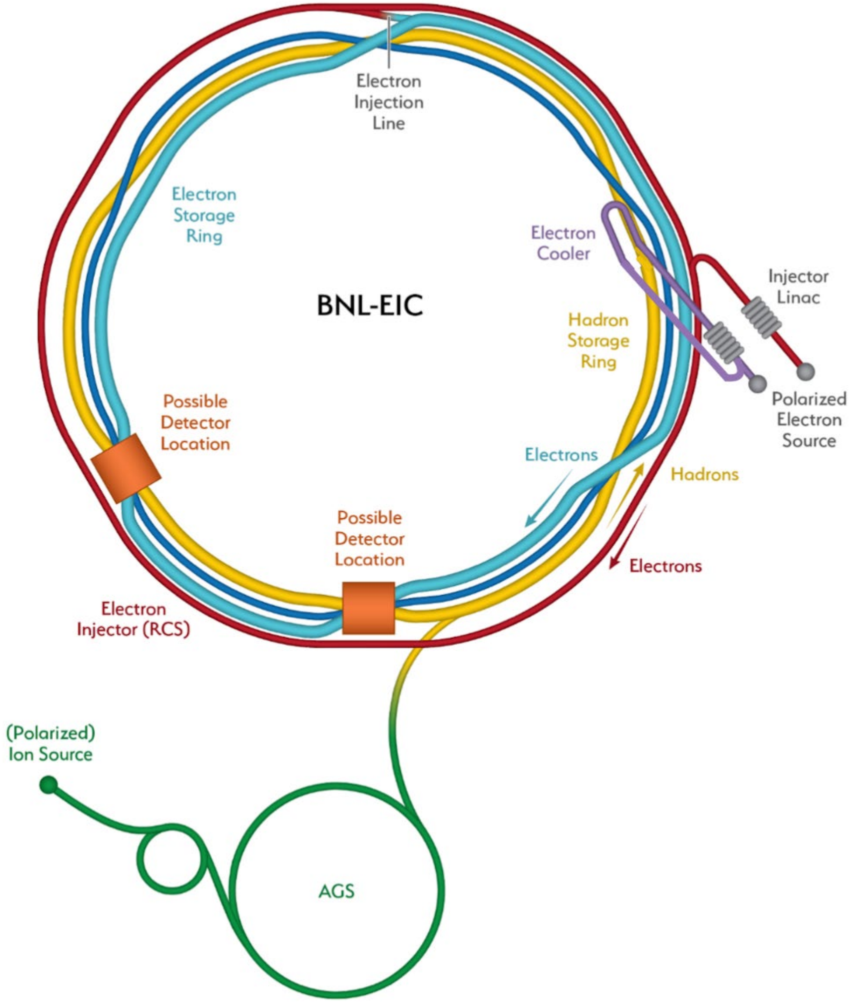
FCC Feasibility Study (FS) will address a recommendation of the 2020 update of the European Strategy for Particle Physics (ESPP):

- “Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.
- Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

Feasibility study timeline



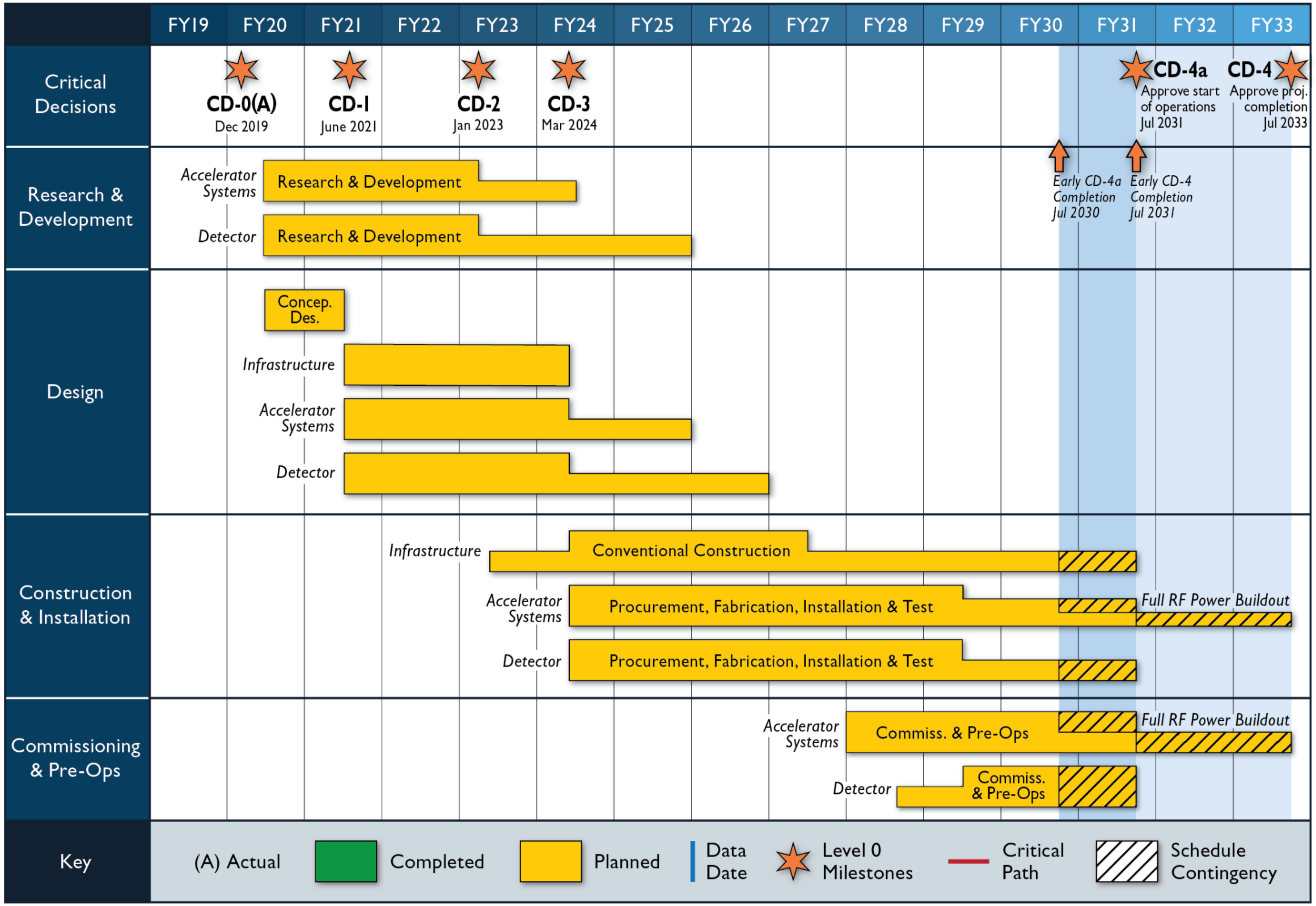




Electron Ion Colliders

F. Willeke

EIC



- E_{cm} range 20 – 140 GeV
- Luminosity 10^{33} – 10^{34}
- 10 – 100/fb per year
- Beams polarization 70%
- Ions: from proton to uranium

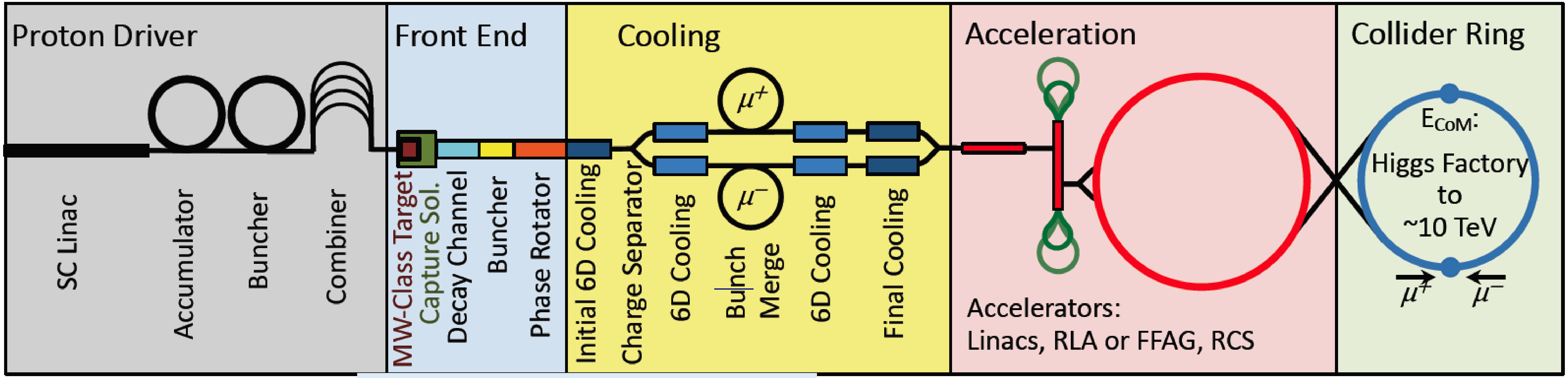
Muon Collider

Highest energy lepton future collider

D. Schulte

International MUON Collider Collaboration

The muon collider has been developed by the MAP collaboration mainly in the US
Muon cooling demonstration by MICE in the UK, some effort on alternative mainly at INFN



Protons produce pions
Pions decay to muons

Acceleration to collision energy

Collisions

Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

International Muon Collider Collaboration

Muon collider has a high potential

- The muon collider presents enormous potential for fundamental physics research at the energy frontier.
- Not as mature as some other lepton collider options such as ILC and CLIC; but promises attractive cost, power consumption and time scale for the energy frontier, reaching beyond linear colliders.

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	$1\ \mathrm{ab}^{-1}$
10 TeV	$10\ \mathrm{ab}^{-1}$
14 TeV	$20\ \mathrm{ab}^{-1}$

Collaboration goal:

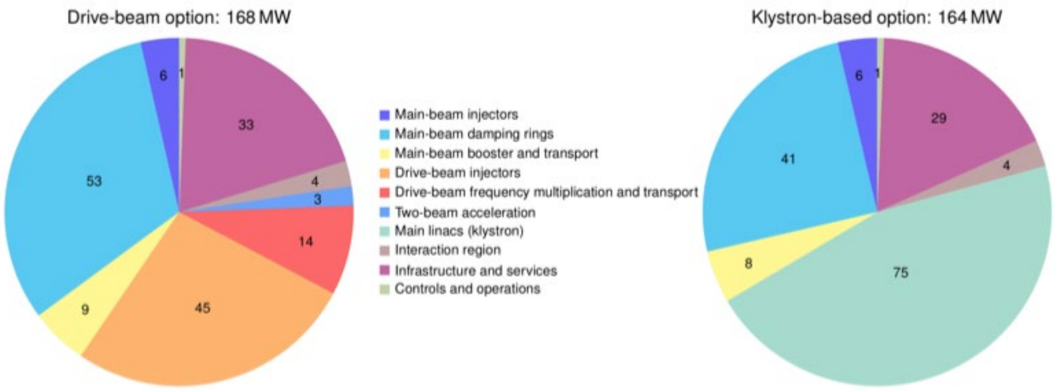
- Aim to develop concept to a maturity level that allows to make informed choices by the next ESPPU and other strategy processes
- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for **construction in 15-20 years**
  - **10+ TeV**, with more advanced technology, **the reason to do muon colliders**
- Explore synergy with other options (neutrino facility / ***Higgs factory at resonance***)
- Define **R&D path**

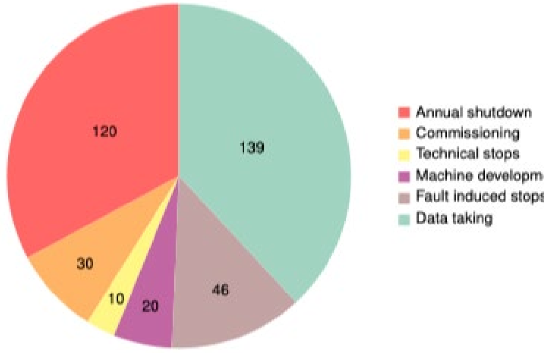
Efficiency of future colliders

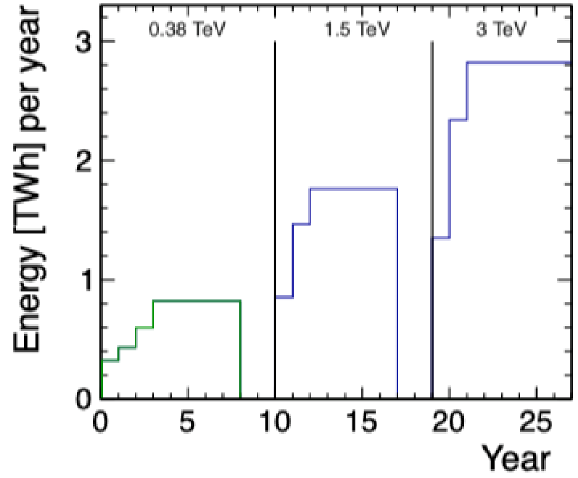
High energy and luminosity need high grid power

Power and energy

Collision Energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	168	25	9
1500	364	38	13
3000	589	46	17







Power estimate bottom up (concentrating on 380 GeV systems)

- Very large reductions since CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimisation, etc

Further savings possible, main target damping ring RF and improved L-band klystrons for drivebeam

From running model and power estimates at various states – the energy consumption can be estimated

CERN is currently consuming ~1.2 TWh yearly (~90% in accelerators)

Will look also more closely at 1.5 and 3 TeV numbers next (in blue in figure to illustrate not optimized as for 380 GeV), Hi-Eff L-band klystrons development (see later), damping ring RF as mentioned, include reduction using permanent magnets

Future colliders and Grid Power

$$P_{SR} \propto \gamma^4 \frac{1}{\rho}$$

	ECM [TeV]	L / IP [$10^{34}cm^{-2}s^{-1}$]	Energy TWh/a	P_{Grid} [MW]	power driving effects
FCC-ee (Z)	0.091	230	**1.2**	**259**	SR Power: 50MW/beam
FCC-ee (t)	0.365	1.5	**1.9**	**359**	SR power: 50MW/beam
CEPC	0.24	5	**1.4**	**300**	SR Power: 30 MW/beam
FCC-hh	100	30	**4**	**580**	SR power: 2.4MW/beam @ 50K, cryogenics
ILC	1	5	**1.4**	**300**	beam power: 13.6 MW/beam, cryogenics
CLIC	3	5.9	**2.8**	**580**	beam power: 14 MW/beam
muon coll.	10	20	**1.2**	**300**	mu decay, 1.6MW/drive beam, cycling magnets, scaling advantages, least developed

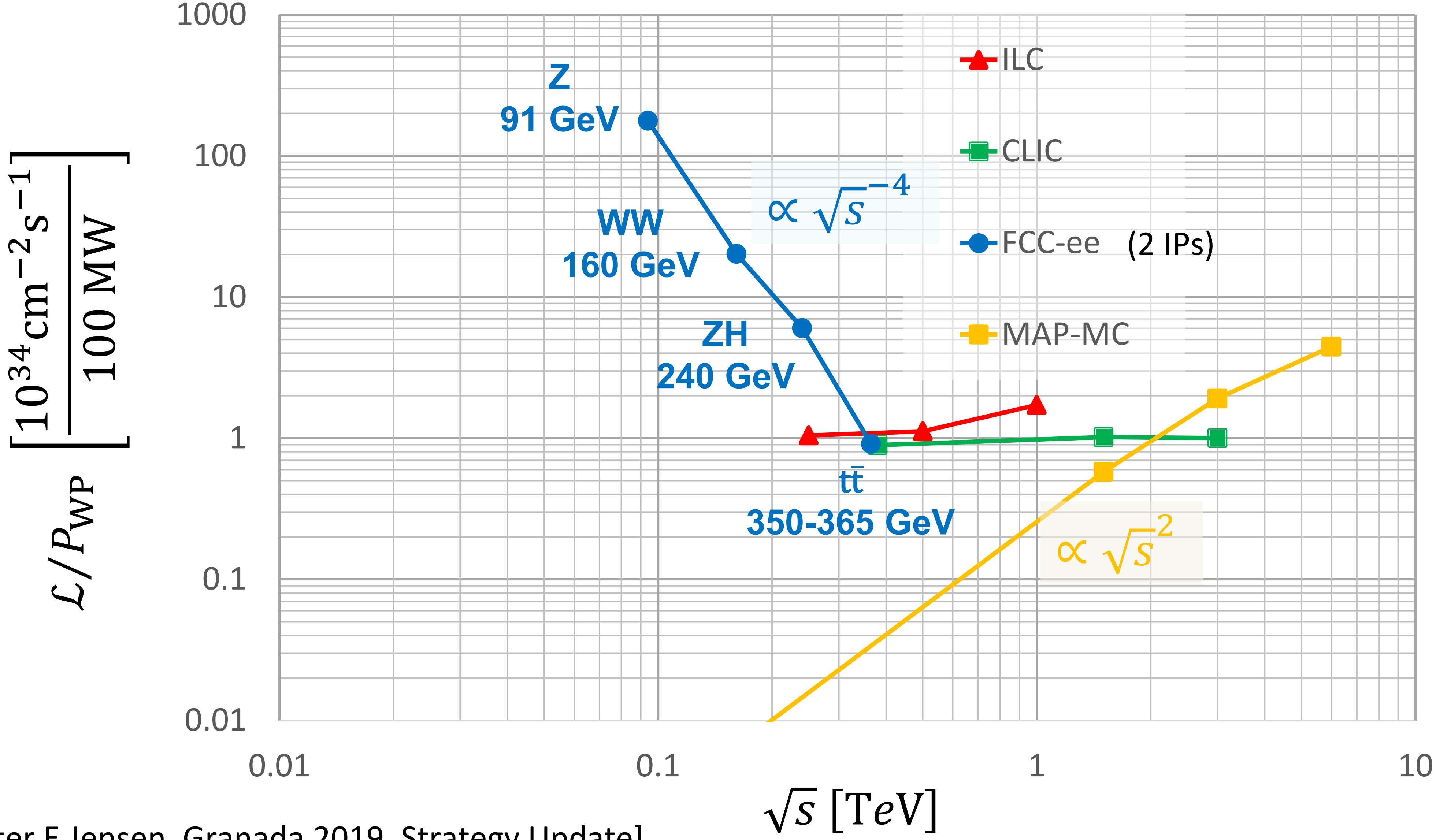
Significant energy cost: 4 TWh ~ 200M€, and sustainability concerns.
→ need more R&D towards efficient concepts & technology, energy management

$$L_{\text{lin.col.}} \propto H_D \sqrt{\frac{\delta_E}{\varepsilon_{x,n}}} P_{\text{beam}}$$

$$L_{\text{mu.col.}} \propto B \frac{N_0}{\varepsilon_{xy,n}} \gamma P_{\text{beam}}$$

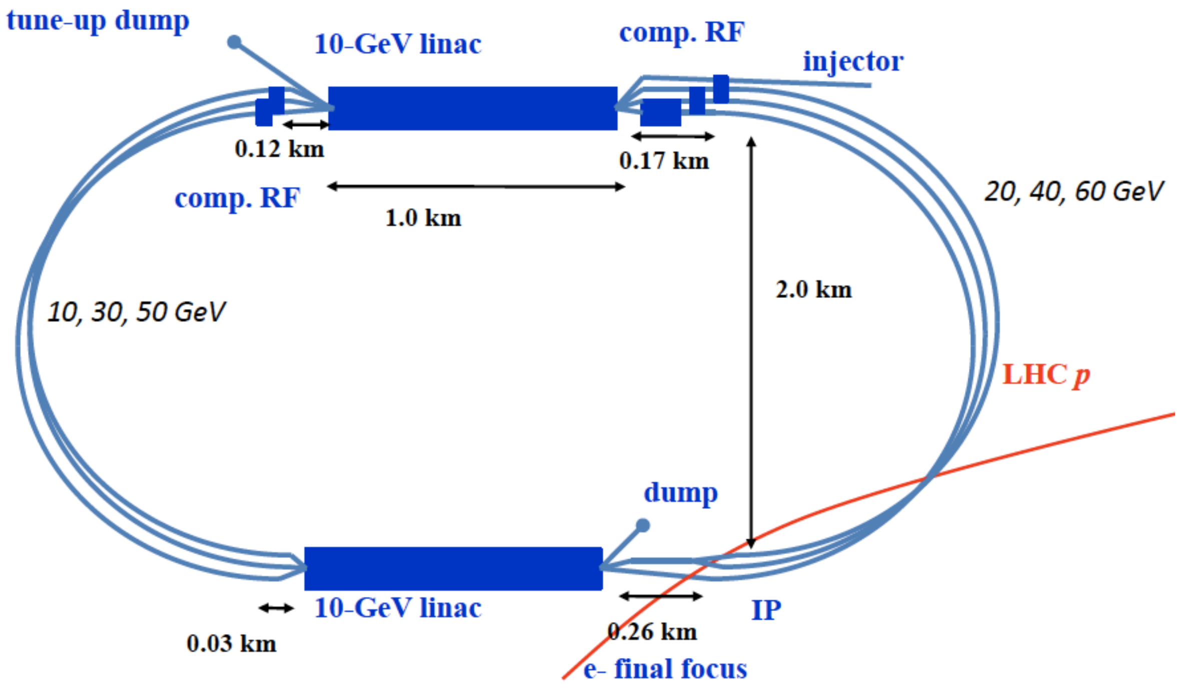
[After M. Seidel, Workshop Sustainable HEP, June 2021]

Lepton collider Proposals: Luminosity per Grid Power

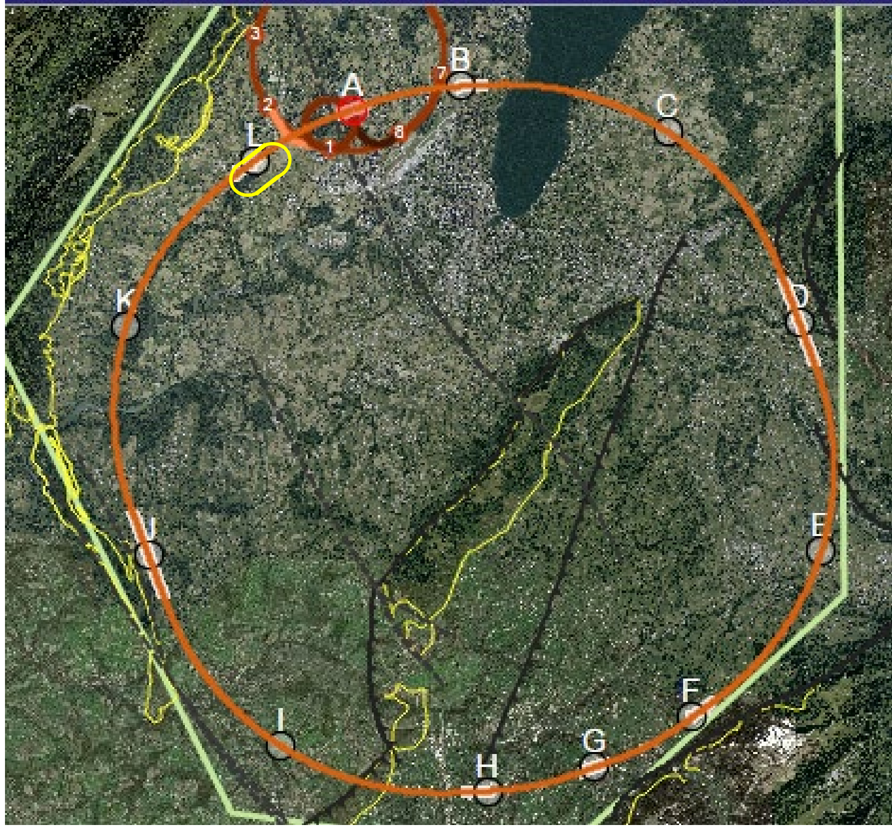


Luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders

[After E.Jensen, Granada 2019, Strategy Update]



LHeC CDR, arXiv:2007.14491



FCC-hh/eh CDR (2019)

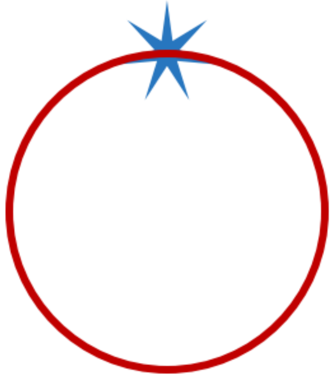
Energy Recovery Linacs based Colliders

LHeC, FCC-eh

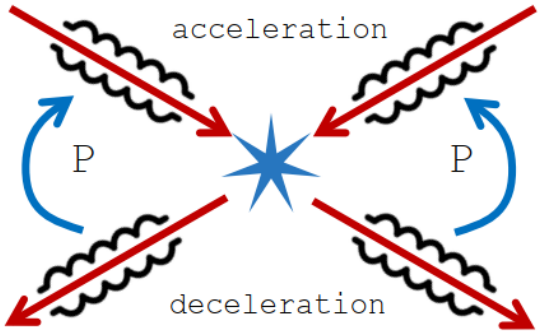
M. Klein

Energy Recovery Linacs (ERLs) based ideas

Ring Collider
beams circulate



ERL
power re-cirulated



Linear Collider
beams collide once

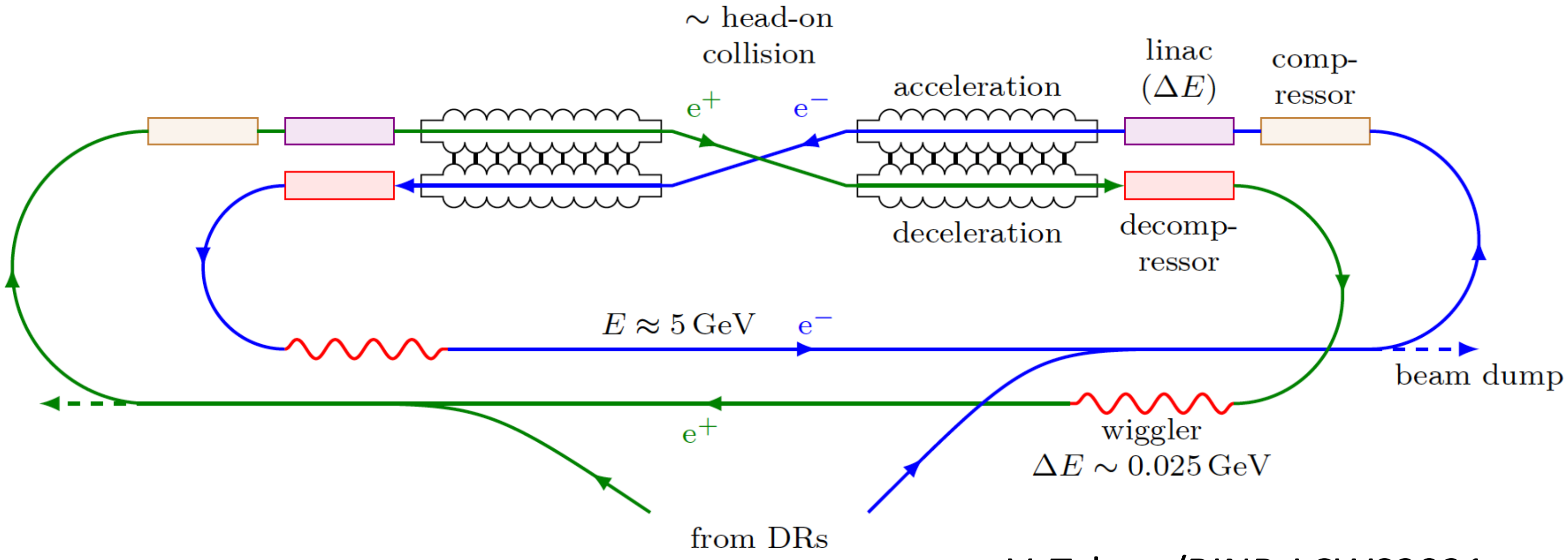
- beam used once
- but power recirculated
- ambitious collision parameters lead to low beam intensity

→ **overall low energy consumption, but higher initial investments**

iFAST

M. Seidel

ERL based version of ILC Collider Concept: ERLC

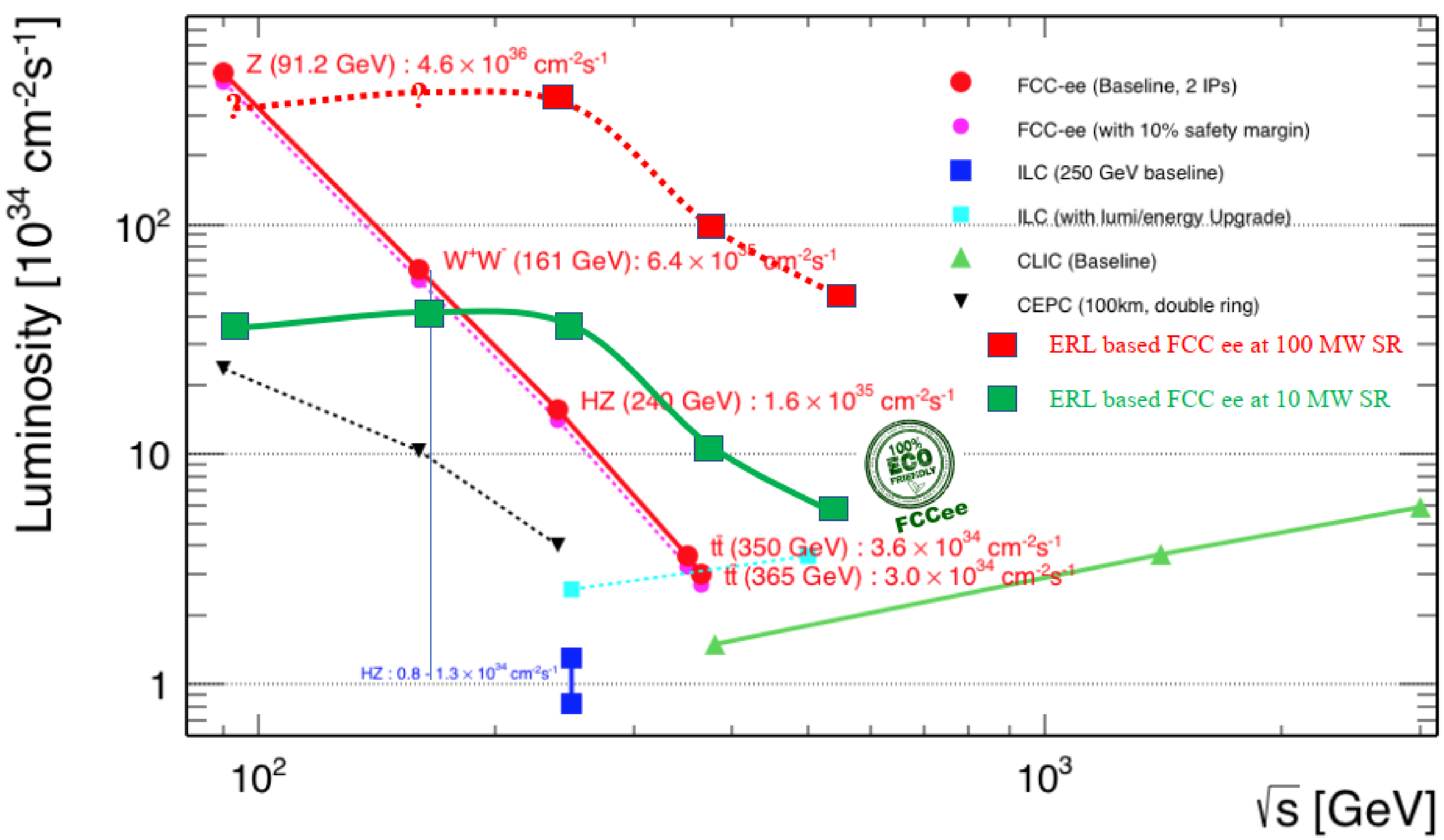


V. Telnov/BINP, LCWS2021,
https://indico.cern.ch/event/995633/contributions/4275159/
…and preprint paper https://arxiv.org/pdf/2105.11015.pdf

- 250 GeV, high luminosity O(10^{36})
- Total power similar to the ILC
- Beams dumped at low energy

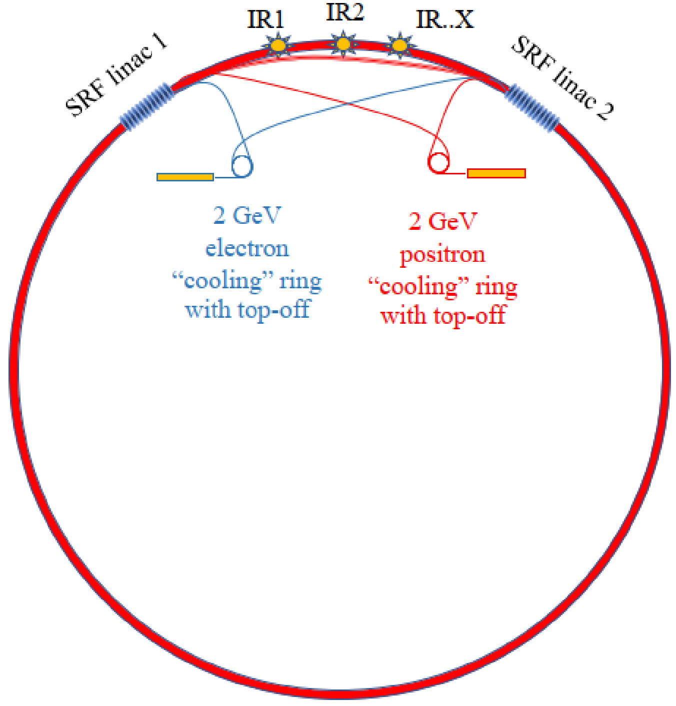
FCC-ee ERL option: boosting luminosity & energy ?

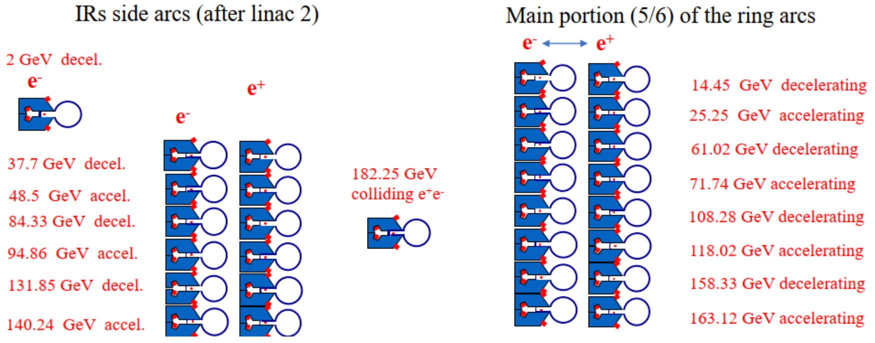
FUTURE CIRCULAR COLLIDER
Innovation Study



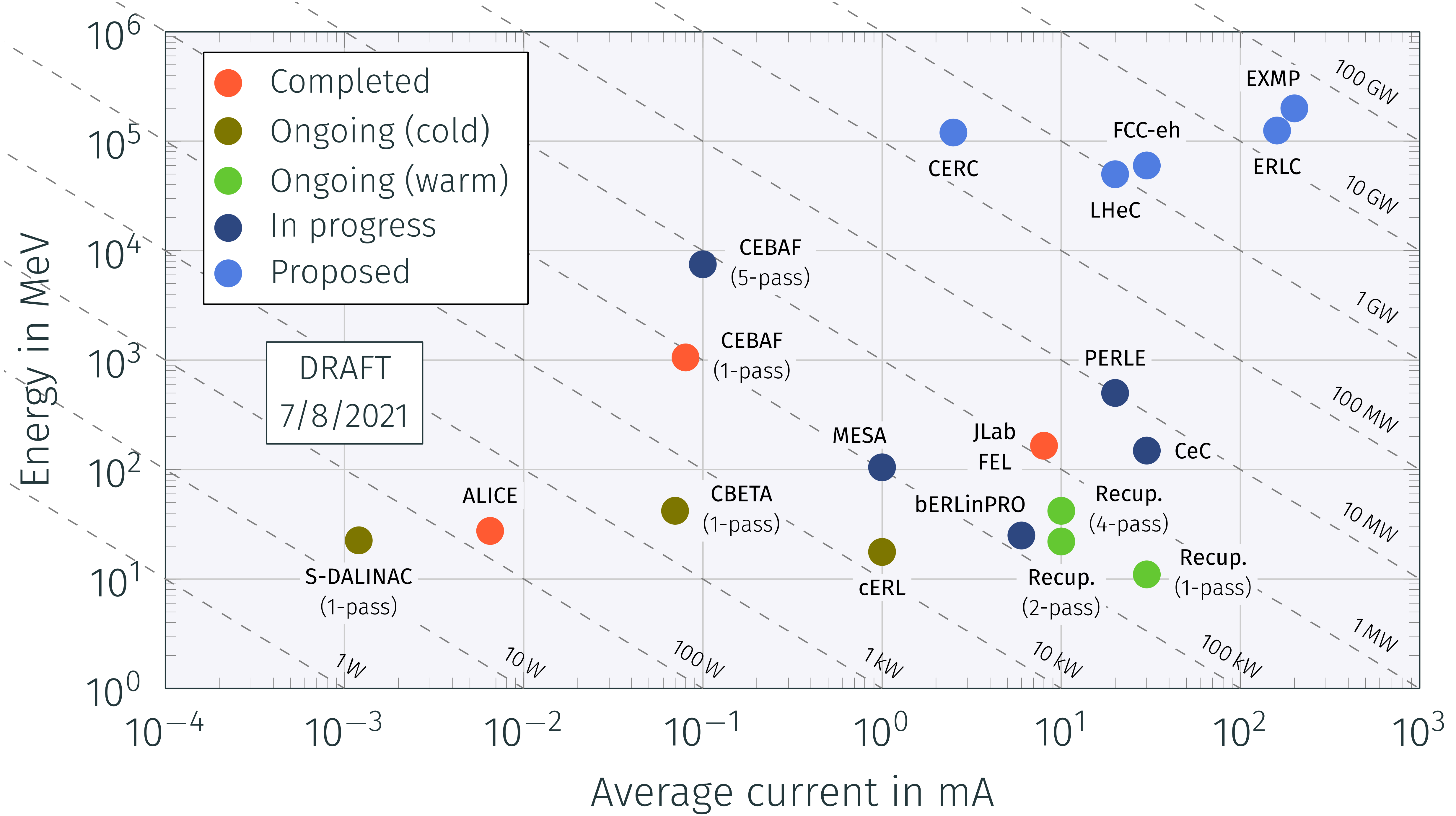
V. Litvinenko, T. Roser, M. Chamizo

"High-energy high-luminosity e$^+$e$^-$ collider using energy-recovery linacs," Phys. Lett. B Vol 804, 135394 (2020)



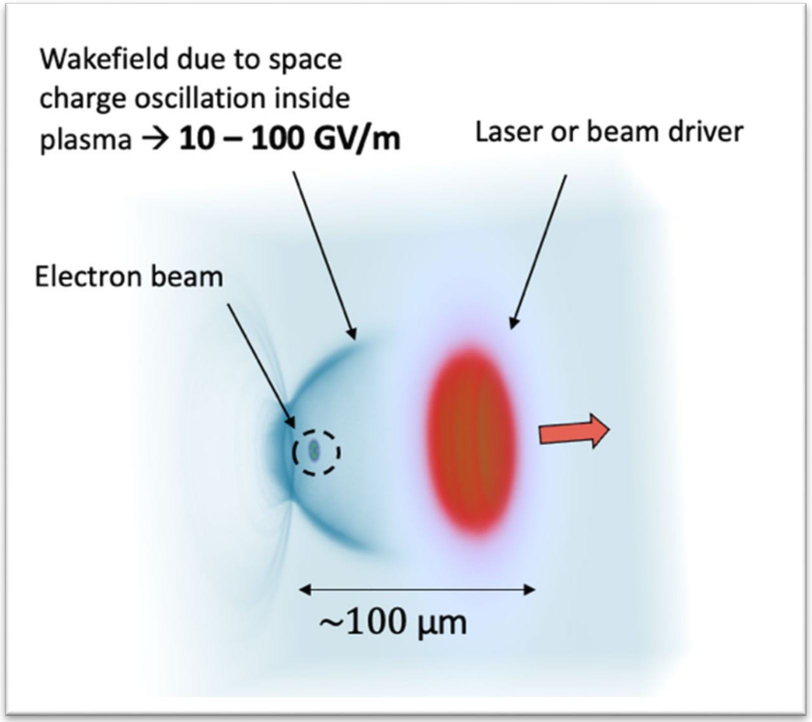


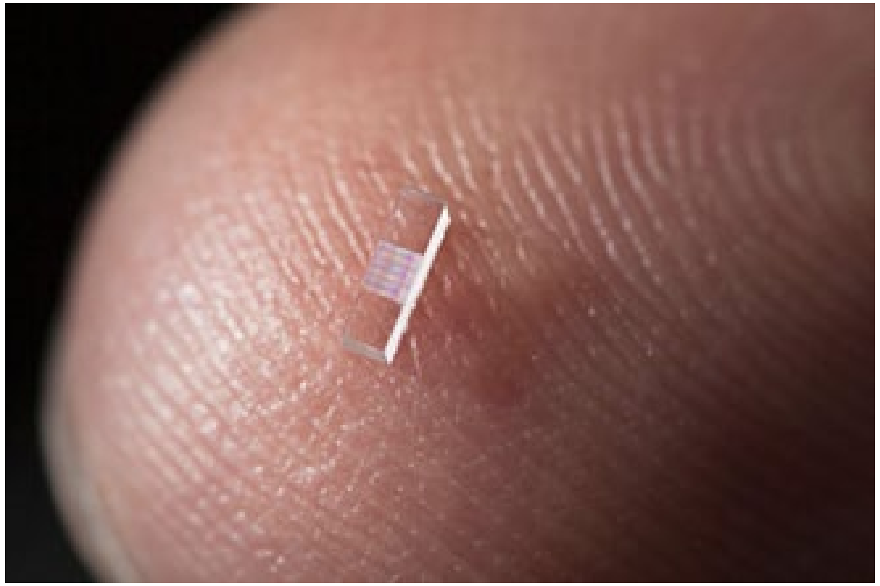
- **predicted luminosity** superior to FCC-ee from ZH running onwards
- the **principle feasibility**, **power consumption**, and **construction cost** are presently **under study by LDG ERL ERL-collider subpanel**
- **ERL could be possible FCC-ee upgrade path** if shown to be feasible



Completed
Ongoing (cold)
Ongoing (warm)
In progress
Proposed
DRAFT
7/8/2021
Energy in MeV
Average current in mA
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
EXMP
ERLC
FCC-eh
LHeC
CERC
CEBAF
(5-pass)
CEBAF
(1-pass)
PERLE
MESA
JLab
FEL
CeC
ALICE
CBETA
(1-pass)
bERLinPRO
Recup.
(4-pass)
Recup.
(2-pass)
Recup.
(1-pass)
S-DALINAC
(1-pass)
cERL
1 W
10 W
100 W
1 kW
10 kW
100 kW
1 MW
10 MW
100 MW
1 GW
10 GW
100 GW

EuPRAXIA, a new ESFRI roadmap project





ACHIP: accelerator on a chip

Plasma acceleration

Laser and beam driven concepts

R. Assmann

Shrinking the Size of Particle Physics Facility

RF Accelerators

> 30,000 operational – many serve for Health

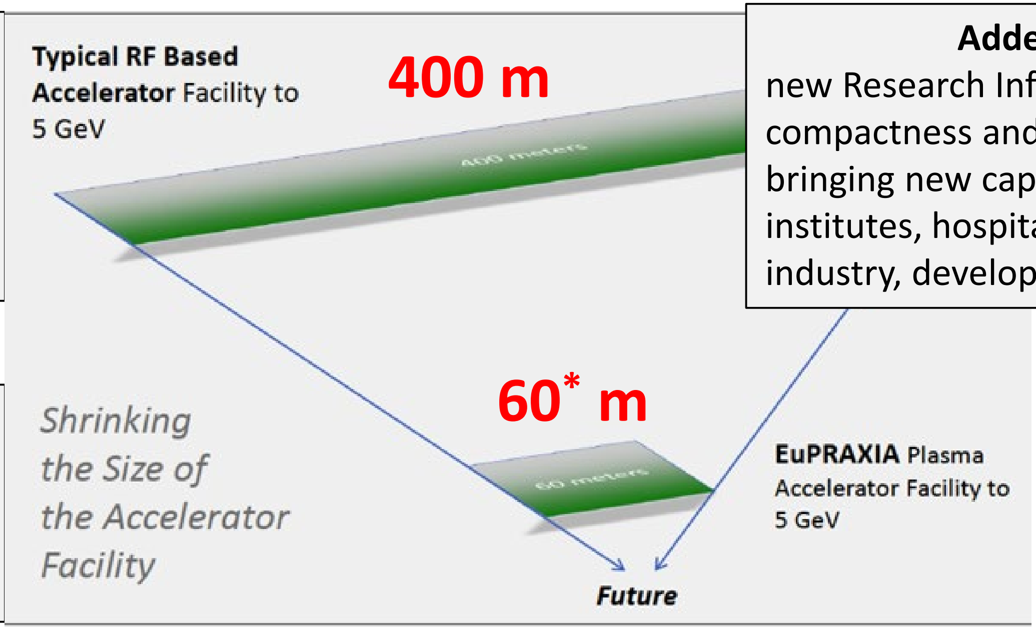
30 million Volt per meter

RF: 90 years of success story for society

Plasma Accelerators

first user facility to be realized

100,000 million Volt per meter



Added value
new Research Infrastructures due to compactness and cost-efficiency bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

5 GeV example

realistic design including all required infrastructure for powering, shielding, …

Can we shrink the Linear Collider, provide e^- and e^+ beams in the **TeV** energy regime and produce **> 10^{34} cm^{-2} s^{-1}** luminosity?

R. Assmann, E. Gschwendtner

Accelerator and Detectors R&D Roadmaps

ECFA – EPS Session earlier this afternoon

Roadmaps requested in the European Strategy for Particle Physics:

LDG mandated with the Accelerator Roadmap — D. Newbold

ECFA mandated with the Detector Roadmap — P. Allport

- To cover the period until the next ESPP update (5 – 6 years)
- To be submitted to the CERN Council by the end of the year

Future colliders with earliest feasible start date