European Strategy Update

Accelerators summary

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Open Symposium towards updating the European Strategy for Particle Physics

May 13-16, 2019, Granada, Spain

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

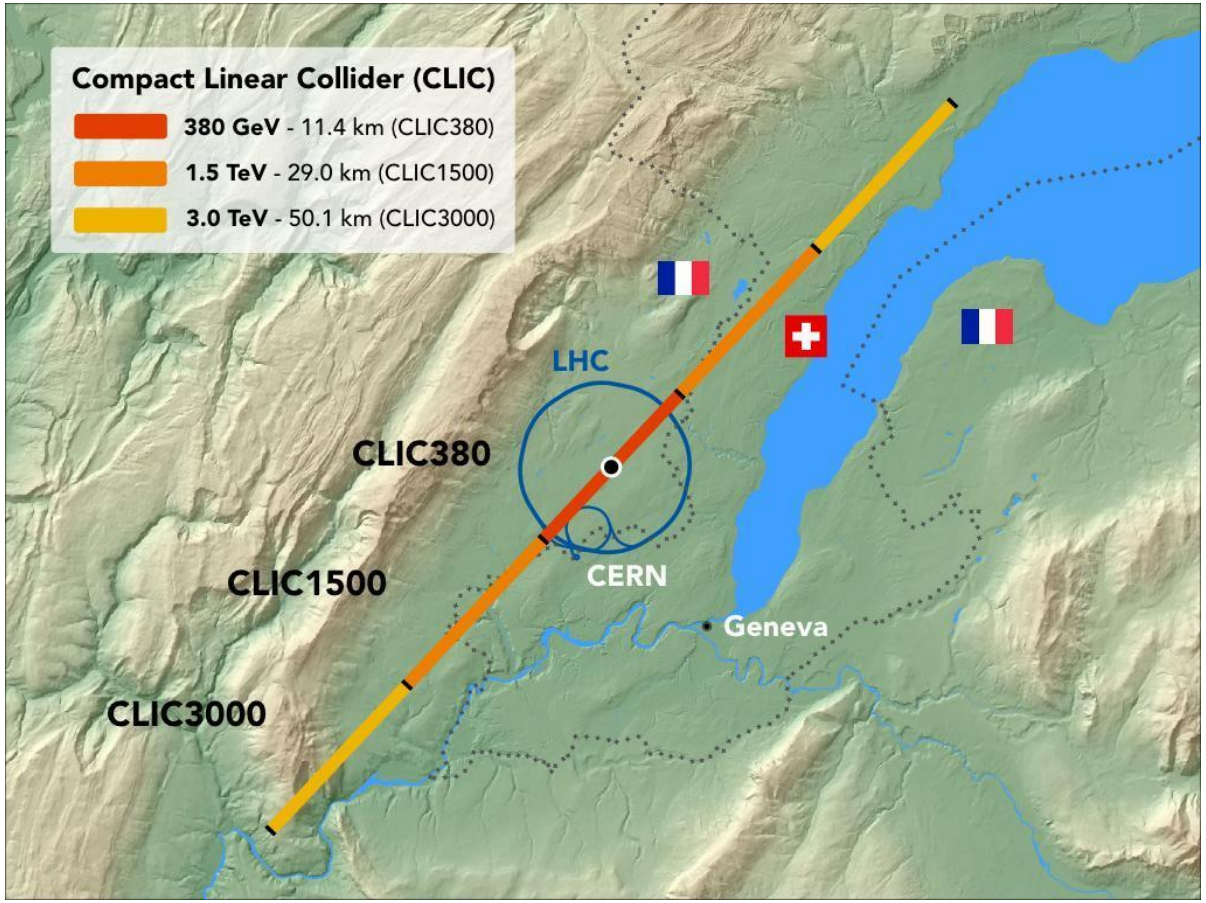
- comprehensive summary of 2-3 slides, including open questions, challenges, opportunities and objectives.

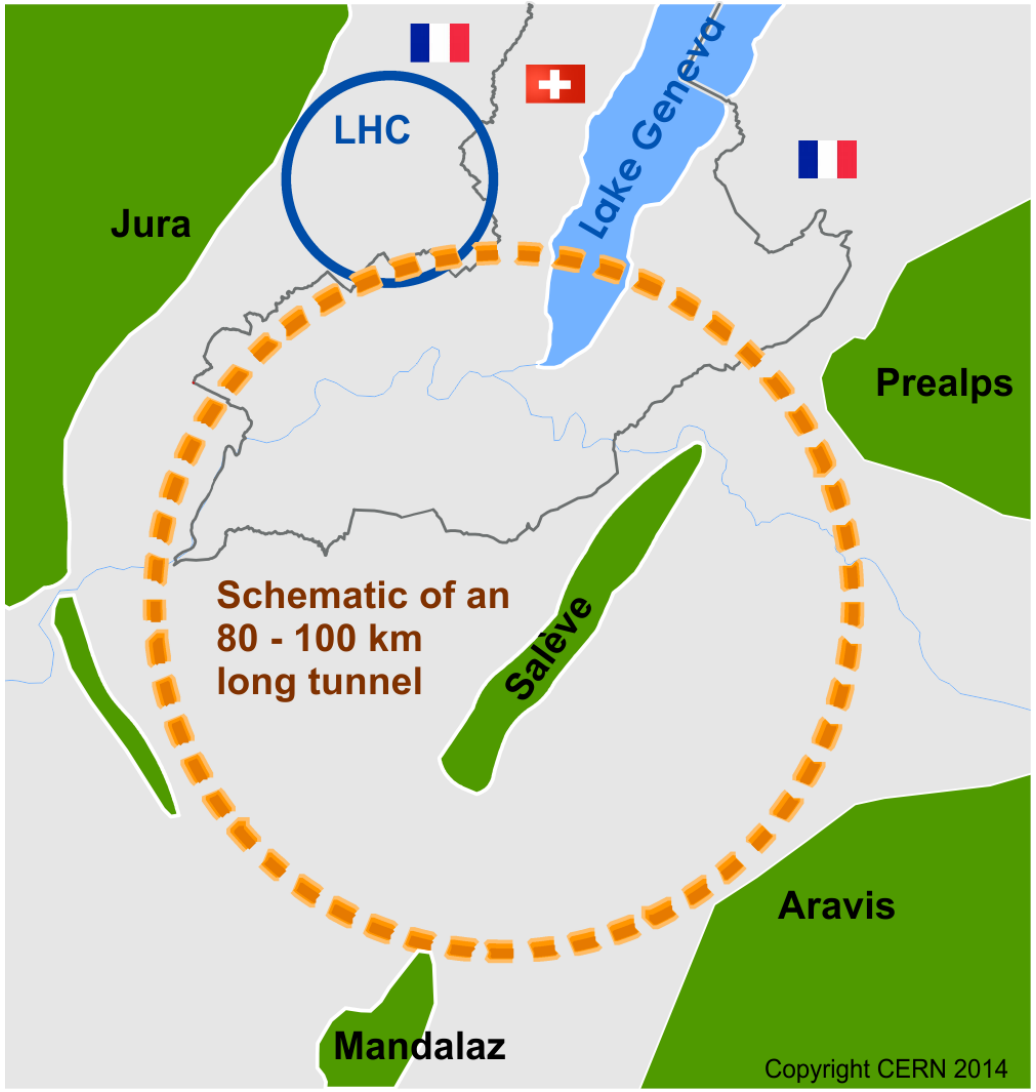
Big Questions

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?

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

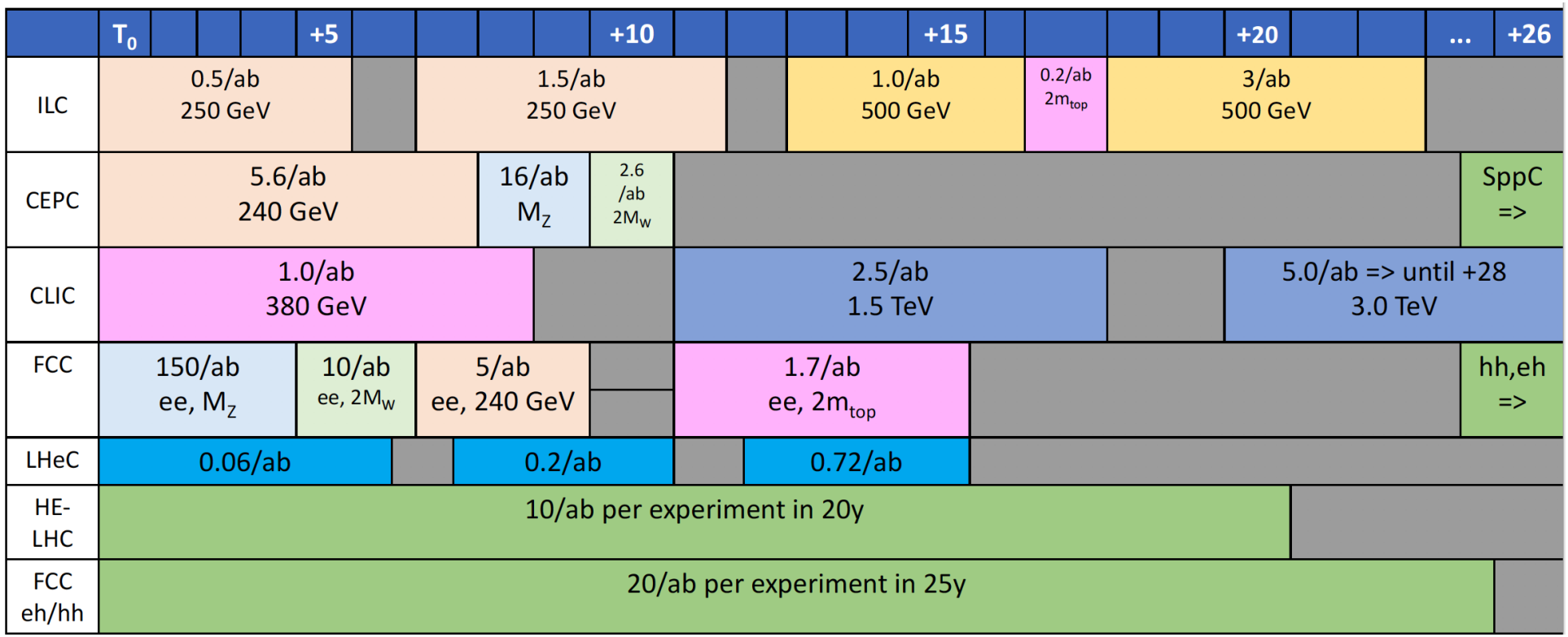




Comparisons

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



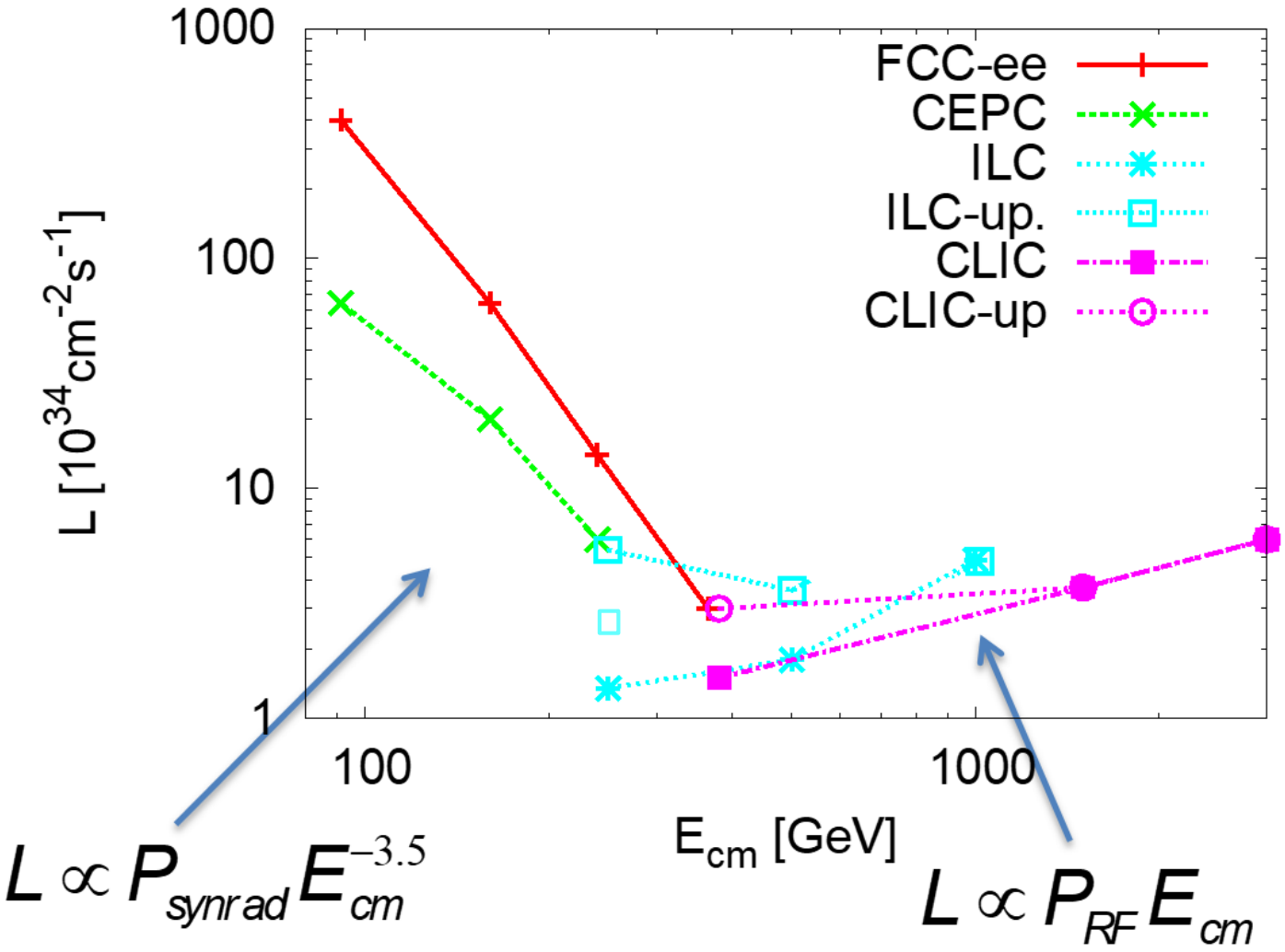
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

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

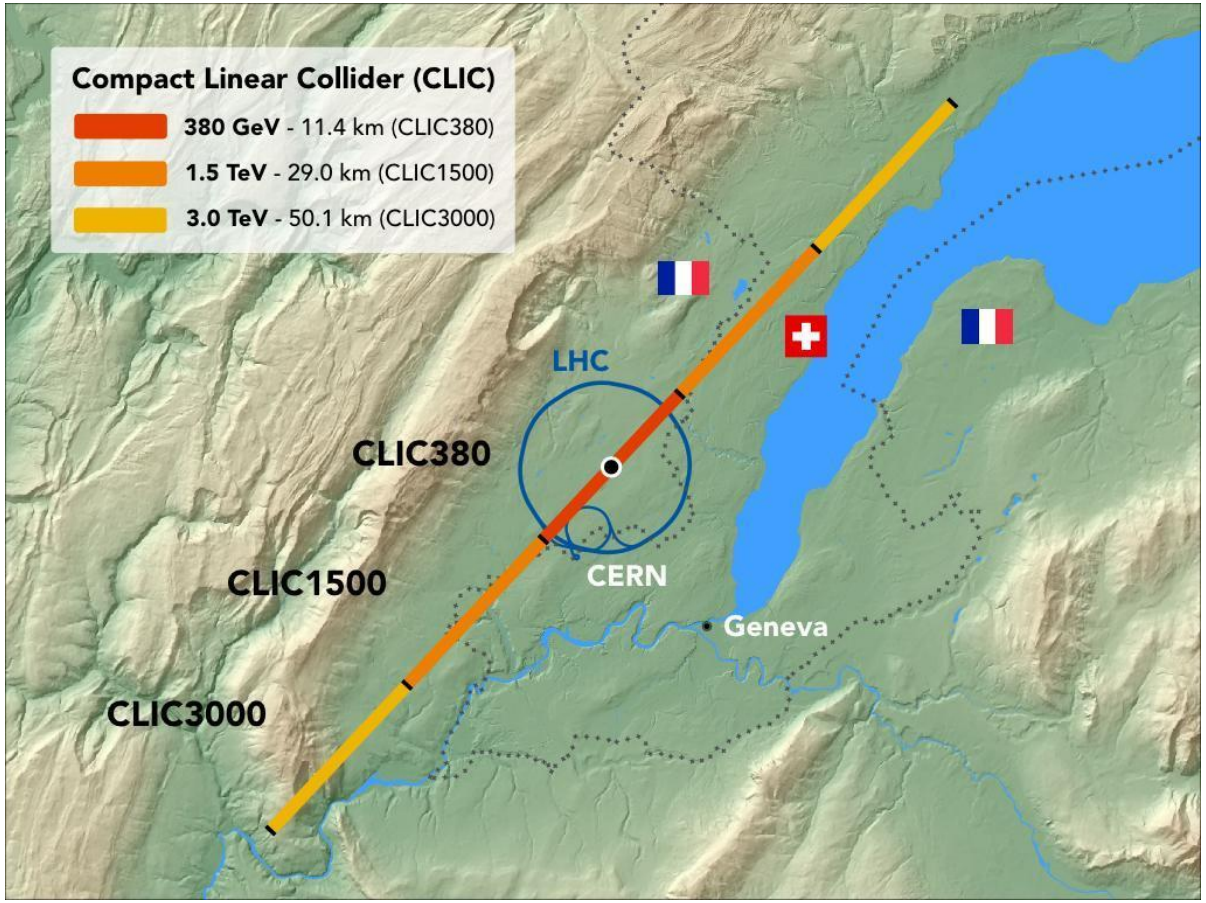
RF technology

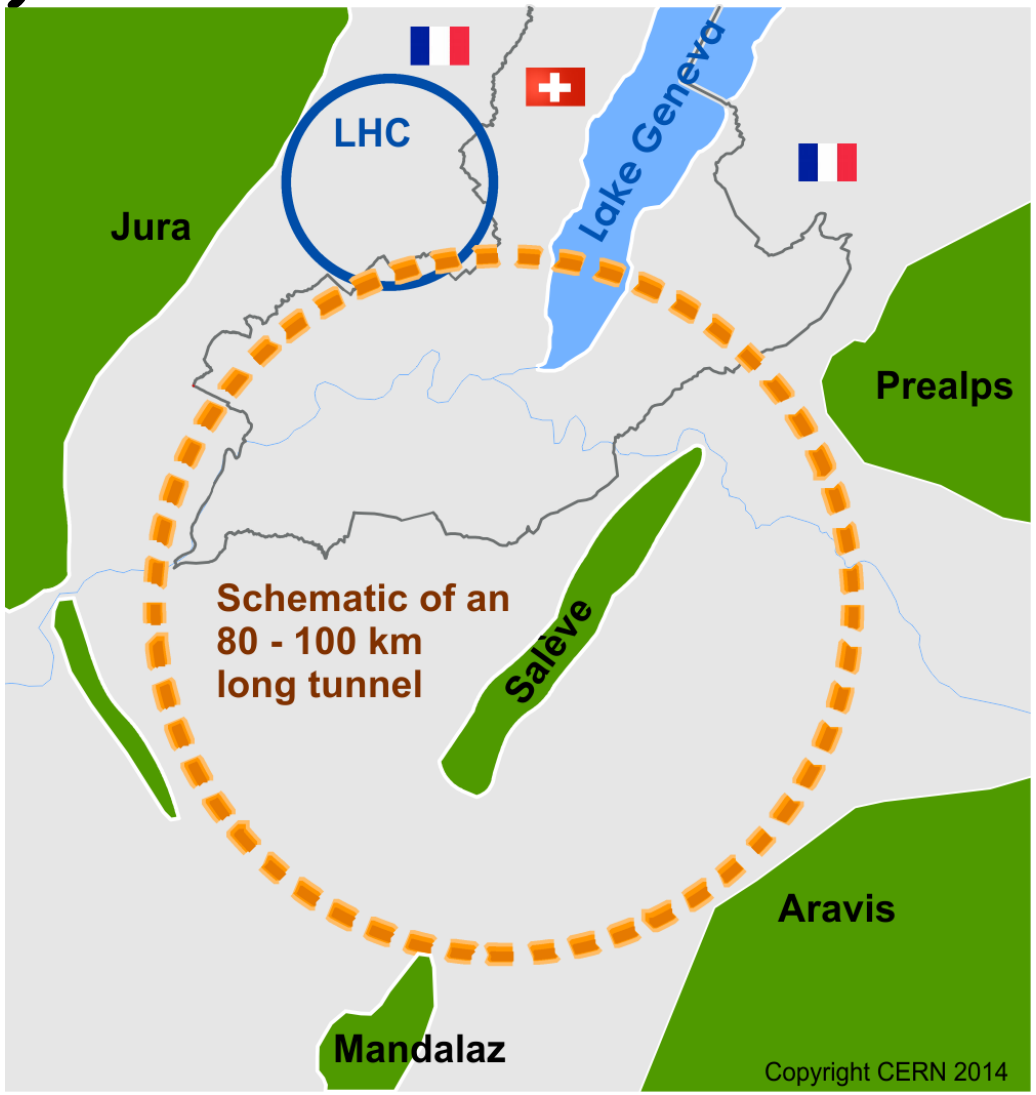
- Accelerator Technologies are ready to go forward for **lepton colliders** (ILC, CLIC, FCC-ee, CEPC), focusing on the Higgs Factory **construction to begin in > ~5 years.**
- SRF accelerating technology is well **matured** for the realization including cooperation with industry.

- 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.**

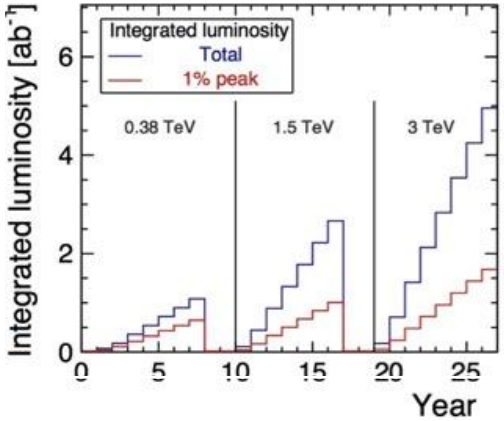
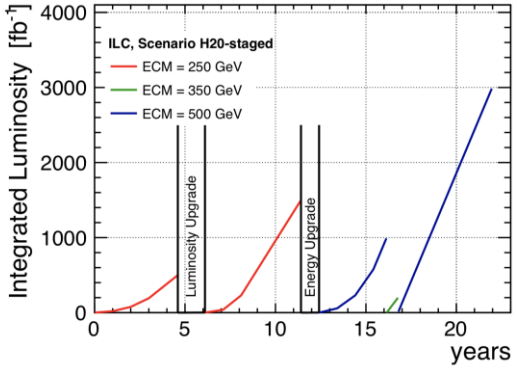
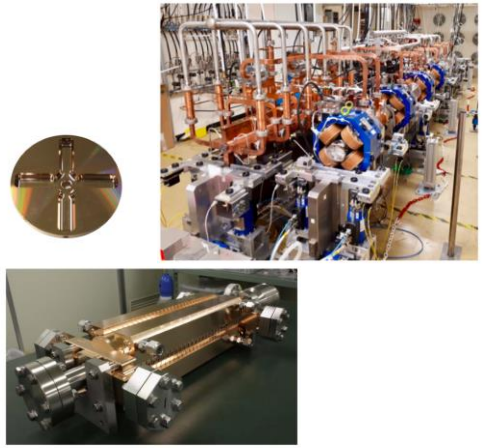
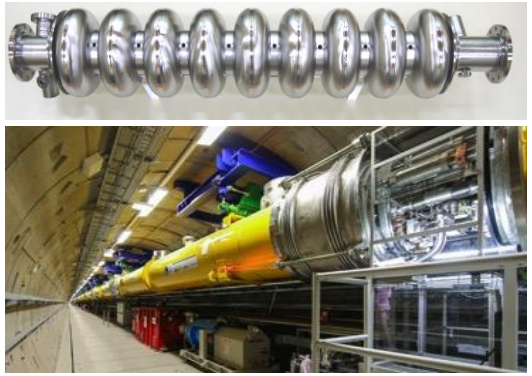
A. Yamamoto, 190512b

Q2: Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?



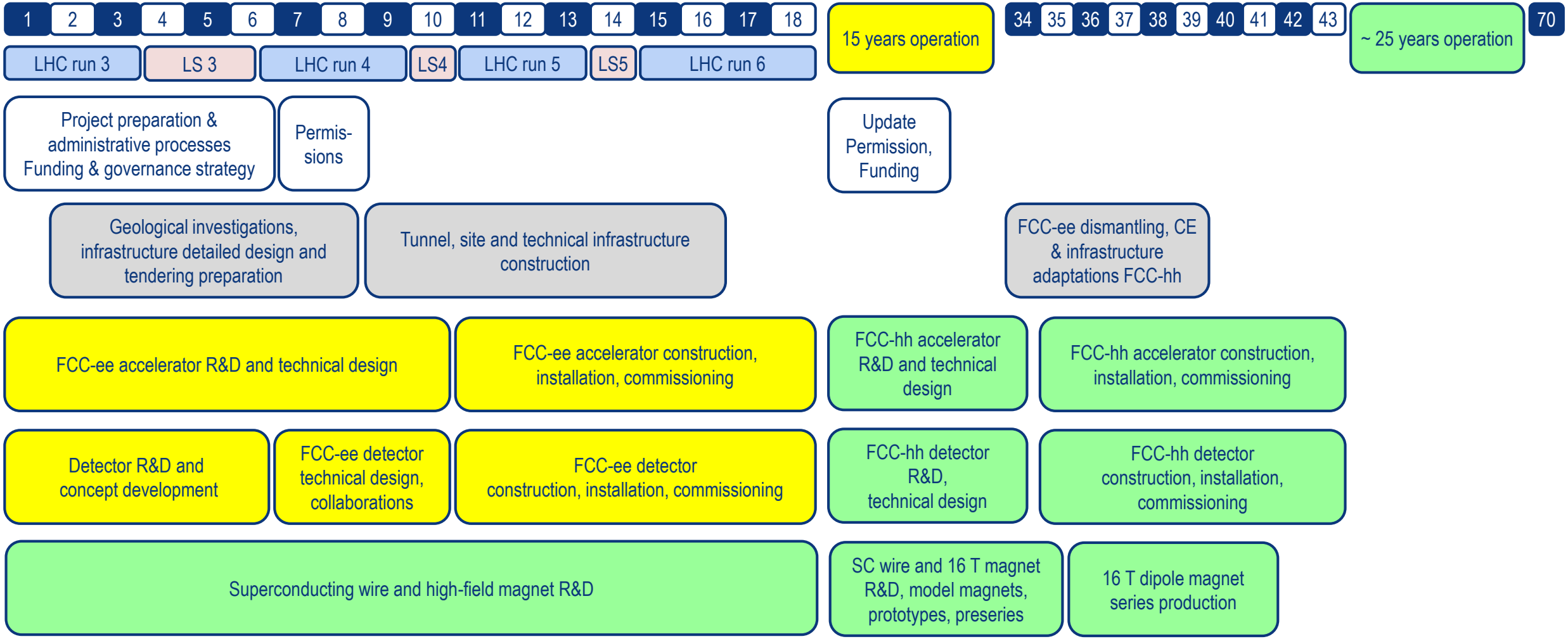


Overview of CLIC and ILC parameters

CLIC illustrations	CLIC parameters	ILC parameters	ILC illustrations
 CLIC y: 75% of 180 days	E: 380, 1500, 3000 GeV (L: 11-50 km) Lum: 1.5-5.9 10^{34} $^{-2}$ cm-2 s-1 * Prep. phase 2020-2025 Constr.+comm. 7y, ready before 2035 Cost: CLIC-380: 5.9 BCHF, Upgrades: deltas of 5 and 7 BCHF Power: ~ 170 MW – 580 MW**	E: 250, 500, 1000 GeV (L: 20-40 km) Lum: 1.35 (2.7) – 1.8(3.6) 10^{34} cm-2 s-1* Prep. phase 2020-2023(4) Constr.+comm. 9-10y, ready before 2035 Cost: ILC-250: 4.9-5.3 BILCU, ILC-500: 8 BILCU (2012 $) Power: ~ 130 – 300 MW	 ILC y: 75% of 240 days
	NCRF X-band now established and industrially available, used in small systems and being introduced in larger ones, relevant reference experience with C-band for larger systems (Swissfel).	SCRF in extensive use in several FELs with parameters close to ILC parameters, the primary one being the E-XFEL at DESY. Technology optimization underway, linking to evolving SCRF R&D for grad. and Q.	
	Nanobeam addressed in design & specifications, benchmarked simulations, low emittance ring progress, extensive prototype and method development (for alignment, stabilization, instrumentation, algorithms and feedback systems, system and facility tests : FACET, light-sources, FELs, ATF2) Extensive prototyping of all parts of these accelerators, for lab-test, use/test in test-facilities, light-sources or FELs (magnets, instrumentation, controls, vacuum, etc)		
	CERN hosted international project (follow LHC model)	Japan hosted international project, initial ideas about European capabilities available (link)	

* Doubling by increasing frequency (to be) studied, ** Power at 1.5 and 3 TeV not updated from CDR 2012

FCC integrated project technical schedule



FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

Consideration on timeline:
LHC possible because SSC developed the superconductor…

9 T - 1 m single bore

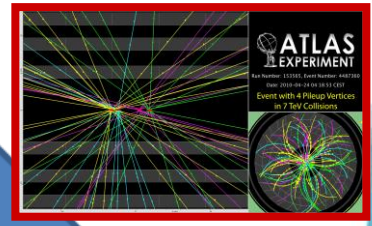
10 T-1m Nb3Sn dipole

9 T -10 m long protoype

9 T-15 m final protoype

Last LHC dipole

1985 1987 1990 1994 2000 2006 2010



Only 2 y to make a short magnet «near to final». Conductor available(SSC)

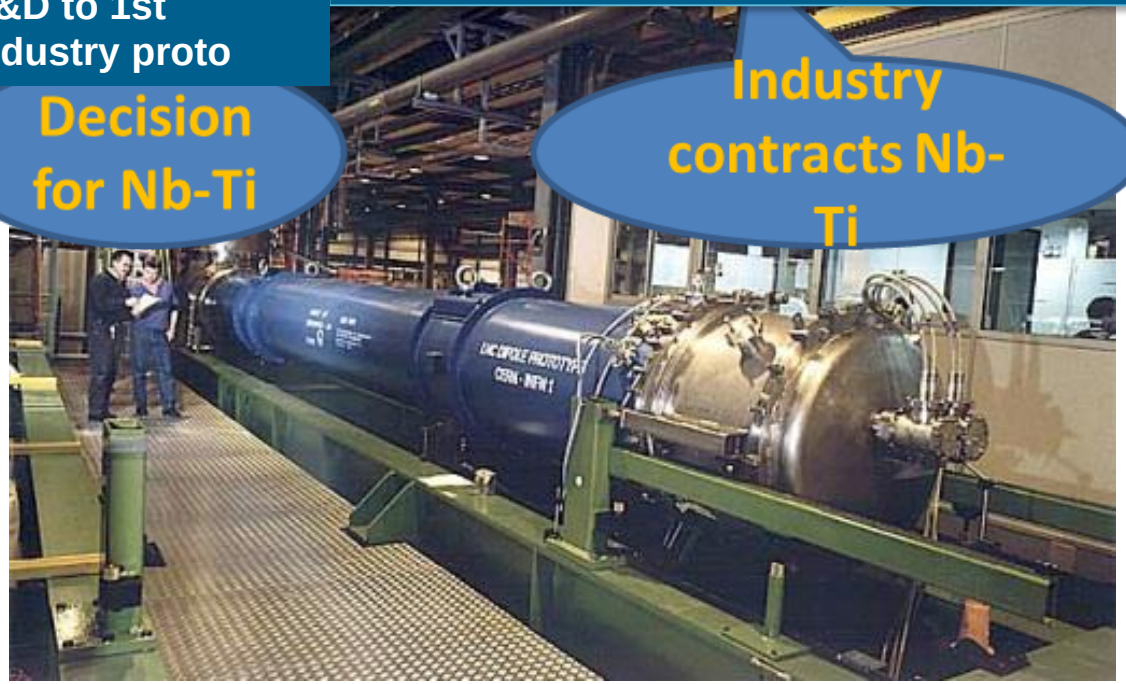
7 years from start R&D to 1st Industry proto

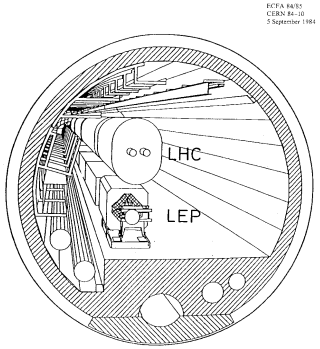
12 y from first working prototype to last magnet

Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up





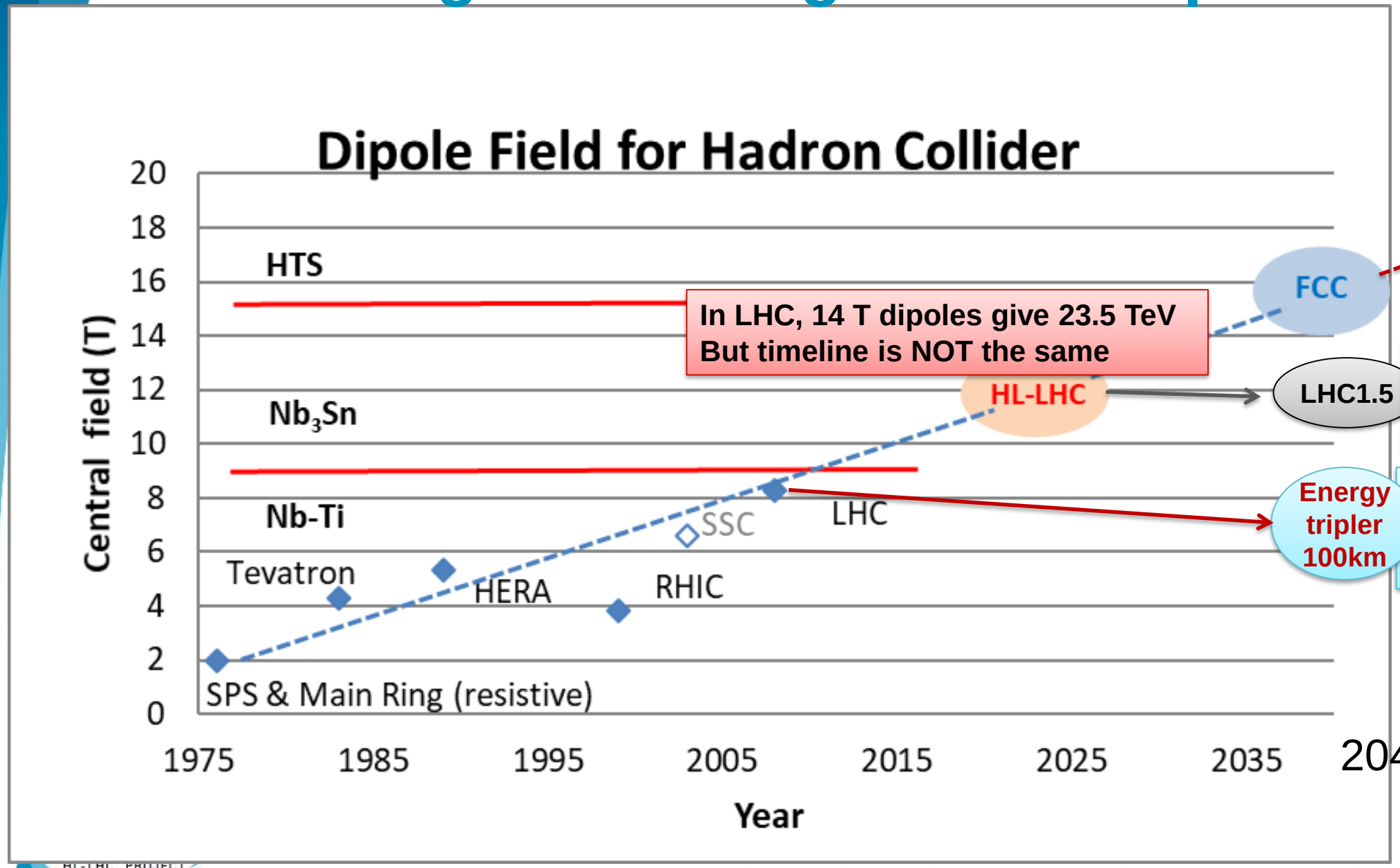
LARGE HADRON COLLIDER IN THE LEP TUNNEL

HiLumi HL-LHC PROJECT

HE-LHC 27 TeV

- Needs some 1700 large magnets in Nb_3Sn (1200 dipole 15 m long) operating at **16 T**. (same as FCC-hh)
- It needs a new generation of Nb_3Sn, beyond HiLumi (like FCC-hh): the 23 y timeline presented is realistic (21 for the magnets) but t_0 is probably 2025 or more because of SC development.
- **The set up of a SC Open Lab for fostering development of superconductors (F. Bordry and L. Bottura proposal) is critical for HEP HC progress.**
- A further upgrade to 42 TeV in HTS at 25 T possible to envisage for longer time. 24 T dipole is the long term goal also of the Chinese SppC.
  (Recently an HTS 32 T special solenoid and a commercial HTS 26 T NMR solenoid have been announced!)

High field magnet development



s.c. magnet technology

- 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.

Intensify HTS accelerator magnet development

A. Yamamoto, 190512b

Personal (A. Yamamoto) 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 Collider (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**

A. Yamamoto, 190512b

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Cost-estimate Value* [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
C C hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
C C ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10 – 20 (0.4 - 0.8)	**High-Q SRF** cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 – (40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
L C ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	4.8- 5.3 (for 0.25 TeV) [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 (for 0.38 TeV) [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

*Cost estimates are commonly for "**Value**" (material) only.

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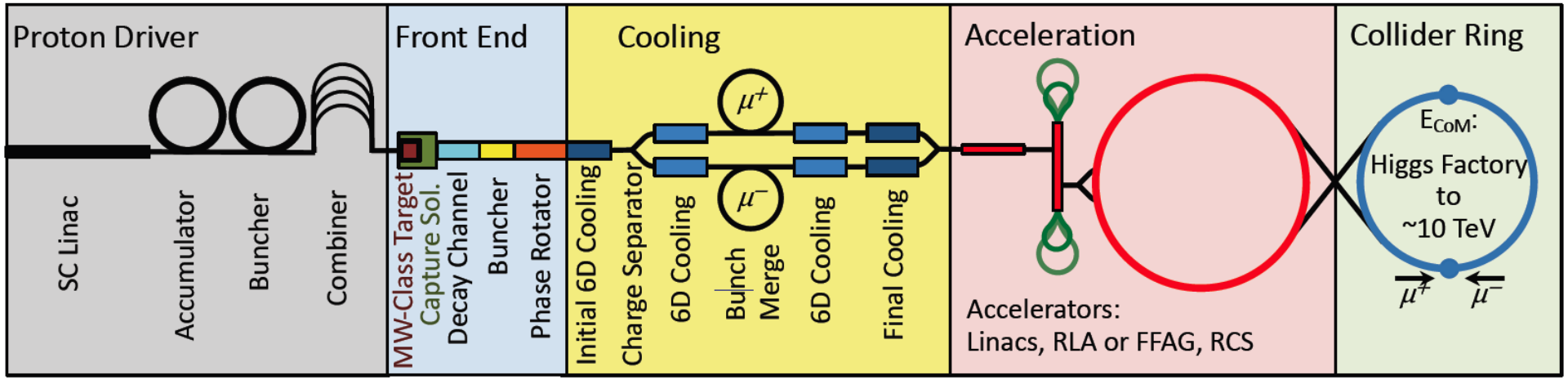
Proton-driven Muon Collider Concept

Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.



Short, intense proton bunches to produce hadronic showers

Pions decay into muons that can be captured

Muon are captured, bunched and then cooled

Acceleration to collision energy

Collision

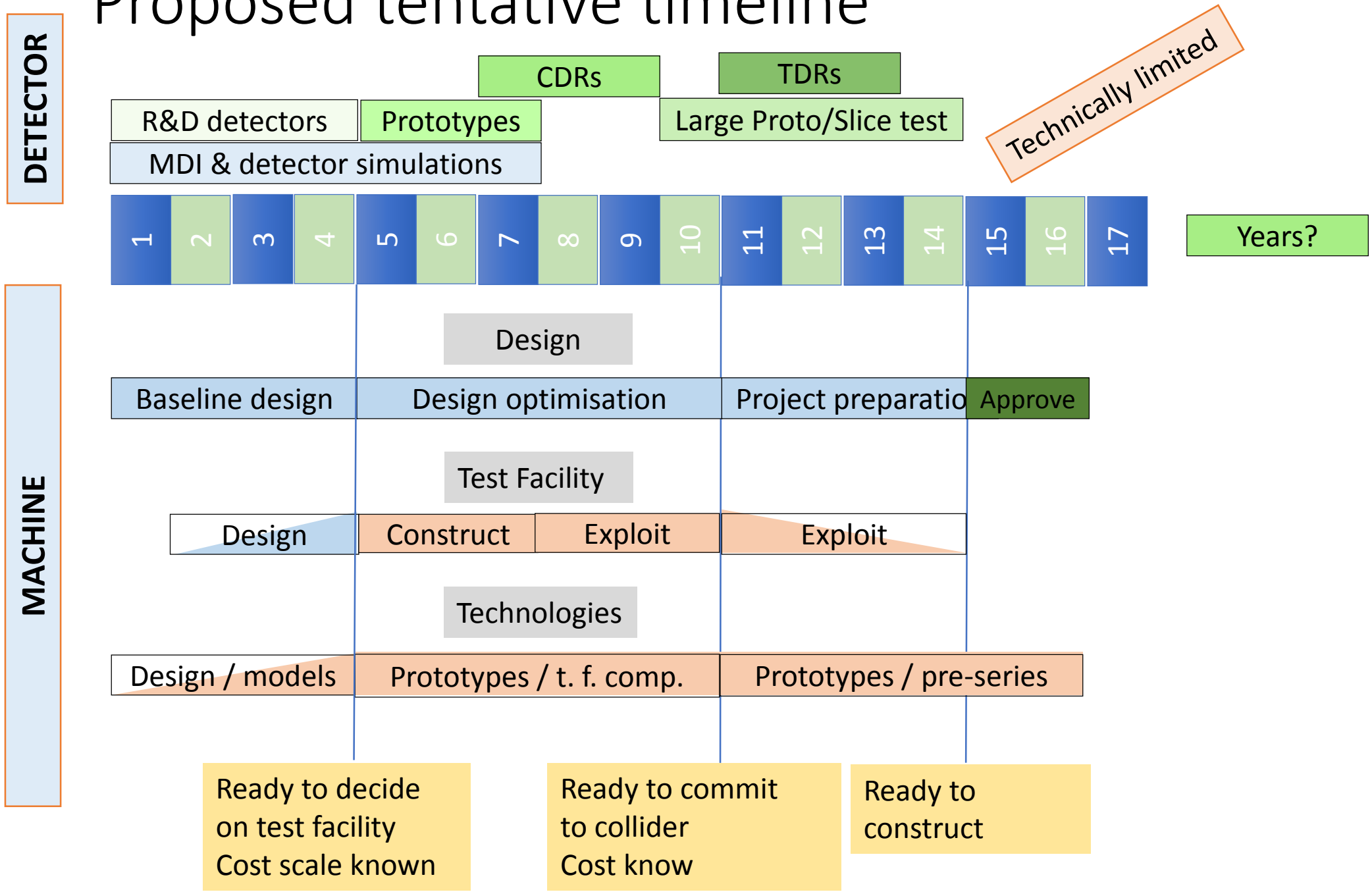
Answers to the Key Questions

- **Can muon colliders at this moment be considered for the next project?**
  - Enormous progress in the proton driven scheme and new ideas emerged on positron one
  - But at this moment not mature enough for a CDR, need a careful design study done with a coordinate international effort

- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other physics experiments
  - **Should not miss this opportunity?**

- **What needs to be done?**
  - Muon production and cooling is key => A new test facility is required.
    - Seek/exploit synergy with physics exploitation of test facility (e.g. nuSTORM)
  - A conceptual design of the collider has to be made
  - Many components need R&D, e.g. fast ramping magnets, background in the detector
  - Site-dependent studies to understand if existing infrastructure can be used
    - limitations of existing tunnels, e.g. radiation issues
    - optimum use of existing accelerators, e.g. as proton source
  - **R&D in a strongly coordinated global effort**

Proposed tentative timeline



Plasma acceleration based colliders

Drive beams

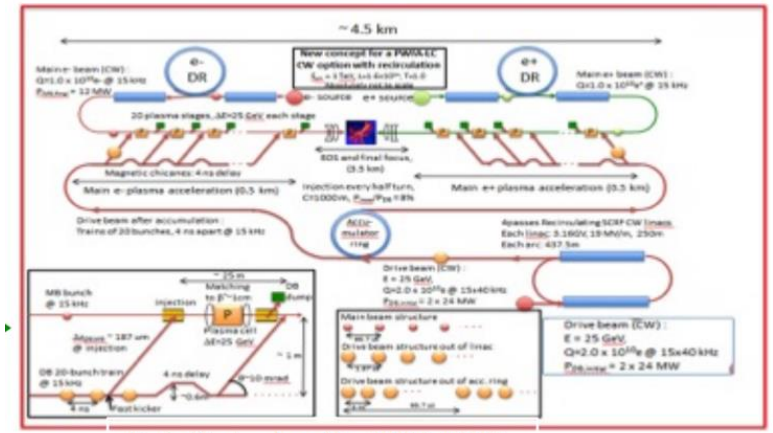
Lasers: ~40 J/pulse

Electrons: 30 J/bunch

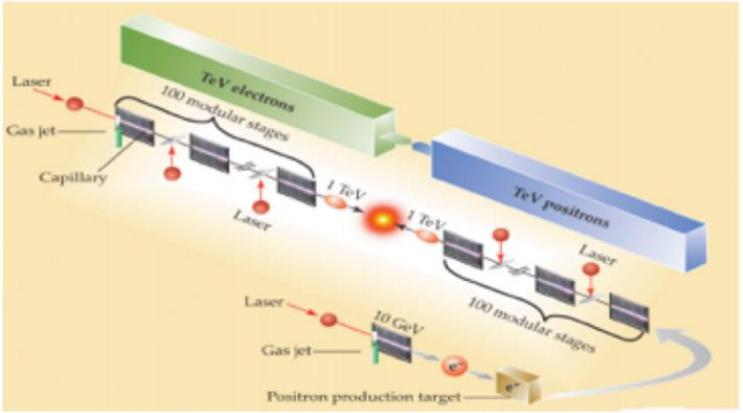
Protons: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams

Electrons: 1010 particles @ 1 TeV ~few kJ



E. Adli et. al.,arXiv:1308.1145



Leemans & Esarey, Phys. Today 63 #3 (2009)

Key achievements in last 15 years in plasma based acceleration using lasers, electron and proton drivers

- Focus is now **on high brightness beams, tunability, reproducibility, reliability, and high average power**

The road to colliders passes through **applications** that need compact accelerators (Early HEP applications, FELs, Thomson scattering sources, medical applications, injection into next generation storage rings …)

Many key challenges remain as detailed in community developed, consensus based roadmaps (ALEGRO, AWAKE, Eupraxia, US roadmap,…)

Strategic investments are needed:

- **Personnel** – advanced accelerators attract large numbers of students and postdocs
- Existing **facilities** (with upgrades) and a few new ones (High average power, high repetition rate operation studies; fully dedicated to addressing the challenges towards a TDR for a plasma based collider)
- **High performance computing** methods and tools

Current initiatives of coordinated programs: EuPRAXIA, ALEGRO, AWAKE.

EuPRAXIA

Horizon 2020 EU design study funded in 2015.
Deliverable: Conceptual Design Report by Oct 2019

The EuPRAXIA Strategy for Accelerator Innovation:
The accelerator and application demonstration facility EuPRAXIA is the required intermediate step between proof of principle and production facility.

PRESENT PLASMA E- ACCELERATION EXPERIMENTS

Demonstrating **100 GV/m** routinely

Demonstrating many **GeV** electron beams

Demonstrating basic **quality**

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator

5 GeV electron beam for the 2020's

Demonstrating user readiness

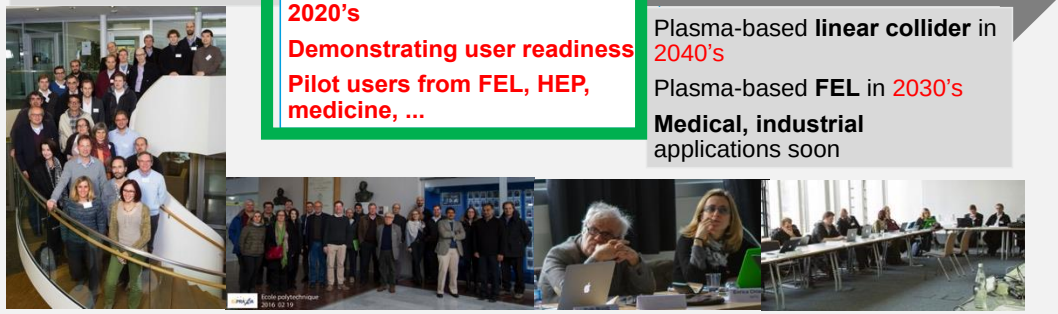
Pilot users from FEL, HEP, medicine, ...

PLASMA ACCELERATOR PRODUCTION FACILITIES

Plasma-based **linear collider** in 2040's

Plasma-based **FEL** in 2030's

Medical, industrial applications soon



ALEGRO

Advanced LinEar collider study GROup, ALEGRO: formed at initiative of the ICFA ANA panel in 2017.

Mission of the ALEGRO community:

- **Foster and trigger Advanced Linear Collider related activities** for applications of high-energy physics.
- **Provide a framework** to amplify international coordination, broaden the community, involving accelerator labs/institutes
- **Identify topics requiring intensive R&D and facilities**.

Goal:

- Long-term design of a e^+/e^-/gamma collider with up to 30 TeV: the **Advanced Linear International Collider (ALIC)**
- **Construction of dedicated Advanced and Novel Accelerators (ANA) facilities** are needed over the next 5 to 10 years in order to reliably deliver high-quality, multi-GeV electron beams from a small number of stages.
  - Today: Existing facilities explore different advanced and novel accelerator concepts and are proof-of-principle experiments.

Status of Today and Goals for Collider Application

	Current	Goal
Charge (nC)	0.1	1
Energy (GeV)	9	10
Energy spread (%)	2	0.1
Emittance (um)	>50-100 (PWFA), 0.1 (LFWA)	$<10^{-1}$
Staging	single, two	multiple
Efficiency (%)	20	40
Rep Rate (Hz)	1-10	10^{3-4}
Acc. Distance (m)/stage	1	1-5
Positron acceleration	acceleration	emittance preservation
Proton drivers	SSM, acceleration	Emittance control
Plasma cell (p-driver)	10 m	100s m
Simulations	days	Improvements by 10^7

Achieved
Individually
And
Not
simultaneously

Table 1: Facilities for accelerator R&D in the multi-GeV range relevant for ALIC and with emphasis on specific challenges

Facility	Readiness	ANA technique	Specific Goal
kBELLA	Design study	LWFA	e-, 10 GeV, KHz rep rate
EuPRAXIA	Design study	LWFA or PWFA	e-, 5 GeV, reliability
AWAKE	Operating	PWFA	e^-/p^+ collider
FACET II	Start 2019	PWFA	e^-, 10 GeV boost, beam quality, e^+ acceleration
Flash FWD	Operating	PWFA	e-, 1.5 GeV, beam quality

The future is in accelerating muons in plasma!

Vladimir Shiltsev

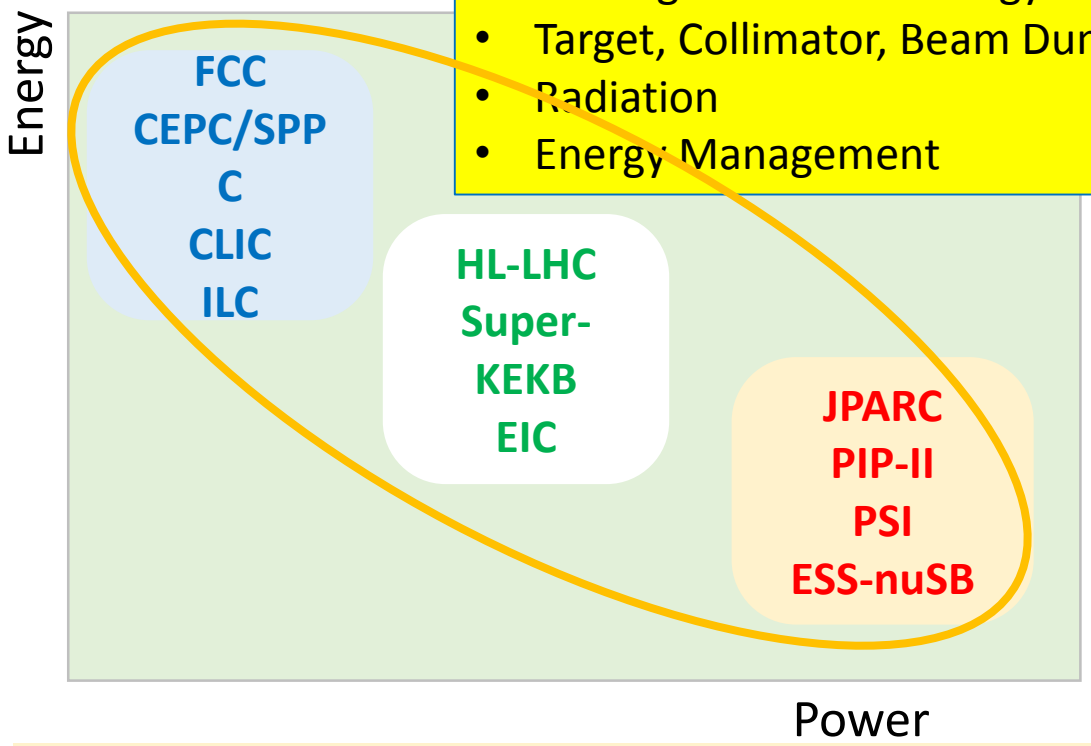
Q3: How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?

Intensity frontier vs. Energy Frontier

Intensity – Acc.	Energy [GeV]	Power [MW]	Acc. Tech. Feature	SC Tech.
SPS*	450		Synchrotron	
Fnal M. Injector	120	0.7	Synchrotron	
J-PARC*	3 30	1 0,49 ~ 1.3	Linac/Synchr Ext. Beam	SCM
PIP-II	60 -120	.2	Linac (SRF) Synchrotron	SRF
PSI-HIPA*	0.59	1.4	Cycrotron	
FAIR (SIS100)	29	0.2	Synchrotron	SCM
(ESS) ESSnuSB *	2 2	2 ~ 5 (+5) 2 x 5	Linac	SRF
CEBAF	12	1	LINAC+Ring	SRF
Super-KEKB		---	Collider	
HL-LHC	2 x 7,000	---	Collider	SCM. SRF
EIC*		---	Collider	SCM, SRF

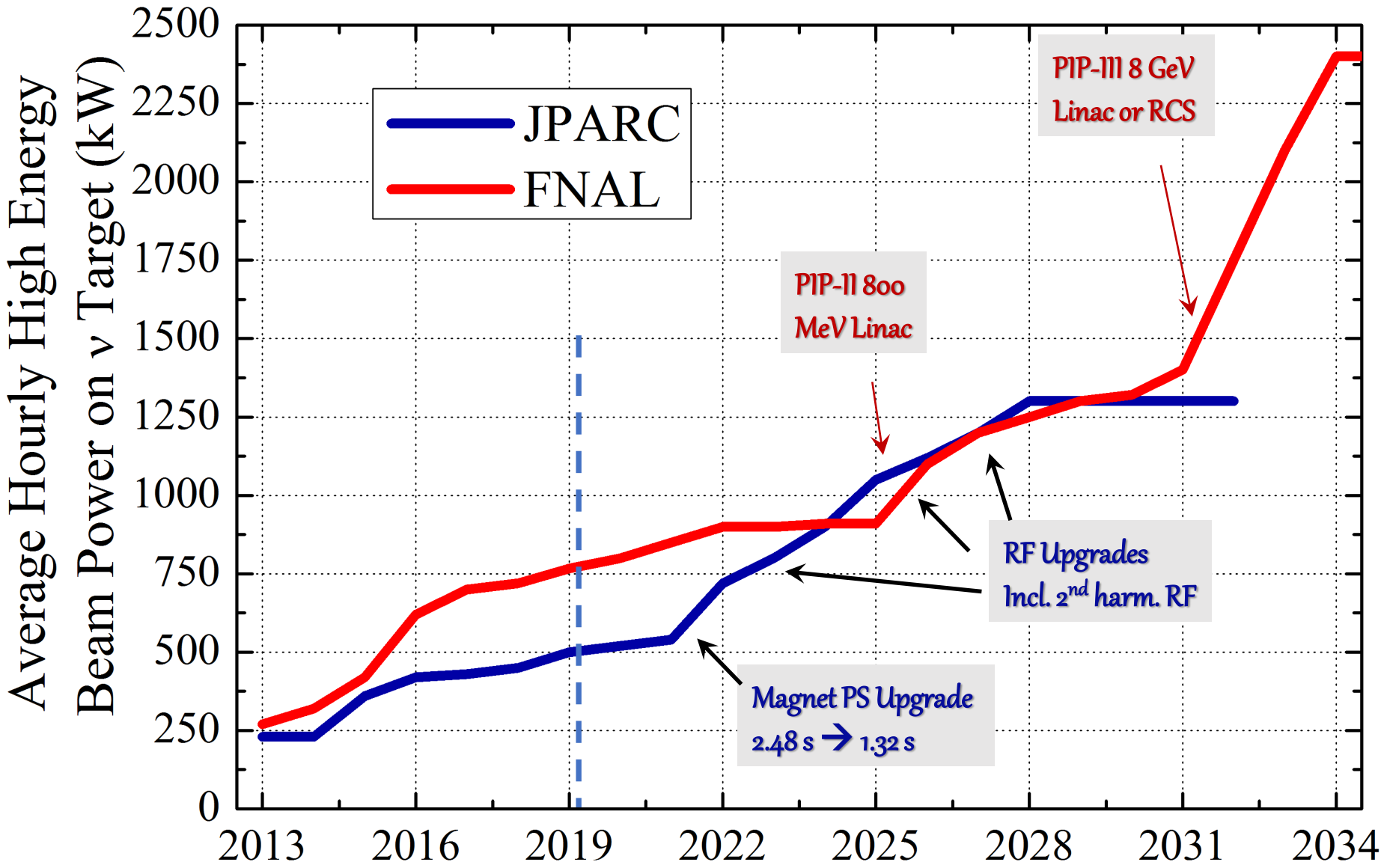
A. Yamamoto, 190512b

Common Issues:
- SC Mag. & SRF technology
- Target, Collimator, Beam Dump
- Radiation
- Energy Management



- Science is complementary, and
- Technology is based on common technology,
- Let us work together and maximize synergy !!

Fermilab and J-PARC: Proton Beam Power on ν Target



The **BSM PBC projects** offer significant discovery potential over a wide range of masses and couplings.

- Very sensitive low energy experiments target the sub-eV mass area.
- SPS Fixed Target beam-dump-like experiments and long lived particle searches at LHC have unique capabilities to target the MeV-GeV domain
- The precision tests of flavor violation (lepton and quark), as well as of CP violation, probe new particles in a mass range exceeding LHC direct searches.

in addition: QCD and others facilities

Hidden sector with "beam dumps"
NA64++ (e,μ)
NA62++
Beam Dump Facility at North Area (SHiP)
LDMX@eSPS
AWAKE++

Rare decays and precise measurements
KLEVER ($K^0_L \rightarrow \pi^0 \nu\nu$)
TauFV@BDF: $\tau \rightarrow 3\mu$
REDTOP (η decays)
MUonE (hadronic vacuum polarization for ($g\text{-}2_\mu$))
EDM proton storage ring

QCD measurements
COMPASS++, DIRAC++
NA61++, NA60++
Fixed target (gas, crystals) in ALICE & LHCb

Long-lived particles from LHC collisions
FASER, MATHUSLA, CODEX-b, milliQAN

Non-accelerator projects
Exploit CERN's technology (RF, vacuum, magnets, optics, cryogenics) for experiments possibly located in other labs.
E.g. axion searches: IAXO (helioscope), JURA (Light Shining through Wall)

Other facilities:
γ-factory from Partially Stripped Ions; nuSTORM

courtesy FG

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

Energy Efficiency

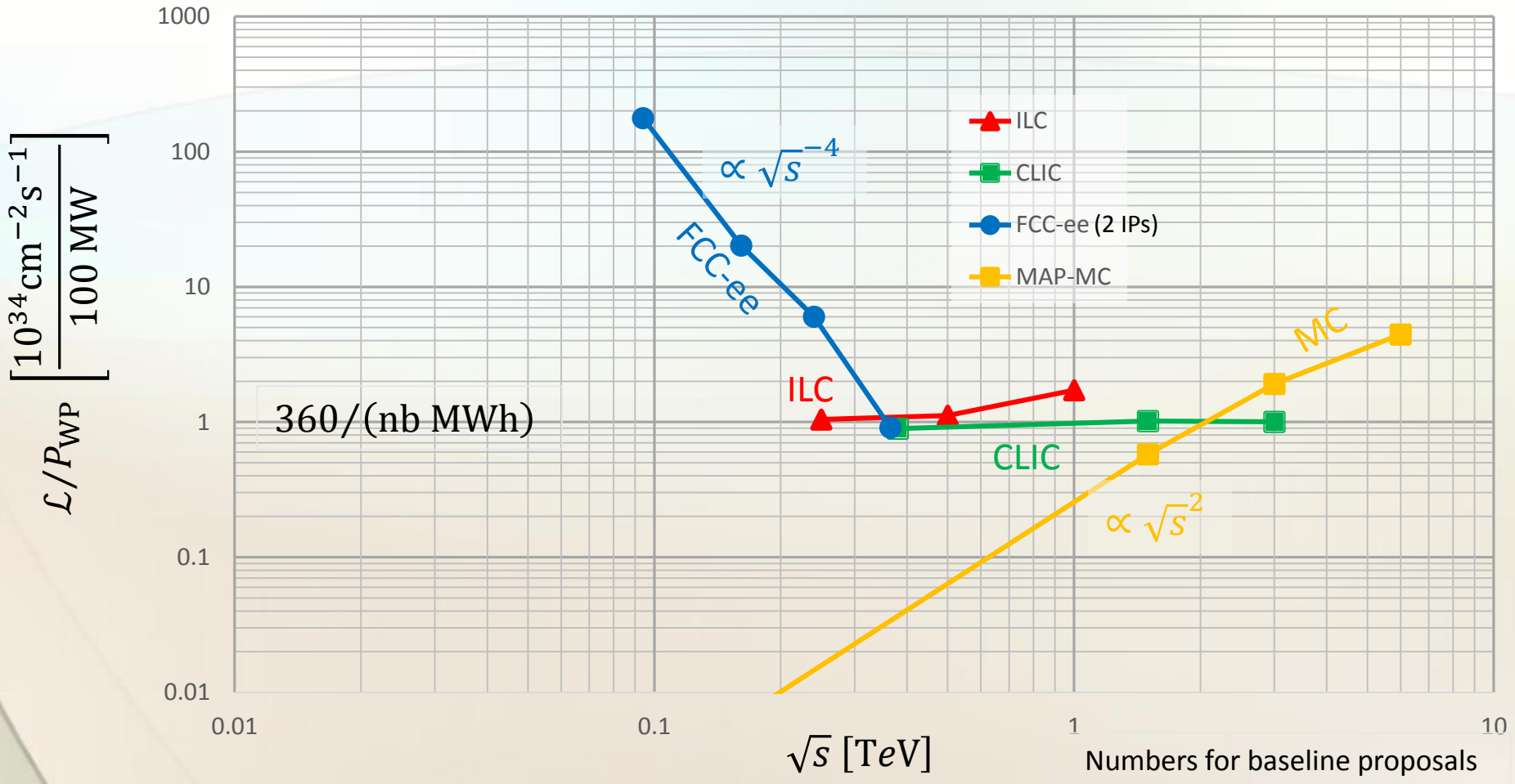
European Strategy Update

- 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

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

Expect Shortage of Expert Accelerator Workforce

- ***"Oide Principle"*** :

  1 Accelerator Expert

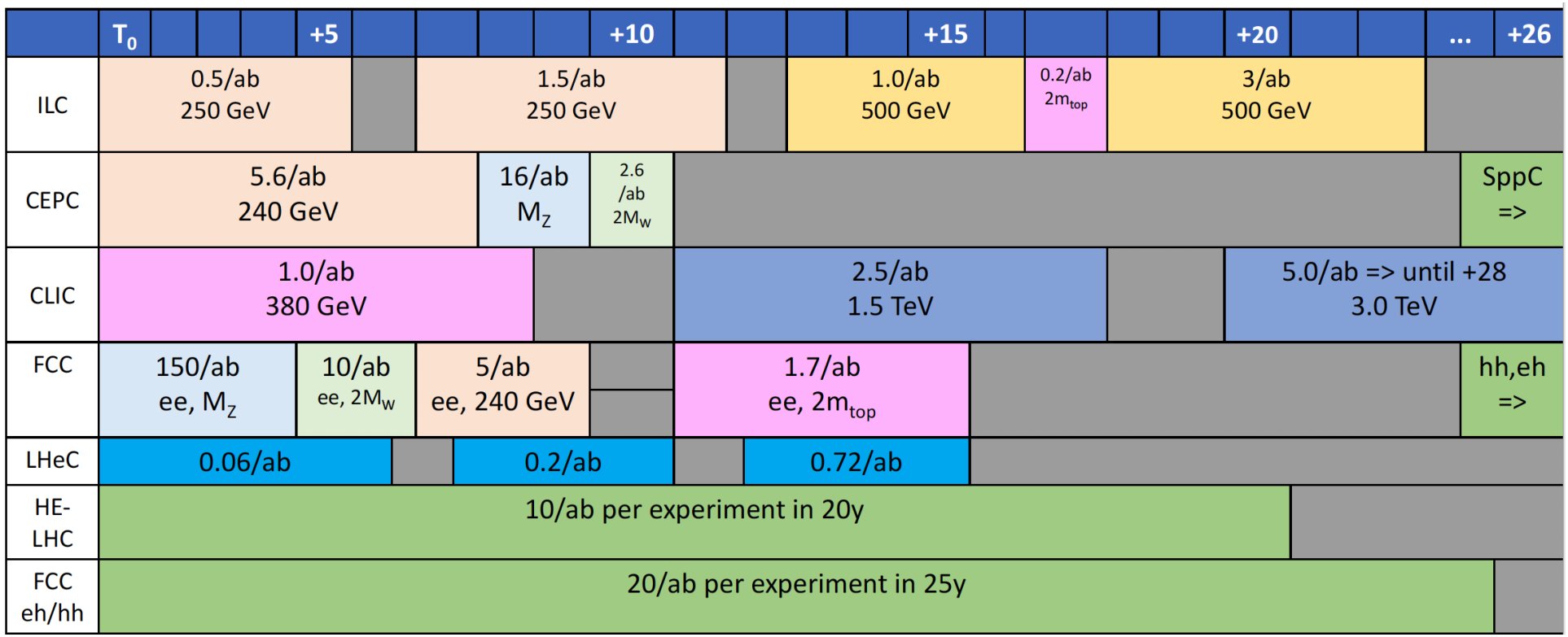
  can spend intelligently

  (only) ~1 M$ a year
- + it takes significant time to get the team together (XFEL, ESS)
- Scale of the team: 10B$/10 years=1 B$/yr → need

  1000 experts ← world's total now ~4500

K.Oide (KEK)

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

Many thanks for the contributions from:

Akira Yamamoto
Vladimir Shiltsev
Lucio Rossi
Michael Benedikt
Steinar Stapnes
Daniel Schulte
Erk Jensen
Edda Gschwendtner
Wim Leemans
Mike Lamont
and all participants in the discussions