Future colliders

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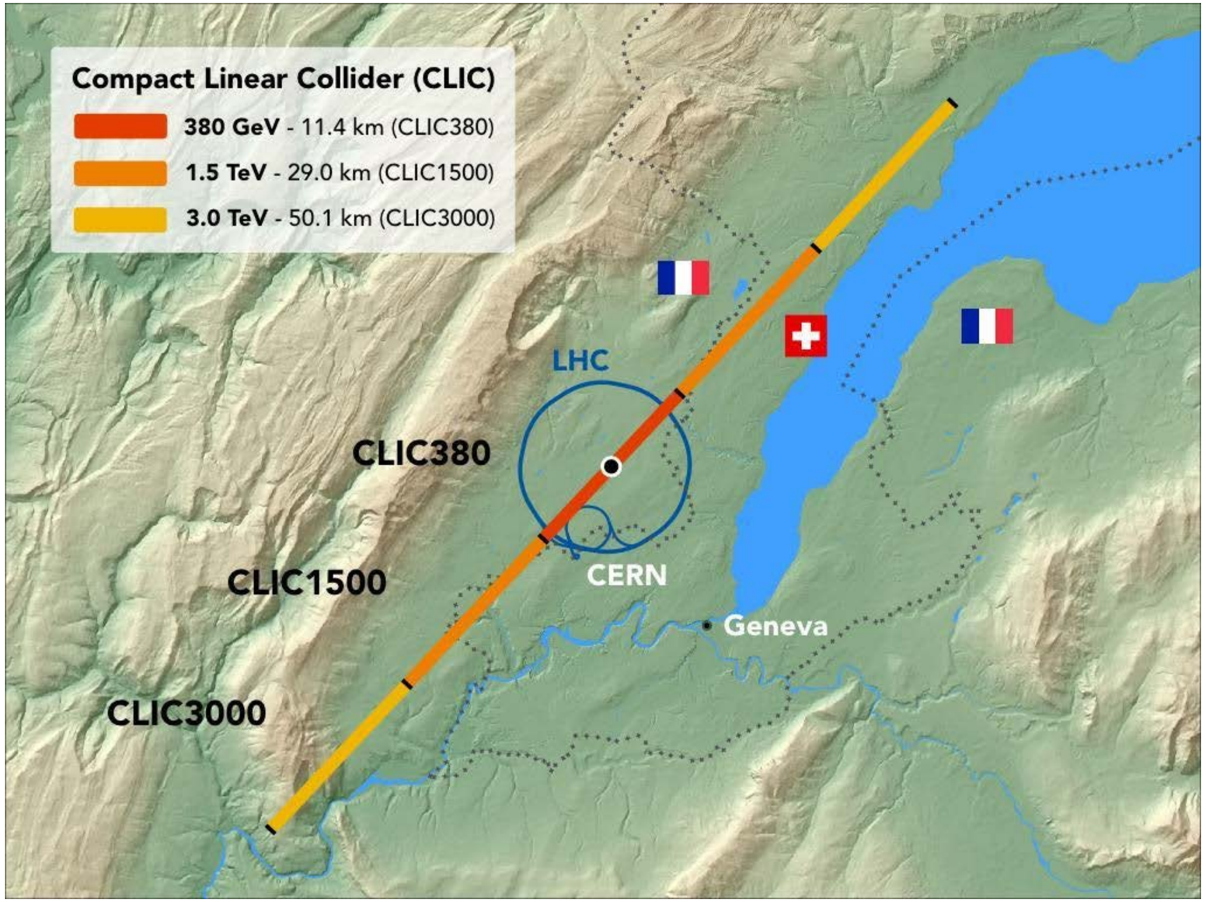
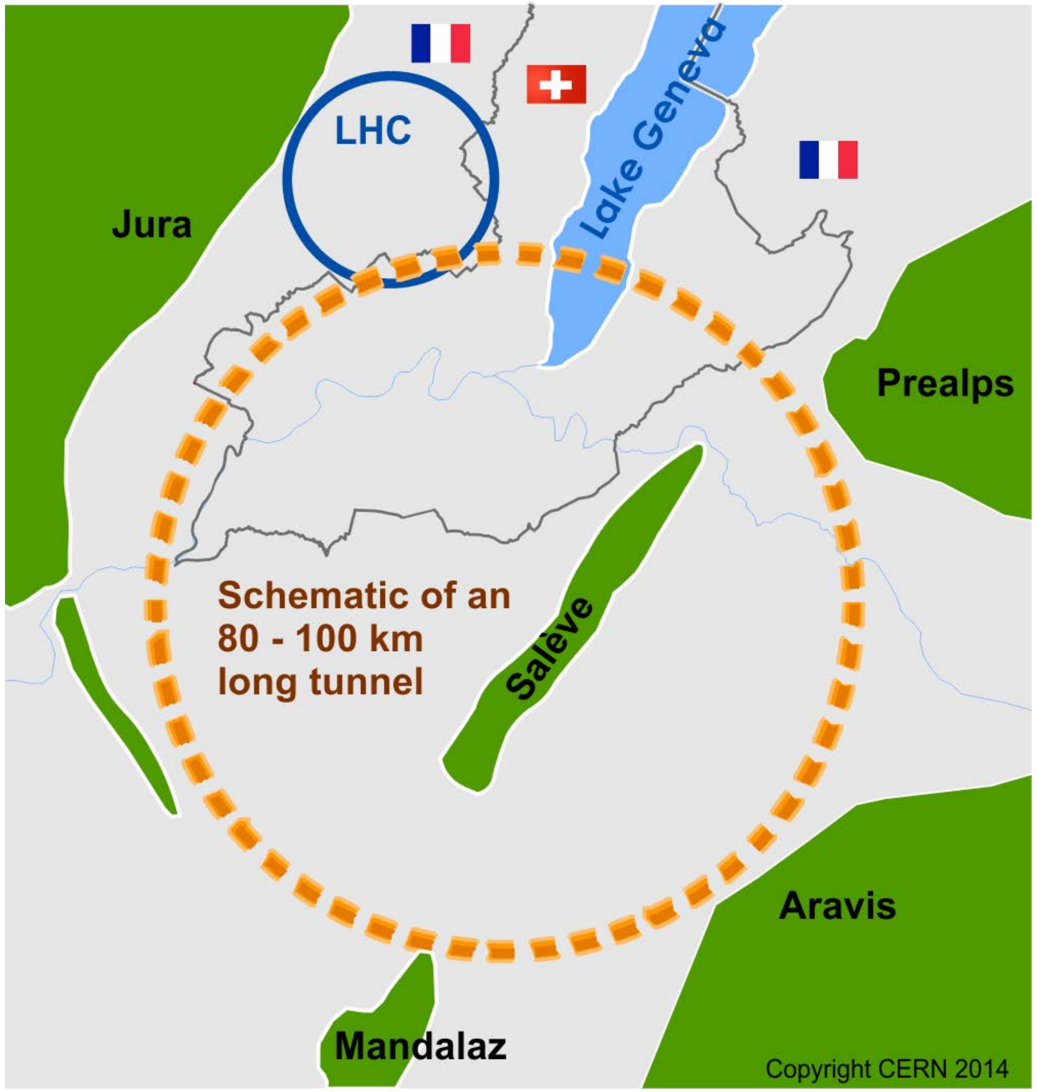
Paul Scherrer Institute and EPFL

Open Symposium in Granada from May 12 to 17, 2019

https://indico.cern.ch/event/808335/

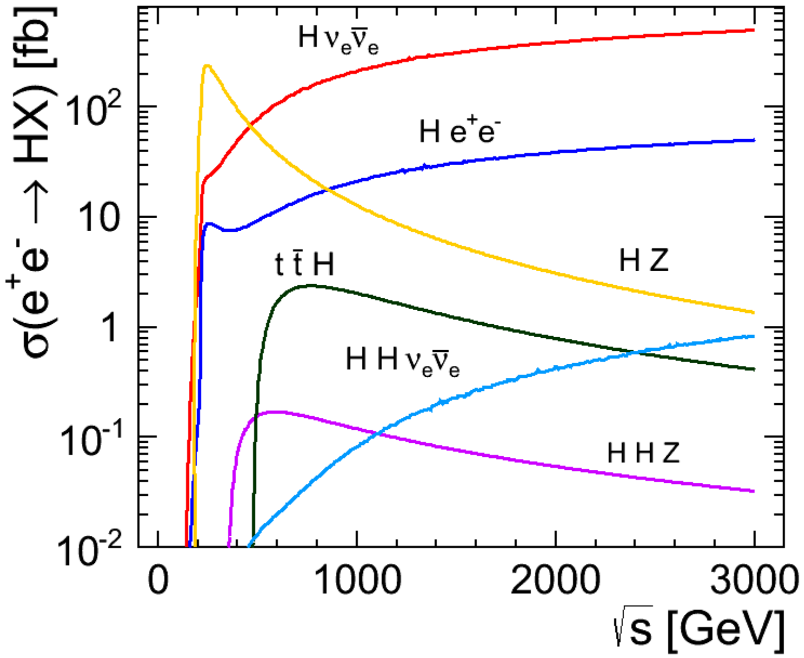
What is the best implementation for a Higgs factory?
Choice and challenges for accelerator technology: linear vs. circular?





Higgs Factories

All new high-energy colliders are also Higgs factories



- 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

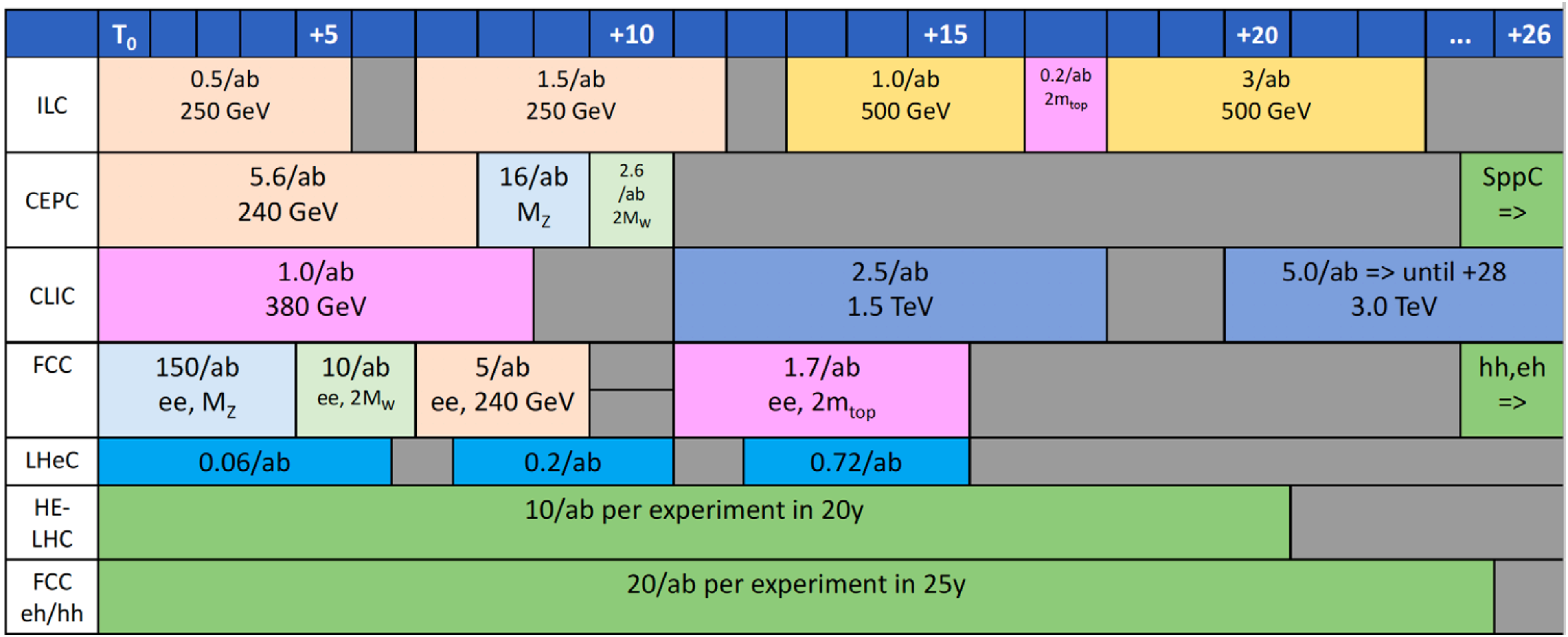
- Lepton-hadron colliders
    - LHeC and FCC-eh
- Muon colliders
- Plasma colliders
- LEP3 and “Low-field” magnets in FCC tunnel

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

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



T$_0$ · +5 · +10 · +15 · +20 · … · +26

ILC: 0.5/ab 250 GeV · 1.5/ab 250 GeV · 1.0/ab 500 GeV · 0.2/ab 2m$_{top}$ · 3/ab 500 GeV

CEPC: 5.6/ab 240 GeV · 16/ab M$_Z$ · 2.6 /ab 2M$_W$ · SppC =>

CLIC: 1.0/ab 380 GeV · 2.5/ab 1.5 TeV · 5.0/ab => until +28 3.0 TeV

FCC: 150/ab ee, M$_Z$ · 10/ab ee, 2M$_W$ · 5/ab ee, 240 GeV · 1.7/ab ee, 2m$_{top}$ · hh,eh =>

LHeC: 0.06/ab · 0.2/ab · 0.72/ab

HE-LHC: 10/ab per experiment in 20y

FCC eh/hh: 20/ab per experiment in 25y

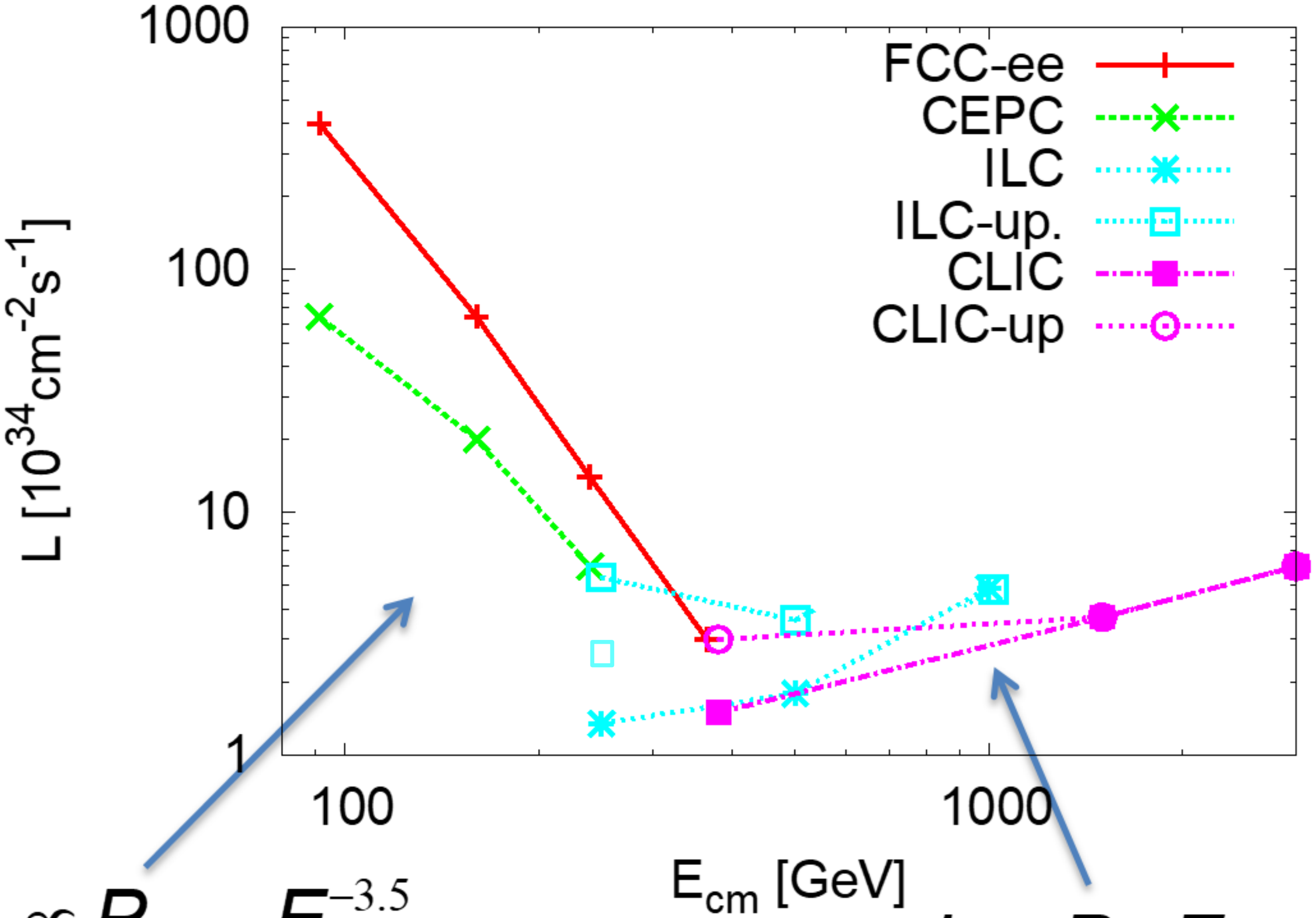
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

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

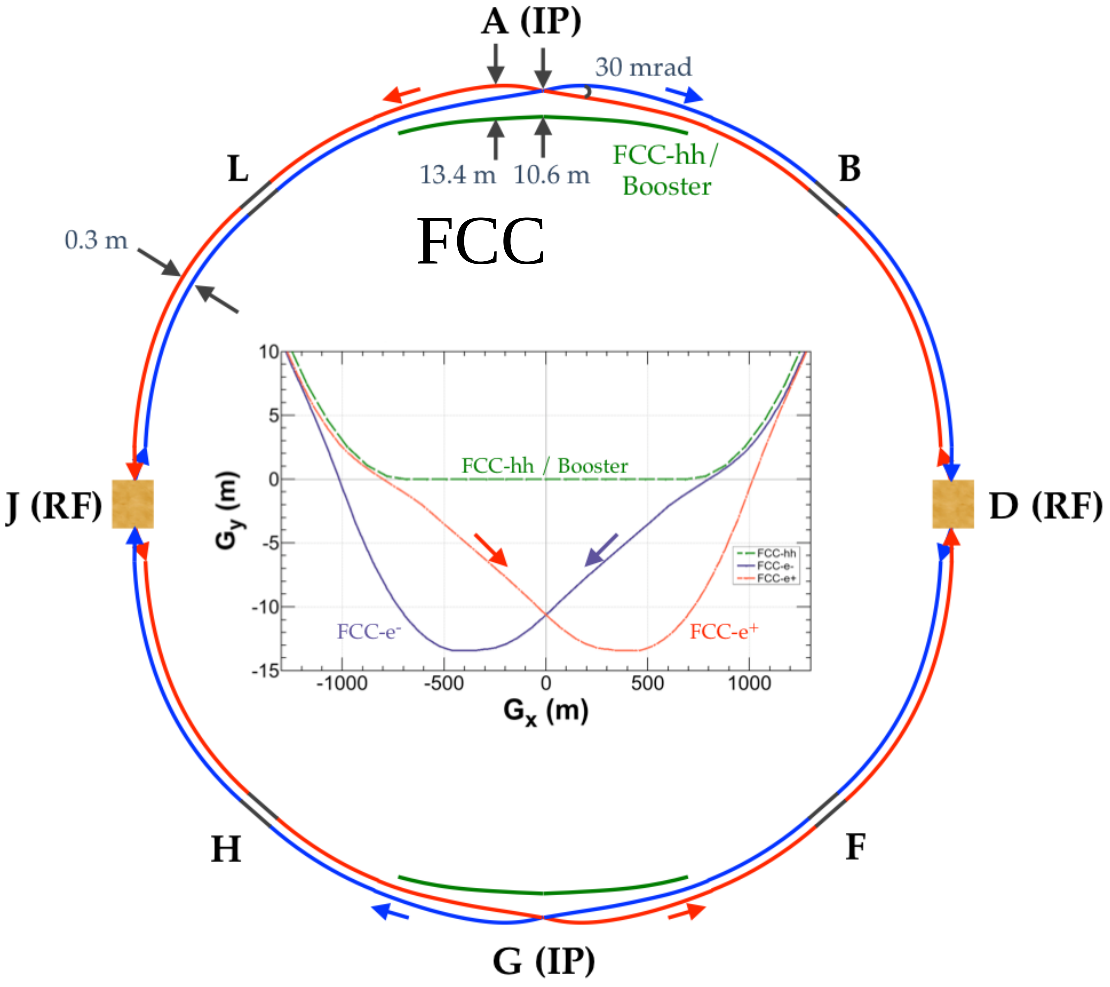


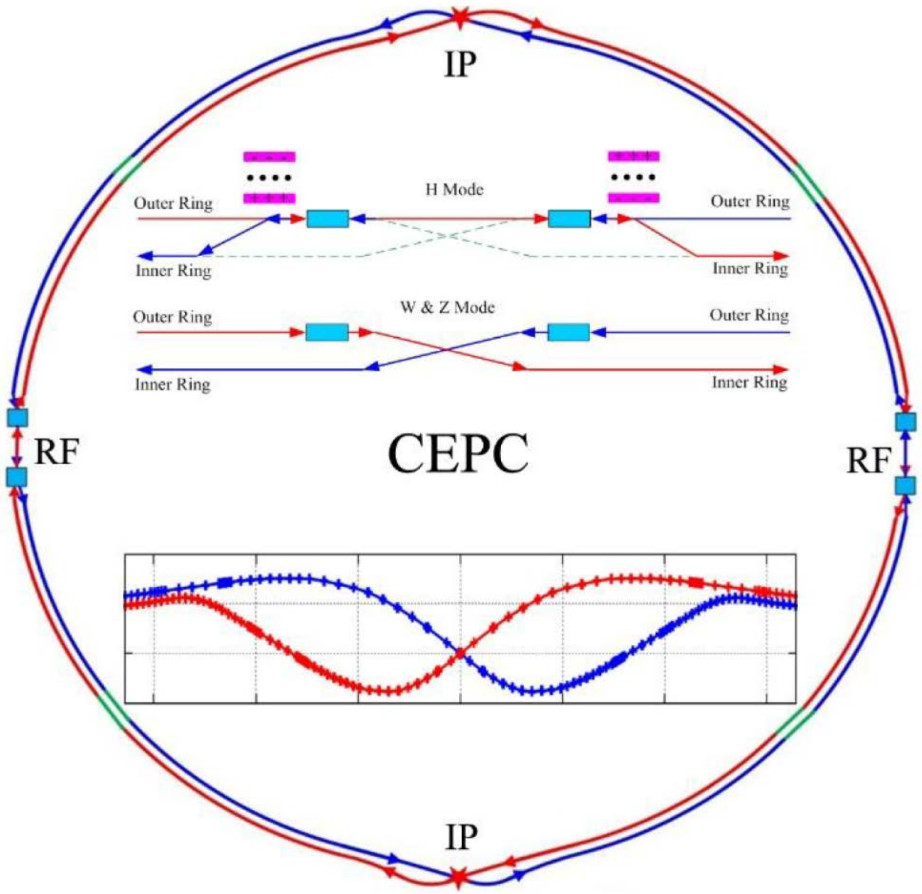
$$L \propto P_{synrad} E_{cm}^{-3.5}$$

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

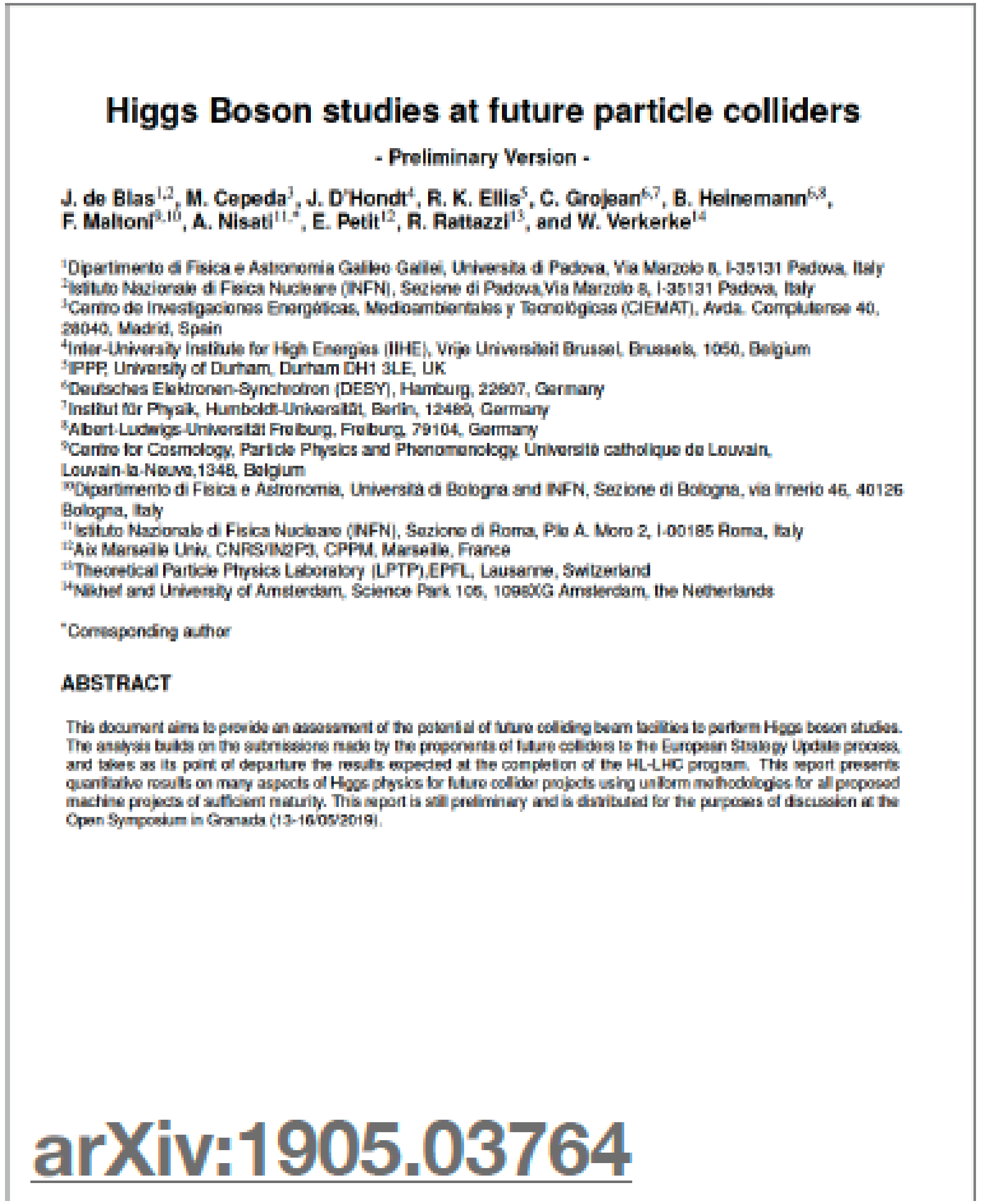
similar solutions for FCC-ee and CEPC

- **Double ring** collider with full-energy **top-up booster** ring,
- **2 IPs, 2 RF straights**, tapering of arc magnet strengths to match local energy
- **Asymmetric IR** layout to limit SR of incoming beams towards detectors and generate large crossing angle
- Common use of RF systems for both beams at highest energy working point (ttbar/ZH for FCC-ee/CEPC)





Report by Higgs@FC Group



Higgs Boson studies at future particle colliders

- Preliminary Version -

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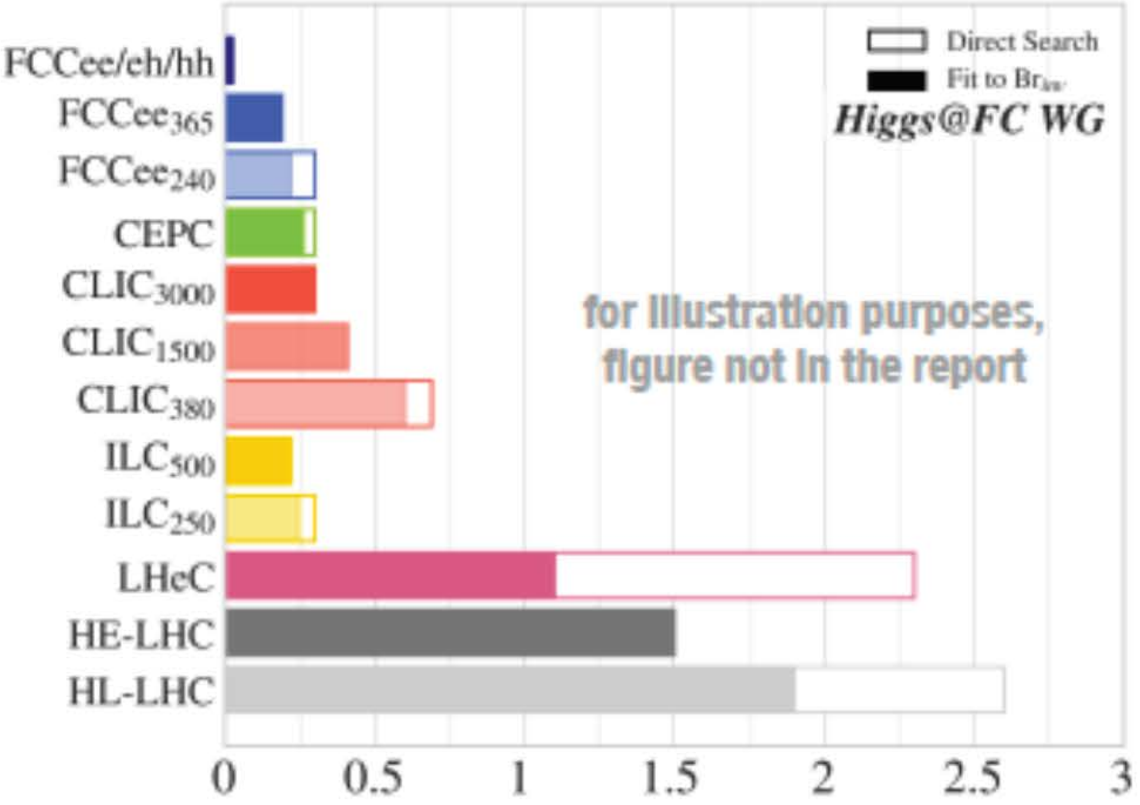
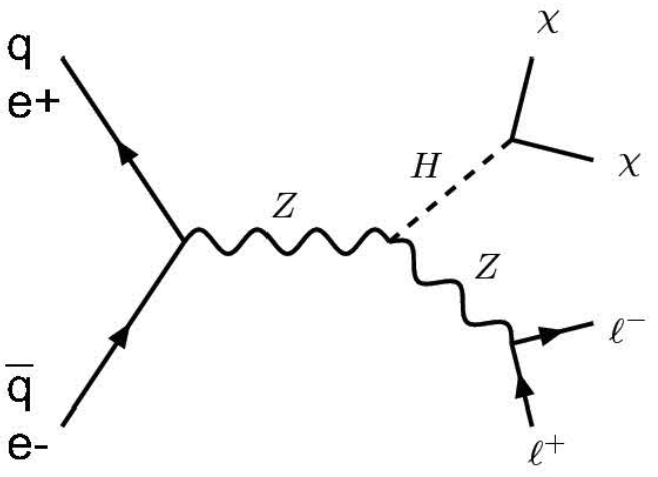
ABSTRACT

This document aims to provide an assessment of the potential of future colliding beam facilities to perform Higgs boson studies. The analysis builds on the submissions made by the proponents of future colliders to the European Strategy Update process, and takes as its point of departure the results expected at the completion of the HL-LHC program. This report presents quantitative results on many aspects of Higgs physics for future collider projects using uniform methodologies for all proposed machine projects of sufficient maturity. This report is still preliminary and is distributed for the purposes of discussion at the Open Symposium in Granada (13-16/05/2019).

arXiv:1905.03764

Invisible H decays: H→E_T^{miss}

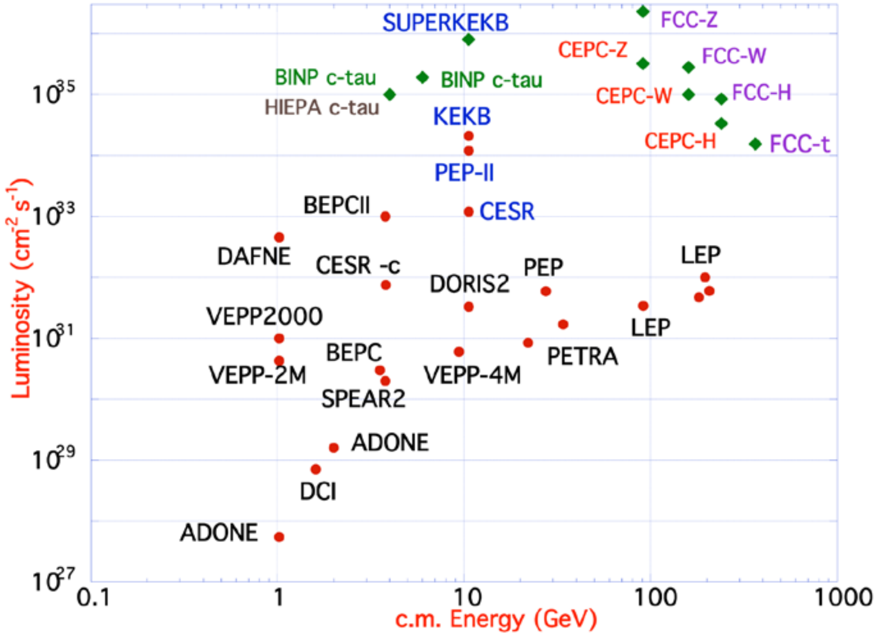




Direct searches dominate sensitivity

- HL-LHC will have sensitivity to ~2.6%
- e+e- colliders improve to ~0.3%
- FCC-hh probes below SM value: ~0.025%

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 records:

LHC 2.1 10^{34}

KEKB 2.1 10^{34}

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

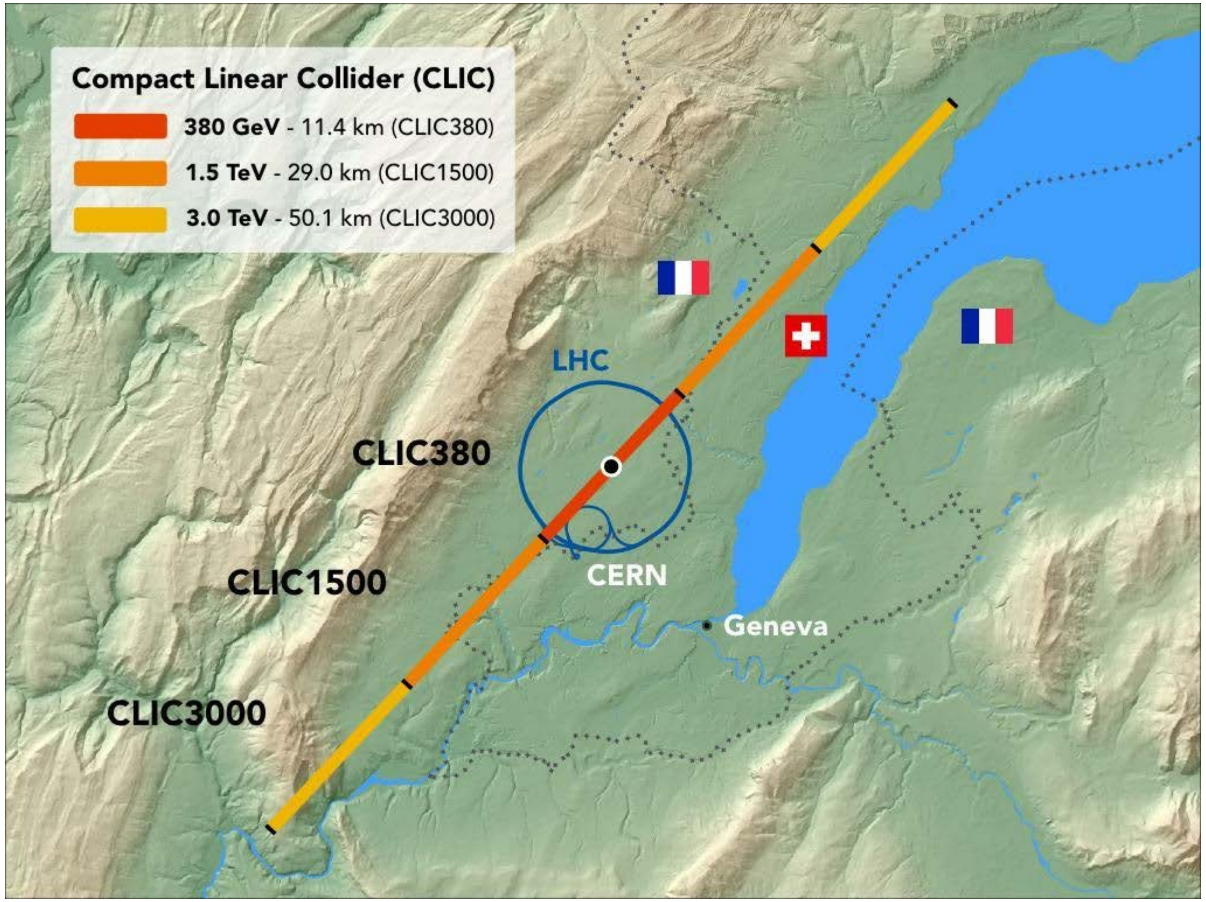
- Guidance on project choice is necessary: Physics potential & Strategic considerations

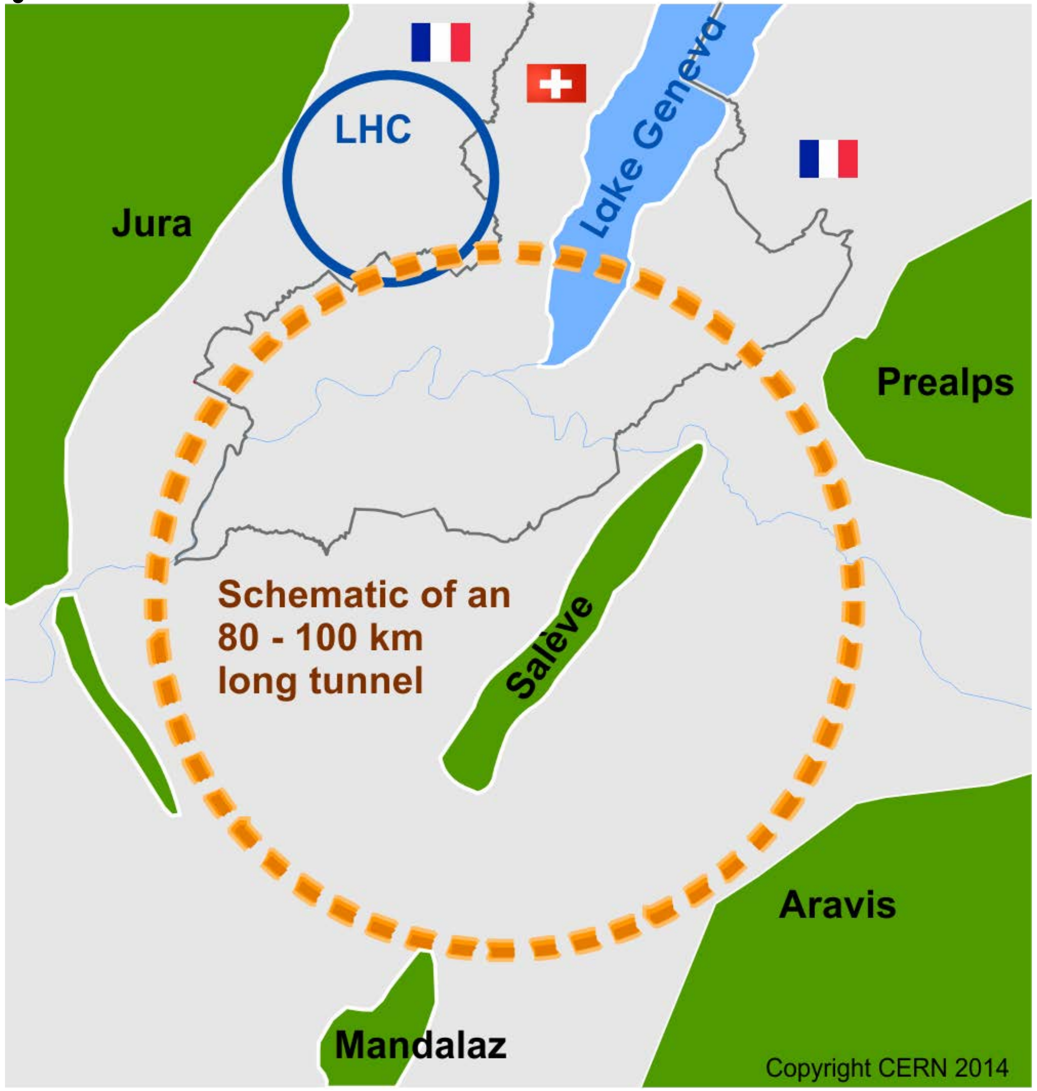
RF technology

- 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

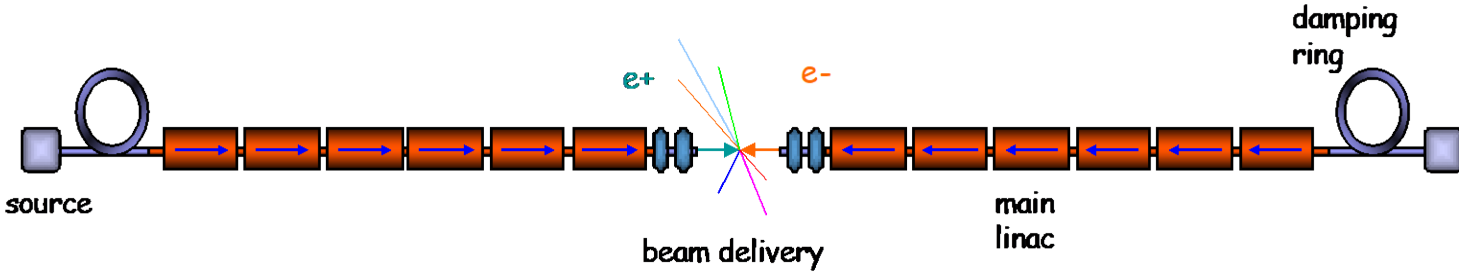
Path towards the highest energies: how to achieve the ultimate performance (including new acceleration techniques)?





Linear Colliders

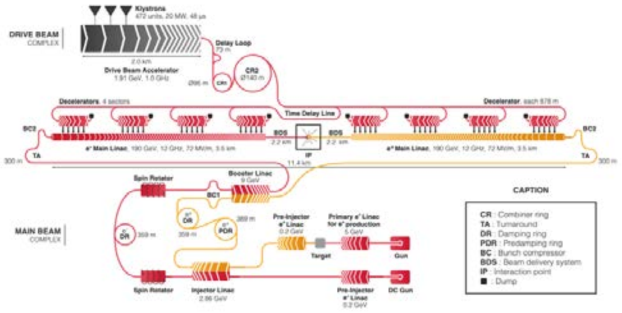
Linear Collider (LC) proposals for CLIC and ILC are very mature: parameters & design, technically developments, in term of performance verifications, project planning – with strong communities behind

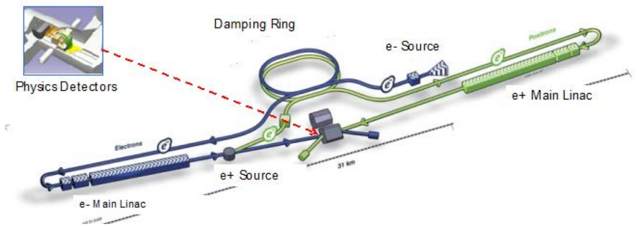


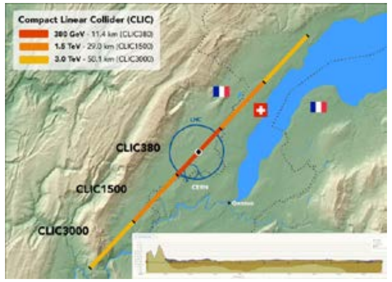
More about CLIC: link & about ILC: link

Key features and technical focus of studies:

- Initial stages with costs and power similar to LHC, further investments will be staged
- Expandable to higher energies – with existing, improved or new RF technologies (as novel acc. technologies) - and in some cases also increased luminosities
- RF (energy) and nanobeams (luminosity) main challenges
- Strong connection and synergies with light-sources and FEL linacs
- Polarized beams foreseen
- Can also run a lower energies (Z) and gamma-gamma is possible (not emphasized in ESPP submissions)

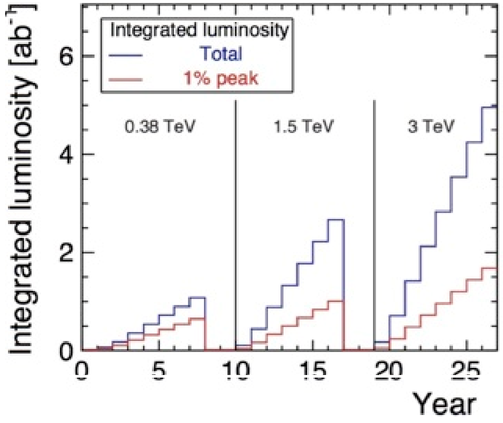




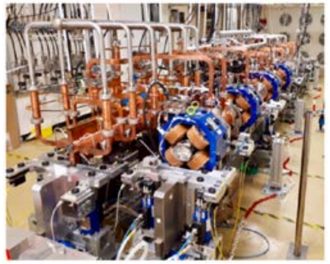


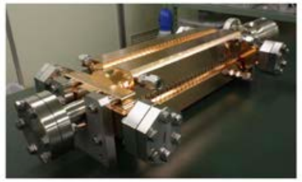
Overview of CLIC and ILC parameters

CLIC illustrations



CLIC y: 75% of 180 days





CLIC parameters

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**

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).

CERN hosted international project (follow LHC model)

ILC parameters

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

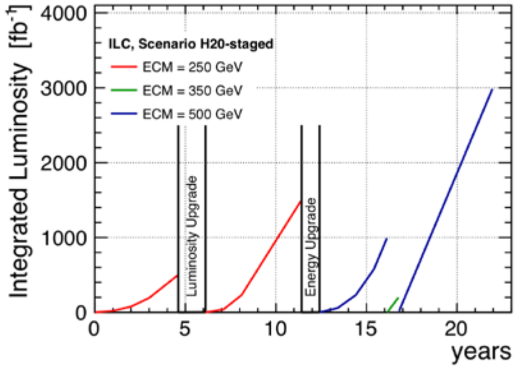
SCRF in extensive use in several FELs with parameters close to ILC parameters, the primary one being the E-XFEL at DESY. Technology optimization underway, linking to evolving SCRF R&D for grad. and Q.

Japan hosted international project, initial ideas about European capabilities available (link)

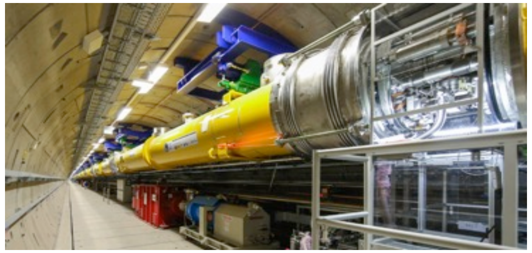
Nanobeam addressed in design & specifications, benchmarked simulations, low emittance ring progress, extensive prototype and method development (for alignment, stabilization, instrumentation, algorithms and feedback systems, system and facility tests : FACET, light-sources, FELs, ATF2)

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)

ILC illustrations



ILC y: 75% of 240 days



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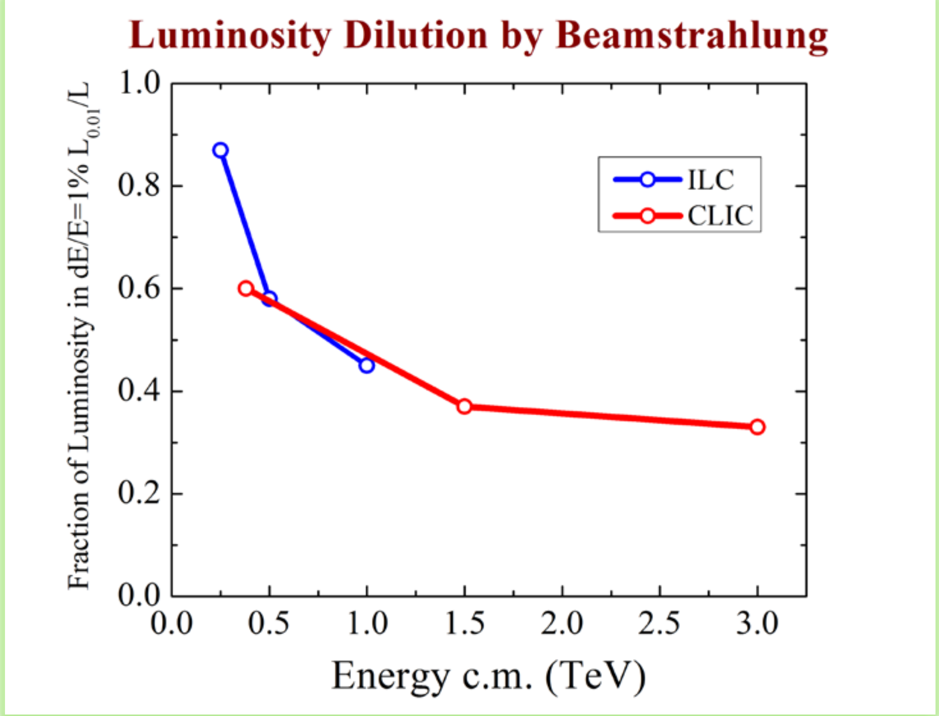
* Doubling by increasing frequency (to be) studied, ** Power at 1.5 and 3 TeV not updated from CDR 2012

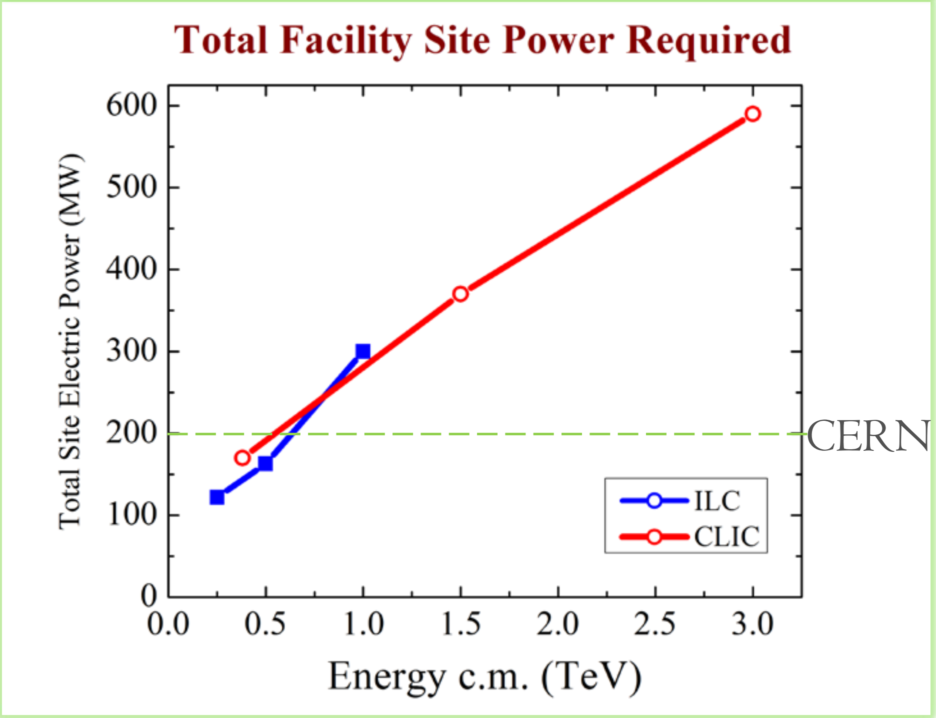


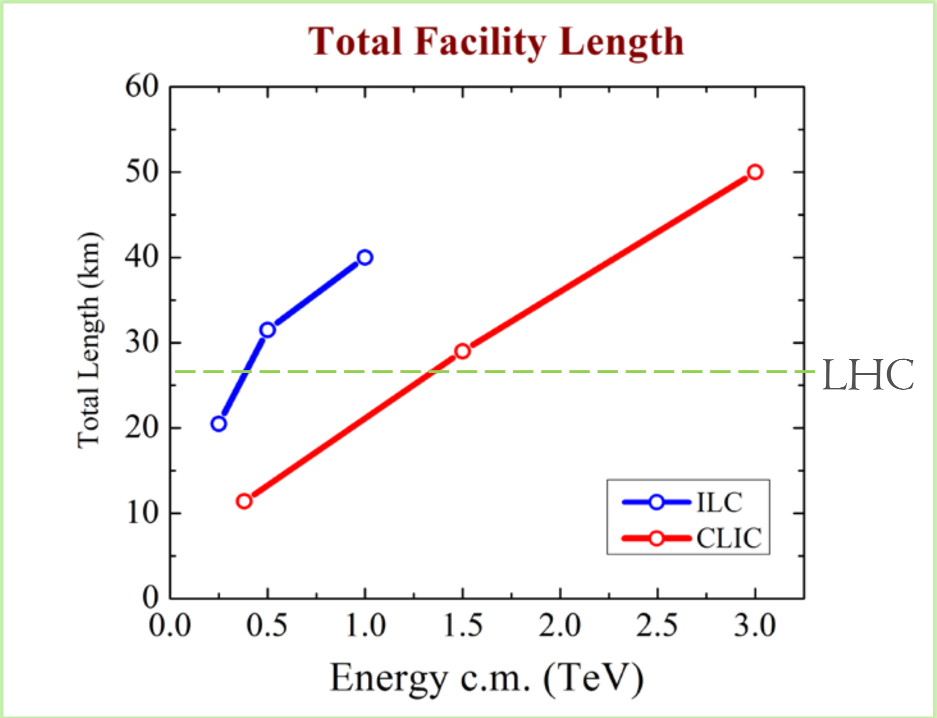
Beamstrahlung rms energy spread :

$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z}\right)\frac{N^2}{\sigma_x^2}$$

→ Luminosity :

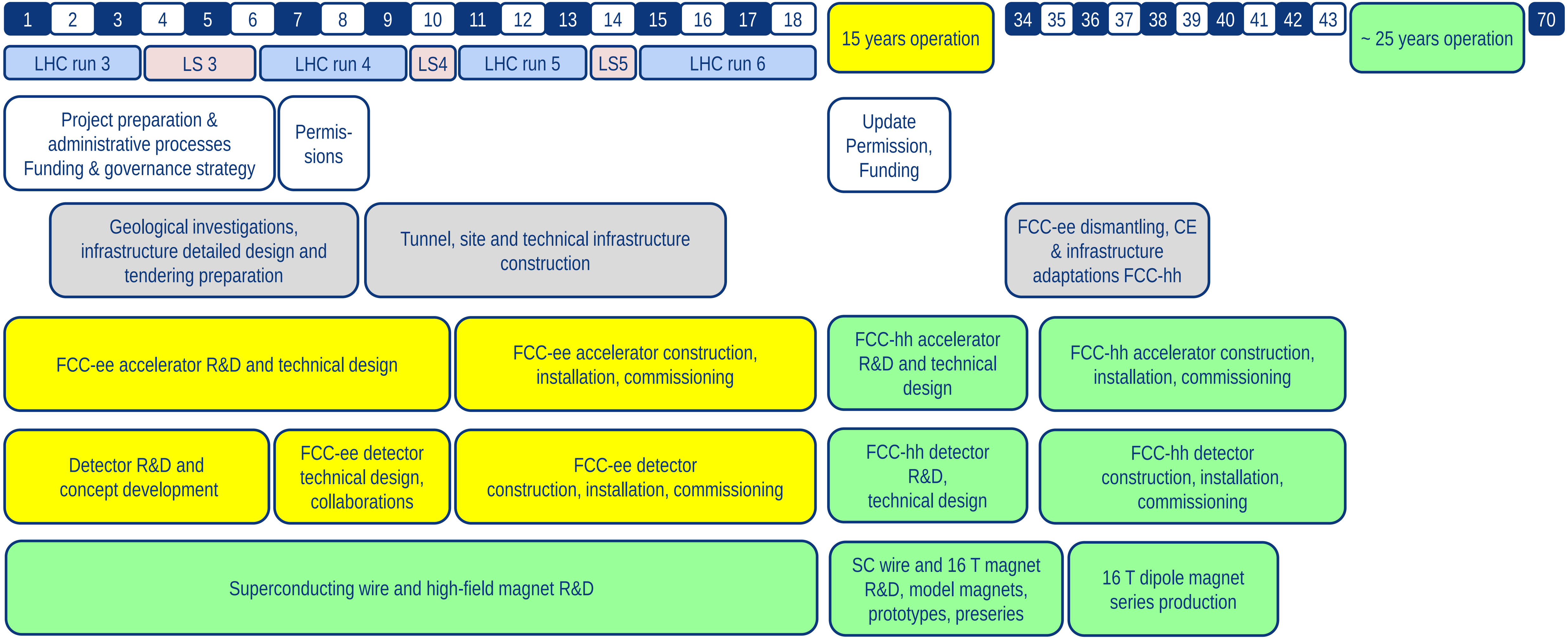
$$L \propto P_{beam}\sqrt{\frac{\delta}{\gamma\varepsilon_y}}H_D$$





V. Shiltsev

FCC integrated project technical schedule



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

15 years operation

34 35 36 37 38 39 40 41 42 43

~ 25 years operation

70

LHC run 3

LS 3

LHC run 4

LS4

LHC run 5

LS5

LHC run 6

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and 16 T magnet R&D, model magnets, prototypes, preseries

16 T dipole magnet series production

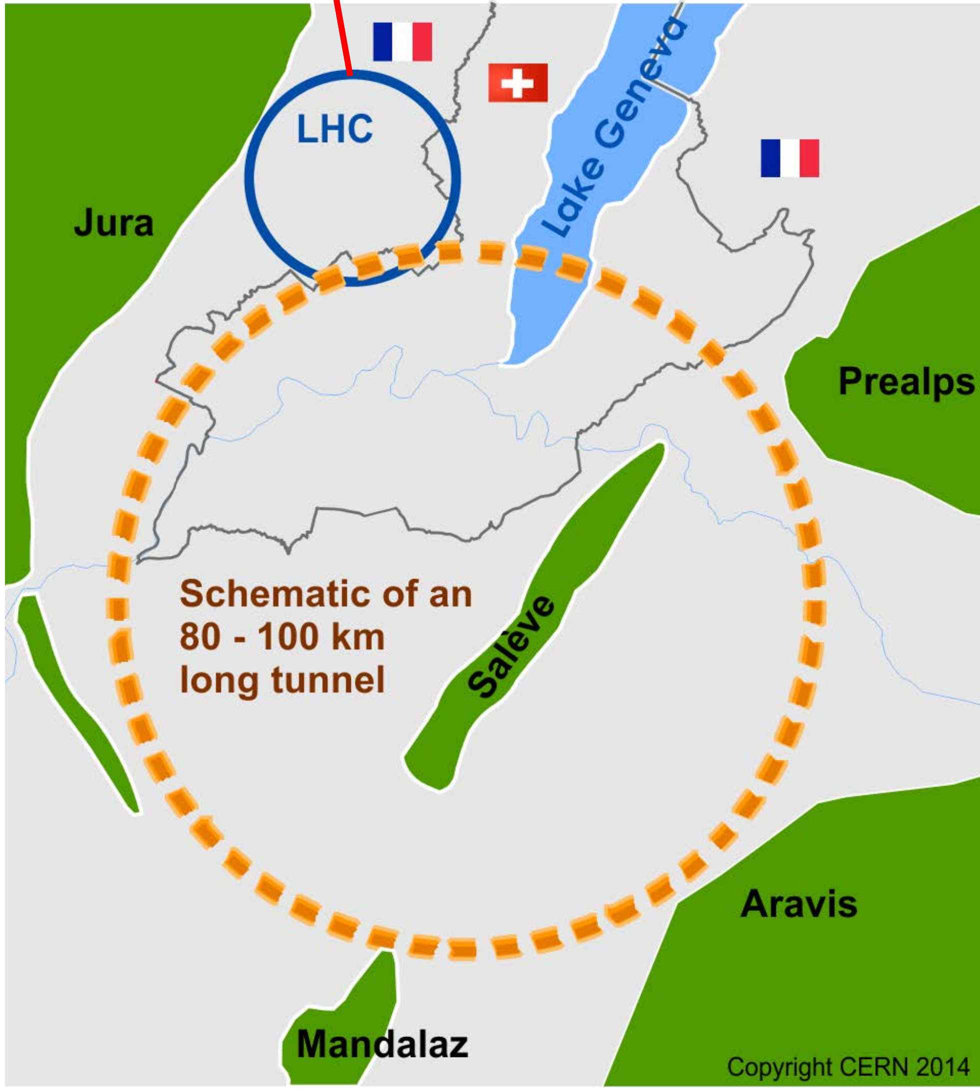
FCC integrated project is fully aligned with HL-LHC exploitation and provides for seamless continuation of HEP in Europe with highest performance EW factory followed by highest energy hadron collider.

Scaling of high energy proton rings

$$B\rho[T\cdot m] = \frac{1}{0.29979\ldots}\, p\left[{}^{GeV}\!/_{c}\right]$$

$$\boxed{\rho, \text{costs} \propto \mathrm{E}}$$

LEP tunnel: 1 TeV per 1 Tesla



High Energy-LHC : 33 TeV with 20 T magnets

Copyright CERN 2014

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

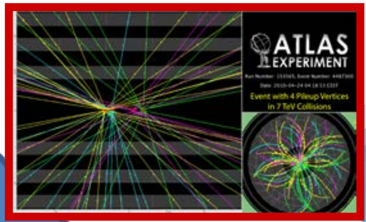
9 T - 1 m single bore

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)

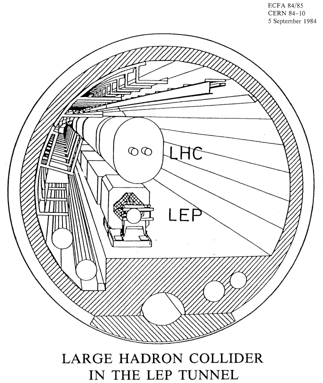
7 years from start R&D to 1st Industry proto

12 y from first working prototype to last magnet

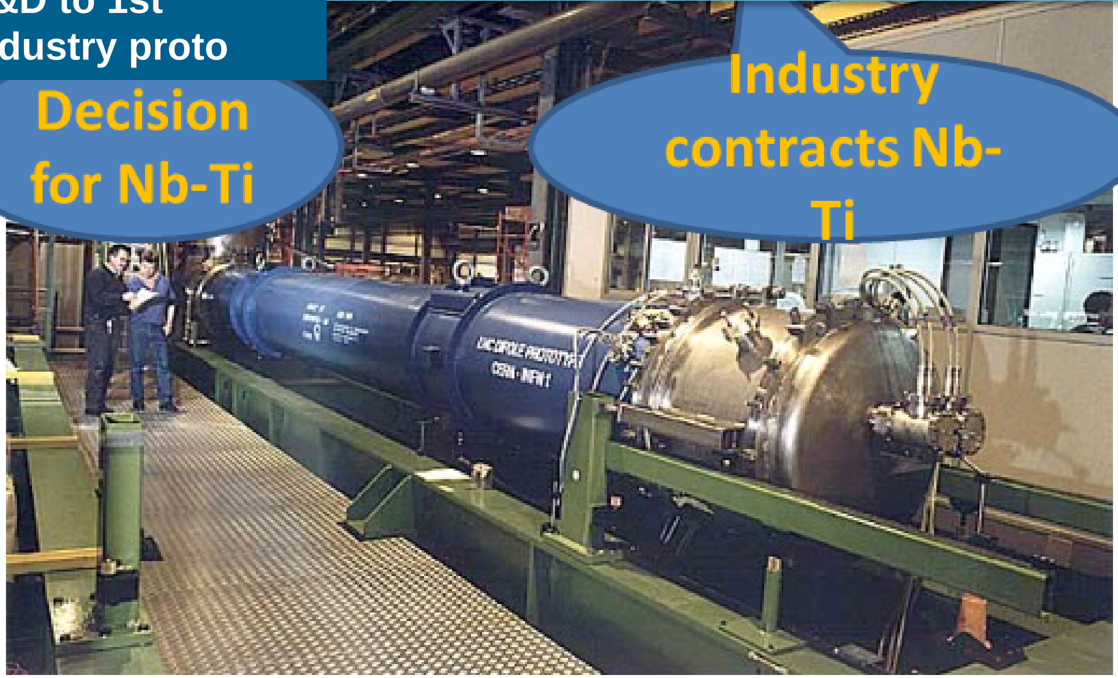
Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up



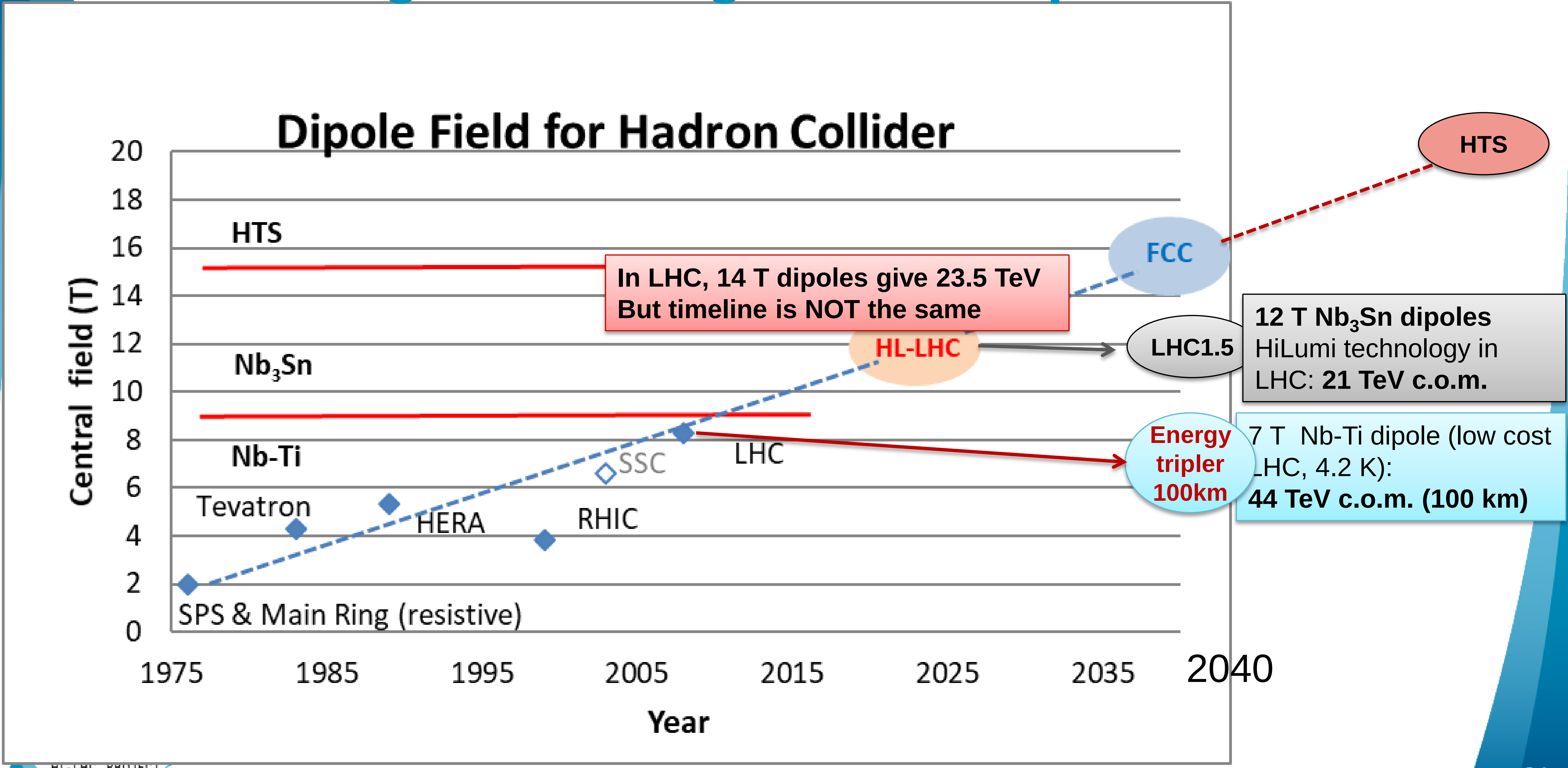
LARGE HADRON COLLIDER
IN THE LEP TUNNEL



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



In LHC, 14 T dipoles give 23.5 TeV
But timeline is NOT the same

12 T Nb$_3$Sn dipoles
HiLumi technology in LHC: **21 TeV c.o.m.**

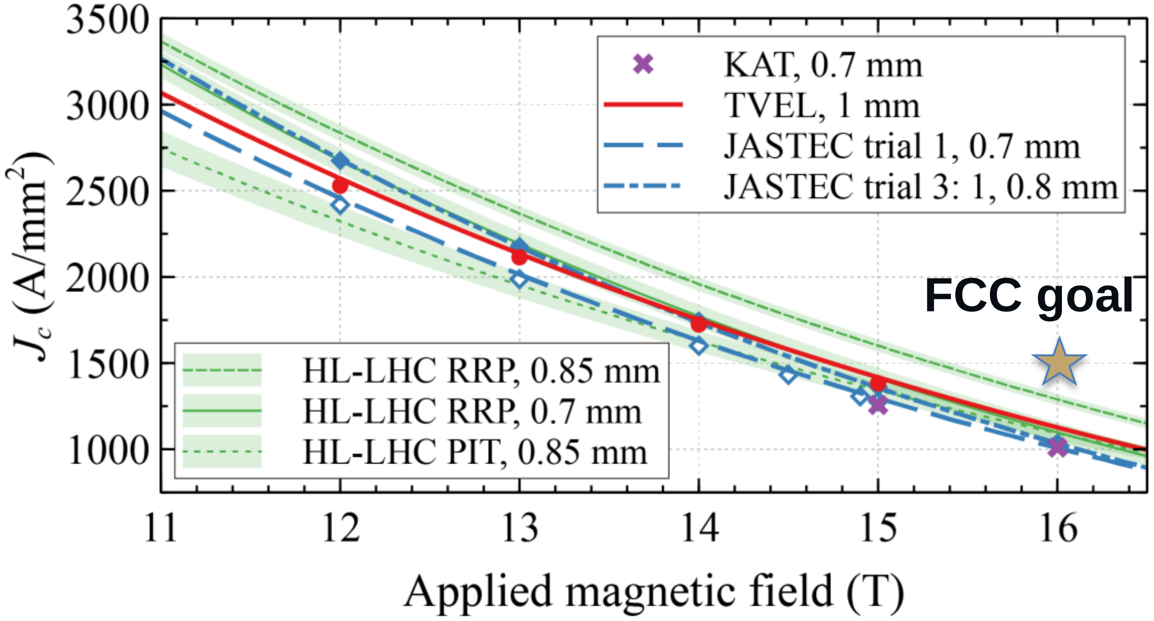
7 T Nb-Ti dipole (low cost LHC, 4.2 K):
44 TeV c.o.m. (100 km)

high-field magnet R&D for FCC-hh

FCC-hh baseline: 16 T magnets, based on Nb_3Sn:

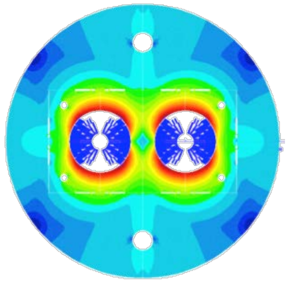
- **Worldwide wire R&D towards J_c (16T, 4.2K) > 1500 A/mm^2 → 50% increase wrt HL-LHC wire**

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

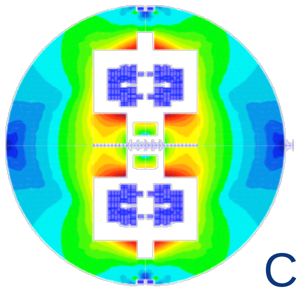


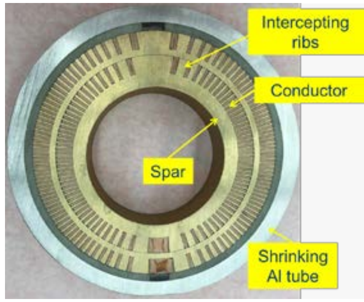
- **Worldwide short model magnet R&D → various coil geometries**
- **2018 – 2024**

Cos-theta

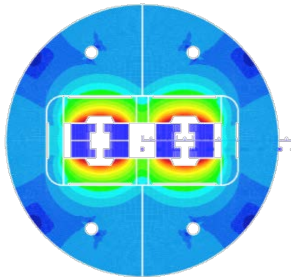


Common coils

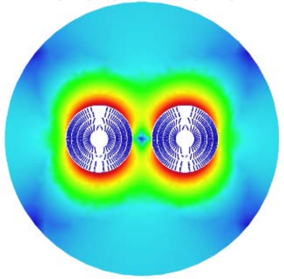


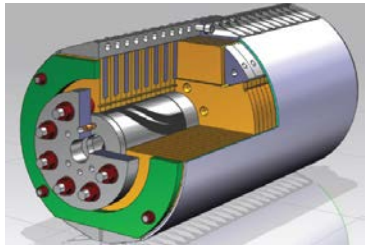


Blocks



Canted Cos-theta

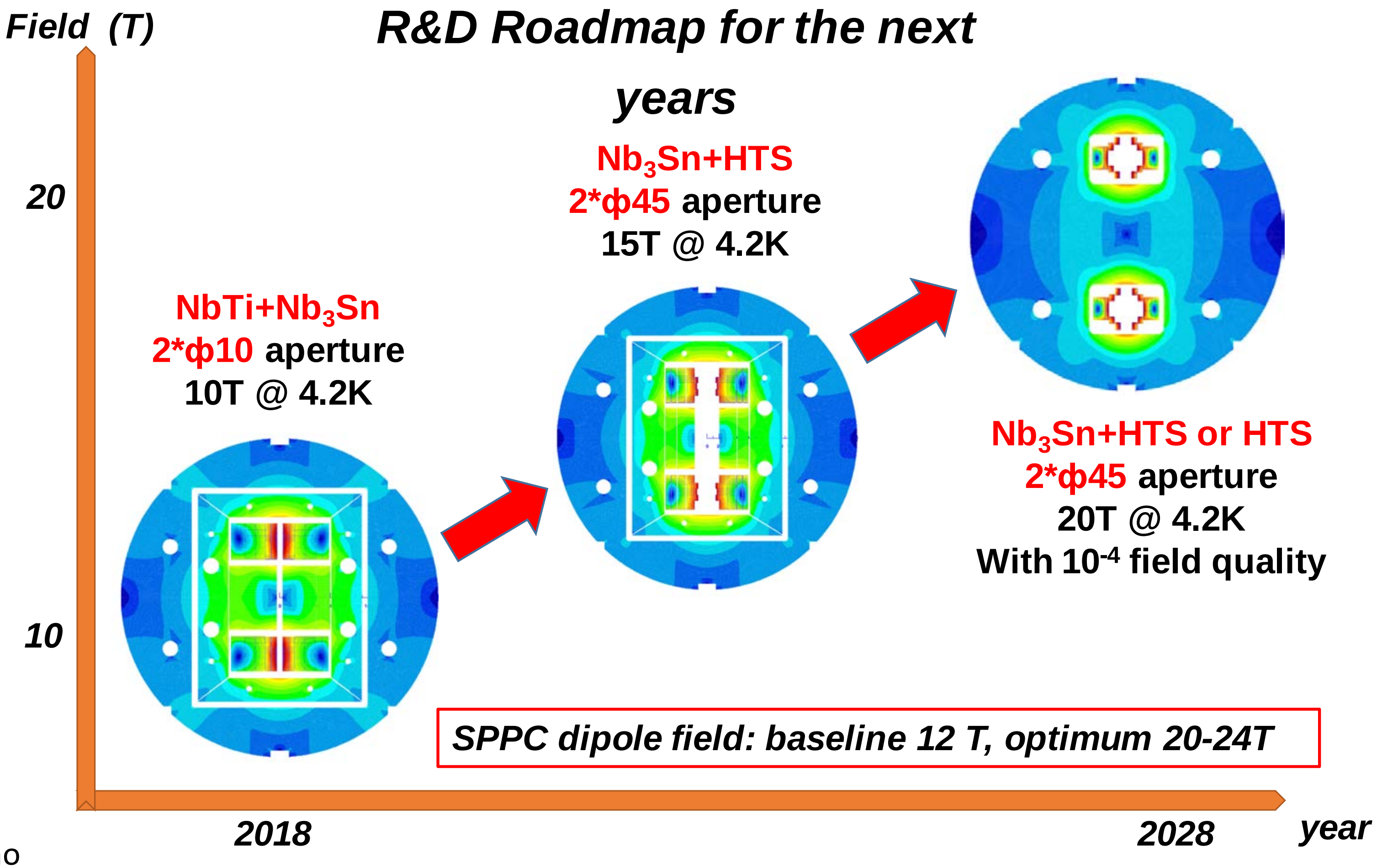




CEA, CIEMAT, INFN, PSI, US-MDP (FNAL, LBNL), BINP

high-field magnet R&D for SppC

SppC baseline: iron-based HTS



R&D Roadmap for the next years

$NbTi+Nb_3Sn$
$2*\phi10$ aperture
10T @ 4.2K

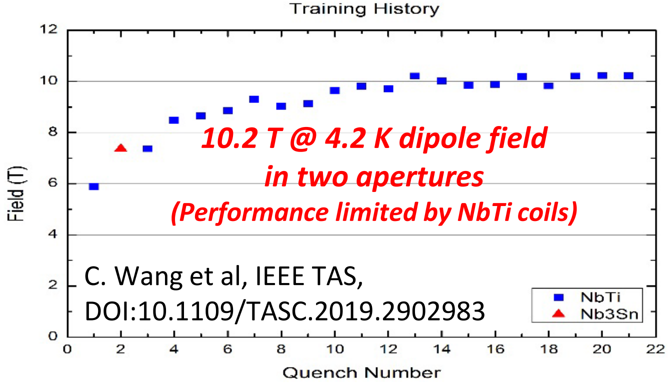
Nb_3Sn+HTS
$2*\phi45$ aperture
15T @ 4.2K

Nb_3Sn+HTS or HTS
$2*\phi45$ aperture
20T @ 4.2K
With 10^{-4} field quality

SPPC dipole field: baseline 12 T, optimum 20-24T

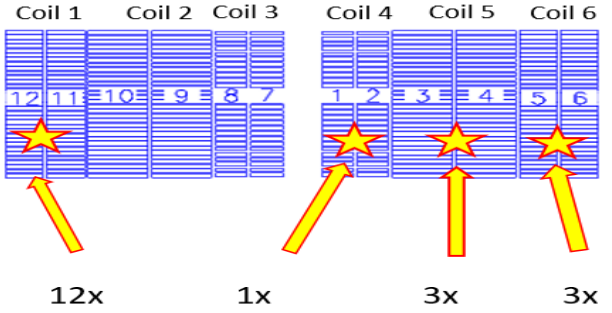
J. Gao

Magnet fabrication @ Beijing



10.2 T @ 4.2 K dipole field in two apertures
(Performance limited by NbTi coils)

C. Wang et al, IEEE TAS, DOI:10.1109/TASC.2019.2902983



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

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***

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
CC 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
CC 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
LC 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

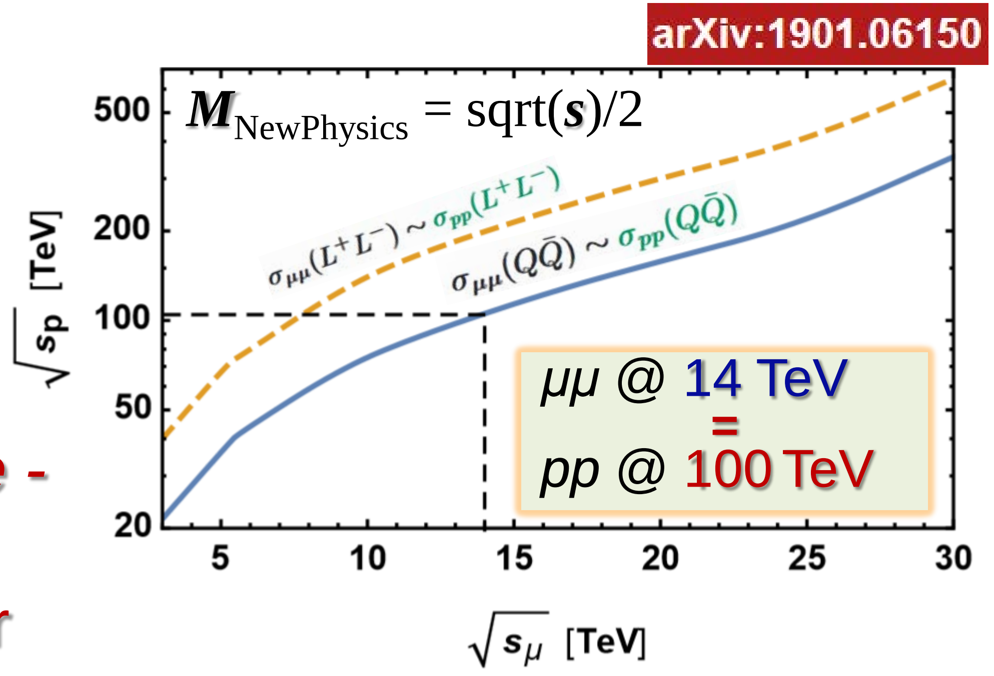
*Cost estimates are commonly for "**Value**" (material) only.

High Energy μ+μ- Colliders

Advantages:

- ***μ***’s do not radiate / no beamstrahlung→ acceleration in rings → *low cost & great power efficiency*
- ~ x7 energy reach vs *pp*

Offer *“moderately conservative - moderately innovative”* path **to cost affordable** energy frontier colliders:


arXiv:1901.06150

μμ @ 14 TeV = pp @ 100 TeV

- US MAP feasibility studies were very successful → MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

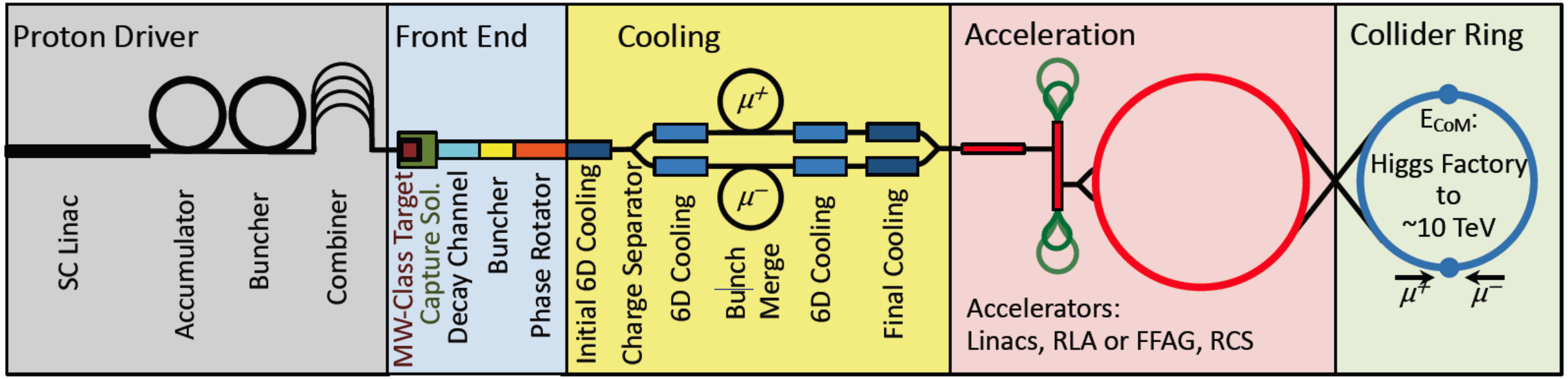
** more like “strawman” parameter table*

Key to success:

- Test facility to demonstrate performance implications - muon production and 6D cooling, study LEMMA e^+-45 GeV + e^- at rest →μ^+-μ^- , design study of acceleration, detector background and neutrino radiation

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

Higgs Factory:
S-channel production
2 x 63 GeV to Higgs

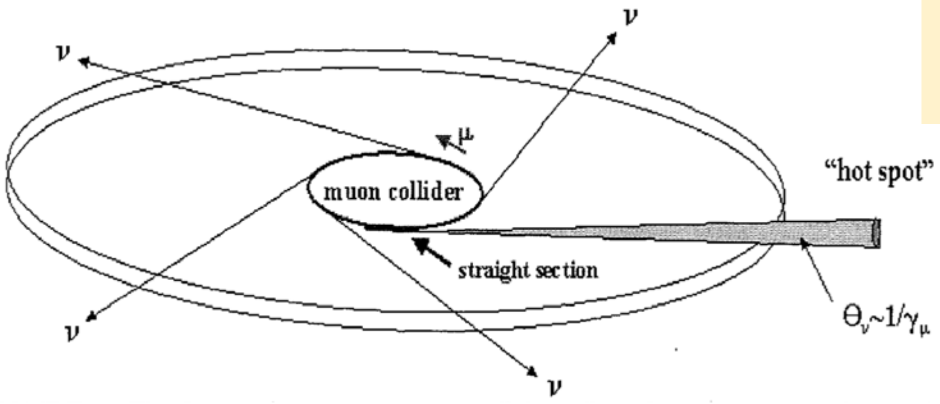
Answers to the Key Questions

- **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

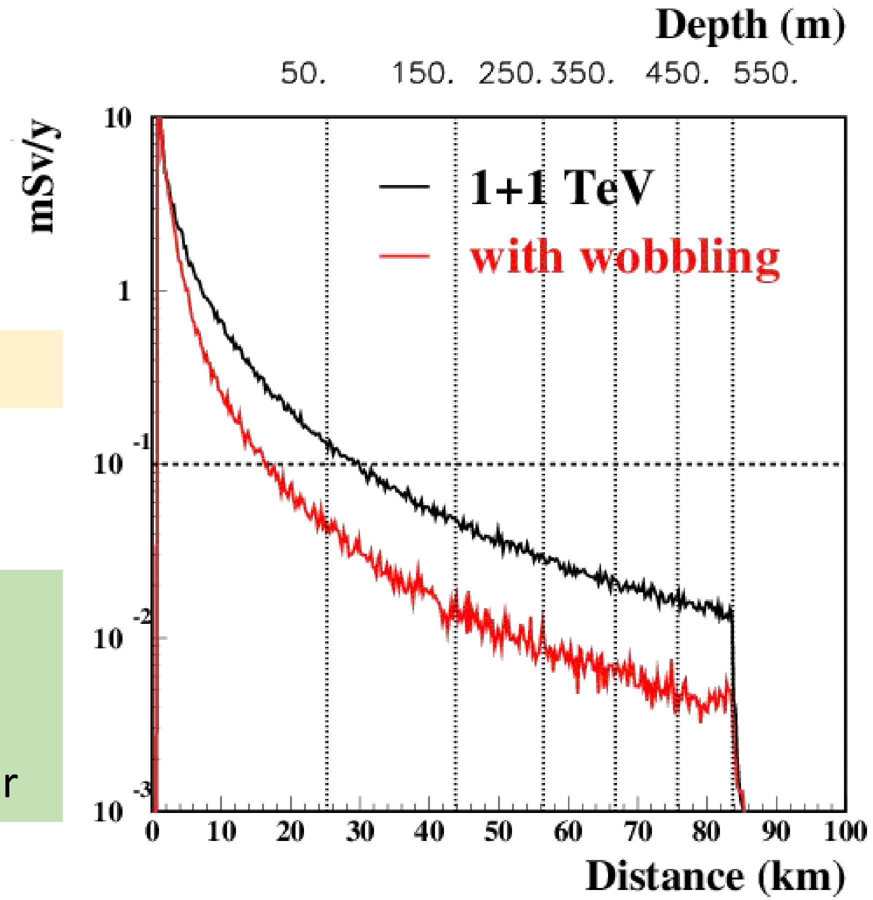
- **Is it worthwhile to do muon collider R&D?**
  - Yes, it promises the potential to go to very high energy
  - It may be the best option for very high lepton collider energies, beyond 3 TeV
  - It has strong synergies with other projects, e.g. magnet and RF development
  - Has synergies with other 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**

Beam induced background studies
neutrino radiation hazard



The source, ring or section, is placed at the fixed depth of 550 m.

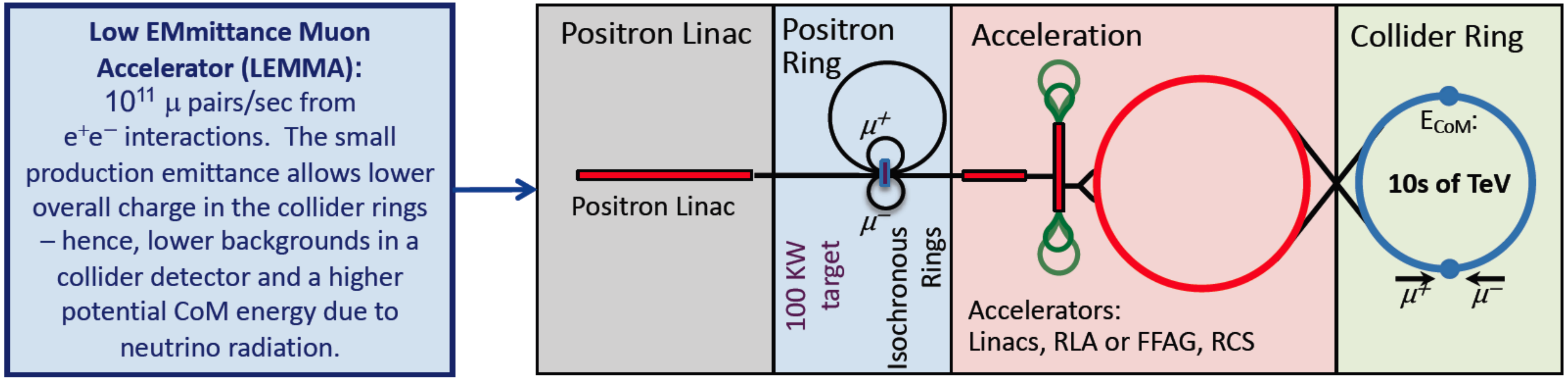


Ambient dose assuming 1.2 × 10^{21} decays/year

Need to study for higher energies (scaling E^3)

Straights in LHC might increase problem
⇒ Another reason to consider this as accelerator

The LEMMA Scheme


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

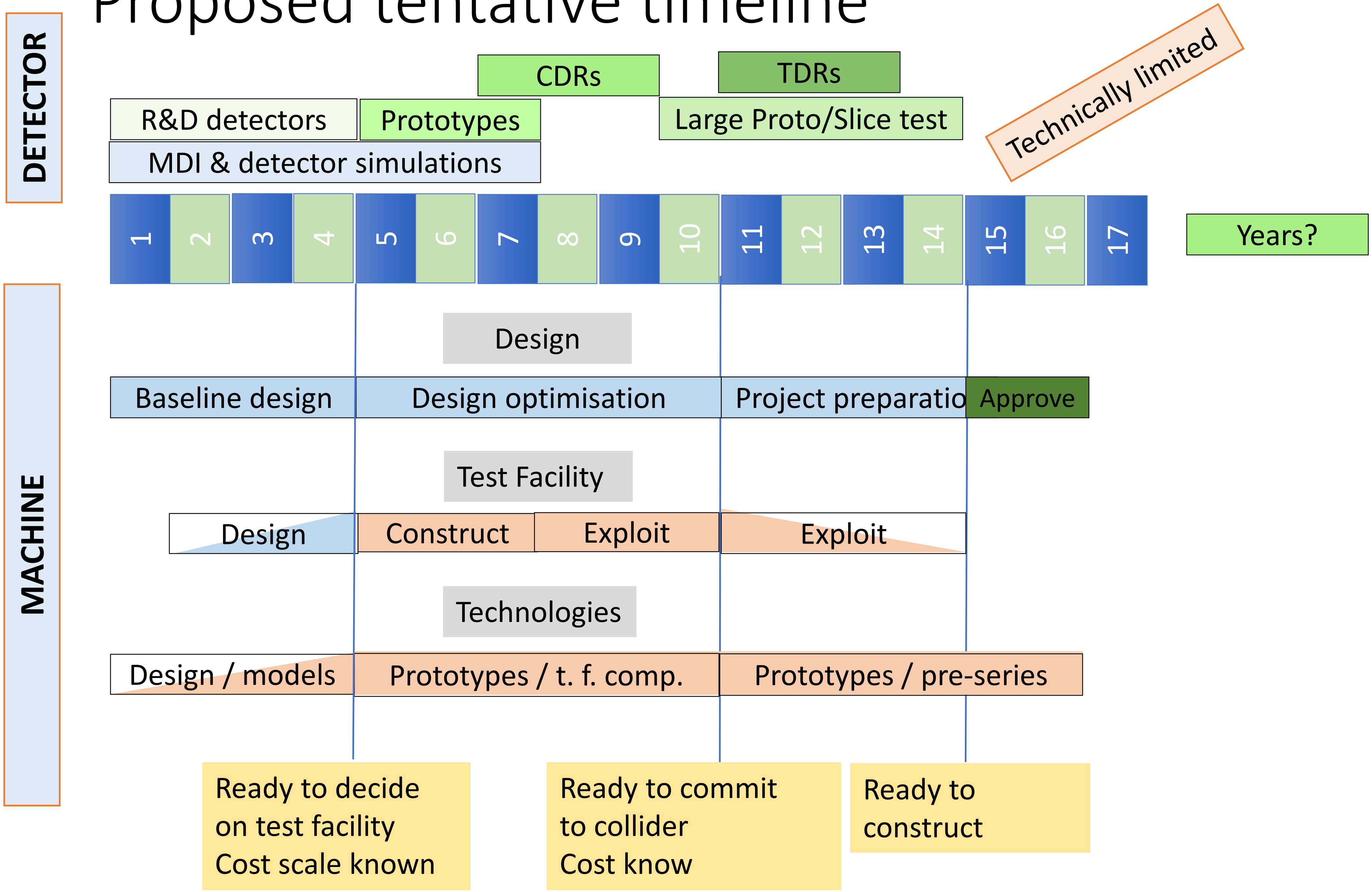
Key concept (original numbers in brackets)

Produce muon beam with low emittance using a positron beam (40 nm vs. 25 µm in proton scheme)

- No cooling required, use lower muon current

- Positron beam (45 GeV, $3\text{x}10^{11}$ particles every 200 ns) passes through target and produces muon pairs
- Muon bunches are circulated through target O(2000) times accumulating more muons ($4.5\text{x}10^7$)
- Every 0.5 ms, the muon bunches are extracted and accelerated
- They are combined in the collider ring, where they collide

Proposed tentative timeline



DETECTOR

CDRs

TDRs

R&D detectors

Prototypes

Large Proto/Slice test

MDI & detector simulations

Technically limited

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

Years?

MACHINE

Design

Baseline design | Design optimisation | Project preparatio | Approve

Test Facility

Design | Construct | Exploit | Exploit

Technologies

Design / models | Prototypes / t. f. comp. | Prototypes / pre-series

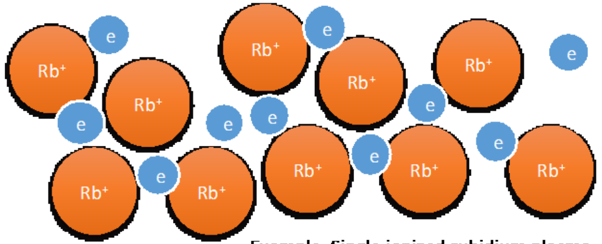
Ready to decide
on test facility
Cost scale known

Ready to commit
to collider
Cost know

Ready to
construct

D. Schulte

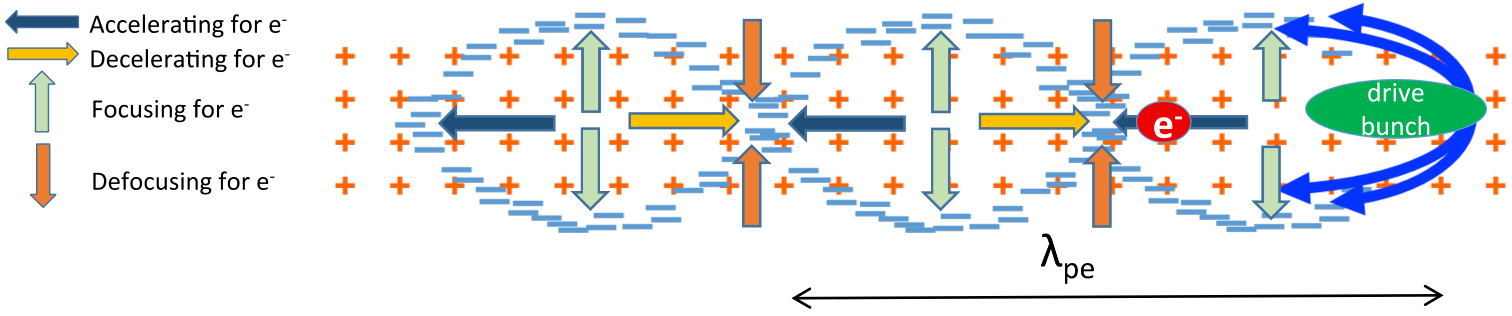
Introduction – Plasma Wakefield Acceleration, PWFA



Example: Single ionized rubidium plasma

Plasma is ionized and can sustain **electric fields up to three orders of magnitude higher** than conventional accelerator technologies**.**
Reach gradients → order of **100 GV/m.**

Using plasma to convert **the transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma.**



Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam
Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

$$\omega_{pe} = \sqrt{\frac{n_{pe}\, e^2}{m_e\, \varepsilon_0}} \rightarrow \lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \rightarrow \lambda_{pe} \approx 1\,\mathrm{mm} \sqrt{\frac{10^{15}\,\mathrm{cm}^{-3}}{n_{pe}}}$$

Example: $n_{pe} = 10^{16}\,\mathrm{cm}^{-3}$
→ $\lambda_{pe} = 0.3\,\mathrm{mm}$

→ Cavities with mm size!

Plasma Wakefield Accelerators

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Key facts:

Three ways to excite plasma (drivers)

laser *dE* ~ 4.3 GeV (10^{18} cm^{-3} 9cm)

e- bunch *dE* ~ 9 GeV (~10^{17} cm^{-3} 1.3m)

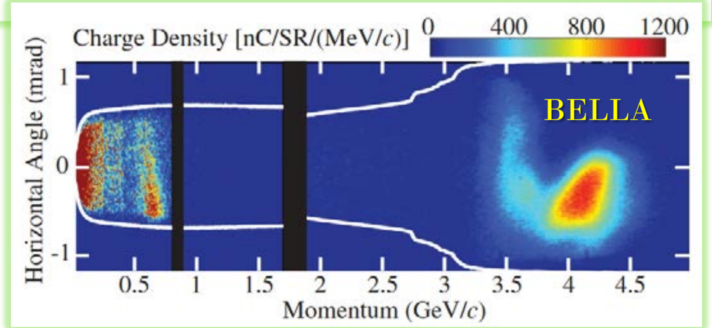
p+ bunch *dE* ~ 2 GeV (~10^{15} cm^{-3} 10m)

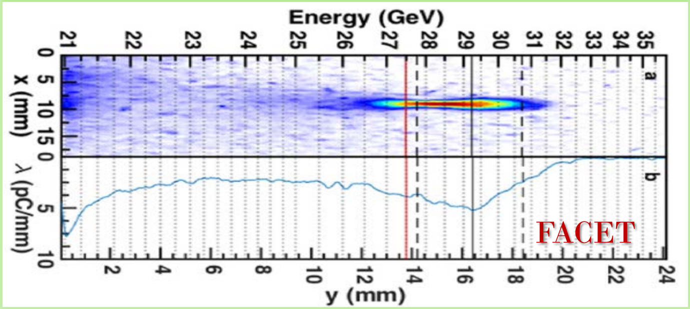
Impressive proof-of-principle demos

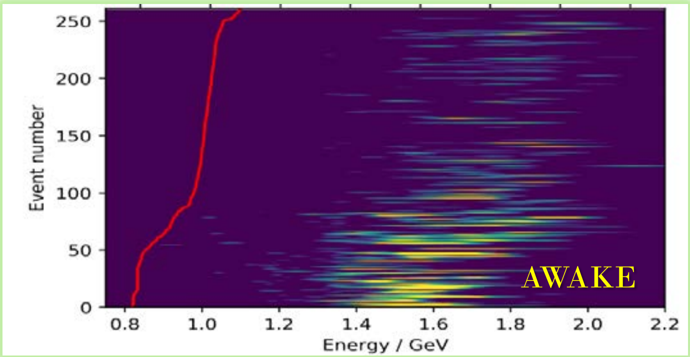
In principle, feasible for *e*+*e*- collisions

Collider cost and power will greatly depend on the driver technology:

- lasers, super-beams of electrons or protons

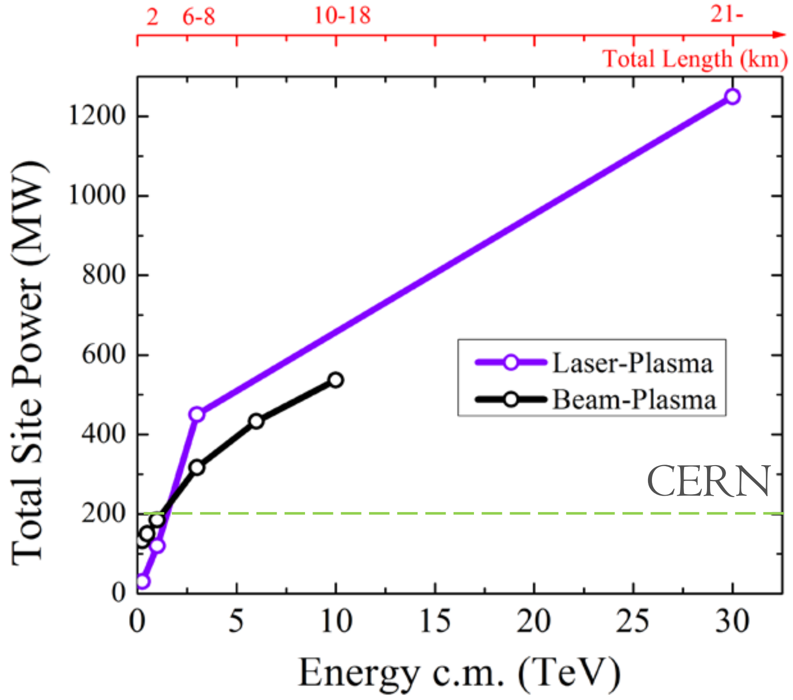


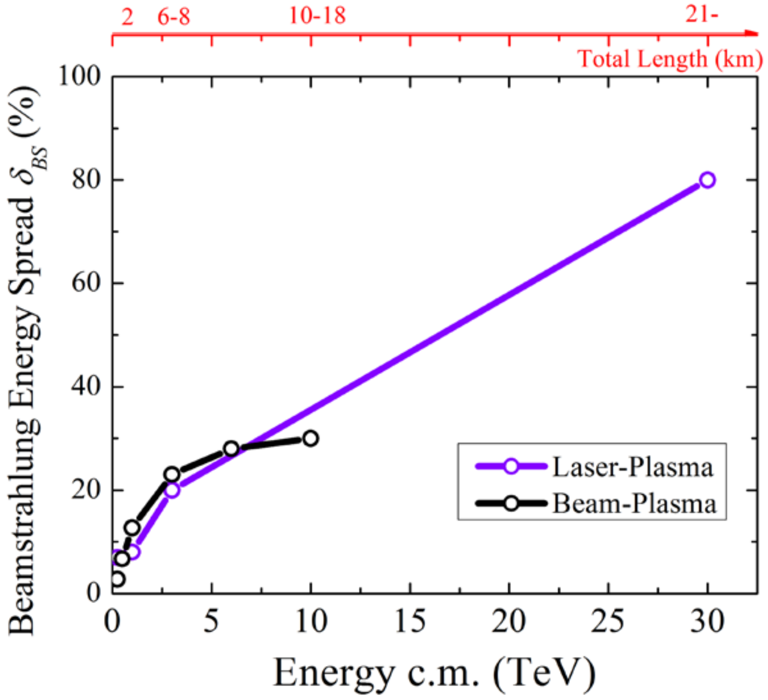




V. Shiltsev

Plasma Colliders





arXiv:1308.1145

- Key Issues to Study:
  - acceleration of positrons
  - Staging efficiency
  - emittance control vs scatter
  - beamstrahlung
  - HP lasers / HP operation
  - power efficiency

  * the first four can be addressed by using μ's in 10^{22} cm^{-3} crystals – up to 1 PeV
- Plenty of interest and opportunities:
  - **Collaborations:** *EuPRAXIA, ALEGRO study, ATHENA*
  - **Facilities:** *PWASC, ELBE/HZDR, AWAKE, CILEX, CLARA and SCAPA, EuPRAXIA @ SPARC_LAB at INFN-LNF, Lund, JuSPARC at FZJ and FLASHFor-ward and SINBAD at DESY; also in Japan (ImPACT), China (SECUF) and in the US (FACET-II, BELLA)*
  - Proposals of plasma *e-* injectors

V. Shiltsev

Plasma acceleration based colliders

Drive beams

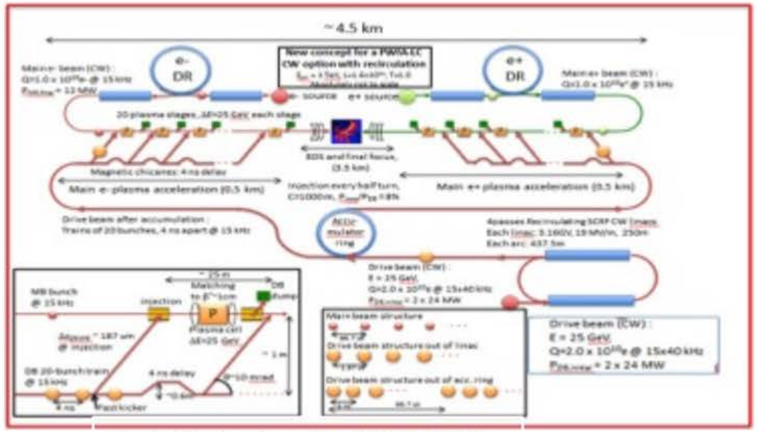
Lasers: ~40 J/pulse

Electrons: 30 J/bunch

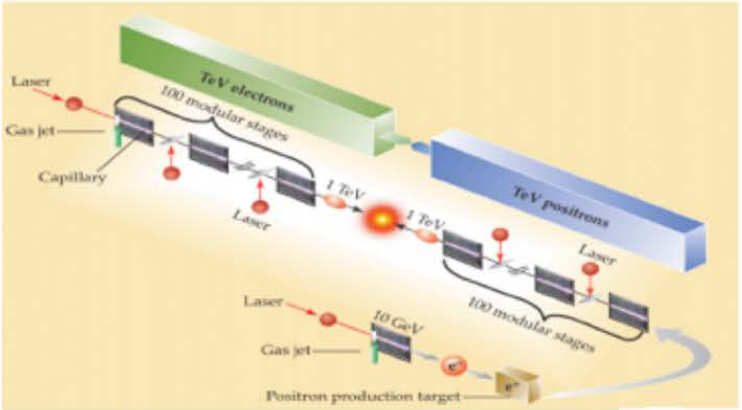
Protons: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams

Electrons: 10^{10} 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:

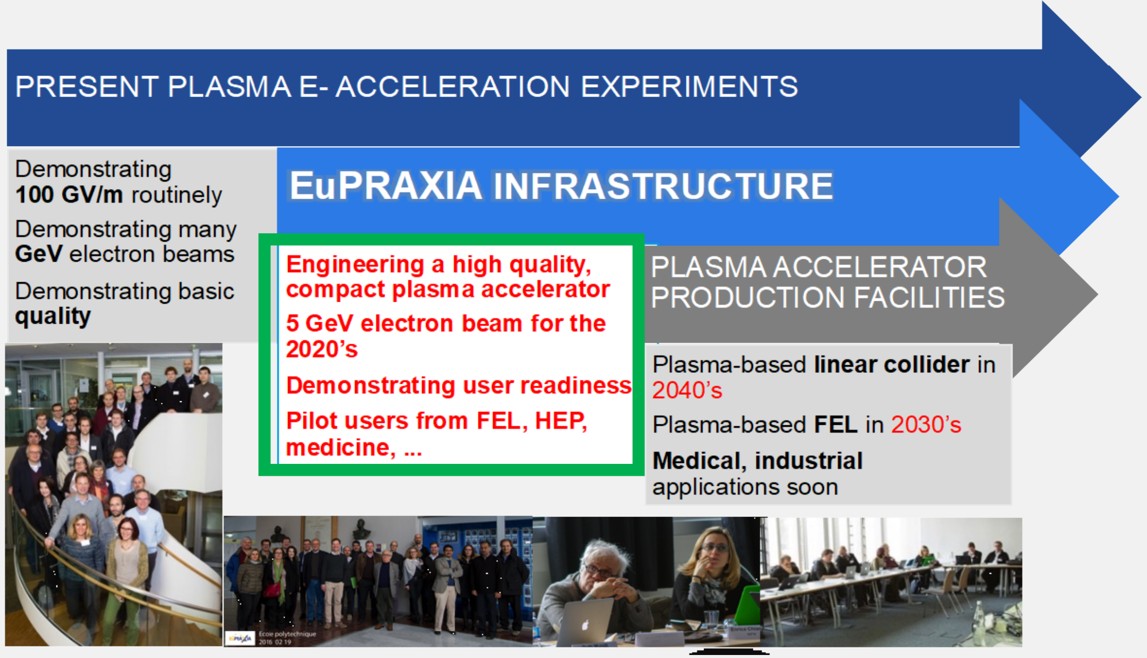
- **Personnel** – advanced accelerators attract large numbers of students and postdocs
- Existing **facilities** (with upgrades) and a few new ones (High average power, high repetition rate operation studies; fully dedicated to addressing the challenges towards a TDR for a plasma based collider)
- **High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

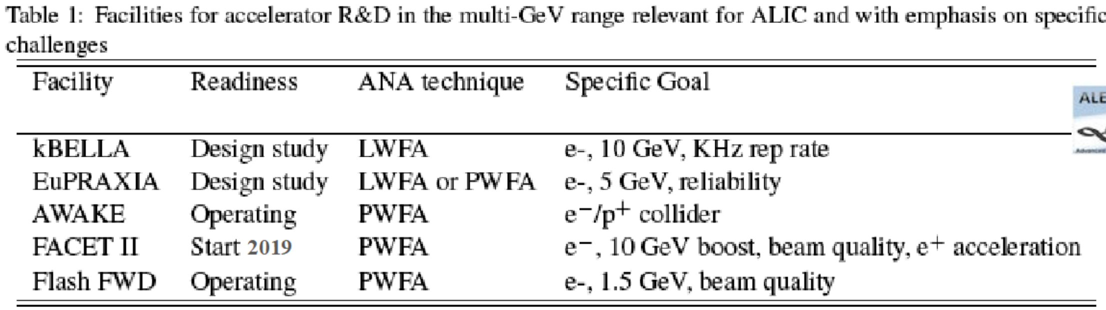


Table 1: Facilities for accelerator R&D in the multi-GeV range relevant for ALIC and with emphasis on specific challenges

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

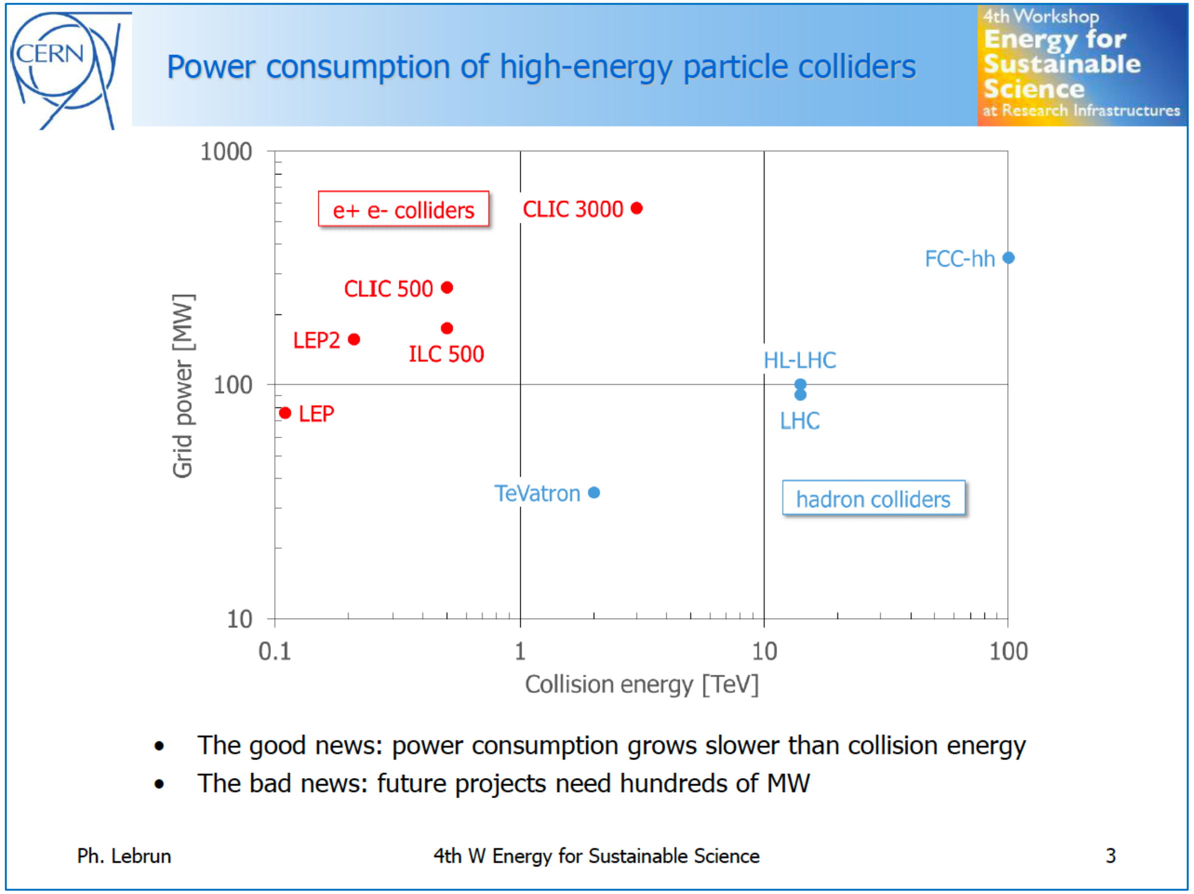
The future is in accelerating muons in plasma!

Vladimir Shiltsev

Energy management
in the age of
high-power accelerators?

Courtesy: Ph. Lebrun

Energy Efficiency and Management in Accelerators

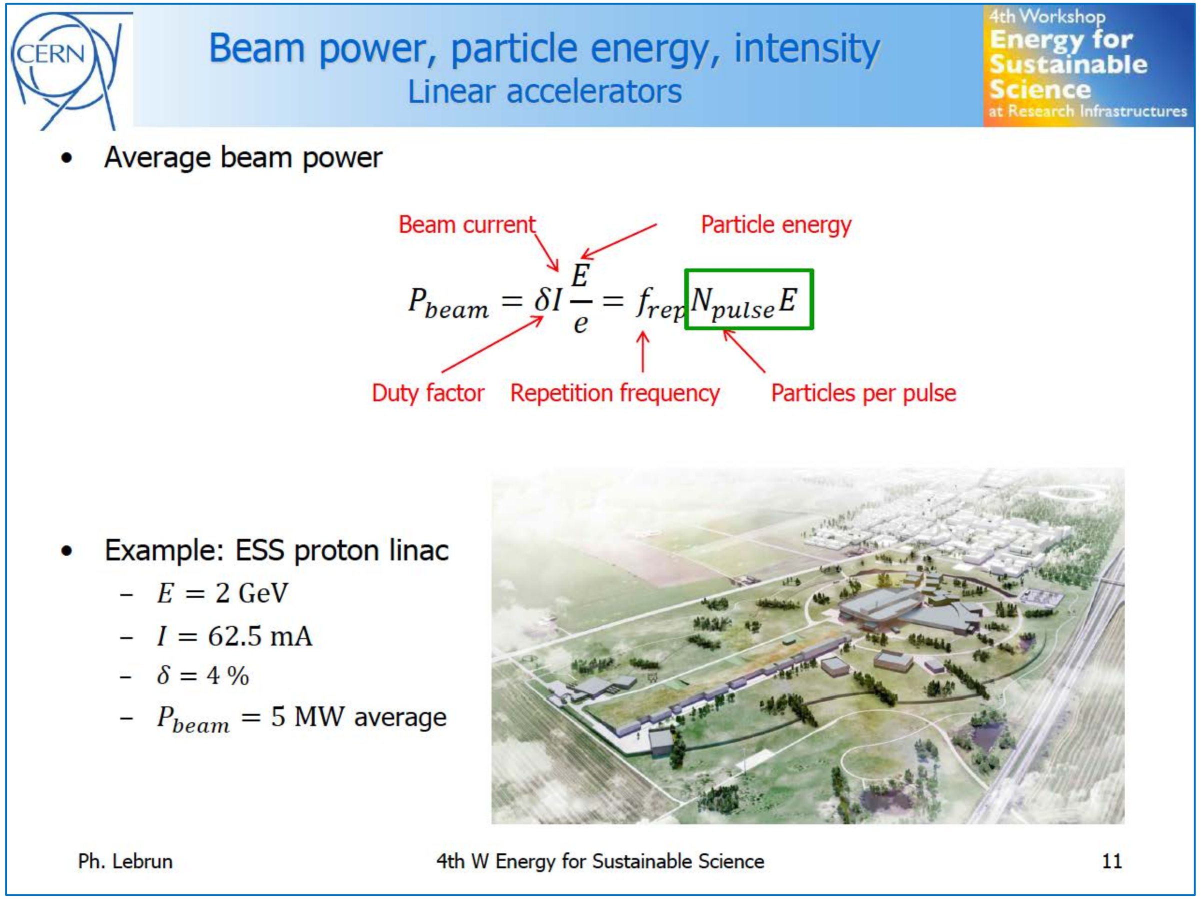


Power consumption of high-energy particle colliders

4th Workshop Energy for Sustainable Science at Research Infrastructures

- The good news: power consumption grows slower than collision energy
- The bad news: future projects need hundreds of MW

Ph. Lebrun 4th W Energy for Sustainable Science 3



Beam power, particle energy, intensity
Linear accelerators

4th Workshop Energy for Sustainable Science at Research Infrastructures

- Average beam power

Beam current Particle energy

$$P_{beam} = \delta I \frac{E}{e} = f_{rep} \boxed{N_{pulse} E}$$

Duty factor Repetition frequency Particles per pulse

- Example: ESS proton linac
  - $E = 2$ GeV
  - $I = 62.5$ mA
  - $\delta = 4\,\%$
  - $P_{beam} = 5$ MW average

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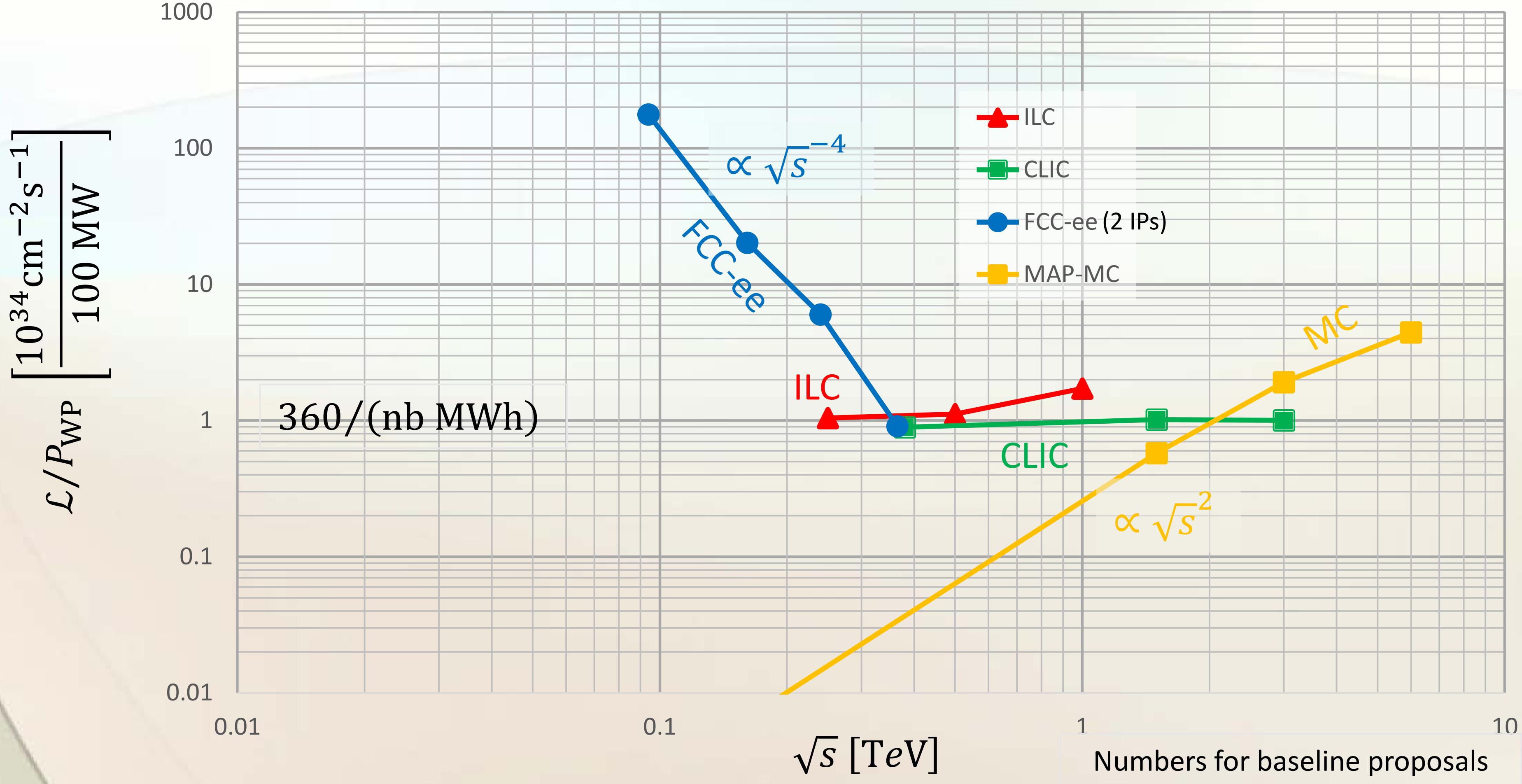
Energy Efficiency

- 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

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"*** :

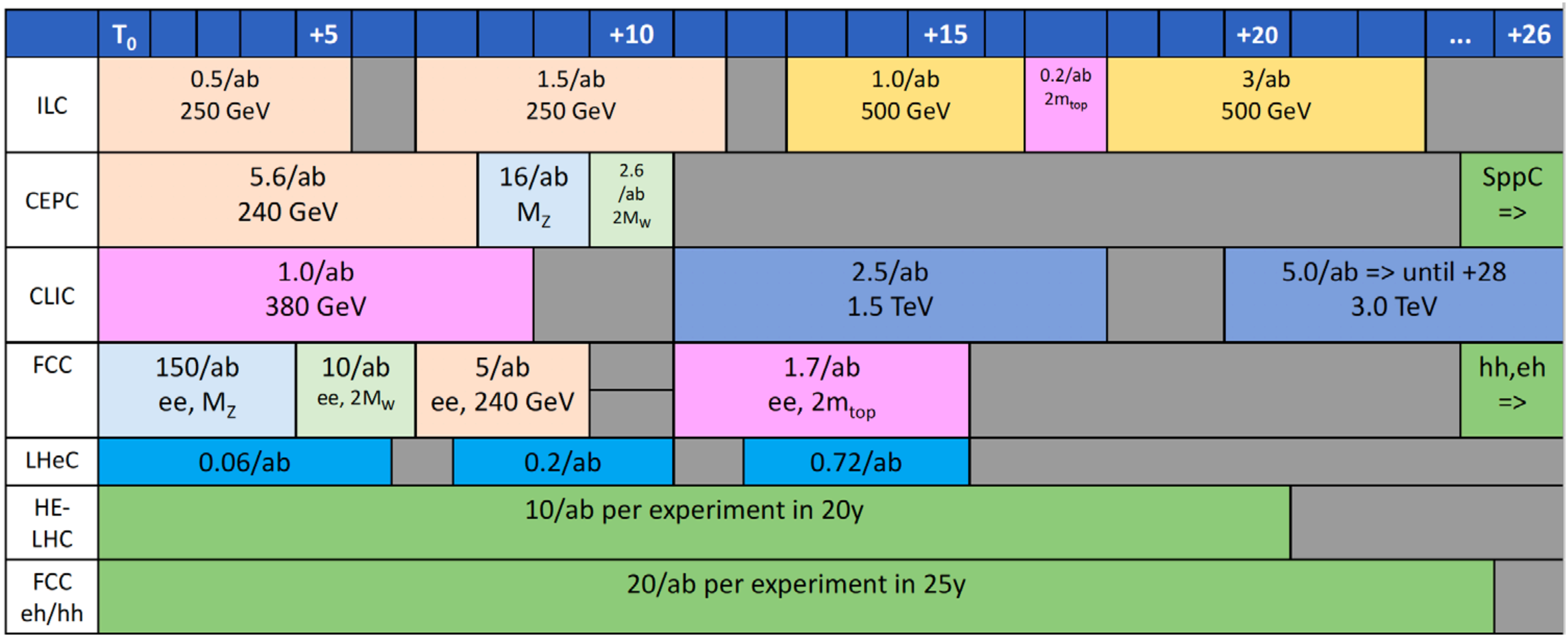
  1 Accelerator Expert

  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



T_0 … +5 … +10 … +15 … +20 … ... +26

ILC	0.5/ab 250 GeV	1.5/ab 250 GeV	1.0/ab 500 GeV	0.2/ab $2m_{top}$	3/ab 500 GeV
CEPC	5.6/ab 240 GeV	16/ab M_Z	2.6 /ab $2M_W$	SppC =>	
CLIC	1.0/ab 380 GeV	2.5/ab 1.5 TeV	5.0/ab => until +28 3.0 TeV		
FCC	150/ab ee, M_Z	10/ab ee, $2M_W$	5/ab ee, 240 GeV	1.7/ab ee, $2m_{top}$	hh,eh =>
LHeC	0.06/ab	0.2/ab	0.72/ab		
HE-LHC	10/ab per experiment in 20y				
FCC eh/hh	20/ab per experiment in 25y				

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

Goal of HL-LHC

From EC-FP7 HiLumi LHC Design Study application of 2010

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

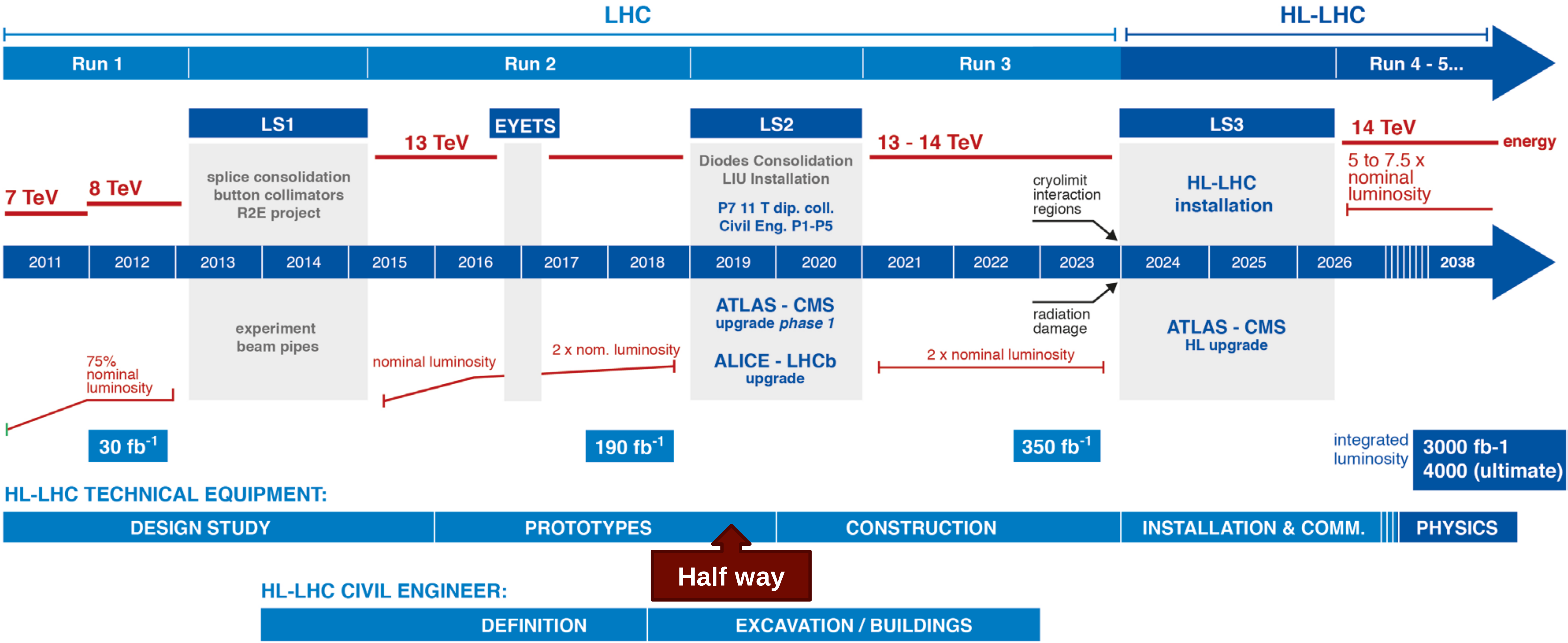
Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult} \cong 7.5\ 10^{34}$ cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult} \sim 4000$ fb^{-1}**

LHC should not be the limit, would

Experiment are designing for this goal.
We need to be compatible with it!

LHC / HL-LHC Plan



LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

LS1

EYETS

LS2

LS3

7 TeV

8 TeV

13 TeV

13 - 14 TeV

14 TeV

energy

splice consolidation
button collimators
R2E project

Diodes Consolidation
LIU Installation

P7 11 T dip. coll.
Civil Eng. P1-P5

cryolimit
interaction
regions

HL-LHC
installation

5 to 7.5 x
nominal
luminosity

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2038

experiment
beam pipes

ATLAS - CMS
upgrade *phase 1*

ALICE - LHCb
upgrade

radiation
damage

ATLAS - CMS
HL upgrade

75%
nominal
luminosity

nominal luminosity

2 x nom. luminosity

2 x nominal luminosity

30 fb^{-1}

190 fb^{-1}

350 fb^{-1}

integrated
luminosity

3000 fb-1
4000 (ultimate)

HL-LHC TECHNICAL EQUIPMENT:

DESIGN STUDY | PROTOTYPES | CONSTRUCTION | INSTALLATION & COMM. | PHYSICS

Half way

HL-LHC CIVIL ENGINEER:

DEFINITION | EXCAVATION / BUILDINGS

Many thanks for the contributions from:

Akira Yamamoto
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and all participants in the discussions at the Granada Symposium

Finding *Common Denominators* * – Three Factors

** to be further discussed in the Symposium’s accelerator sessions*

- ***F1*** **“Technology Readiness” :**

  Green - TDR
  Yellow - CDR
  Red - R&D

- ***F2*** **“Energy Efficiency”**

  Green : 100-200 MW
  Yellow : 200-400 MW
  Red : > 400 MW

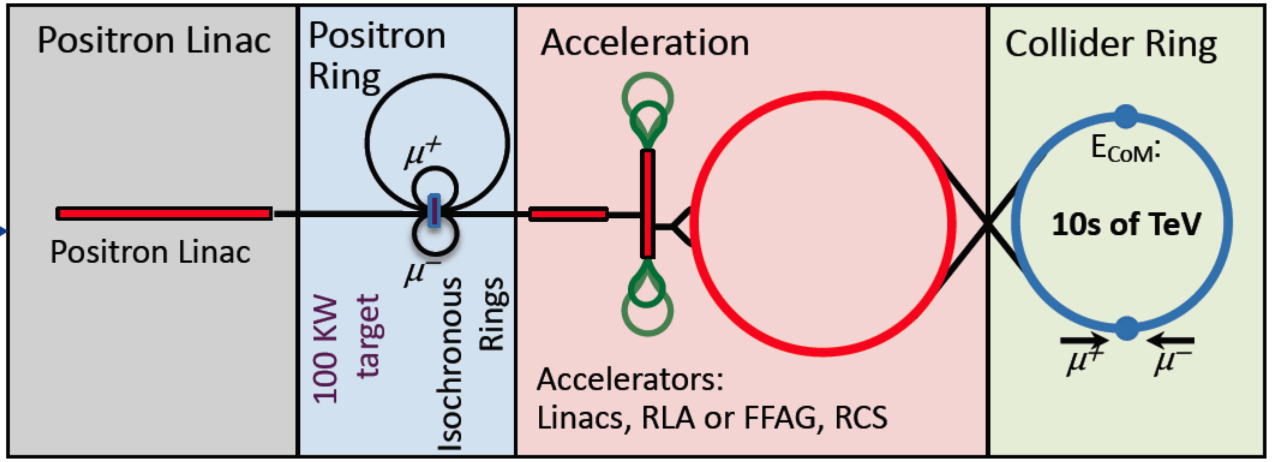
- ***F3*** **“Cost” :**

  Green : < LHC
  Yellow : 1-2 x LHC
  Red : > 2x LHC

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*	🟥	🟨	🟩🟨 *

The LEMMA Scheme

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



Key concept (original numbers in brackets)

Produce muon beam with low emittance using a positron beam (40 nm vs. 25 µm in proton scheme)

- No cooling required, use lower muon current

- Positron beam (45 GeV, 3×10^{11} particles every 200 ns) passes through target and produces muon pairs
- Muon bunches are circulated through target O(2000) times accumulating more muons (4.5×10^{7})
- Every 0.5 ms, the muon bunches are extracted and accelerated
- They are combined in the collider ring, where they collide

Key Issues

Small efficiency of converting positrons to muon pairs

- Muon pair production is only small fraction of overall cross section ($O(10^{-5})$)
- Most positrons lost with no muon produced
- Have to produce many positrons (difficult)
- O(100MW) synchrotron radiation
- High heat load and stress in target (also difficult)

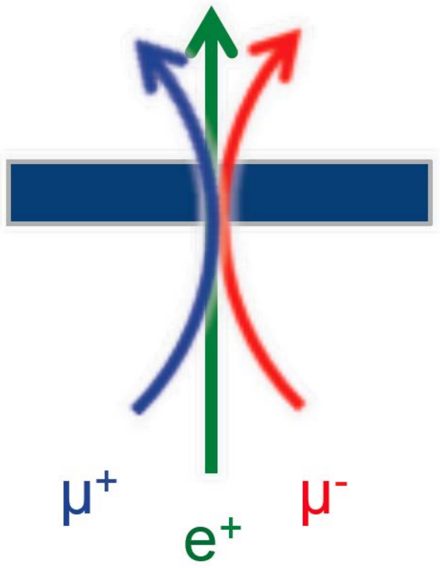
$$e^+e^- \to \mu^+\mu^- \quad O(1\mu b)$$

$$e^+e^- \to e^+e^-\gamma$$

O(100mb), $E_\gamma \geq 0.01\, E_p$

Two additional severe issues were identified

- The multiple scattering of the muons in the target
  - Theoretical best emittance of 600 nm instead of assumed 40 nm
  - Reduction of luminosity by factor 15
- Small bunches were accelerated and later merged but no design exists for the merger
  - The combination factor is proportional to beam energy
  - If the combination does not work, loose a large factor of luminosity



Working on a better design but have to wait and see the outcome

Ongoing LEMMA Effort

Address found issues

- Large emittance from target
    - use sequence of thin targets
- Difficulty of combining bunches at high energy
    - producing bunches in pulses fashion
- Positron ring challenge
    - larger ring
- Positron production
    - Improved concepts

Did not yet reach competitive performance

- but work is ongoing