Prospect in Accelerators

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WIN 2019

Bari, 4 June 2019

Future Accelerators for the EU- Strategy

A comprehensive review of future accelerators for High Energy Physics
has been presented at the **European Strategy for Particle Physics**
13-16 May 2019 in Granada

In the following I will summarize the material from the meeting

Thanks to all the speakers:
Caterina Biscari and Lenny Rivkin, Phil Burrows, Frank Zimmermann
Akira Yamamoto, Vladimir Shiltsev, Lucio Rossi, Michael Benedikt, Steinar Stapnes, Daniel Schulte, Erk Jensen, Edda Gschwendtner, Wim Leemans, Mike Lamont

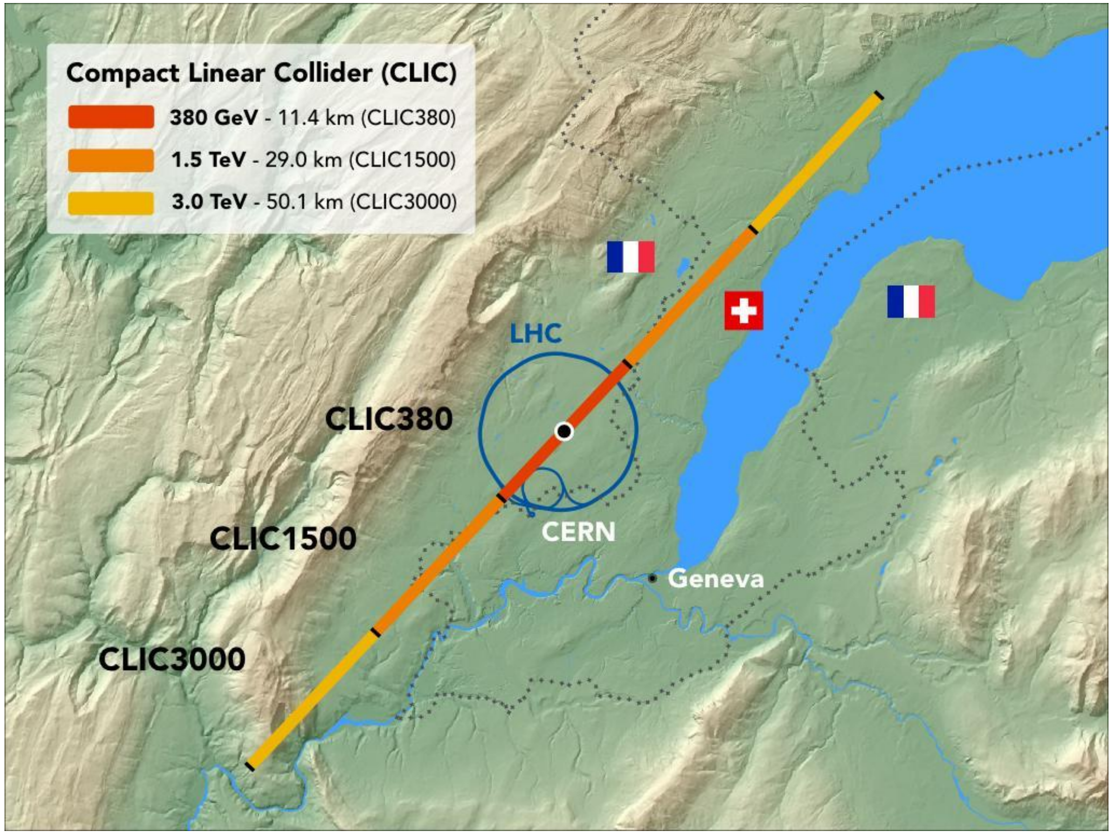
Big Questions

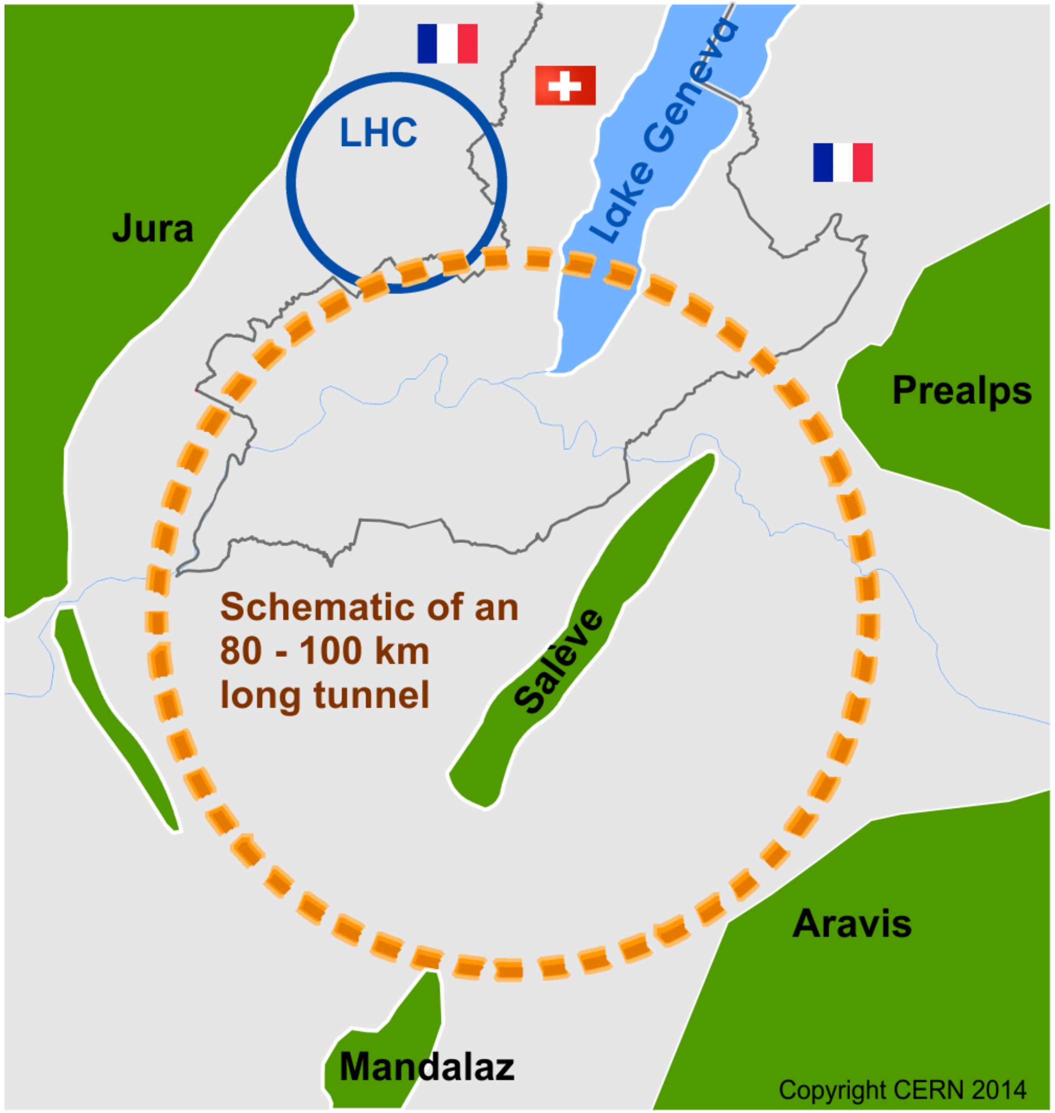
In particular for the Accelerator Science and Technology

- **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?**

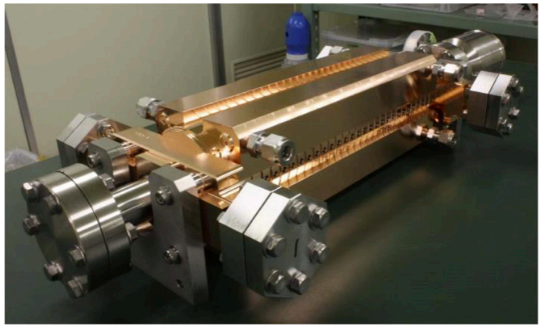
Caterina Biscari

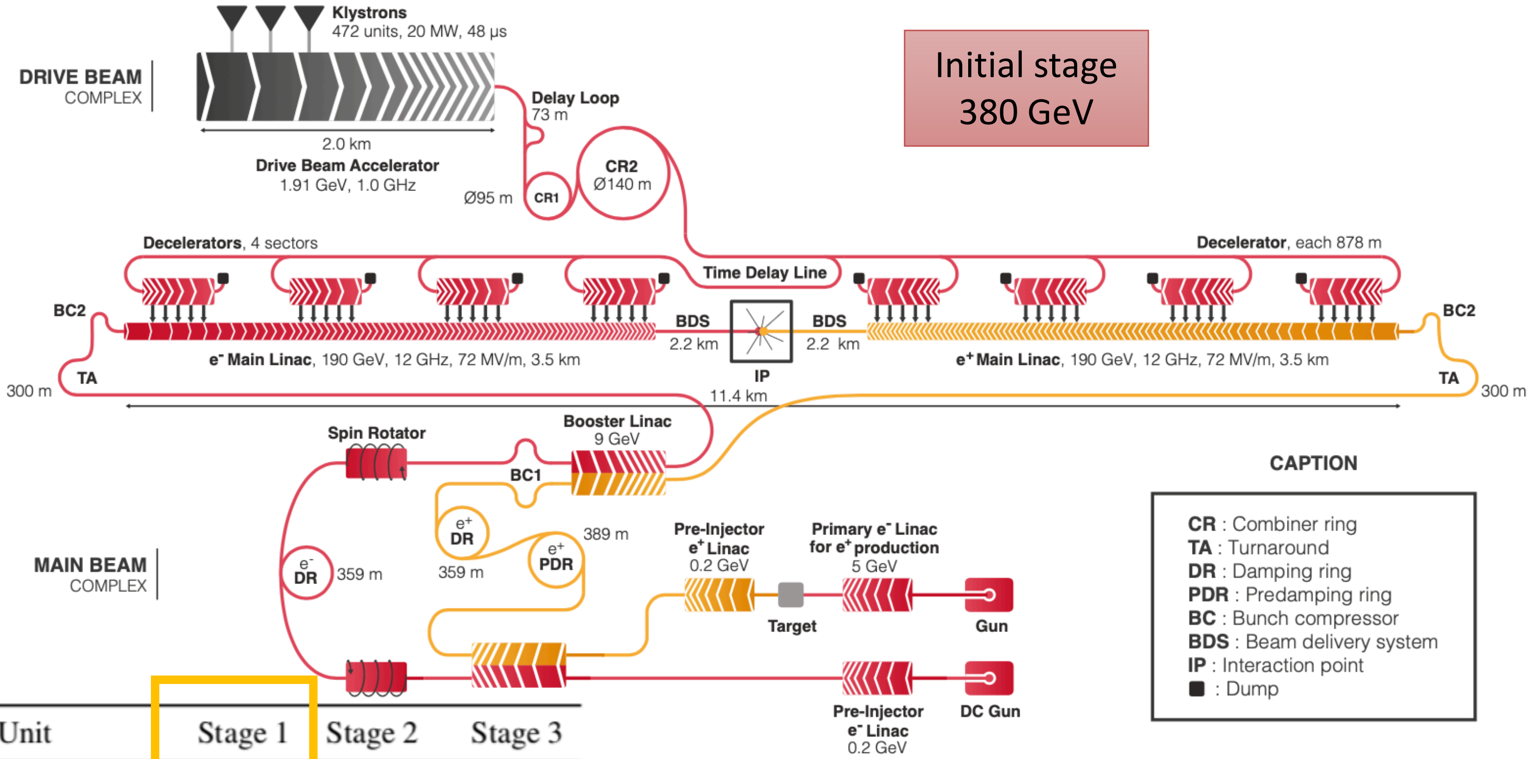
Q1: What is the best implementation for a Higgs factory? Choice and challenges for accelerator technology: linear vs. circular?





CLIC
X-Band NCRF





Initial stage
380 GeV

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2} s^{-}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2} s^{-}	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\text{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	~ 60/1.5	~ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

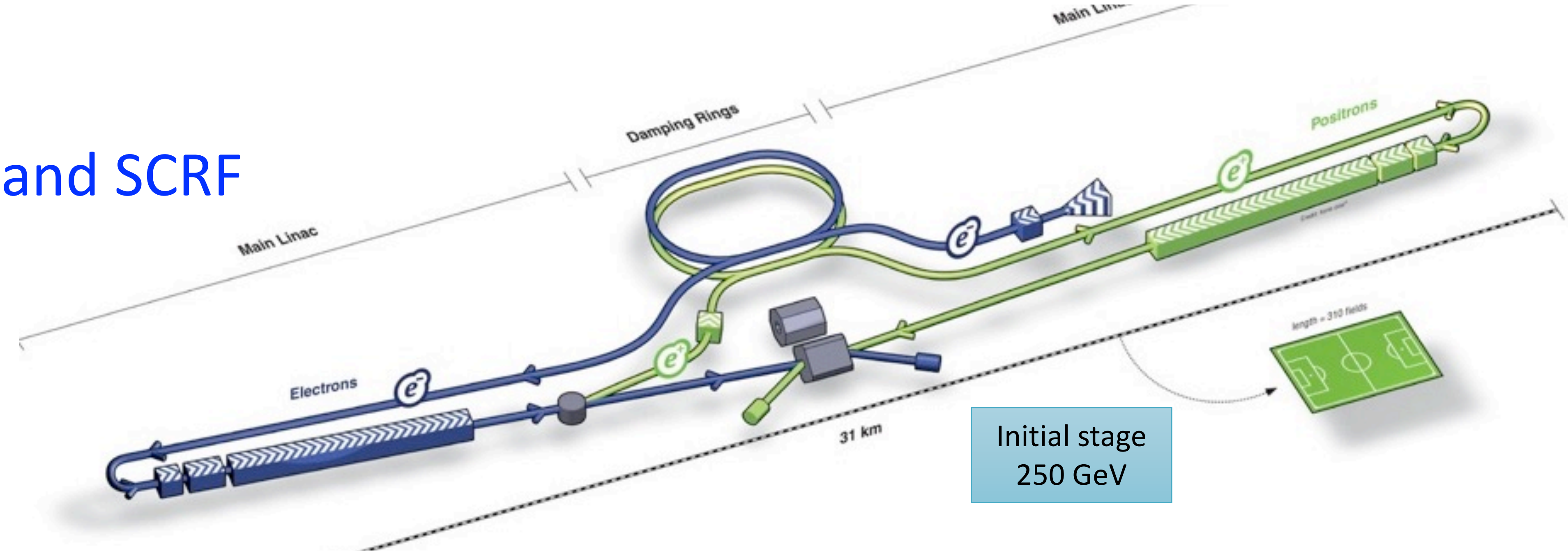
Normal Conductng RF NCRF:
Higher Gradient - Higher energy reach, shorter facility

Strategy Documents:
https://clic.cern/european-strategy

CLIC CDR 2012
https://cds.cern.ch/record/1500095/files/CERN-2012-007.pdf

Updated baseline for a staged CLIC 2016
https://arxiv.org/abs/1608.07537

ILC
L-Band SCRF

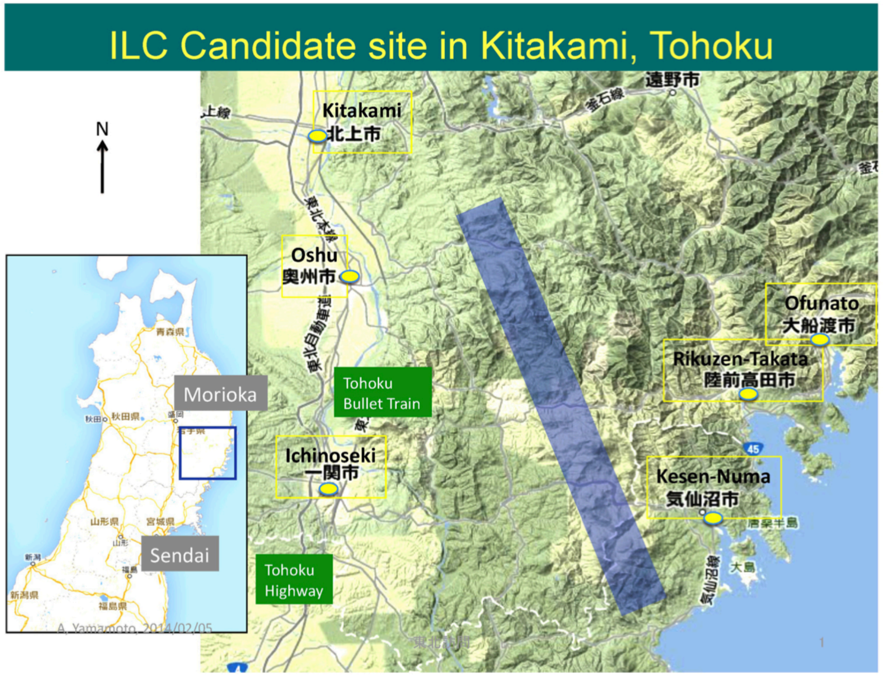


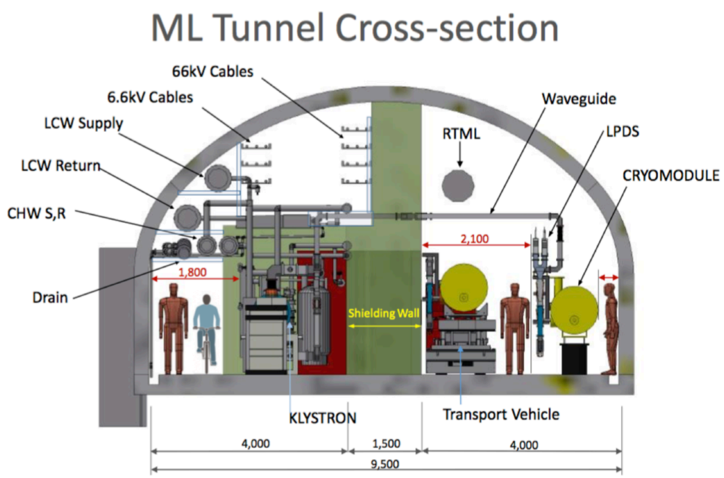
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	TDR	Upgrades	
Centre of mass energy	$\sqrt{s}$	GeV	250	250	250	500	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.82	1.8/3.6	4.9
Polarisation for $e^-(e^+)$	$P_-(P_+)$		80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(30 %)	80 %(20 %)
Repetition frequency	f_{rep}	Hz	5	5	5	5	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312	1312/2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554	554/366	366
Beam current in pulse	I_{pulse}	mA	5.8	5.8	8.8	5.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727	727/961	897
Average beam power	P_{ave}	MW	5.3	10.5	10.5	10.5/21	27.2
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	729	474	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	7.7	5.9	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	87.1 %	58.3 %	44.5 %
Energy loss from beamstrahlung	δ_{BS}		2.6 %	2.6 %	0.97 %	4.5 %	10.5 %
Site AC power	P_{site}	MW	129		122	163	300
Site length	L_{site}	km	20.5	20.5	31	31	40

Strategy Documents:
https://ilchome.web.cern.ch/content/ilc-european-strategy-document
ILC Staging Report 2017
https://arxiv.org/abs/1711.00568

ILC TDR 2013 http://www.linearcollider.org/ILC/Publications/Technical-Design-Report

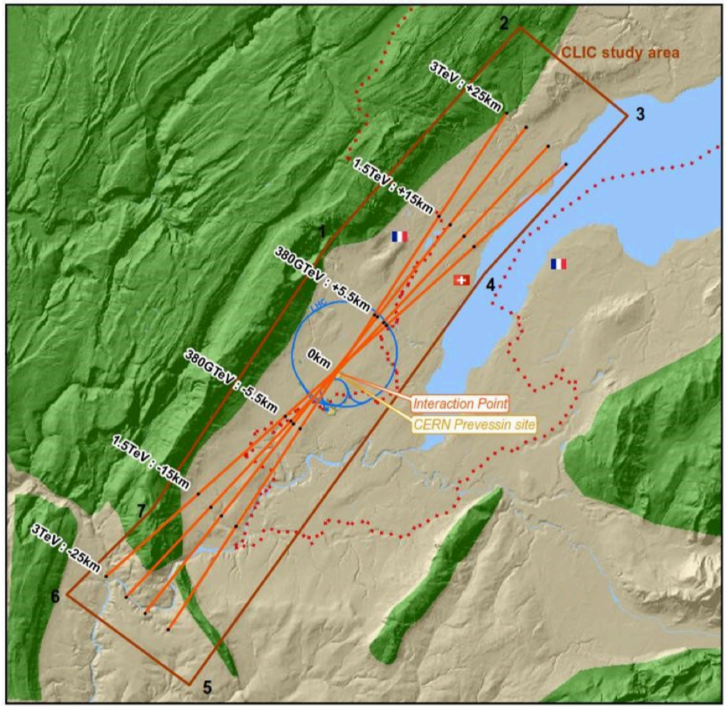
ILC in Japan

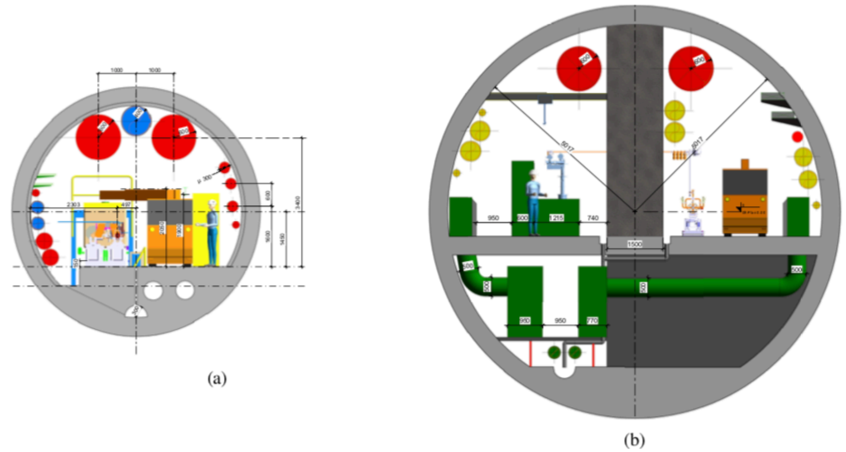




Extensive studies of civil engineering, local layout of accelerator and lab, general and specific infrastructure for the Kitakami site

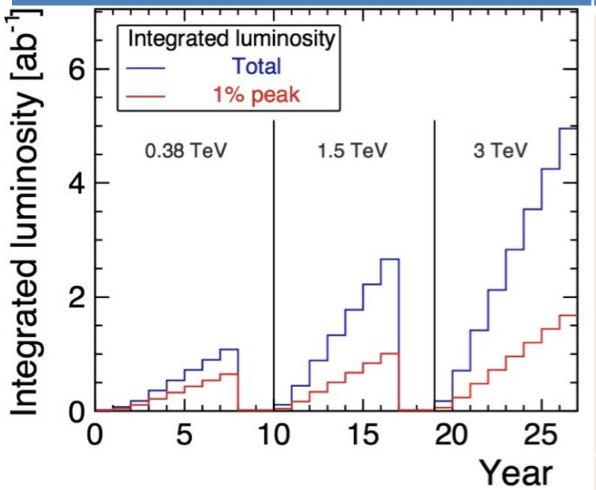
CLIC at CERN



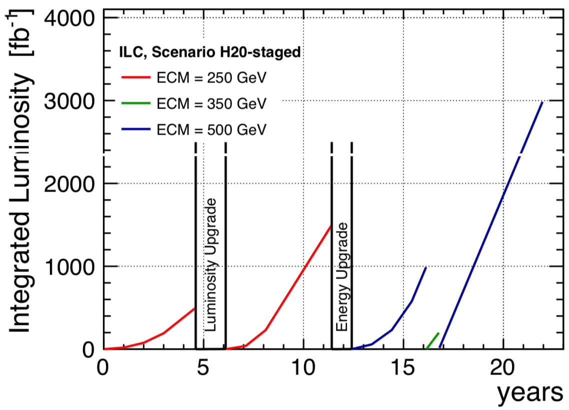


Studies of: Civil engineering, Electrical systems, Cooling and ventilation, Transport, logistics and installation, Safety, access and radiation protection systems. Crucial for cost/power/schedule

Overview of CLIC and ILC parameters



CLIC y: 75% of 180 days



ILC y: 75% of 240 days

CLIC parameters	ILC 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**	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
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 (SACLA, 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 Q and gradient

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)

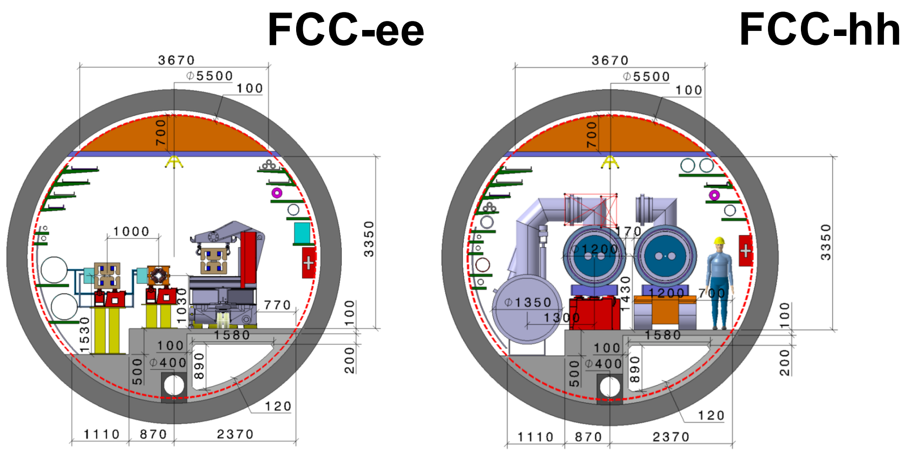
* Doubling by increasing frequency (to be) studied, ** Power at 1.5 and 3 TeV not updated from CDR 2012

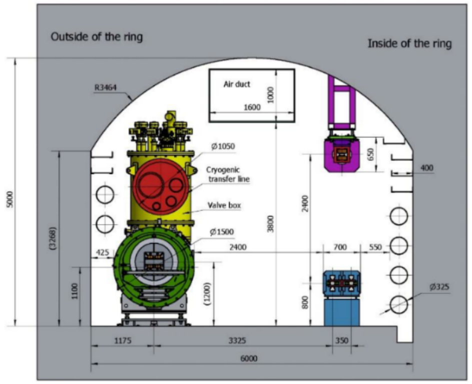
Steinar Stapnes

FCC-ee and CEPC – lepton energy frontier

double ring e^+e^- colliders as Z, W, H and t factory at $E_{c.o.m.}$ of 90 - 365 GeV; As Higgs factory: **design luminosities 17 (6) x 10^{34} $cm^{-2}s^{-1}$** (2 IPs) ; **β_y^*= 1.0 (1.5) mm; crab waist** collision scheme; **beam lifetime >12 minutes**; **top-up** injection, **e^+ rate ~ $1x10^{11}$ /s** ; **CDRs complete**

- **FCC-ee and CEPC are part of integrated proposals and each followed by a hadron collider with common footprint.**
- **Circumference** ~100 km
- **Presently 2 IPs,** alternatives with 3 / 4 IPs under study
- **Synchrotron radiation power 50 (30) MW/beam** at all beam energies, cf. LEP2 with 11 MW/beam; SR power/length ~factor 10 below light sources
- **Top-up injection** scheme requires **booster synchrotron in collider tunnel**

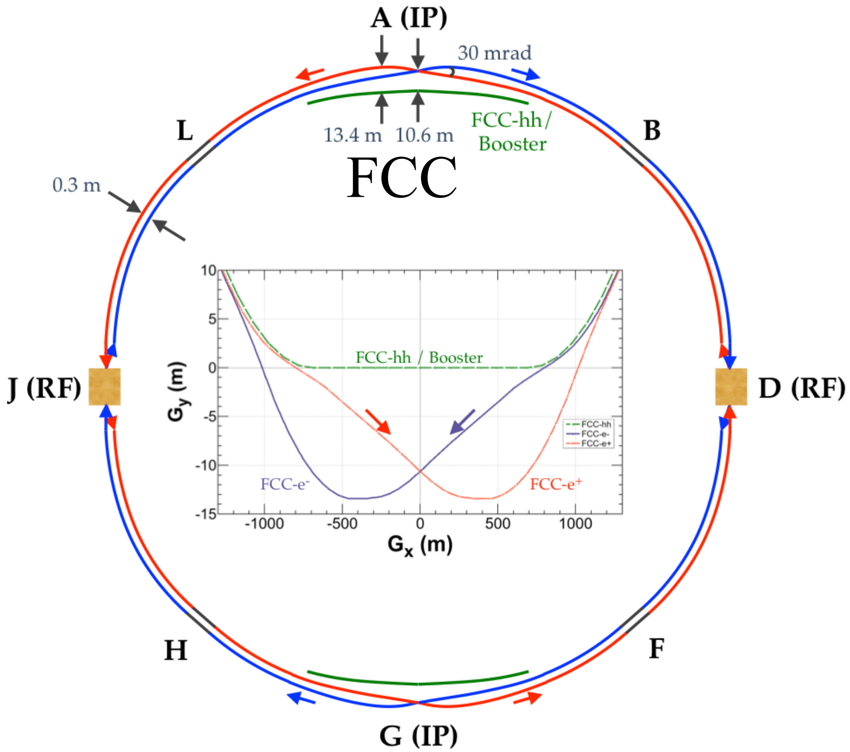




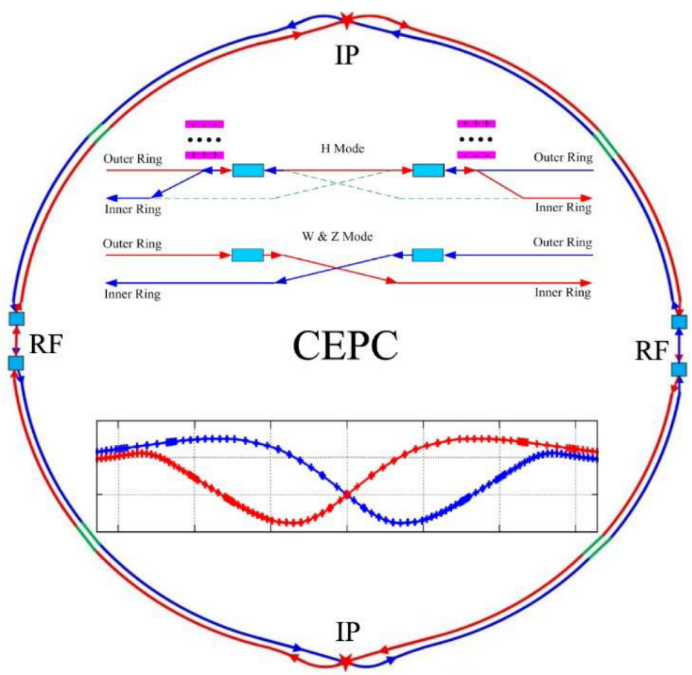
values in brackets refer to CEPC

similar solutions for FCC-ee and CEPC

- **Double ring** colliders with full-energy **top-up booster** ring,
- **CEPC evolved** from initial 54 km - single-ring design, practically **to the FCC-ee 100 km design**.
- **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)



FCC CDR https://fcc-cdr.web.cern.ch/



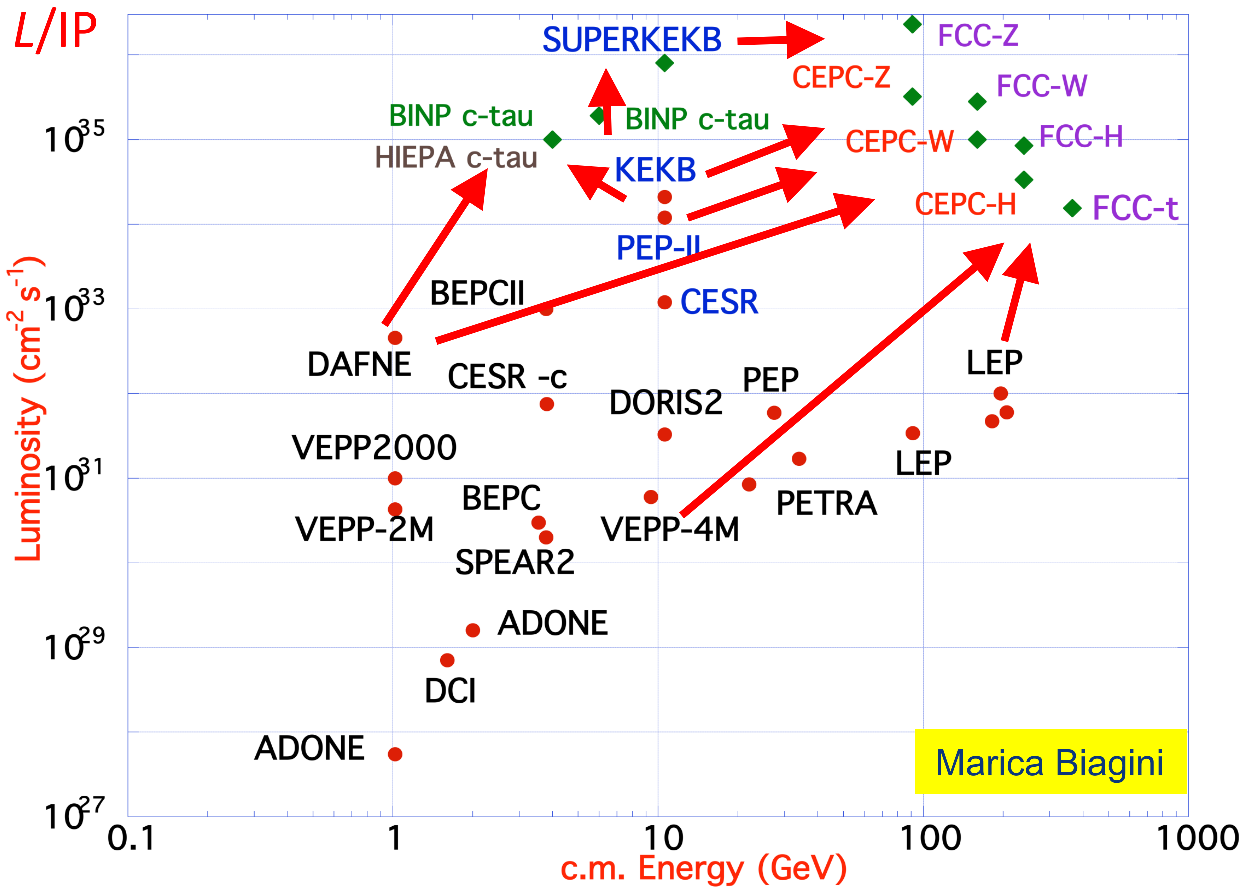
CEPC CDR https://arxiv.org/abs/1809.00285

key parameters of future circular e^+e^- colliders

Collider (all double rings)	Beam energy [GeV]	Peak luminosity (per IP) [10^{34} cm^{-2}s^{-1}]	β_y^* [mm]	beam current [mA]	Collision scheme	Beam lifetime [min]	e^+ top-up rate [10^{11}/s]
SuperKEKB	4 (e^+), 7 (e^-)	**80**	**0.3**	**3600 (e^+), 2600 (e^-)**	**Nano-beam**	**<5**	**10**
BINP c-t	1-3	**5-20**	**0.5**	**2200**	**Crab waist**	**<10**	**1**
HIEPA c-t	1.5-3.5	**~10**	**0.6**	**2000**	**Crab waist**	**<10**	**1**
FCC-ee (Z)	45.6	**230**	**0.8**	**1500**	**Crab waist**	**68**	**7**
FCC-ee (H)	120	**8.5**	**1.0**	29	**Crab waist**	**12**	**1**
FCC-ee (t)	182.5	1.6	**1.6**	5	**Crab waist**	**12**	**0.2**
CEPC (Z)	45.5	**32**	**1.0**	**460**	**Crab waist**	150	**1.1**
CEPC (H)	120	3	**1.5**	17	**Crab waist**	**26**	**0.2**

Many similar parameters and strong synergies for design

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



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

DAFNE: crab waist, double ring

Super B-factories, S-KEKB: low β_y*

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

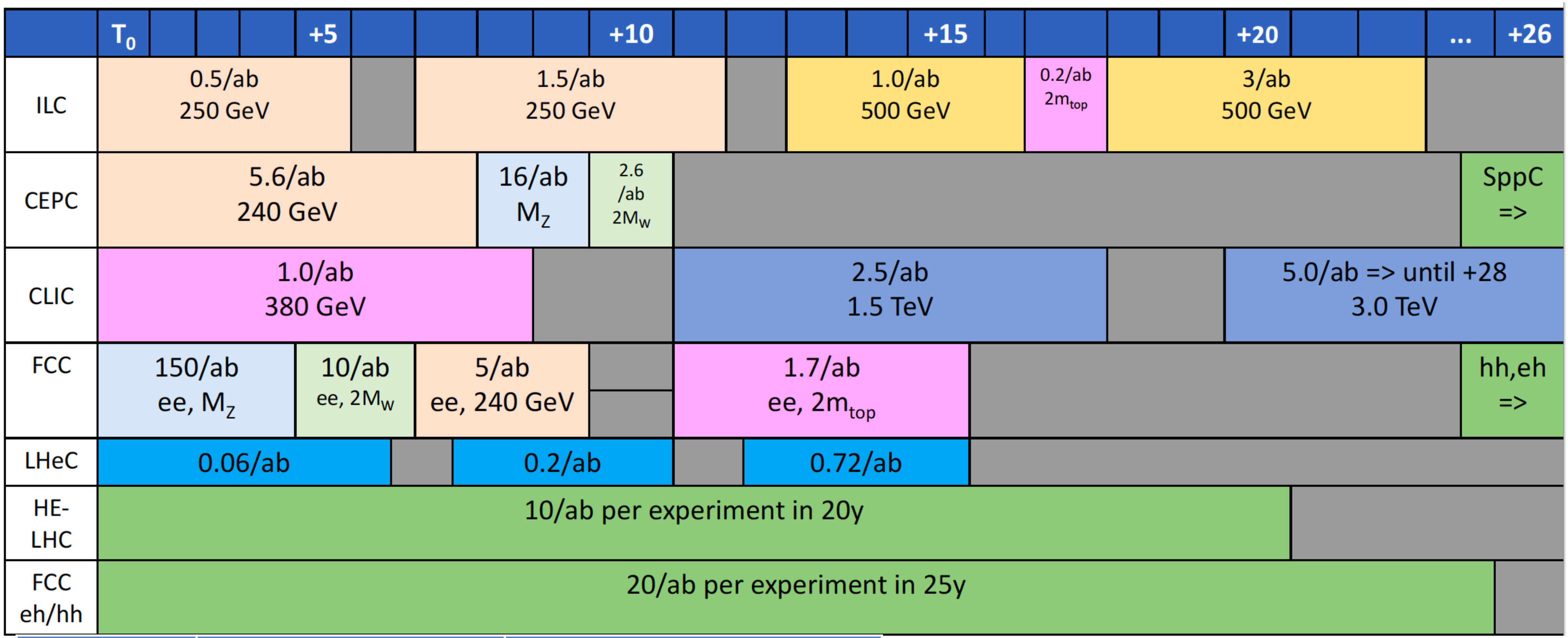
HERA, LEP, RHIC: spin gymnastics

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

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



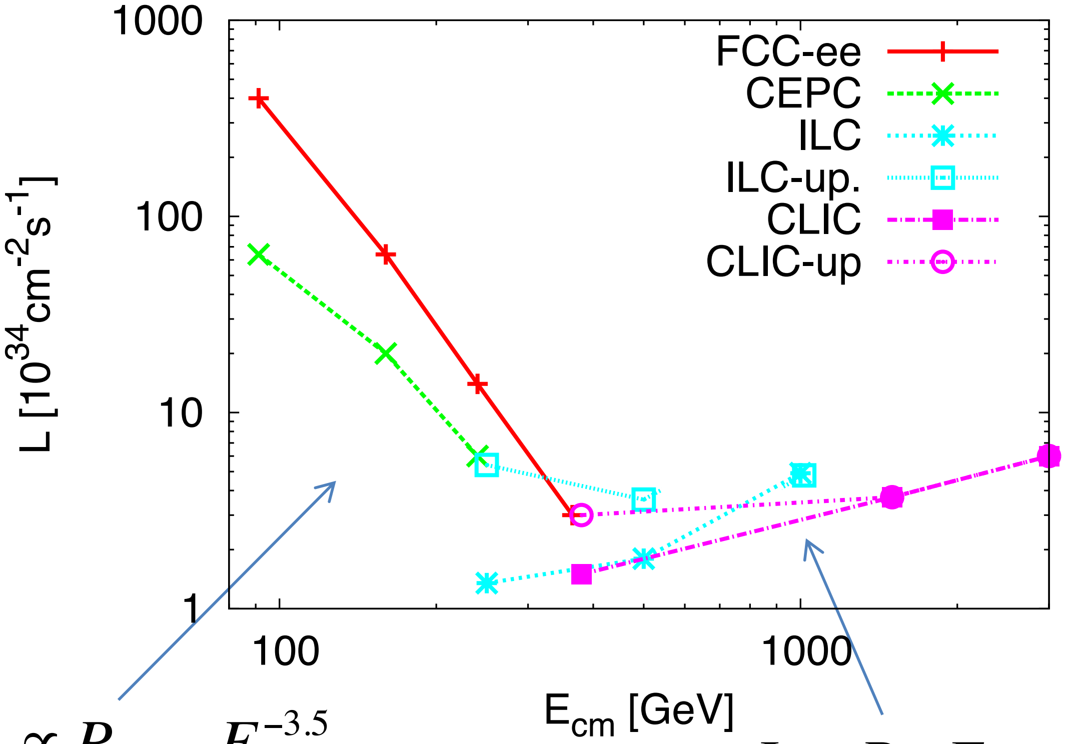
Project	Start construction	Start Physics (higgs)
CEPC	2022	2030
ILC	2024	2033
CLIC	2026	2035
FCC-ee	2029	2039 (2044)
LHeC	2023	2031

Proposed dates from projects

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

Luminosity

Luminosity per facility



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

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

Energy dependence:

At low energies circular colliders trump

- Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel

- Luminosity per beam power roughly constant

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

Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung

- All included in the physics studies

The picture is much clearer at lower or higher energies

Luminosity 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 fully 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.**

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

Circular hadron colliders: FCC-hh and SppC

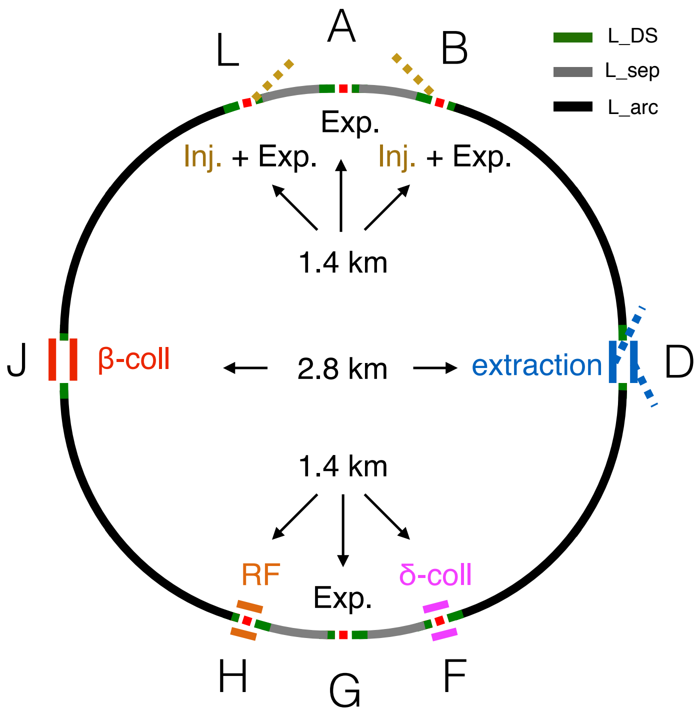
circumference ~100 km, two high-luminosity experiments up to 3 (1) x 10^{35} $cm^{-2}s^{-1}$, two additional experiments possibly combined with injection section, collimation insertions (betatron and momentum cleaning), extraction/dump insertion, RF insertion

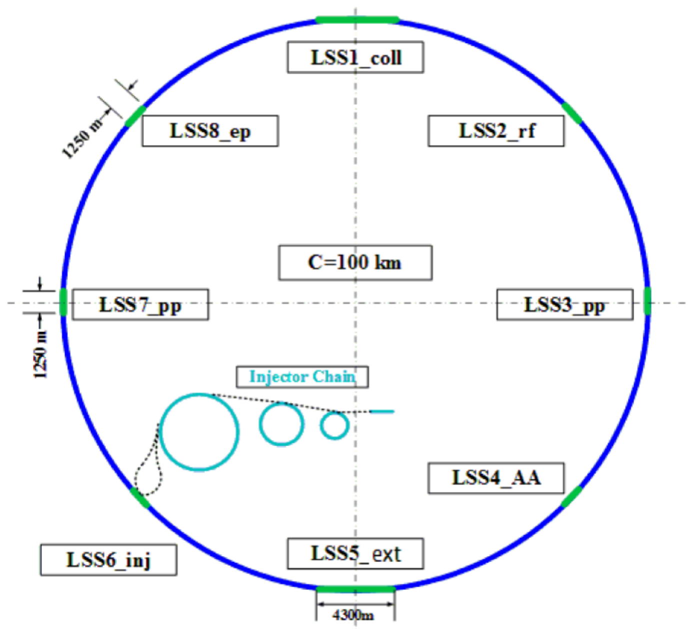
values in brackets refer to SppC

FCC-hh

based on existing CERN injector chain,

Luminosity goal ~20 ab-1 per main IP within 25 years





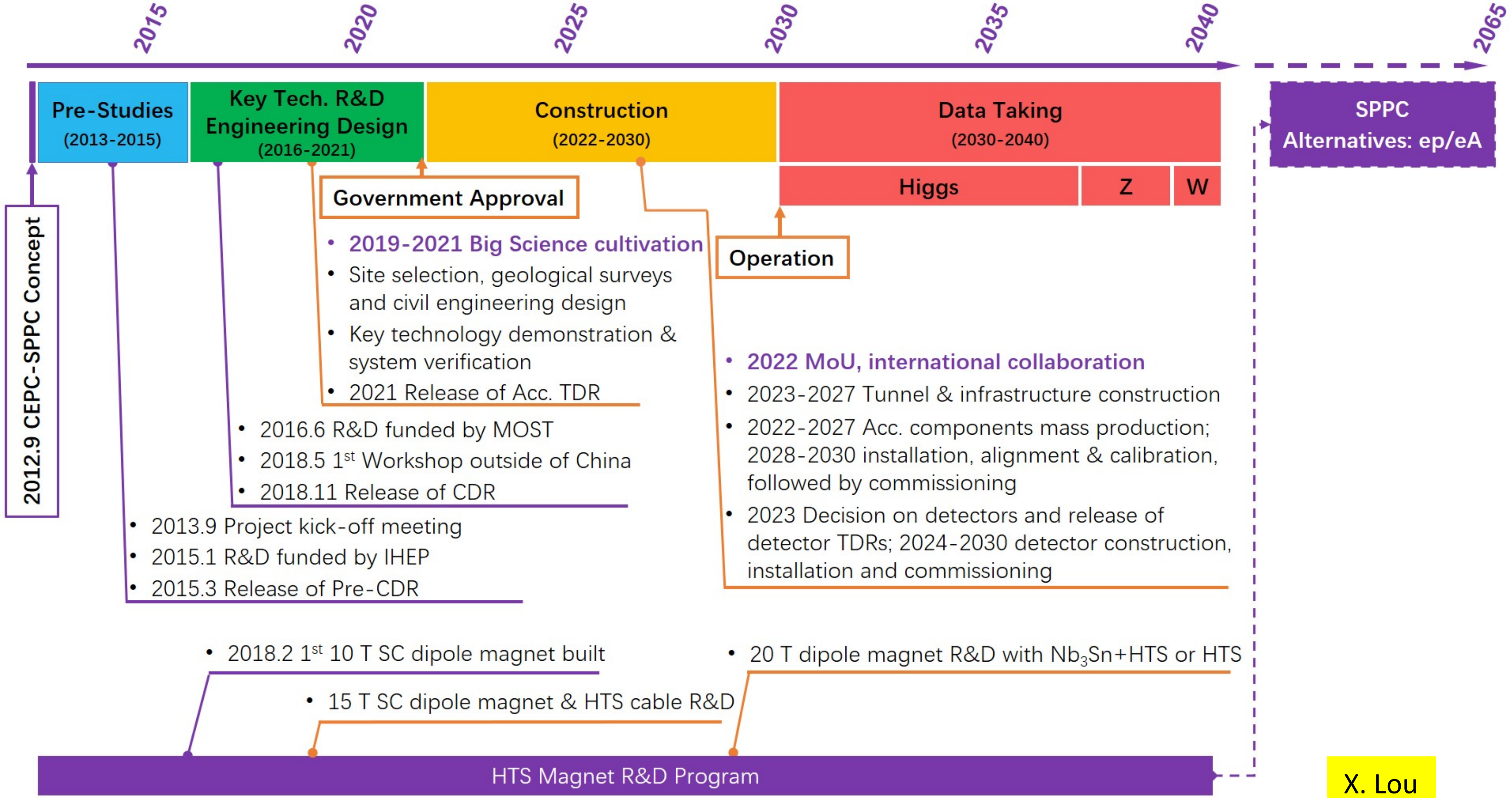
SppC

new injector chain,

simultaneous operation with e+e- collider

parameter	FCC-hh		SppC
collision energy cms [TeV]	100		75
dipole field [T]	16		12
beta* [m]	1.1	0.3	0.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	10

CEPC-SppC timeline



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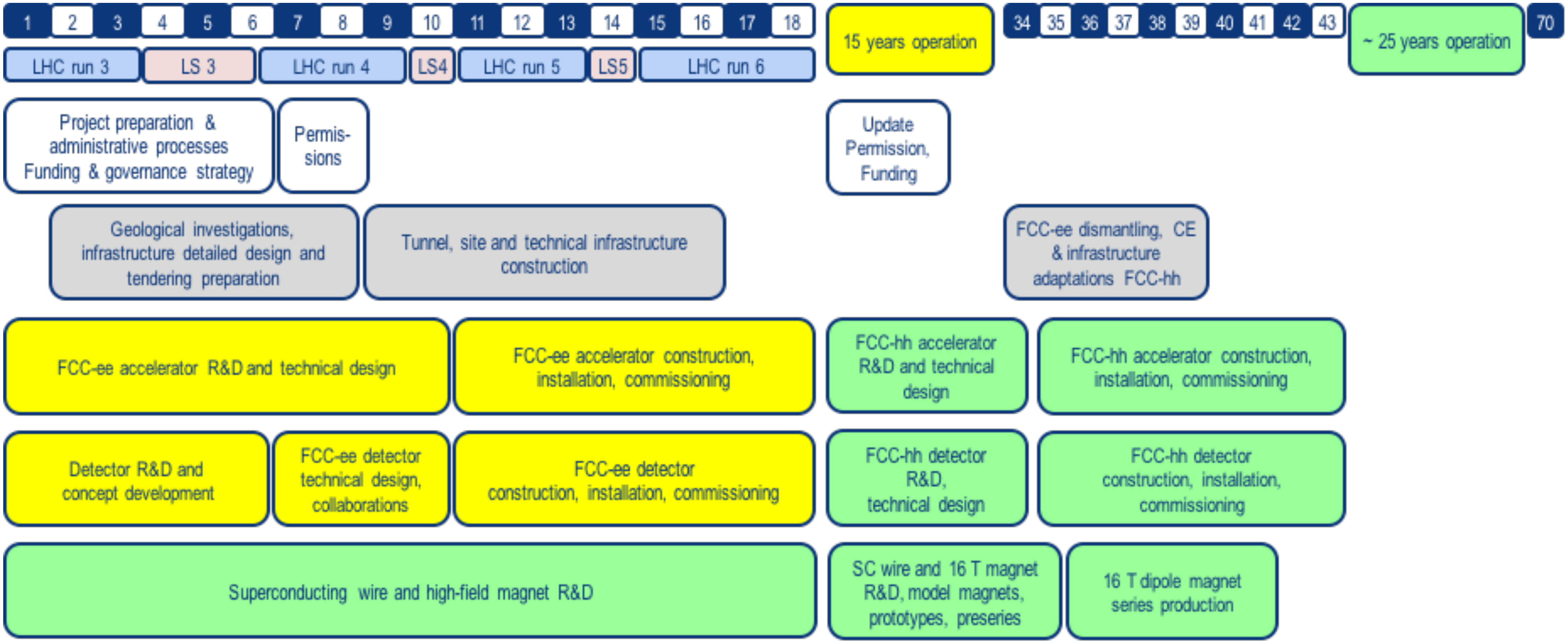
FCC integrated project technical schedule



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

HE-LHC

- **21 TeV c.m.** with **12 T** dipoles, Hi-Lumi SC, ready for installation 2035-2040
- **27 TeV c.m.** 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!)

The 25 y LHC construction time line possible only 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)

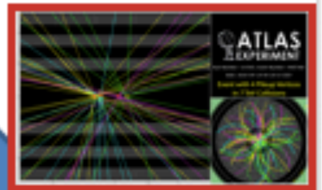
7 years from start R&D to 1st industry proto

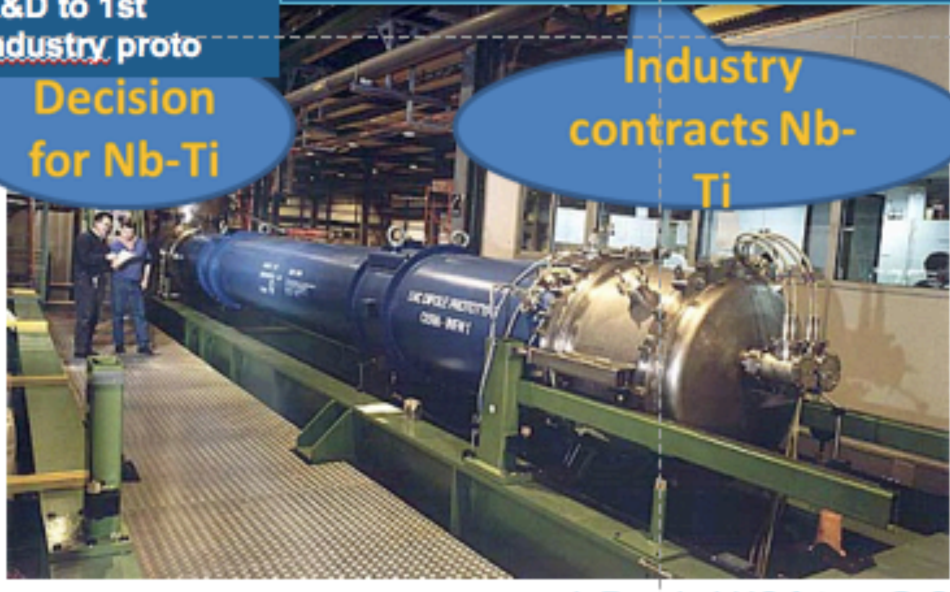
12 y from first working prototype to last magnet

Decision for Nb-Ti

Industry contracts Nb-Ti

LHC start-up





HiLumi HL-LHC PROJECT

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 View on Relative Timelines

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

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

A. Yamamoto, 190513bb

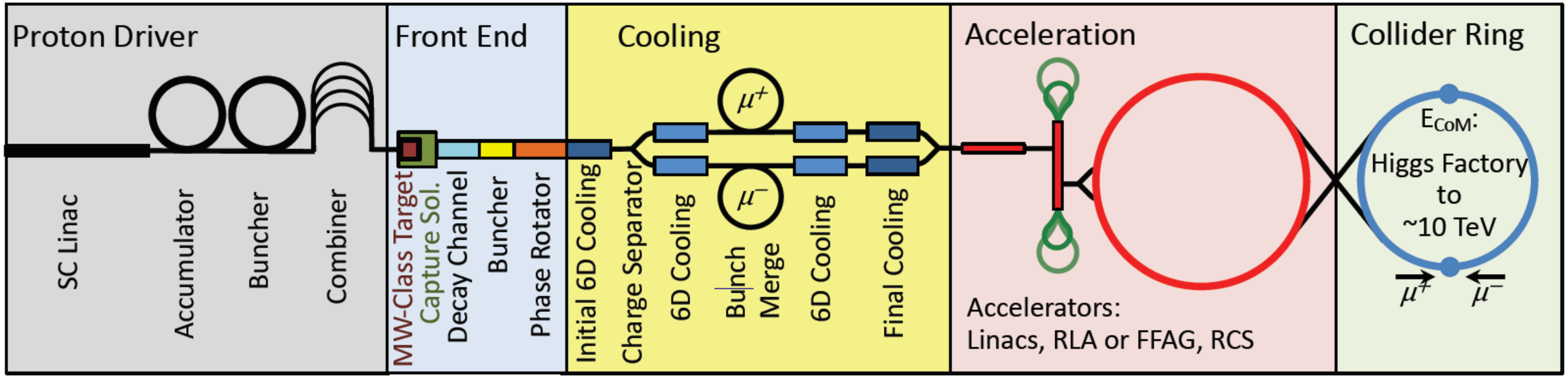
Technical Challenges in Energy-Frontier Colliders proposed

		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 (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 (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

A. Yamamoto, 190513bb

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

Proton-driven Muon Collider Concept



Acceleration to collision energy

Collision

Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled

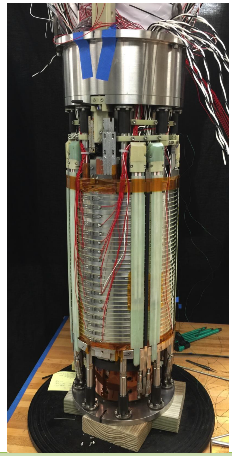
Pions decay into muons that can be captured

Ref. to MAP studies

Tests

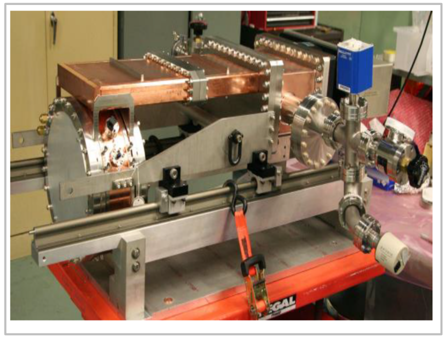
FNAL
Breakthrough in HTS cables

NHFML
32 T solenoid with low-temperature HTS



FNAL
12 T/s HTS
0.6 T max

MuCool: >50MV/m in 5 T field



Mark Palmer

- ✓ 6D Ionization Cooling Designs
  - Designs in hand that meet performance targets in simulations with stochastic effects
  - Ready to move to engineering design and prototyping
  - Able to reach target performance with Nb_3Sn conductors (NO HTS)
- ✓ RF operation in magnetic field (MTA program)
  - Gas-filled cavity solution successful and performance extrapolates to the requirements of the NF and MC
  - Vacuum cavity performance now consistent with models
  - MICE Test Cavity significantly exceeds specified operating requirements in magnetic field
- ✓ MICE Experiment data now in hand
- ✓ Final Cooling Designs
  - Baseline design meets Higgs Factory specification and performs within factor of 2.2× of required transverse emittance for high energy MC (while keeping magnets within parameters to be demonstrated within the next year at NHMFL).
  - Alternative options under study

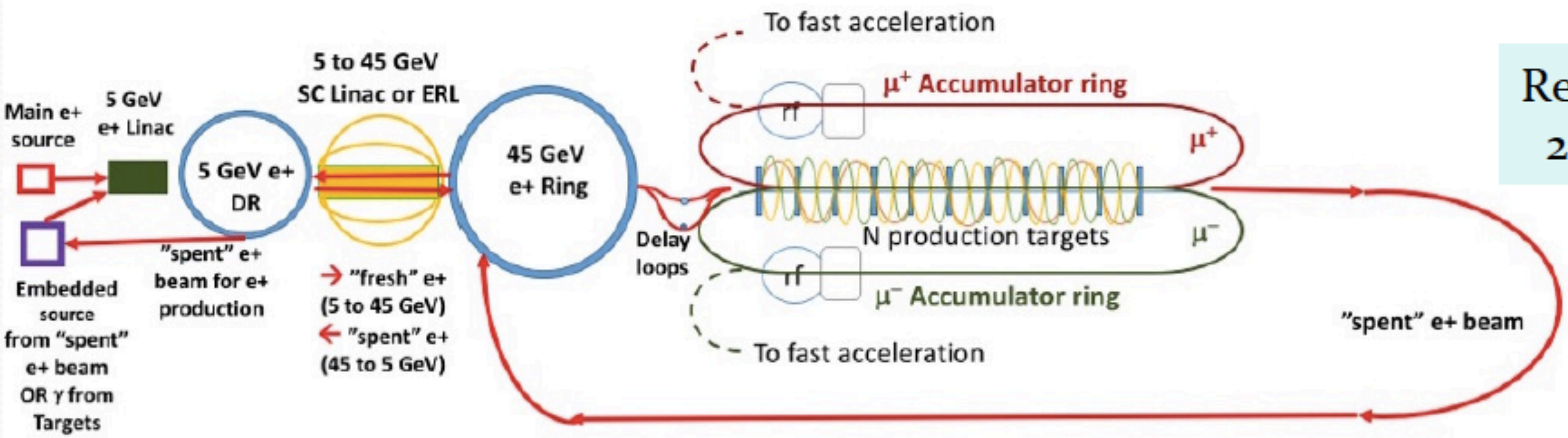
Mice results see V. Palladino

Low EMittance Muon Accelerator

- A Muon Collider is the only cost-effective opportunity for lepton colliders to go to $E_{cm} > 3$ TeV
- LEMMA concept (P. Raimondi & M. Antonelli, first presented at Snowmass 2013):
  - $\mu^{\pm}$ produced by e^{+} beam interacting with e^{-} in a target in a ring → small $\mu^{\pm}$ beam emittance and long laboratory lifetime due to the $\mu^{\pm}$ boost in the laboratory frame
  - average $\mu^{\pm}$ energy **22 GeV** (average laboratory lifetime of **~500 μs**) eases the acceleration scheme
  - Aimed at obtaining high luminosity with relatively small $\mu^{\pm}$ fluxes thus reducing background rates and activation problems due to high energy $\mu^{\pm}$ decays
- Advantages: final state $\mu^{\pm}$ highly collimated and with small emittance → muon cooling not required

Complex layout

- e^+ **Source** @ 300 MeV + 5 GeV **Linac**
- **5 GeV e^+ Damping Ring** (damping ~10 ms)
- **SC Linac or ERL** from 5 to 45 GeV and from 45 to 5 GeV to cool *spent* e^+ beam after $\mu^\pm$ production
- **45 GeV e^+ Ring** to accumulate 1000 bunches, 5×10^{11} part/bunch needed for $\mu^\pm$ production, and e^+ *spent* beam after $\mu^\pm$ production, for slow extraction towards decelerating Linac and the DR
- **Delay loops** to synchronize e^+ and $\mu^\pm$ bunches
- **One (or more) Target Lines** where e^+ beam collides with targets for the direct $\mu^\pm$ production
- **2 Accumulation Rings** where $\mu^\pm$ are stored until the bunch has ~10^9 μ/bunch
- **"Embedded" e^+ source** for the production of e^+ needed to restore the design e^+ beam current, either using the γ coming from the $\mu^\pm$ production targets, or the 45 GeV e^+ *spent* beam



Rep rate
20 Hz

Recommendations of Muon Collider Working Group

Set-up an international collaboration to promote muon colliders and organize the effort on the development of both accelerators and detectors and to define the road-map towards a CDR by the next Strategy update. As demonstrated in past experiences, the resources needed are not negligible in terms of cost and manpower and this calls for a well-organized international effort. For example, the MAP program required an yearly average of about 10M$ and 20 FTE staff/faculty in the 3-year period 2012-2014.

Develop a muon collider concept based on the proton driver and considering the existing infrastructure. This includes the definition of the required R&D program, based on previously achieved results, and covering the major issues such as cooling, acceleration, fast ramping magnets, detectors, ...

Consolidate the positron driver scheme addressing specifically the target system, bunch combination scheme, beam emittance preservation, acceleration and collider ring issues.

Carry out the R&D program toward the muon collider. Based on the progress of the proton-driver and positron-based approaches, develop hardware and research facilities as well as perform beam tests. Preparing and launching a conclusive R&D program towards a multi-TeV muon collider is mandatory to explore this unique opportunity for high energy physics. A well focused international effort is required in order to exploit existing key competences and to draw the roadmap of this challenging project. The development of new technologies should happen in synergy with other accelerator projects. Moreover, it could also enable novel mid-term experiments.

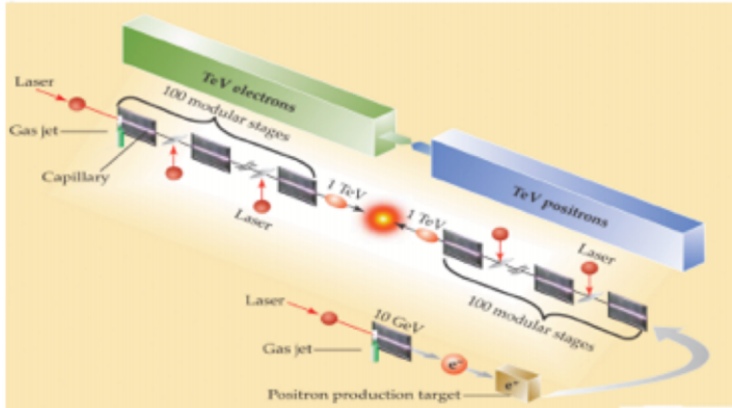
Muon Collider WG appointed by CERN Laboratory Directors Group in September 2017
to prepare the Input Document to the European Strategy Update

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

Status of Today and Goals for Collider Application

(Achieved individually and **not** simultaneously)

	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

Advanced LinEar collider study GROup, **ALEGRO** (ICFA ANA panel - 2017)

Goal:

- Long-term design of a e^+/e^-/gamma collider with up to 30 TeV: **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.

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

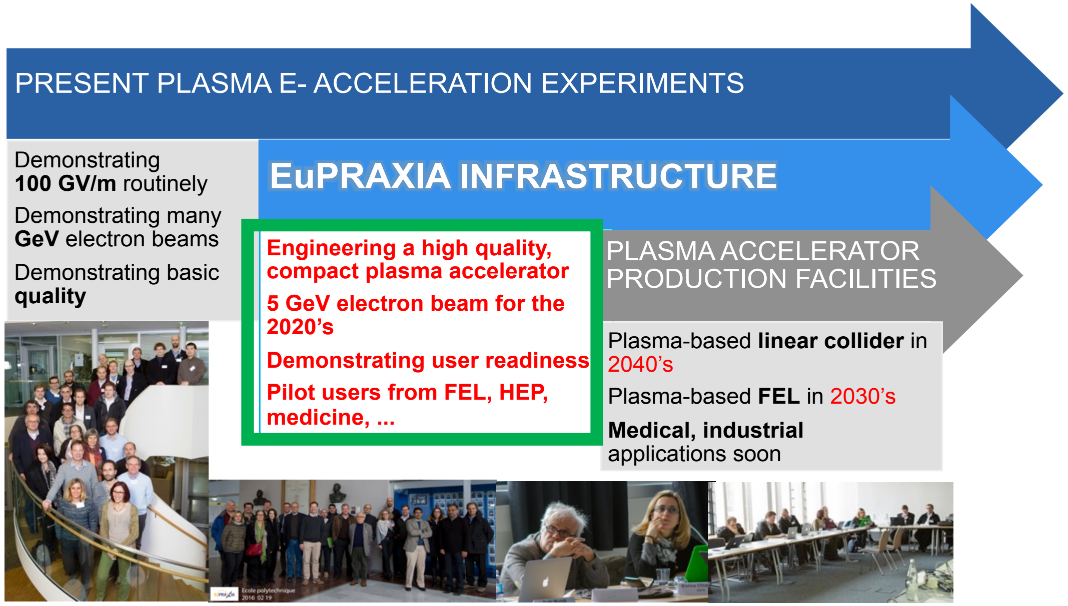
EuPRAXIA

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!

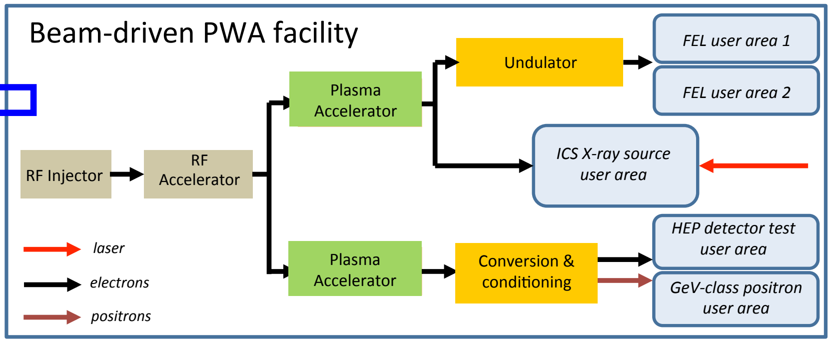
Scientific and technical goals:

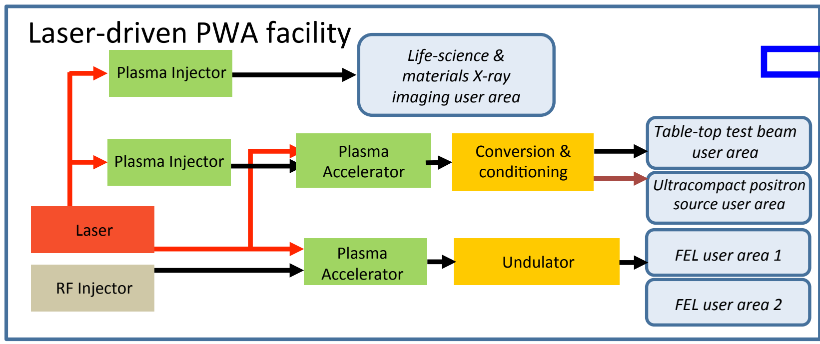
- **Single and multi-stage** acceleration of electrons to **1 – 5 GeV,** transverse emittance of **1 mm-mrad**, energy spread between **% to 10^{-3}**
- **Highly compact** machine layout (factor 3 gain in floor space, up to factor 10)
- **PW pulsed lasers** developed together with industry and laser institutes. → Operation with high stability at **20 – 100Hz**.
- **Compact beam driver** based on X-band RF technology from CERN.
- **Versatile user area**



SPARCLab at LNF: candidate to host EuPRAXIA

DESY candidate to host EuPRAXIA



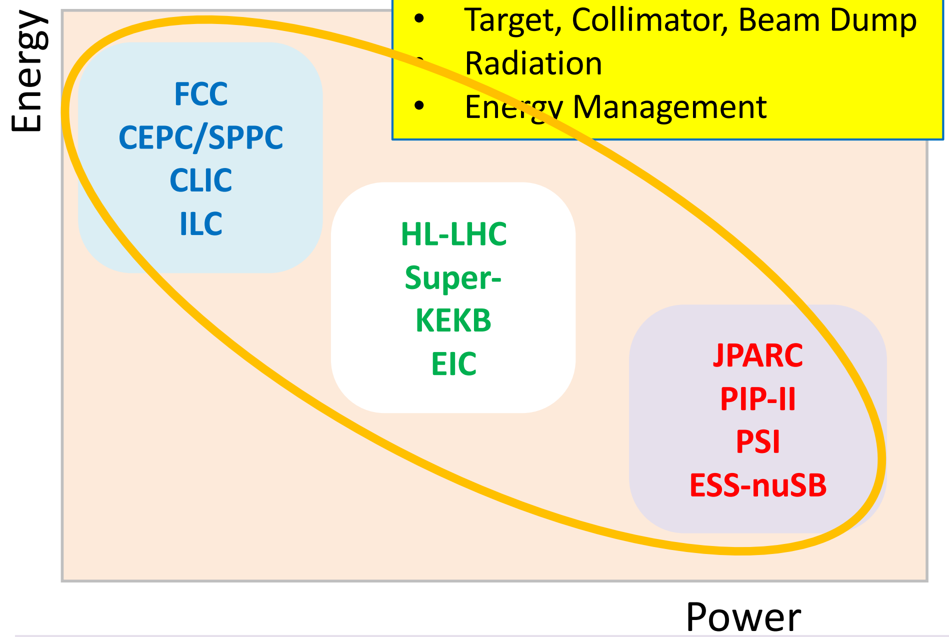


Q3: How to achieve proper complementarity for the high intensity frontier vs. the high-energy frontier?

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

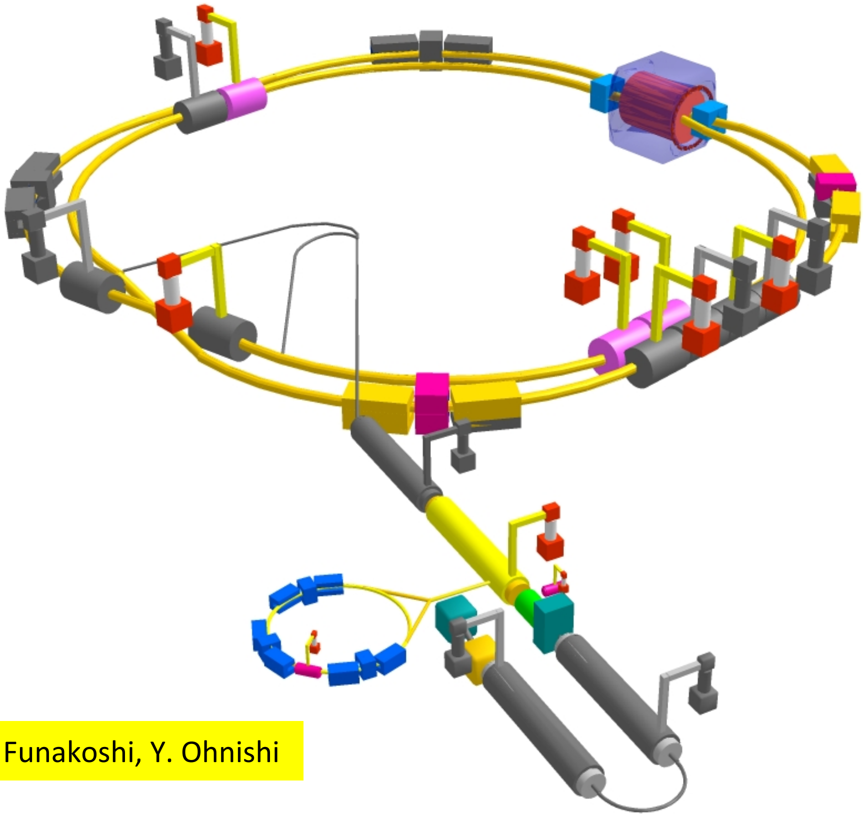


Common Issues:
- SC Mag. & SRF technology
- Target, Collimator, Beam Dump
- Radiation
- Energy Management

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

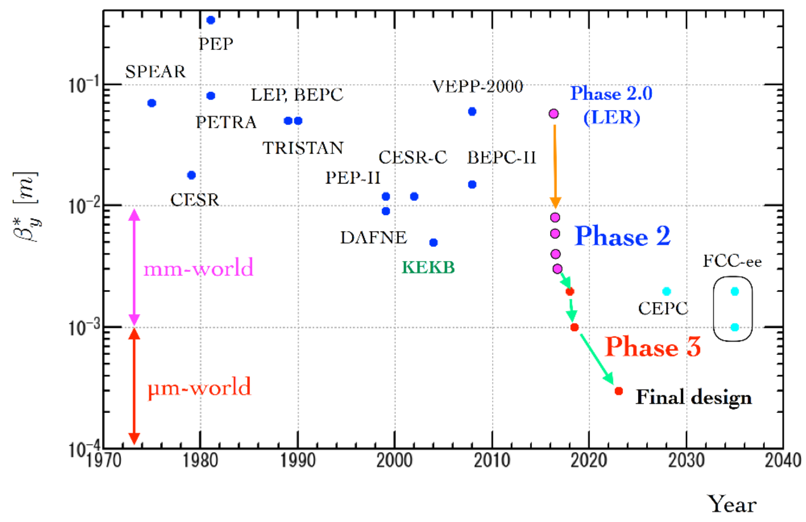
Super KEKB – pushing the frontiers of *L* & β^*

double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; **design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$**; **$\beta_y^* \sim$ 0.3 mm; nano-beam – large crossing angle** collision scheme **(crab waist w/o sextupoles)**; **beam lifetime ~5 minutes**; **top-up** injection; **e^+ rate up to ~ 2.5 10^{12} /s** ; **under commissioning**



Y. Funakoshi, Y. Ohnishi

Strategy of beta squeezing for Phase 2 and Phase 3

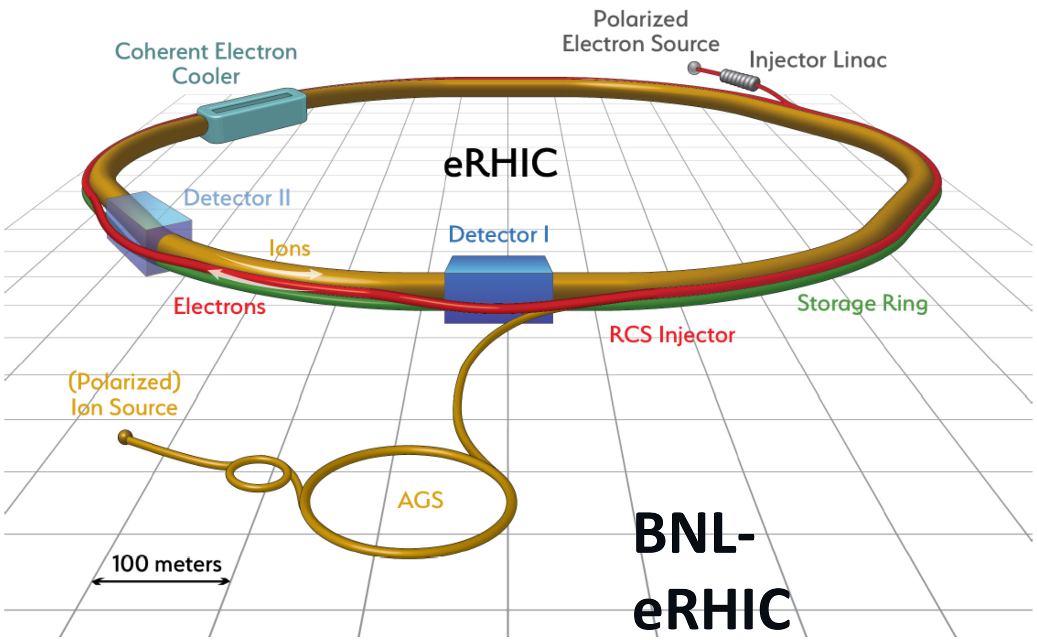


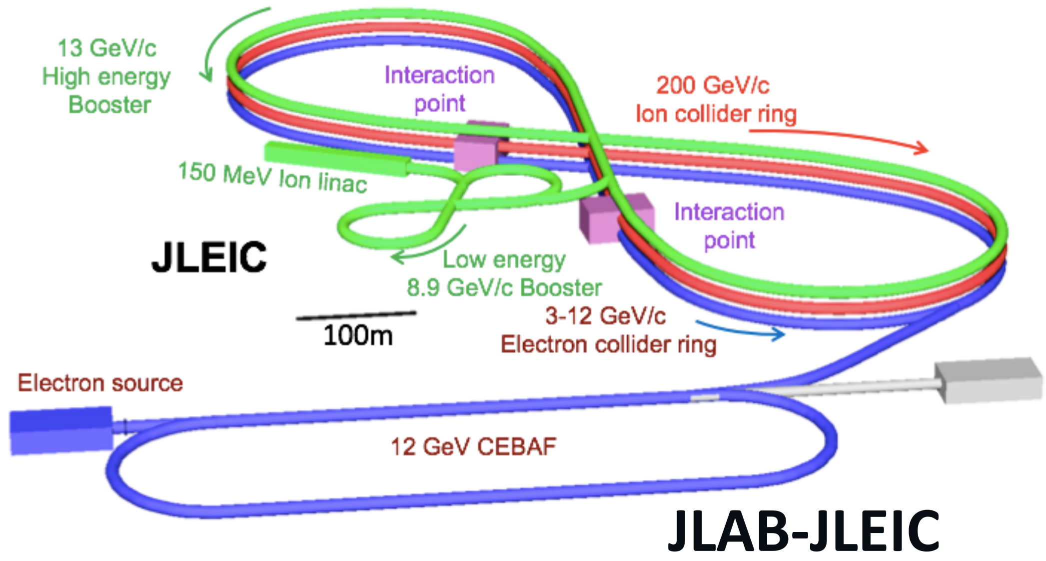
Phase-2 goal of β_y^* = 3 mm achieved in spring 2018

Further commissioning in progress this year but impacted by budget constraints.

electron-ion colliders

two collider rings (e-, A) at c.o.mass energies from 20 - 100 GeV, upgradable to 140 GeV; **high luminosity ~$10^{33\text{-}34}$ cm^{-2} s^{-1}, highly polarised electron and nucleon beams**; possibility of **2 IPs,** ion beams from deuteron to the heaviest nuclei (uranium or lead); **pre-CDRs completed**



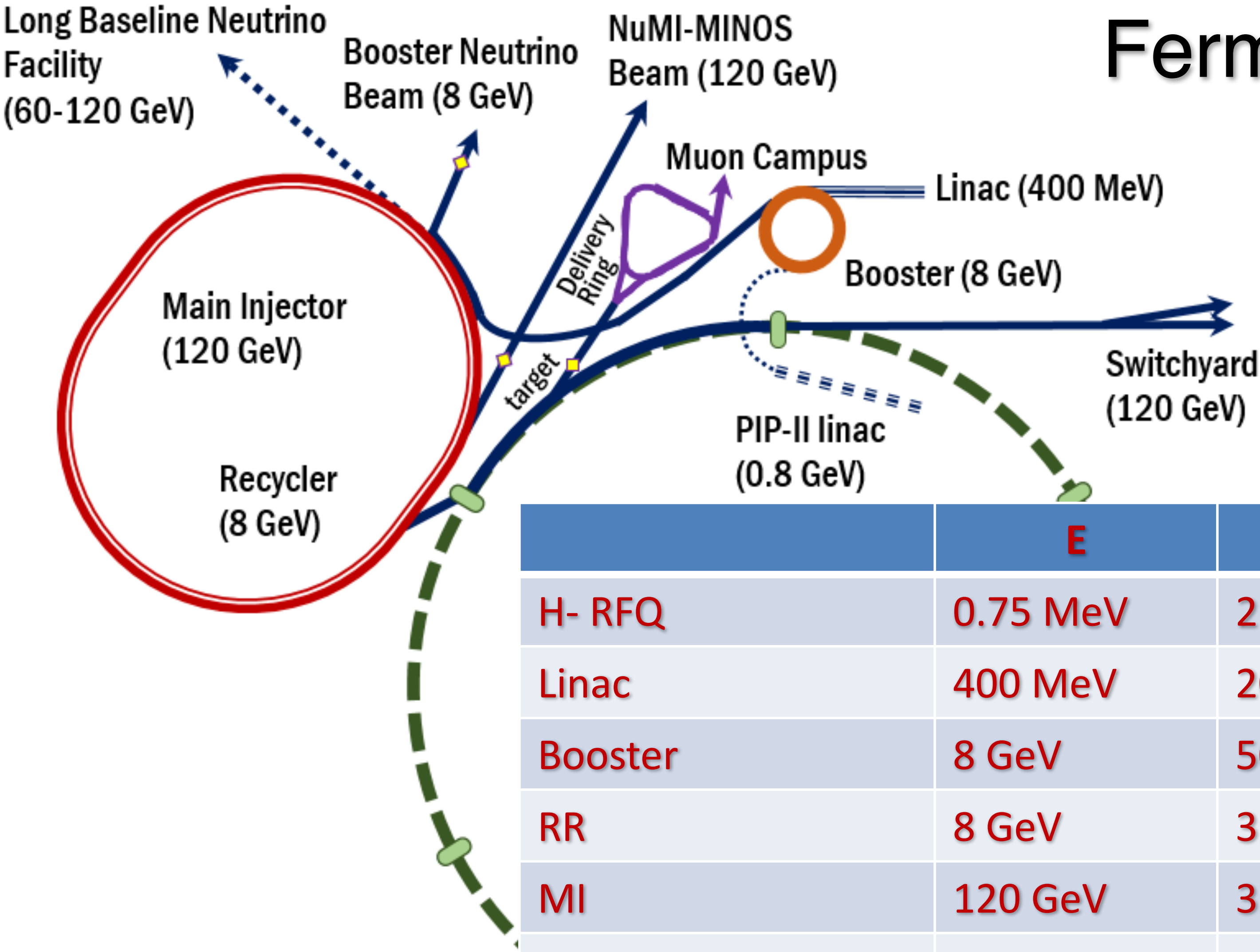


Some key ingredients: efficient SRF cavities; crab cavities; high-energy hadron beam cooling (IBS) for high luminosity, high field magnets for the interaction points, etc.

Electron ion colliders combine challenges of circular ee & hh colliders → strong opportunities for collaborations

1. **Super-Beam Facilities and Upgrades**
    - Fermilab
    - J-PARC
2. **New Proposals**
    - Protvino/ORKA: U-70 p+ synchrotron, 70 GeV protron beam, *P*_beam = **15 kW -> 90 kW** by 2026
    - ESSνSB; ESS Neutrino Super Beams, 2 GeV SC linac, *P*_beam = **5 MW -> 10 MW**
    - ENUBET: SPS-based Short base-line ν's , *E*=400 GeV protron beam, *P*_beam = 510kW
    - νSTORM: Neutrinos from Muons stored in a decay ring, SPS at CERN could be used as primary beam

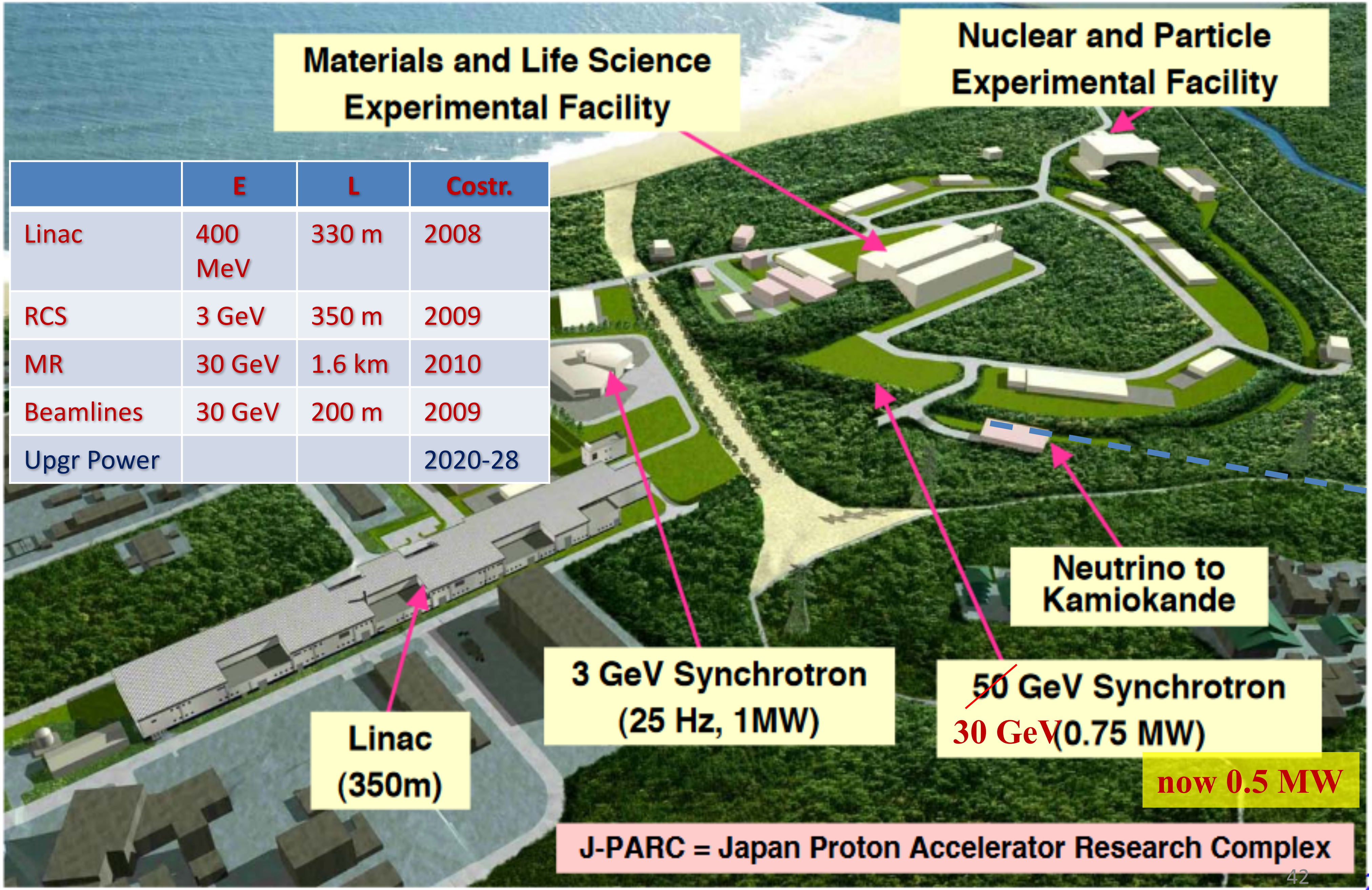
Fermilab Proton Complex



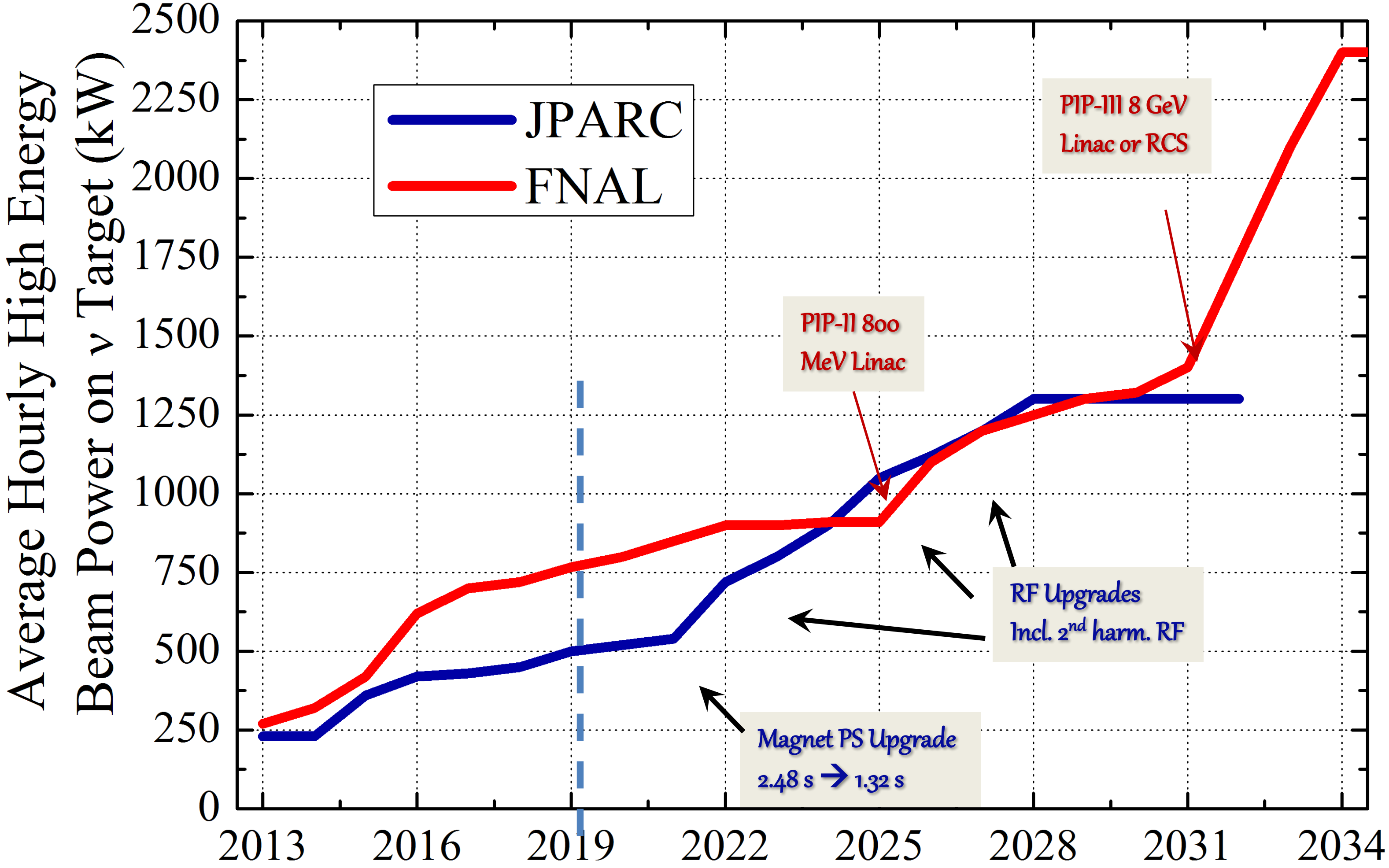
	E	L	Costr.
H- RFQ	0.75 MeV	2 m	2013
Linac	400 MeV	200 m	1970/93
Booster	8 GeV	500 m	1971
RR	8 GeV	3.3 km	1999
MI	120 GeV	3.3 km	1999
Delivery Ring	3.8-8 GeV	500 m	1985/2014
Beamlines	3-120 GeV	3.5 km	1970's-now
Upgr: PIP-II	800 MeV	240 m	2026
Upgr :PIP-III	8 GeV	500 m	Ca 2032
Upgr: beamlines	0.8-8 GeV	500 m	2026

J-PARC sends neutrinos to Super-K (Hyper K)

	E	L	Costr.
Linac	400 MeV	330 m	2008
RCS	3 GeV	350 m	2009
MR	30 GeV	1.6 km	2010
Beamlines	30 GeV	200 m	2009
Upgr Power			2020-28



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



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

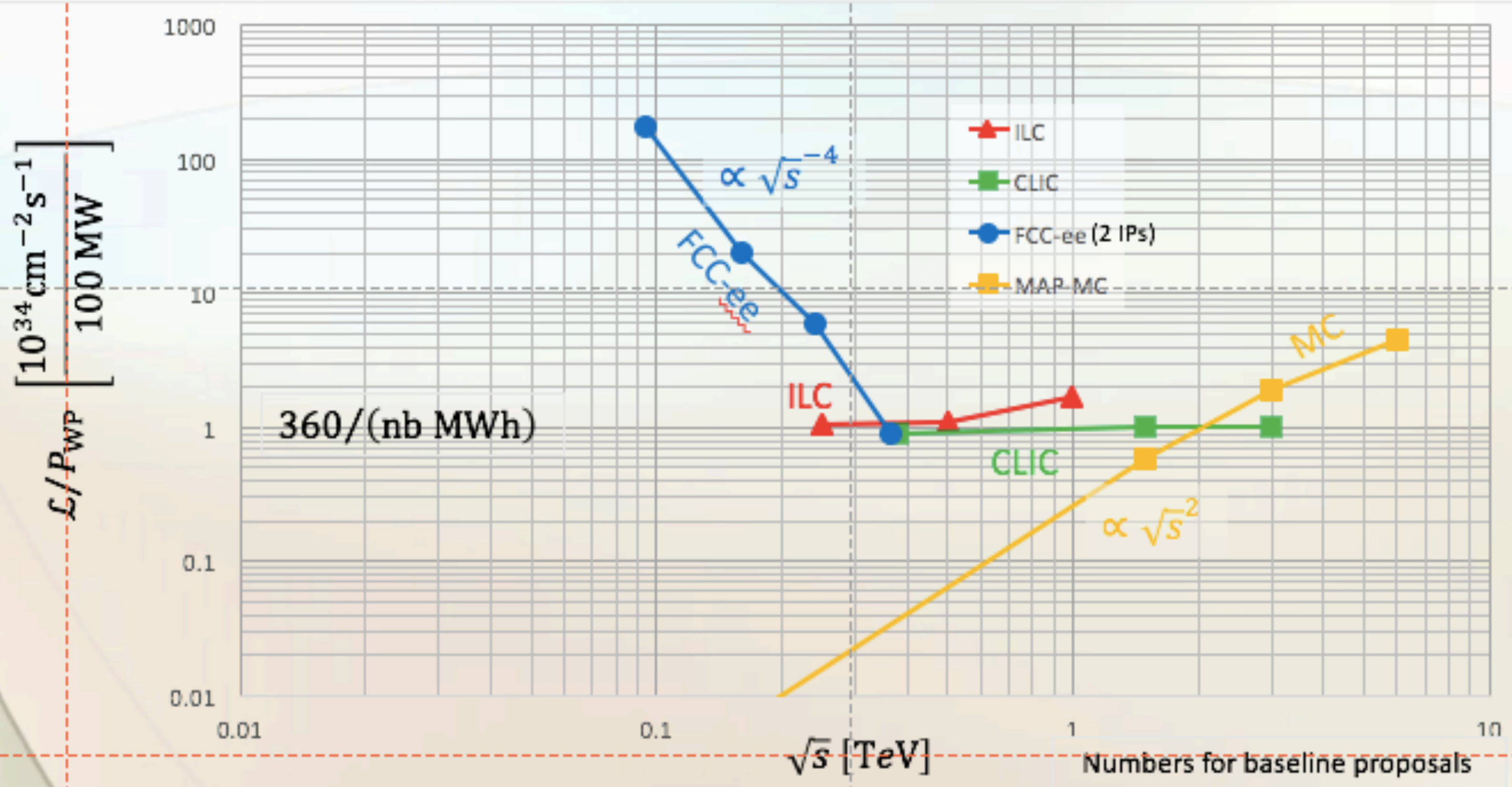
Energy Efficiency

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