Future Colliders

Jacqueline Keintzel

Acknowledgements: Many colleauges from various design studies

4th Baltic School of High Energy Phyiscs and Accelerator Technologies

Kuldiga, Latvia

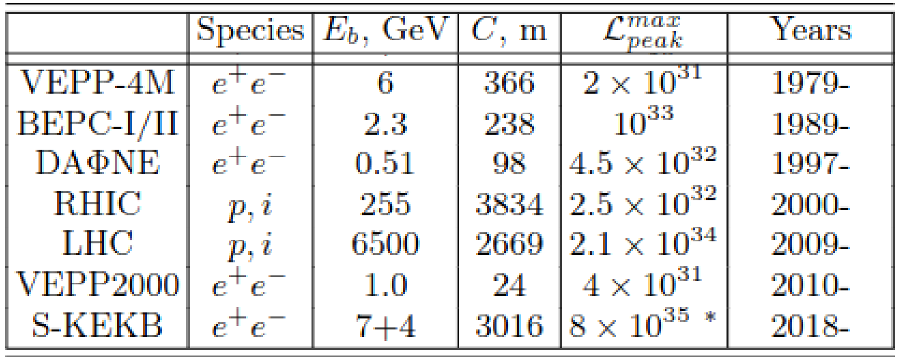
05 – 09 August 2024

Current Accelerators

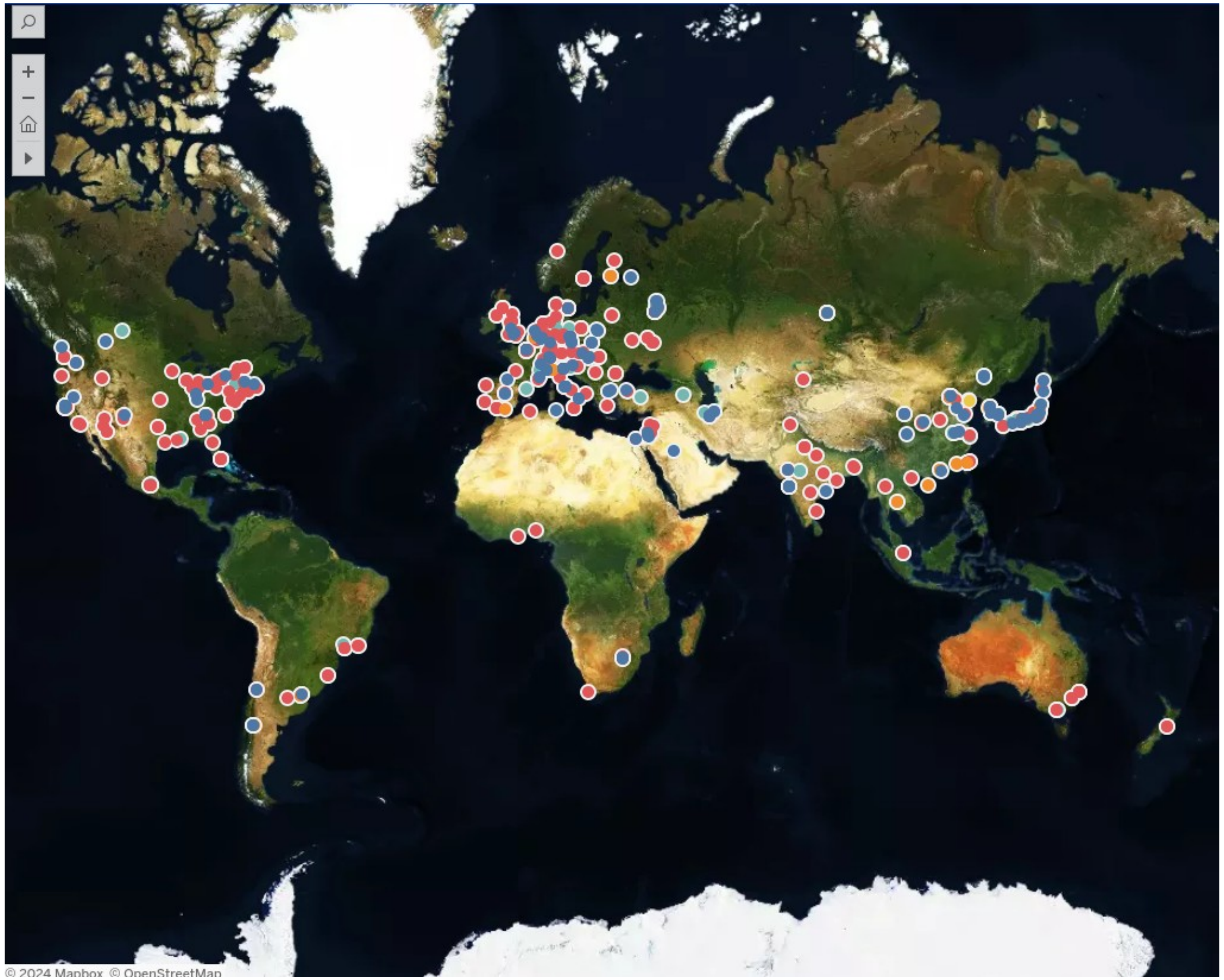
Ref :
https://nucleus.iaea.org/sites/accelerators/Pages/Interactive-Map-of-Accelerators.aspx

https://www-elsa.physik.uni-bonn.de/accelerator_list.html

- Many applications
  - Medical accelerators
  - Light sources
  - Accelerator based neutron sources
  - High Energy Physics (HEP) research
    - 7 colliders currently in operation
    - e.g: RHIC, LHC, SKEKB



	Species	E_b, GeV	C, m	$\mathcal{L}_{peak}^{max}$	Years
VEPP-4M	e^+e^-	6	366	2×10^{31}	1979-
BEPC-I/II	e^+e^-	2.3	238	10^{33}	1989-
DAΦNE	e^+e^-	0.51	98	4.5×10^{32}	1997-
RHIC	p, i	255	3834	2.5×10^{32}	2000-
LHC	p, i	6500	2669	2.1×10^{34}	2009-
VEPP2000	e^+e^-	1.0	24	4×10^{31}	2010-
S-KEKB	e^+e^-	7+4	3016	8×10^{35} *	2018-

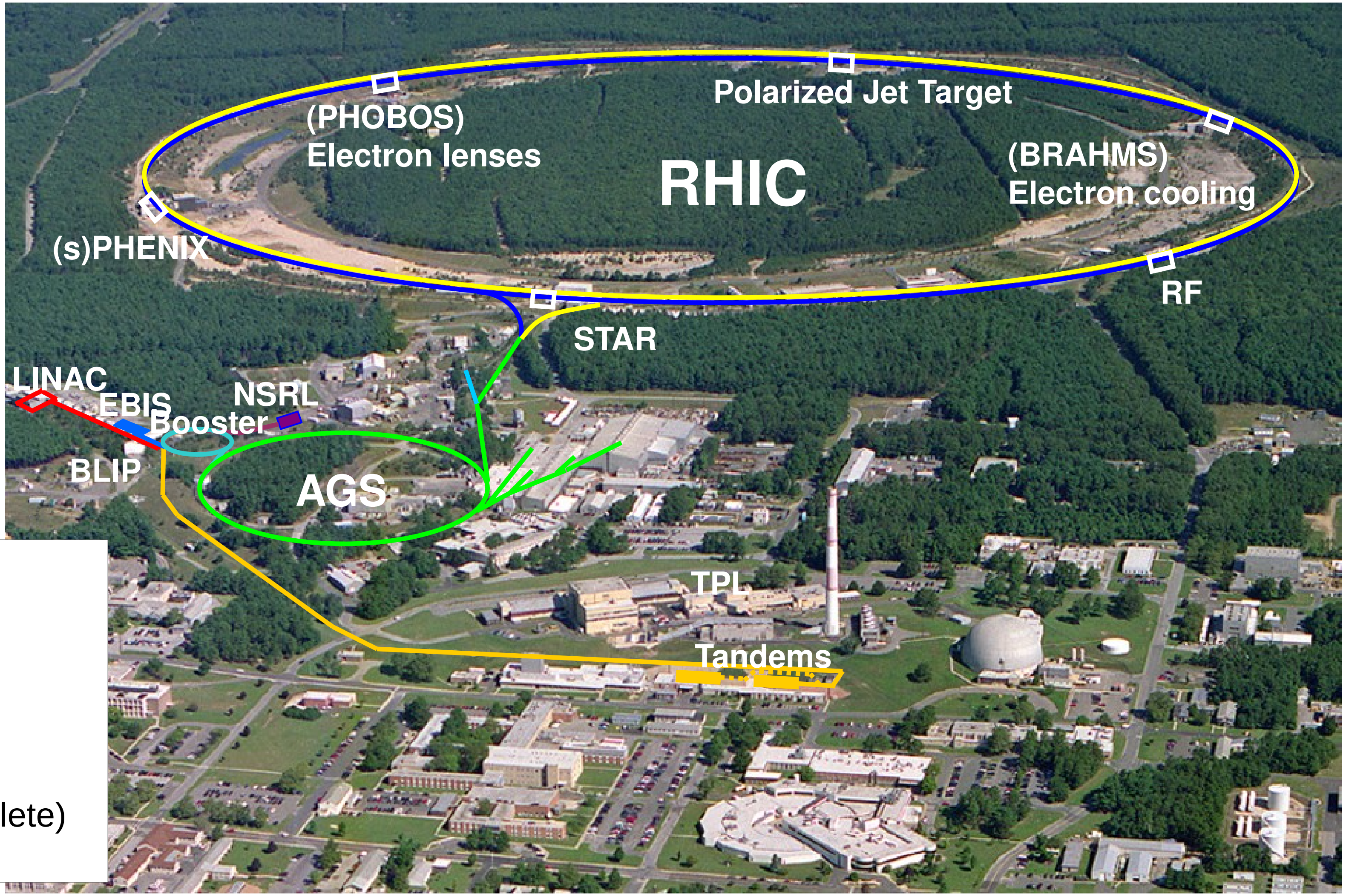


Courtesy: S. Nagaitsev

RHIC at BNL

- **R**elativistic **H**eavy **I**con **C**ollider
- Located at

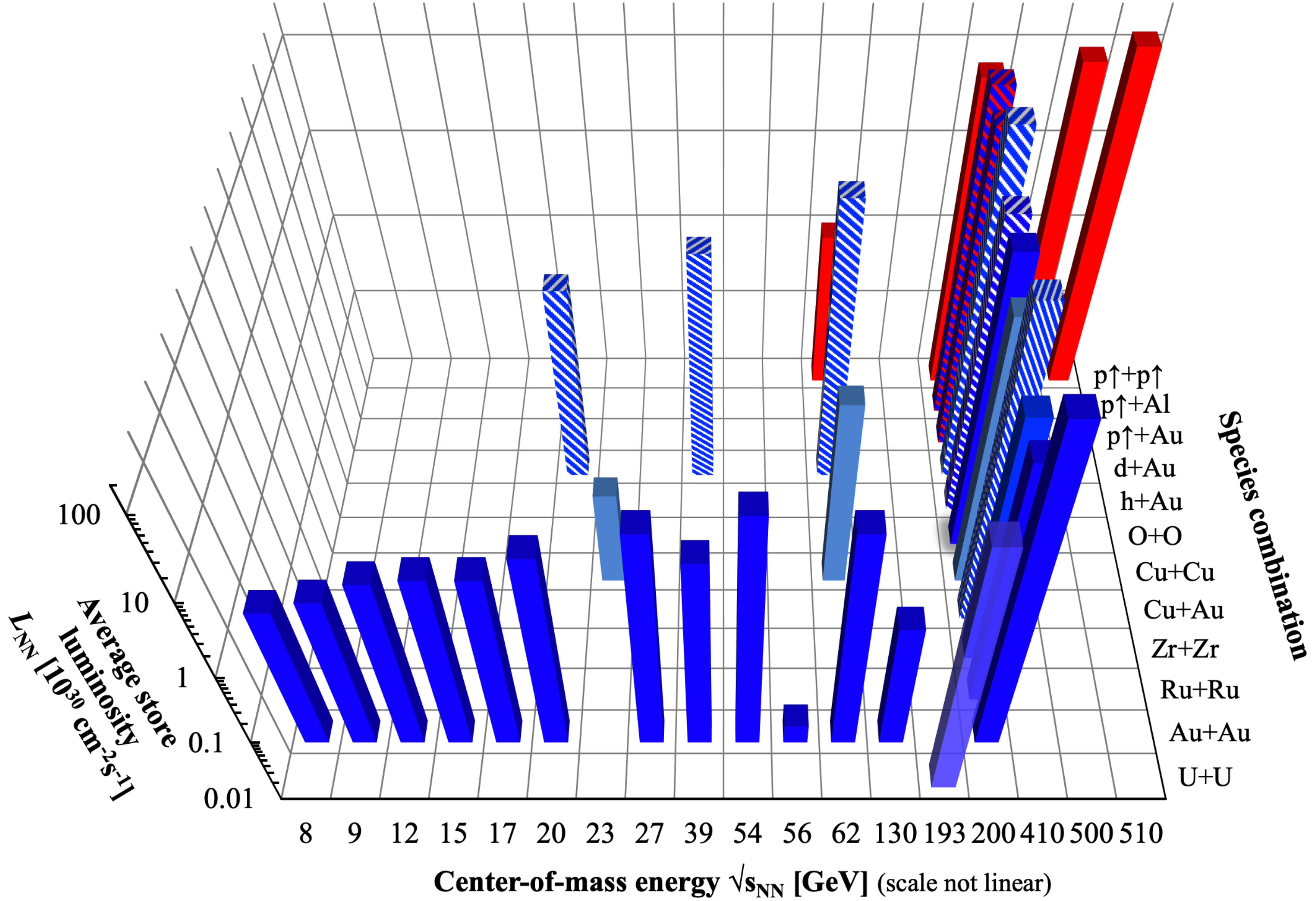
  Brookhavn National Laboratory (BNL)
- First collider ever build dedicated to collide heavy ions



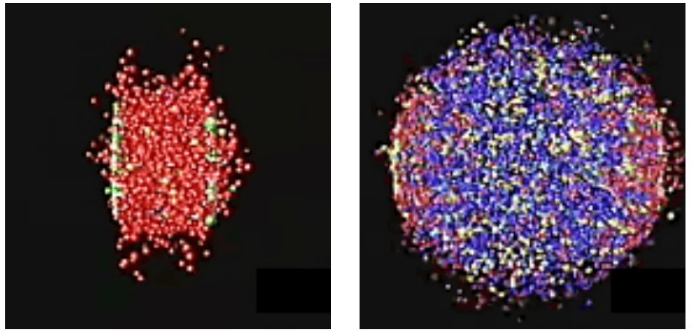
Operation : 2000 – 2025 (planned)
Circumference : 3.8 km
Max dipole field : 3.5 T
Energy : 255 GeV polarized p
: 100 GeV/nucleon Au
Species : p to U (incl. asymmetric)
Experiments : BRAHMS, PHOBOS (complete)
STAR, PHENIXgsPHENIX

Courtesy: S. Nagaitsev

RHIC Flexibility

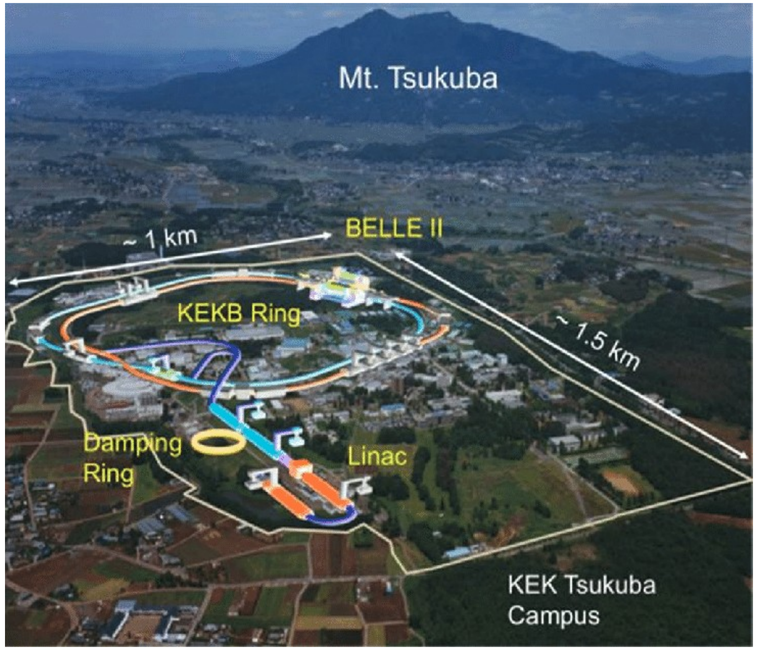


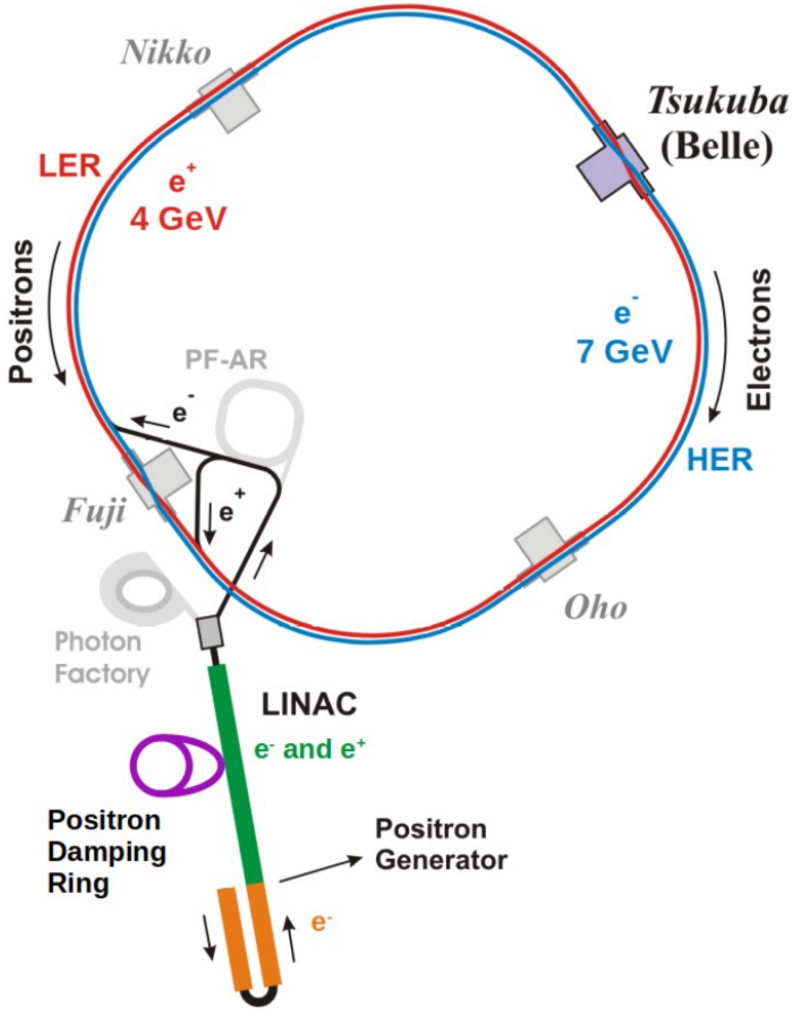
- Great flexibility of ion collisions
  - Creation of quark gluon plasma
- Operation with polarized protons
  - Spin physics



SuperKEKB at KEK

- SuperKEKB at KEK (**K**ō **E**nerugī **K**asokuki Kenkyū Kikō)
- Largest currently operating electron-positron collider
- Record instantaneous luminosity of $4.65 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Asymmetric beam energies of 4 and 7 GeV for b-physics



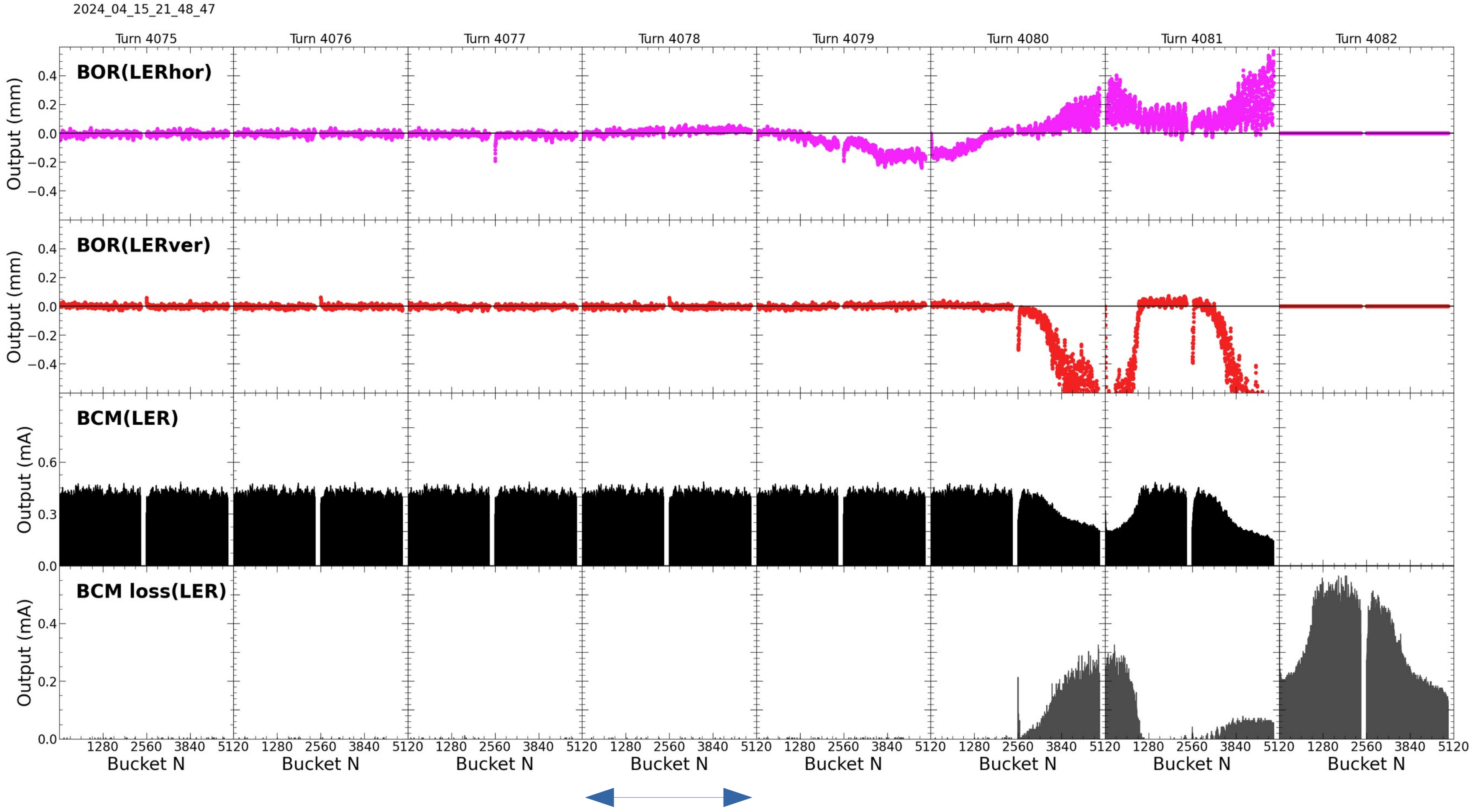


Courtesy: H. Ikeda

Sudden Beam Loss - Example

- Timeline of SBL:
  - Horizontal oscillation
  - Vertical oscillation
  - Beam Losses

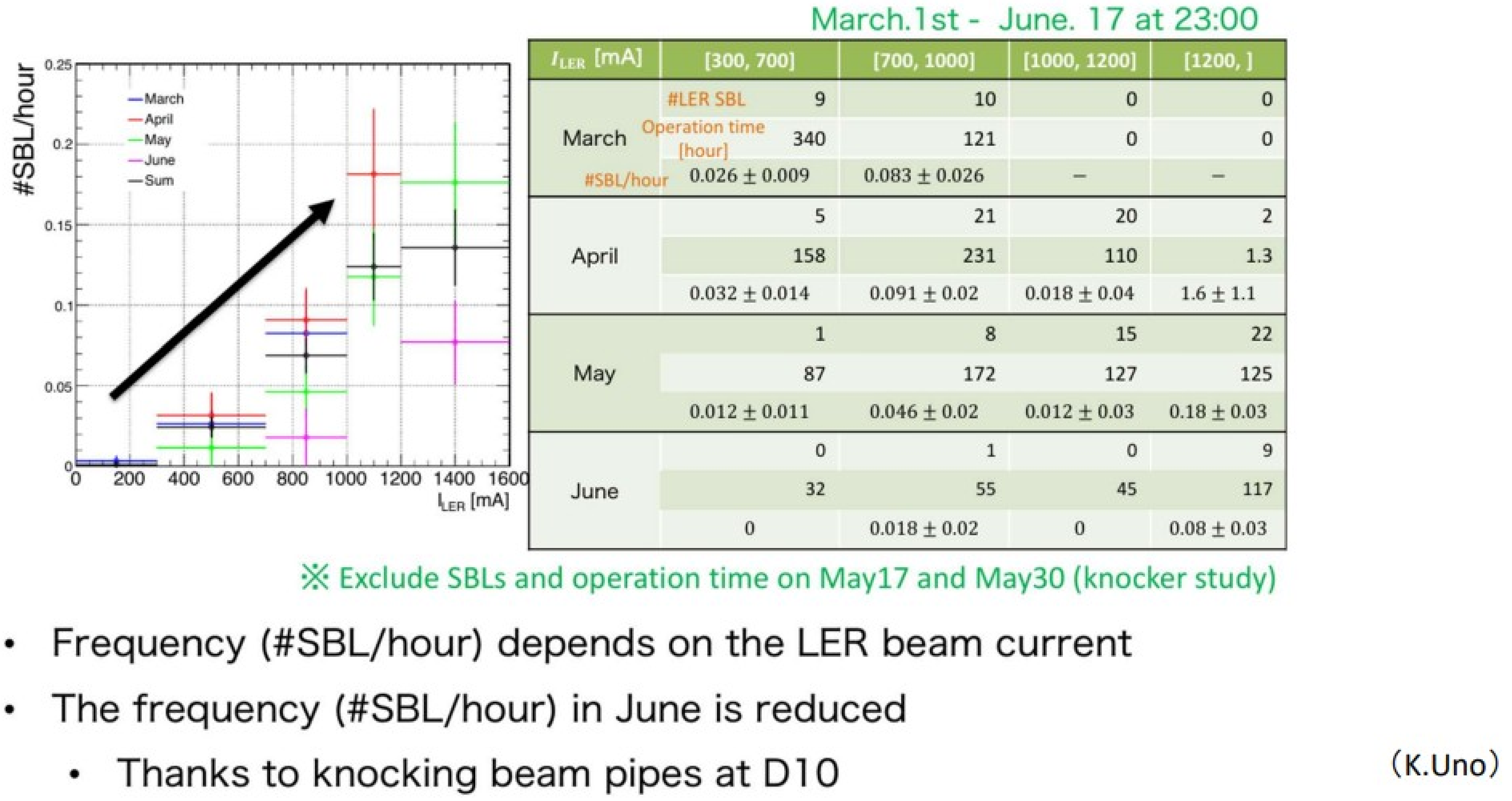
- Pressure burst at same time
  - Cause or consequence of SBL?



1 turn

Courtesy: H. Ikeda

Beam Current Dependency



March.1st - June. 17 at 23:00

I_{LER} [mA]		[300, 700]	[700, 1000]	[1000, 1200]	[1200,]
March	#LER SBL	9	10	0	0
	Operation time [hour]	340	121	0	0
	#SBL/hour	0.026 ± 0.009	0.083 ± 0.026	–	–
April		5	21	20	2
		158	231	110	1.3
		0.032 ± 0.014	0.091 ± 0.02	0.018 ± 0.04	1.6 ± 1.1
May		1	8	15	22
		87	172	127	125
		0.012 ± 0.011	0.046 ± 0.02	0.012 ± 0.03	0.18 ± 0.03
June		0	1	0	9
		32	55	45	117
		0	0.018 ± 0.02	0	0.08 ± 0.03

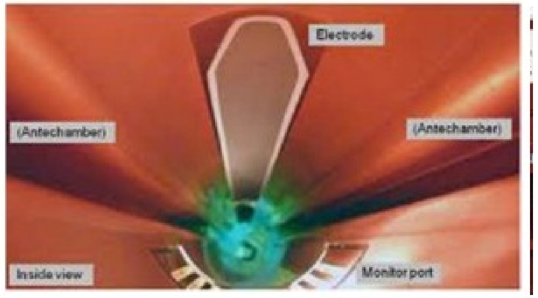
※ Exclude SBLs and operation time on May17 and May30 (knocker study)

- Frequency (#SBL/hour) depends on the LER beam current
- The frequency (#SBL/hour) in June is reduced
  - Thanks to knocking beam pipes at D10

（K.Uno）

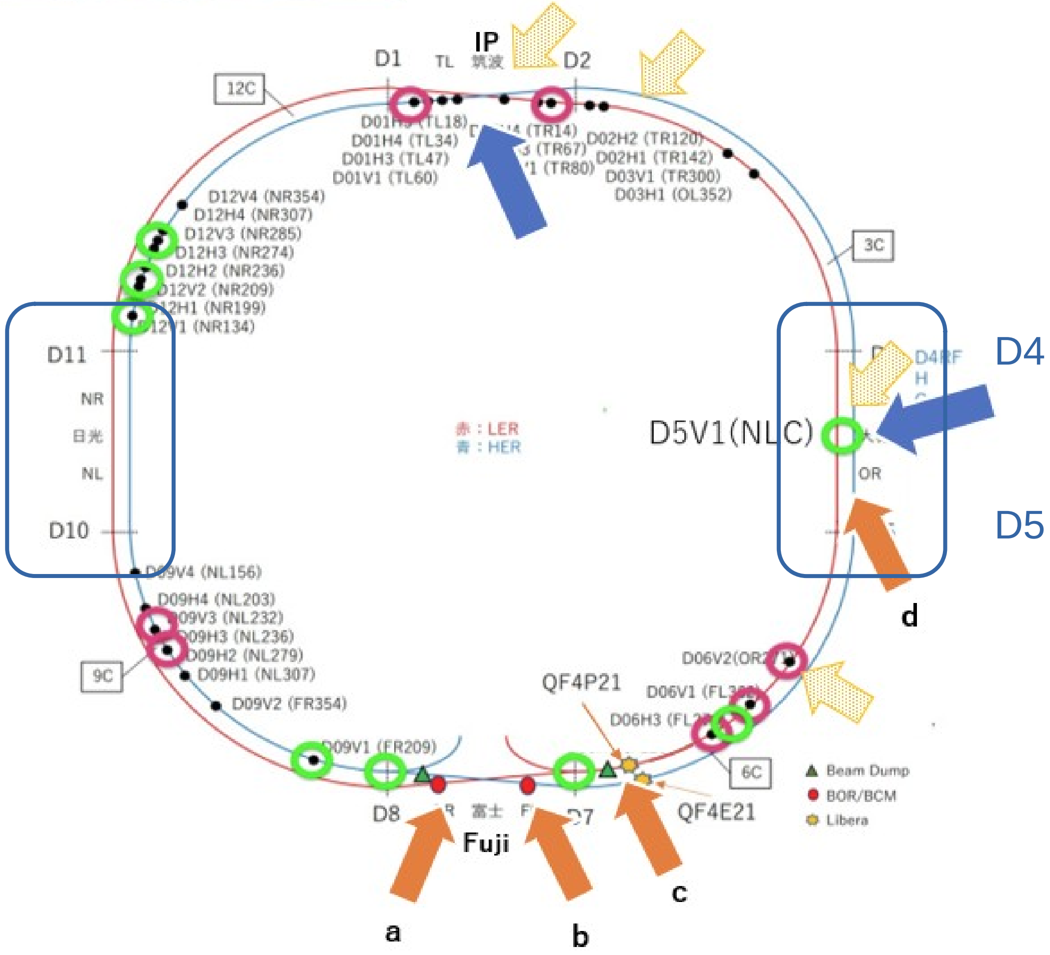
Courtesy: H. Ikeda, S. Terui, Nakayama

Working Theory



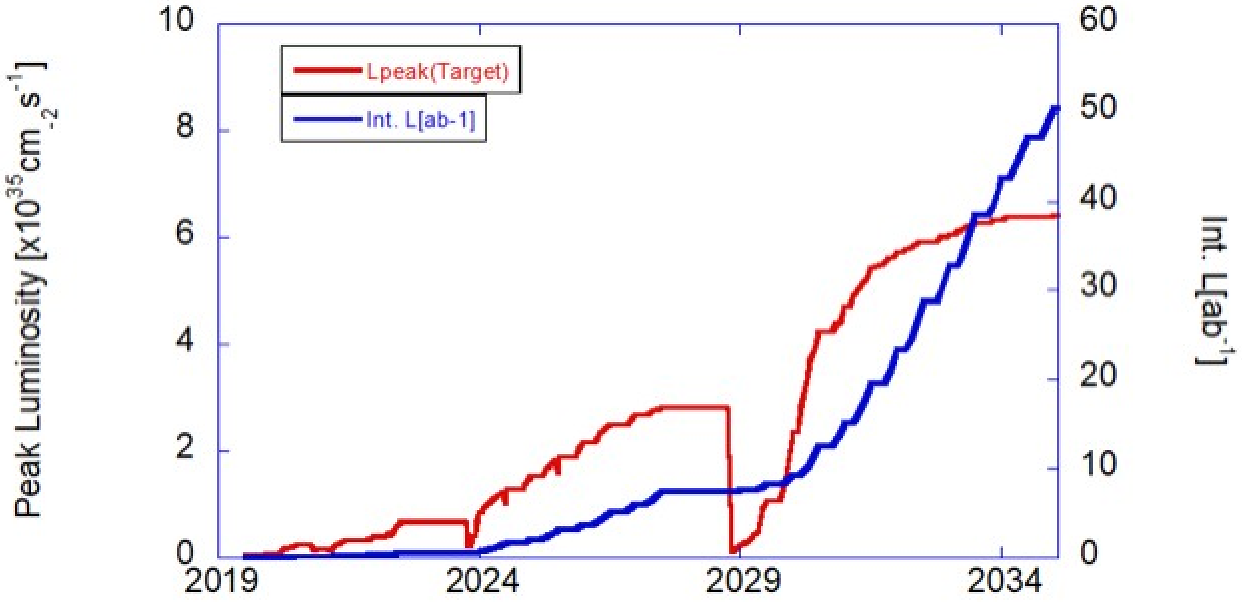
- Clearing electrode(s) in wiggler(s) damaged
- Dust particles fall into beam, leading to SBL

- Knocker study has been performed
  - Knocker installed at D4 location
  - 3 SBL events have been triggered
  - Vacuum team investigating mitigation theories
  - Further knocking at same current did not lead to SBL
  - Future: installation of knocker at D10



Courtesy: H. Ikeda

Luminosity Projection

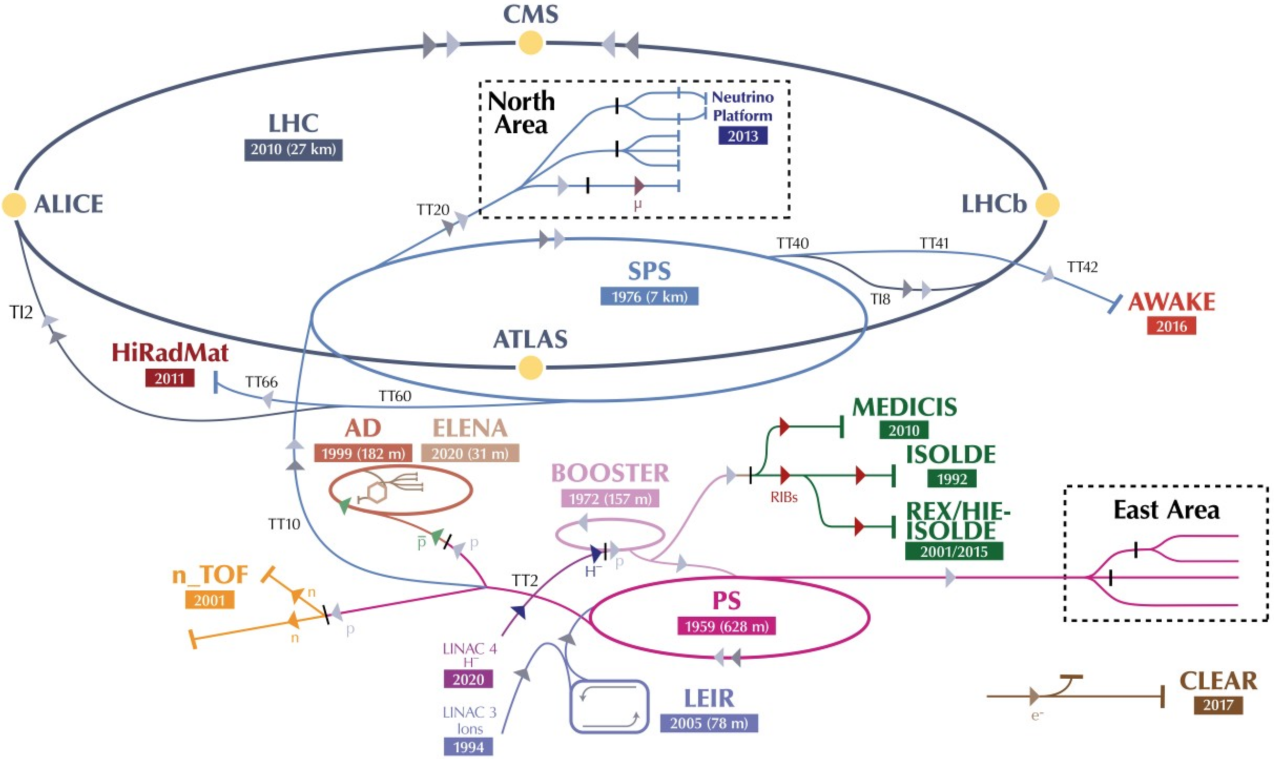


- Goal: 60 x 10^{34} $cm^{-2}s^{-1}$ instantaneous luminosity
- Current SuperKEKB challenges:
  - Sudden Beam Loss, mainly in positron ring
  - Beam Blow-Up
  - Beam-beam Blow-Up
  - Injection efficiency

Courtesy: R. Bruce

LHC at CERN

- **L**arge **H**adron **C**ollider (LHC) at CERN for hadron collisions with four big experiments
- Largest collider in existence with 27 km; last stage of the accelerator chain
- 14 TeV collision energy for proton-proton collisions; also heavy-ion collisions

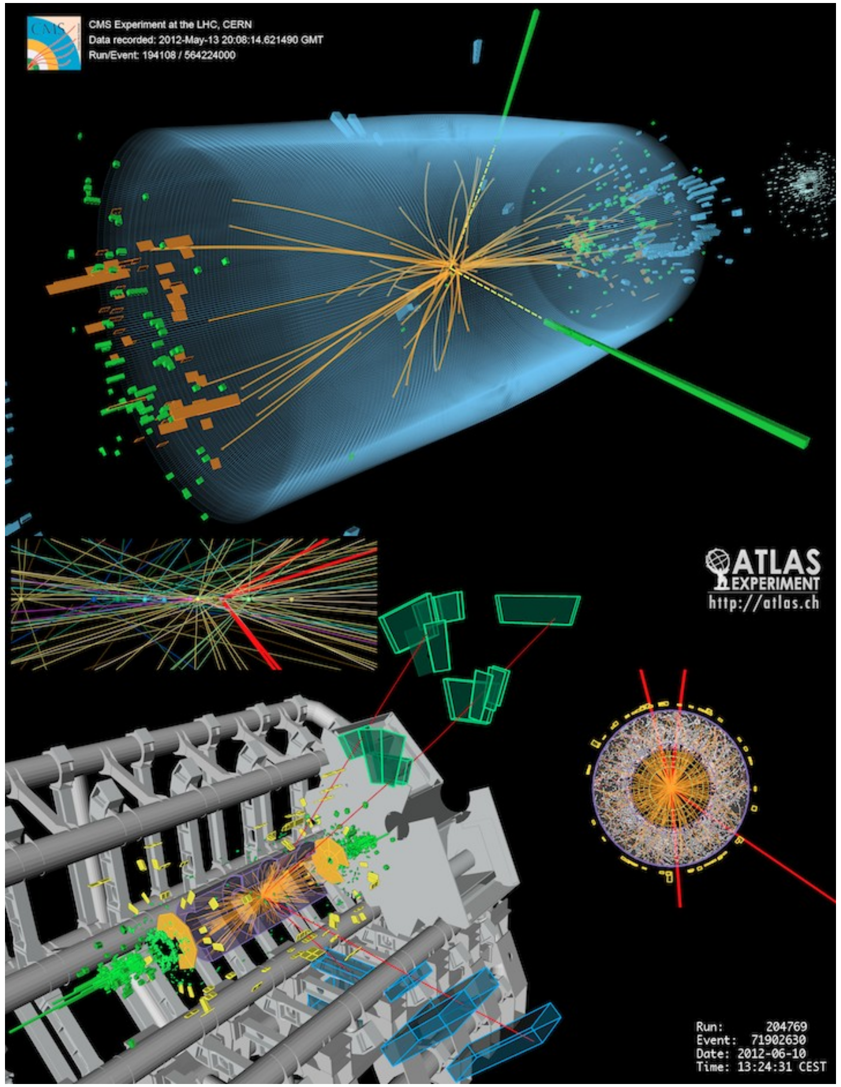


Higgs Discovery at LHC

- Most recent nobel prize

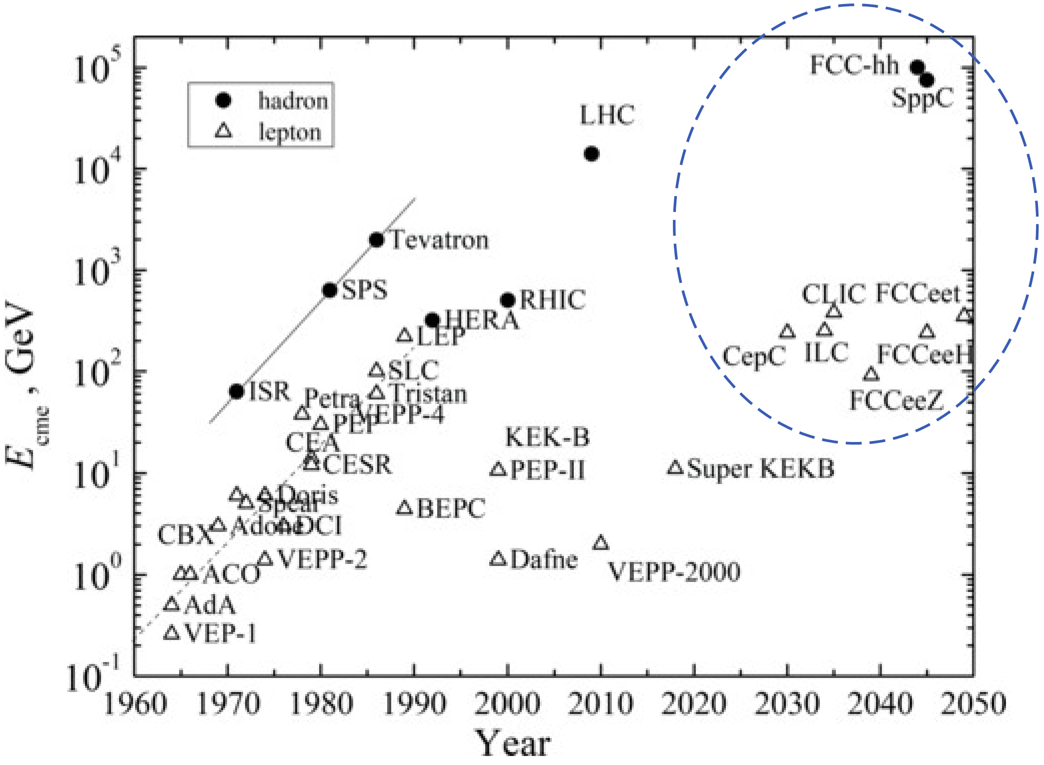
  for high-energy physics in 2013

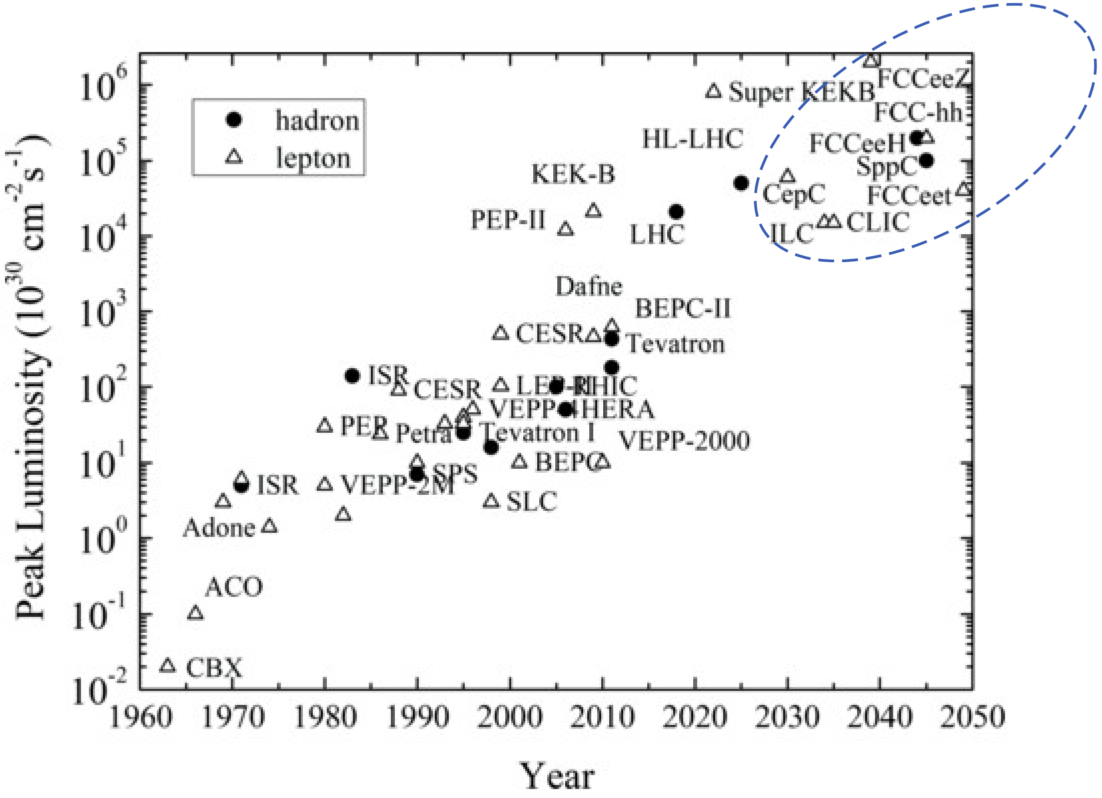
- Peter Higgs and Francois Englert



History

- Electron-positron colliders started in the 1960s





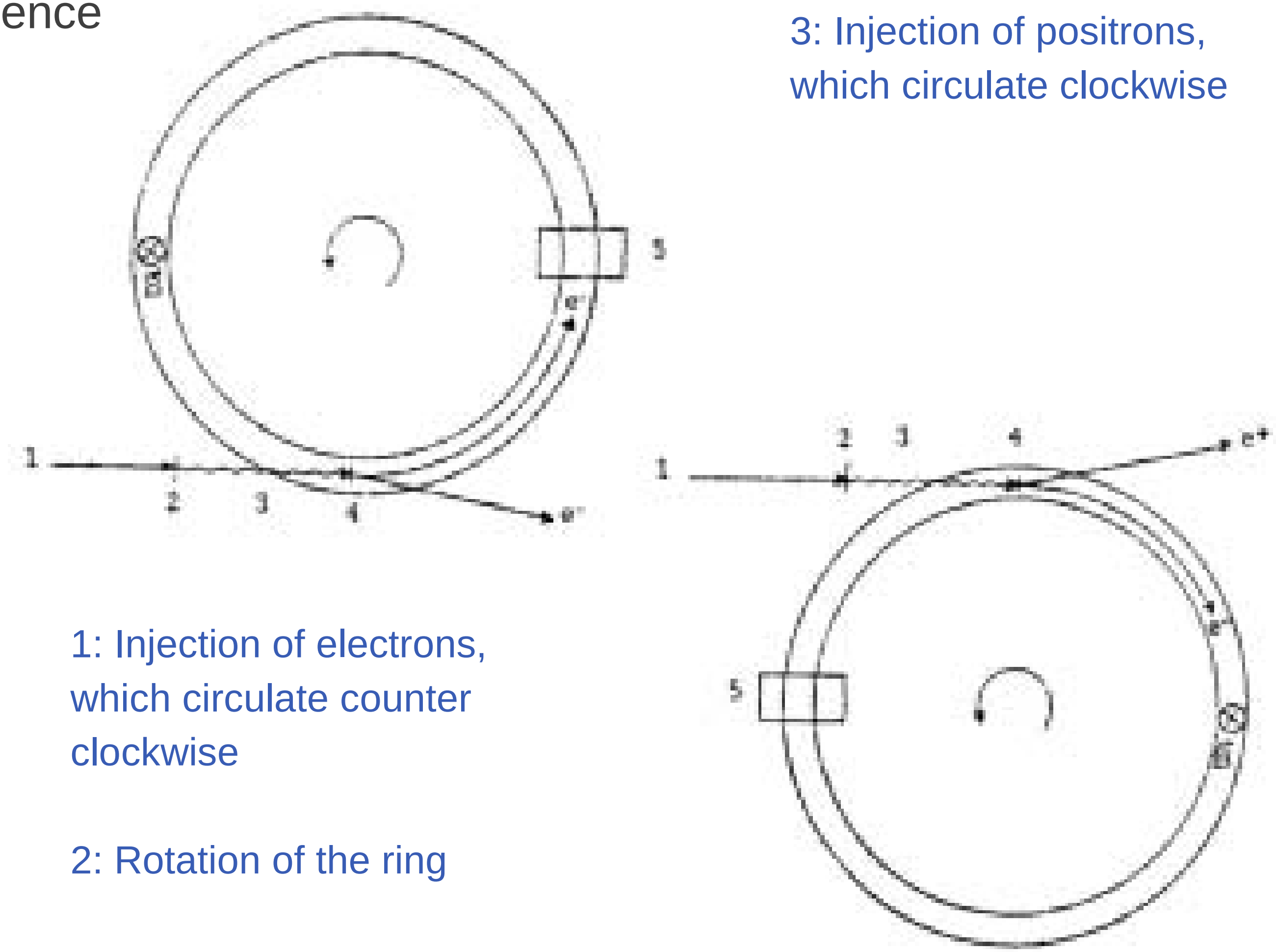
Ref: V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006, 2021.

Note: Possible start for various future machines later than shown in plots

The Very First: AdA

- Anello Di Accumulazione (AdA) with 4 m circumference
- Located at Frascati, Italy
- Operation from 1961 – 1965

- First proof of principle of e^+e^- storage ring
- First observations of e^+e^- annihilations
- Observation of the Touschek Effect



3: Injection of positrons, which circulate clockwise

1: Injection of electrons, which circulate counter clockwise

2: Rotation of the ring

C. Bernardini, AdA:The First Electron-Positron Collider. Phys. perspect. 6, 156–183 (2004).

Nobel Prizes HEP

- 2013: Francois Englert and Peter **Higgs** - “for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider”

- 2008: Makoto Kobayashi and Toshihide Maskawa - “for the discovery of the origin of the **broken symmetry** which predicts the existence of at least three families of quarks in nature”

- 2004: David J. Gross, H. David Politzer and Frank Wilczek - “for the discovery of asymptotic freedom in the theory of the **strong interaction**”

- 1995: Martin L. Perl - “for the discovery of the **tau** lepton” and Frederick Reines - “for the detection of the **neutrino**”

- 1992: Georges Charpak - “for his invention and development of particle detectors, in particular the **multiwire proportional chamber**”

Nobel Prizes HEP

- 1990: Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor - “for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the **quark model** in particle physics”

- 1984: Carlo Rubbia and Simon van der Meer - “for their decisive contributions to the large project, which led to the discovery of the field particles **W and Z**, communicators of weak interaction”

- 1979: Sheldon Glashow, Abdus Salam and Steven Weinberg - “for their contributions to the theory of the **unified weak and electromagnetic** interaction between elementary particles, including, inter alia, the prediction of the weak neutral current”

- 1976: Burton Richter and Samuel C.C. Ting - “for their pioneering work in the discovery of a **heavy elementary particle** of a new kind”

- 1996: Murray Gell-Mann - “for his contributions and discoveries concerning the classification of **elementary particles and their interactions**”

Nobel Prizes HEP

- 1986: Luis Alvarez - “for his decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible through his development of the technique of using **hydrogen bubble chamber** and data analysis”

- 1965: Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman - “for their **fundamental work in quantum electrodynamics**, with deep-ploughing consequences for the physics of elementary particles”

- 1960: Donald A. Glaser - “for the invention of the **bubble chamber**”

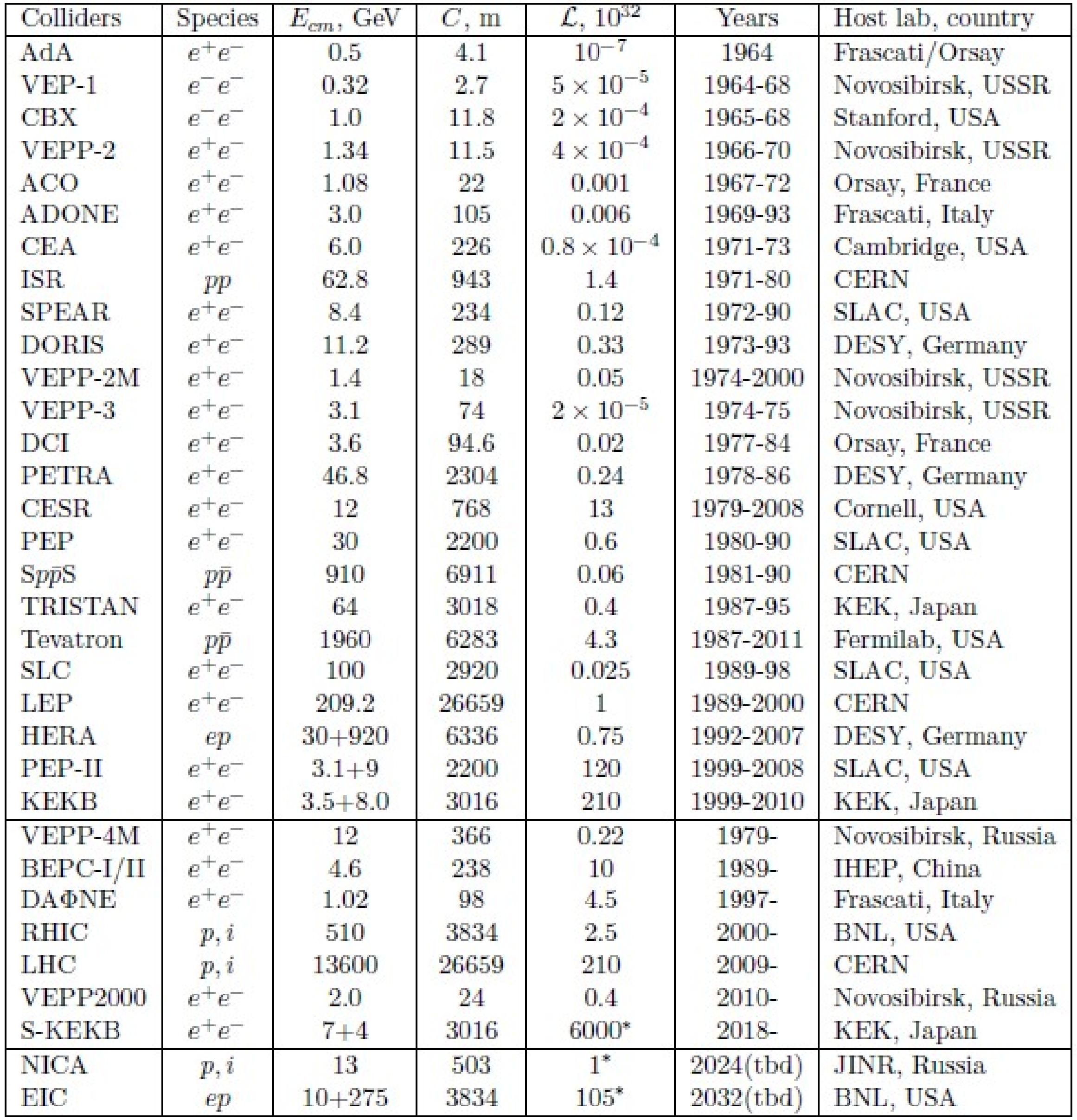
- 1959: Emilio Segrè and Owen Chamberlain - “for their discovery of the **antiproton**”
- 1957: Chen Ning Yang and Tsung-Dao Lee - “for their penetrating investigation of the so-called **parity laws** which has led to important discoveries regarding the elementary particles”
- 1951: John Cockcroft and Ernest T.S. Walton - “for their pioneer work on the **transmutation of atomic nuclei** by artificially accelerated atomic particles”
- 1949: Hideki Yukawa - “for his prediction of the existence of **mesons** on the basis of theoretical work on nuclear forces”

History

- About 14 past circular electron-positron colliders
- About 3 past circular hadron colliders
- So far 1 electron-hadron collider

- 7 colliders currently in operation
- 2 approved future collider projects + 1 upgrade

- Possible option for the future
    - Circular, linear, novel concepts ?
    - Americas, Europe, Asia ?



Colliders	Species	E_{cm}, GeV	C, m	$\mathcal{L}$, 10^{32}	Years	Host lab, country
AdA	e^+e^-	0.5	4.1	10^{-7}	1964	Frascati/Orsay
VEP-1	e^-e^-	0.32	2.7	5×10^{-5}	1964-68	Novosibirsk, USSR
CBX	e^-e^-	1.0	11.8	2×10^{-4}	1965-68	Stanford, USA
VEPP-2	e^+e^-	1.34	11.5	4×10^{-4}	1966-70	Novosibirsk, USSR
ACO	e^+e^-	1.08	22	0.001	1967-72	Orsay, France
ADONE	e^+e^-	3.0	105	0.006	1969-93	Frascati, Italy
CEA	e^+e^-	6.0	226	0.8×10^{-4}	1971-73	Cambridge, USA
ISR	pp	62.8	943	1.4	1971-80	CERN
SPEAR	e^+e^-	8.4	234	0.12	1972-90	SLAC, USA
DORIS	e^+e^-	11.2	289	0.33	1973-93	DESY, Germany
VEPP-2M	e^+e^-	1.4	18	0.05	1974-2000	Novosibirsk, USSR
VEPP-3	e^+e^-	3.1	74	2×10^{-5}	1974-75	Novosibirsk, USSR
DCI	e^+e^-	3.6	94.6	0.02	1977-84	Orsay, France
PETRA	e^+e^-	46.8	2304	0.24	1978-86	DESY, Germany
CESR	e^+e^-	12	768	13	1979-2008	Cornell, USA
PEP	e^+e^-	30	2200	0.6	1980-90	SLAC, USA
$Sp\bar{p}S$	$p\bar{p}$	910	6911	0.06	1981-90	CERN
TRISTAN	e^+e^-	64	3018	0.4	1987-95	KEK, Japan
Tevatron	$p\bar{p}$	1960	6283	4.3	1987-2011	Fermilab, USA
SLC	e^+e^-	100	2920	0.025	1989-98	SLAC, USA
LEP	e^+e^-	209.2	26659	1	1989-2000	CERN
HERA	ep	30+920	6336	0.75	1992-2007	DESY, Germany
PEP-II	e^+e^-	3.1+9	2200	120	1999-2008	SLAC, USA
KEKB	e^+e^-	3.5+8.0	3016	210	1999-2010	KEK, Japan
VEPP-4M	e^+e^-	12	366	0.22	1979-	Novosibirsk, Russia
BEPC-I/II	e^+e^-	4.6	238	10	1989-	IHEP, China
DAΦNE	e^+e^-	1.02	98	4.5	1997-	Frascati, Italy
RHIC	p, i	510	3834	2.5	2000-	BNL, USA
LHC	p, i	13600	26659	210	2009-	CERN
VEPP2000	e^+e^-	2.0	24	0.4	2010-	Novosibirsk, Russia
S-KEKB	e^+e^-	7+4	3016	6000*	2018-	KEK, Japan
NICA	p, i	13	503	1*	2024(tbd)	JINR, Russia
EIC	ep	10+275	3834	105*	2032(tbd)	BNL, USA

Ref: V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006, 2021; S. Nagaitesev

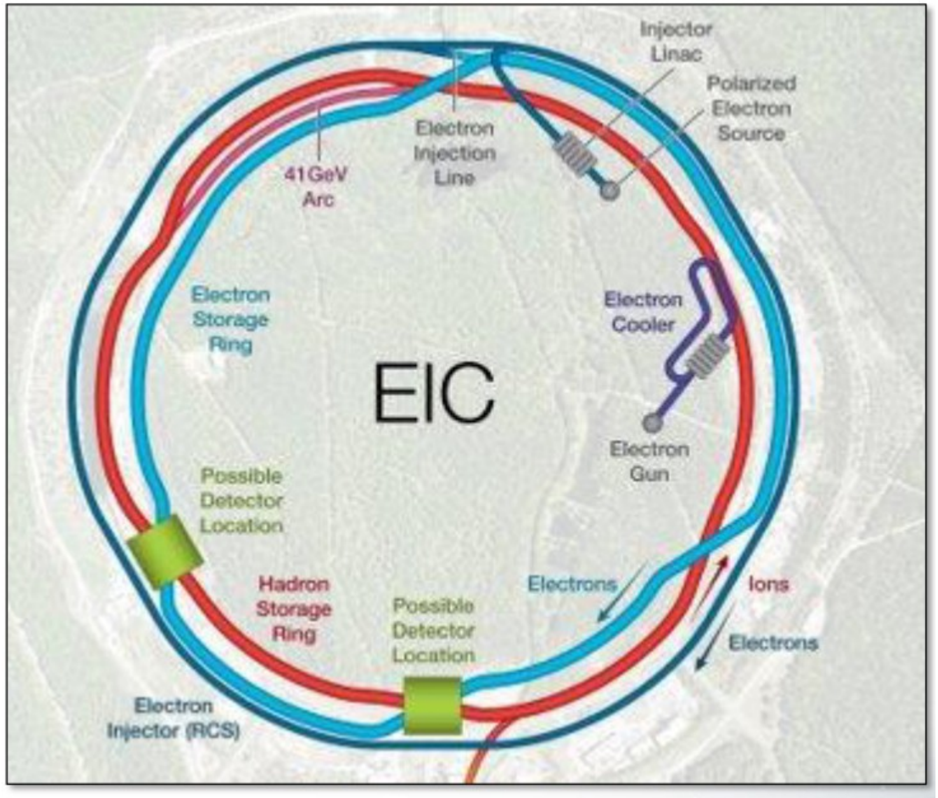
Courtesy: T. Satogata

EIC at BNL

- **E**lectron-**I**on **C**ollider, re-using RHIC tunnel

- Not a high-energy physics collider, but a nuclear physics collider
  - Nuclear physics scattering experiments
  - Collective and single-partice effects in strong interaction

- Aims to answer 3 fundamental nuclear physics questions:
  - How does nuclear mass arise?
  - How does nuclear spin arise?
  - What are emergent properties of dense gluon systems?



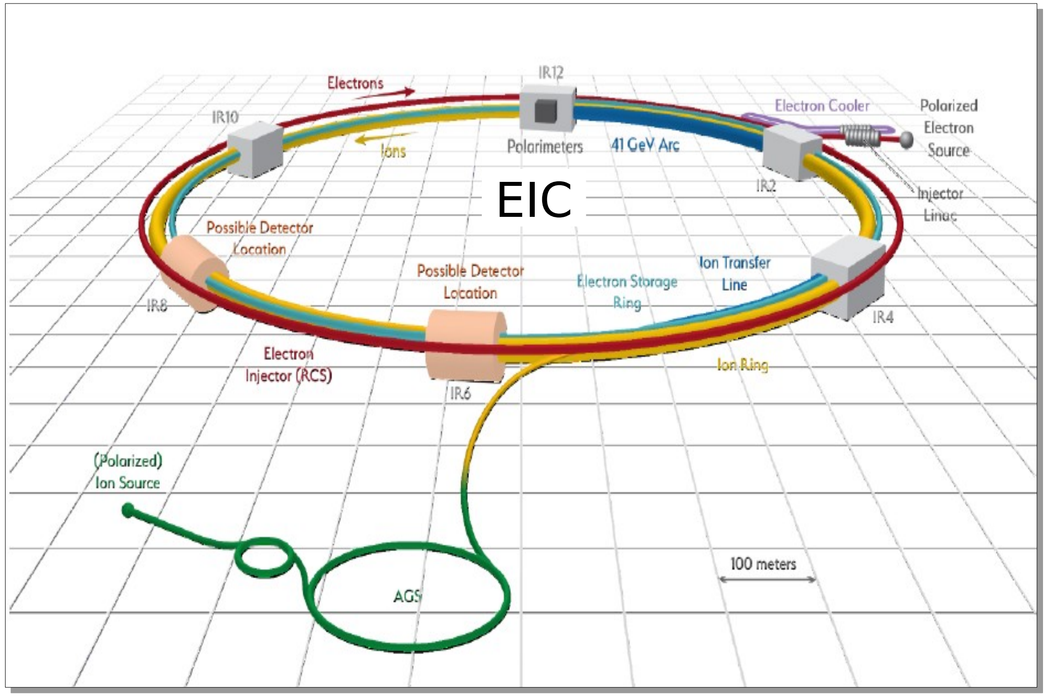
Courtesy: T. Satogata

EIC at BNL

- **Hadron storage ring: 40 – 275 GeV (existing)**
  - 1160 bunches, 1 A beam current
  - Small vertical emittance
  - Strong cooling

- **Electron storage ring: 2.5 – 18 GeV (new)**
  - Up to 1160 polarized bunches
  - Large beam current of 2.5 A → 9 MW SR power
  - Superconducting RF

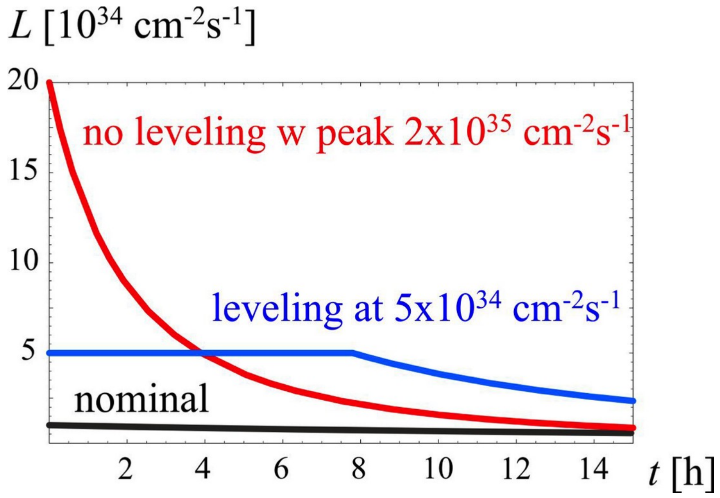
- **Rapid cycling synchrotron (RCS): 0.4 – 18 GeV (new)**
- **High luminosity interaction regions: (new)**



Courtesy: M. Zerlauth

High-Luminosity LHC

- HL-LHC is major upgrad of the LHC
- Main goals:
  - Total integrated luminosity of 3000 fb^{-1} (10 x LHC)
  - Target of ~ 250 fb^{-1} integrated luminosity per year
- Some changes:
  - New 11 T magnets with collimators in between
  - Higher bunch-charge
  - Smaller beta-function at the interaction point, achieved by Achromatic Telescopic Squeeze (ATS) Optics



	LHC 2024	**HL-LHC**
Protons per bunch	1.6 x 10^{11}	2.2 x 10^{11}
Number of bunches	2352	2750
Normalized emittance	1.8 micron	2.5 micron
Beta*	30 cm	15 cm
Full crossing angle	320 microrad	500 microrad
Geometric reduction factor F	0.6	0.35
“Virtual” luminosity	4.2 x 10^{34} $cm^{-2}s^{-1}$	2.4 x 10^{35} $cm^{-2}s^{-1}$
Levelled luminosity	2.1 x 10^{34} $cm^{-2}s^{-1}$	5 x 10^{34} $cm^{-2}s^{-1}$

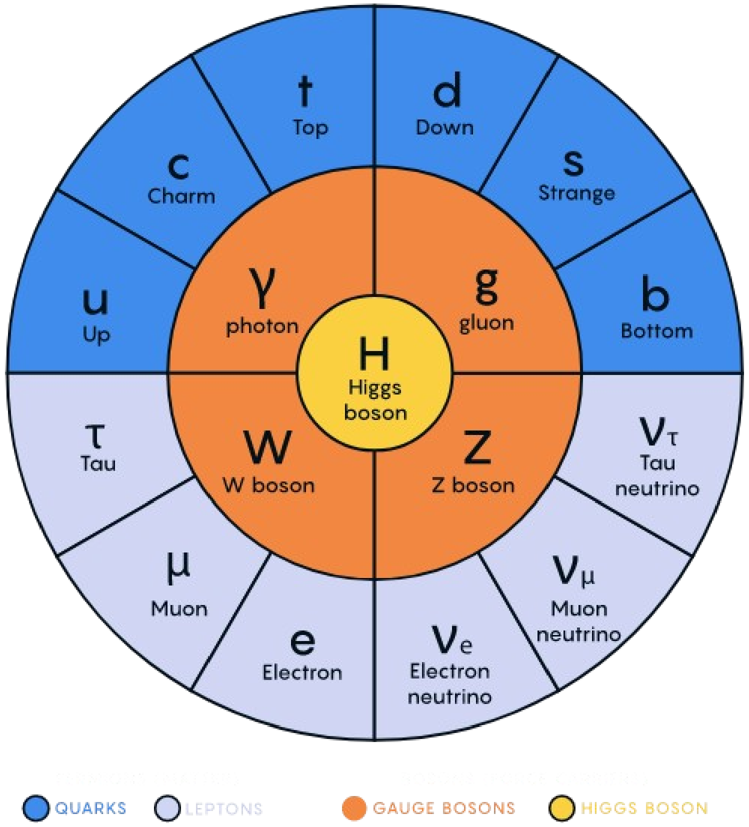
Particle Physics - Status

- Standard Model (SM) confirmed to high accuracy up to several TeV

- Higgs-boson discovered
  - At the mass predicted within the SM by LEP precision electro-weak measurements

- Absence of new physics at the TeV scale

Need for a new, broad and ambitious program
→ **more precision**
→ **more energy**
→ **for more sensitivity for new physics**



https://forumias.com/blog/the-standard-model-of-particle-physics-gets-a-jolt/#gsc.tab=0

Courtesy: R. Bruce, E. Metral

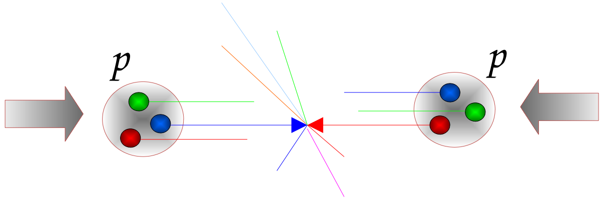
Considerations

- ***The What?***

Hadrons (protons or ions)

- Mix of quarks and gluons
- Variety of processes
- Discoveries at physics frontiers
- Huge QCD background
- Typically high collision energy

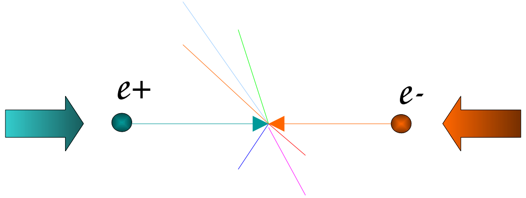
- Main limitation: dipole field and ring size



Leptons

- Elementary particles colliding
- Low back-ground in experiments
- High-precision measurements
- Well-defined center-of-mass energy

- Main limitation: energy loss from synchrotron radiation



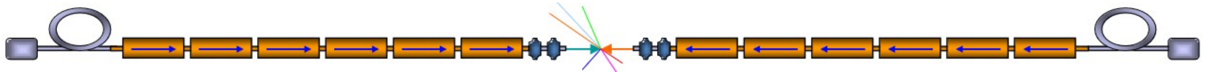
Considerations

- ***The What?***
- ***The How?***

Linear Collider

- Single-pass
- Single experiment
- Few magnets, many RF-cavities

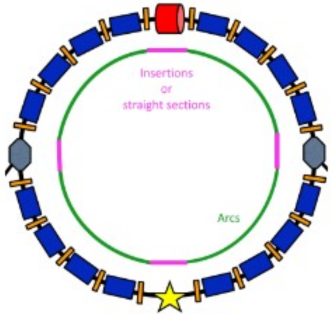
- Main limitation: length of collider and accelerating technology



Circular Collider

- Multi-pass
- Multiple experiments
- More magnets, fewer RF-cavities

- Main limitation: Circumference of colliding to bend particles; SR energy loss for light particles



Considerations

- ***The What?***
- ***The How?***
- ***The When?***

Technological readiness

- Completeness of designs/proposals
- High-field magnet technology
- Accelerating gradients
- Energy efficiency and sustainability

Order

- Would a new lepton or hadron machine be the logical next step?

Ressources

- Are there enough ressources to build as many as we want?

Considerations

- ***The What?***
- ***The How?***
- ***The When?***
- ***The Why?***

Next Energy Scale

- Need to probe parton collisions up to 10 TeV

Higgs Particle

- Precision studies at a Higgs-Factory ~ 250 GeV

SM and Dark Matter

- SM seems incomplete
- Answers on dark matter and dark energy
- Matter – antimatter asymmetry

Electro-weak Measurements

- Studies at the ttbar-threshhold up to ~ 500 GeV

What We Want:

20 GeV to 150 TeV

First physics soon

Cost effective and low consumption

Leptons and Hadrons

https://www.persoenlich.com/kategorie-werbung/eine-eierlegende-wollmilchsau-fur-vw

Decisions for the Future

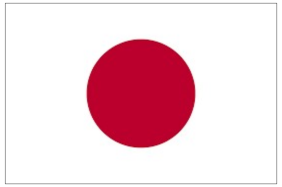
- Europe: European strategy upgrade of particle physics (ESPP)
- USA: Particle Physics Project Priorization Panel (P5) and Snowmass Process
- China: Five year plan to decide on funding
- Japan: Yearly budget plan

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

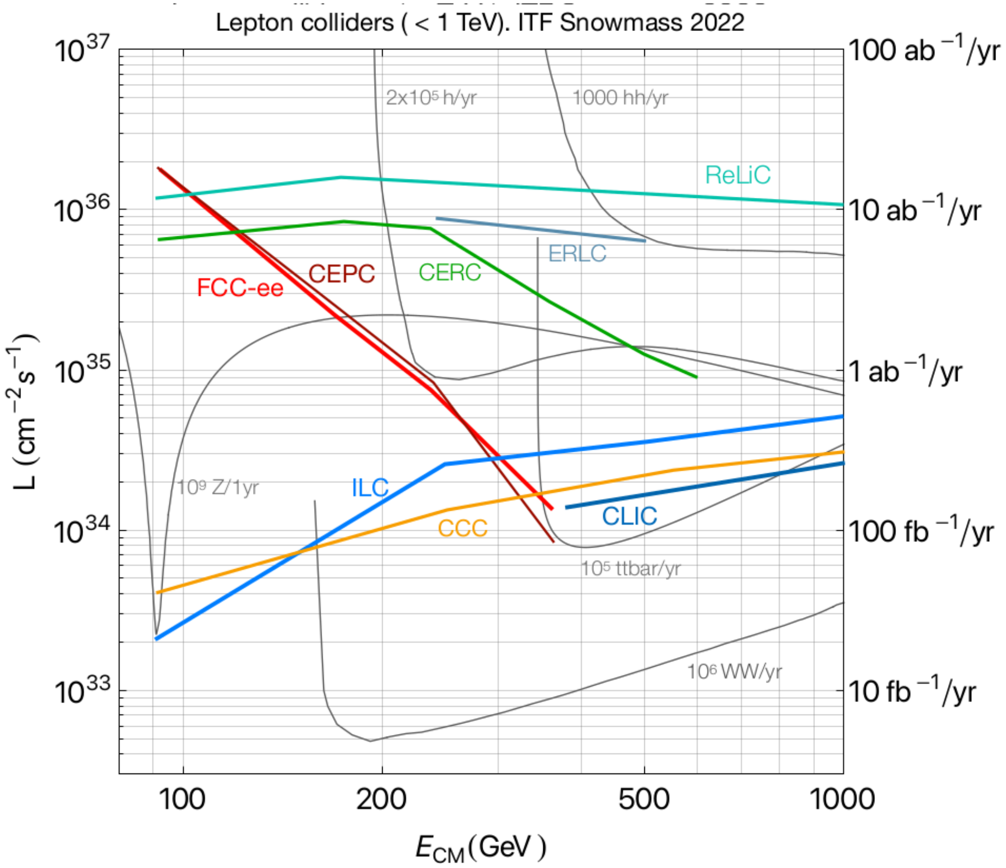
Exploring the Quantum Universe



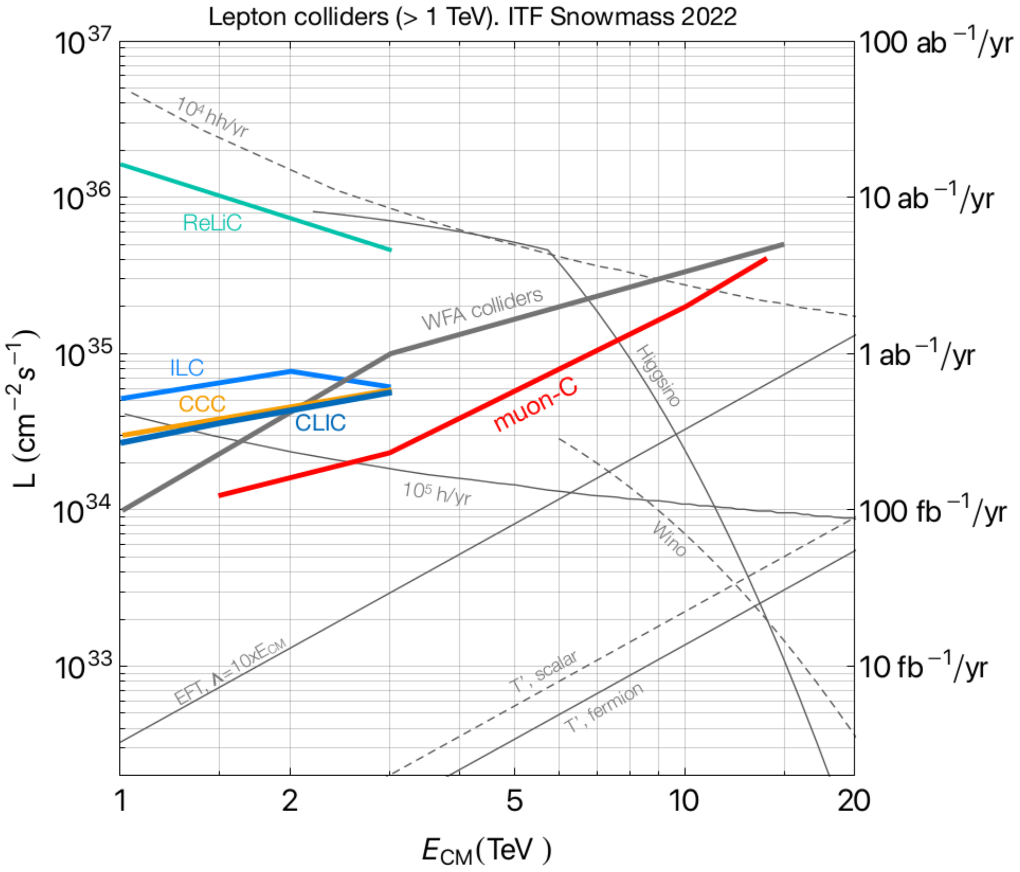
Courtesy: Snowmass Report

Future Landscape - Leptons

- Lower energy regime
  - Higgs and electroweak factories



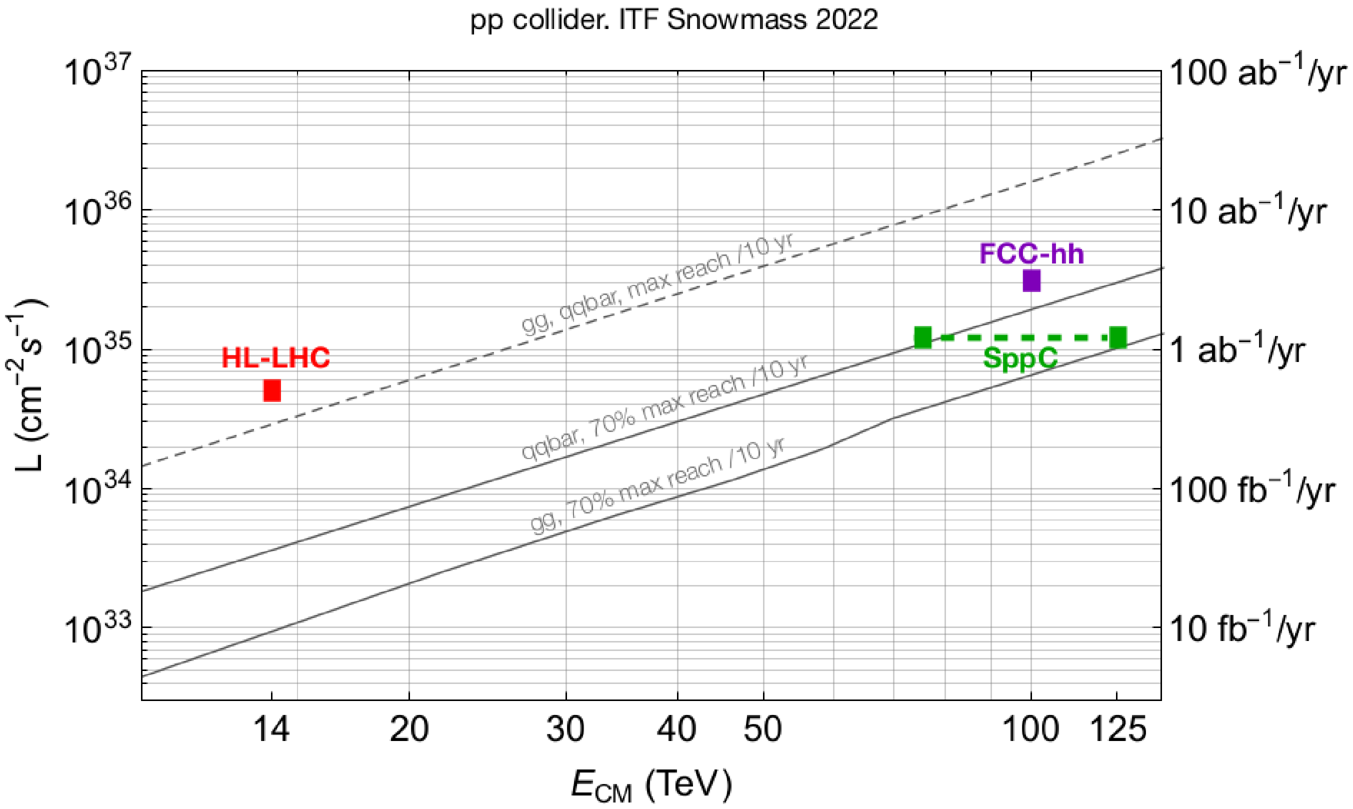
- Higher energy regime
  - Energy frontier with leptons



Courtesy: Snowmass Report

Future Landscape - Hadrons

- Next generation of circular hadron colliders to probe next order of magnitude of energies



Circular e+e- Colliders

2 Studies

- CERN, Switzerland
  - **Future e+e- Circular Collider, FCC-ee**
  - Future hadron Circular Collider, FCC-hh
- IHEP, China
  - **Circular Electron Positron Collider, CEPC**
  - Super proton-proton Collider, SppC

FCC Feasibility Study

Long-Term Goal: World-leading high energy physics infrastructure for 21st century to push particle-physics precision and energy frontiers far beyond present limits

***More than
140 institutes
from
33 countries***

FCC Mid-Term Report

- **MTR Goal:** Asses progress of feasibility study towards the final report by February 2024

Future Circular Collider
Midterm Report

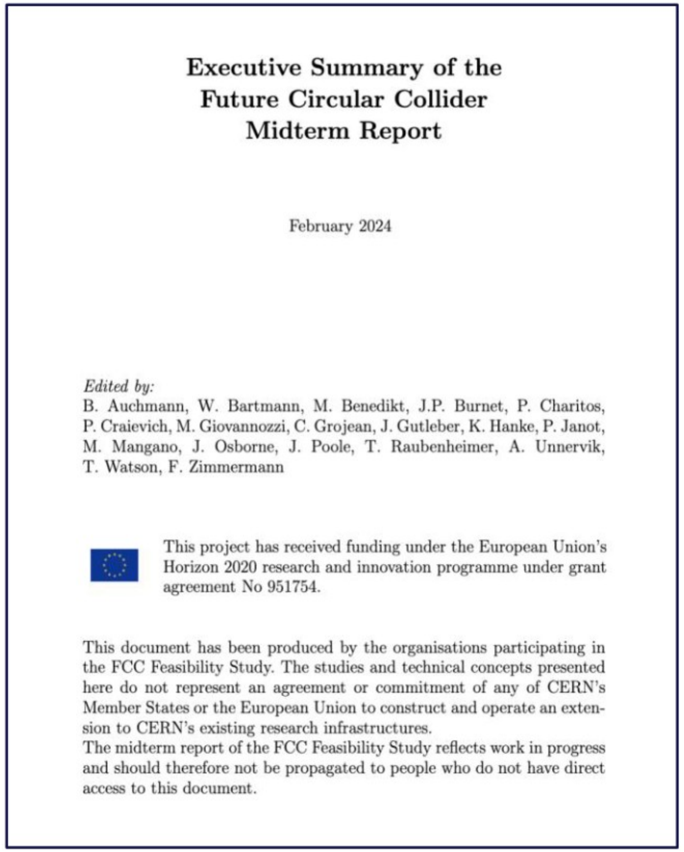
February 2024

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, T. Watson, F. Zimmermann

This project has received funding under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

This document has been produced by the organisations participating in the FCC feasibility study. The studies and technical concepts presented here do not represent an agreement or commitment of any of CERN's Member States or of the European Union for the construction and operation of an extension to CERN's existing research infrastructures.
The midterm report of the FCC Feasibility Study reflects work in progress and should therefore not be propagated to people who do not have direct access to this document.

8 Chapters
~ 700 pages
~ 16 editors
~ 300 contributors



Executive Summary of the
Future Circular Collider
Midterm Report

February 2024

Edited by:
B. Auchmann, W. Bartmann, M. Benedikt, J.P. Burnet, P. Charitos, P. Craievich, M. Giovannozzi, C. Grojean, J. Gutleber, K. Hanke, P. Janot, M. Mangano, J. Osborne, J. Poole, T. Raubenheimer, A. Unnervik, T. Watson, F. Zimmermann

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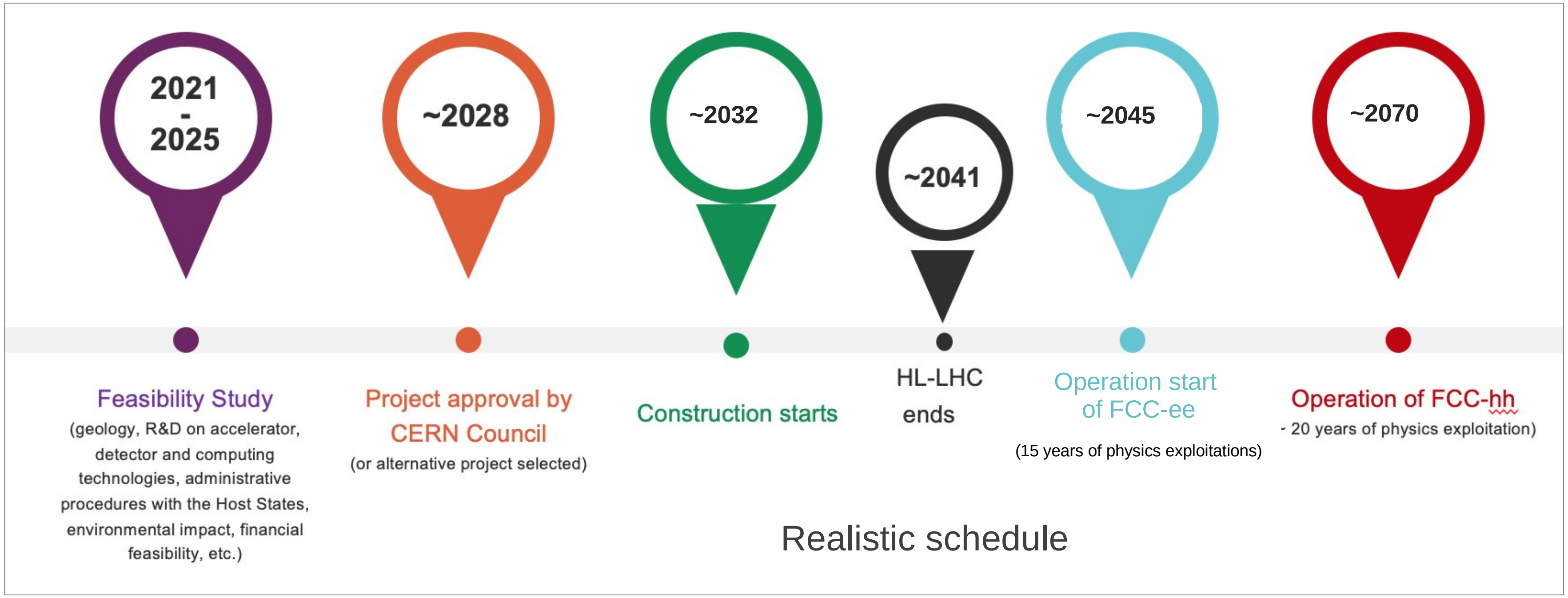
8 Chapters
~ 45 pages
~ 16 editors

Feasibility Study and Schedule

- **Goal:** Demonstration of the geological, technical, environmental, financial and administrative feasibility of the FCC-ee, including its optimisation
- Project preparatory phase with adequate resources immediately after Feasibility Study

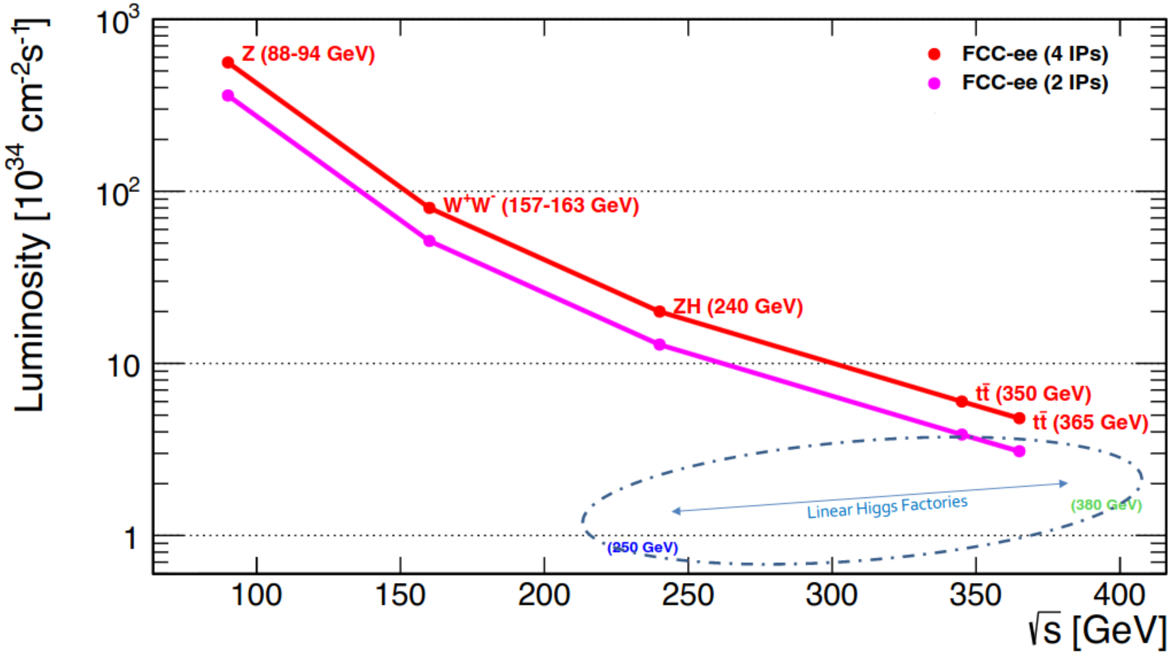


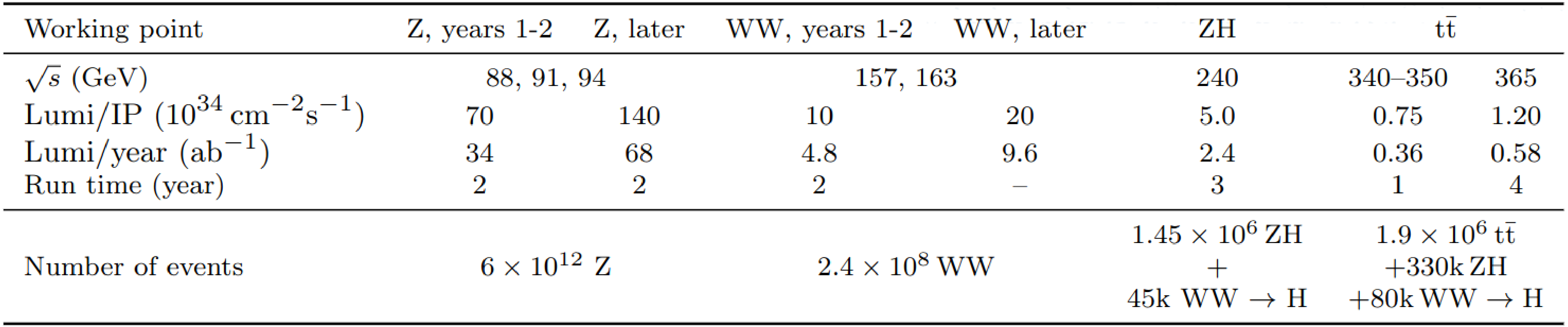
Realistic schedule

Courtesy: C. Grojean

FCC-ee Run Plan

- In principle 4 different energy stages
  - Z-pole
  - W-pair-production
  - ZH-production
  - top-pair threshhold



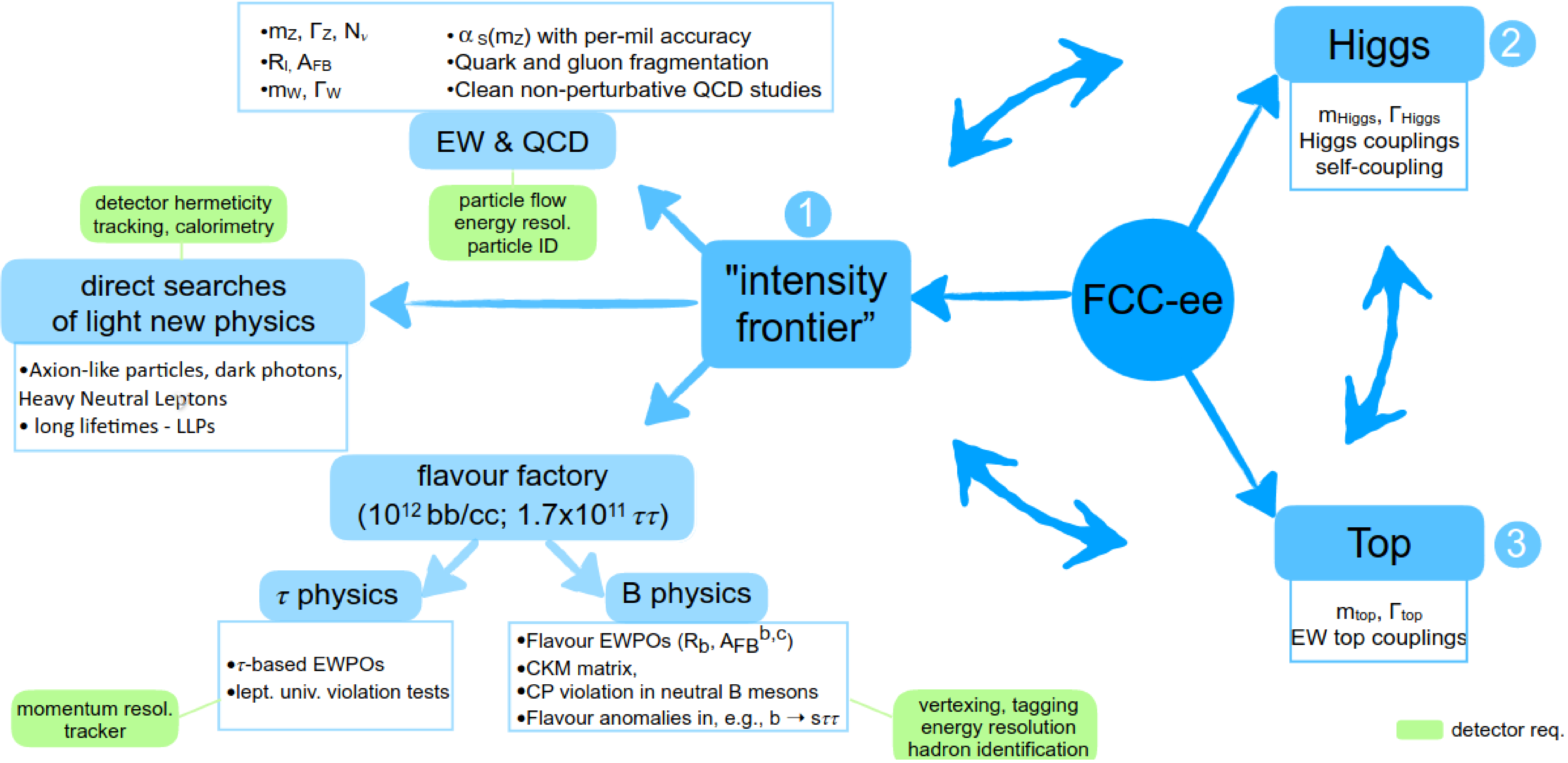


Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW → H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW → H	

Number of events are for the current baseline with 4 Interaction Points

Courtesy: C. Grojean

FCC-ee Physics Programme



- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W

- $\alpha_s(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

EW & QCD

particle flow
energy resol.
particle ID

detector hermeticity
tracking, calorimetry

direct searches
of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

1

"intensity frontier"

FCC-ee

Higgs

2

m_{Higgs}, Γ_{Higgs}
Higgs couplings
self-coupling

Top

3

m_{top}, Γ_{top}
EW top couplings

flavour factory
(10^{12} bb/cc; $1.7\text{x}10^{11}$ $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

momentum resol.
tracker

B physics

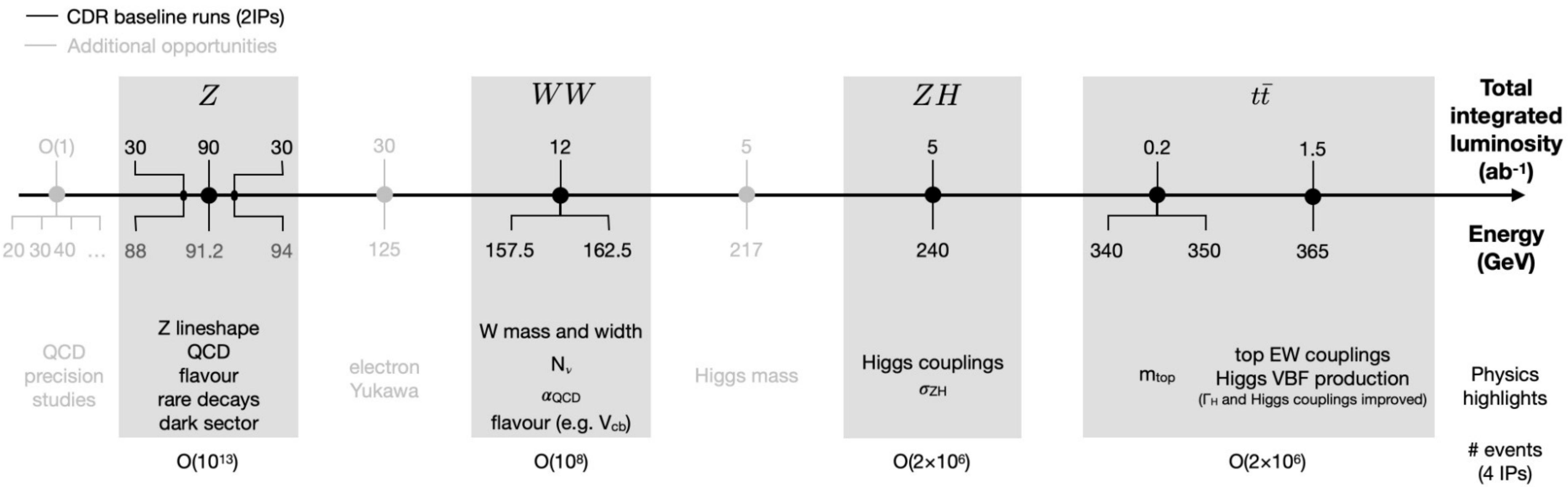
- Flavour EWPOs (R_b, $A_{FB}{}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., b → $s\tau\tau$

vertexing, tagging
energy resolution
hadron identification

🟩 detector req.

Courtesy: C. Grojean

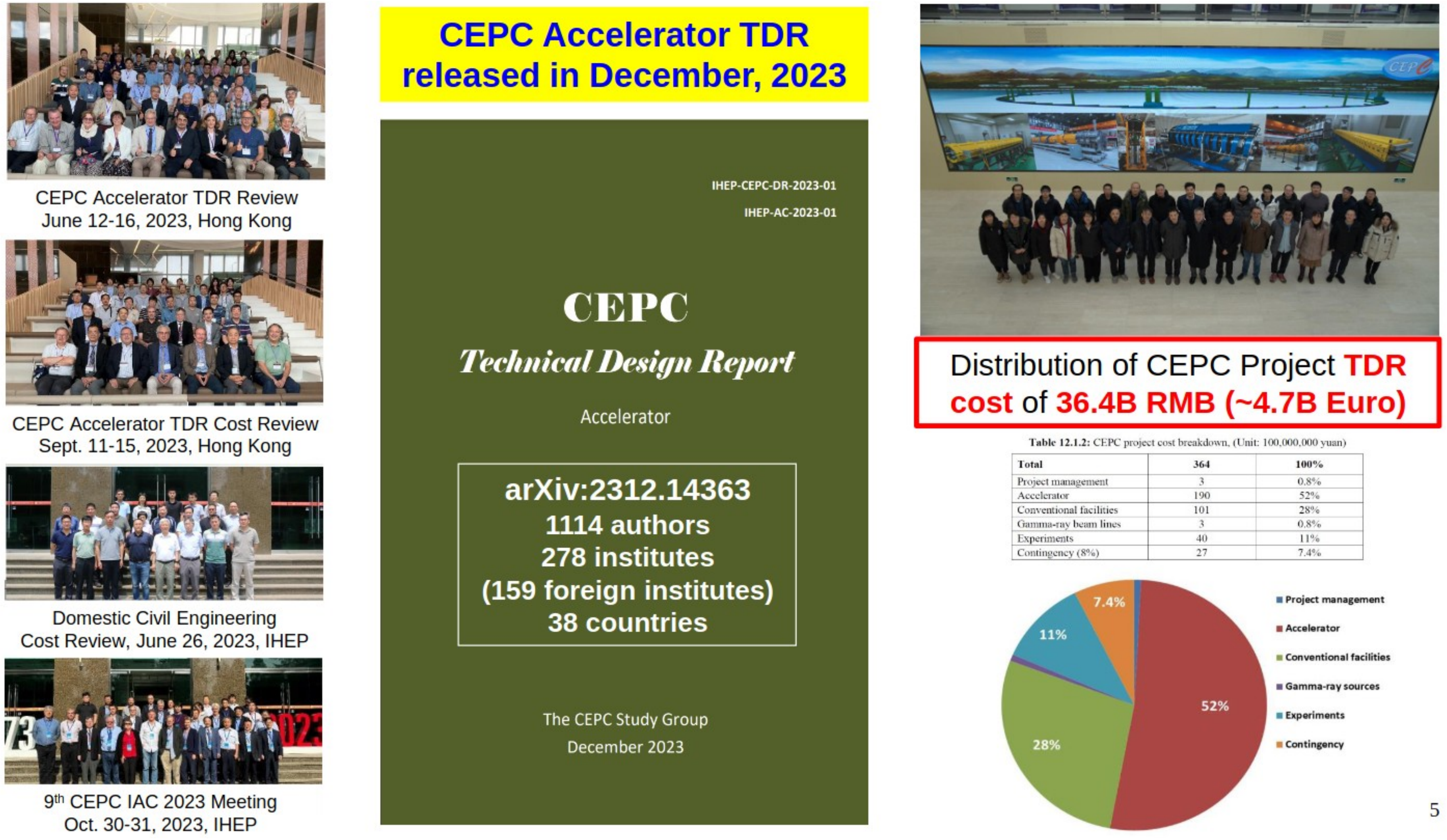
Beyond the Collider Programme



- Many opportunities beyond the baseline plan
- Complementary experiments using e.g. beam dump, re-using synchrotron radiation photons

Courtesy: H. Yang, CEPC Workshop 2024

CEPC Status



CEPC Accelerator TDR Review
June 12-16, 2023, Hong Kong

CEPC Accelerator TDR Cost Review
Sept. 11-15, 2023, Hong Kong

Domestic Civil Engineering
Cost Review, June 26, 2023, IHEP

9th CEPC IAC 2023 Meeting
Oct. 30-31, 2023, IHEP

CEPC Accelerator TDR released in December, 2023

IHEP-CEPC-DR-2023-01
IHEP-AC-2023-01

CEPC
Technical Design Report
Accelerator

arXiv:2312.14363
1114 authors
278 institutes
(159 foreign institutes)
38 countries

The CEPC Study Group
December 2023

Distribution of CEPC Project **TDR cost** of **36.4B RMB (~4.7B Euro)**

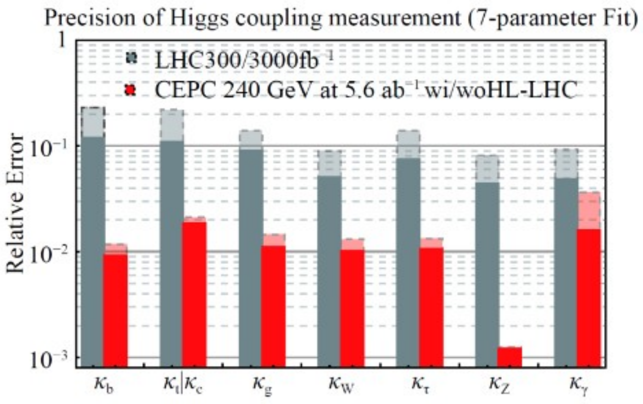
Table 12.1.2: CEPC project cost breakdown, (Unit: 100,000,000 yuan)

Total	**364**	**100%**
Project management	3	0.8%
Accelerator	190	52%
Conventional facilities	101	28%
Gamma-ray beam lines	3	0.8%
Experiments	40	11%
Contingency (8%)	27	7.4%

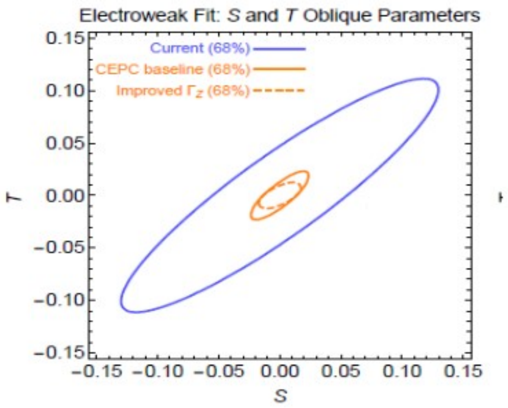
Courtesy: H. Yang, CEPC Workshop 2024

CEPC Physics Progam

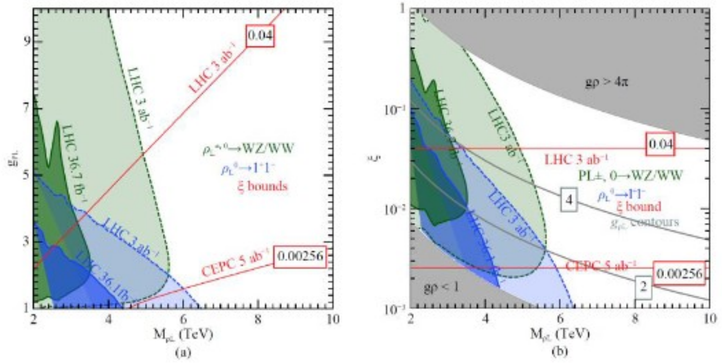
Higgs coupling precision can be improved by an order of magnititude

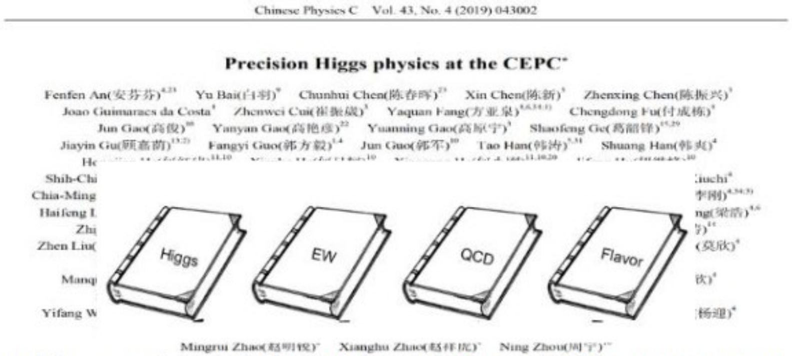


EW measurement can be improved by a large factor



Direct and indirect probe to new physics up to 10 TeV, an order of magntitude higher than the HL-LHC




Chinese Physics C Vol. 43, No. 4 (2019) 043002

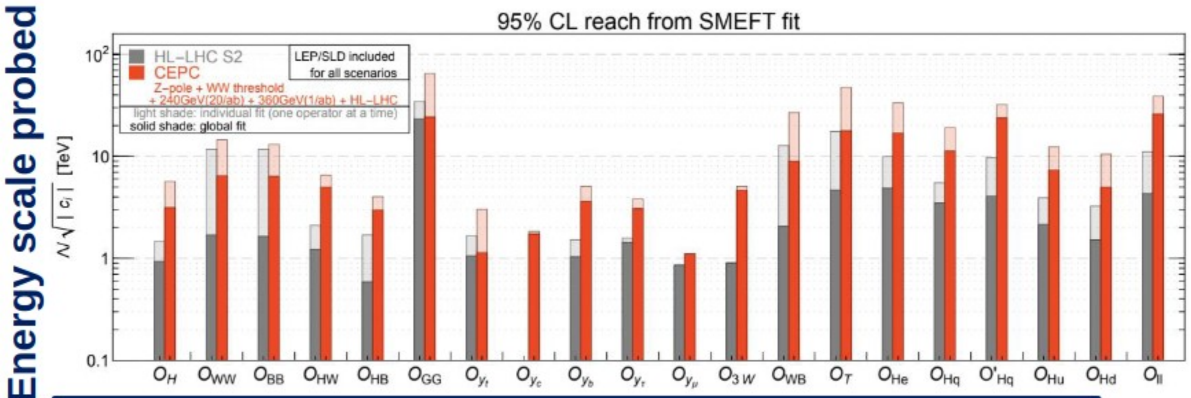
Precision Higgs physics at the CEPC*

Fenfen An(安芬芬) Yu Bai(白羽) Chunhui Chen(陈春晖) Xin Chen(陈新) Zhenxing Chen(陈振兴)
Joao Guimaraes da Costa Zhenwei Cui(崔振崴) Yaquan Fang(方亚泉) Chengdong Fu(付成栋)
Jun Gao(高俊) Yanyan Gao(高艳彦) Yuanning Gao(高原宁) Shaofeng Ge(葛韶锋)
Jiayin Gu(顾嘉荫) Fangyi Guo(郭方毅) Jun Guo(郭军) Tao Han(韩涛) Shuang Han(韩爽)

Mingrui Zhao Xianghu Zhao Ning Zhou

Chinese Physics C Vol. 43, No. 4 (2019) 043002

- ❖ ~ 300 Journal / arXiv papers

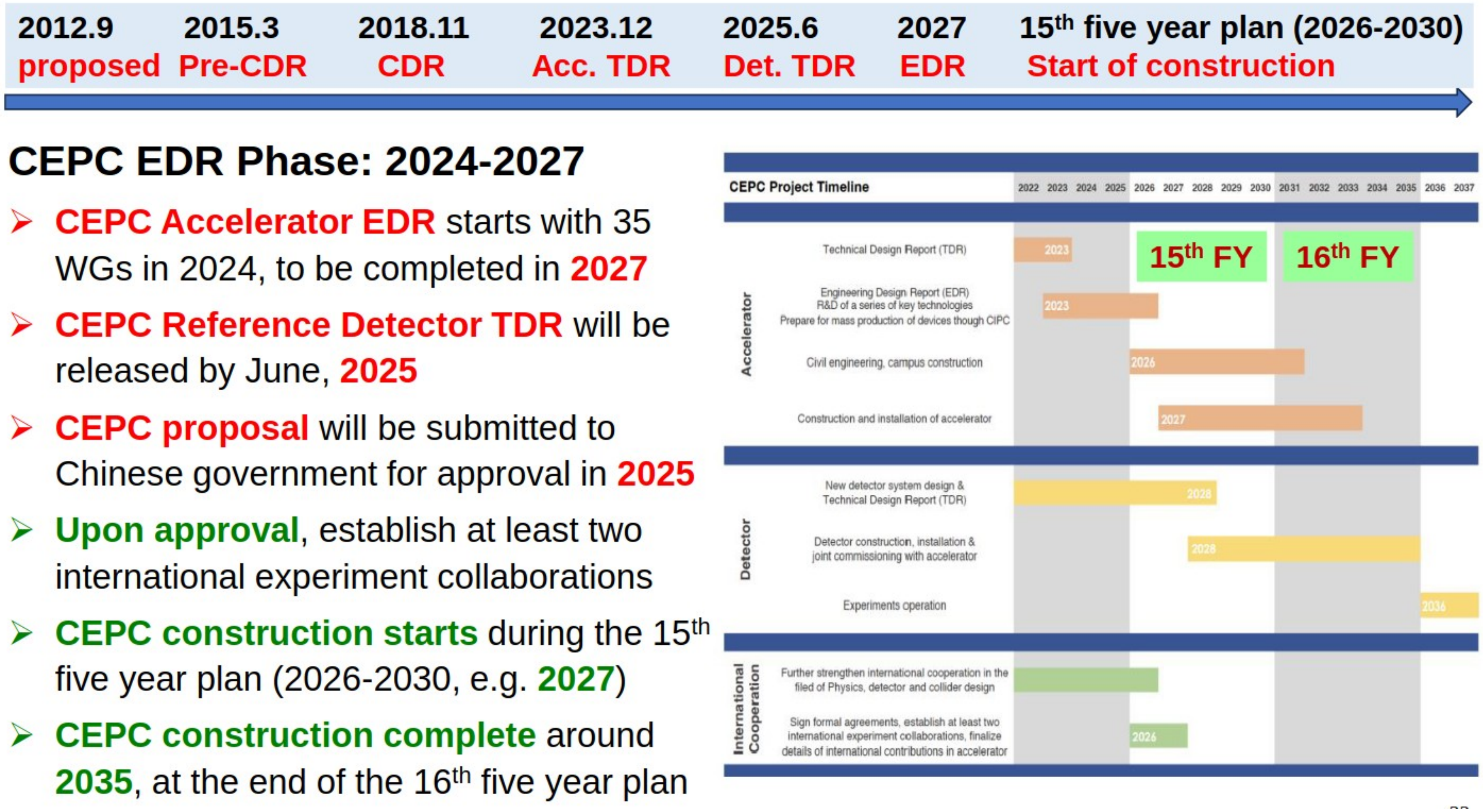


CEPC can reveal new physics at energy ~ 10 TeV or higher

9

Courtesy: H. Yang, CEPC Workshop 2024

CEPC Timeline



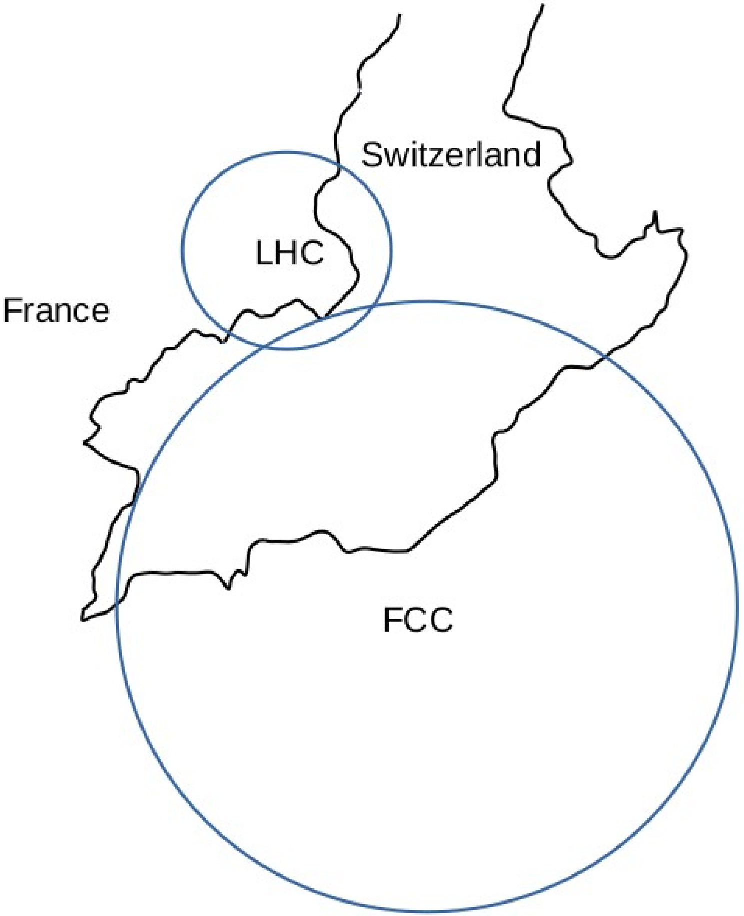
2012.9	2015.3	2018.11	2023.12	2025.6	2027	15th five year plan (2026-2030)
proposed	Pre-CDR	CDR	Acc. TDR	Det. TDR	EDR	Start of construction

CEPC EDR Phase: 2024-2027

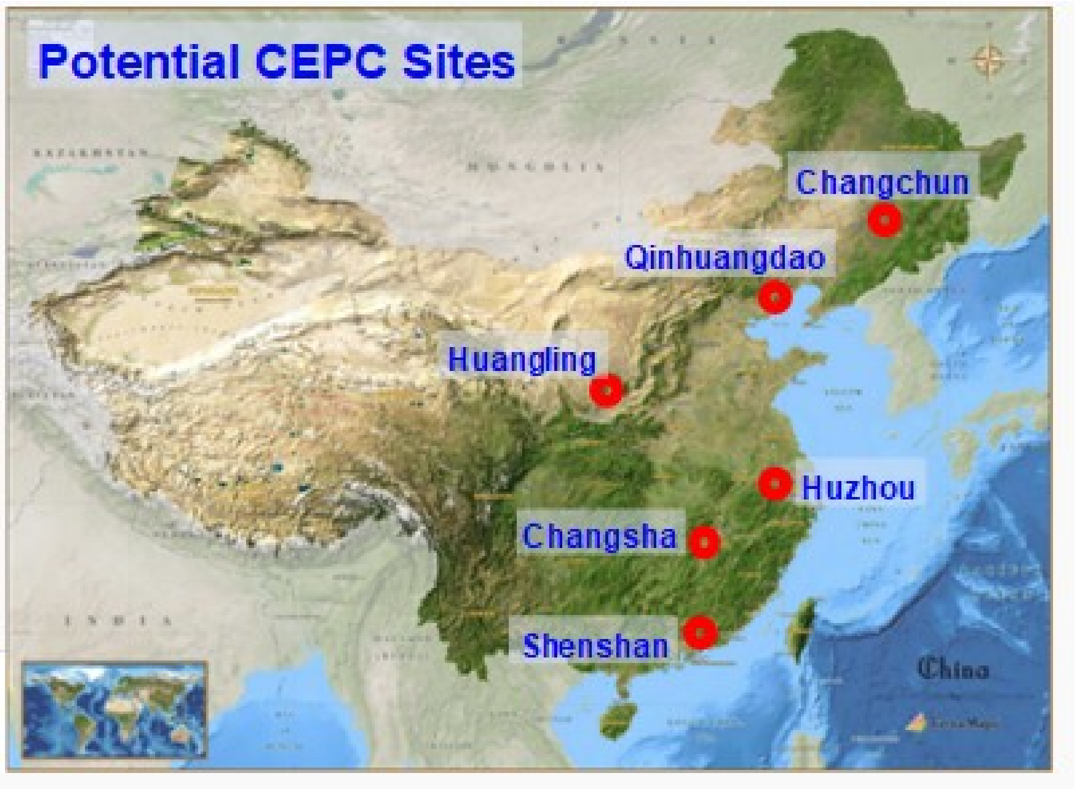
- **CEPC Accelerator EDR** starts with 35 WGs in 2024, to be completed in **2027**
- **CEPC Reference Detector TDR** will be released by June, **2025**
- **CEPC proposal** will be submitted to Chinese government for approval in **2025**
- **Upon approval**, establish at least two international experiment collaborations
- **CEPC construction starts** during the 15th five year plan (2026-2030, e.g. **2027**)
- **CEPC construction complete** around **2035**, at the end of the 16th five year plan

Placement

- FCC-ee: 91 km circumference



- CEPC: 100 km circumference

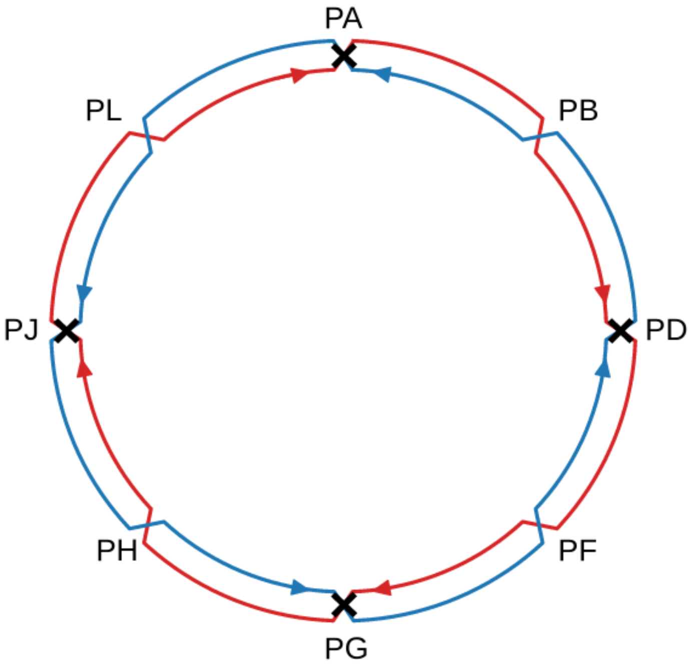


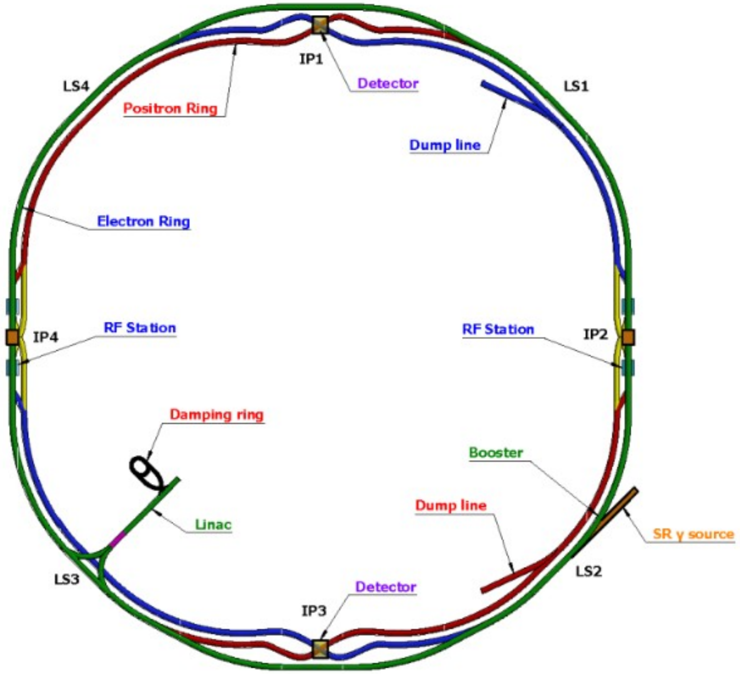
Courtesy: CEPC

Timeline and Schematic Layout

- FCC-ee:
  - Project approval possible in 2027
  - **First collisions ~ 2045**

- CEPC:
  - Project approval possible in 2026
  - **First collisions ~ 2040** Optimistic?





Courtesy: CPC TDR

Energy Stages

- CERN, Switzerland
  - Future e+e- Circular Collider, FCC-ee
  - **4 Interaction Points**

- IHEP, China
  - Circular Electron Positron Collider, CEPC
  - **2 Interaction Points**

E_{Beam} [GeV]	Mode
45.6	Z-lineshape
62.5	H-energy
80	WW
120	ZH-production peak
182.5	Top-pair-threshold

First measurements of

Special mode, **monochromatization**

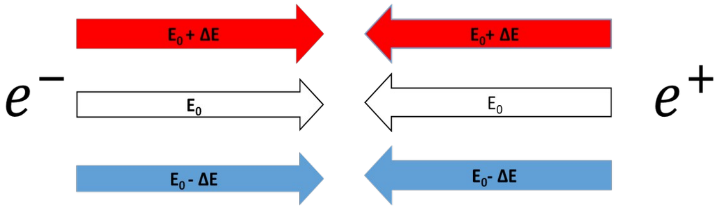
Not mentioned in TDR

First measurements of

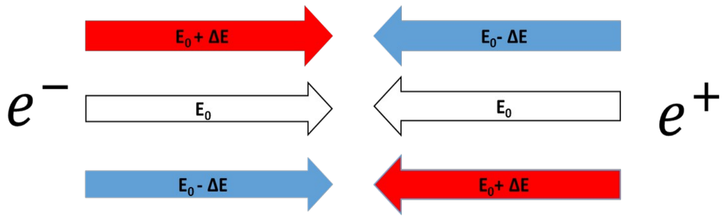
Monochromatization

- 62.5 GeV beam energy corresponds to the **peak of Higgs-production** with narrow width of 4.2 MeV
- For **minimization of collision energy spread** –> monochromatization techniques required

Introducing dispersion



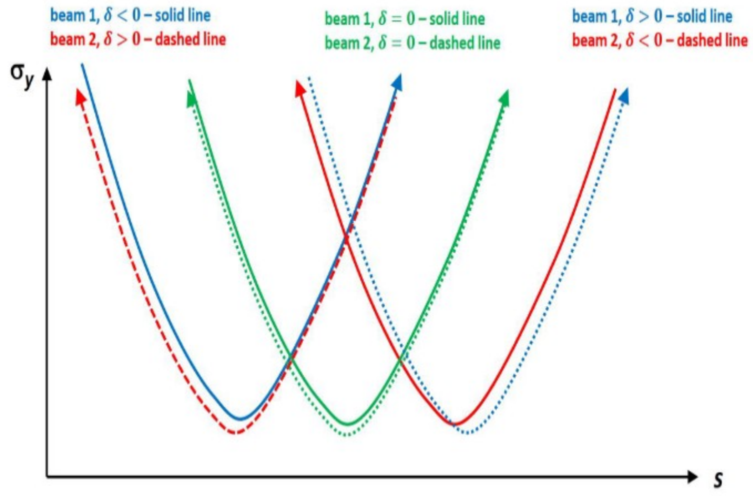
Same sign dispersion at the interaction point leads to increase of E_{CM} spread



Opposite sign dispersion helps reducing E_{CM} spread

Courtesy: A. Faus-Golfe, H. Jiang and P. Raimondi

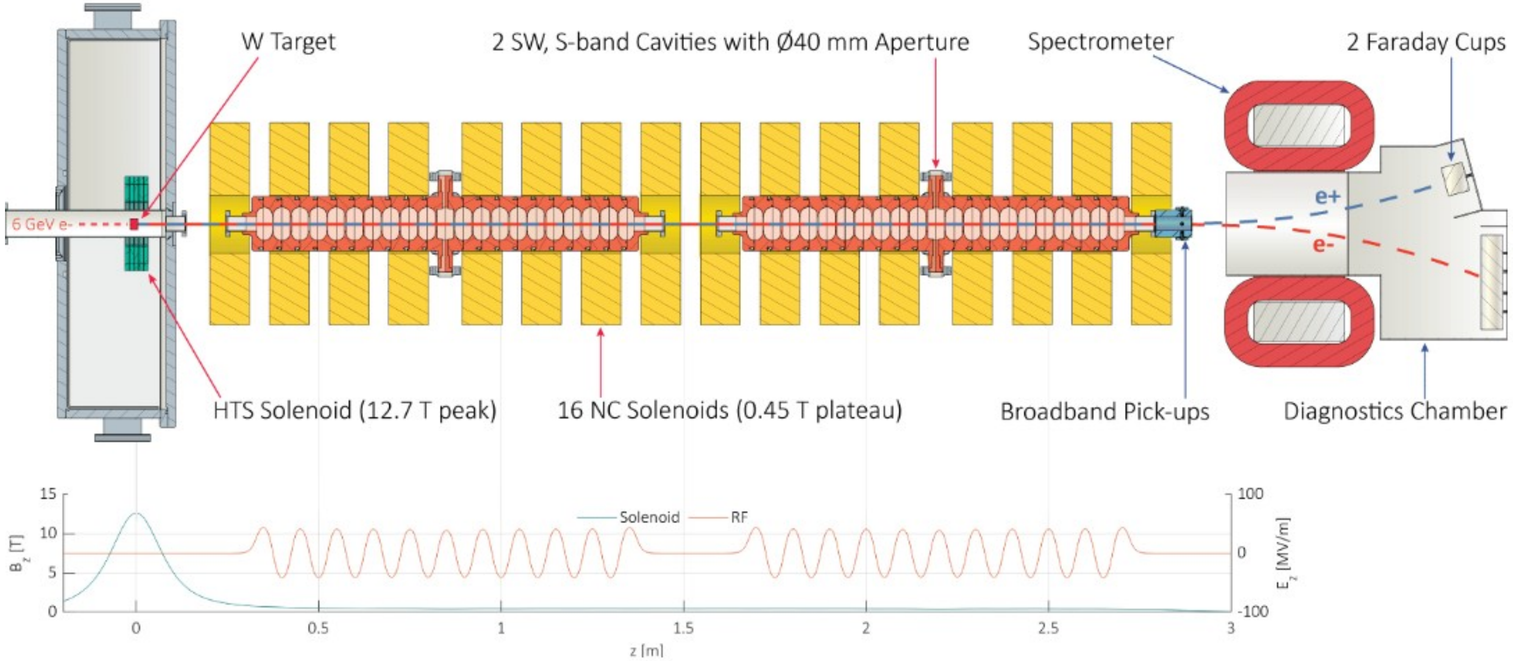
Introducing chromaticity



Non-zero local vertical chromaticity to reduce collision energy spread presently explored

Positron Production

- Positrons generated by electrons hitting high-Z-target
- Generated positrons have **large emittance and energy spread** → must be reduced
- Novel capture techniques tested at **P³** (PSI Positron Production), relevant for future colliders



N. Vallis et al, arXiv:2308.16803v2, 2023.

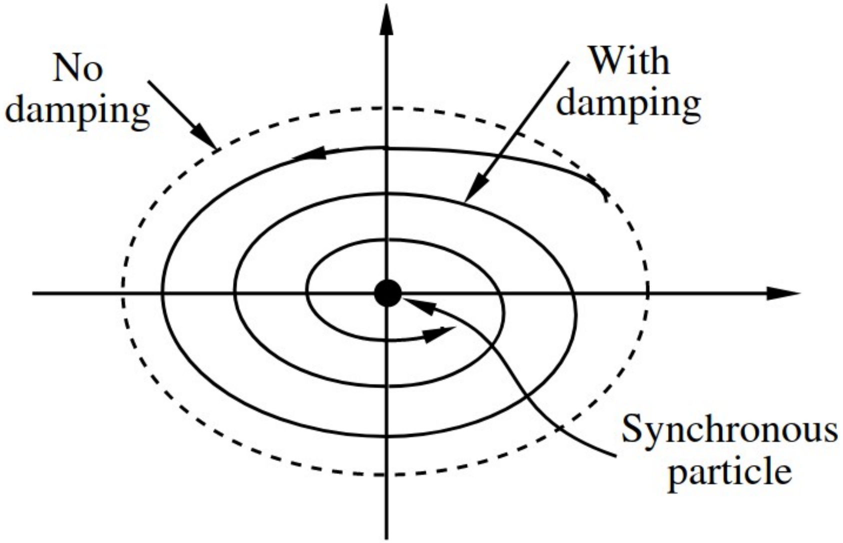
Synchrotron Radiation (SR)

- Electrons/Positrons about 2000 times lighter than protons → 10^{13} greater radiation losses

$$P_\gamma = \frac{2}{3} r_0 E_0 c \frac{\gamma_{\mathrm{rel}}^4 \beta_{\mathrm{rel}}^4}{\rho^2}$$

- Leads to a **natural damping** of the emittance over time

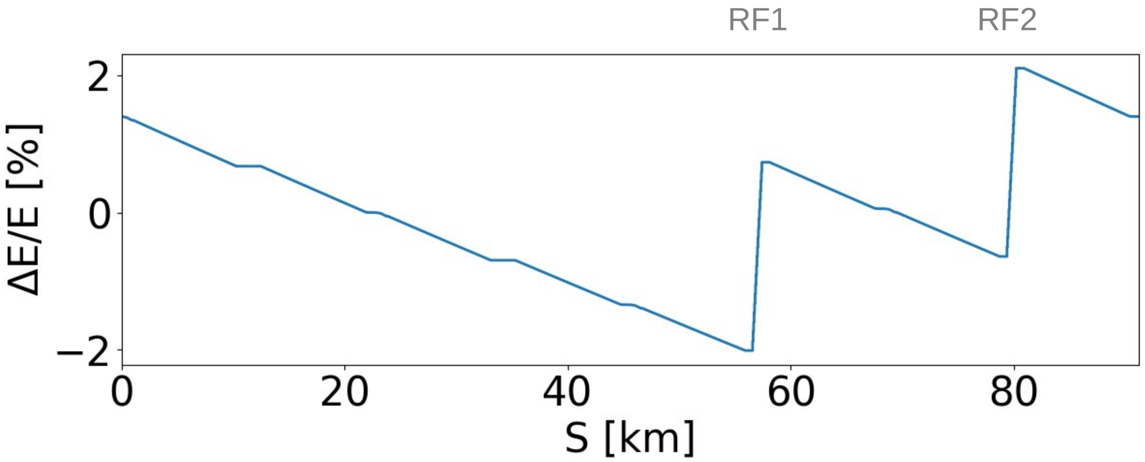
$$\varepsilon(t) = e^{-2\,t/\tau_{\mathrm{SR}}} \qquad \tau_{\mathrm{SR}} = \frac{T_0 E}{j_{x,y} U}$$

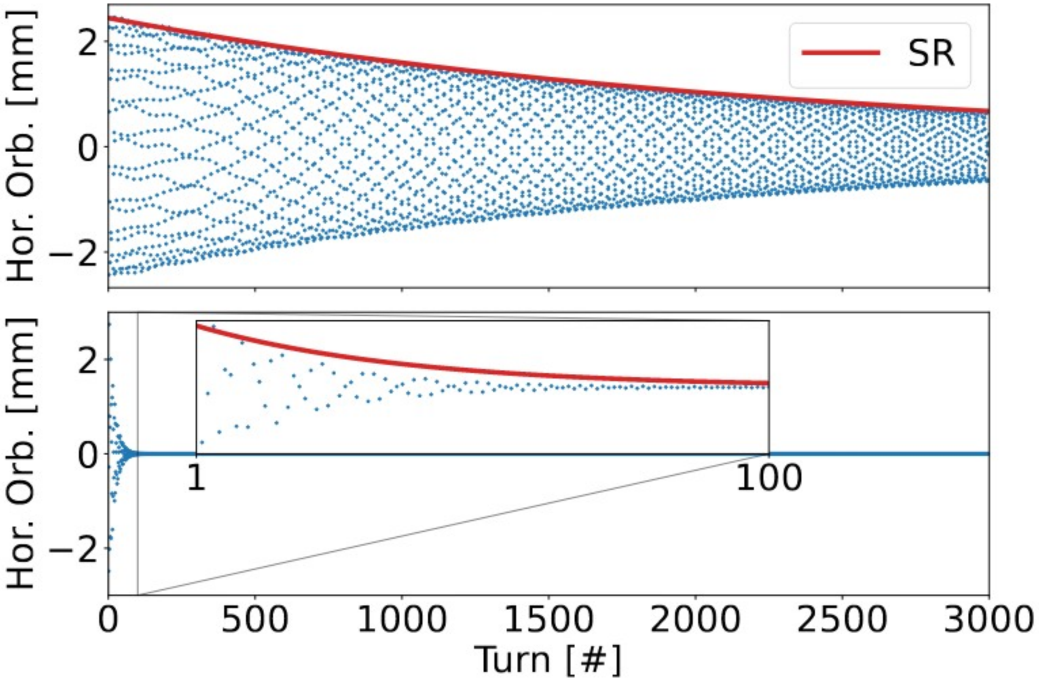


W. Barletta, USPAS lectures on synchrotron radiation, 2009.

Synchrotron Radiation Challenges

- At highest proposed energy mode of 182.5 GeV up to almost **10 GeV energy losses** per turn
- Synchrotron radiation damping only **~ 40 turns**, while about 2300 turns at 45.6 GeV
- Significant energy variation of a few % over the circumference
- Large energy gain required by RF-system
- Machine protection challenges
- ...



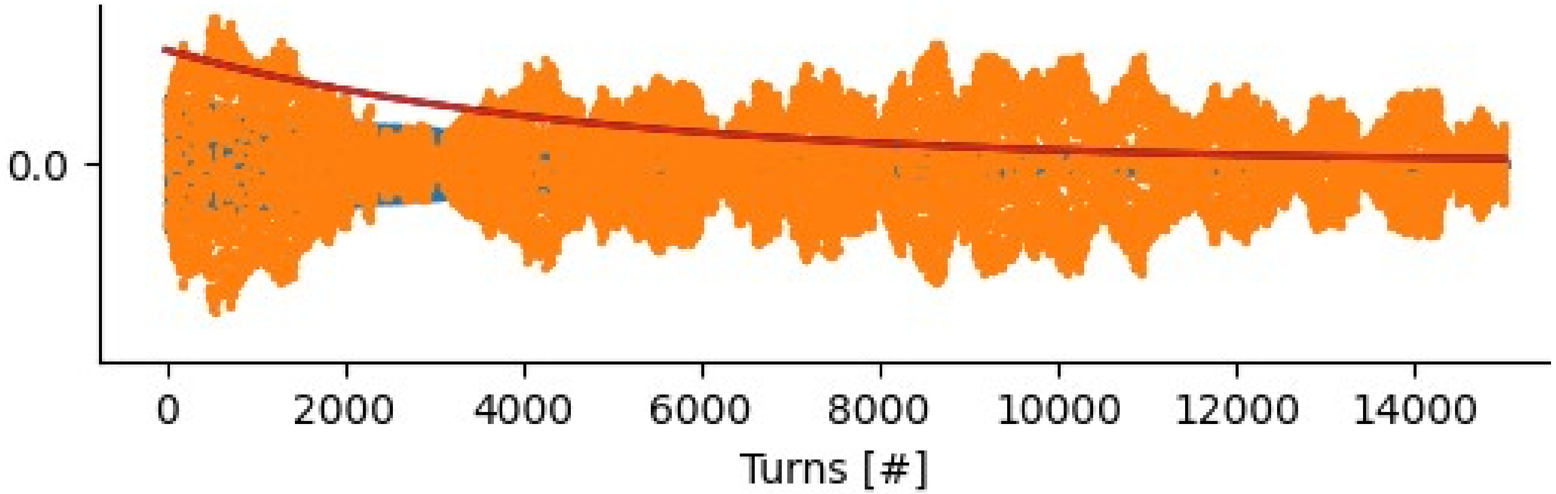


Quantum Excitation

- Photons emitted in discrete quanta following a **random Poisson process**
- Sudden loss leads to an instantaneous jump of the particle if emitted in dispersive region
- Introduced **noise** leads to emittance growth towards equilibrium

$$\epsilon_0 = C_q \gamma_0^2 \frac{I_5}{j_x I_2}$$

Cq… quantum radiation constant
I_2/I_5 … radiation integrals
jx … partition number



Blue: only synchrotron radiation; Orange: with quantum excitation

Parameters – CEPC

	Higgs	**Z**	**W**	**tt**
Number of IPs	2			
Circumference (km)	**100.0**			
SR power per beam (MW)	**30**			
Energy (GeV)	**120**	**45.5**	**80**	**180**
Bunch number	268	11934	1297	35
Emittance (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF frequency (MHz)	650			
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**5.0**	**115**	**16**	**0.5**

Start at Higgs-mode

Design and parameters dominated by choice to allow for 30 MW synchrotron radiation power per beam

Defines
→ RF system
→ Beam parameters

Longer circumference than FCC

Parameters – FCC-ee

	Z	WW	ZH	ttbar
Beam energy [GeV]	45.6	80	120	182.5
SR power/beam [MW]	**50**			
SR losses/turn [GeV]	0.0394	0.374	1.89	10.42
Beam current [mA]	1270	137	26.7	4.9
Bunches/beam [-]	11200	1780	440	60
Bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
RF voltage 400/800MHz [GV]	0.08/0	1.0/0	2.1/0	2.1/9.4
Horizontal β-function at IP [mm]	110	200	240	1000
Vertical β-function at IP [mm]	0.7	1.0	1.0	1.6
Horizontal emittance [nm]	0.71	2.17	0.71	1.59
Vertical emittance [pm]	1.9	2.2	1.4	1.6
Luminosity/IP [10^{34}cm^{-2}s^{-1}]	141	20	5	1.25
Integrated luminosity/IP/year [ab^{-1}]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 ttbar pairs

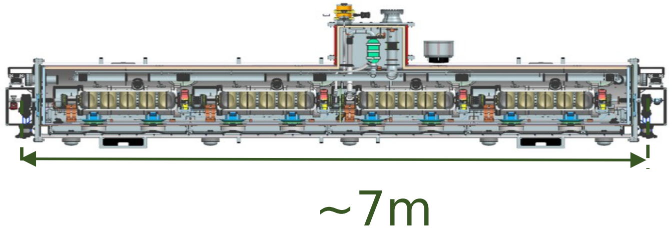
Design and parameters dominated by choice to allow for 50 MW synchrotron radiation power per beam

Defines
→ RF system
→ Beam parameters

RF R&D Activities

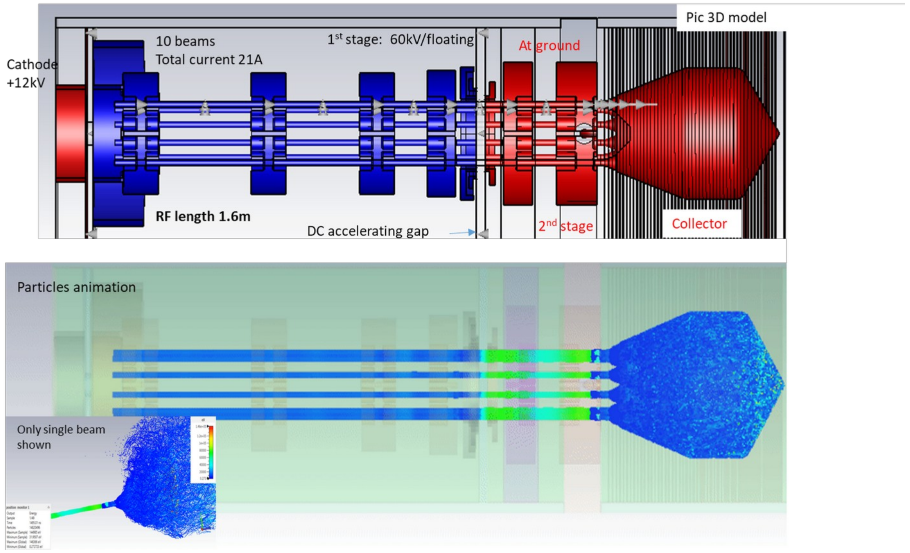
- RF system is key technology for increasing energy efficiency for the FCC-ee and to reduce the power consumption
- Nb on Cu 400 MHz cavities, seamless cavity production and coating techniques
- Bulk Nb 800 MHz cavities, surface treatment techniques, cryomodule design
- RF power source R&D in synergy with HL-LHC

800 MHz cavity and CM design
collaborations with **JLAB** and **FNAL**

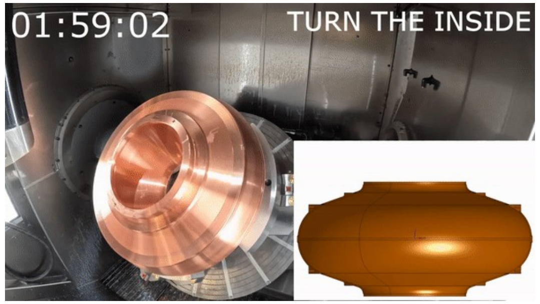


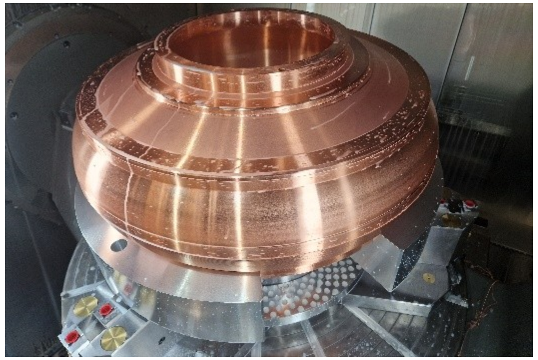
High-efficiency klystron R&D
in collaborations with **THALES & CANON**

Novel two-stage MBK klystron: CW, 400MHz, 1.28MW.

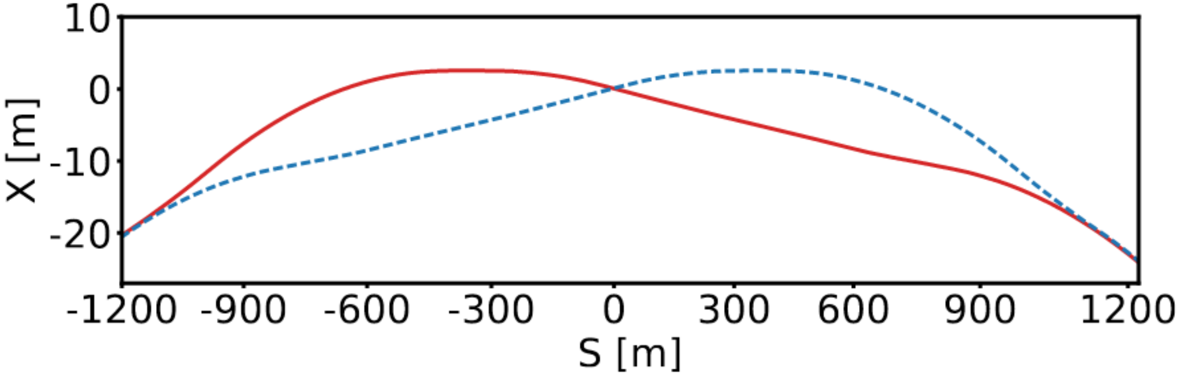


400 MHz cavity production
in collaboration with **KEK**

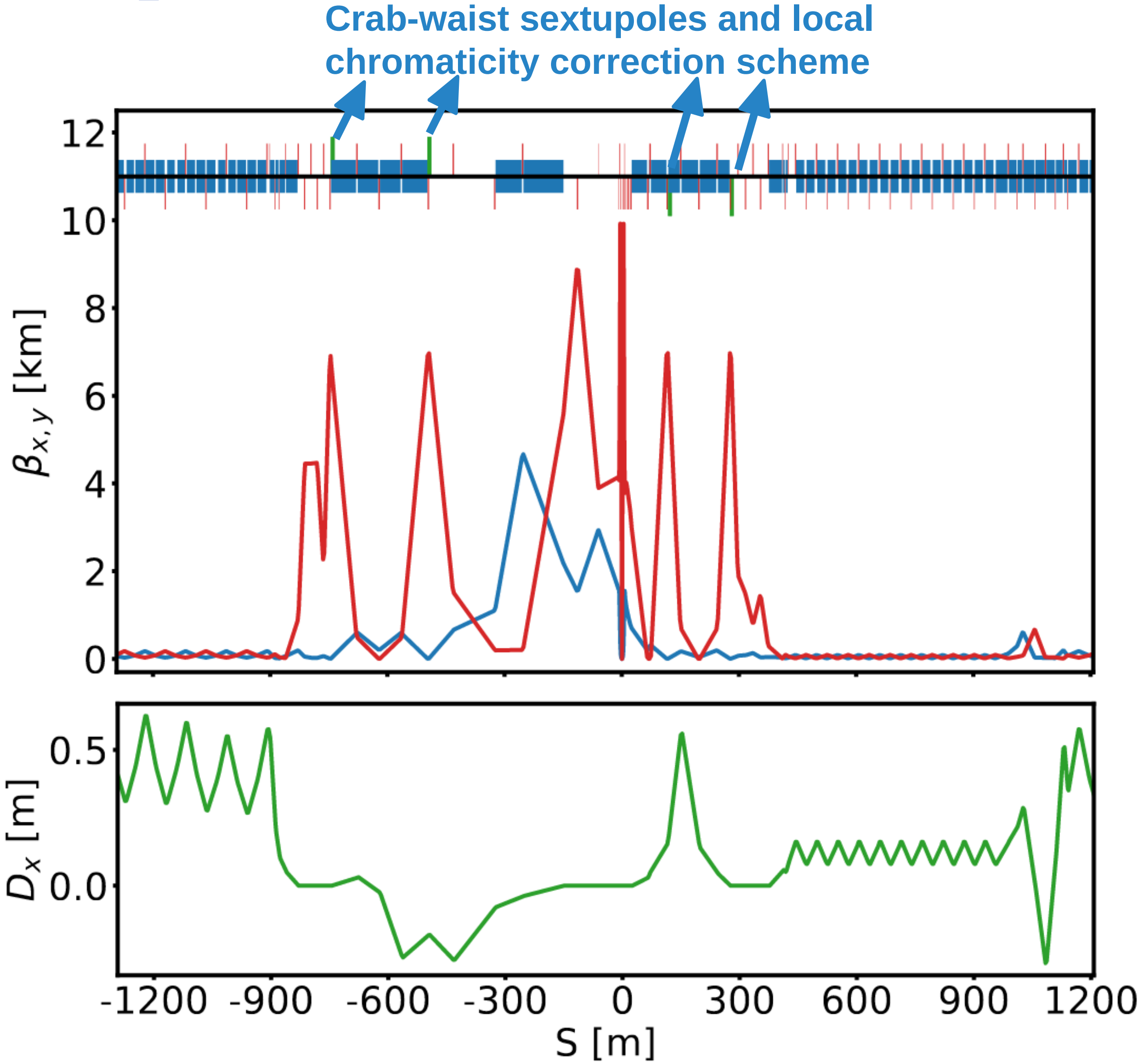




Interaction Region Optics

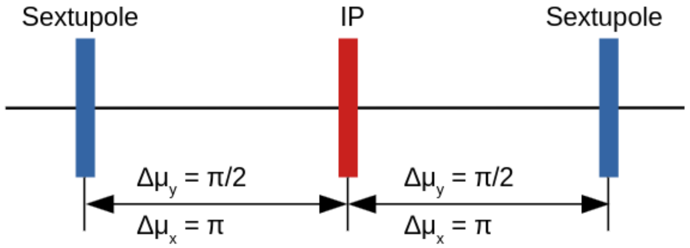


- Collision of small emittance, high current beams
- Crossing from the inside to limit SR photons to 100 keV
- Crab-waist collision scheme
- Local final focus chromaticity correction

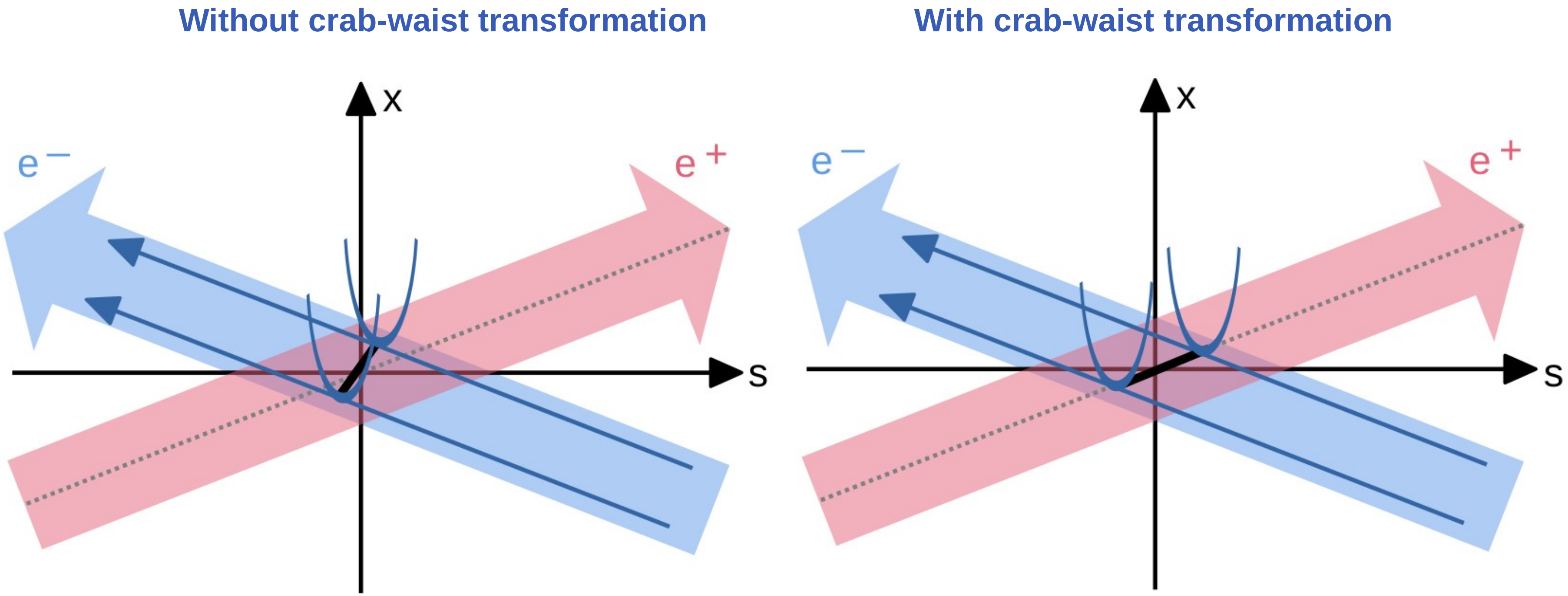


Crab-Waist Scheme

- Large crossing angle and horizontal beam size
- Vertical β-function comparable to overlap area
- **Crab-waist** transformation with **sextupoles**



Powering sextupoles rotates the vertical β-function and aligns the minimum on the longitudinal axis on the other beam


Without crab-waist transformation **With crab-waist transformation**

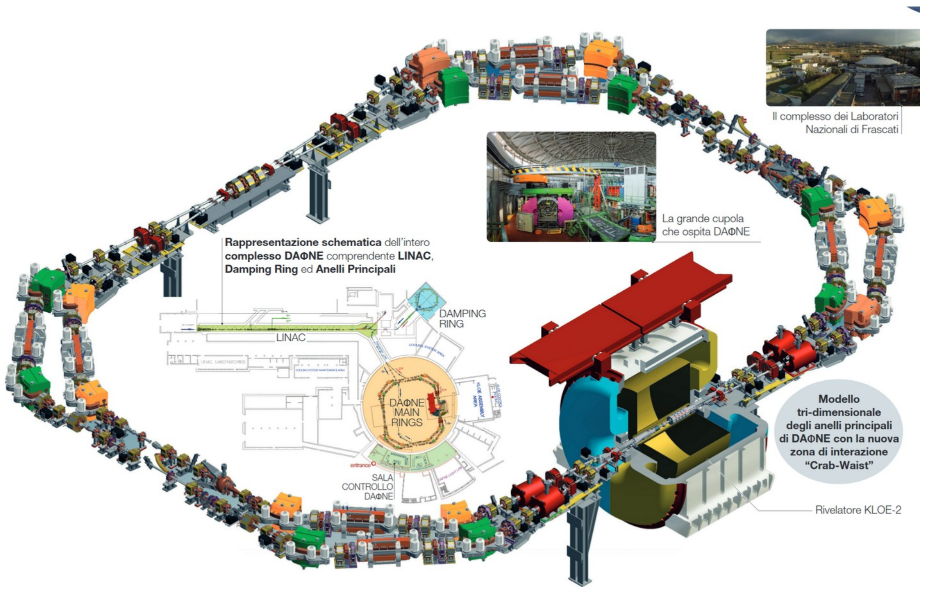
Crab-Waist Demonstration

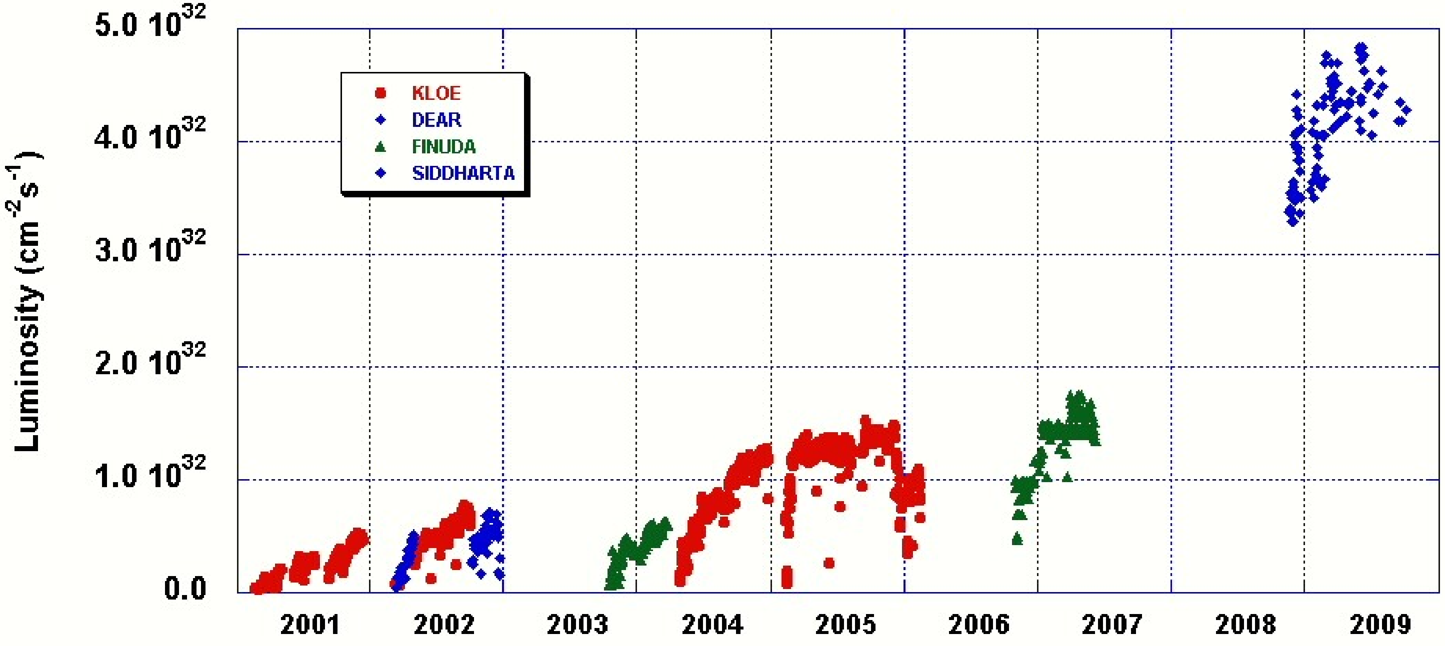
- Crab-waist scheme successfully depolyed at DAFNE, Italy → Luminosity increase

- Currently being commissioned at SuperKEKB

P. Raimondi et al., arXiv:physics/0702033, 2007.
M. Zobov et al., arXiv:1608.06150, 2016.

Y. Ohnishi et al., Progr. of Theoretical and Experimental Physics, 2013 (3), 2013



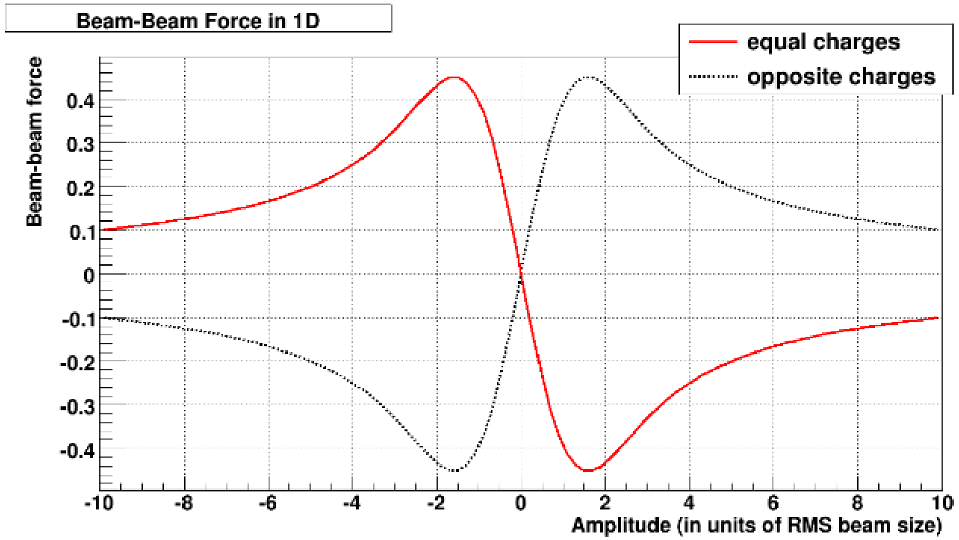


DAFNE, 2016.

Non-Linear Beam-Beam Force

- For small amplitudes effect similar to focusing quadrupole for e^+e^- collisions
- Leads to **beam-beam tune shift**
- For head-on collisions:

$$\Delta Q_{y,\max} = \xi_y = \frac{N r_e \beta_y^*}{2\pi \gamma \sigma_y^* \left(\sigma_x^* + \sigma_y^*\right)}$$



M. Schaumann, Master Thesis, 2011.

$$\boxed{L = \frac{N^2 n_b f}{4\pi \sigma_x^* \sigma_y^*} G \approx \frac{1}{e r_e}\left(\frac{1+\sigma_y^*/\sigma_x^*}{2}\right) \xi_y I_{\text{beam}} \frac{1}{\beta_y^*}}$$

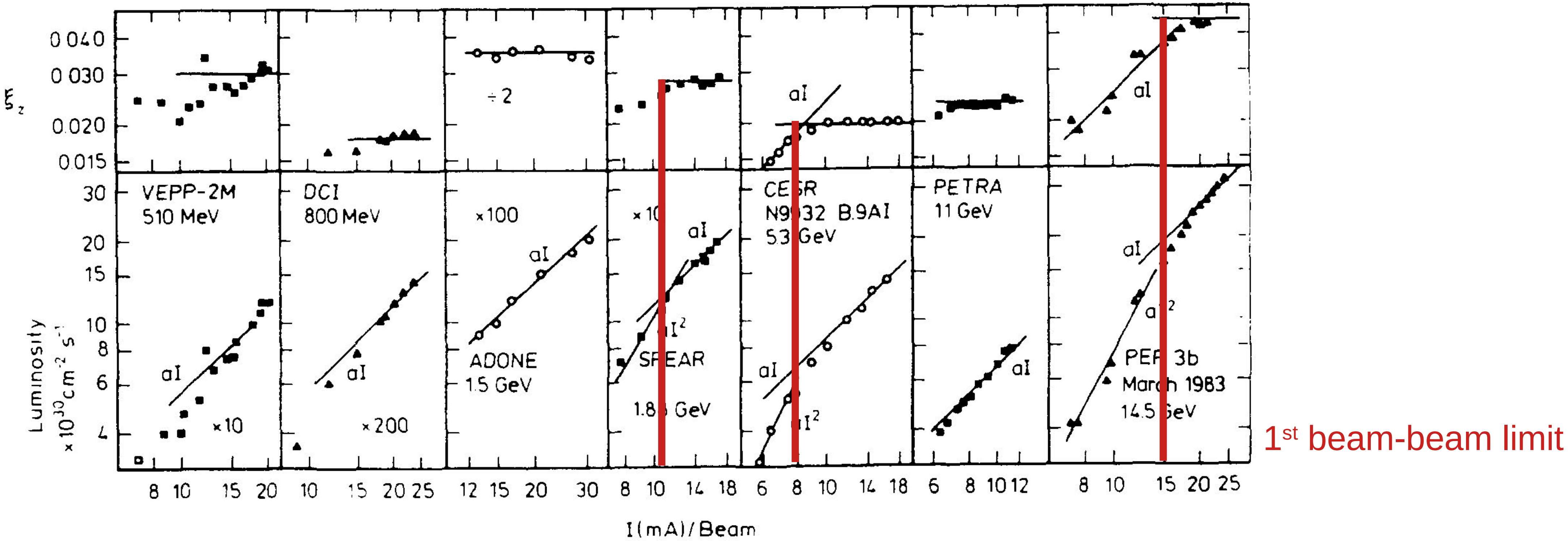
Center of opposing bunch

Increases with decreasing vertical β-function!

Beam-beam tune shift

Total beam current
Limited by e.g. synchrotron radiation power

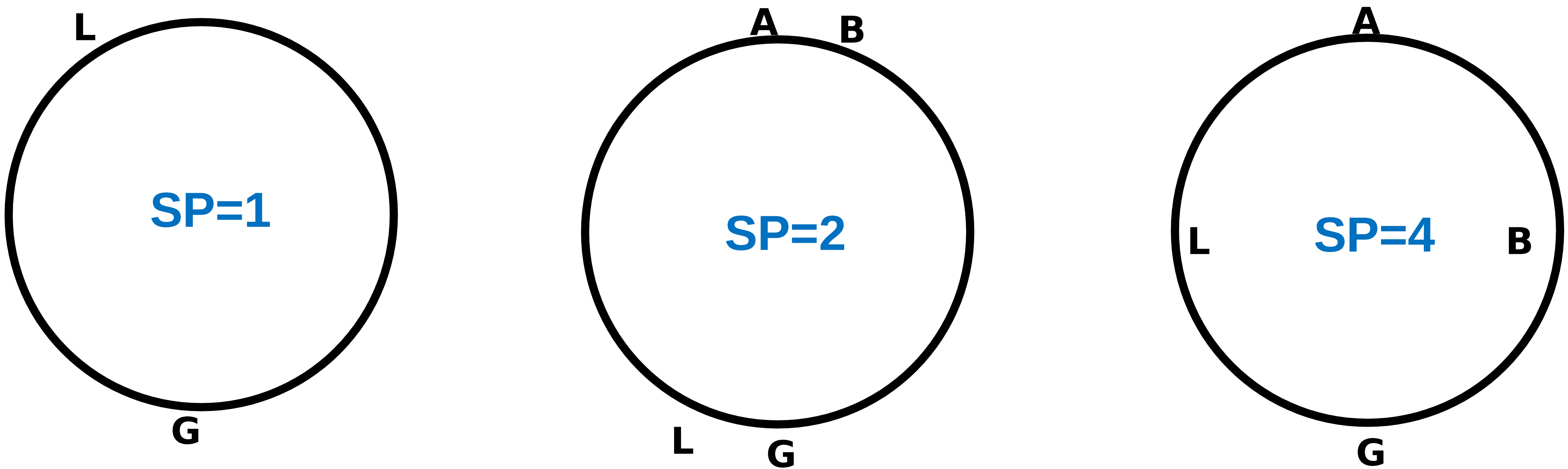
Beam-Beam Limit



- Luminosity and vertical tune-shift parameter versus beam current for various e+e- colliders
- The **tune shift saturates** at some current value, above which the luminosity grows linearly
- Later “**2nd beam-beam limit**” found due to beam blow and tails at LEP

Multiple Interaction Points

- Question of superperiodicity (SP) depends on location of IPs (A, B, L, G)
- If machine is fully superperiodic (SP = 4) --> a ¼ turn equivalent to smaller ring with 1 collision per turn
- Superperiodicity broken due to lattice imperfections → **measurement and correction techniques**



$$mQ_x+nQ_y=p$$

$$mQ_x+nQ_y=2p$$

$$mQ_x+nQ_y=4p$$

Top-Up Injection

- Used at SuperKEKB
- First demonstrated at KEKB and PEP-II
- **Injection at collision energy** into collider rings
- Continous injection to keep **constant beam current**
- Average luminosity ~ peak luminosity

$$N_\pm n_b e = I_\pm \epsilon_\pm \tau_\pm$$

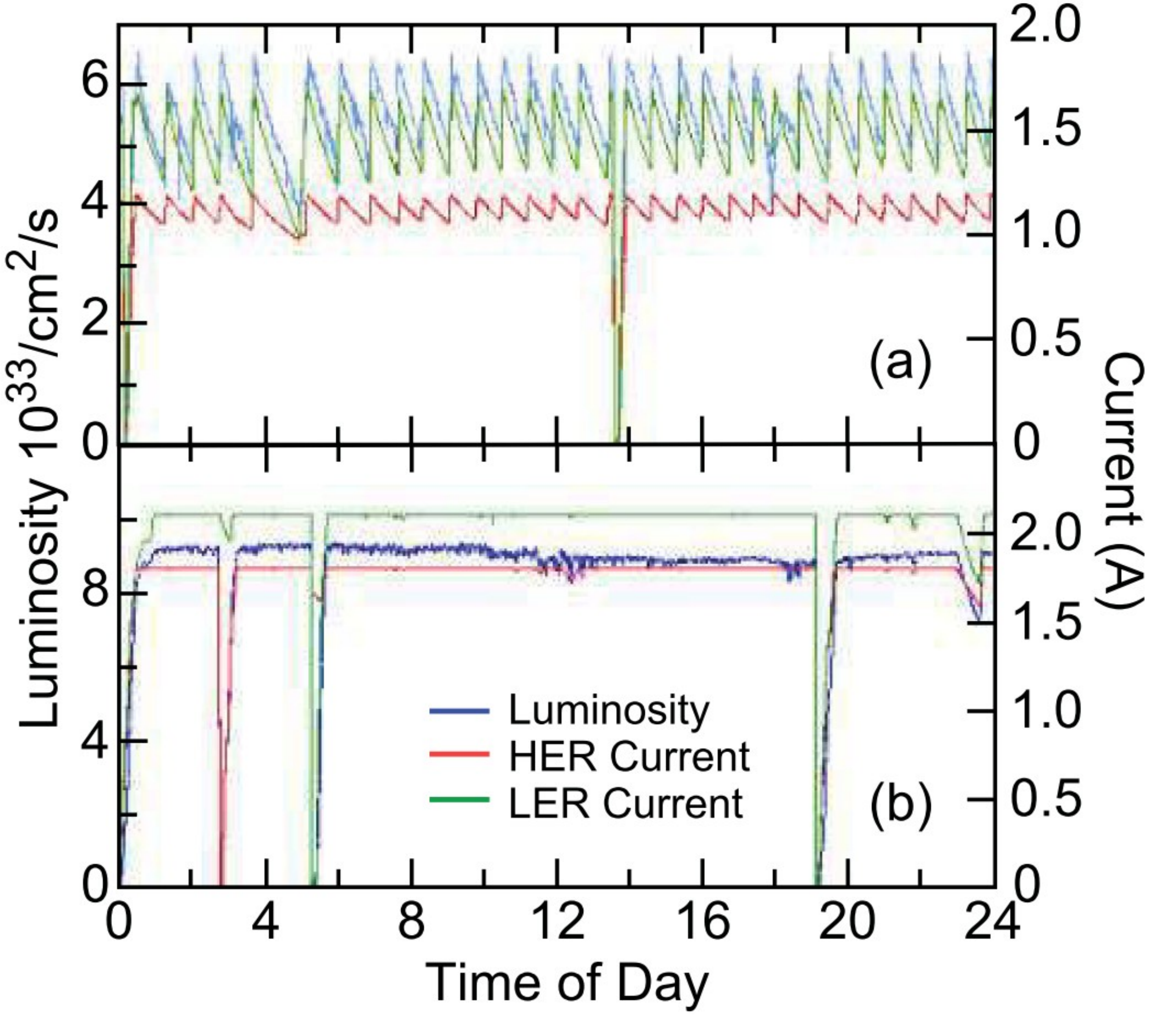
maximum injector current just replenishes lost particles → maximum current in collider

$e^\pm$ injector beam currents

beam lifetimes in collider

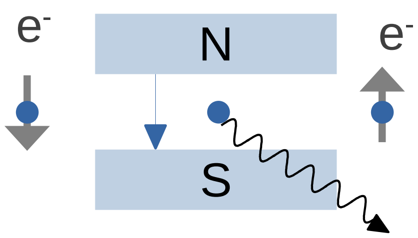
injection efficiencies

$$\mathcal{L} \approx \frac{f}{4\pi e^2 \sigma_x^* \sigma_y^*} \frac{1}{n_b} I_\pm \epsilon_\pm \tau_\pm$$

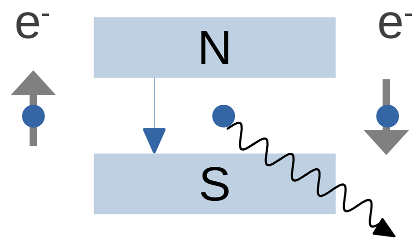


Polarization Build-Up

More likely
(by factor ~25)



Less likely



- Statistically every 10^{10}th emitted synchrotron photon flips the spin
- Probability depends on the initial spin orientation

- Leads to a natural **polarization build-up** over time
- Orientation is **anti-parallel** to the guiding magnetic field for e^-
- In a flat synchrotron only vertical bending → vertical spin orientation
- Known as Solokov-Ternov-Effekt

- Maximum theoretical polarization of **92.4 %**
- In real accelerator max. polarization depends on various factors

Spin Tune

- Spin precesses through the lattice
- Spin tune ν: Number of spin precessions per turn

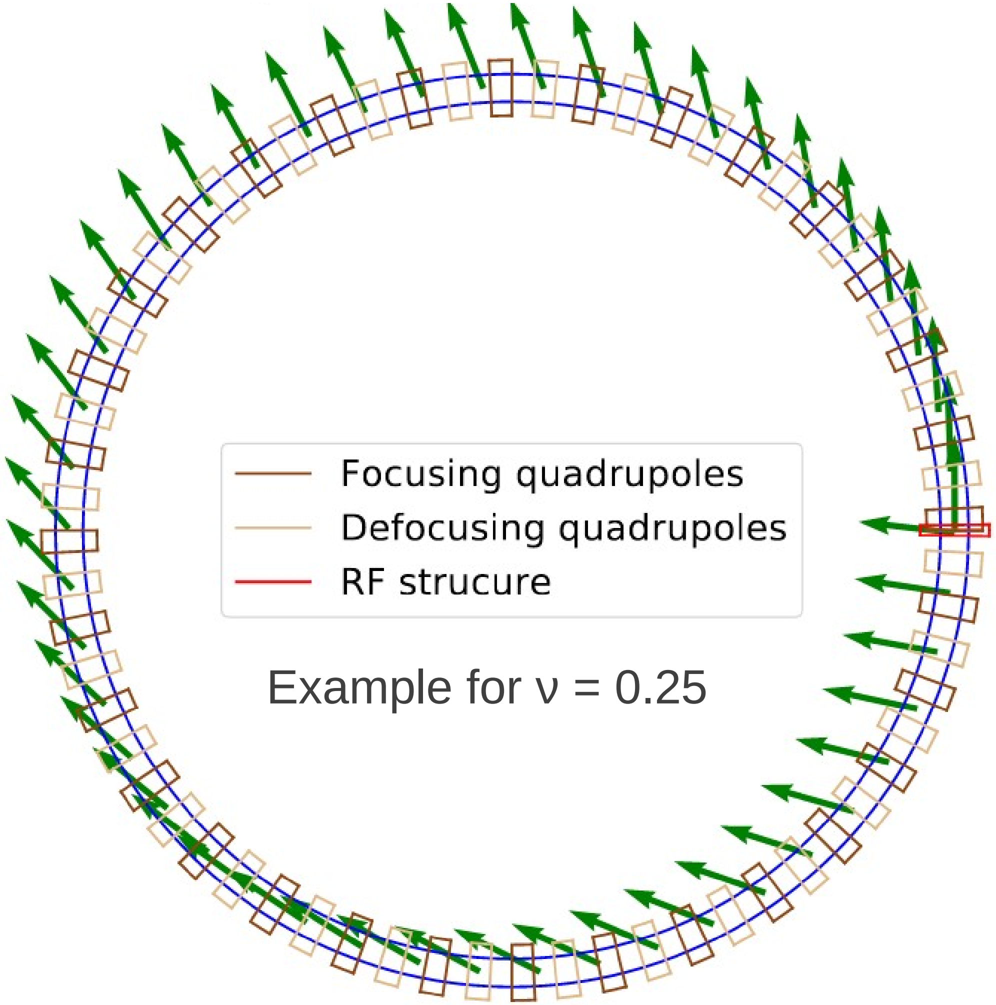
- In an error-free flat machine without solenoids:
- 45.6 GeV e^+/e^- –> 103.5 spin tune
- Purely vertical spin orientation

a … gyro-magnetic anomaly
γ_{Rel} … Lorentz-factor

$$\boxed{\nu = a * \gamma_{Rel}}$$

Principle:

Spin tune measurement ⟺ **Beam energy determination**

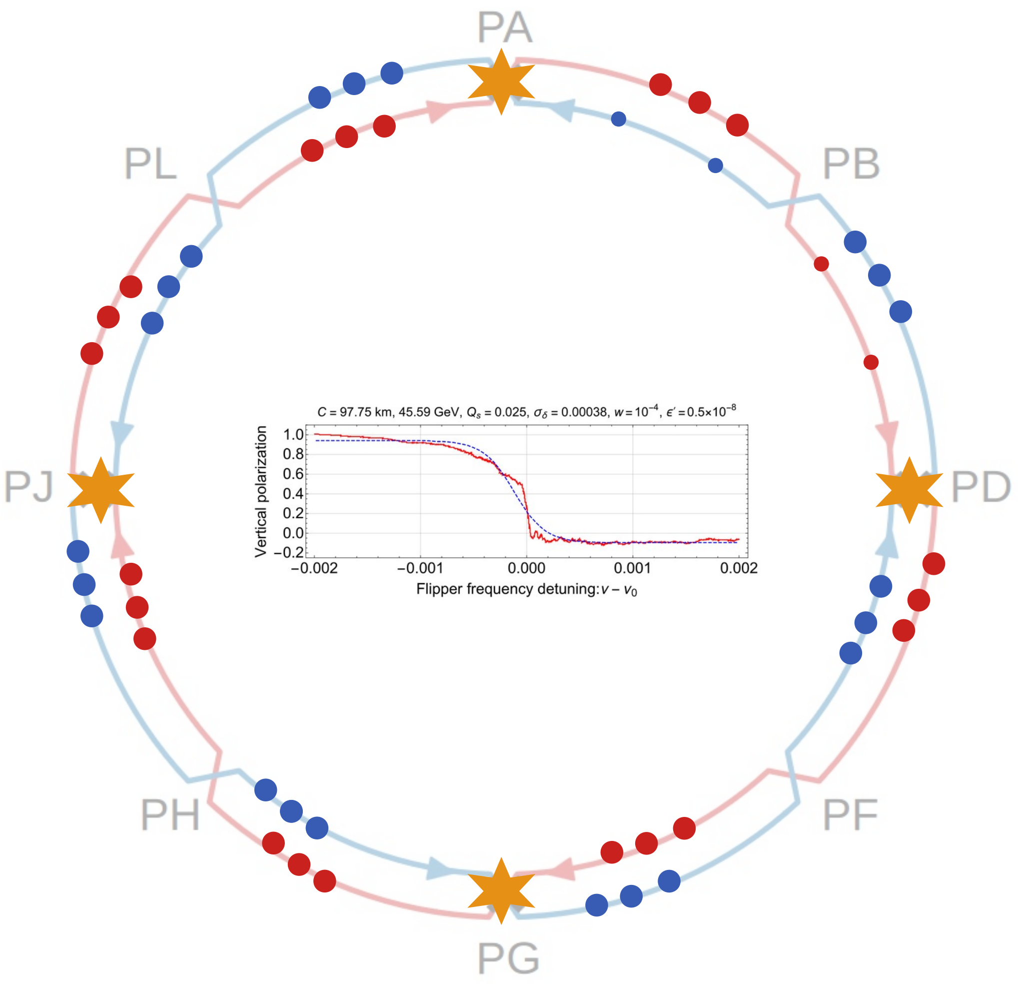


Example for ν = 0.25

Courtesy: V. Caudan

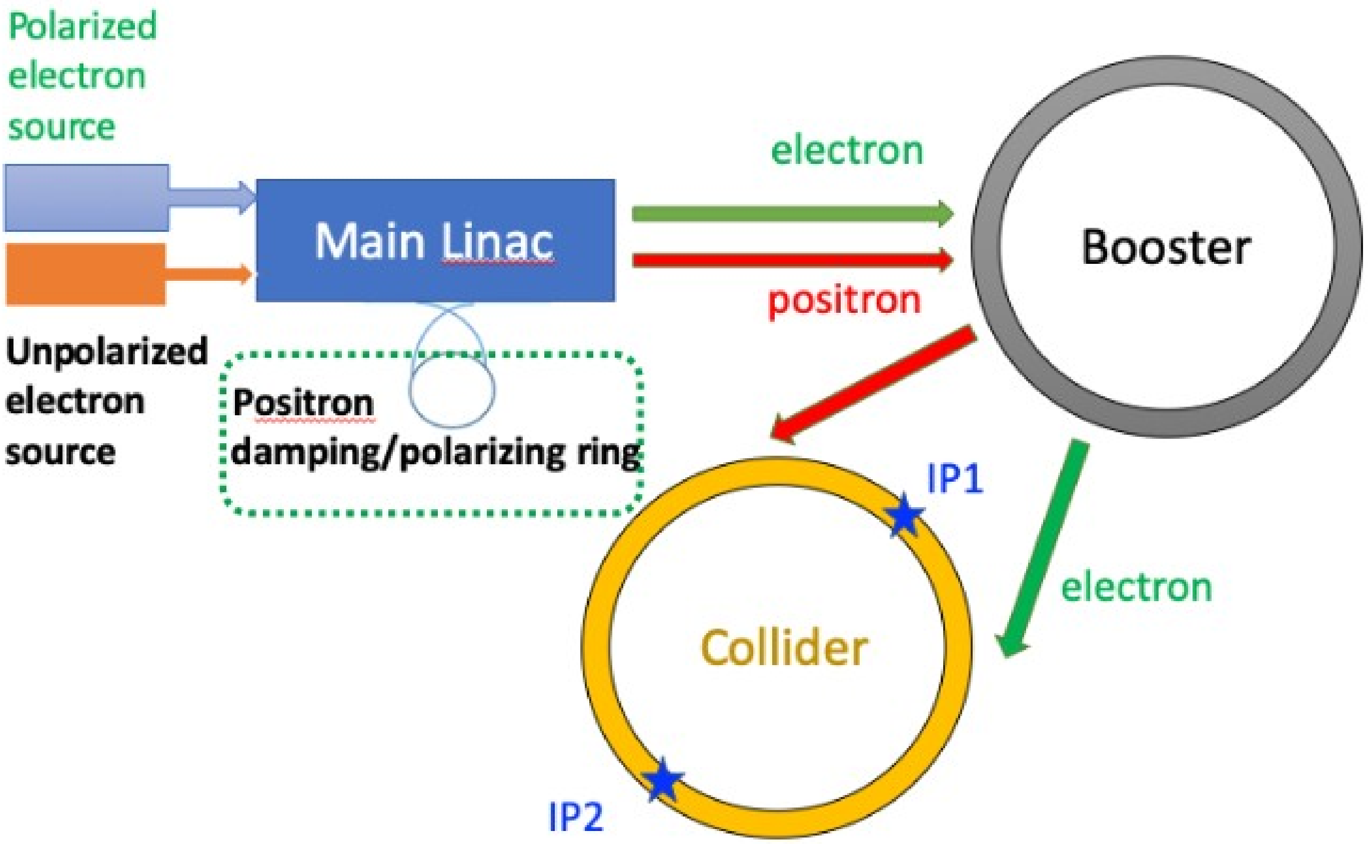
FCC Polarization Scheme

- Inject a few (100-200) non-colliding pilot bunches (~10^{10} ppb)
- Use on wigglers until ~5-10 % **vertical polarization** reached
- Switch wigglers off
- Inject ~10000 colliding bunches (~2 x 10^{11} ppb)
- Measure beam energy with pilots while collisions take place
- Polarization used only to retrieve beam energy



Courtesy: Z. Duan

CEPC Polarization Scheme



- Injection of polarized electrons and positrons in collider rings at Z and W
  - Longitudinal polarization for physics bunches
  - Transverse polarization for pilot bunches
  - More time for physics

- Possibly also polarized beams at H

Test Facility?

KEKB, SKEKB
Japan

LEP/LEP2
CERN

… and more

Circular Lepton Colliders

DAFNE
Italy

RHIC, EIC
USA

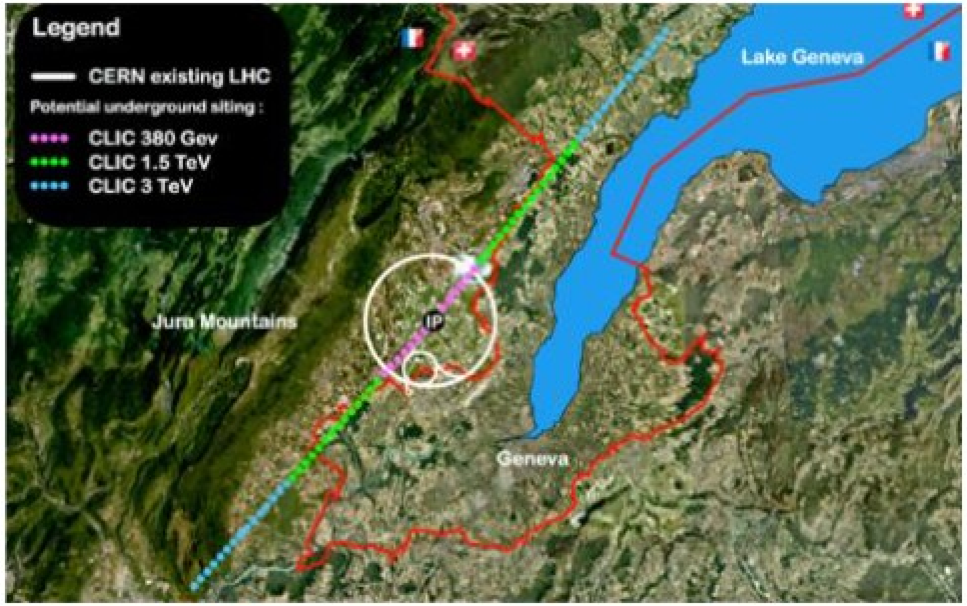
Light sources

Linear RF e+e- Colliders

Courtesy: S. Stapnes

2 Major Studies

- CERN: Compact Linear Collider (CLIC)

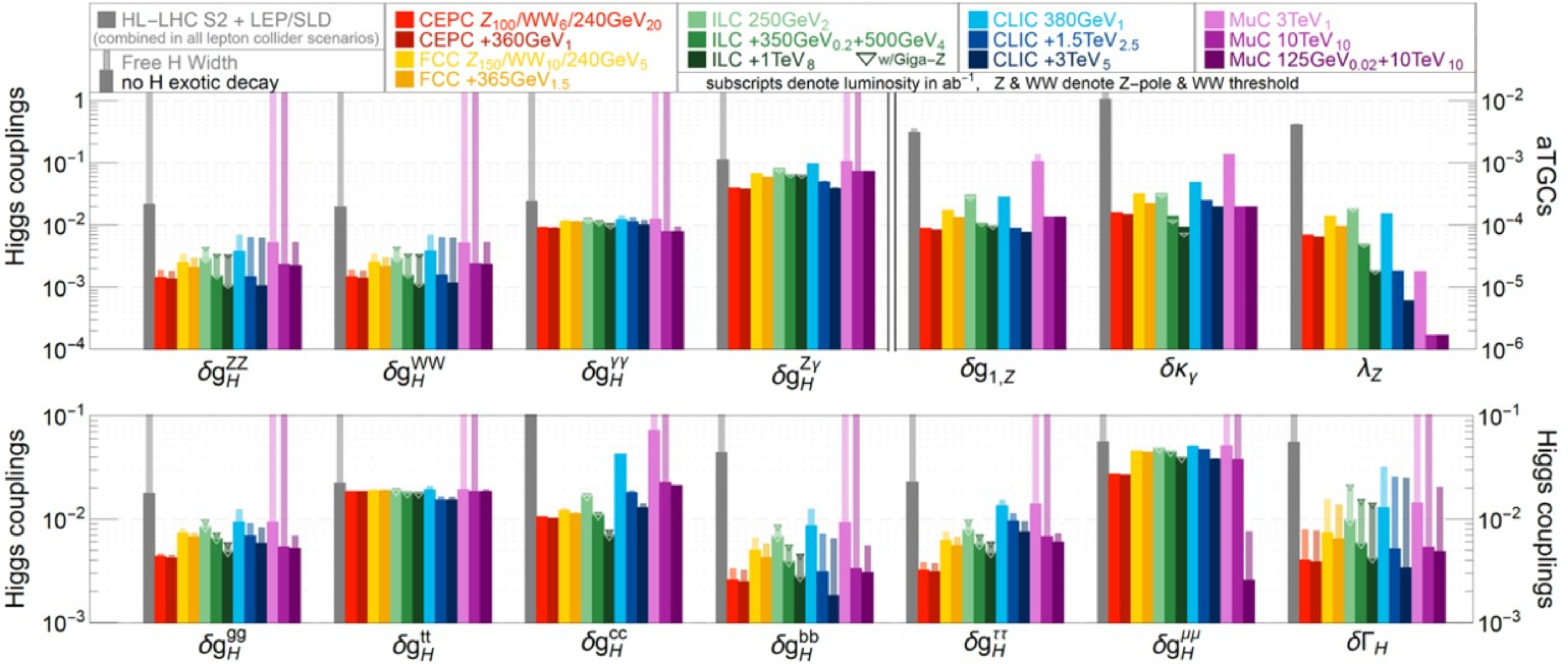


- Japan: International Linear Collider (ILC)

Courtesy: S. Stapnes

Physics Potential

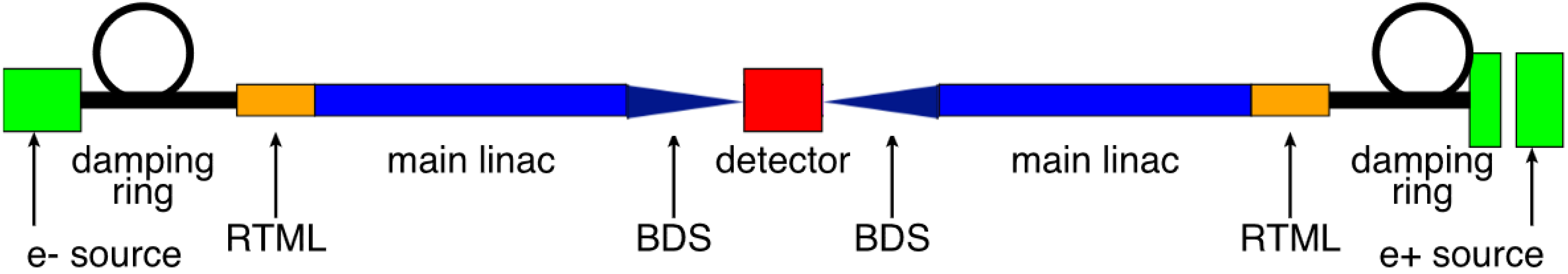
- Higgs and electro-weak factory up to a few TeV collision energy
- High longitudinally polarized beams (80 / 20-30 % electrons / positrons) essential part of physics program



Courtesy: S. Stapnes

General Linear Collider

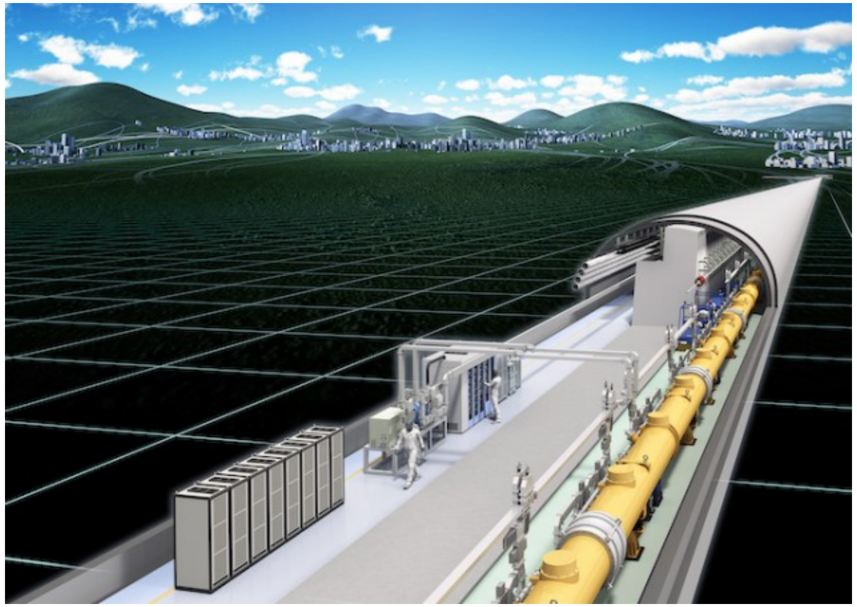
- Main parts of linear colliders:
  - RTML (Ring To Main Linac): injectors to achieve low emittance
  - Main linac for electrons and positrons → RF and acceleration main technological challenges
  - BDS: beam delivery system to achieve nano-beams
- Staged:
  - Possibility to expand to reach higher energies with new/improved technology



Courtesy: S. Stapnes

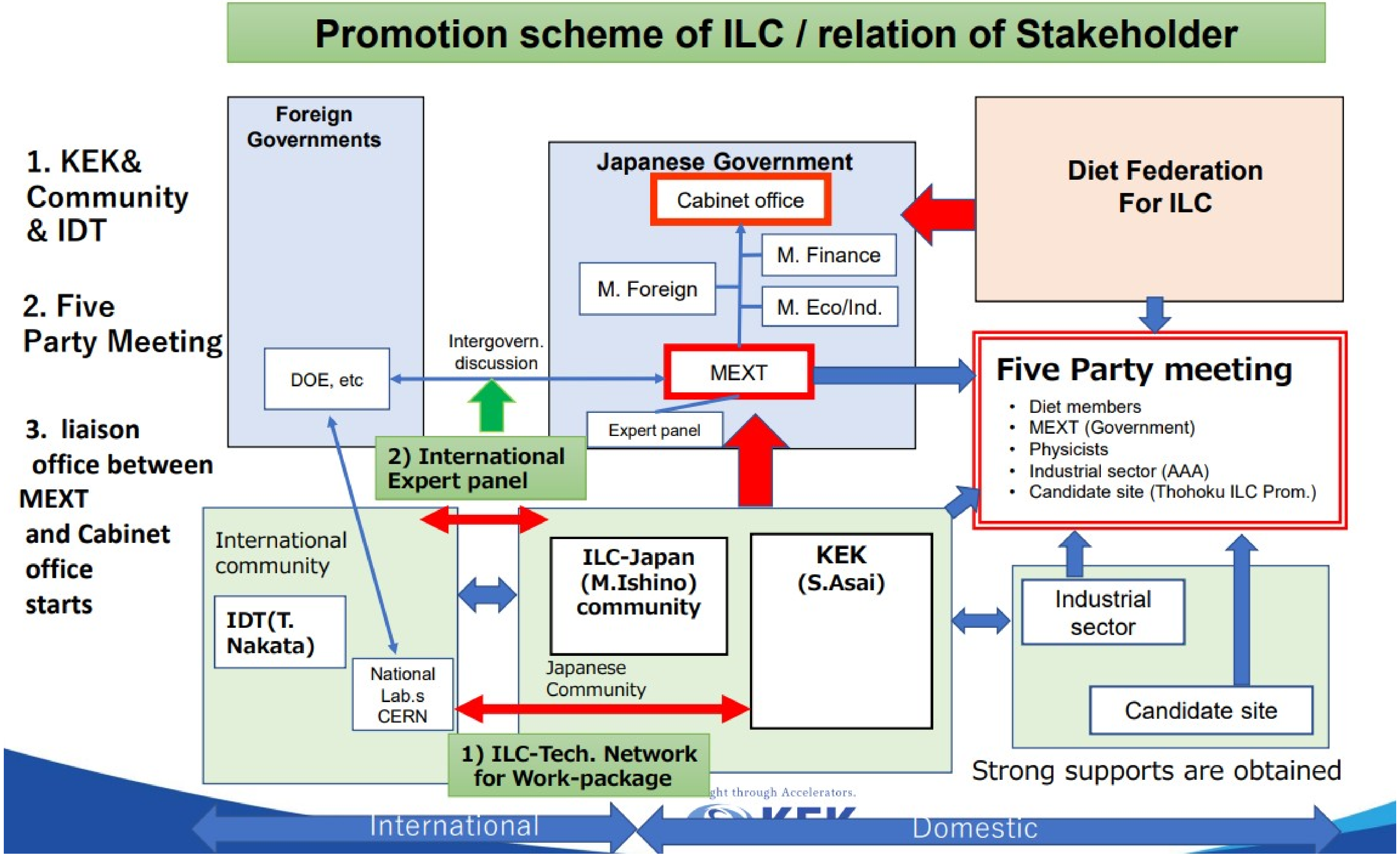
ILC

- 1.3 GHz superconducting RF
- 35 MV/m accelerating gradient
- Located in Japan
- TDR published in 2013



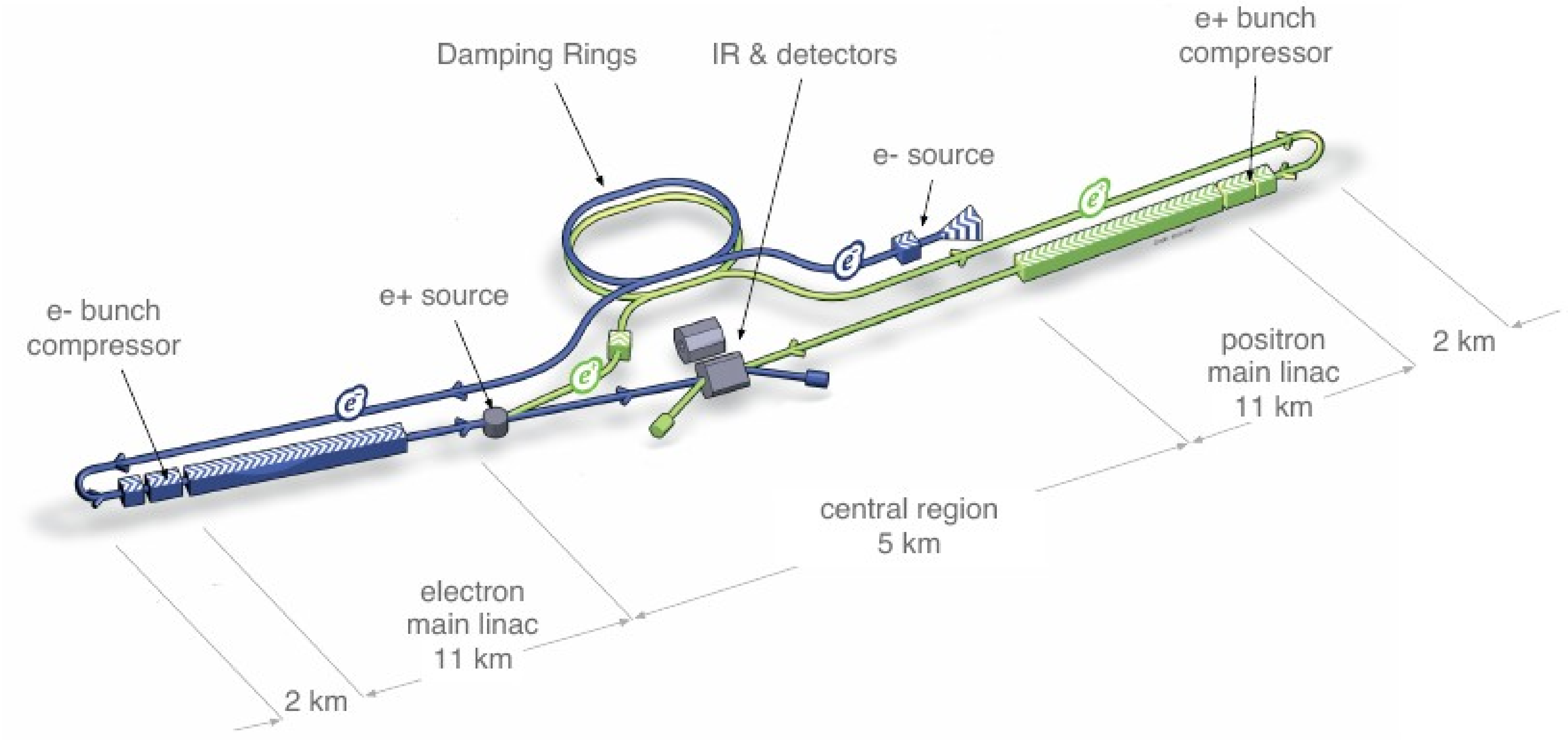
Courtesy: S. Asai

ILC Approval Process



Courtesy: S. Stapnes

ILC Scheme



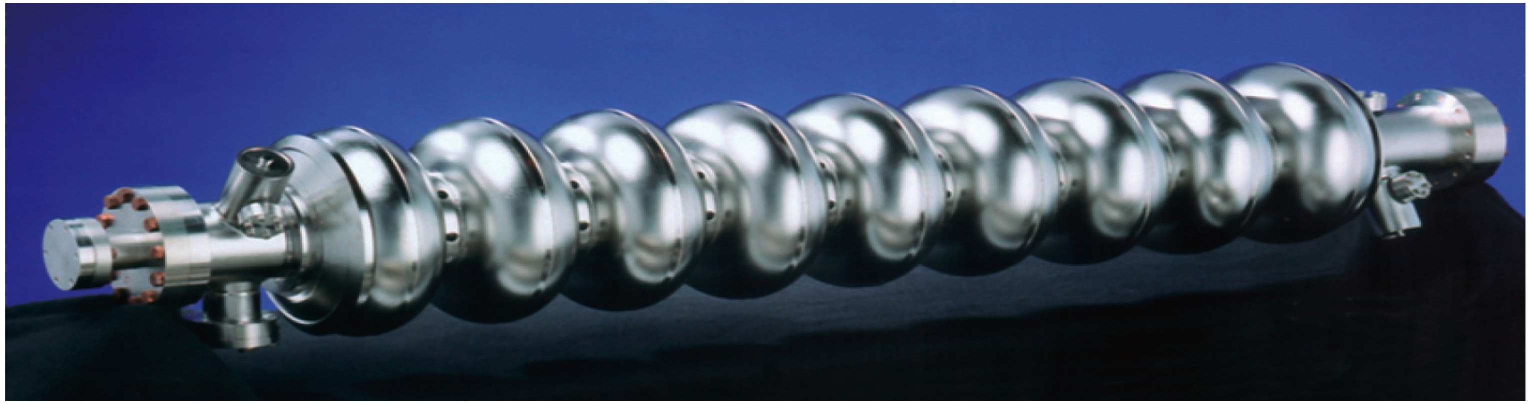
Courtesy: S. Stapnes

ILC Cavities

- 1.3 GHz superconducting RF
- 35 MV/m accelerating gradient

- Standing wave structure
- Theoretical field limit 50 – 60 MV/m
- 8000 cavities needed

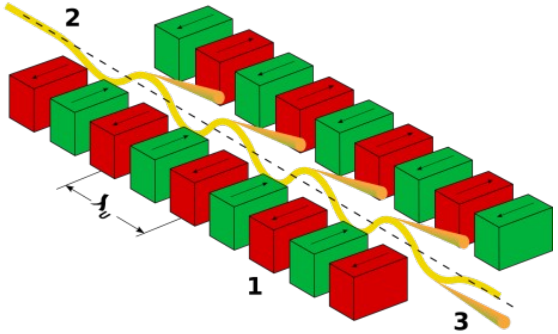
- Long pulse
- Large structure → low wakefields
- High effiviency thanks to superconductivity
- Long linac due to limited gradient
- Large damping ring

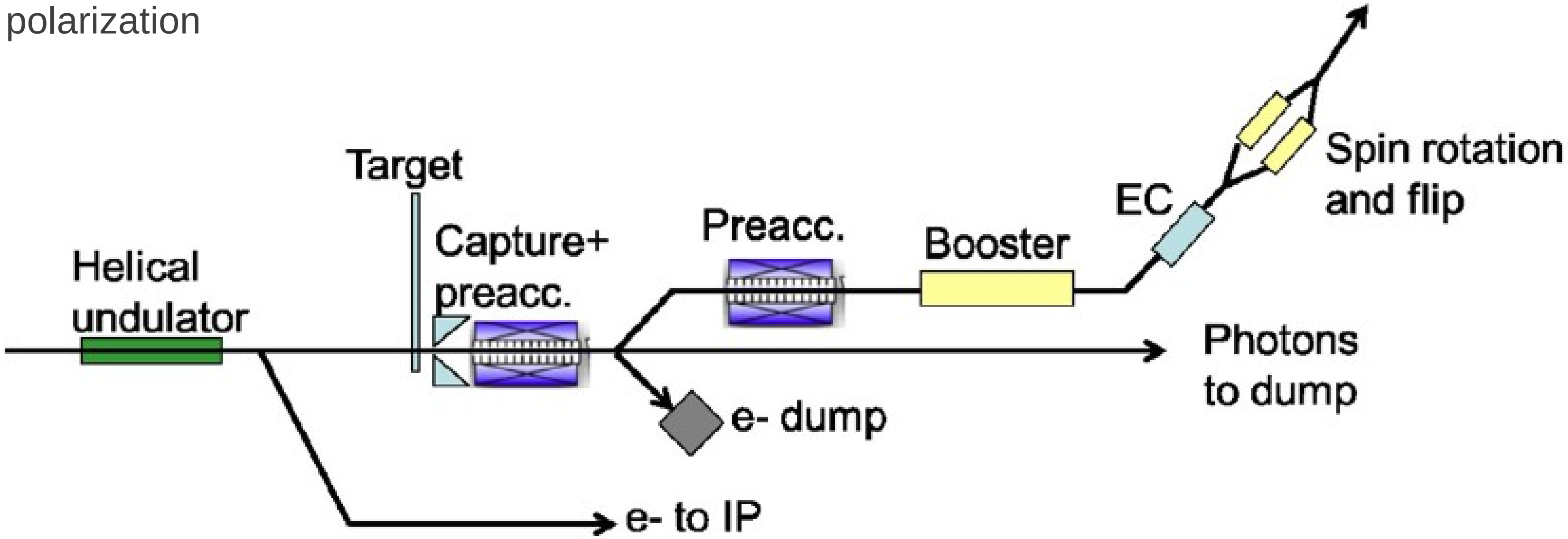


Courtesy: S. Stapnes

Positron Production

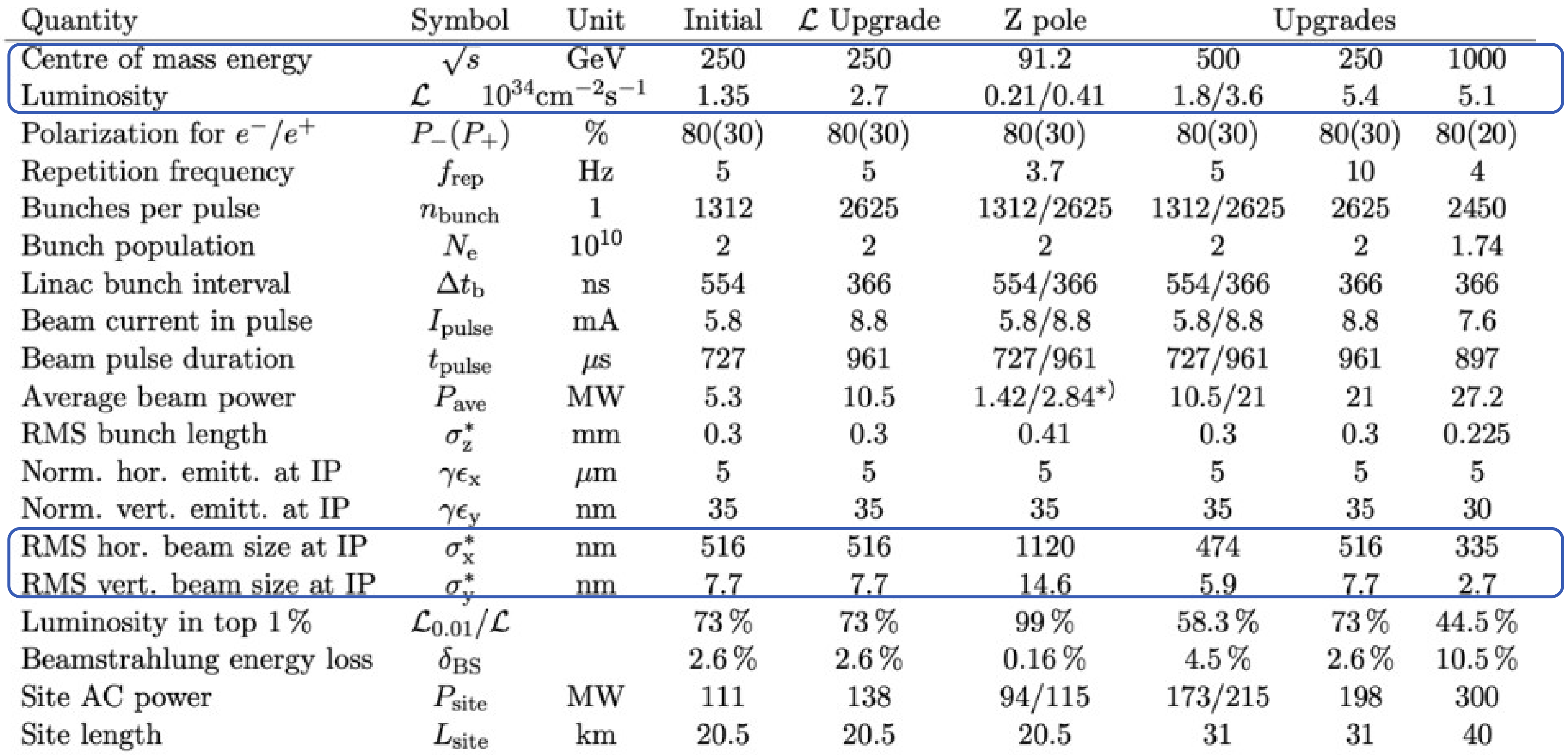
- Electrons pass undulator
- Radiate photons
- Hit Ti-alloy target to create e+e- pairs
- Goal: positron yield of 1.5
- 30% positron polarization





Courtesy: S. Stapnes

ILC Parameters

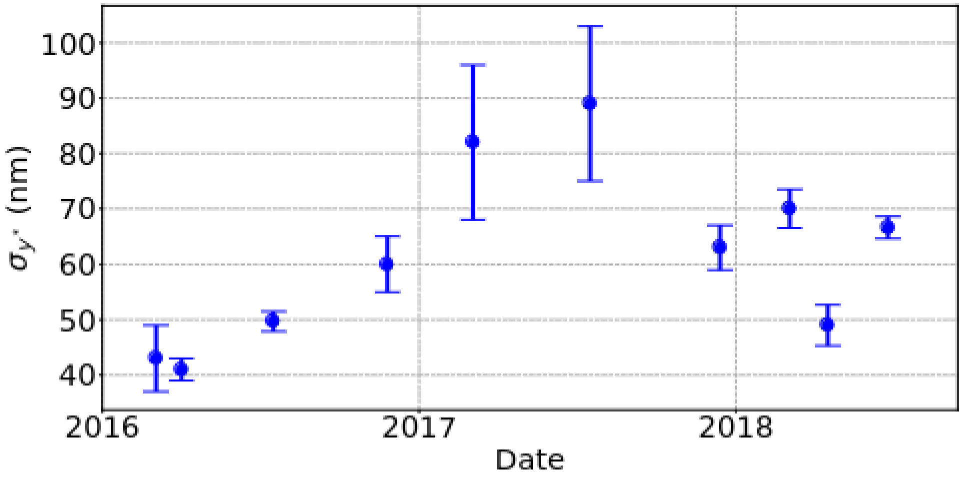


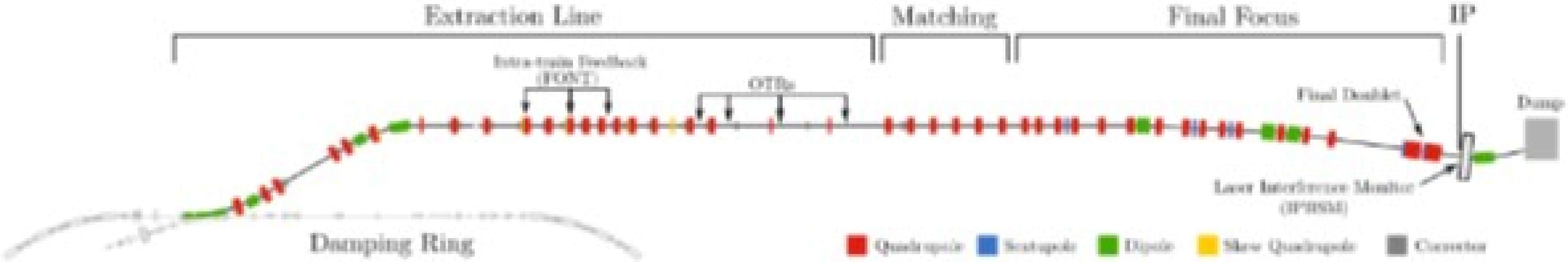
Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	$1.42/2.84^{*)}$	10.5/21	21	27.2
RMS bunch length	σ_{z}^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ_{x}^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_{y}^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Courtesy: P. Korysko

ATF

- Accelerator Test Facility, located at KEK, Japan
- Goal: Demonstrate key challenges for future linear colliders
  - Achieving small vertical beam size of a few nm
  - Demonstrate a few nm orbit stabilisation at the IP

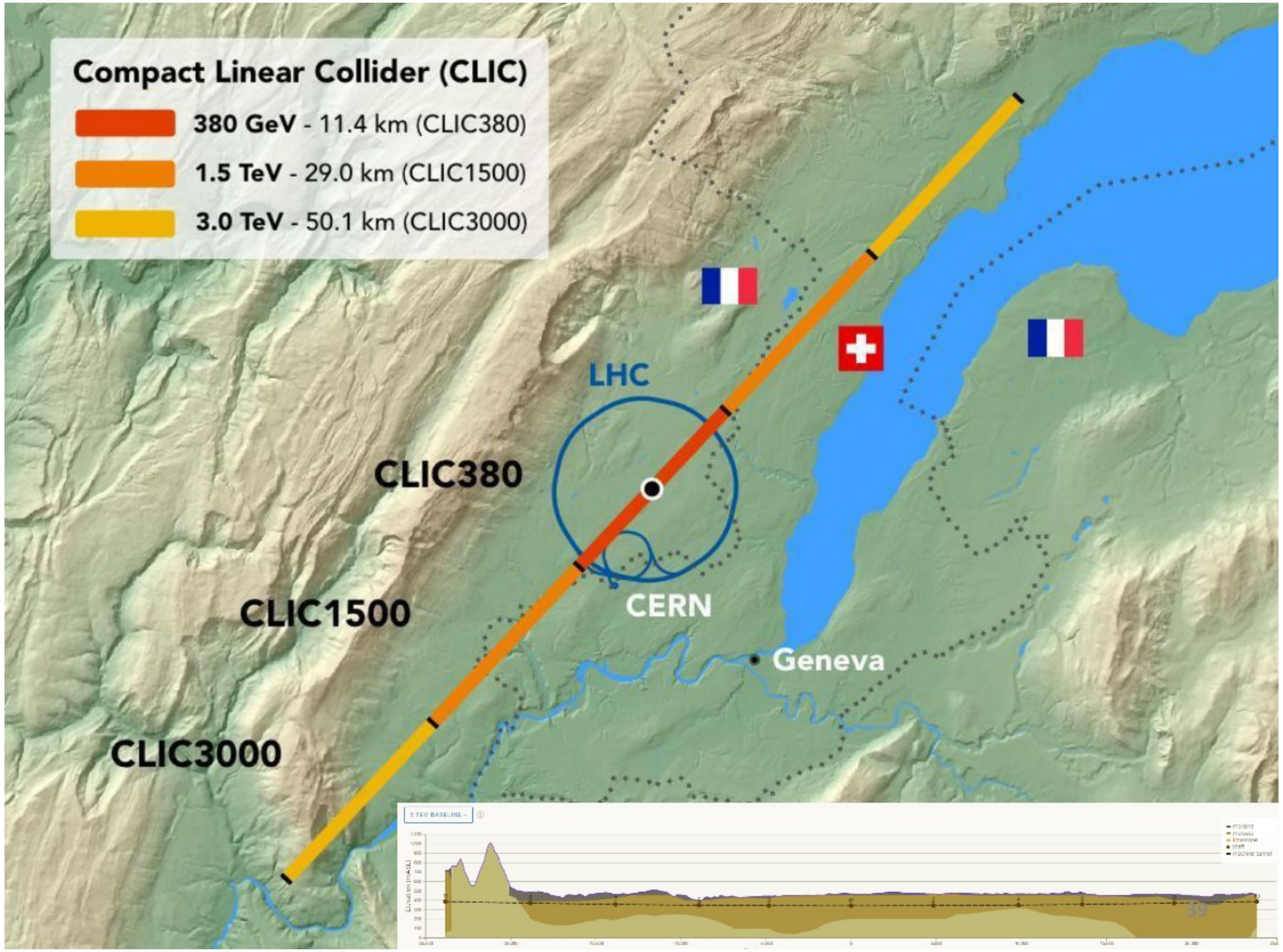




Courtesy: S. Stapnes

CLIC

- 12 GHz nomal conducting cavitiy
- 100 MV/m acceleration
- Initial phase:
  - 11 km length
  - 380 GeV center-of-mass energy
- Final stage:
  - Extentable up to 50 km
  - Up to 3 TeV center-of-mass energy
- Novel acceleration scheme



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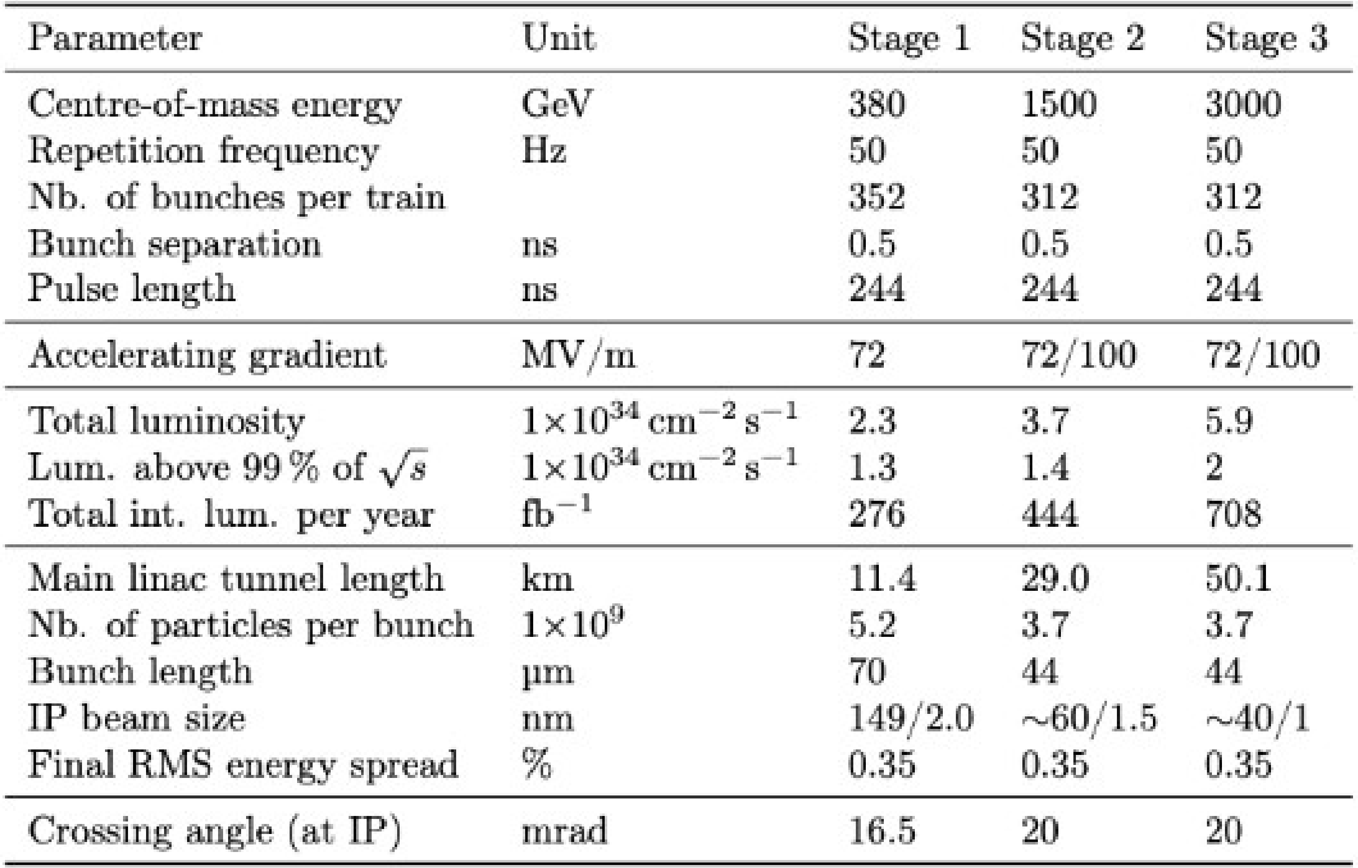
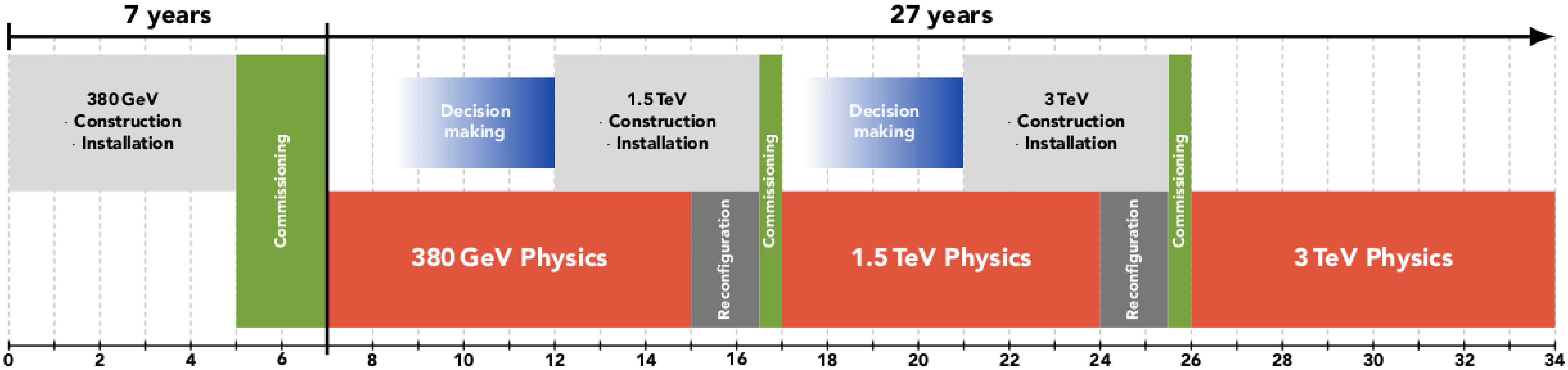


Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	µm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

Courtesy: P. Burrows

CLIC Timeline

- Technology-driven schedule from start of construction
- Preparation phase before estimated to ~5 years



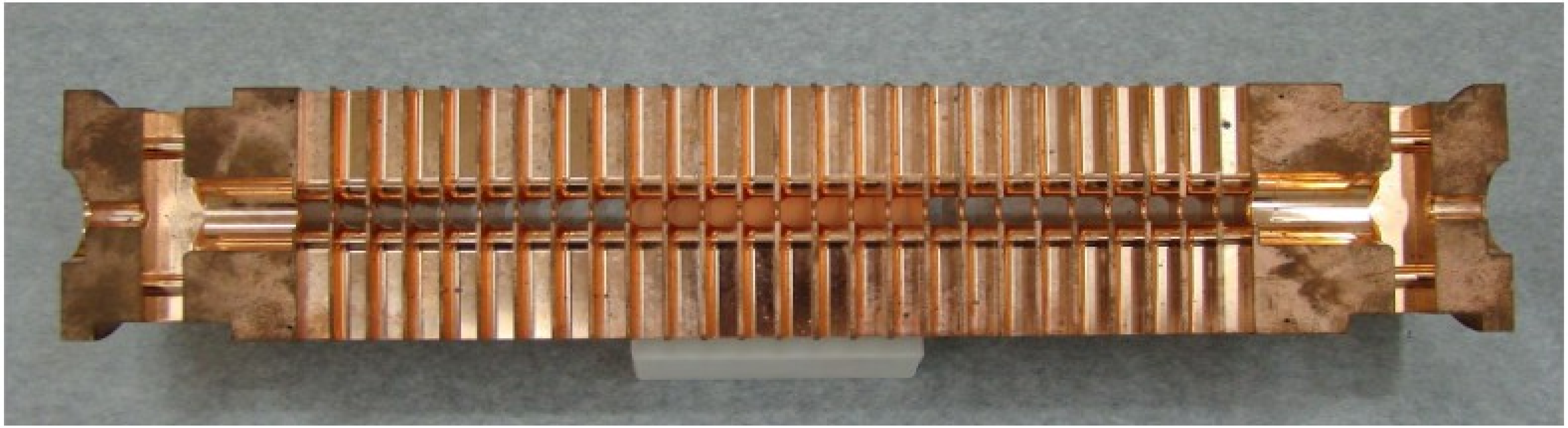
Courtesy: S. Stapnes

CLIC Cavities

- 12 GHz nomal conducting cavitiy
- 100 MV /m

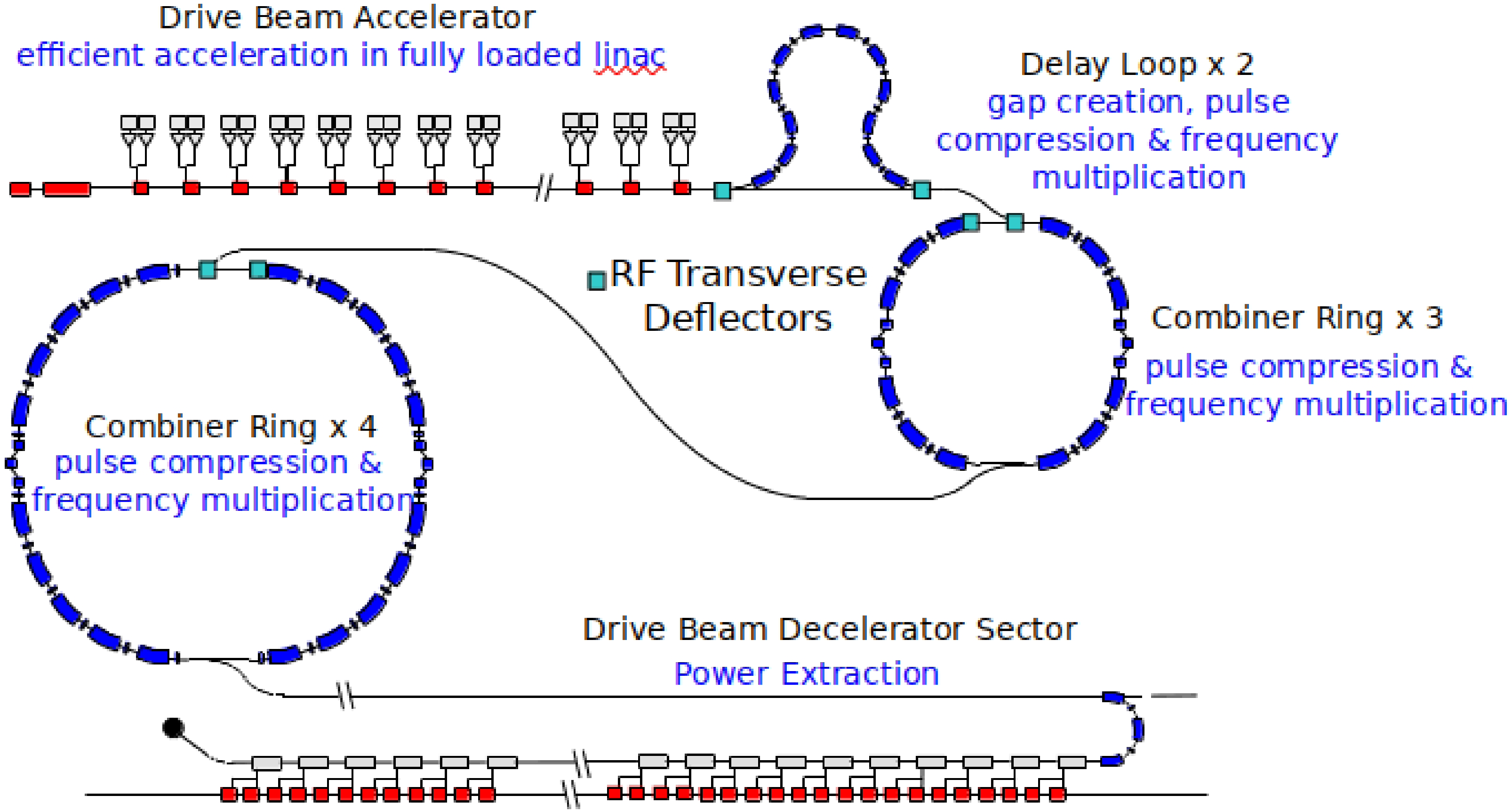
- 25000 cavities needed

- High gradient → short linac
- Small structure → strong wakefields
- Small daming ring



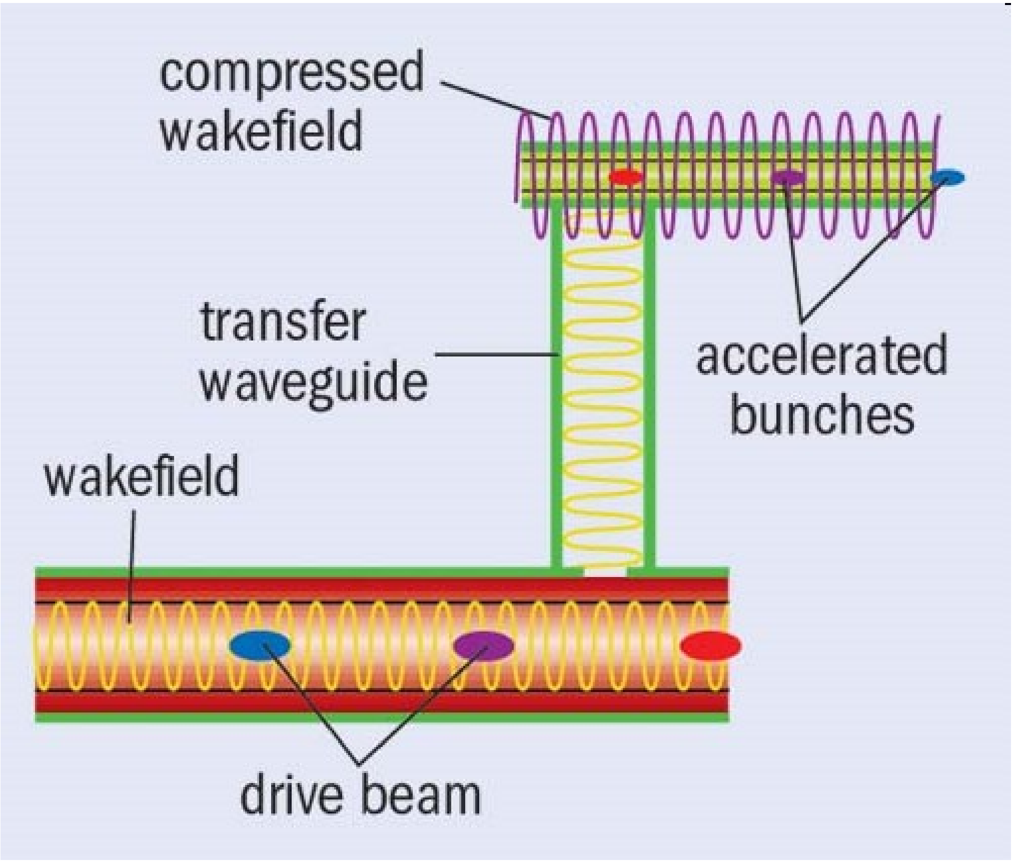
Courtesy: R. Bruce

Drive Beam Acceleration



Courtesy: R. Bruce

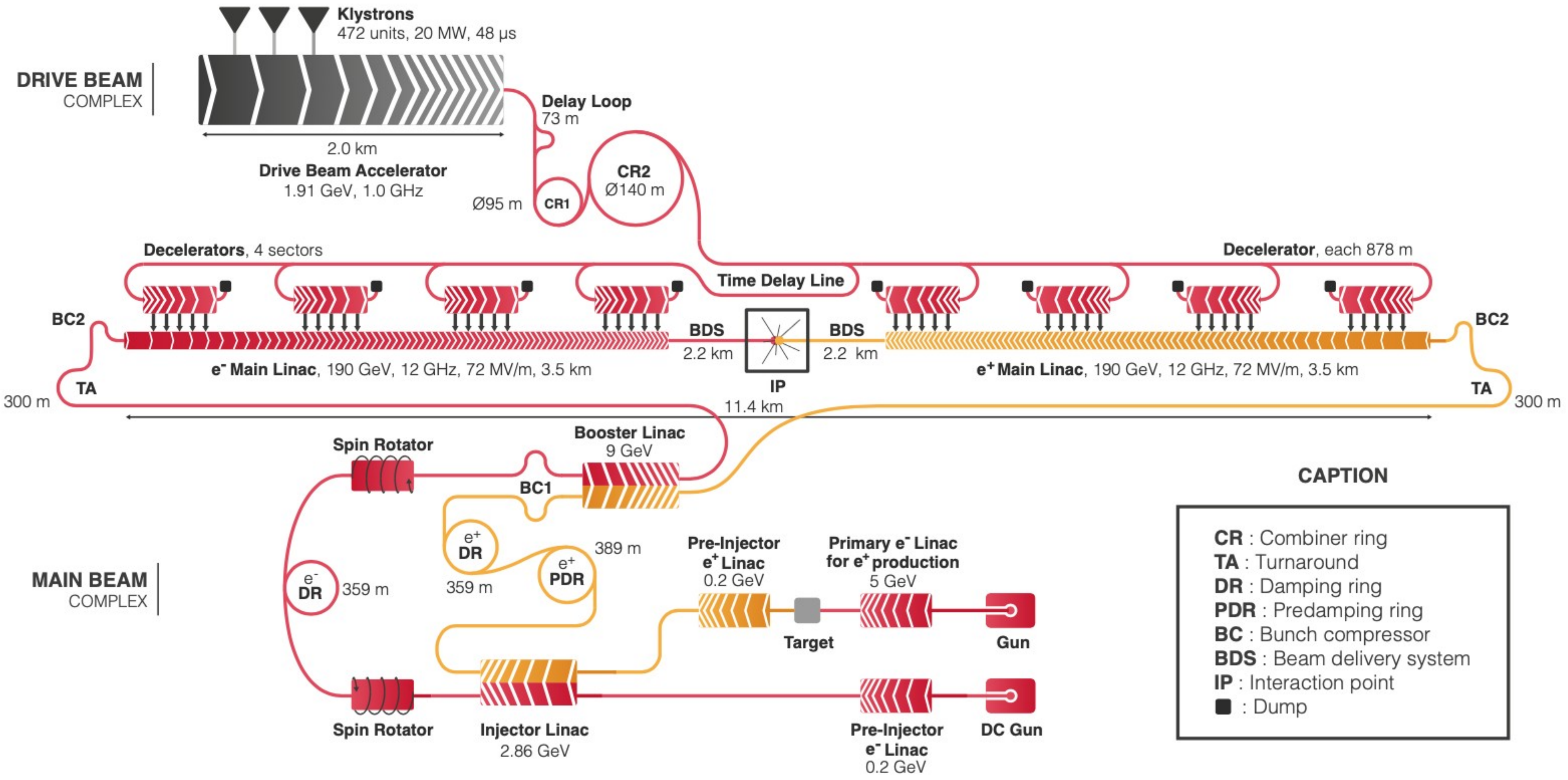
Acceleration Scheme



- High current drive beam is decelerated
- Generates electro-magnetic field
- Transferred in waveguides to beam

Courtesy: S. Stapnes

CLIC 380 GeV

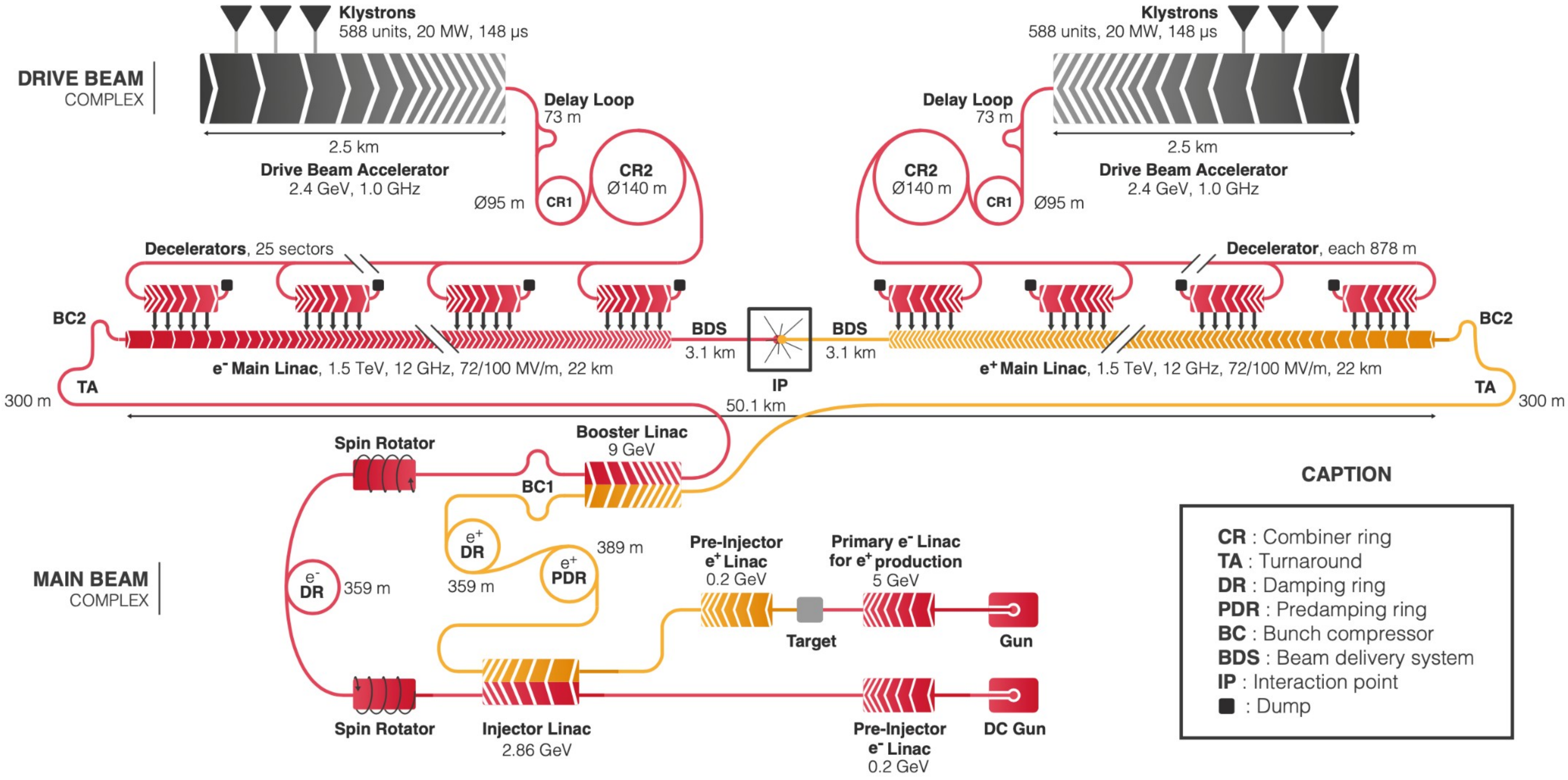


CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

Courtesy: S. Stapnes

CLIC 3 TeV



CAPTION

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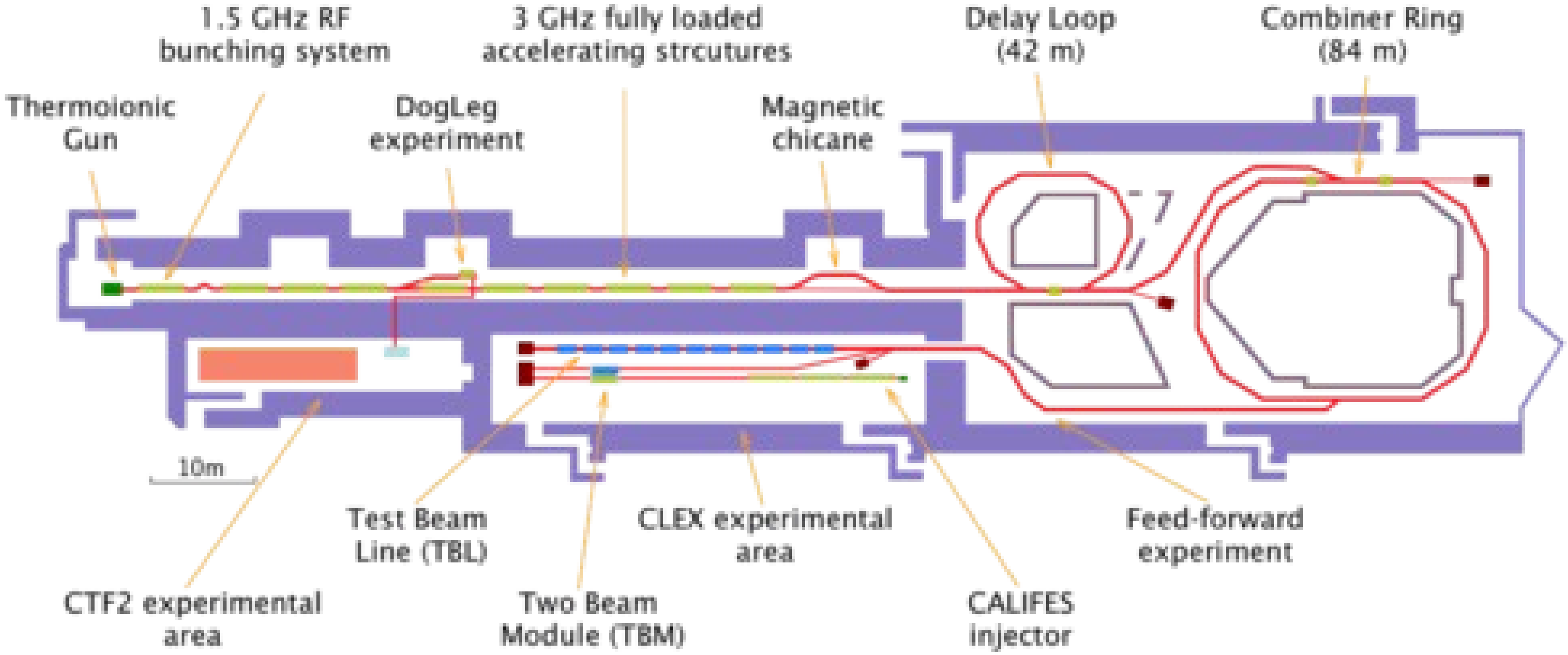
Courtesy: R. Bruce

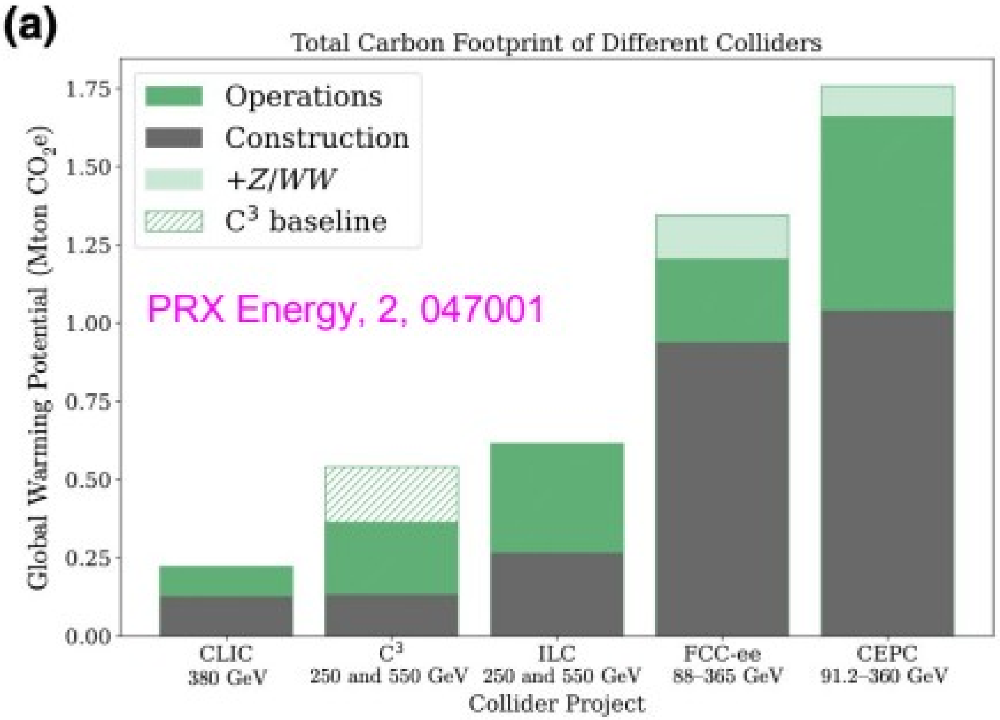
CTF3

- Experimental validation at CLIC Test Facility at CERN, decommissioned in 2016, parts re-used for CLEAR
- For CLIC required 100 MV/m accelerating gradient achieved

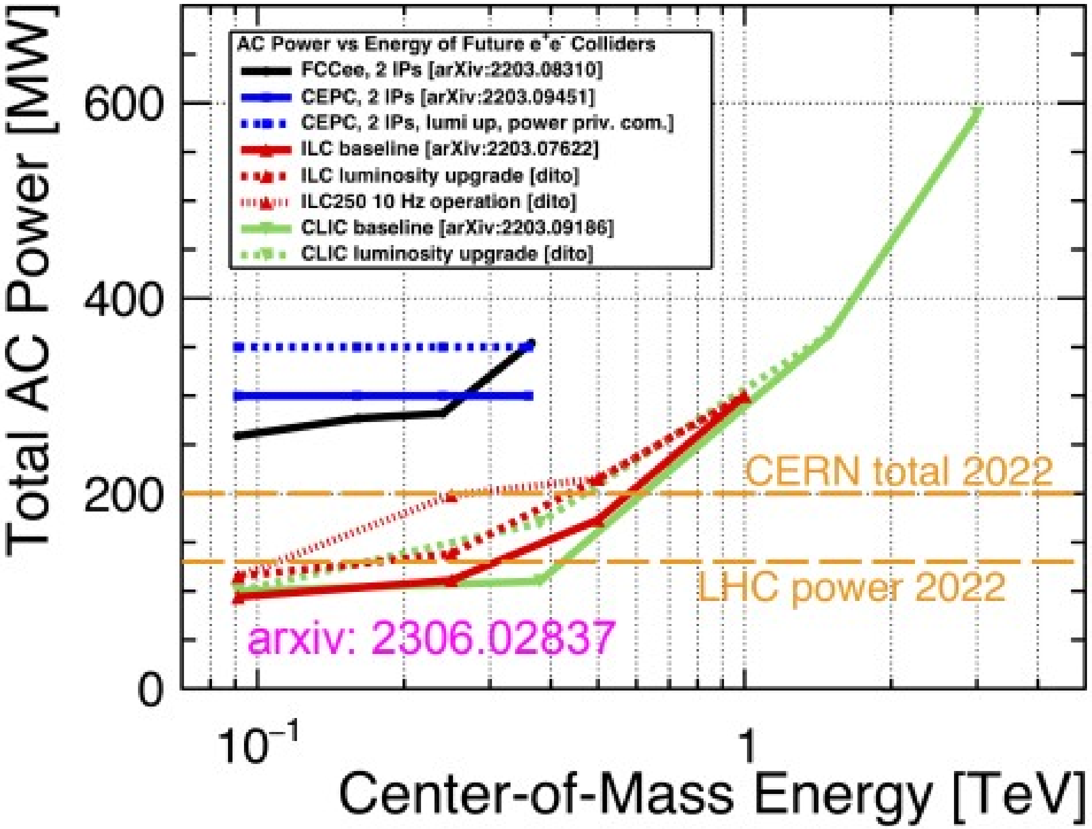


Courtesy: R. Pöschl

ILC at CERN



PRX Energy, 2, 047001

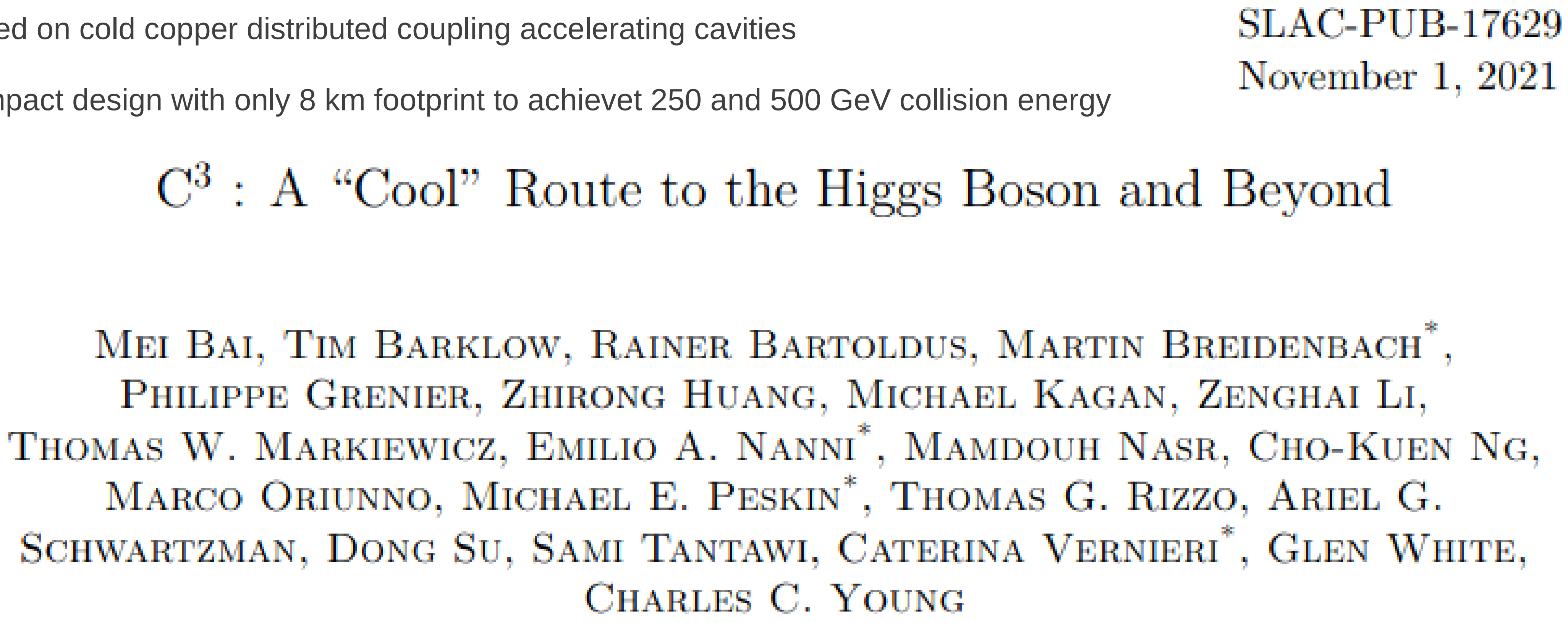


arxiv: 2306.02837

- Carbon footprint of all LC projects << Carbon footprint of circular machines
- Until ~500 GeV power consumption remains in ball park of current CERN power consumption
- Estimated operation cost for ILC ~390 MILC (plus 700-1000 FTE)
  - Compare with 1.3 BCHF for FCCee as estimated by German BMBF

Cool Copper Collider - C^3

- New approach for a normal conducting linear electron collider
- Based on cold copper distributed coupling accelerating cavities
- Compact design with only 8 km footprint to achievet 250 and 500 GeV collision energy

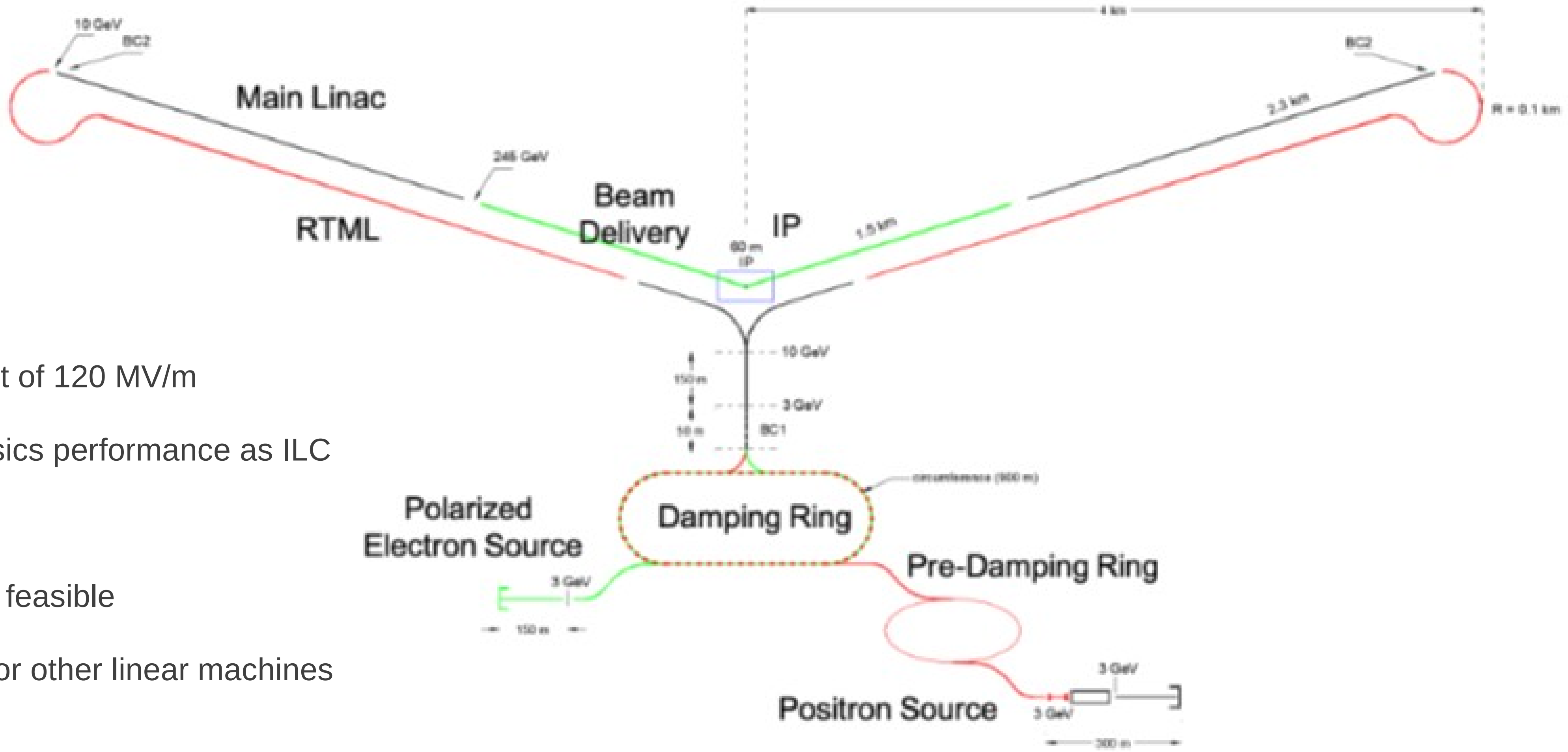


SLAC-PUB-17629
November 1, 2021

C^3 : A "Cool" Route to the Higgs Boson and Beyond

MEI BAI, TIM BARKLOW, RAINER BARTOLDUS, MARTIN BREIDENBACH*,
PHILIPPE GRENIER, ZHIRONG HUANG, MICHAEL KAGAN, ZENGHAI LI,
THOMAS W. MARKIEWICZ, EMILIO A. NANNI*, MAMDOUH NASR, CHO-KUEN NG,
MARCO ORIUNNO, MICHAEL E. PESKIN*, THOMAS G. RIZZO, ARIEL G.
SCHWARTZMAN, DONG SU, SAMI TANTAWI, CATERINA VERNIERI*, GLEN WHITE,
CHARLES C. YOUNG

Cool Copper Collider - C^3



- Footprint of 8 km
- Accelerating gradient of 120 MV/m
- Promises same physics performance as ILC

- If technology proven feasible

  → possibility to use for other linear machines

Circular Hadron Colliders

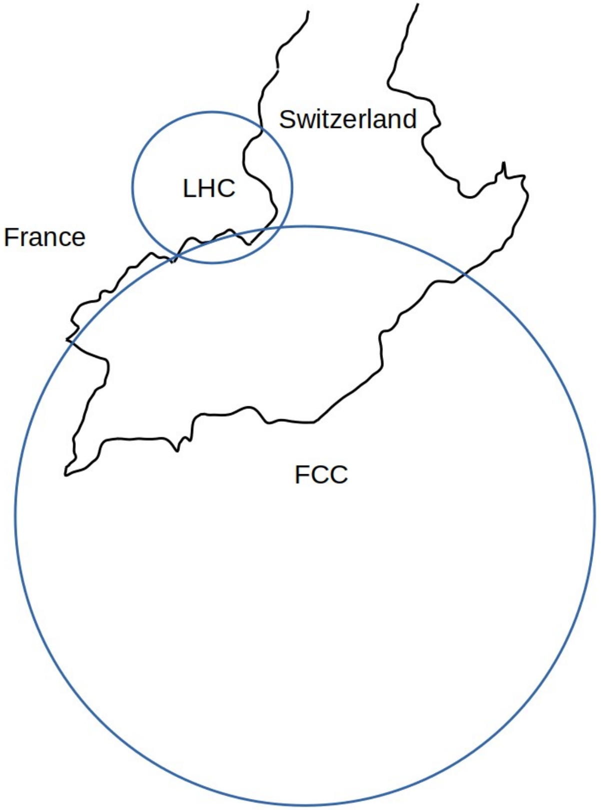
2 Studies

- CERN, Switzerland
  - Future e+e- Circular Collider, FCC-ee
  - **Future hadron Circular Collider, FCC-hh**
- IHEP, China
  - Circular Electron Positron Collider, CEPC
  - **Super proton-proton Collider, SppC**

FCC Integrated Program

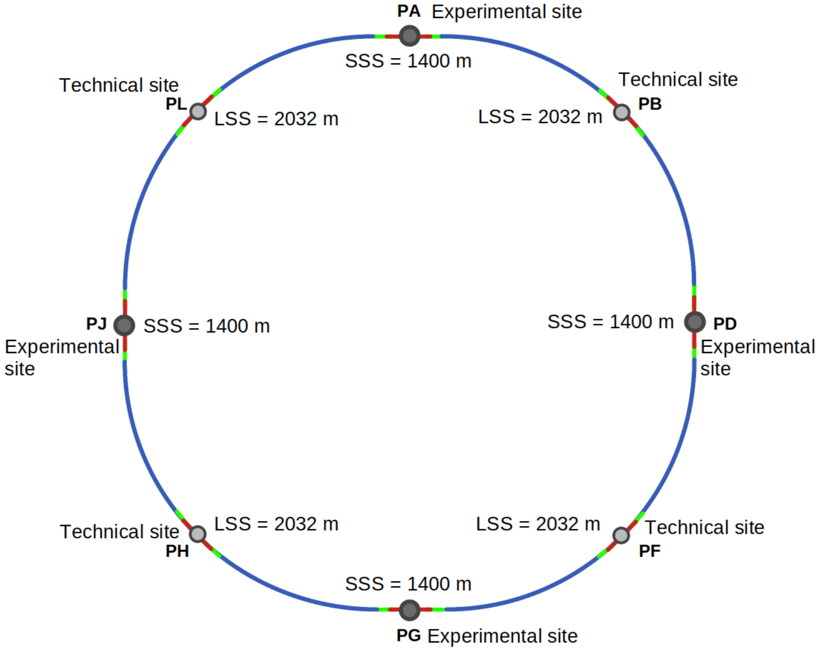
Inspired by LEP-LHC programm

Re-using CERN infrastructure



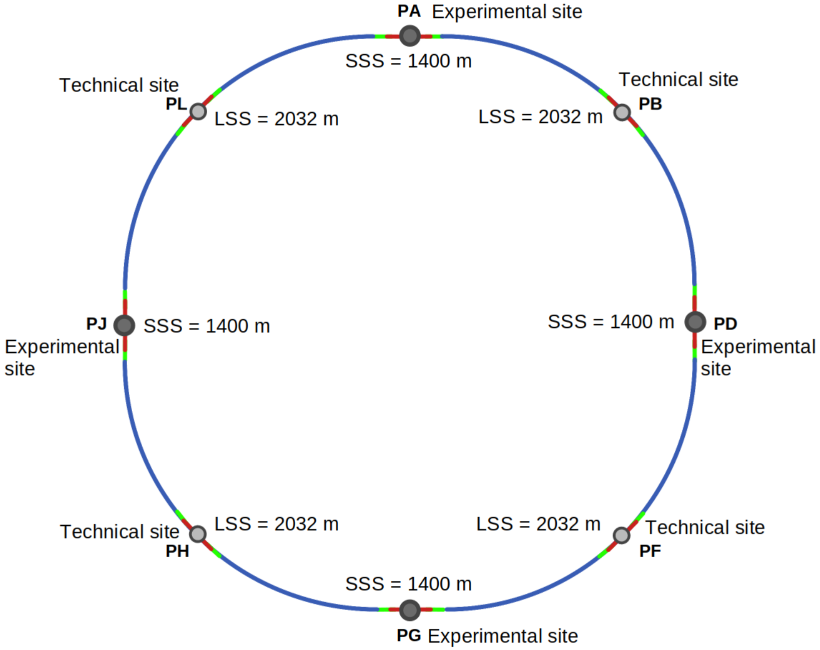
Compatible lattice designs

FCC-ee
Electron-positron collider



~ 2045 - 2060

FCC-hh
Proton-proton collider



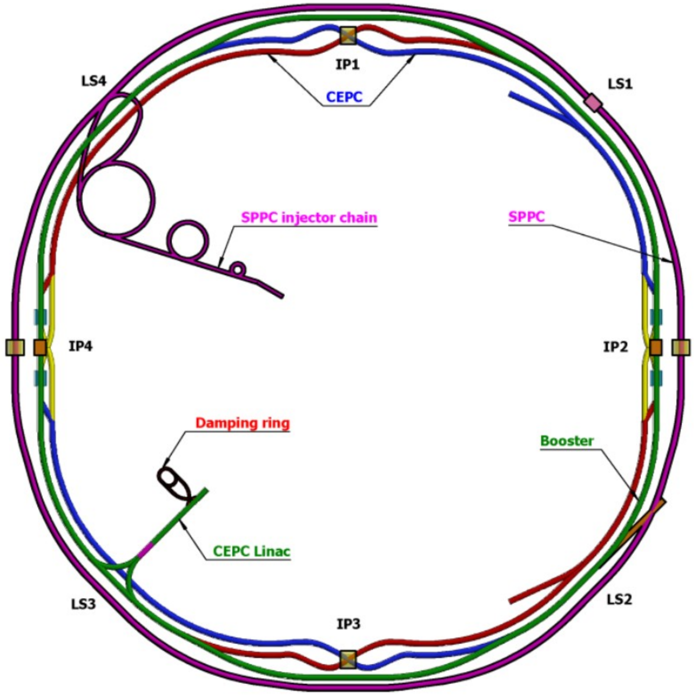
~ 2070 - 2090

CEPC-SppC Program

Compatible lattice designs

CEPC
Electron-positron collider

SppC
Proton-proton collider

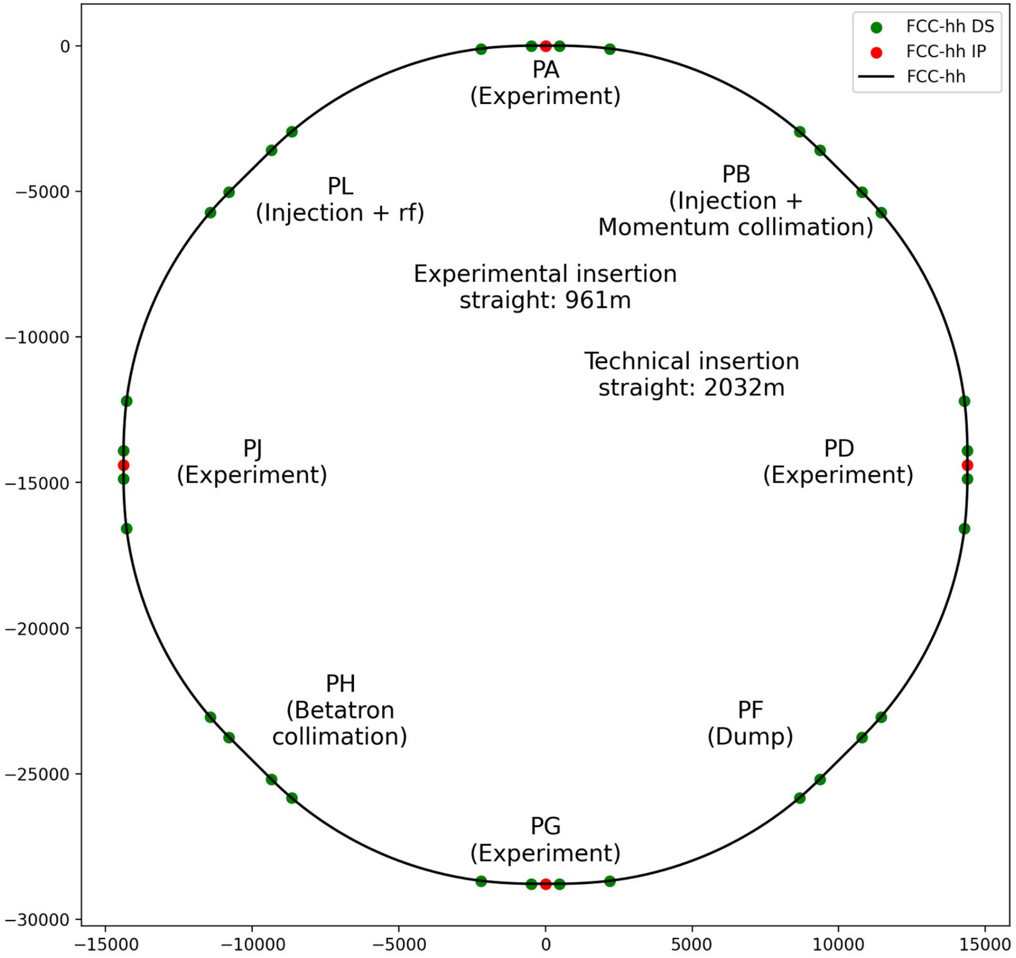


FCC-hh Overview

- 91 km hadron collider as successor of the FCC-ee

- 14 – 20 T dipole magnets
- 81 – 115 TeV center-of-mass energy

- 8 long straight sections with various functionalities
- 4 IPs for hadron-hadron collissions
- Electron-hadron IP could be included

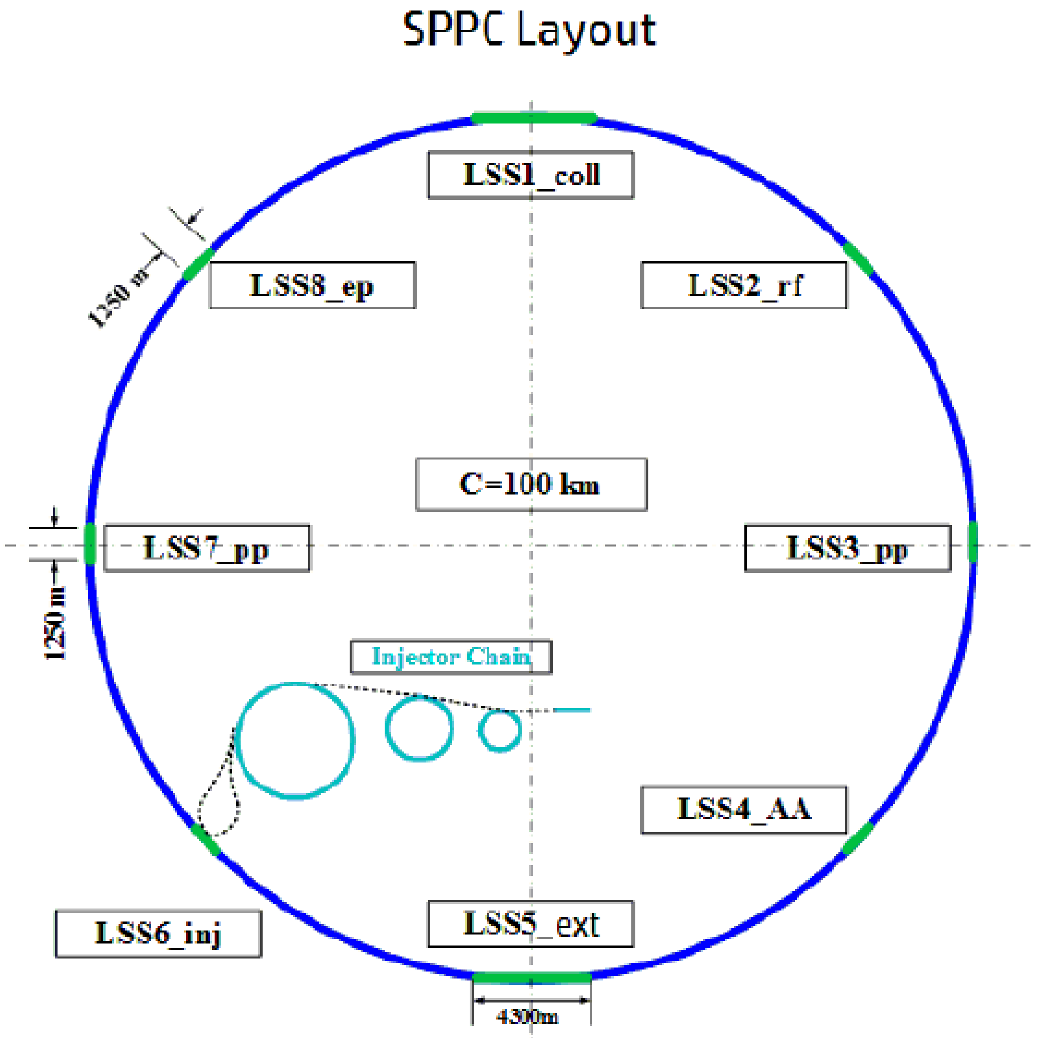


SppC Overview

- 100 km hadron collider as successor of CEPC in same tunnel

- Previously: 12 T for 75 TeV center-of-mass energy
- TDR: 24 T for 125 TeV center-of-mass energy

- 8 long straight sections with various functionalities
- 2 IPs for hadron-hadron collissions
- 1 IP for hadron-electron collissions

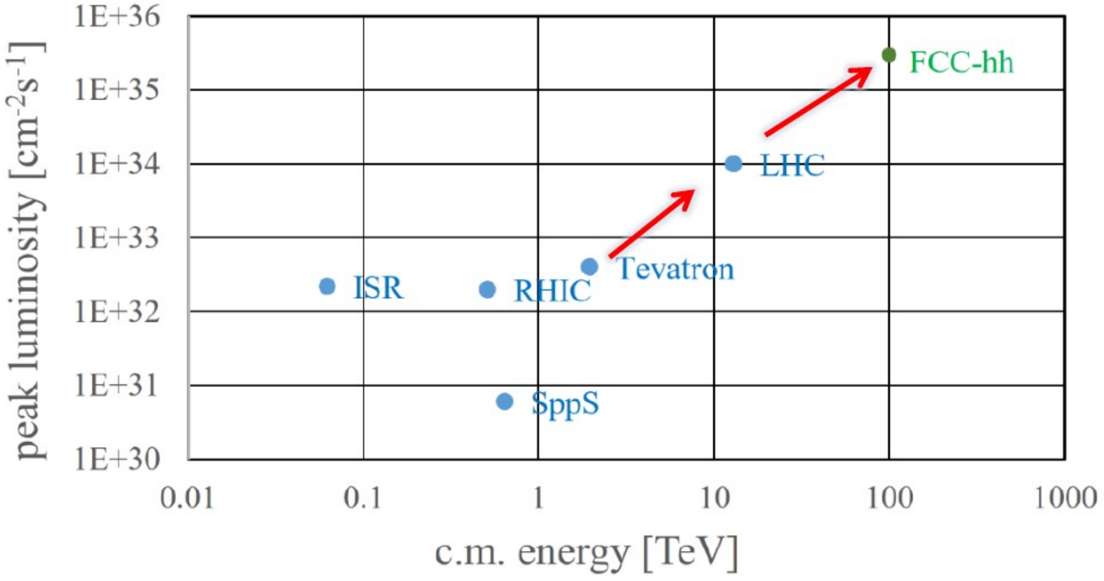


Physics Goals

- Aim to explore next order of magnitude of HEP collision experiments → beam energy of 42 to 60 TeV for protons
  - → Increase beam energy by factor 6 to 8.5 compared to LHC
  - → Increase circumference by almost factor 3 compared to LHC

- Huge integrated luminosity of 20 000 fb-1 per experiment over full operation time
  - → Increase by factor ~7 with respect to HL-LHC

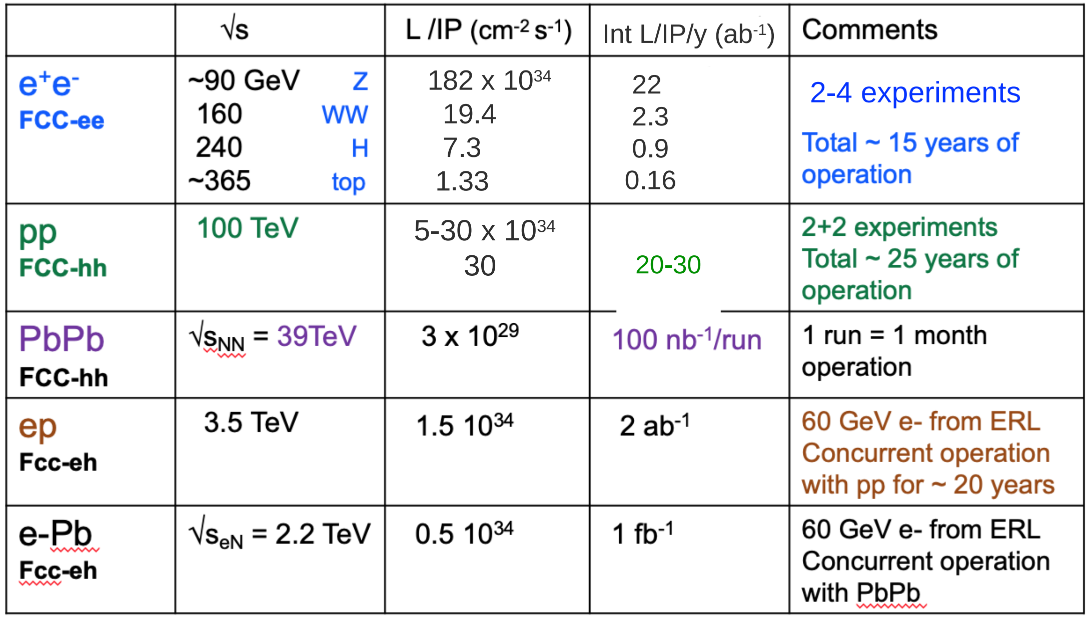
- Possibility to perform electron-ion collisions in one IP
  - → Incredibly rich physics program



Courtesy: F. Gianotti

FCC Physics Potential

- Integrated FCC offers multi-stage facility with broad and diverse physics potential



	√s	L /IP ($cm^{-2} s^{-1}$)	Int L/IP/y (ab^{-1})	Comments
e^+e^- **FCC-ee**	~90 GeV Z 160 WW 240 H ~365 top	182 x 10^{34} 19.4 7.3 1.33	22 2.3 0.9 0.16	2-4 experiments Total ~ 15 years of operation
pp **FCC-hh**	100 TeV	5-30 x 10^{34} 30	20-30	2+2 experiments Total ~ 25 years of operation
PbPb **FCC-hh**	$\sqrt{s_{NN}}$ = 39TeV	3 x 10^{29}	100 nb^{-1}/run	1 run = 1 month operation
ep **Fcc-eh**	3.5 TeV	1.5 10^{34}	2 ab^{-1}	60 GeV e- from ERL Concurrent operation with pp for ~ 20 years
e-Pb **Fcc-eh**	$\sqrt{s_{eN}}$ = 2.2 TeV	0.5 10^{34}	1 fb^{-1}	60 GeV e- from ERL Concurrent operation with PbPb

- FCC-ee:
  - Highest luminosities at Z, W and H of all proposed Higgs and electro-weak factories
  - Indirect discovery potential up to 70 TeV
- FCC-hh:
  - Direct exploration of next energy frontier (~10x LHC)
  - Also heavy ion collision experiments possible
- FCC-eh:
  - Possibly also electron-proton (ion) collisions

Courtesy: M. Benedikt

FCC-hh Parameters

	FCC-hh	HL-LHC	LHC
Collision energy [TeV]	81 - 115	14	
Dipole field [T]	14 - 20	8.33	
Circumference [km]	90.7	26.7	
Beam current [A]	0.5	1.1	0.58
Bunch intensity [10^{11}]	1	2.2	1.15
SR power/ring [kW]	1020 - 4250	7.3	3.6
SR power/length [W/m/A]	13-54	0.33	0.17
Events/bunch crossing [#]	~1000	132	27
Stored beam energy [GJ]	6.1 – 8.9	0.7	0.36
Luminosity/IP [10^{34}cm^{-2}s^{-1}]	~30	5*	1
Integrated luminosity/IP/year [ab^{-1}]	20000	3000	300

Direct discovery potential up to 40 TeV

With fixed circumference the dipole field defines achievable beam and collission energy

Challenges
- **High field superconducting magnets up to 20 T**
- **Power load from SR (cryo, vacuum, ..)**
- **Stored beam energy 9 GJ**
- **Number of events in detectors**
- **...**

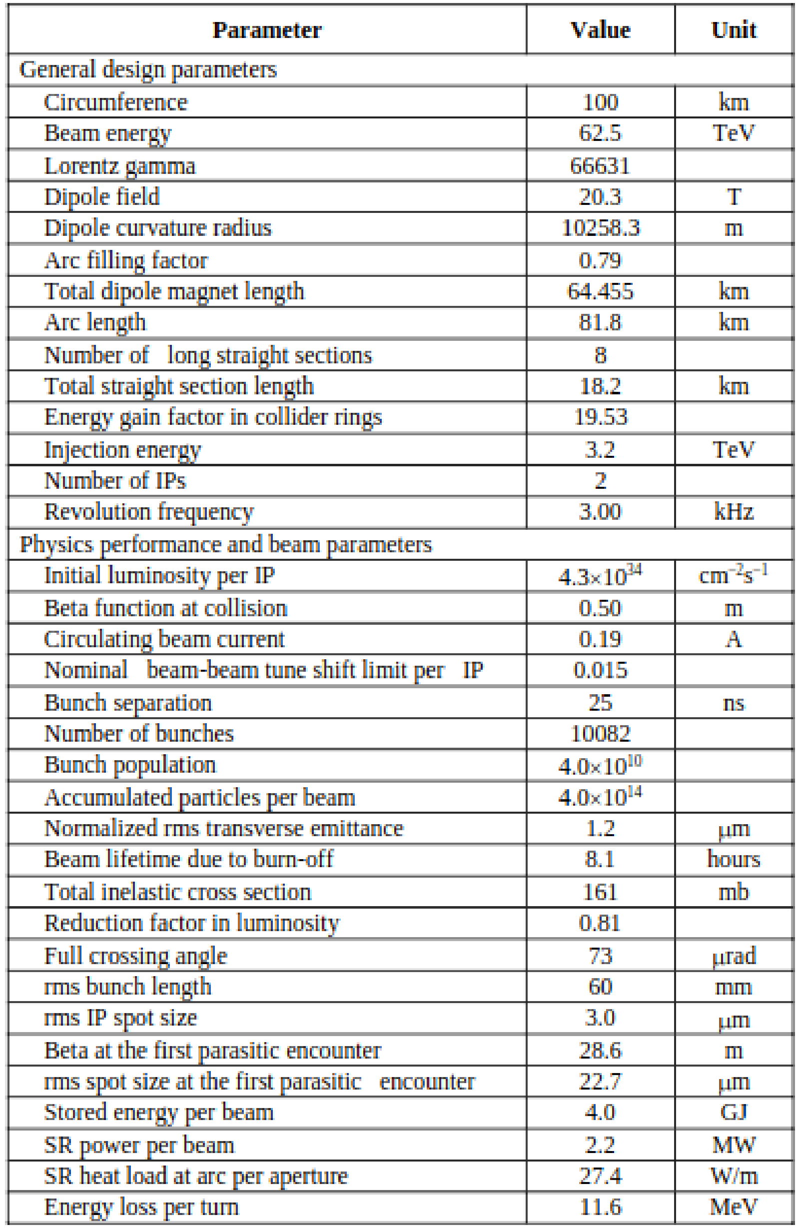
With FCC-hh after FCC-ee significantly more time for high-field magnet R&D

SppC Parameters

Courtesy: CEPC-SppC TDR

With fixed circumference the dipole field defines achievable beam and collission energy

Compared to FCC-hh higher collision energy of 125 GeV



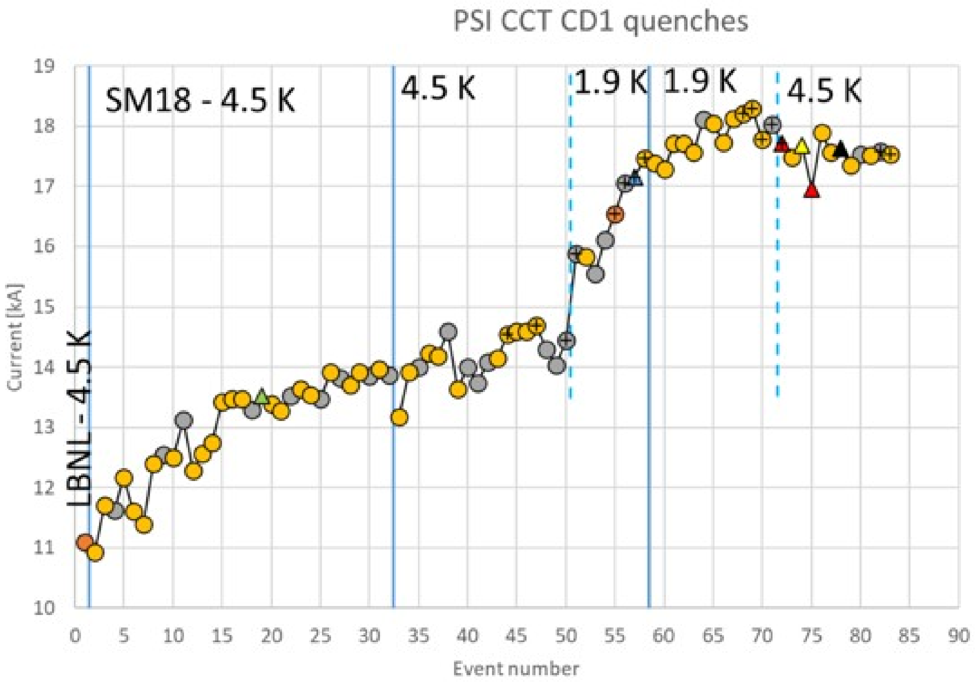
Parameter	Value	Unit
General design parameters		
Circumference	100	km
Beam energy	62.5	TeV
Lorentz gamma	66631	
Dipole field	20.3	T
Dipole curvature radius	10258.3	m
Arc filling factor	0.79	
Total dipole magnet length	64.455	km
Arc length	81.8	km
Number of long straight sections	8	
Total straight section length	18.2	km
Energy gain factor in collider rings	19.53	
Injection energy	3.2	TeV
Number of IPs	2	
Revolution frequency	3.00	kHz
Physics performance and beam parameters		
Initial luminosity per IP	4.3×10^{34}	$cm^{-2}s^{-1}$
Beta function at collision	0.50	m
Circulating beam current	0.19	A
Nominal beam-beam tune shift limit per IP	0.015	
Bunch separation	25	ns
Number of bunches	10082	
Bunch population	4.0×10^{10}	
Accumulated particles per beam	4.0×10^{14}	
Normalized rms transverse emittance	1.2	μm
Beam lifetime due to burn-off	8.1	hours
Total inelastic cross section	161	mb
Reduction factor in luminosity	0.81	
Full crossing angle	73	μrad
rms bunch length	60	mm
rms IP spot size	3.0	μm
Beta at the first parasitic encounter	28.6	m
rms spot size at the first parasitic encounter	22.7	μm
Stored energy per beam	4.0	GJ
SR power per beam	2.2	MW
SR heat load at arc per aperture	27.4	W/m
Energy loss per turn	11.6	MeV

Challenges
- **High field superconducting magnets of 20.3 T**
- **Power load from SR (cryo, vacuum, ..)**
- **Stored beam energy 4 GJ**
- **Number of events in detectors**
- **...**

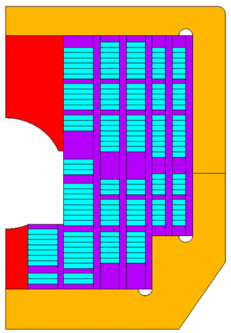
Courtesy: B. Auchmann

High Field Magnets: Nb_3Sn

- PSI Nb_3Sn main test carried out in 2022/2023
- Training via quenches (loss of superconductivity)
  - Controlled quenches help to achieve full field
- 100 % of maximum field achieved at 4.5 K
- Goal: demonstrate robust and cost efficient Nb_3Sn technology for next ESPPU



B_0 target of 14 T, at T_{op}: 4.2 K
Eng margin of 10%
B_0 short sample @ 1.9 K: 16 T

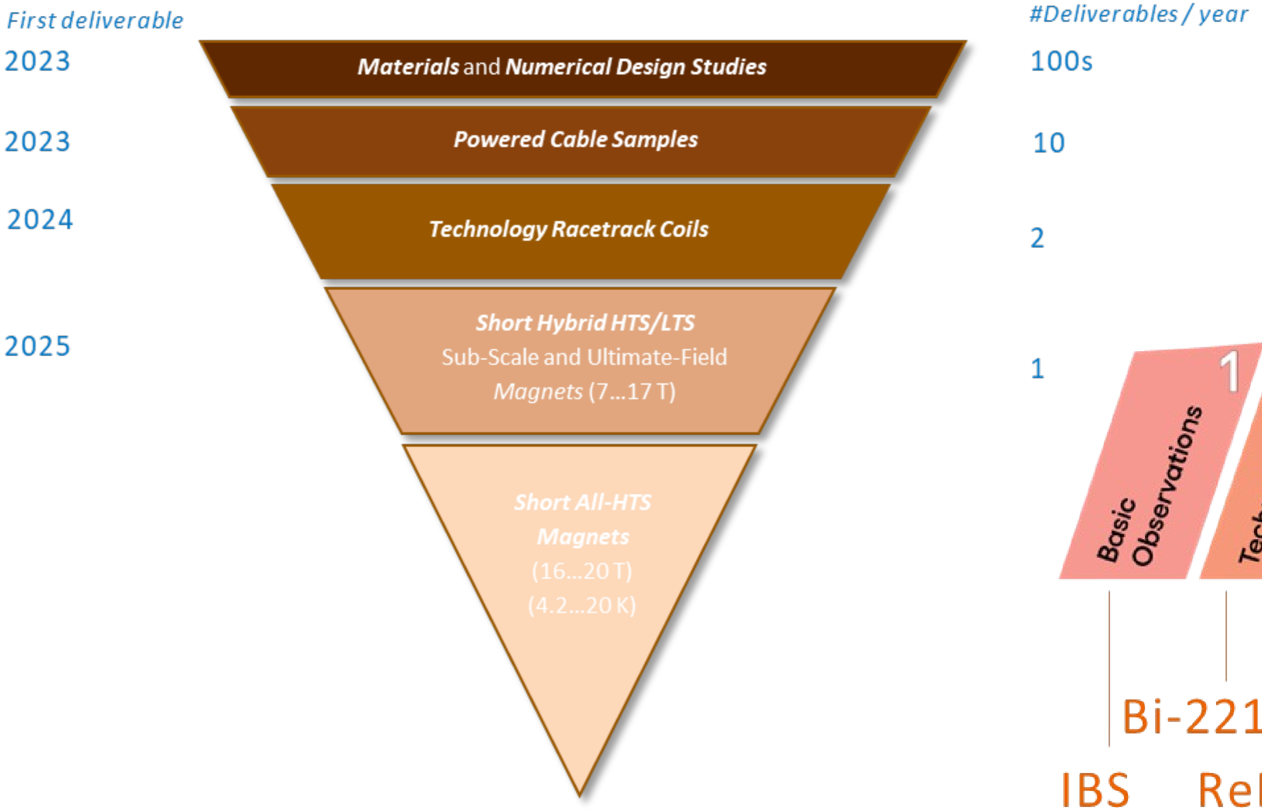


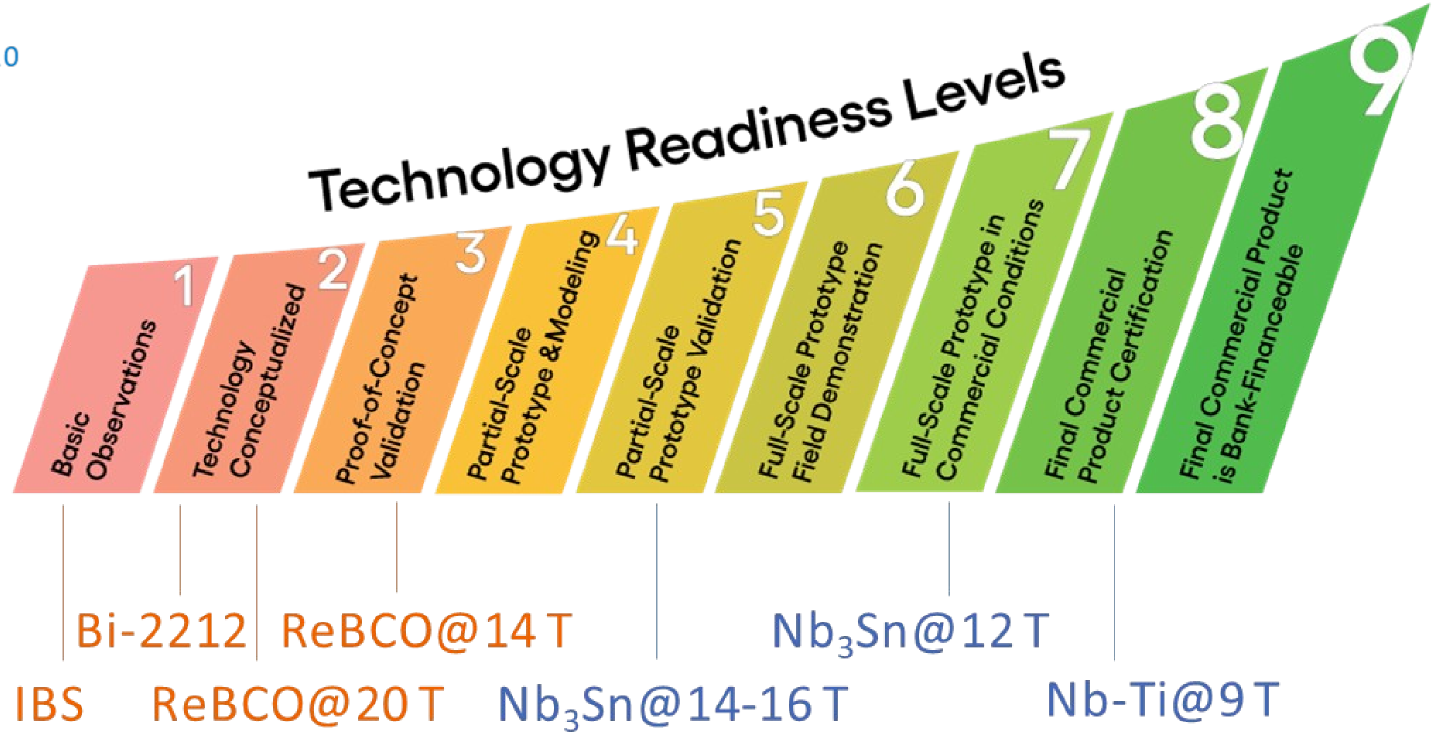
Stainless steel shell
Iron yoke
Coil collar
Former
Non-magnetic poles
Nb_3Sn conductor

Courtesy: B. Auchmann

High Field Magnets: HTS

- **Bottom line:** HTS technology must catch up over the coming 10 years

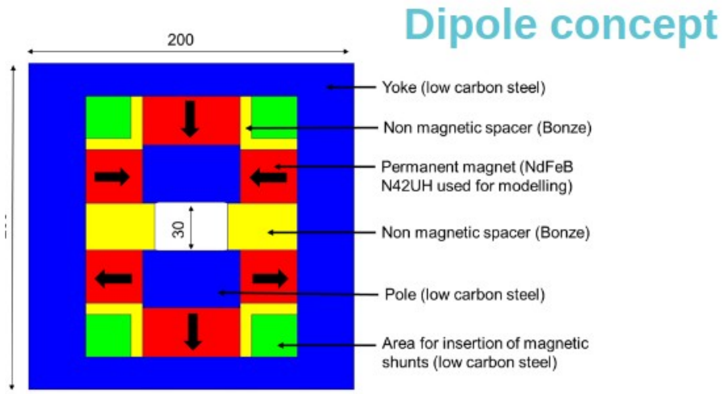




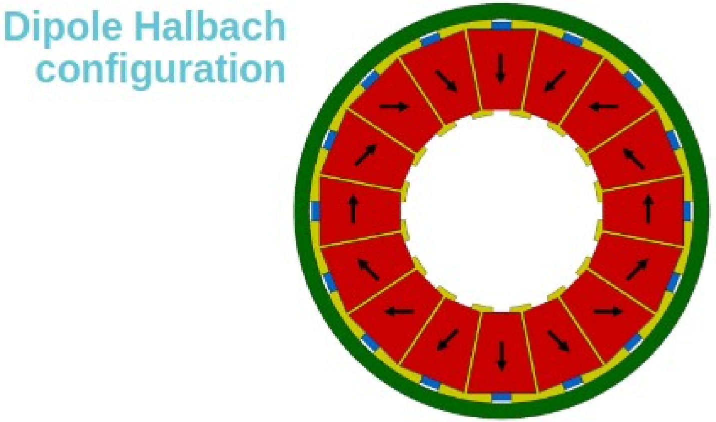
Permanent Magnets

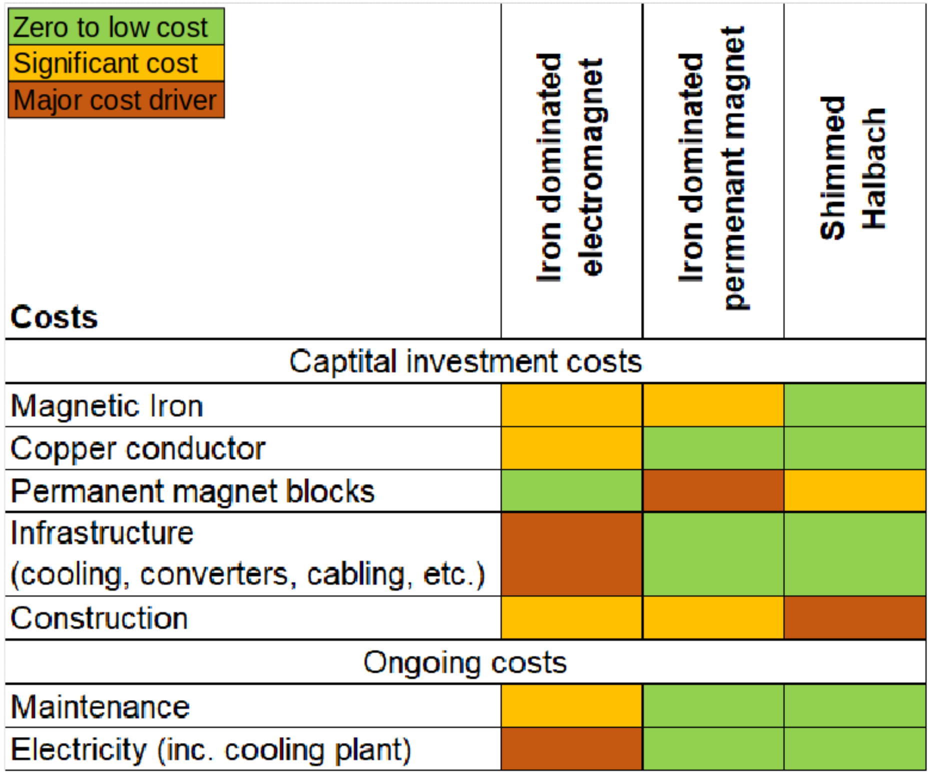
- Permanent magnets highly suitable for transfer line specifications
  - Less stringent field requirements
  - Already used in accelerators, although smaller scale
  - Small temperature dependence
  - Could be more cost effective

Iron dominated concept



Shimmed Halbach Concept





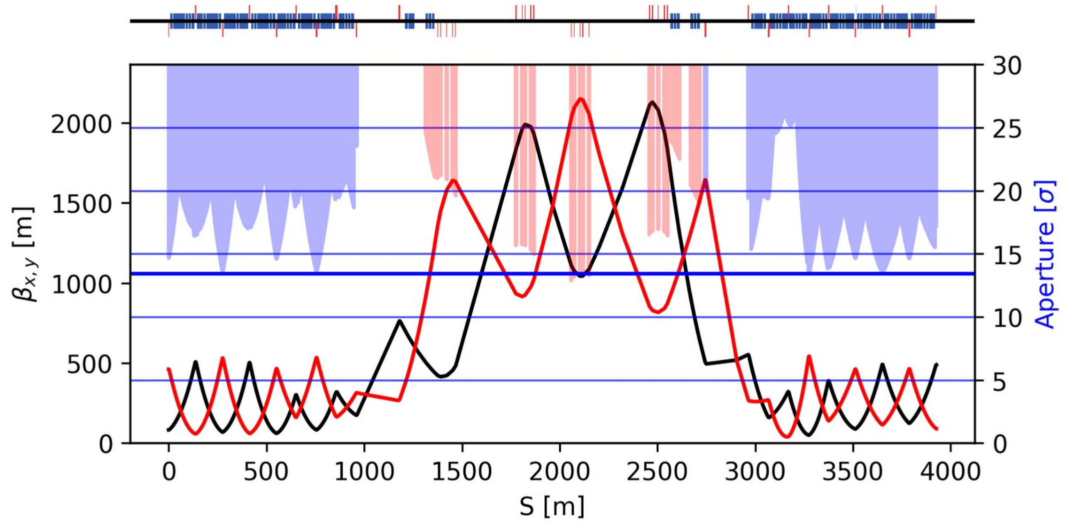
🟩 Zero to low cost
🟨 Significant cost
🟧 Major cost driver

Costs	Iron dominated electromagnet	Iron dominated permenant magnet	Shimmed Halbach
Captital investment costs			
Magnetic Iron	🟨	🟨	🟩
Copper conductor	🟨	🟩	🟩
Permanent magnet blocks	🟩	🟧	🟨
Infrastructure (cooling, converters, cabling, etc.)	🟧	🟩	🟩
Construction	🟨	🟨	🟧
Ongoing costs			
Maintenance	🟨	🟩	🟩
Electricity (inc. cooling plant)	🟧	🟩	🟩

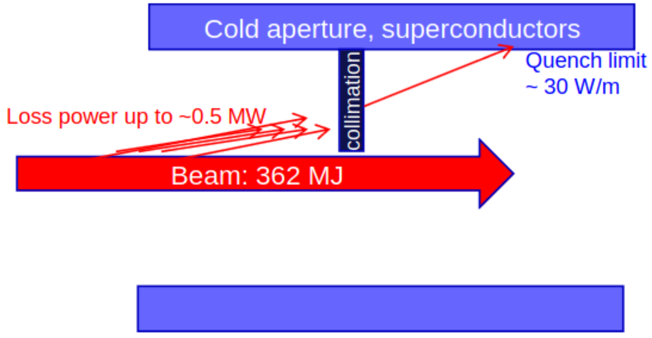
Courtesy: A. Abramov, R. Bruce, M. Giovannozzi

Collimation

- LHC: **362 MJ** and FCC: **8.3 GJ** stored beam energy
- Loss of even very small fraction of the beam could cause
  - Damage to impacted elements
  - Heating of superconducting magnets and quench
- Collimator robustness to be addressed



LHC


Cold aperture, superconductors

collimation

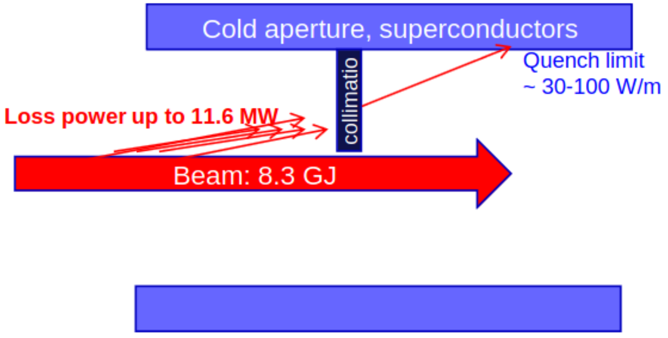
Quench limit
~ 30 W/m

Loss power up to ~0.5 MW

Beam: 362 MJ

Needed loss attenuation: factor ~2×10^4

FCC-hh


Cold aperture, superconductors

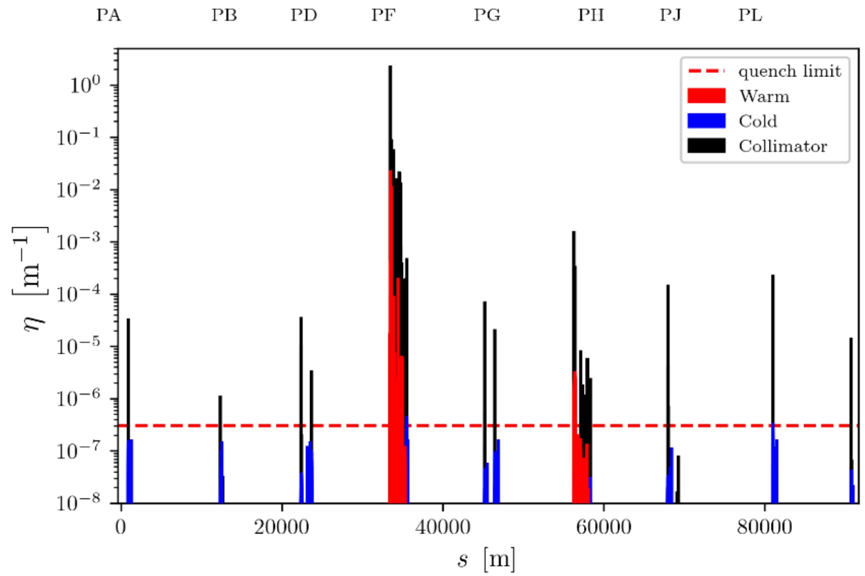
collimatio

Quench limit
~ 30-100 W/m

Loss power up to 11.6 MW

Beam: 8.3 GJ

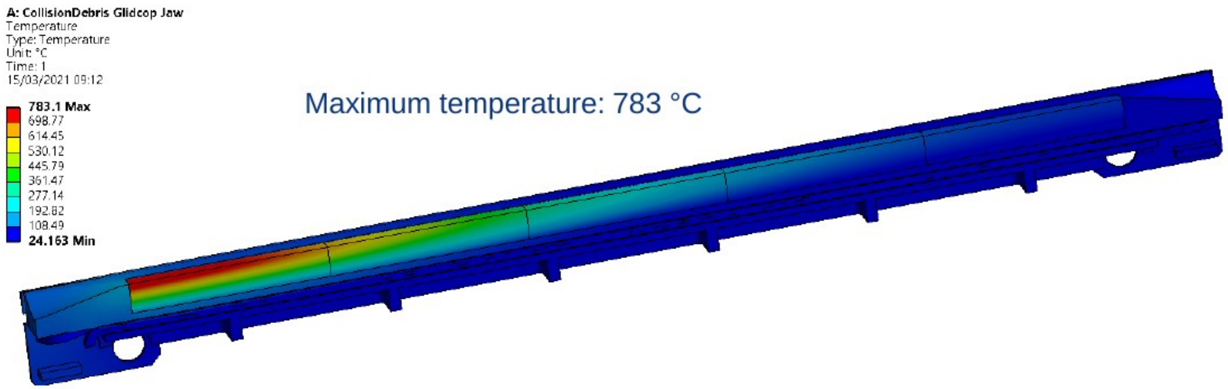
Needed loss attenuation: factor >10^5
Higher energy ➔ smaller collimator gaps



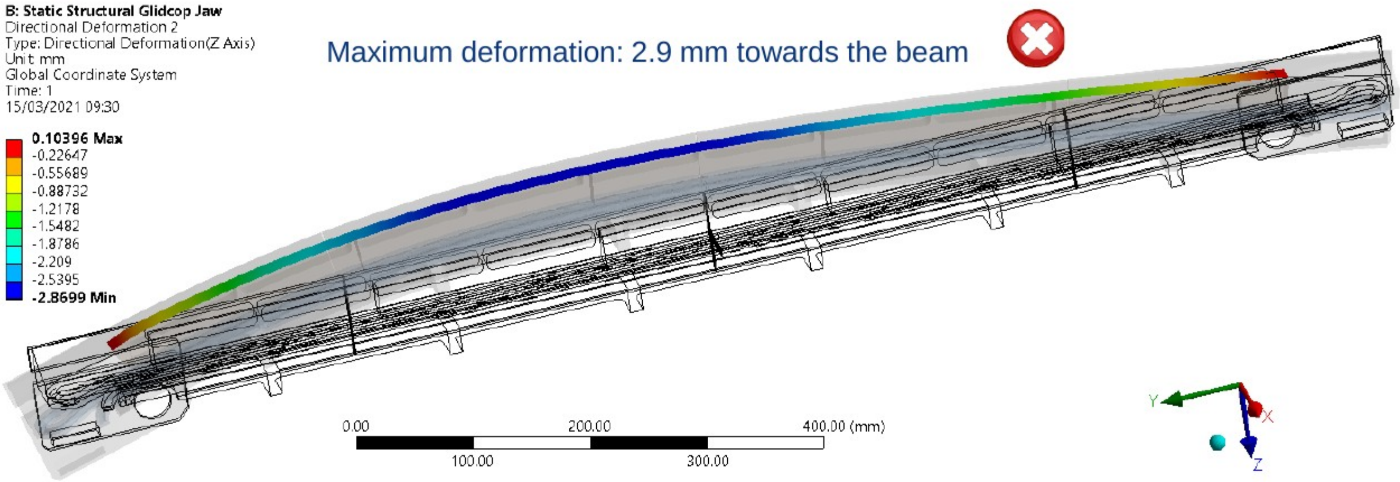
Courtesy: R. Bruce

Material Robustness

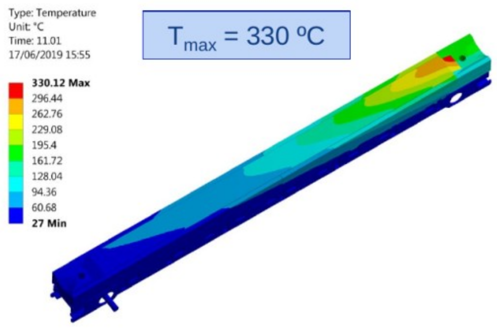
- Very challenging to find materials and engineering design
- Typically multi-particle simulations to evaluate e.g.
  - Energy deposition
  - Peak power and power density
  - Peak temperatures
  - Deformations
  - Melting



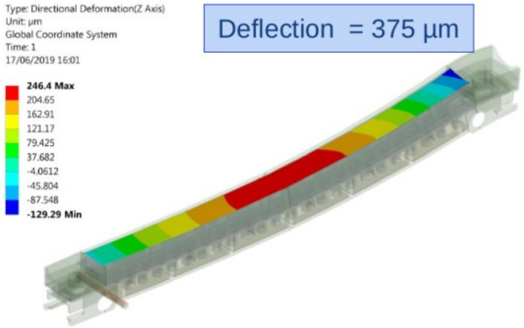
Maximum temperature: 783 °C



Maximum deformation: 2.9 mm towards the beam



T_{max} = 330 ºC

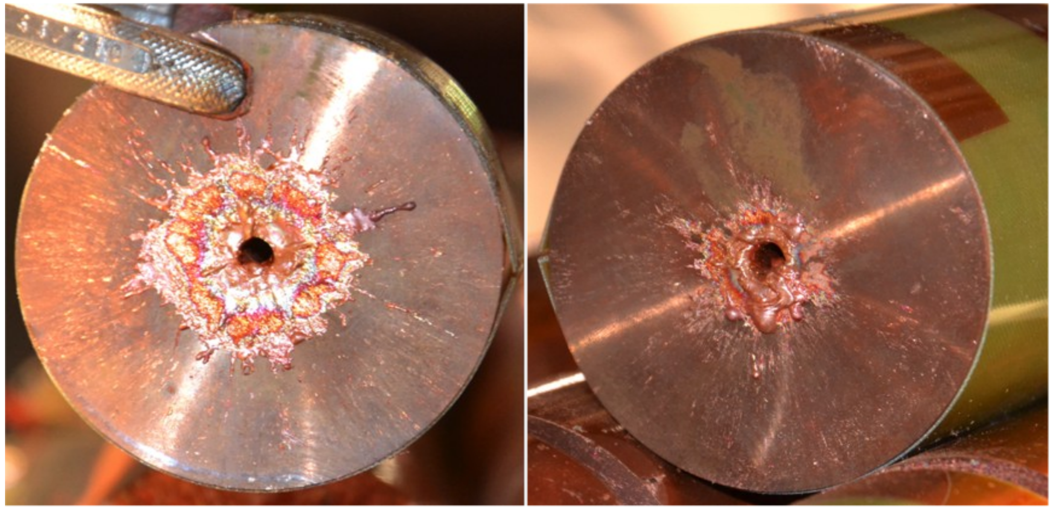


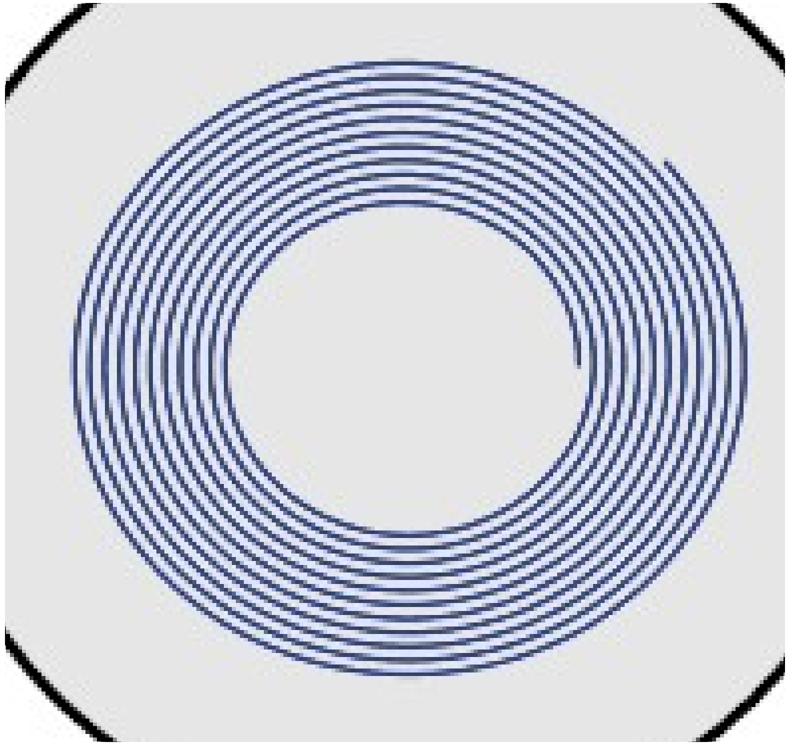
Deflection = 375 µm

Courtesy: R. Bruce

Beam Dump

- Beam dump system to extract and dispose full beam within one turn (failure or at the end of a fill)
- FCC-hh with 8.3 GJ could drill 300 m long hole in copper
- Beam distributed transversely onto beam dump
  - Dynamic magnetic field
  - Material with low density

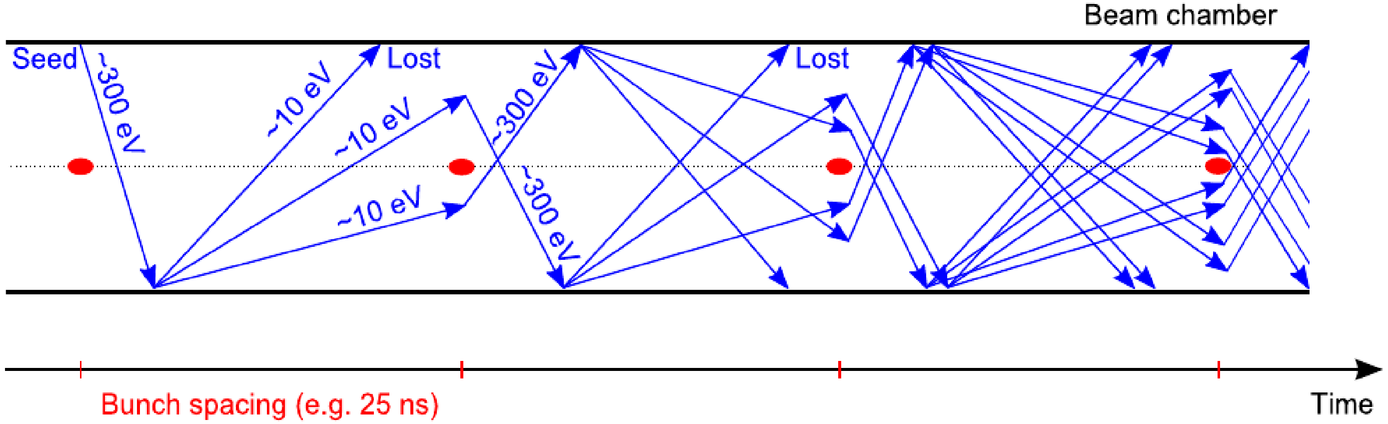


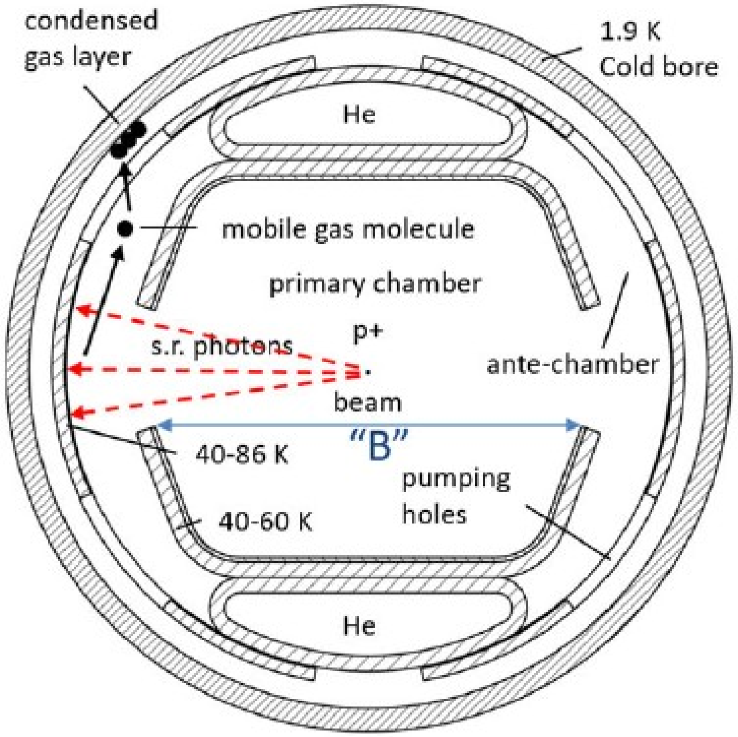


Beam Screen

- About 5 MW synchrotron radiation power loss per beam around the ring
- Beam screen design to intercept photons
- Cooling of beamscreen essential to keep temperature of 50 K

- Electrons inside vacuum chamber release more electrons → electron cloud
- Leads to heating, instabilities, vacuum issues, etc.
- Special beam screen designs and coatings required



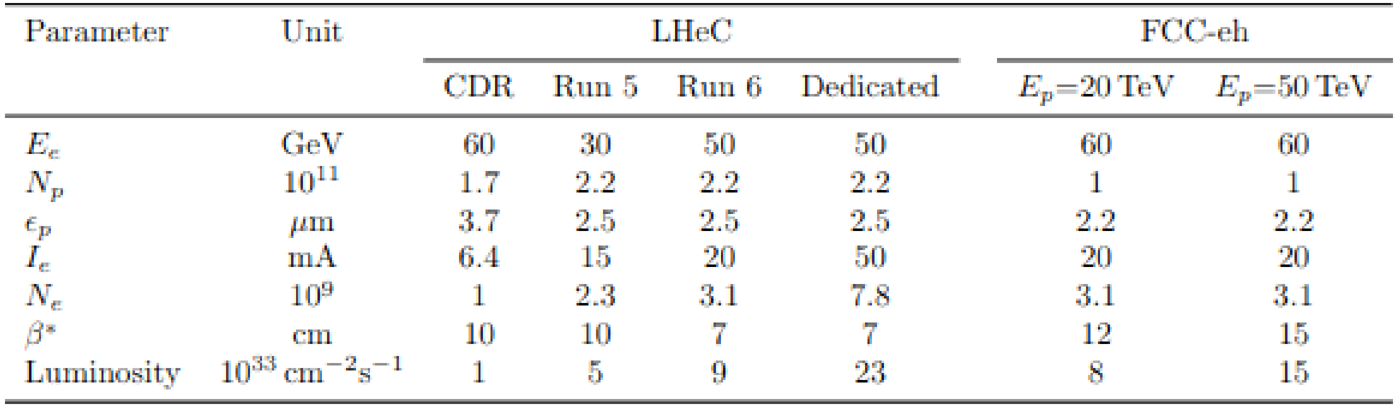


Energy Recovery Linacs

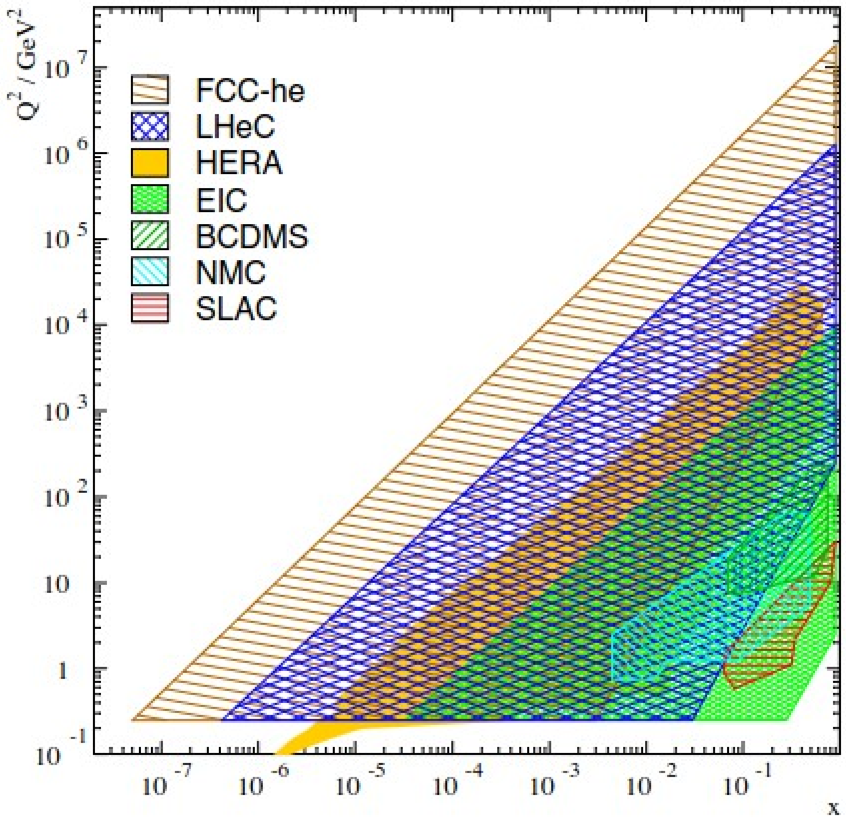
Courtesy: R. Bruce

Motivation

- Could be combined with hadron storage ring → LHeC or FCC-eh
- Improved understanding of deep inelastic lepton-hadron scattering
- Novel insights on QCD → high intensity electron beam required
- First electron-hadron collisions since HERA, Germany



Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	10^{33} cm^{-2}s^{-1}	1	5	9	23	8	15



Source: https://arxiv.org/pdf/2007.14491

Principle

- Same accelerating structure in straight part
- Bend of particles in arc structure
- Multi-turn acceleration

- Small footprint, especially if permanent magnets are used
- High intensities
- High brilliance
- Use for high-power electron-hadron colliders

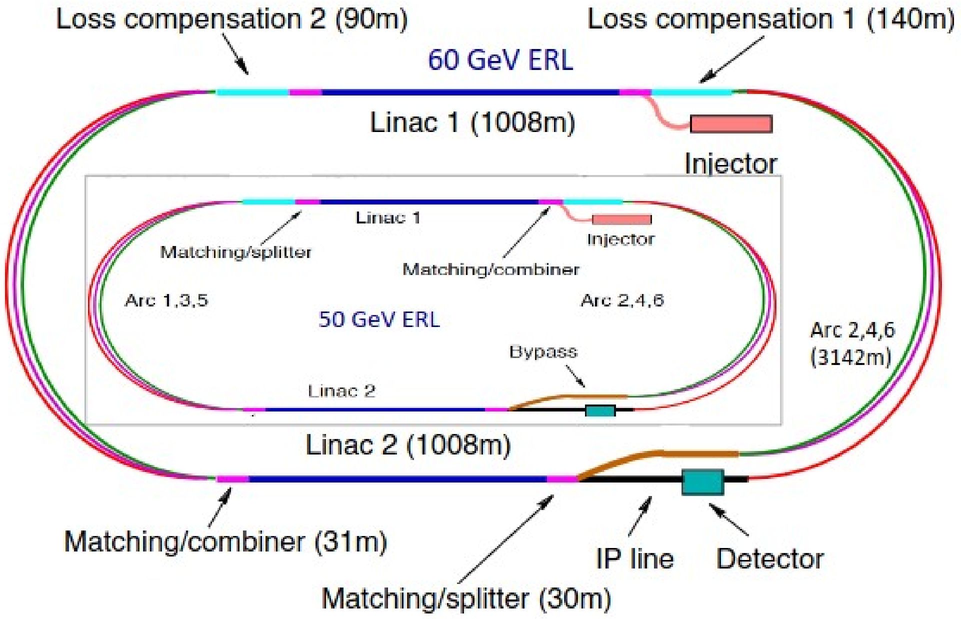
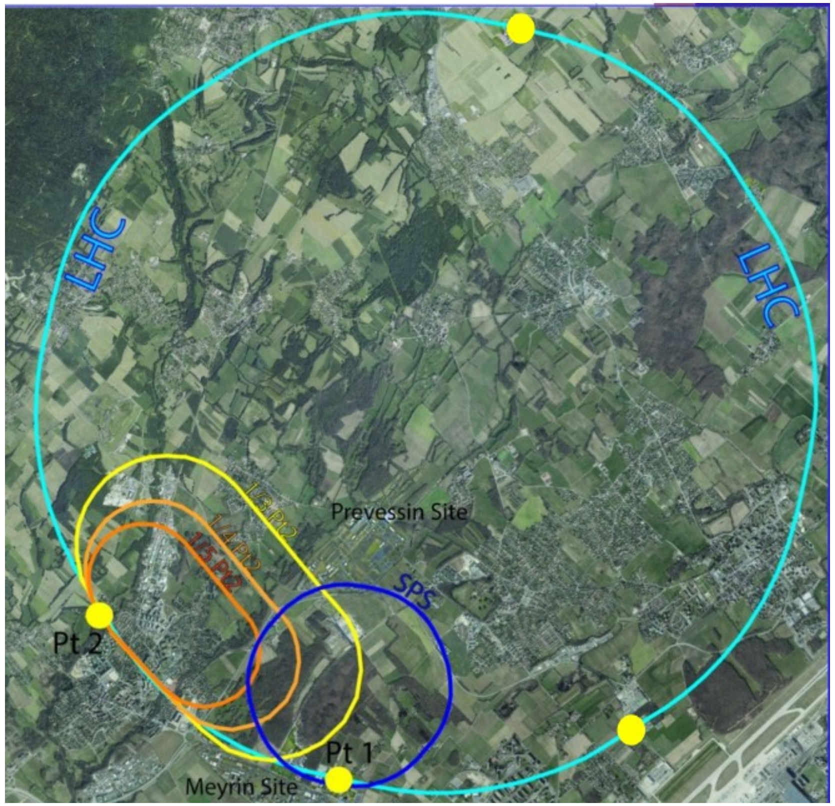


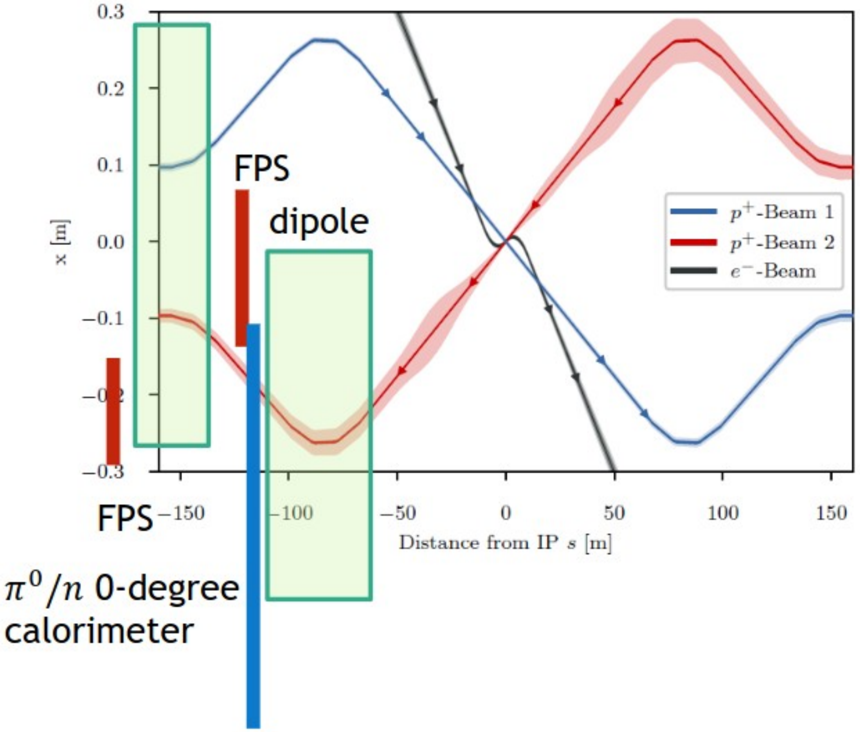
Figure 2.2: Schematic view of the three-turn LHeC configuration with two oppositely positioned electron linacs and three arcs housed in the same tunnel. Two configurations are shown: Outer: Default $E_e = 60\,\text{GeV}$ with linacs of about 1 km length and 1 km arc radius leading to an ERL circumference of about 9 km, or 1/3 of the LHC length. Inner: Sketch for $E_e = 50\,\text{GeV}$ with linacs of about 0.8 km length and 0.55 km arc radius leading to an ERL circumference of 5.4 km, or 1/5 of the LHC length, which is smaller than the size of the SPS. The 1/5 circumference configuration is flexible: it entails the possibility to stage the project as funds of physics dictate by using only partially equipped linacs, and it also permits upgrading to somewhat higher energies if one admits increased synchrotron power losses and operates at higher gradients.

Courtesy: T. van Witzleben, Y. Yamazaki

The LHeC

- With 50 GeV electron and 7 TeV proton beam → 1.2 TeV center-of-mass energy; requires re-design of IR2
- Additional infrastructure for ERL required



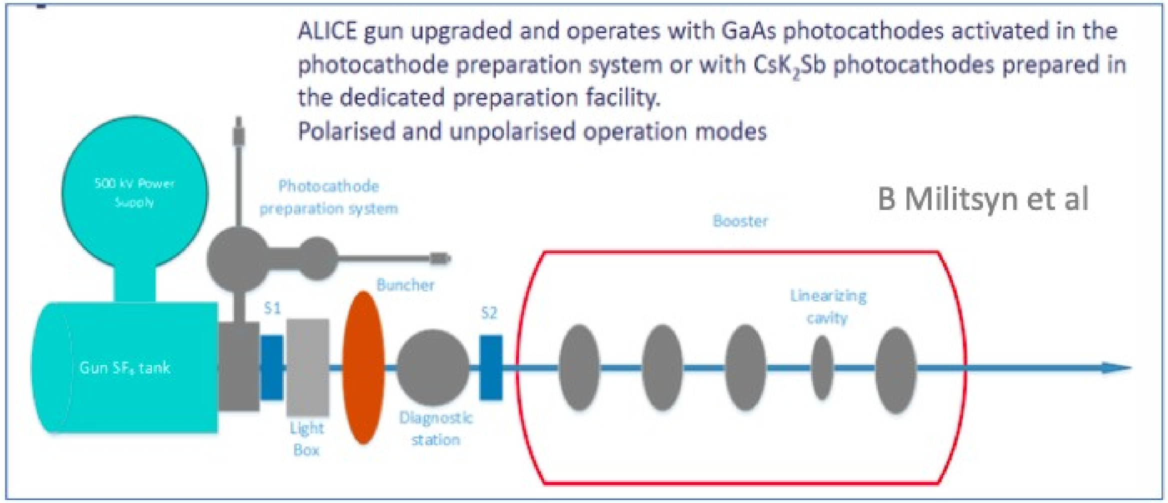


IP design 2020 and the candidate places for forward detectors

Courtesy: O. Brüning, B. Holzer

Main Challenges

- Compact and efficient electron acceleration
  - → SRF technologies, limit power consumption
- IR region design and integration in LHC and FCC-hh
  - → Optics, synchrotron radiation
- Integrated luminosity of 1000 x HERA

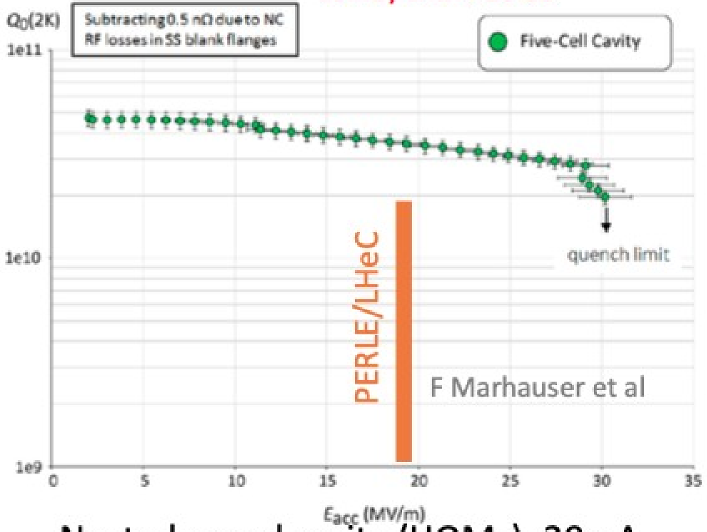

ALICE gun upgraded and operates with GaAs photocathodes activated in the photocathode preparation system or with CsK_2Sb photocathodes prepared in the dedicated preparation facility.
Polarised and unpolarised operation modes

PERLE will begin with 5mA ALICE source, which has been transferred from Daresbury to Orsay while UK was in EU..

BINP, BNL/Cornell (cBETA), Daresbury, IJC, Jlab, +

SCRF: High Q_0, complete Cryomodule

Jointly with FCC-ee



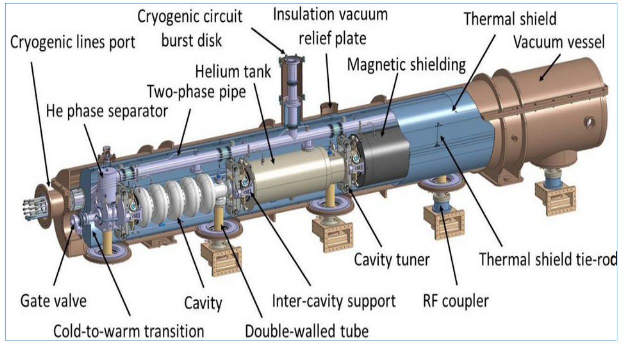
Next: dressed cavity (HOMs), 20mA
Adapt SPL Cryomodule for PERLE

CERN, Jlab, Orsay +

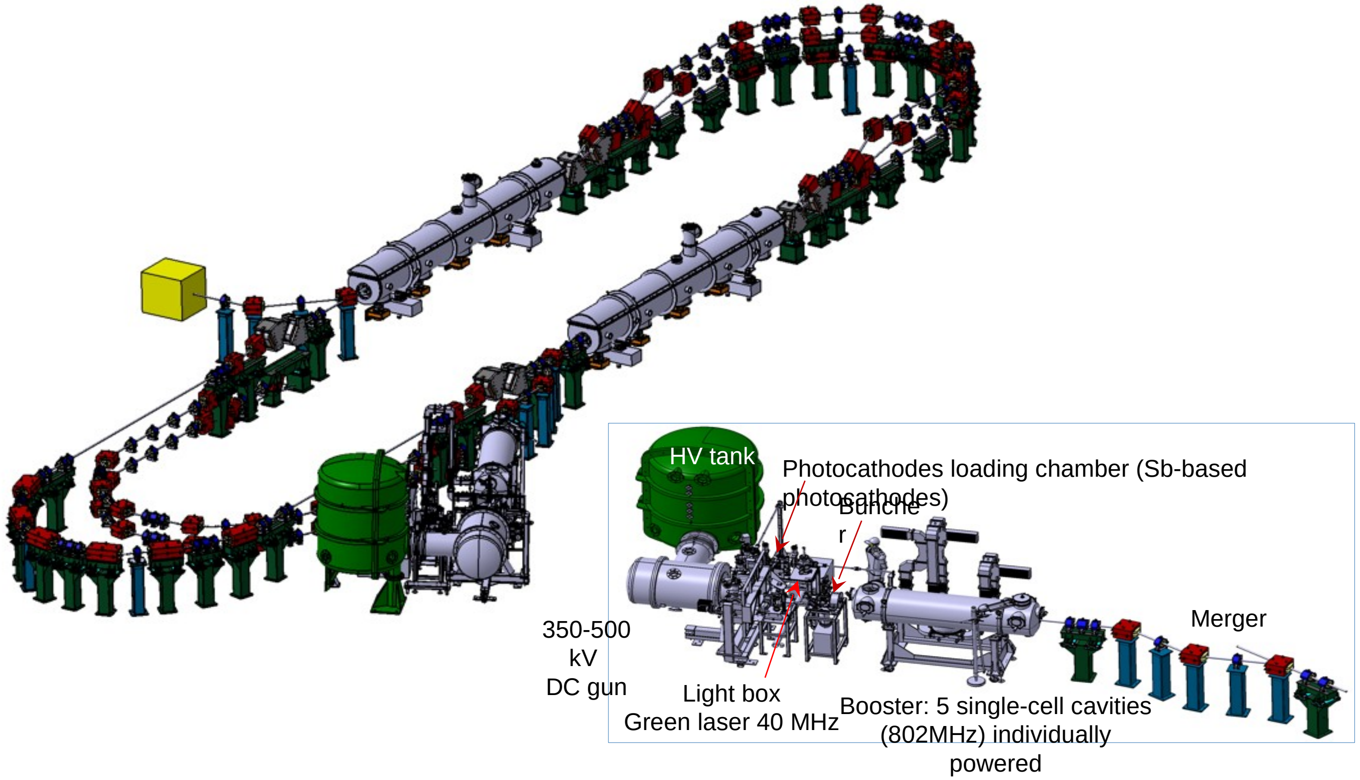
Courtesy: W. Kaabi, M. Klein

PERLE

- ERL located at Orsay, aims to
- Demonstrate high current (20 mA) multi (3) turn ERL operation
- Test technology of 5-cell 800 MHz SRF cavities (also requried for ttbar at FCC)



Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

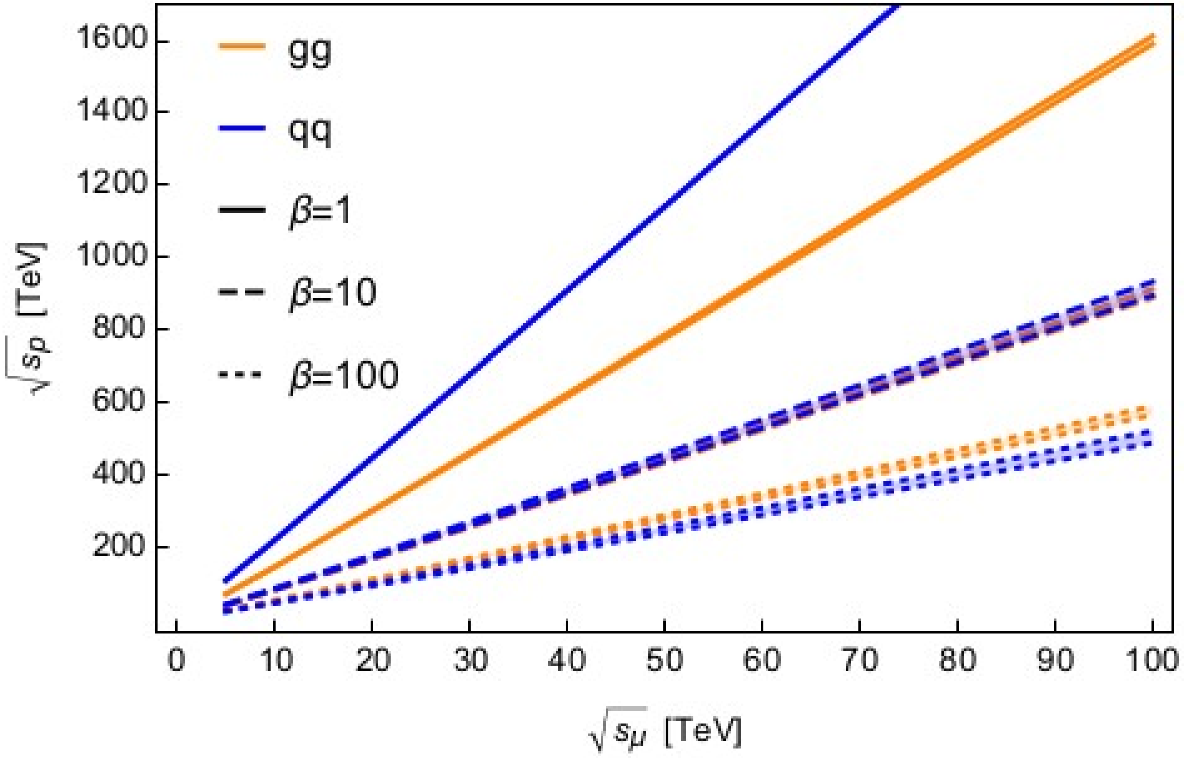


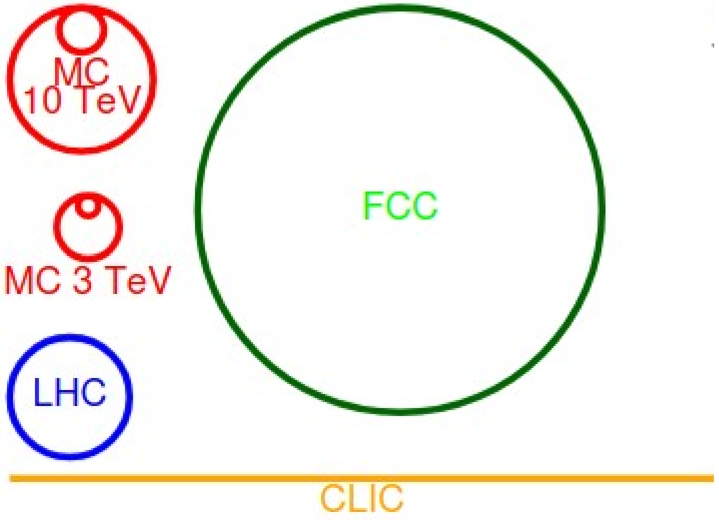
μ+μ- Colliders

Courtesy: D. Schulte

Motivation

- µ are elementary particles → full collision energy available for particle production
- 10 to 14 TeV µ collisions comparable to 100 to 200 TeV proton collisions
  - → Significant energy reach for possible physics discoveries



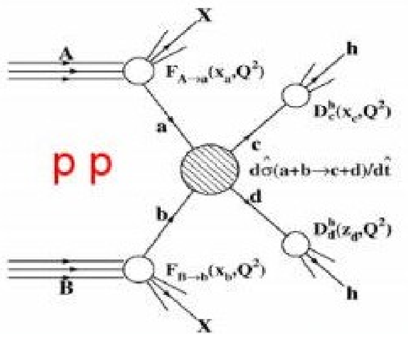


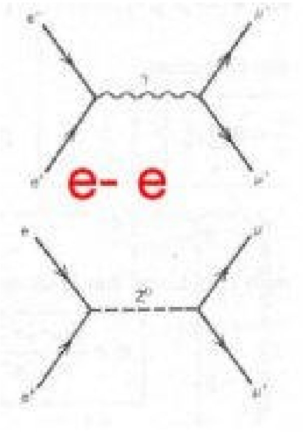
Courtesy: D. Schulte

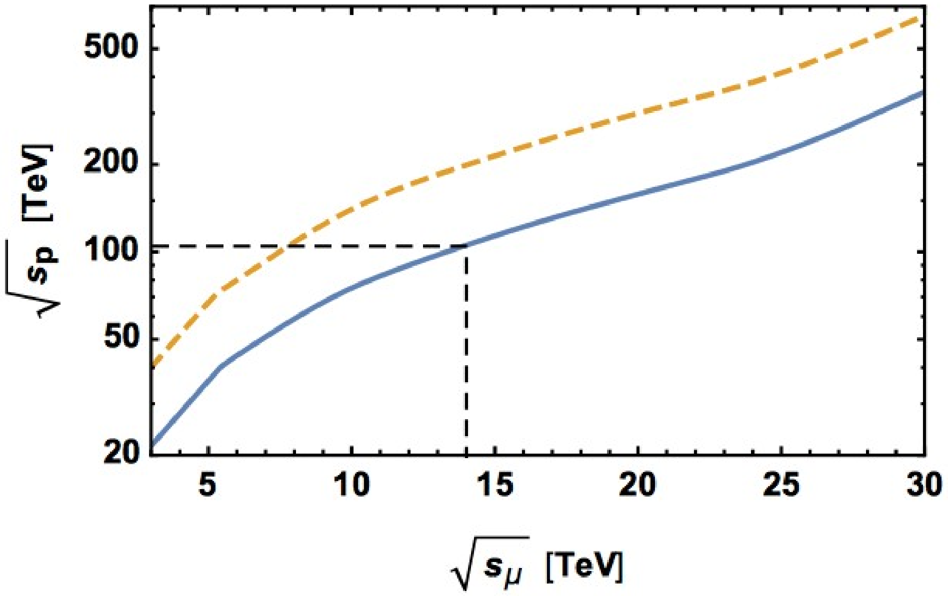
Motivation

- μ are elementary particles → full collision energy available for particle production
- 10 to 14 TeV μ collisions comparable to 100 to 200 TeV proton collisions
  - → Significant energy reach for possible physics discoveries
- Luminosity must increase with beam energy
- A new type of collider:
  - With m_μ = 106 MeV/c^2 lower SR than electrons
  - Center-of-mass energy equivalent to possible future hadron colliders

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





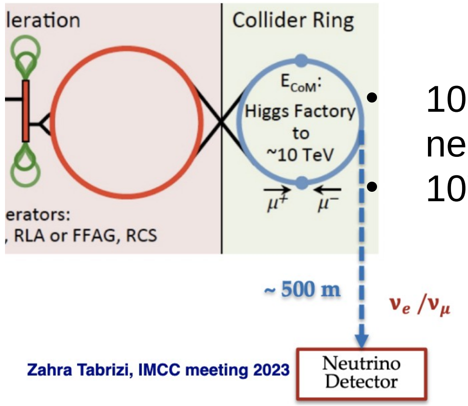


Courtesy: B. Stechauner, D. Schulte

Physics Motivation

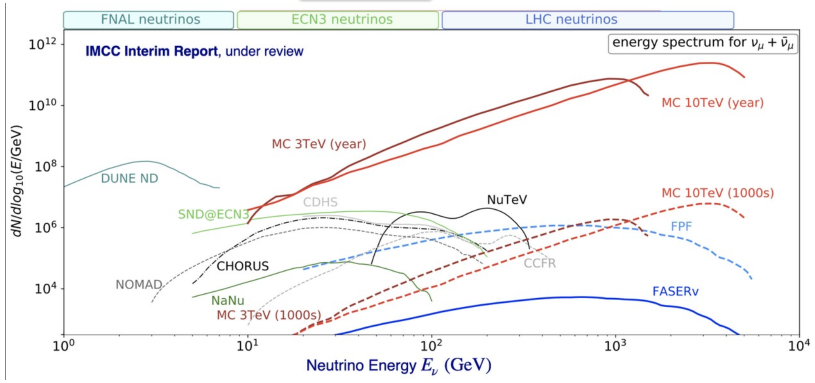
- μ are elementary particles → full collision energy available for particle production

Neutrino beam physics

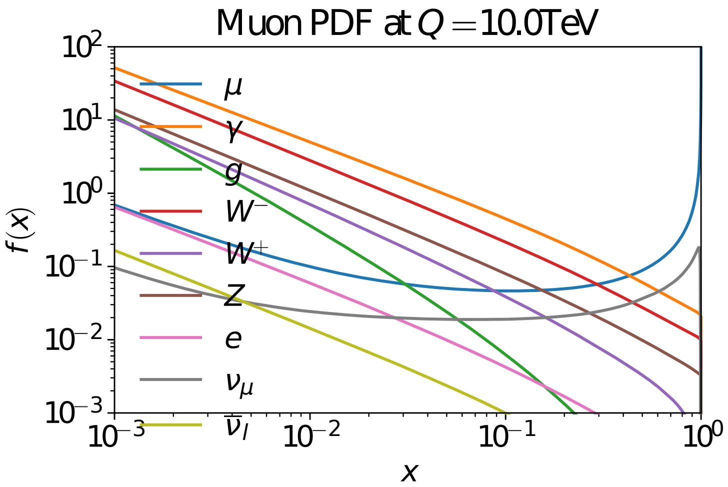


Zahra Tabrizi, IMCC meeting 2023

- 10 TeV collider: 10^{17} neutrinos/year
- 10^7 detector events



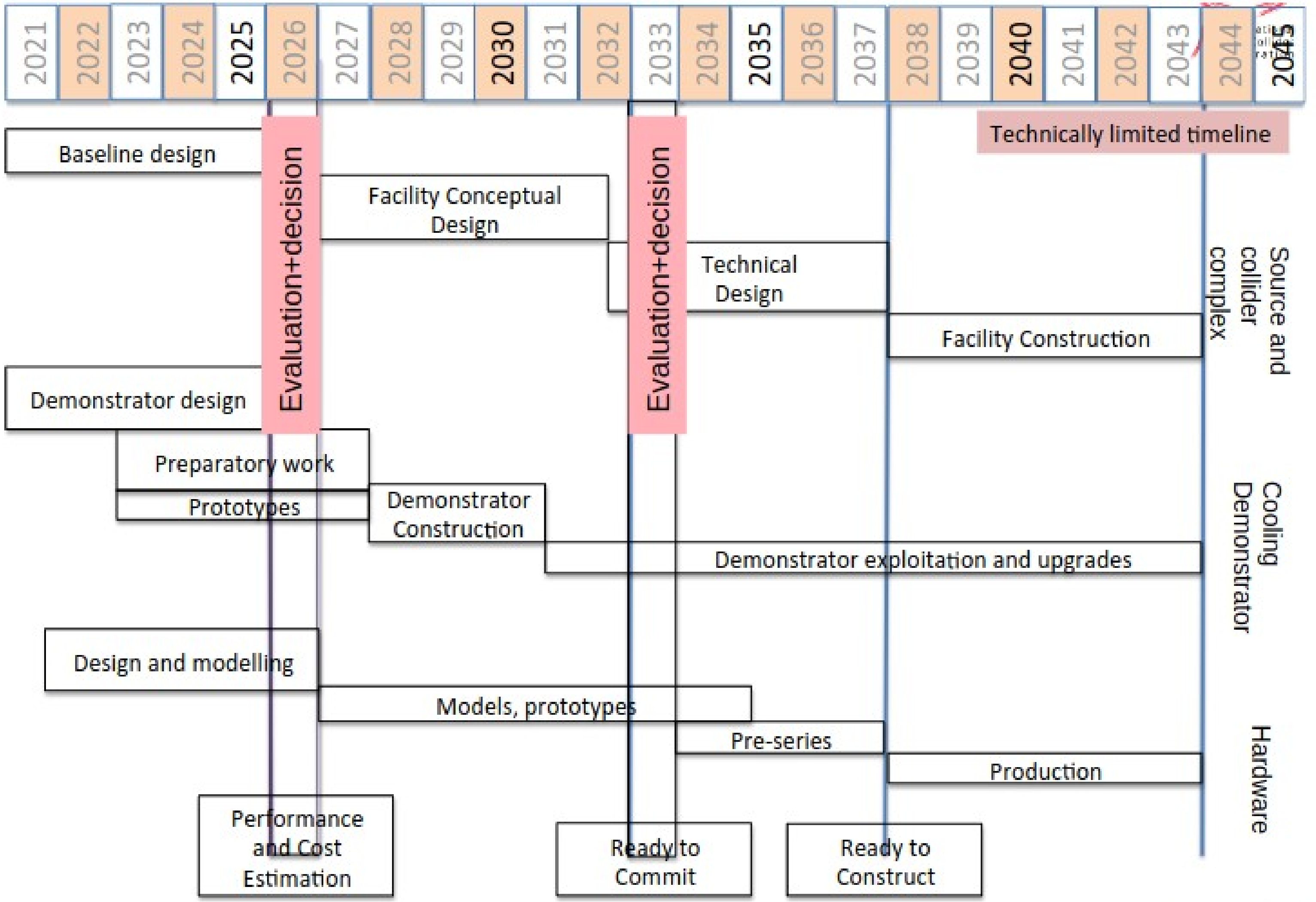
Lepton PDF



- High energy fundamental particles can split themselves in other particles.
- Derived from first principles.
- Can be tested in multi-TeV colliders.

Courtesy: D. Schulte

Tentative Timeline



2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045

Technically limited timeline

Evaluation+decision

Evaluation+decision

Baseline design

Facility Conceptual Design

Technical Design

Facility Construction

Source and collider complex

Demonstrator design

Preparatory work

Prototypes

Demonstrator Construction

Demonstrator exploitation and upgrades

Cooling Demonstrator

Design and modelling

Models, prototypes

Pre-series

Production

Hardware

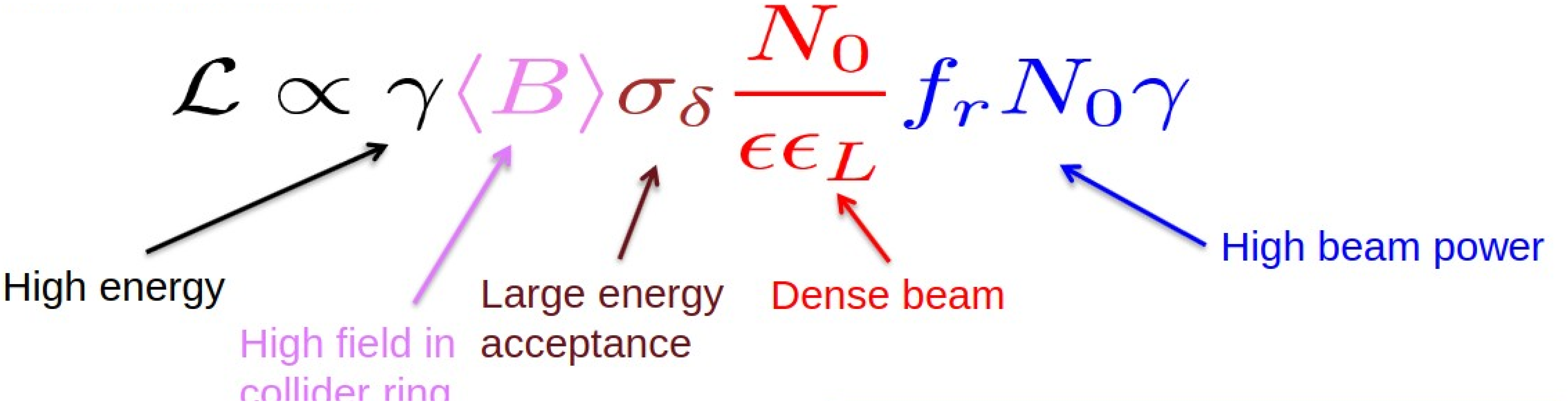
Performance and Cost Estimation

Ready to Commit

Ready to Construct

Courtesy: D. Schulte

Luminosity



$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring

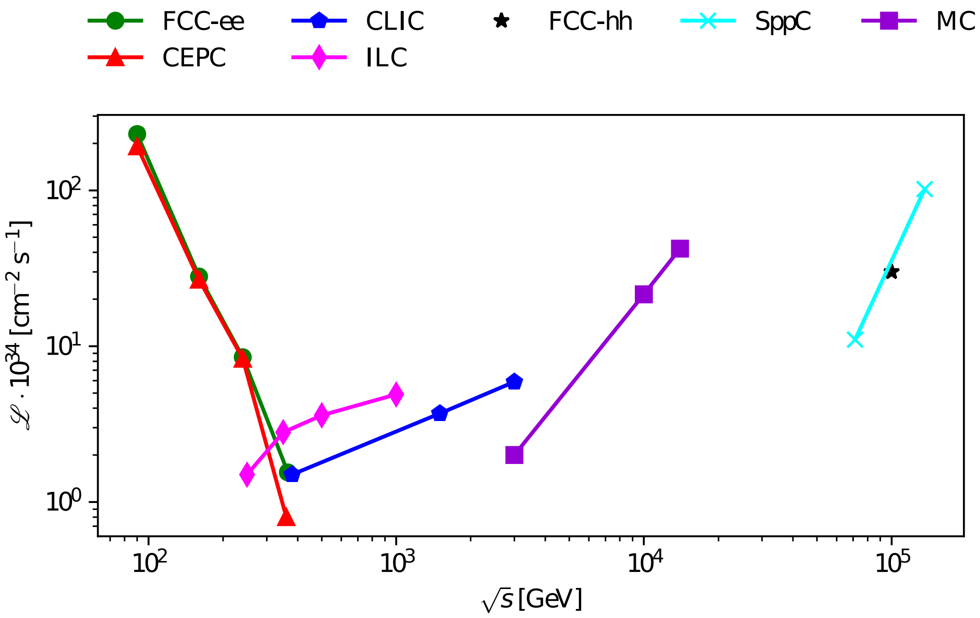
Large energy acceptance

Dense beam

High beam power

Courtesy: D. Schulte

Tentative Parameters

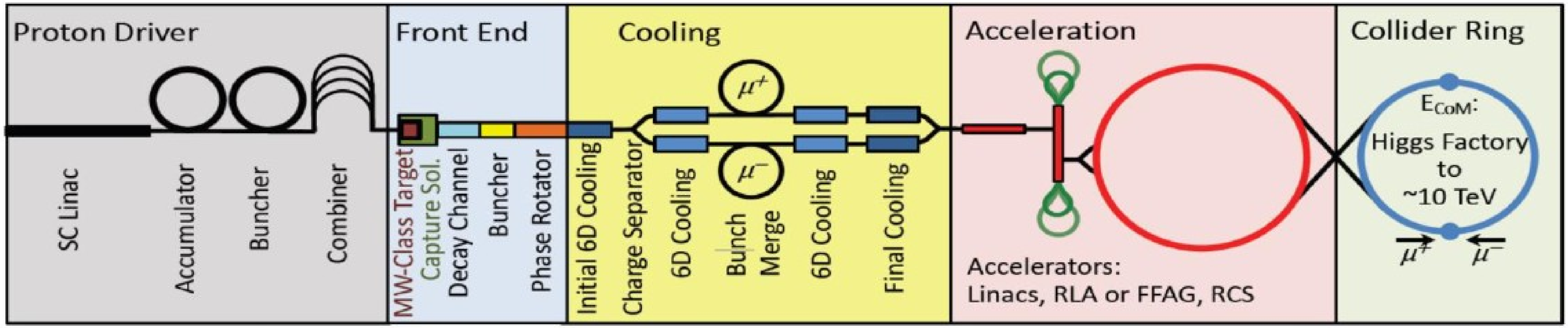


Parameter	Unit	3 TeV	10 TeV	14 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**40**
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	**MW**	**5.3**	**14.4**	**20**
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Courtesy: D. Schulte

Overview

- **BUT: μ decay is only γ* 2.2 μs**



- High power proton beam (short intense bunches) and low repetition rate on target.

- Target and capture channel, protons produce pions which decay into muons.
- Large energy spread μ beam split to sequence of bunches.

- Stages of muon ionisation cooling in matter.
- Merging of μ bunches into one bunch.

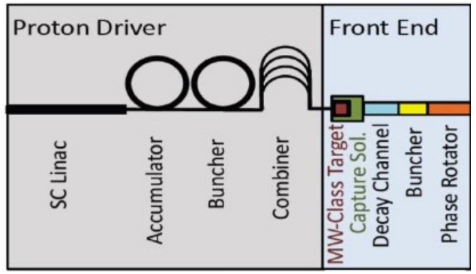
- Low energy acceleration with recirculating linacs.
- Acceleration to collision energy in a sequence of pulsed synchrotrons.

- Collider packed with high field magnets to minimise circumference and maximise luminosity.

Courtesy: D. Schulte

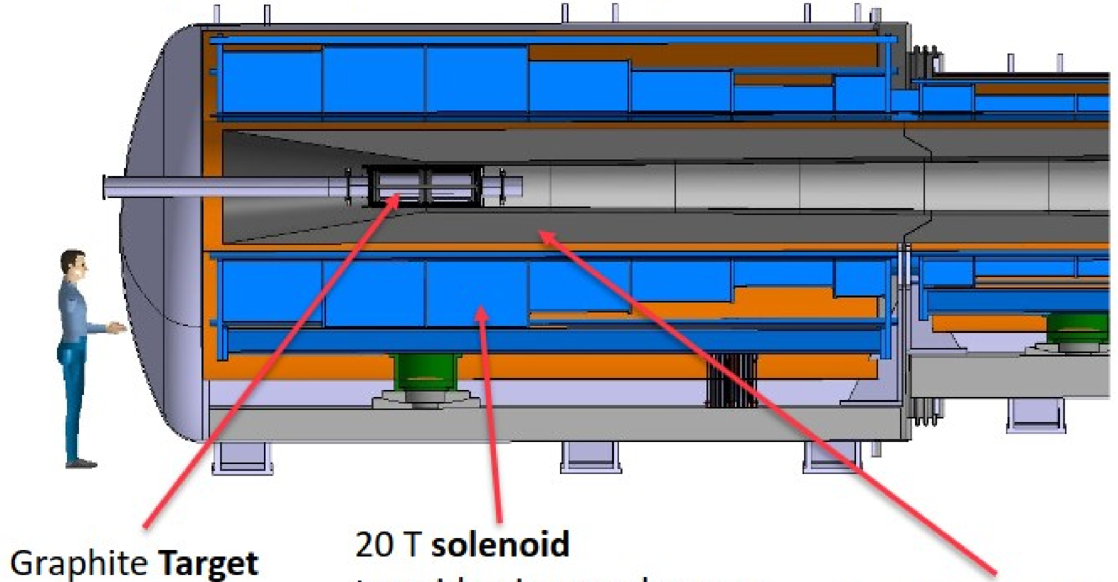
Production of μ

- High power proton beam for μ-production via pions decay
  - 5 GeV proton beam
  - 5 x 10^{14} protons / pulse
  - 5 Hz repetition
- Proton bunches must be collected, transport to target
- High muon/pion production yield for target



protons → (in target) → pions → (decay) → muons

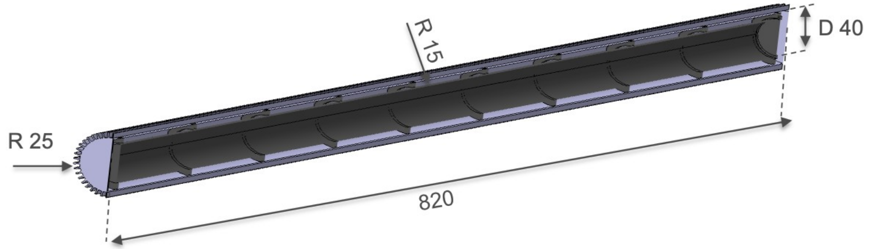
400 kJ protons to produce 5 x 10^{13} captured muon pairs



Graphite **Target**

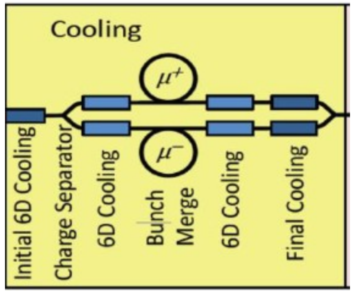
20 T **solenoid**
to guide pions and muons

Tungsten shielding
To protect magnet

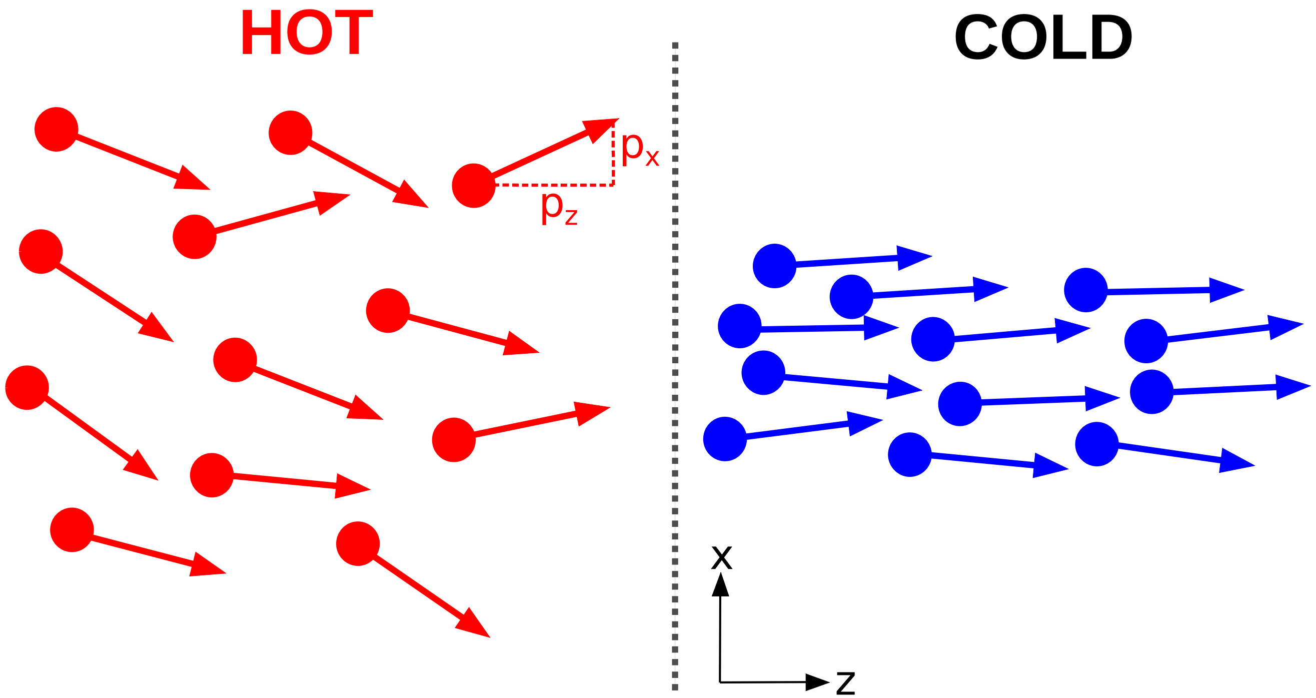


Courtesy: D. Schulte

Cooling



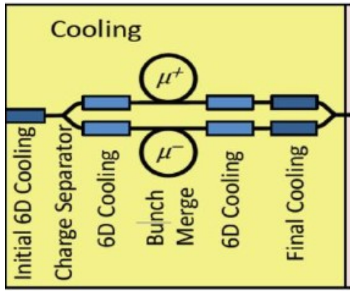
- Generated μ-bunch has too large emittances
- 6D cooling techniques required to reduce emittances (ionization cooling)



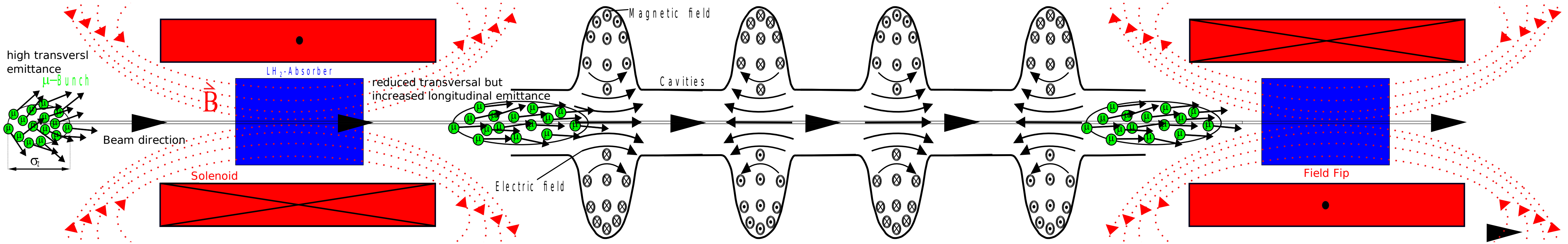
$$\mathcal{L} = \frac{\gamma^2 \tau_0 c}{2C} \frac{N_0^2}{4\pi\epsilon_{\perp,\mathrm{N}}\beta_\perp^*} f_\mathrm{r}$$

Courtesy: D. Schulte

Ionization Cooling



- 4D cooling: Transverse emittance reducing on the costs of the longitudinal one
- High field solenoids to minimize beta-function and reduce scattering
- High RF gradients to quickly compensate for ionization energy loss



$$\frac{d\varepsilon_{\perp,\mathrm{N}}}{ds} = -\frac{\varepsilon_{\perp,\mathrm{N}}}{\beta^2 E}\left\langle\frac{\partial E}{\partial s}\right\rangle + \frac{\beta_\perp\, pc}{2\, m_\mu c^2}\,\frac{d\langle\vartheta^2\rangle}{ds}.$$

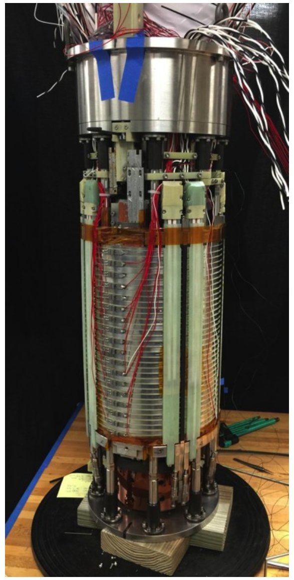
Cooling due to energy deposition

Heating due to scattering

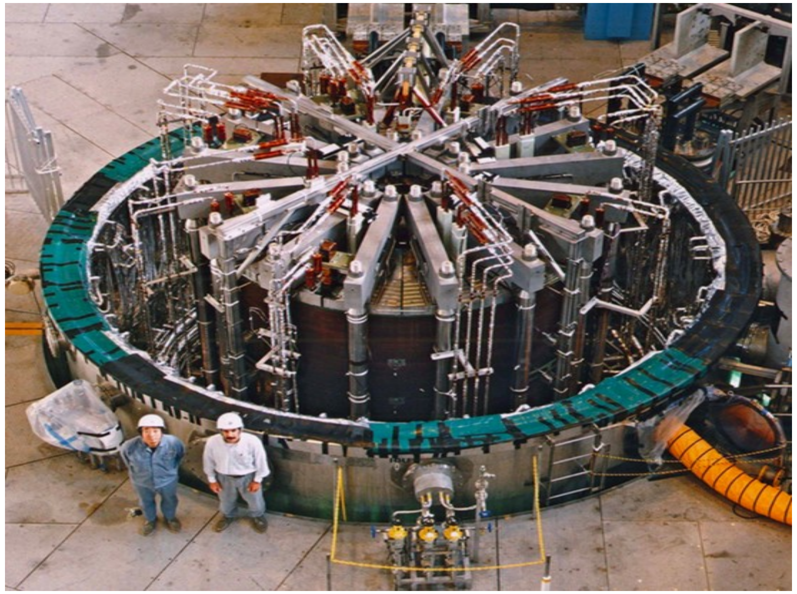
Courtesy: D. Schulte

Solenoids

- HTS solenoid developments
  - Goal for final cooling: 40 T

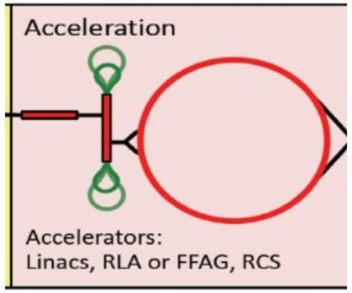


- Target solenoid
  - Goal: 20 T at 20 K
  - 15 T Nb_3Sn with 5 T resistive insert or 20 T HTS seems feasible

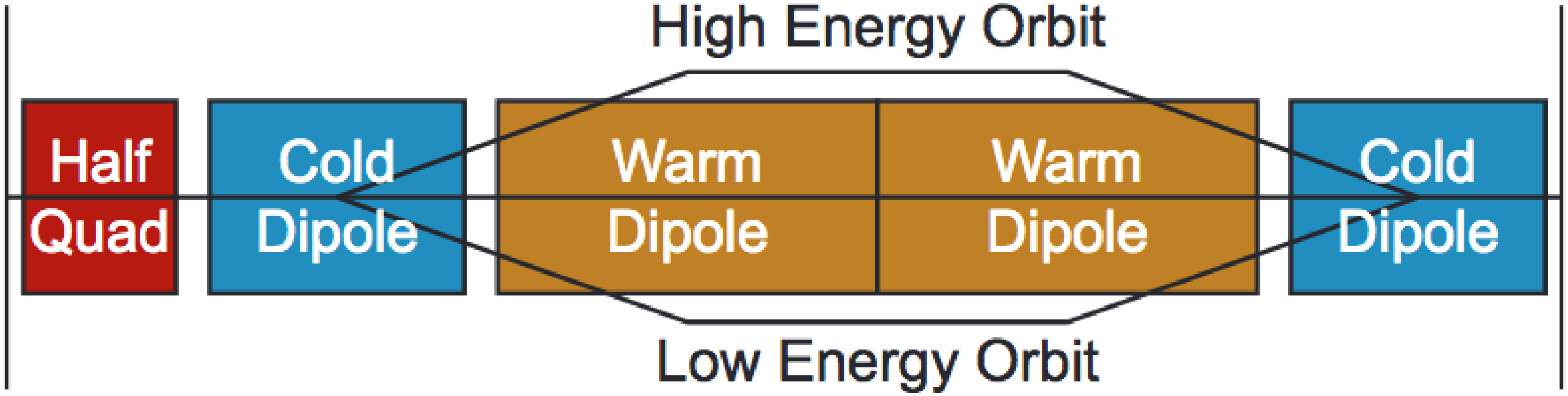


Courtesy: D. Schulte

Acceleration Complex



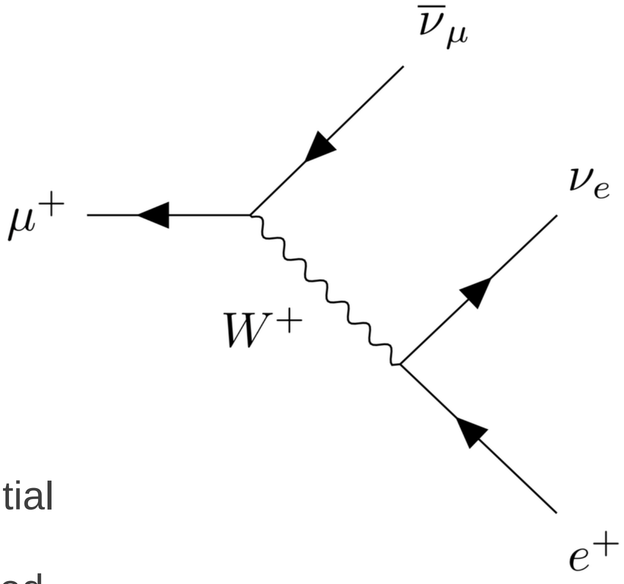
- Core is sequence of hybrid pulsed synchrotrons, since conventional rapid cycling too slow
- Key challenges
  - Fast-ramping normal conducting magnets with HTS alternative
  - RF with transient beam loading
  - Efficient power converters

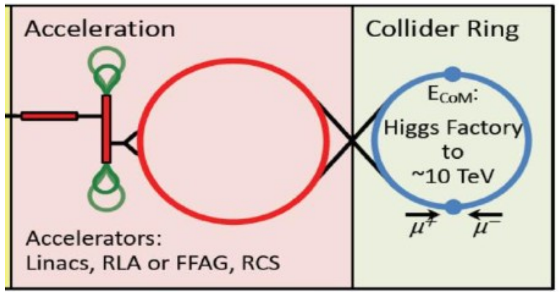


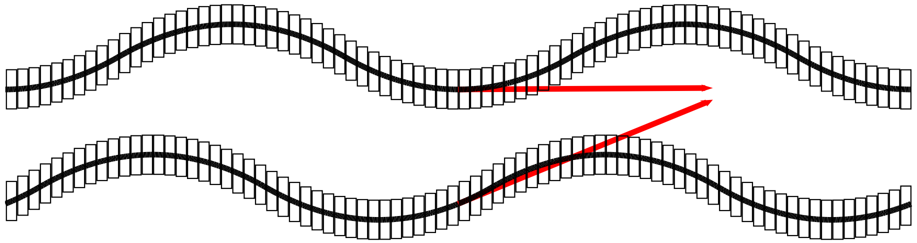
Courtesy: D. Schulte

Muon Decay and Neutrino Flux

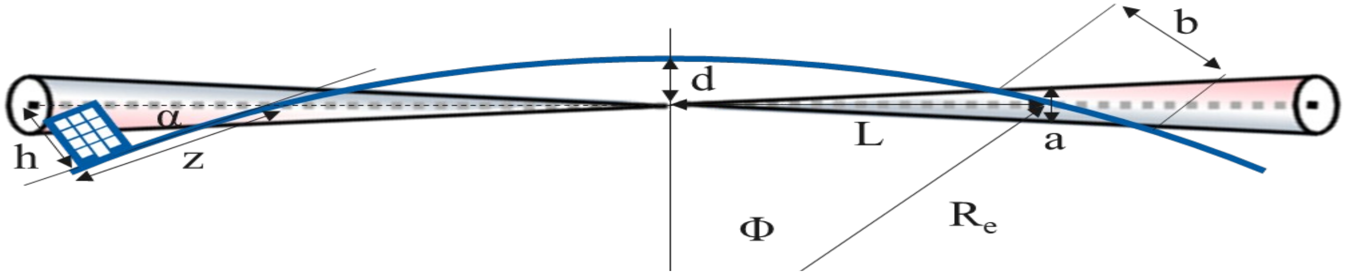
- Muons decay
  - 235 000 m^{-1} at 3 TeV
  - 58 000 m^{-1} at 10 TeV





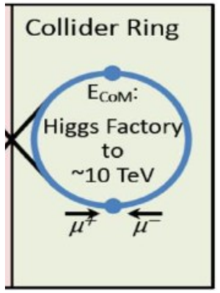


- Increased background at detector
- Negligible impact from arcs essential
  - Mover system for 10 TeV studied

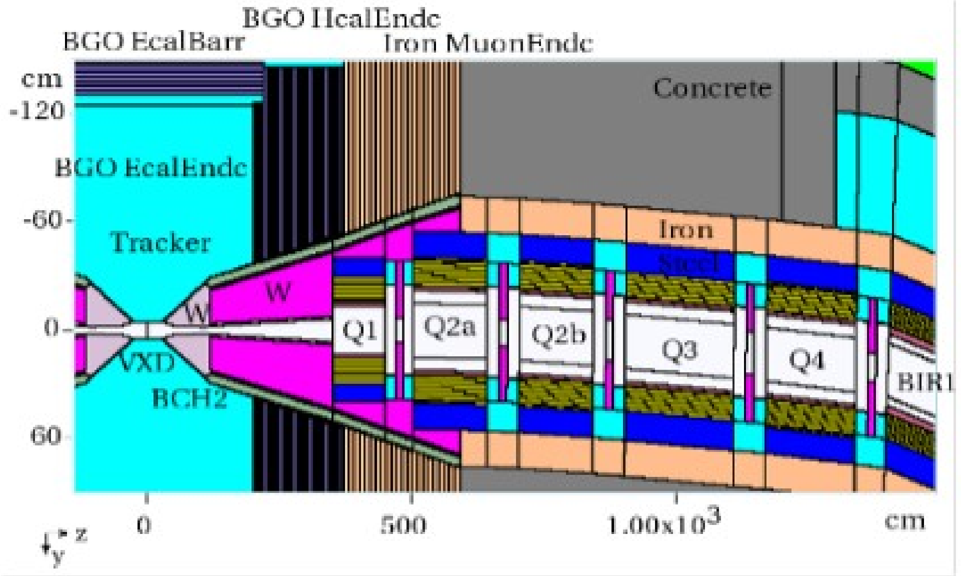


Courtesy: D. Schulte

Collider Ring

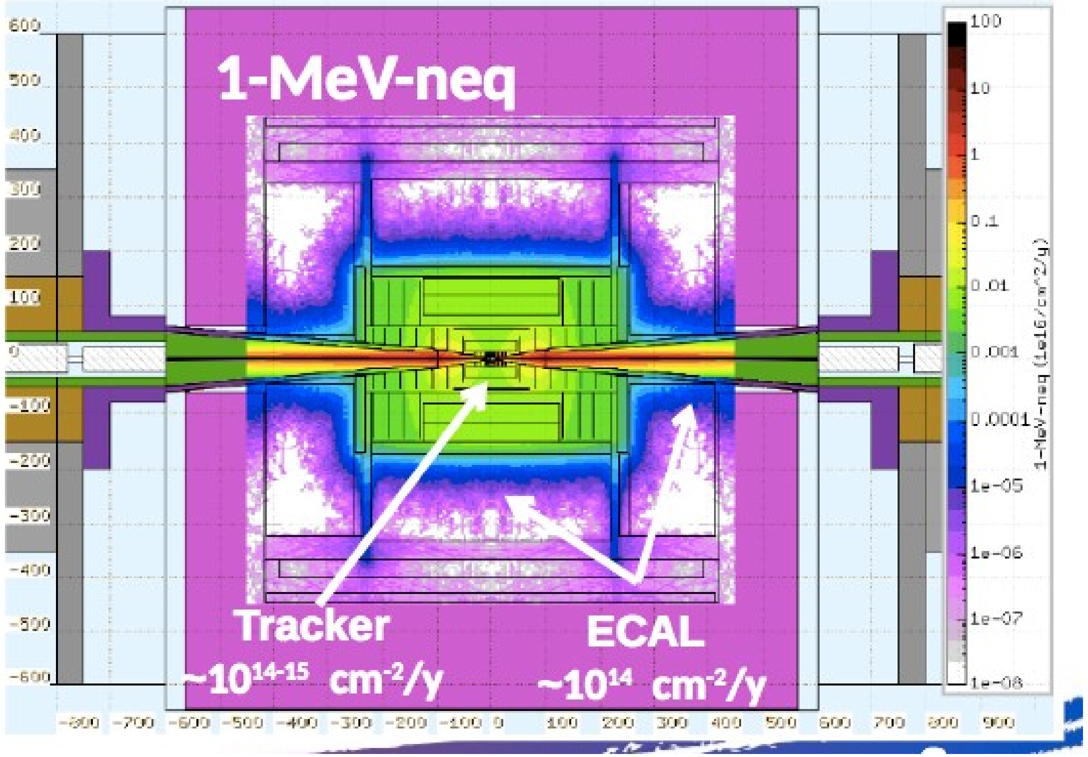


- Up to 2 interaction points
- Beam optics designed and required parameters achieved at the interaction point
- Significant shielding required due to decay of muons
- Generated neutrinos could create secondary particles → backgrounds



Courtesy: D. Schulte

Muon Decay - Detector Background



- Muons decays produce electons and positrons
  - First results show background independent of energy

- Detector design considerations, based on CLIC detector
  - Masks to mitigate backgrounds
  - Tracking of detector radiation level
  - Studies with beam-induced background ongoing

- Detector concepts up to 3 TeV
- For 10 TeV being investigated

Courtesy: D. Schulte

MICE

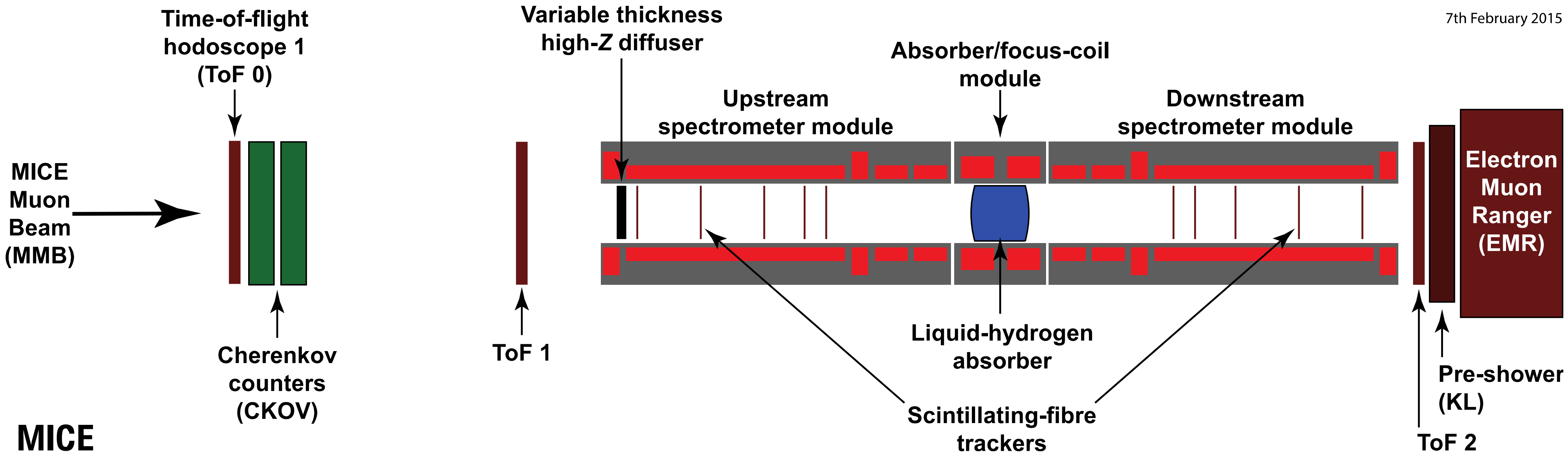
- Muon Ionization Cooling Experiment: Principle of ionization cooling has been demonstrated
- Outlook: integration of magnets, RF, absorbers, vacuum remains challenge

Article | Open access | Published: 05 February 2020

Demonstration of cooling by the Muon Ionization Cooling Experiment

MICE collaboration

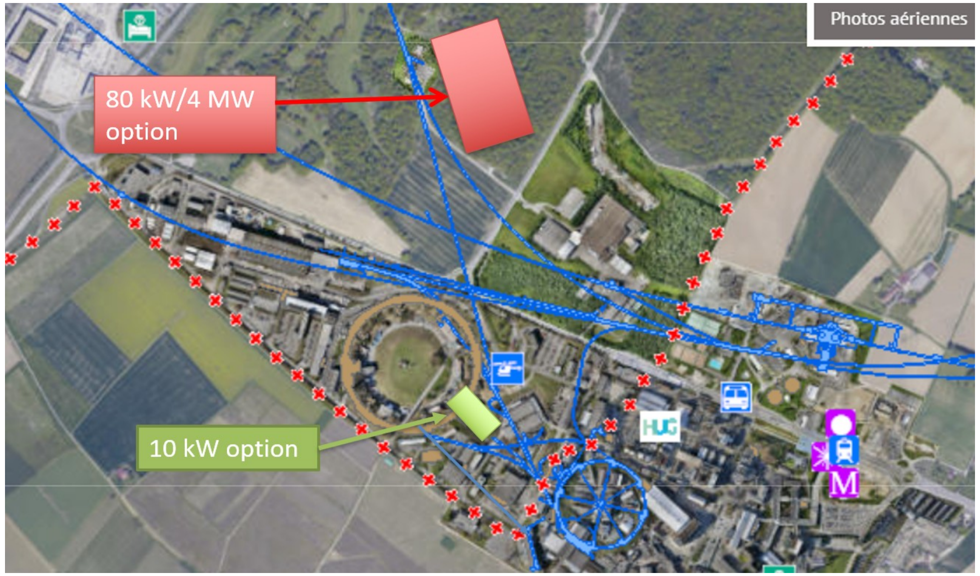
Nature **578**, 53–59 (2020) | Cite this article

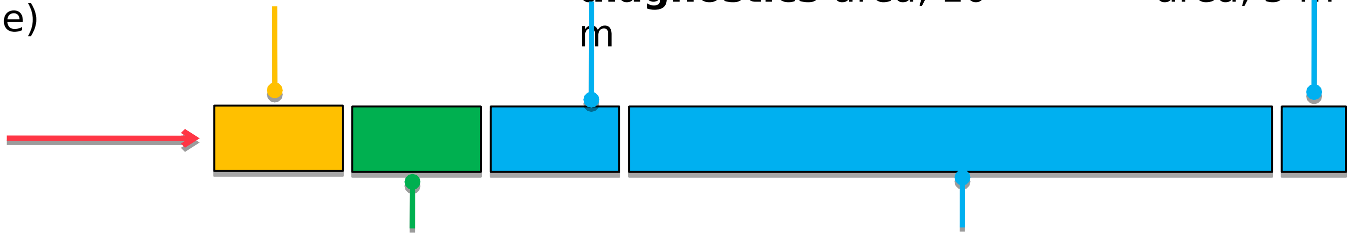


Courtesy: D. Schulte

Test Facility

- Requires high power proton beam (e.g. CERN, FNAL, ESS)
- Main goal: Demonstrate future μμ collider
  - Muon cooling technologies
  - Magnet technology and prototypes
  - Detector technology





Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

Collimation and **upstream diagnostics** area, 10 m

Downstream diagnostics area, 5 m

Momentum selection chicane, 10 m

Cooling area, 50 m

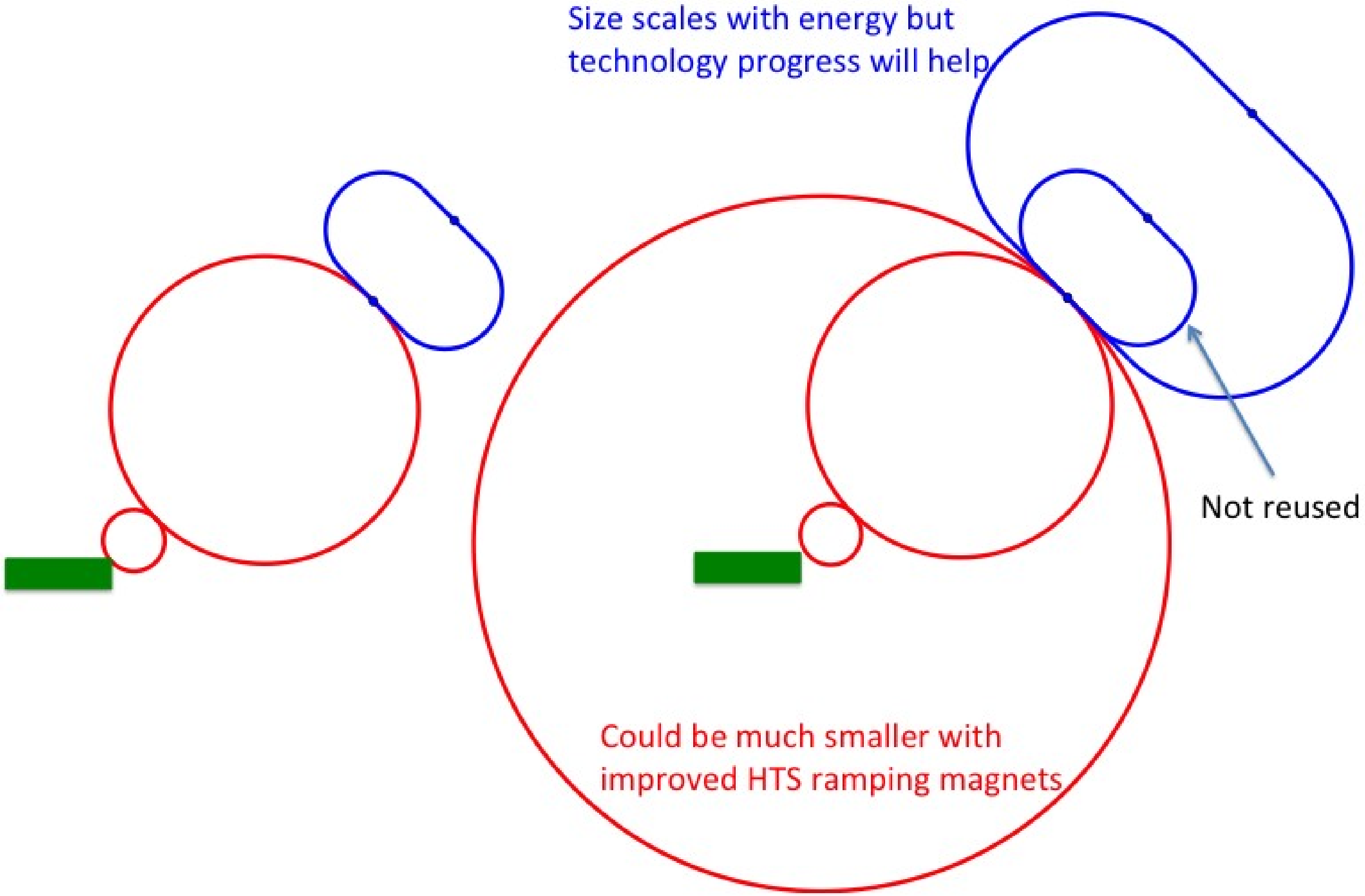
- Timeline for magnet technology for 3 TeV
  - HTS solenoids
  - Nb3Sn 11 T magnets for collider ring

Courtesy: D. Schulte

Staging Approaches

- Scenario 1: Energy staging
  - Start at lower energy, e.g. 3 TeV
  - Construction of additional rings later
  - First stage requires fewer budget

- Scenario 2: Luminosity staging
  - Start at full energy, but less performant magnets
  - More power for collider required


Size scales with energy but technology progress will help

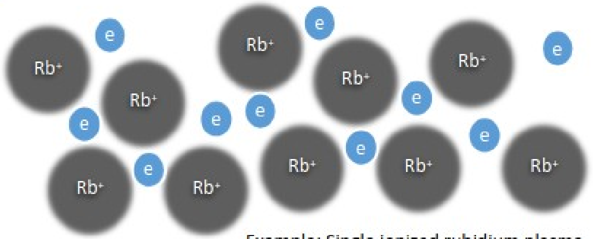
Not reused

Could be much smaller with improved HTS ramping magnets

Detour:
Plasma Wakefield Acceleration

Courtesy: E. Gschwendtner

Plasma Wakefield Acceleration



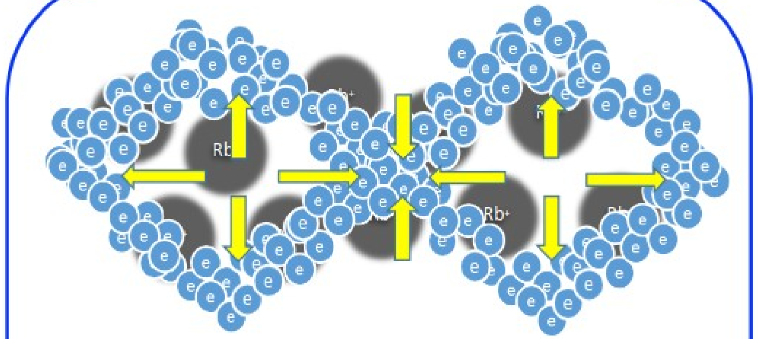
Example: Single ionized rubidium plasma

PLASMA is the 4th state of matter

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together
that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.



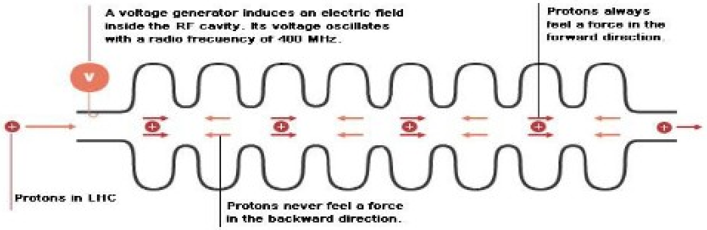
Plasma WAKEFIELDS are the fields created by collective motion of plasma particles are called.

ACCELERATION of charged particles when they experience an electric field.
Strength of the acceleration:
'Accelerating gradient' : ~MV/m

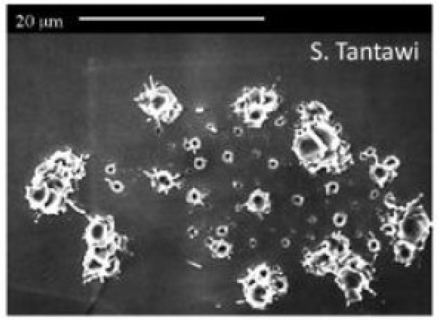
Courtesy: E. Gschwendtner

Acceleration

- RF based acceleration



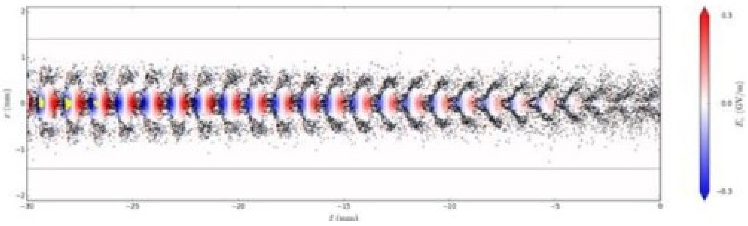
Surface of Copper Cell After Breakdown Events

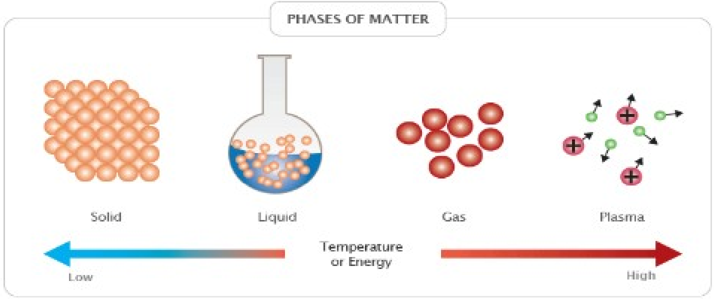


Accelerating fields are **limited to <100 MV/m**

In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge. Fields cannot be sustained; structures might be damaged.

- Plasma wakefield acceleration





Plasma is already ionized or “broken-down” and can sustain **electric fields up to three orders of magnitude higher gradients**

→ order of 100 GV/m.

→ ~1000 factor stronger acceleration!

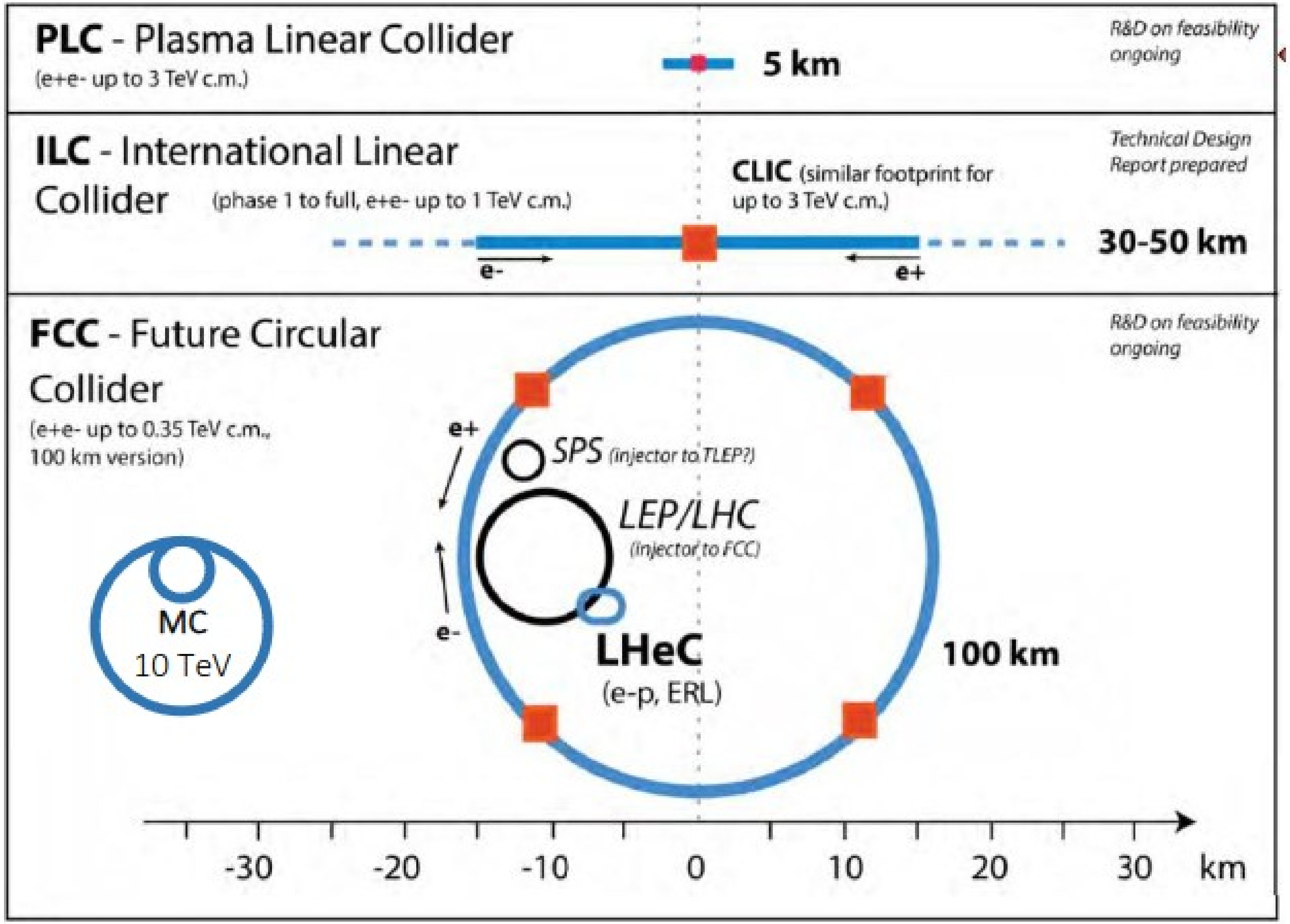
Courtesy: E. Gschwendtner

Comparison

- In linear colliders:

→ energy reach = length x gradient

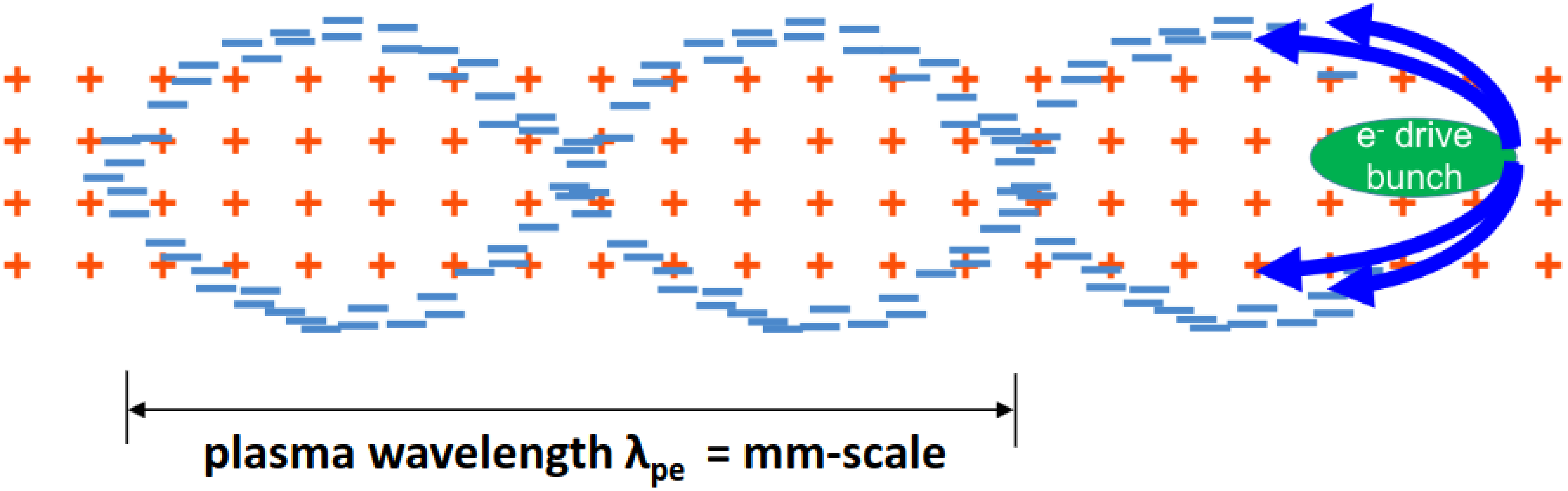
- Same beam energy achieved despite drastically smaller facilities if based on plasma wakefield acceleration



Courtesy: E. Gschwendtner

Principle

- Drive beam (laser or charged particle beam) excites plasma wave and wake
- Due to space charge electrons from plasma are expelled and rush back on axis
- Converion of the transverse electric field of a drive bunch into a longitudinal electric field in the plasma

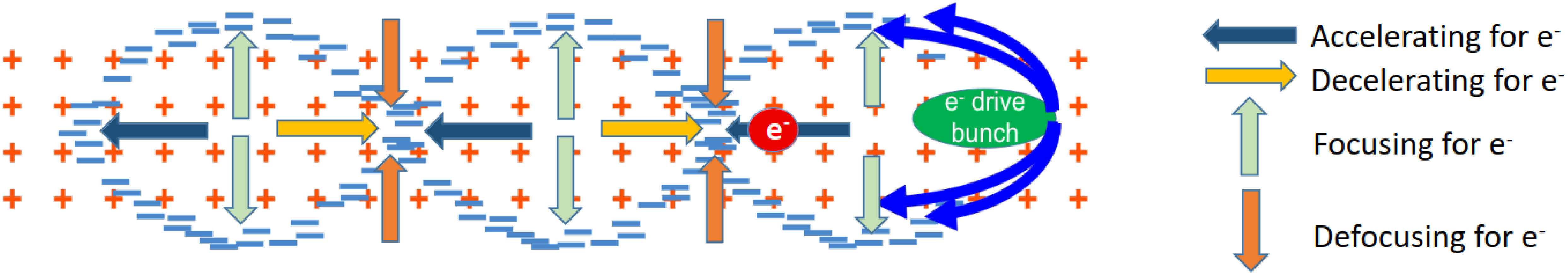


Courtesy: E. Gschwendtner

Principle

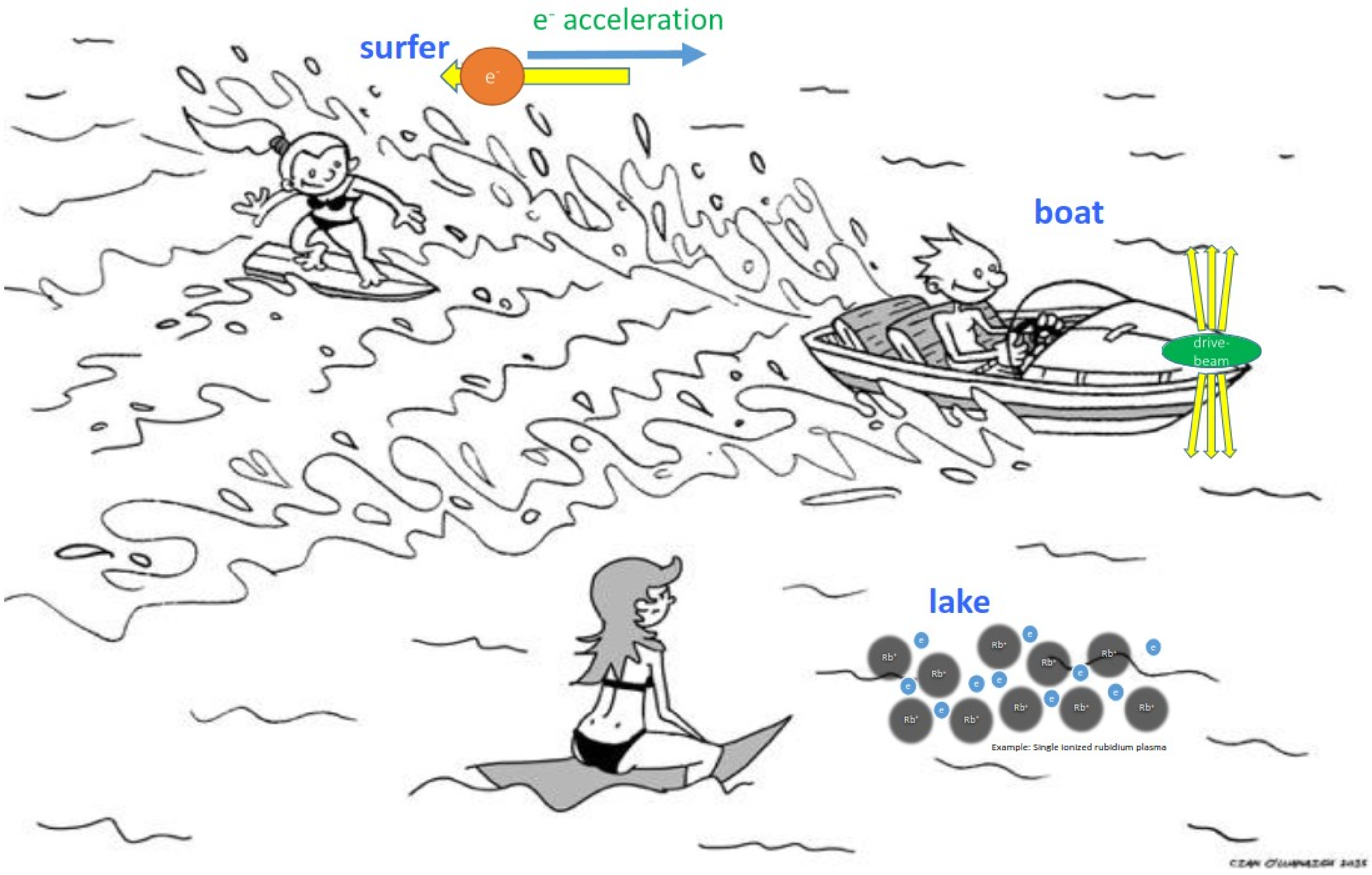
- Drive beam (laser or charged particle beam) excites plasma wave and wake
- Due to space charge electrons from plasma are expelled and rush back on axis
- Converion of the transverse electric field of a drive bunch into a longitudinal electric field in the plasma

- Witness bunch accelerated with gradients of ~ GV/m (e.g. at AWAKE at CERN)



Courtesy: E. Gschwendtner

Analogy



Analogy:

lake → plasma

Boat → particle beam (drive beam)

Surfer → accelerated particle beam (witness beam)

Courtesy: E. Gschwendtner

AWAKE

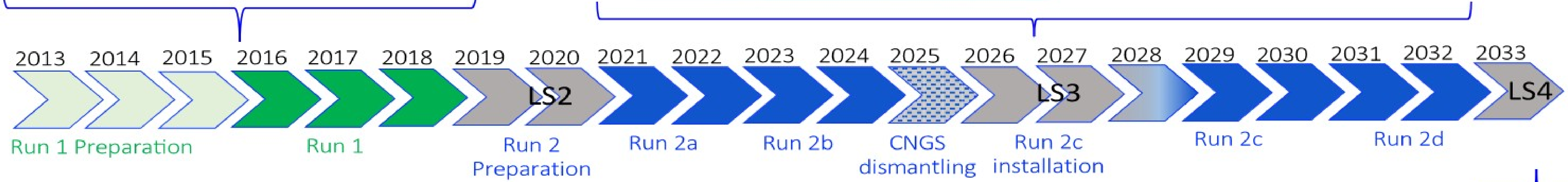
RUN 1 (2016-2018)

p+ self-modulation

2 GeV e- acceleration

RUN 2 (2021-2032)

e- acceleration to several GeV,
beam quality control, scalability



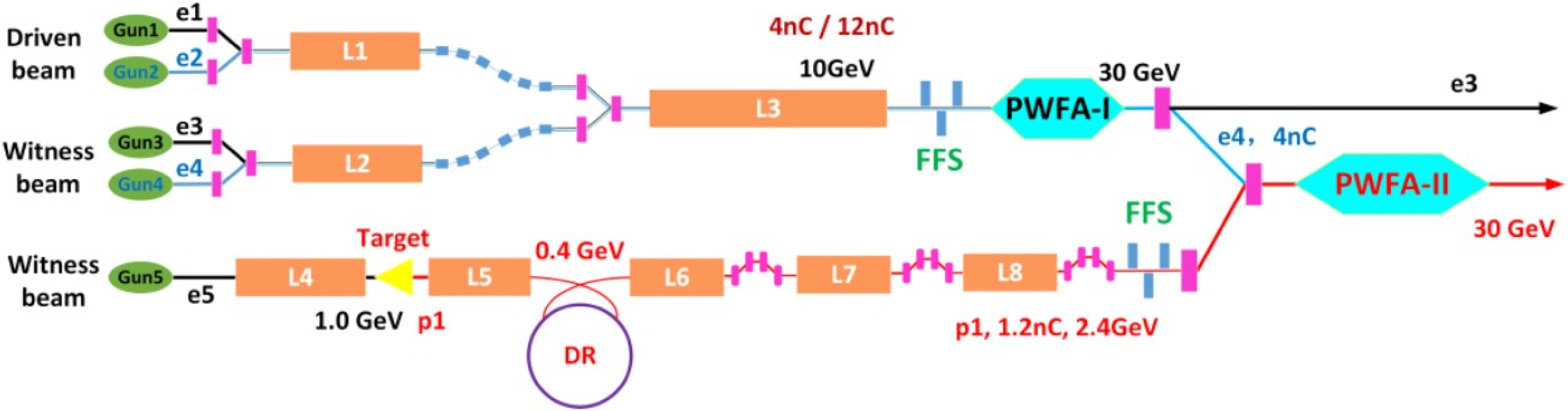
- Advanced WAKEfield experiment
- Accelerator R&D experiment at CERN
  - Unique facility driving wakefields in plasma with a proton bunch
  - Highly relativistic protons with high energy (>kJ) available
  - Accelerating externally injected electrons to GeV scale

➔First applications >2033

Courtesy: E. Gschwendtner

CEPC Alternative Injector

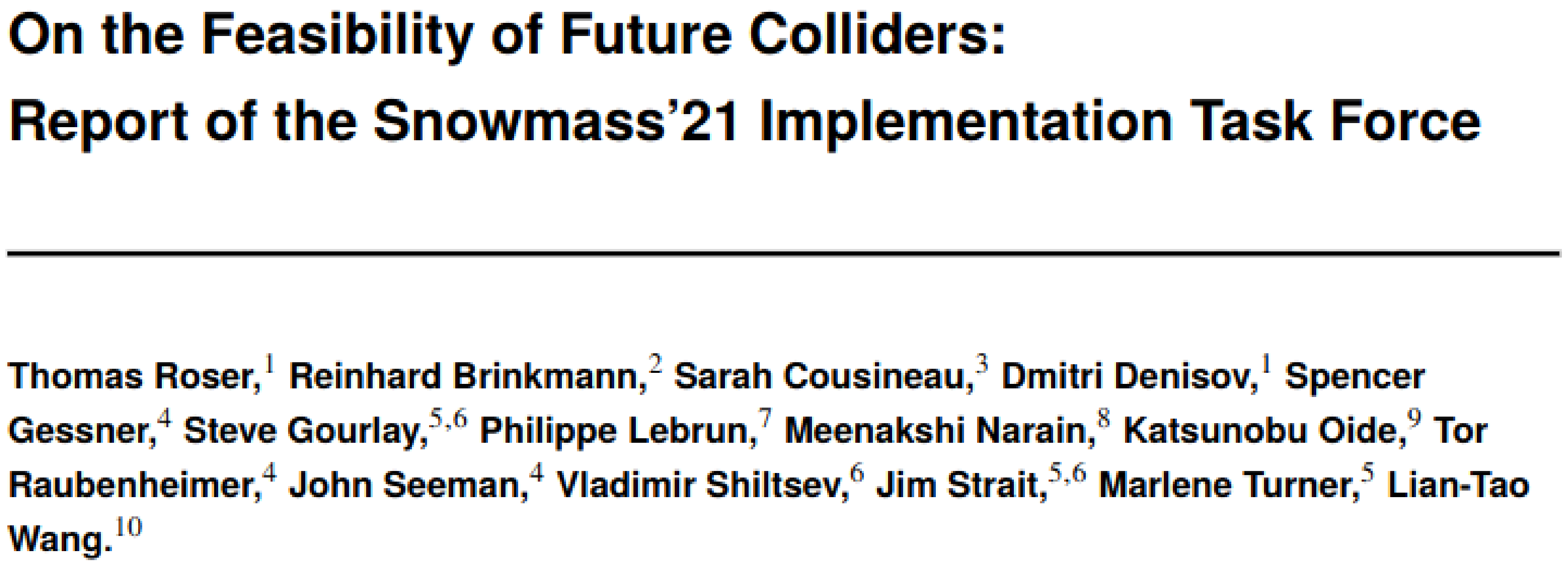
- Idea: compact wakefield accelerator as pre-injector for CEPC complex



Comparison

Courtesy: Snowmass Report, 2022.

Snowmass Report



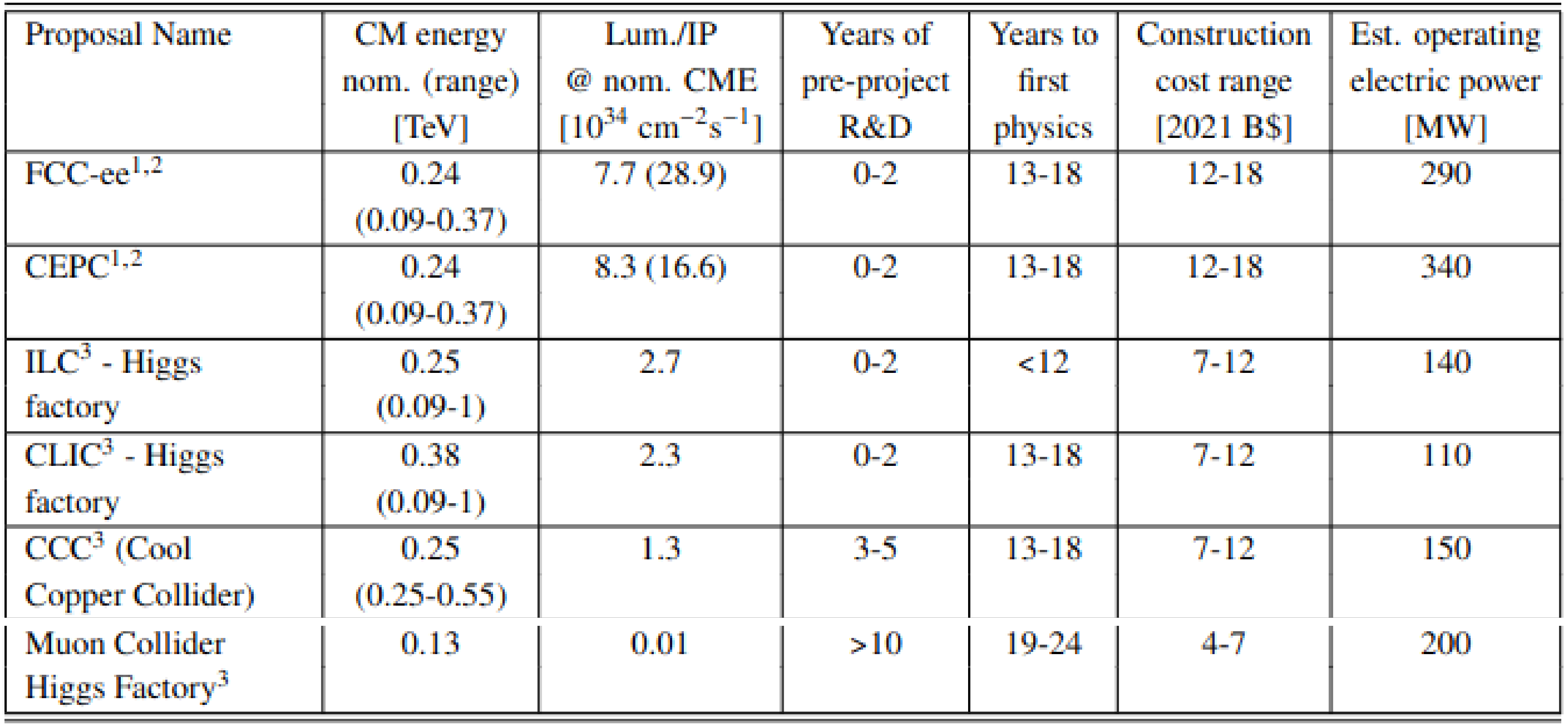
On the Feasibility of Future Colliders:
Report of the Snowmass'21 Implementation Task Force

Thomas Roser,[1] Reinhard Brinkmann,[2] Sarah Cousineau,[3] Dmitri Denisov,[1] Spencer Gessner,[4] Steve Gourlay,[5,6] Philippe Lebrun,[7] Meenakshi Narain,[8] Katsunobu Oide,[9] Tor Raubenheimer,[4] John Seeman,[4] Vladimir Shiltsev,[6] Jim Strait,[5,6] Marlene Turner,[5] Lian-Tao Wang.[10]

https://arxiv.org/pdf/2208.06030

Courtesy: Snowmass Report, 2022.

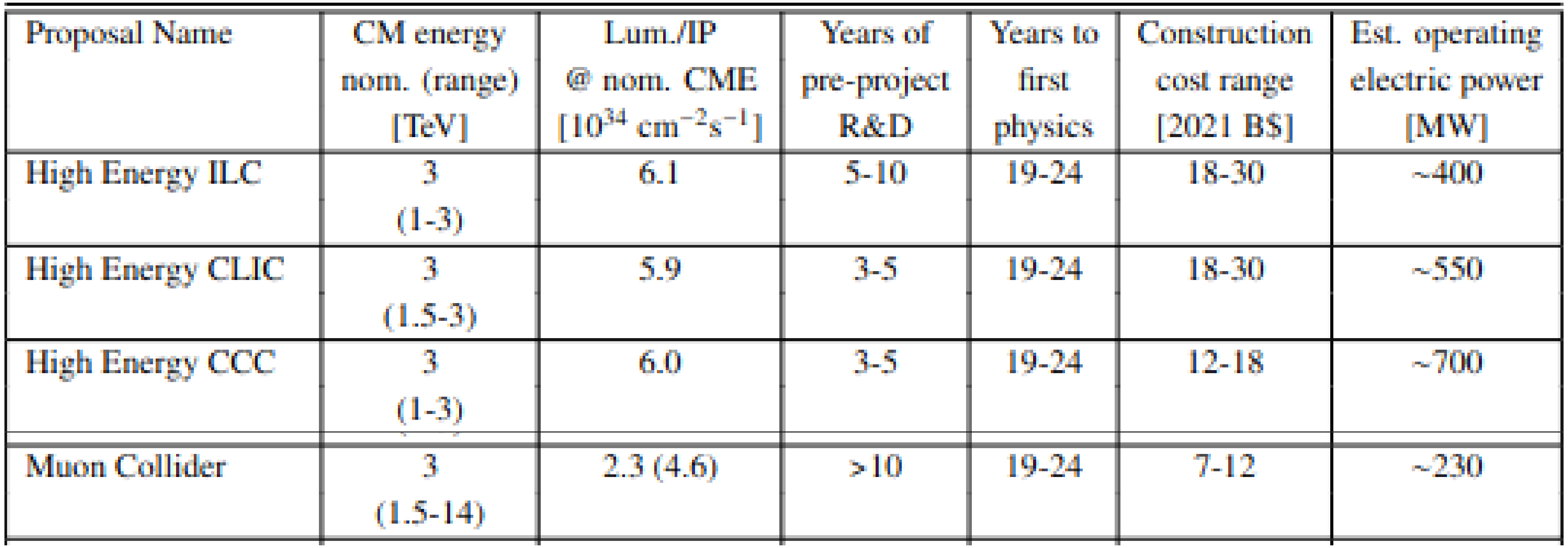
Higgs Factories



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME $[10^{34}\ \text{cm}^{-2}\text{s}^{-1}]$	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
Muon Collider Higgs Factory[3]	0.13	0.01	>10	19-24	4-7	200

Courtesy: Snowmass Report, 2022.

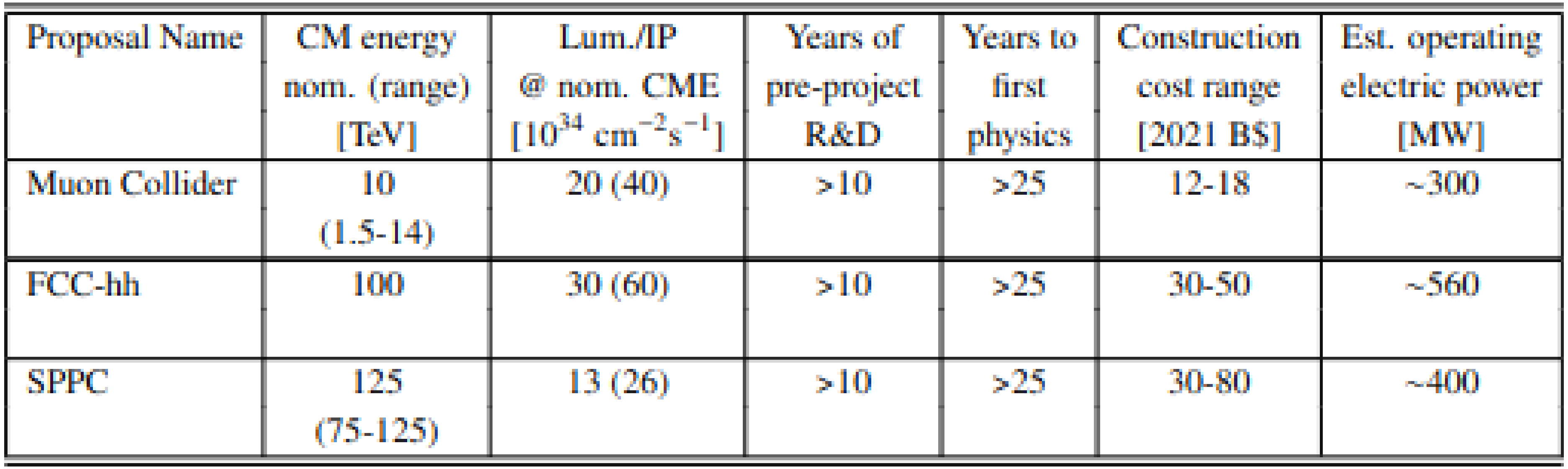
TeV Lepton Machines



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
High Energy ILC	3 (1-3)	6.1	5-10	19-24	18-30	~400
High Energy CLIC	3 (1.5-3)	5.9	3-5	19-24	18-30	~550
High Energy CCC	3 (1-3)	6.0	3-5	19-24	12-18	~700
Muon Collider	3 (1.5-14)	2.3 (4.6)	>10	19-24	7-12	~230

Courtesy: Snowmass Report, 2022.

Energy Frontier



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5-14)	20 (40)	>10	>25	12-18	~300
FCC-hh	100	30 (60)	>10	>25	30-50	~560
SPPC	125 (75-125)	13 (26)	>10	>25	30-80	~400

Summary

Colliders

	Circular e+e- colliders	Linear RF e+e- colliders	Circular hadron colliders	Muons
Machines	FCC-ee, CEPC	CLIC, ILC, C^3	FCC-hh, SppC	Muon collider
Collision energy up to	~ 365 GeV	~ few TeV	+/- 100 TeV	10 TeV
Key Technology	RF	RF	High-field magnets	High-field magnets, cooling, demonstrator
First collisions	~ 15 years	<~ 15 years	> 25 years	~ 20 years

Optimistic?

Novel acceleration concepts based on plasma wakefield acceleration
→ Higher gradients achievable
→ More compact accelerators

Can be combined with energy recovery linacs → FCC-eh

Detour: Linear Proton Colliders

- Not sufficient energy reach for frontier physics, but used for e.g. nuclear applications
- Myrrha designed with 400 m proton linac to achieve 600 GeV beam energy for 4 mA current

The world's 1st large scale Accelerator Driven System

MYRRHA (**M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications) is the world's first large scale Accelerator Driven System (ADS) that consists of a subcritical nuclear reactor driven by a high power linear accelerator. With the subcritical concentration of fission material, the nuclear reaction is sustained by the particle accelerator only. Turning off the proton beam results in an immediate and safe halt of the nuclear reactions.

https://www.myrrha.be/

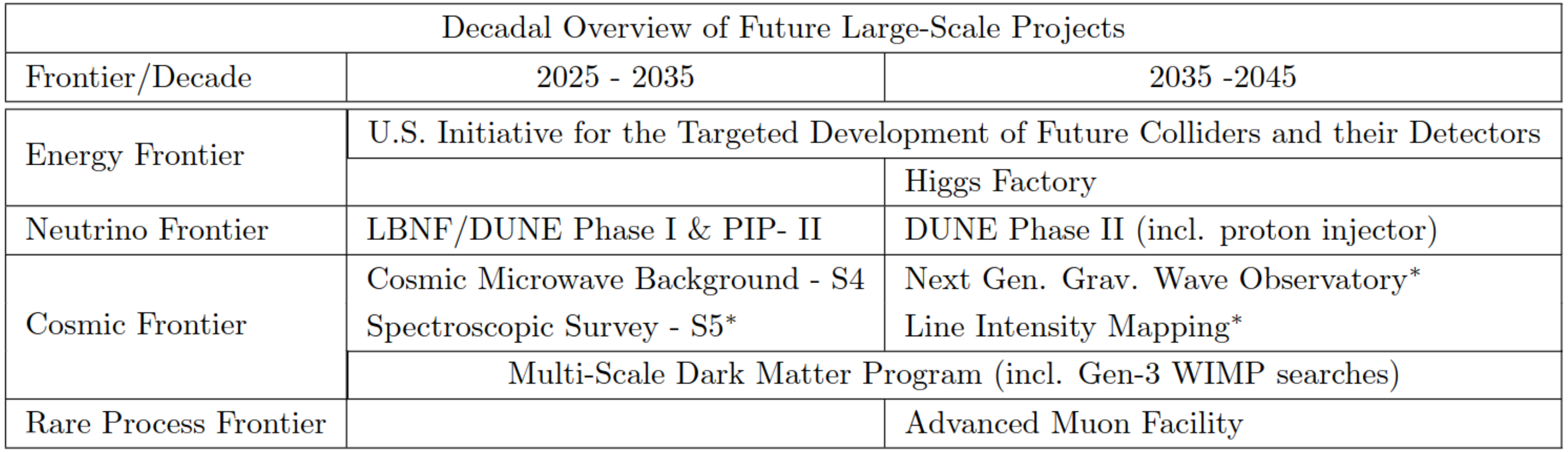
Recommendations

Courtesy: H. Murayama

P5 – USA

- Particle Physics Project Priorization Panel (P5), every 10 years in the US, recently in 2023
- Recommendation 1: Reaffirm critical importance of the ongoing projects
  - HL-LHC including ATLAS and CMS detectors
- Recommendation 2: New exciting initiatives
  - An off-shore Higgs factory with international partners, FCC/ILC

Exploring the Quantum Universe



Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4 Spectroscopic Survey - S5*	Next Gen. Grav. Wave Observatory* Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

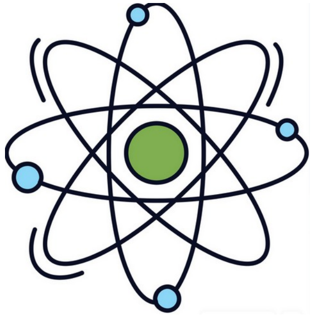
ESPP – Europe

- In 2020 the European strategy upgrade of particle physics (ESPP) expressed the long-term plan for particle colliders:
  - An electron-positron Higgs factory is the highest-priority next collider.
  - Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a center-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage.

Courtesy: F. Gianotti

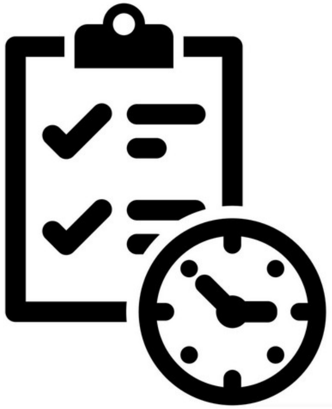
Personal Opinion: Why FCC?

Physics



- Immense physics potential for lepton and hadron colliders
- Luminosity frontier: Precision physics experimements
- Energy frontier: Discovery potential thanks to 100 TeV E_{cm} for FCC-hh

Timeline



- FCC-ee technology is mature; collisions could start few years after HL-LHC
- Integrated FCC project allows for ~20 more years magnet R&D
- Optimized overall investment

Community

- 4 collision points for high-energy physics experiments
- Many other possibilities (fixed-target, use of beam dump, ..)
- Only facility to commensurate the size of the CERN community

Thank you!

Jacqueline Keintzel

Acknowledgements: Many colleauges from various design studies

4th Baltic School of High Energy Phyiscs and Accelerator Technologies
Kuldiga, Latvia
05 – 09 August 2024