Future Colliders: Possibilities and Challenges

Jacqueline Keintzel

Acknowledgements: Many colleauges from various design studies

Prisma+ Colloquium

Mainz, Germany

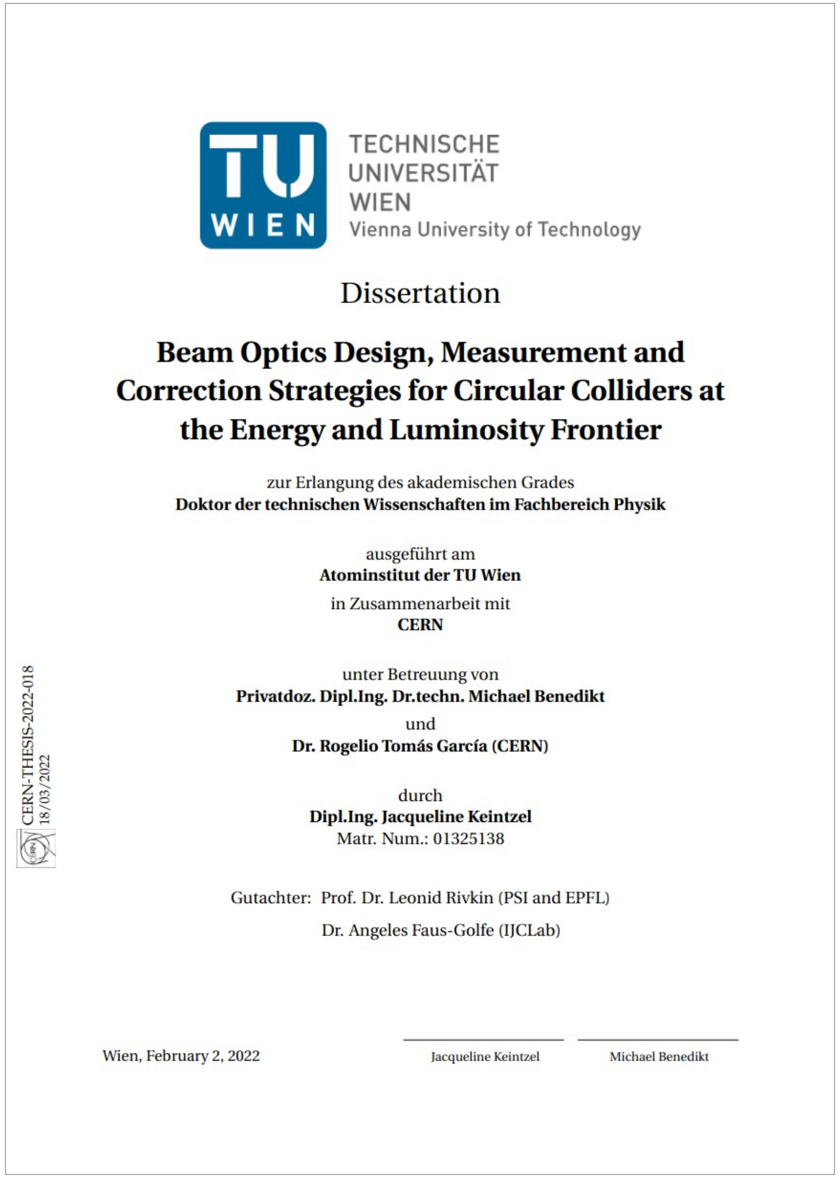
28 May 2025

jacqueline.keintzel@cern.ch

Short CV

- Sep 2013: Start studying technical physics at Vienna University of Technology
- Sep 2017: Start undergraduate studentship at CERN
- Nov 2018: Start PhD at CERN as doctoral student
- Nov 2021: Start CERN senior fellow
- Nov 2023: Start CERN staff LD

- Research areas:
  - Accelerator physics
  - Beam dynamics and beam optics
  - Spin dynamics and polarization
  - Experimental tests and simulations
  - LHC, FCC, SuperKEKB, KARA, ...



TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

Dissertation

Beam Optics Design, Measurement and Correction Strategies for Circular Colliders at the Energy and Luminosity Frontier

zur Erlangung des akademischen Grades
Doktor der technischen Wissenschaften im Fachbereich Physik

ausgeführt am
Atominstitut der TU Wien
in Zusammenarbeit mit
CERN

unter Betreuung von
Privatdoz. Dipl.Ing. Dr.techn. Michael Benedikt
und
Dr. Rogelio Tomás García (CERN)

durch
Dipl.Ing. Jacqueline Keintzel
Matr. Num.: 01325138

Gutachter: Prof. Dr. Leonid Rivkin (PSI and EPFL)
Dr. Angeles Faus-Golfe (IJCLab)

Wien, February 2, 2022

Jacqueline Keintzel   Michael Benedikt

CERN-THESIS-2022-018
18/03/2022

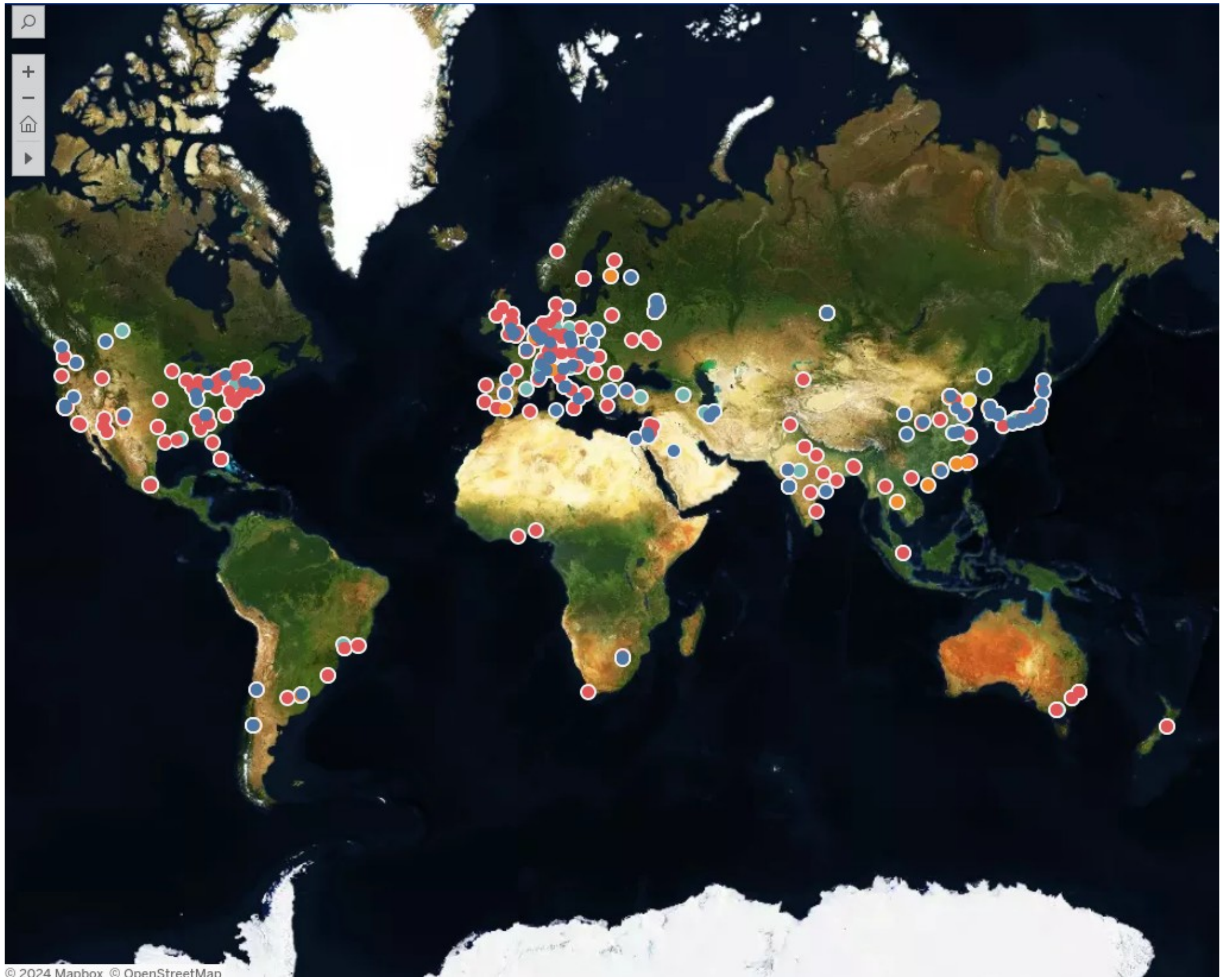
Current Accelerators

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-

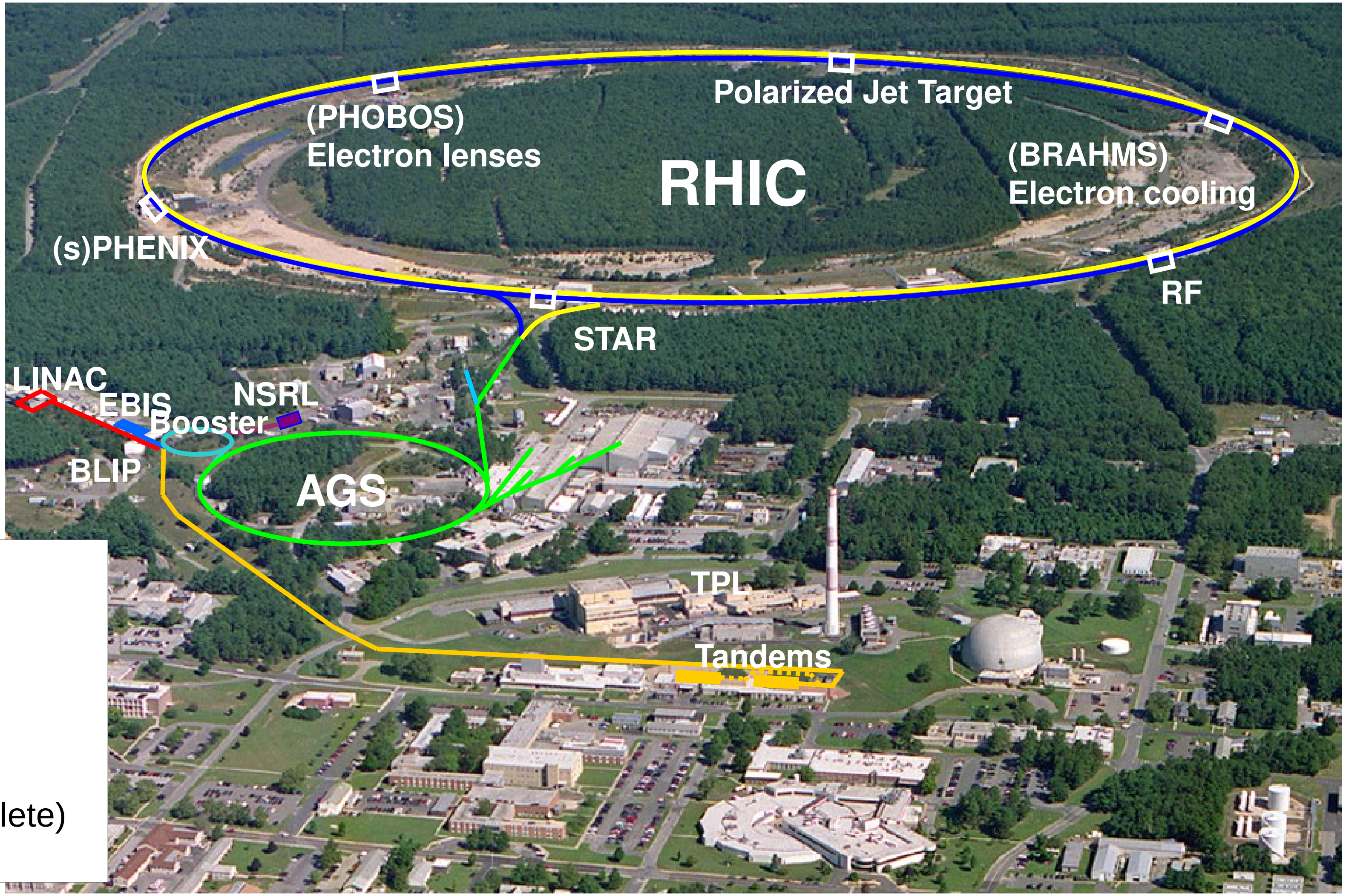


Courtesy: S. Nagaitsev

RHIC at BNL

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

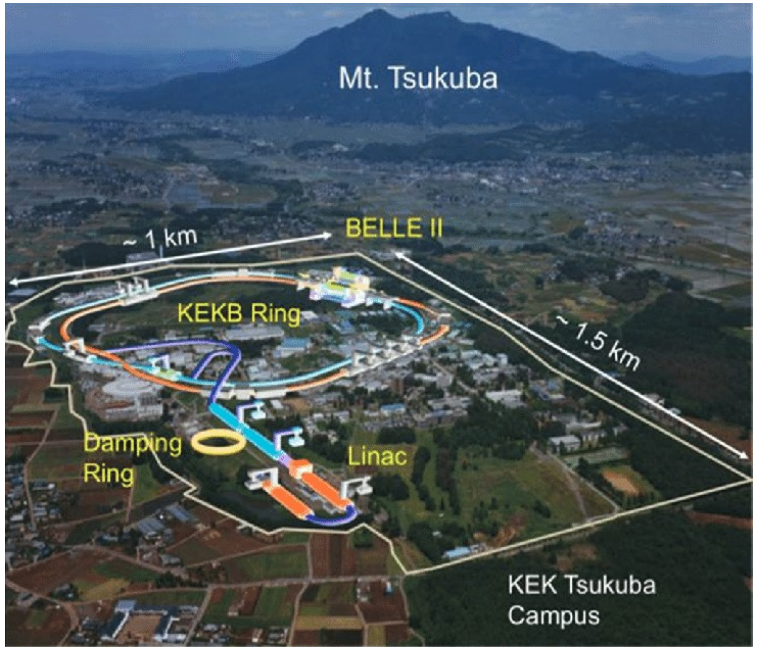
  Brookhavn National Laboratory (BNL)
- First collider ever build dedicated to collide heavy ions

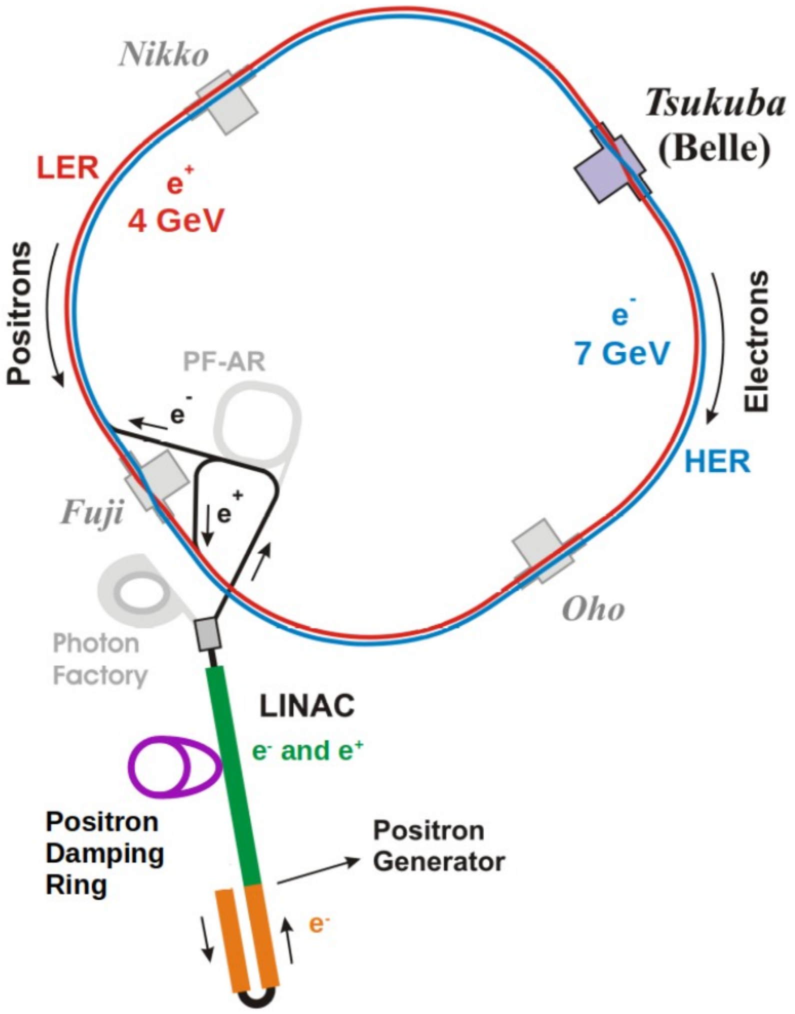


Operation	: 2000 – 2025 (planned)
Circumference	: 3.8 km
Max dipole field	: 3.5 T
Energy	: 255 GeV polarized p
	: 100 GeV/nucleon Au
Species	: p to U (incl. asymmetric)
Experiments	: BRAHMS, PHOBOS (complete)
	STAR, PHENIXgsPHENIX

SuperKEKB at KEK

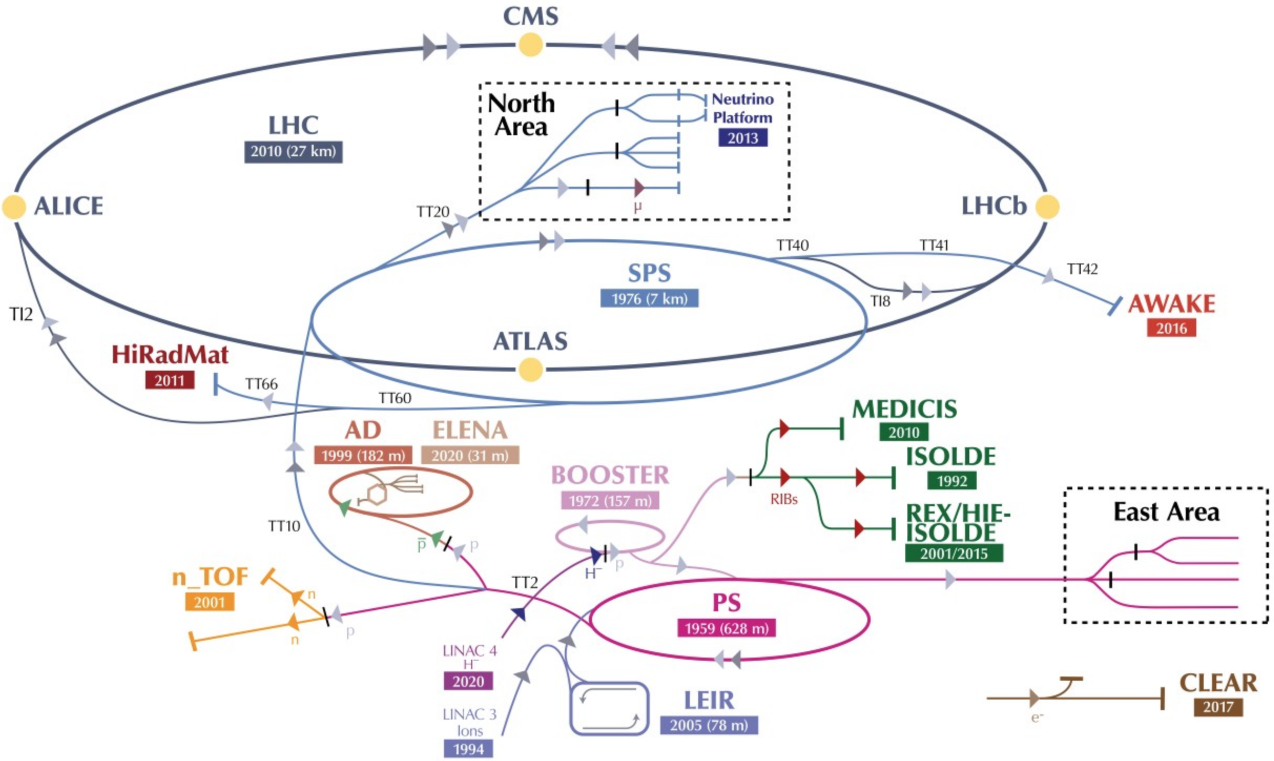
- SuperKEKB at KEK (**K**ō **E**nerugī **K**asokuki Kenkyū Kikō)
- Largest currently operating electron-positron collider
- Record instantaneous luminosity of 5 x 10^{34} $cm^{-2}s^{-1}$
- Asymmetric beam energies of 4 and 7 GeV for b-physics





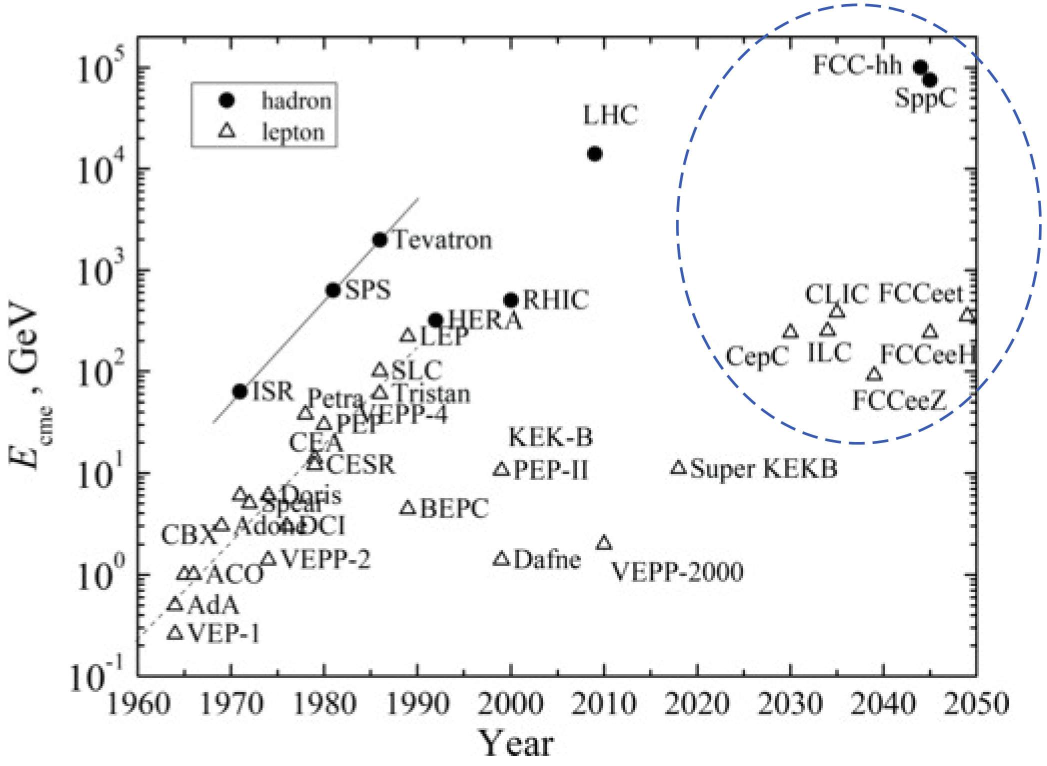
LHC at CERN

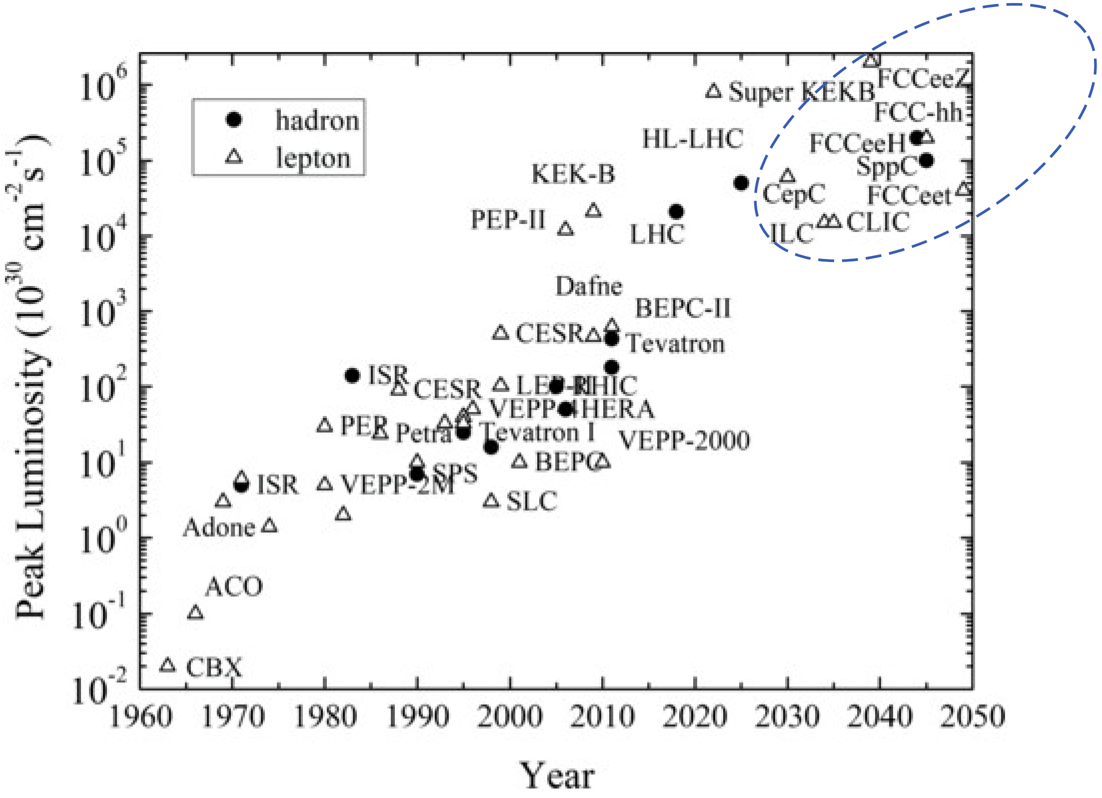
- **L**arge **H**adron **C**ollider (LHC) at CERN for hadron collisions with four big experiments
- Largest collider in existence with 27 km; last stage of the accelerator chain
- 14 TeV collision energy for proton-proton collisions; also heavy-ion collisions



History

- Colliders started in the 1960s





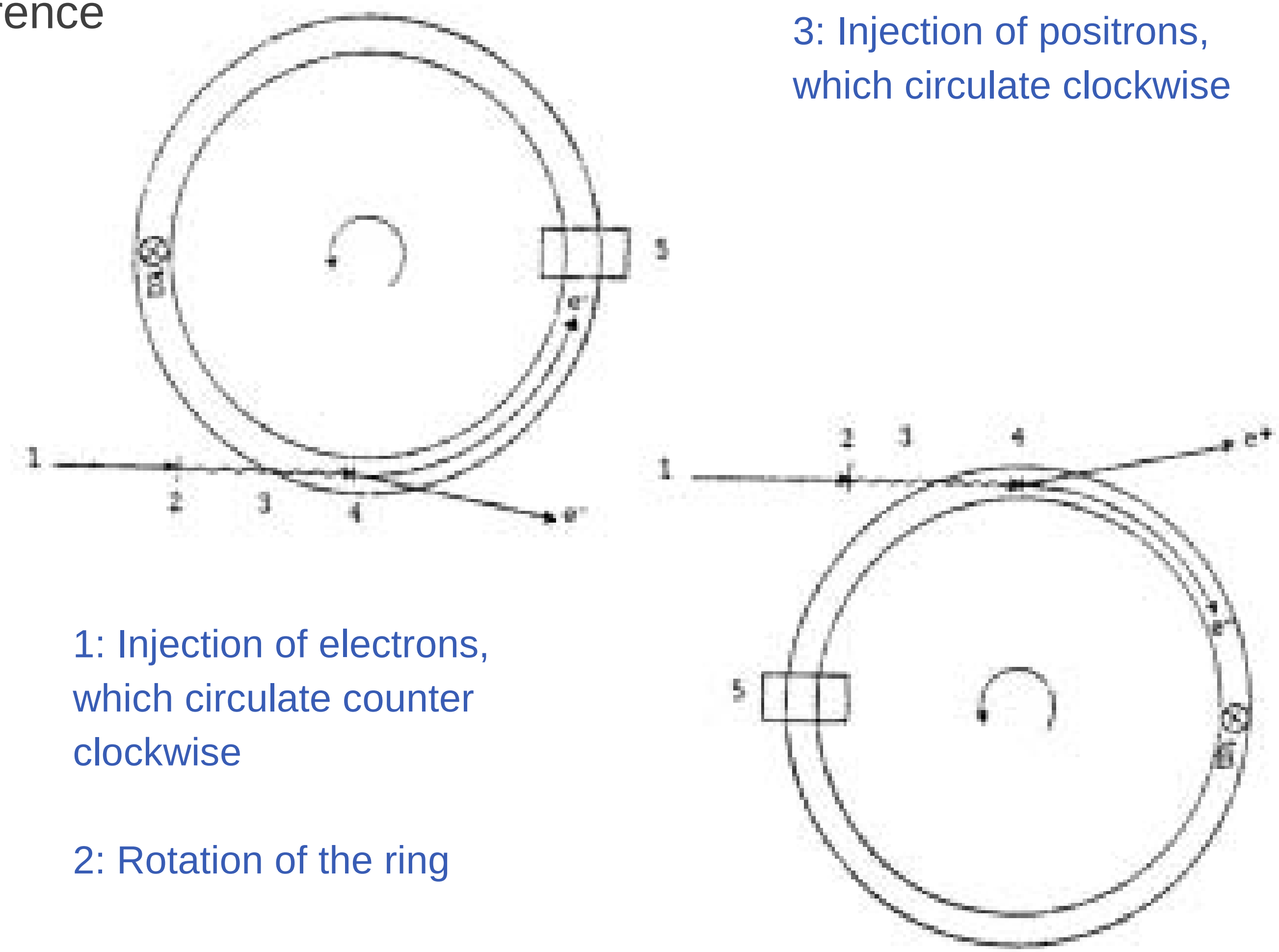
Ref: V. Shiltsev and F. Zimmermann, Rev. Mod. Phys. 93, 015006, 2021.

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

- 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
S$p\bar{p}$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: K. Hock

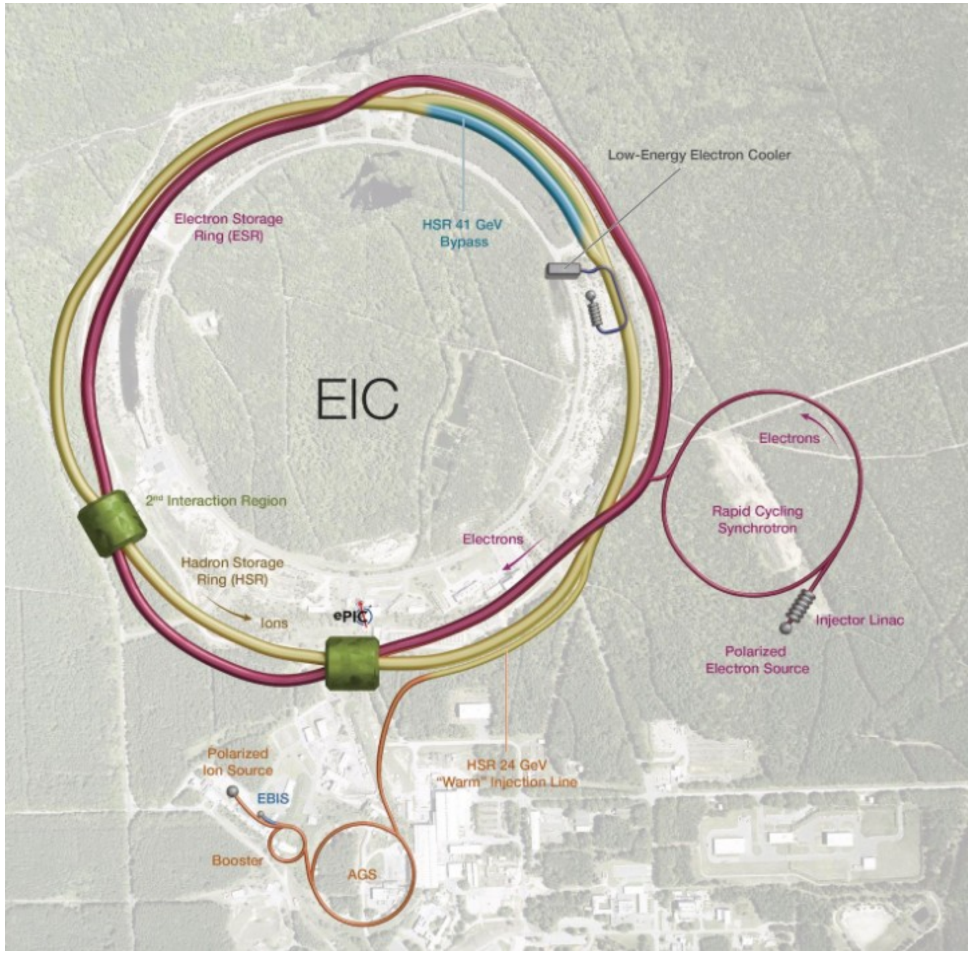
EIC at BNL

- **E**lectron-**I**on **C**ollider

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

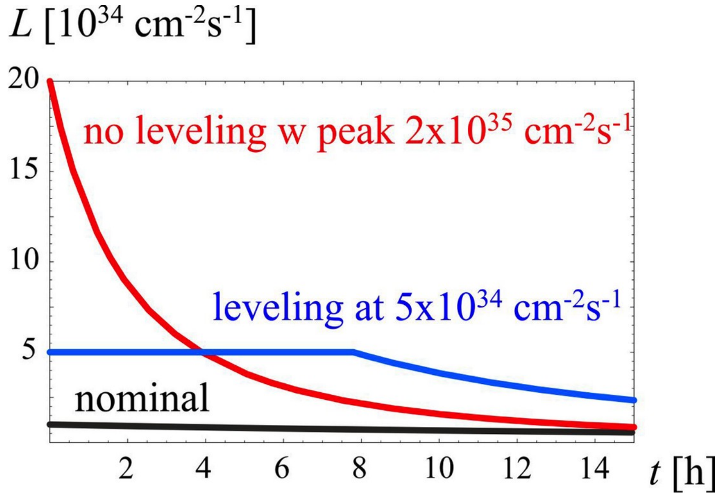
- **Electron storage ring: 2.5 – 18 GeV (new)**
  - Up to 1160 polarized bunches
  - Large beam current of 2.5 A → 9 MW SR power
  - Superconducting RF

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



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



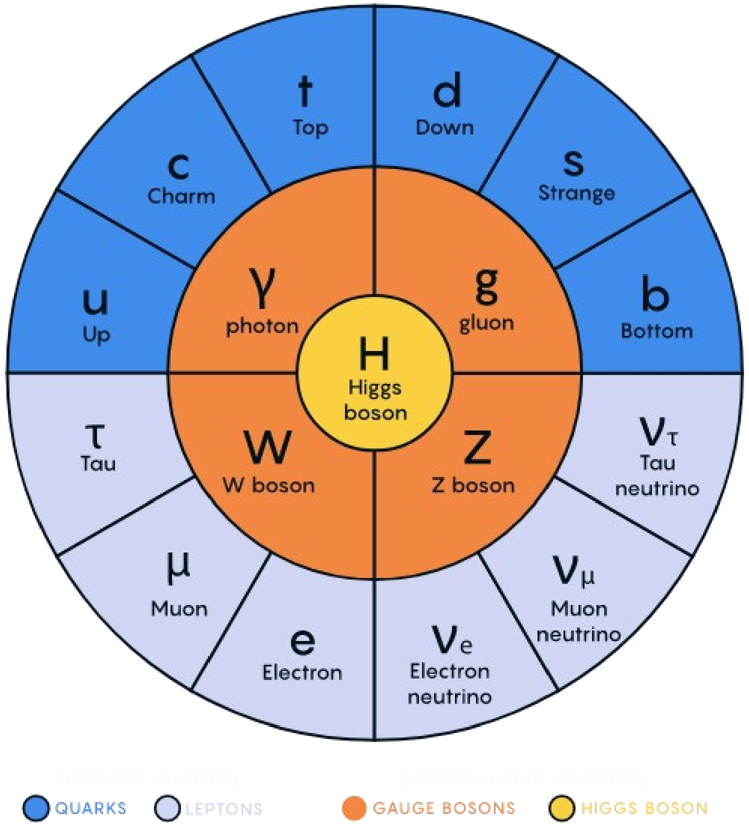
	LHC 2024	HL-LHC
Protons per bunch	1.6×10^{11}	2.2×10^{11}
Number of bunches	2352	2750
Normalized emittance	1.8 micron	2.5 micron
Beta*	30 cm	15 cm
Full crossing angle	320 microrad	500 microrad
Geometric reduction factor F	0.6	0.35
“Virtual” luminosity	4.2×10^{34} $cm^{-2}s^{-1}$	2.4×10^{35} $cm^{-2}s^{-1}$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

Considerations

- ***The What?***

Hadrons (protons or ions)

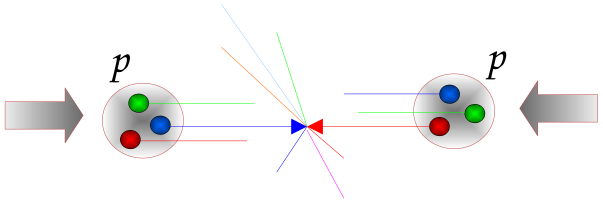
- Mix of quarks and gluons
- Discoveries at physics frontiers
- Typically high collision energy

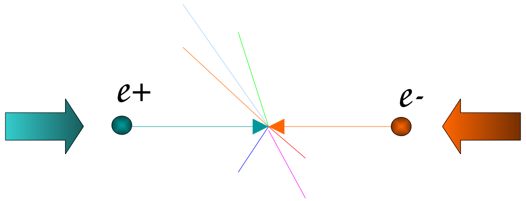
- Main limitation: dipole field and ring size

Leptons

- Elementary particles colliding
- High-precision measurements
- Well-defined center-of-mass energy

- Main limitation: energy loss from synchrotron radiation





Considerations

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

Linear Collider

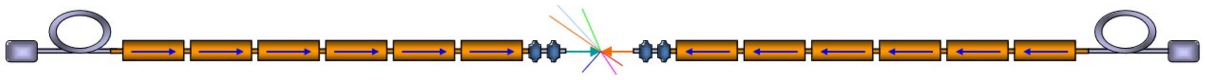
- Single-pass
- Few magnets, many RF-cavities

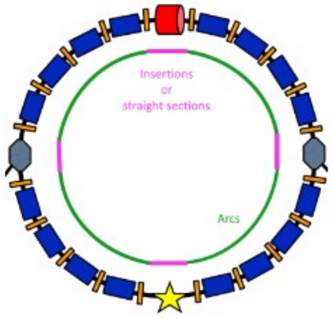
- Main limitation: length of collider and accelerating technology

Circular Collider

- Multi-pass
- 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 an electron-positron or hadron machine be the logical next step?
- Or should we go for muons?

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

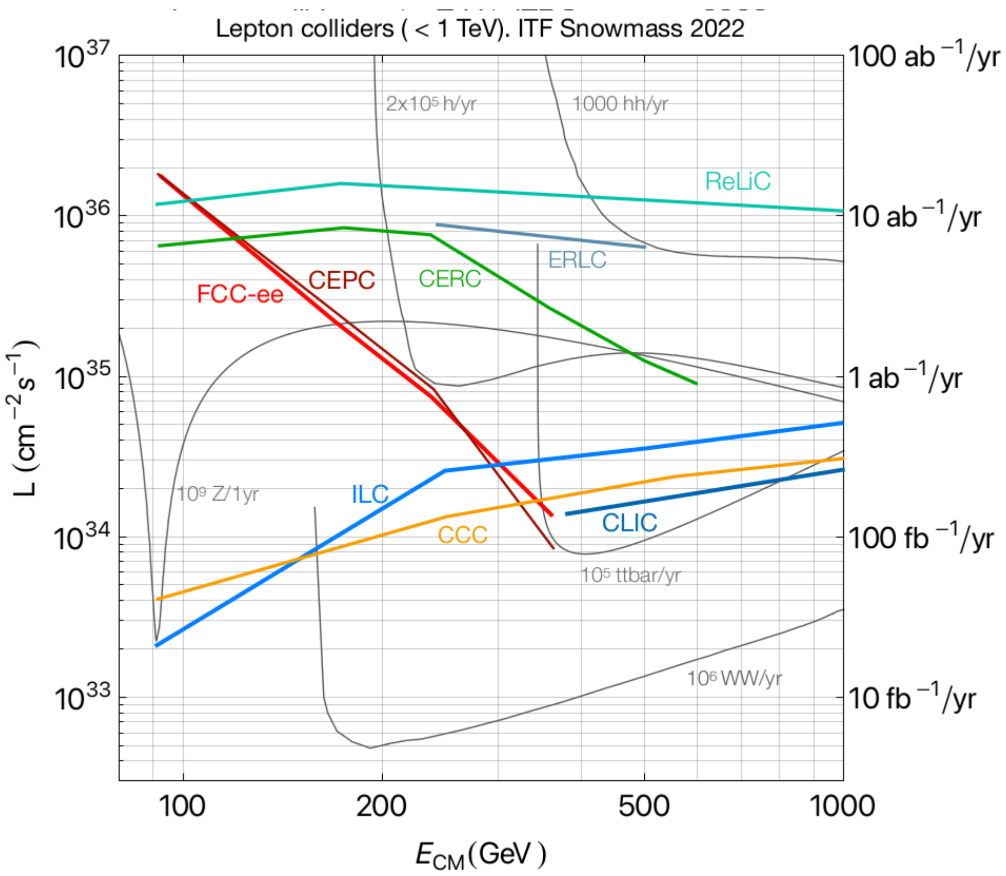
- Studies at the ttbar-threshhold up to ~ 500 GeV

What We Want:

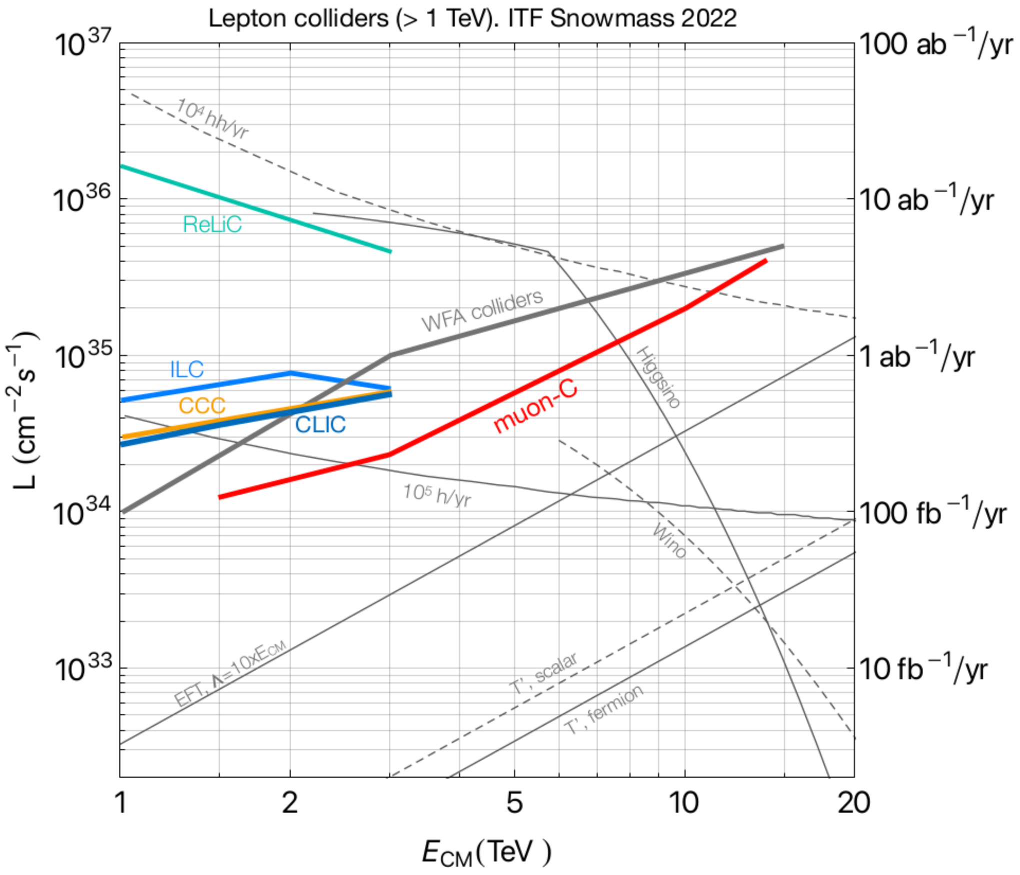
https://www.persoenlich.com/kategorie-werbung/eine-eierlegende-wollmilchsau-fur-vw

Future Landscape - Leptons

- Lower energy regime
  - Higgs and electroweak factories

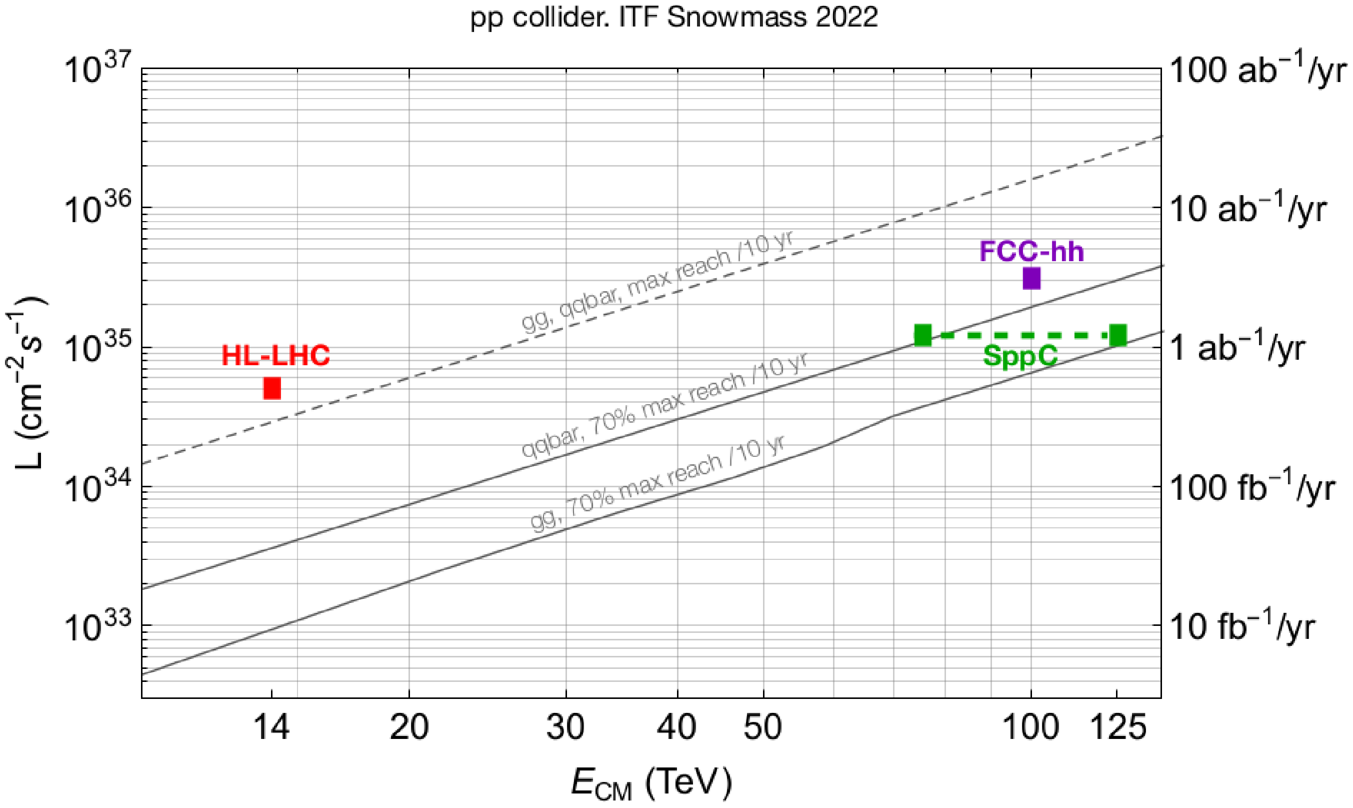


- Higher energy regime
  - Energy frontier with leptons



Future Landscape - Hadrons

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



Circular e+e- Colliders

Proposals

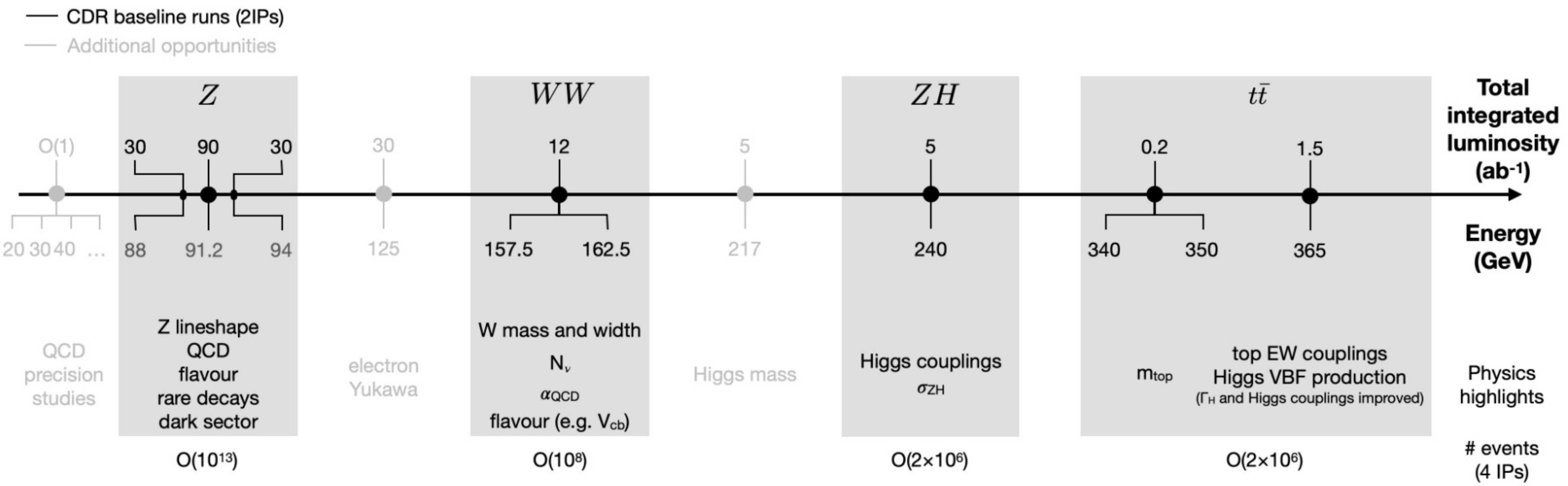
- CERN, Switzerland
  - **Future e+e- Circular Collider, FCC-ee**
  - Future hadron Circular Collider, FCC-hh

- CERN, Switzerland
  - **Large Electron Positron Collider 3, LEP3**

- IHEP, China
  - **Circular Electron Positron Collider, CEPC**
  - Super proton-proton Collider, SppC

Courtesy: C. Grojean

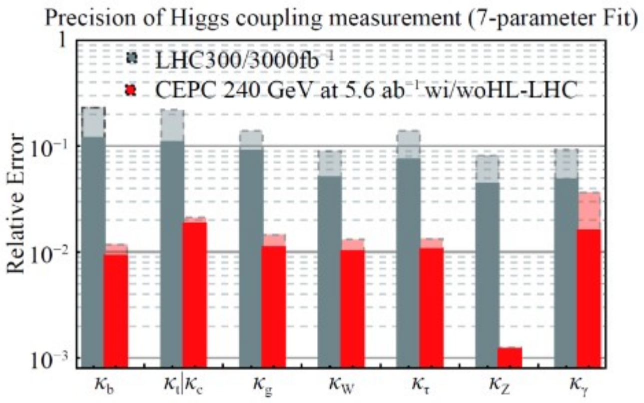
FCC-ee Physics Potential



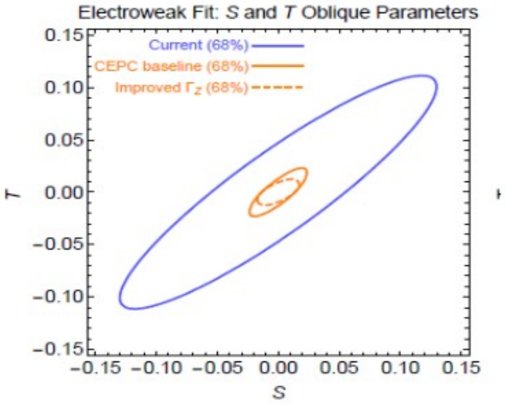
- Many opportunities beyond the baseline plan
- Complementary experiments using e.g. beam dump, re-using synchrotron radiation photons

CEPC Physics Progam

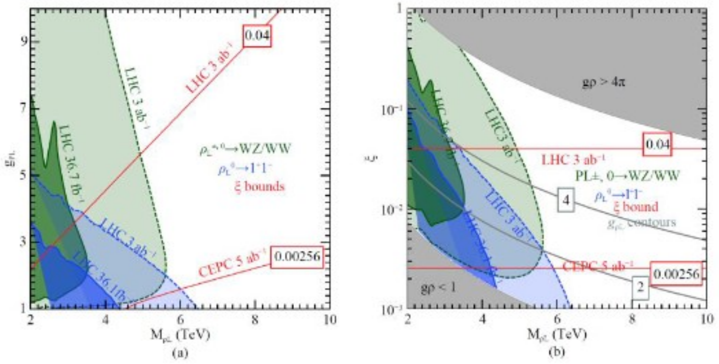
Higgs coupling precision can be improved by an order of magnititude

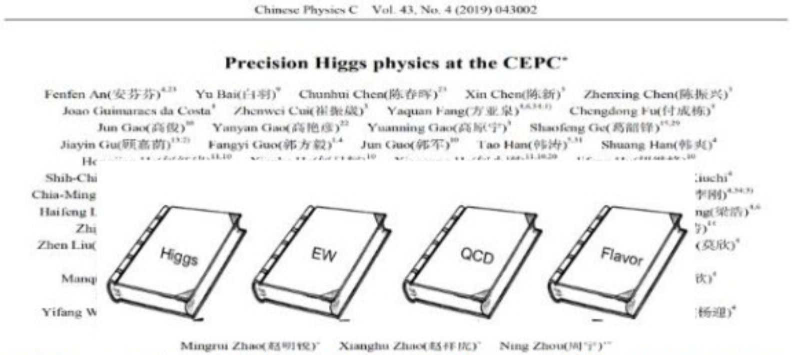


EW measurement can be improved by a large factor



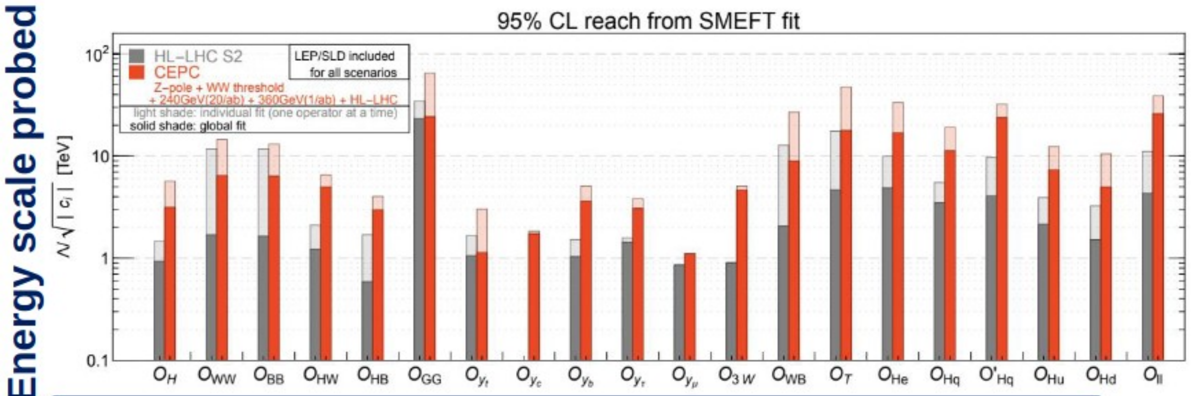
Direct and indirect probe to new physics up to 10 TeV, an order of magntitude higher than the HL-LHC





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

❖ ~ 300 Journal / arXiv papers



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

9

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	
First measurements of	45.6	Z-lineshape	
Special mode, **monochromatization**	62.5	H-energy	Not mentioned in TDR
	80	WW	
LEP3 limit	120	ZH-production peak	First measurements of
	182.5	Top-pair-threshold	

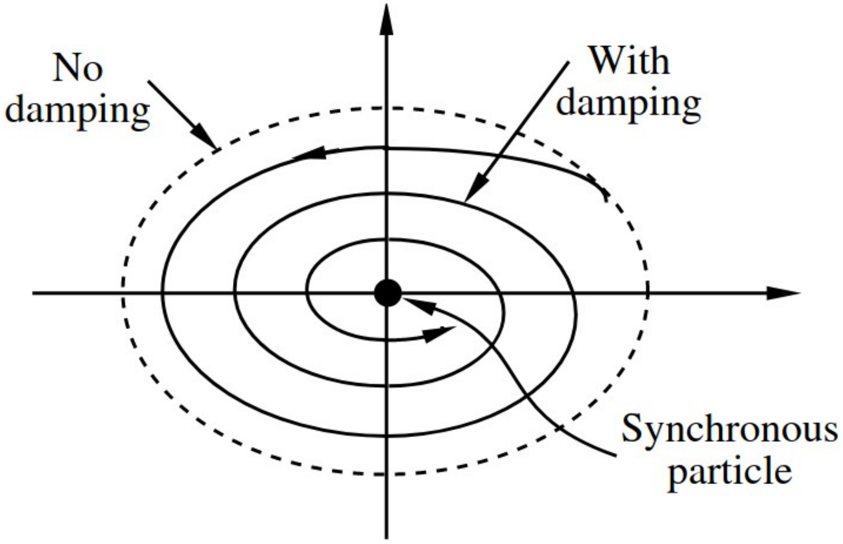
Synchrotron Radiation (SR)

- 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

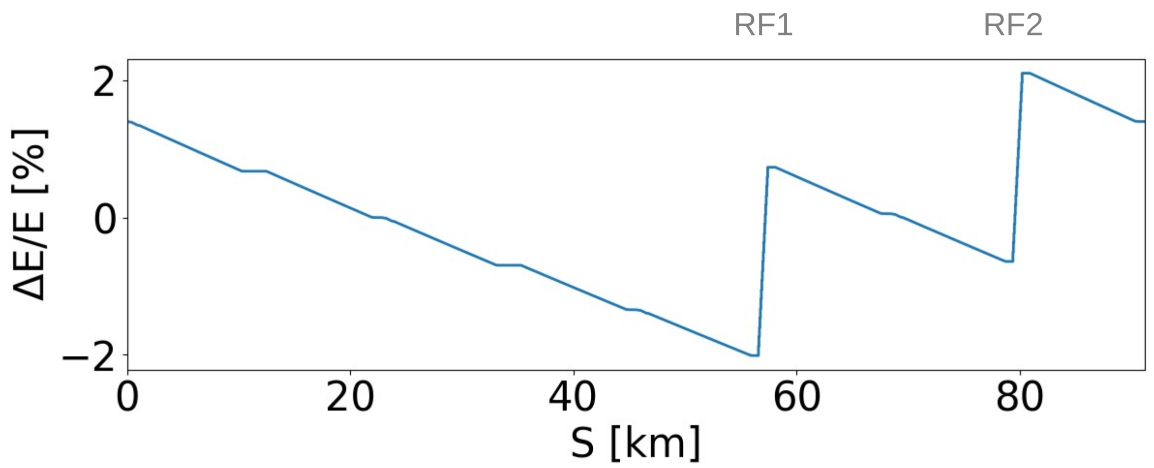
$$\varepsilon(t) = e^{-2\, t/\tau_{\mathrm{SR}}} \qquad \tau_{\mathrm{SR}} = \frac{T_0 E}{j_{x,y} U}$$

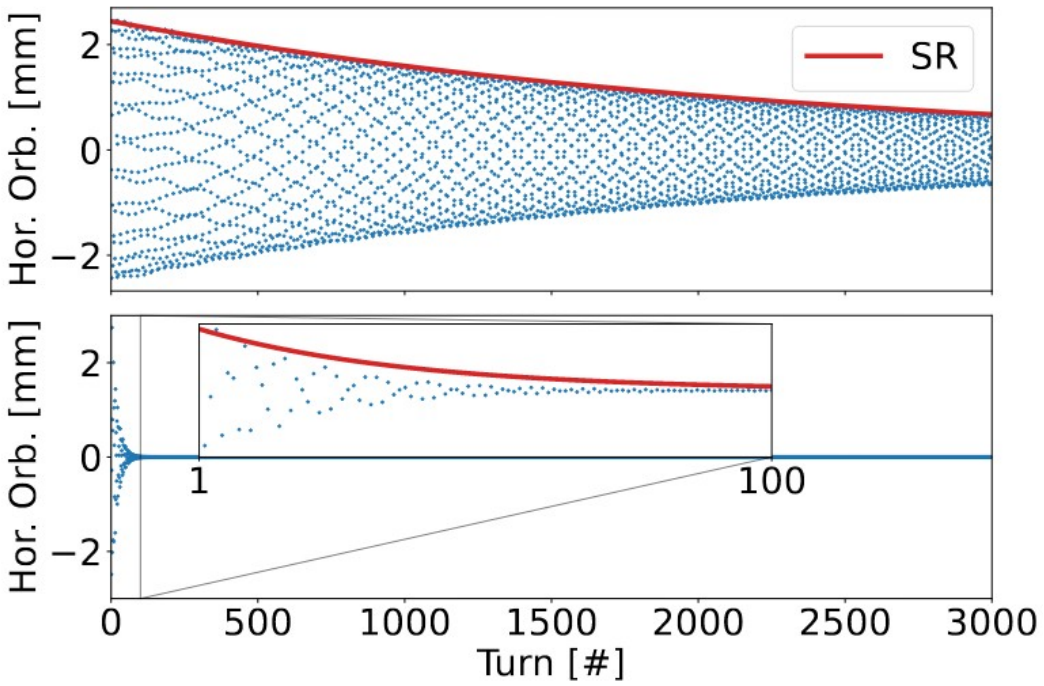


W. Barletta, USPAS lectures on synchrotron radiation, 2009.

Synchrotron Radiation Challenges

- At highest proposed energy mode of **182.5 GeV at FCC-ee or CEPC** 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
- ...



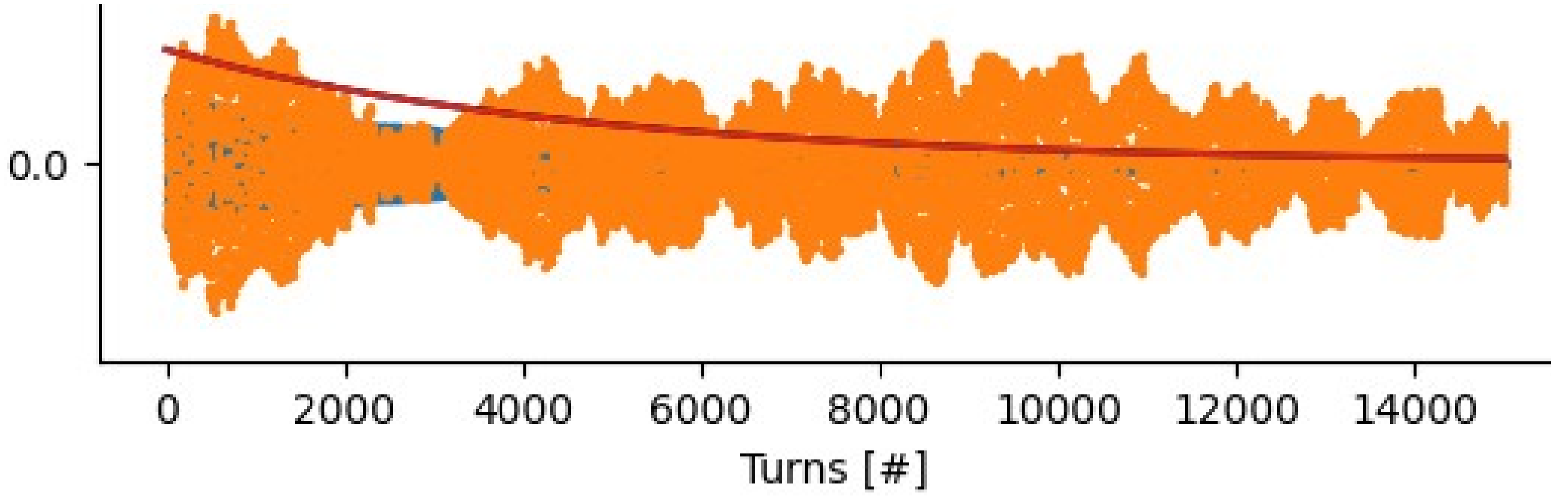


Quantum Excitation

- 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

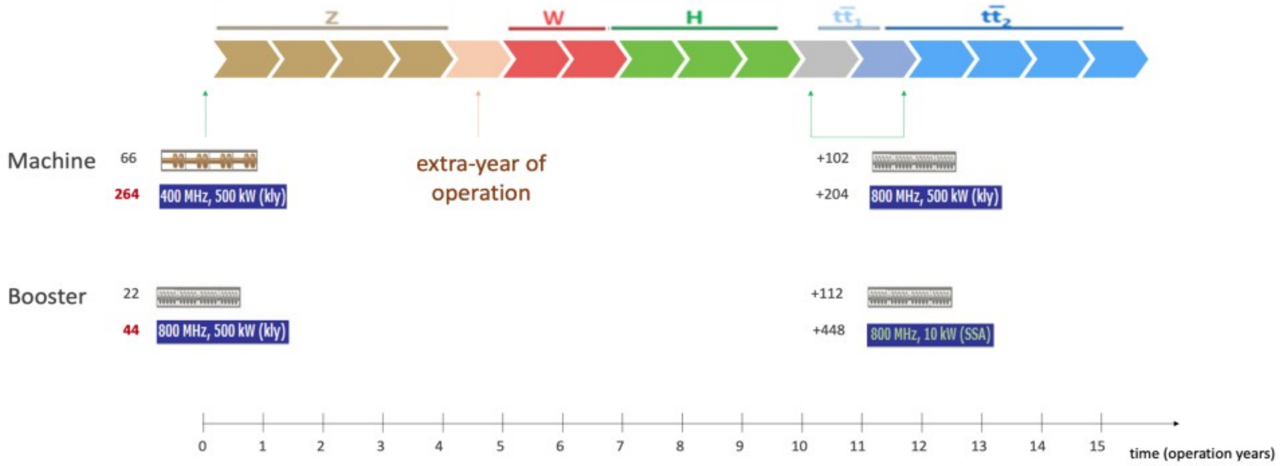
	Z	WW	ZH	ttbar
	4 years 5×10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2×10^6 H	5 years 2×10^6 ttbar pairs

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

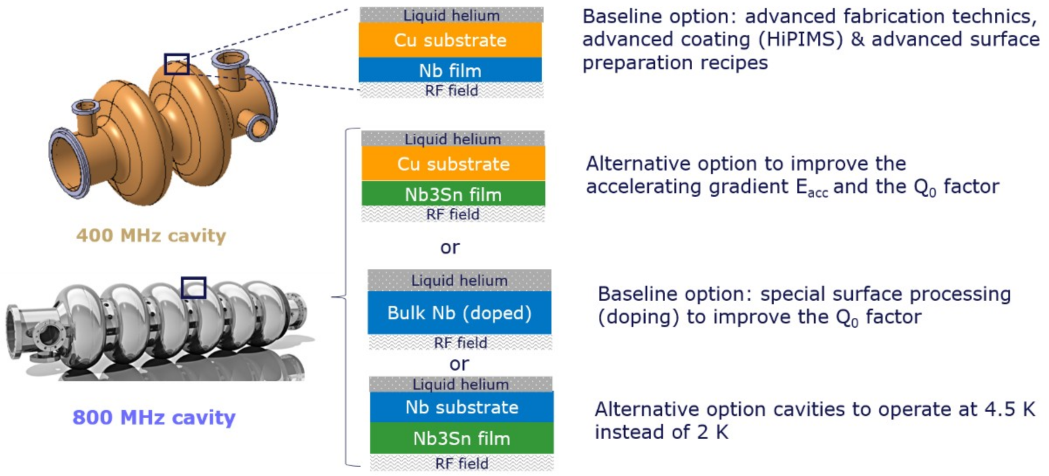
Defines
→ RF system
→ Beam parameters

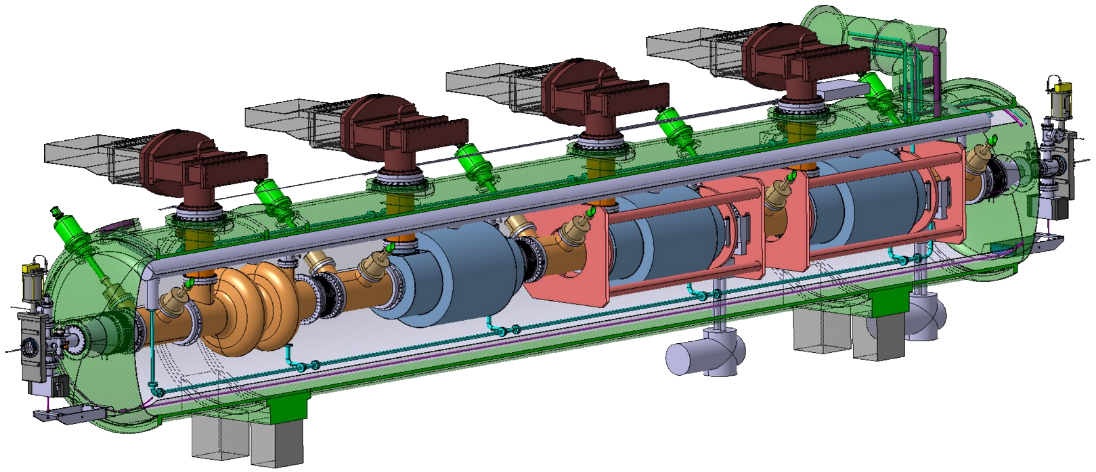
Superconducting RF Cavities

- 2-Cell 400MHz cavities for Z, W, H, ttbar
- Copper Nb coated, 1.5m long, 4.5K
- Reverse Phase Operation (RPO), all 400MHz cavities installed for Z to H operation modes
- 6-cell 800MHz for ttbar



Material	λ(nm)	ξ(nm)	κ	T_c(K)	H_{c1}(T)	H_c(T)	H_{sh}(T)
Nb	40	27	1.5	9	0.13	0.21	0.25
Nb_3Sn	111	4.2	26.4	18	0.042	0.5	0.42





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

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

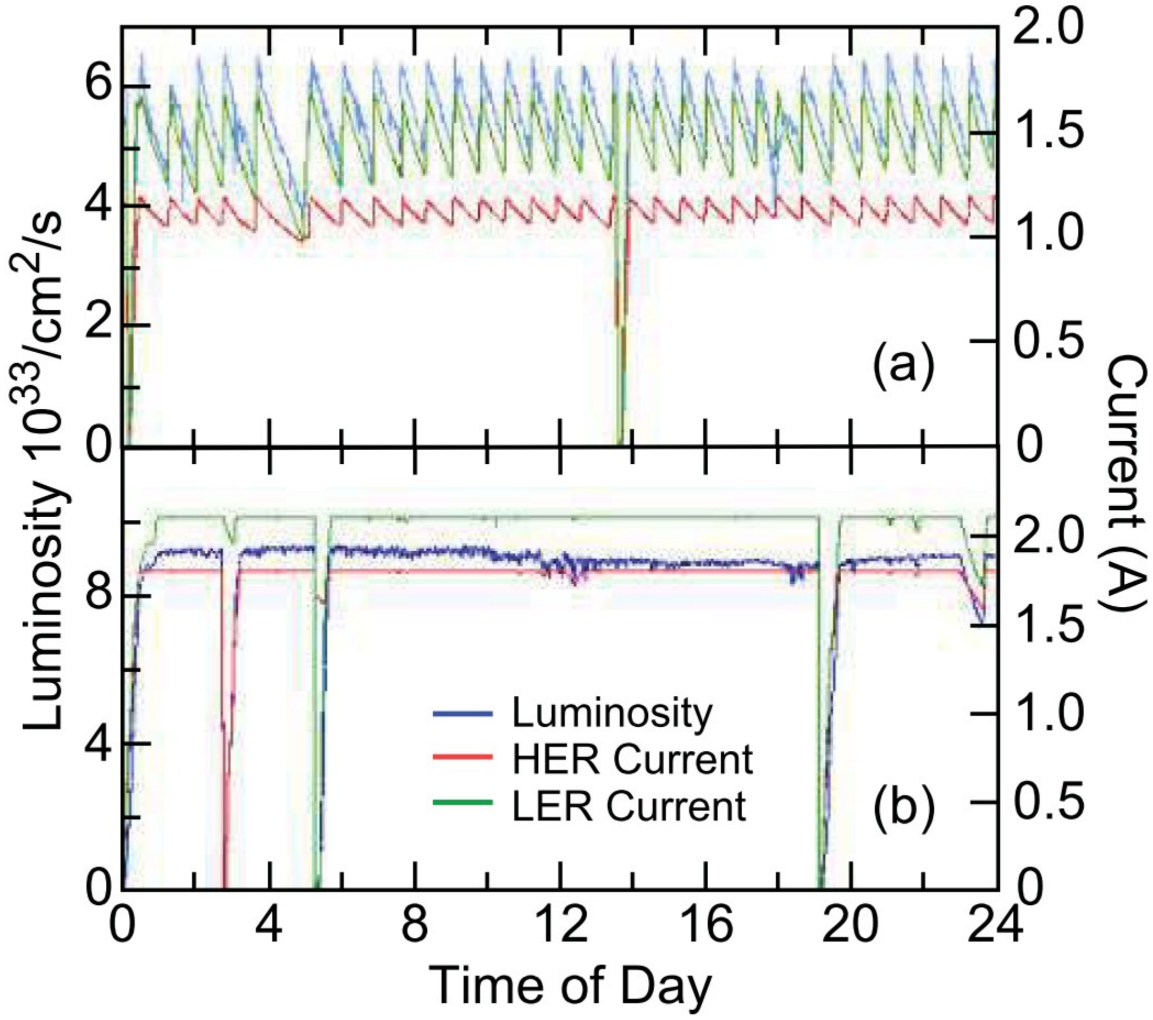
maximum injector current just replenishes lost particles → maximum current in collider

e± injector beam currents

injection efficiencies

beam lifetimes in collider

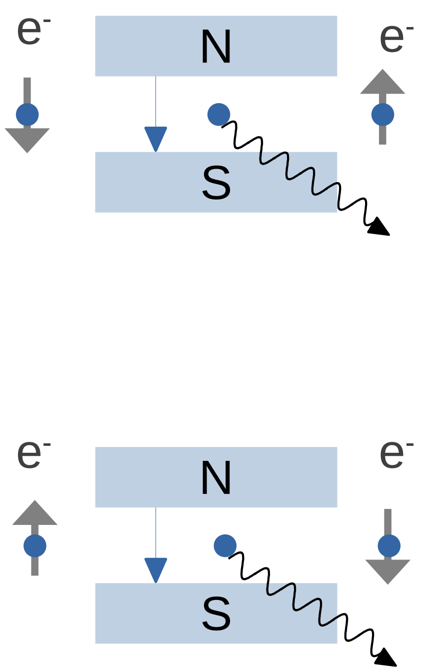
$$\mathcal{L} \approx \frac{f}{4\pi e^2 \sigma_x^* \sigma_y^*} \frac{1}{n_b} I_{\pm} \epsilon_{\pm} \tau_{\pm}$$



Polarization Build-Up

More likely
(by factor ~25)

Less likely



- Statistically every 10^{10th} 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 Sokolov-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

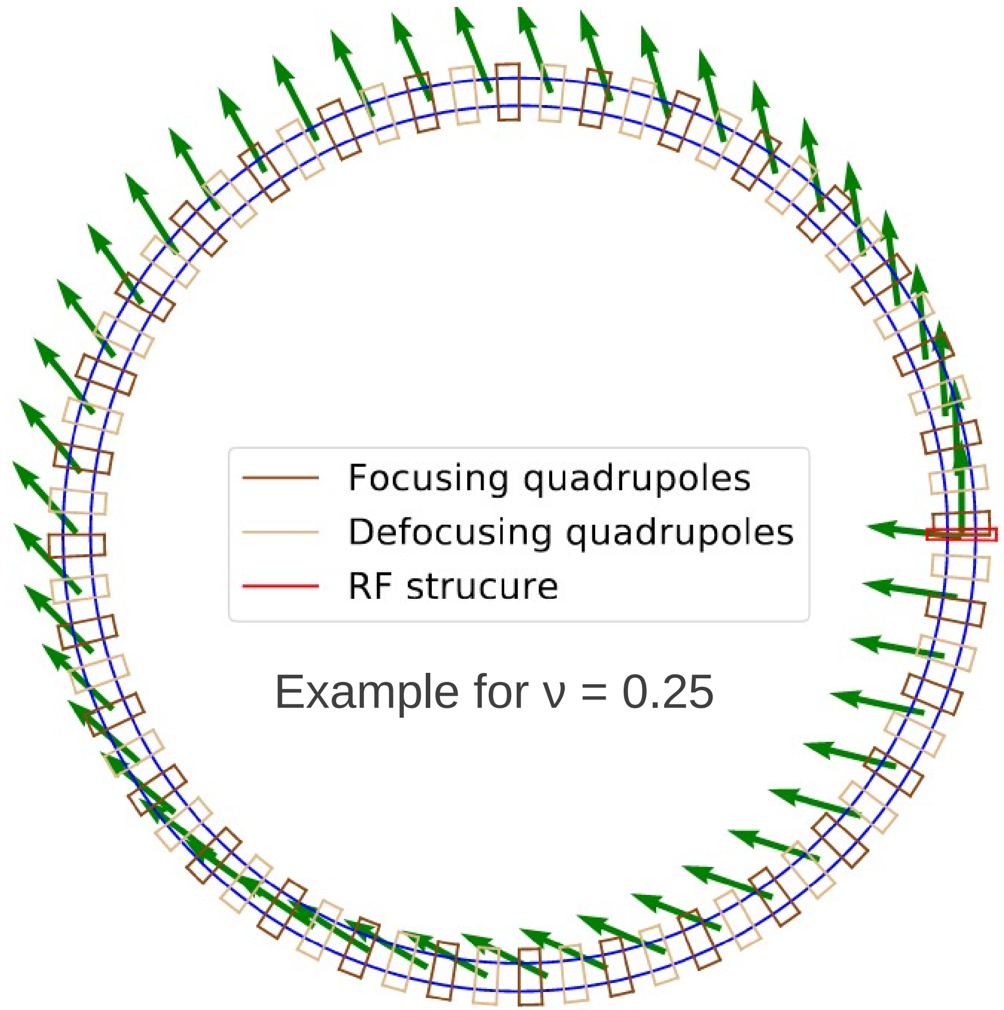
- In an error-free flat machine without solenoids:
- 45.6 GeV e^+/e^- –> 103.5 spin tune
- Purely vertical spin orientation

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

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

Principle:

Spin tune measurement ⟺ Beam energy determination



Courtesy: V. Caudan

Linear RF e+e- Colliders

Courtesy: S. Stapnes

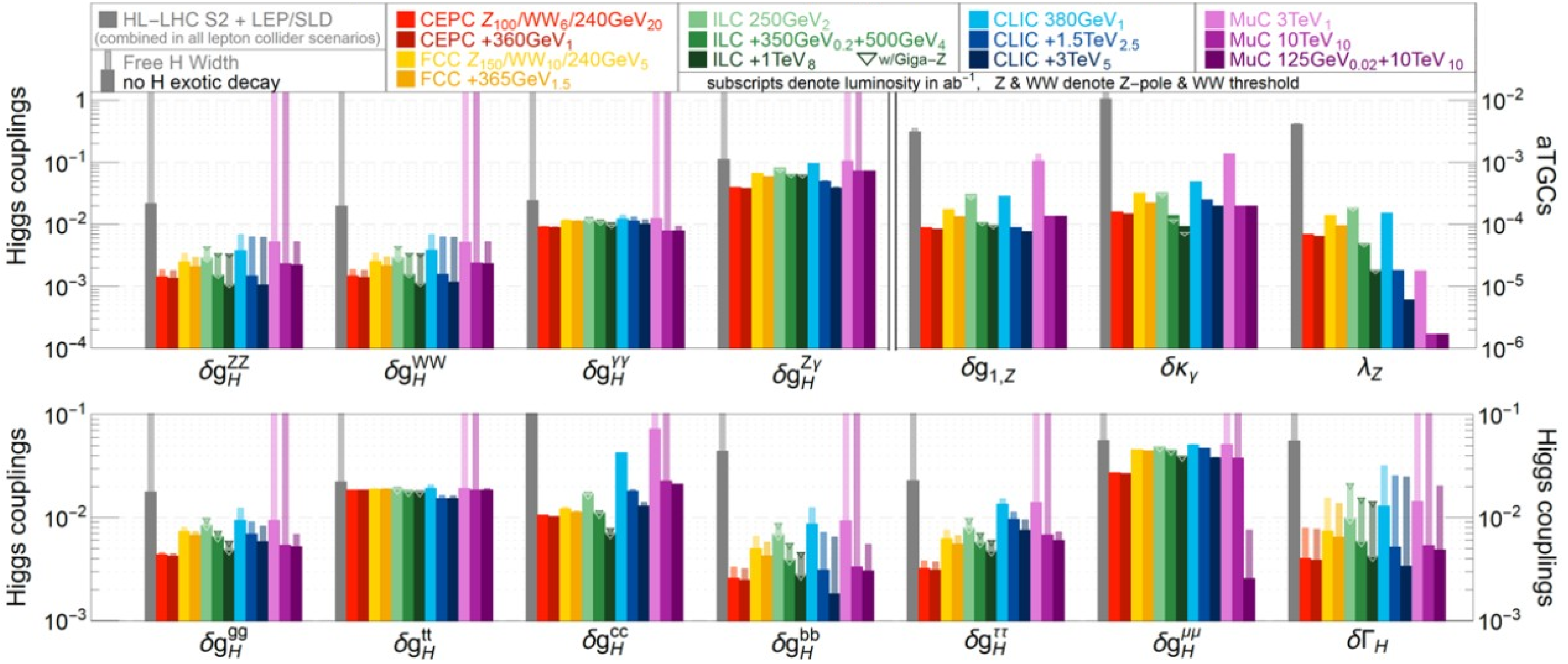
Proposals

- CERN:
  - Compact Linear Collider (CLIC)
  - Linear collider facility
- Japan:
  - International Linear Collider (ILC)
- USA:
  - Cool Copper Collider

Courtesy: S. Stapnes

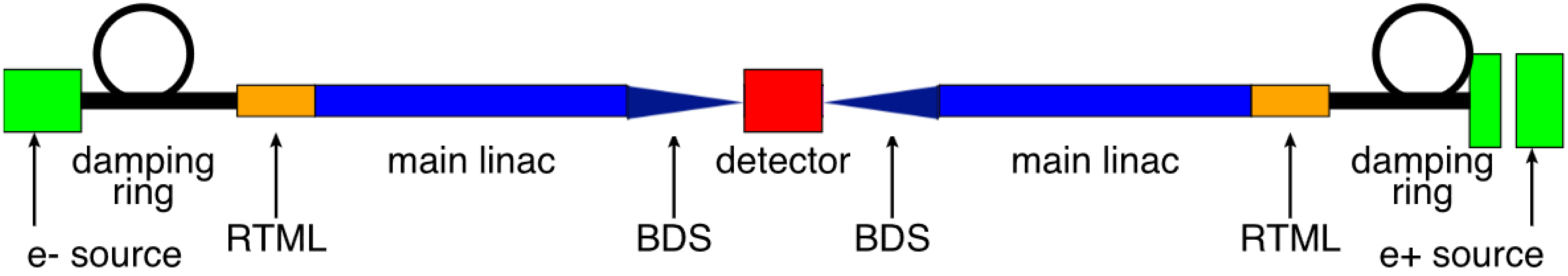
Physics Potential

- 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



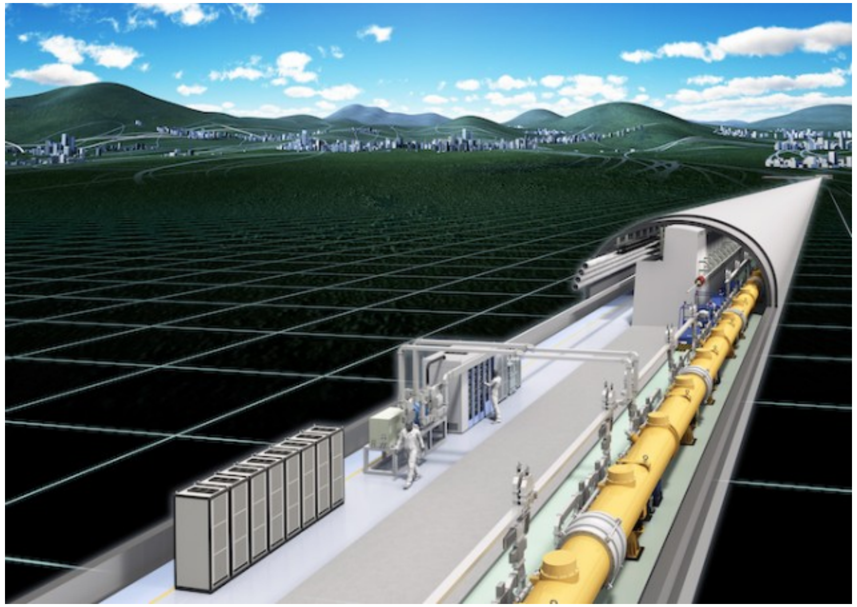
General Linear Collider

- 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



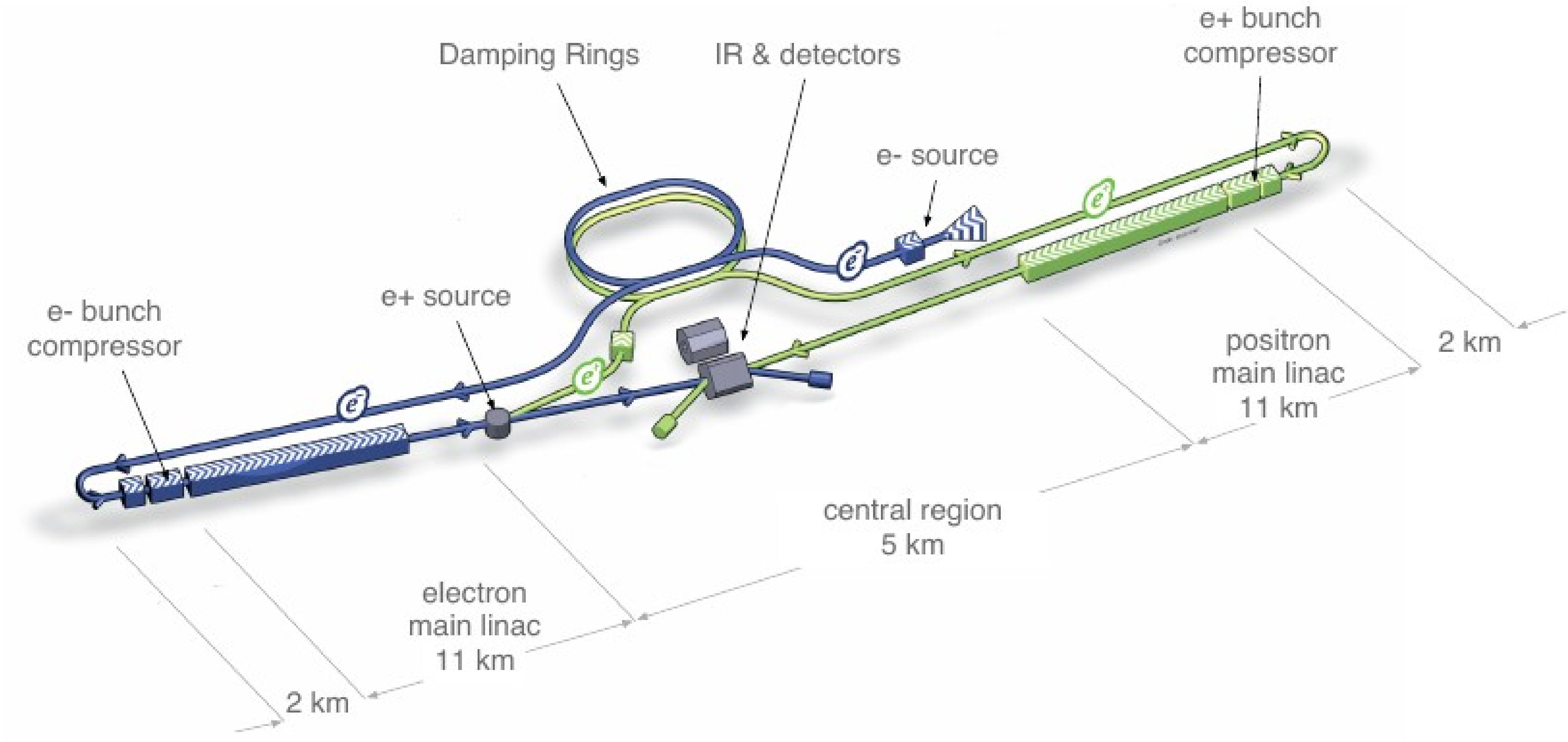
ILC

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



ILC Scheme

Courtesy: S. Stapnes

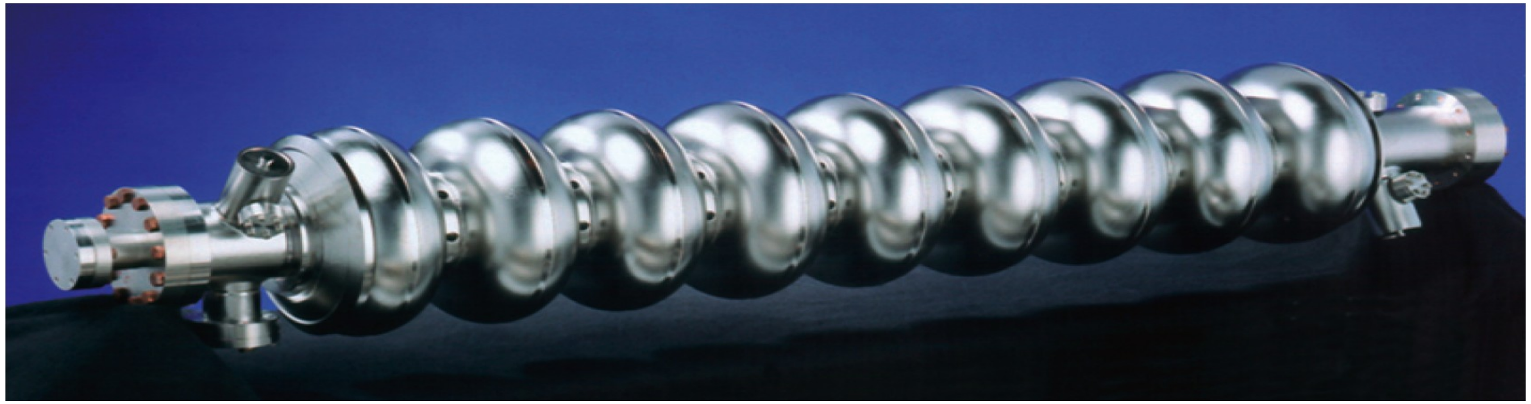


Courtesy: S. Stapnes

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

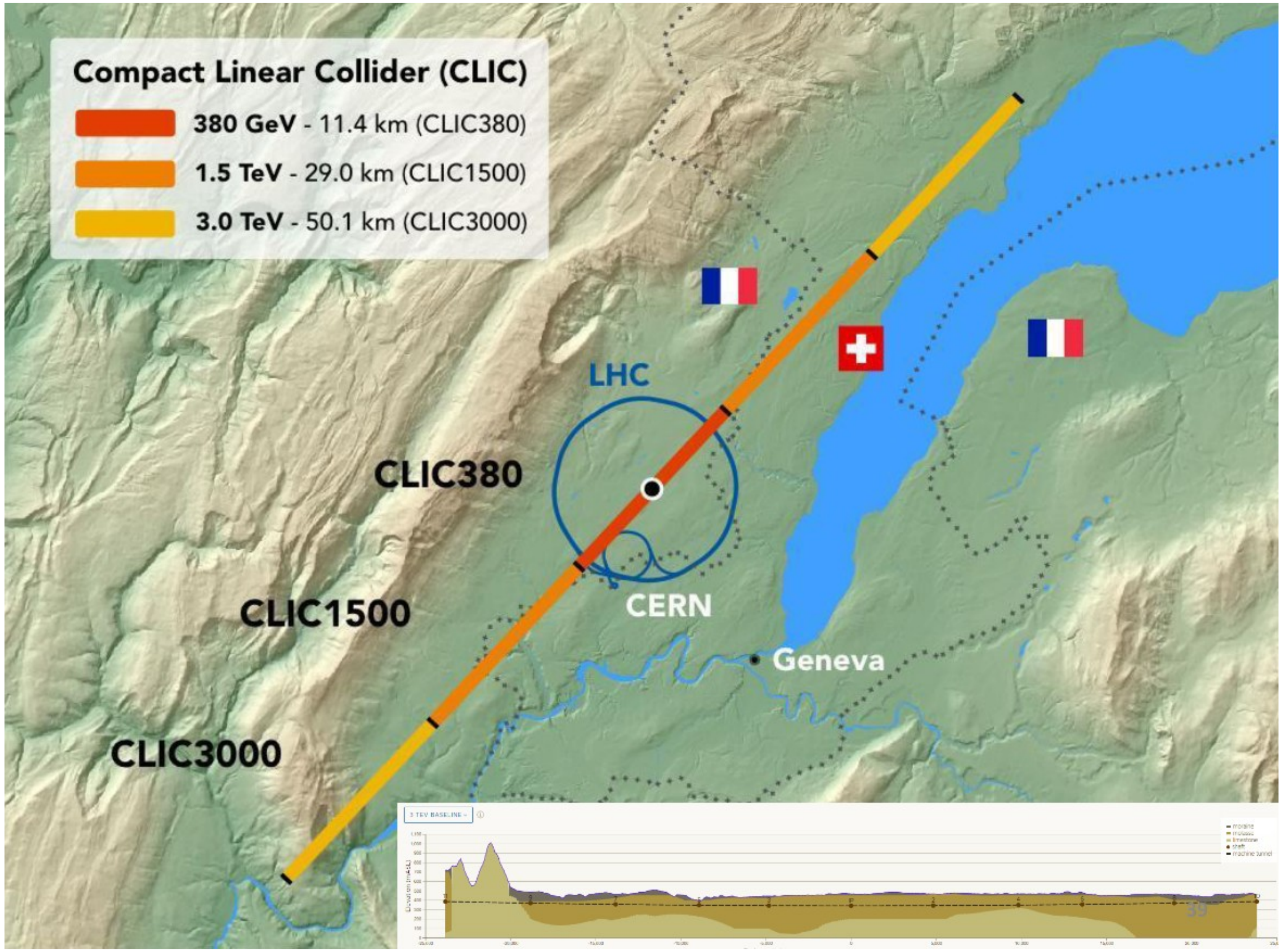
ILC Parameters

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	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	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	$\gamma\epsilon_x$	µm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	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: 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



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

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	$1\times10^{34}\,cm^{-2}\,s^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,cm^{-2}\,s^{-1}$	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

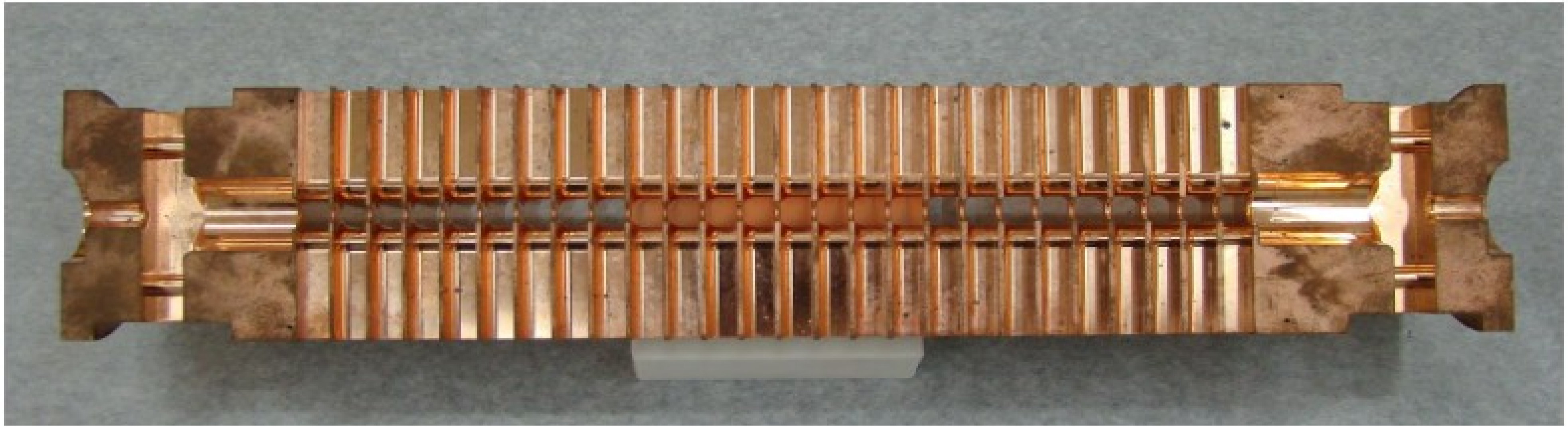
Add:
- 250 GeV parameters
- 100 Hz running for both 250 and 380 GeV

Courtesy: S. Stapnes

CLIC Cavities

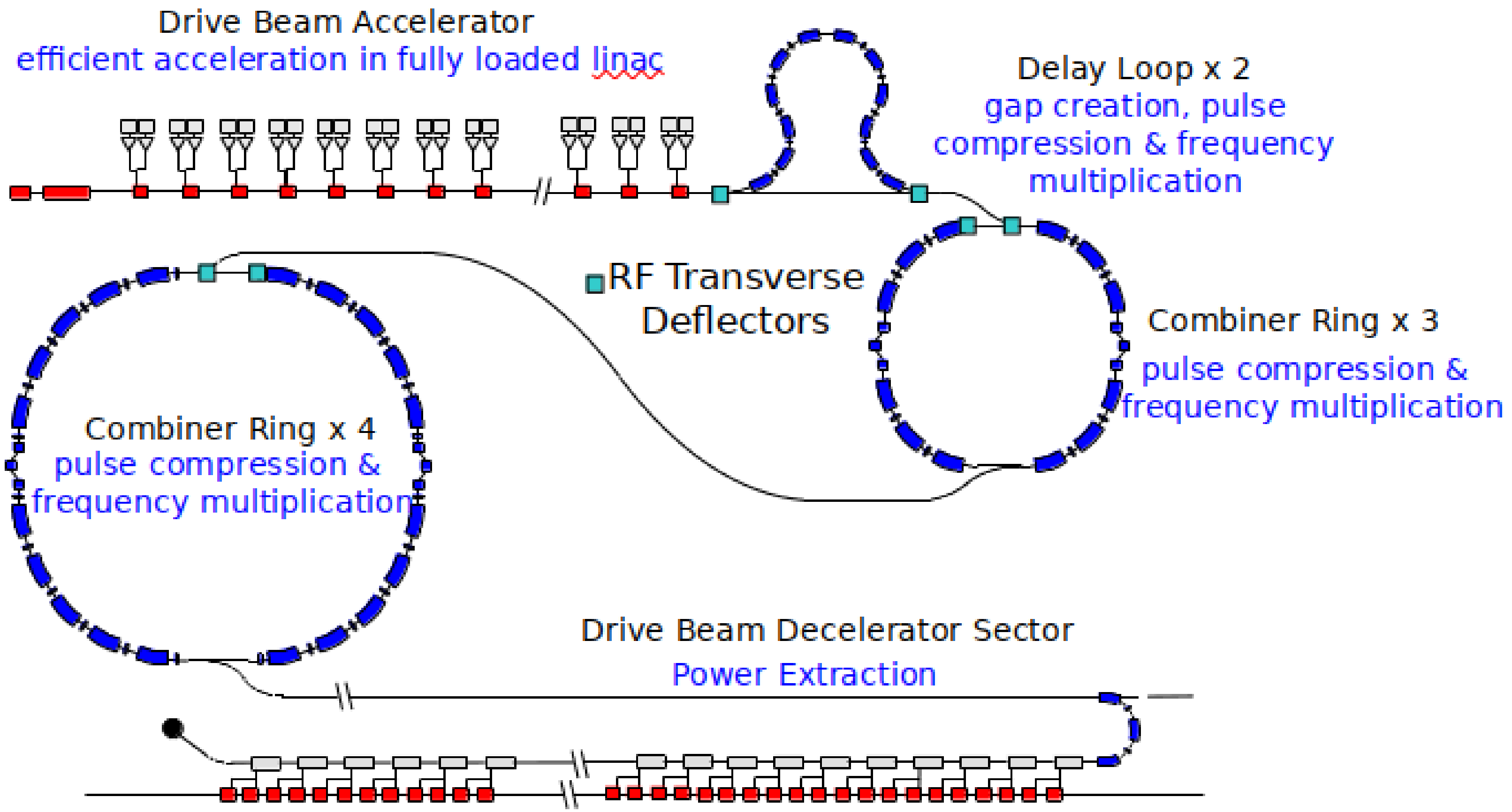
- 12 GHz nomal conducting cavitiy
- 100 MV /m
- 25000 cavities needed

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



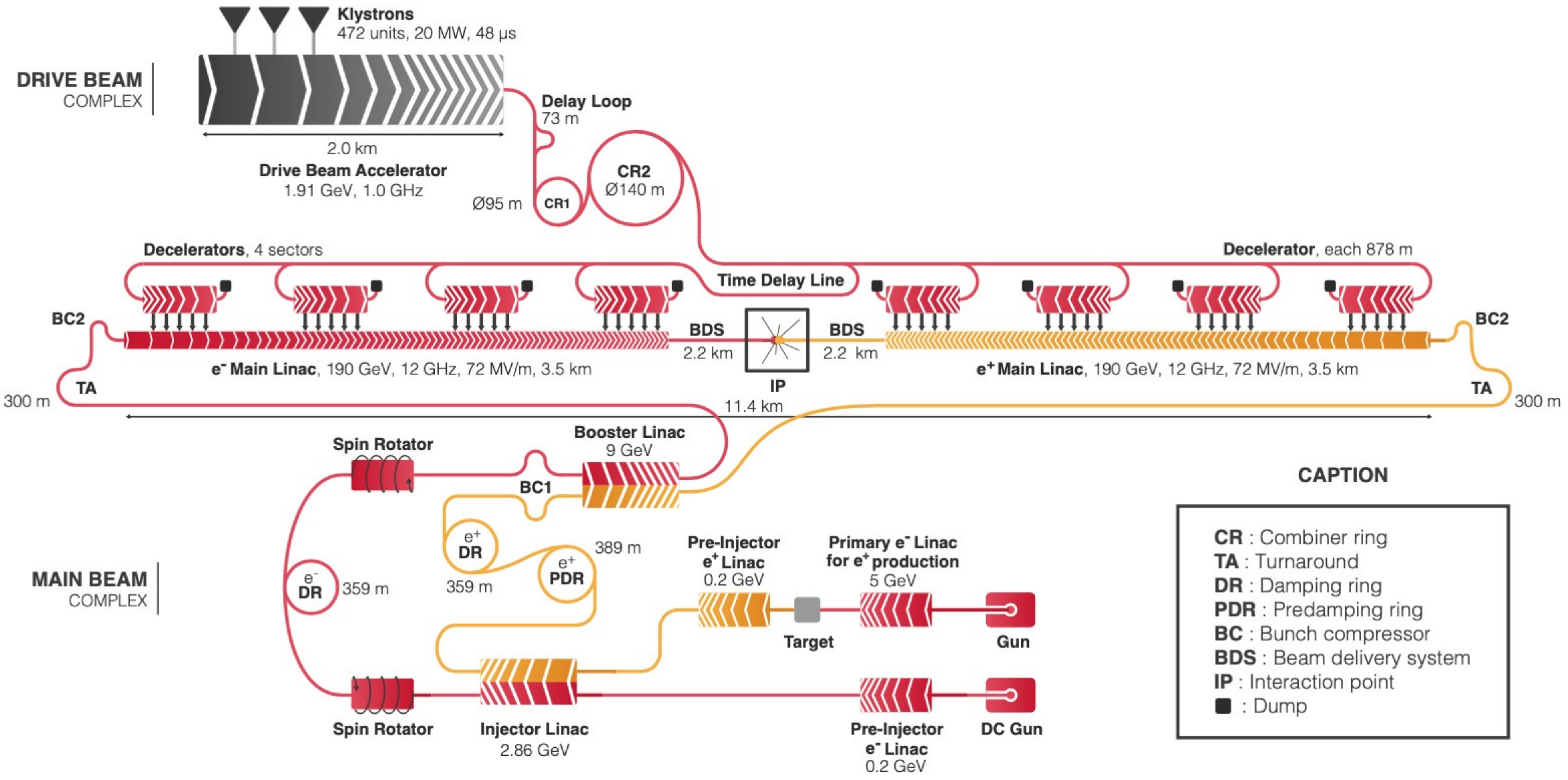
Courtesy: R. Bruce

Drive Beam Acceleration



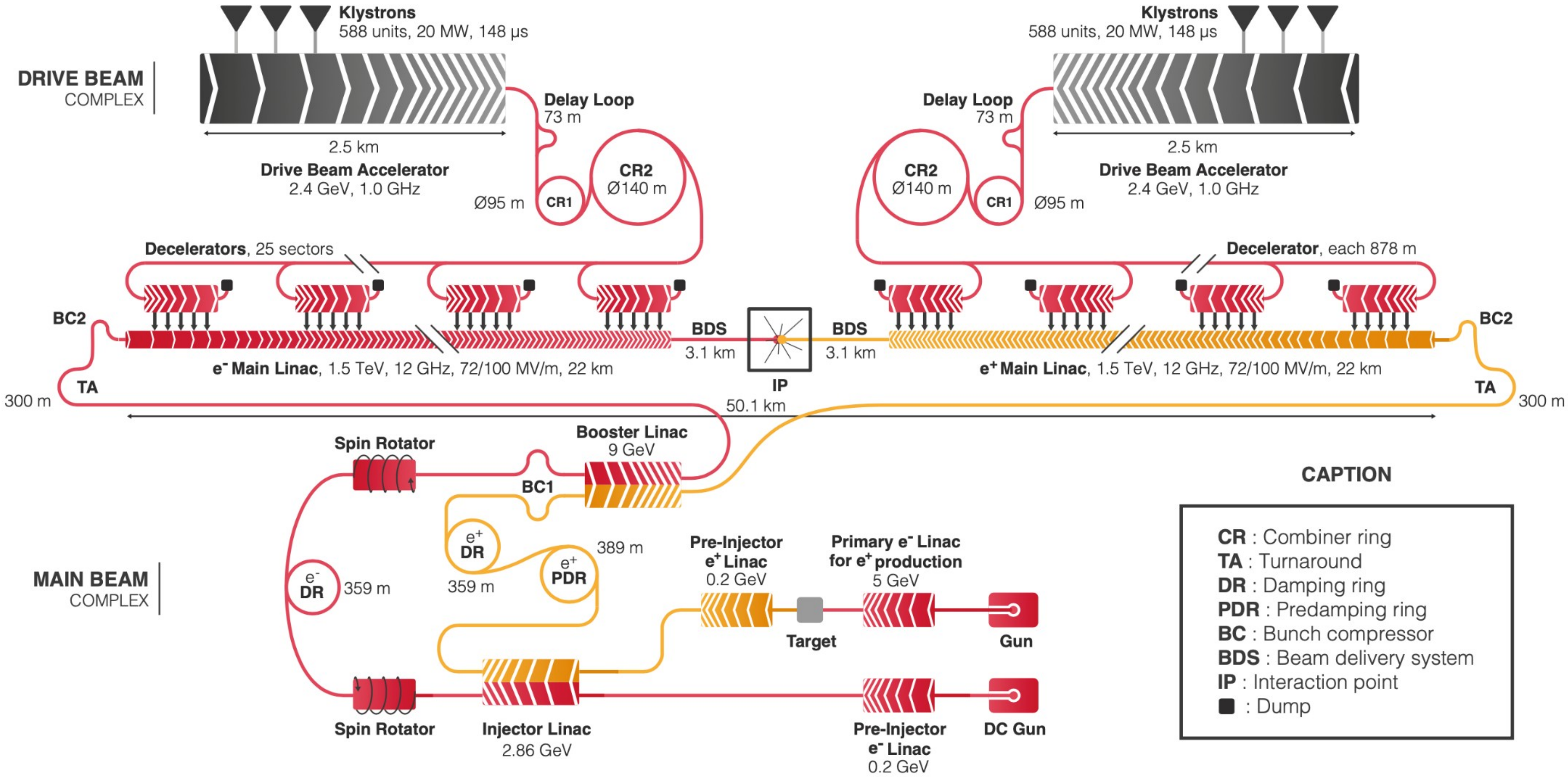
Courtesy: S. Stapnes

CLIC 380 GeV



Courtesy: S. Stapnes

CLIC 3 TeV



Cool Copper Collider - C^3

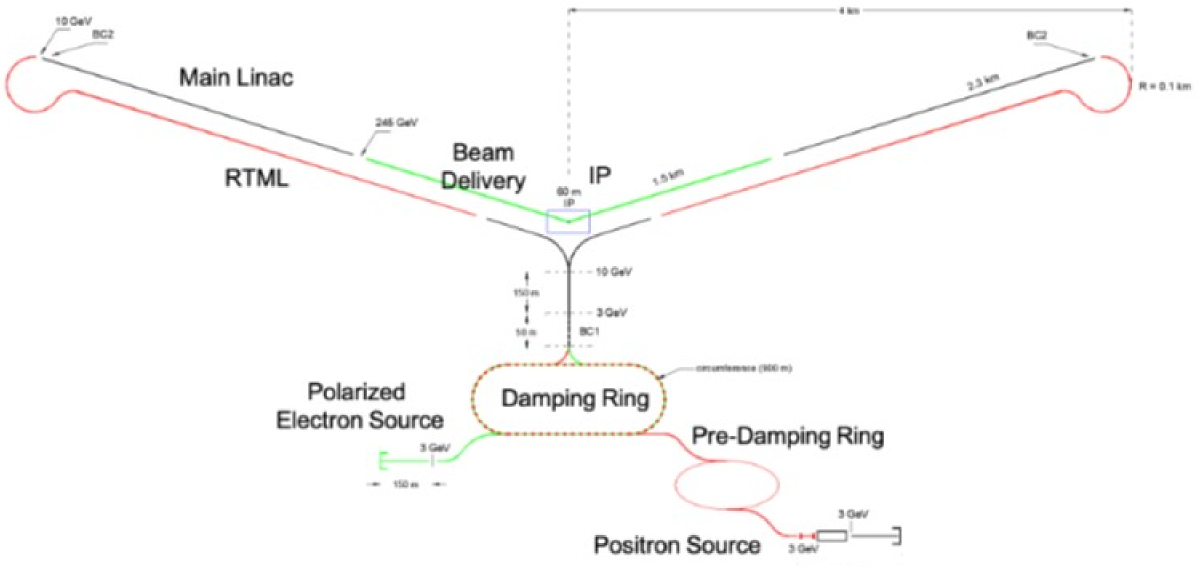
- New approach for a normal conducting linear electron collider
- Based on cold copper distributed coupling accelerating cavities
- Compact design with only 8 km footprint to achievet 250 and 500 GeV collision energy

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

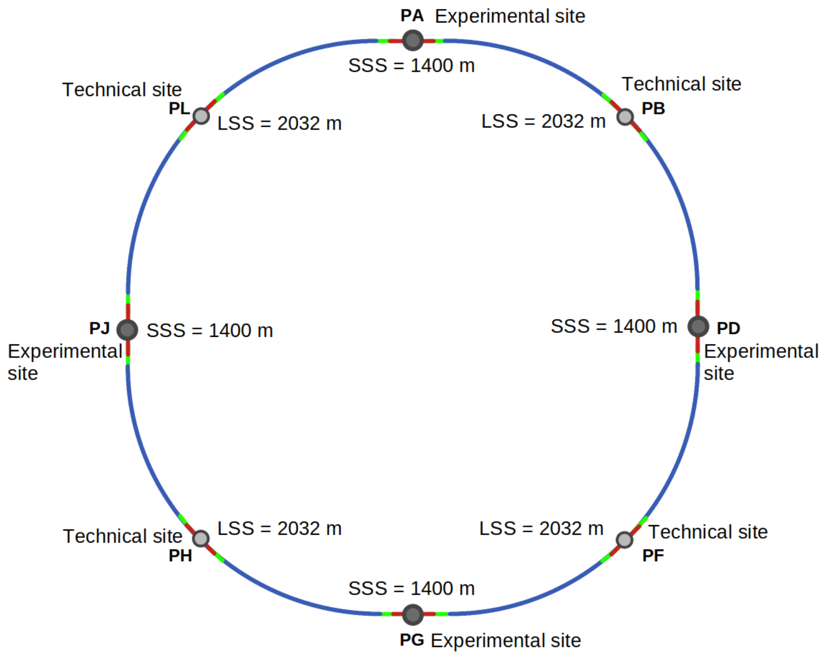
  → possibility to use for other linear machines

Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125

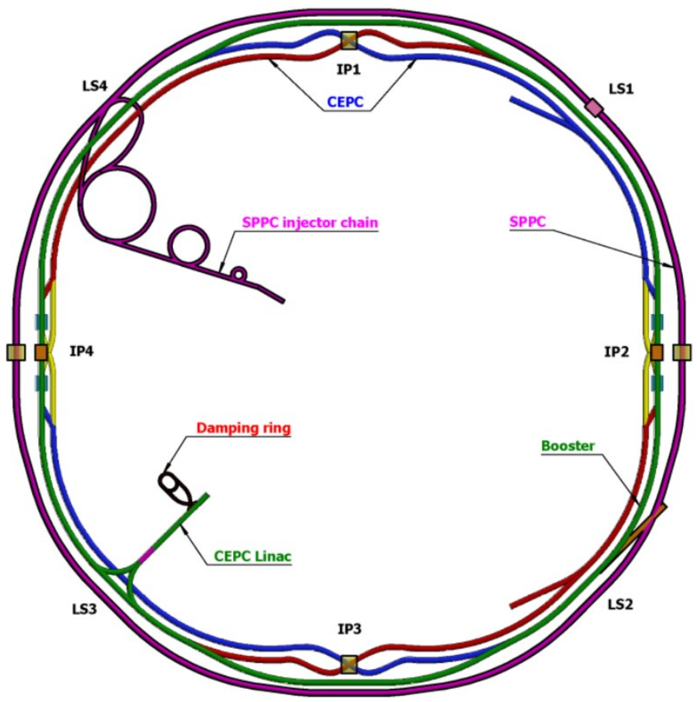
Circular Hadron Colliders

Proposals

- 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**

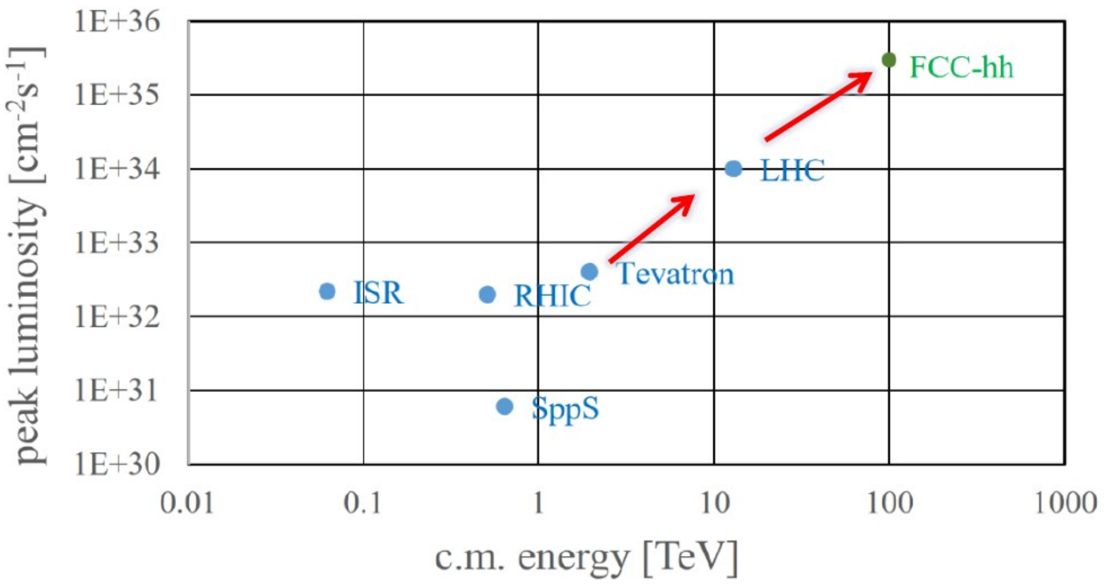


Physics Goals

- 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: 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

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
- ...

Direct discovery potential up to 40 TeV

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

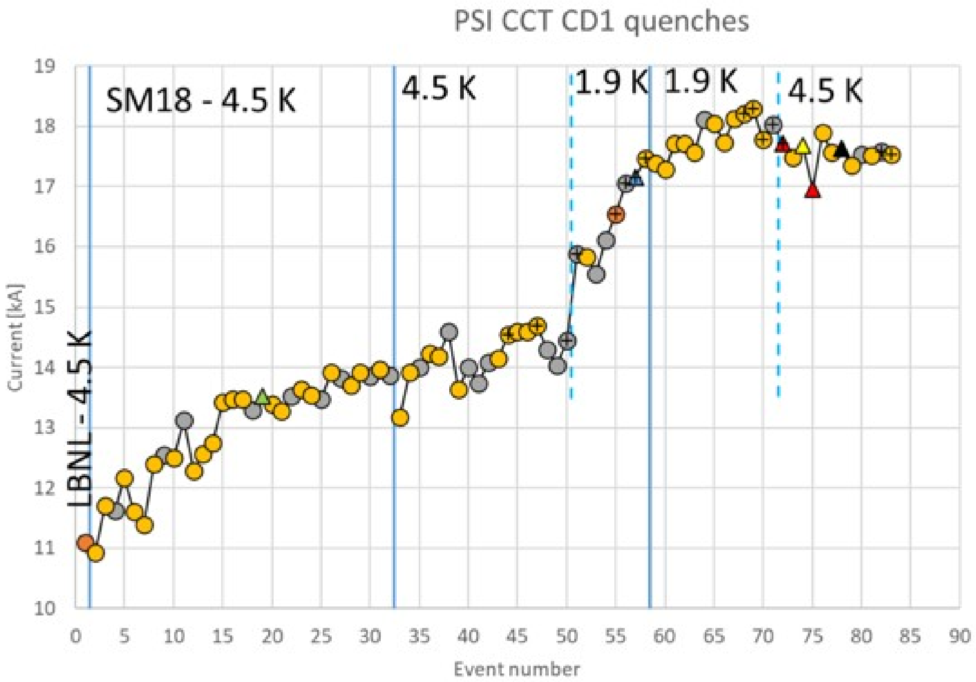
Compared to FCC-hh higher collision energy of 125 GeV

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
- ...

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

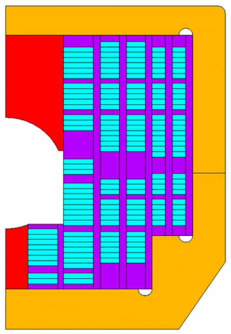
Courtesy: B. Auchmann

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
- More relaxed cyro-systems compared to ~2K

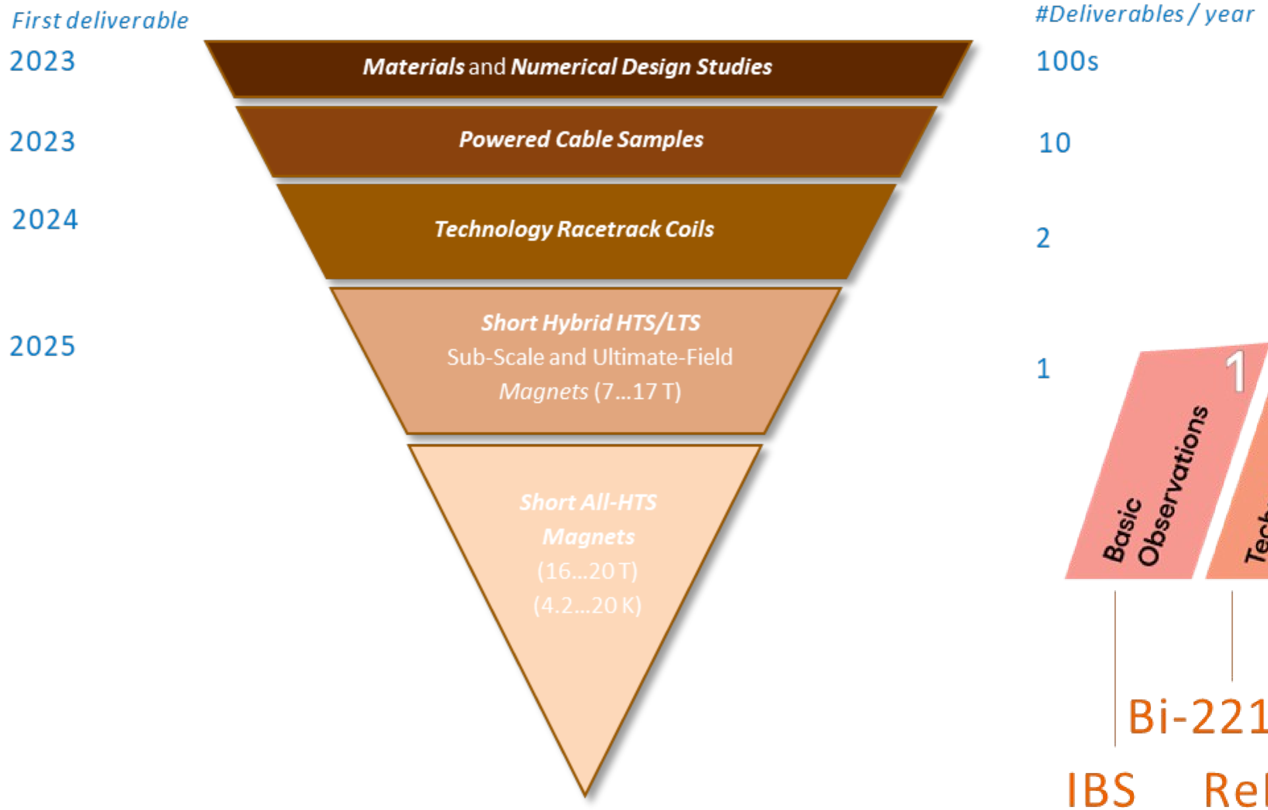
B_0 target of 14 T, at T_{op}: 4.2 K
Eng margin of 10%
B_0 short sample @ 1.9 K: 16 T

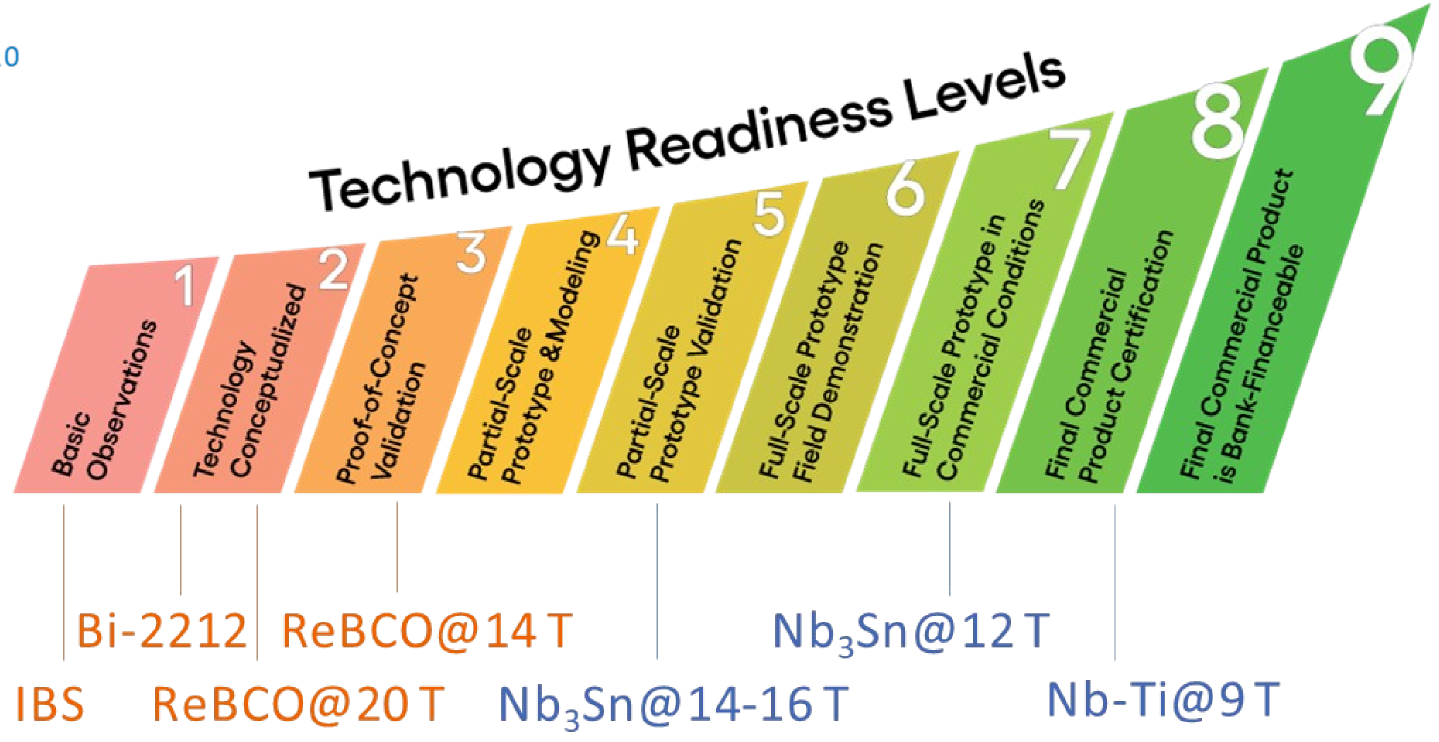


Courtesy: B. Auchmann

High Field Magnets: HTS

- **Bottom line:** HTS technology must catch up over the coming 10 years
- Significant power savings possible if HTS at 20-30 K feasible



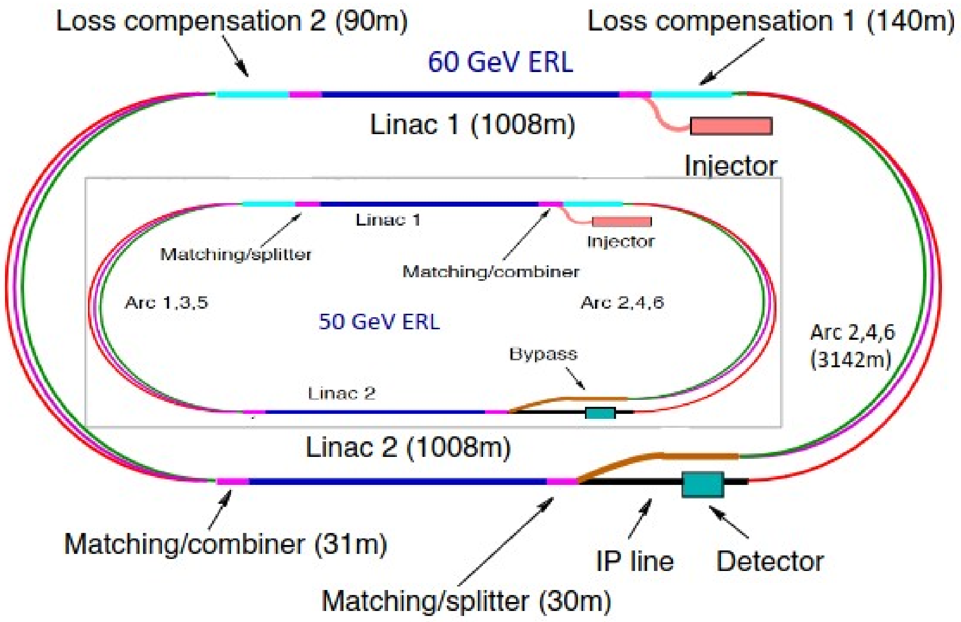


Energy Recovery Linacs

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

Principle

- Combination of linear and circular machine design principles
- Same accelerating structure in straight part
  - Constraints on RF design
- Bend of particles in arc structure
  - Constraints on accelerator design
- Multi-turn acceleration



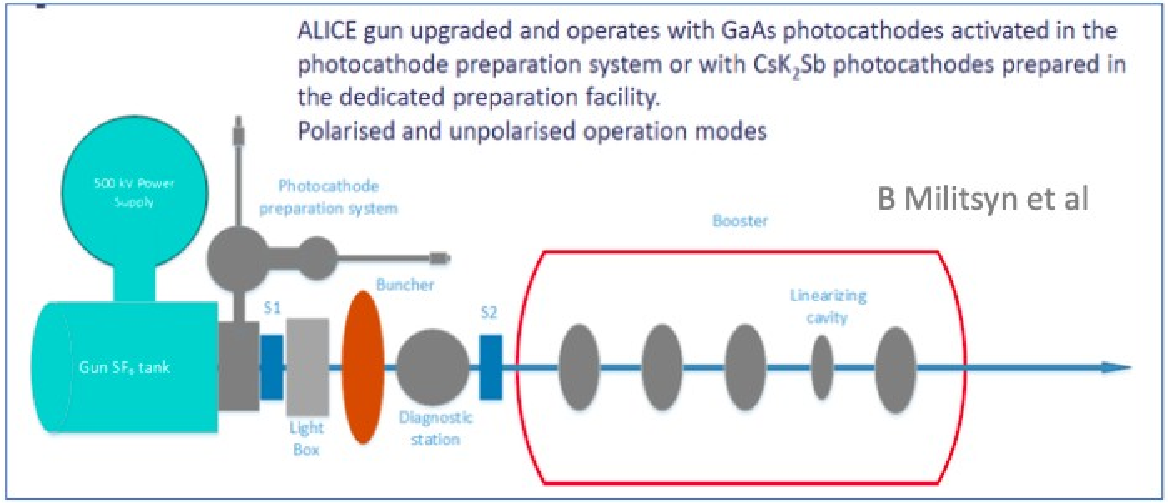
- Small footprint, especially if permanent magnets are used
- High intensities
- High brilliance
- Use for high-power electron-hadron colliders

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 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 $E_e = 50$ 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: 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

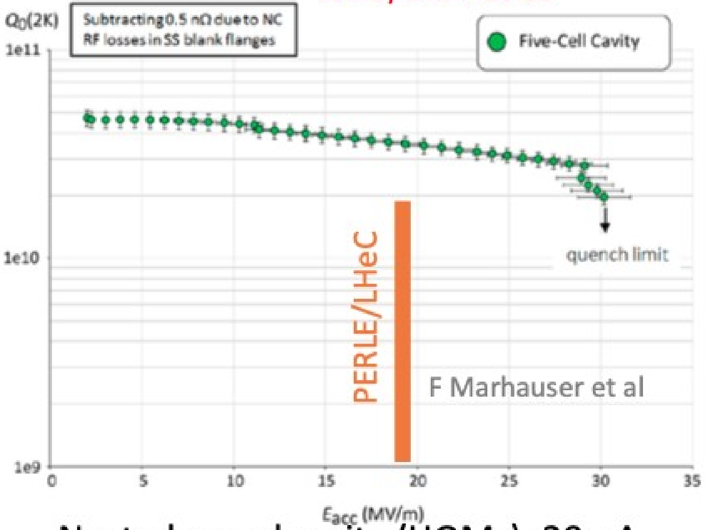


PERLE will begin with 5mA ALICE source, which has been transferred from Daresbury to Orsay while UK was in EU..

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

SCRF: High Q_0, complete Cryomodule

Jointly with FCC-ee



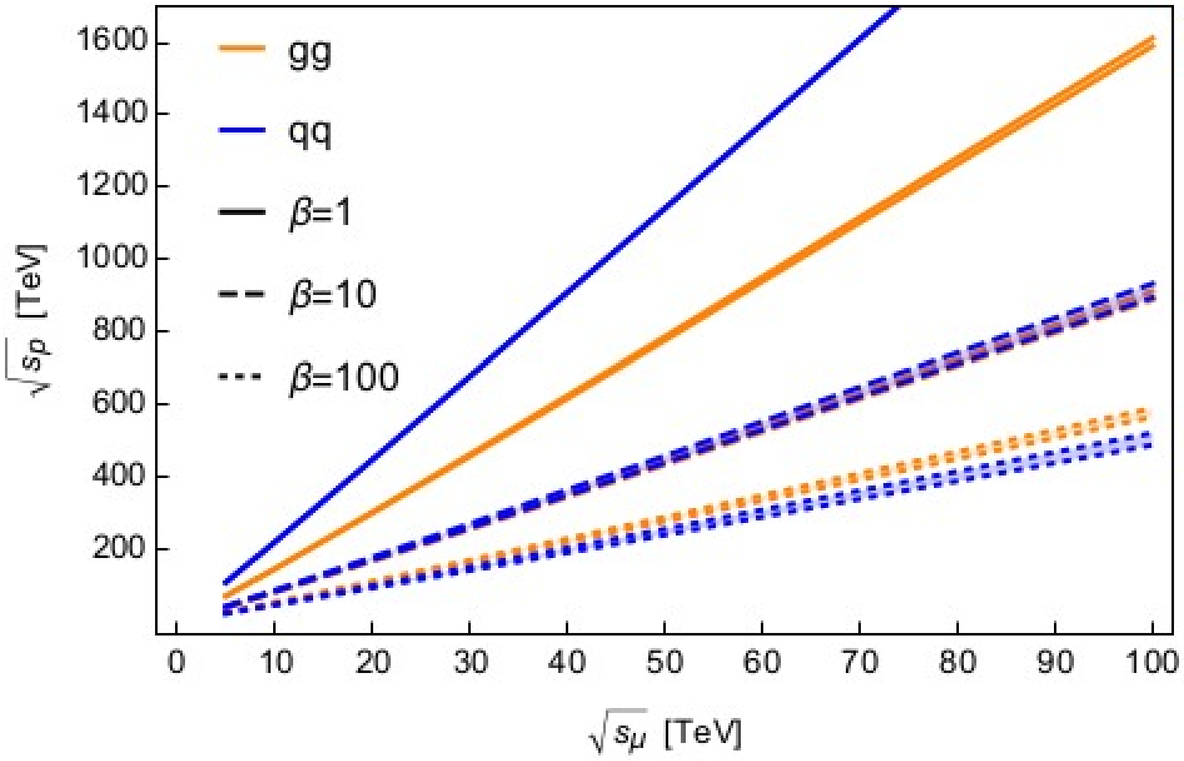
Next: dressed cavity (HOMs), 20mA
Adapt SPL Cryomodule for PERLE

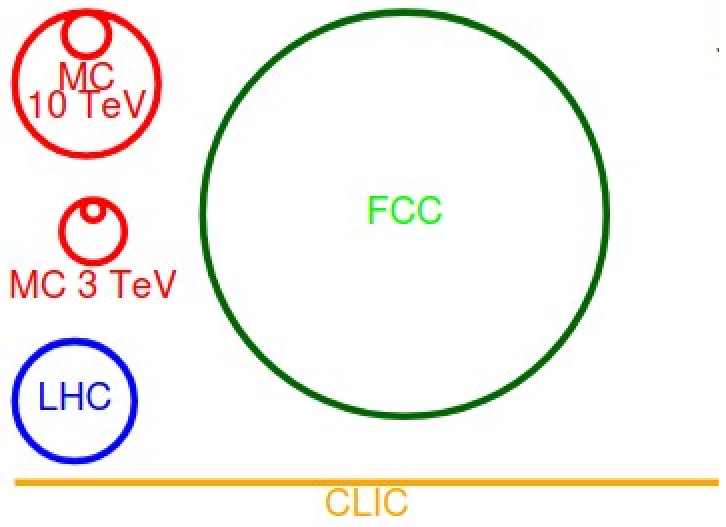
CERN, Jlab, Orsay +

$\mu^+\mu^-$ Colliders

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





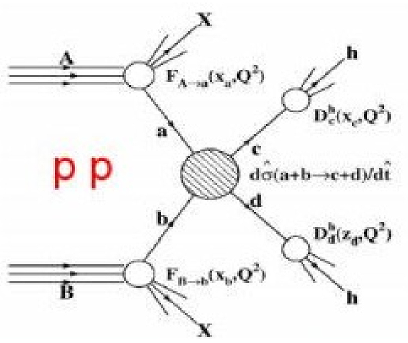
Courtesy: D. Schulte

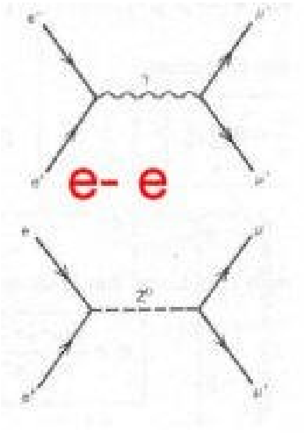
Motivation

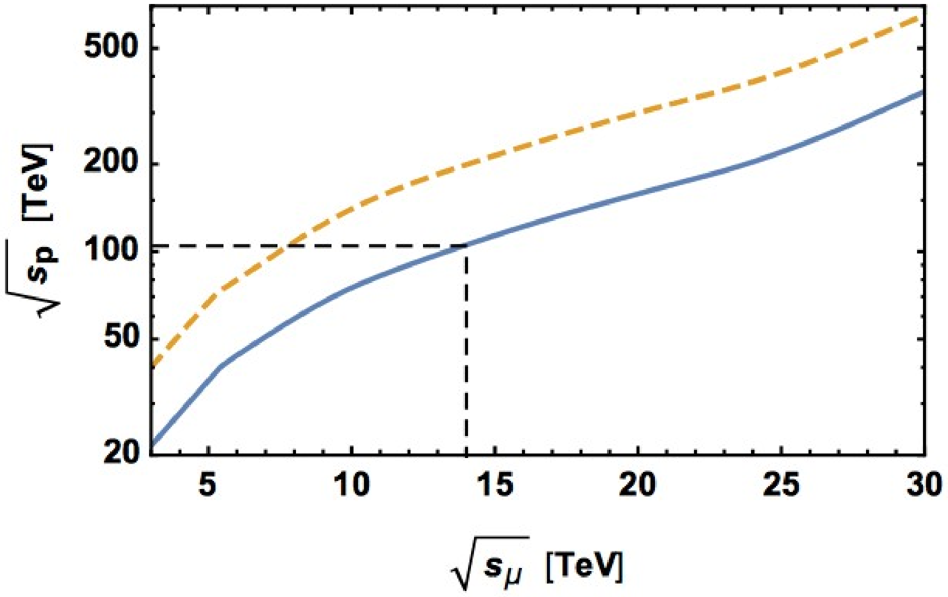
- μ are elementary particles → full collision energy available for particle production
- 10 to 14 TeV μ collisions comparable to 100 to 200 TeV proton collisions
  - → Significant energy reach for possible physics discoveries

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

- 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

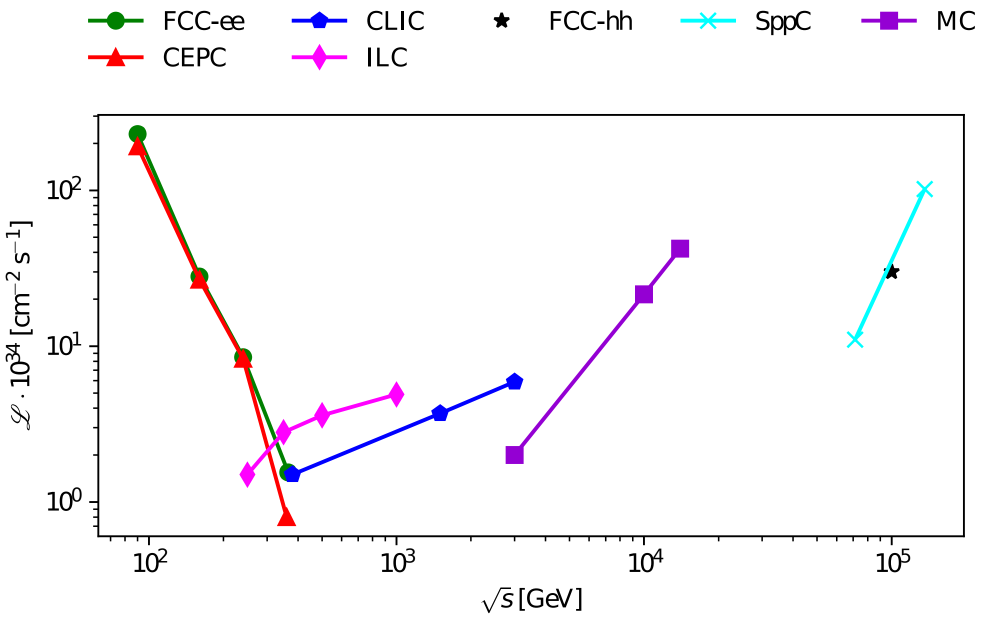






Courtesy: D. Schulte

Tentative Parameters

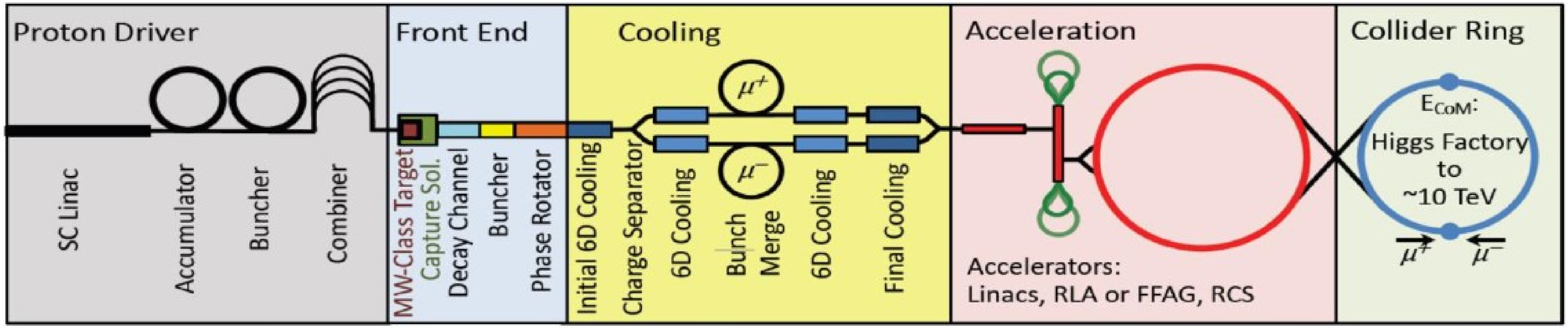


Parameter	Unit	3 TeV	10 TeV	14 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**20**	**40**
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	**MW**	**5.3**	**14.4**	**20**
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm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

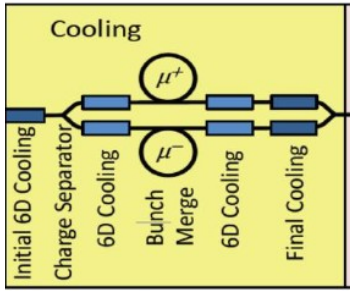
- Stages of muon ionisation cooling in matter.
- Merging of μ bunches into one bunch.

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

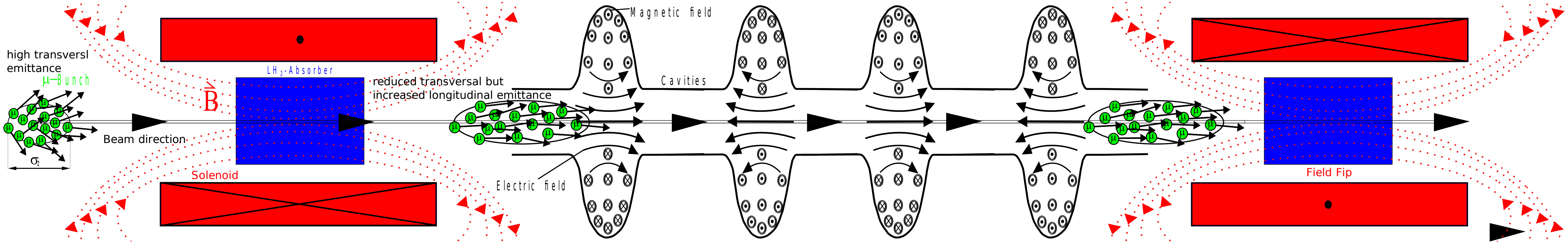
- Collider packed with high field magnets to minimise circumference and maximise luminosity.

Courtesy: D. Schulte

Ionization Cooling



- 4D cooling: Transverse emittance reducing on the costs of the longitudinal one
- High field solenoids (O(30 T)) to minimize beta-function and reduce scattering
- High RF gradients (O(30 MV/m)) and repitition rate (O(300 Hz)) to quickly compensate for ionization energy loss



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

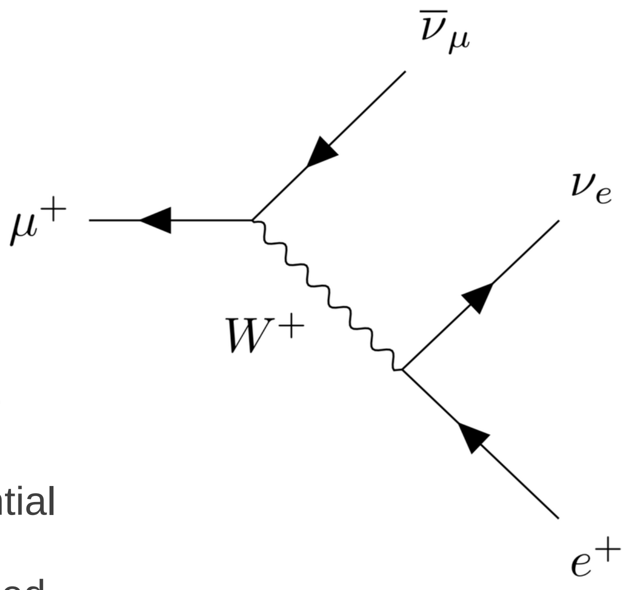
Cooling due to energy deposition

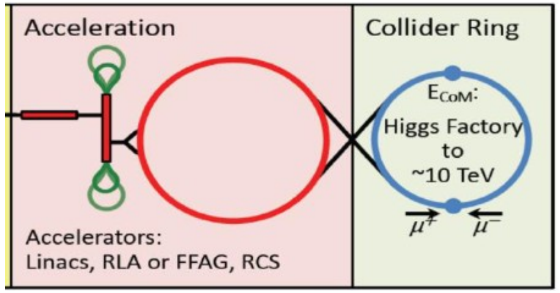
Heating due to scattering

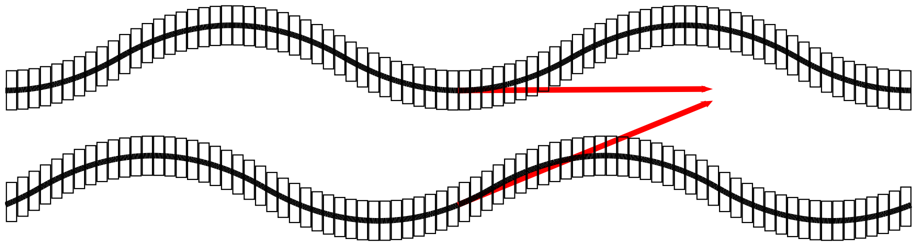
Courtesy: D. Schulte

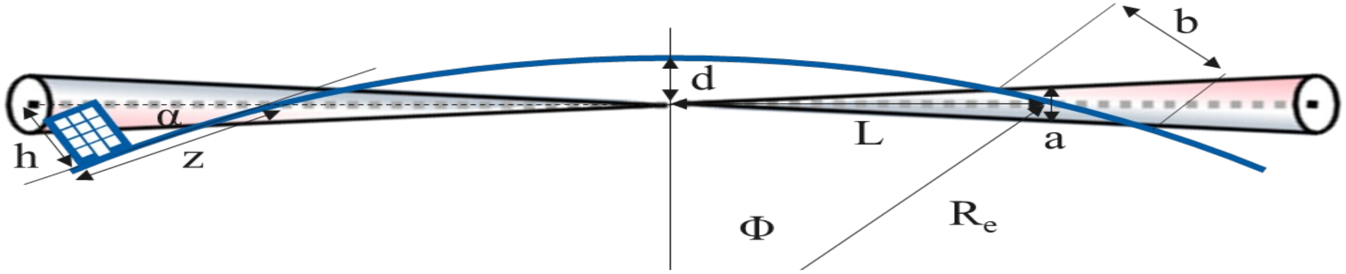
Muon Decay and Neutrino Flux

- 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







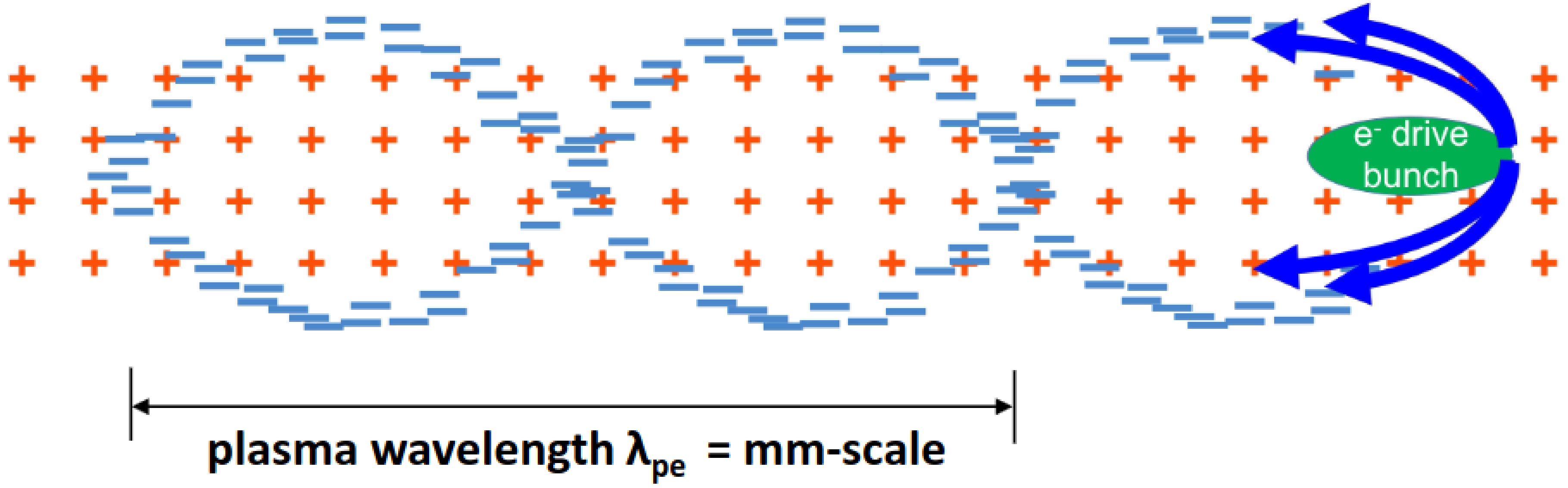


Plasma Wakefield Acceleration

Courtesy: E. Gschwendtner

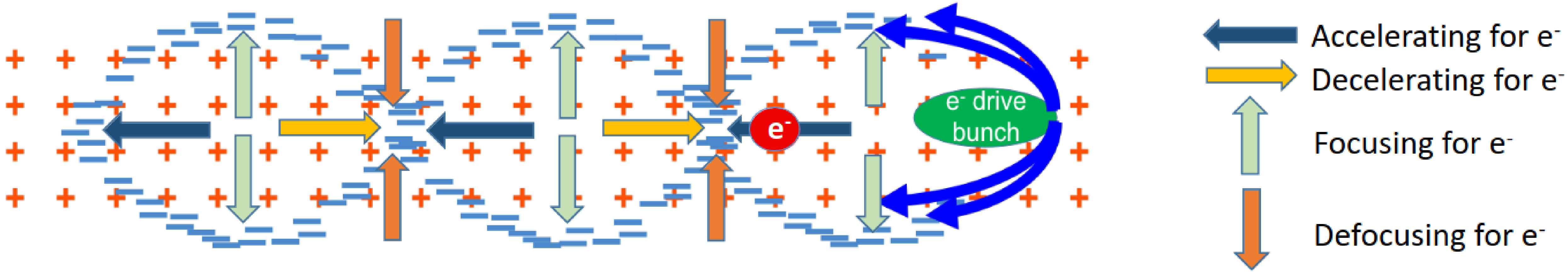
Principle

- 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



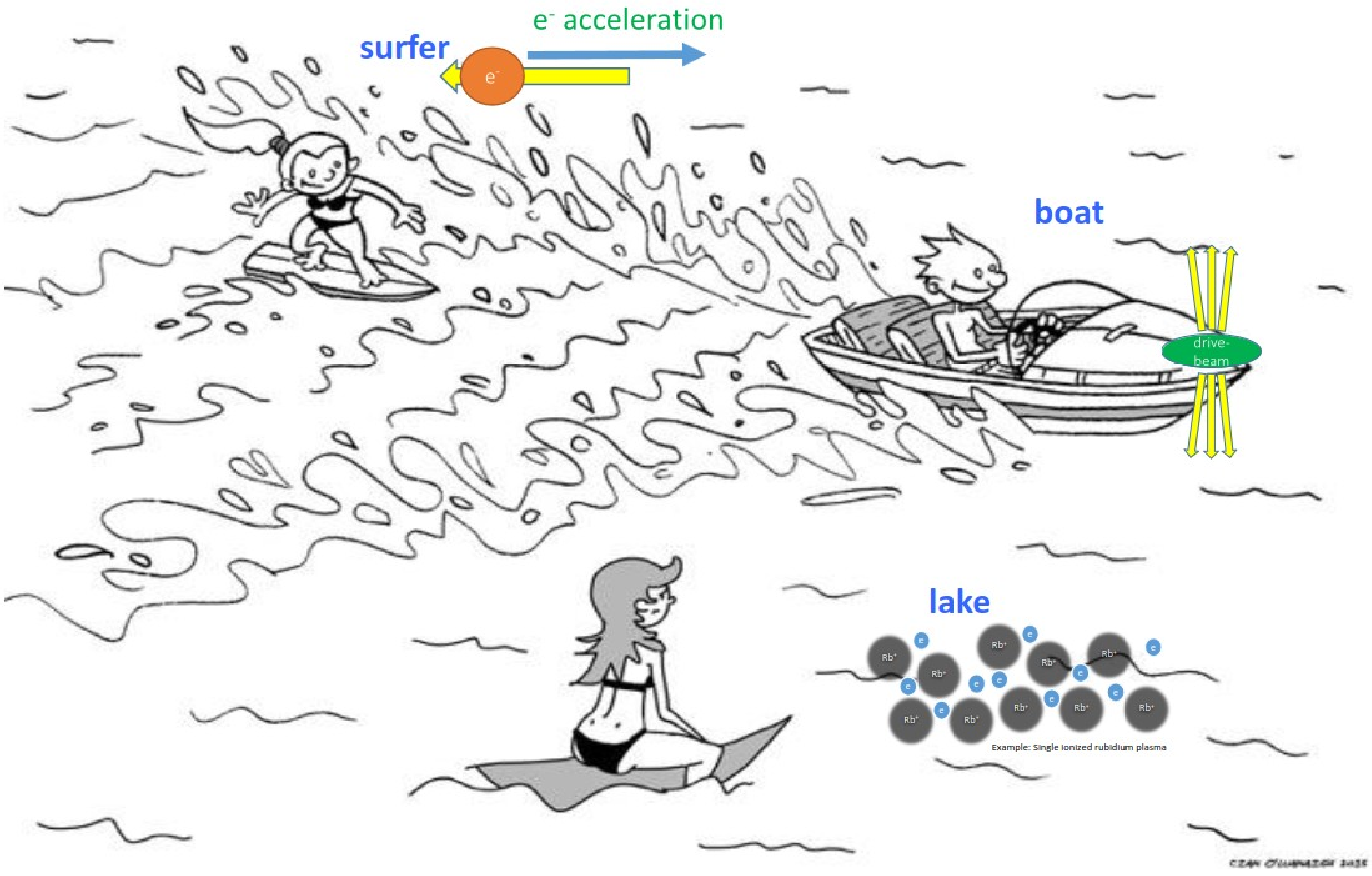
Principle

- 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)

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?

Can be combined with energy recovery linacs → FCC-eh

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

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

ESPPU and P5

- In 2020 the **European** Particle Physics Strategy Update (EPPSU) expressed the long-term plan for particle colliders:
  - 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**.
- Particle Physics Project Prioritization Panel **(P5)** published recommendations in 2023, high priority projects:
  - Expliotation of LHC and HL-LHC
  - Oversea **Higgs and electroweak factory**
- **New EPPSU recommendation in 2026 !**

Thank you!

Jacqueline Keintzel

Acknowledgements: Many colleauges from various design studies

Prisma+ Colloquium

Mainz, Germany

28 May 2025

jacqueline.keintzel@cern.ch

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} $cm^{-2}s^{-1}$]	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} $cm^{-2}s^{-1}$]	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