Colliders and related accelerators

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IPAC'26 Student tutorials

Deauville, France

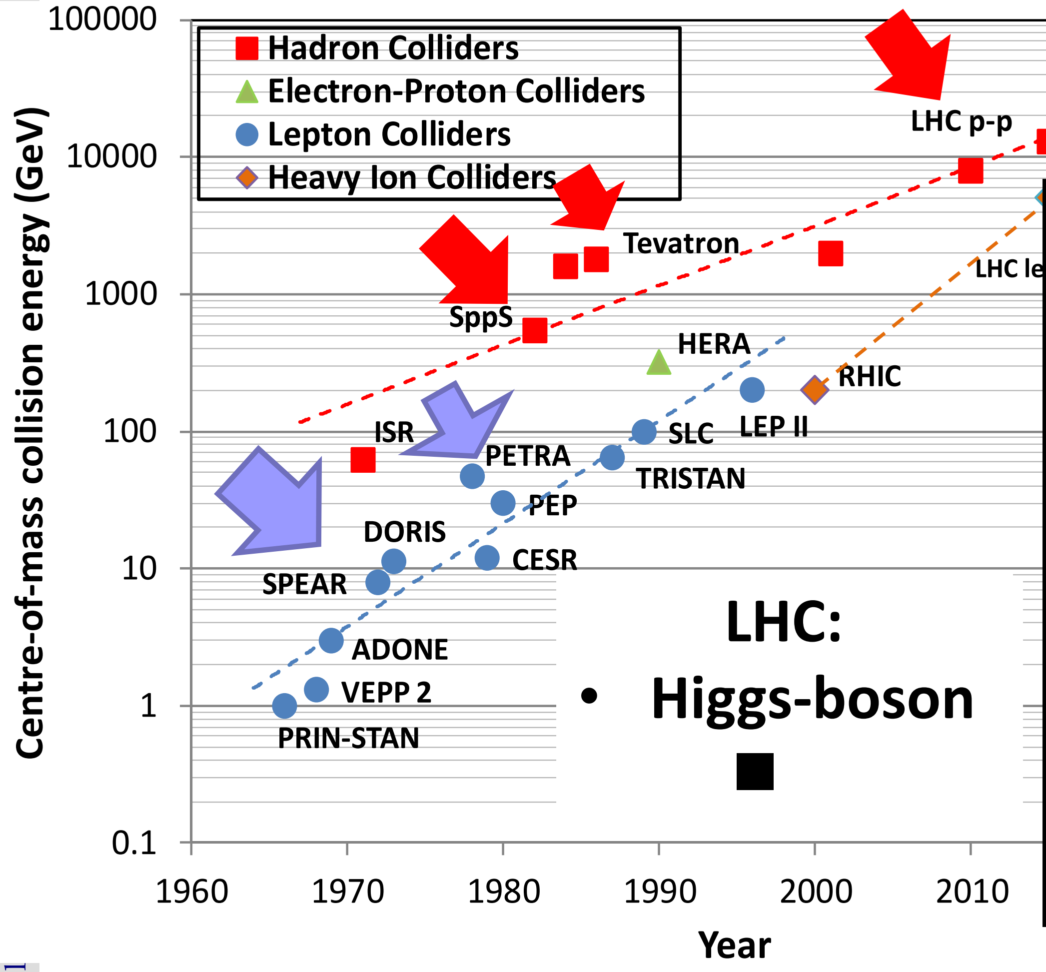
May 16th, 2026

Contents

- Purpose of **colliders**
- Colliders' **figures of merit**
  - **c.m. energy** and **luminosity**
- Present-future **hadron colliders** and their **challenges**
  - LHC, HL-LHC, FCC-hh
- Present-future **e^+e^- colliders** and their **challenges**
  - **Circular** (SuperKEKb, FCCee, CEPC)
  - **Linear** (CLIC, LCF, Plasma-Wakefield colliders)
- Future electron-hadron colliders and their **challenges**
  - EiC, LHeC
- Future muon collider and its **challenges**

Purpose of colliders

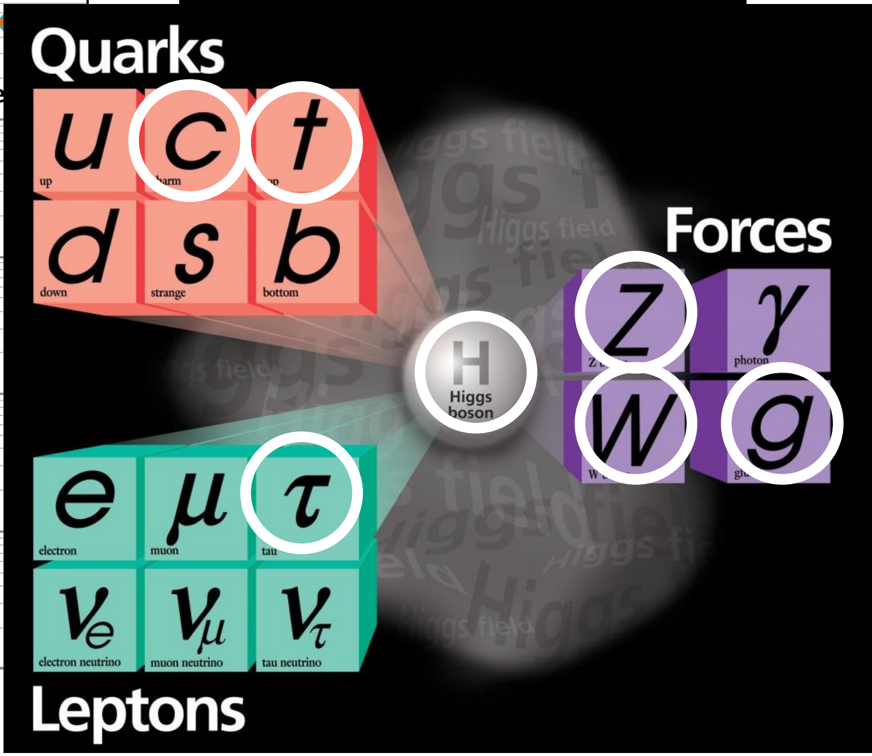
Discoveries by colliders



LHC:

- **Higgs-boson ■**

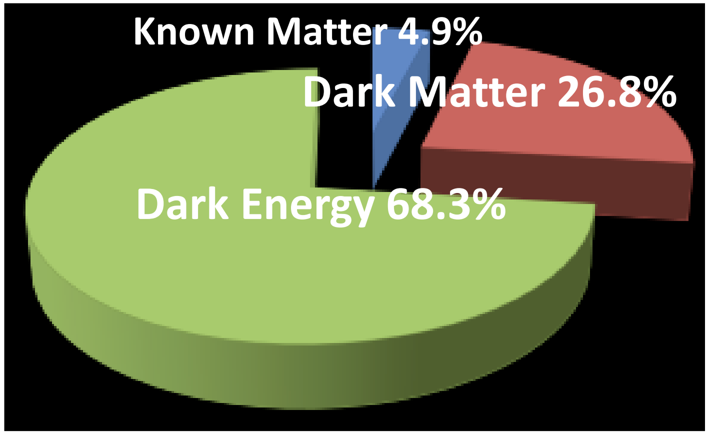
Standard Model Particles and forces

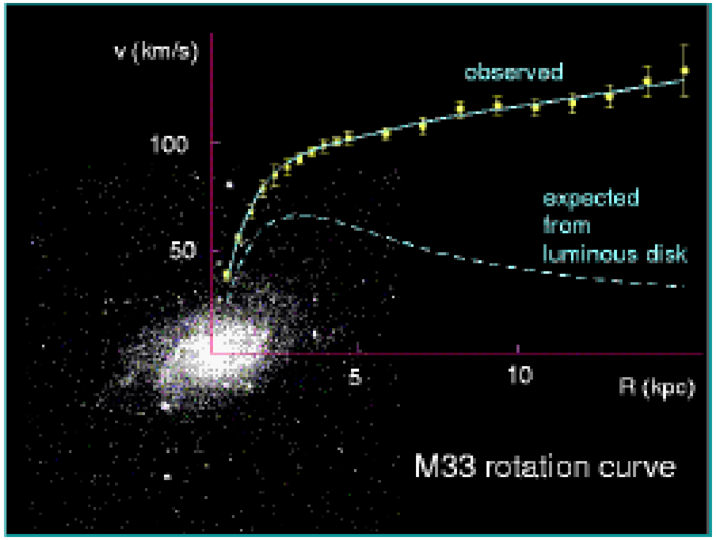


Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements

Open questions

- Standard model describes known matter, i.e. 5% of the universe!





galaxy rotation curves, 1933 - Zwicky

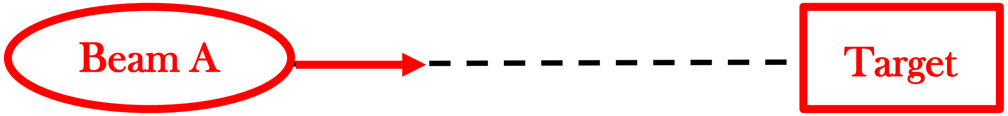
- what is dark matter?
- what is dark energy?
- why is there more matter than antimatter?
- why do the masses differ by more than 13 orders of magnitude?
- do fundamental forces unify in single field theory?
- what about gravity?
- Is there a “world equation – theory of everything”? …

Colliders' figures of merit

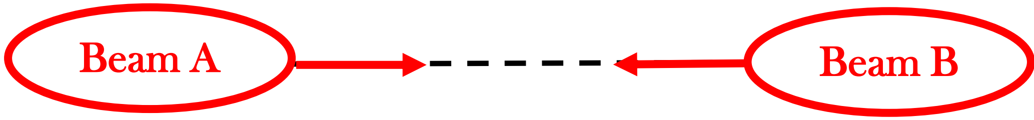
Colliders: energy frontier

- Figure of merit: **c.m. energy** and **luminosity**

$$E^\star \approx \sqrt{2E_A mc^2}$$

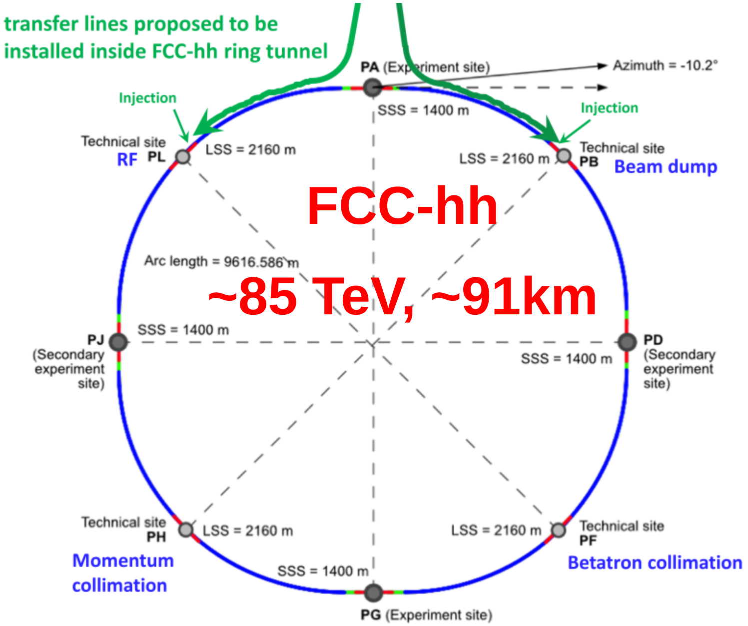


$$E^\star = E_A + E_B$$



Colliders: energy frontier

- Figure of merit: **c.m. energy** and **luminosity**
- **Higher energy** means larger **size** (particularly for **hadrons**)
- Drives key **technologies: magnets** (high-field), **RF cavities** (high-gradient),…



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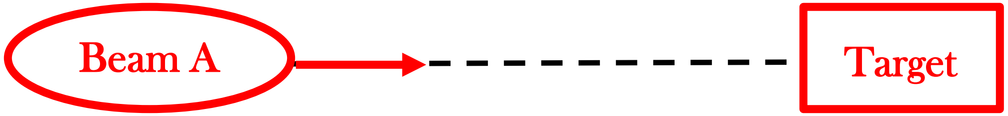

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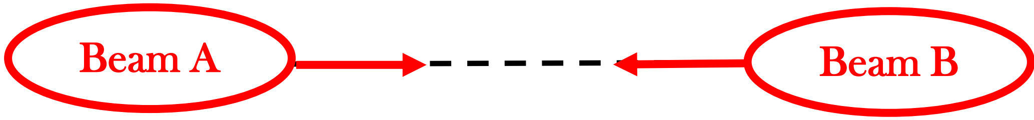
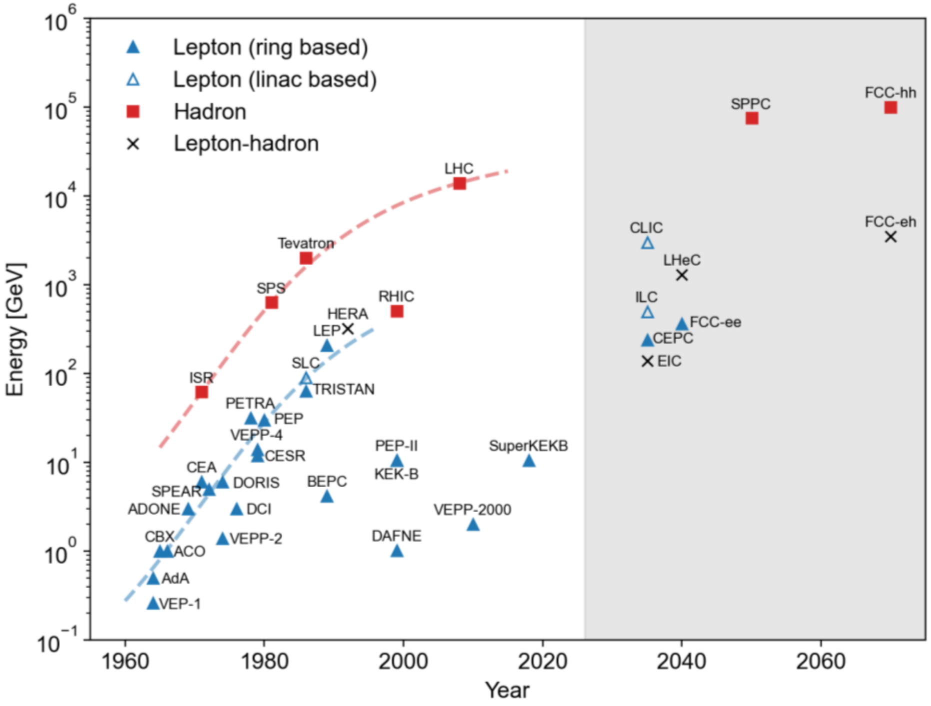
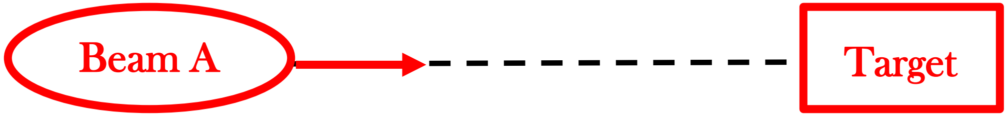


Colliders: energy frontier

- Figure of merit: **c.m. energy** and **luminosity**
- **Higher energy** means larger **size** (particularly for **hadrons**)
- Drives key **technologies: magnets** (high-field), **RF cavities** (high-gradient),…
- **“Livingston chart” energy vs time** shows succession of **principles/technologies** pushing energies over time (1.5 orders of magnitude/decade)
- Present state of the art **no longer** supports past **exponential growth** in particle energy



$$E^{\star} \approx \sqrt{2E_A mc^2}$$



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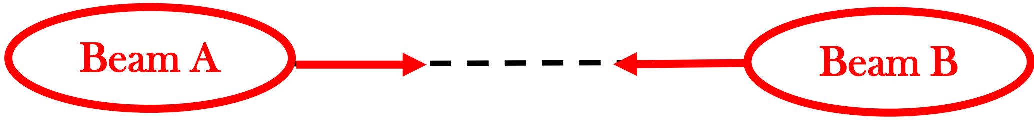
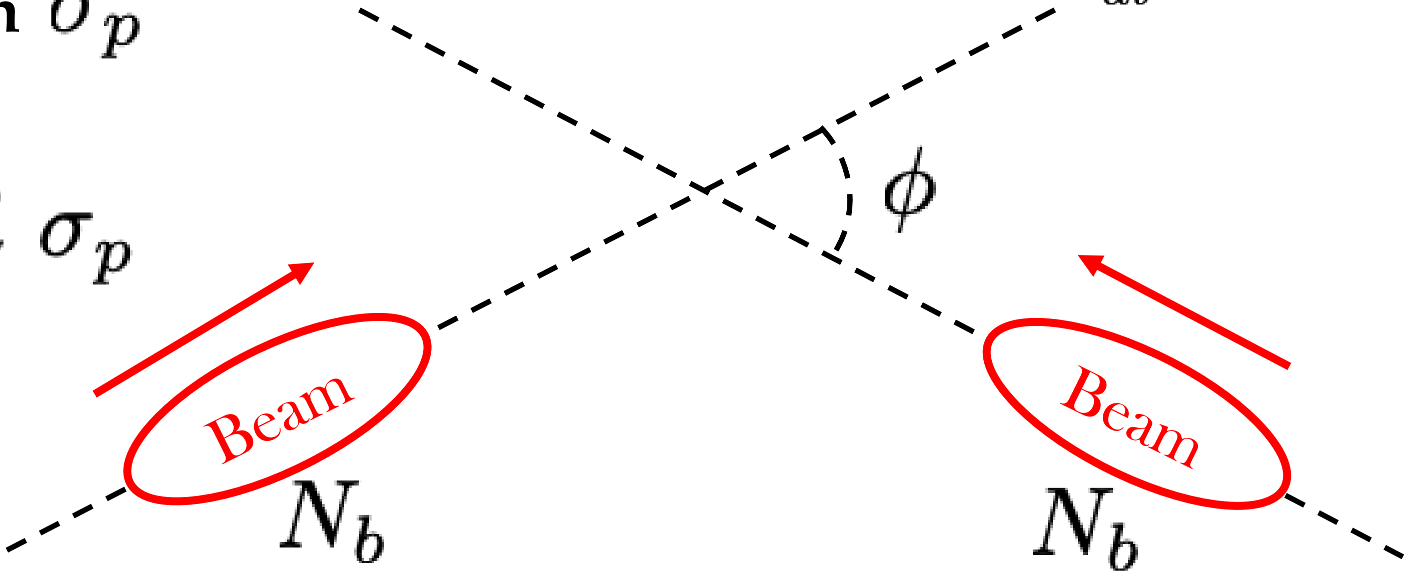


Luminosity

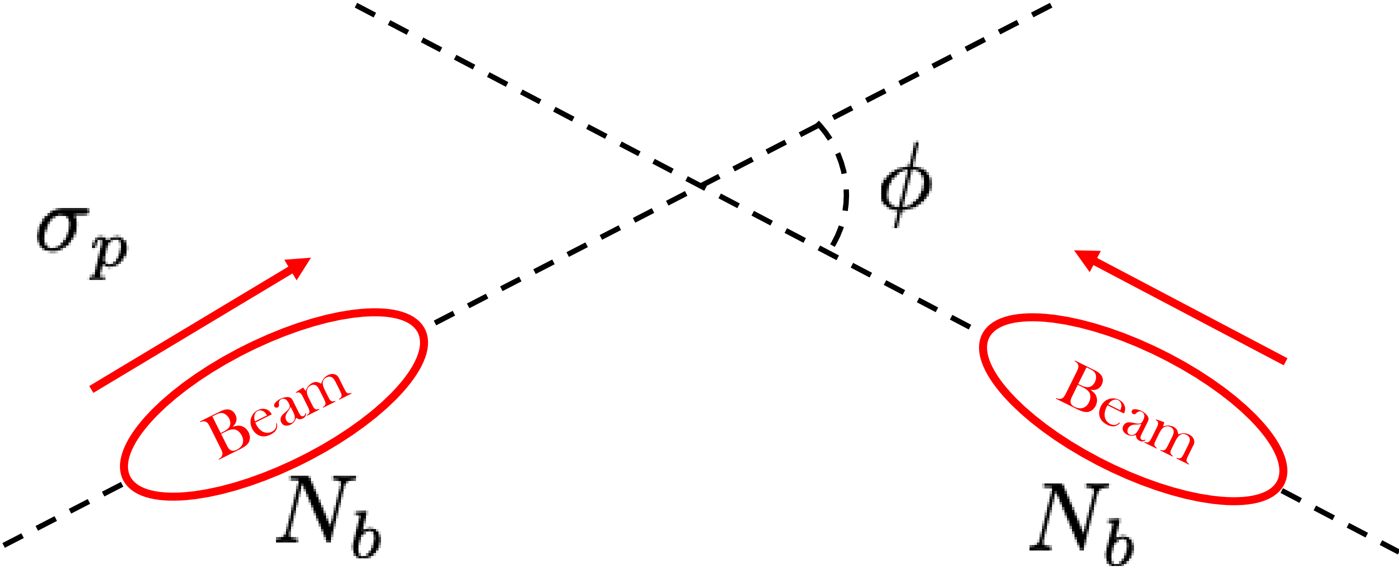
- **Luminosity**: rate of particle production, i.e. **proportionality** factor connecting **number** of **events** per unit time $\frac{dR}{dt}$ and **cross section** σ_p

$$\frac{dR}{dt} = \mathcal{L}\, \sigma_p$$



Luminosity: colliders

$$\frac{dR}{dt} = \mathcal{L}\ \sigma_p$$

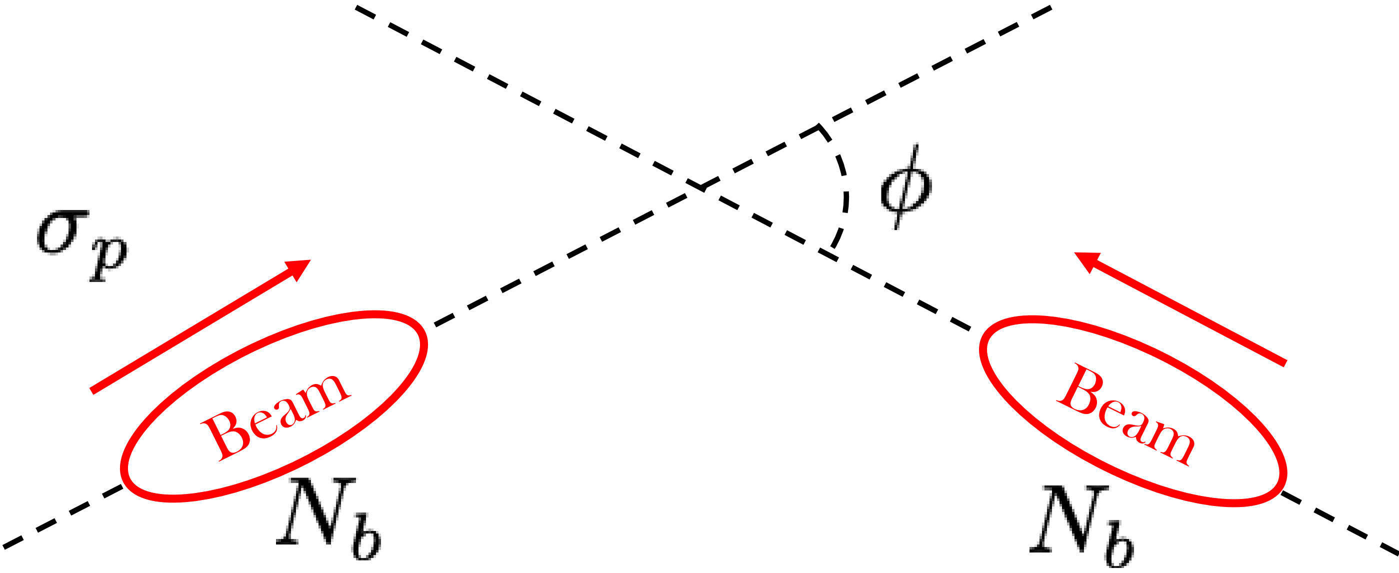


- **Luminosity** for two identical “round” Gaussian colliding beams
  - N_b **bunch population**
  - k_b **number** of **bunches**
  - f_{rev} the **revolution frequency**
  - γ relativistic **reduced energy**
  - ε_n normalized **emittance**
  - ***β**** **“betatron” amplitude function** at collision point
  - $\mathcal{R}(\varphi)$ **geometric reduction factor** due to crossing angle

$$\mathcal{L} = \frac{N_b^2 k_b f_{\mathrm{rev}} \gamma}{4\pi \epsilon_n \beta^*} \mathcal{R}(\phi)$$

Luminosity: colliders

$$\frac{dR}{dt} = \mathcal{L}\,\sigma_p$$

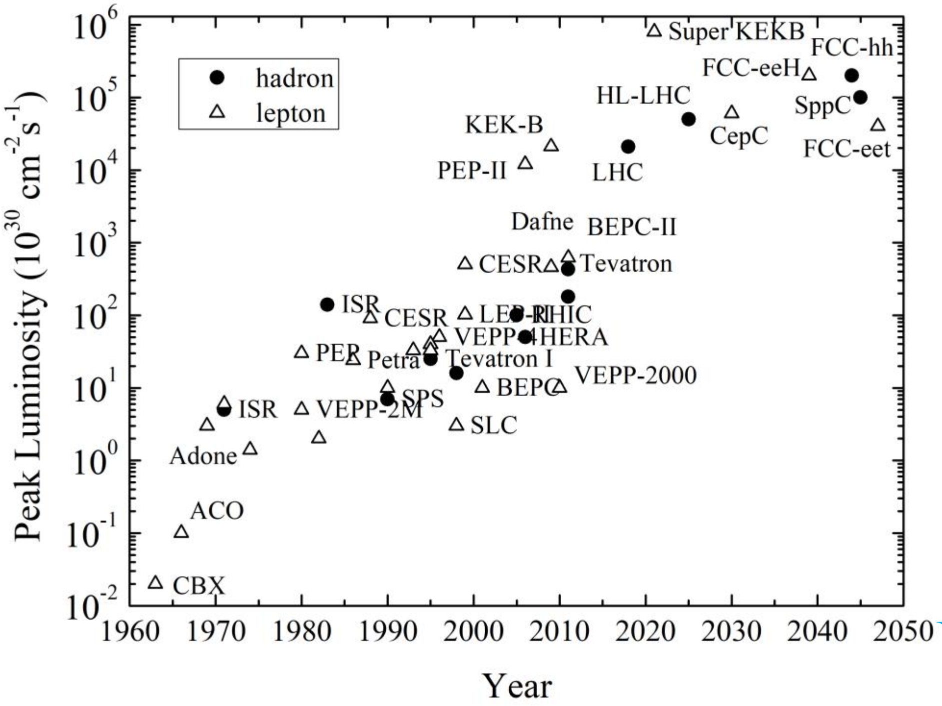


- Proportional to **square** of **bunch intensity**
- Proportional to **number** of **bunches** (or total intensity/beam)
- Inversely proportional to **square** of **beam size**
- **Brightness** $\mathcal{B} = \dfrac{N_b}{\epsilon_n}$ **reach** $\mathcal{L} = \dfrac{N_b^2 k_b f_{\mathrm{rev}} \gamma}{4\pi\epsilon_n \beta^*}\mathcal{R}(\phi)$

depends on **injector chain** while **brightness preservation** depends on collider

Luminosity optimization

- Logarithmic increase of **peak luminosity** over time
- Recipe for **luminosity increase** - - → **Beam dynamics** and **HW implications**

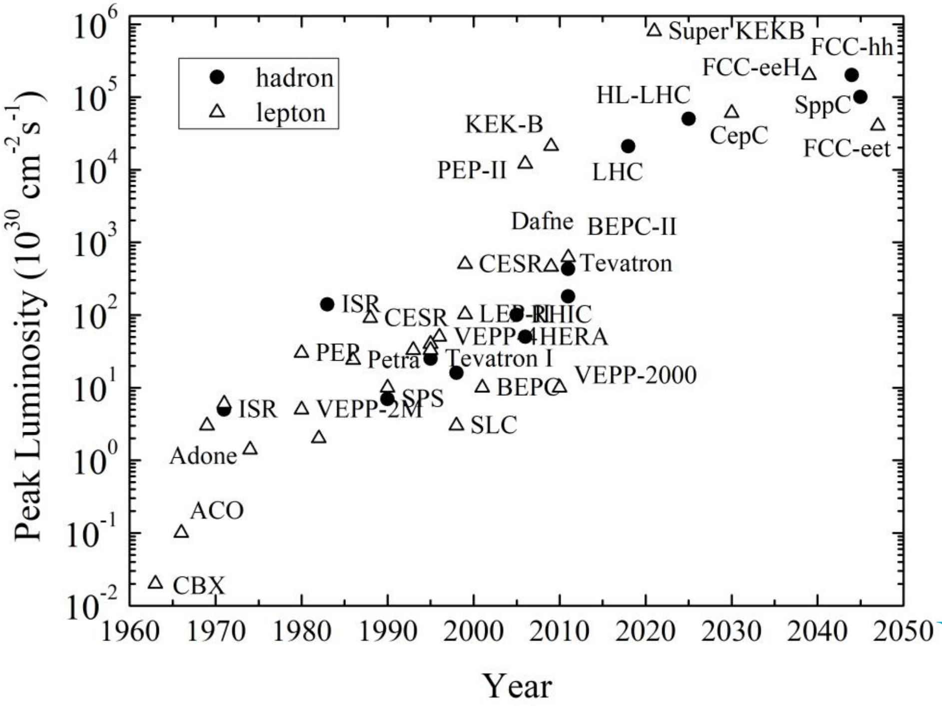


V. Shitsev, F. Zimmermann, 2021

$$\mathcal{L} = \frac{N_b^2 k_b f_{\mathrm{rev}} \gamma}{4\pi \epsilon_n \beta^*} \mathcal{R}(\phi)$$

Luminosity optimization

- Logarithmic increase of **peak luminosity** over time
- Recipe for **luminosity increase** - - → **Beam dynamics** and **HW implications**
  - maximize intensities, minimize emittance - - → **Brightness** reach (injectors) and **preservation** (collider)
  - minimize beam size - - → **Optics** and **magnet** technology
  - compensate for geometric reduction factor - - → **Crabbing, beam-beam**
  - maximize number of bunches (beam power) - - → Minimise **bunch spacing**
  - improve machine efficiency i.e. maximize **integrated luminosity**

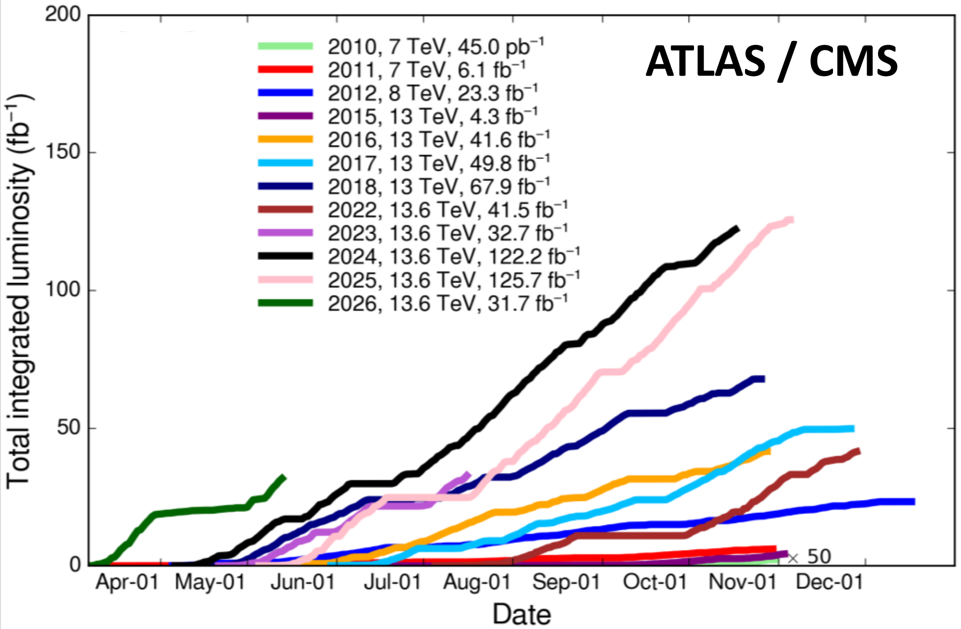


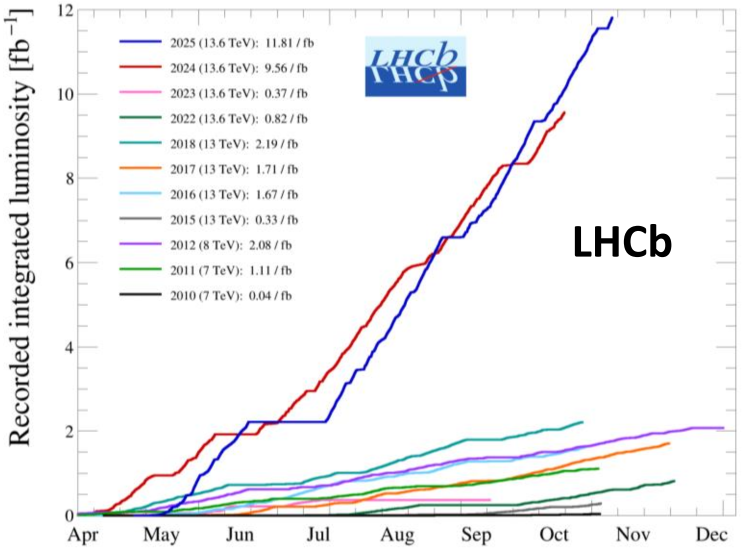
$$\mathcal{L} = \frac{N_b^2 k_b f_{\mathrm{rev}} \gamma}{4\pi \epsilon_n \beta^*} \mathcal{R}(\phi)$$

V. Shitsev, F. Zimmermann, 2021

Hadron Colliders

LHC success story (for protons)





- LHC intensity increased from **1.1e11** (design) to **1.8e11** ppb, while β* reduced down to **15cm** (flat optics and luminosity **leveling**) more then **doubling peak** luminosity
- 2025 was the single most productive year in LHC history so far!
- Over **500 fb-1** delivered to both ATLAS and CMS since 2010
- **LHCb** more then **doubled** their Run 1 + Run 2 + Run 3 data set
- … despite limitations from **e-cloud** (heat load and cryo capacity), **beam induced heating** due to **impedance** (vacuum modules’ RF fingers)
- Reached **1.8e11 ppb** by end of Run3 (2026) for physics conditions and **HL-LHC intensities** of **2.3e11 ppb** in machine studies

Performance optimisation example: HL-LHC

$$L = \frac{n_b \times N_1 \times N_2 \times \gamma \times f_{rev}}{4\pi \times \beta^* \times \varepsilon_n} \times F(\phi, \beta^*, \varepsilon, \sigma_s)$$

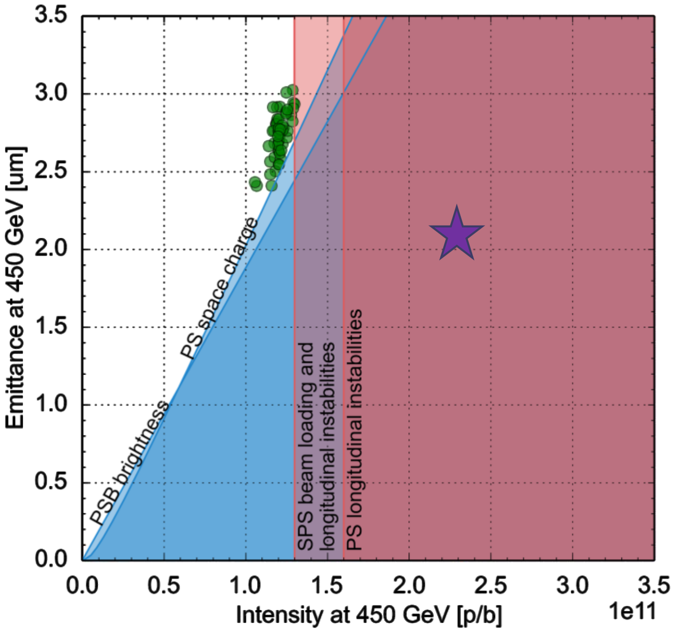
1) maximize bunch intensities 2) minimize the beam emittance	➔ Injector complex Upgrade LIU
3) minimize beam size (constant beam power);	➔ triplet aperture
4) maximize number of bunches (beam power);	➔ 25ns
5) compensate for 'F';	➔ Crab Cavities
6) Improve machine 'Efficiency'	➔ minimize number of unscheduled beam aborts

Route to high hadron brightness: LIU
(LHC injector upgrade)

- Connection of PSB to **Linac4** and acceleration to **2 GeV** in PSB
- PS & SPS **RF upgrades** + **e-cloud** & **impedance reduction**, **new SPS optics**, new **dumps** & **stoppers**,…

PSB new power supply building

PSB injection Line from Linac4



New SPS beam dump

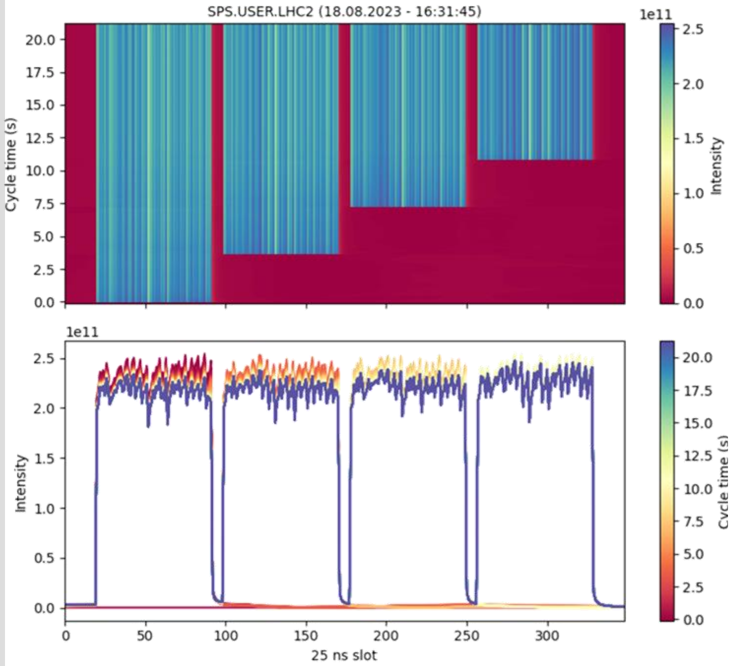
PS longitudinal damper

New SPS RF amplifier towers

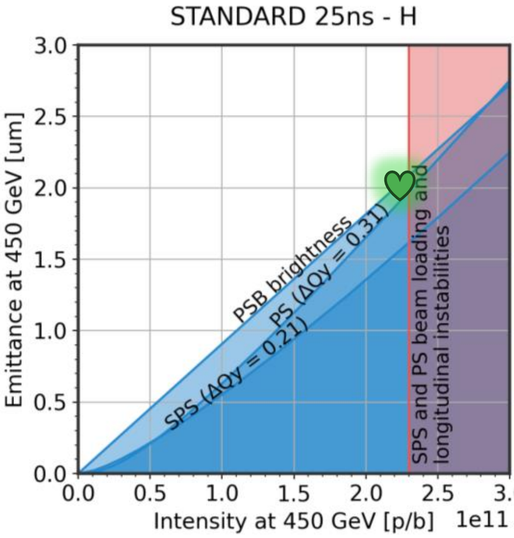
G. Rumolo et al., HB 2023

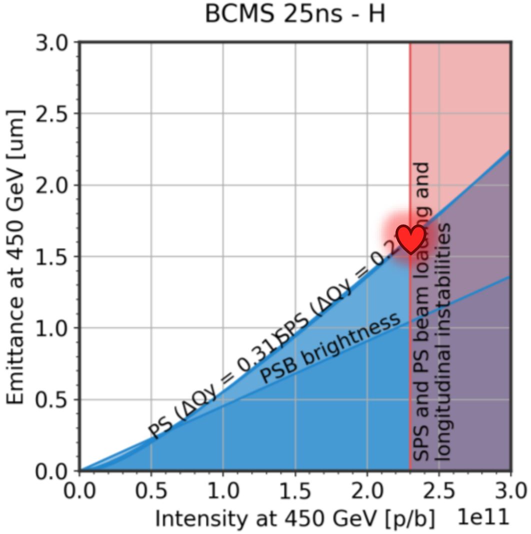
LIU achievement

- LIU beam intensity reached during **scrubbing** run (**e-cloud**)
- Established ~LIU parameters, repeatedly, with 25 ns standard @ 4 x 72 bunches and with BCMS @ 5 x 48 bunches



I_{FB} = 2.3e11; eps_{avg} = 1.9 um





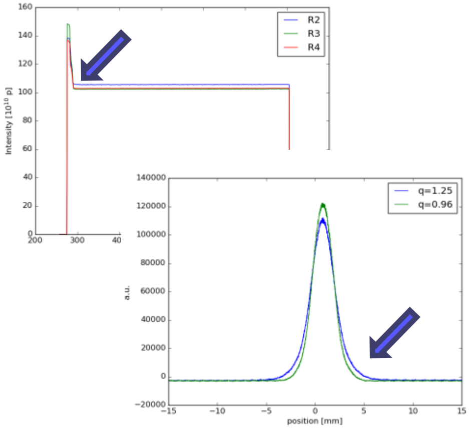
I_{FB} = 2.3e11; eps_{avg} = 1.5 um

H. Bartosik, K. Li, G. Rumolo et al.

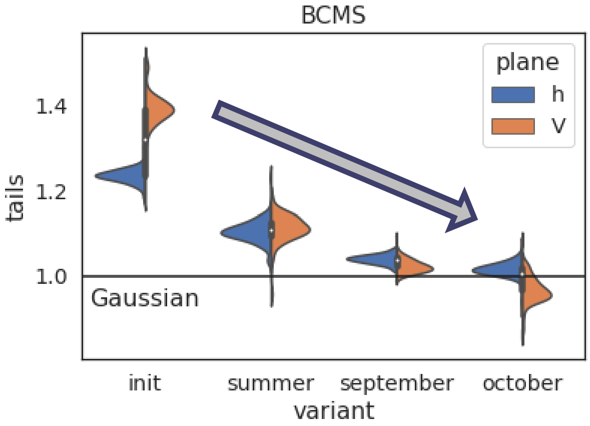
LHC brightness towards HL-LHC

- LHC **beam quality** optimization along injector chain for increasing **brightness** and reducing **losses**

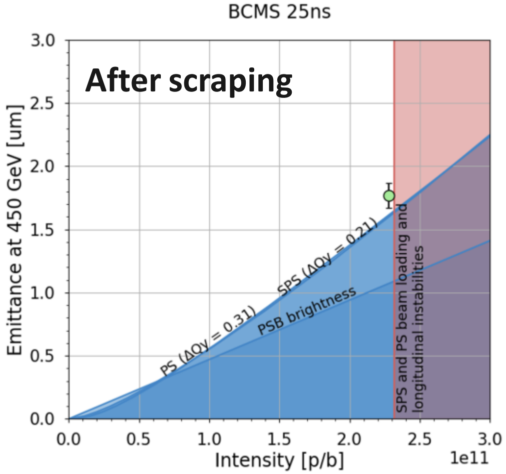
- **PSB**
  Introduced **transverse scraping** at low energy to maintain **Gaussian** profiles



- **PS**
  Working point optimization, around transition crossing, to maintain **Gaussian** profiles along the year



- **SPS**
  Working point optimization and **Laslett correction** to push brightness → ~LIU BCMS target

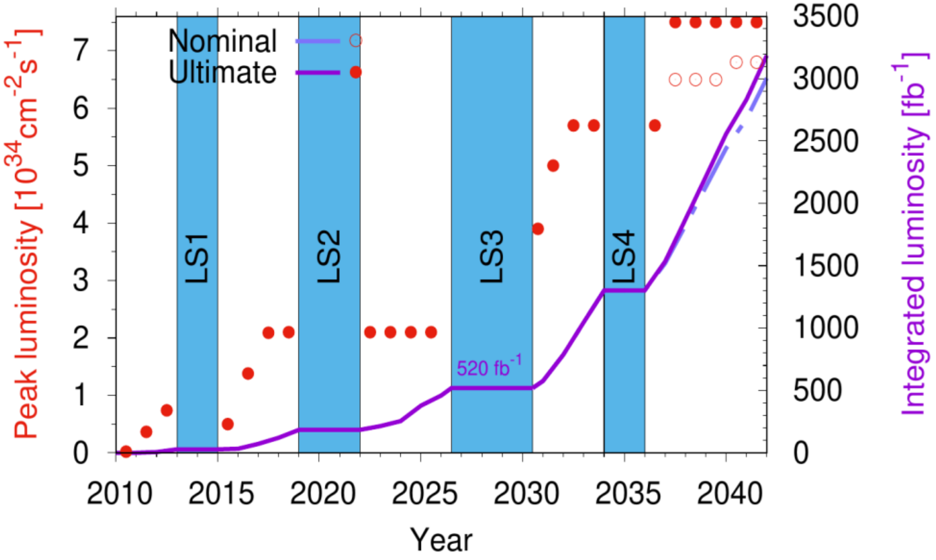


H. Bartosik, G. Rumolo et al.

Experimental status of HL parameters

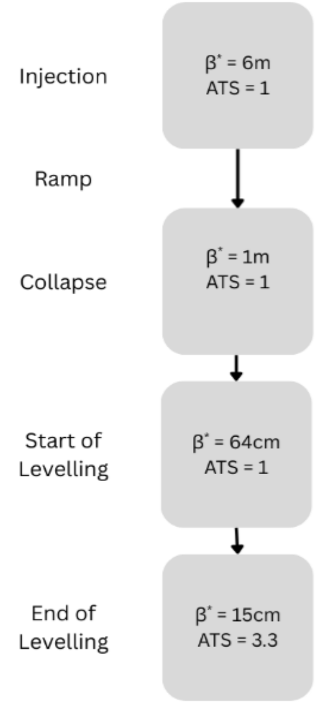
Parameter	Design	Achieved
# of bunches with 2.3×10^{11} ppb		
SPS→LHC injection (Standard)	4×72	**4×72**
LHC injection energy (Standard)	2760	**1152**
SPS→LHC injection (BCMS)	5×48	**2** $\times$ 48
LHC injection energy (BCMS)	2748	**972**
SPS→LHC injection (8b4e)	4×56	**2** $\times$ 56
LHC injection energy (8b4e)	1972	**560**
Emittance [μm] (at 2.3×10^{11} ppb)		
SPS (Standard)	2.1	**2.1**
LHC injection (Standard)	2.1	**2.2**
SPS (BCMS)	1.7	**1.7**
LHC injection (BCMS)	1.7	**2.0**
SPS (8b4e)	1.7	**1.7**
LHC injection & Flattop (8b4e)	1.7	**1.6**
β functions [m] (achieved in operation / MD 10^{10} p)		
Peak β in the arcs	600	**600/1040**
Minimum β^* at the IP	0.15	**0.18/0.1**
Tune shift (for 36 bunches each 1.8×10^{11} p)		
Beam-beam head-on (2 IPs)	0.020	**0.02**
Beam-beam long-range (1 IP)	0.004	**0.009**

HL-LHC new baseline



HL-LHC optics cycle

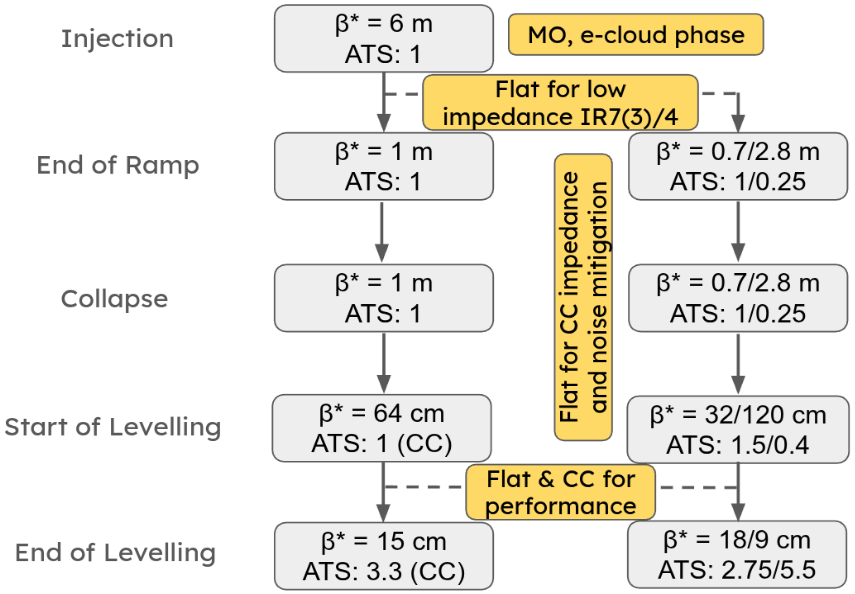
Round Optics baseline



Injection	β* = 6m ATS = 1
Ramp	
Collapse	β* = 1m ATS = 1
Start of Levelling	β* = 64cm ATS = 1
End of Levelling	β* = 15cm ATS = 3.3

Flat optics potential benefits

HL-LHC cycle under development



	Round	Flat
Injection	β* = 6 m ATS: 1	
End of Ramp	β* = 1 m ATS: 1	β* = 0.7/2.8 m ATS: 1/0.25
Collapse	β* = 1 m ATS: 1	β* = 0.7/2.8 m ATS: 1/0.25
Start of Levelling	β* = 64 cm ATS: 1 (CC)	β* = 32/120 cm ATS: 1.5/0.4
End of Levelling	β* = 15 cm ATS: 3.3 (CC)	β* = 18/9 cm ATS: 2.75/5.5

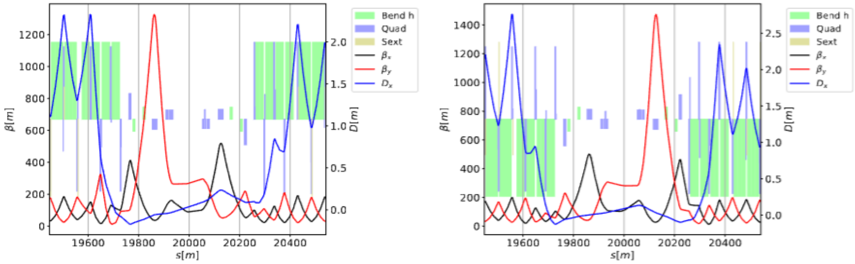
MO, e-cloud phase

Flat for low impedance IR7(3)/4

Flat for CC impedance and noise mitigation

Flat & CC for performance

New IR7 after global phase optimization

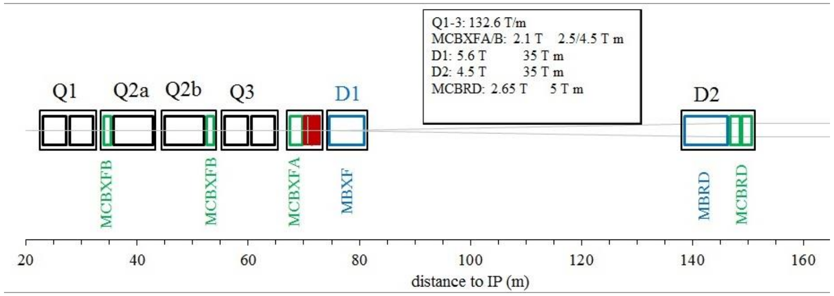


Critical Phases @15 cm with new IR7

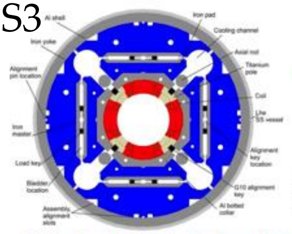
CC-TCP	**B1** Left	Right	**B2** Left	Right	**Purpose**
CC1H	13.30	11.86	-29.10	-27.74	Machine prot.
CC5V	24.18	22.72	22.10	23.46	Machine prot.
MKD-TCT	MKD.A	MKD.0	MKD.A	MKD.0	
TCTH1	9.98	15.93	-20.55	-16.43	$\beta^\star$ reach in Pt1
TCTH5	-30.16	-24.20	-32.34	-28.21	$\beta^\star$ reach in Pt5
TCTH8	20.28	26.24	41.41	45.54	$\beta^\star$ reach in Pt8
TCP-TCT	H	V	H	V	
TCT1	-81.34	52.66	-40.35	80.04	Background in Pt1
TCT5	58.52	-88.68	-52.14	-88.01	Background in Pt5
TCT8	-71.04	30.41	21.61	30.53	Background in Pt8

HL-LHC magnet types

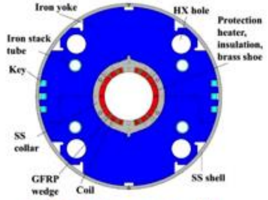
- Design, engineering, construction, test and installation the Insertion Region (IR) magnets of IR1 and IR5 for the HL-LHC upgrade.
    - Q1/Q3 cryoassemblies: from AUP (US)
    - Q2: from CERN
    - MCBXF nested corrector magnets: from CIEMAT (Spain)
    - HO corrector magnets: from INFN-LASA (Italy)
    - D1 cold masses: from KEK (Japan)
    - D2 magnets: from INFN-Ge (Italy)
    - D2 corrector magnets: from IHEP (China)
    - Interconnection modules DCM/DQM: from CERN
- Refurbishment LHC Q4, Q5 and Q10 during LS3



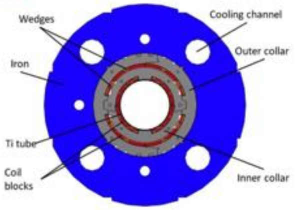
Q1-3: 132.6 T/m
MCBXFA/B: 2.1 T 2.5/4.5 T m
D1: 5.6 T 35 T m
D2: 4.5 T 35 T m
MCBRD: 2.65 T 5 T m



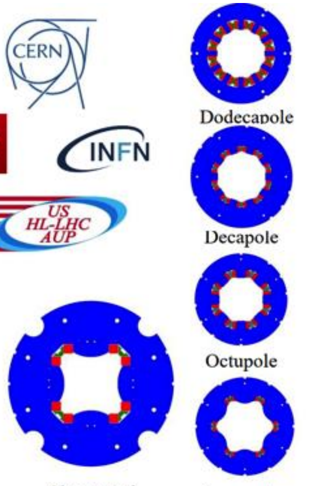
Triplet [G. Ambrosio, P. Ferracin et al.]



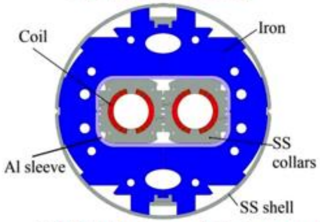
D1 [T. Nakamoto, et al.]



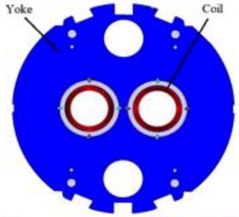
MCBXF [F. Toral, et al.]



Skew quad Sextupole
[M. Sorbi, M. Statera, et al.]



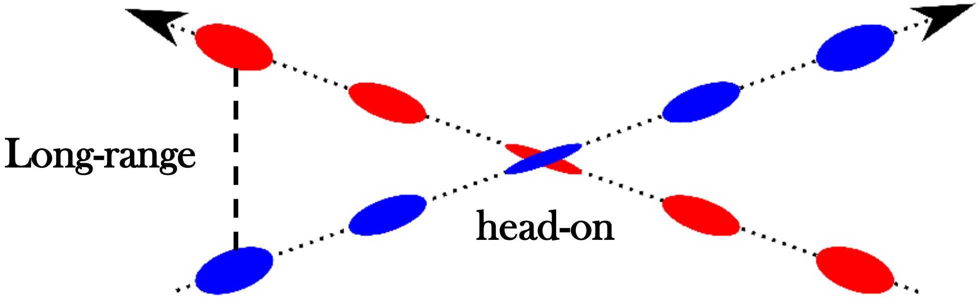
D2 [P. Fabbricatore, S. Farinon, et al.]



D2 correctors [G. Kirby, Q. Xu, et al.]

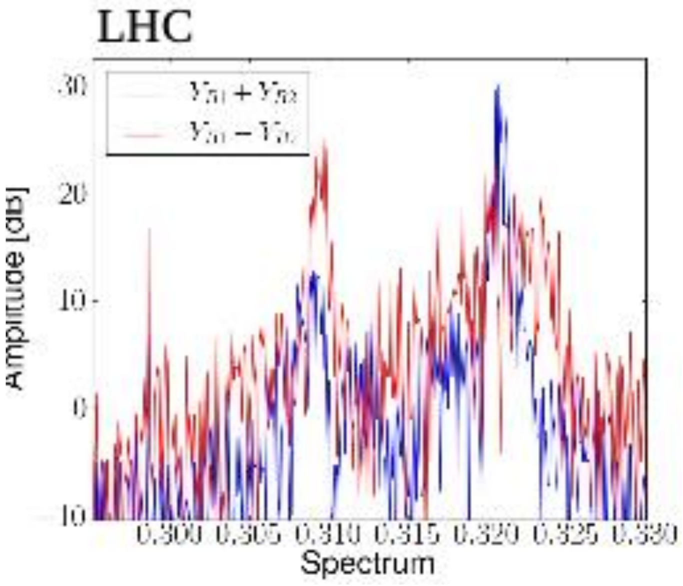
Limitations: Beam-beam effect

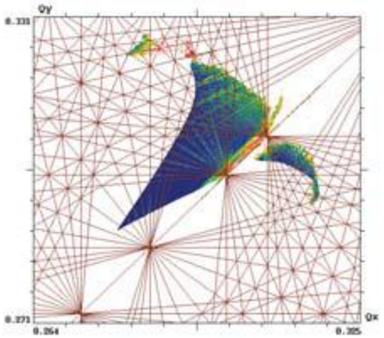
- E/M interaction due to crossing of two beams in collision point (**head-on**) but also while separated in common beam pipe (**long-range**) induces

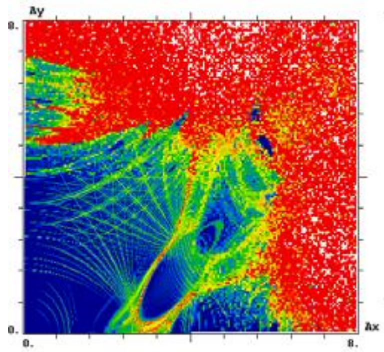


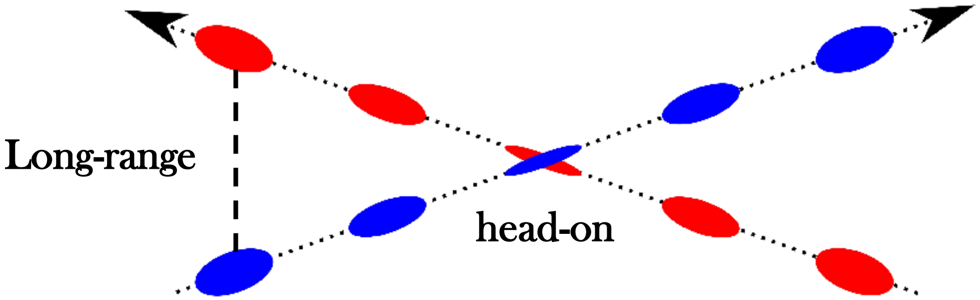
Limitations: Beam-beam effect

- E/M interaction due to crossing of two beams in collision point (**head-on**) but also while separated in common beam pipe (**long-range**) induces
  - **Coherent instabilities**
  - **Incoherent** effects, i.e. beam losses and slow emittance growth



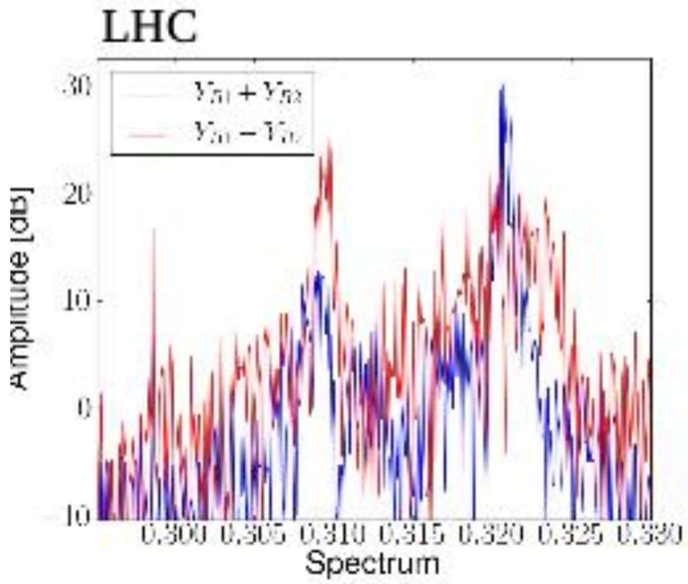


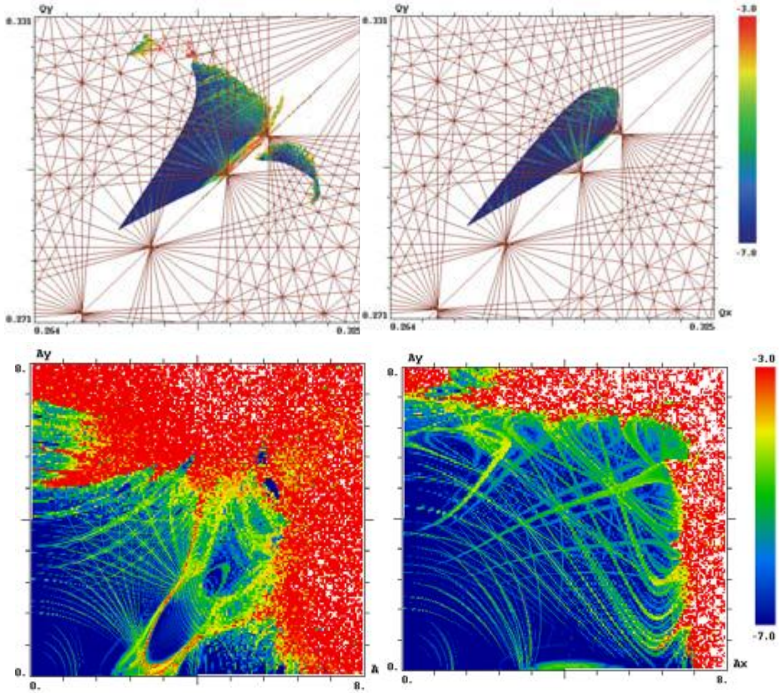


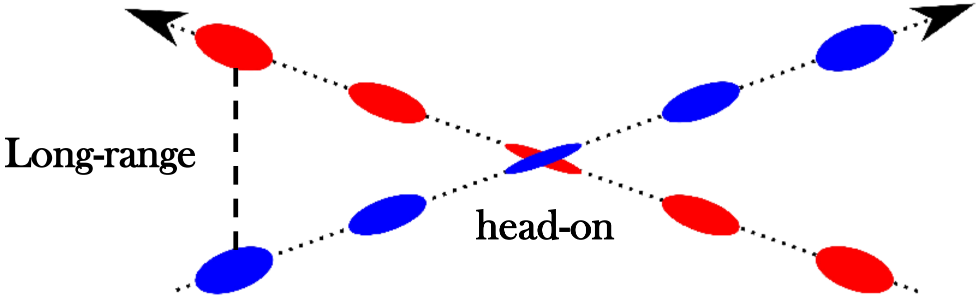


Limitations: Beam-beam effect

- E/M interaction due to crossing of two beams in collision point (**head-on**) but also while separated in common beam pipe (**long-range**) induces
  - **Coherent instabilities**
  - **Incoherent** effects, i.e. beam losses and slow emittance growth
- **Mitigation** methods
  - non-linear magnets, e-lenses, **DC wires** and crab cavities



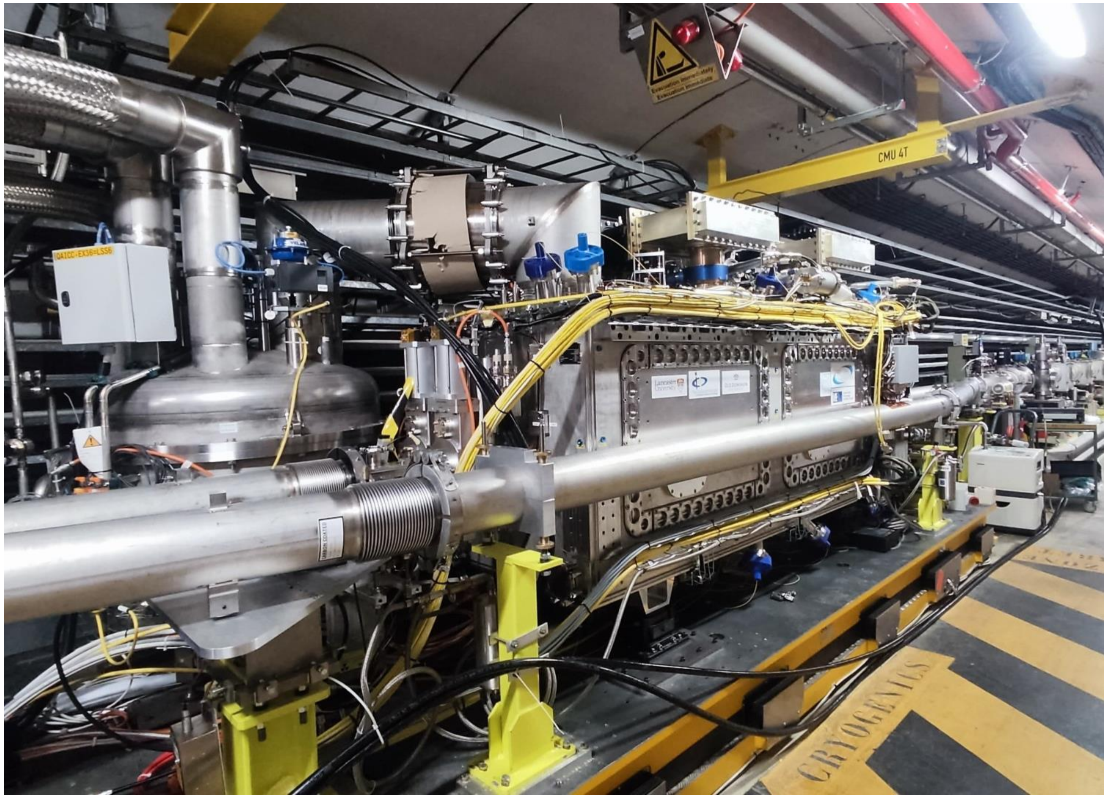


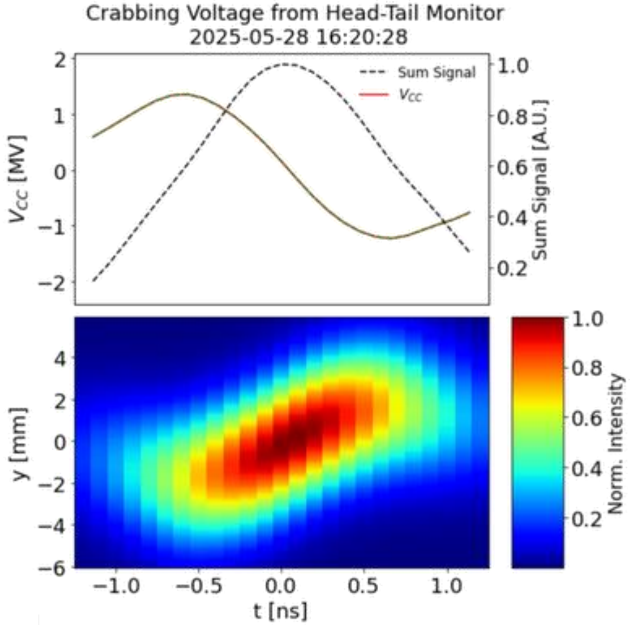


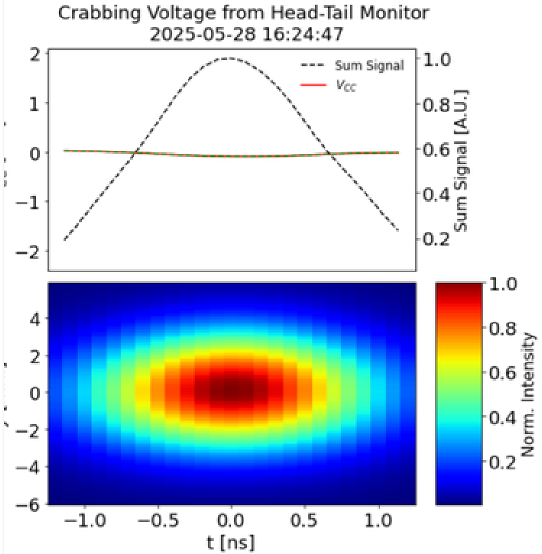
Crab Cavities

Tilt beams longitudinally for increasing overlap with **crab cavities**

CC tests in the SPS demonstrated crabbing with protons – for the first time !



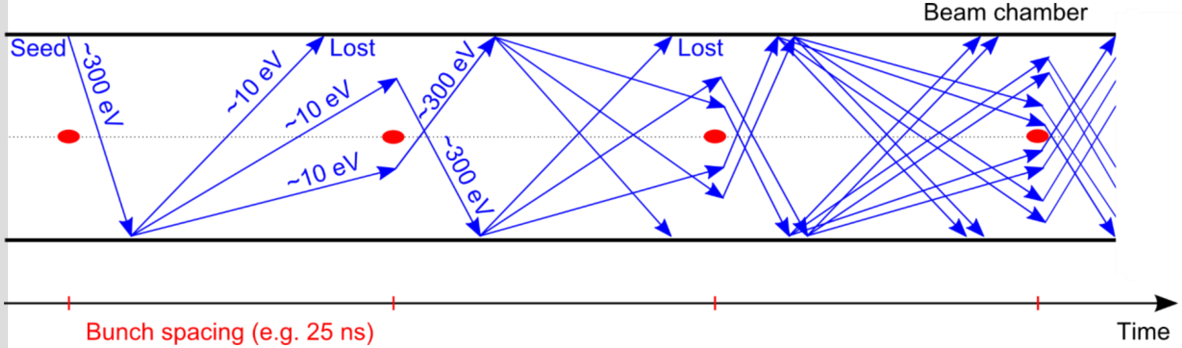


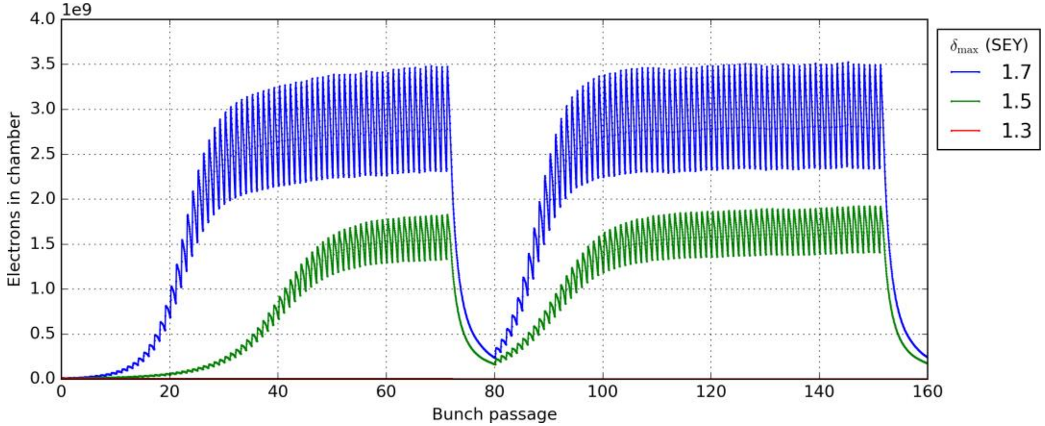


Limitations: e-cloud

Generation of charged particles inside the vacuum chamber (primary, or seed, electrons)

- **Acceleration of primary electrons in the beam field**
- **Secondary electron production when hitting the wall**
- **Avalanche electron multiplication if SEY > 1**





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⇩

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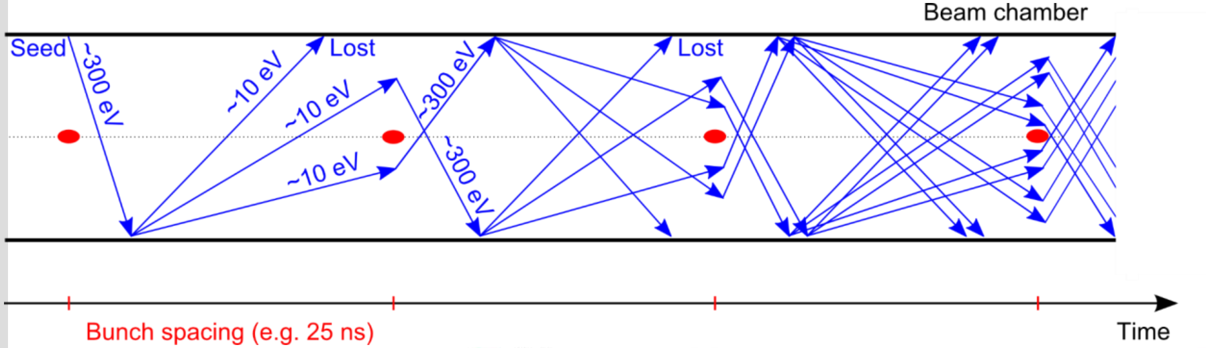
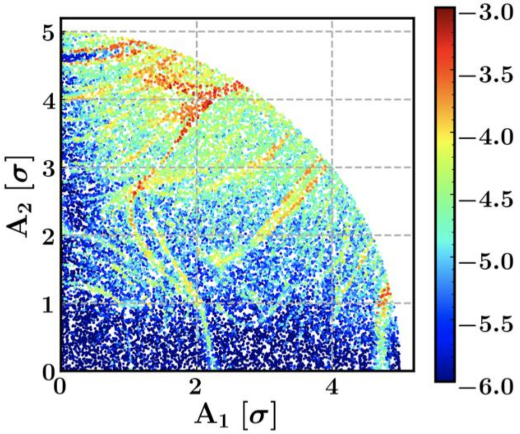
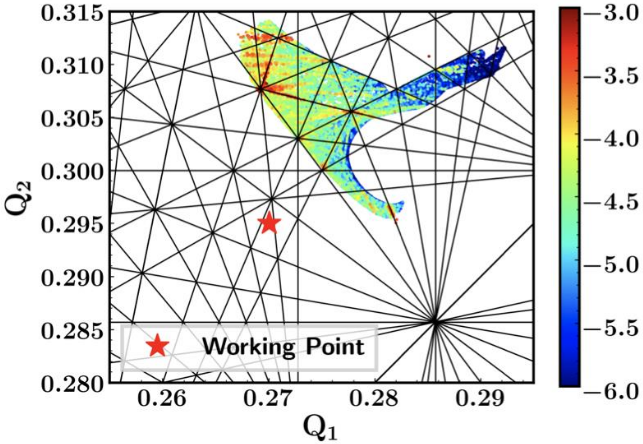
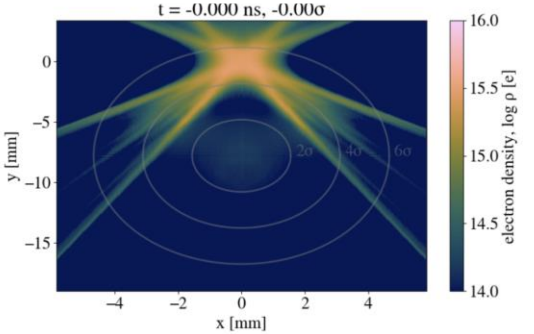




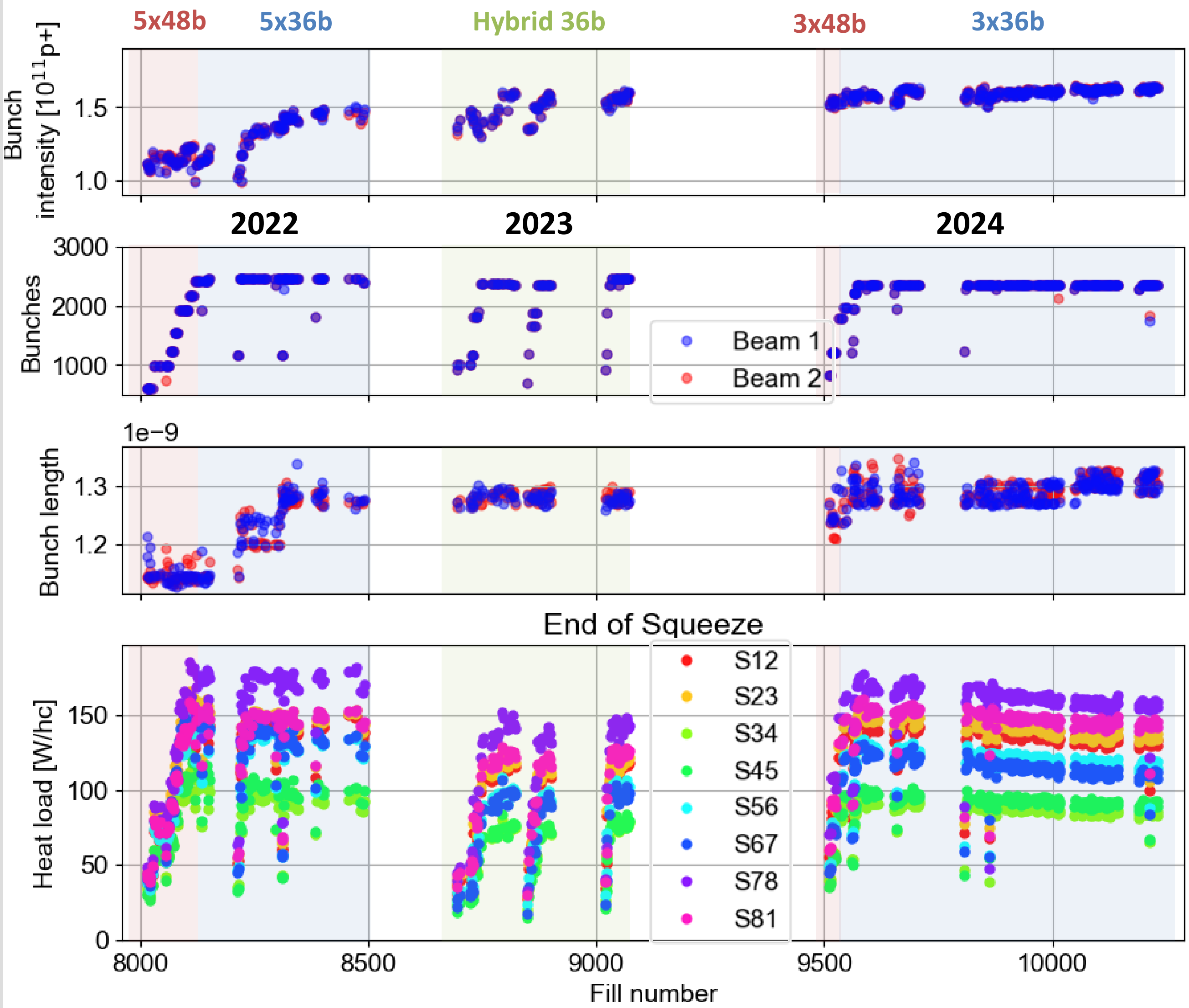


- **Coherent instabilities**
- **Incoherent** effects, i.e. beam losses and slow emittance growth

Effective electron cloud in triplets



Limitations: e-cloud



- **Coherent instabilities**
- **Incoherent** effects, i.e. beam losses and slow emittance growth
- **Pressure rise, heat load**
- **Mitigation** methods
  - **Non-linear magnets, bunch spacing** increase/variation, **coatings, scrubbing**

Beam Screen Treatment in LHC arcs

Issue

Non-uniform heat load in LHC arcs, **degradation** observed following each **Long Shutdown**

Origin

Presence of **CuO oxide** and **reduced carbon concentration at beam screen surface**

→ reduced conditioning efficiency

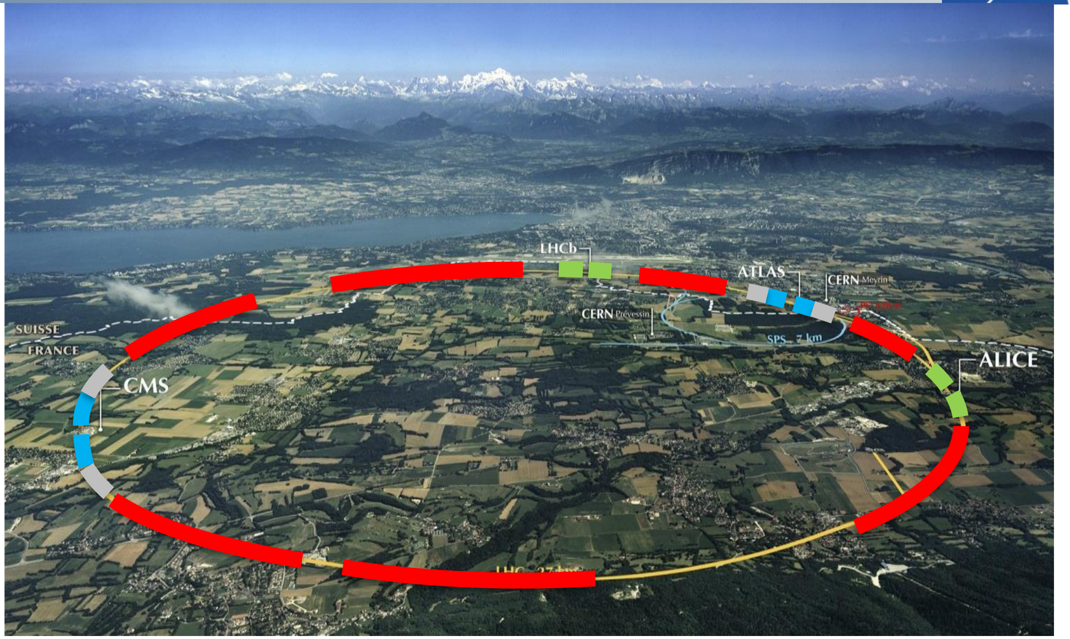
→ **Secondary Electron Yield > e-cloud threshold**

Mitigation strategy

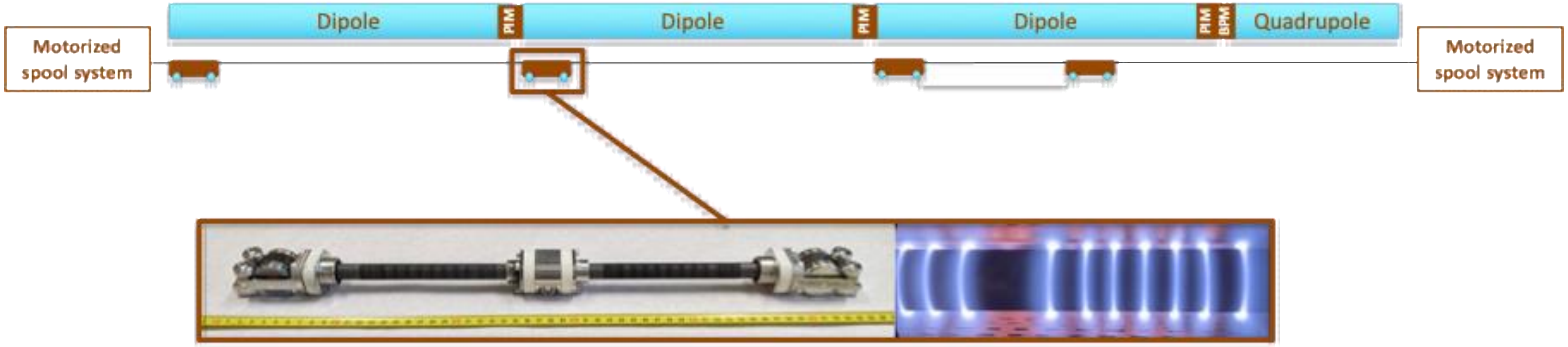
Deposit a **thin amorphous carbon layer** on the beam screens of **120 selected arc half-cells**

→ recover **conditioning efficiency**

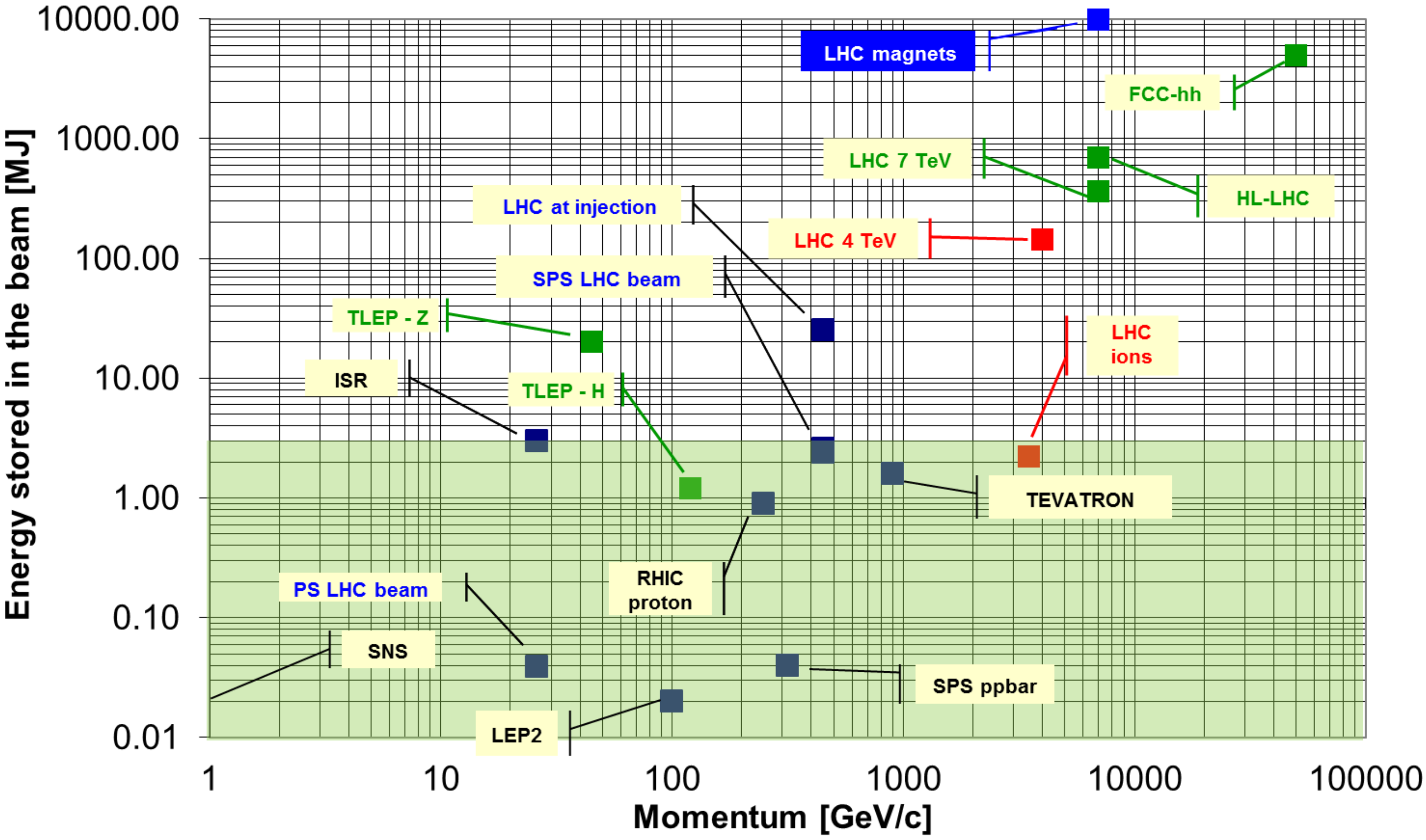
→ ensure **surface robustness** against ventings (LS)



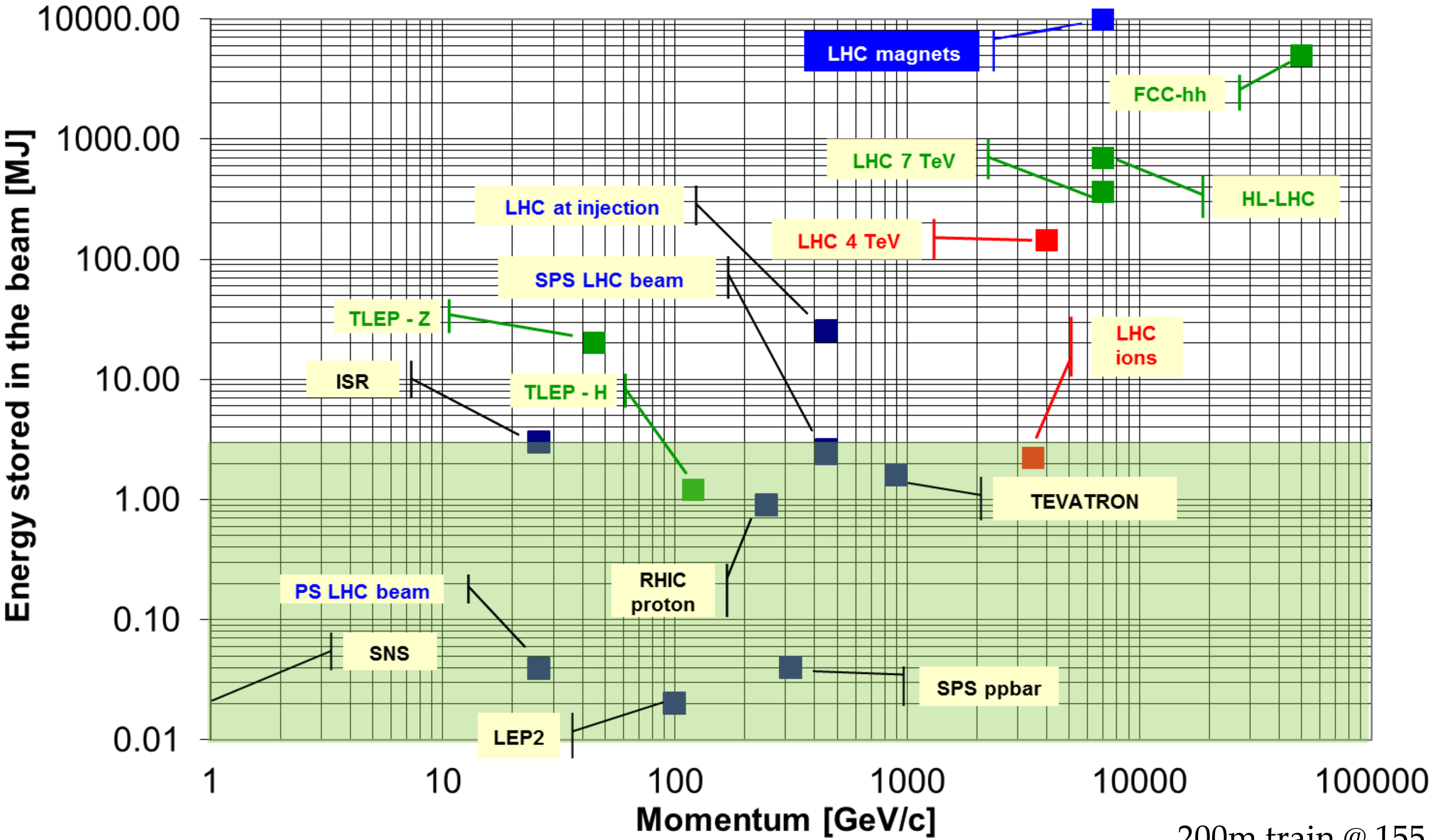
In. Triplets IP2/8	**In. Triplets IP1/5**	**Matching sections**	**Arcs**
In-situ	Ex-situ	Ex-situ, in magnet	In-situ
190 m total	320 m total	20 m total	≈ 12 km total **BST**



Stored energy



Stored energy



90kg of TNT

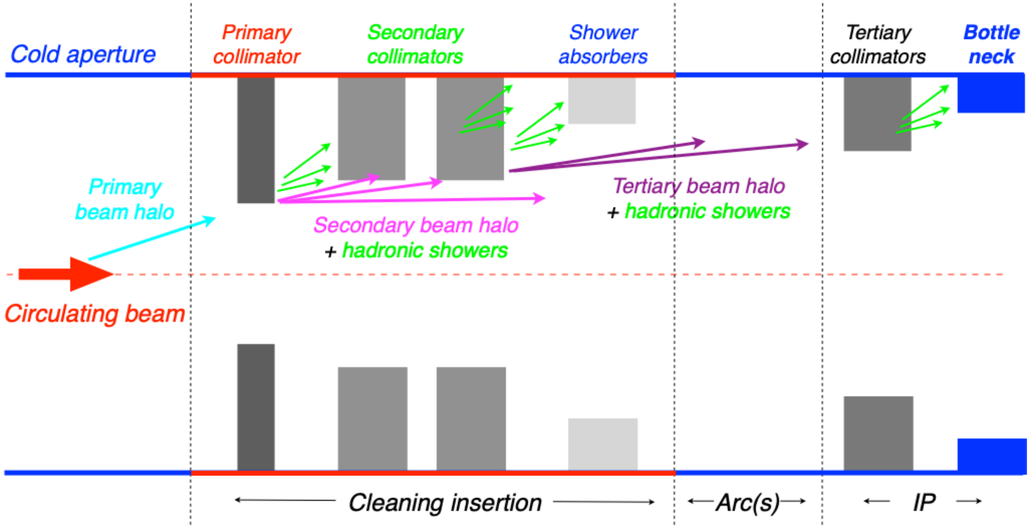
8L of gasoline

15kg of chocolate

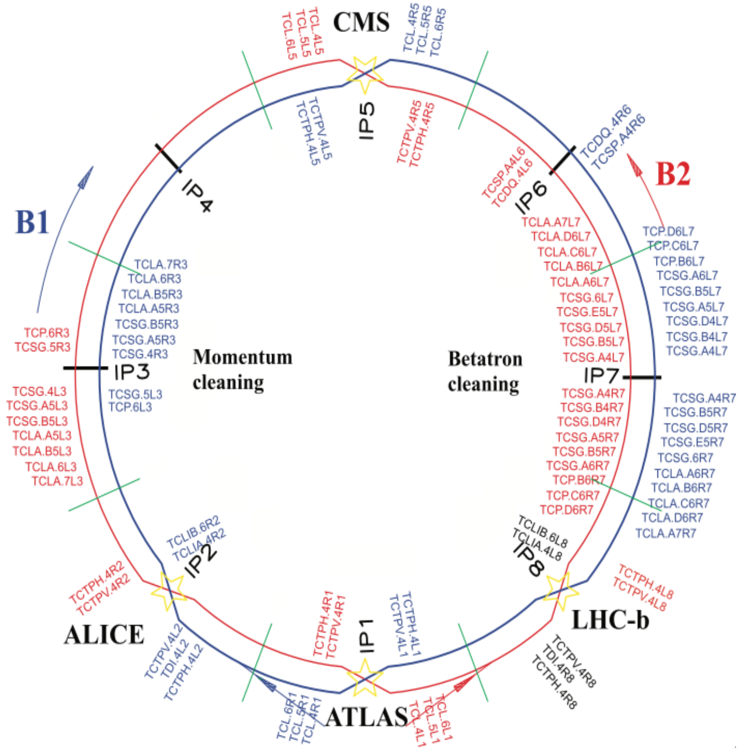
200m train @ 155 km/h

S. Redaelli, CAS2024

LHC multi-stage collimation



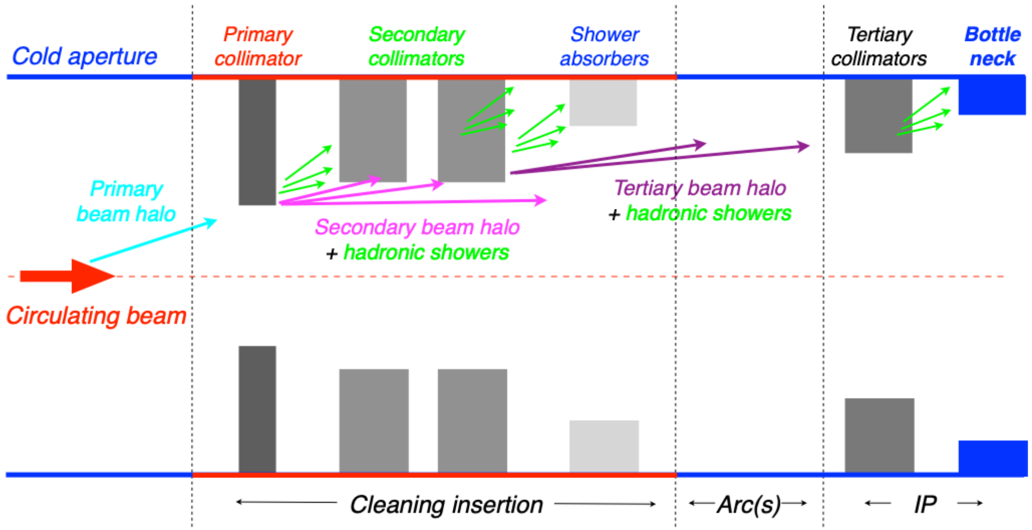
Multi-stage collimator system



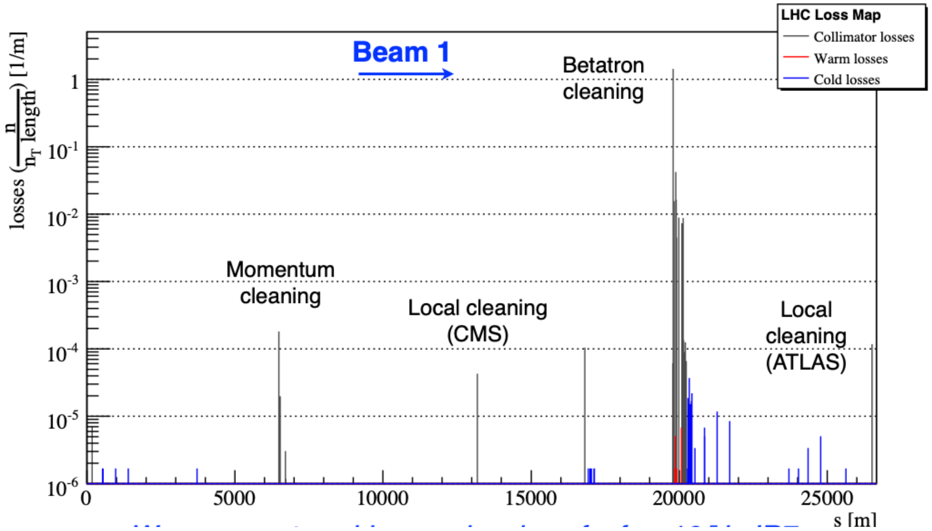
Total of 118 two-sided collimators

S. Redaelli, CAS2024

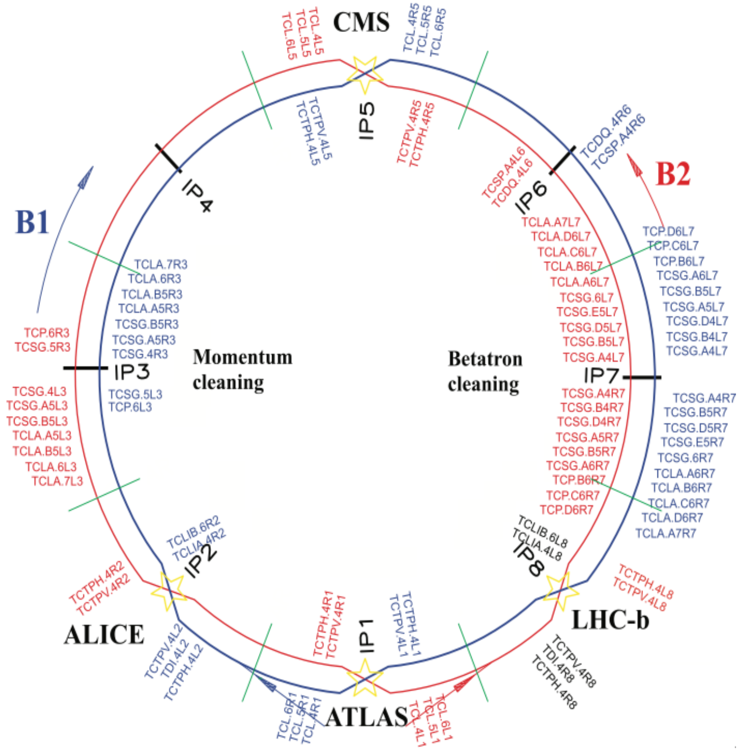
LHC multi-stage collimation



Multi-stage collimator system



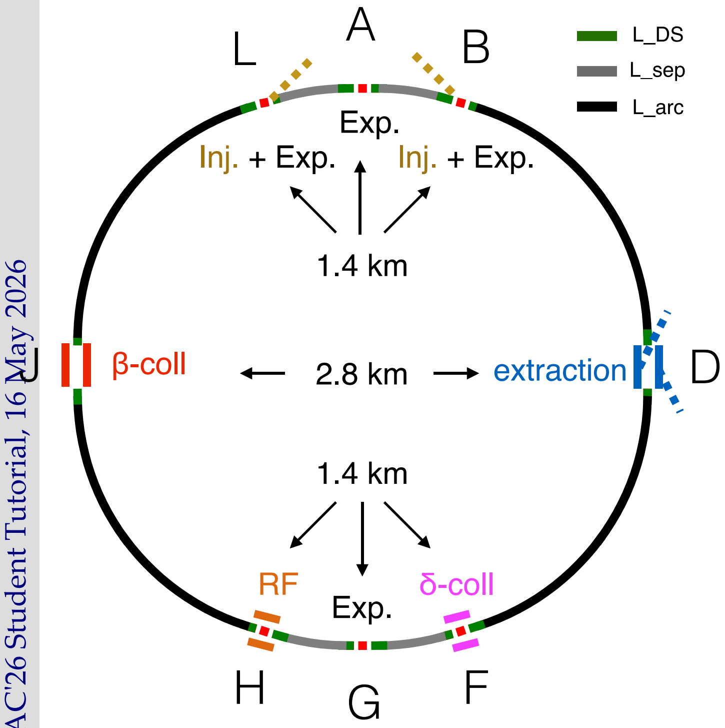
Loss maps achieving a few 10^{-5}efficiency



Total of 118 two-sided collimators

S. Redaelli, CAS2024

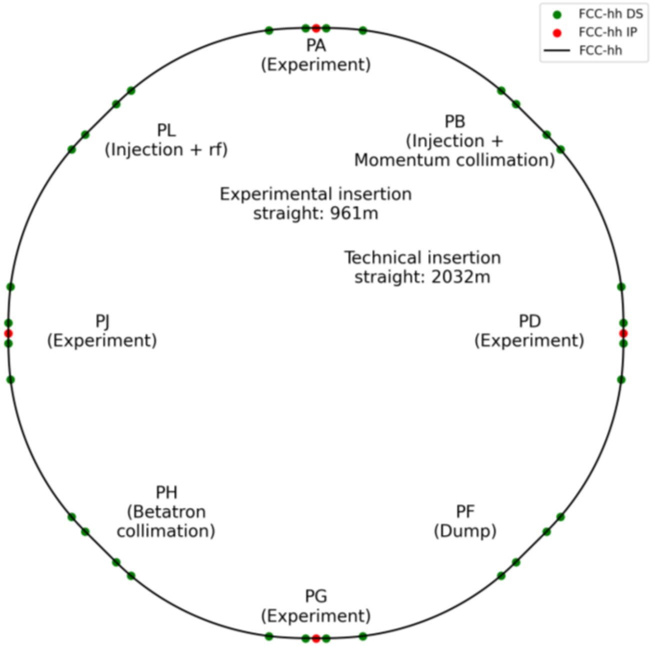
FCC-hh: from CDR to current baseline



Circumference: 97.75 km

Main geometrical differences:

- Circumference length
- Straight section length
- Arc length
- Symmetry of experimental insertions
- Transverse position of interaction points
- Functional organisation of straight sections



Circumference: 90.66 km

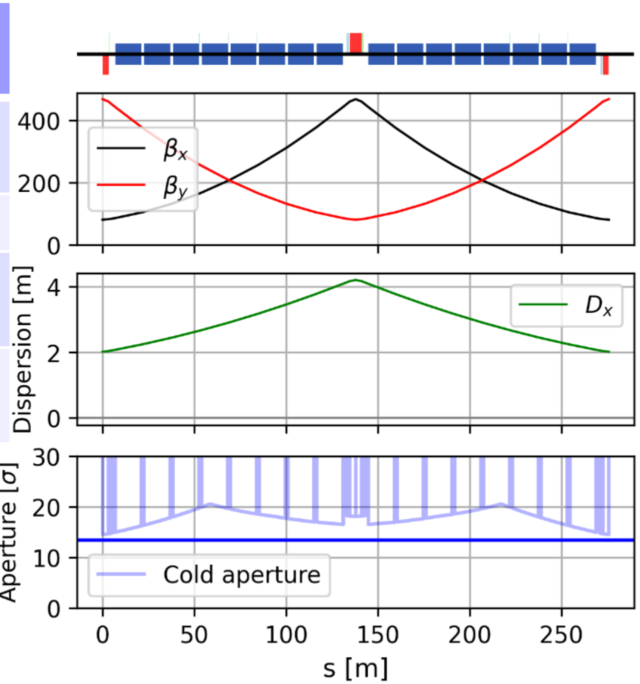
Parameter	Value
CoM energy [TeV]	84.6 – 120.8
Dipole field [T]	14 (Nb_3Sn/HTS) - 20 (HTS)
Dipole length [m]	14.187
Number of dipoles	4464
Circumference [km]	90.657

- **Maximized dipole filling factor to maximize collision energy**

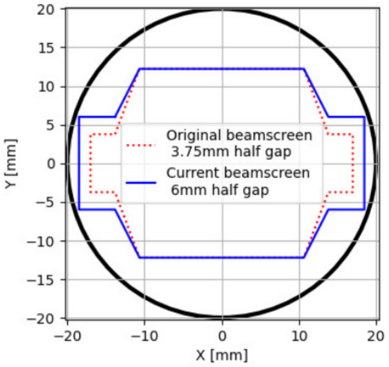
M. Giovannozzi, et al.

Regular arc cell of FCChh

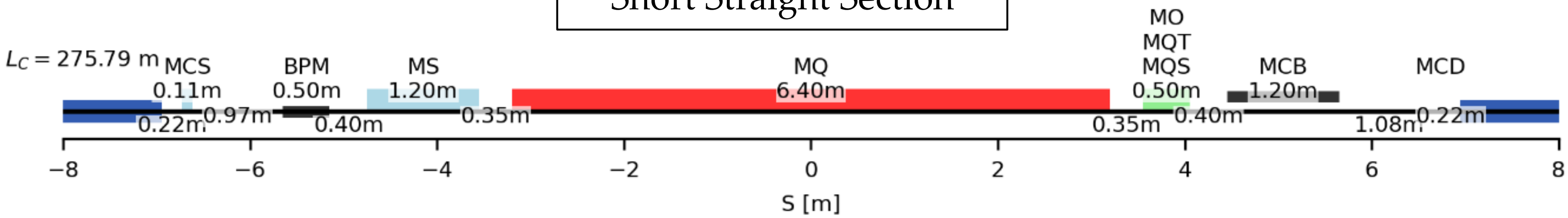
Parameter	CDR cell 12-dipole	12-dipole	16-dipole
Number of dipoles	4668	4288	4464
Cell length [m]	213.030	213.030	**275.792**
Circumference [km]	97.75	**90.657**	**90.657**
CoM energy @14 T [TeV]	88.48	81.28	**84.61**



~275m

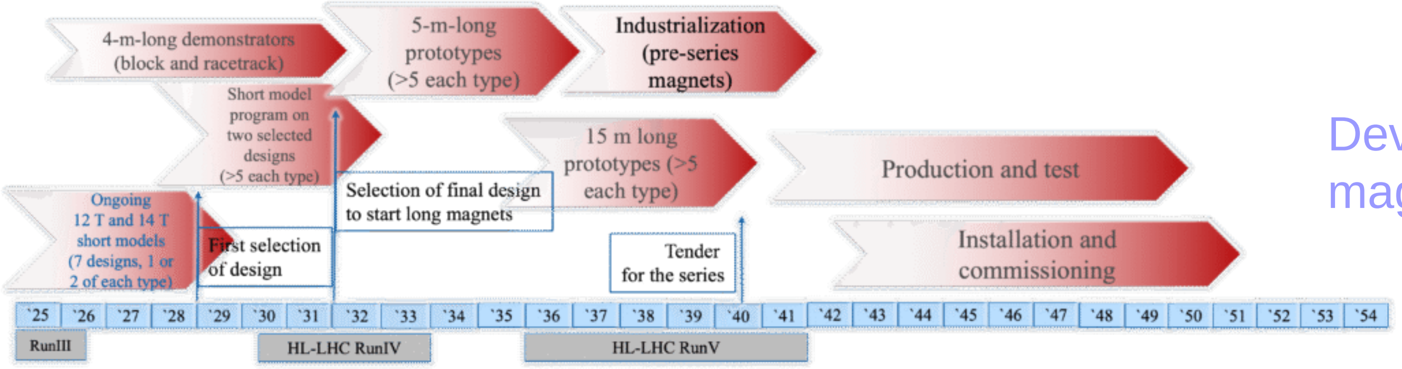


Short Straight Section

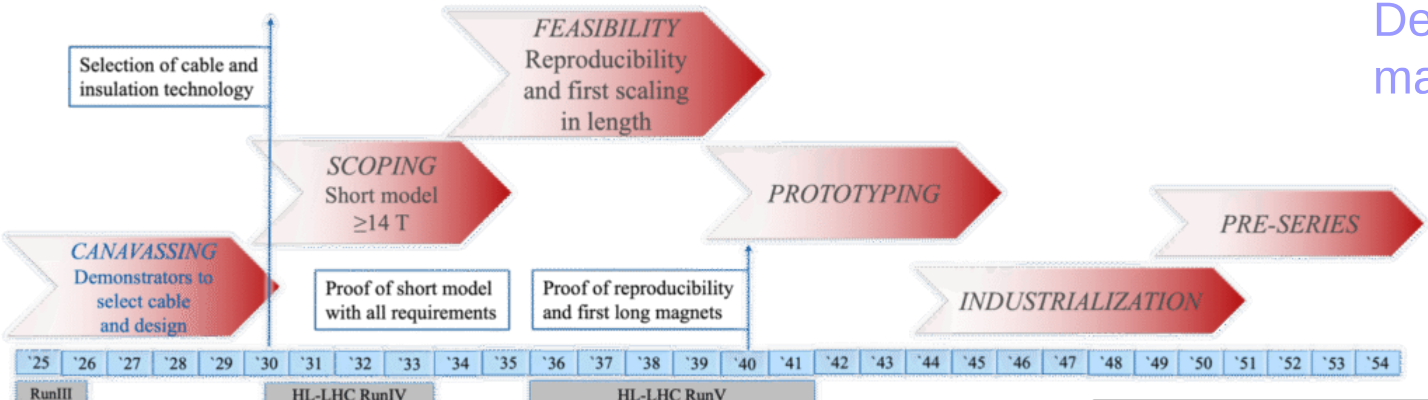


M. Giovannozzi, et al.

High-field magnets for FCChh

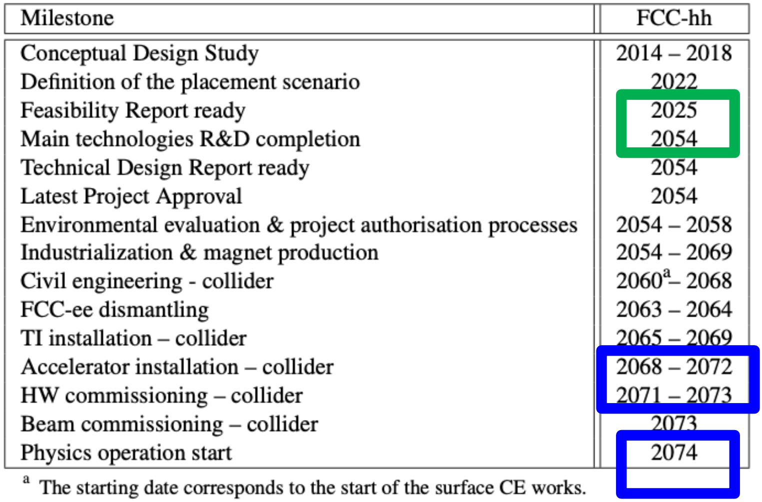


Development of Nb$_3$Sn magnets



Development of HTS magnets

Full compatibility of the HFM activities with the FCC-hh schedule.



Milestone	FCC-hh
Conceptual Design Study	2014 – 2018
Definition of the placement scenario	2022
Feasibility Report ready	2025
Main technologies R&D completion	2054
Technical Design Report ready	2054
Latest Project Approval	2054
Environmental evaluation & project authorisation processes	2054 – 2058
Industrialization & magnet production	2054 – 2069
Civil engineering - collider	2060[a]– 2068
FCC-ee dismantling	2063 – 2064
TI installation – collider	2065 – 2069
Accelerator installation – collider	2068 – 2072
HW commissioning – collider	2071 – 2073
Beam commissioning – collider	2073
Physics operation start	2074

[a] The starting date corresponds to the start of the surface CE works.

M. Giovannozzi,, E. Todesco, et al.

e^+e^- Colliders

Synchrotron Radiation power

$$\mathbf{p} = m_0 \mathbf{v} \qquad v << c$$

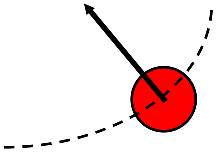
$$P_s = \frac{e^2}{6\pi\varepsilon_0 m_0^2 c^3} \left(\frac{d\mathbf{p}}{dt}\right)^2$$

Larmor Power radiated by non-relativistic particles is very small

$$\mathbf{p} = \gamma m_0 \mathbf{v} \qquad v \approx c$$

$$P_s = \frac{e^2}{6\pi\varepsilon_0 m_0^2 c^3} \left(\frac{dp}{dt}\right)^2$$

Power radiated by relativistic particles in linear accelerators is negligible



$$P_s = \frac{e^2 c}{6\pi\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho^2}$$

Power radiated by relativistic particles in circular accelerators is very strong (Liénard, 1898)

SR impact on colliders

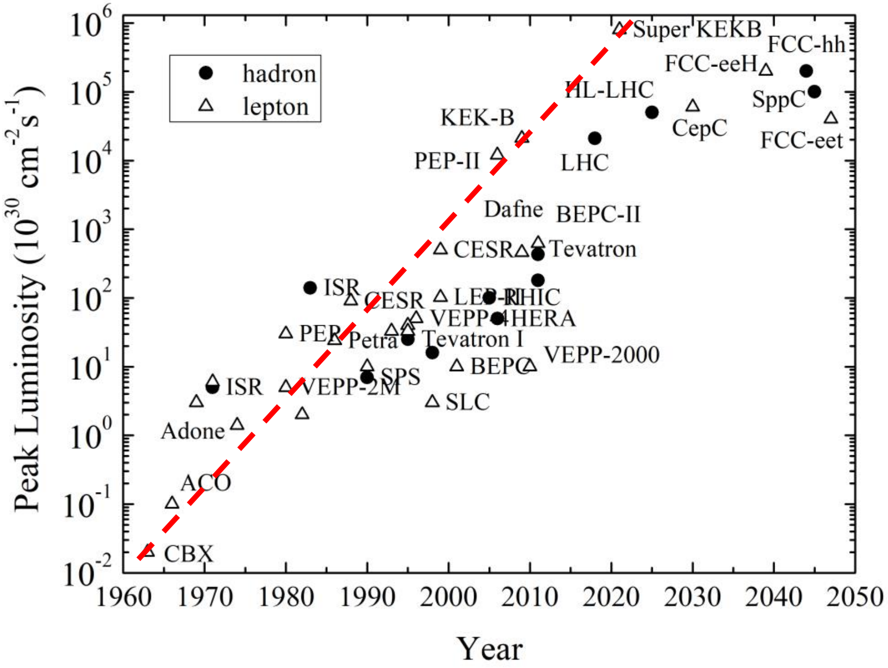
$$P_s = \frac{e^2 c}{6\pi\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho^2}$$

- Inversely proportional to **4th power** of **rest mass** (e- mass ~2e3 x p mass), proportional to **4th power of energy**, inversely proportional to **2nd power** of **bending radius**
- For multi TeV hadron colliders (LHC, FCChh) **handling** of **SR** still **important** (protection of SC magnets with beam screens)

$$\Delta E = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho}$$

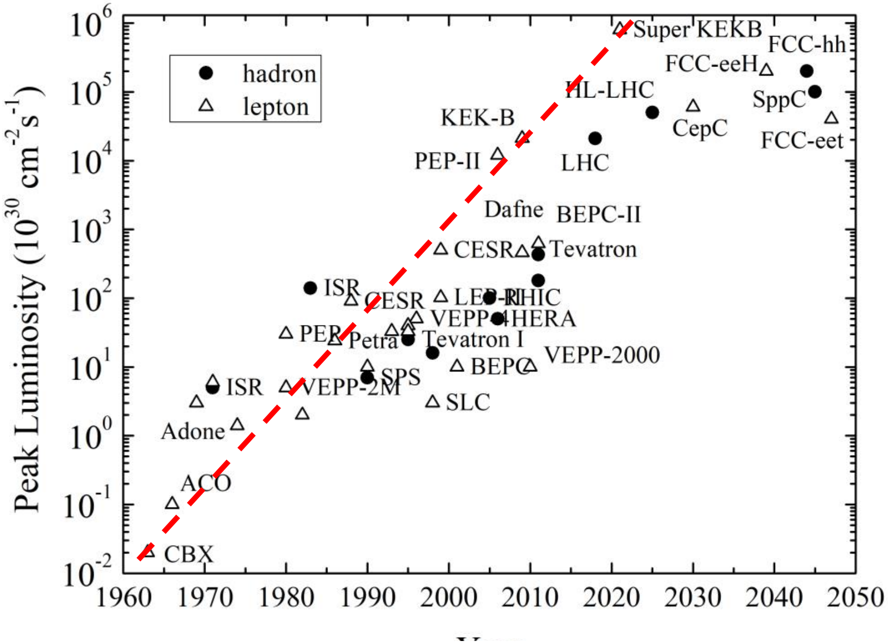
- **Energy loss per turn** obtained by integral of power over one revolution
- ESRF storage ring (ESB, 6GeV): ~**2.5 MeV/turn**.
- LEPII (**120 GeV**): ~**6 GeV/turn**, or FCCee (ttbar flavor at **175 GeV**): **7.5GeV/turn**
- **Circular e+/e- machines** of ~100s GeV quite demanding with respect to **RF power** (and extremely long)

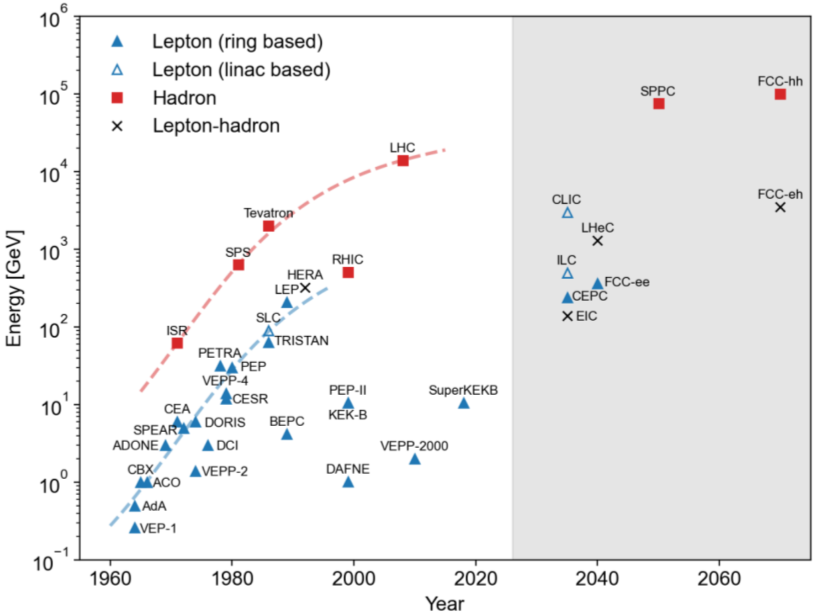
e^+e^- colliders flavors



- **High-luminosity** frontier
  - **Factories, high precision** physics measurements

e^+e^- colliders flavors





- **High-luminosity** frontier
  - **Factories**, **high precision** physics measurements
- **High-energy** frontier
  - **Discovery** measurements
  - **Before** Higgs discovery
    - LEP2 last large circular **high-energy** collider (120 GeV)
    - **Linear colliders** (ILC, CLIC) considered for future (0.5 to 1.5 TeV)
  - **After** Higgs discovery at **126 GeV**
    - **Large circular colliders** re-considered (FCCee, CEPC)
    - **Integrated programs** from Z up to the top, with possibility to reuse tunnel for hadrons (LEP-LHC paradigm)

Beam-beam tune shift

- **Beam-beam tune-shift**, i.e. 1st order approximation to betatron tune change

$$\xi_{x,y} = \frac{N r_e}{2\pi\gamma} \frac{\beta^*_{x,y}}{\sigma^*_{x,y}(\sigma^*_x + \sigma^*_y)}$$

- The luminosity becomes $L = f_{coll} \frac{\pi\gamma^2}{r_e^2} \frac{\xi_x \xi_y \varepsilon_x}{\beta_y} (1 + \frac{\sigma_x}{\sigma_y})$

Beam-beam tune shift

- **Beam-beam tune-shift**, i.e. 1st order approximation to betatron tune change

$$x_{x,y} = \frac{Nr_e}{2pg}\frac{b^*_{x,y}}{s^*_{x,y}(s^*_x + s^*_y)}$$

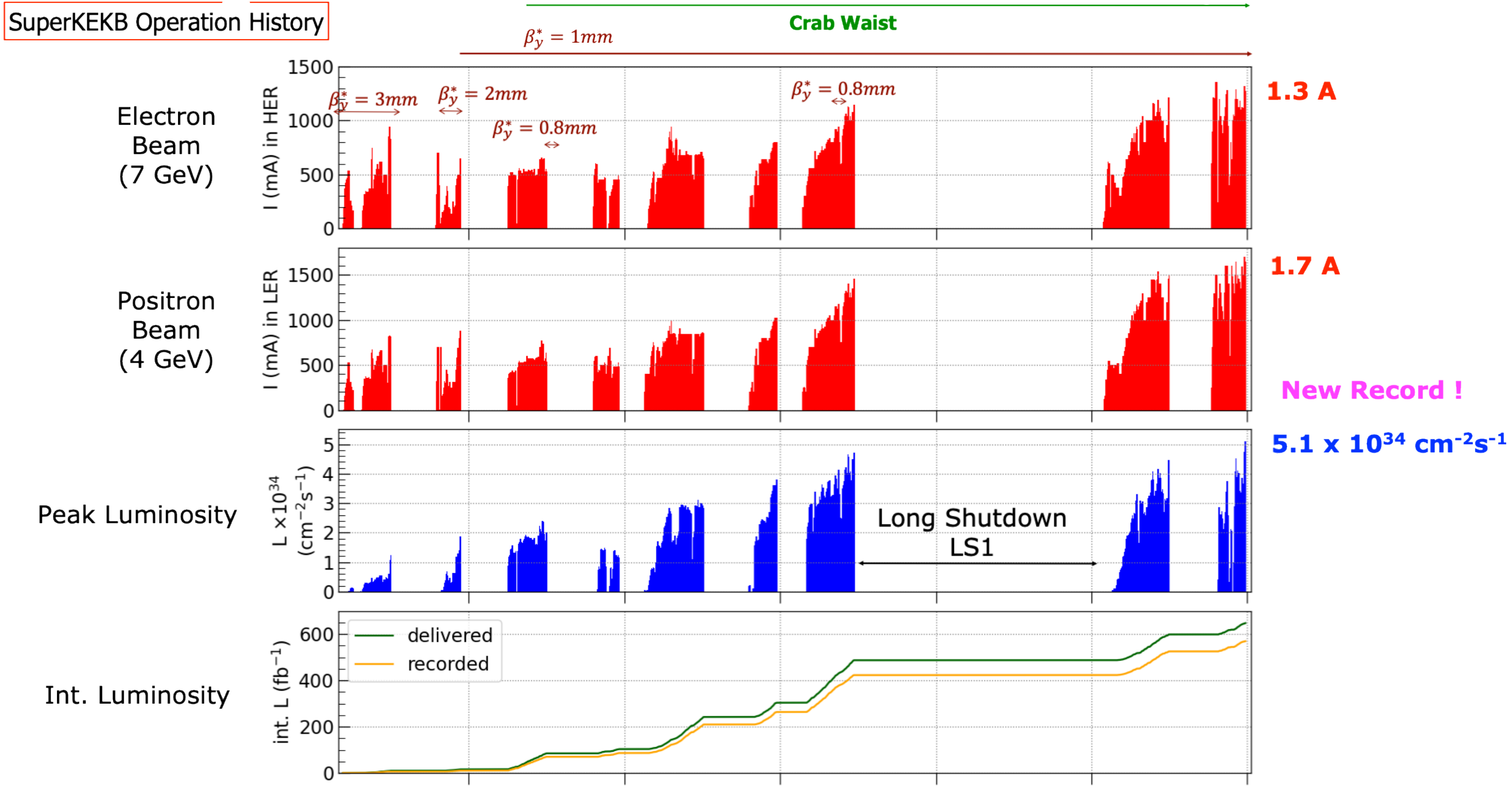
- The luminosity becomes $L = f_{coll}\frac{\pi\gamma^2}{r_e^2}\frac{\xi_x\xi_y\varepsilon_x}{\beta_y}(1+\frac{\sigma_x}{\sigma_y})$

- For **flat beams** $\varepsilon_y/\varepsilon_x = \kappa << 1$ and $\kappa_\beta = \beta_y/\beta_x$

- **Horizontal** tune-shift $x_x \gg \frac{r_e}{2pg}\frac{N}{e_x}$ and **vertical** one $\xi_y \approx \frac{r_e}{2\pi\gamma}\frac{N}{\varepsilon_x}\sqrt{\frac{\kappa_\beta}{\kappa}}$

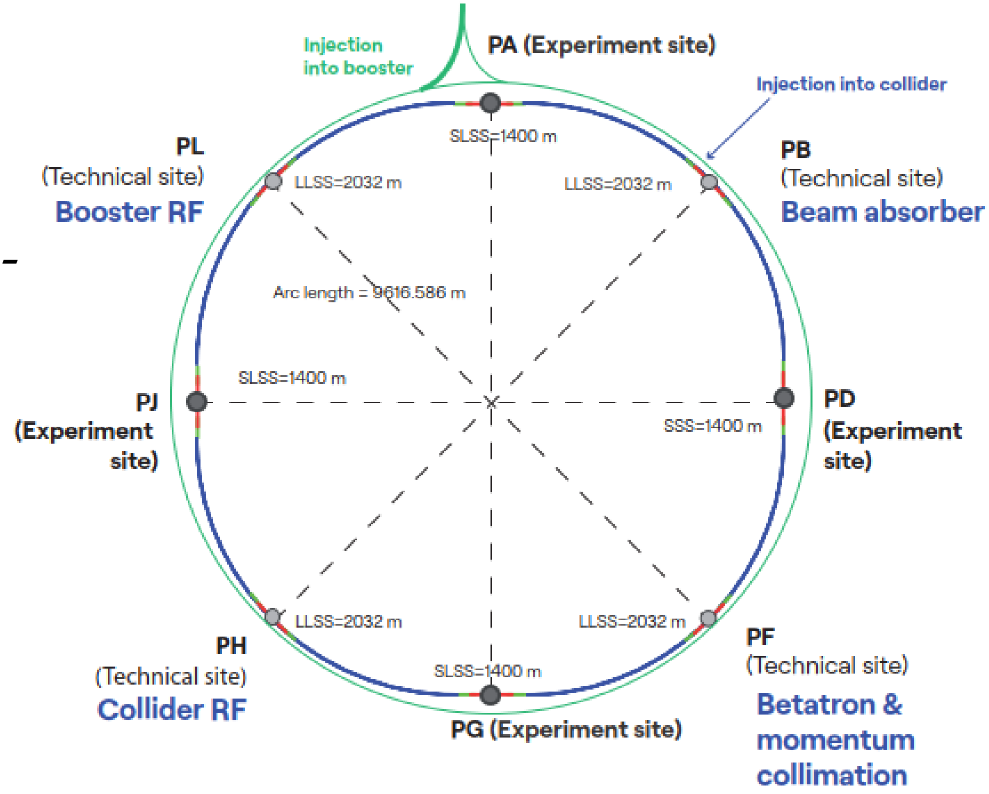
- **Luminosity** becomes $L \gg f_{coll}\, gN\frac{x_y}{b_y}$

SuperKEKb luminosity



FCCee key concepts

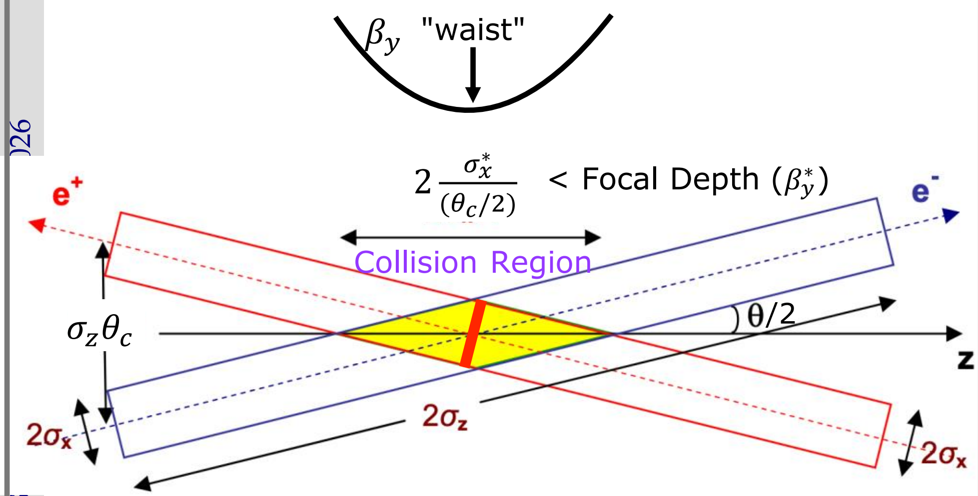
- Very large **90.7 km circumference** electron-positron collider to reach high luminosity (Z) and energy (top) with **4 IPs**
  - Reuse of tunnel for **hadron collider**
- **50 MW SR power** per beam
  - Main driver for **beam intensity**
- Two **separated rings** for e+ and e-
  - **Large crossing angle** of **30 mrad**
- **Small equilibrium emittances** reached with large tunes
  - **Different optics** depending on **energy**
- **Top-up injection**
  - **Full energy booster** sharing tunnel with collider
- **Injector complex**
  - Linacs, positron conversion target, damping ring, transfer lines …
- Many similarities with **CEPC**



Key concepts for e+/e-

Nano-Beam Scheme

P. Raimondi



Effectively Very Short Bunch → "Hourglass"

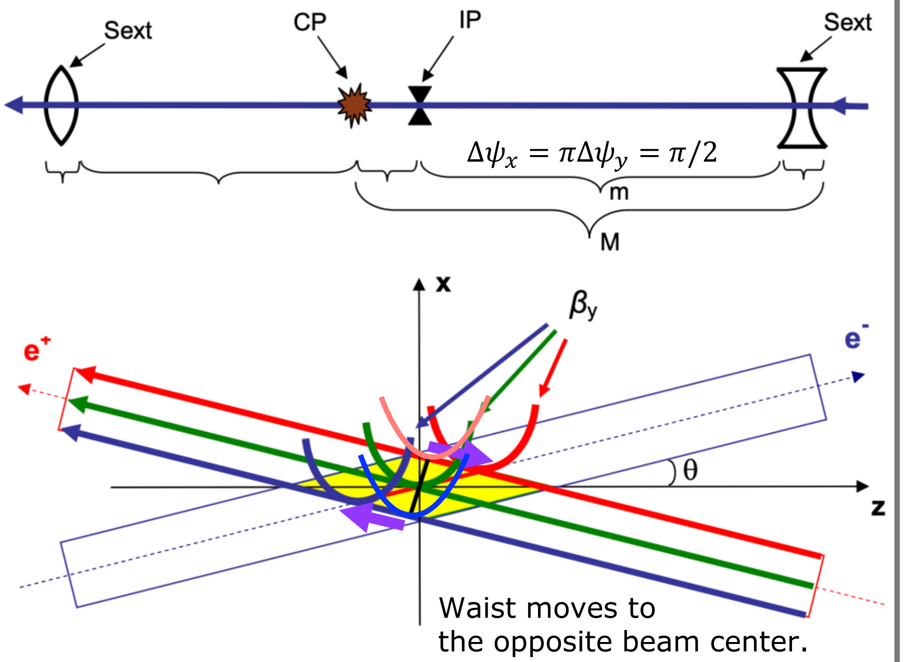
"Head-On Collision"

$$\tilde{\sigma_z} = \frac{\sigma_z}{\Phi} = \frac{\sigma_x^*}{(\theta_c/2)} < 1mm$$

⟷ σ_z = 6 mm SuperKEKB

Key: Large Crossing Angle with Low ε_x

Crab-Waist Scheme



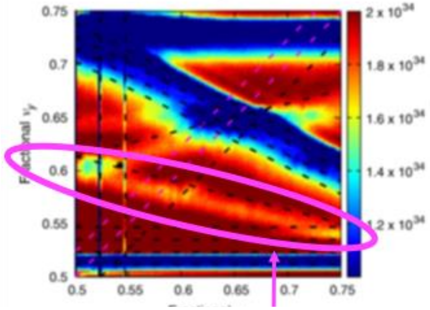
Waist moves to the opposite beam center.

Suppression of Betatron Resonance

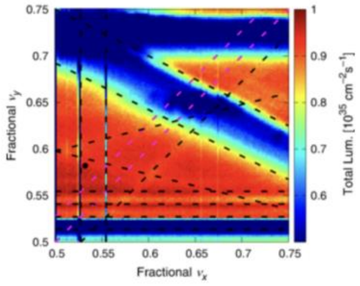
Related to Beam-Beam Interaction

Key: Strong Sextupoles with Specific Optics

CW OFF



CW ON



D. Zhou, et al.

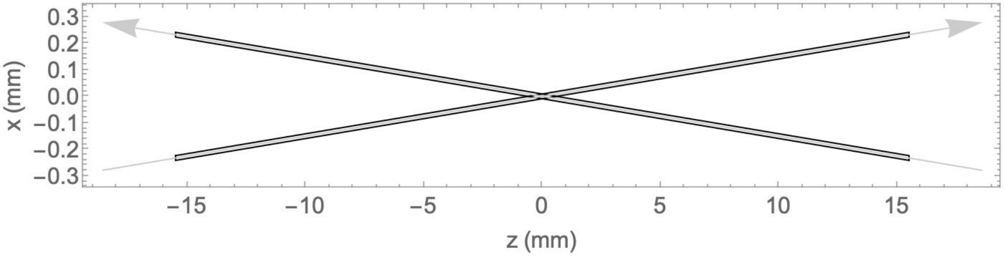
Colliders and related accelerators, IPAC'26 S

Beam-Beam Effect driving parameters

- Luminosity

$$L = \frac{\gamma}{2e\,r_e}\,\frac{I_{tot}\,\xi_y}{\beta_y^*}\,R_G$$

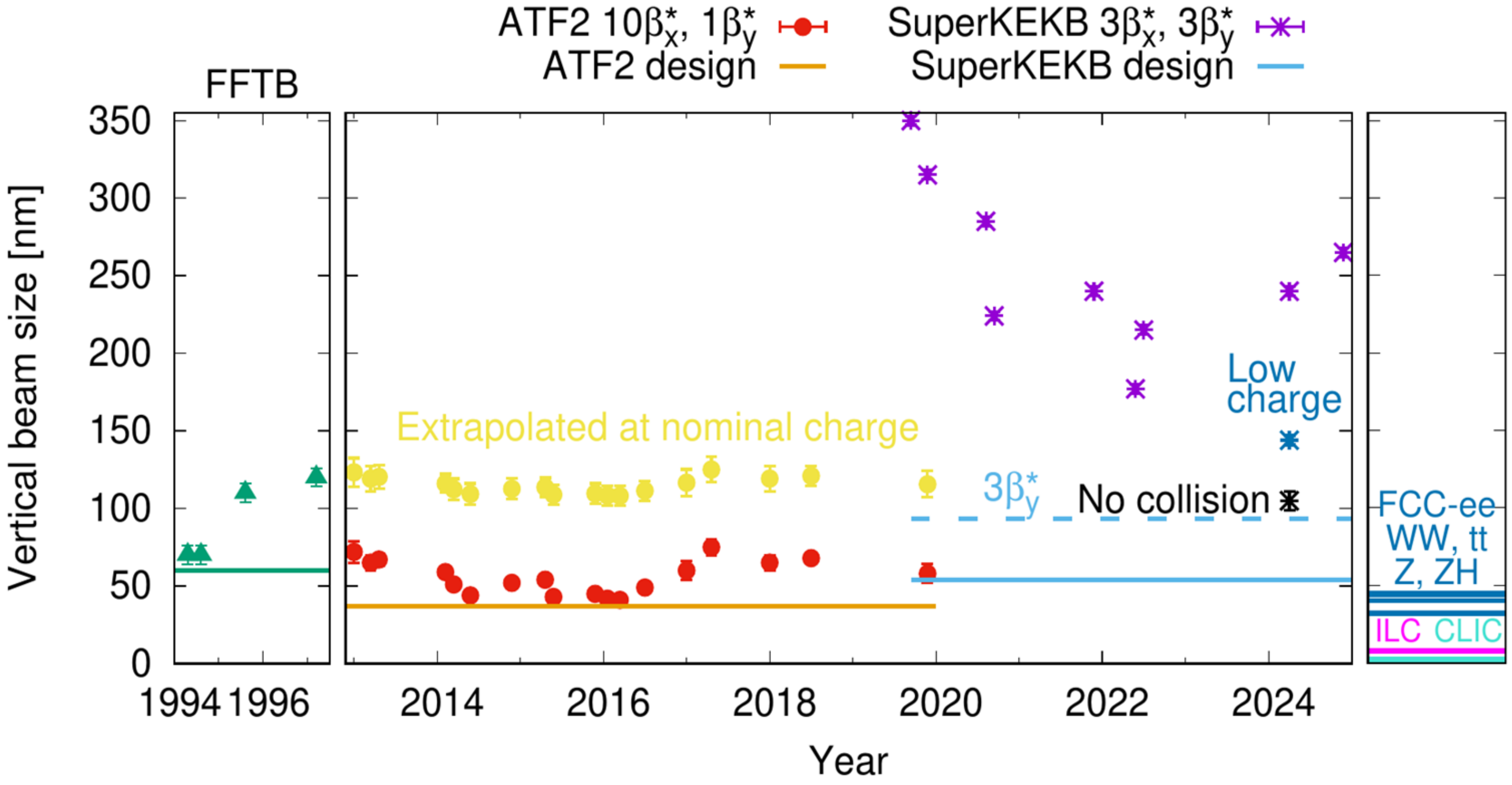
  - ☐ R_G a **geometric reduction factor**
  - ☐ **Total intensity I_{tot}** given by SR power, assuming absence of other intensity limitations
  - ☐ Maximized with **large beam-beam tune shift** ξ_y
    - At Z mode $\xi_y = 0.09$ per IP (compared with $\xi_y = 0.045$ per IP achieved at Z energy in LEP)
  - ☐ Maximized with **small $\beta_y^* \approx 1$ mm** creating challenges for lattice design
    - Strong **chromatic aberrations** to be corrected locally
    - Small **Dynamic Aperture** (DA) require small **emittances**
    - For Z mode with **"nano-beam" scheme**
      - **Small peak bunch current**
      - **Large number of long bunches** required for large **I_{tot}**
      - **Maximum number** of bunches limited by **e-cloud** build-up



- "Nano-beam" collision scheme
  - ☐ Kind of **ribbons** at the interaction point
  - ☐ **Only fraction** of bunch interacts with opposite bunch at a given moment **(large Piwinski angle)**

C. Carli et al.

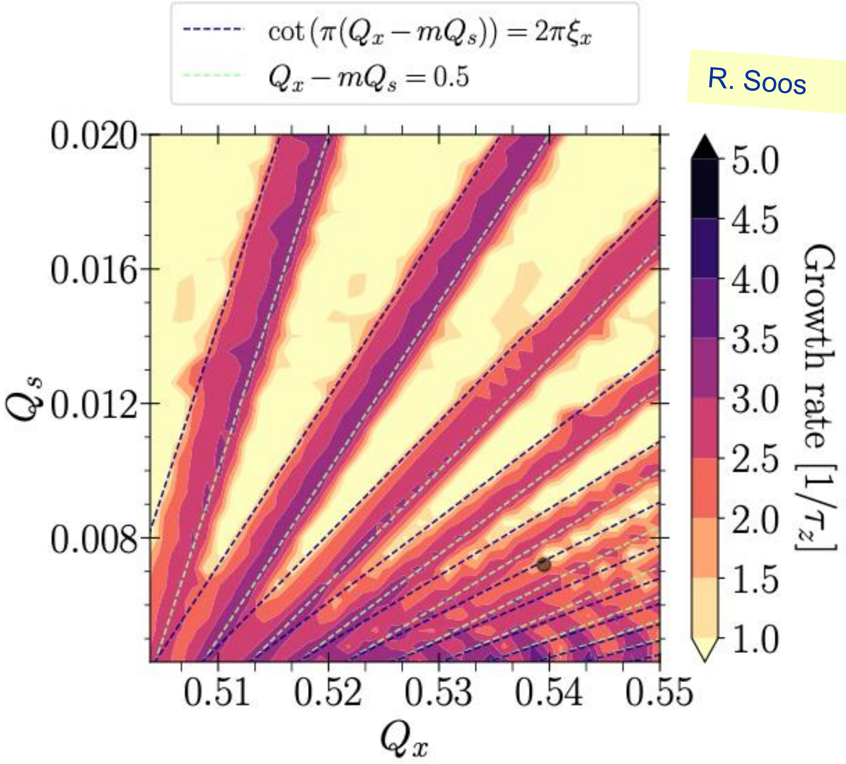
Minimum vertical beam size



R. Tomas

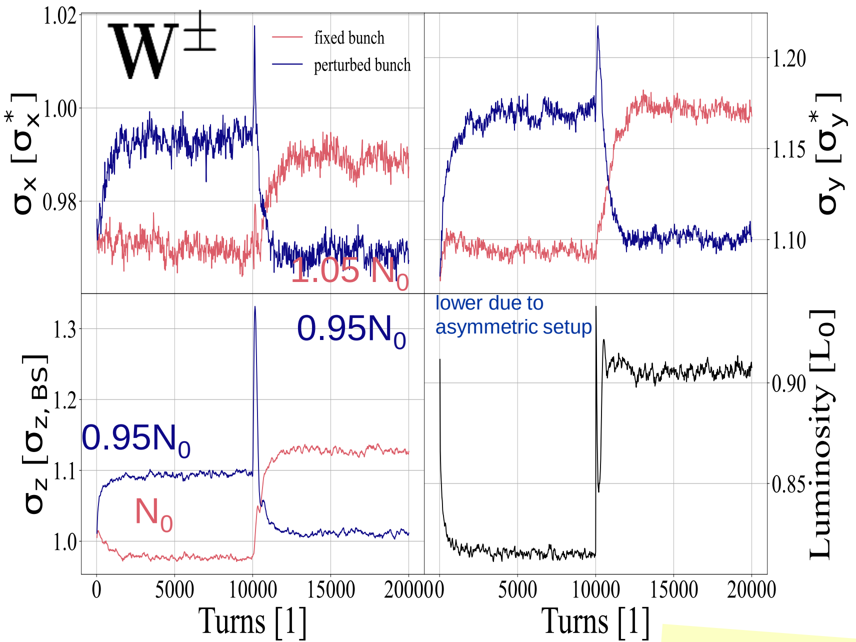
Other two-beam effects

- **Beam-strahlung**, i.e. SR due to field of opposing bunches, potential limitation
  - Increase of **equilibrium momentum spread** and **bunch length** (beneficial at low energy)
  - **Interception** of **hard beam-strahlung photons challeng**ing
- Limitations from **beam-beam effects**
  - **Synchro-horizontal betatron resonance** and instability constraining synchrotron and horizontal tunes



R. Soos

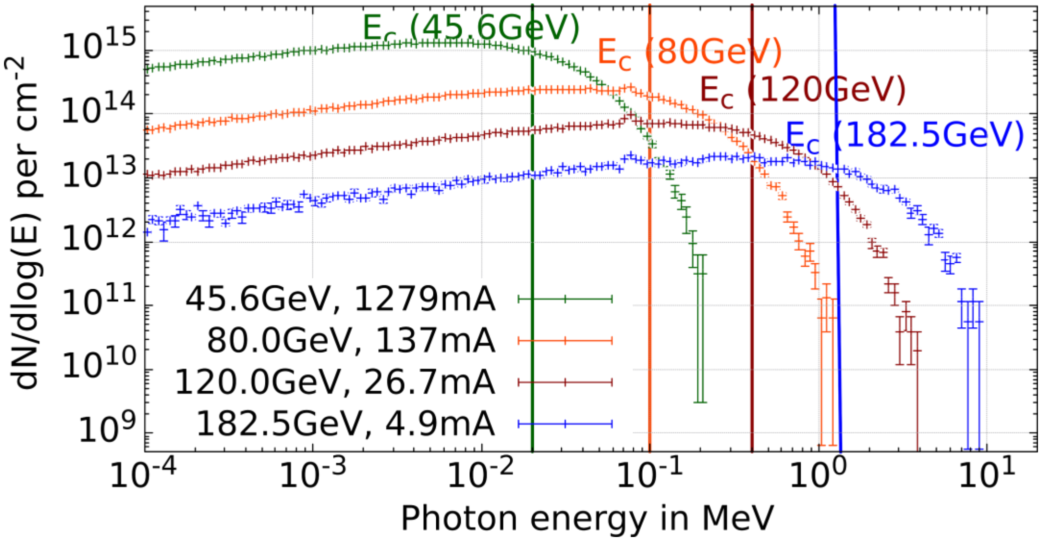
- **Flip-flop** mechanism
  - Low (high) intensity bunch with more (less) perturbation
  - Asymmetric effect on bunches

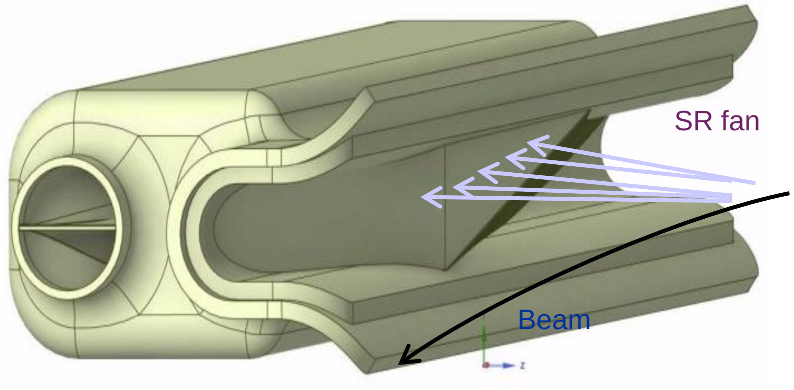


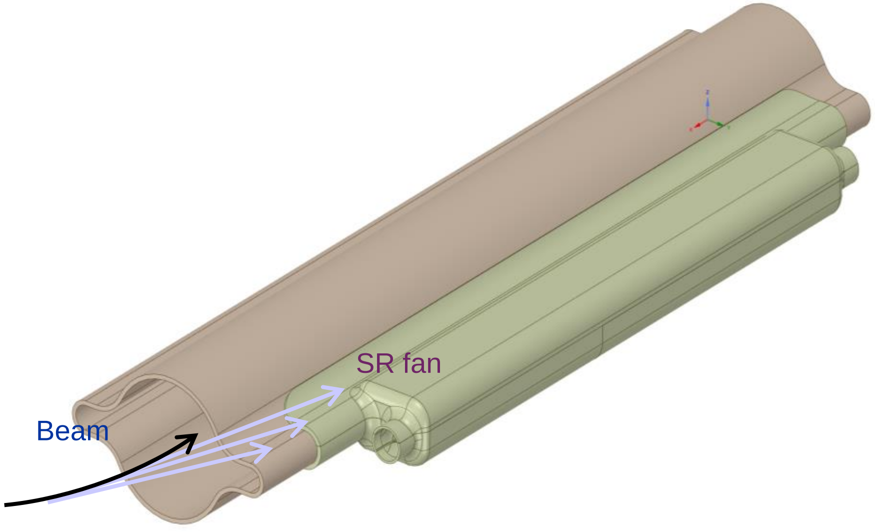
P. Kicsiny

Vacuum system for SR absorption

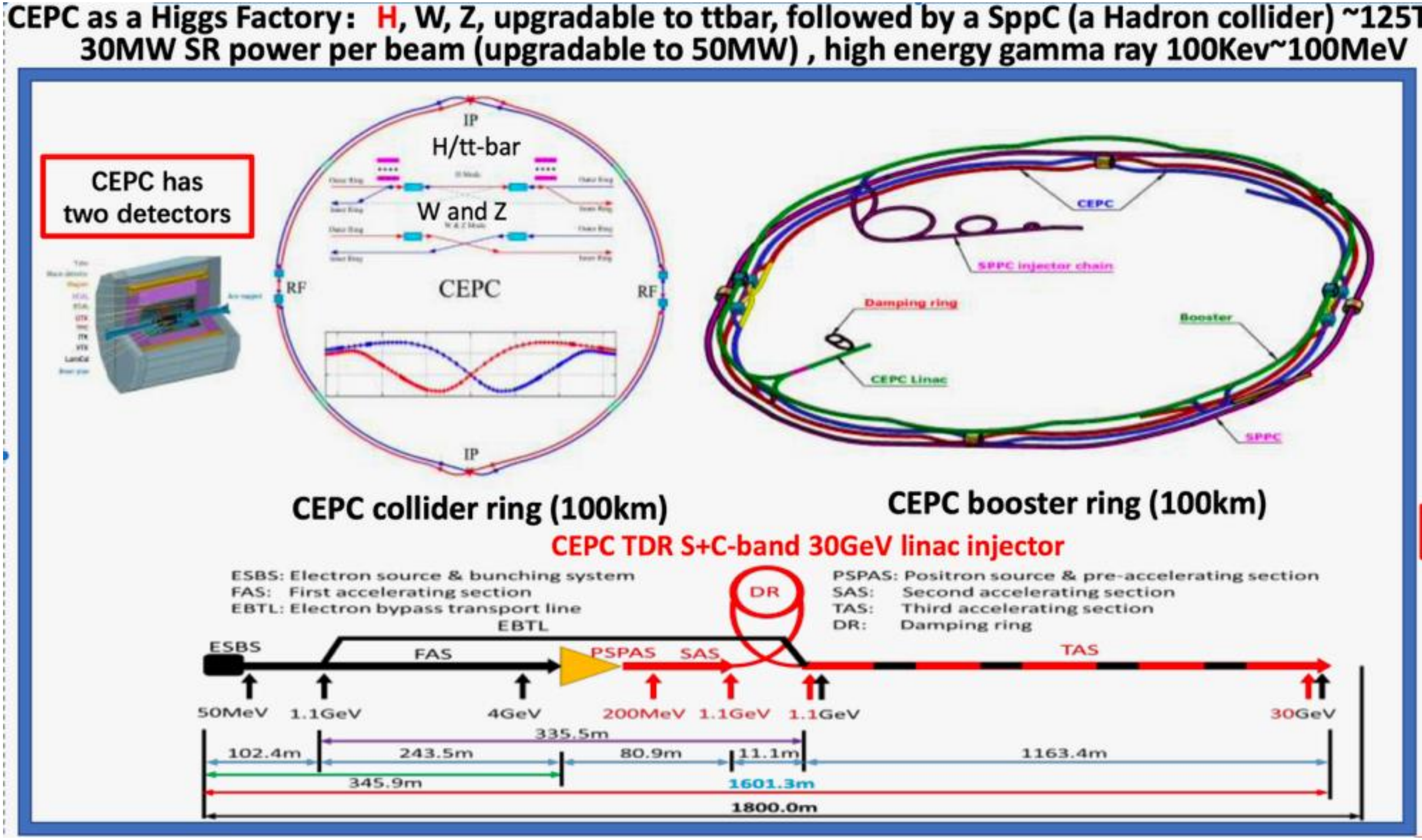
- ◆ **SR Absorbers** (SRAs) intercept photons with 50 MW total power per beam
  - □ Challenge to absorb power deposit on SRAs
  - □ Optimized for **high efficiency** to limit generation of **photo-electrons** (e-cloud)
  - □ At high beam energies, generation of **neutrons**
    - ▪ Absorbed as much as possible by lead blocks inside magnet
    - ▪ Residual radiation in tunnels







CEPC as a Higgs factory



CEPC as a Higgs Factory: H, W, Z, upgradable to ttbar, followed by a SppC (a Hadron collider) ~125T
30MW SR power per beam (upgradable to 50MW) , high energy gamma ray 100Kev~100MeV

CEPC has two detectors

CEPC collider ring (100km)

CEPC booster ring (100km)

CEPC TDR S+C-band 30GeV linac injector

ESBS: Electron source & bunching system
FAS: First accelerating section
EBTL: Electron bypass transport line

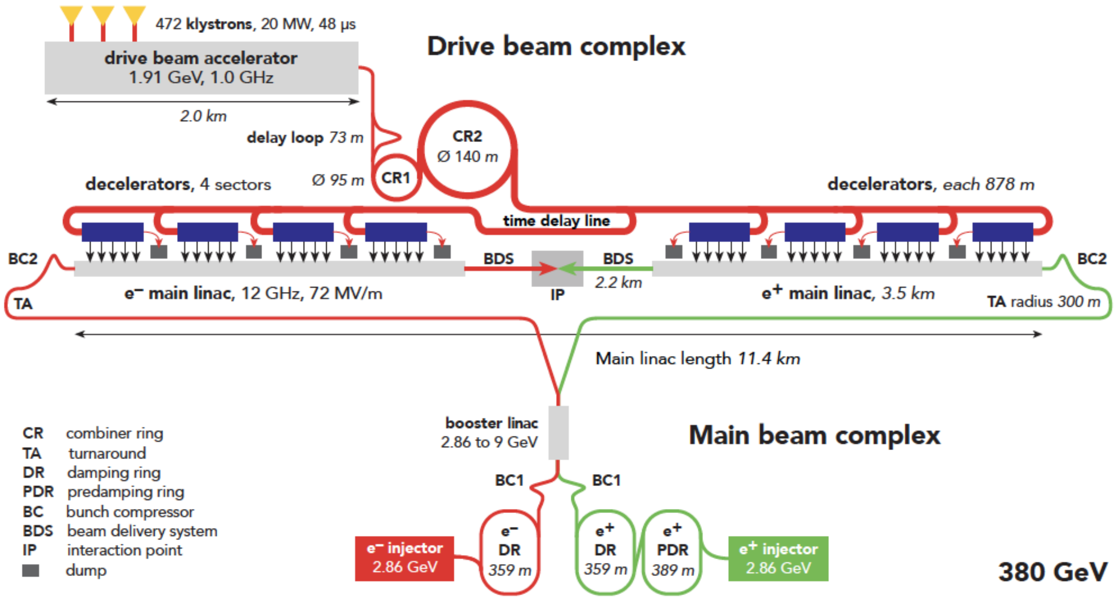
PSPAS: Positron source & pre-accelerating section
SAS: Second accelerating section
TAS: Third accelerating section
DR: Damping ring

J. Gao et al.

Compact Linear Collider - CLIC

Baseline

- √s = **380 GeV**, **2 IPs**
- **Main Linac length**: **11.4 km**
- Option for 550 GeV: +5 km from start
- Using **drive beam** for increasing RF efficiency @ high gradient (copper cavities)



Upgrade to 1.5 TeV

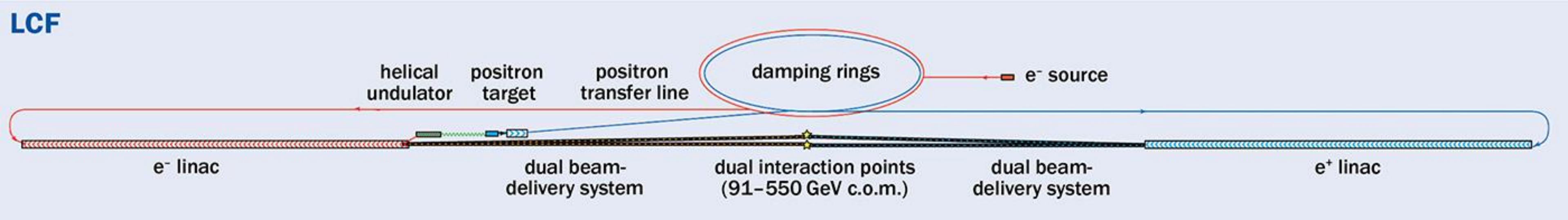
- After ~10 years at 380 GeV
- Tunnel length extended to 29.6 km
- New high-gradient (100 MV/m) modules added
- One IP (with push-pool detectors), two IPs with higher rep. rate

Positives

- Polarization
- Above ttbar threshold
- Compact footprint, staged spending profile
- Mature technology demonstrated at CTF3

S. Stapnes, et al.

Linear collider facility - LCF



Baseline

- √s = **250 GeV**, **2 IPs**
- Total length: 33.5 km
- Phased through Low power (LP) to Full power (FP)

Upgrade to 550 GeV

- After ~10 years at 250 GeV
- Requires a 2-year long shutdown, installation of additional SRF cryomodules
- No additional Civil Engineering

Positives

- Mature technology (ILC…)
- Polarised beams
- Staged
- Relatively small footprint

J. List, et al.

e+/e- colliders performance

	CLIC	FCC-ee				LCF LP	LCF FP	
Circumference/length collider tunnel [km]	12.1	90.7				33.5		
Number of experiments (IPs)	2	4				2		
c.o.m. energy [GeV].	380	91.2	160	240	365	250	91.2	250
Longitudinal polarisation (e− / e+) [%]	80/0	-				80/30		
Nominal years of operation (equivalent)	8	3	2	3	4.5	3	1	3
Luminosity per IP above 0.99 $\sqrt{s}$ [10e34 cm−2 s−1]	1.3	140	20	7.5	1.4	1	0.28	2
Int. luminosity all IPs above 0.99 $\sqrt{s}$ per year [ab-1]	0.32	69	9.6	3.6	0.67	0.24	0.067	0.48

- **Efficiency (≤300–350 GeV):** FCC-ee delivers more luminosity per MW, more Higgs for shorter time
- **Flexibility:** FCC-ee can scan 90→240 GeV @ very high luminosity
- **Polarisation:** linear collider baselines include e^- polarisation; LCF can add e^+ polarisation

Plasma-wakefield Collider Studies

ALEGRO

Advanced LinEar collider study GROup

Since 2023

HALHF

Hybrid, **A**symmetric, **L**inear **H**iggs **F**actory

- e^- acceleration in **e^- beam–driven plasma wakefields**
- e^+ acceleration in radiofrequency cavities (C^3 technology)
- To make most effective use of space → collision of polarised 375 GeV e^- with 42 GeV e^+

Advantages:

+ most advanced wakefield collider concept → avoids e^+ acceleration in plasma

+ compact footprint, ~5 km

Since 2024

ALiVE

A Linear accelerator for **V**ery high **E**nergies

- e^- and e^+ acceleration in single stage **p^+ beam-driven plasma wakefields**
  - Enabled by the energetic and short **p^+** drivers
  - **p^+** drivers: high-rep.-rate 500 GeV synchrotron

Advantages:

+ avoids staging

+ compact footprint

+ scaling to higher energies (10 TeV)

Since 2025

10 TeV

Design Initiative for a **10 TeV** pCM Wakefield Collider

Technology candidates:

- Laser-Driven Plasma Wakefields
- Beam-Driven Plasma Wakefields
- Structure Wakefields

Collider type:

- e^+e^-
- e^-e^-
- γγ

Exploring the Quantum Universe

Goals include delivery of:

+ end-to-end design study report in 2028

+ roadmaps and resource estimates

Plasma-wakefield Collider Challenges

ALEGRO
Advanced LinEar collider study GROup

Since 2023

HALHF
Hybrid, **A**symmetric, **L**inear **H**iggs **F**actory

Challenges:

High repetition rate plasma operation and cooling, Staging, Production and acceleration of polarized beams, BDS design,…

10-15 years of R&D

ESPP Input #57: HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration (link)

Since 2024

ALiVE
A Linear accelerator for **V**ery high **E**nergies

Challenges:

High power synchrotron, Proton Bunch Compression, Plasma Source Development, Positron Acceleration, Energy Transfer Efficiency, Beam Quality Preservation,…

ESPP Input #210: Proton-Driven Plasma Wakefield Acceleration for Future HEP Colliders (link)

Since 2025

10 TeV
Design Initiative for a **10 TeV** pCM Wakefield Collider

Chosen design constraints:

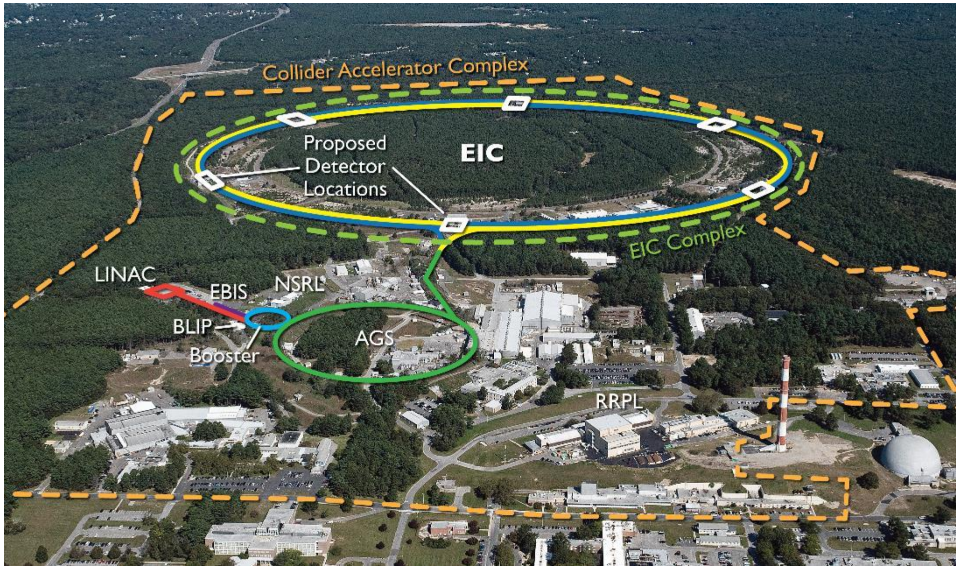
$E_{z,avg} > 500$ MeV/m
$\mathcal{L}/P_{tot} > 10^{32}\ \mathrm{cm^{-2}s^{-1}\ MW^{-1}}$

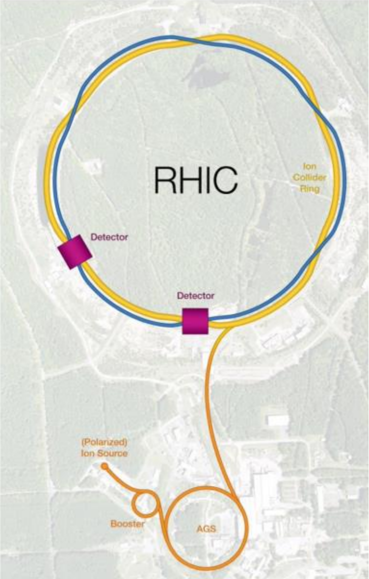
ESPP Input #98: Design Initiative for a 10 TeV pCM Wakefield Collider (link)

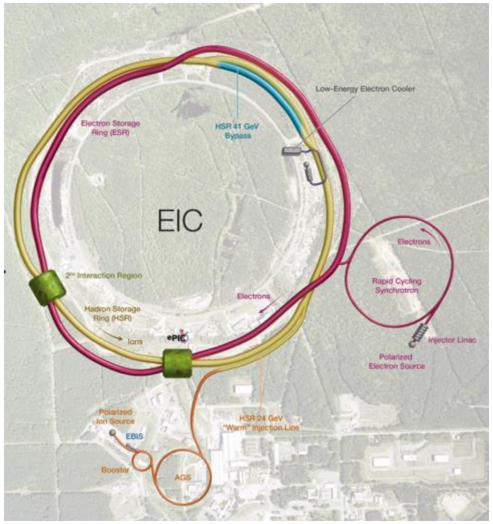
electron-hadron Colliders

Electron-Ion collider

- **Hadron storage Ring (RHIC Rings) 40-275 GeV** **(existing)**
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - Strong hadron cooling
- **Electron storage ring 5–18 GeV, ~3.8 km**
  - many bunches (1160 – 290)
  - large beam current, 2.5 A ➔ 9 MW S.R. power
  - S.C RF cavities
  - Polarized bunches (up to 70%)
- **Electron rapid cycling synchrotron 0.75-18GeV**
  - 1-2 Hz
  - Spin transparent due to high periodicity
- **High luminosity interaction region(s)**
  - $L = 10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad Crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation

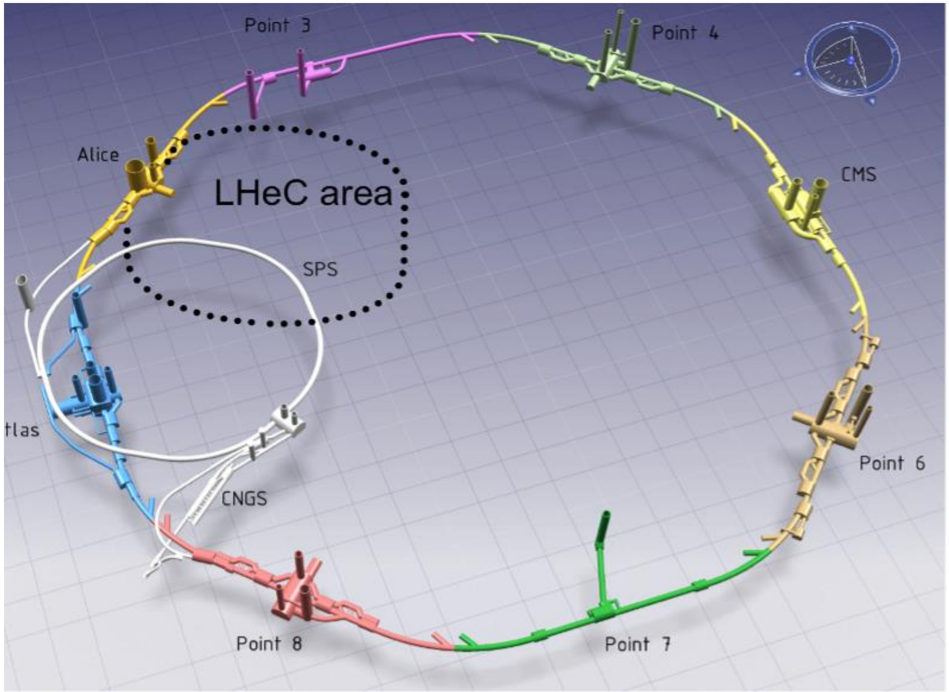






LHeC challenges

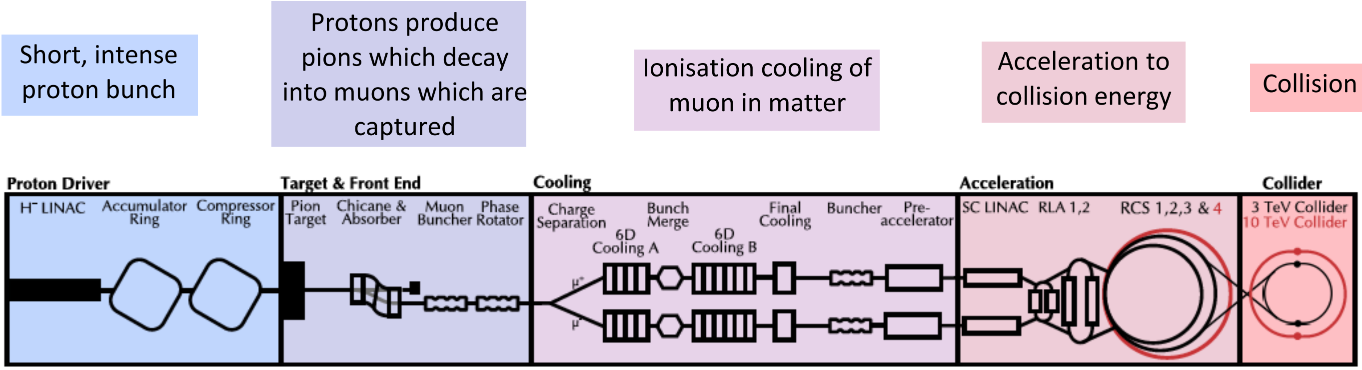
- **50 GeV electrons** on **7 TeV protons**
- **Accelerator** :
  - **3-turn** high-current **Energy Recovery Linac (ERL)** in a new tunnel tangential to the LHC at IP2 (~**9 km** long)
  - **High-intensity** operation to be demonstrated inn PERL, including challenges in **recovery efficiency** + **beam-loss** control
- **Performance**:
  - Total integrated luminosity **~1 ab^{-1}** over ~6 years



Muon Collider

Muon Collider

A credible *non-parton* route to probing the **"10 TeV energy scale"** with lepton collisions, if the key feasibility issues can be cracked. Clean lepton initial state at multi-TeV; strong direct reach for heavy new states.



Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

- CERN implementation: reuse **SPS & LHC** tunnels for parts of the acceleration chain; could reach up to ~7.6 TeV c.m, with a practical first stage ~3.2 TeV

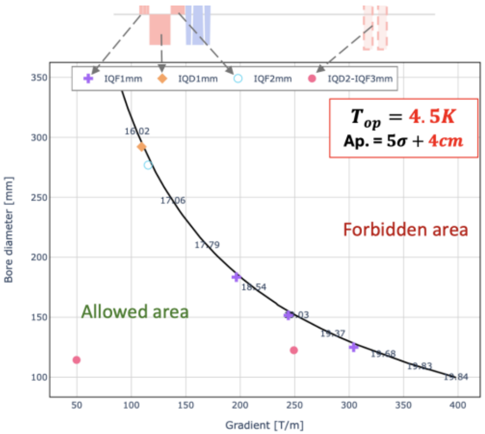
Parameter	Unit	3 TeV	10 TeV	3.2 TeV	7.6 TeV
L	**10^{34} cm^{-2}s^{-1}**	**1.8**	**18.75**	**0.74**	**7.9**
N	10^{12}	2.2	1.8	2.2	1.8
f_r	Hz	5	5	5	5
P_{beam}	**MW**	**5.3**	**14.4**	**5.3**	**11**
C	km	4.5	10.7	11	11
B_{dipole}	T	11	15	4.8	11
Collider techn.		Nb3Sn	HTS	NbTi	Nb3Sn

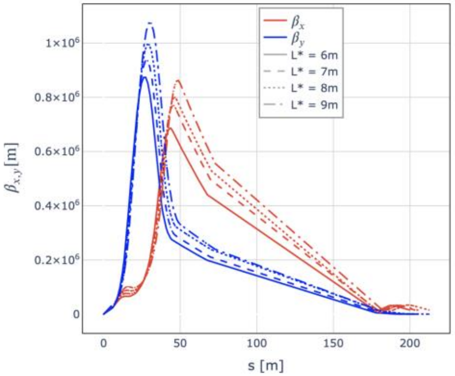
D. Schulte et al

Muon Collider @ 10 TeV

More realistic constraints in the design

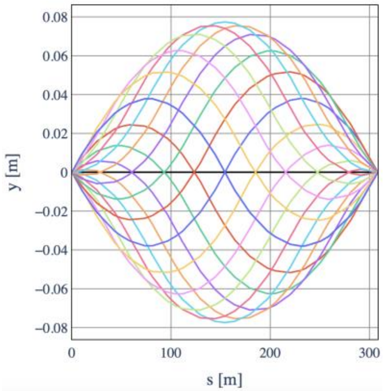
- IR quadrupoles meet magnet requirements.
- Assess impact of L*, shielding thickness, and interconnect length on optics and performance.
- *Proof of concept* shows combined-function magnet constraints are manageable.

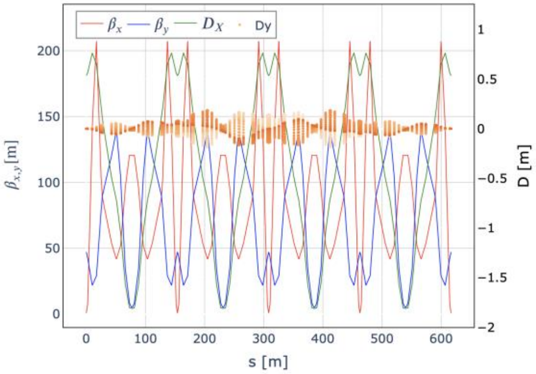




Vertical periodic machine deformation (spread neutrino radiation)

- Implemented in regular arc cells, with cancellation of vertical dispersion.
- Ongoing studies to evaluate feasibility in local chromatic correction sections.





M. Vanwelde, C. Carli, D. Schulte et al

Luminosity Summary

Angela Taliercio

Project	IP	Z-pole (91.2 GeV)	WW (160 GeV)	Higgs (230-250 GeV)	Top (365 GeV)	Higher Energy
FCC-ee	4	205 ab^{-1} 4 year	19 ab^{-1} 2 year	11 ab^{-1} 3 year	3 ab^{-1} 5 year	–
FCC-hh	2	–	–	–	–	84.6 TeV: 0.6 ab^{-1} / year /IP
LEP3	2	53 ab^{-1} 5 years	5 ab^{-1} 4 years	2.5 ab^{-1} 6 years	–	–
Linear colliders	1	0.07 ab^{-1} 1 year	–	2 ab^{-1} 3 years	CLIC: 4.4 ab^{-1} 10 years	550 GeV: 8 ab^{-1} 1.5 TeV: 4 ab^{-1} 10 years
LHeC	1	–	–	–	–	1 TeV for 6 years
Muon Collider	2	–	–	–	–	10 TeV: 1.1 ab^{-1} 8 year

Operation at 550 GeV or higher would offer competitive programmes in Higgs and top-quark physics,

Thank you for your attention…