Accelerators for Collider Experiments

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2024 HCPSS
23 July 2024

Today’s plan

3. Key technologies
4. Collider operations
5. Proposals for the future and challenges

Collider Luminosity

For equal intensity round beams with Gaussian profile

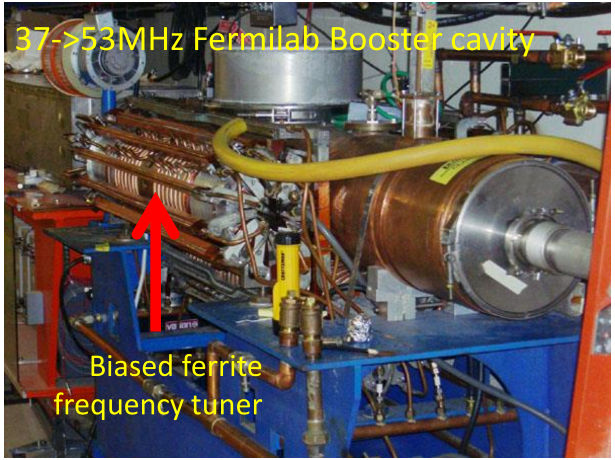
$$L = f_0 n \frac{\gamma}{4\pi} \frac{1}{\beta^*} \frac{N_b^2}{\epsilon_N} R(\sigma_s, \theta)$$

The parameters are

– f_0-revolution frequency	smaller rings are more advantageous
– N_b-number of particles per bunch	produce and maintain high beam current
– n-number of bunches	maximize number of bunches in the ring
– β^*- beta-function at the collision point	focus as strongly as possible (magnet technology)
– γ- relativistic factor	beam energy
– ϵ_N- normalized beam emittance	produce and maintain brightest beams
– R-geometrical factor <1	collide head-on or ‘crab’ beams

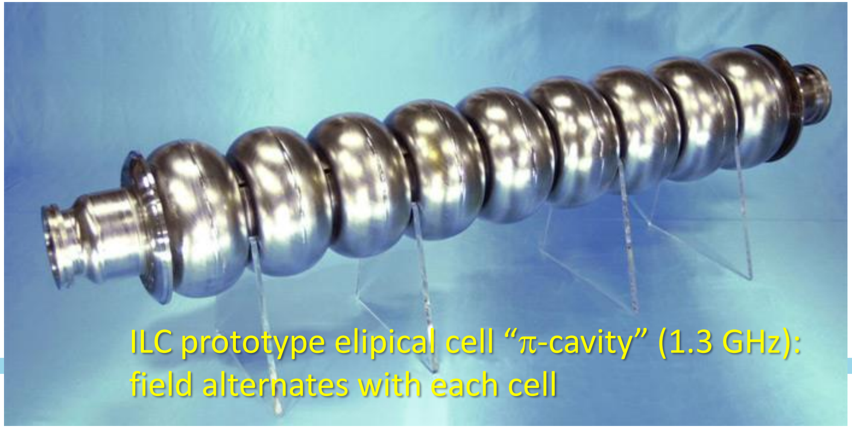
Beam energy – accelerating RF structures

Fermilab Drift Tube Linac (200MHz): oscillating field uniform along length



37->53MHz Fermilab Booster cavity

Biased ferrite frequency tuner



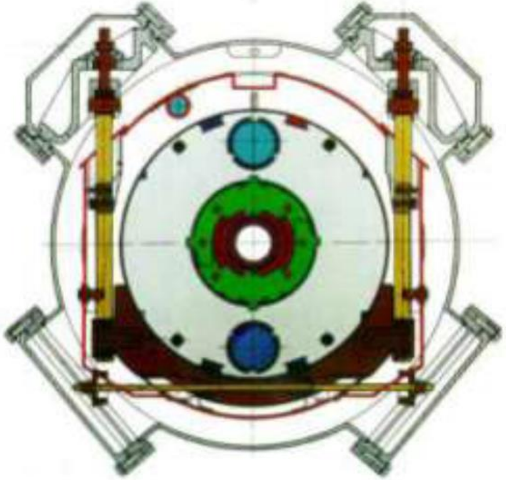
ILC prototype elipical cell “π-cavity” (1.3 GHz): field alternates with each cell

Beam energy – magnet technology

Tevatron,
6 m, 76 mm
774 dipoles

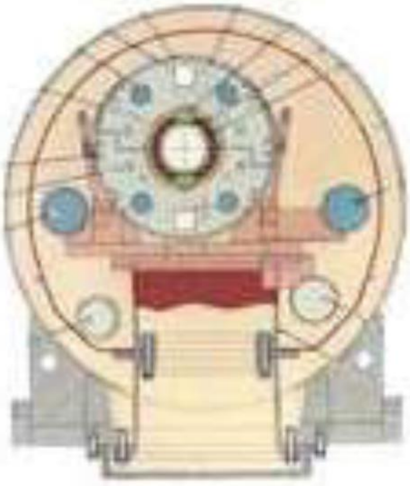
4.5T

HERA,
9 m, 75 mm
416 dipoles



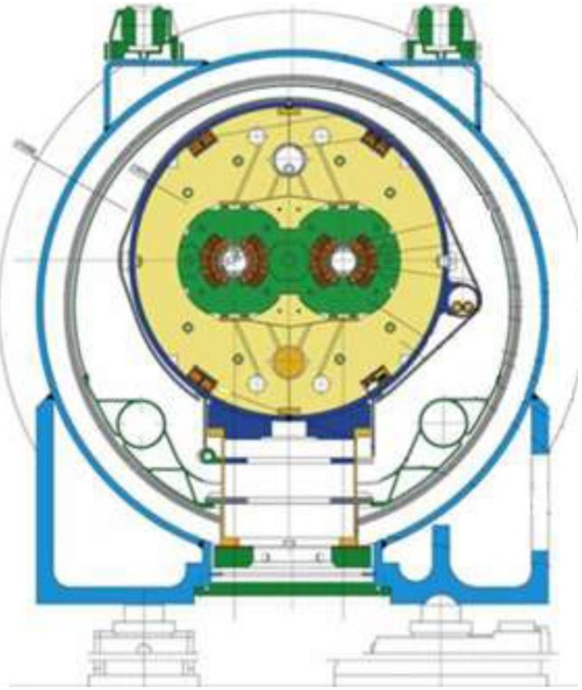
5.3T

RHIC,
9 m, 80 mm
264 dipoles



3.5T

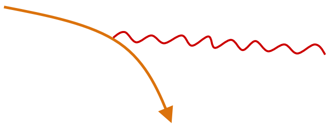
LHC,
15 m, 56 mm
1276 dipoles



8.3T

Synchrotron radiation

- Charged particle traveling on a curved trajectory emits photons = synchrotron radiation

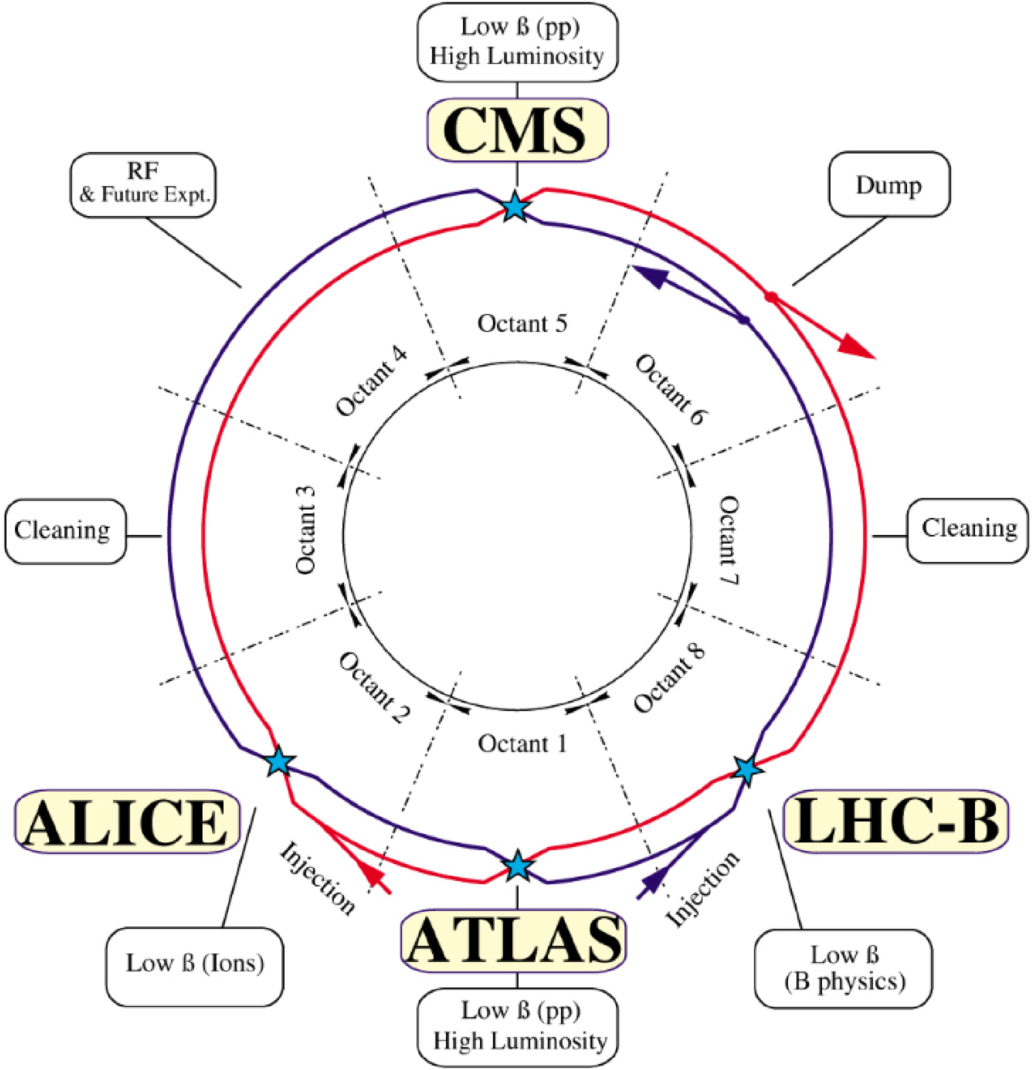


$$Radiated\ power\ \propto \frac{1}{\rho^2}\left(\frac{E}{m}\right)^4$$

An electron will radiate about *10^{13} times more power* than a proton of the same energy!!!!

- Protons: synchrotron radiation does not affect kinematics very much
  - Energy limited by strength of magnetic fields and size of ring
- Electrons: Synchrotron radiation dominates kinematics
  - To reach higher energy, we have to lower the magnetic field and go to huge rings
  - Eventually, we lose the benefit of a circular accelerator, because we lose all the energy each time around
  - Since the beginning, the “energy frontier” has belonged to proton (and/or antiproton) machines, while electrons are used for precision studies

LHC layout



$E = 7$ TeV

$B = 8.3$ T

$C = 27$ km

$$\rho = \frac{pc}{eB}$$

$$\frac{2\pi\, pc}{C\ eB} = 0.66$$

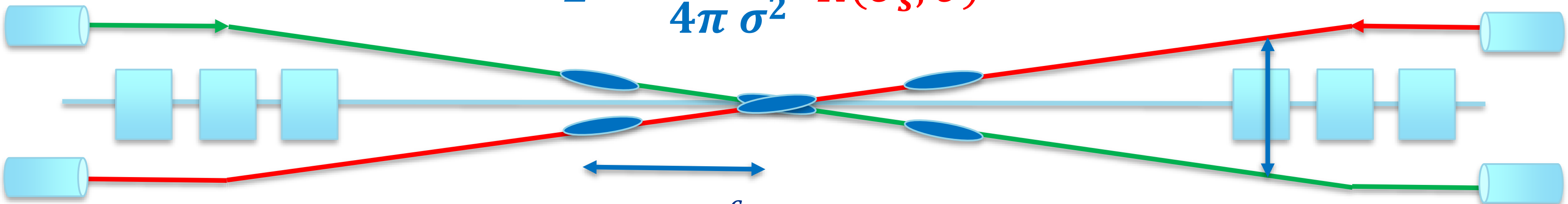
packing factor

Beam crossing scheme

Sketch not to scale!

$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_s, \theta)$$

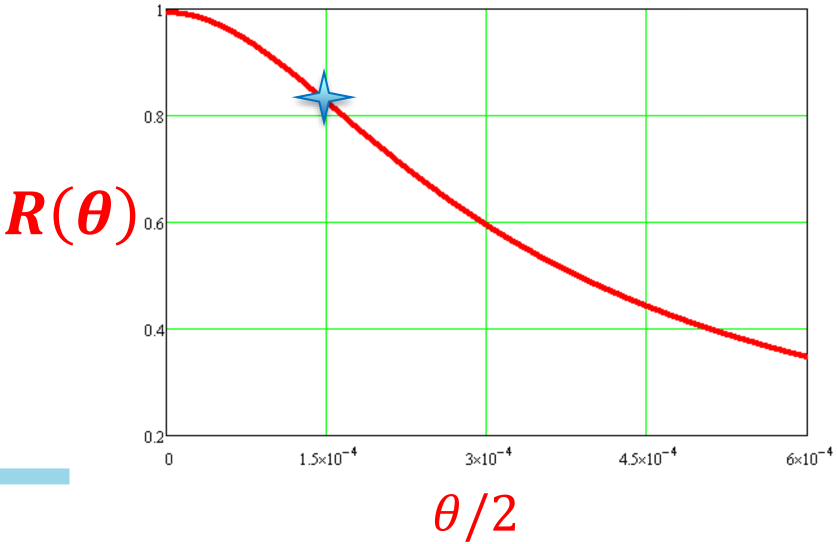
$A_{FF} \approx L^* \times \theta = 10$ mm



$z_{LR} = 25ns \times \frac{c}{2}$ =3.75m

Beams must be separated in parasitic crossings

- Too small angle → disruptive electromagnetic interaction (*beam-beam*)
- Too large angle →
  - Geometric luminosity loss R
  - Aperture limitation in triplet A_{FF}
- LHC design crossing angle θ =300 μrad

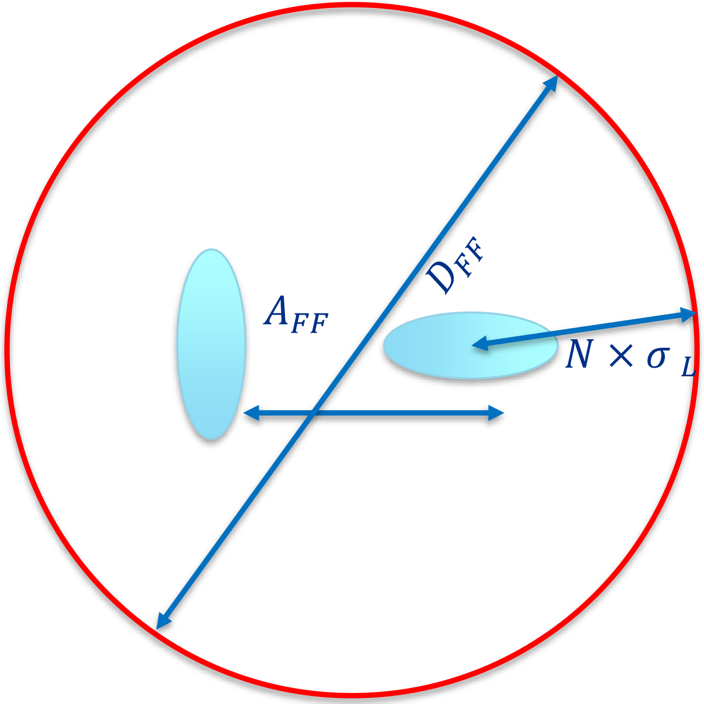


Beam focusing – Final Focus (a.k.a. Low-Beta Triplet) quads

$$L = \frac{n_b N_p^2 f_0}{4\pi\, \sigma^2} R(\sigma_s, \theta)$$

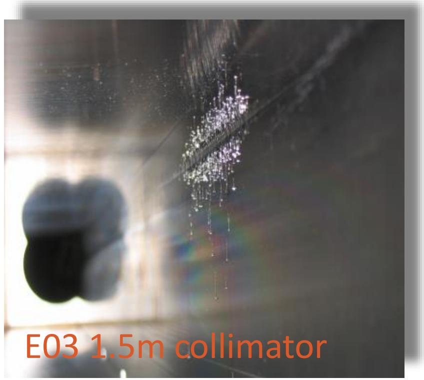
Final Focus Quadrupole Magnet Challenges

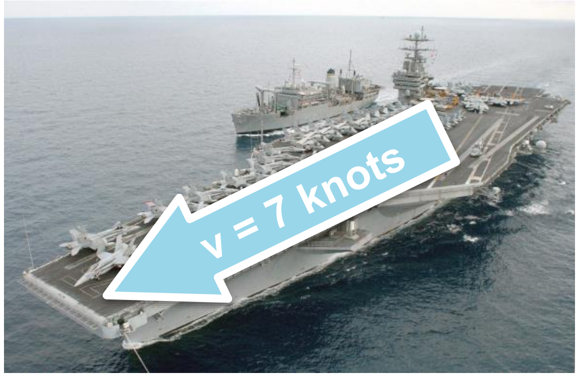
- Bore is determined by beam size and crossing angle/separation $D_{FF} = L^* \times \theta + 2 \times 10 \times \sigma_L = 63\ mm$
- Gradient is determined by beam energy, magnet length, beta-function, magnet technology
  - NbTi conductor, 70 mm coil bore
  - Gradient $G = 215\ T/m$
  - Peak field in coil 7.7 T
- Must possess high field uniformity
- Must withstand high levels of radiation / heat load near IP



High beam current issues

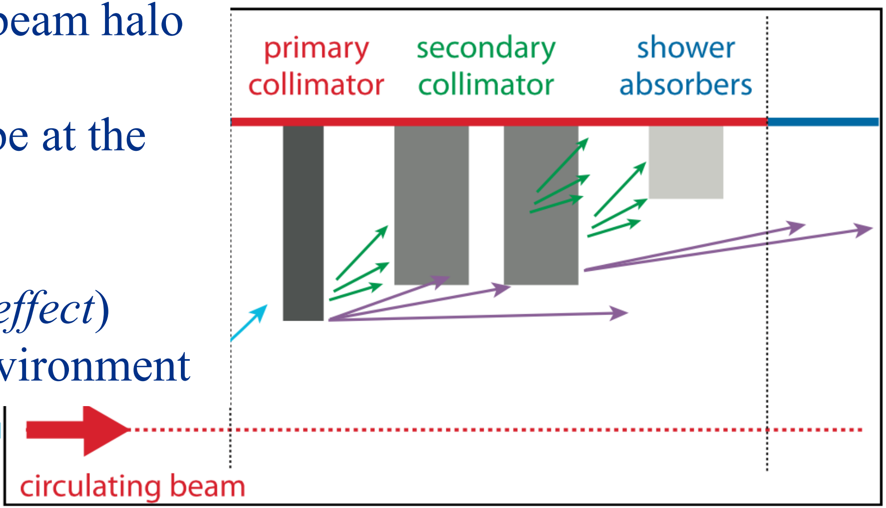
$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_s, \theta)$$





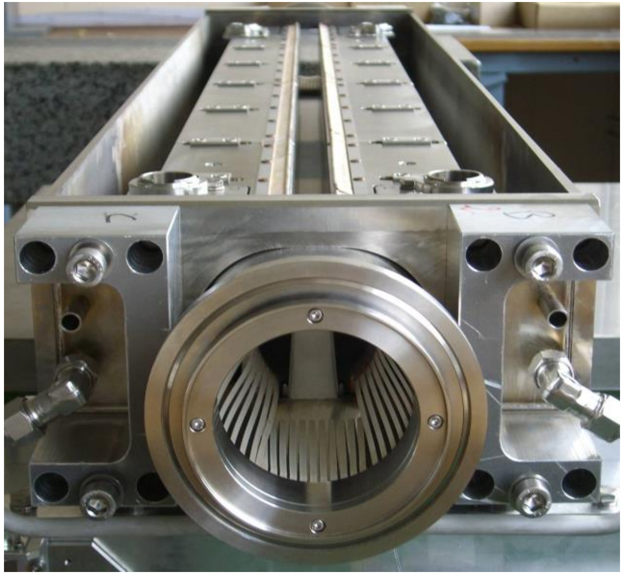
Energy stored in the beam is significant $\sim 400MJ$. Even %-scale beam loss can damage components

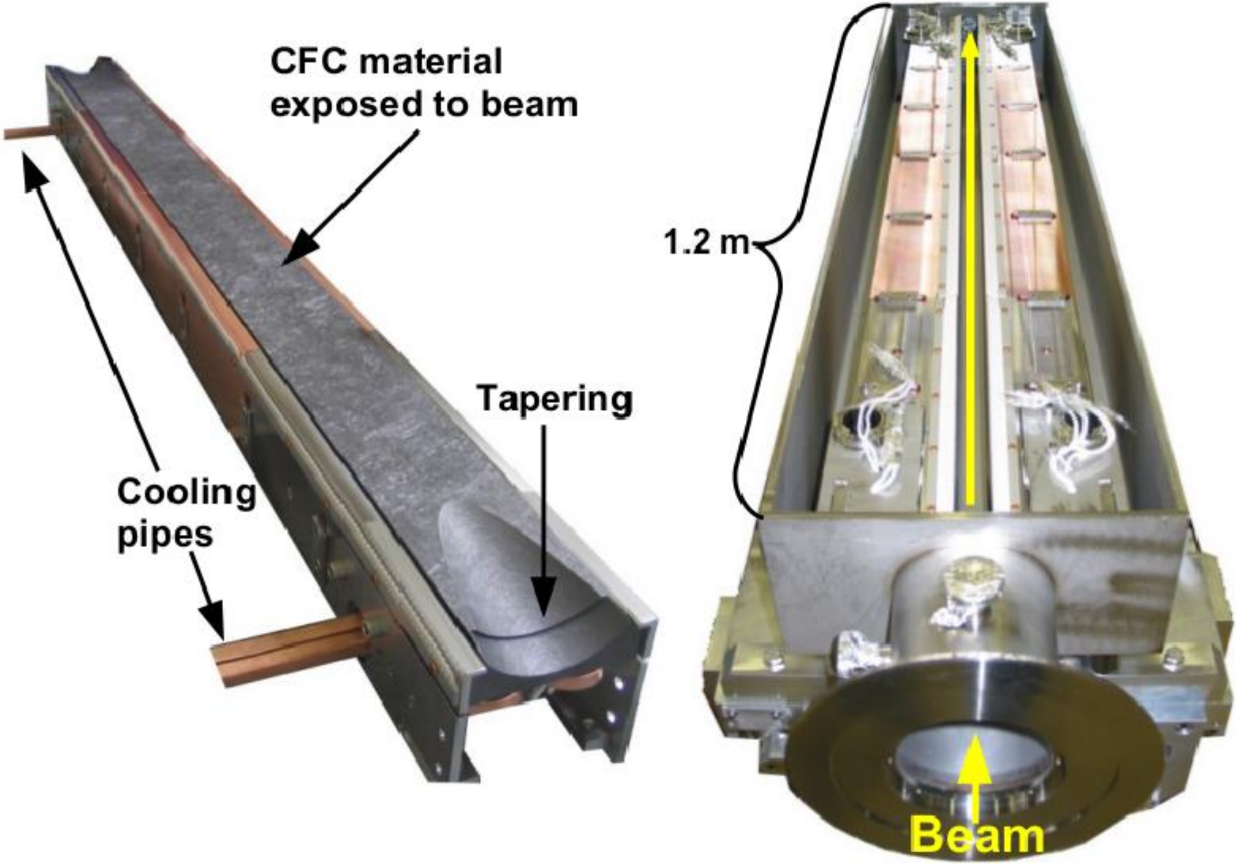
- Collimation system to safely remove/absorb beam halo and protect the machine
- Beam dynamics understanding/control must be at the highest level
  - Interaction of colliding bunches via electromagnetic fields (aka *beam-beam effect*)
  - Interaction of beams with accelerator environment



LHC collimator

- Two jaws, beam passing in between, most are 1 m long





LHC collimation system layout

Two warm cleaning insertions, 3 collimation planes

- **IR3: Momentum cleaning**
  - **1 primary (H)**
  - **4 secondary (H)**
  - **4 shower abs. (H,V)**
- **IR7: Betatron cleaning**
  - **3 primary (H,V,S)**
  - **11 secondary (H,V,S)**
  - **5 shower abs. (H,V)**

Local cleaning at triplets

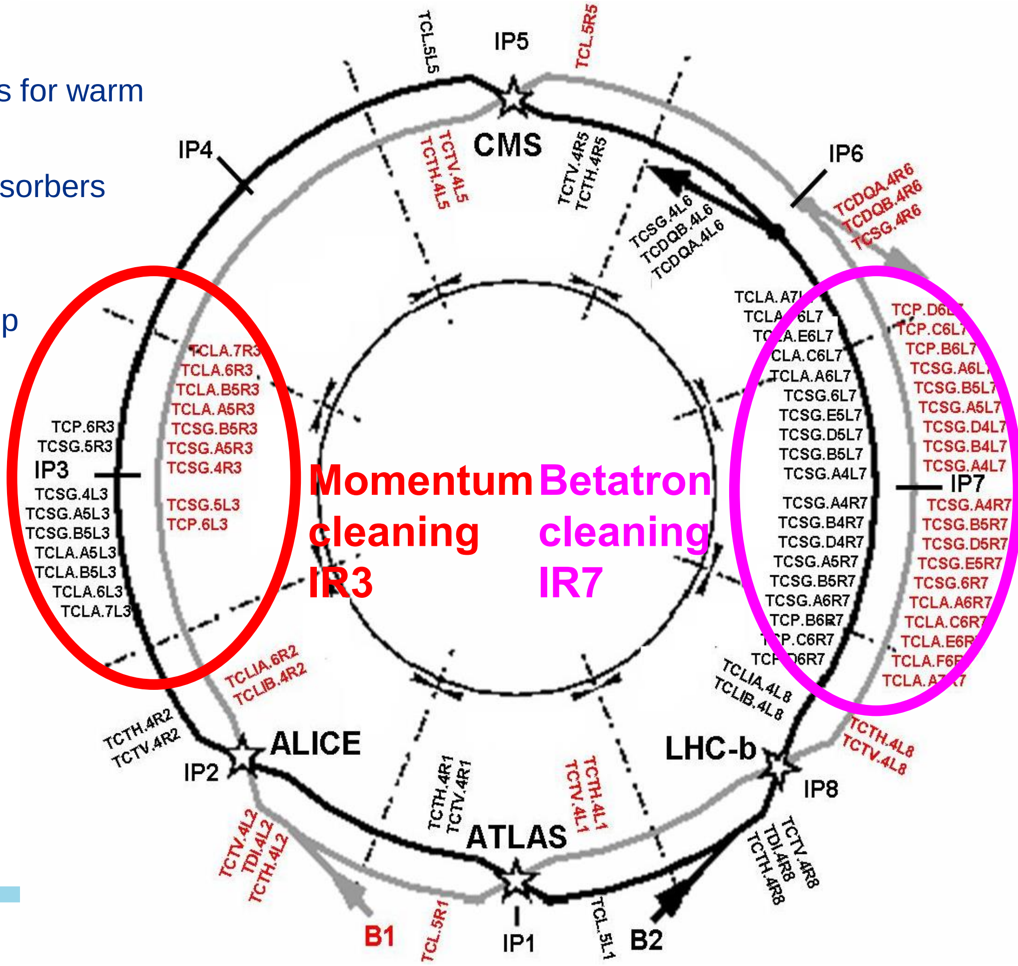
- **8 tertiary (2 per IP)**

Passive absorbers for warm magnets

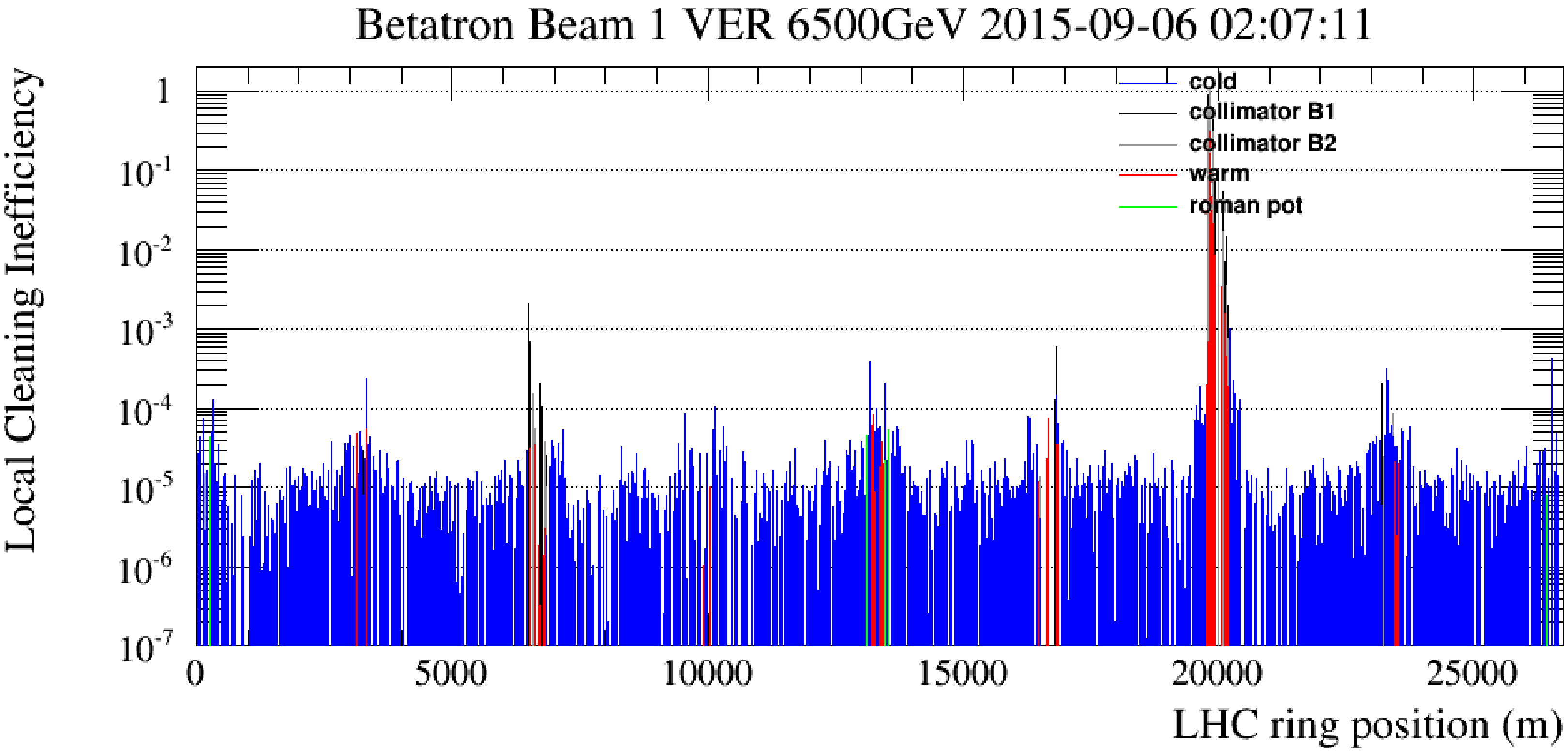
Physics debris absorbers

Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 108 collimators (100 movable).
Two jaws (4 motors) per collimator!



Efficient beam halo cleaning in the LHC



Aberrations to linear focusing

- The key principle of everything we considered so far – linear focusing

$$H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

- What about higher order terms?
  - Imperfections in magnet construction
  - Chromatic aberrations ∝ quadrupole gradient
  - Coulomb self-interaction inside beams
  - E/M interaction of beam with environment (image charges, etc)
  - E/M interaction between beams
  - Intentionally introduced multipole magnets (e.g. sextupoles to correct chromaticity)

$$F \propto \frac{e}{(p_0 + \Delta p)c} \frac{\partial B_y}{\partial x} x$$

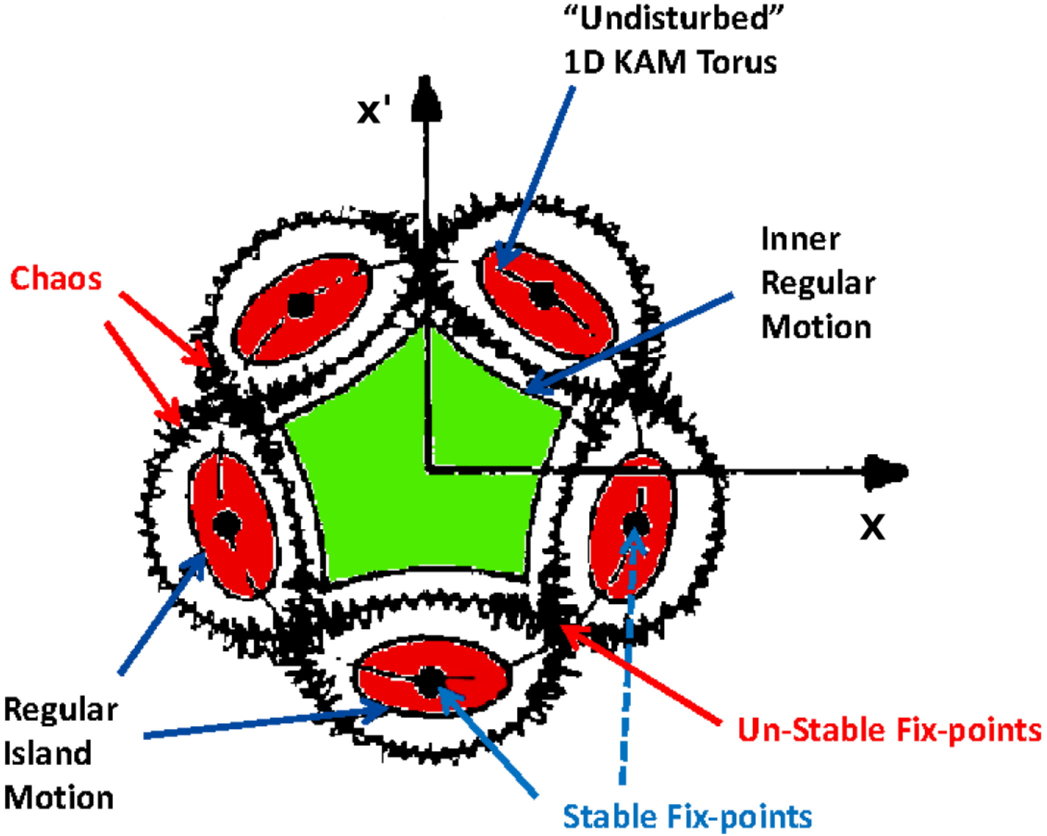
- All are aberrations to the initially decoupled system of two linear oscillators
  - Since the 60ies, thousands of papers on mitigation
  - Accelerator physics on crossroads of plasma, nonlinear dynamics, etc.

Aberrations of linear focusing

$$x'' + K_x(s)x = S(s)x^2 + O(s)x^3 + \cdots$$

- Nonlinearities result in dependence of oscillation frequency (tune) on amplitude
- Explicit time-dependence of multipole coefficients results in resonances
- Coupling between x and y further complicates the dynamics
- Ultimately, chaos and loss of stability
  - Beam quality degradation (blow-up)
  - Particle loss from accelerator
- We call this single particle stability or Dynamical Aperture

Phase space portrait



graphics courtesy
F.Schmidt CERN

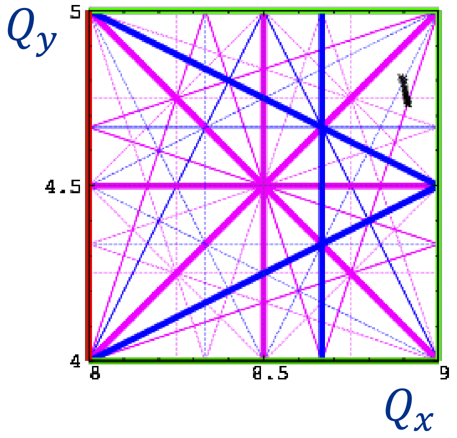
Tune, Stability, and the Tune Plane

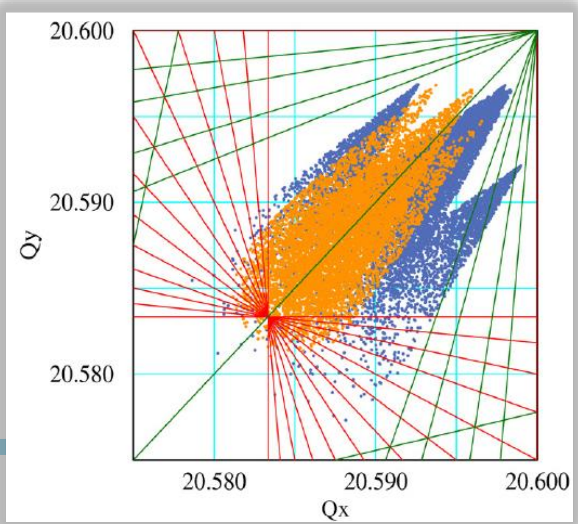
- If the tune is an integer, or low order rational number, then the effect of any imperfection or perturbation will tend be reinforced on subsequent orbits.
- When we add the effects of coupling between the planes, we find this is also true for *combinations* of the tunes from both planes, so in general, we want to avoid

$$k_x \nu_x \pm k_y \nu_y = \text{integer} \Rightarrow (\text{resonant instability})$$

“small” integers

➔Avoid lines in the “tune plane”

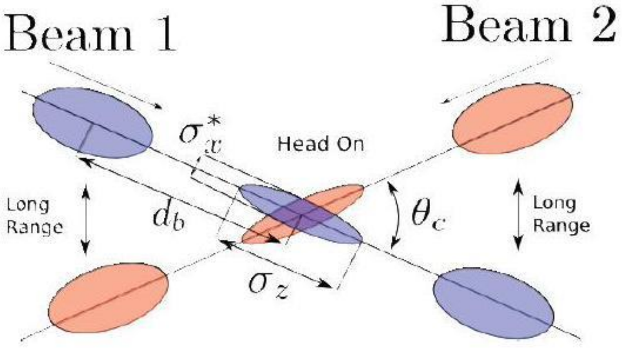




- Many instabilities occur when something perturbs the tune of the particle, until it falls onto a resonance, thus you will often hear effects characterized by the “tune shift” they produce.
  - For example: the maximum tune shift sets the absolute luminosity limit in a collider

Beam-beam interactions

In colliders in addition to the focusing magnets, particles experience interactions with electromagnetic field of counter-rotating beam.



$$F_{BB} \propto \Delta\nu_{BB}\frac{1}{r}\left(1-e^{-\frac{r^2}{2\sigma^2}}\right)$$

$$\boxed{\Delta\nu_{BB} = \xi = \frac{N r_0 \beta}{4\pi\gamma\sigma^2}}$$

b-b tuneshift

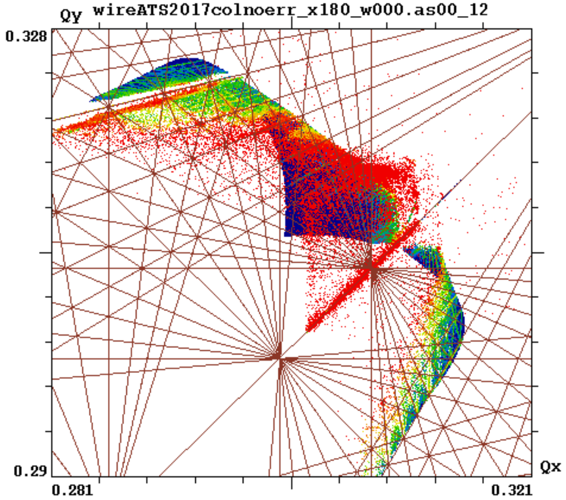
$$x'' + K_x(s)x = F_{BB}(x, y, s)$$

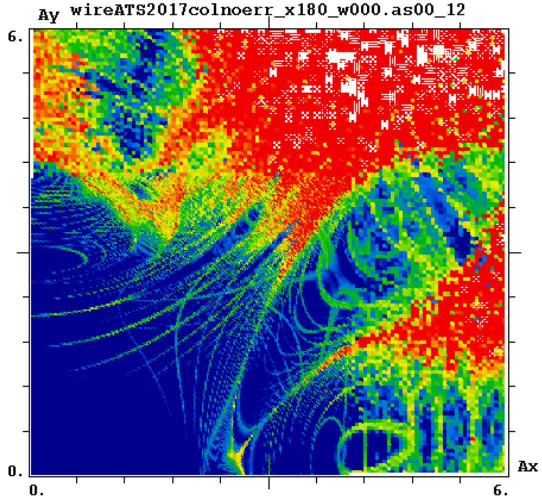
Even though beam-beam adds relatively little to focusing (typical tune shift for LHC is 0.02 at lattice tune of 60), the beam-beam force is strongly nonlinear and localized in time → **unstable motion and losses**

Example of single-particle dynamics limitations – HL-LHC

- Nonlinearity caused by E/M interactions between colliding beams (beam-beam)
- Note that frequency spread ∝ beam brightness
  - Characteristic spread

    0.02 for LHC





  - Frequency Map Analysis invented for analysis of motion of Solar system
    - J. Laskar, Icarus 88, 266-291 (1990) “The Chaotic Motion of the Solar System: A Numerical Estimate of the Size of the Chaotic Zones”

Collective instabilities

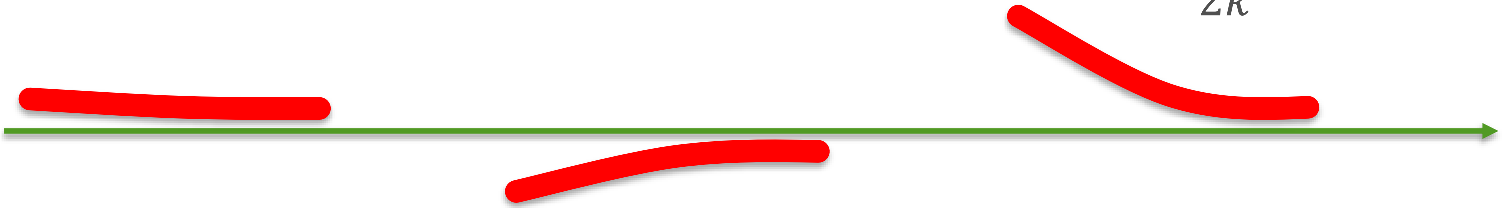
In addition to the single-particle chaos, the beam can become unstable as a whole if resonantly excited by external field or via self-interaction through environment

- Simple example: beam breakup instability
  - Two particles – leading (head) particle and trailing (tail) particle
  - Head particle motion

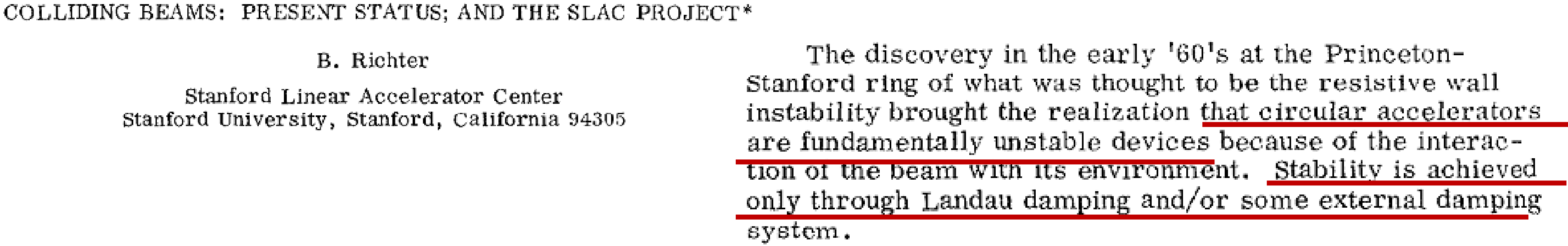
$$x_1'' + k^2 x_1 = 0, x_1 = a_1 \cos ks$$

  - Head particle through interaction with environment leaves E/M wake acting on tail particle

$$x_2'' + k^2 x_2 = W x_1, \qquad x_2 = a_2 \cos ks + \frac{W a_1 s}{2k} \sin ks$$



Landau Damping of collective instabilities



COLLIDING BEAMS: PRESENT STATUS; AND THE SLAC PROJECT*

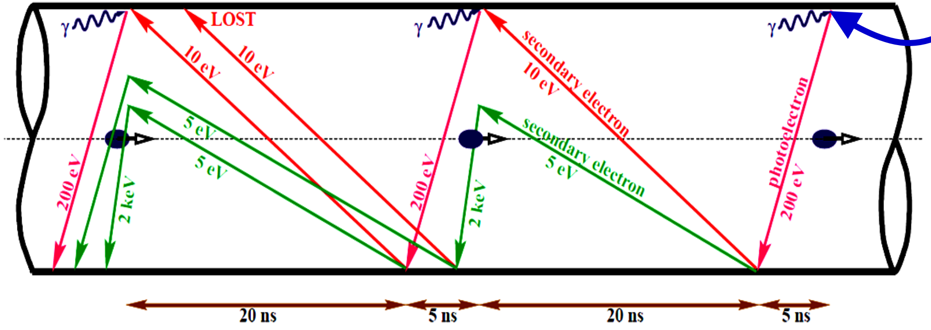
B. Richter

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

The discovery in the early '60's at the Princeton-Stanford ring of what was thought to be the resistive wall instability brought the realization that circular accelerators are fundamentally unstable devices because of the interaction of the beam with its environment. Stability is achieved only through Landau damping and/or some external damping system.

- 1965 Priceton-Stanford CBX: First mention of an 8-pole magnet
  - Observed vertical resistive wall instability
  - With octupoles, increased beam current from ~5 to 500 mA
- CERN PS: In 1959 had 10 octupoles; not used until 1968
  - At 10^{12} protons/pulse observed (1st time) head-tail instability. Octupoles helped.
  - Once understood, chromaticity jump at transition was developed using sextupoles.
  - More instabilities were discovered; helped by octupoles, feed-back
- LHC has 336 octupoles that run at 500A to create 0.001 tune spread
- FCC will require ~ 20,000 octupoles to retain stability

One particular source of instabilities – electron cloud



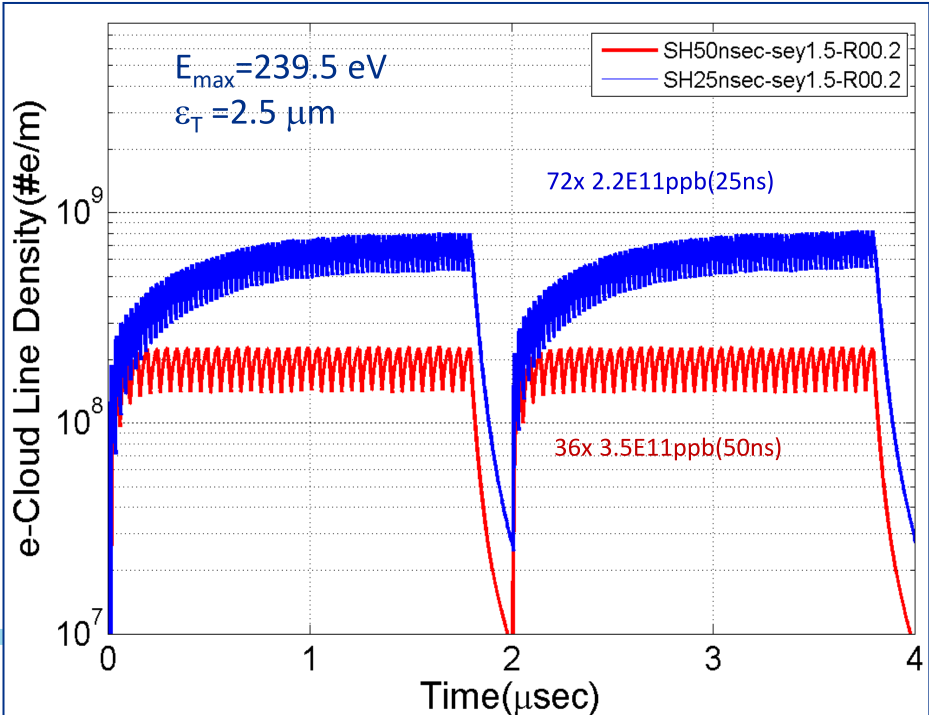
The critical energy of the photons at 7 TeV ~ 44 eV

- Primary sources of electrons in the LHC
  - At Injection (450 GeV) gas ionization
  - At 7 TeV Synchrotron Radiation

Consequences:

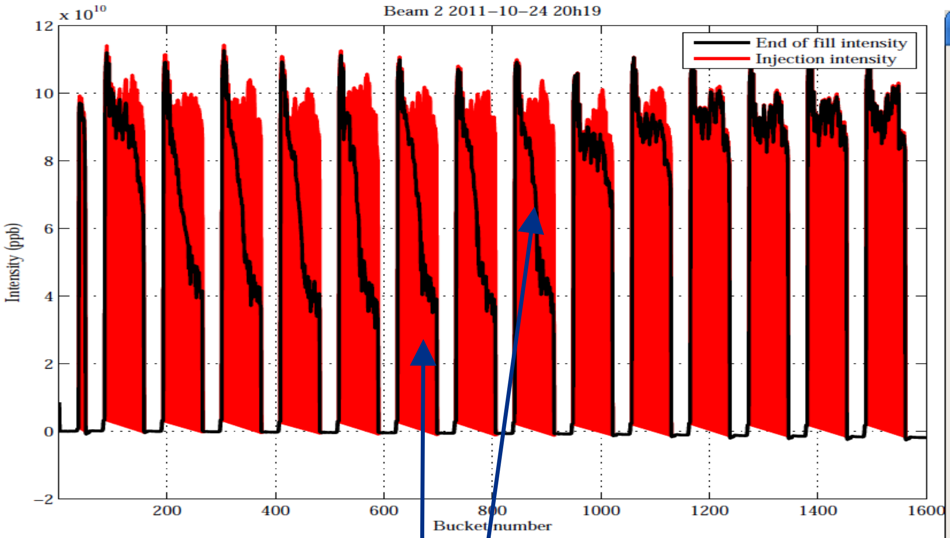
- instabilities, emittance growth, desorption ←bad vacuum, beam loss

- excessive energy deposition in the cold sectors


E_{max}=239.5 eV

ε_T =2.5 μm

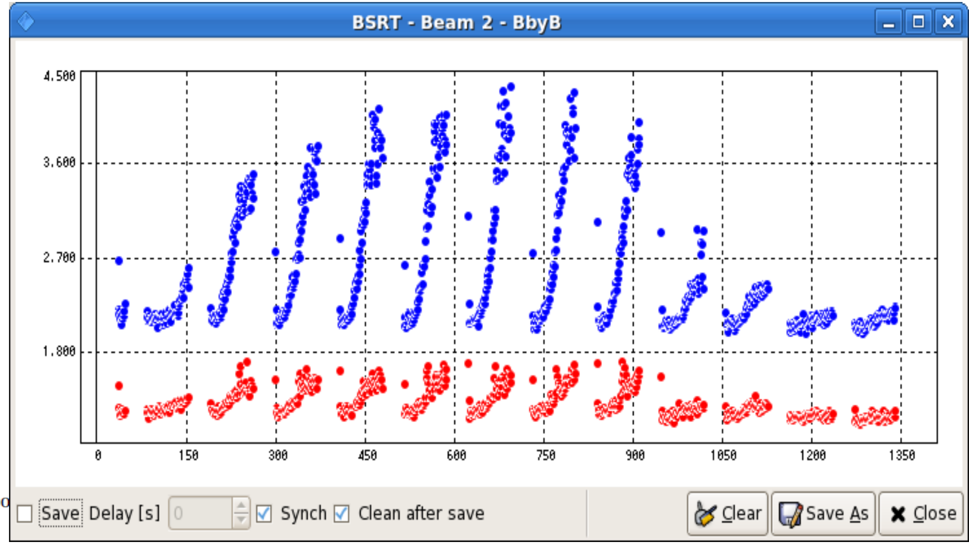
Effect of electron cloud on beam



Injection Intensity

End of fill Intensity

Bunch #



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Measured Emittance Growth

~33% Horizontal

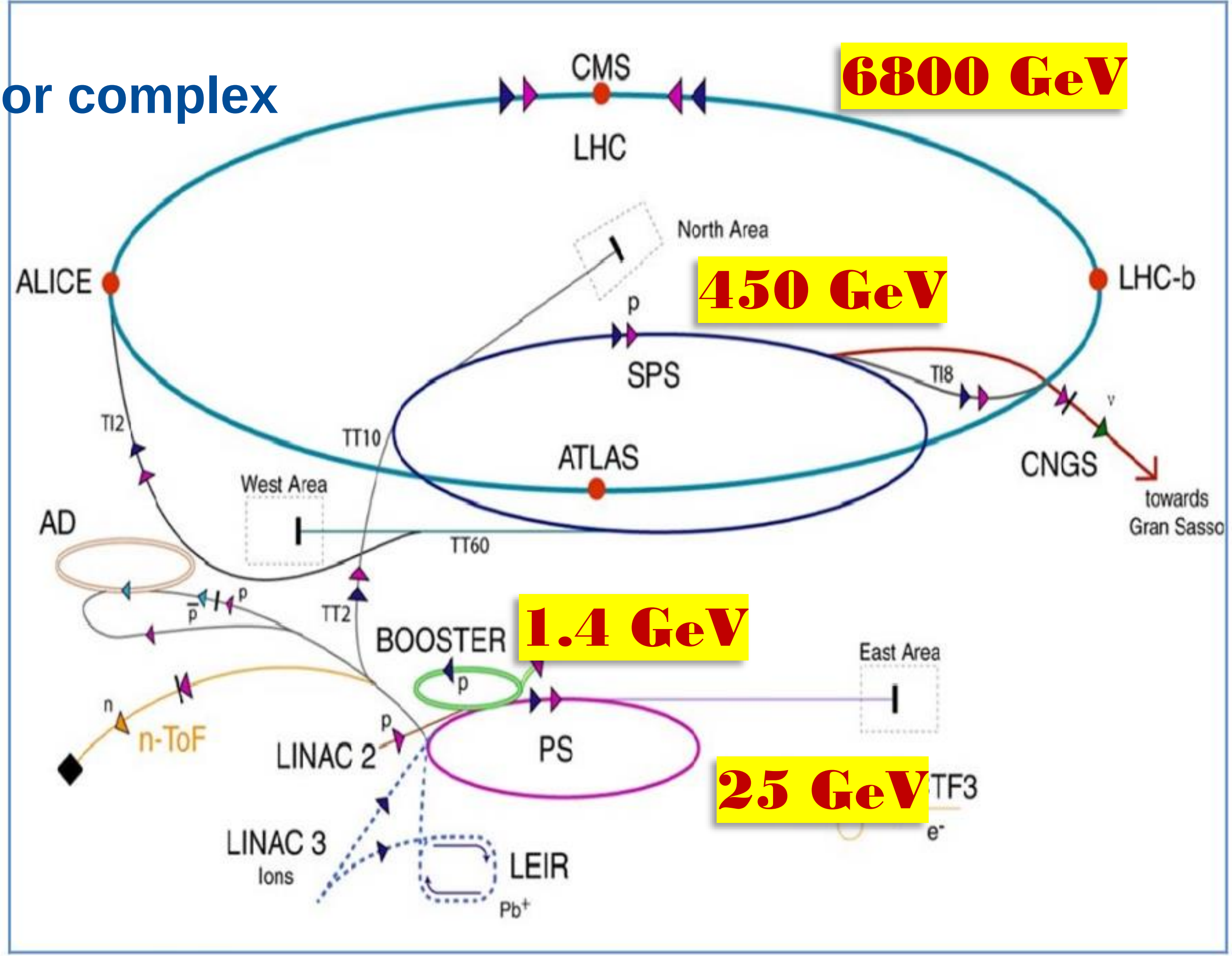
~110% Vertical

Associated beam loss

Collider operations

Over 100,000 signals are generated by the cryogenics, machine protection and beam monitoring systems.

CERN accelerator complex



6800 GeV

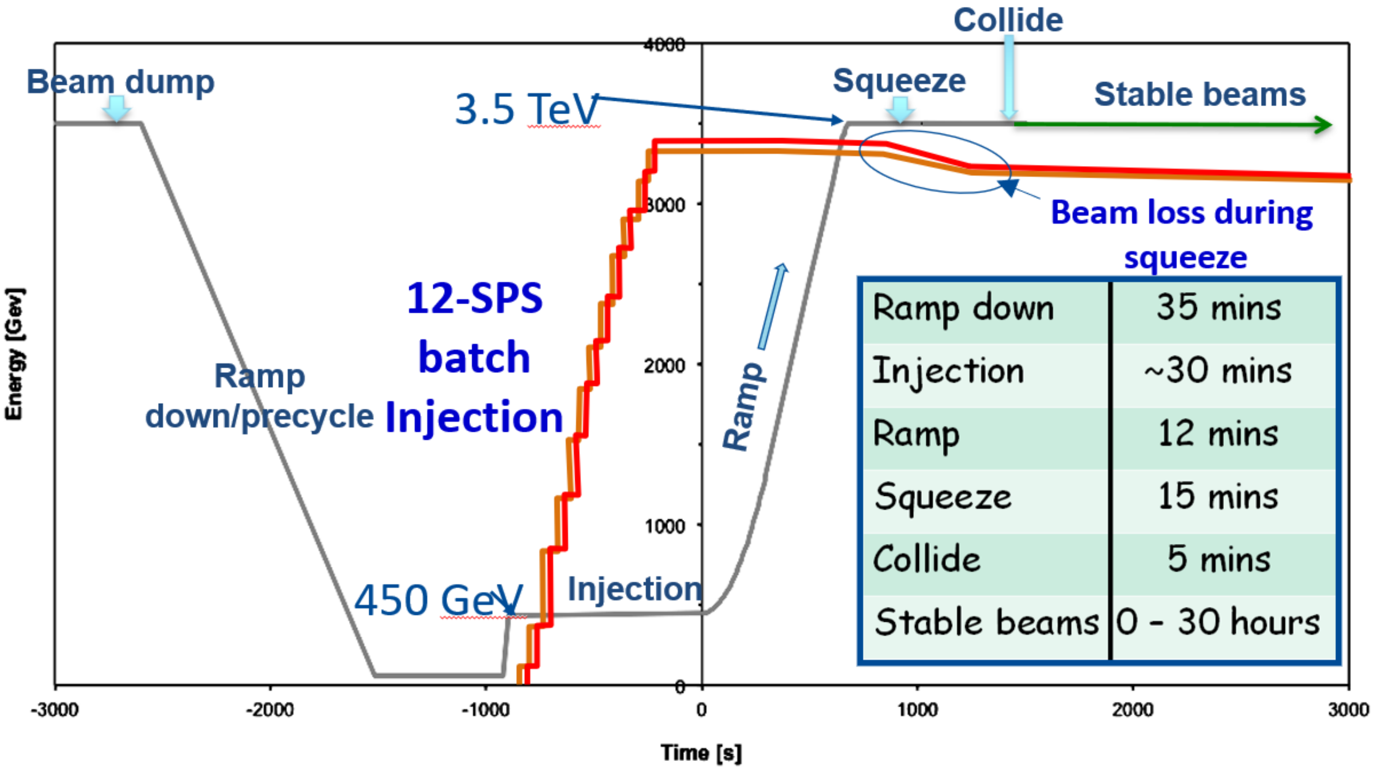
450 GeV

1.4 GeV

25 GeV

Collider cycle

A Schematic of LHC Operational Cycle at half nominal energy



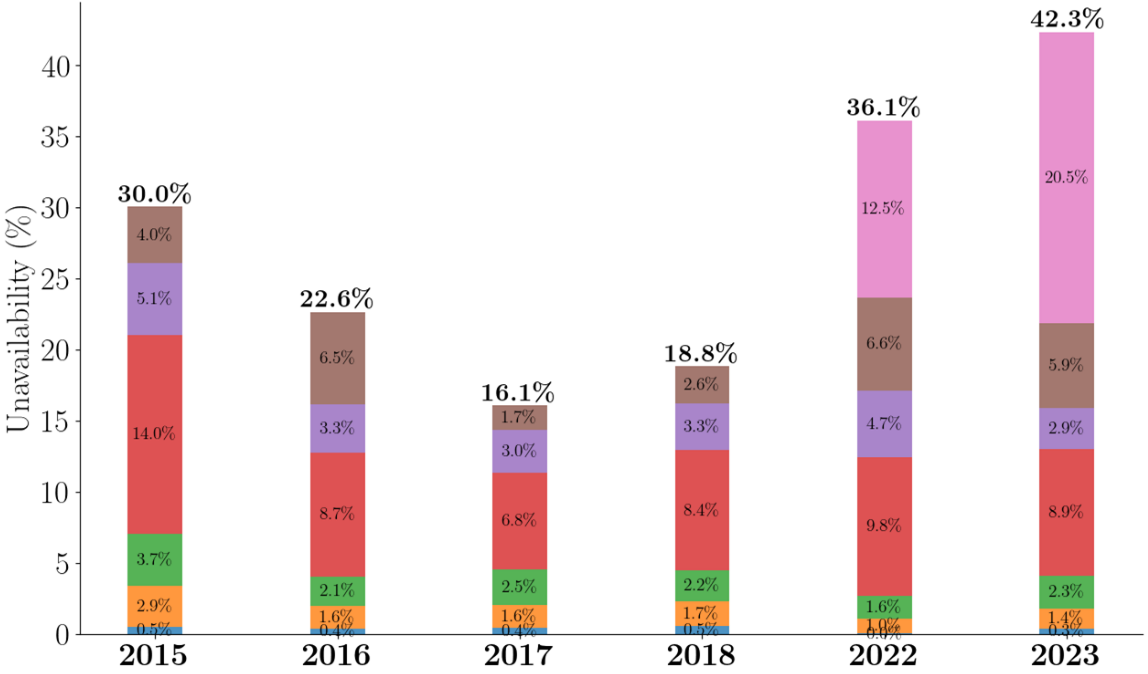
Ramp down	35 mins
Injection	~30 mins
Ramp	12 mins
Squeeze	15 mins
Collide	5 mins
Stable beams	0 - 30 hours

LHC design parameters

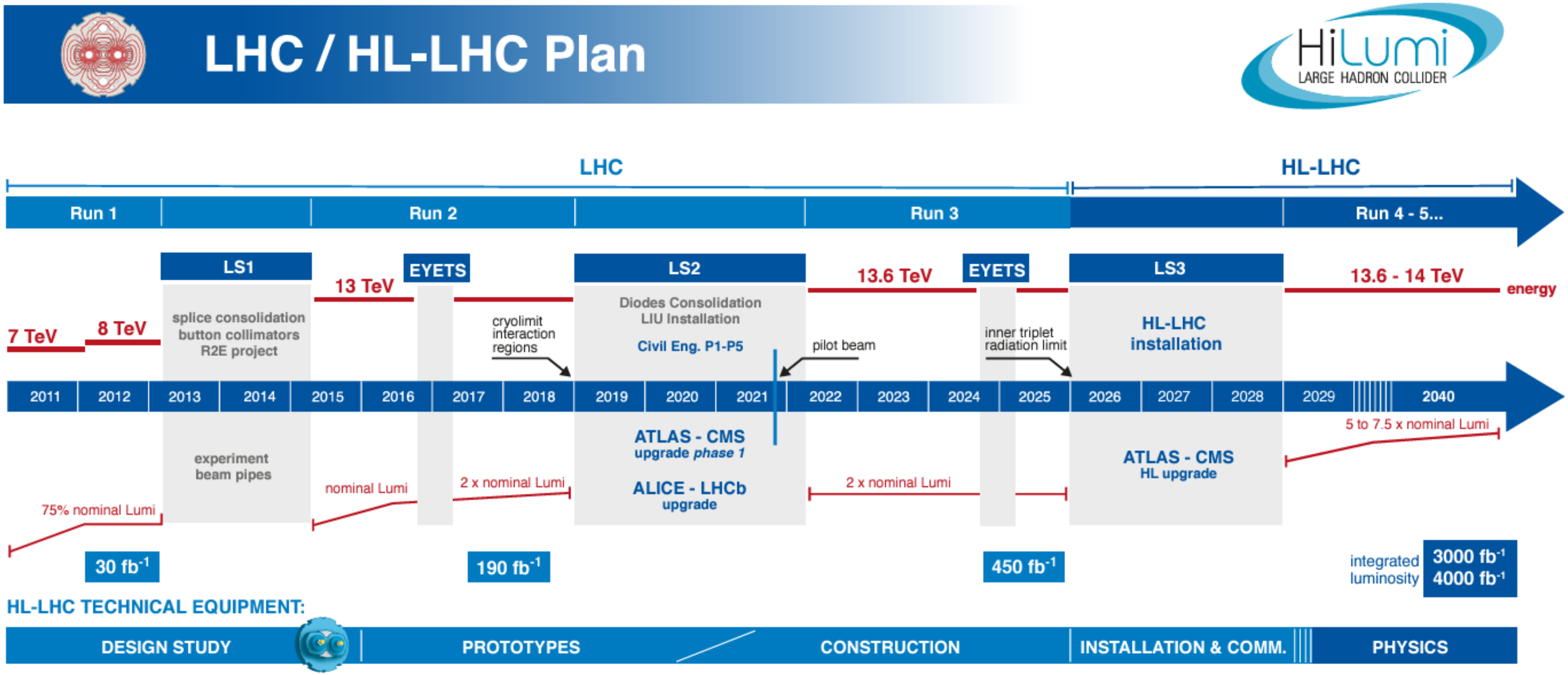
	LHC nominal
Beam energy	7 TeV
Number of bunches	2808
protons / bunch [10^{11}]	1.15 (0.58A)
Energy in one beam [MJ]	360
$\gamma\varepsilon_{x,y}$ [μm], rms	3.75
β^* [m] at IP1-5	0.55
X-angle [μrad], separation	285, 9.3 σ
Geometrical Luminosity loss factor	0.83
Quadrupole bore [mm], gradient [T/m]	70, 215
Peak luminosity [10^{34}]	1.0
Pile up	27

LHC availability

- Availability: Fraction of scheduled operational time that machine is available for operation



The next step – HL-LHC

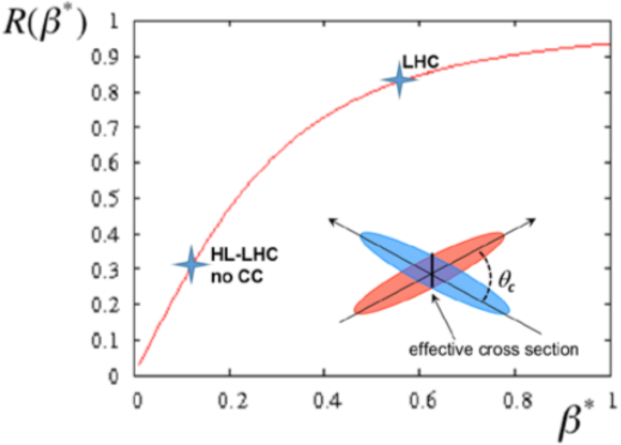


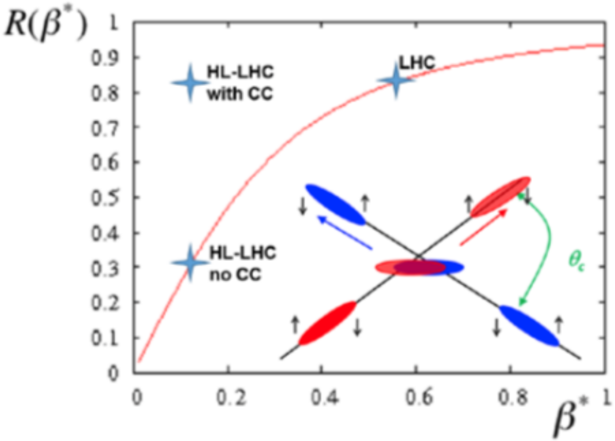
HL-LHC luminosity ingredients

$$L = \frac{n_b N_p^2 f_0}{4\pi\, \sigma^2} R(\sigma_s, \theta)$$

1. 1.9× number of particles N_p
2. 0.4× beam size at IP σ
3. 2× crossing angle θ → 0.3× luminosity reduction R

- The result is L=7×10^{34} BUT pile-up density > 3mm^{-1}
- Crab Cavities for luminous area control!
  - RF transversely deflecting cavity where deflection depends on longitudinal position in bunch





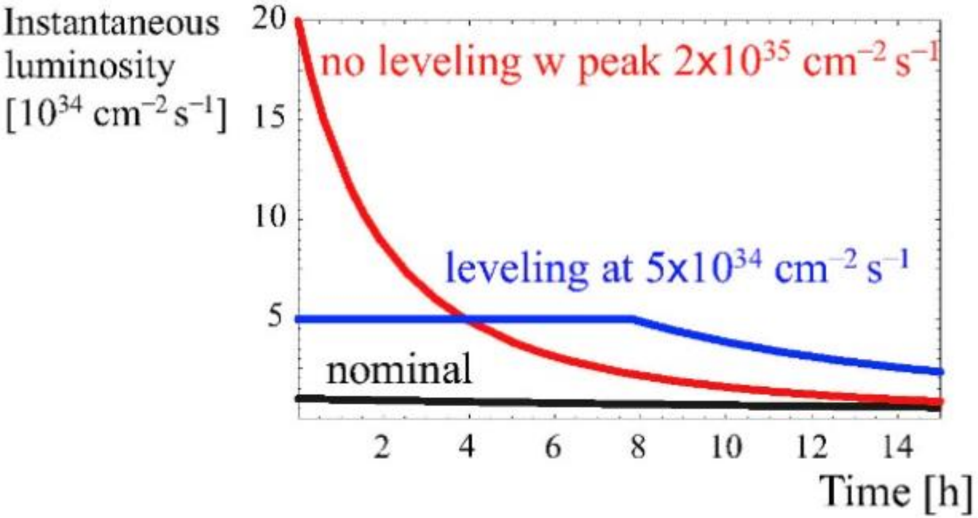
HL-LHC luminosity ingredients

$$L = \frac{n_b N_p^2 f_0}{4\pi\,\sigma^2} R(\sigma_s, \theta)$$

1. 1.9× number of particles N_p
2. 0.4× beam size at IP σ
3. 2× crossing angle θ AND Crab Cavities 1 × luminosity reduction *R*

- The result is L=19×10^{34} – too high!

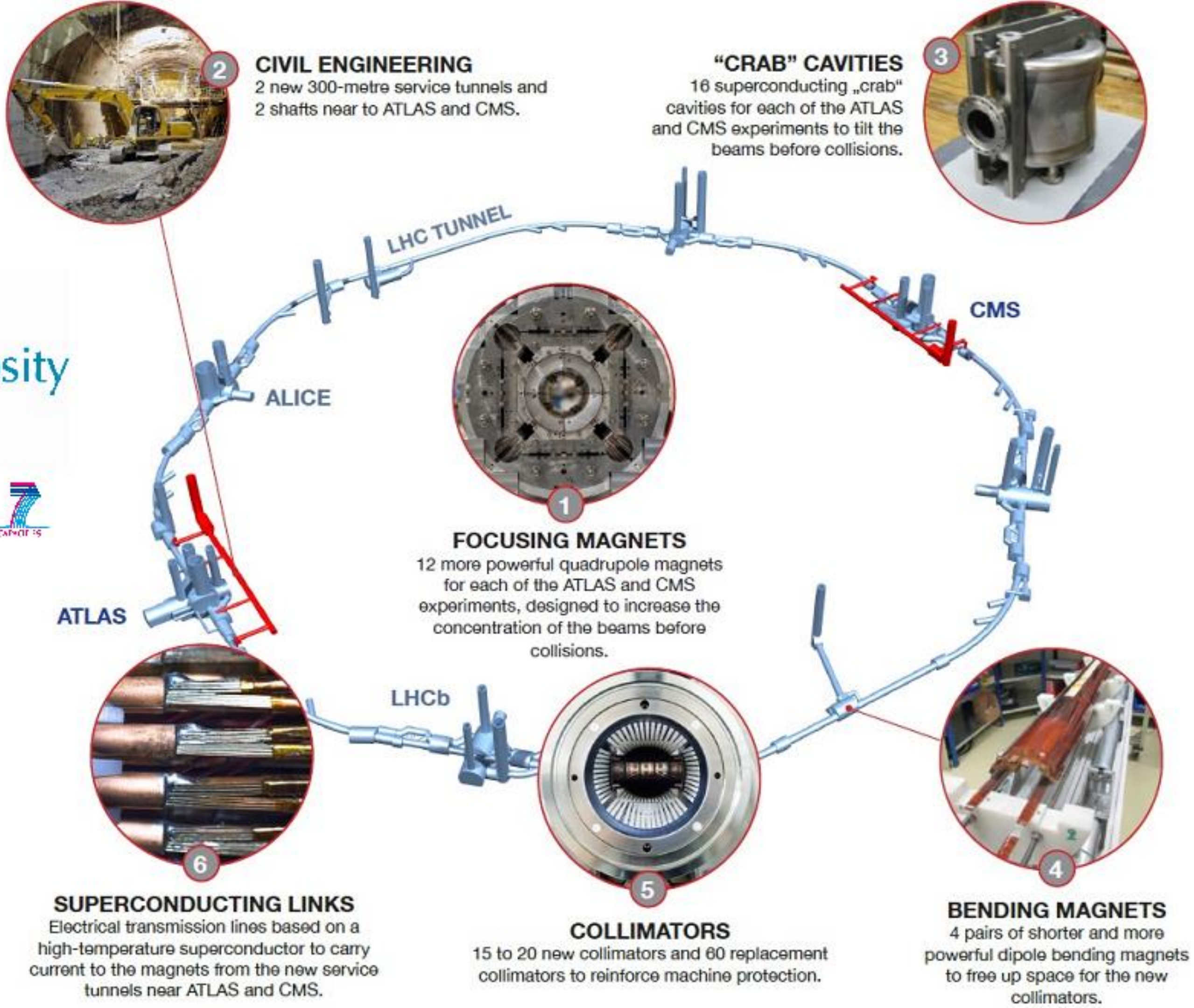
4. Luminosity levelling by dynamically changing focusing (β^* =0.7→0.15m) in store



High Luminosity LHC

The HiLumi LHC Design Study (a sub-system of HL LHC) is cofunded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404

CAPACITIES



2 CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

3 "CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

1 FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

6 SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

5 COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

4 BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

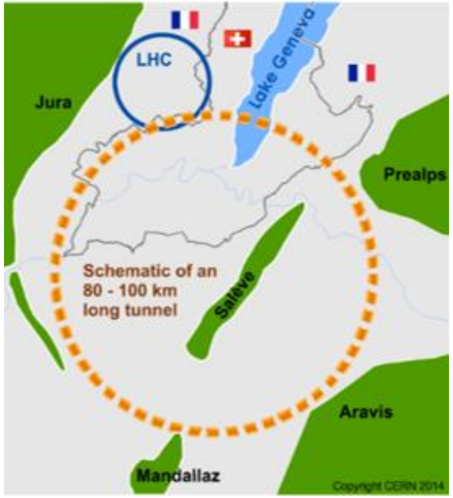
vembre 2015

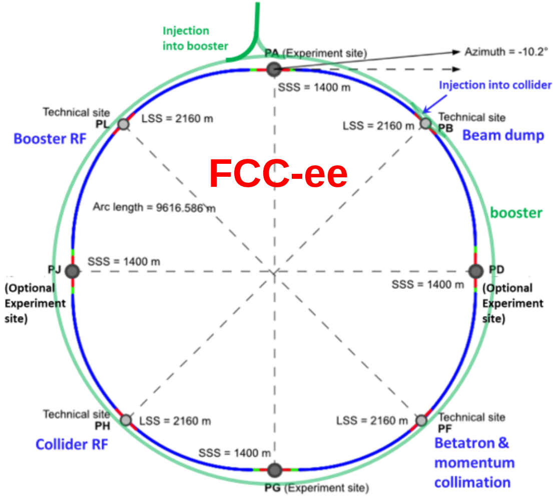
What comes after HL-LHC?

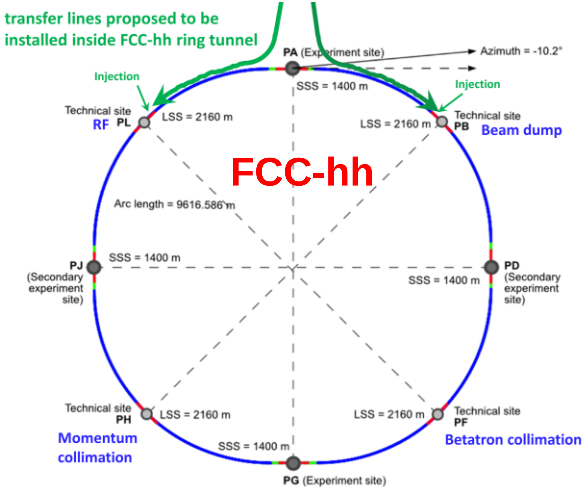
FCC integrated program

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, pp & AA collisions; e-h option**
- highly synergetic and complementary programme boosting the physics reach of both colliders
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC



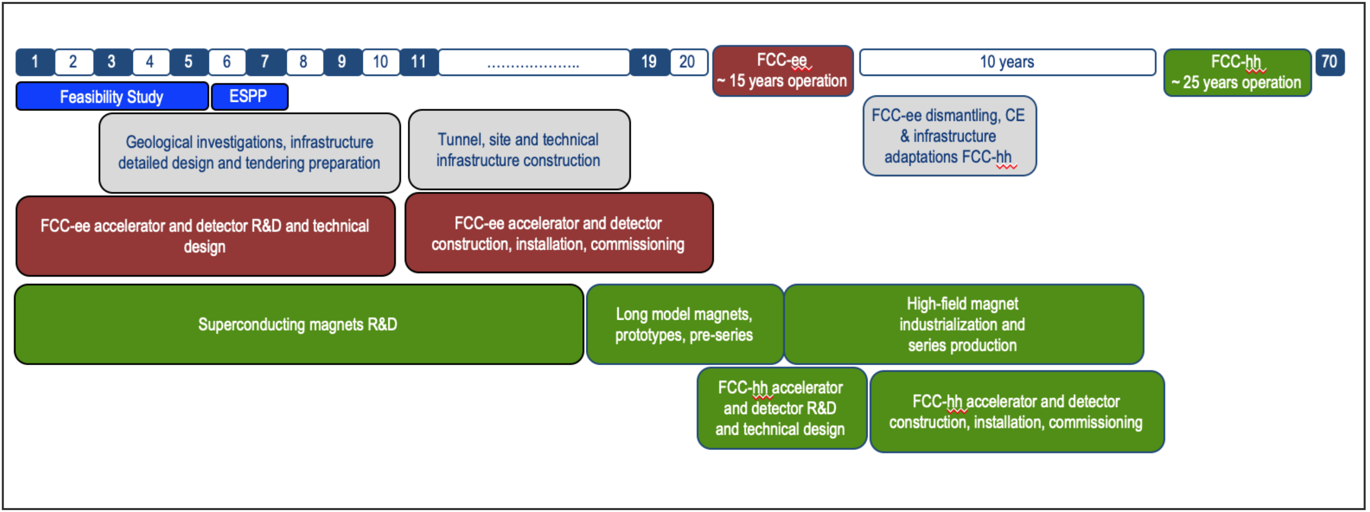




2020 - 2046 **2048 - 2063** **2073 -**

FUTURE
CIRCULAR
COLLIDER

FCC integrated program - timeline



Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

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

FCC-ee accelerator and detector R&D and technical design

FCC-ee accelerator and detector construction, installation, commissioning

Superconducting magnets R&D

Long model magnets, prototypes, pre-series

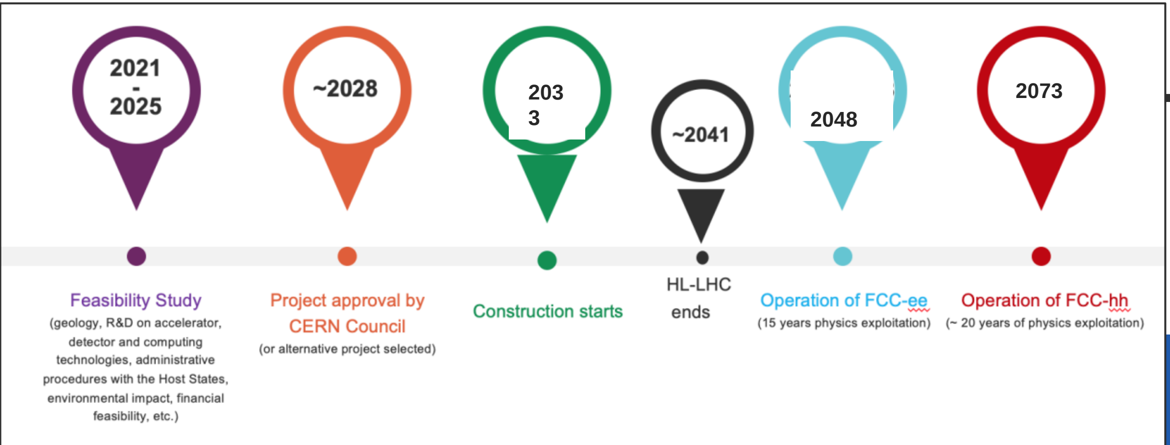
High-field magnet industrialization and series production

FCC-hh accelerator and detector R&D and technical design

FCC-hh accelerator and detector construction, installation, commissioning

Note: FCC Conceptual Design Study started in 2014 leading to CDR end 2018.

FCC Feasibility Study started in 2021, to be completed in 2025.



Feasibility Study
(geology, R&D on accelerator, detector and computing technologies, administrative procedures with the Host States, environmental impact, financial feasibility, etc.)

Project approval by CERN Council
(or alternative project selected)

Construction starts

HL-LHC ends

Operation of FCC-ee
(15 years physics exploitation)

Operation of FCC-hh
(~ 20 years of physics exploitation)

Realistic schedule takes into account:

- ☐ CERN Council approval timeline
- ☐ past experience in building colliders at CERN
- ☐ that HL-LHC will run until ~ 2041

Presently investigating possibilities to shorten project duration and advance FCC-ee start date

Why Muons?

Physics Frontiers

- **Intense and cold muon beams ➩ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\, MeV/c^2$$

$$\tau_\mu = 2.2\, \mu s$$

Colliders

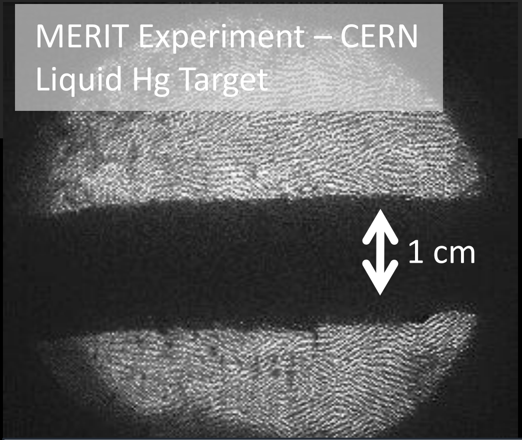
- **Opportunities**
  - s-channel production of scalar objects ➩ strong coupling to Higgs
  - Reduced synchrotron radiation (**E^4/m^4**) ➩ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects (**E^4/m^4**) are suppressed at the collider IP relative to e^+e^- colliders
- ***BUT* the accelerator complex and detector must be able to handle the impacts of μ decays**

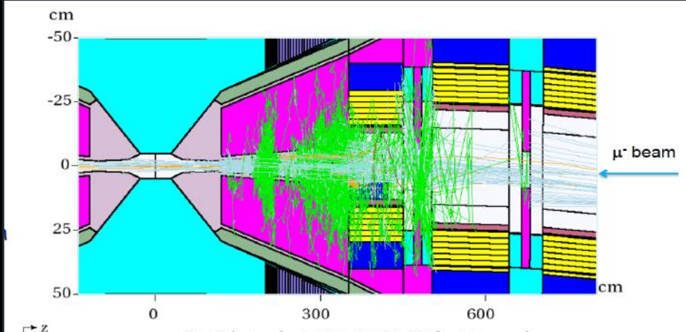
Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations
- Applications beyond HEP

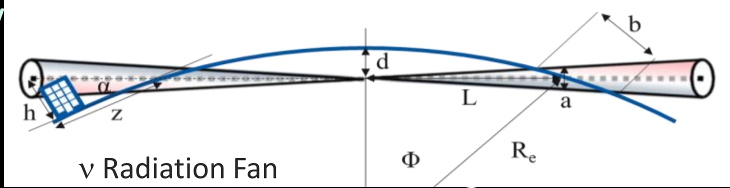
The Physics Challenges

- Muons are difficult to produce
  - Most effective route is tertiary production from a multi-MW proton beam on a target: **p □ π □ μ**
  - Beams must be bunched and cooled to produce luminosity in a collider
- Muons decay
  - All beam manipulations must be rapidly carried out to deliver useable beams to a collider
    - Bunching
    - Cooling
    - Acceleration
  - Electrons from the muon decays deposit significant energy in the accelerator components and physics detector
  - Neutrinos from the muon decays can produce ionizing radiation far from the accelerator complex


MERIT Experiment – CERN
Liquid Hg Target



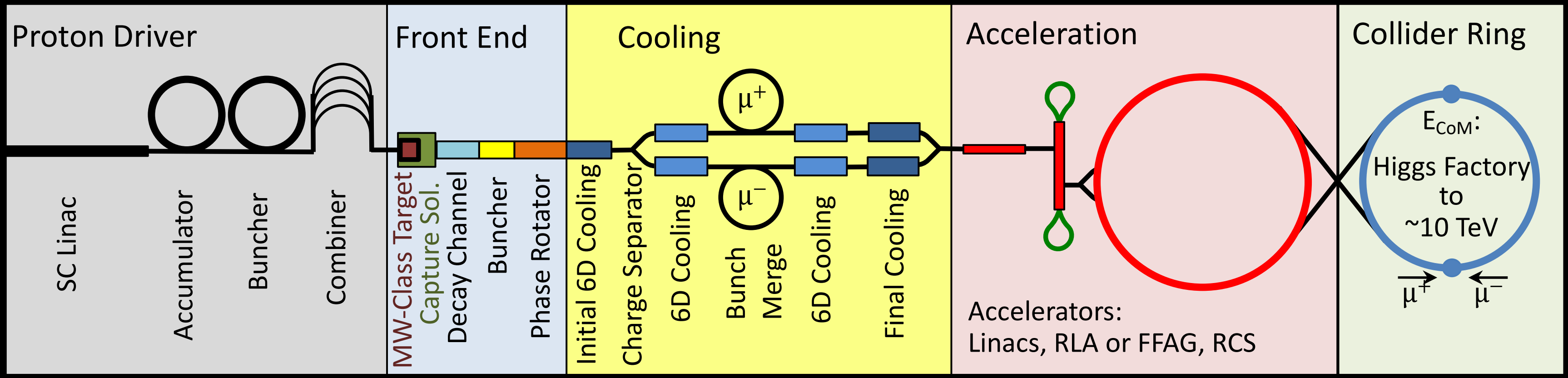
Particle tracks (> 0.1 - 0.5 MeV) for 15 mu- decays



ν Radiation Fan

Proton-Driven MC Concept

Muon Collider



Short & intense proton bunches to deliver hadronic showers

p→π→μ → bunched beams

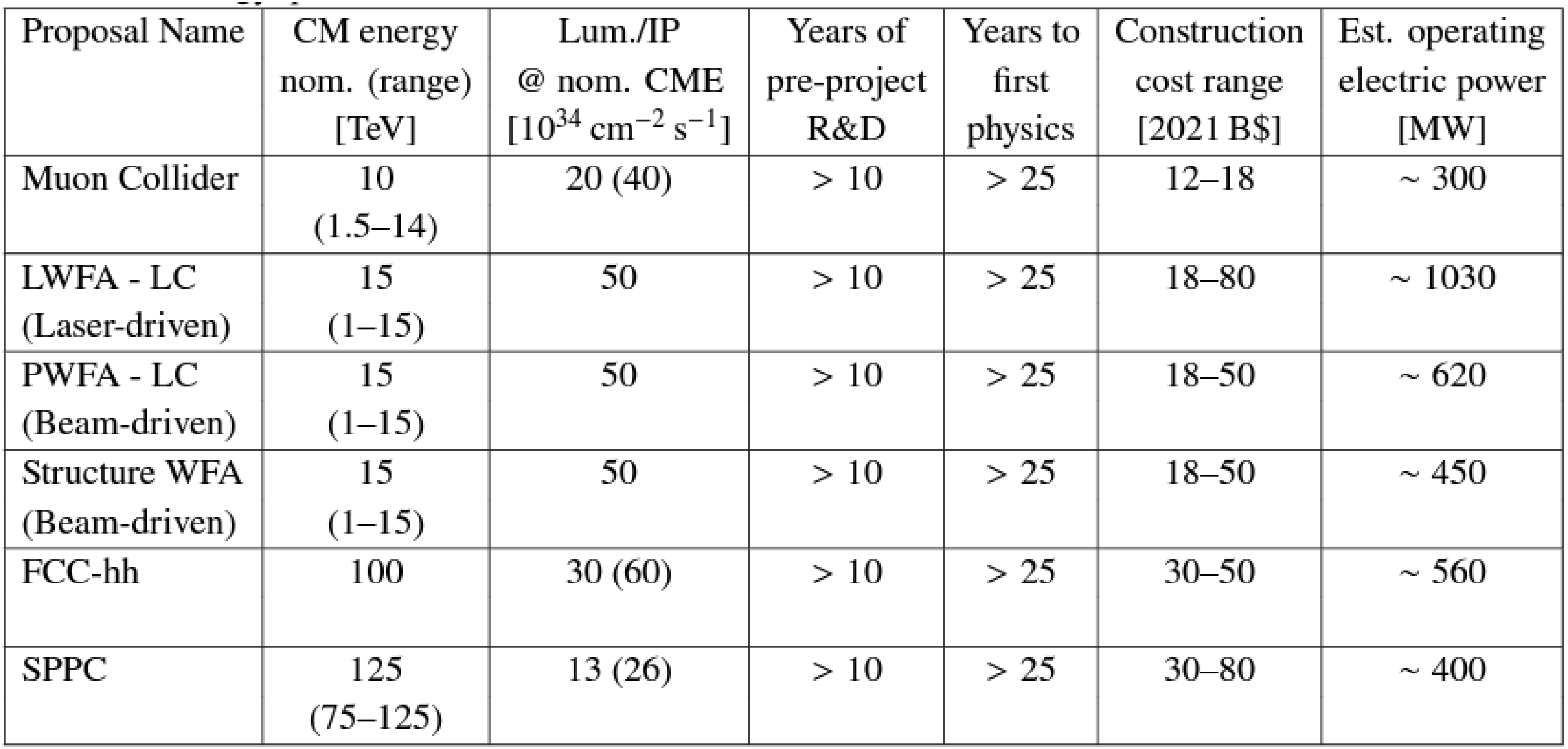
Ionization cooling reduces the transverse & longitudinal emittance

Rapid acceleration to high energy to avoid μ losses. Multi-pass acceleration offers energy efficiency.

∝-Collider Goals:
126 GeV ➪
~14,000 Higgs/yr
Multi-TeV ➪
Lumi > 10^{34}cm^{-2}s^{-1}

Accelerator design is driven by the short muon lifetime

Main parameters of collider proposals with >10TeV CM energy



Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME $[10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Muon Collider	10 (1.5–14)	20 (40)	> 10	> 25	12–18	~ 300
LWFA - LC (Laser-driven)	15 (1–15)	50	> 10	> 25	18–80	~ 1030
PWFA - LC (Beam-driven)	15 (1–15)	50	> 10	> 25	18–50	~ 620
Structure WFA (Beam-driven)	15 (1–15)	50	> 10	> 25	18–50	~ 450
FCC-hh	100	30 (60)	> 10	> 25	30–50	~ 560
SPPC	125 (75–125)	13 (26)	> 10	> 25	30–80	~ 400

Thank you for your attention!