THE CERN FCC DESIGN

TATIANA PIELONI

LABORATORY OF PARTICLE ACCELERATOR PHYSICS EPFL

Material from: M. Benedikt, F. Zimmermann, K. Oide, M. Boscolo
FCC Week 10-14 June 2024 San Francisco USA
https://fccweek2024.web.cern.ch

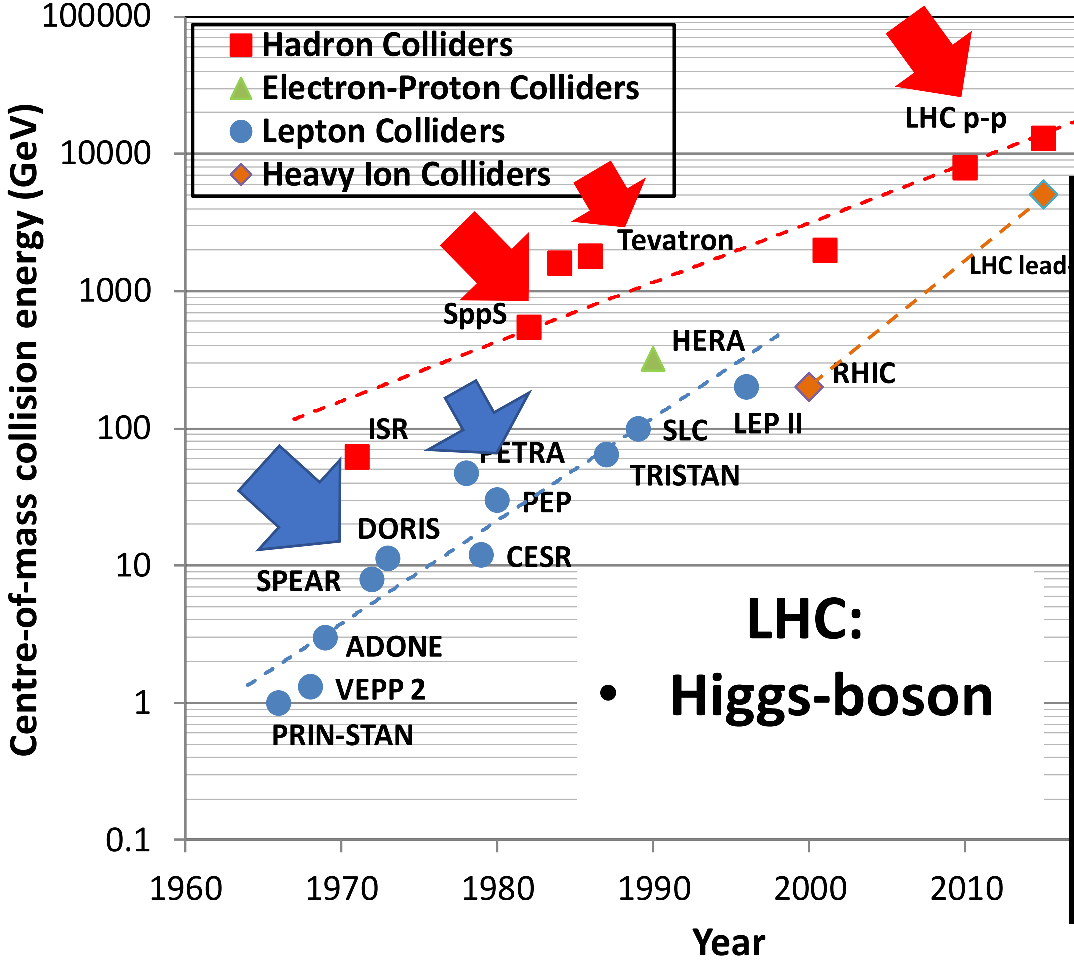
Outline

- Accelerators for High Energy Physics exploration
- European Strategy for HEP and CERN future accelerators studies
- Circular Colliders basics:
  - basic accelerator physics consepts
  - Colliders: Center of Mass Energy and luminosity
  - Leptons versus Hadrons: synchrotron Radiation
- LHC and HL-LHC full exploitation
- FCC-ee description
  - Plans and General parameters
  - Optics and allignment
  - Beam dynamics with collisions: Beam-beam, Beamstrahlung, BhBar and Synchrotron radiations
  - Electron Clouds and photon electrons
  - Radiation in the interaction region and detectors challenges
- FCC-hh essentials

Outline

- Accelerators for High Energy Physics exploration
- European Strategy for HEP and CERN future accelerators studies
- Circular Colliders basics:
    - basic accelerator physics consepts
    - Colliders: Center of Mass Energy and luminosity
    - Leptons versus Hadrons: synchrotron Radiation
- LHC and HL-LHC full exploitation
- FCC-ee description
    - Plans and General parameters
    - Optics and allignment
    - Beam dynamics with collisions: Beam-beam, Beamstrahlung, BhBar and Synchrotron radiations
    - Electron Clouds and photon electrons
    - Radiation in the interaction region and detectors challenges
- FCC-hh essentials

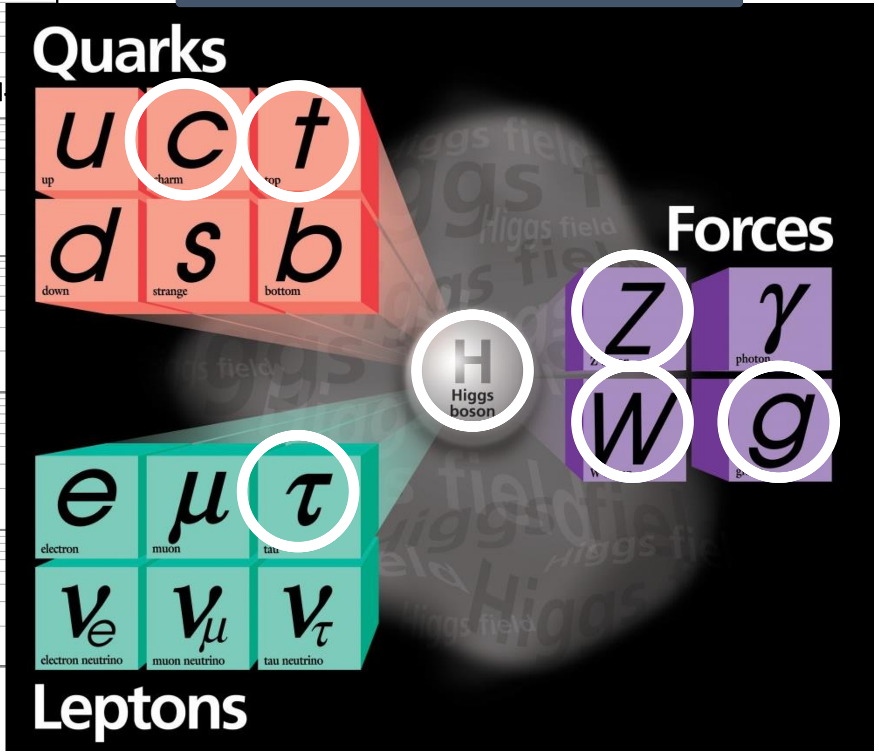
Discoveries by colliders



LHC:

- **Higgs-boson**

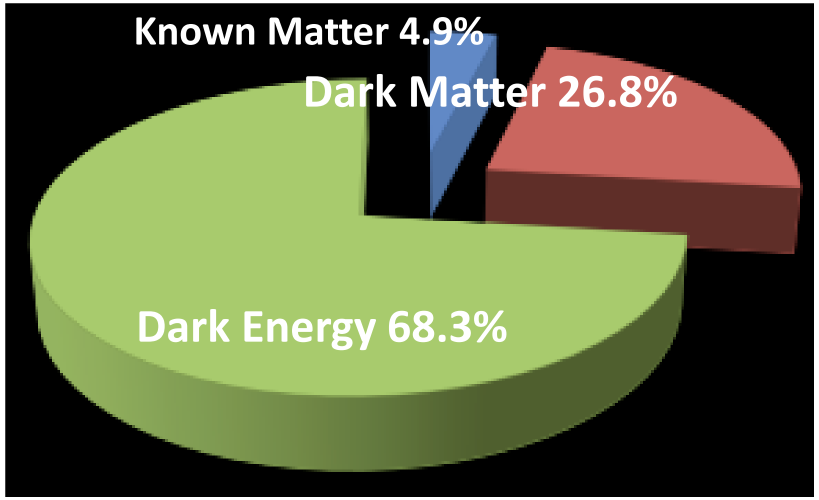
Standard Model
Particles and forces

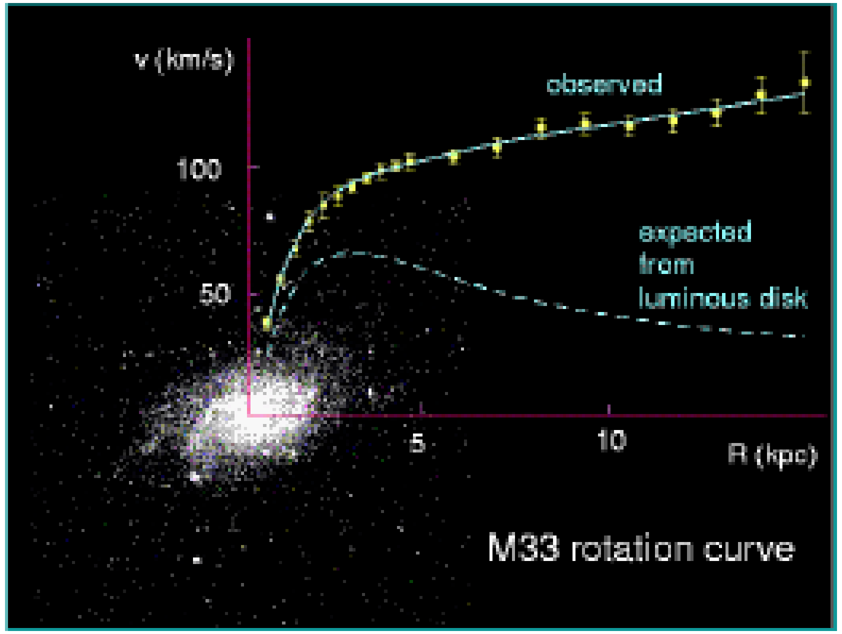


Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements

Many open questions remaining

- 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”? …

K. Borras

European Strategy for Particle Physics

2013 Update of European Strategy for Particle Physics:

"CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines."

→ FCC Conceptual Design Reports (2018/19)

Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC

CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,
EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

2020 Update of European Strategy for Particle Physics:

"Europe, together with its international partners, should investigate technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage."

Future Circular Collider Study

GOAL: CDR+ and cost review for the next ESU (2025)

International FCC collaboration (CERN as host lab) to study:

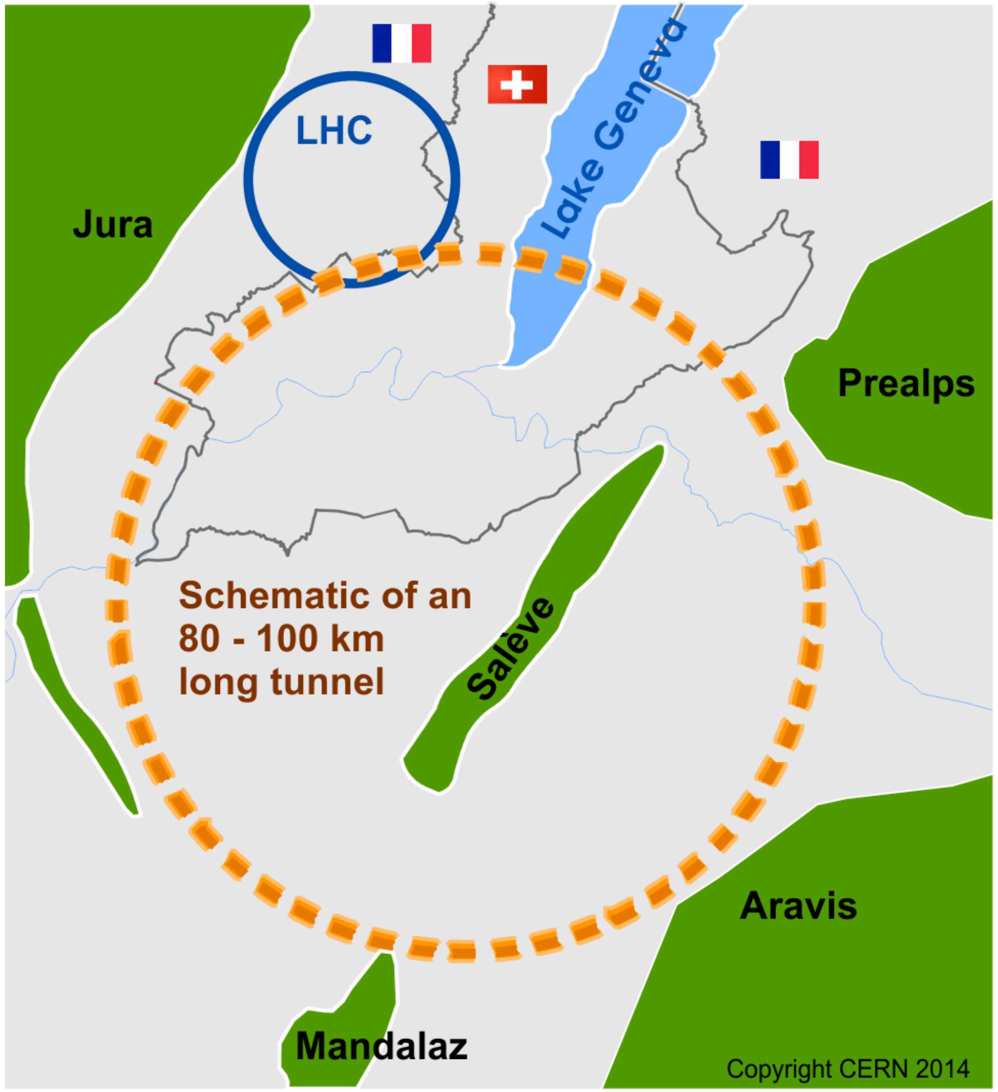
- ***Full exploitation of the LHC and HL***
- ***e^+e^-* collider (*FCC-ee*),** as first step

Feasibility study and CDR++ by next ESPP 2025

- ***pp*-collider (*FCC-hh*) →** main emphasi, defining infrastructure requirements and dev

~16 T ⇒ 100 TeV *pp* in 100 km

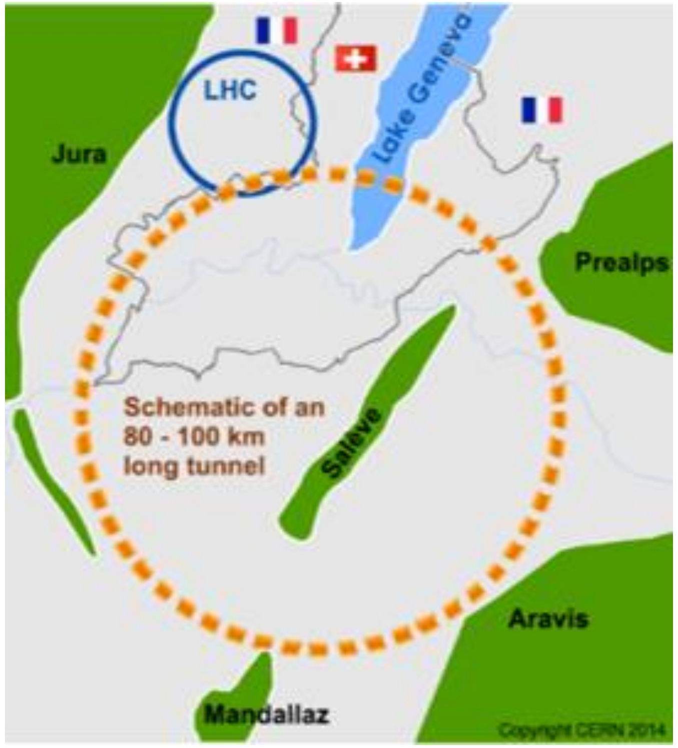
- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL

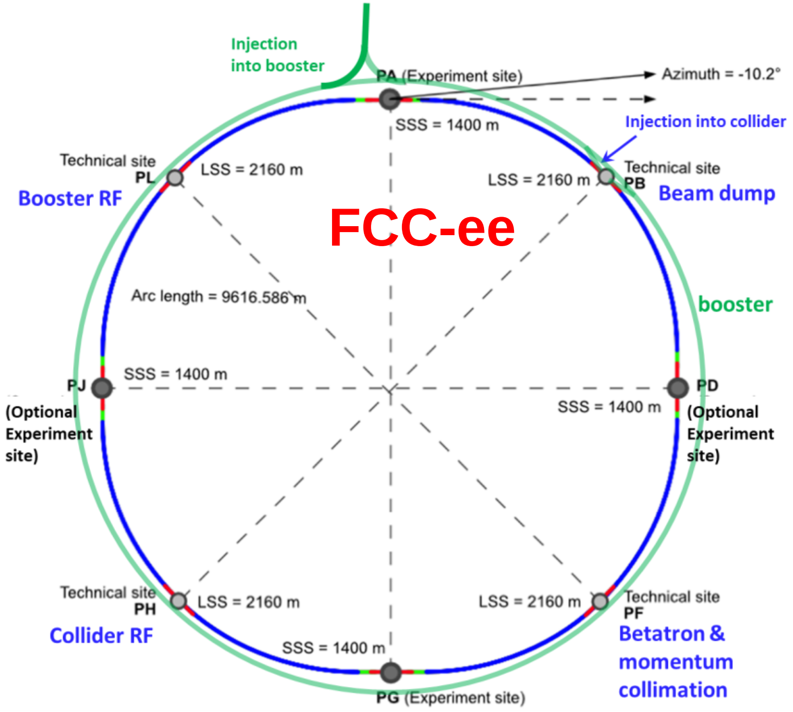


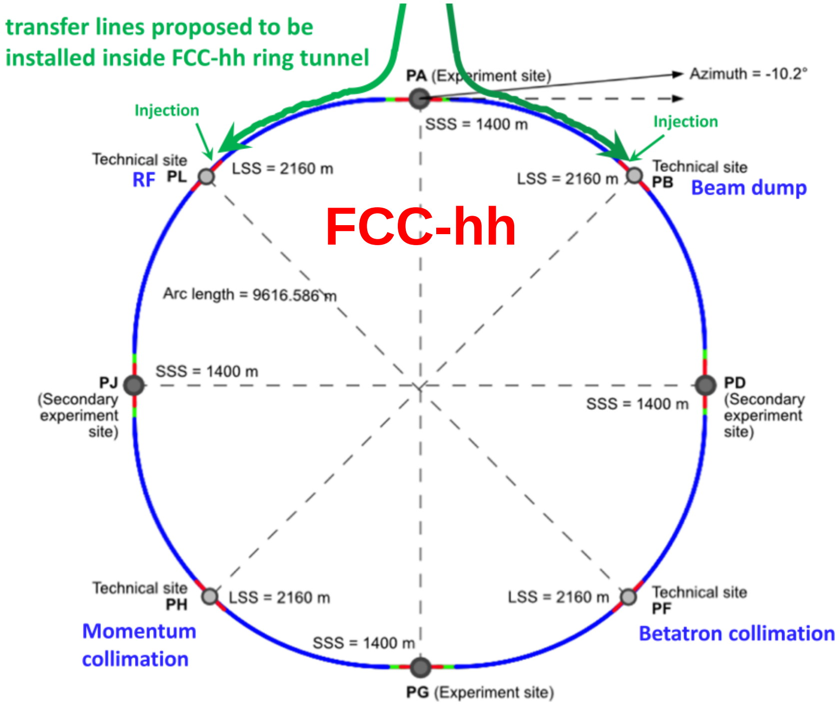
FCC integrated program

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







M. Benedikt FCC week 2024

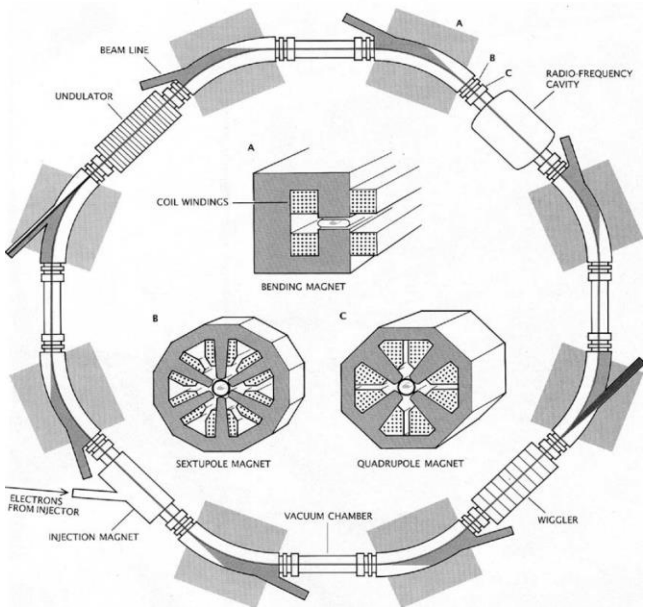
Outline

- Accelerators for High Energy Physics exploration
- European Strategy for HEP and CERN future accelerators studies
- Circular Colliders basics:
    - basic accelerator physics consepts
    - Colliders: Center of Mass Energy and luminosity
    - Leptons versus Hadrons: synchrotron Radiation
- LHC and HL-LHC full exploitation
- FCC-ee description
    - Plans and General parameters
    - Optics and allignment
    - Beam dynamics with collisions: Beam-beam, Beamstrahlung, BhBar and Synchrotron radiations
    - Electron Clouds and photon electrons
    - Radiation in the interaction region and detectors challenges
- FCC-hh essentials

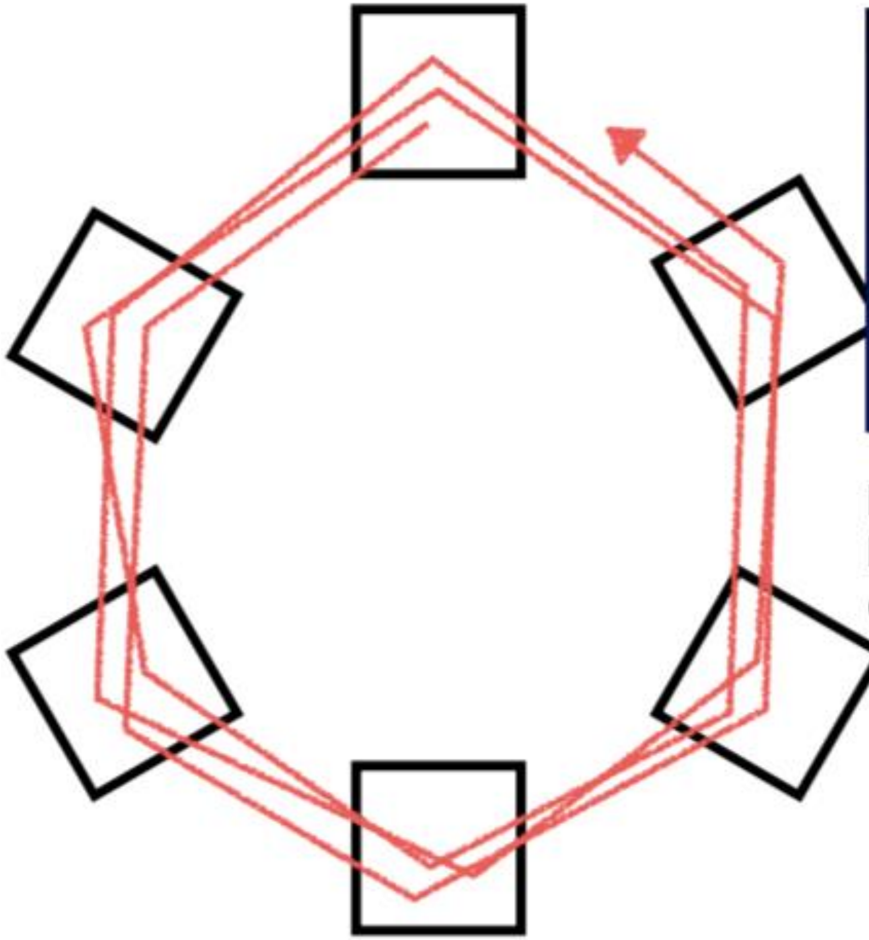
Introduction to accelerators and particle dynamics

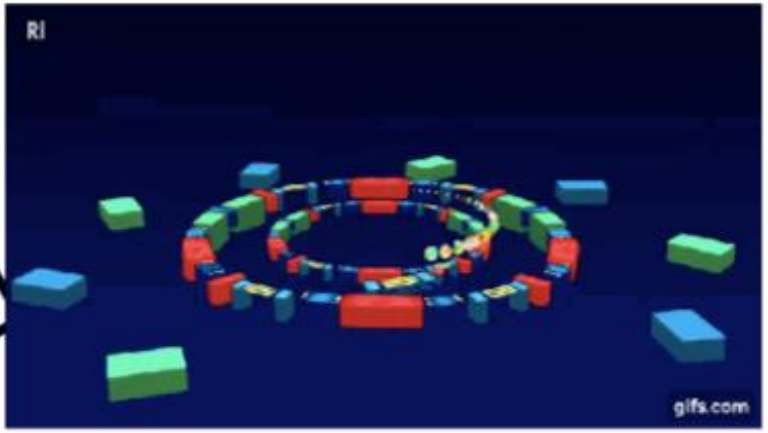
Accelerator = series of elements for **beam guiding** (bending, focusing) and **acceleration of particles**

- **guiding fields** must ensure stability of circulating particles on designed trajectory
- often arranged in a **closed loop** (ring) → acceleration occurs at every turn
- or in a periodic **“straight” sequence** (linacs) → acceleration all along the length



MAPS





Each of these ‘elements’ (and drifts) can be thought of as transforming the particle co-ordinates

$$\vec{x} = (x, p_x, y, p_y, z, \delta)$$

$$\vec{x}(s_1) = \vec{M}(\vec{x}(s_0))$$

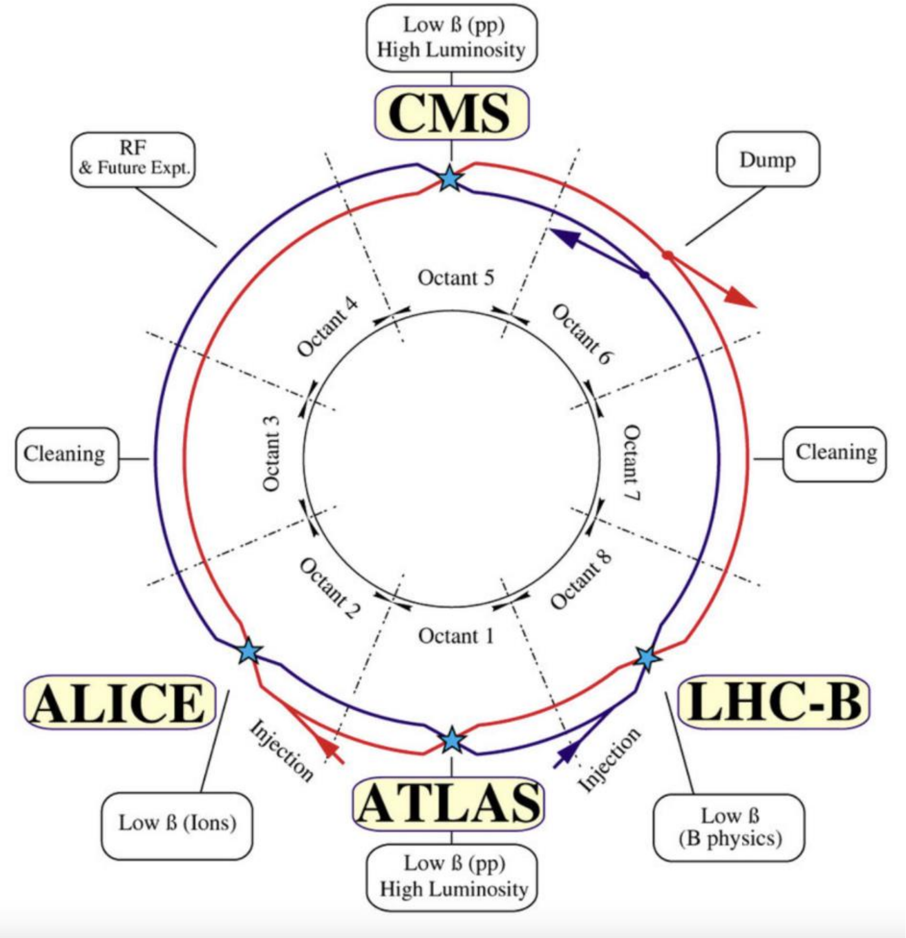
Mathematically, they are ‘maps’

Basic accelerator concepts

Injection and filling of the machine

Acceleration

Beam circulation at high energies for hours



LHC schematic

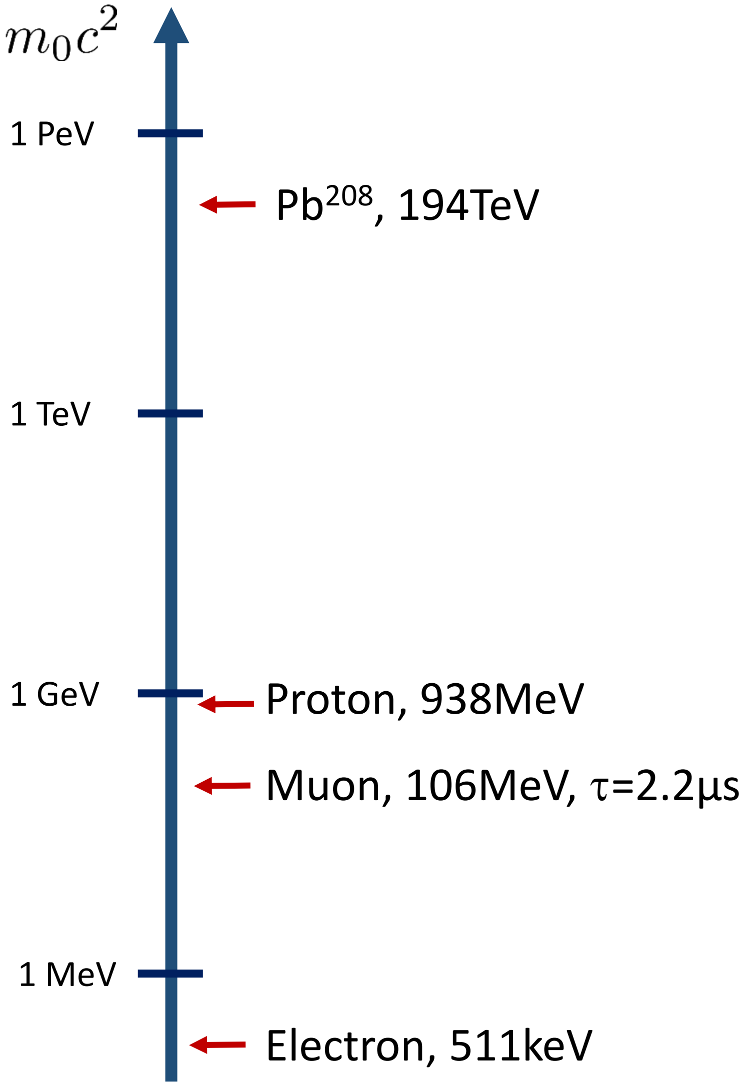
Low beta insertions for smallest beam sizes

Collimation

Beam steering, collisions and luminosity levelling

Collective particle effects

Particles to Accelerate



Pb^{208}, 194TeV

Proton, 938MeV

Muon, 106MeV, τ=2.2μs

Electron, 511keV

Wide range of rest masses from electron to heavy ions

The accelerators differ vastly, e.g.

- particle speed in cavities
- synchrotron radiation power
- activation by losses
- requirements for vacuum

Accelerator design depends on particle type and properties Energy

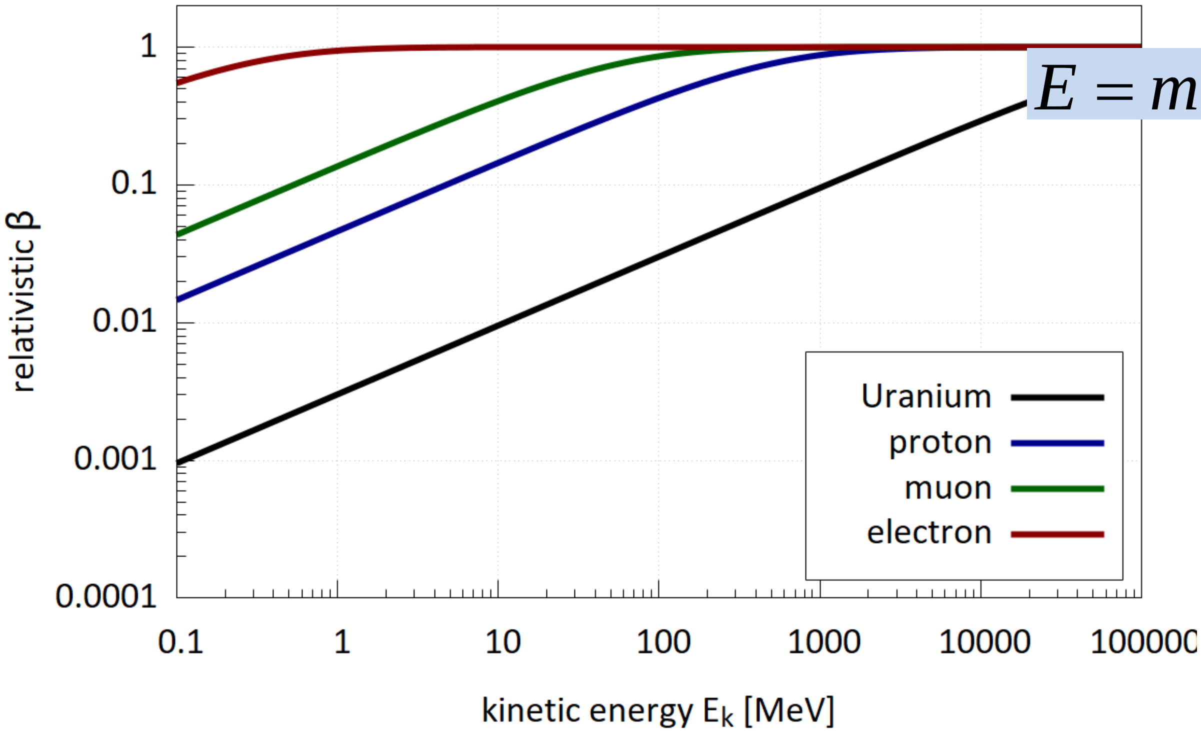
Accelerating particles →Towards Relativity

relativistic energy-momentum relation:

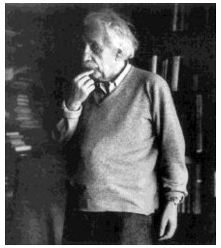
$$E = \sqrt{m_0^2 c^4 + c^2 p^2}$$
$$= m_0 c^2 + E_k$$

$$\boxed{\begin{aligned}\gamma &= \frac{E}{m_0 c^2} = 1 + \frac{E_k}{m_0 c^2} \\ \beta &= \sqrt{1 - 1/\gamma^2}\end{aligned}}$$

Relativistic electrons at ~ MeV
Relativistic protons ~ GeV



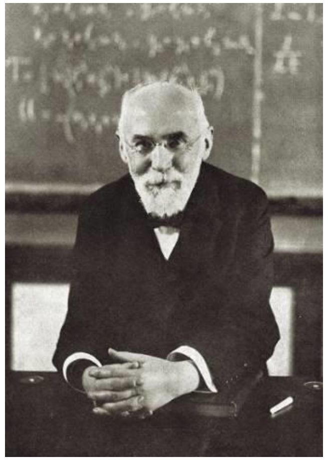
$$E = mc^2$$



Guiding charged particles: Lorentz Force

$$\vec{F} = e\vec{E} + e\vec{v} \times \vec{B}$$

(charge = e)



H.A.Lorentz
1853-1928

electric field

energy gain: $\Delta E_k = eU$

Longitudinal Motion

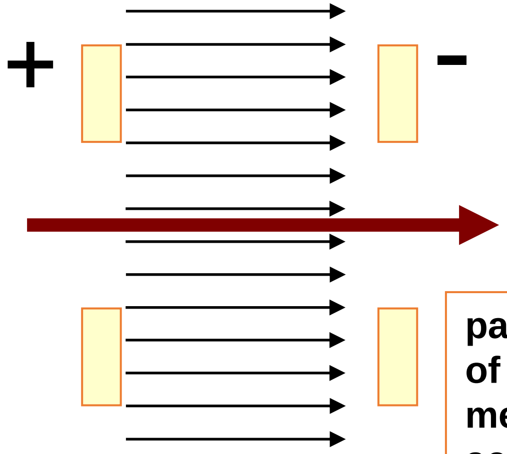
Parallel to the direction of motion.
Used to accelerate charged particles.

magnetic field

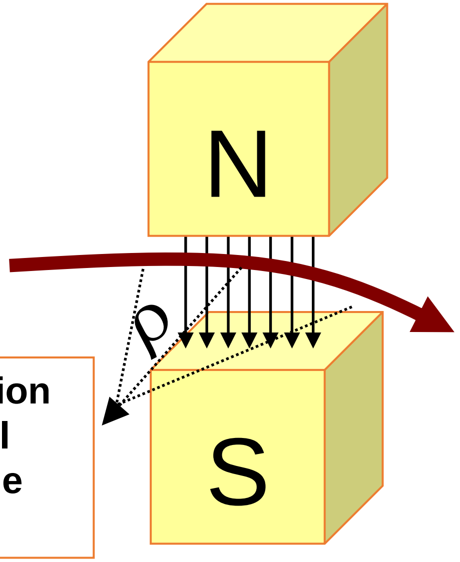
bending: $B\rho = p/e,\ \Delta E_k = 0$

Transverse Motion

Perpendicular to the direction of motion.
Used to keep circulating orbit and beam steering.

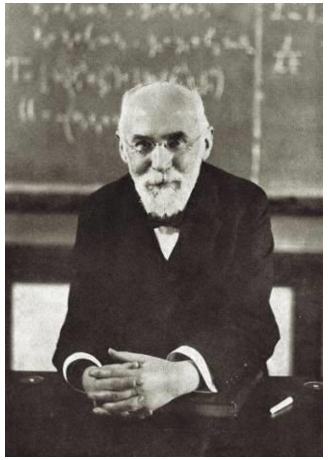


path bending and acceleration of particles are fundamental mechanisms of each particle accelerator



Guiding charged particles: Lorentz Force

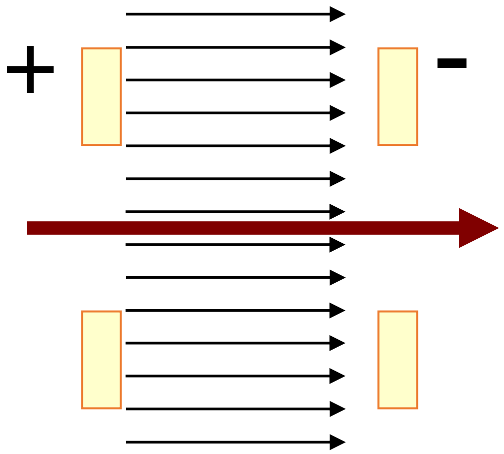
$$\vec{F} = e\vec{E} + e\vec{v} \times \vec{B}$$ (charge = e)


H.A.Lorentz
1853-1928

electric field

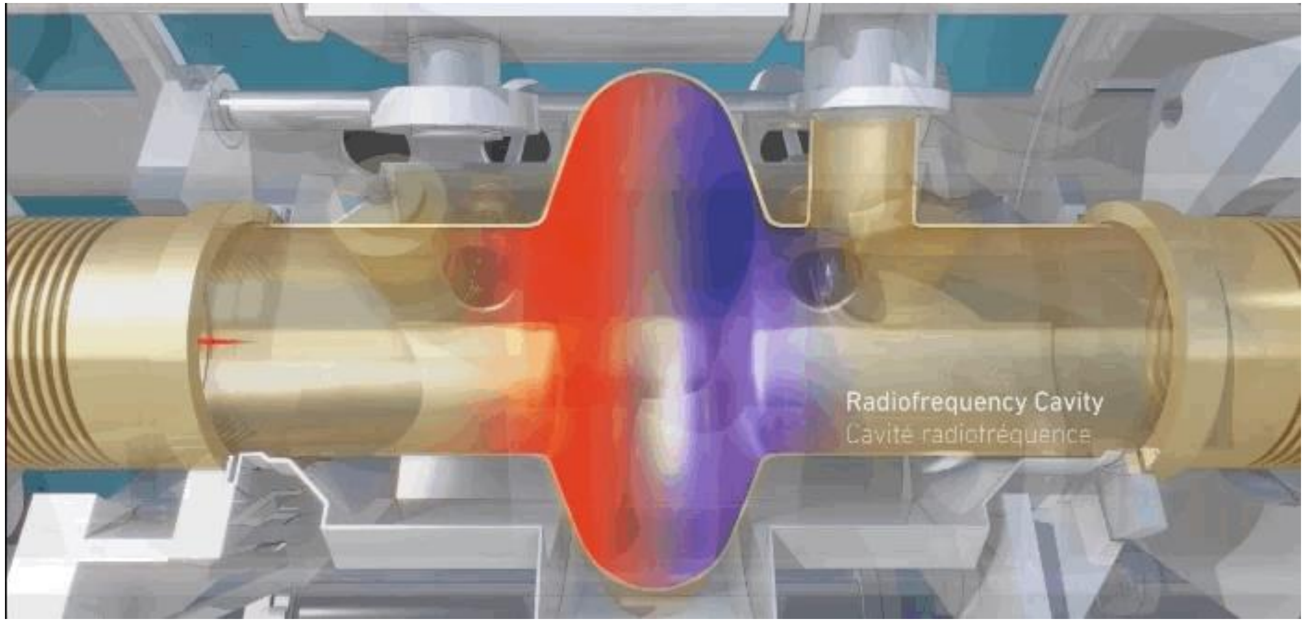
energy gain: $\Delta E_k = eU$

Longitudinal Motion
Parallel to the direction of motion.
Used to accelerate charged particles.



Acceleration: Radio-frequency cavities

- Reach of higher energetic collisions (ions, protons and leptons)
- Compensate for energy loss due to emission of synchrotron radiation (leptons)



Apply an E-field which is reversed while the particle travels inside the tube
→ it gets accelerated at each passage.

Could accelerate in linear and circular machines

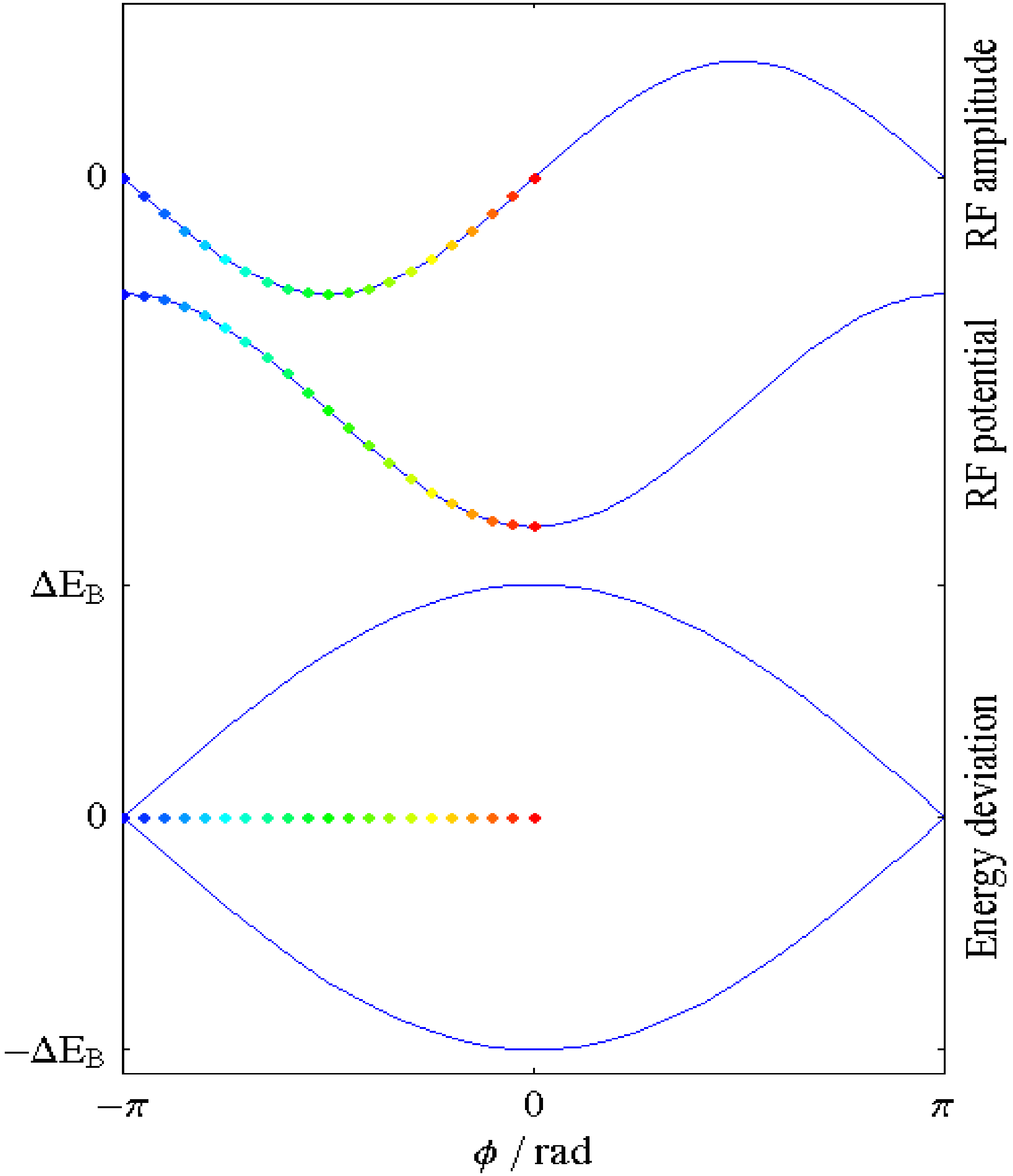
Only particles synchronized with RF will be accelerated → particles are bunched in packages

Longitudinal motion: Synchrotron oscillations in phase space

The accelerating force is a restoring force and keeps the particles locked in a stable motion

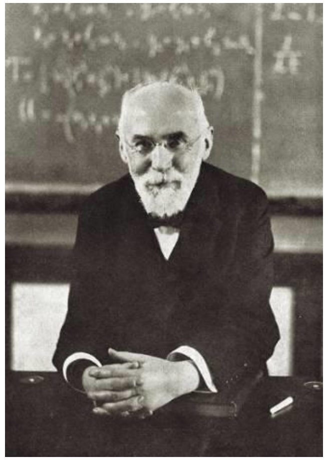
The restoring force is non-linear.
⇒speed of motion depends on
particle coordinates in phase space

(here shown for a stationary bucket)



Guiding charged particles: Lorentz Force

$$\vec{F} = e\vec{E} + e\vec{v} \times \vec{B}$$ (charge = e)



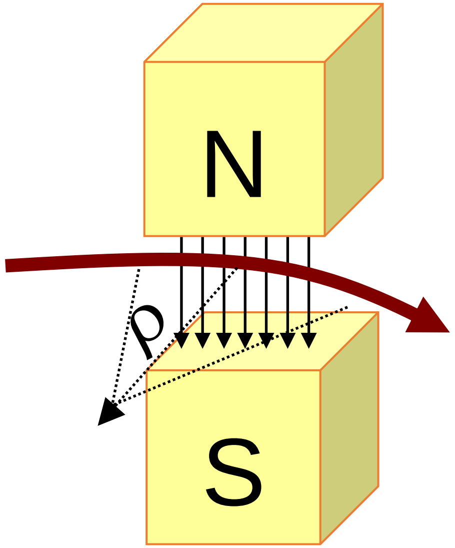
H.A.Lorentz
1853-1928

magnetic field

bending: $B\rho = p/e, \ \Delta E_k = 0$

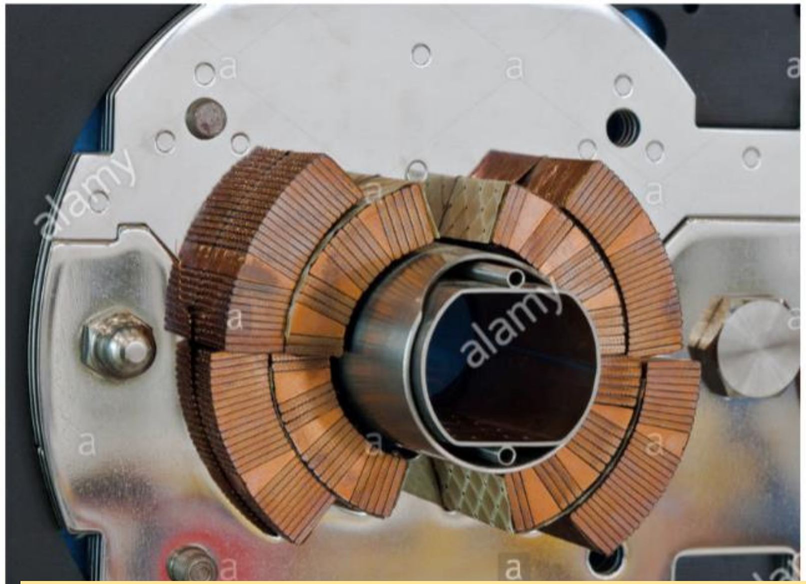
Transverse Motion

Perpendicular to the direction of motion.
Used to keep circulating orbit and beam steering.



Bending Magnet and magnetic rigidity

Iron dominated
Field defined by the geometry of poles
→ 2 flat poles

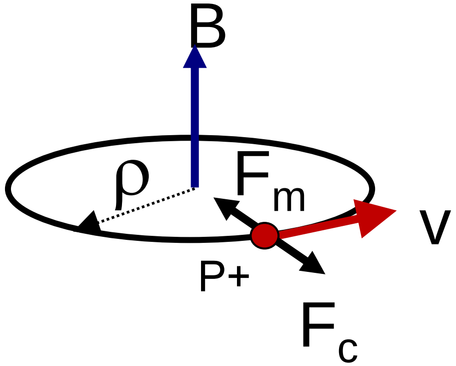


Superconducting
Field defined by the geometry of coils
→ Current distribution Cosϕ

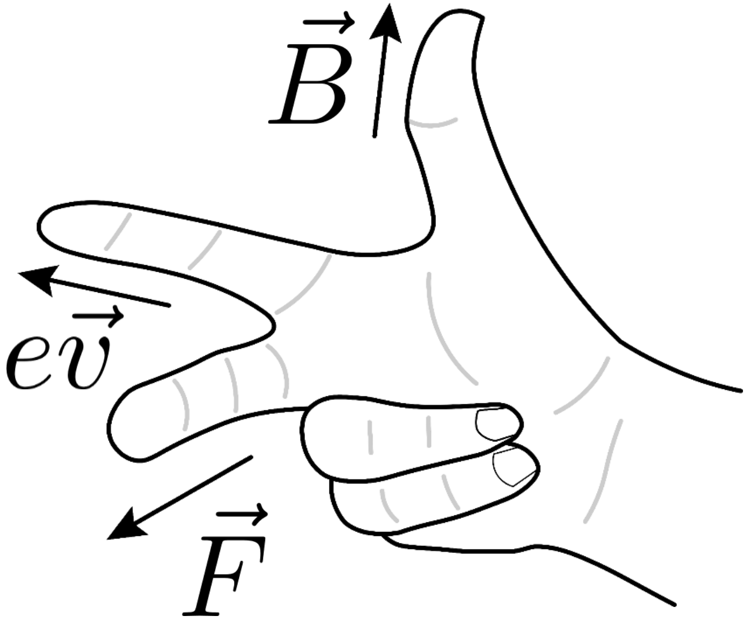
Magnetic rigidity:

$$B\rho = \frac{p}{e}$$

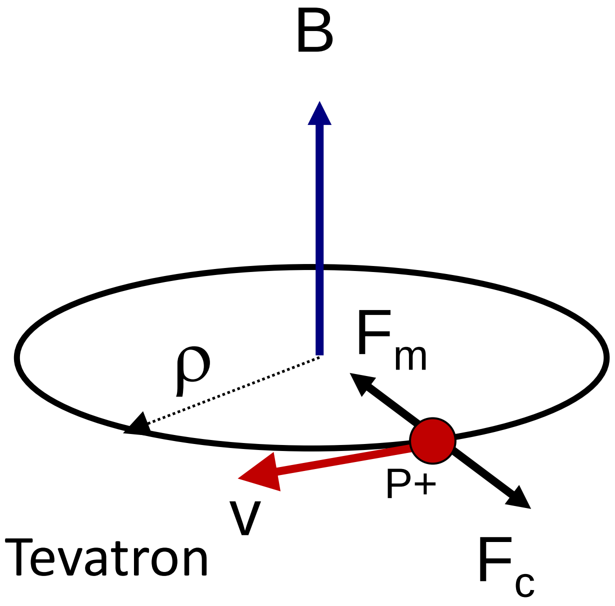
- accelerate beams → increase B
- at fixed B: higher p → increase bending angle



Lorentz Force – getting it right

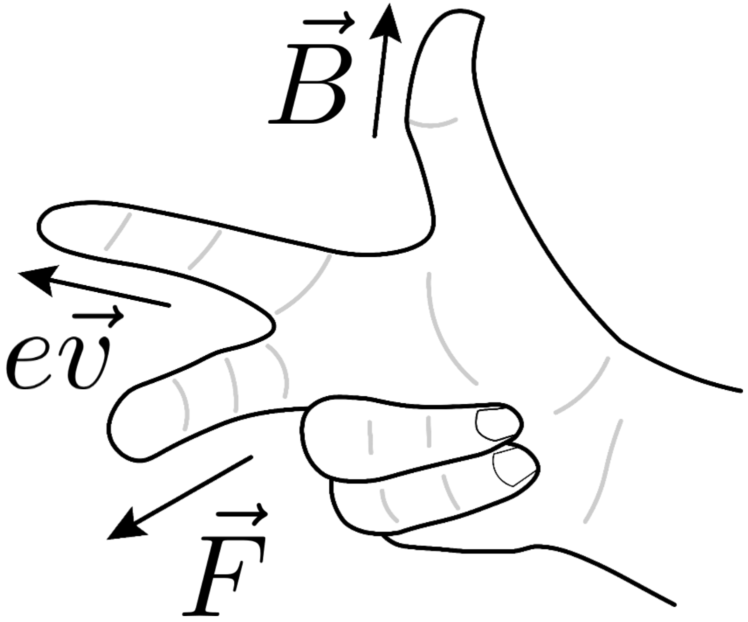


$$B\rho[\mathrm{Tm}] \quad = \quad 3.3356 \cdot \beta E_{\mathrm{tot}}[\mathrm{GeV}]$$

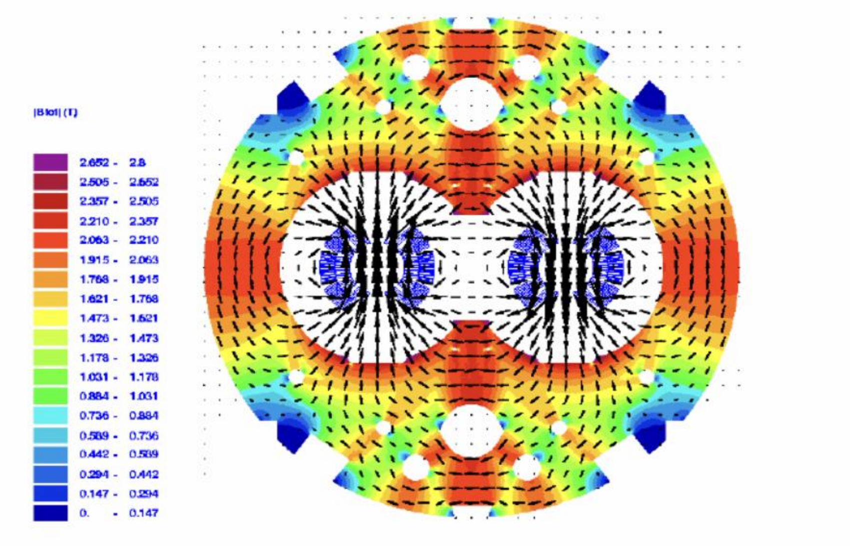


- accelerate beams → increase B → Synchrotrons: LHC, Tevatron
- at fixed B: higher p → increase bending angle→ Cyclotrons

Lorentz Force – getting it right



$$B\rho[\mathrm{Tm}] \quad = \quad 3.3356 \cdot \beta E_{\mathrm{tot}}[\mathrm{GeV}]$$



Tevatron p-pbar collider → same B field→difficult to have pbar beams
LHC p-p collider → opposite B field → complex magnet design so called 2 in 1

Why B fields for steering?
Comparison E vs B field

Bending radius for protons in B and E:

example: electric and magnetic force on protons

$$\vec{F_E} = e \cdot \vec{E}, \quad \vec{F_B} = e \cdot \vec{v} \times \vec{B}$$

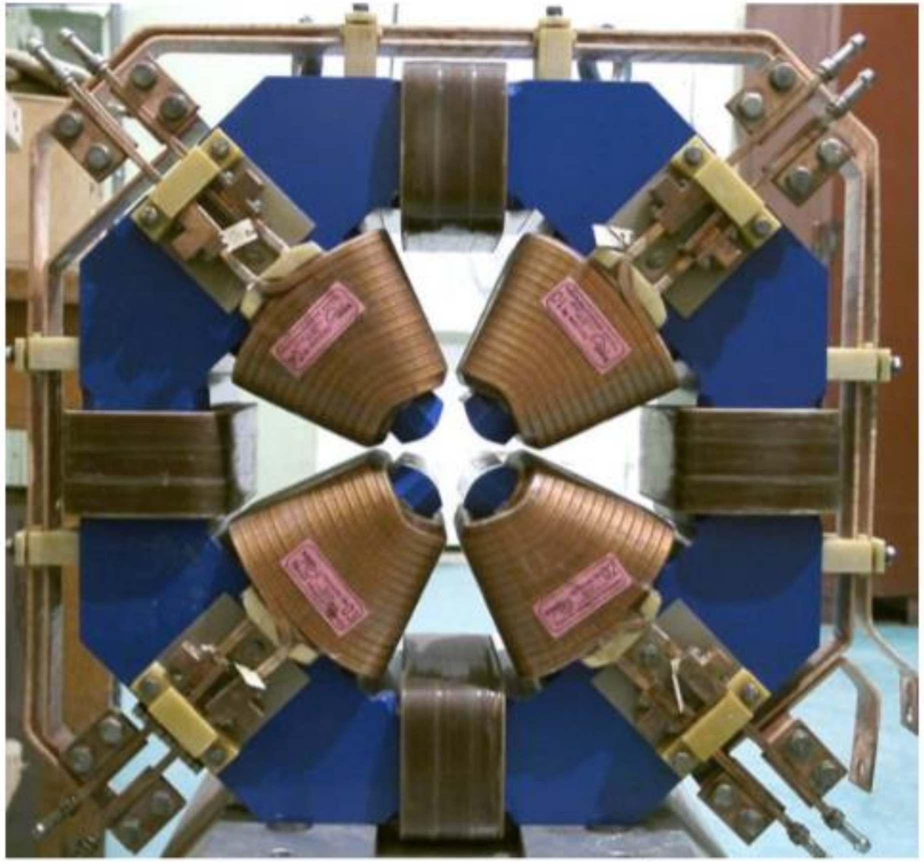
table: bending radius, varying E_k

E_k	B = 1T	E = 10MV/m
60 keV	35 mm	12 mm
1 MeV	140 mm	200 mm
1 GeV	5.6 m	150 m

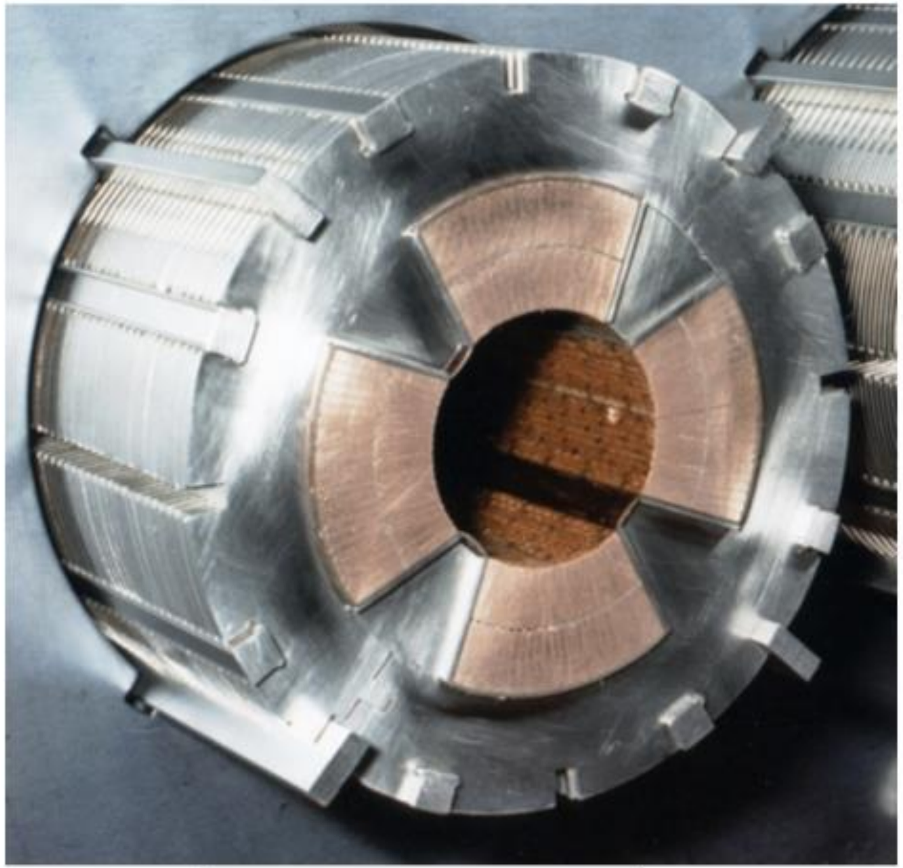
Magnetic fields are used exclusively to bend and focus ultra-relativistic particles

Quadrupole Magnet - Focusing Element

Quadrupole magnets:

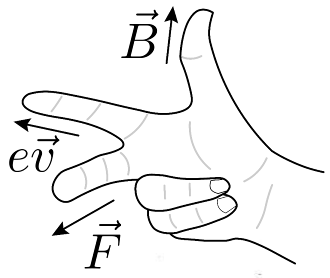


Iron dominated:
field determined by
geometry of poles
→ 4 hyperbolic poles



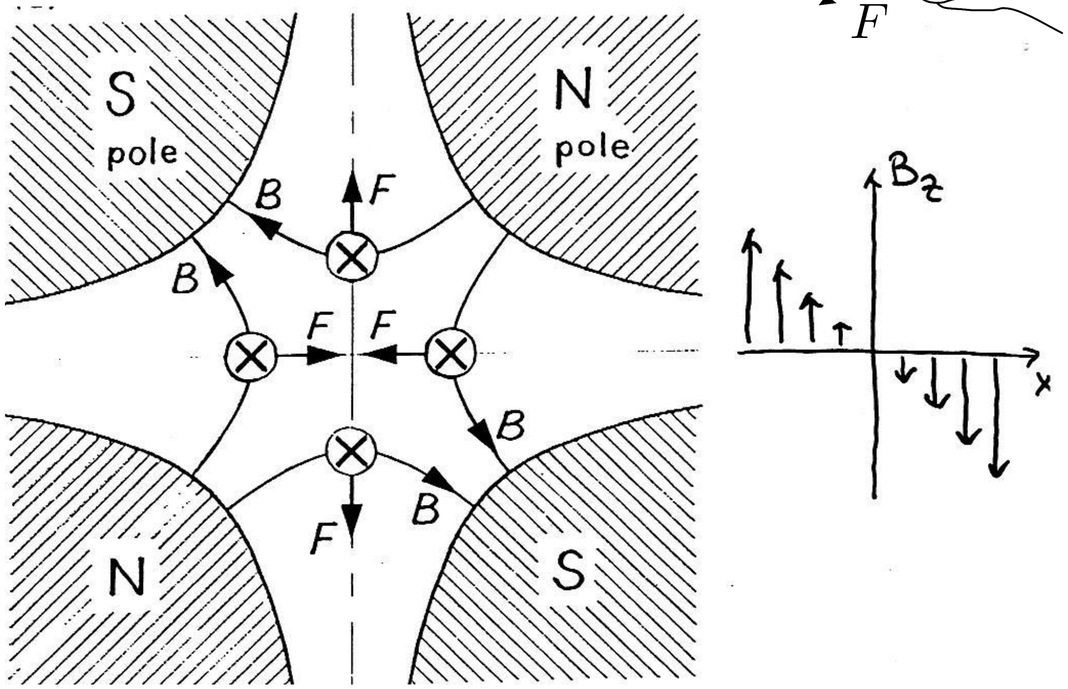
Superconducting:
field determined by
geometry of coils
→ $j(\phi) \sim \cos 2\phi$

Quadrupole magnets



- Focusing in one plane X

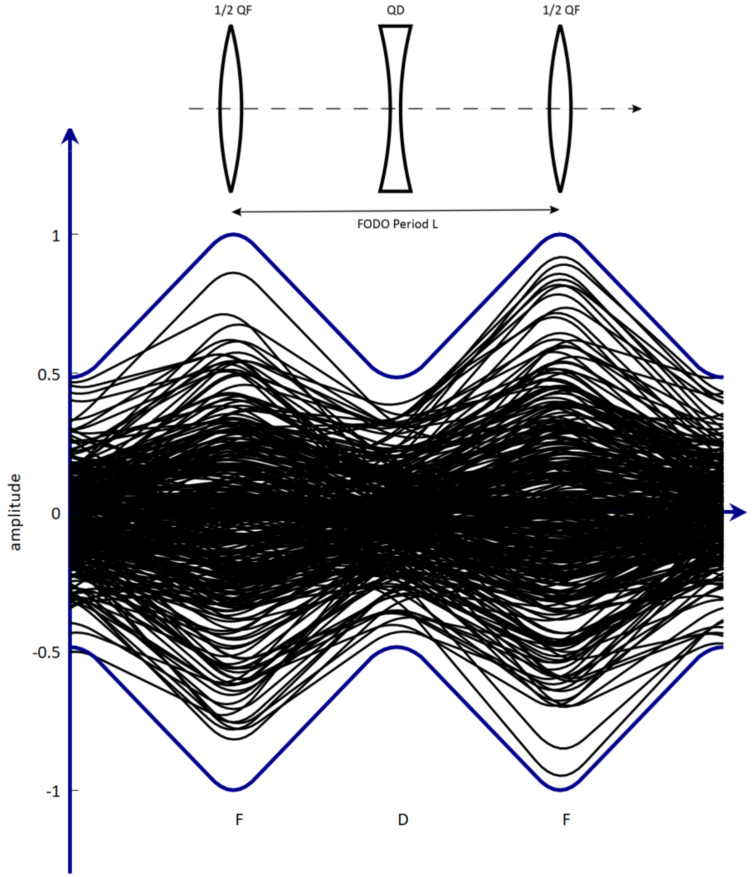
- Defocusing in the other plane Y



$$\nabla \times \boldsymbol{B} = 0 \rightarrow \frac{\partial B_y}{\partial x} = \frac{\partial B_x}{\partial y}$$

Gradient g

Alternating Gradient→ Strong focusing



FODO cell

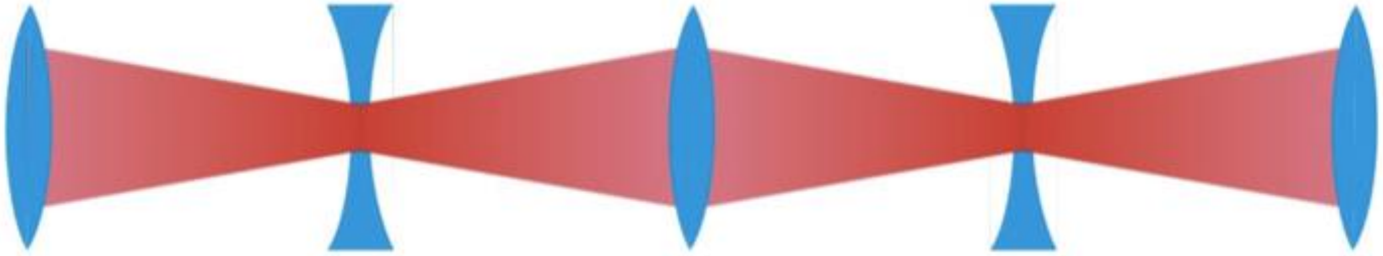
Unit sequence of magnets used to build any accelerator
Focusing-Drift-Defocusing-Drift

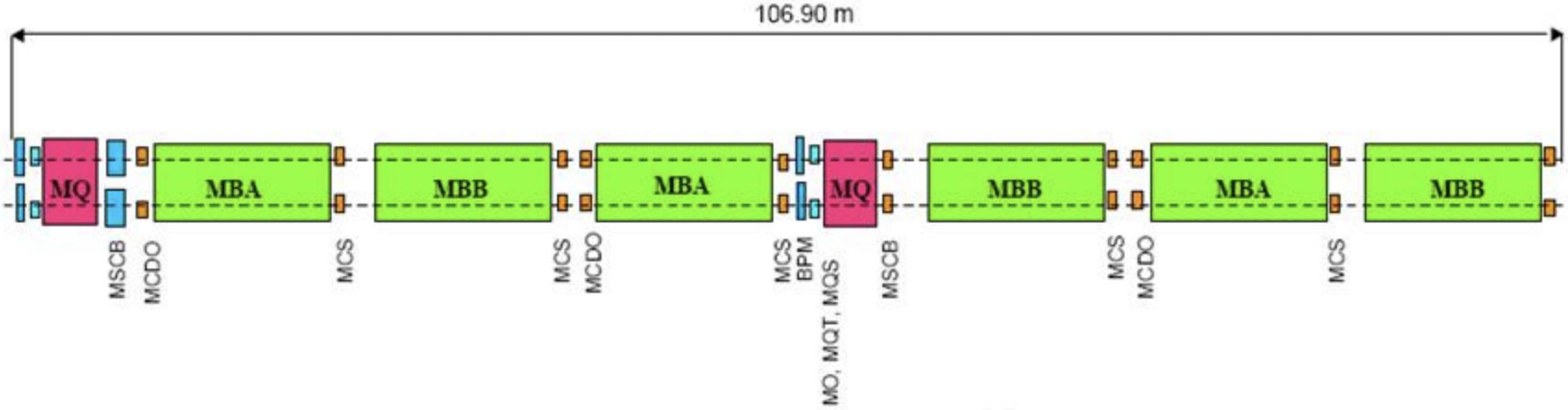
Alternating gradients → net focusing in both transverse dimensions (x,y)!

Magnets act on particles like optical lenses on light!

Accelerator Optics

Focusing in both planes possible in case of alternating gradient – well know from light optics:



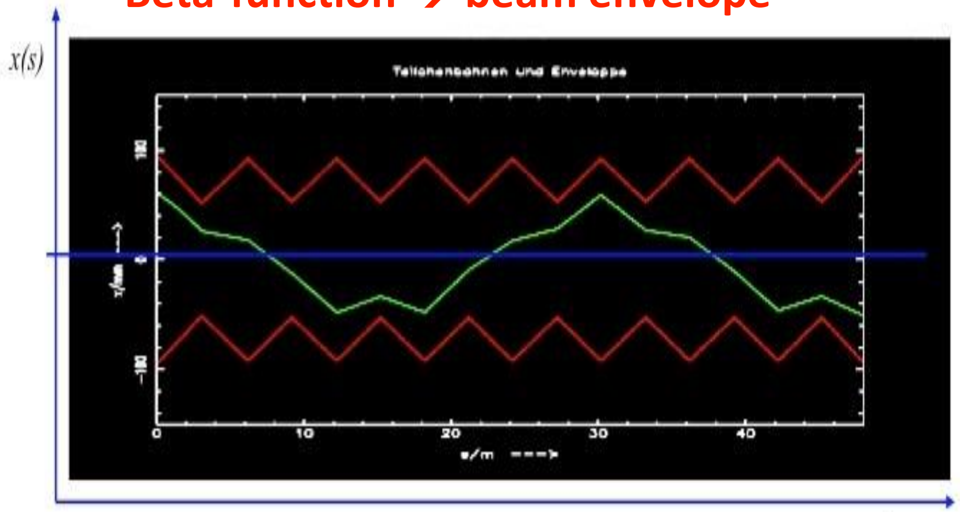


Alternating Gradients: confined motion

The optical Beta-function is a periodic function entirely defined by the lattice (the magnets). Envelop function

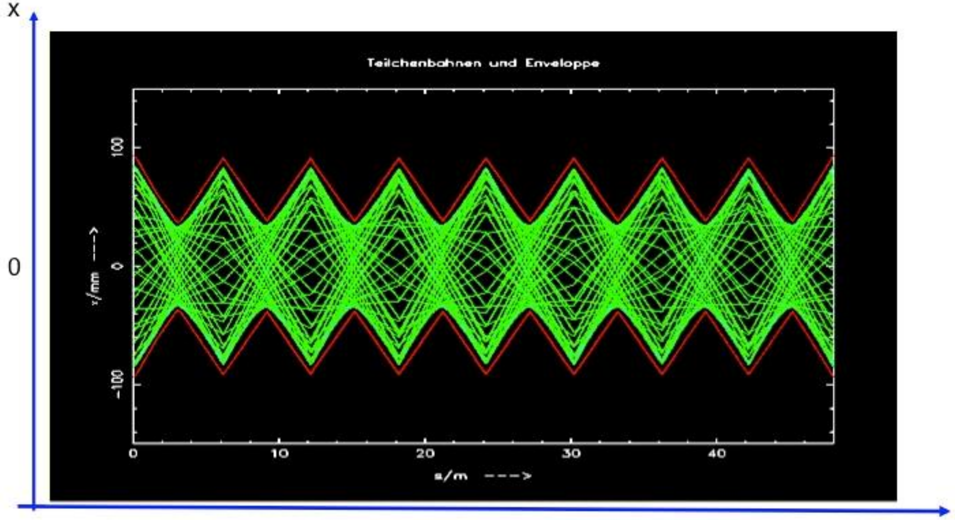
This function is calculated by means of accelerator design software codes. An examples of this is the **Methodical Accelerator Design (MAD-X)** that describes particle accelerators, simulate beam dynamics and optimise the optics.
In case you want to play http://cern.ch/madx

Beta-function → beam envelope



Trajectory of a single particle

Turn, after turn, after turn…betatron oscillations

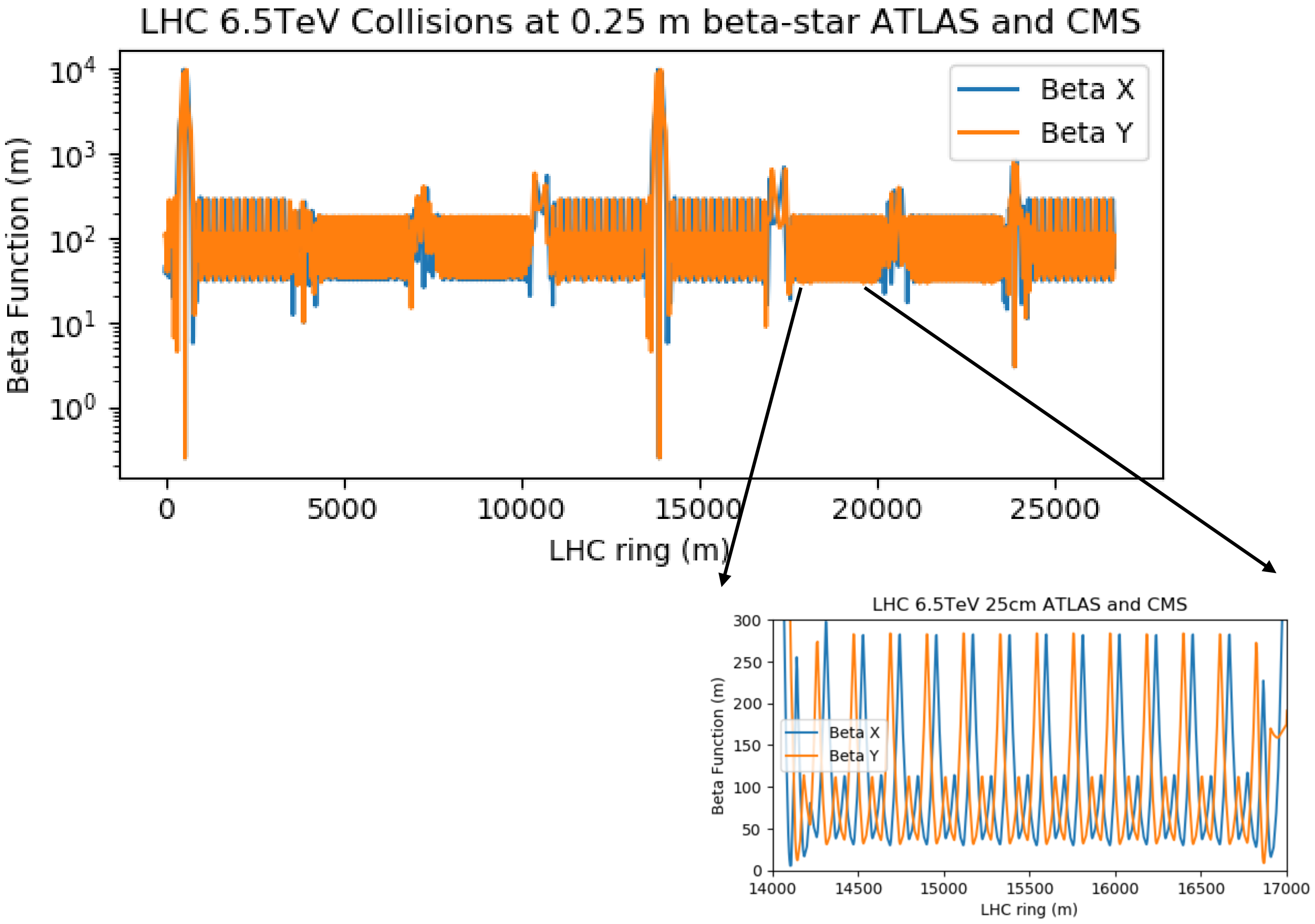


Trajectory of a many particles defining the beam envelope

LHC beams contain about 3x10^{14} protons/beam

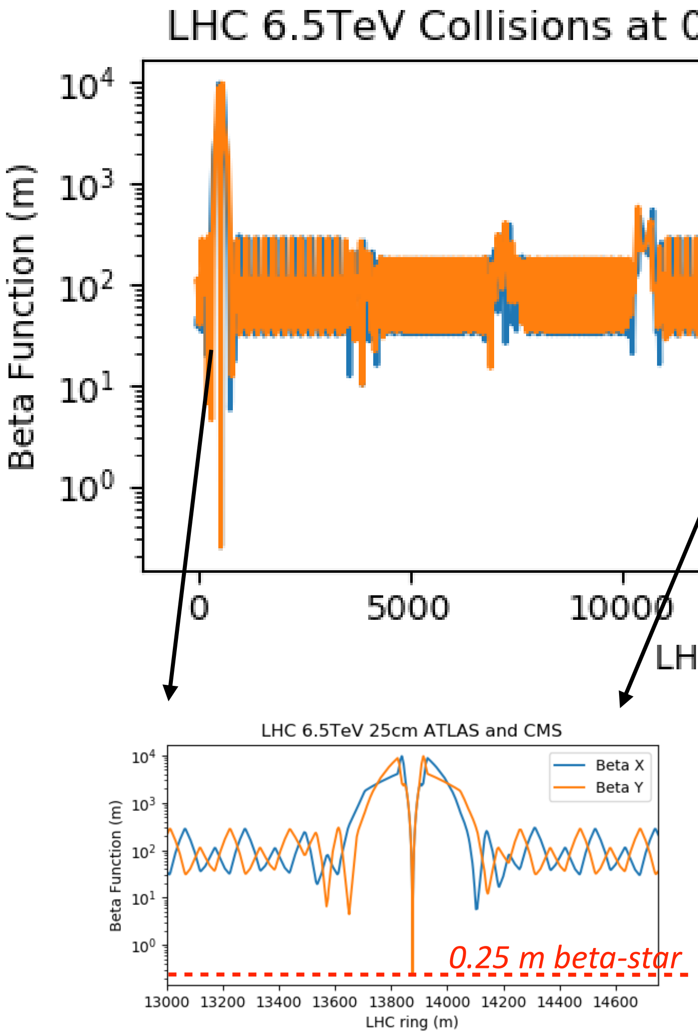
Beta Function at LHC

Examples of real optics used in the LHC at the very small beta-star of 0.25 m in ATLAS and CMS.



Beta Function at LHC

Examples of real optics used in the LHC at the very small beta-star of 0.25 m in ATLAS and CMS.



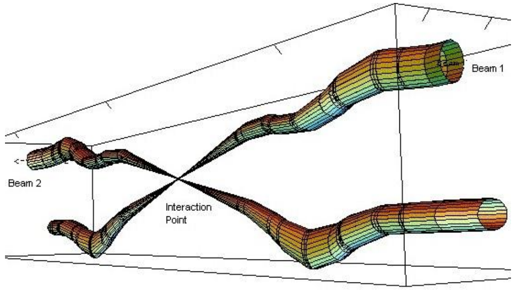
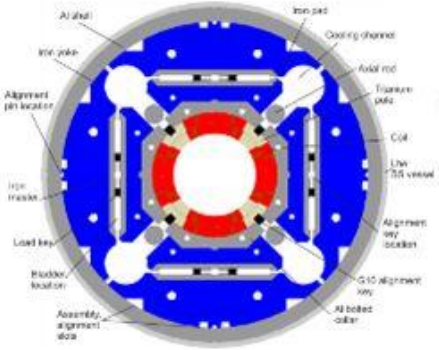
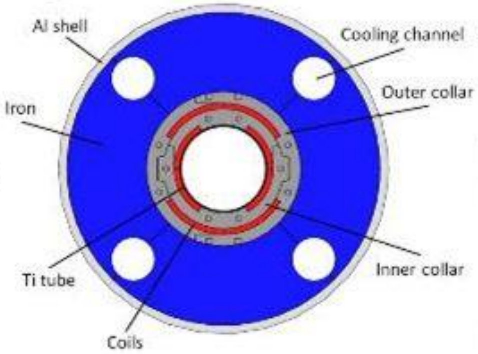


Image credit: J.Jowett

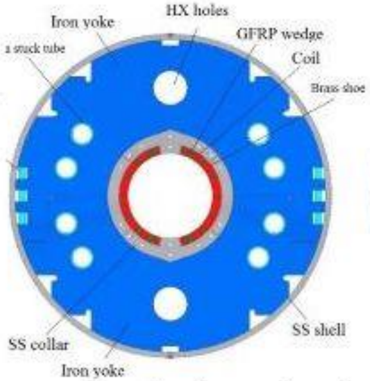
HiLumi LHC magnet zoo



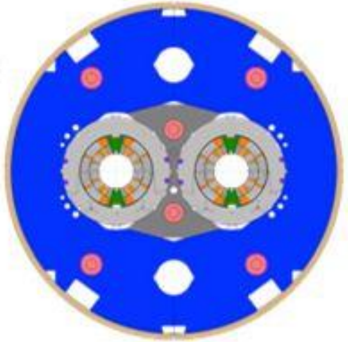
Triplet QXF (LARP and CERN)



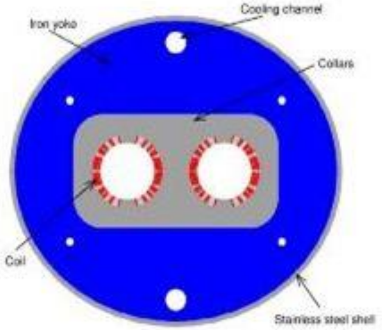
Orbit corrector (CIEMAT)



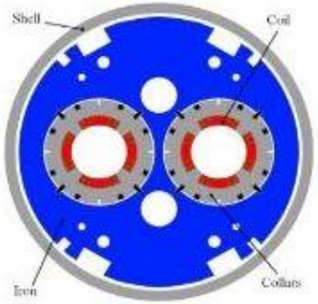
Separation dipole D1 (KEK)



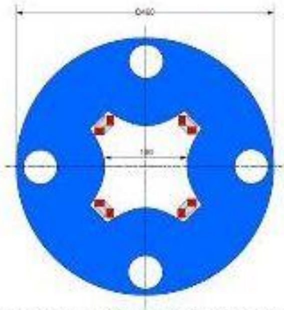
11 T dipole (CERN)



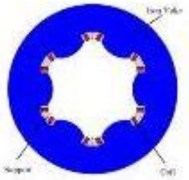
Recombination dipole D2 (INFN design)



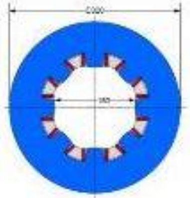
Q4 (CEA)



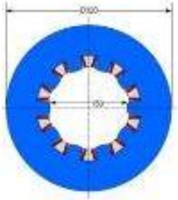
Skew quadrupole (INFN)



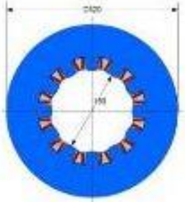
Sextupole (INFN)



Octupole (INFN)



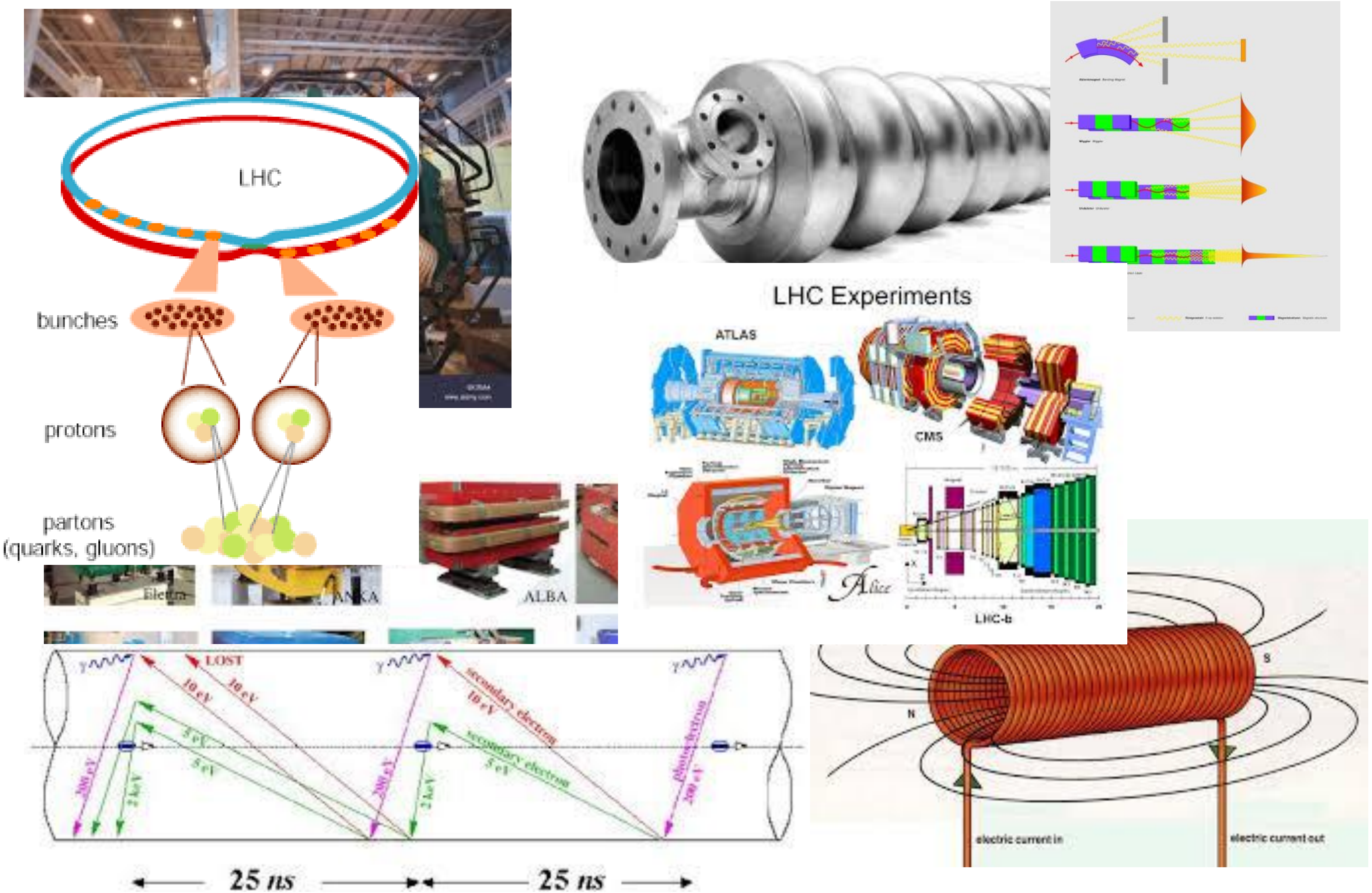
Decapole (INFN)



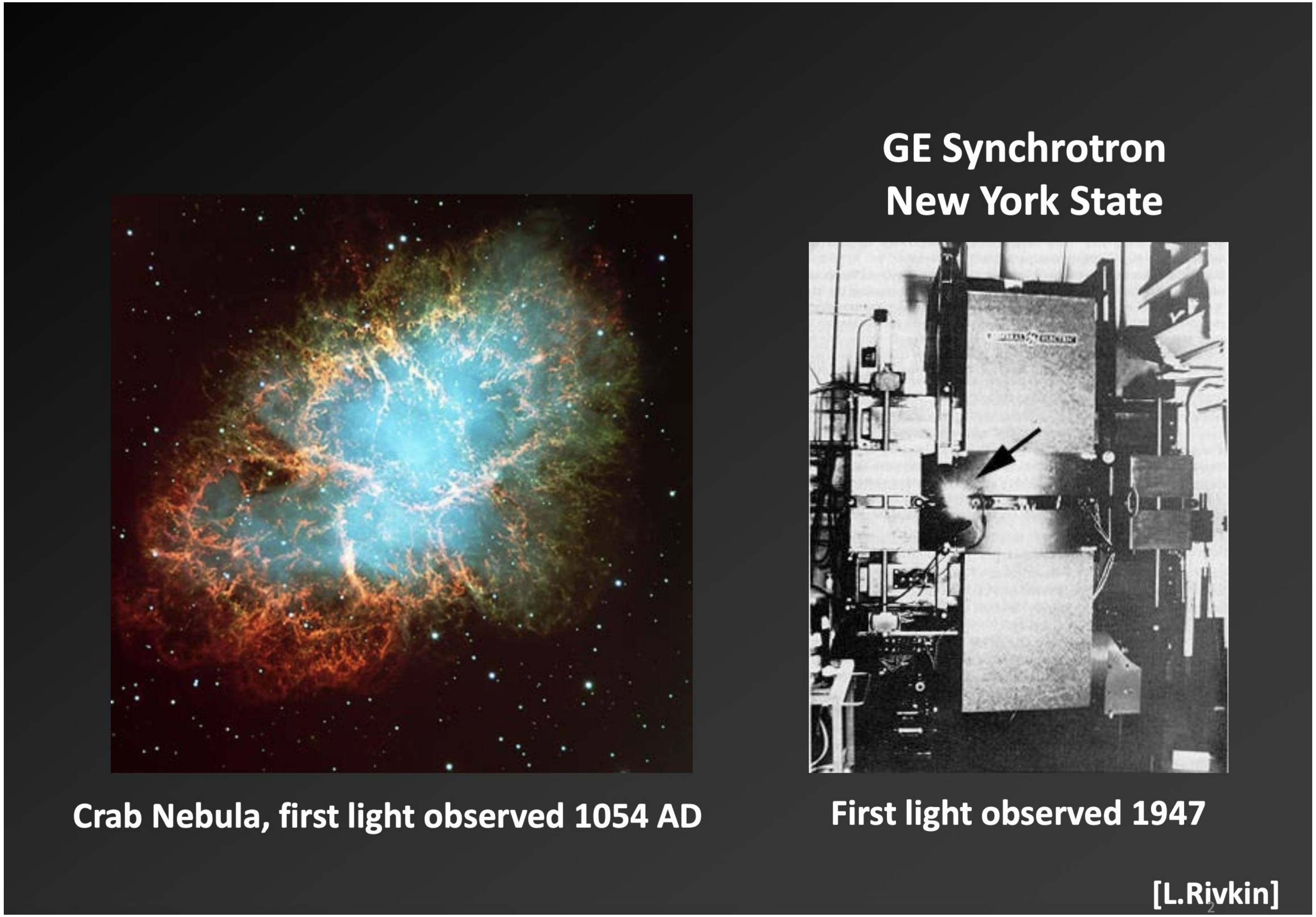
Dodecapole (INFN)

Overall, about 150 magnets are needed

Accelerator elements



Synchrotron radiation



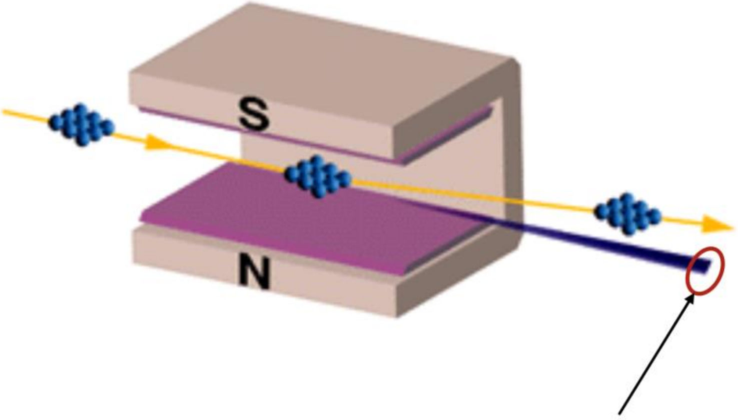
GE Synchrotron
New York State

Crab Nebula, first light observed 1054 AD

First light observed 1947

[L.Rivkin]

Synchrotron radiation



radiation fan

$$\boxed{v \approx c}$$

Radiation Power from accelerated charge

result for radiation power:

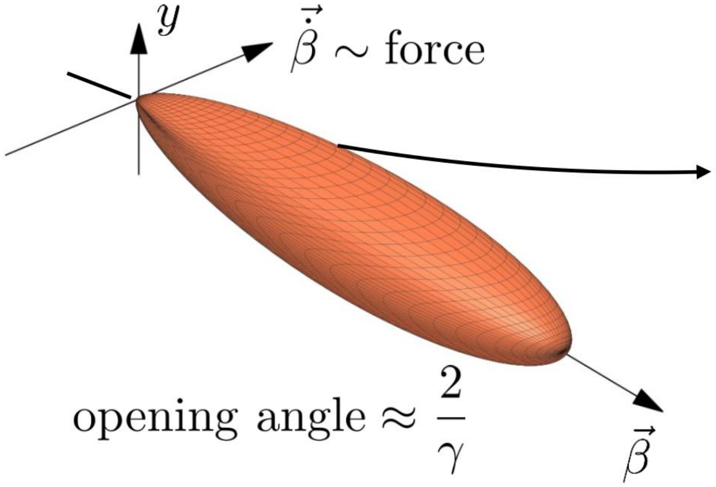
$$P_\gamma = \frac{2}{3} r_e c\, m_0 c^2 \frac{\gamma^4}{\rho^2}$$

strong scaling with energy

bending radius

classical electron radius:

$$r_e = \frac{e^2}{4\pi\varepsilon_0 m_0 c^2} = 2.82 \times 10^{-15}\ \mathrm{m}$$

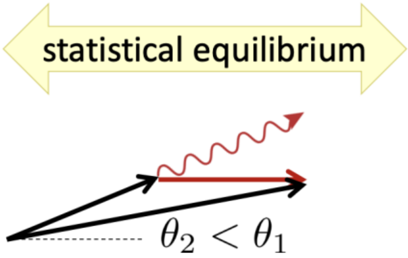


[see Wiedemann 25.3.1]

LEP 20MW losses → 3 GeV per turn at highest energy
FCC-ee designed to have maximum 50MW per beam at all energies

Transverse dimensions

Amazing Properties of Accelerators:
Quantum Effects in Electron Storage Rings

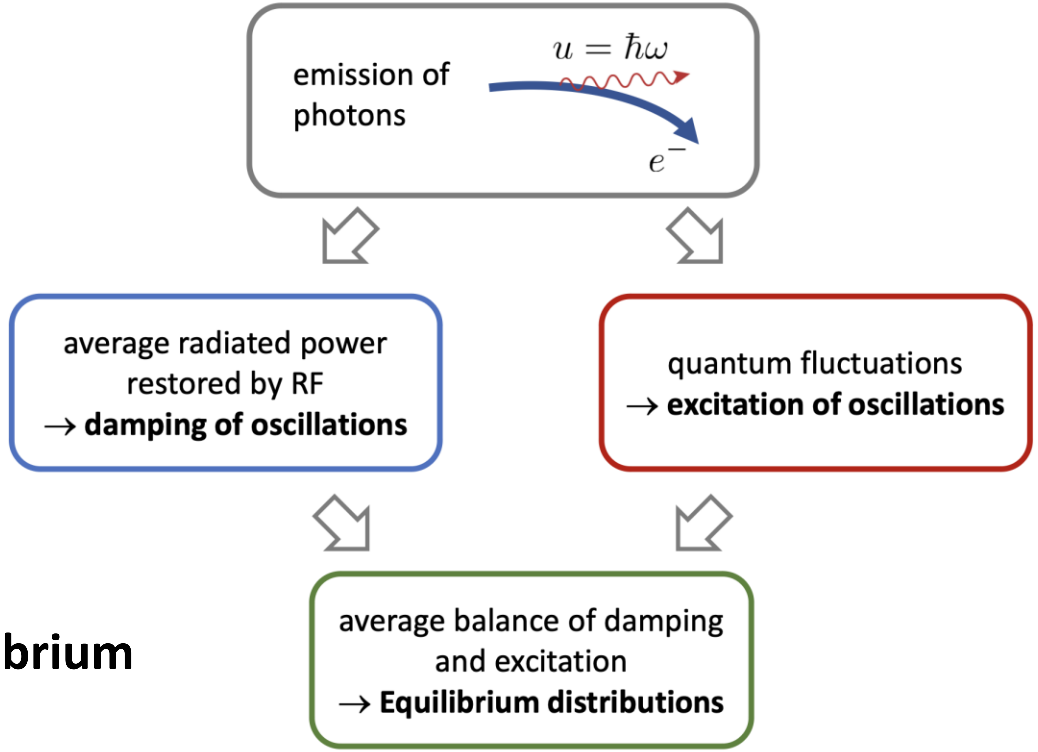


radiation damping by replacing lost momentum

excitation by emission of individual photons

Transverse dimensions of electron storage rings is an equilibrium

Radiation Effects in Electron Rings



emission of photons

average radiated power restored by RF
→ **damping of oscillations**

quantum fluctuations
→ **excitation of oscillations**

average balance of damping and excitation
→ **Equilibrium distributions**

Colliders versus Fixed Target Experiments

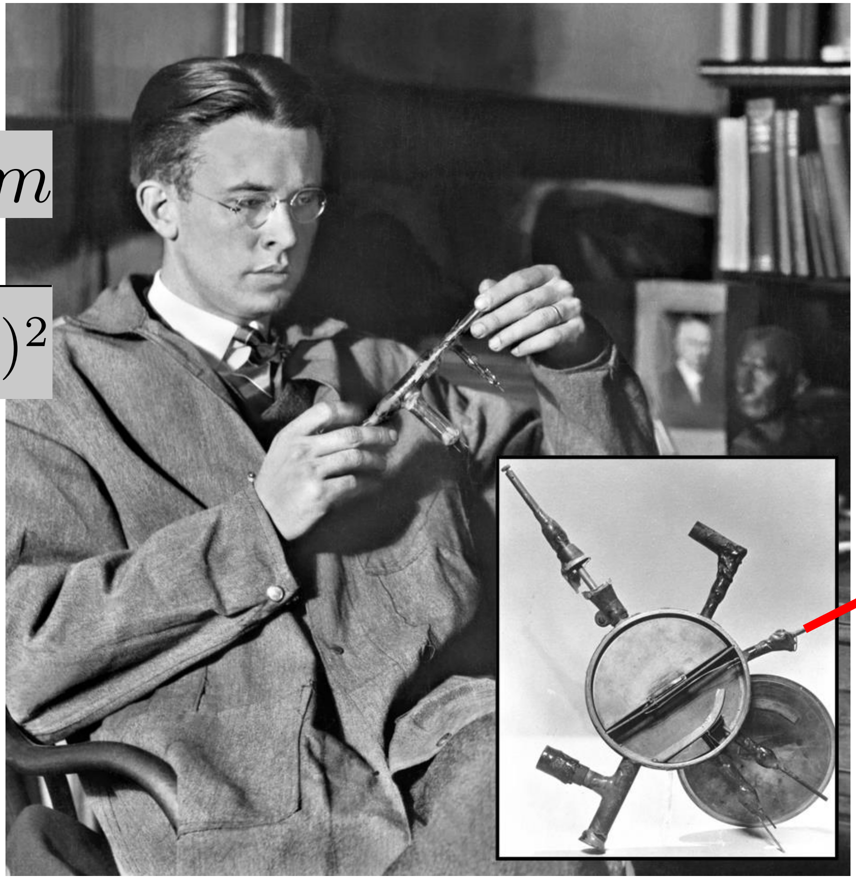
Two Beams of

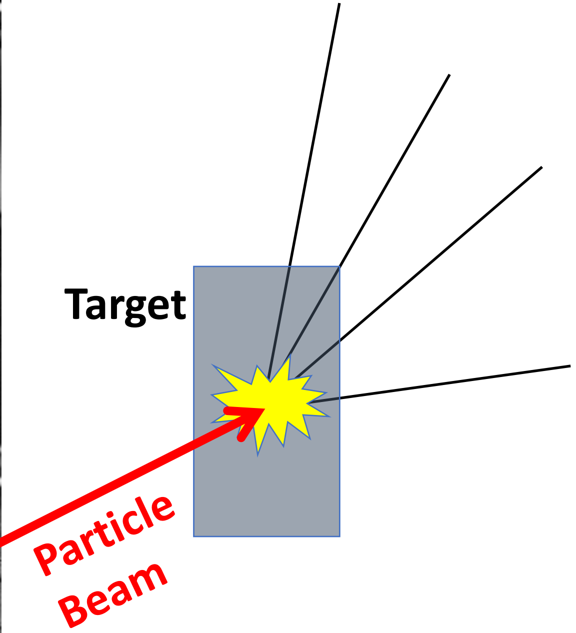
$$E_1, \overrightarrow{p_1}, E_2, \overrightarrow{p_2}, m_1 = m_2 = m$$

$$E_{cm} = \sqrt{(E_1 + E_2)^2 - (\overrightarrow{p_1} + \overrightarrow{p_2})^2}$$

Beam 2 is a Target → $\overrightarrow{p_2} = 0$

$$E_{cm} = \sqrt{2m^2 + 2E_1 m}$$

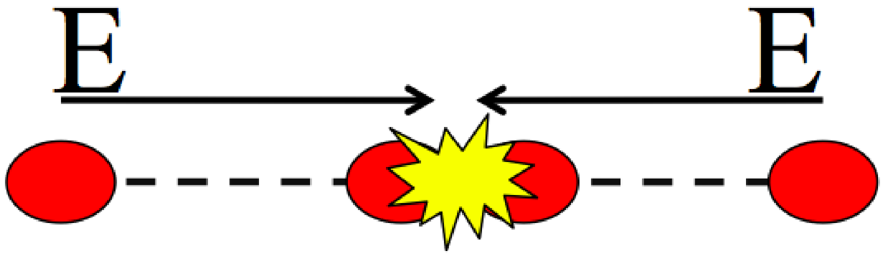




7 TeV proton beam against fix target →115 GeV

Colliders versus Fixed Target Experiments

Anello di
Accumulazione AdA
B. Touschek 1960
INFN @ Frascati
Laboratory



Colliders versus Fixed Target Experiments

Two Beams of

$$E_1, \overrightarrow{p_1}, E_2, \overrightarrow{p_2}, m_1 = m_2 = m$$

$$E_{cm} = \sqrt{(E_1 + E_2)^2 - (\overrightarrow{p_1} + \overrightarrow{p_2})^2}$$

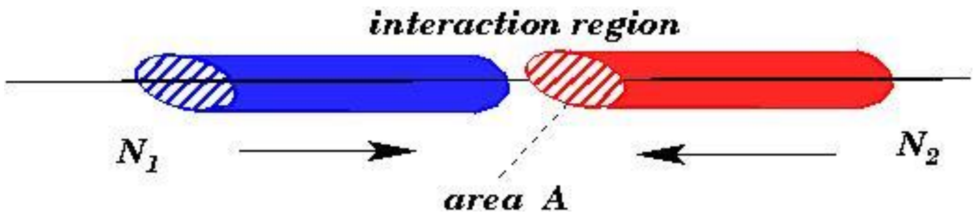
Beam 2 is a counter rotating beam

$$\overrightarrow{p_1} = \overrightarrow{p_2}$$

$$E_{cm} = E_1 + E_2$$

7 TeV proton beam colliding → 14 TeV

Luminosity



For accelerator people **this IS the quantity used to optimise the machine.**

The higher the luminosity the better.

$$N_{\text{event}} = L\sigma_{\text{event}}$$

Accelerator

Nature

Number of particles per bunch

Number of bunches

$$L \propto \frac{N_1 N_2 n_b f_{rev}}{4\pi A} \cdot F$$

Geometric Reduction factor

$$A = \epsilon_n \beta^*$$

$$F = 1/\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

Transverse Emittance

Optical Beta-star

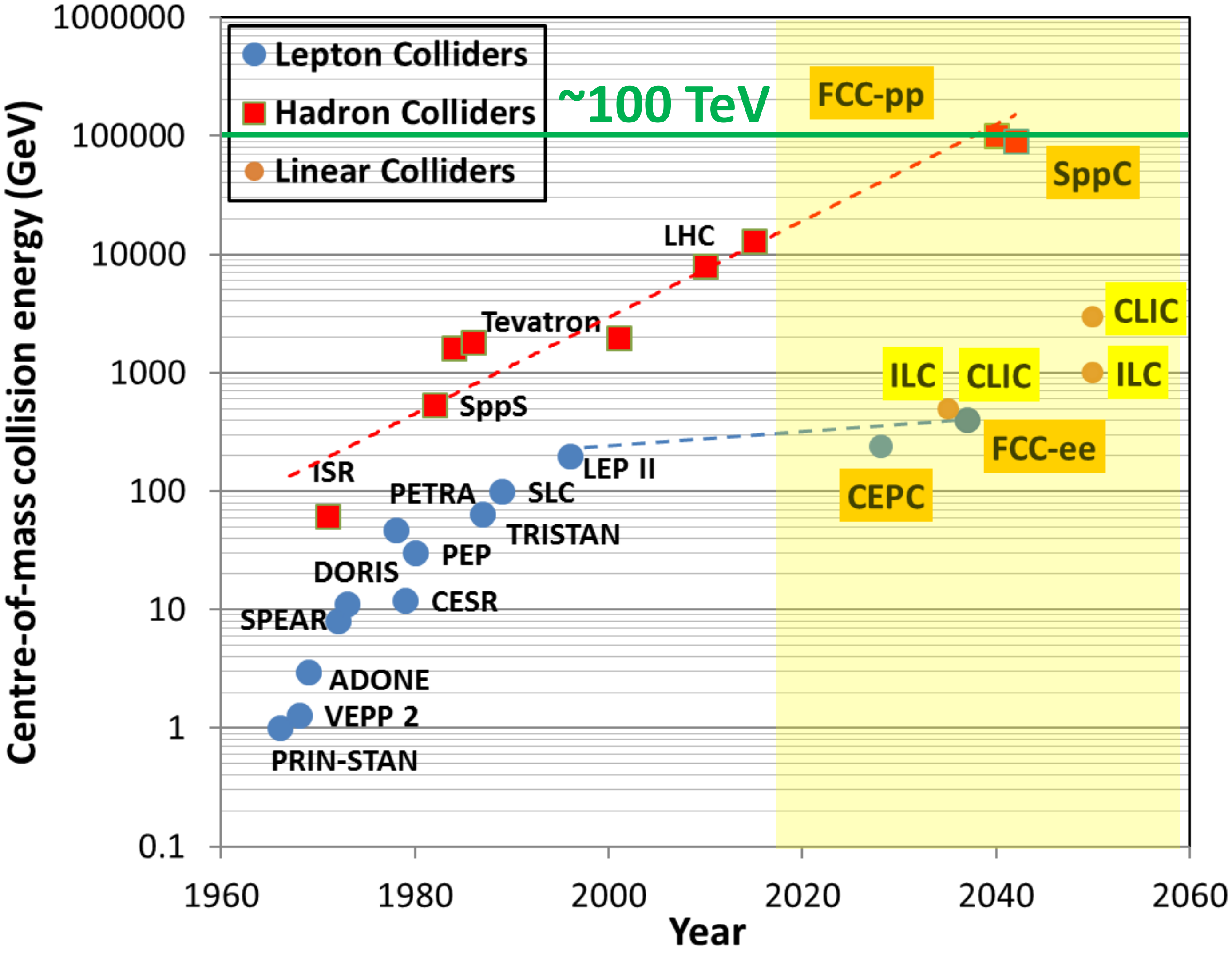
Crossing Angle

Bunch length

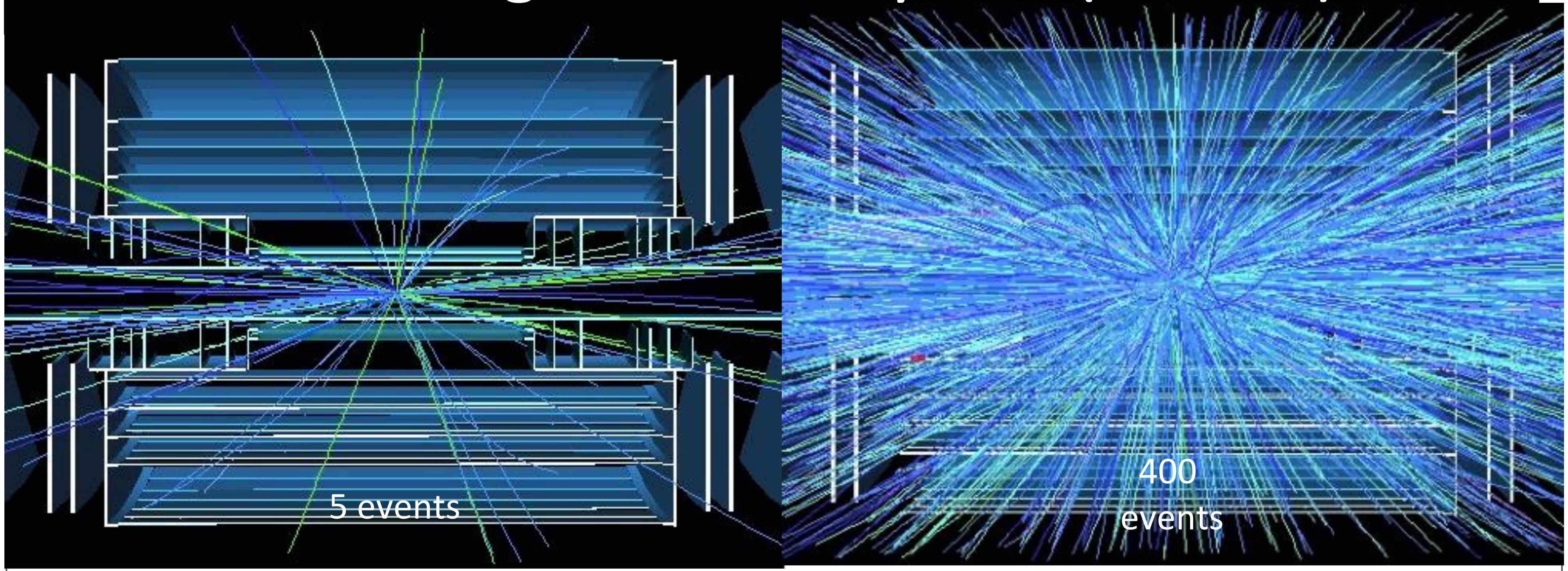
Outline

- Accelerators for High Energy Physics exploration
- European Strategy for HEP and CERN future accelerators studies
- Circular Colliders basics:
  - basic accelerator physics consepts
  - Colliders: Center of Mass Energy and luminosity
  - Leptons versus Hadrons: synchrotron Radiation
- LHC and HL-LHC full exploitation
- FCC-ee description
  - Plans and General parameters
  - Optics and allignment
  - Beam dynamics with collisions: Beam-beam, Beamstrahlung, BhBar and Synchrotron radiations
  - Electron Clouds and photon electrons
  - Radiation in the interaction region and detectors challenges
- FCC-hh essentials

High Energy Colliders under study



Goal of High Luminosity LHC (HL-LHC)



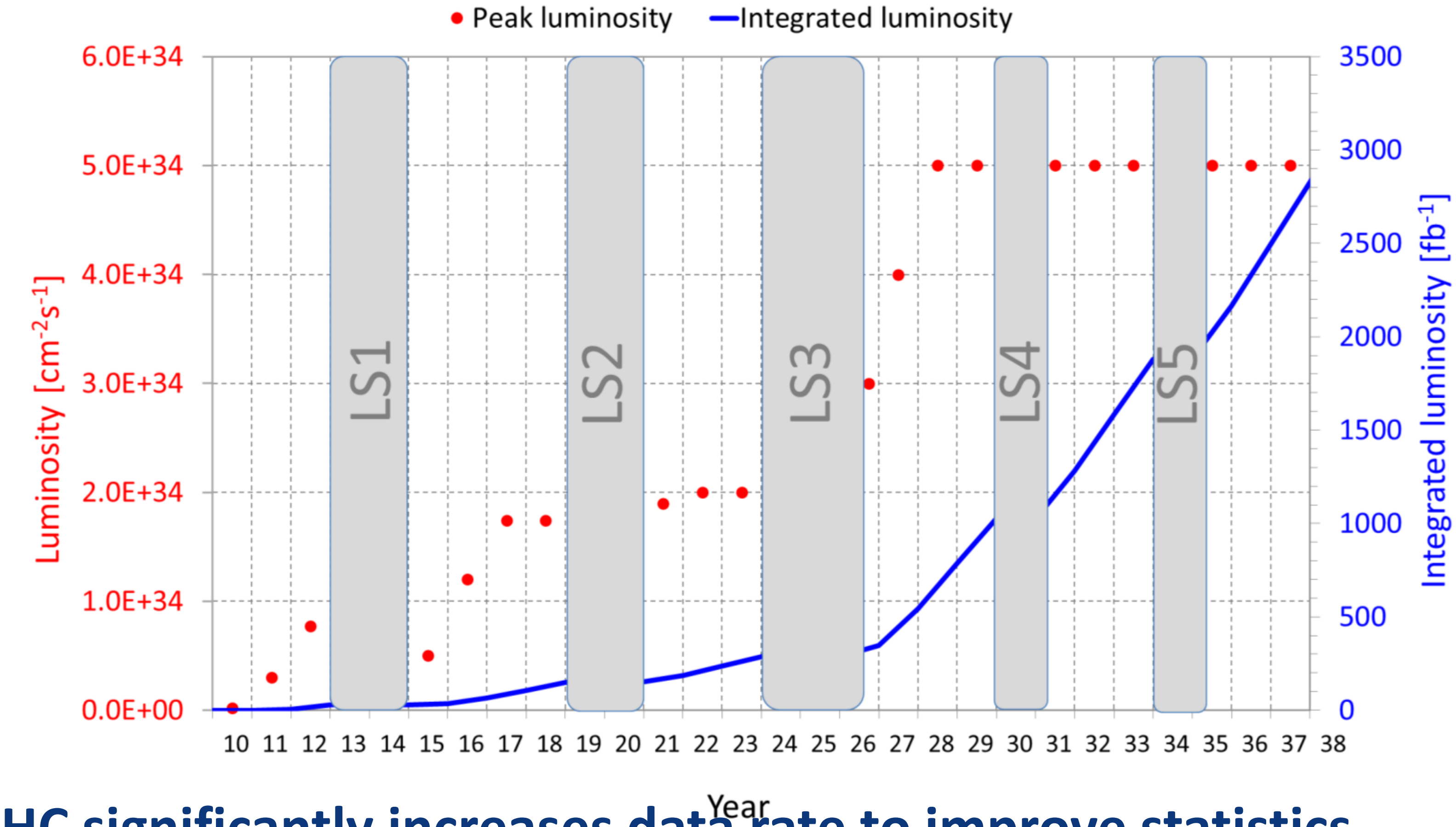
implying an integrated luminosity of **250 fb^{-1} per year**,

design oper. for $\mu = \mathbf{140}$ (➔ peak luminosity **5 10^{34} cm^{-2} s^{-1}**)

➔ Operation with levelled luminosity! (beta*, crossing angle & crab cavity)

➔10x the luminosity reach of first 10 years of LHC operation!!

HL-LHC upgrade – full LHC exploitation

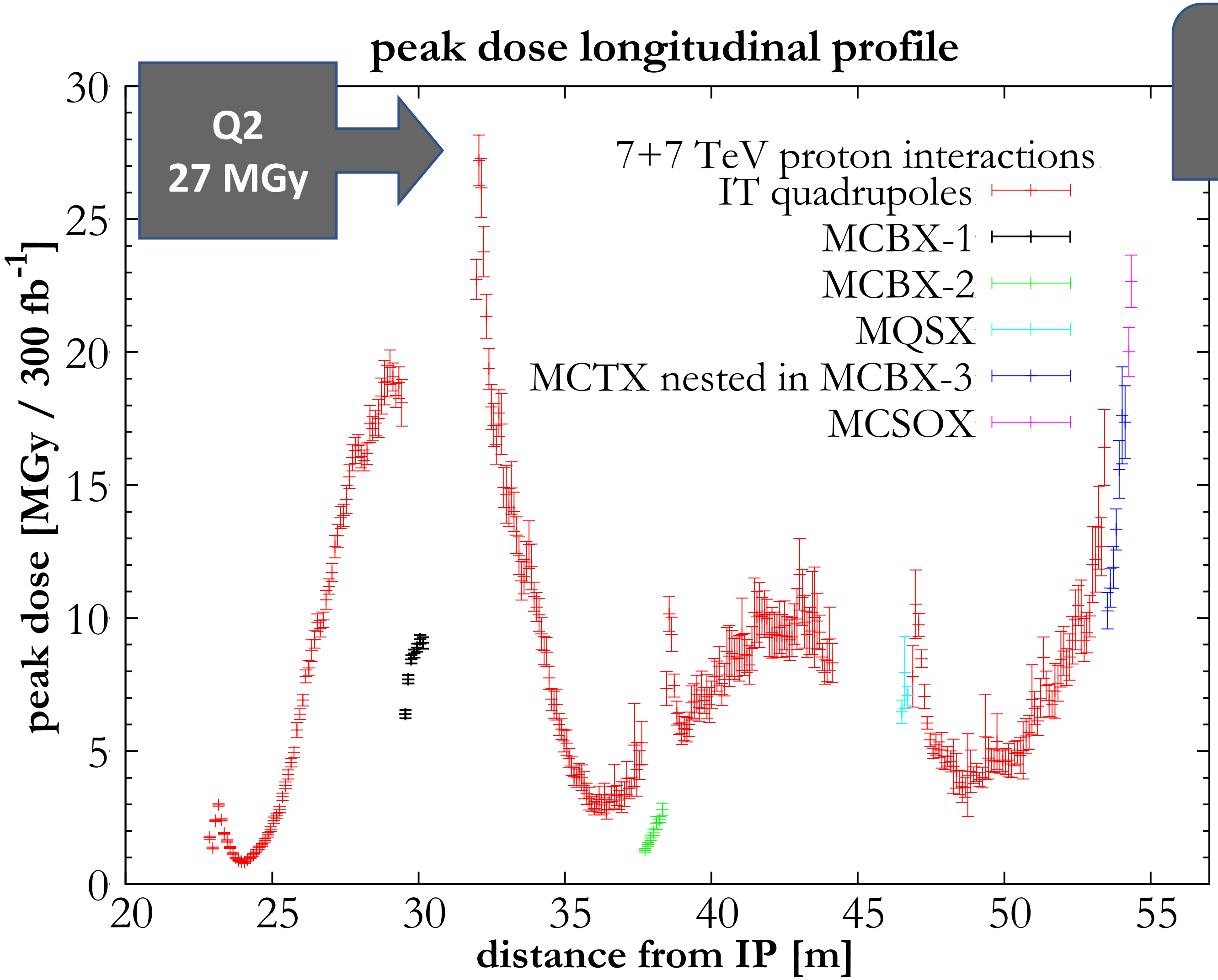


HL-LHC significantly increases data rate to improve statistics, measurement precision, and energy reach in search of new physics

Gain of a factor 5 in rate, factor 10 in integral data wrt initial design

Operation till 2040

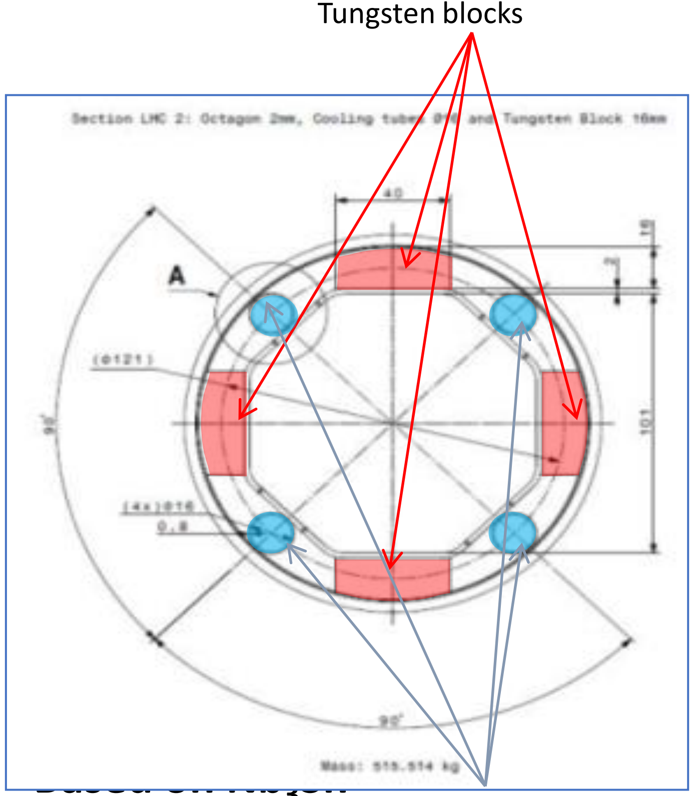
LHC technical bottleneck:
Radiation damage to triplet magnets at 300 fb-1



Q2
27 MGy

Cold bore insulation ≈ 35 MGy

HL-LHC technical bottleneck:
Radiation damage to triplet magnets



Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity 3000 fb^{-1}! ➔ Shielding!

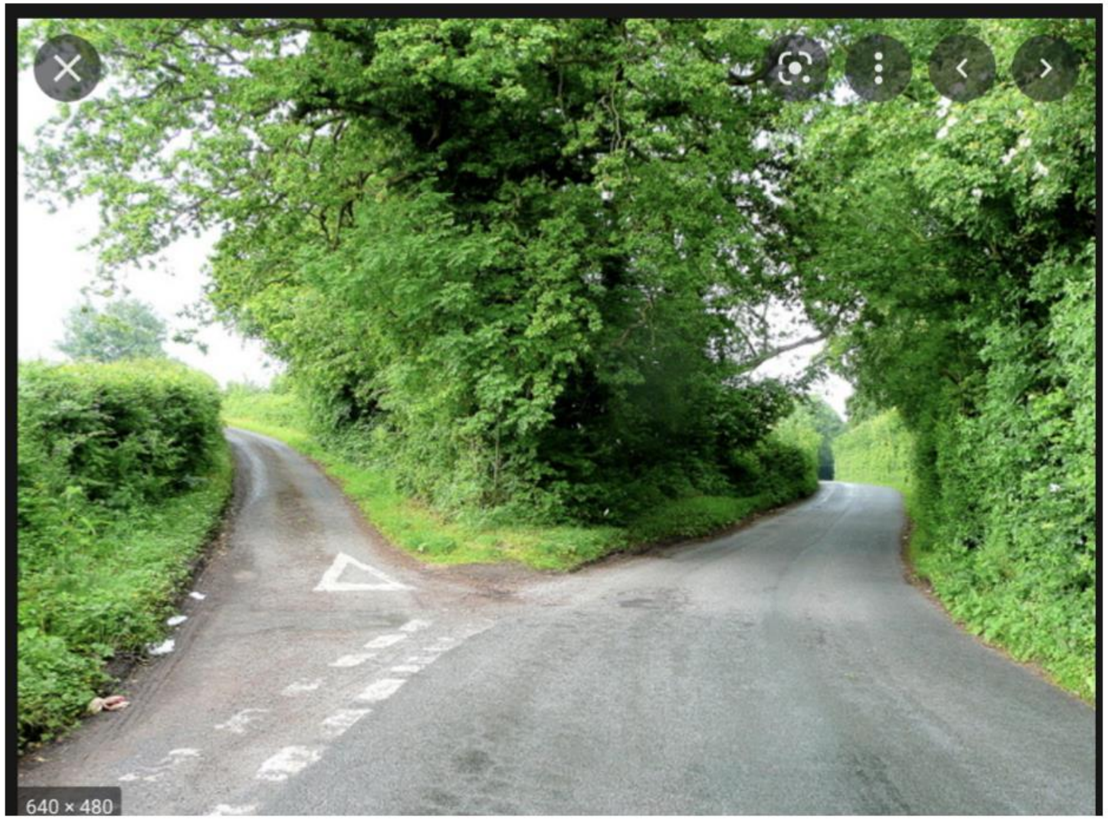
- ➔ Requires larger aperture!
- ➔ New magnet technology
- ➔ LHC: 70mm at 210 T/m ➔HL@ 150mm diameter 140 T/m
- ➔ LHC: 8T peak field at coils ➔ HL> 12T field at coils (Nb_3Sn)!

technology

Outline

- Accelerators for High Energy Physics exploration
- European Strategy for HEP and CERN future accelerators studies
- Circular Colliders basics:
    - basic accelerator physics consepts
    - Colliders: Center of Mass Energy and luminosity
    - Leptons versus Hadrons: synchrotron Radiation
- LHC and HL-LHC full exploitation
- FCC-ee description
    - Plans and General parameters
    - Optics and allignment
    - Beam dynamics with collisions: Beam-beam, Beamstrahlung, BhBar and Synchrotron radiations
    - Electron Clouds and photon electrons
    - Radiation in the interaction region and detectors challenges
- FCC-hh essentials

Where does CERN go from here?



FCC Week 2024
San Francisco US

DECISION TIMES - WITH HISTORICAL PERSPECTIVE

President of CERN council
E. Rabinovici

Stage 1: FCC-ee – highest luminosity lepton collider

4 Operational energies:
Z → 45.6 GeV
WW → 80 GeV
H(ZH) → 120 GeV
ttbar → 182.5 GeV

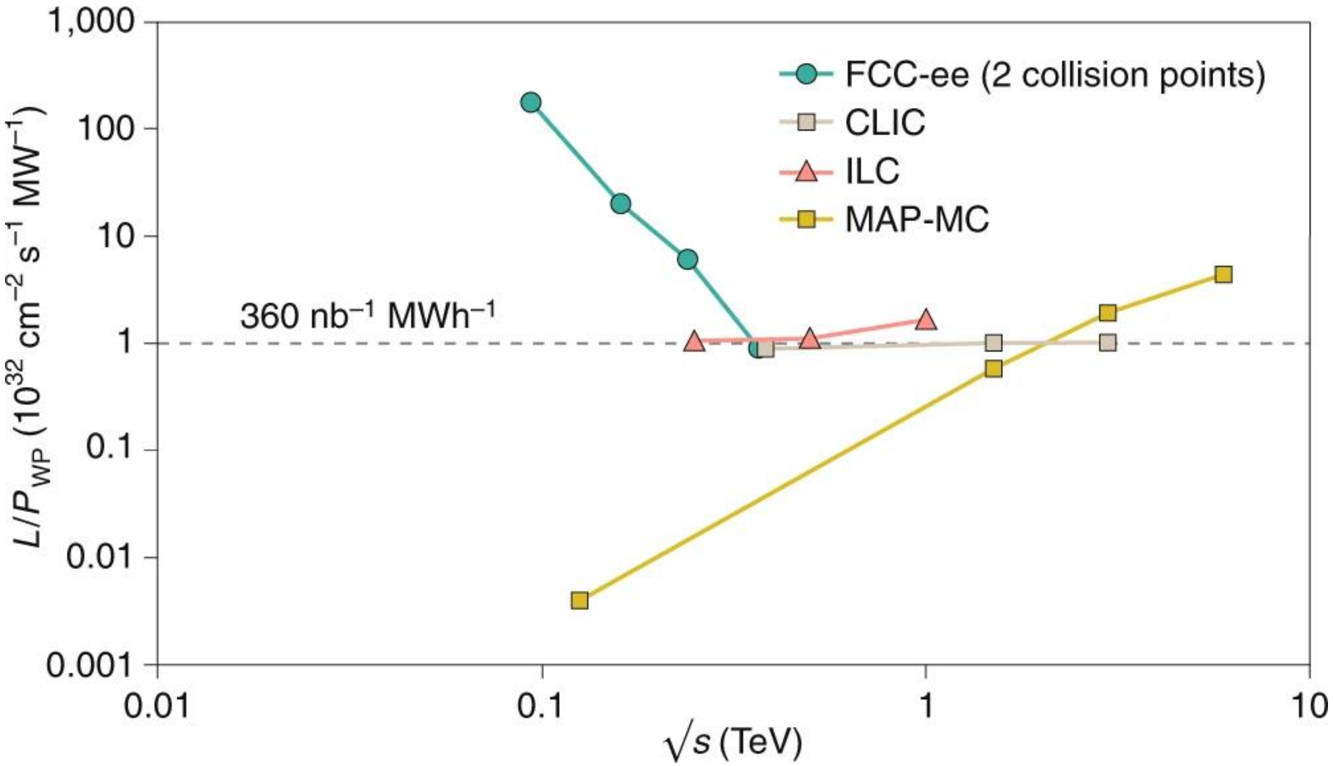
efficient $\mathcal{L}$ from Z to $t\bar{t}$

>2.5 ab^{-1} with ~0.5×10^6 H / IP (3y)

>75 ab^{-1} with ~2×10^{12} Z / IP (4y)

enormous performance increase:
collects LEP data statistics in few minutes

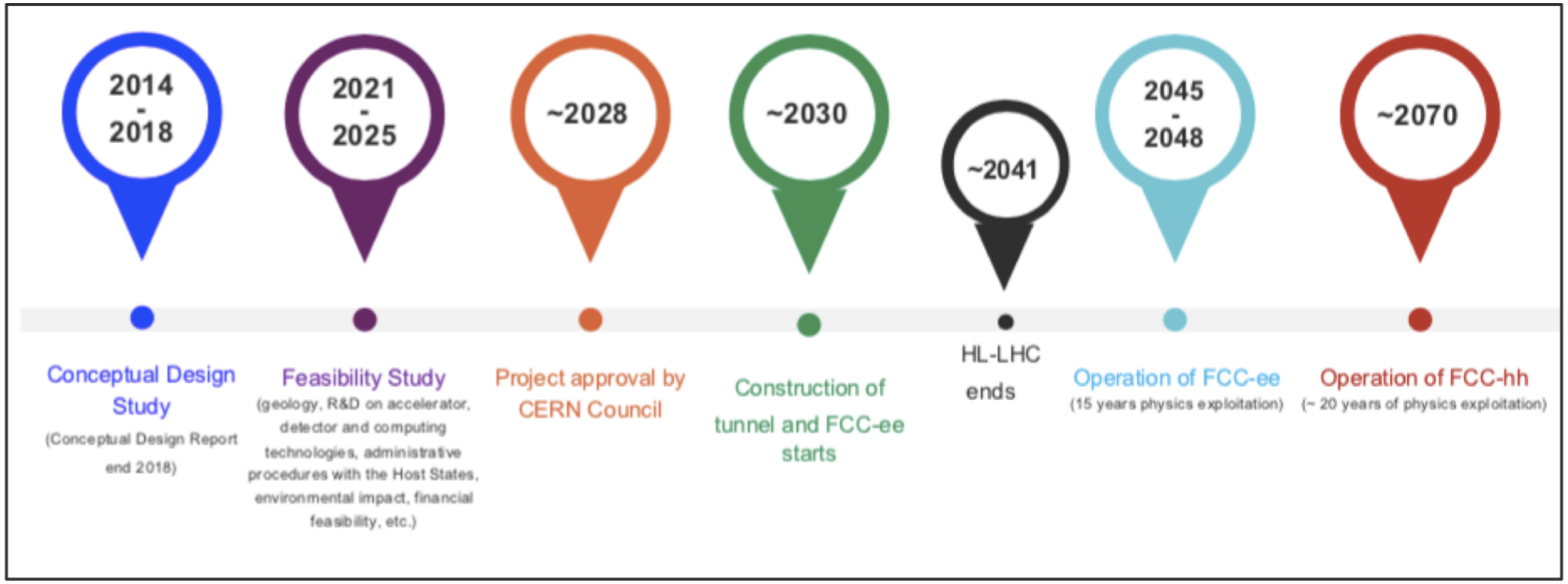
luminosity vs. electricity consumption



highest lumi/power of all *H* fact. proposals

Nature Physics 16, 402–407 (2020)

FCC timeline



1st stage collider FCC-ee:
electron-positron collisions 90-360 GeV: electroweak and Higgs factory
2nd stage collider FCC-hh:
proton-proton collisions at ~ 100 TeV

"Realistic" schedule taking into account:

- ❑ past experience in building colliders at CERN
- ❑ the various steps of approval process: ESPP update, CERN Council decision
- ❑ HL-LHC will run until ~ 2041

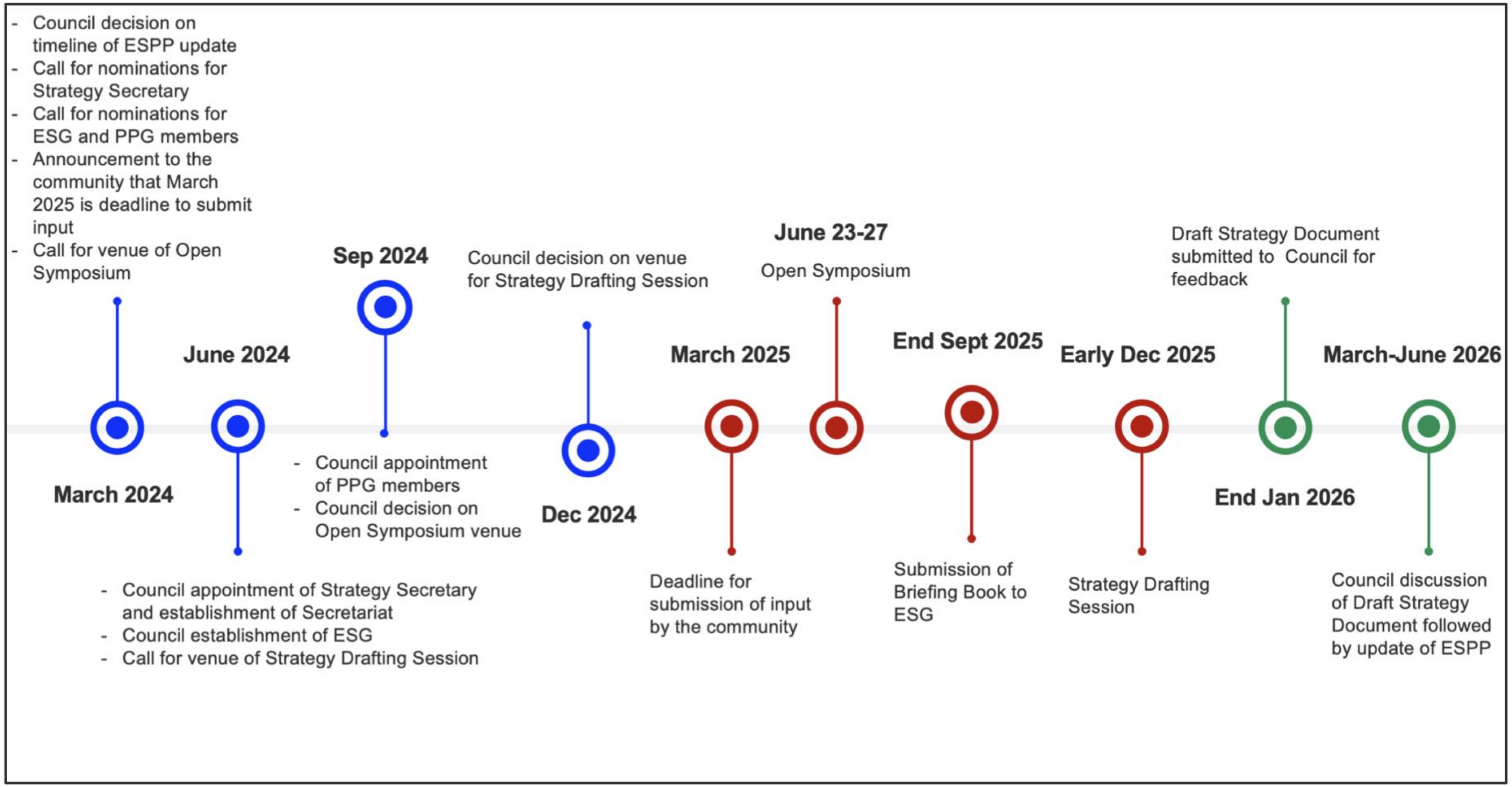
→ ANY future collider at CERN cannot start physics operation before ~ 2045 (but construction will proceed in parallel to HL-LHC operation)

Care should be taken when comparing to other proposed facilities, for which in most cases only the (optimistic) technical schedule is shown. In particular, studies related to **territorial implementation** (surface sites, roads, connection to water and electricty, environmental impact, admin procedures, etc.), which for FCC are being carried out in the framework of the Feasibility Studies, **take years.**

F. Gianotti FCC week 2024

Timeline of European Strategy update

- Next week: appointment of Strategy Secretary, Strategy Secretariat and European Strategy Group (ESG) by CERN Council
- March 2025: deadline for submission of community input
- June 23-27, 2025: Open Symposium
- Early Dec 2025: Strategy Drafting Session
- June 2026: Strategy update by CERN Council → end of the process



March 2024

- Council decision on timeline of ESPP update
- Call for nominations for Strategy Secretary
- Call for nominations for ESG and PPG members
- Announcement to the community that March 2025 is deadline to submit input
- Call for venue of Open Symposium

June 2024

- Council appointment of Strategy Secretary and establishment of Secretariat
- Council establishment of ESG
- Call for venue of Strategy Drafting Session

Sep 2024

- Council appointment of PPG members
- Council decision on Open Symposium venue

Dec 2024

Council decision on venue for Strategy Drafting Session

March 2025

Deadline for submission of input by the community

June 23-27

Open Symposium

End Sept 2025

Submission of Briefing Book to ESG

Early Dec 2025

Strategy Drafting Session

End Jan 2026

Draft Strategy Document submitted to Council for feedback

March-June 2026

Council discussion of Draft Strategy Document followed by update of ESPP

Why FCC ?

F. Gianotti

1) **Physics : best overall physics potential of all proposed future colliders; matches the vision of the 2020 European Strategy:** "An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."

- ☐ FCC-ee : **ultra-precise** measurements of the Higgs boson, indirect exploration of next energy scale (~ x10 LHC)
- ☐ FCC-hh : **only** machine able to explore next **energy frontier** directly (~ x10 LHC)
- ☐ Also provides for heavy-ion collisions and, possibly, ep/e-ion collisions
- ☐ **4 collision points** → robustness; specialized experiments for maximum physics output

2) **Timeline**

- ☐ **FCC-ee technology is "mature"** → construction can start in the early 2030s and physics a few years after the end of HL-LHC operation (currently 2048, earlier if more resources available) → This would keep the community, in particular the young people, engaged and motivated.
- ☐ **FCC-ee before FCC-hh** would also allow:
  - cost of the (more expensive) FCC-hh machine to be spread over more years
  - **20 years of R&D work towards affordable magnets providing the highest achievable field (HTS)**
  - **optimization of overall investment** : FCC-hh will reuse same civil engineering and large part of FCC-ee technical infrastructure

3) It's the **only facility commensurate with the size of the CERN community** (4 major experiments)

Is it feasible? Isn't it too ambitious?

-- Ongoing Feasibility Study showing spectacular progress

-- **FCC is big and audacious project, but so were LEP and LHC when first conceived** → they were successfully built and performed far beyond expectation → demonstration of capability of our community to deliver on very ambitious projects

-- FCC is the **best project for future of CERN** (for above reasons) → **we have to work to make it happen**

FUTURE
CIRCULAR
COLLIDER

FCC-ee: main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
horizontal rms IP spot size [μm]	9	21	13	40
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

4 years
5 x 10^{12} Z
LEP x 10^{5}

2 years
> 10^{8} WW
LEP x 10^{4}

3 years
2 x 10^{6} H

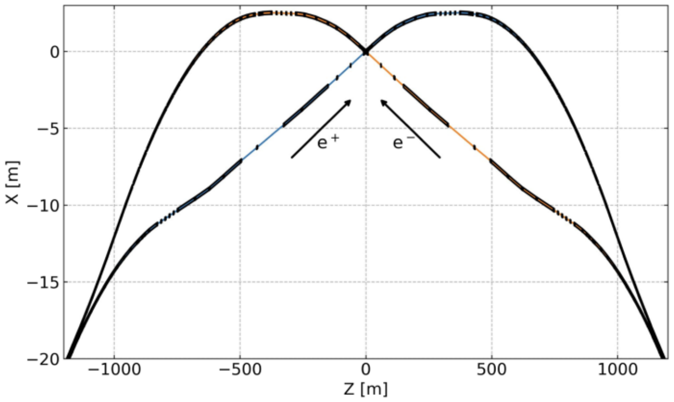
5 years
2 x 10^{6} tt pairs

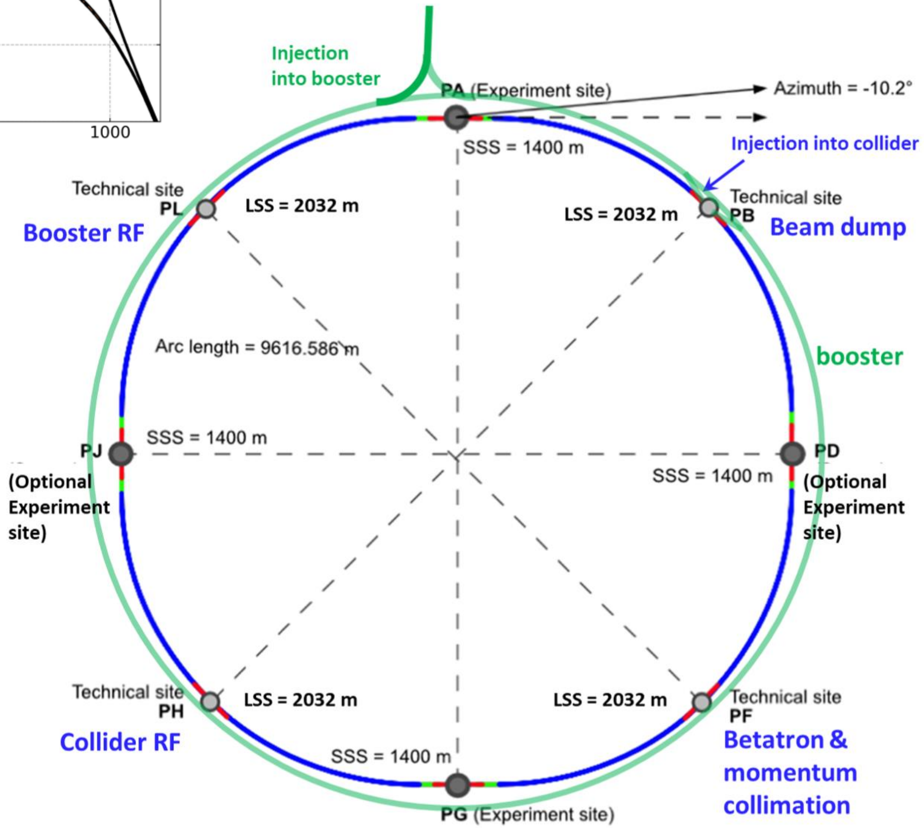
Design and parameters dominated by the choice to allow for 50 MW synchrotron radiation per beam.

- ☐ x 10-50 improvements on all EW observables
- ☐ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ☐ x10 Belle II statistics for b, c, τ
- ☐ indirect discovery potential up to ~ 70 TeV
- ☐ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

FCC-ee collider





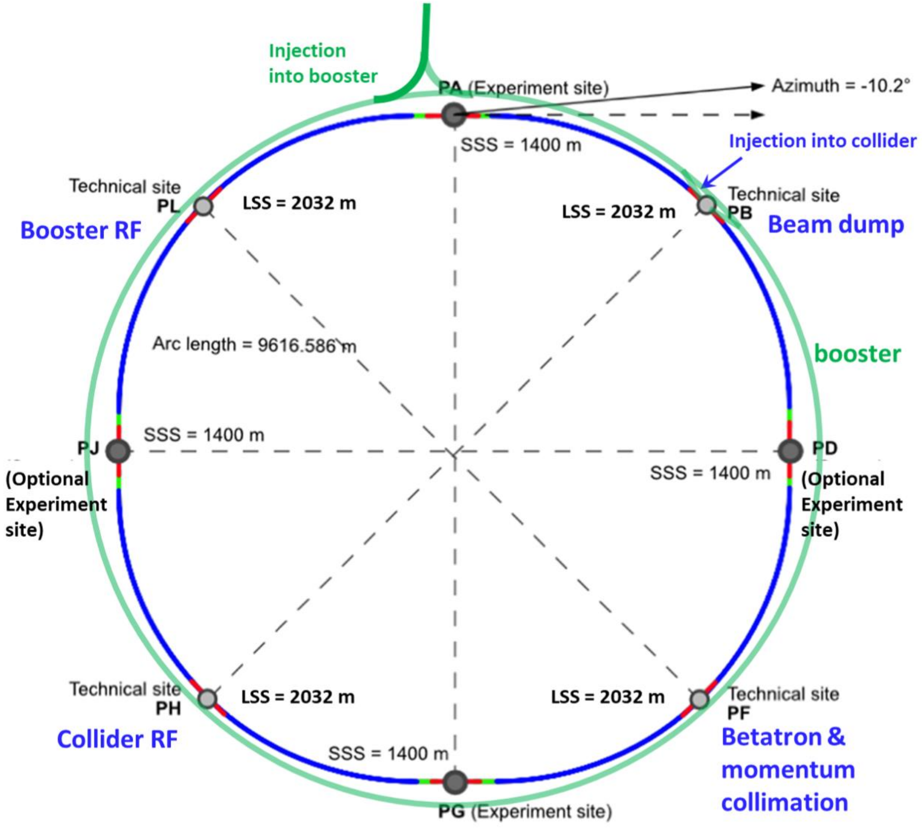
- 90.7 Km circumference
- Double ring e^+e^- collider baseline normal conducting magnets
- Full-energy booster
- Top-Up injection
- Four-fold super periodicity → 2 or 4 collision points (experiments) beams cross from in to outside.

Layout	circumference	arc	techn. LSS	exp. LSS
PA31-3.0	90657.400	9616.175	2032.000	1400.000
CDR	97765		2760	1450

FCC-ee challenges

Performance limitations:

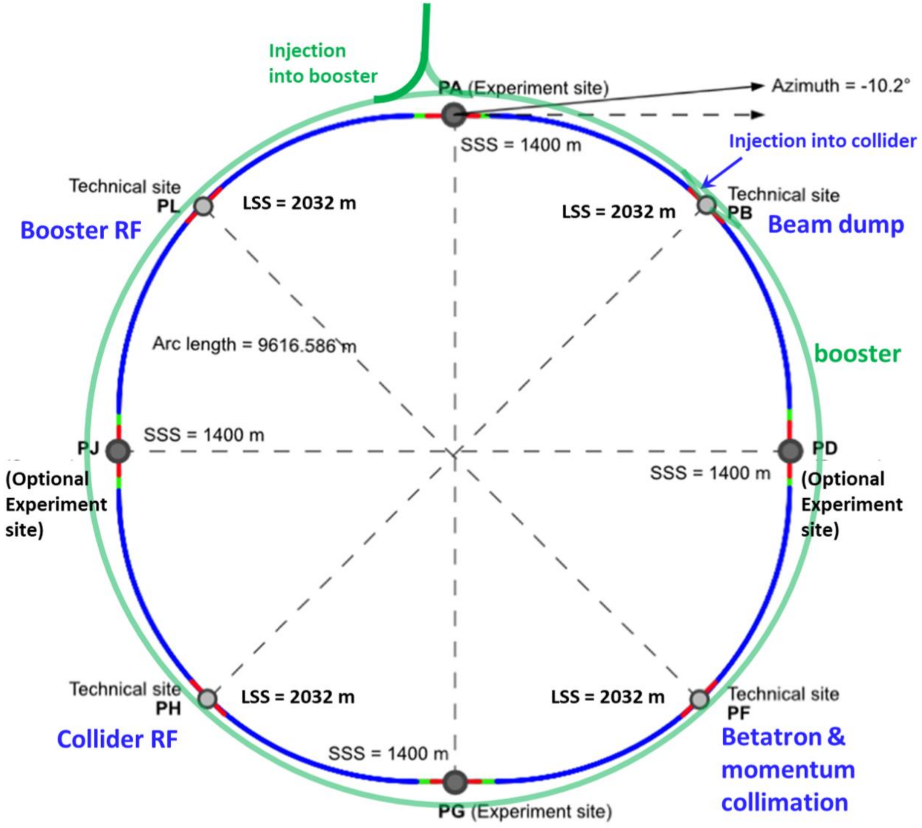
- beamstrahlung
- coherent beam-beam instability in collisions with very large crossing angle
- Synchrotron betatron resonances
- Polarization requirements
- machine impedance
- Photon electrons



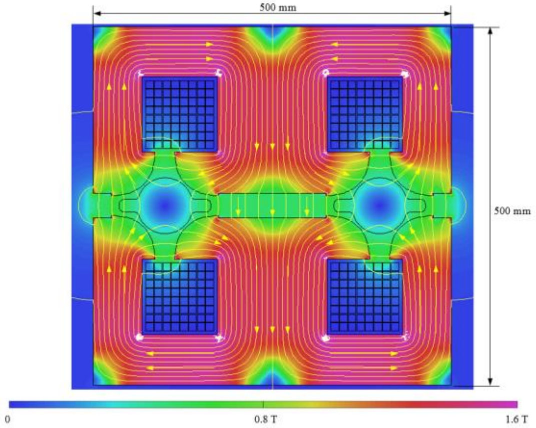
FCC-ee beams

Beams

- At the Z→ 11200 bunches (25 ns bunch spacing, 1.2 mus train separations)
- W→ 1780 bunches (bunch spacing 150 ns, train-train 2 mus)
- ZH and ttbar → bunches uniformely distributed around the ring



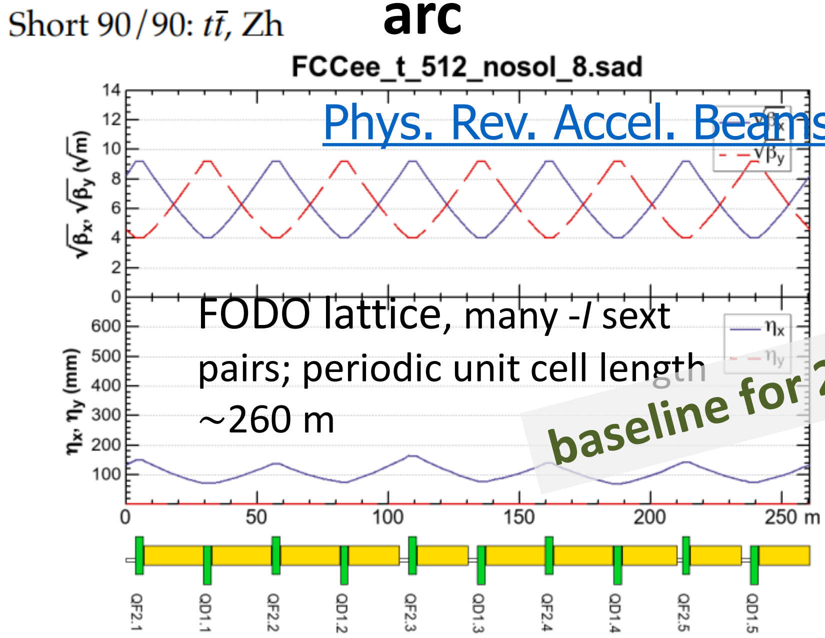
Baseline → normal conducting magnets
Studies to have option using High Temperature Superconductors technology



FCC-ee collider optics: two viable options

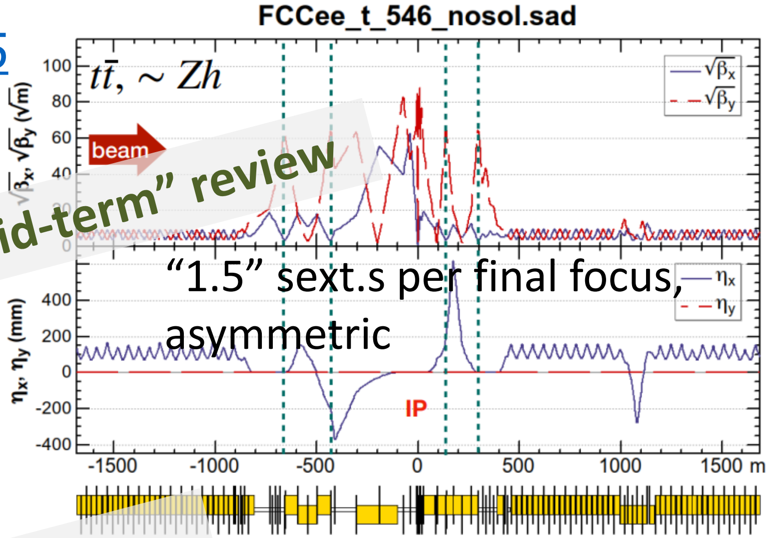
arc

interaction region



[Phys. Rev. Accel. Beams **19**, 111005]

FODO lattice, many -*I* sext pairs; periodic unit cell length ~260 m

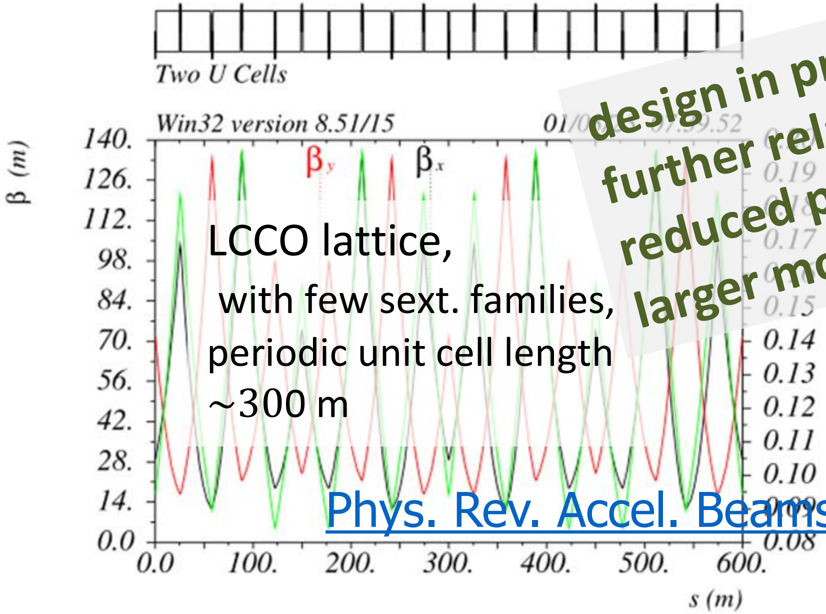


"1.5" sext.s per final focus, asymmetric

baseline for 2023 FCC "mid-term" review

K. Oide, 2023 EPS

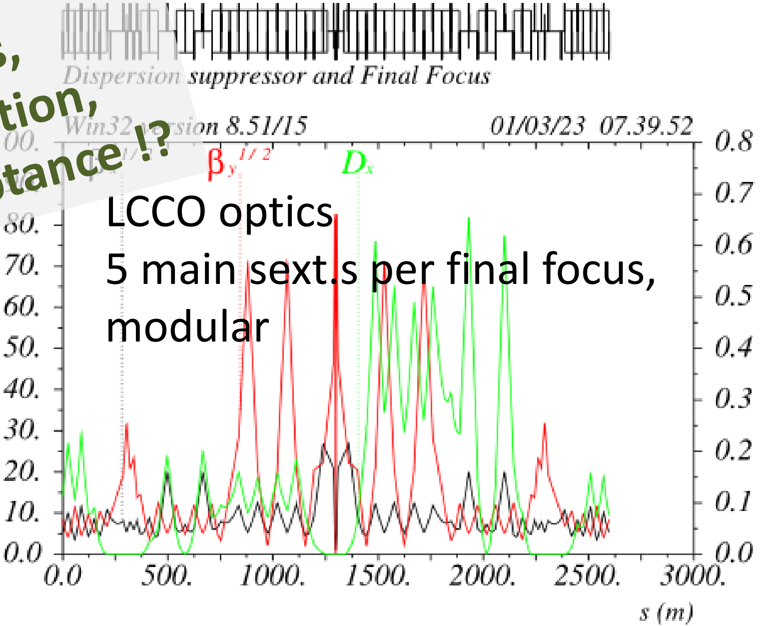
Rolf Wideroe award winner



LCCO lattice,
with few sext. families, periodic unit cell length ~300 m

[Phys. Rev. Accel. Beams **26**, 021601]

design in progress - further relaxed tolerances, reduced power consumption, larger momentum acceptance !?



LCCO optics
5 main sext.s per final focus, modular

P. Raimondi, 2017 EPS

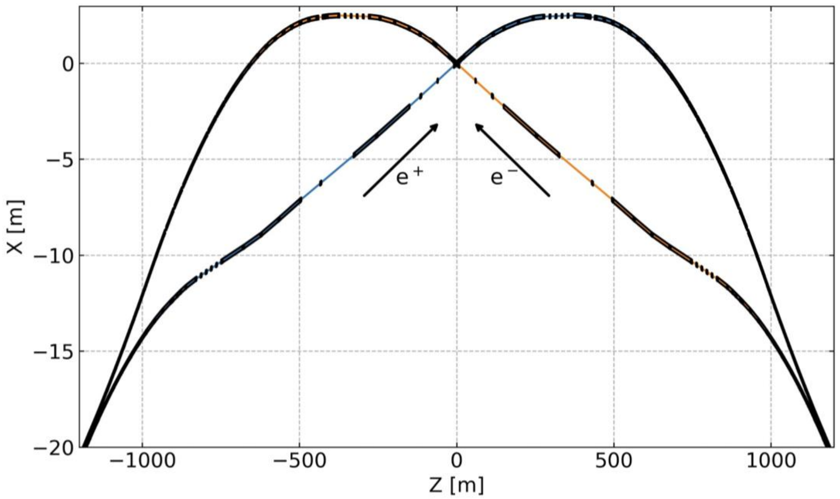
Gersh Budker award winner

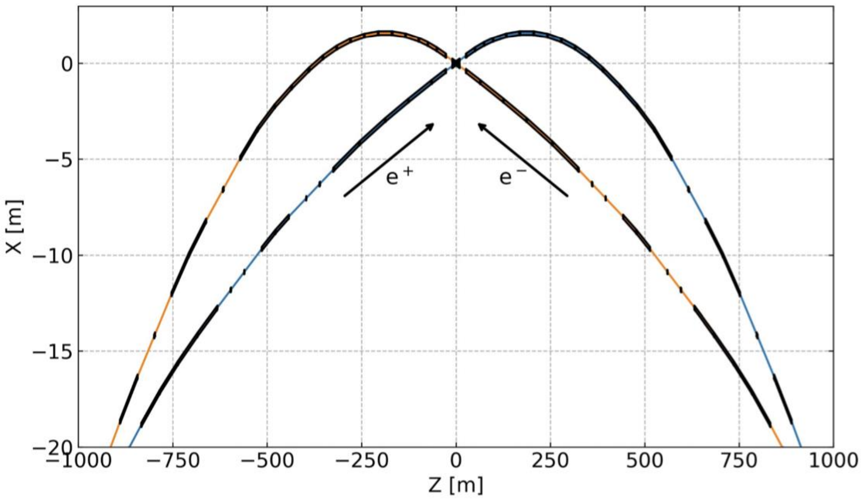
Interaction Region design

β* = 0.11 m
β * = 0.7 mm

nm RMS beam spots at the IP

FCC-ee lattice | baseline and LCCO IR design





The lattice design upstream the IP is based on weak dipoles (**100 keV critical energy**), long straight sections and implements a **30 mrad crossing angle** at the IP.

The model features: the (anti-)solenoid field map, a detailed central beam pipe with a **10mm** radius, **6 synchrotron radiation collimators**, and **2 masks.**

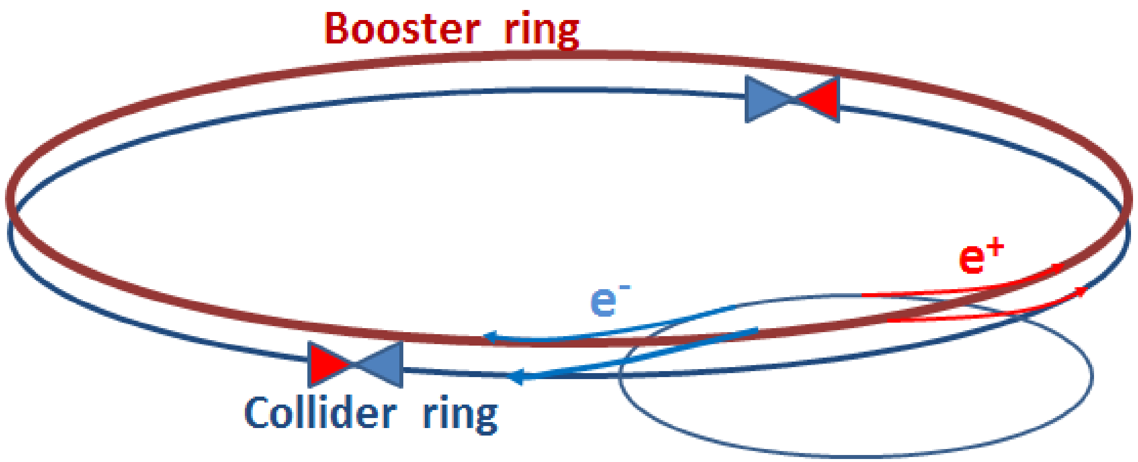
The lattice design upstream the IP is based on weak dipoles (**156 keV critical energy**), short straight sections and implements a **30 mrad crossing angle** at the IP.

The model features: the (anti-)solenoid field map, a detailed central beam pipe with a **10mm** radius, **2 synchrotron radiation collimators**, and **2 masks.**

Top-up injection concept

Beside the collider ring(s), a booster of the same size (same tunnel) must permanently provide beams for top-up injection

- **same RF voltage, but low power (~ MW)**
- **top up frequency ~0.1 Hz**
- **booster injection energy ~10-20 GeV**
- **bypass around the experiments**



Injector complex for e^+ and e^- beams of 10-20 GeV

- **Injector similar to Super-KEKB injector is suitable**

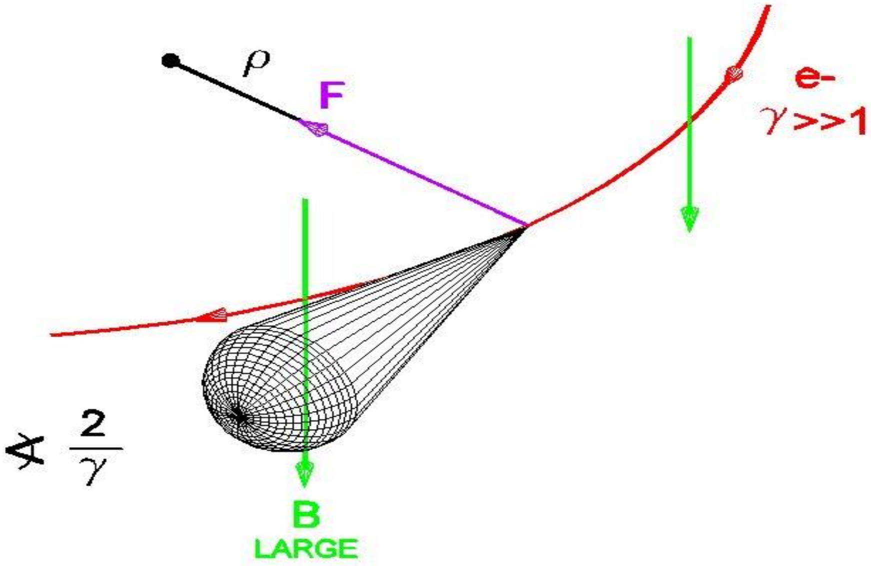
Synchrotron radiation

- Lepton colliders: name of the game here - **luminosity: as many collisions as possible → high beam current, small beam size→ high brilliance N/A**
- Energy reach of circular e^+e^- colliders is limited due to synchrotron radiation of charged particles on curved trajectory:
- FCC-ee design based on 50 MW power loss due to SR per beam (0.04-10.5 GeV per turn)

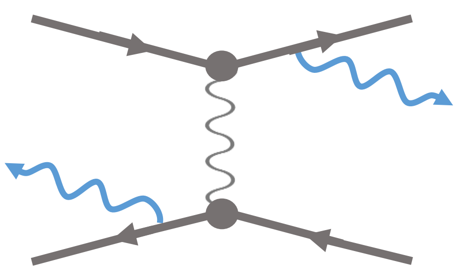
$$\Delta E \propto (E_{kin}/m_0)^4/\rho$$

$m_{prot} = 2000\ m_{electr}$

$\Delta E_{electron} \sim 10^{13}\ \Delta E_{proton}$

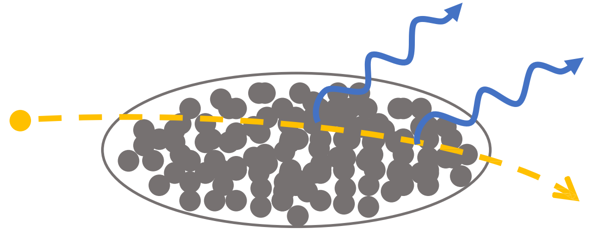


Radiation at FCC-ee collisions



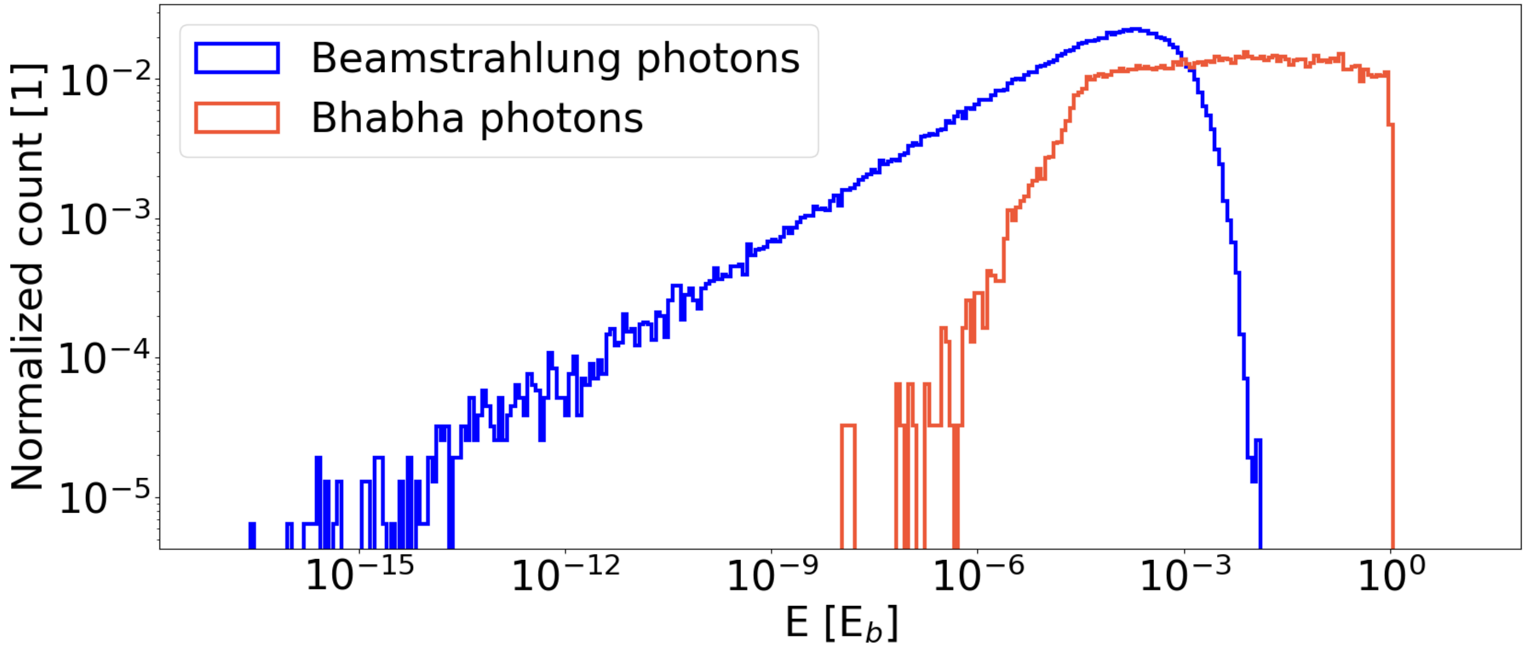
Incoherent

- Radiative Bhabha scattering
- Deflection in field of single particle of opposite bunch



Collective

- Beamstrahlung
- Deflection in collective field of opposite bunch



- Radiation → particle losses

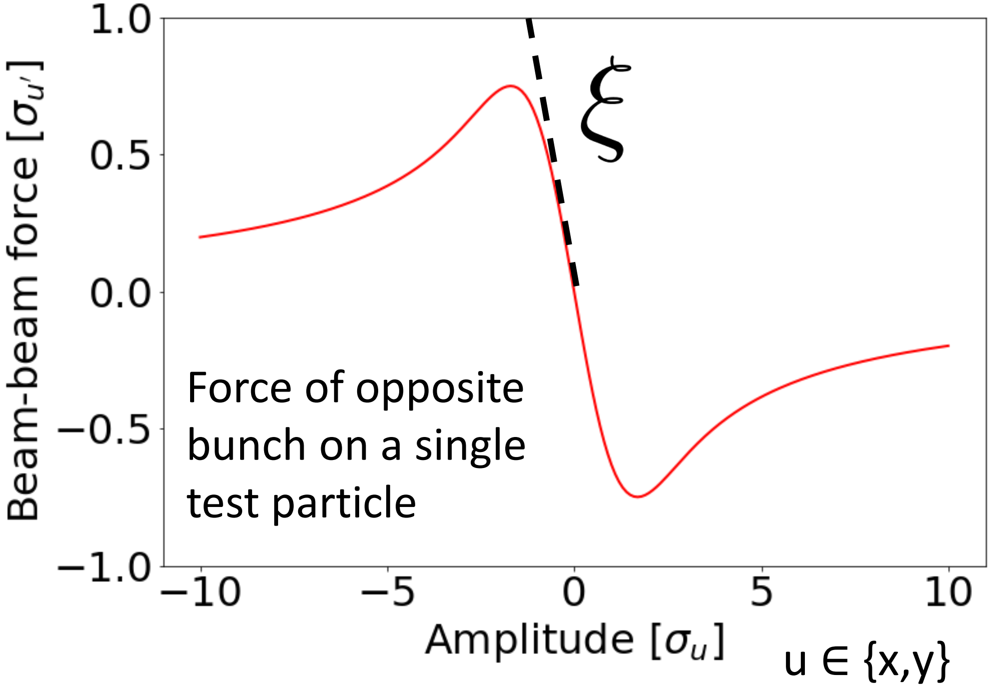
$\tau \mathcal{L}$ ⇊ $\sigma_z \sigma_\delta$ ⇈

lifetimes:
BS ~100 min
BH ~30 min

Beam-beam interaction

- Beam = EM potential for all other charges
- Beam acts with a force on other beam
    - **Nonlinear** beam-beam force
    - Linear strength characterized by beam-beam parameter ξ
    - Harmful consequences on beam dynamics
    - No theory, simulations have to be used

$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$



Force of opposite bunch on a single test particle

Beam-beam force

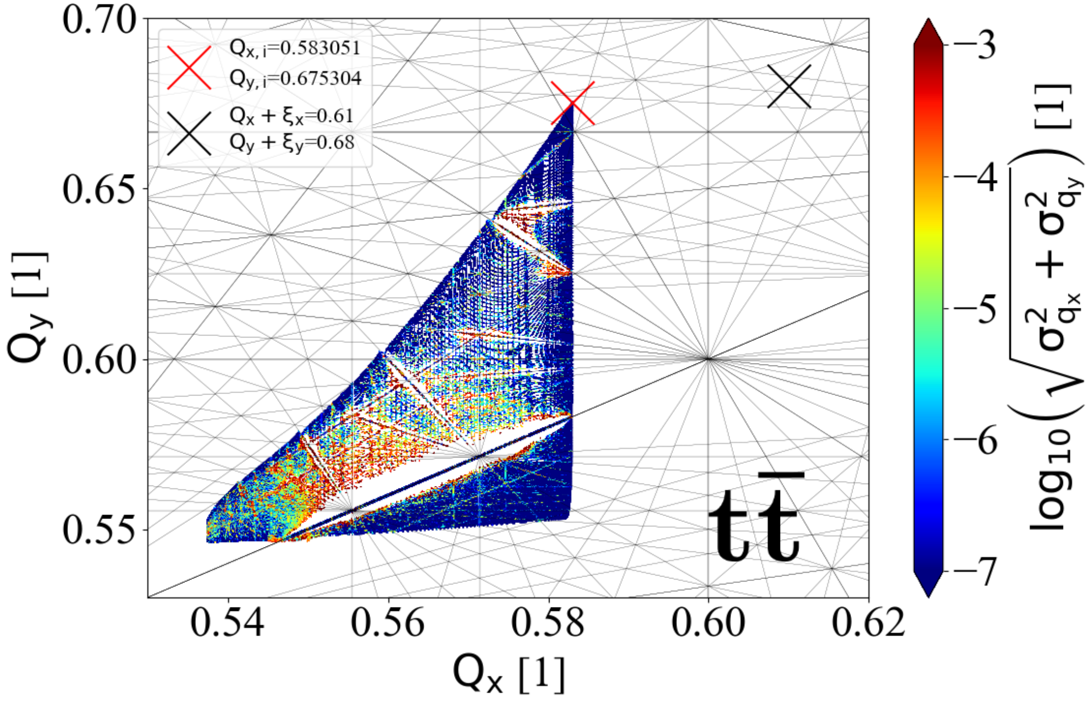
$$\xi_{x,y} = \frac{N r_0 \beta^*_{x,y}}{2\pi\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}$$

High lumi → strong beam-beam force

$$L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta^*_y} \cdot R_{hg}$$

Consolidation...

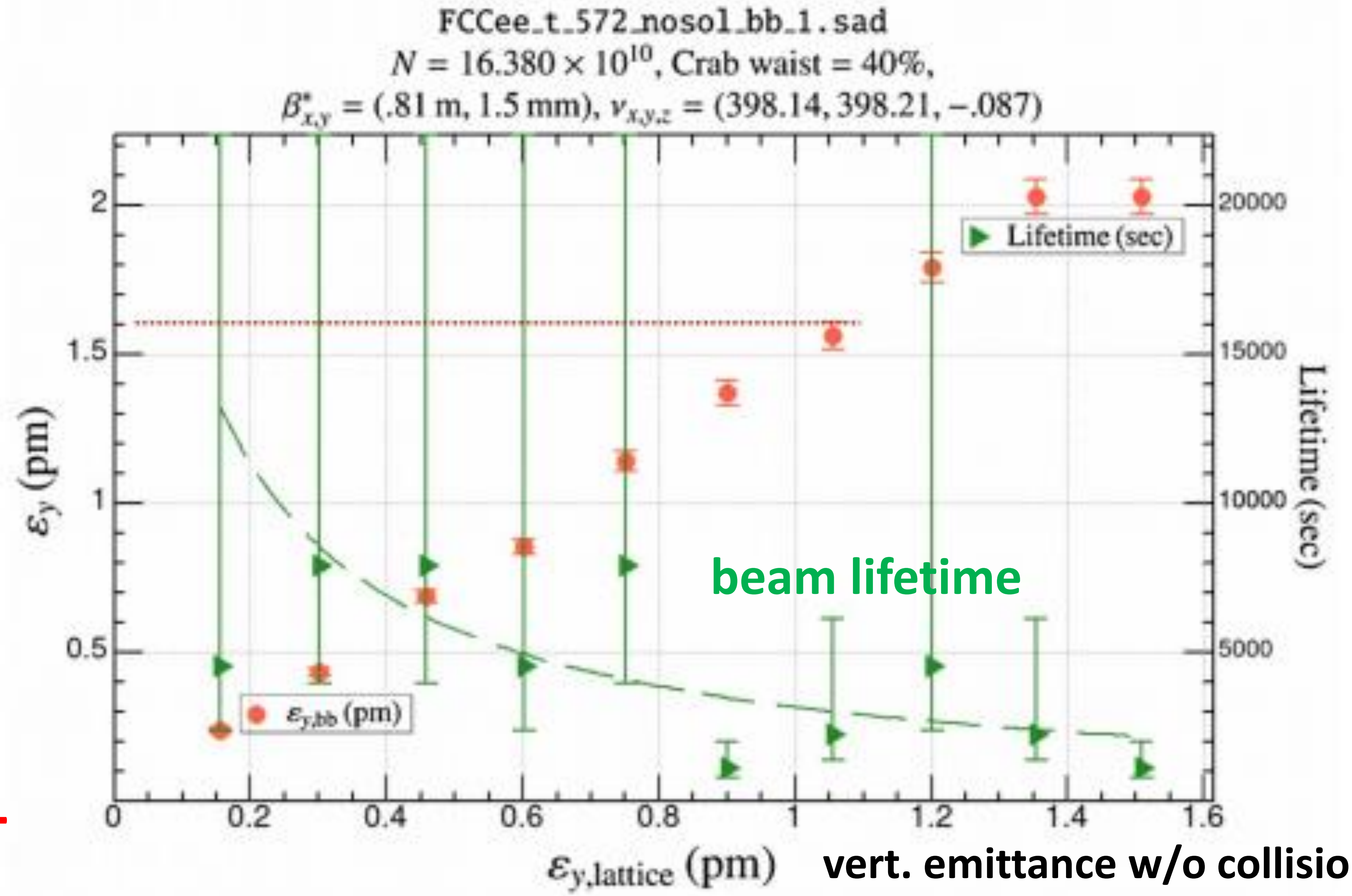
- Radiation (synchrotron radiation, beamstrahlung, Bhabha)
- IP tuning & feedback
- Beam asymmetries
- Top-up injection



linear model
w/o radiation

FUTURE CIRCULAR COLLIDER

beam-beam performance @ $t\bar{t}$



equilibrium emittance in collisions

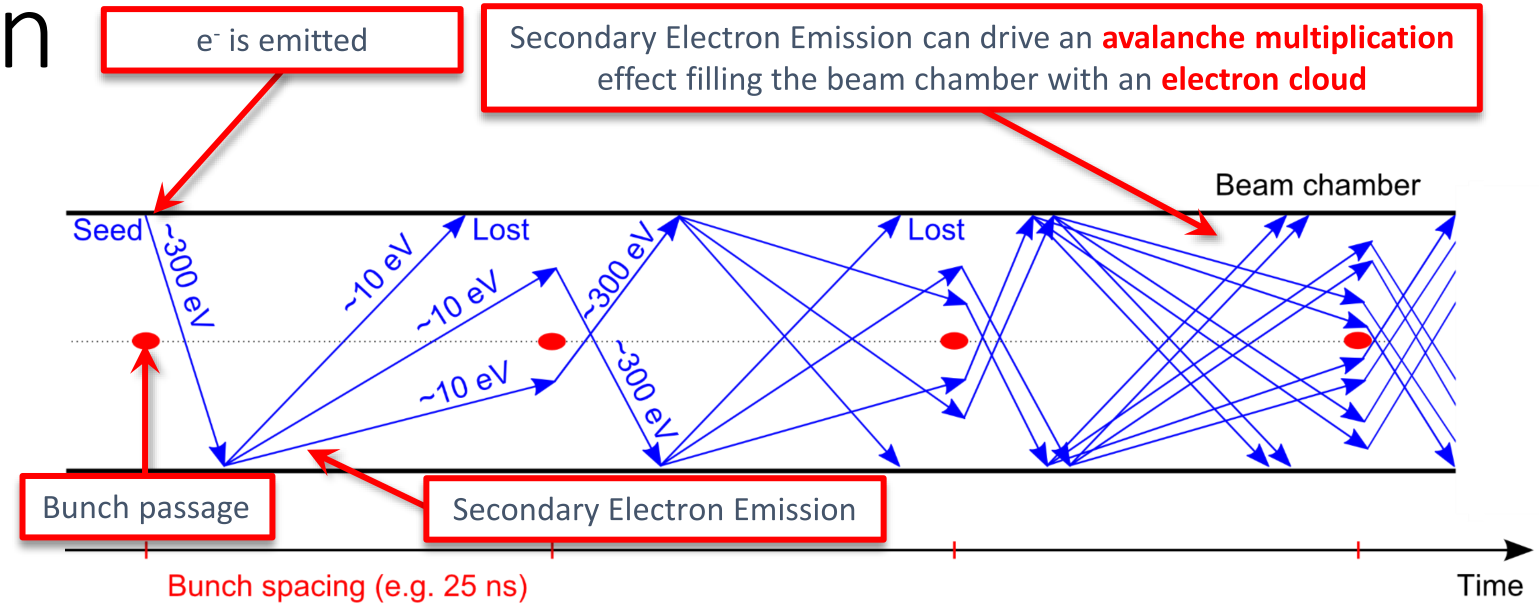
beam lifetime

vert. emittance w/o collision

need for a small vertical "lattice emittance" ; ~50% blow up in collision; beam lifetime dominated by burn-off (not included here)

K. Oide, UNIGE

E-Cloud Formation



e^- is emitted

Secondary Electron Emission can drive an **avalanche multiplication** effect filling the beam chamber with an **electron cloud**

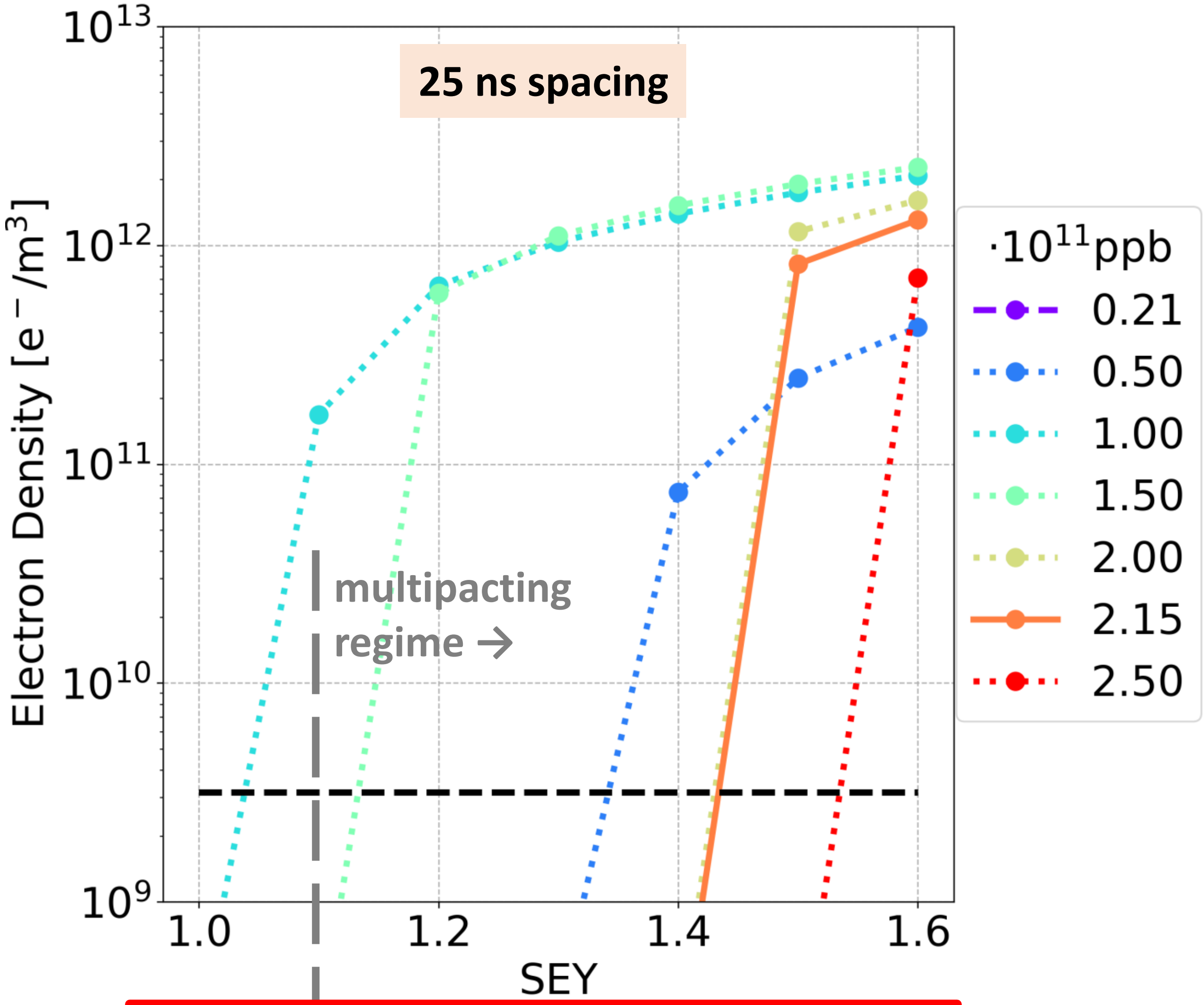
Bunch passage

Secondary Electron Emission

Courtesy of G. Iadarola

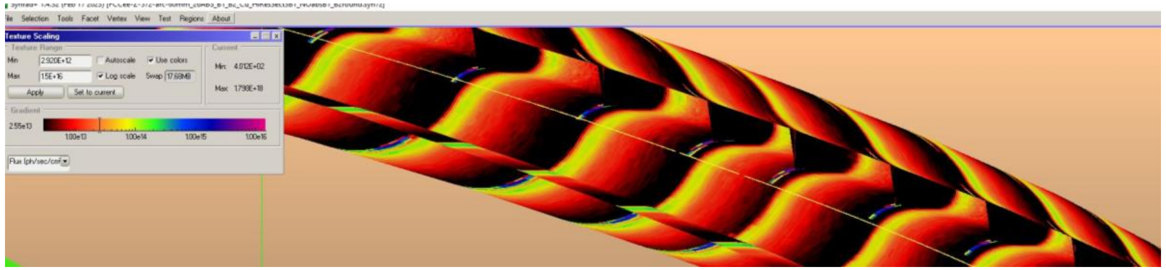
- The circulating beam particles can produce primary electrons (seed)
    - ○ ionisation of the residual gas in the beam chamber
    - ○ photoemission from the chamber's wall due to the synchrotron radiation emitted by the beam
- With the particle bunch passage
    - primary electrons can be accelerated to energies up to hundreds of eV
    - after impacting the wall, secondary electrons can be emitted
- Secondary electrons have energies of tens of eV
    - after impacting the wall, they can be either absorbed or elastically reflected
    - if they survive until the passage of the following bunch, they can be accelerated, projected onto the wall and produce secondaries
- Secondary electron emission can drive an avalanche multiplication effect

Photon electrons and e-cloud @ Z



intermediate bunch intensities impose tightest requirements (as in the LHC)

Color-coded SR flux revealing “zebra”-like photon absorption profile along the beampipe with absorbers



The circulating beam particles can produce primary electrons (seed) by **photoemission** from the chamber’s wall due to the synchrotron radiation emitted by the beam

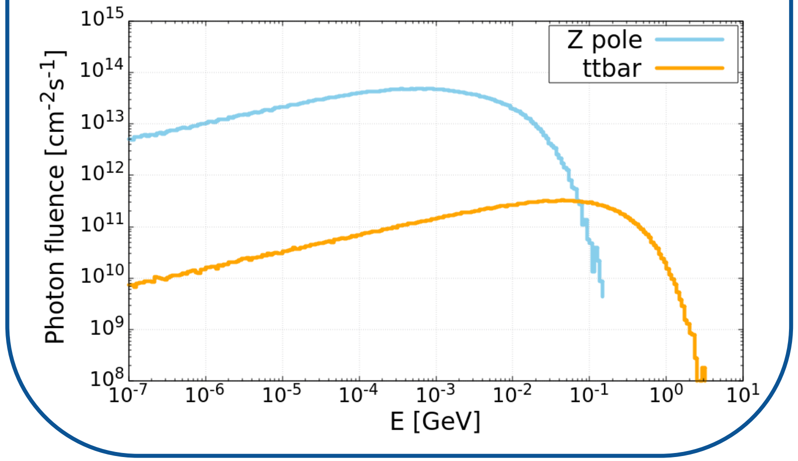
The beam could be unstable even below the SEY multipacting threshold

In order to reach a primary photoelectron rate η_γ as low as $10^{-4}/e^+/m$,
the **antechamber with its photon stops must absorb 99% of the photons** without reflection into the circular part of the vacuum chamber

Sources of radiation in Interaction regions

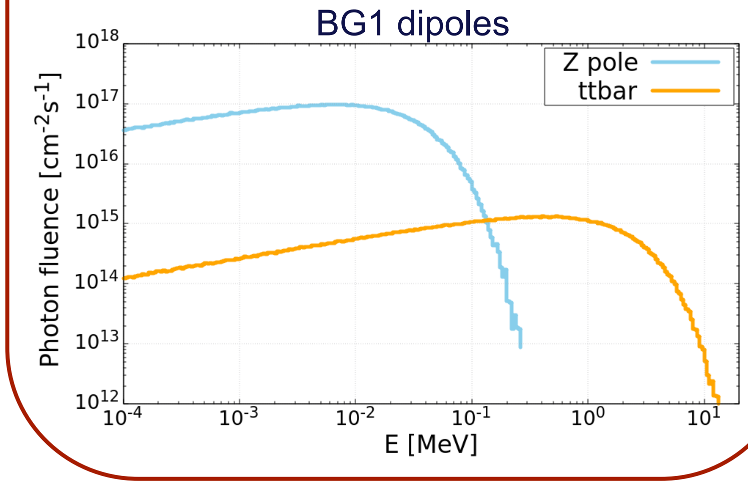
Beamstrahlung photons

- photons emitted in the EM field of the counter-rotating bunch at the IP
- intense photon flux (nominally **370kW** @Z-pole, **77kW** @ttbar)
    - ○ dedicated dump



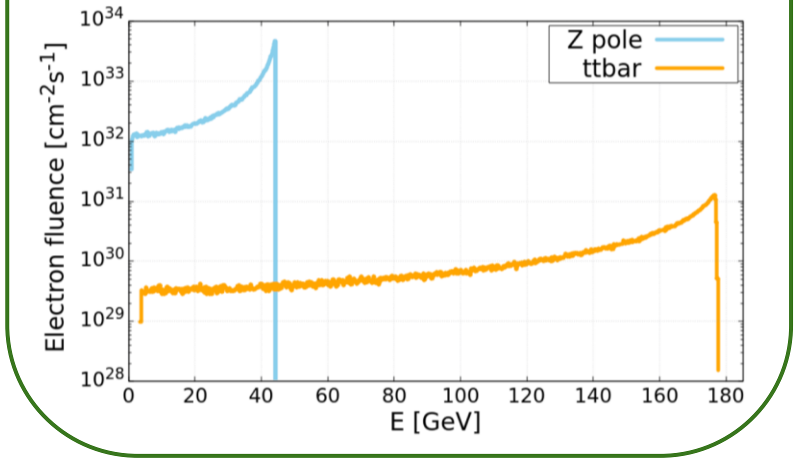
Synchrotron radiation

- photons emitted by beam particles when bent by the magnets
- SR from the beam incoming to the IP neglected (1kW in 500m)
- SR from the outgoing beam much more intense (**164kW** in 500m)

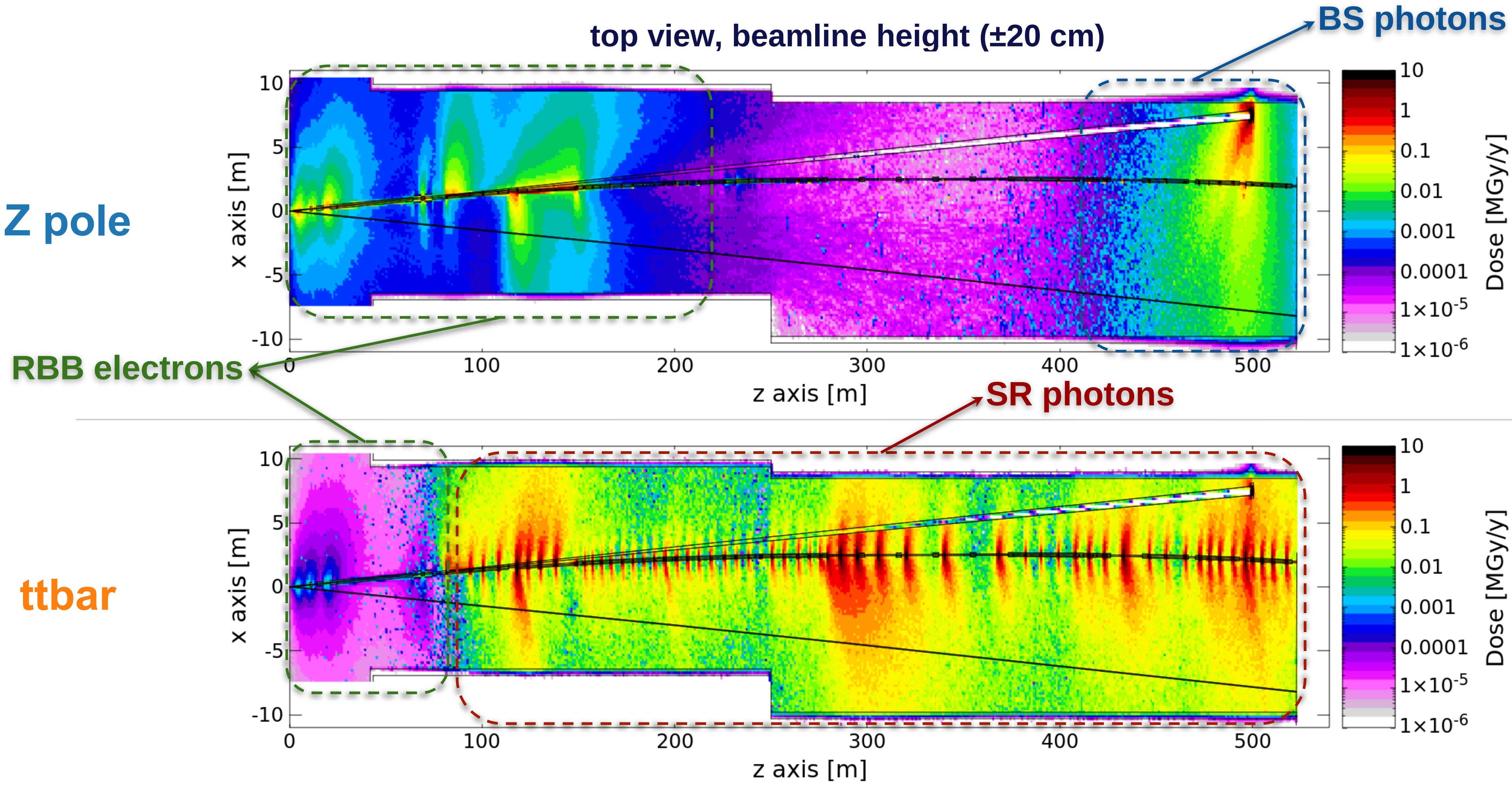


Radiative Bhabha electrons

- electrons scattered in radiative Bhabha at the IP and radiating one or more photons (up to 100% of their energy)
- off-momentum electrons outgoing from the IP with significant angle
    - ○ lost downstream



Annual TID in the tunnel from BS, SR, and RBB



top view, beamline height (±20 cm)

Z pole

ttbar

BS photons

RBB electrons

SR photons

Detector Requirements

Challenges at FCC-ee

- At the Z pole, high beam currents with bunch spacing 20 ns
  - Almost continuous beam has implications on power management/cooling, density, readout,…
- Extremely high luminosities L ~ 1.8 x 10^{36}/cm^{2}s at Z-pole
  - Require absolute luminosity measurements to 10^{-4} to achieve desired physics sensitivity
  - Online/Offline handling of high data rates/total volume.
- Physics interaction rate at Z pole ~ 100 kHz
  - Implications on detector response time, event size, FE electronics and timing
- Beam dynamics
  - 30 mrad crossing angle sets constraints on the solenoid field to 2 T → larger tracker volume
  - Backgrounds from incoherent pair production (IPC) and synchrotron radiation (SR) to a lesser extent (tungsten masks significantly reduces SR toward IP)
- High Luminosities
  - High statistical precision: Requires control of systematics down to 10^{-6} – 10^{-5} level.
  - Online and Offline data handling O(10^{13}) events
  - Physics events up to 100 kHz imposes requirements on detector response time, FE electronics and DAQ.

Outline

- Accelerators for High Energy Physics exploration
- European Strategy for HEP and CERN future accelerators studies
- Circular Colliders basics:
  - basic accelerator physics consepts
  - Colliders: Center of Mass Energy and luminosity
  - Leptons versus Hadrons: synchrotron Radiation
- LHC and HL-LHC full exploitation
- FCC-ee description
  - Plans and General parameters
  - Optics and allignment
  - Beam dynamics with collisions: Beam-beam, Beamstrahlung, BhBar and Synchrotron radiations
  - Electron Clouds and photon electrons
  - Radiation in the interaction region and detectors challenges
- FCC-hh essentials

Stage 2: FCC-hh – parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 119	14	
dipole field [T]	14 - 20	8.33	
circumference [km]	90.7	26.7	
arc length [km]	76.9	22.5	
beam current [A]	0.5	1.1	0.58
bunch intensity [10^{11}]	1	2.2	1.15
bunch spacing [ns]	25	25	
synchr. rad. power / ring [kW]	1020 - 4250	7.3	3.6
SR power / length [W/m/ap.]	13 - 54	0.33	0.17
long. emit. damping time [h]	0.77 – 0.26	12.9	
peak luminosity [10^{34} cm^{-2}s^{-1}]	~30	5 (lev.)	1
events/bunch crossing	~1000	132	27
stored energy/beam [GJ]	6.1 - 8.9	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

With FCC-hh after FCC-ee: significantly more time for high-field magnet R&D aiming at highest possible energies

High Temperature Superconductors (ReBCO, IBS): an enabling technology for high field (>15 T) magnets → R&D on HTS conductor

Formidable challenges:

- ☐ high-field superconducting magnets: 14 - 20 T
- ☐ power load in arcs from synchrotron radiation: 4 MW → cryogenics, vacuum
- ☐ stored beam energy: ~ 9 GJ → machine protection→highly distructive beams
- ☐ pile-up in the detectors: ~1000 events/xing
- ☐ energy consumption: 4 TWh/year → R&D on cryo, HTS, beam current, …

Formidable physics reach, including:

- ☐ Direct discovery potential up to ~ 40 TeV
- ☐ Measurement of Higgs self to ~ 5% and ttH to ~ 1%
- ☐ High-precision and model-indep (with FCC-ee input) measurements of rare Higgs decays ($\gamma\gamma$, Zγ, μμ)
- ☐ Final word about WIMP dark matter

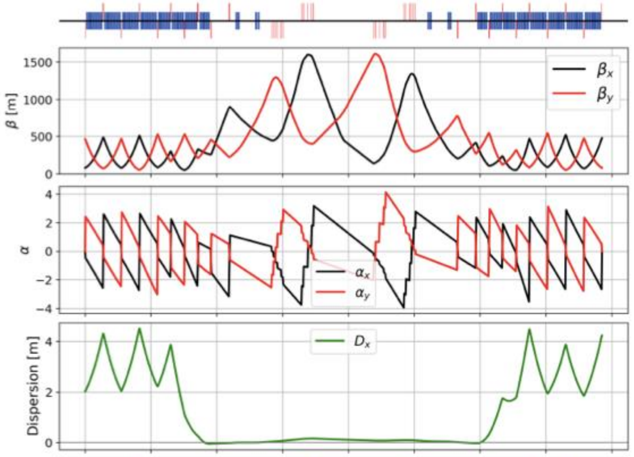
F. Gianotti

FUTURE CIRCULAR COLLIDER

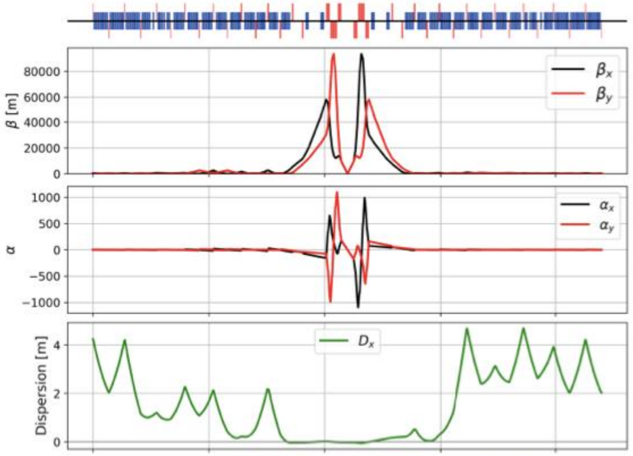
Key activities on FCC-hh: cryo magnet system, optics design

Optics design activities:

- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)

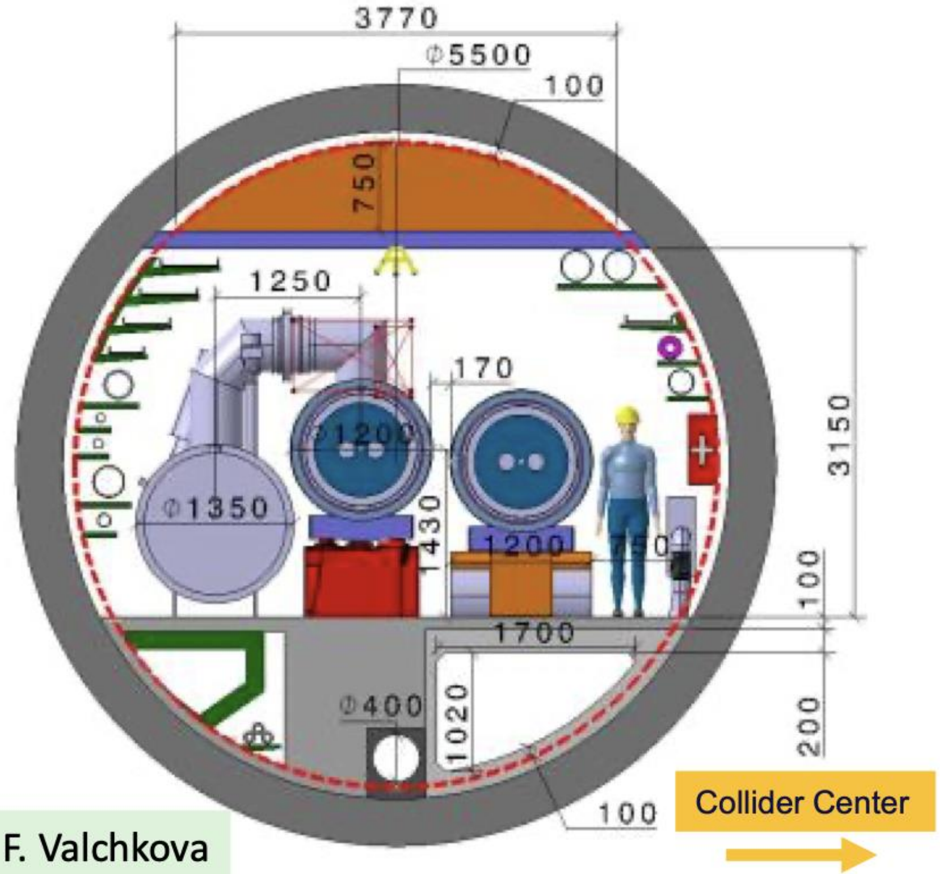


betatron collimation straight



experimental straight

M. Giovannozzi. G. Perez, T. Risselada



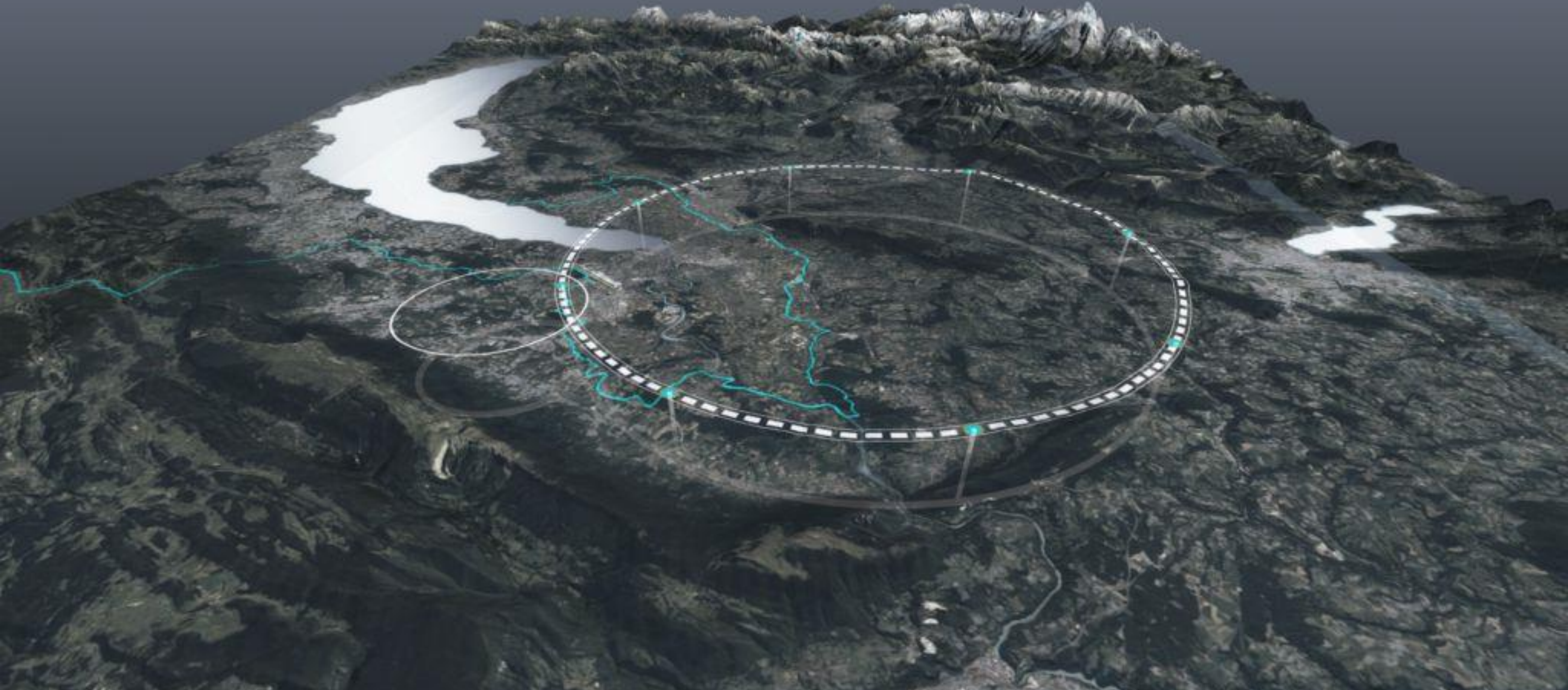
F. Valchkova

High-field cryo-magnet system design

- Conceptual study of cryogenics concept and temperature layout for LTS and HTS based magnets, in view of electrical consumption.
- Update of integration study for the ongoing HFM designs and scaling to preliminary HTS design.

  → **Confirmation of tunnel diameter!**
- HFM R&D (LTS and HTS) on technology and magnet design, aiming also at bridging the TRL gap between HTS and Nb_3Sn.

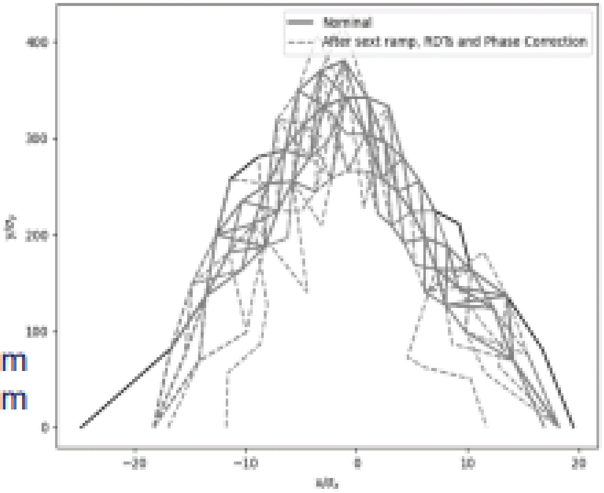
“It always seems impossible until it’s done.”
Nelson Mandela



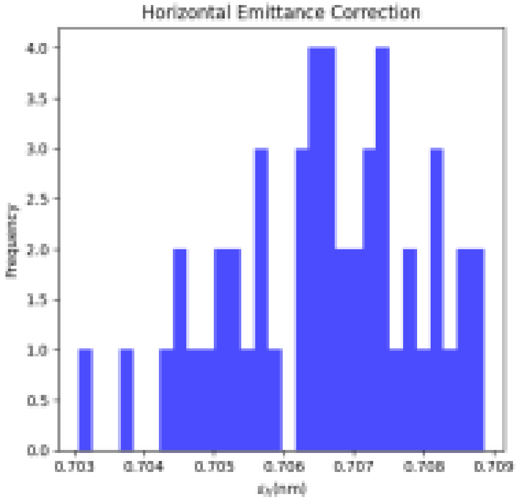
Questions?

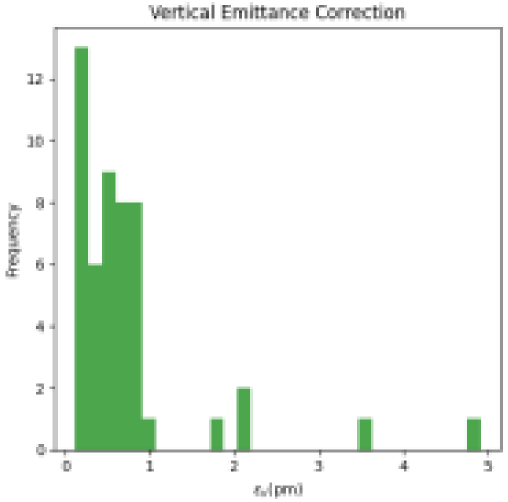
phase & RDTs/D_y correction for arc misalignments

50 seeds (mean values)		rms orbit x (µm)	rms orbit y (µm)	$\Delta\beta x/\beta x$ %	$\Delta\beta y/\beta y$ %	Δ ηx (mm)	Δ ηy (mm)	ε_h (nm)	ε_v (pm)
100 µm on arc quads & sexts	With err	6224.8	7276.7	1e-6	1e-4	11985	73458	-	-
	After Sext ramping	8.55	8.35	5.98	9.91	45.23	45.96	0.71	9.61
	RDTs & ηy Cor	8.58	8.42	6.01	9.94	45.09	4.49	0.71	2.32
	Phase Cor	8.55	8.35	0.35	0.79	2.94	4.36	0.70	0.88
	Final cor. result	8.55	8.35	0.35	0.89	2.94	4.37	0.70	0.73



@FRF.1
Sigma_x =0.000362m
Sigma_y =0.000012m

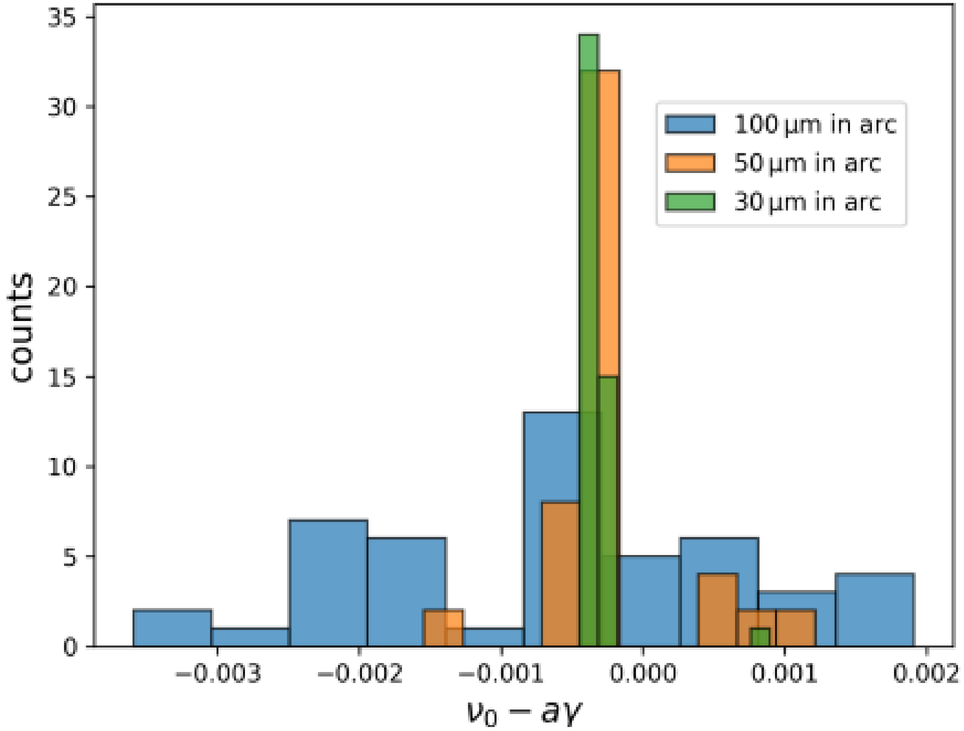




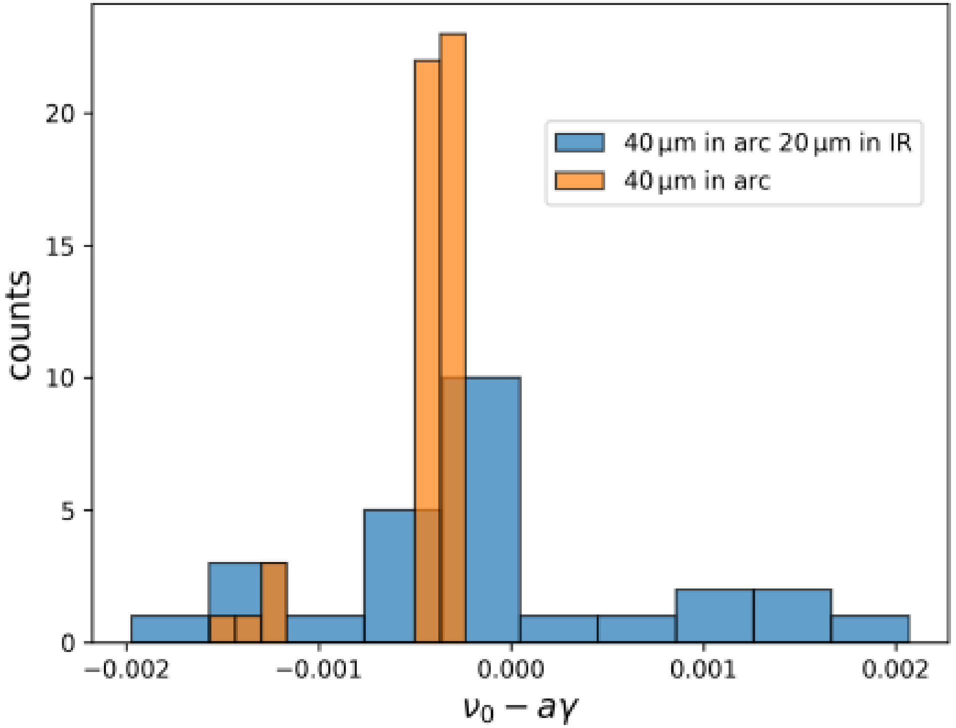
E. Musa, DESY

misalignment impact on energy calibration

spin tune shifts away from *aγ* due to errors



different levels of arc misalignments



with and without IR misalignments

we need to achieve $|\nu_0 - a\gamma| \leq 10^{-4}$ – within reach

Y. Wu

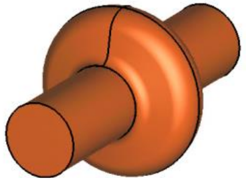
FUTURE CIRCULAR COLLIDER

FCC-ee SRF system

F. Peauger, O. Brunner

Z

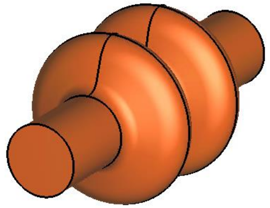
1-cell
400 MHz,
Nb/Cu



low R/Q, HOM damping, powered by 1 MW RF coupler and high efficiency klystron

W, H

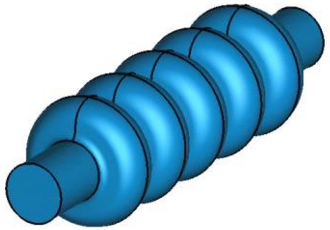
2-cell
400 MHz,
Nb/Cu



moderate gradient and HOM damping requirements; 500 kW / cavity, allowing reuse of klystrons already installed for Z

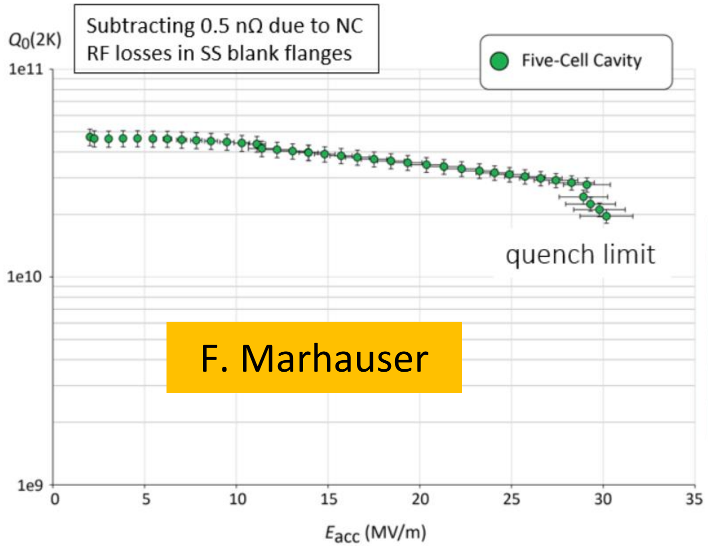
ttbar, booster

5-cell
800 MHz,
bulk Nb



high RF voltage and limited footprint thanks to multicell cavities and higher RF frequency; 200 kW/ cavity

5-cell cavity development (2018), successful collaboration with JLAB



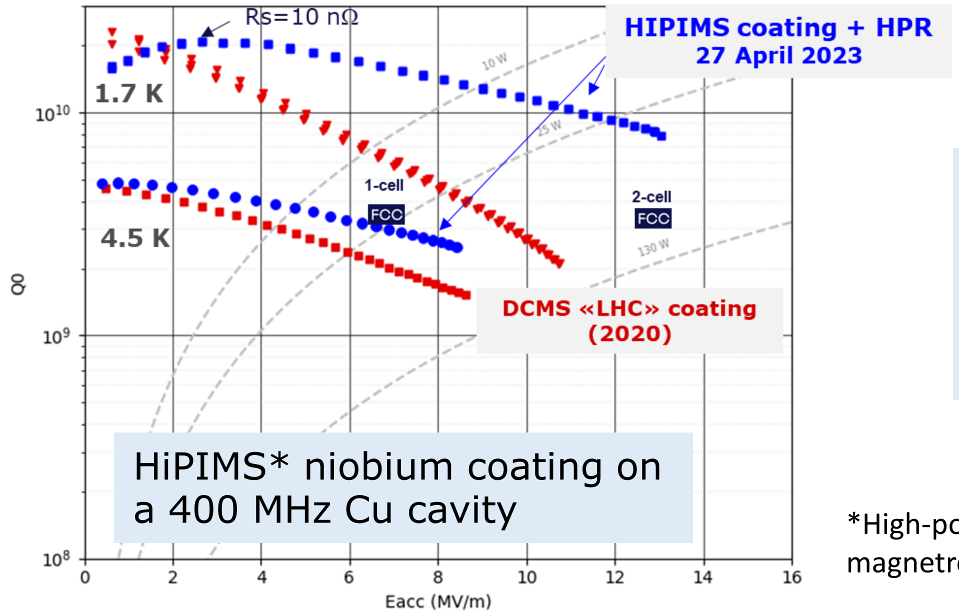
F. Marhauser

Main post-processing steps

	Unit	*CRN5*
Bulk BCP	µm	216
High-T heat treatment	°C, hrs.	800, 3
Final EP	µm	30
HPR cycles		4
Low-T bake-out	°C, hrs.	120, 12

FCC Week 2018, 9-13 April 2018, Beurs van Berlage, Amsterdam, Netherlands

Jefferson Lab 17



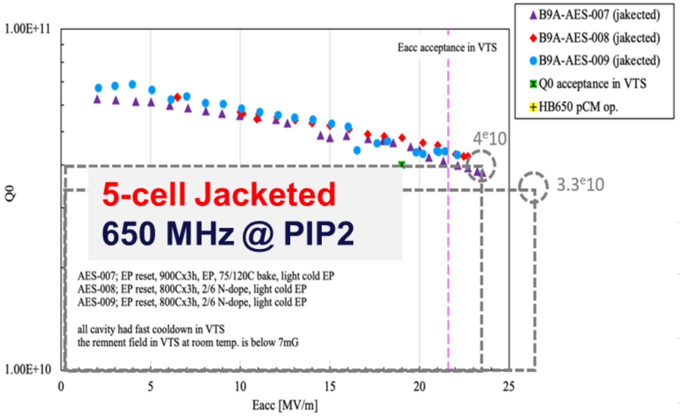
**HIPIMS coating + HPR
27 April 2023**

DCMS «LHC» coating (2020)

HiPIMS* niobium coating on a 400 MHz Cu cavity

*High-power impulse magnetron sputtering

Promising R&D towards ultra-high Q_0. Collaboration with FNAL

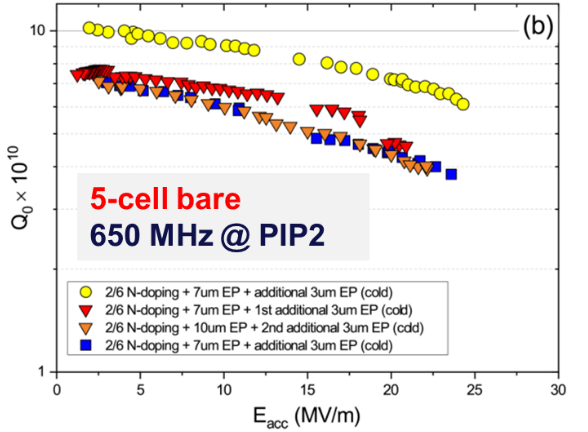


**5-cell Jacketed
650 MHz @ PIP2**

AES-007; EP reset, 900Cx3h, EP, 75/120C bake, light cold EP
AES-008; EP reset, 800Cx3h, 2/6 N-dope, light cold EP
AES-009; EP reset, 800Cx3h, 2/6 N-dope, light cold EP

all cavity had fast cooldown in VTS
the remnent field in VTS at room temp. is below 7mG

**Q0 = 3.5e10 @ 25 MV/m
with 2/6 N-doping or midT bake + EP**



**5-cell bare
650 MHz @ PIP2**

**Q0 = 6e10 @ 25 MV/m
with 2/6 N-doping + EP + cold EP**