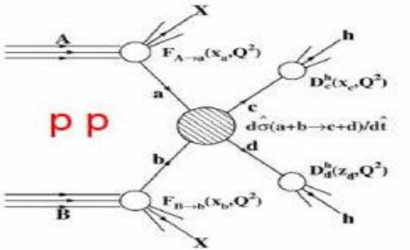
Accelerator Technologies I

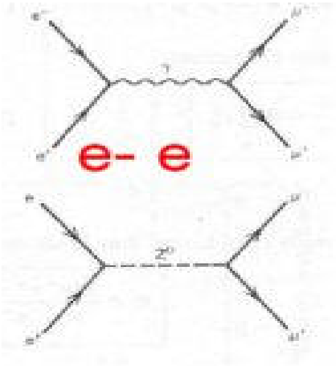
D. Schulte, CERN

Collider Particle Choices

- Hadron collisions: compound particles
  - Protons or ions
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
  - Hadron collisions $\Rightarrow$ can typically achieve higher collision energies



- Lepton collisions: elementary particles
  - Sofar always electrons and positrons
  - Muons are an option but have limited lifetime
  - Collision process known
  - Well defined energy
  - Lepton collisions $\Rightarrow$ precision measurements



- Photons also possible

Considered High Energy Frontier Collider

Circular colliders:

- HL-LHC
- FCC (Future Circular Collider)
    - FCC-hh: 100 TeV proton-proton cms energy, ion operation possible
    - FCC-ee: First step 90-350 GeV lepton collider
    - FCC-he: Lepton-hadron option
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)
    - CepC : e^+e^- 90 - 240 GeV cms
    - SppC : pp 70 TeV cms

Linear colliders

- ILC (International Linear Collider): e^+e^- 250 GeV cms energy, Japan considers hosting project
- CLIC (Compact Linear Collider): e^+e^- 380 GeV - 3 TeV cms energy (also lower possible), CERN hosts collaboration

Other options

- Muon collider, past effort in US, new interest also in Europe and Asia
- Plasma acceleration in linear collider
- Photon-photon collider
- LHeC

Key Technologies

Typically the key cost and power drivers and hence the defining technologies:

- **Magnet technology**
  - superconducting dipoles are the key for hadron colliders and very important for muon collider
  - beam-guiding quadrupoles are important for all
- **RF technology**
  - critical for linear colliders, superconducting ILC or normal-conducting CLIC, and for circular high-energy lepton colliders
  - important for circular hadron colliders

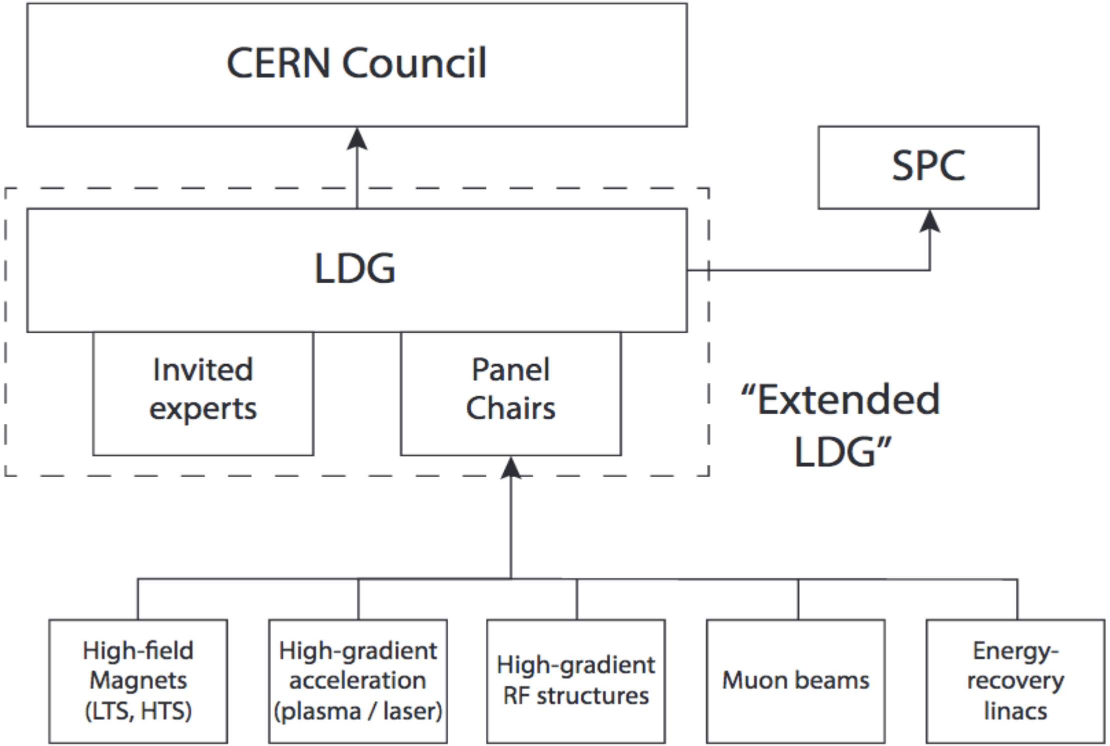
Many other technologies are also important and can drive the design

- Cryogenics
- Machine protection
- Collimation
- Vacuum
- Beam instrumentation
- CLIC stabilisation and alignment system
- …

Example: European Accelerator R&D Roadmap

Council charged the lab directors group (LDG) to deliver a **European Accelerator R&D Roadmap**

The extended LDG will deliver to **council** a report with a **prioritised workplan**



Five panels:
High-field magnets: P. Vedrine
Plasma accelerators: R. Assmann
RF: S. Bousson
Muons: D. Schulte
Energy recovery linacs: M. Klein

Hadron Colliders

High Energy Protons: Overview

The LHC is the current high energy frontier collider

- Target centre-of-mass energy 14 TeV
- Currently reached 13 TeV
- 27 km circumference collider at CERN
- Discovery of the Higgs boson in 2012
- Upgrade to higher luminosity ongoing: HL-LHC

Studies of future proton colliders that use a larger tunnel are FCC-hh and SppC
An option to use FCC-hh magnets in the LHC tunnel has been studied (HE-LHC) but is not maintained

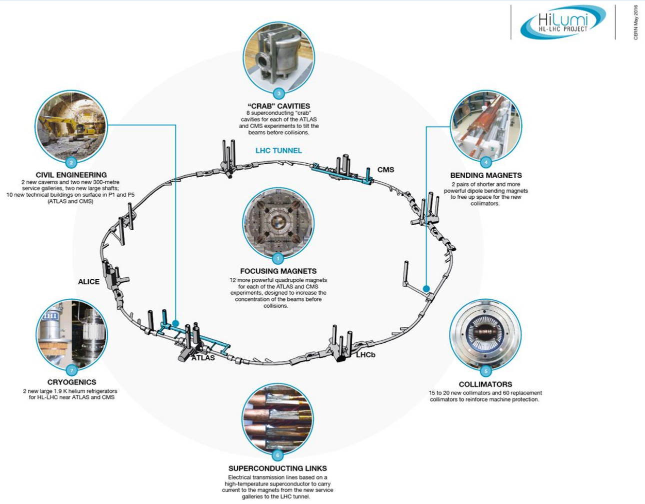
Also the option to collide the LHC or FCC-hh beam with electrons is considered

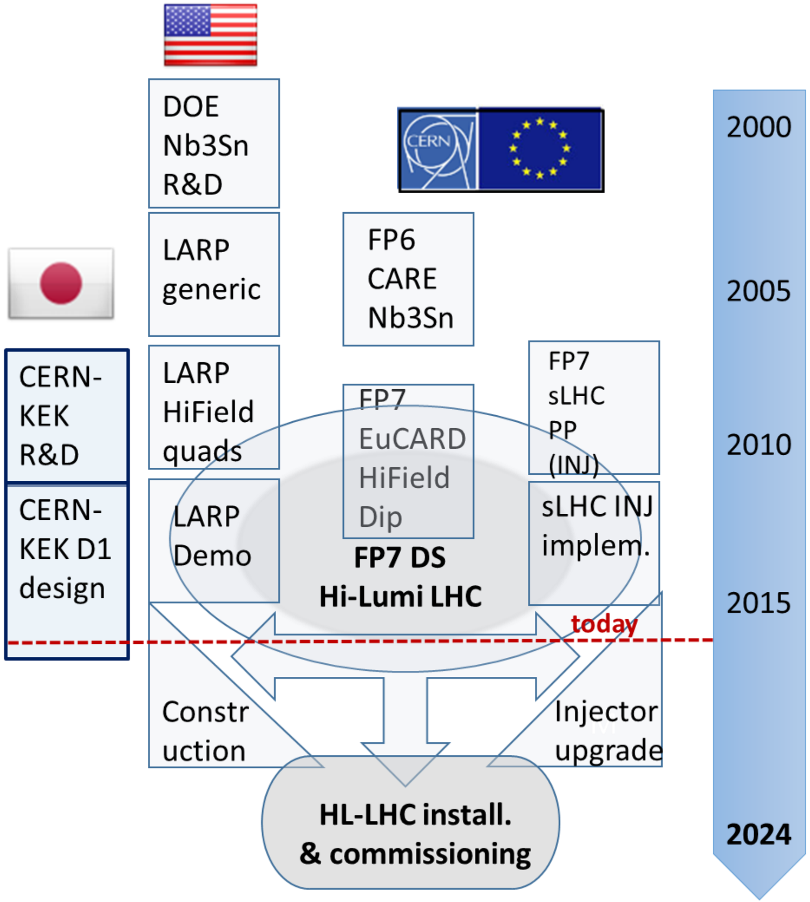
- Named LHeC and FCC-eh

HL-LHC

Upgrade of existing LHC

- A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:
- An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of
- **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.





LHC

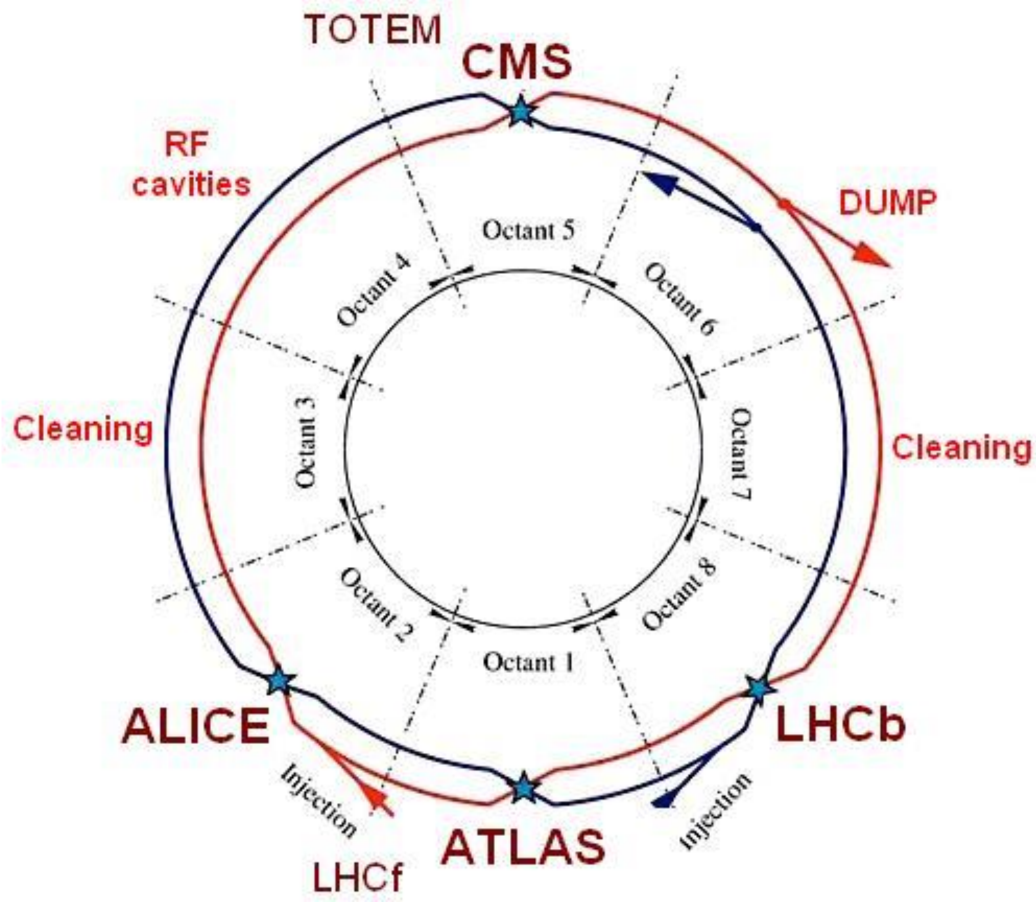
I guess, everybody is familiar

Two multi-purpose experiments
- ATLAS and CMS

Two specialised experiments
- ALICE and LHCb
- Combined with injection

Other insertions
- Betatron cleaning
- Momentum cleaning
- RF insertion
- Dump insertion

Machine is producing physics since 2010



FCC Goal

FCC study develops a conceptual design of a new facility

FCC-hh defines infrastructure

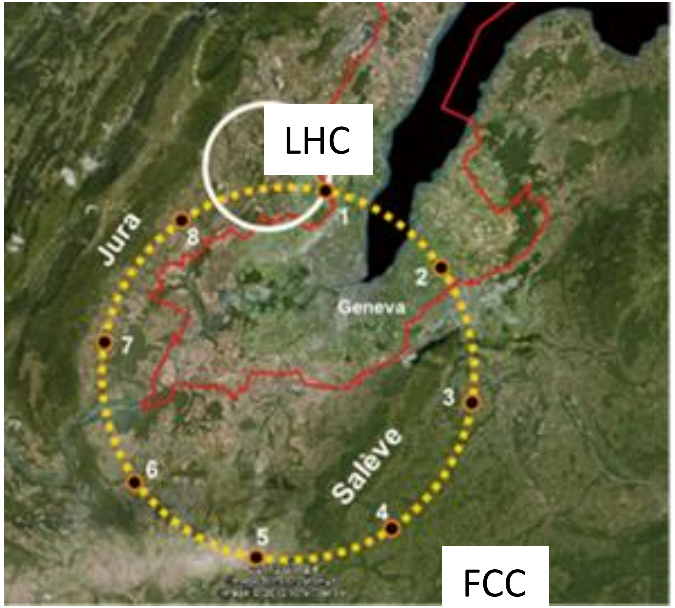
- 100 TeV proton-proton collisions, 20 ab^{-1}
- 7x LHC energy and 7x HL-LHC integrated luminosity
- Use existing infrastructure to generate beam
- New ~100km-long collider ring

(Potential) first stage **FCC-ee** offers electron-positron collisions from 90 GeV to 365 GeV

- Unprecedented electron-positron collision energies >208 GeV
- Much higher event rates at previously reached energies ($O(10^5)$ times as many Z as at LEP/LEP2)

FCC-eh Proton-electron option is also possible

HE-LHC Proton-proton option in LHC tunnel with FCC-hh technology

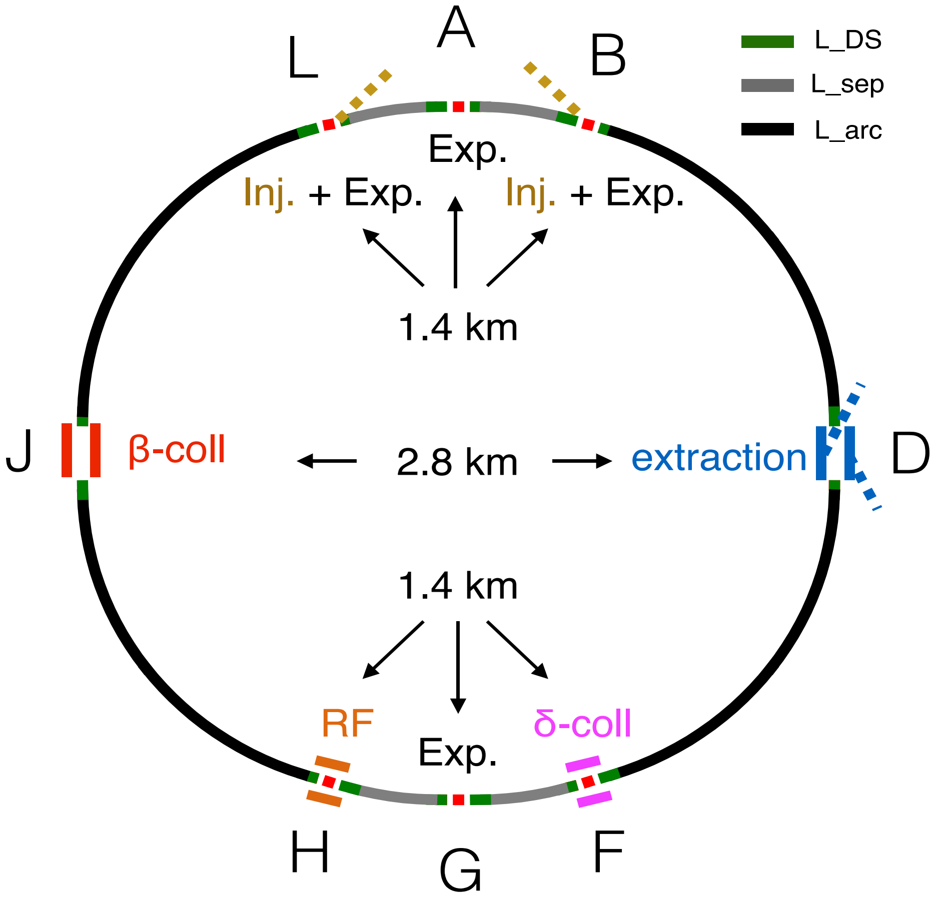


Consistent with implementation at CERN

FCC-hh Layout

Layout for CERN site

- Two high-luminosity experiments (A and G)
- Two other experiments combined with injection at 3.3 TeV (L and B)
- Two collimation insertions
  - Betatron cleaning (J)
  - Momentum cleaning (E)
- Extraction insertion (D)
- Clean insertion with RF (H)
- Circumference 97.75km
- Can be integrated into the area
- Can use LHC or SPS as injector



Hadron Collider Parameters

	LHC	HL-LHC	FCC-hh Initial	FCC-hh Final	SppC	SppC ultimate
Cms energy [TeV]	14	14	100	100	75	150
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5	< 30	10	?
Machine circumference	27	27	97.75	97.75	100	100
Arc dipole field [T]	8	8	16	16	12	24
Bunch distance [ns]	25	25	25	25	25	?
Background events/bx	27	135	170	< 1020	490	?
Bunch length [cm]	7.5	7.5	8	8	7.55	?

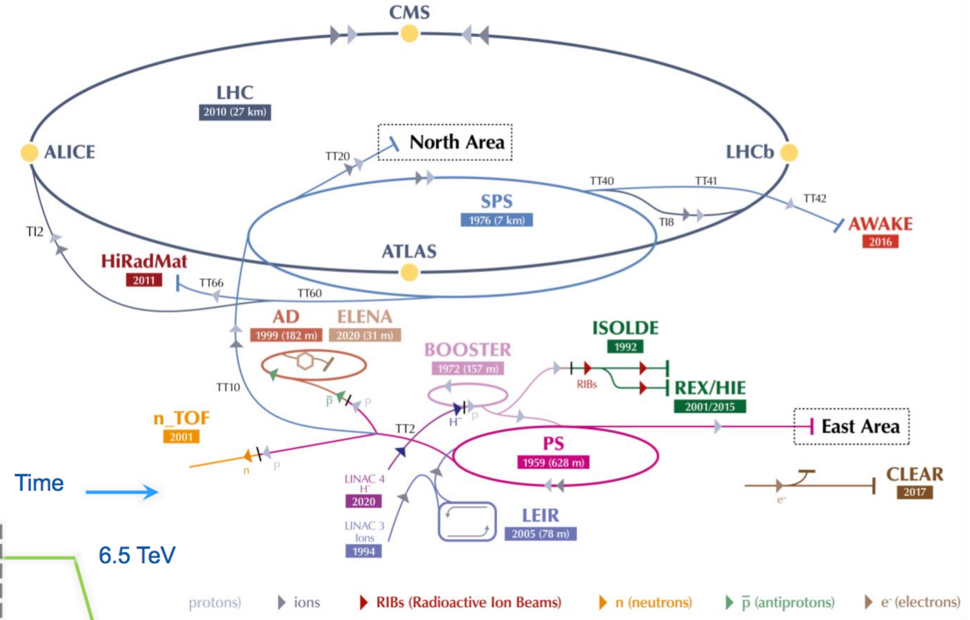
HL-LHC promises more luminosity

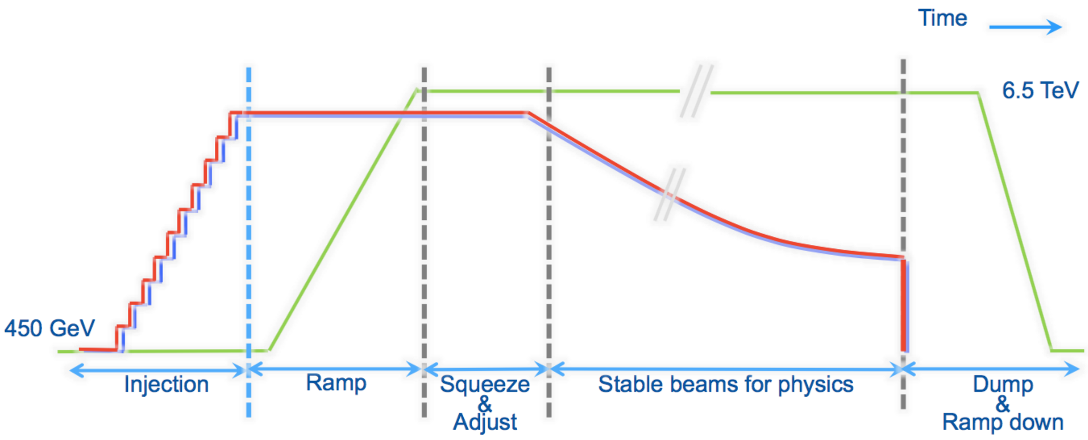
FCC-hh promises more energy and luminosity, requires larger ring

LHC Injection Complex

The LHC obtains its beam from a chain of injectors

Typically few hours to fill and several hours of luminisity

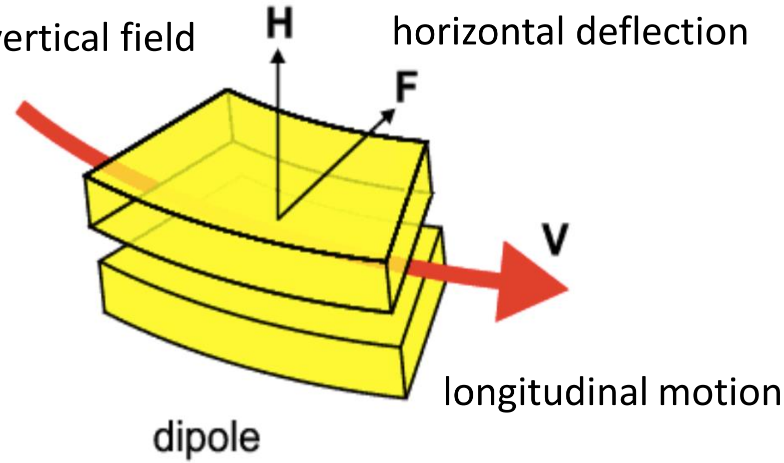


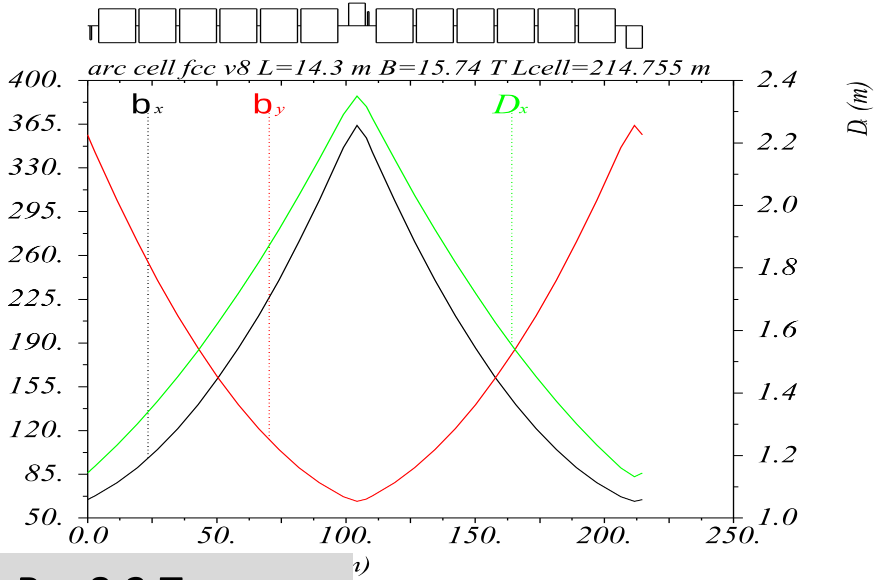


Hadron Collider Energy

Magnets and Energy

Arcs consist mainly of dipoles to bend the beam (80% dipoles in LHC or shown FCC-hh arcs)
Maximum field and size of ring then define maximum collision energy



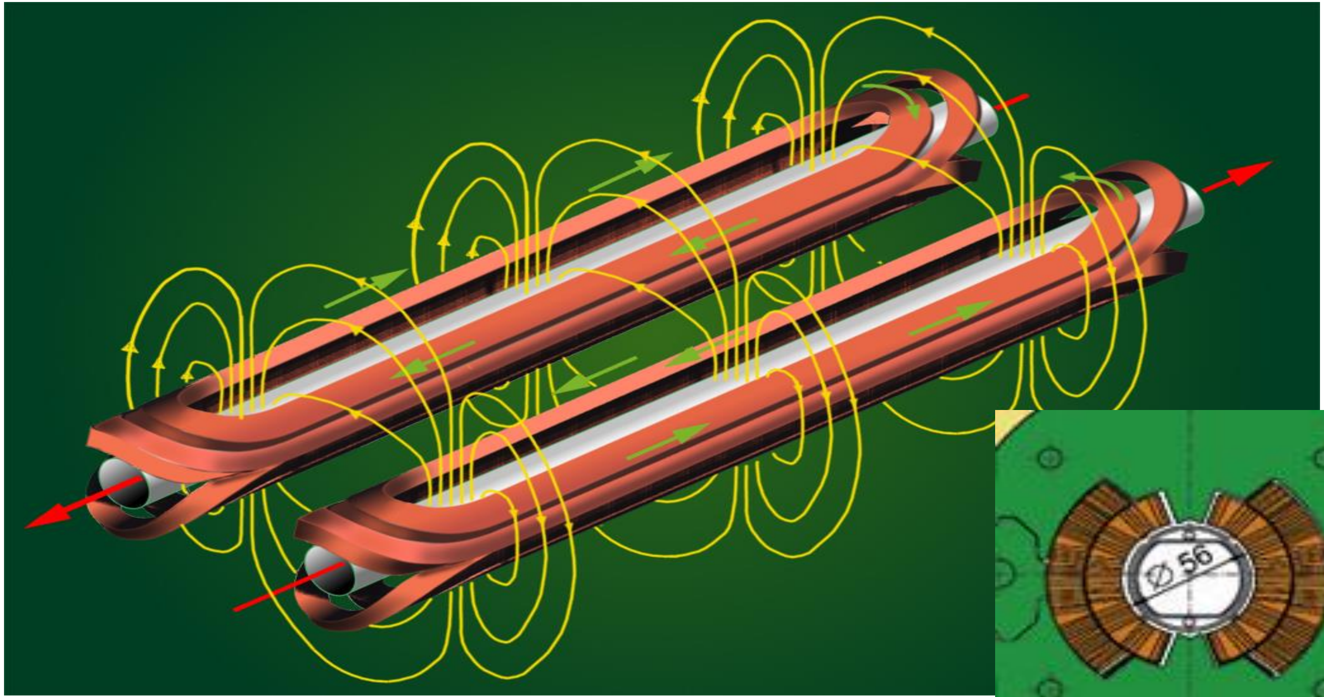


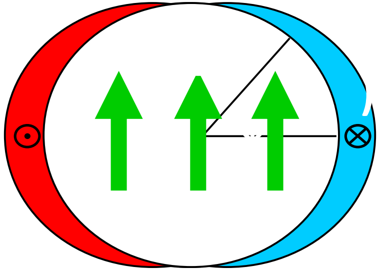
$$r = \frac{T}{0.3GeV}\frac{E}{B}$$

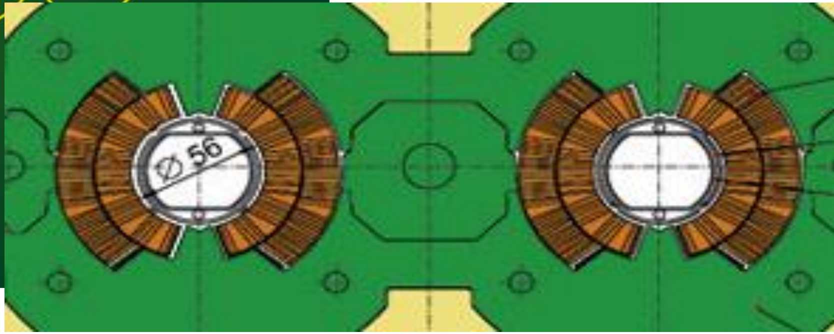
LHC: E=7 TeV, ρ=2.8 km, B = 8.3 T

FCC-hh: E=50 TeV, ρ=10.6 km, B = 15.6 T

Dipole Basic Concept ("Cosine Theta")







Need two apertures with opposite field to bend both proton beams
If the beams had different signs of charge one aperture could be sufficient

High-field Magnet Technologies

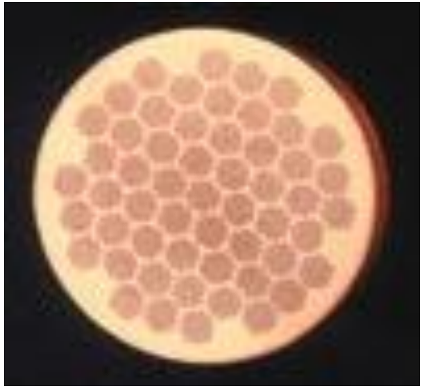
Superconducting magnets reach highest fields, three main technologies for the cables

NbTi (niob-titanium)
- is standard, **used in LHC** limited to O(8 T)

Nb_3Sn (niobium-tin)
- can reach O(16 T)
- but difficult technology and needs to mature further
- expensive
- Used in some points for HL-LHC
- Foreseen for FCC-hh also in arcs

HTS (high-temperature superconductor)
- can reach O(20 T) or more
- in solenoids > 30 T
- very expensive

Cut through a cable with superconductor embedded in copper, so some remains conductivity in case of a quench

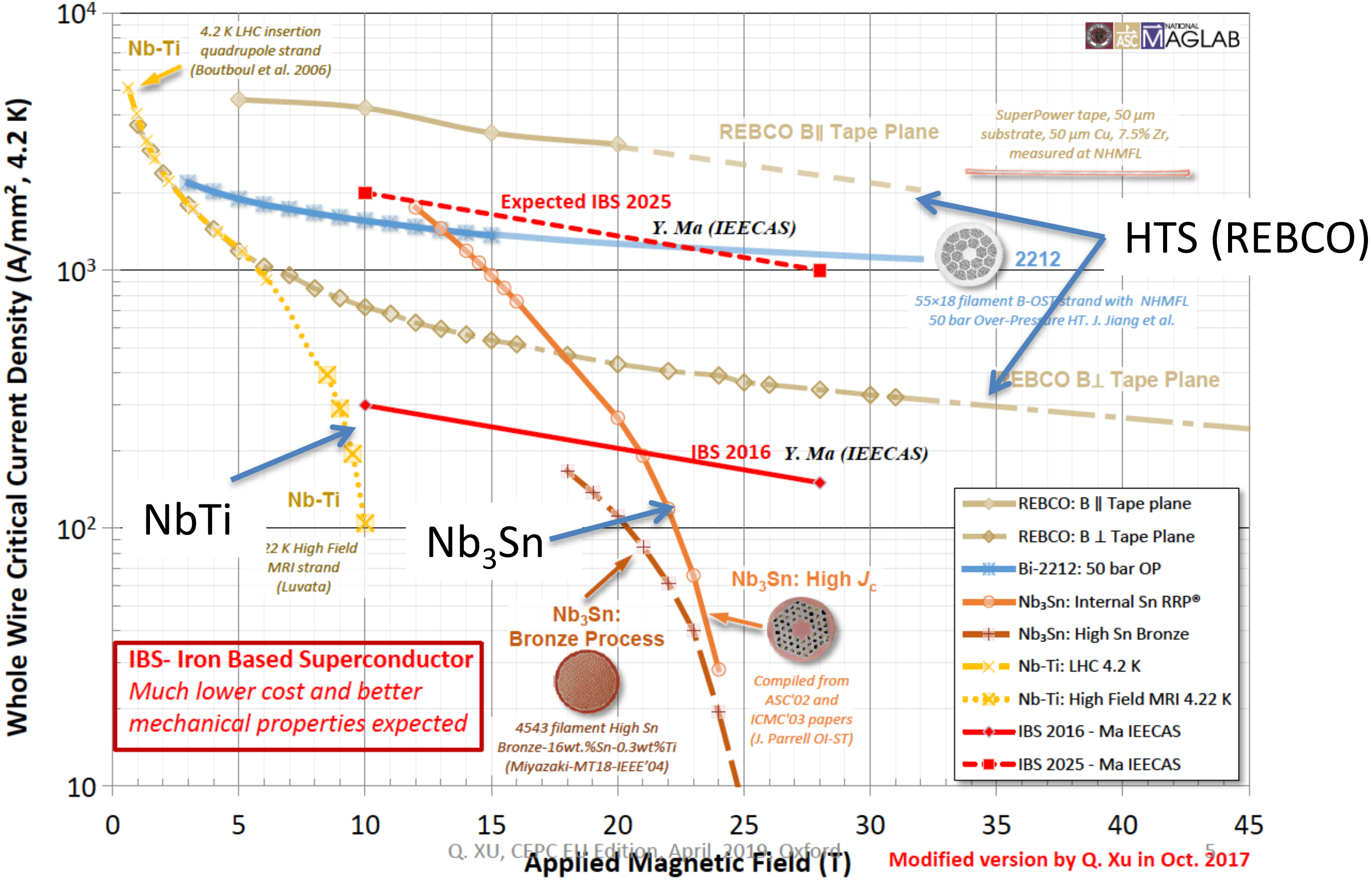


Conductors

The cables are only superconducting below a certain field and current

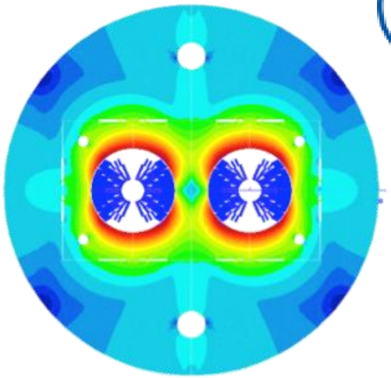
Depends also in the temperature

Above the magnet "quenches",
this can cause machine protection issues



Magnet Designs (FCC-hh)

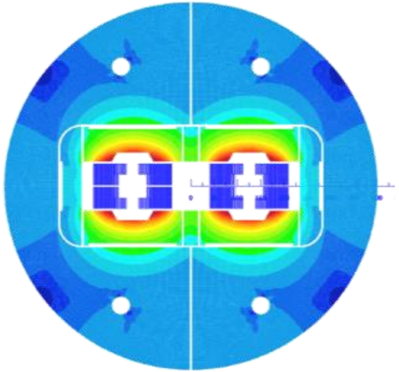
Cos-theta



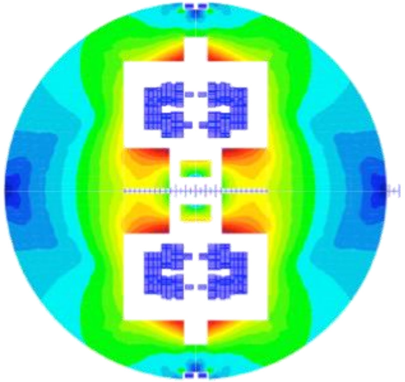
This is similar to LHC

EuroCirCol
A key to New Physics

Blocks



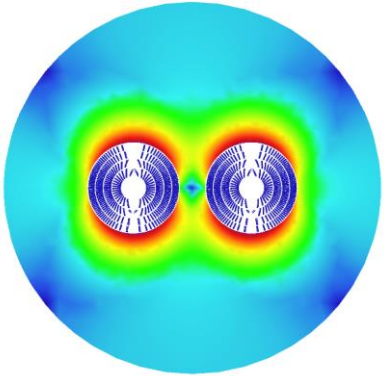
Common coils



Swiss contribution

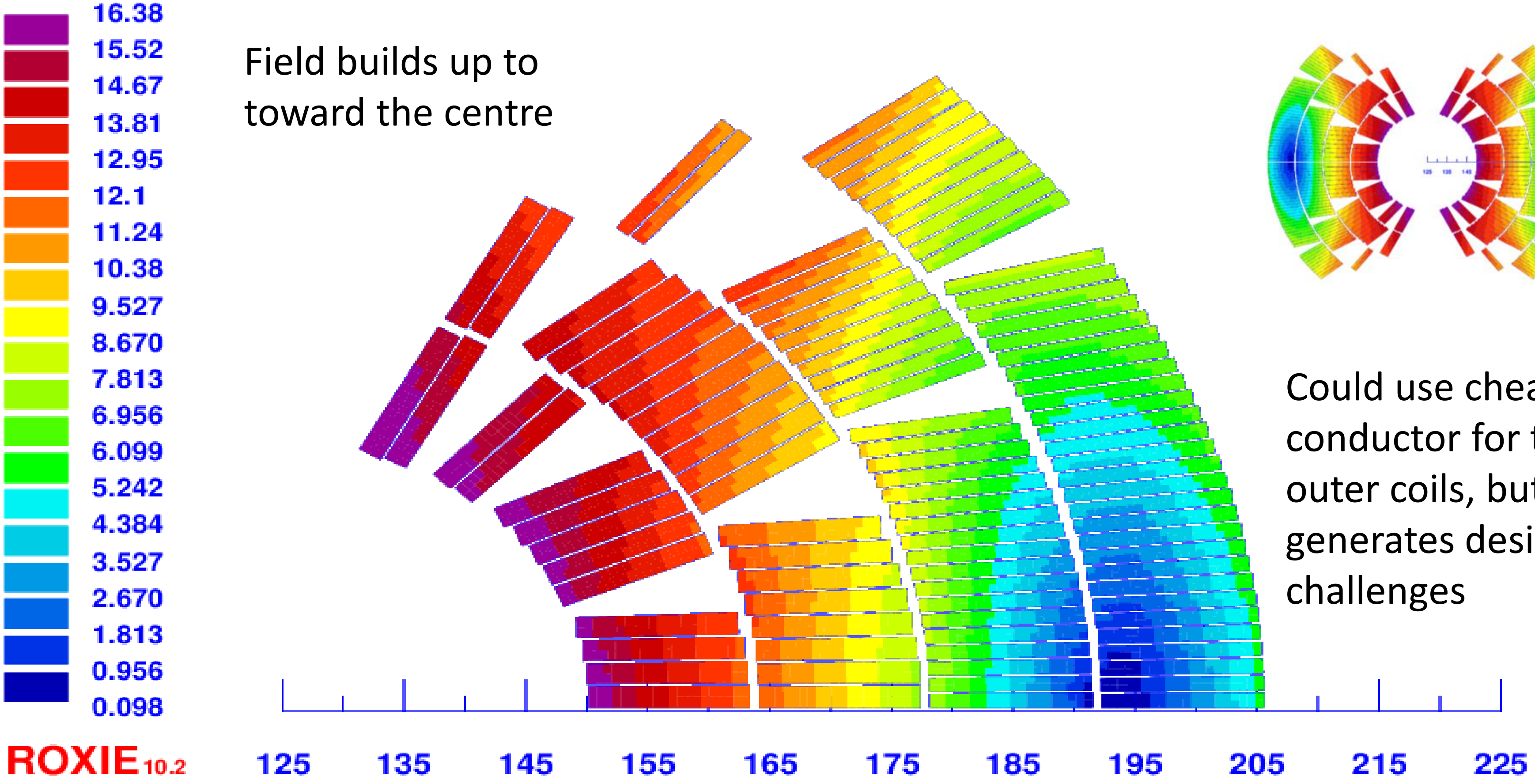
via PSI

Canted
Cos-theta



Criteria: Amount of conductor, stress in magnets, …
The conductor is a major cost item of the magnet
$\Rightarrow$ try to minimise the amount

Cost Effective Magnet Design



Field builds up to toward the centre

Could use cheaper conductor for the outer coils, but generates design challenges

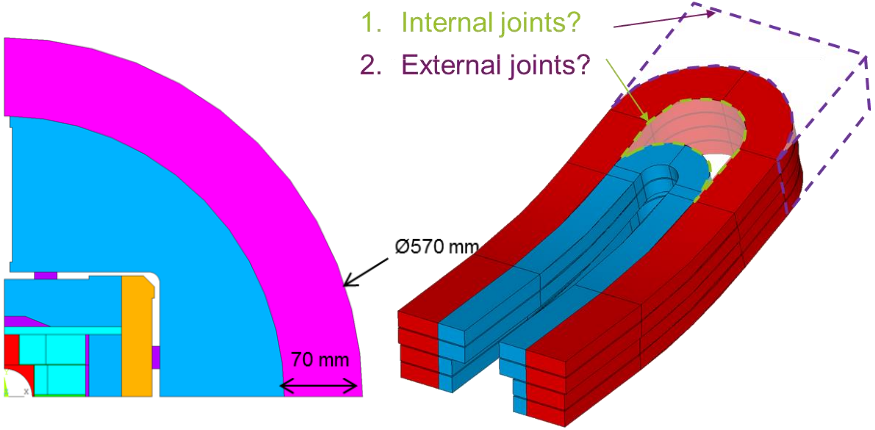
Magnet Models

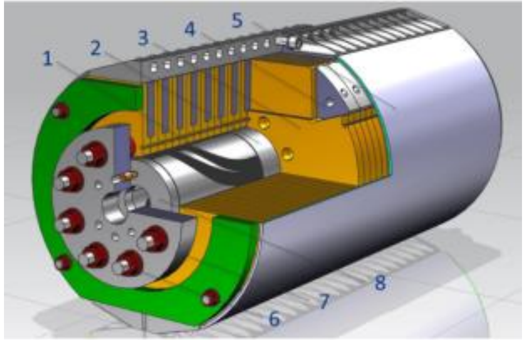
With today's state of the art conductors:

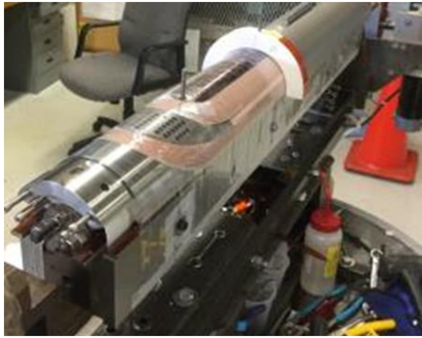
- 15 T achievable at 14 % margin
- 17 T at short sample

- Cos-theta and common-coil model magnet programs are under preparation

15 T dipole demonstrator
60-mm aperture
4-layer graded coil



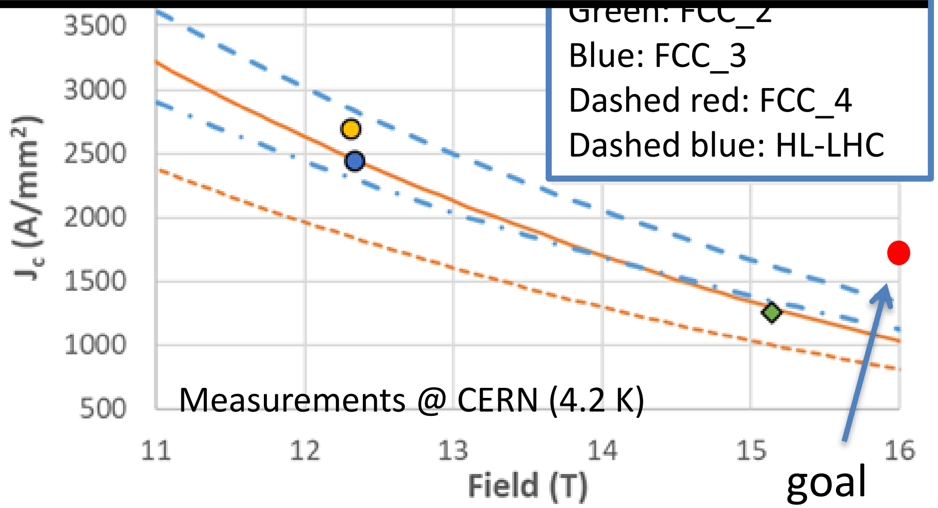




Conductor

New activity with many collaborators started in 2017 with ambitious targets

Wire diameter	mm	~ 1
Non-Cu Jc (16 T, 4.2 K)*	A/mm²	≥ 1500
Unit length	km	≥ 5
Cost	€/kA m**	≤ 5



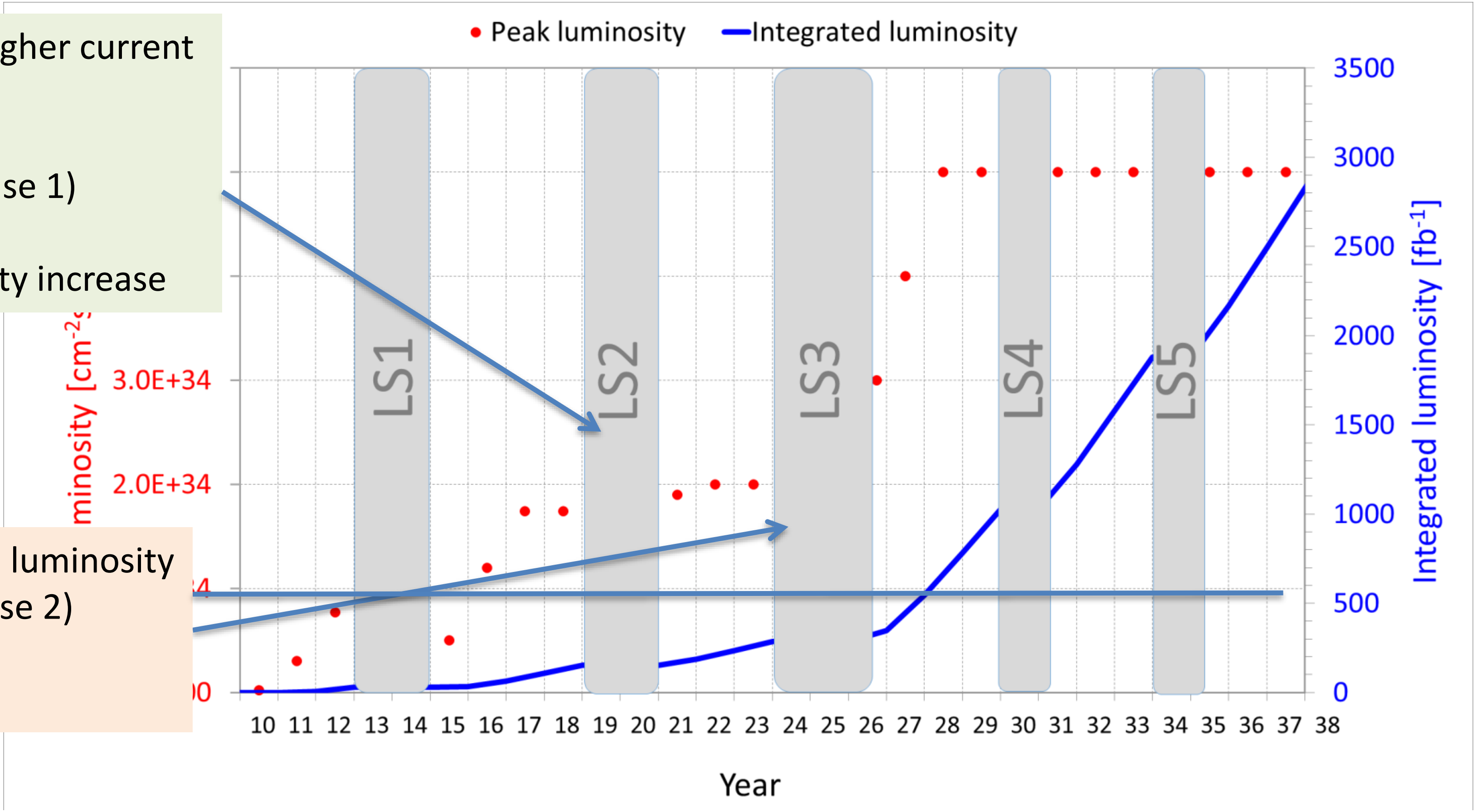
First wires almost reached HL-LHC requirements

HL-HLC and Hadron Collider Luminosity

HL-LHC Goal

Upgrades to higher current
Injectors
Collimation
Detectors (phase 1)
…
Small luminosity increase

Upgrade to full luminosity
Detectors (phase 2)
Triplets
…

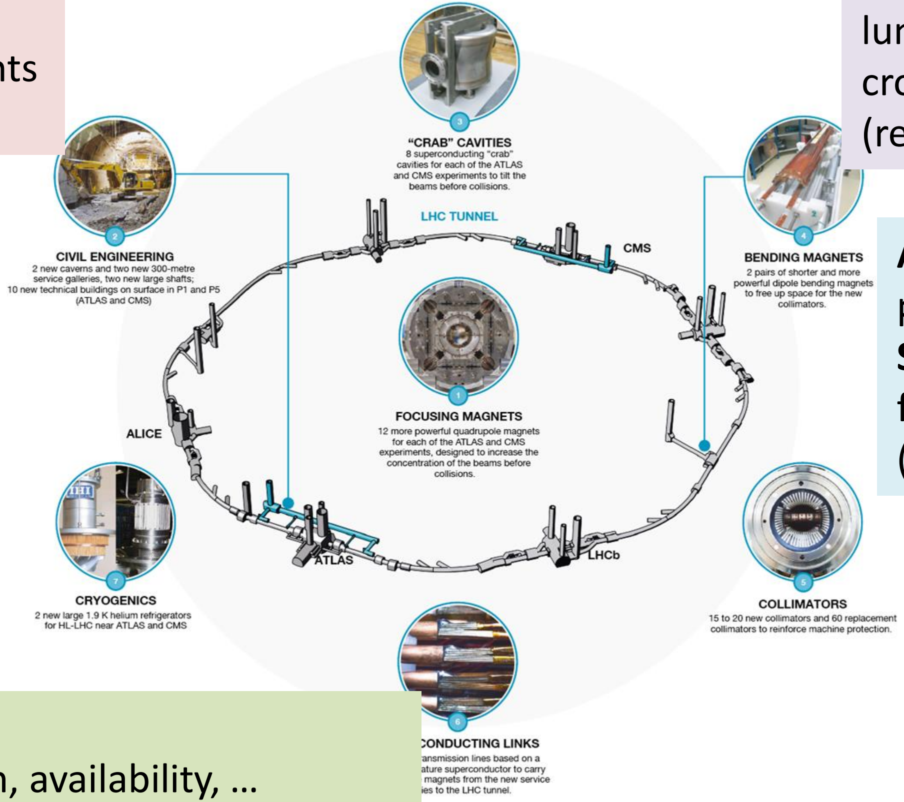


Some Key HL-LHC Ingredients

Higher field focusing magnets at experiments
Models tested

Crab cavities to reduce luminosity reduction by crossing angle
(recent first tests in SPS)

Injector upgrade



Additional collimators to protect arcs
Stronger dipoles to make space for additional collimators
(recent first prototype)

Civil engineering and more **kryogenics**

Improved collimators design and material

And many **more**
Instrumentation, vacuum, availability, …
Optics design, electron cloud, impedances, …

Luminosity

Luminosity $\mathcal{L}$ determines the event rate

It depends on the geometrical overlap of the colliding beams

$$\mathcal{L} = \frac{N^2}{4\pi\sigma_x\sigma_y} f_r$$

Bunch charge ($N^2=N_1N_2$)

Number of bunch collisions per second

Horizontal rms beam size (Gaussian beam)

Vertical rms beam size (Gaussian beam)

Beam Size

Lattice property

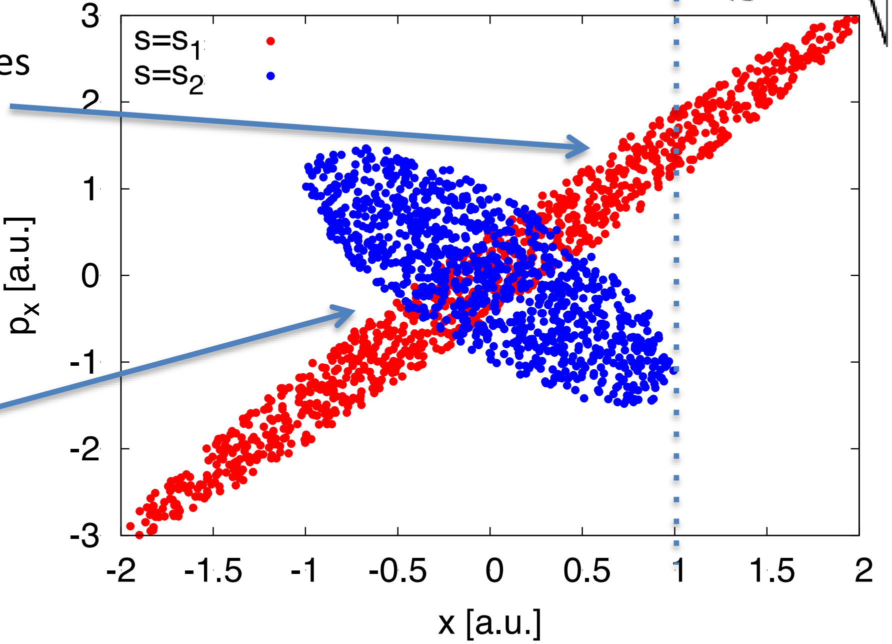
Beam property

$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$

Particle coordinates at one location

Area ε does not change

Particle coordinates at other location



Hadron Collider Luminosity Drivers

$$\mathcal{L} \propto \frac{N}{\epsilon} \frac{1}{\beta} N n_b f_r$$

Use high beam current

Risks:

- High stored energy and losses
- Impedance and electron cloud
- Aperture should be minimised for dipole cost
- High synchrotron radiation load due to high beam energy

Squeeze the beam as much as possible
Mitigate more collision debris due to higher luminosity and energy

Make small emittance and large charge

Limited by emittance growth, imperfections and particle losses

For integrated luminosity:

- Fast turn-around critical for luminosity
- Minimise time for stops etc.
- High availability with more components than LHC
- Maximising current also maximises time between new fills

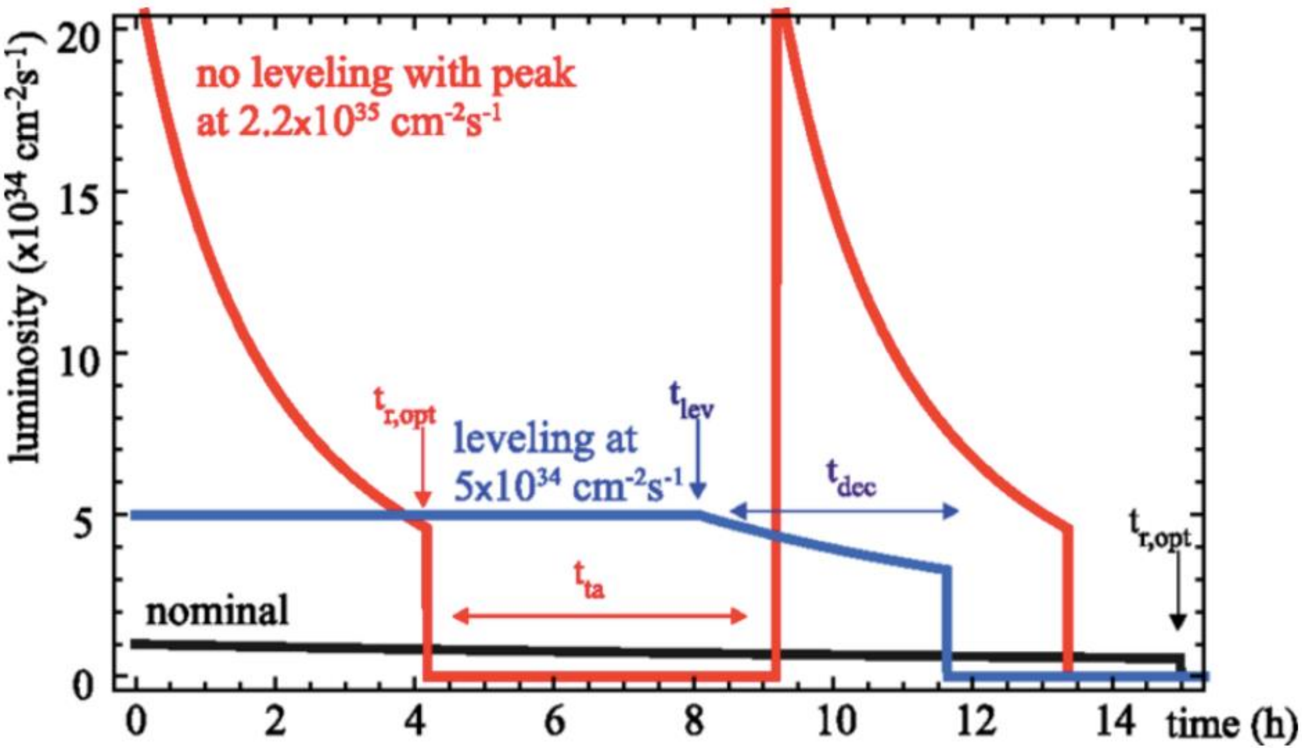
HL-LHC Luminosity Run

Peak luminosity is leveled to limit background

Luminosity decays because beam particles are lost in the collisions

Time between fills is a few hours

- ramp magnets down
- inject beam in small batches
- Ramp beam energy and magnets up

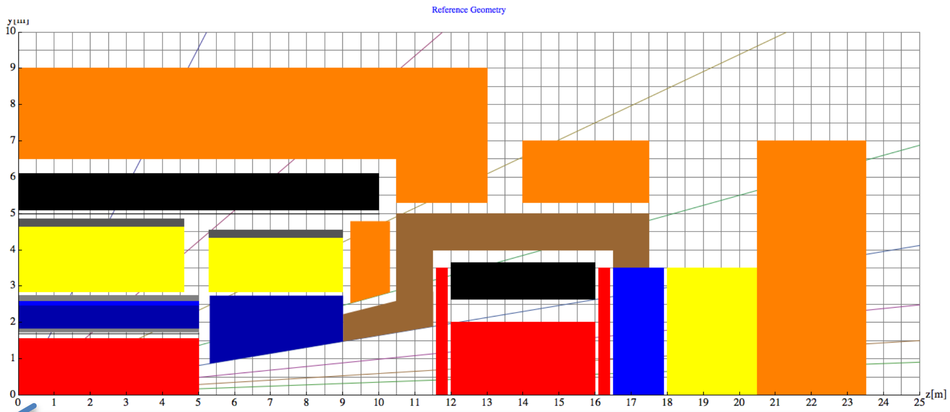


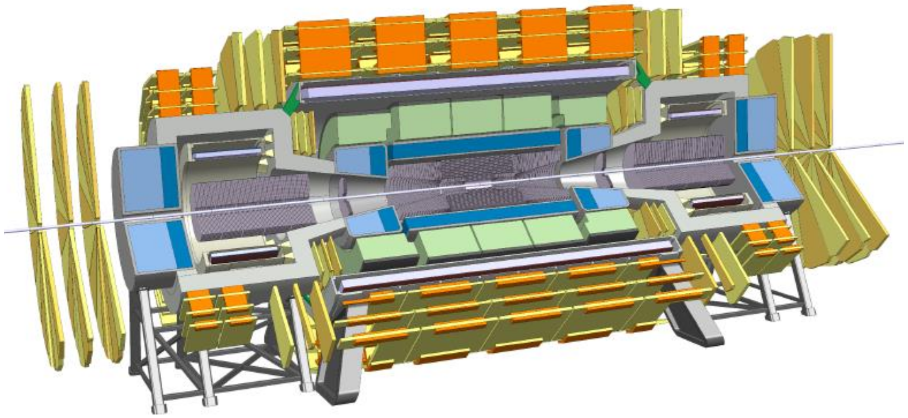
Detector and Machine

Tracking
Ecal
HCAL
Magnets and cryostat
Muons

Uses forward solenoid

Alternative option with forward dipole considered





Add. protection
TAS
Triplet

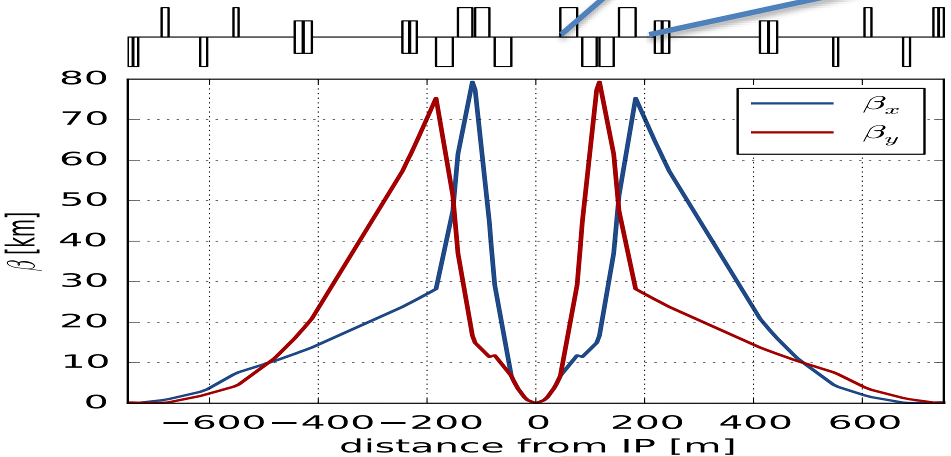
Hall half length: 33m
Tunnel before triplet: 7m
L^*=40 m
Detector half length 23.5m
Space to open 9.5m

FCC-hh example

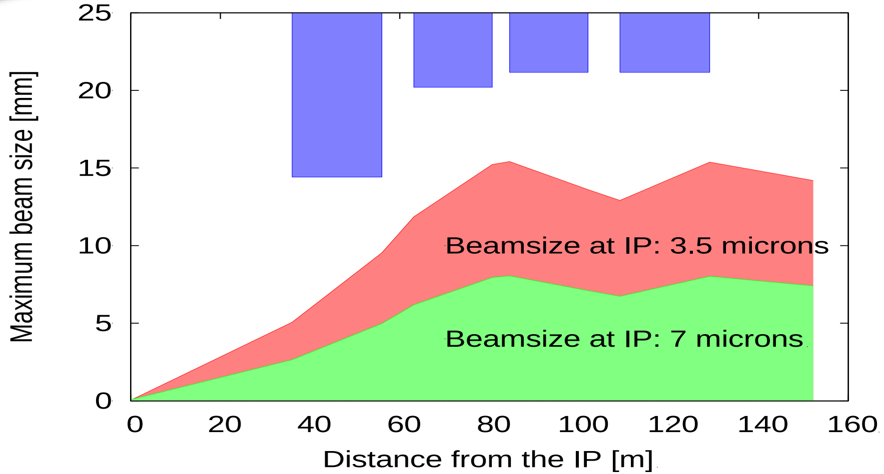
Interaction Region and Final Focus Design

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Beam size is limited by aperture in the magnets



FCC-hh example

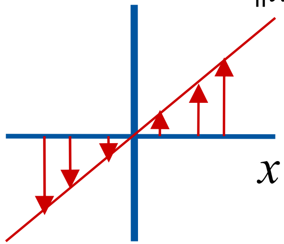


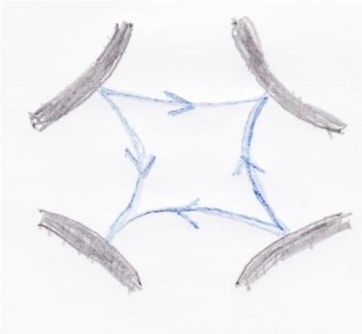
Smaller beta-function requires larger aperture

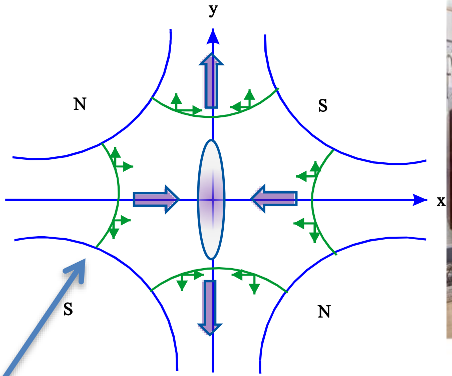
Quadrupole Design

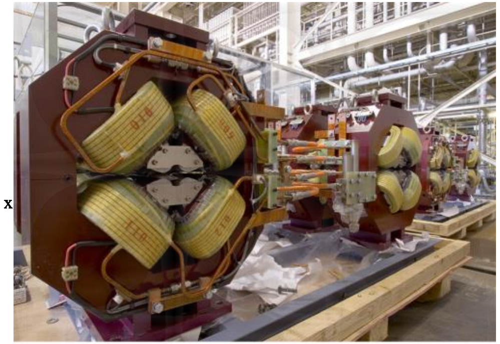
Quadrupoles can focus the beam
The vertical field is proportional to x
$\Rightarrow$ horizontal force is proportional to x

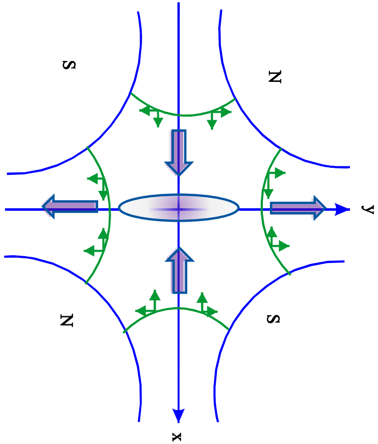
$$B_y = \frac{\partial B_y}{\partial x} x$$

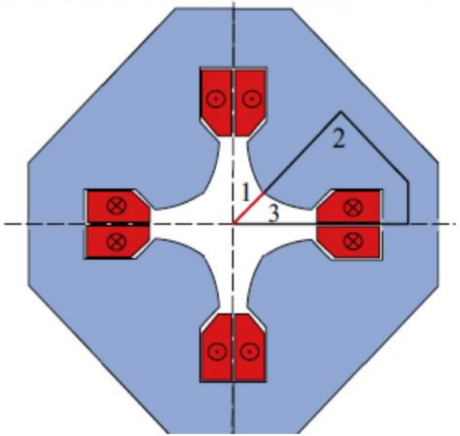












Maximum field in quadrupole depends on product of focal strength and aperture
$\Rightarrow$ LHC can use NbTi
$\Rightarrow$ HL-LHC needs Nb_3Sn (and FCC-hh) need 11 T

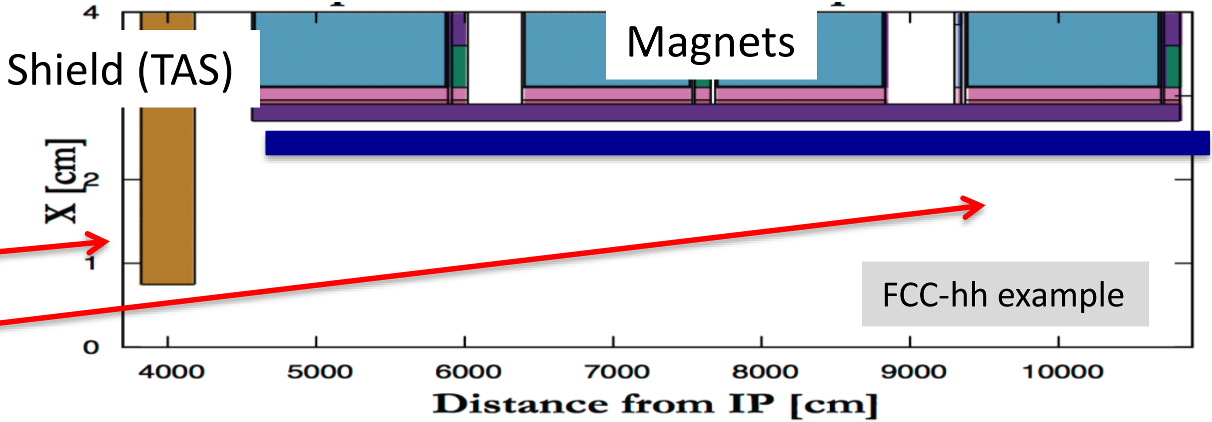
Radiation from Beam-beam

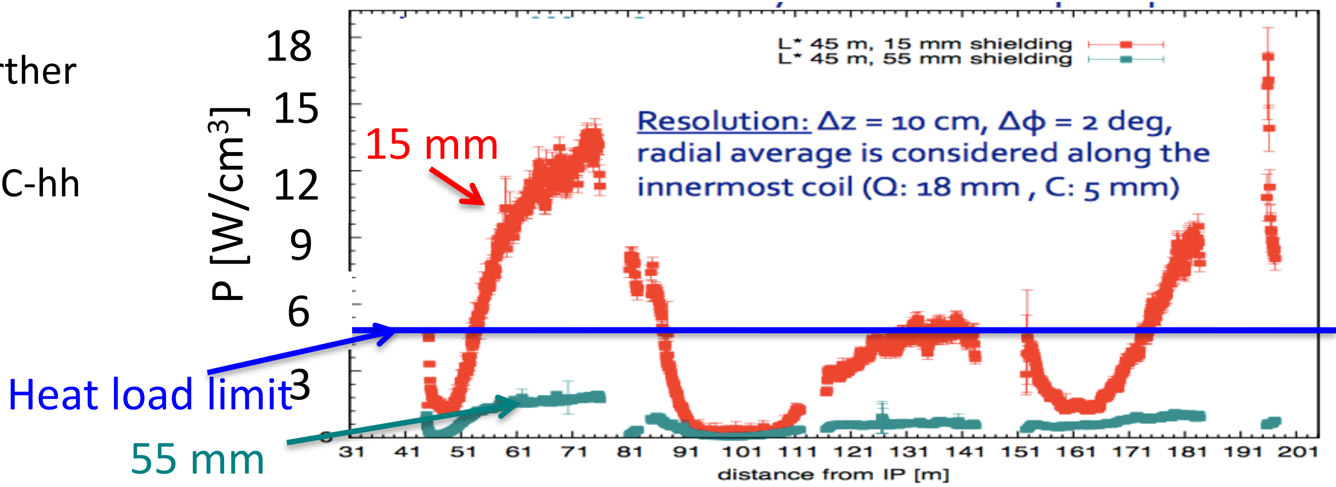
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Total collision debris per experiment

- O(10 kW) for HL-LHC
- LHC magnets have to be replaced due to the accumulated radiation
- Shielding is required and further increases magnet aperture
- note: up to O(500 kW) in FCC-hh

FCC-hh example shown

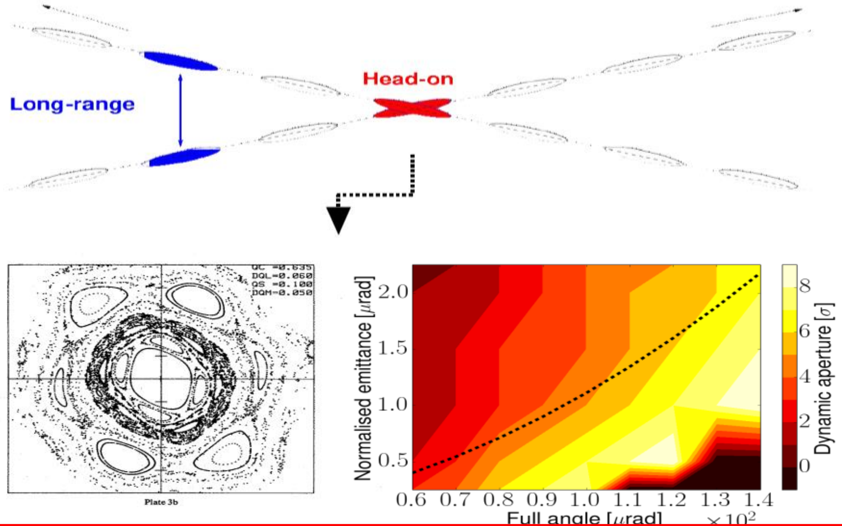




Beam Physics Limitations

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Beam-beam studies ongoing, promising results



$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

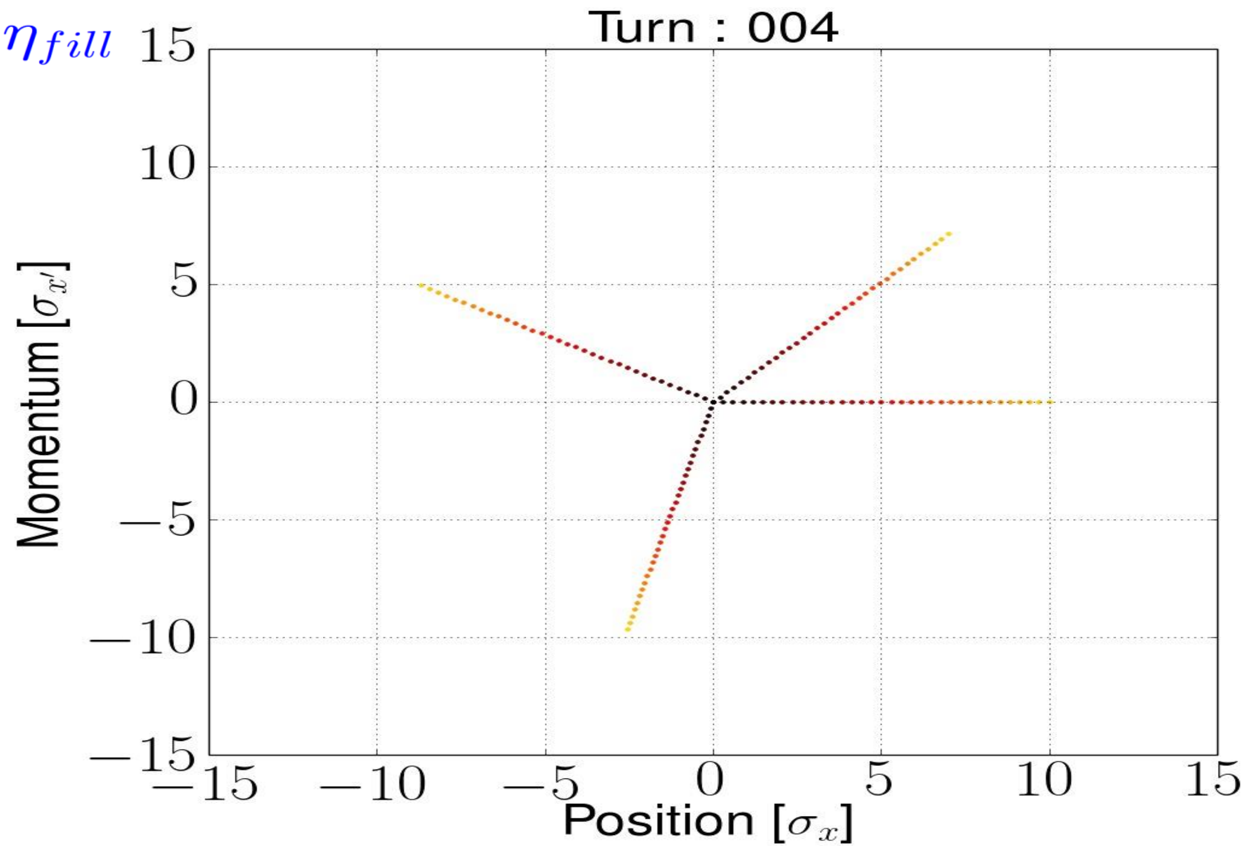
Many limitation for the beam current exist:

- Impedances
  - parasitic electromagnetic fields induced by the beam
- Electron cloud
  - electrons hitting the beam screen can produce avalanche of more electrons
- Losses in
  - Collimation
  - Injection
  - Extraction
- …

Beam-beam Effects

X. Buffat

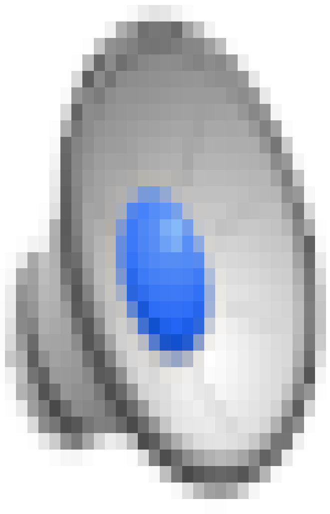
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$



Beam-beam Effects

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

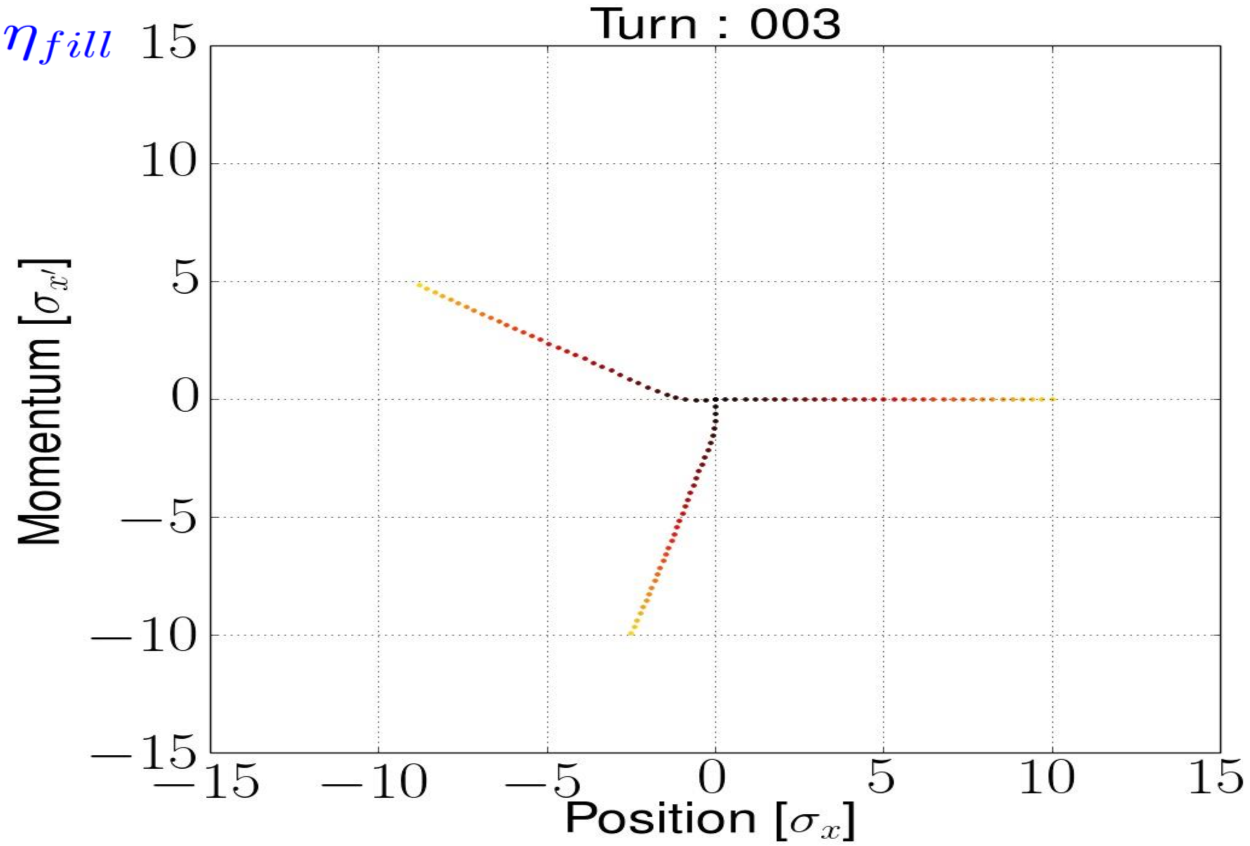
X. Buffat



Beam-beam Effects

X. Buffat

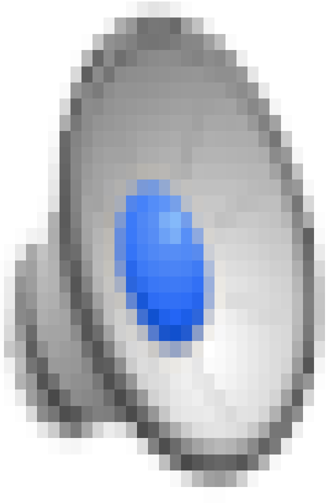
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$



Beam-beam Effects

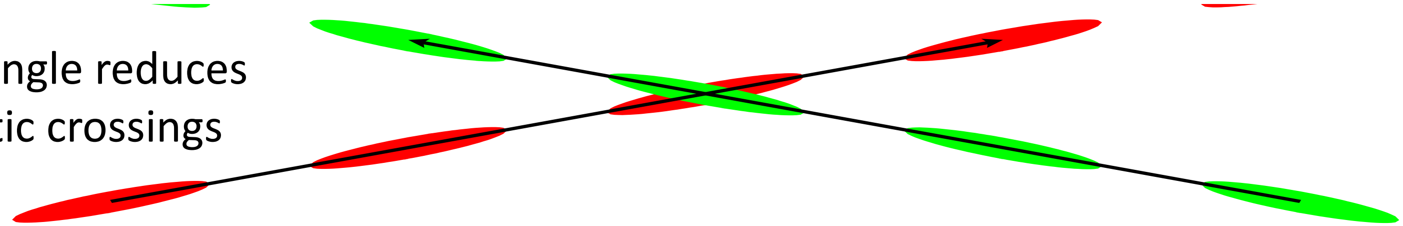
X. Buffat

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$



Crossing angle and Crab Cavities

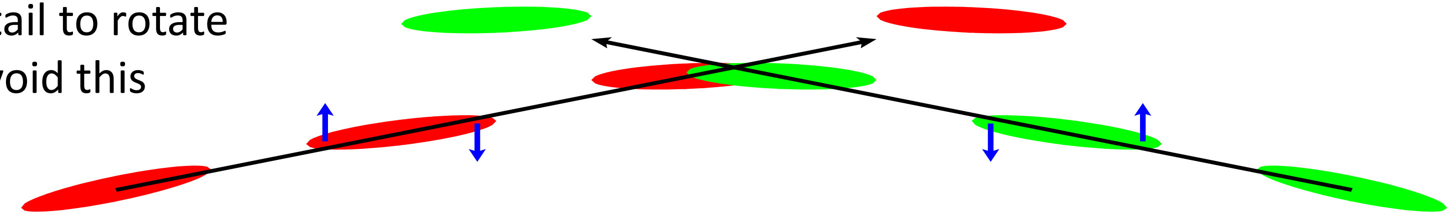
Larger crossing angle reduces impact of parasitic crossings



But reduces luminosity

$$\mathcal{L} = H_D \frac{N^2 f_r n_b}{4\pi\sigma_x\sigma_y} \frac{1}{\sqrt{1+\left(\frac{\sigma_z}{\sigma_x}\tan\frac{\theta_c}{2}\right)^2}}$$

Crab cavities give a kick to beam head and tail to rotate it the beam to avoid this



Collimation System

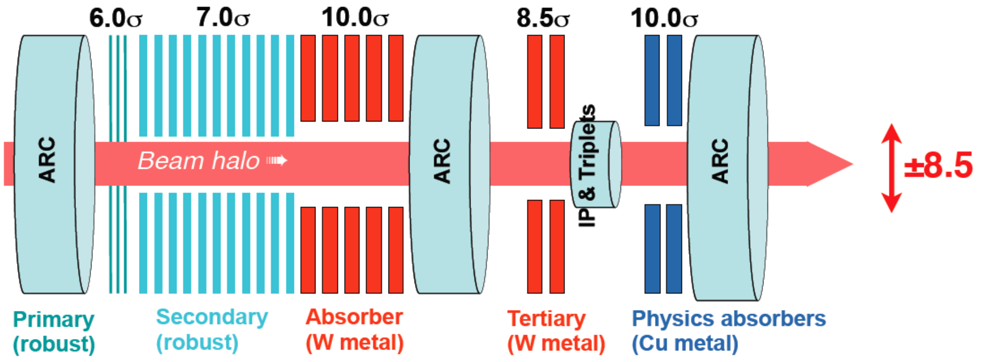
At collision, the final triplets at experiments are the bottleneck

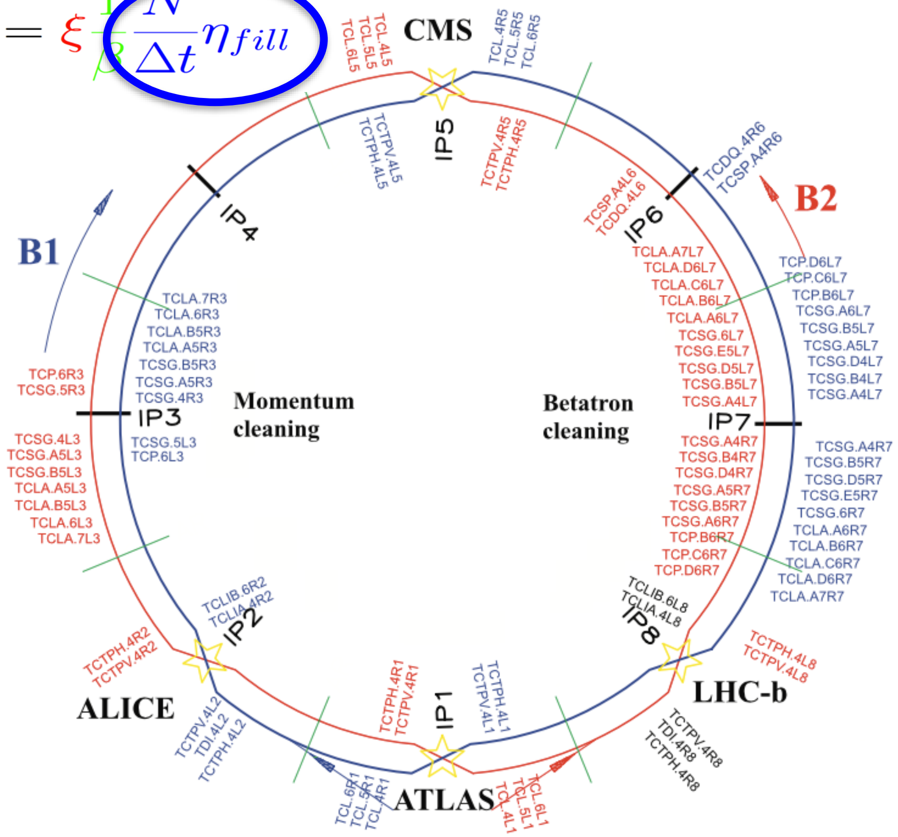
$\Rightarrow$ particles that drift into the tails get lost here

$\Rightarrow$ Need to introduce a new, smaller bottleneck to have losses in less sensitive region, the collimation system

Collimation also protects from injection failure, asynchronous beam dump, …

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$





Collimation System

Transverse collimation ("betatron") system is most challenging
FCC-hh design is shown, but a copy of LHC system

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

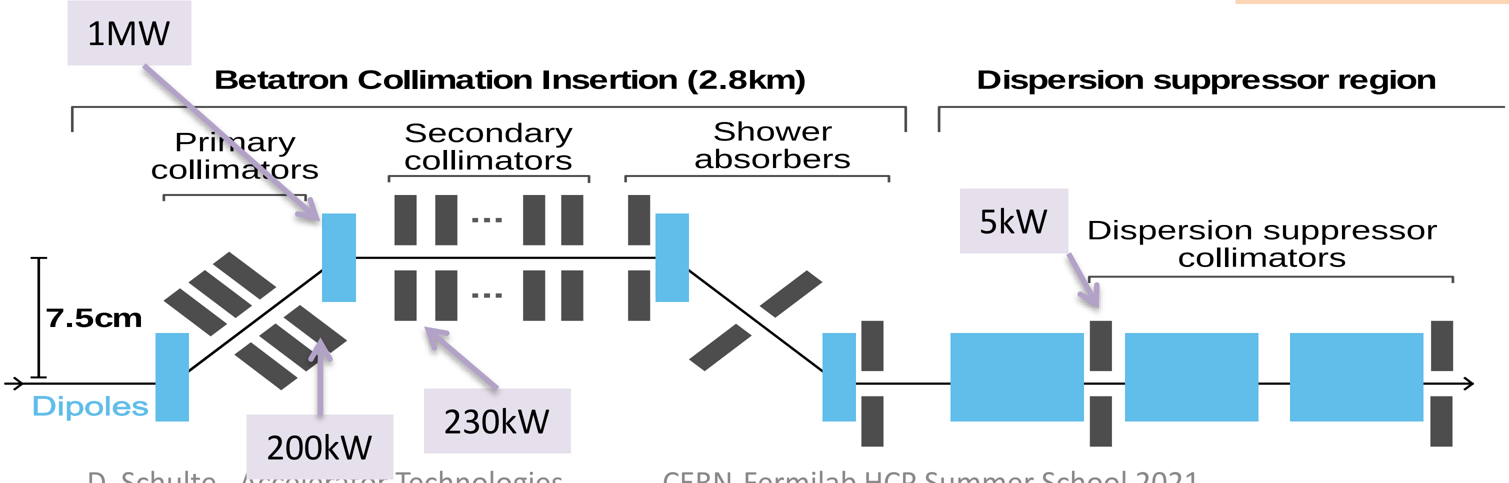
Protect arcs with additional collimators
- No space in LHC

$\Rightarrow$ replace some 8 T dipoles with shorter 11 T ones
- Foreseen in FCC-hh

Primary collimators intercept protons

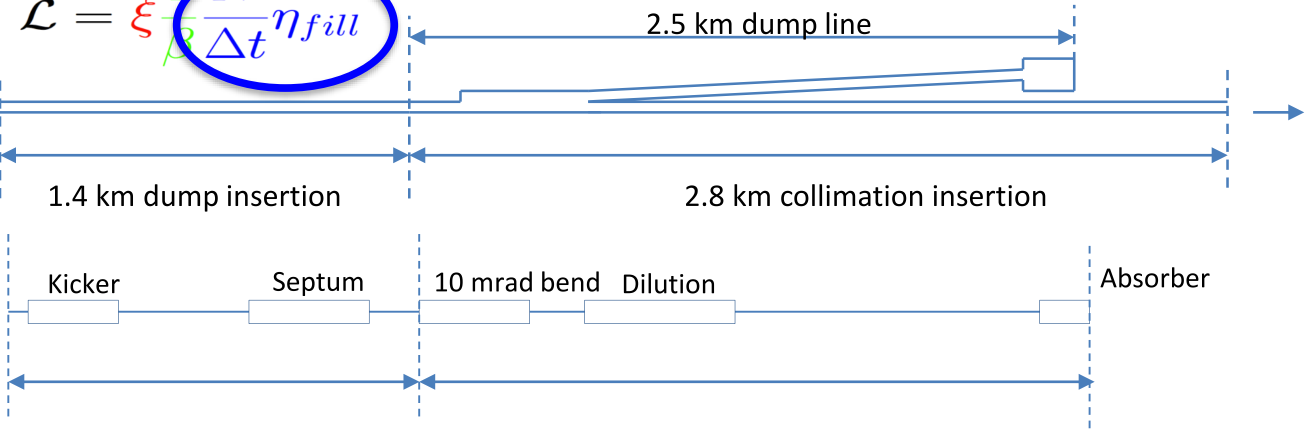
Secondary collimators and absorbers intercept showers

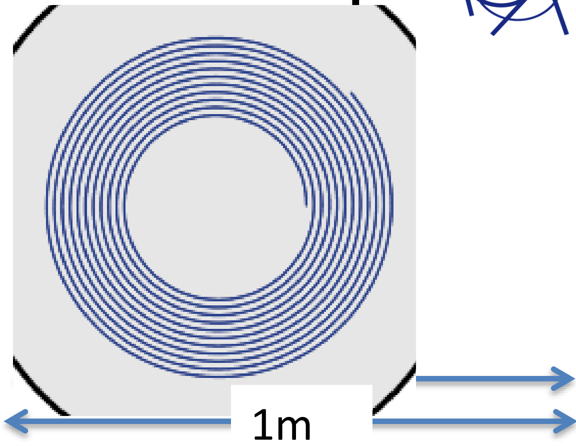
Some protons only lose energy and make it to next arc, where they are lost



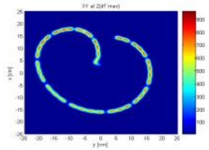
Intensity Limitation: Beam Energy and Dump

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$





LHC pattern
(same scale)



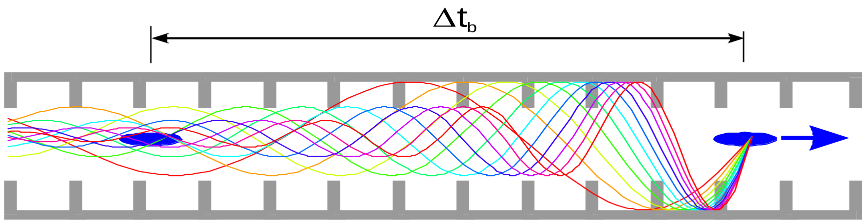
In LHC / HL-LHC 400 to 800 MJ per beam

In FCC-hh 8 GJ kinetic energy per beam

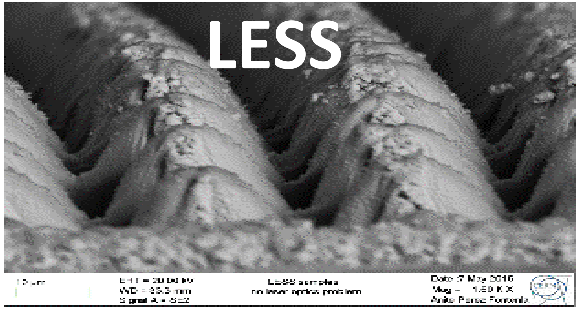
- Airbus A380 at 720 km/h
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC
- Can drill 300 m long hole in copper

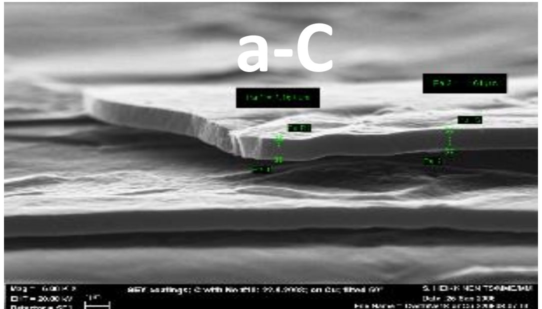
Other Intensity Limitation Examples

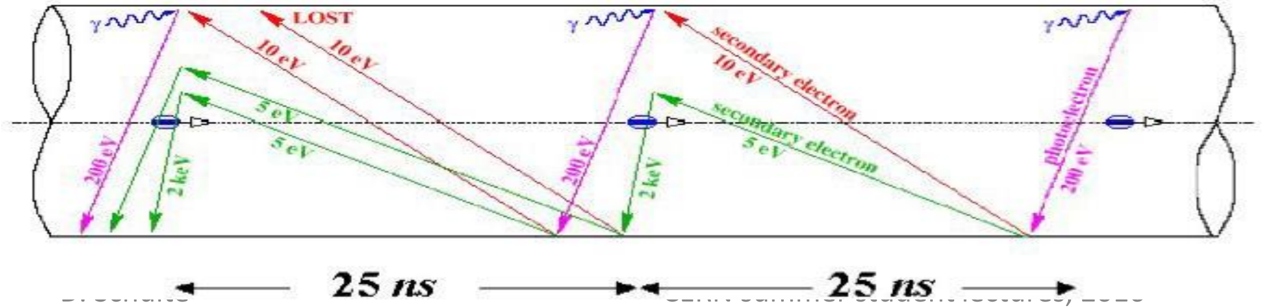
Impedance
Beam produces parasitic electromagnetic fields in collimators, beam screen etc that can kick beam and induce instability



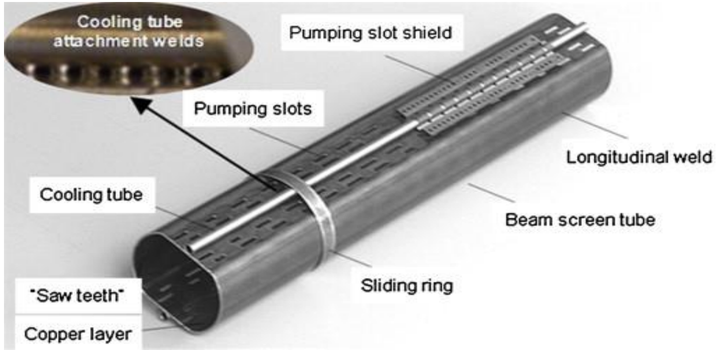
Electron cloud
free electrons are kicked into wall by proton beam and can produce secondary electrons which can build-up to cloud of electrons and render beam unstable



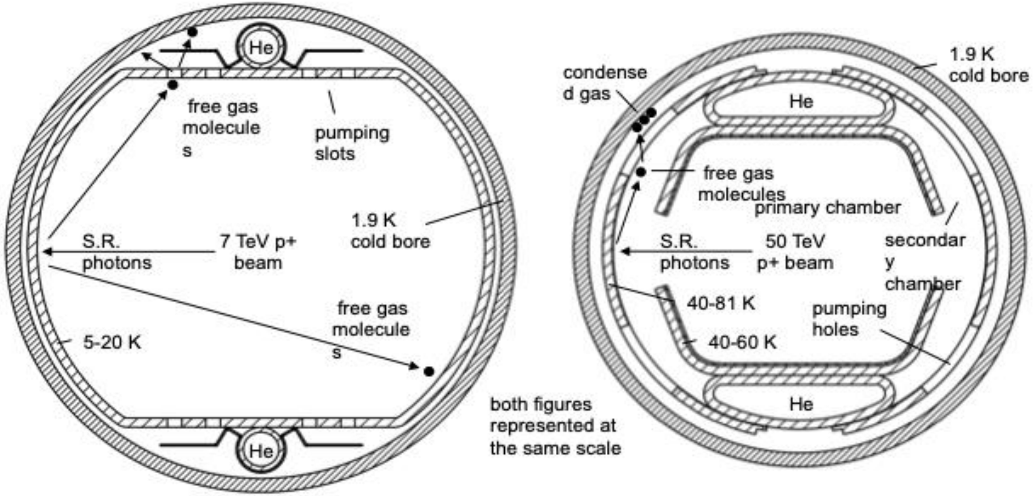




Beamscreen Design



LHC beamscreen



FCC-hh beamscreen

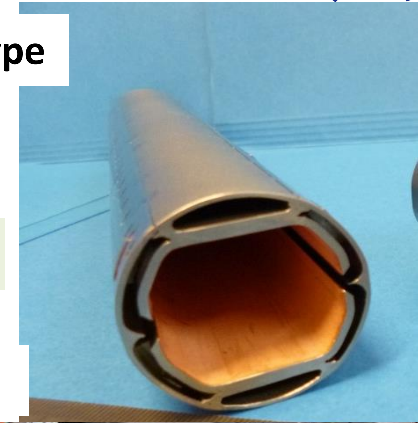
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

FCC-hh Technology Example

30 W/m synchrotron radiation (LHC: 1 W/m)
Make it small to make magnet cheap

Magnet aperture 50 mm (LHC 56 mm)

Prototype



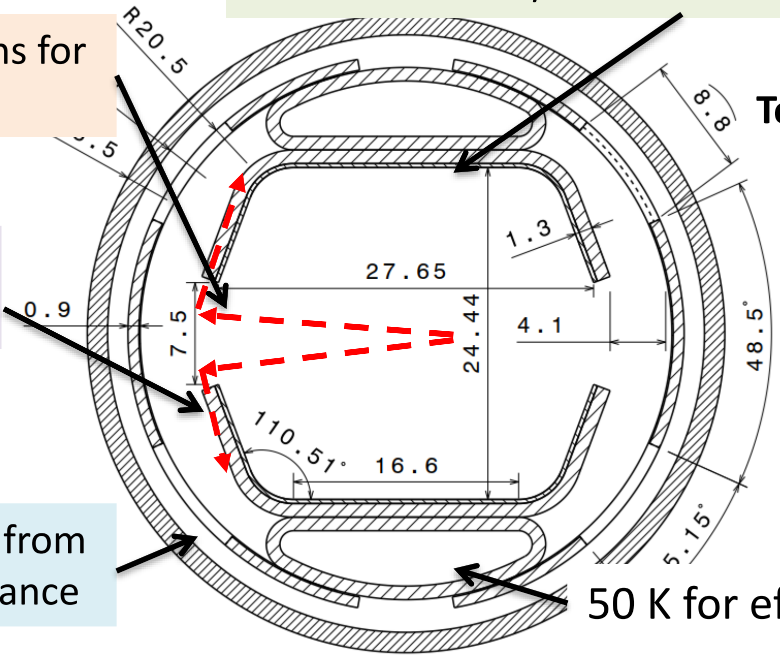
Laser treatment / carbon coating against ecloud

Extract photons for great vacuum

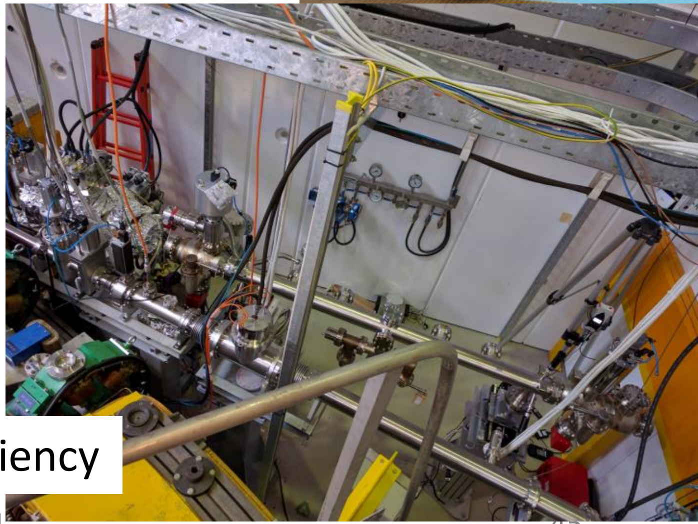
Strong to withstand quench

Hide pumping holes from beam for low impedance

50 K for efficiency



Test station in ANKA

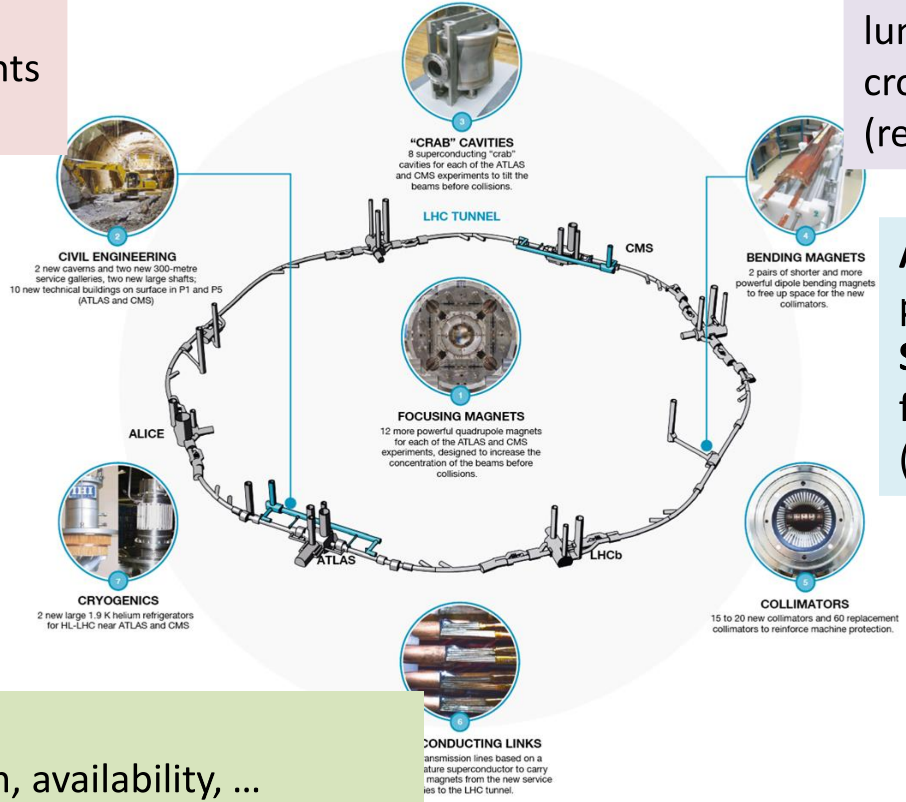


Some Key HL-LHC Ingredients

Higher field focusing magnets at experiments
Models tested

Injector upgrade

Civil engineering
and more **kryogenics**



Crab cavities to reduce luminosity reduction by crossing angle
(recent first tests in SPS)

Additional collimators to protect arcs
Stronger dipoles to make space for additional collimators
(recent first prototype)

Improved collimators design and material

And many **more**
Instrumentation, vacuum, availability, …
Optics design, electron cloud, impedances, …