Accelerators Physics and Challenges for Future Colliders I

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Introduction

Accelerator development has initially been driven by nuclear and particle physics

- Now, accelerators have many applications and are also driven by other fields

Will focus on the high-energy frontier accelerators for particle physics

- Important application
- Helps to understand basic accelerator concepts
- Could be the next flagship project

Will address the accelerators with a project view

- Not an introduction into the principles first
- Rather look at the goal and see which tools we need
- Cannot cover all relevant physics, concepts, technologies, …

Note:

- Not all project parameters are fully up to date
- Does not harm understanding the concepts

Proposed Colliders at Last ESPPU

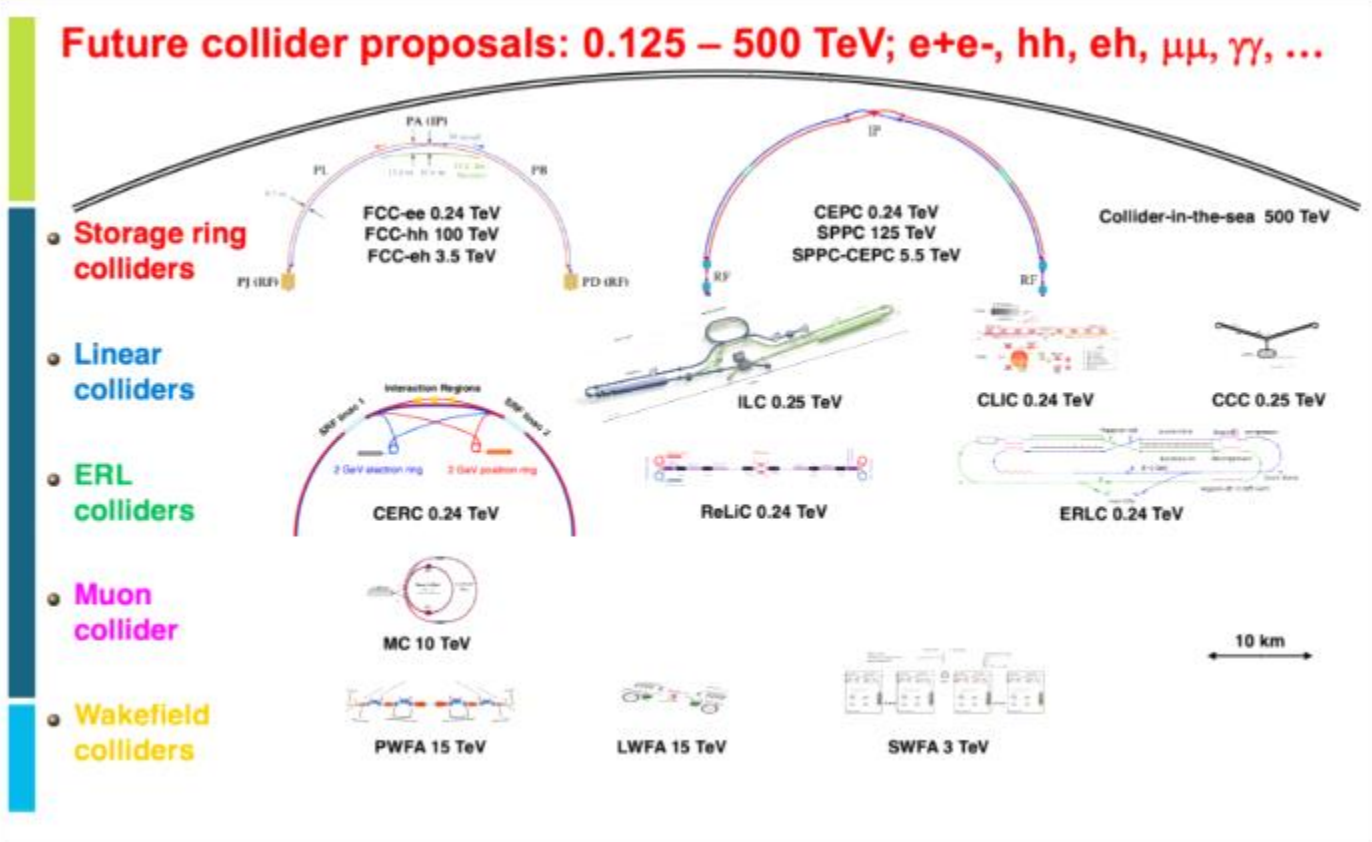
Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Collider Proposals at Snowmass

Implementation Task Force (ITF) looked at many different proposals

Cannot cover them all

Select according to European view



Key Collider Options

Europe:

Last ESPPU concluded

- Long term ambition is high-energy hadron collider
- Higgs factory is most urgent project after HL-LHC

Plan A is **FCC**

- **FCC-ee**, e^+e^- circular collider, 91.2-365 GeV
- **FCC-hh**, hadron collider, O(100 TeV), same tunnel

Prudently prepare plan B

- **CLIC**, an e^+e^- linear collider 380 GeV-3 TeV
- **Muon collider**, as initiated by ESPPU, 3-10+ TeV

Also in the R&D Roadmap

- Energy recovery linacs (**LHeC, FCC-eh,** electron-proton)
- Plasma technology

US:

P5 process recommended

- No higgs factory in US
- **10 TeV parton-parton collider**
  - e+e-, pp, but in particular **muon collider**

Japan:

ILC, 0.25-1 TeV, waiting for governement to move

China:

Interest in **CepC/SppS**, comparable to FCC-ee/FCC-hh

- Aim to have decision by Chineese government 2025

Many more less mature proposals

Will not give all details but short reminder of key projects and a bit on the novel ones

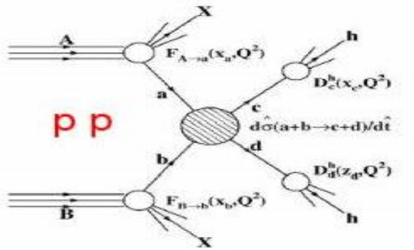
Key Collider Factors

Particle type
Collision energy
Luminosity
Background conditions in the detector

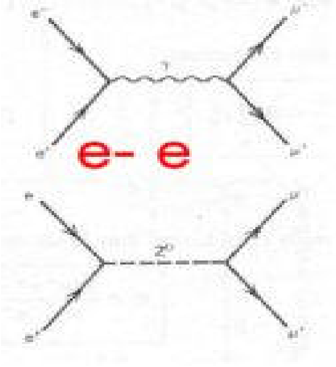
Site availability
Technical risk
Cost
Power consumption
Environmental impact
Support by society

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

Particle Accelerator Fundamentals

Accelerate charged particle
Force on charged particle is given by

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Typically particles are accelerated to gain energy using RF cavities that have longitudinal fields

Typically particles are guided on the trajectory by magnets that have transverse fields

Note: gamma-gamma collider transforms electron to photons just before the collision

Spoiler: Key Technologies

Typically the key technical 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
- …

Hadron Colliders

High Energy Protons: Overview

The LHC is the current high energy frontier collider

- Centre-of-mass energy 14 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

LHC

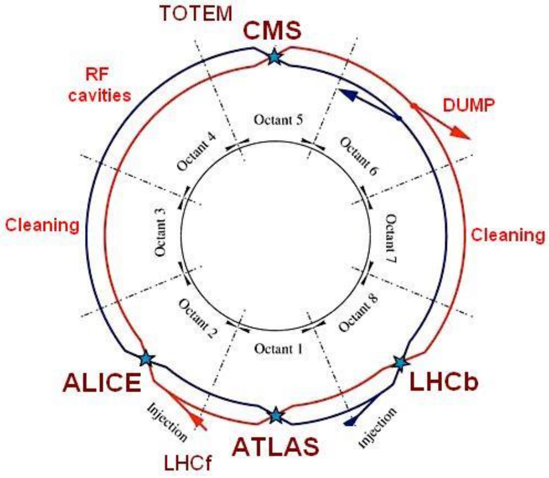
I guess, everybody is familiar

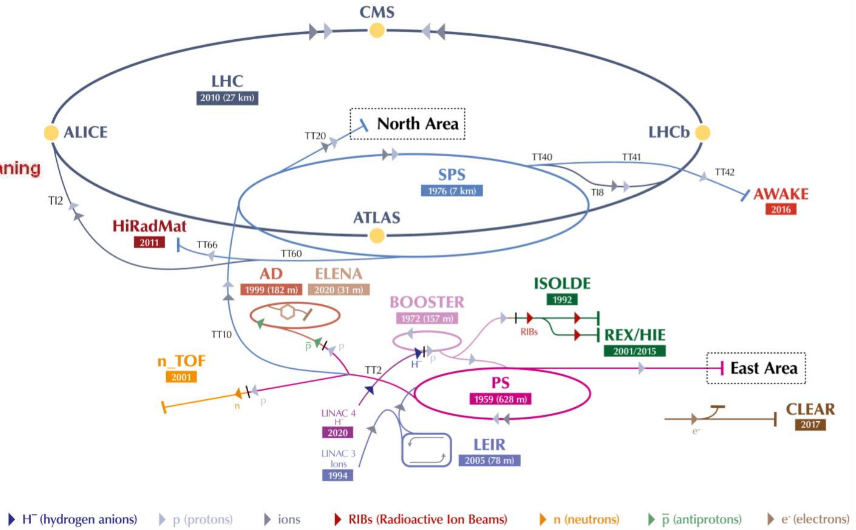
Two multi-purpose experiments

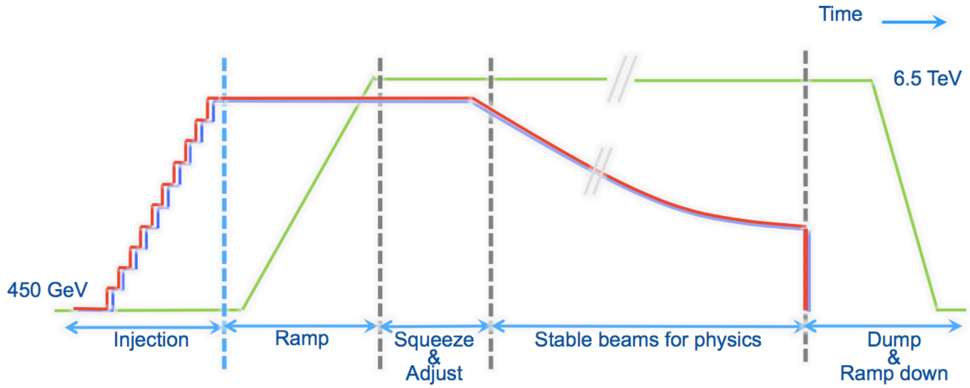
- ATLAS and CMS

Two specialised experiments

- ALICE and LHCb







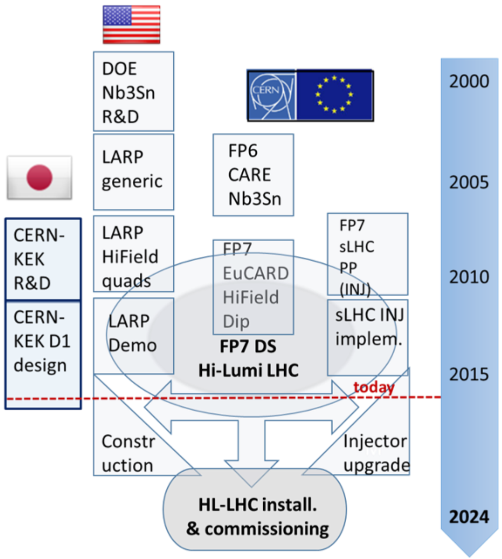
The LHC obtains its beam from a chain of injectors

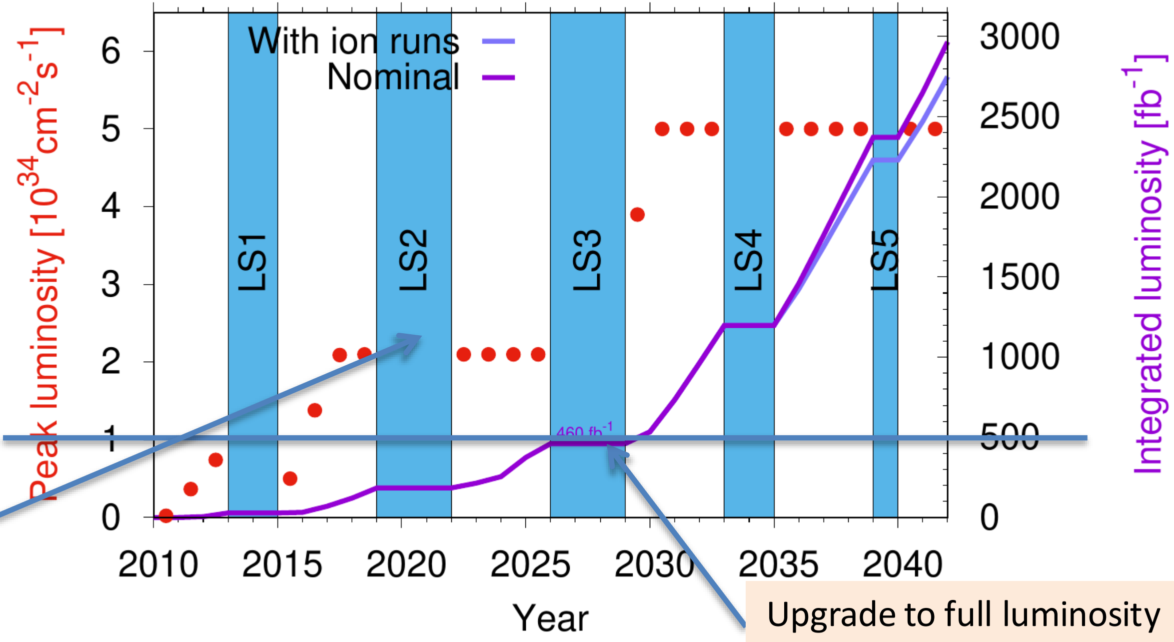
Typically, few hours to fill and several hours of luminosity

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.





Upgrades to higher current

- Injectors
- Collimation
- Detectors (phase 1)
- …

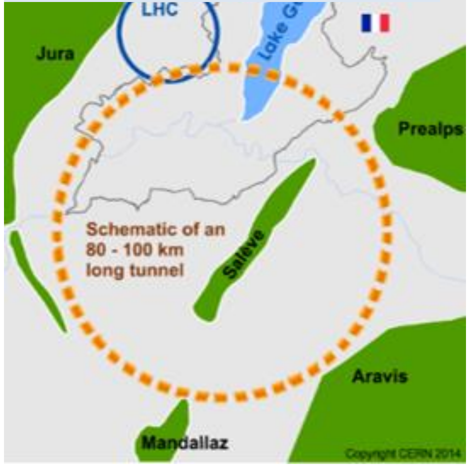
Small luminosity increase

Upgrade to full luminosity

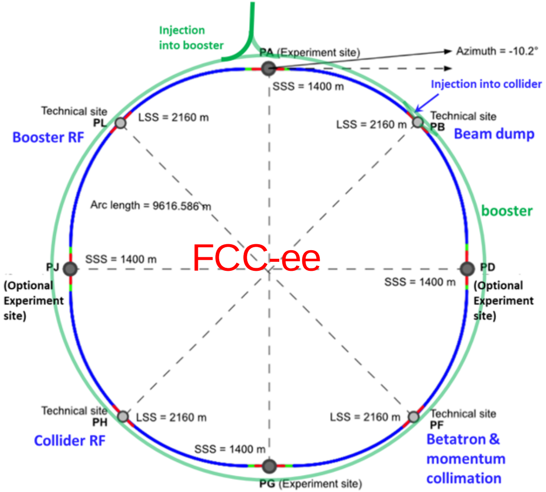
- Detectors (phase 2), triplets, …

FCC Overview

Similar to LEP/LHC staging
Focus on site studies

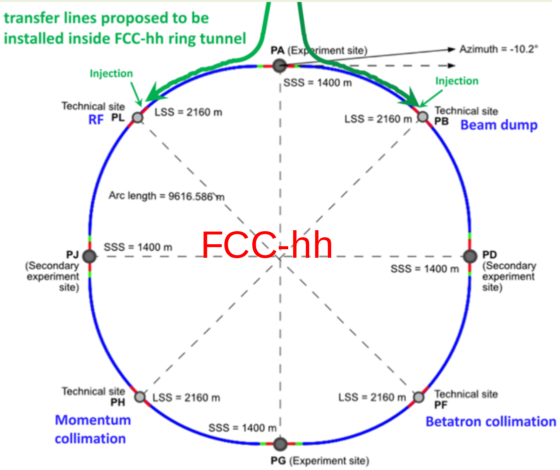


FCC-ee at Z, WW, ZH and tt



Start 2045 ?

FCC-hh at 80-116 TeV, depending on magnet technology (Nb_3SN vs HTS)



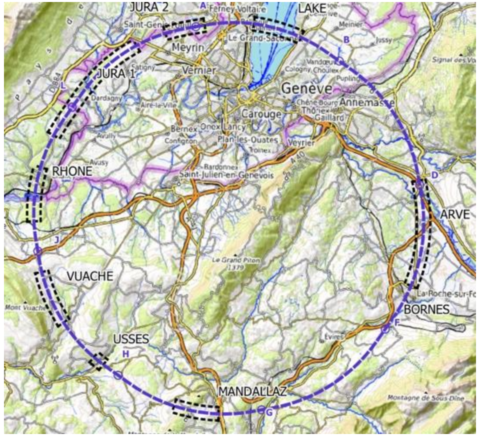
Start 2070 ?

CepC and SppC is a similar approach in China

FCC Goals for 2021-2025

- Demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- Pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- Optimising design of colliders and their injector chains, supported by R&D to develop the needed key technologies;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- consolidation of the physics case and detector concepts for both colliders.

Site development ongoing

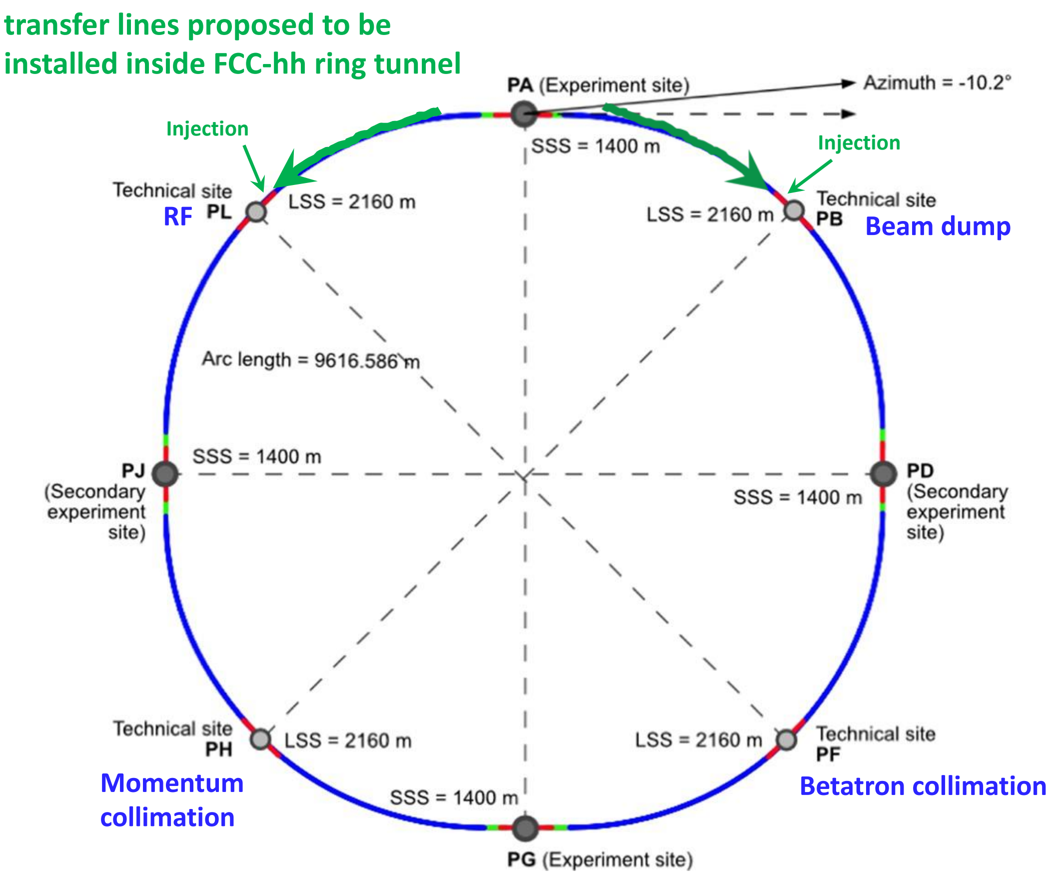


Technical and scientific preparation
Other preparation

Taken from F. Zimmermann

New FCC-hh Layout

- **Exact four-fold symmetry (FCC-ee layout)**
- Four experiments (A, D, G, & J)
- Two collimation insertions
  - betatron cleaning (F)
  - momentum cleaning (H)
- Extraction insertion + injection (B)
- RF insertion + injection (L)
- **Last part of transfer lines in the ring tunnel, normal-conducting magnets**
- Compatible with LHC or SPS as injector



Hadron Collider Parameters

parameter	FCC-hh	HL-LHC	LHC
collision energy cms [TeV]	84 - 120	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]	1100 - 4570	7.3	3.6
SR power / length [W/m/ap.]	14 - 58	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]	6.3 – 9.2	0.7	0.36
Integrated luminosity/main IP [fb^{-1}]	20000	3000	300

Hadron Collider Energy

Arc Cell (FCC-hh CDR)

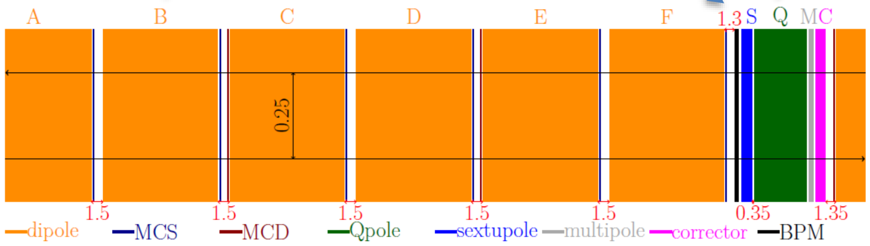
Arcs consist mainly of dipoles to bend the beam (80% dipoles in LHC or shown FCC-hh arcs)
Maximum field and size of ring then define maximum collision energy

Simplified hardware layout

Dipoles to make beam go around the ring

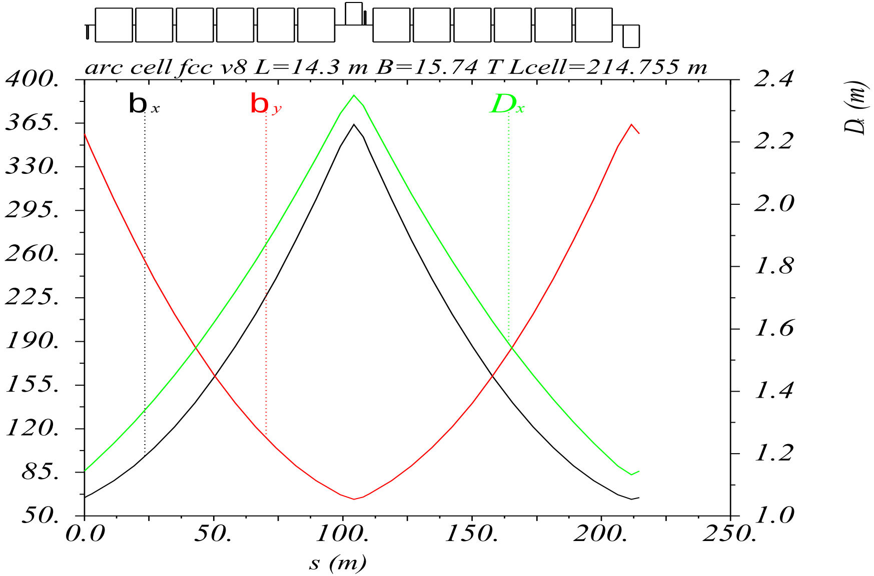
Beam position monitors (BPM) to know where the beam is

Quadrupoles so that particles stick together

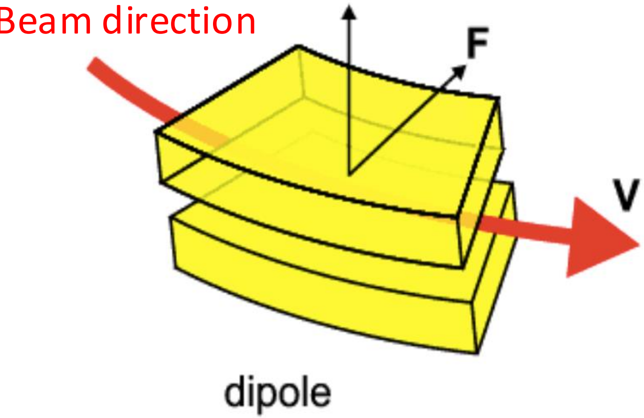


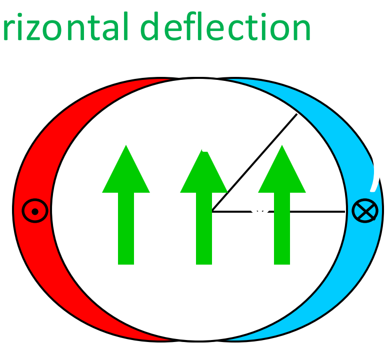
Plenty of correctors, spool pieces etc

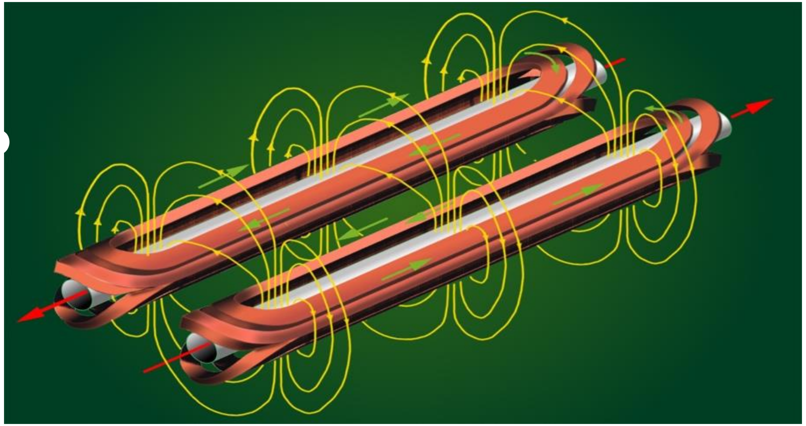
Optics functions (accelerator physicists view)



Dipole Basic Concept



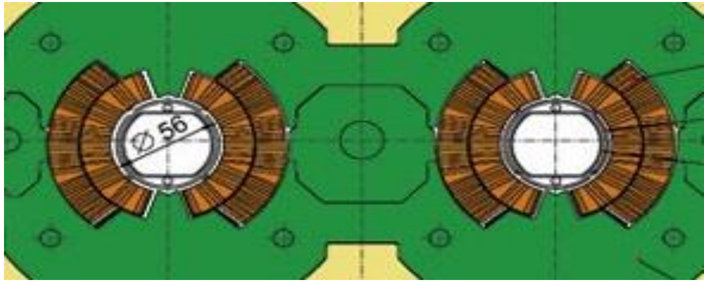




LHC magnet concept (“Cosine Theta”)

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

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



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

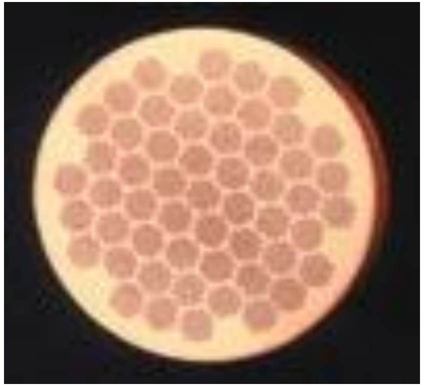
Superconducting magnets reach highest fields, three main technologies for the cables

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 demonstrated
- very expensive

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

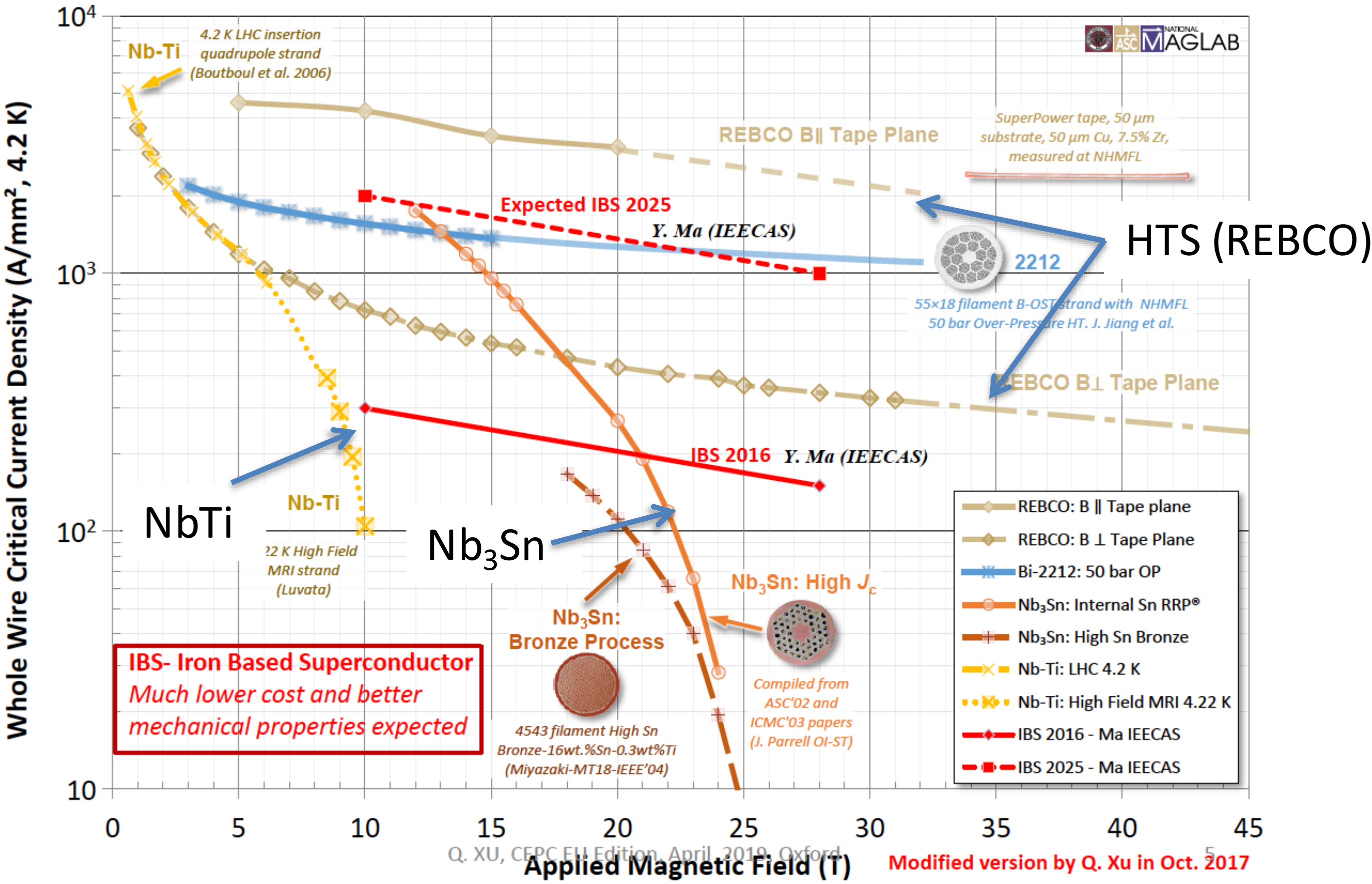


Conductors

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



Previous Magnet Designs (FCC-hh)

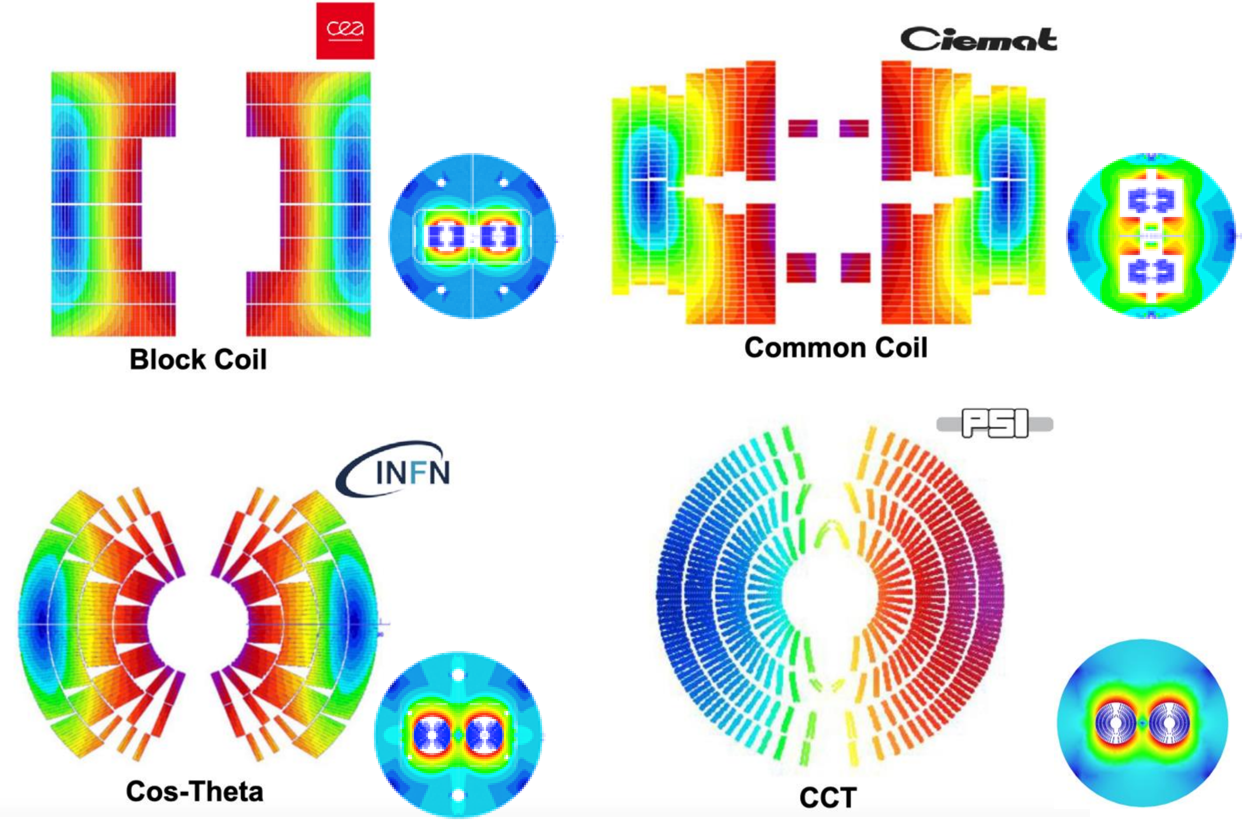
Several configurations are possible

- All with advantages and drawbacks

Criteria: Amount of conductor, stress in magnets, …

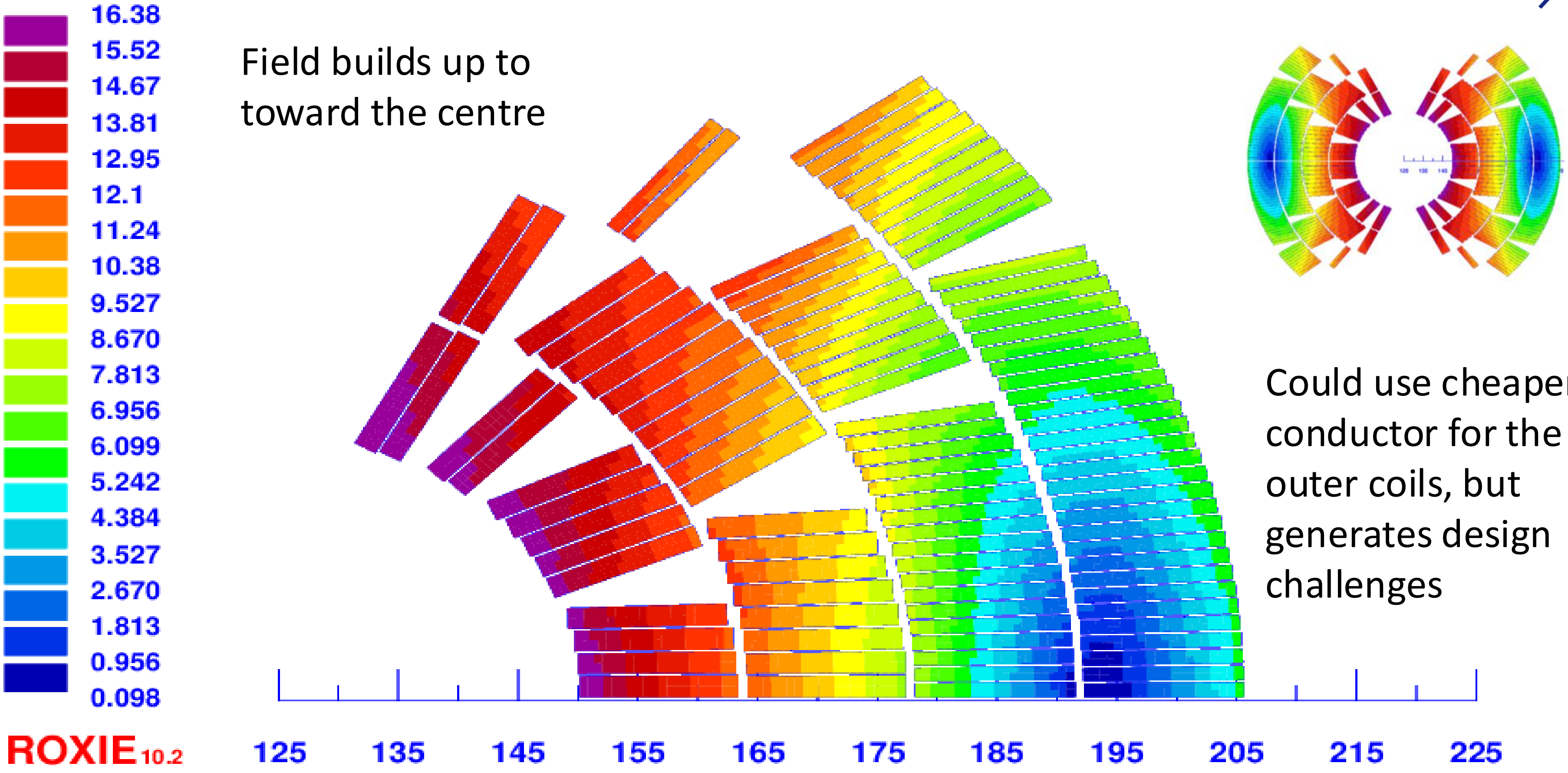
The conductor is a major cost item of the magnet

⇒ 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

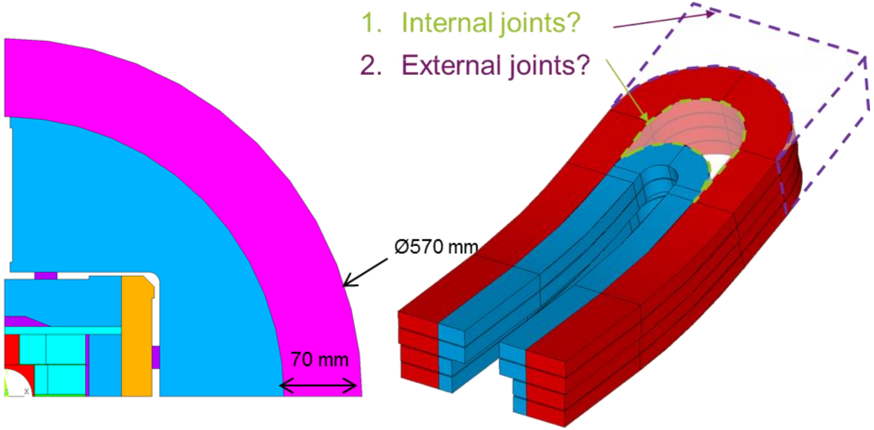
Magnet Models

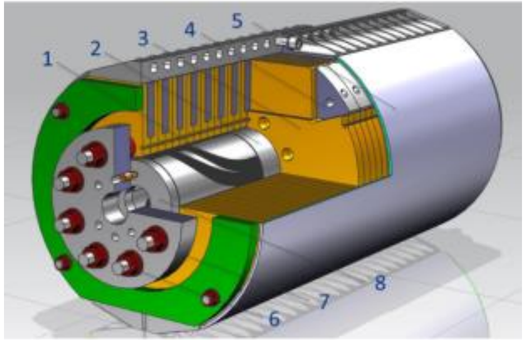
With today's state of the art conductors:

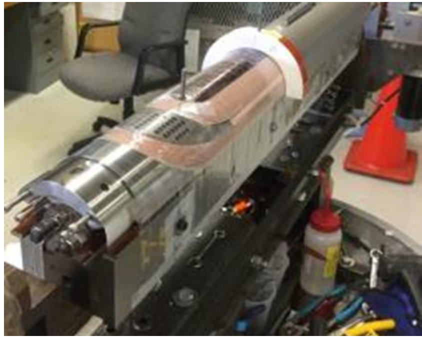
- 15 T achievable at 14 % margin
- 17 T at short sample

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

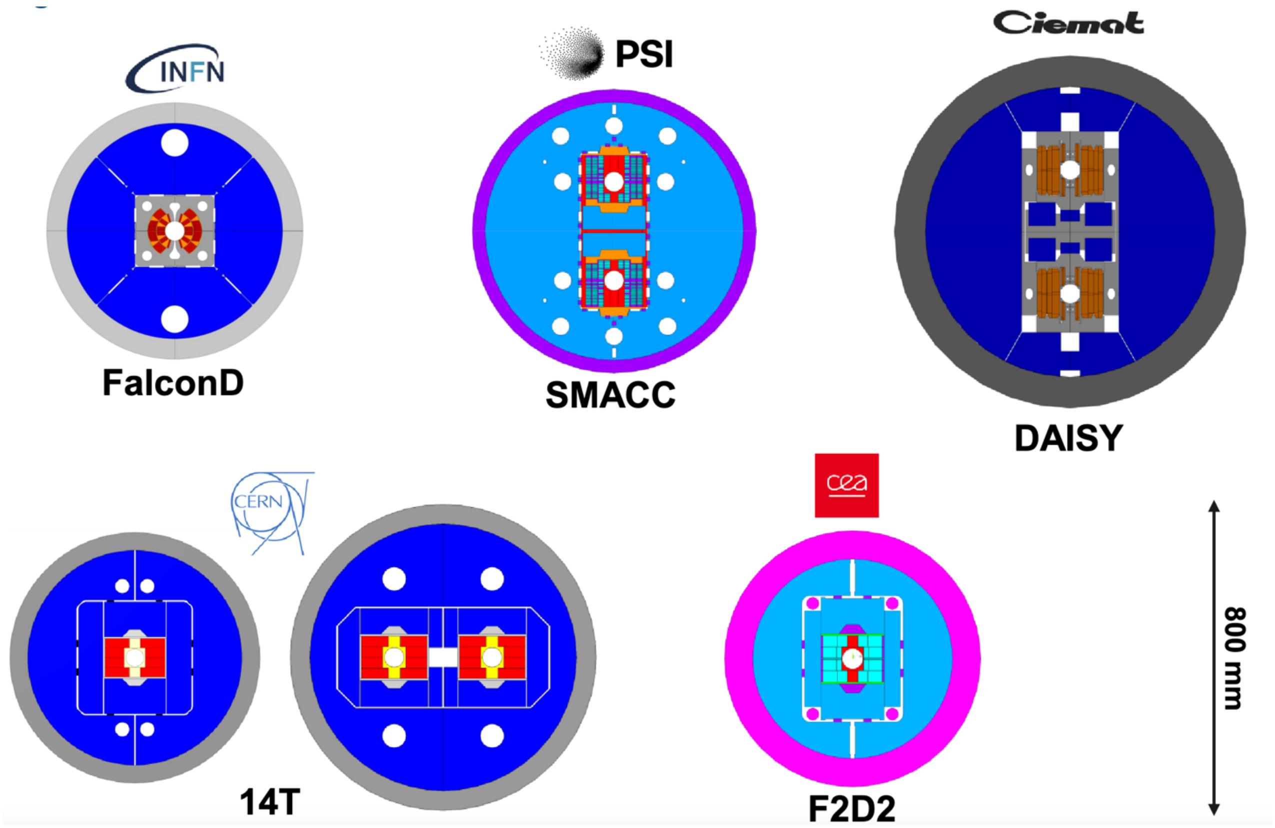
15 T dipole demonstrator
60-mm aperture
4-layer graded coil







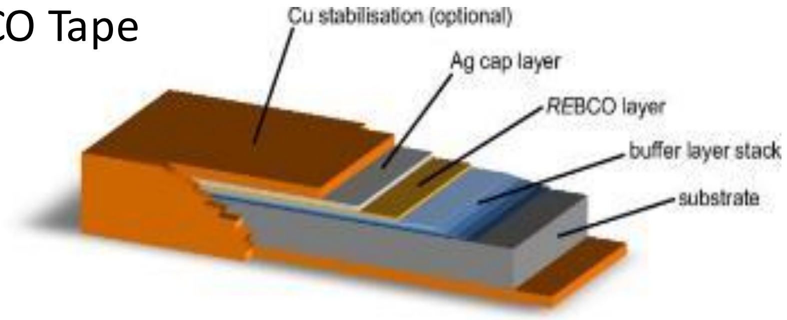
High-field Magnet Programme



HTS

Explore different HTS solutions
- Much effort on REBCO
  - Some on iron-based HTS (China and some INFN effort)

REBCO Tape



Kabel challenges
- Improvement of REBCO tapes with industry
- Develop cables for accelerators

Magnet challenges
- Dealing with high forces
- Quench protection

Strong synergy with applications in society
- Funsion reactors, power generators for windmills, motors, power transmission, medical applications, …

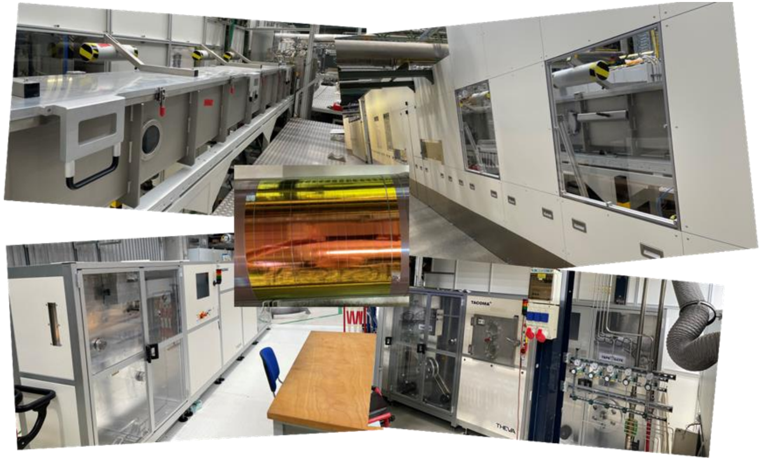
Spoiler:
- Solenoids are already achieving high fields
- No insulation required if magnets operate at fixed field

HTS

R&D effort in the HFM programme

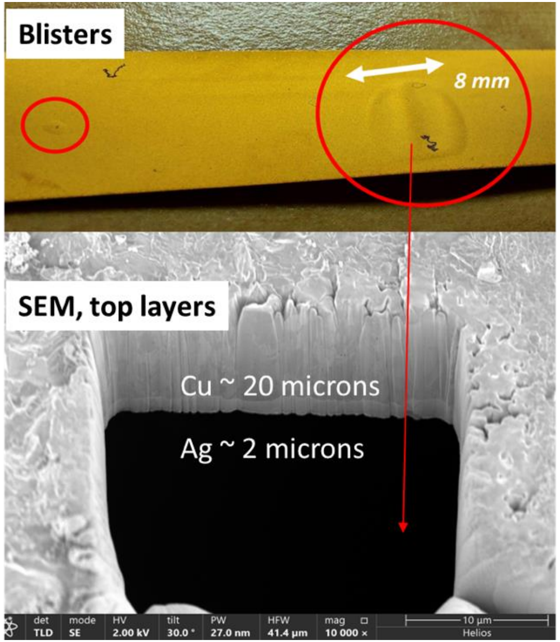
But also important efforts in industry

KIT: Production of tape to improve quality



CERN: Winding of coils

Twente: Study to prevent blisters on tape



HL-HLC and Hadron Collider Luminosity

Emittance

Particles come in bunches

- The bunch has a nominal energy, longitudinal position, transverse positions, and transverse angles

However, each particle has a slightly different energy, longitudinal position, transverse positions and angles with respect to the bunch

- For technical reasons
- But actually, particles are fermions, they must differ a bit

$$(x, y, z, p_x, p_y, p_z)$$

The beam occupies a volume in phase space, this volume is normally preserved ("Liouville's Theorem")

$$\frac{d\rho}{dt} = \frac{\partial \rho}{\partial t} + \sum_{i=1}^{N} \left[\frac{\partial \rho}{\partial q_i} \dot{q}_i + \frac{\partial \rho}{\partial p_i} \dot{p}_i \right] = 0$$

Note: Emittance

For some reason accelerator physicists used angles instead of momenta

$$(x, y, z, p_x, p_y, p_z) \qquad\qquad (x, y, z, x', y', E)$$

This geometric emittance is not preserved when the beam is accelerated

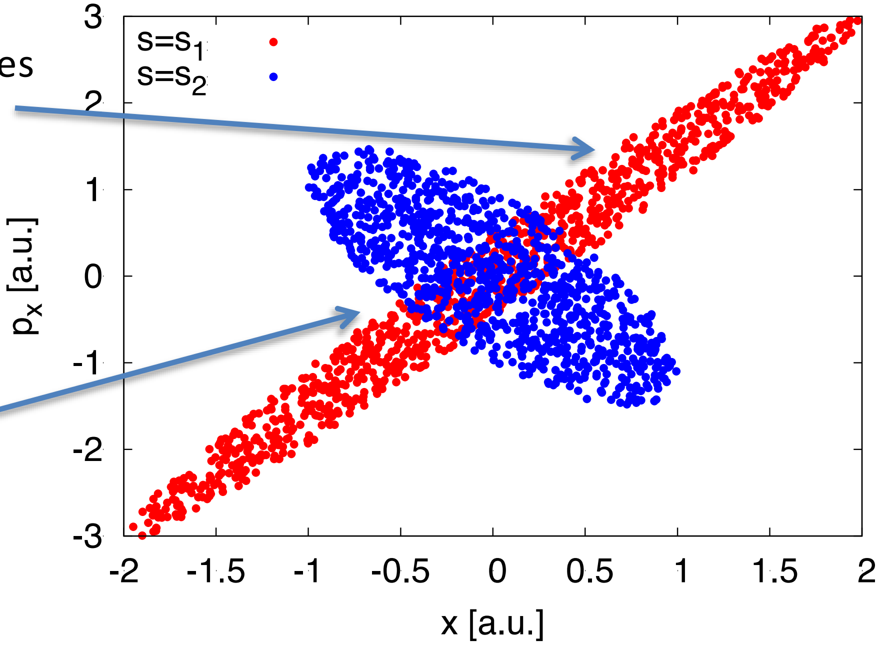
Linac and other reasonable people cure this by multiplying the “geometric emittence” with beta c to obtain the “normalised emittance”

Example

2D emittance (most often the directions are not coupled)

Particle coordinates at one location

Particle coordinates at other location



The emittance ε corresponds to the surface of the beam and does not change

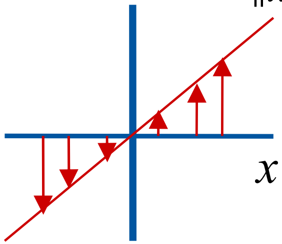
However, the beam size and angular spread change as well as the correlation between position and angle

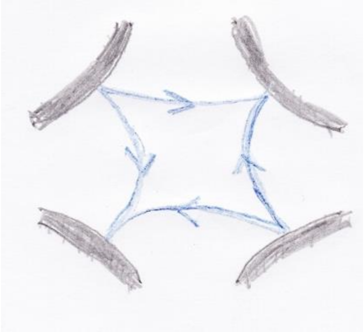
Why correlation?

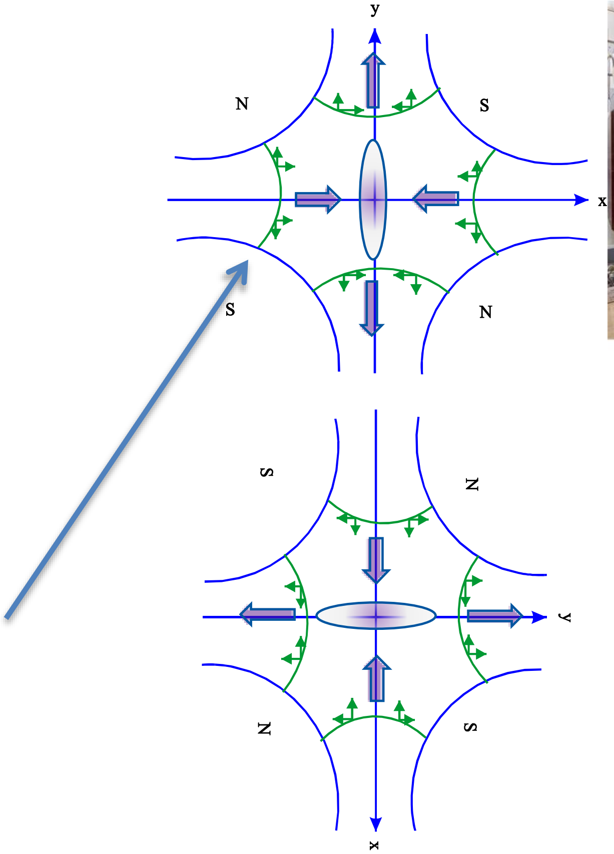
Quadrupole Design

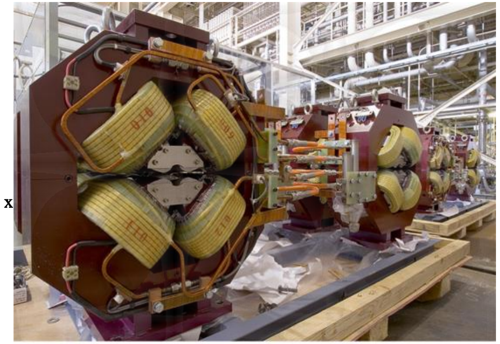
Quadrupoles can focus the beam
The vertical field is proportional to x
⇒ horizontal force is proportional to x

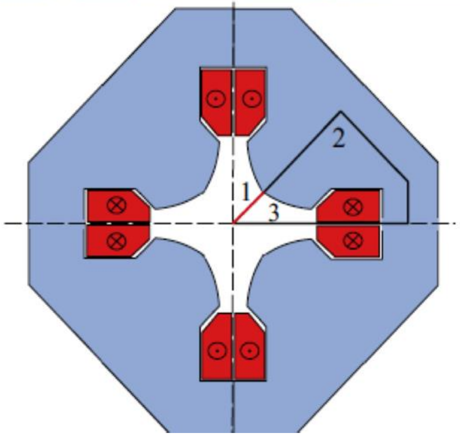
$$B_y = \frac{\partial B_y}{\partial x} x$$





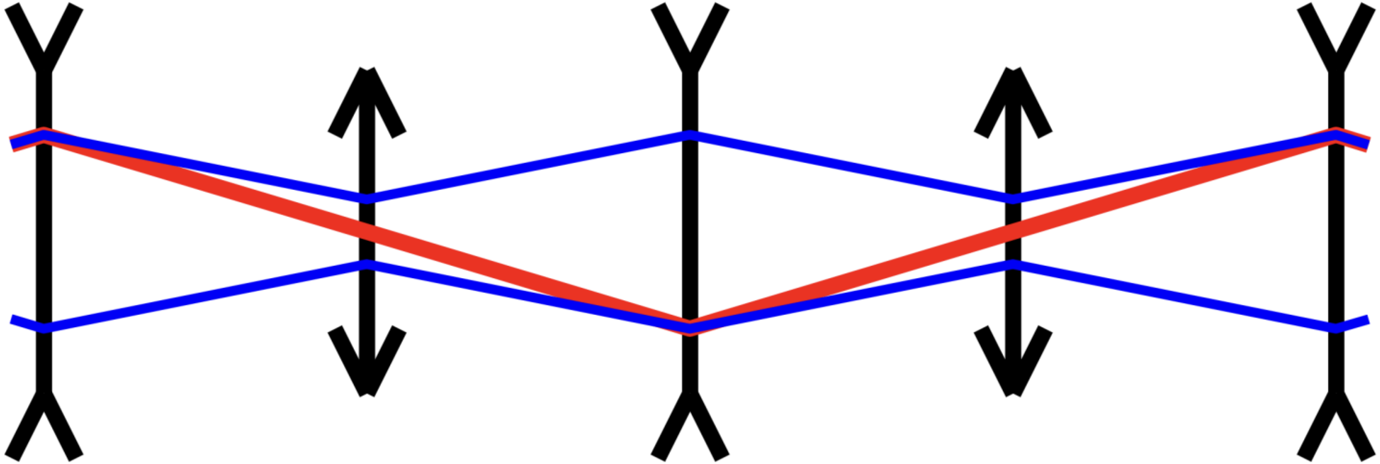






Maximum field in quadrupole depends on product of focal strength and aperture
⇒ LHC can use NbTi
⇒ HL-LHC needs 11 T
⇒ This requires Nb_3Sn (also for FCC-hh)

FODO-lattice



One can alternate the quadrupole orenitations

- One is focusing in our plane, the next defocusing
- Inverted order in the other direction

If quadrupoels are not too far spaced, the beam is overall focused and oscillates

Beta-function

The particles experience a transverse force along the collider

$$x''(s) + K(s)x(s) = 0$$

K varies along the accelerator because the focusing strength (the "spring constant") changes

If K were constant the solution would be

$$x(s) = \sqrt{\epsilon\beta}\cos\left(\frac{s}{\beta} + \phi_0\right)$$

Particle property

$$x'(s) = -\sqrt{\frac{\epsilon}{\beta}}\sin\left(\frac{s}{\beta} + \phi_0\right) \qquad K\beta^2 = 1$$

Lattice property

Beta-function

Because K varies along the accelerator the solution is more complex

$$x(s) = \sqrt{\epsilon\beta(s)}\cos\left(\phi(s)+\phi_0\right)$$

$$x'(s) = \sqrt{\frac{\epsilon}{\beta(s)}}\left[\frac{\beta'}{2}\cos\left(\phi(s)+\phi_0\right) - \sin\left(\phi(s)+\phi_0\right)\right]$$

Correlation between x and x'

$$\phi(s) = \int_0^s \frac{1}{\beta(s')}ds'$$

$$\frac{\beta''\beta}{2} - \frac{\beta'^2}{4} + K\beta^2 = 1$$

Beam Size

Lattice property

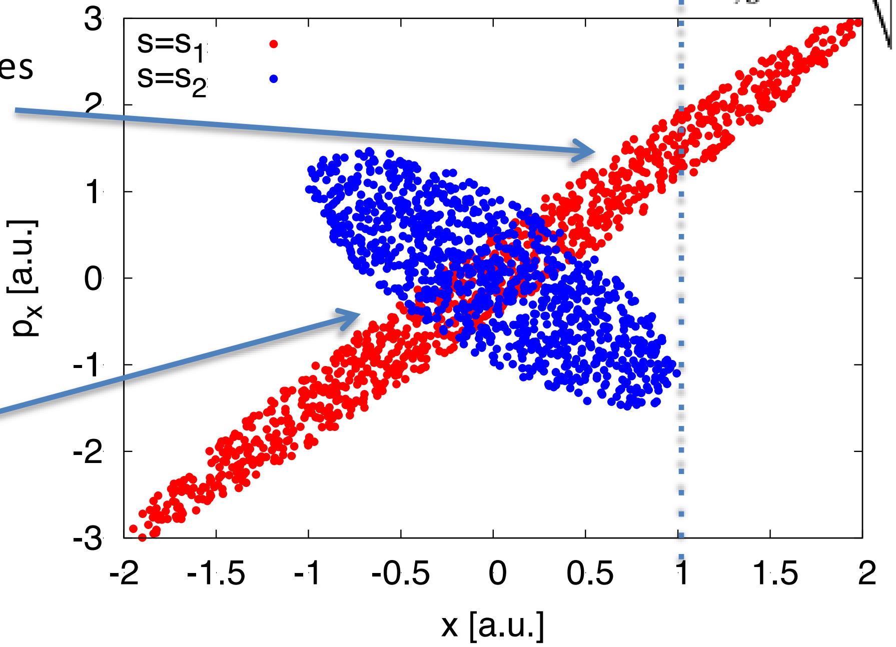
Beam property

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

Particle coordinates at one location

Area ε does not change

Particle coordinates at other location



Luminosity

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

It depends on the geometrical overlap of the colliding beams

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

Bunch charge ($N^2=N_1N_2$)

Number of bunches times circulation frequency = collisions per second

Horizontal rms beam size (Gaussian beam)

Vertical rms beam size (Gaussian beam)

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:

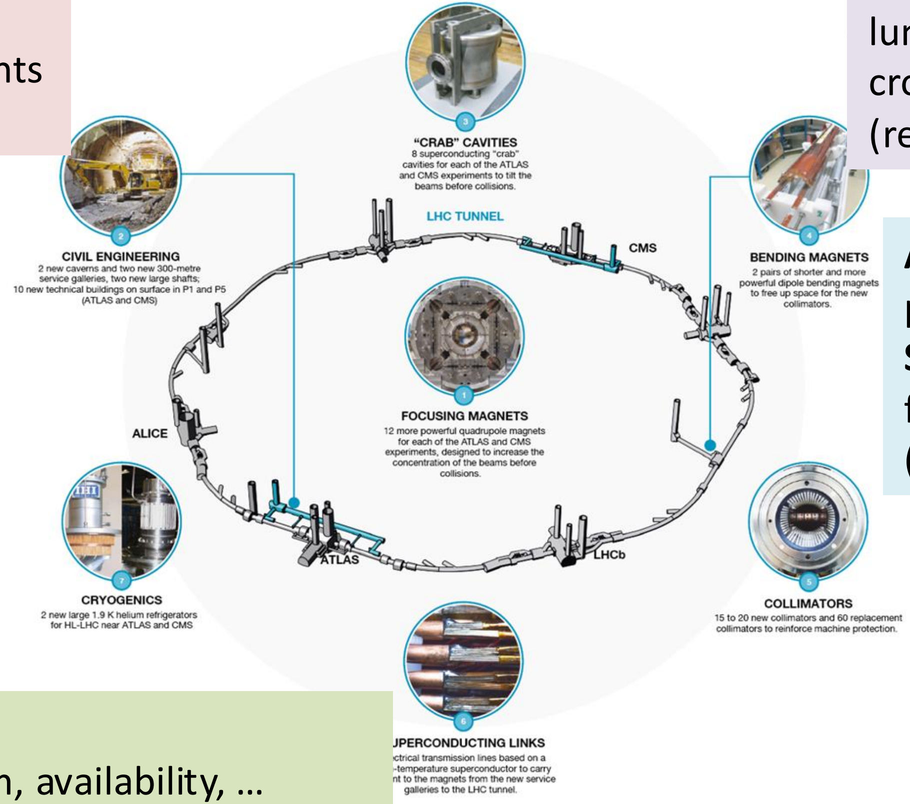
- Fast turn-around critical for luminosity
- Minimise time for stops etc.
- High availability with more components than LHC
- Maximising current also maximises time between new fills

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, …

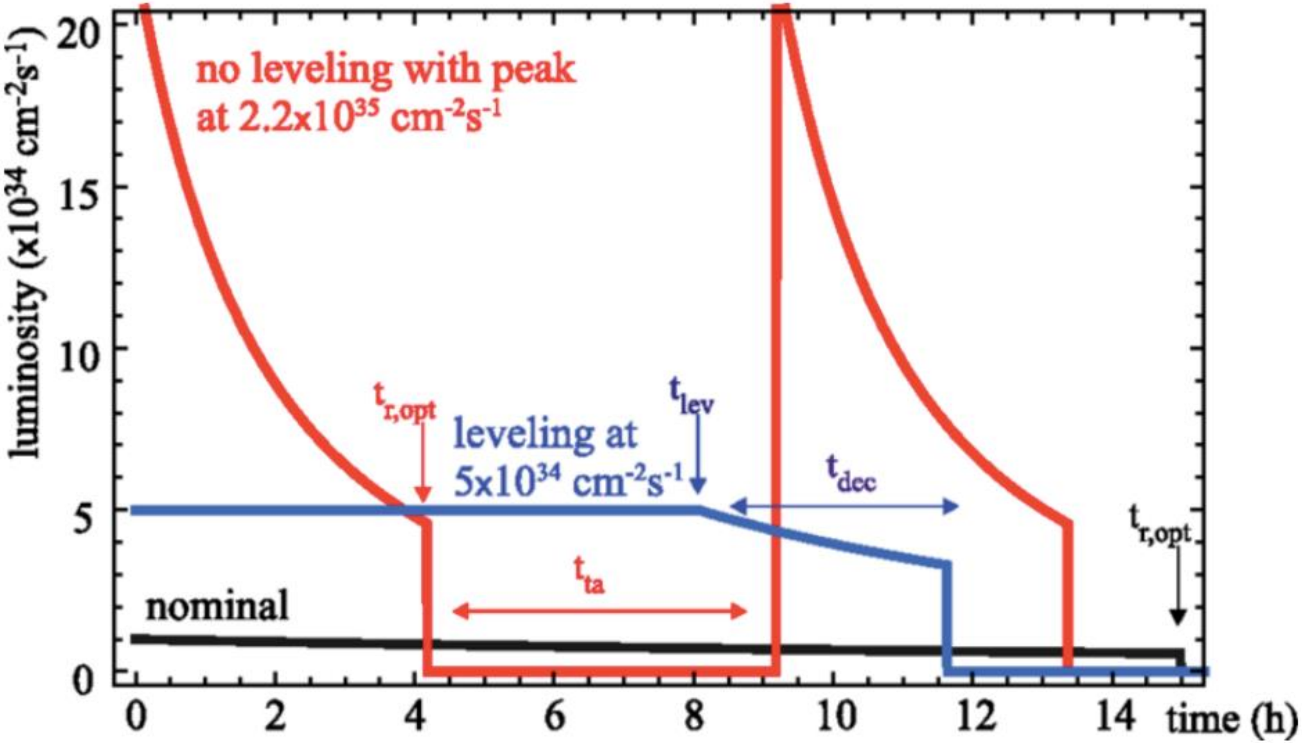
HL-LHC Luminosity Run

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



Beam Burn-off

Proton-proton cross section is O(100 mb)

- Many events per bunch crossing
- Not very interesting (we assume…) but annoying

Power in burn-off O(10kW) in LHC and O(500 kW) in FCC-hh

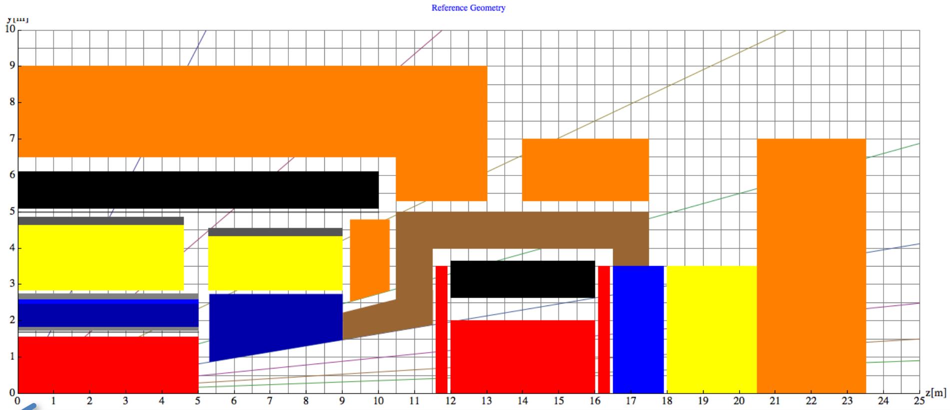
	LHC	HL-LHC	FCC-hh Initial	FCC-hh Final	SppC	SppC ultimate
Cms energy [TeV]	14	14	96	96	75	150
Luminosity [$10^{34}cm^{-2}s^{-1}$]	1	5	5	30	10	?
Machine circumference	27	27	91	91	100	100
Arc dipole field [T]	8	8	16	16	12	24
Bunch distance [ns]	25	25	25	25	25	?
Background events/bx	27	135	170	1020	490	?
Bunch length [cm]	7.5	7.5	8	8	7.55	?

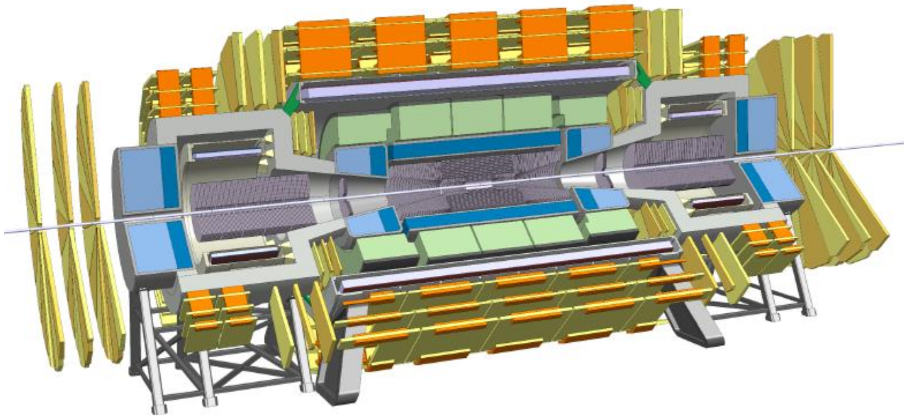
Detector and Machine

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

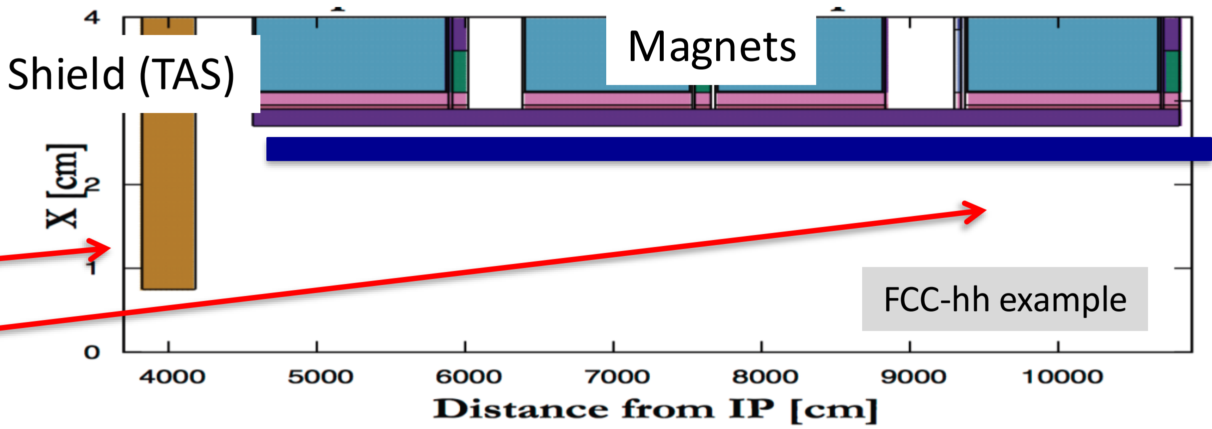
FCC-hh example

Radiation from Beam-beam

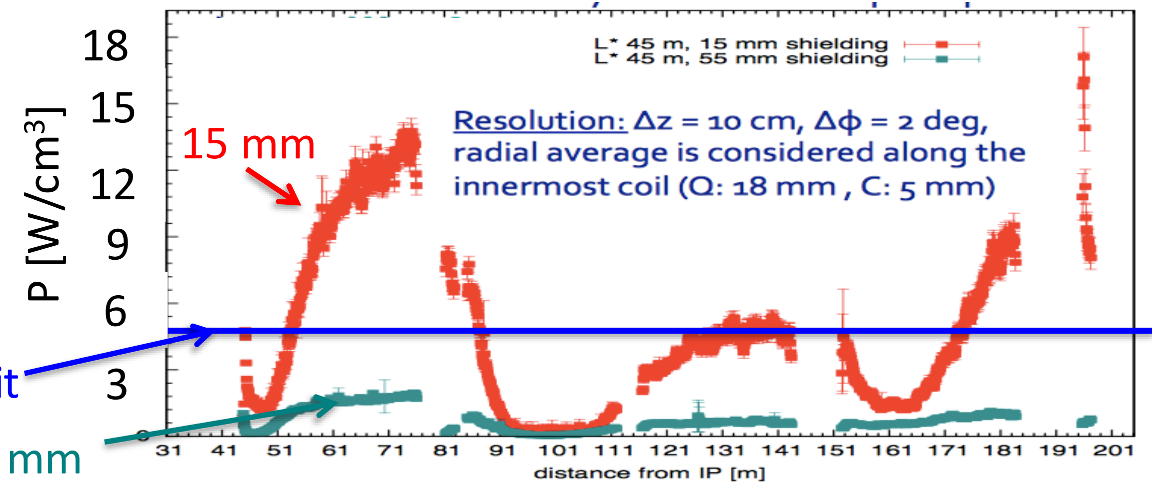
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Total collision debris per experiment

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



FCC-hh example shown

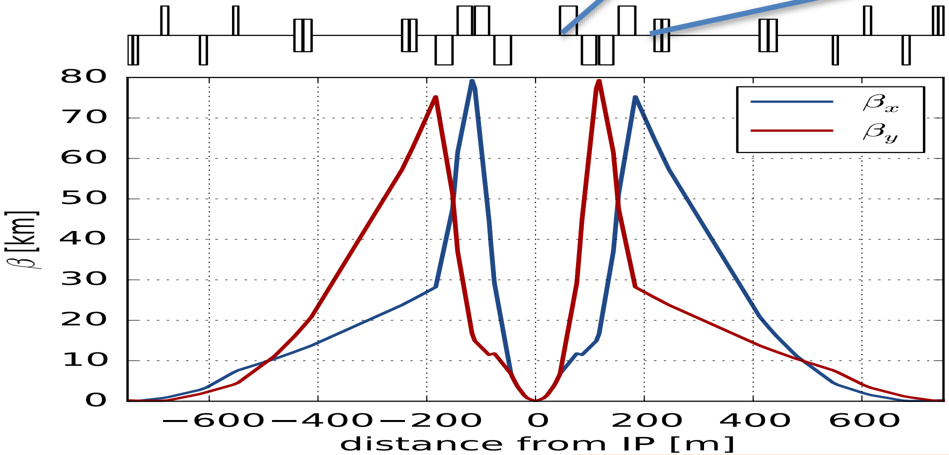


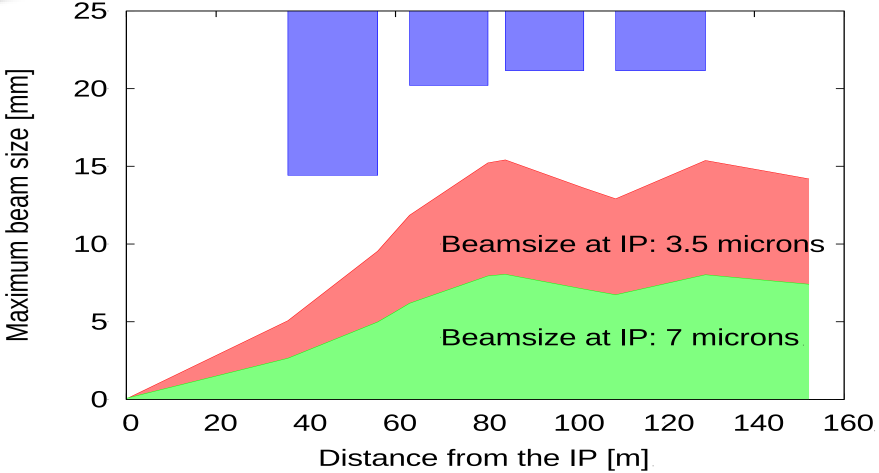
Interaction Region and Final Focus Design

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

Beam size is limited by aperture in the magnets

FCC-hh example





Smaller beta-function requires larger aperture

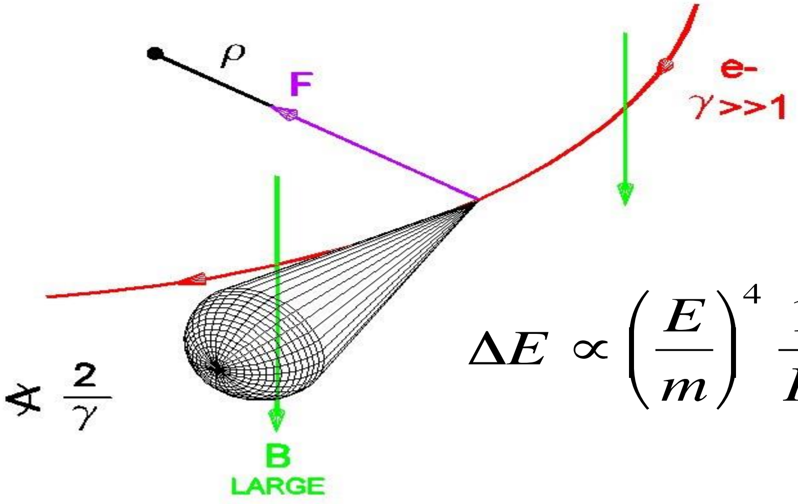
Synchrotron Radiation

Use FCC-hh CDR parameters

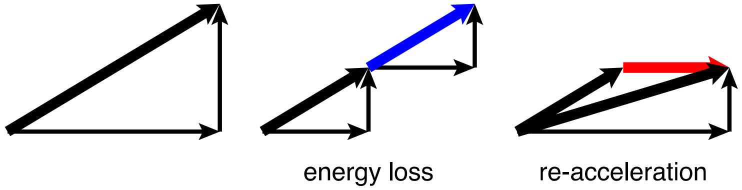
At 100 TeV even protons radiate significantly

Total power of 5 MW
$\Rightarrow$ Needs to be cooled away

Equivalent to 30W/m /beam in the arcs

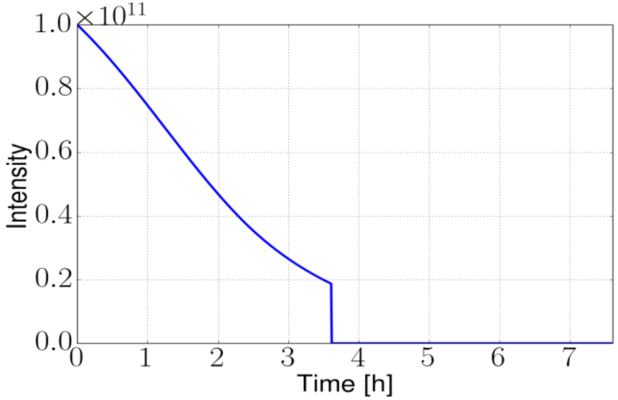


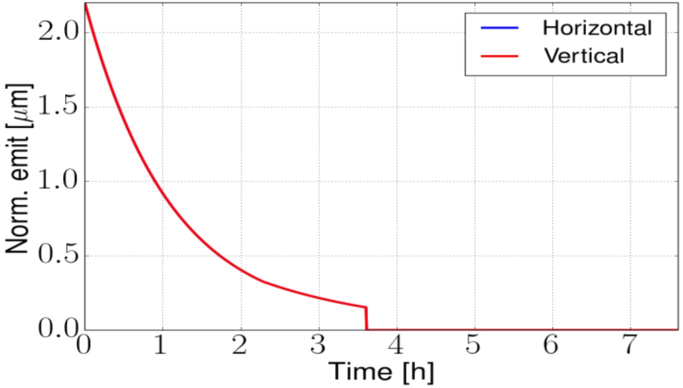
$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$



Protons loose energy
$\Rightarrow$ They are damped
$\Rightarrow$ Emittance improves with time
- Typical damping time 1 hour

Luminosity Evolution





Example with ultimate parameters shown

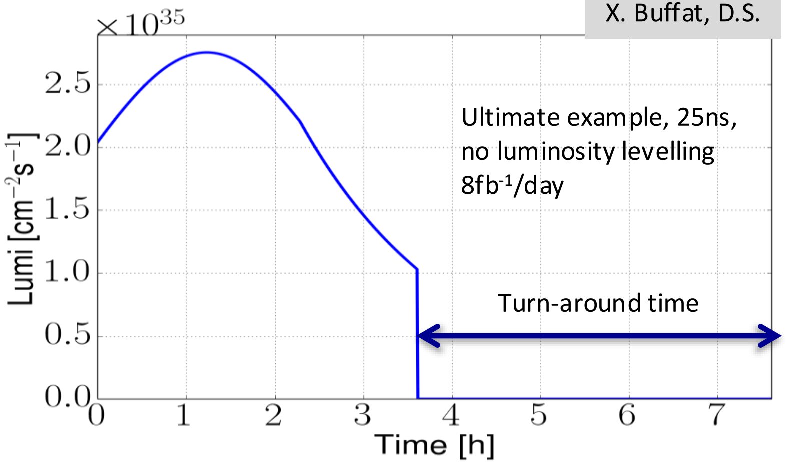
Burn beam quickly

But emittance shrinks

$\Rightarrow$ Can reach 8fb^{-1}/day

$\Rightarrow$ 5000fb^{-1} per 5 year cycle

X. Buffat, D.S.



Cooling

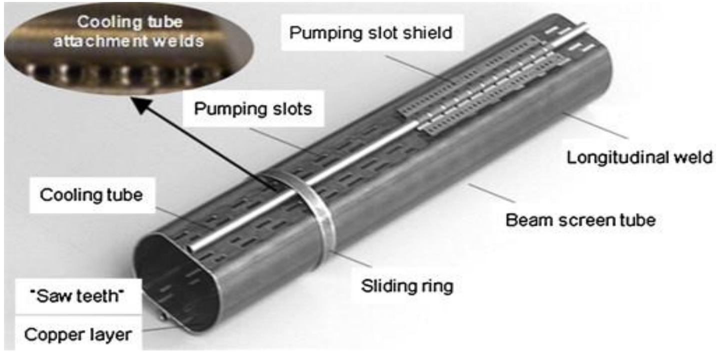
To cool 5 MW at 2 K requires about 6 GW electrical power

Rule of thumb
Carnot inefficiency and O(25%) technical efficiency

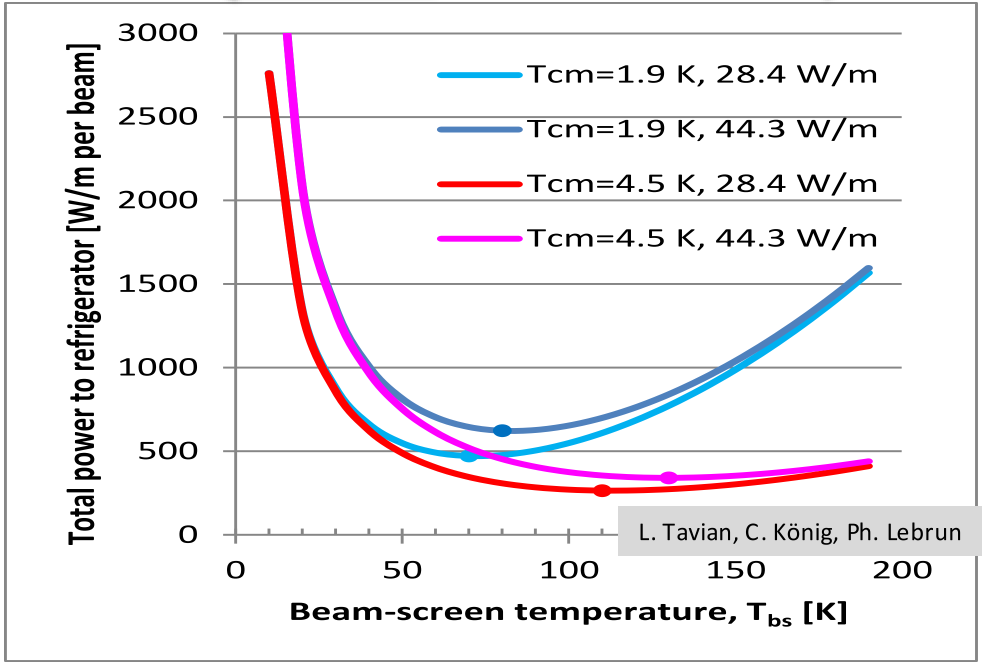
About a factor three better at 4 K (from 4 to 2 K is hard)

Solution is a beam screen at higher temperature that captures the radiation

LHC beamscreen (16 K)



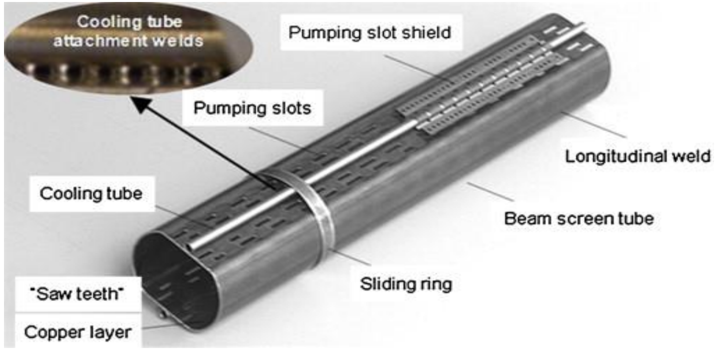
Less efficiency | More heat from screen into magnet



16K beamscreen would require 300MW for cooling

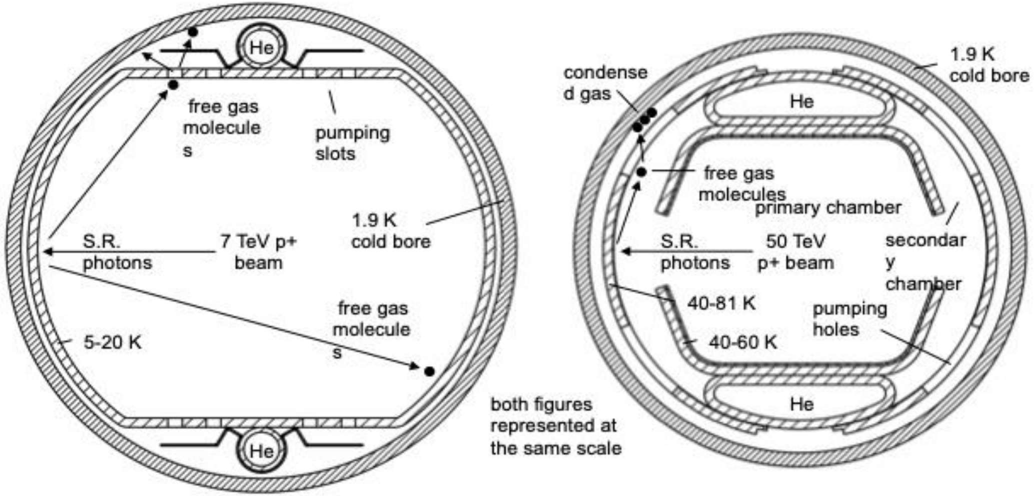
50K requires 100MW => current baseline

Beamscreen Design



LHC beamscreen

FCC-hh beamscreen



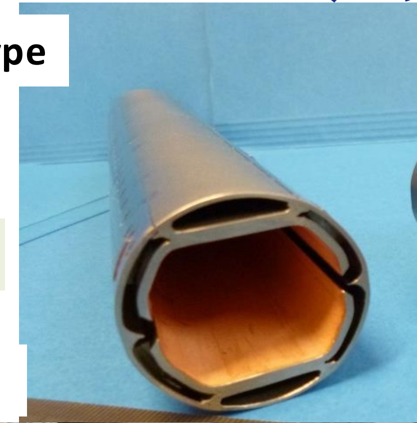
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

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

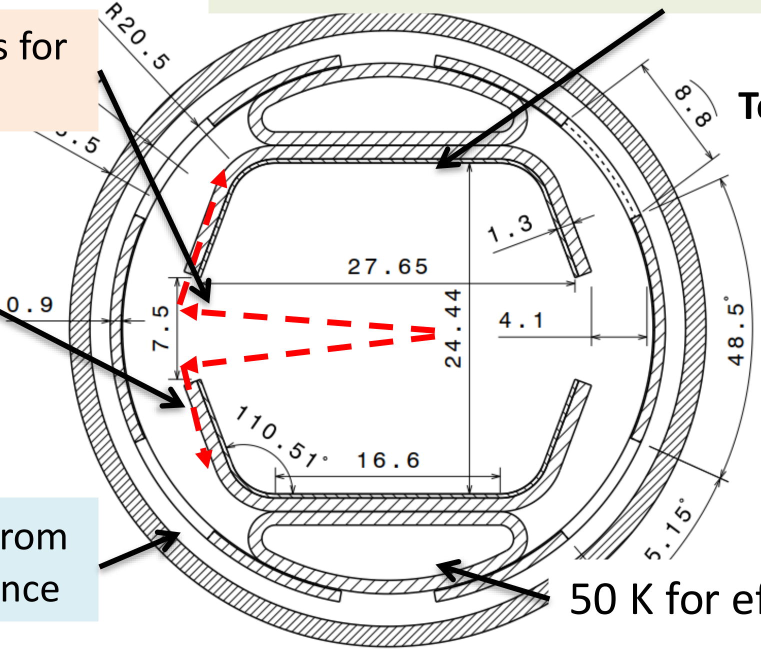


Laser treatment / carbon coating against ecloud

Extract photons for great vacuum

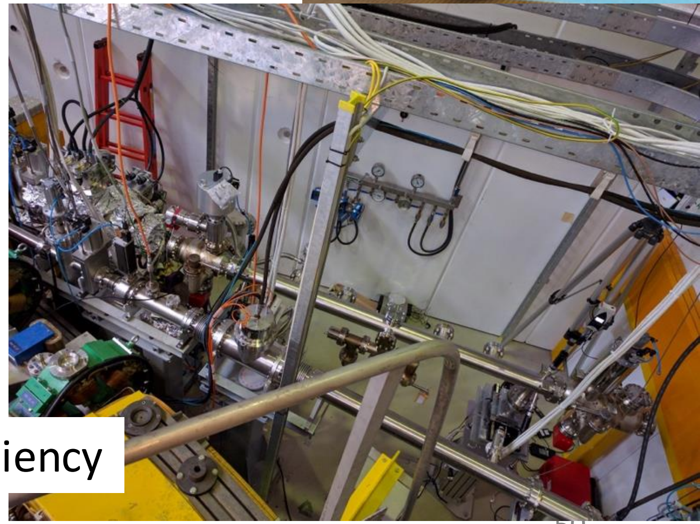
Strong to withstand quench

Hide pumping holes from beam for low impedance



50 K for efficiency

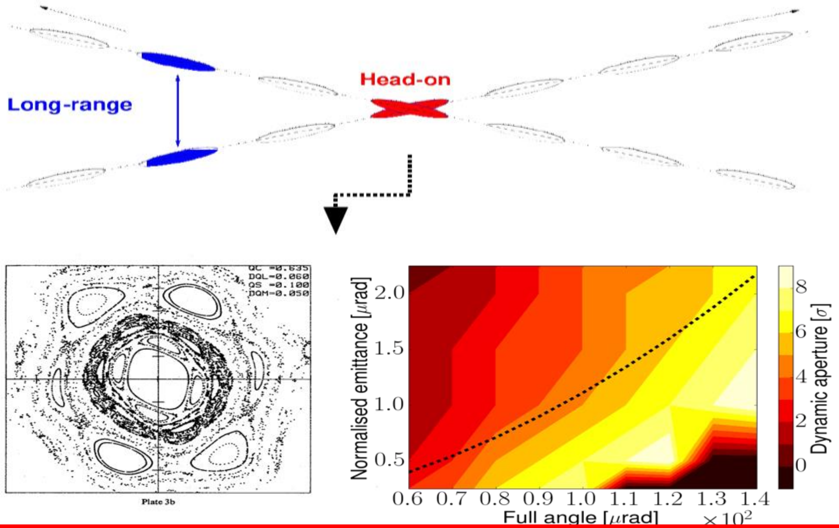
Test station in ANKA



Beam Physics Limitations

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

Beam-beam studies ongoing, promising results



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

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
- …

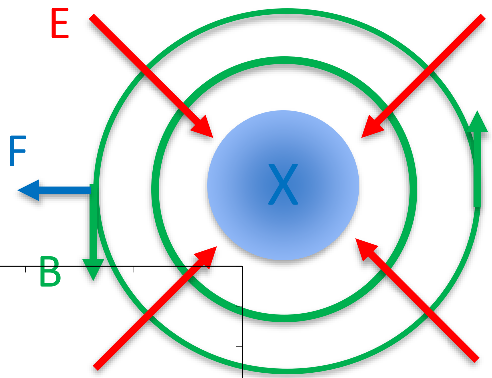
Beam-Beam Force

Beams produce electric and magnetic fields around them

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

For particles travelling in the same direction the two forces almost cancel

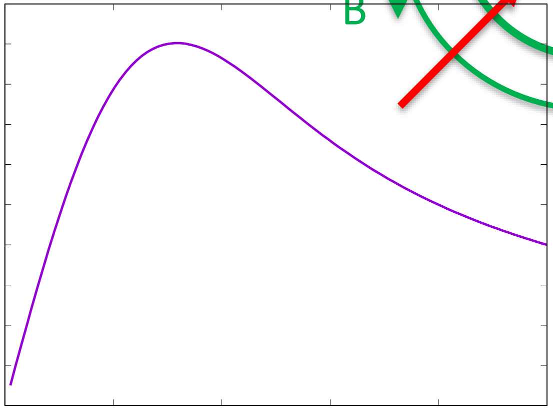
- In the frame of the bunch, it is very long (Lorentz transformation)
- Magnetic fields are the relativistic correction of electric fields



For particles travelling in the opposite direction the two forces add up

- For the same charge in both beams the force is deflecting
- For the opposite charge it is attractive

$$\frac{d^2 r}{dz^2} = \frac{1}{\gamma m}\frac{2e}{2\pi\epsilon_0 c^2 r}\int_0^r f(z)\frac{-Ne}{2\pi\sigma_r^2}\exp\left(-\frac{r'^2}{2\sigma_r}\right)2\pi r' dr'$$
$$= \frac{-4Nr_e}{\gamma r}\left(1-\exp\left(-\frac{r^2}{2\sigma_r^2}\right)\right)f(z)$$

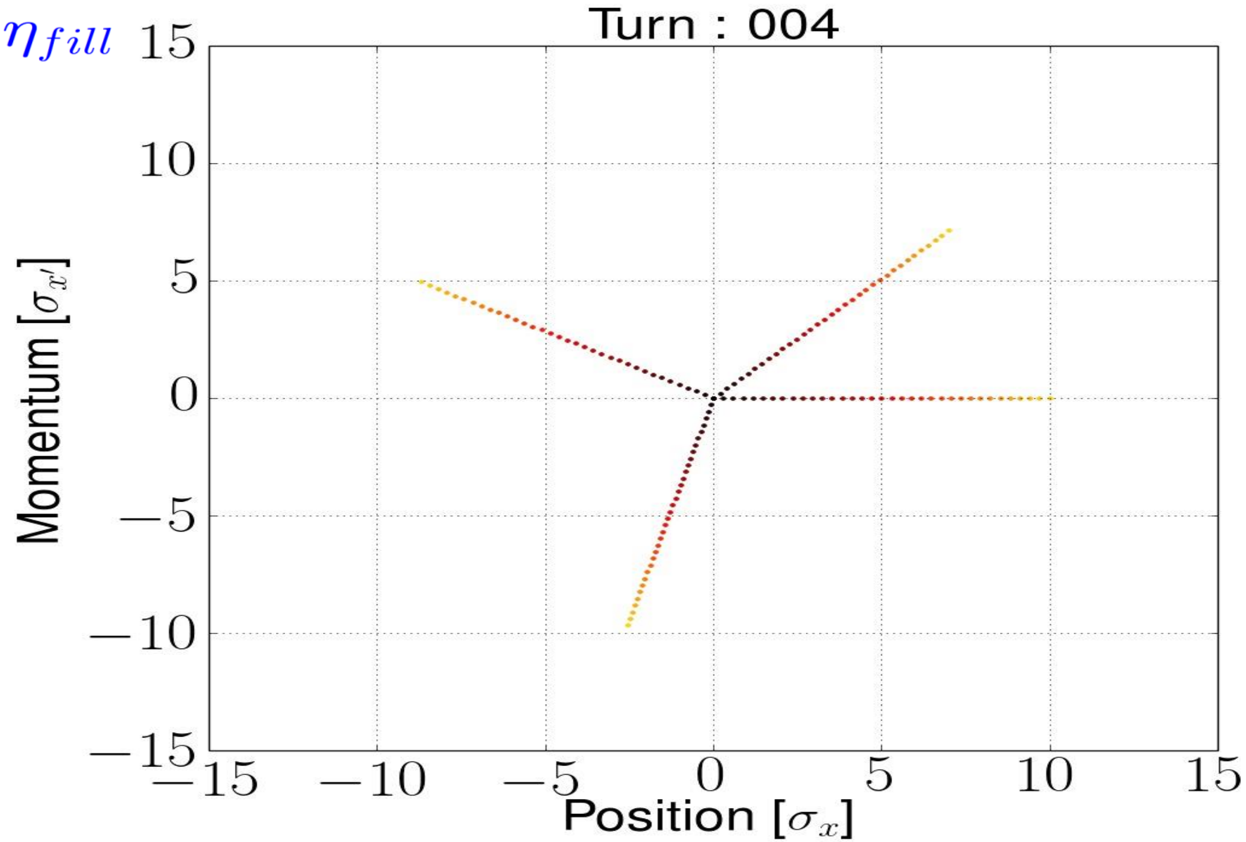


σ

Beam-beam Effects

X. Buffat

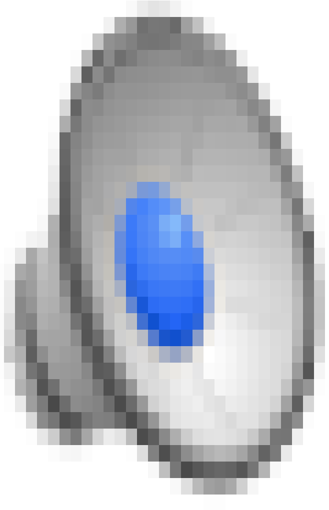
$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$



Beam-beam Effects

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

X. Buffat



Beam-beam Effects

X. Buffat

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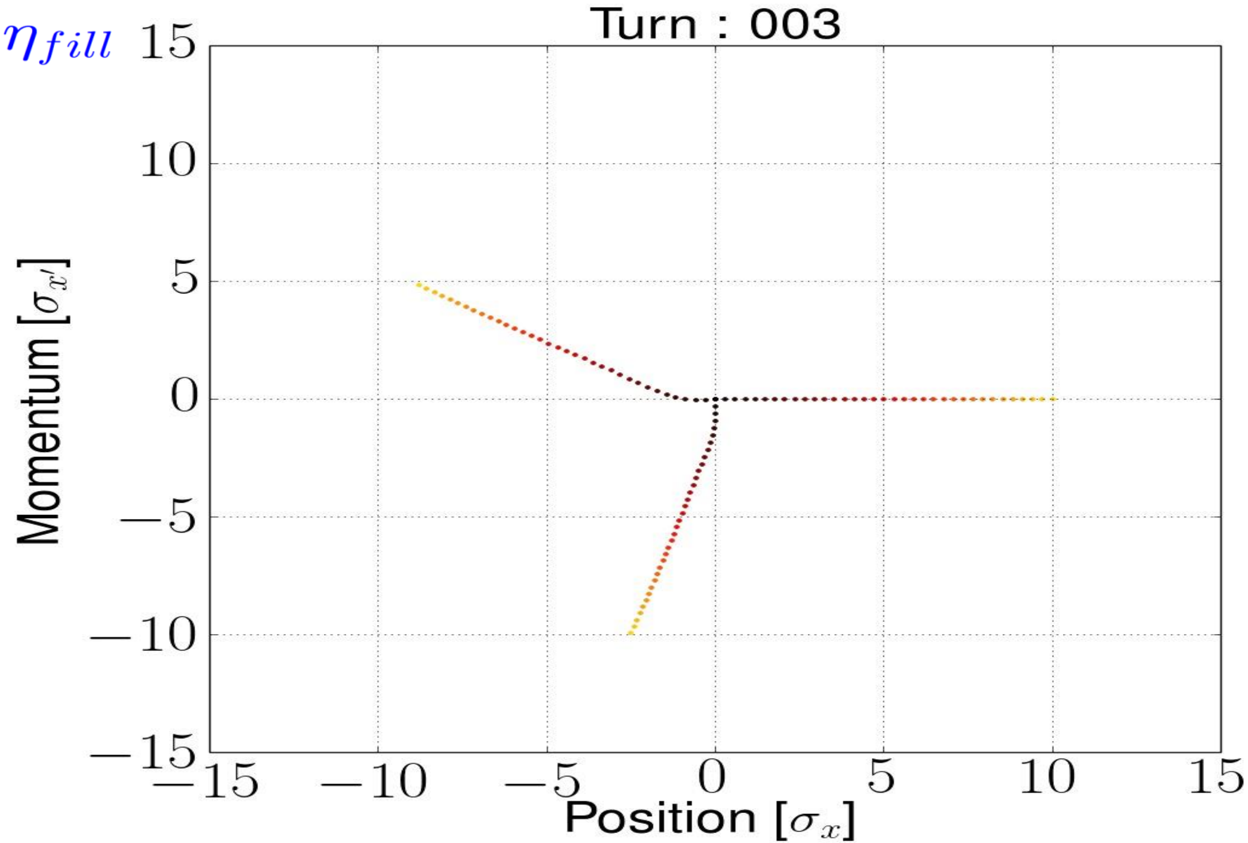
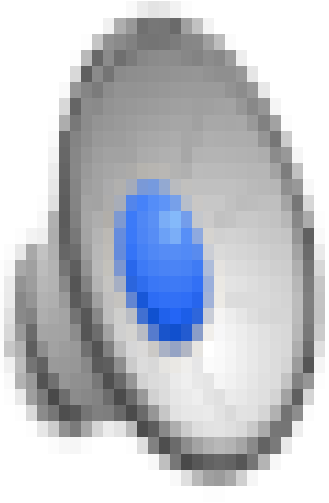


Beam-beam Effects

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

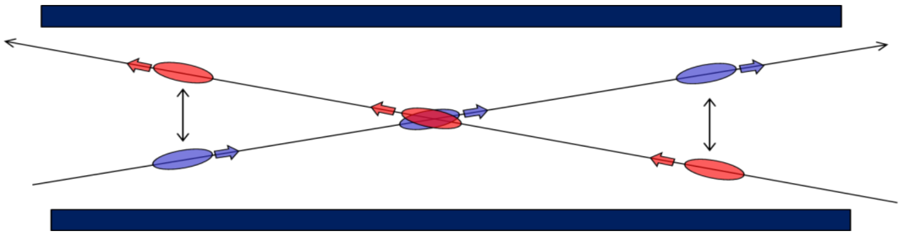
X. Buffat



Crossing angle and Crab Cavities

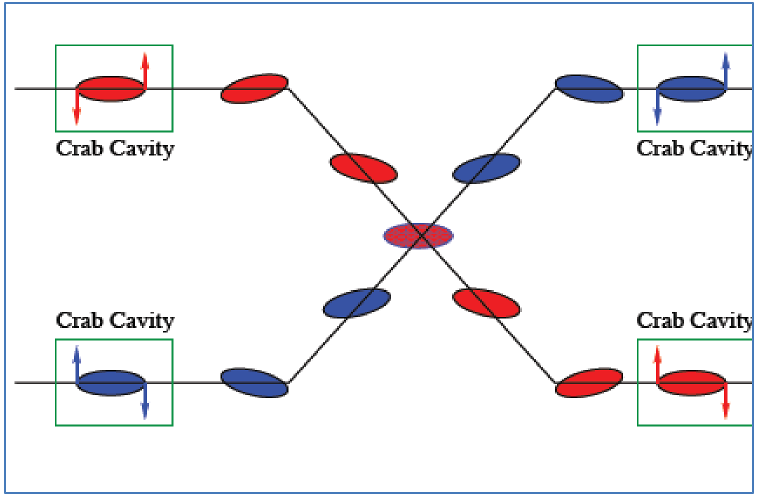
Larger crossing angle reduces impact of parasitic crossings

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



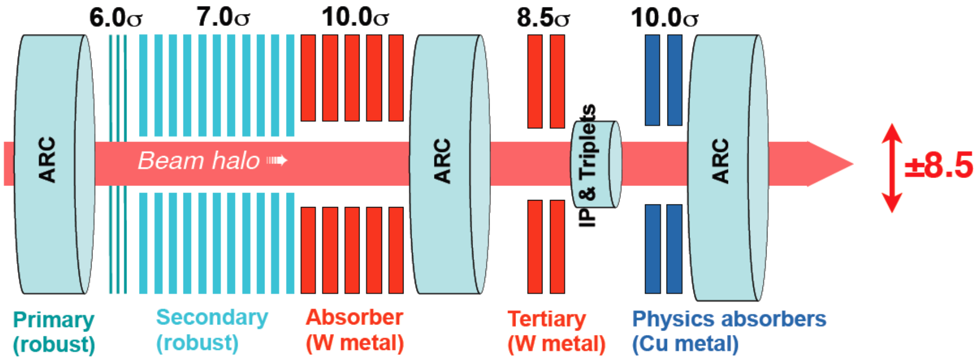
Collimation System

At collision, the final triplets at experiments are the bottleneck

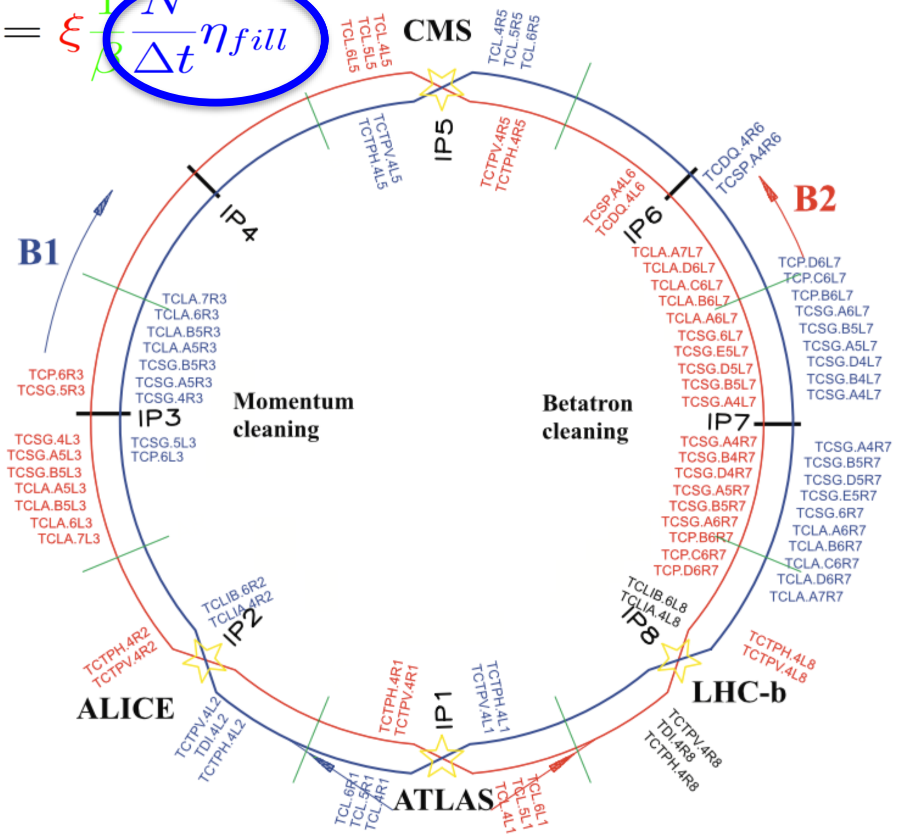
$\Rightarrow$ particles that drift into the tails get lost here

$\Rightarrow$ 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

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

Primary collimators intercept protons

Secondary collimators and absorbers intercept showers

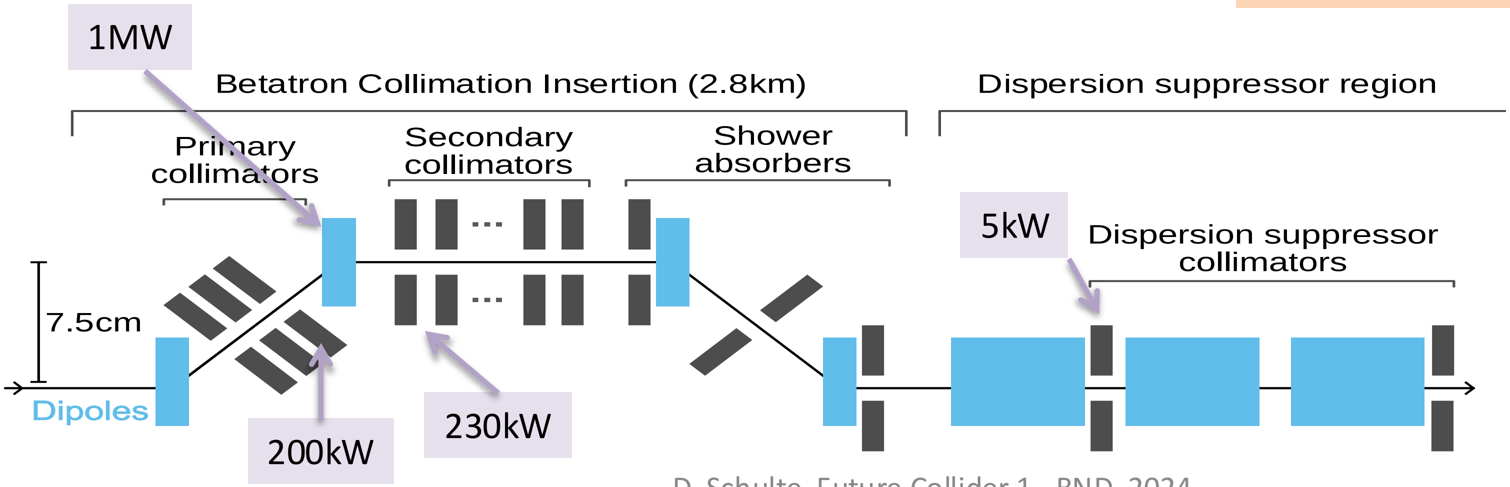
Some protons only lose energy and make it to next arc, where they are lost

Protect arcs with additional collimators

- No space in LHC

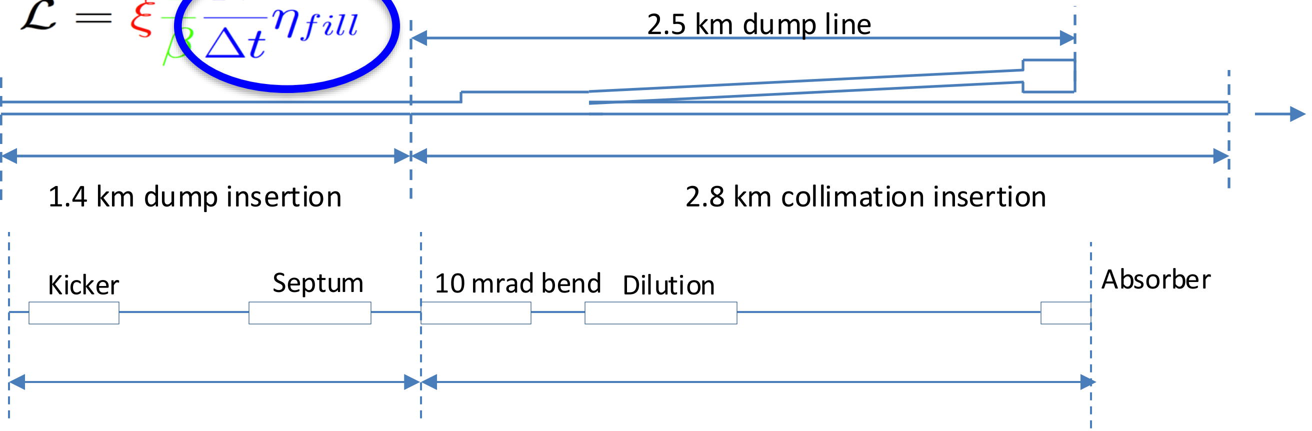
$\Rightarrow$ replace some 8 T dipoles with shorter 11 T ones

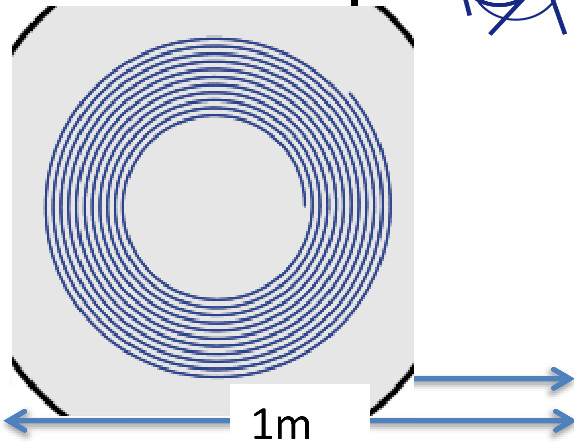
- Foreseen in FCC-hh



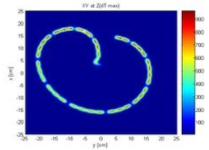
Intensity Limitation: Beam Energy and Dump

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





LHC pattern
(same scale)



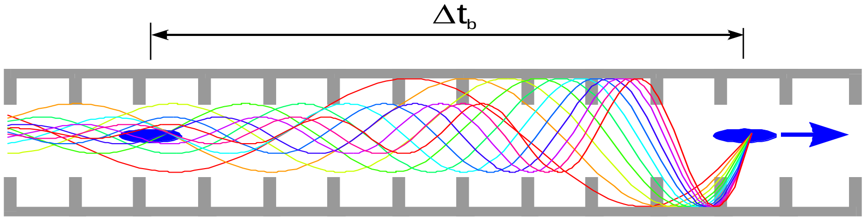
In LHC / HL-LHC 400 to 800 MJ per beam

In FCC-hh 8 GJ kinetic energy per beam

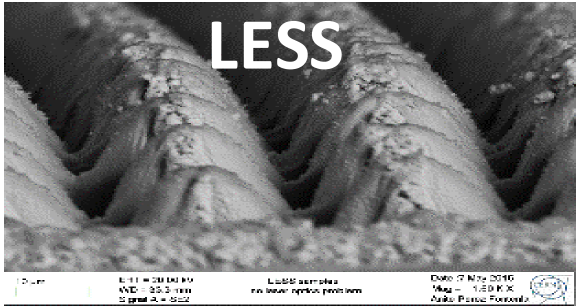
- Airbus A380 at 720 km/h
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC
- Can drill 300 m long hole in copper

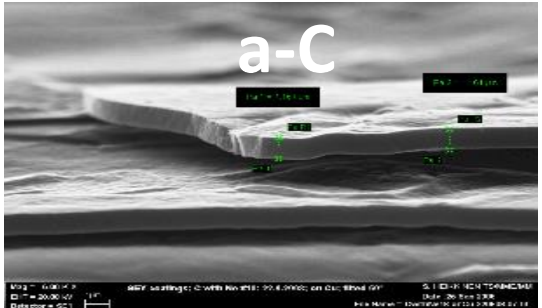
Other Intensity Limitation Examples

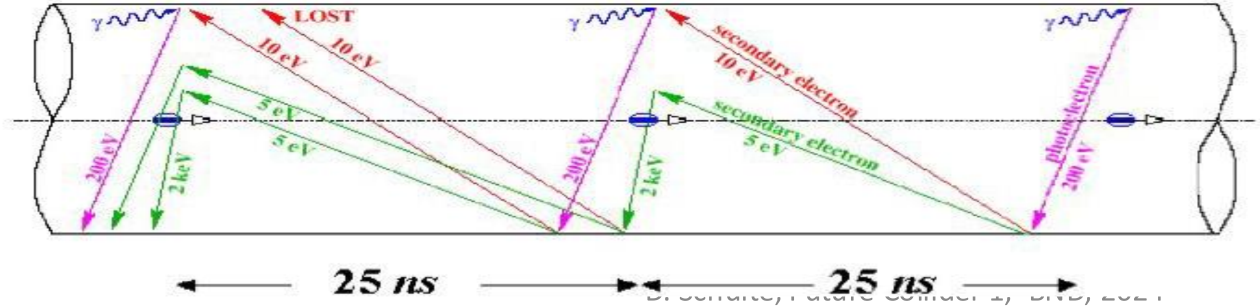
Impedance
Beam produces parasitic electromagnetic fields in collimators, beam screen etc that can kick beam and induce instability



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







Reserve

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

LHC

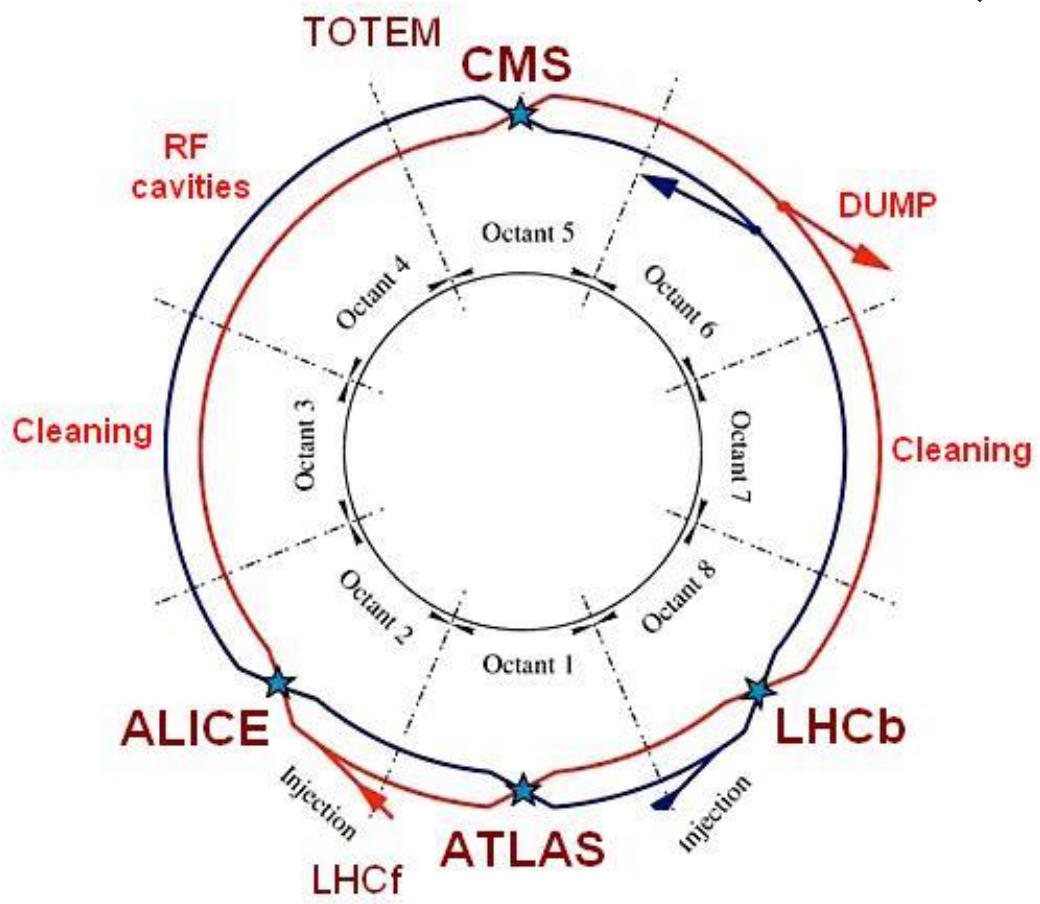
I guess, everybody is familiar

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

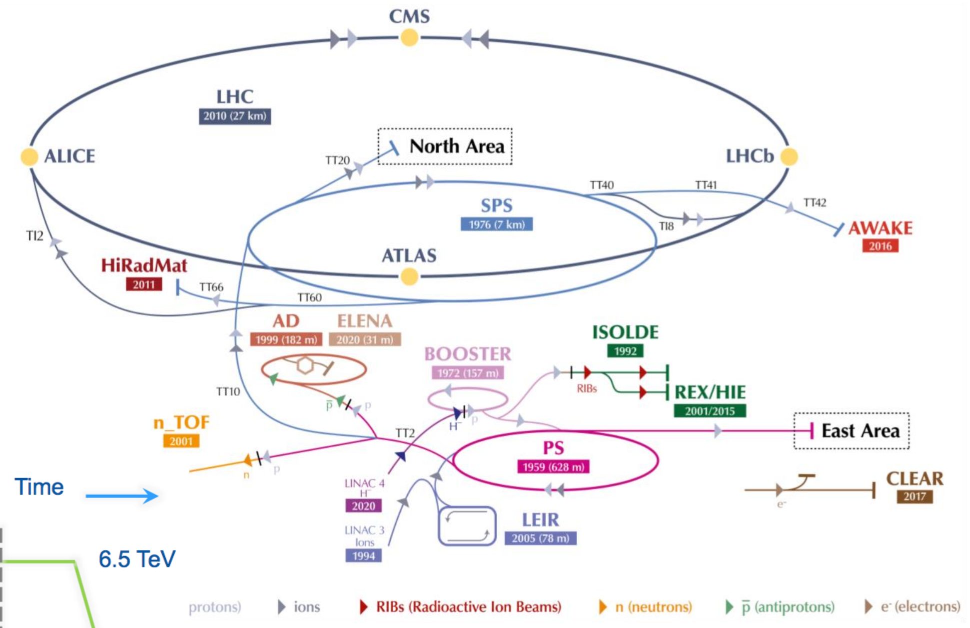
Machine is producing physics since 2010

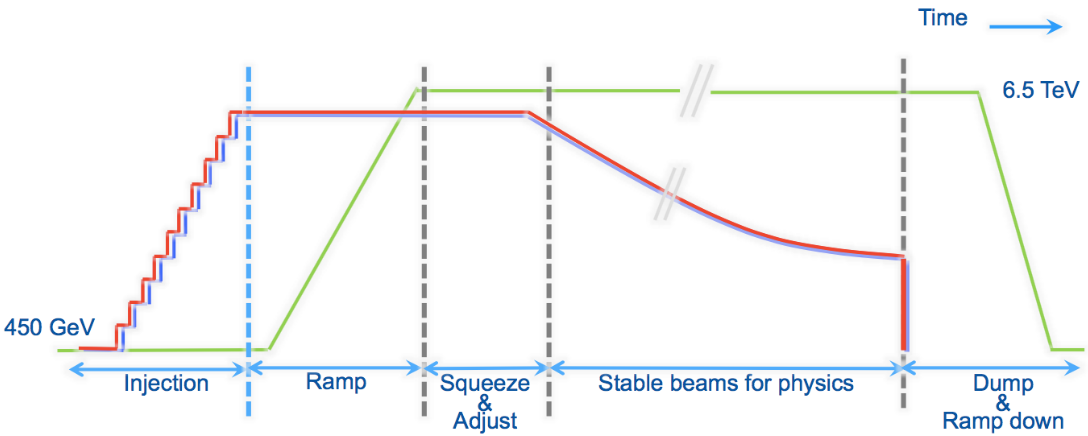


LHC Injection Complex

The LHC obtains its beam from a chain of injectors

Typically few hours to fill and several hours of luminosity

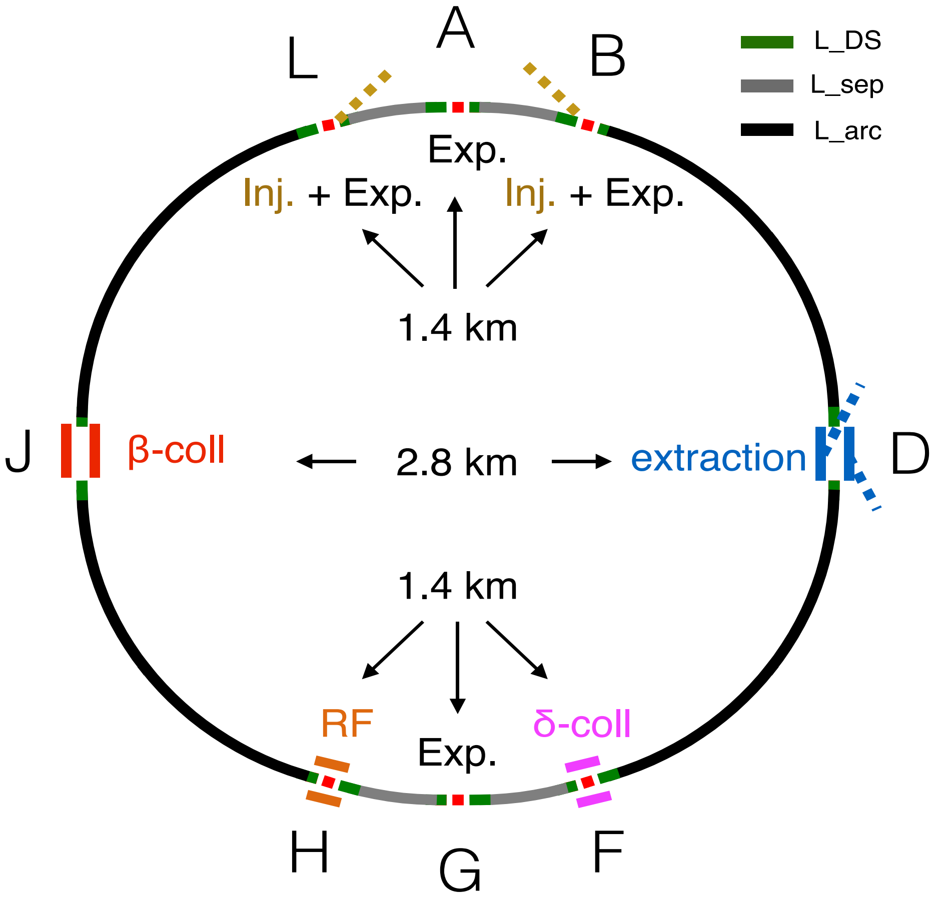




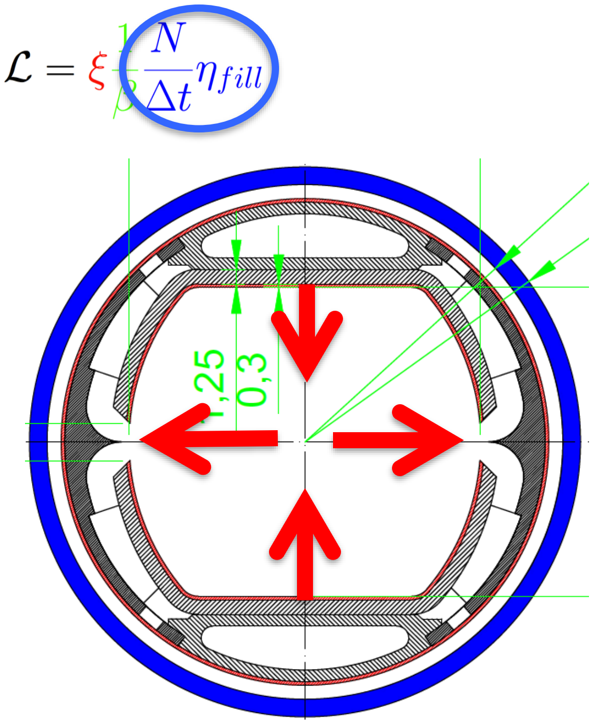
Previous FCC-hh Layout

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



FCC Beam Screen Mechanical Design



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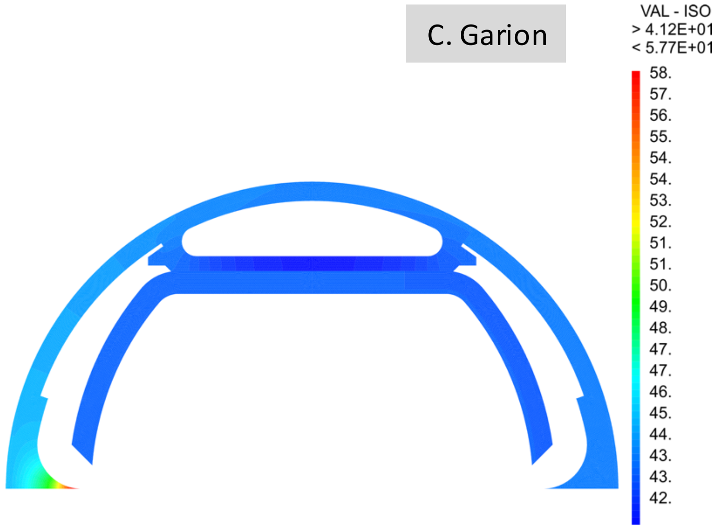


Beam screen remains relatively cool

Stress is acceptable from heat

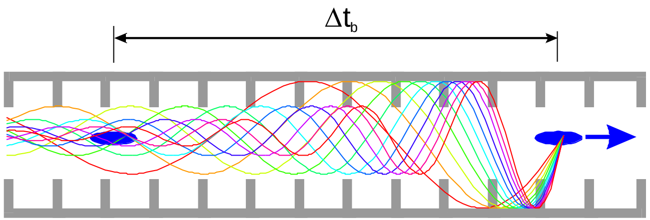
Worry about sheer stress in quench

- attachment copper steel

Low Frequency Impedances

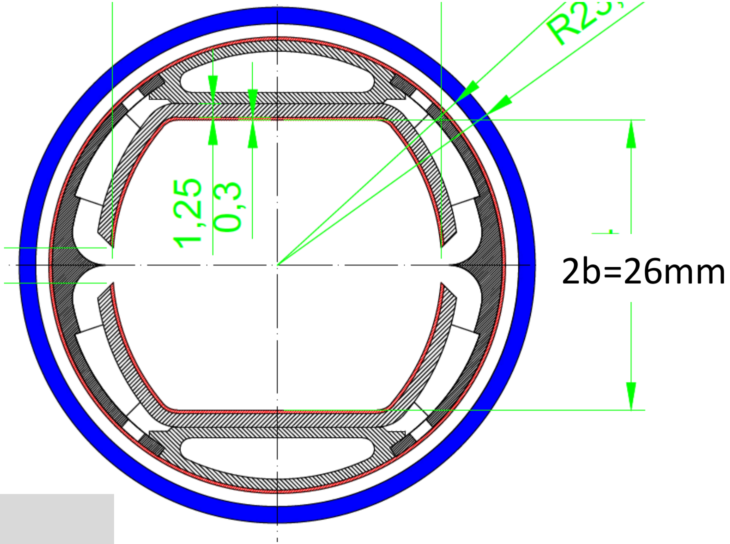
At injection multi-bunch instability is driven by resistivity of arc beam screen

Resistivity increases with temperature



Minimium radius is defined by strong dependence of impedance

$$Z_\perp \propto \frac{\sqrt{r}}{b^3}$$



⇒ Multi-bunch instability O(10) worse than in LHC

⇒ Assumes fast feedback

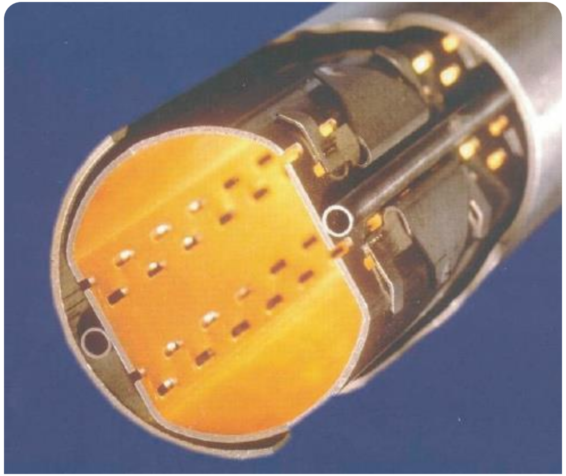
N. Mounet, G. Rumolo, O. Boine-Frankeheim, U. Niedermayer, F. Petrov, B. Salvant, X. Buffat, E. Metral, D.S.

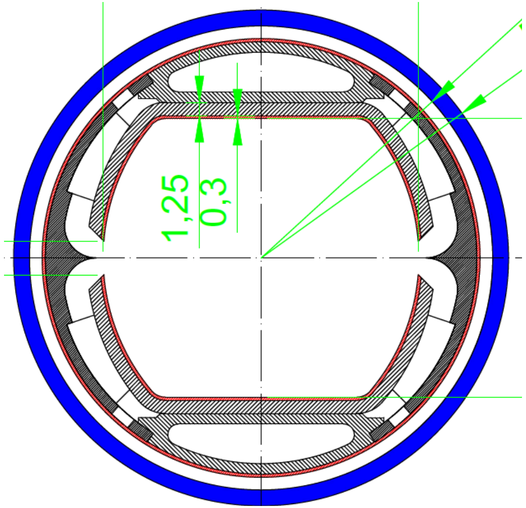
High Frequency Impedance

In LHC pumping holes are important contribution to high frequency impedance at injection

Pumping holes in LHC-like design would lead to instability (TMCI) at $1.5\text{x}10^{11}$

$\Rightarrow$ Way to little margin for charge of $1\text{x}10^{11}$





In FCC holes are shielded

$\Rightarrow$ Removes impedance

$\Rightarrow$ Other sources need to be studied (e.g. collimation system, …)

X. Buffat, O. Boine-Frankeheim, U. Niedermayer, F. Petrov, B. Salvant, D.S.

Conductor

New activity with many collaborators started in 2017 with ambitious targets

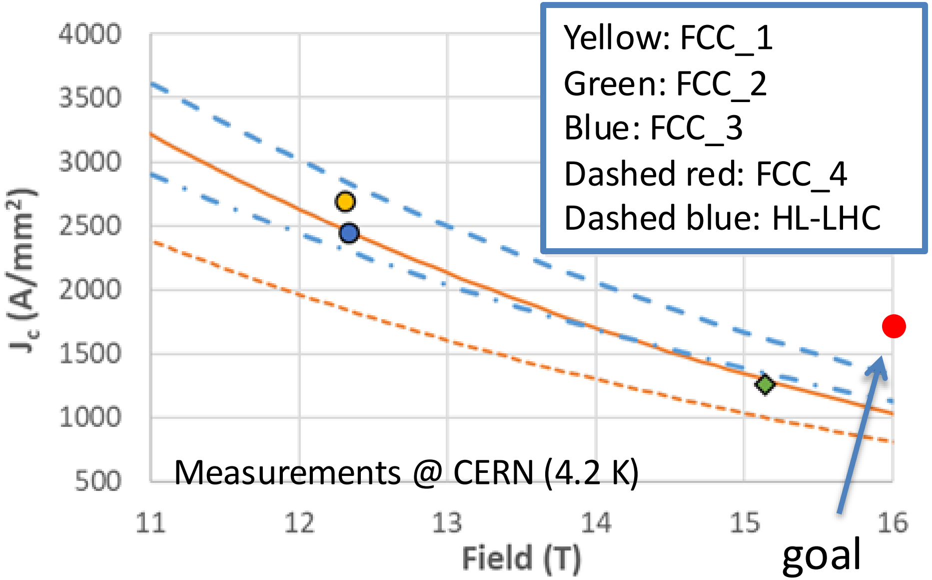
Wire diameter	mm	~ 1
Non-Cu Jc (16 T, 4.2 K)*	A/mm^2	≥ 1500
Unit length	km	≥ 5
Cost	€/kA m**	≤ 5

FCC Conductor Development Workshop at CERN, 5-6 March 2018

Participants

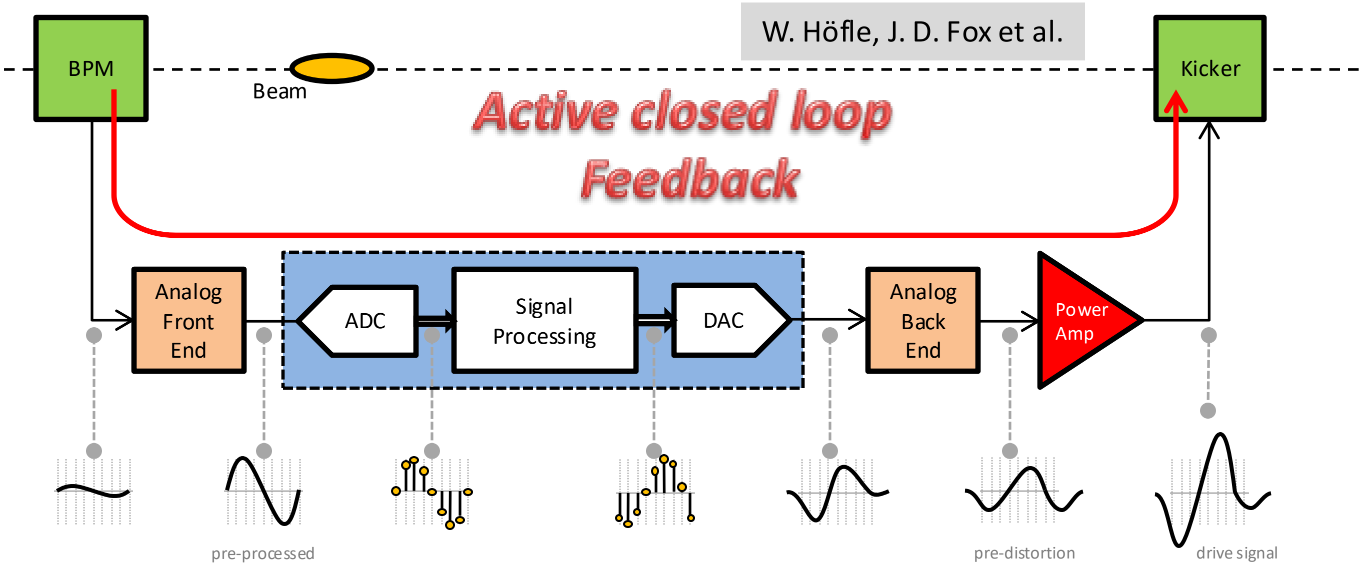
Switzerland: CERN
Japan: KEK, Furukawa Electric, JASTEC
Russia: Bochvar Institute of Inorganic Materials JSC VNIINM, TVEL
Korea: Kiswire
China: Western Superconducting Technologies Co., Ltd.
Austria: TU Wien
Germany: Technische Universität Bergakademie Freiberg
Italy: Columbus Superconductors
Finland/USA: Luvata Special Products
Italy: SPIN
Switzerland: Université de Genève

7 companies, two universities and two national research institutes



First wires almost reached HL-LHC requirements

Feedback



Higher bandwidth than in LHC (5ns bunch spacing)

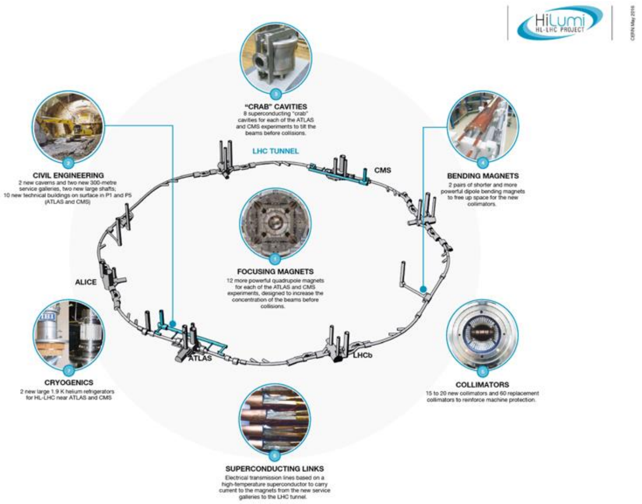
Faster feedback allows to rise beam screen temperature

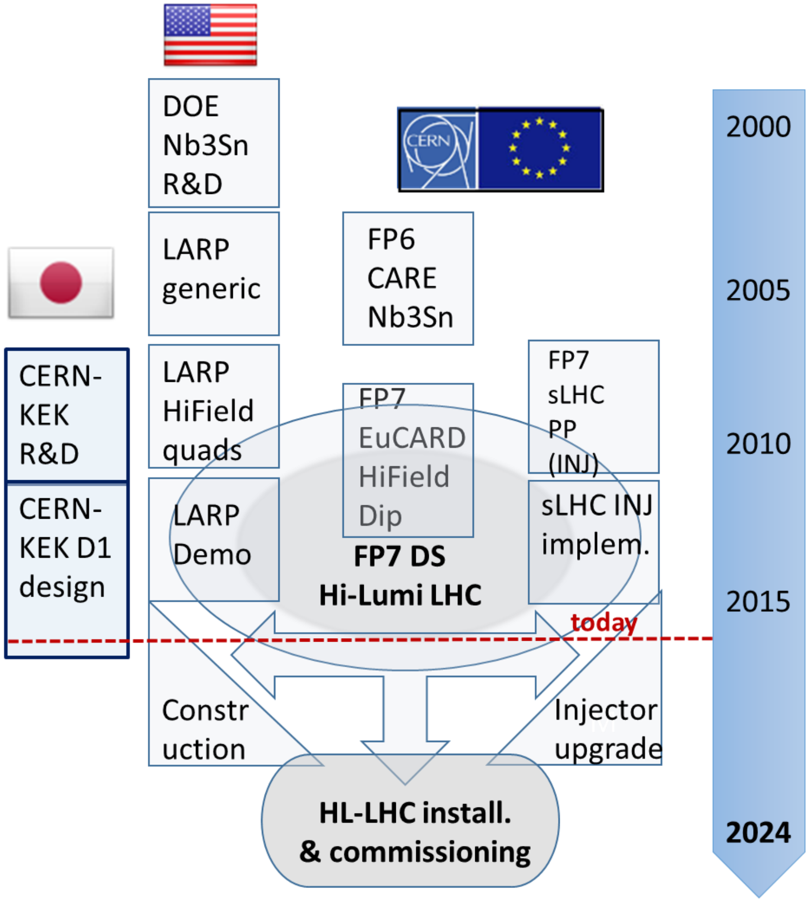
Even intra-bunch feedback is considered

HL-LHC

Upgrade of existing LHC

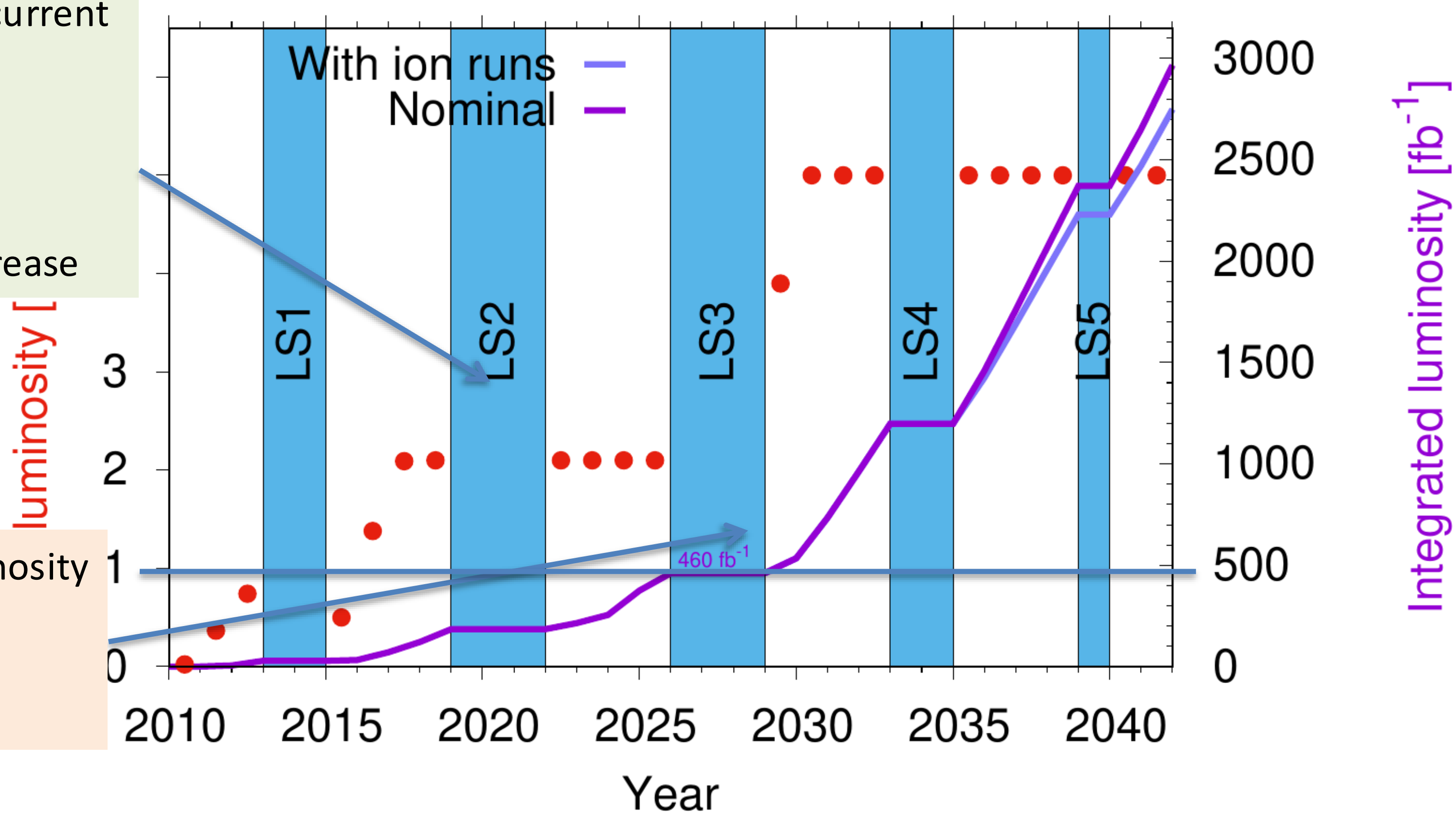
- A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:
- An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of
- **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.





HL-LHC Goal

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



Upgrade to full luminosity
Detectors (phase 2)
Triplets
…

HL-LHC Timeline