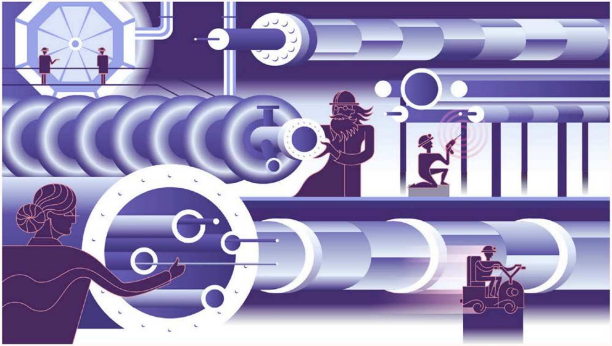
Accelerator Physics and the LHC

Ewen .H. Maclean

L-Università ta' Malta

CERN

symmetry topics follow +



Artwork by Sandbox Studio, Chicago with Ana Kova

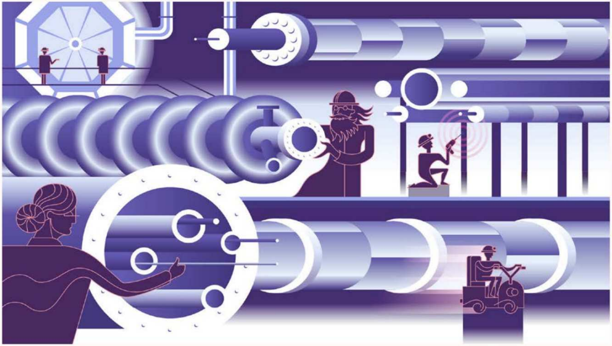
The hottest job in physics?

04/26/16 | By Troy Rummler

Accelerator scientists are in demand at labs and beyond.

While the supply of accelerator physicists in the United States has grown modestly over the last decade, it hasn't been able to catch up with demand fueled by industry interest in medical particle accelerators and growing collaborations at the national labs.

symmetry topics follow +



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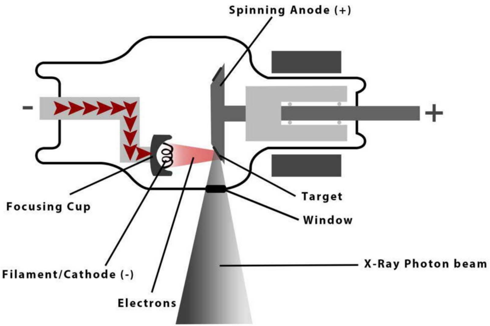
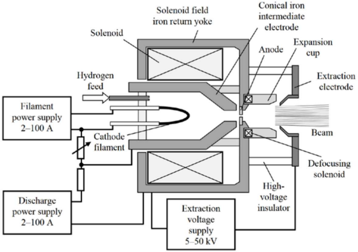
~35,000 particle accelerators world-wide

Medicine



X-ray tube: a very basic electro-static accelerator

- But similar principles to proton source



Medicine

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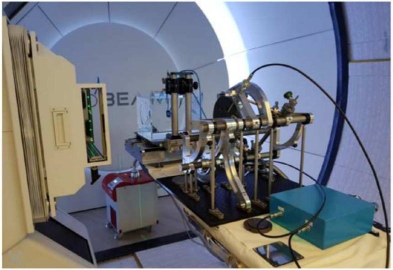
particle therapy

PARTICLE THERAPY | ANALYSIS

Proton therapy on an upward trajectory

16 Feb 2019



Setting the standard: NPL's portable calorimeter provides a more accurate reference point for proton-beam dosimetry. (Courtesy: NPL)

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Wales cancer patients to get proton beam therapy on NHS

12 December 2018

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The centre in Newport will be the second in the UK to offer proton beam therapy on the NHS

Medicine

Center for proton therapy, Paul Scherrer Institute, Villigen, Switzerland

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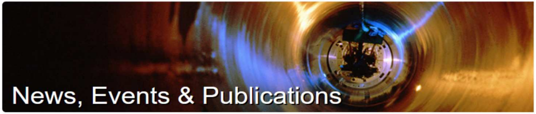

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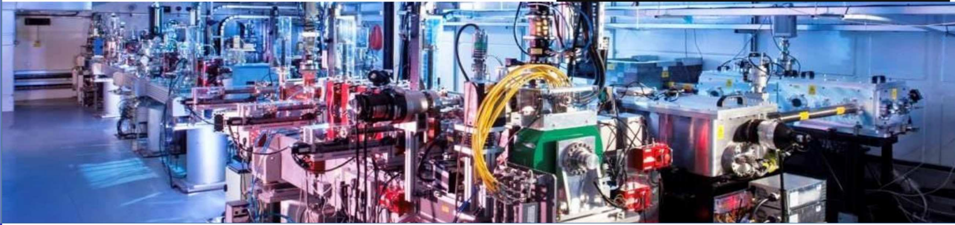
STFC launches VELA – bringing a new imaging capability for UK industry

13 March 2015



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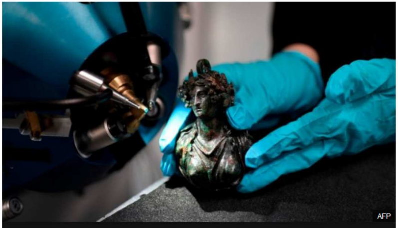
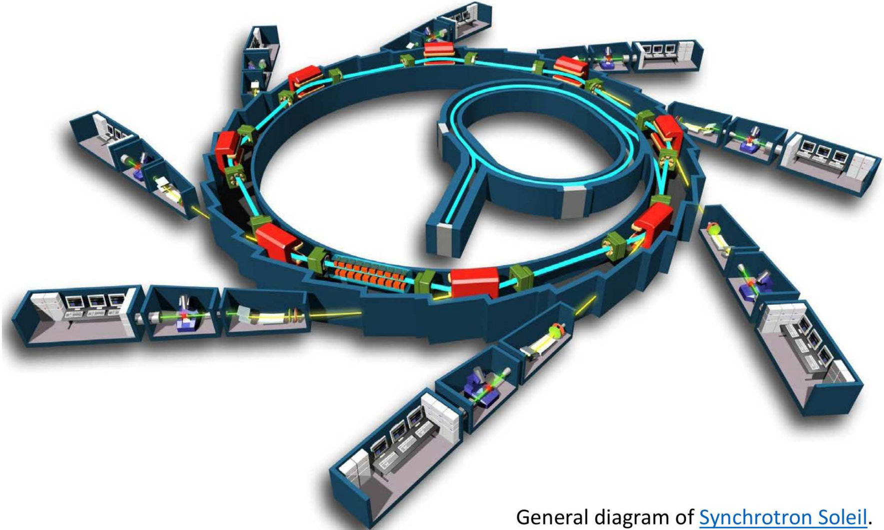
World's only particle accelerator for art is back at the Louvre

23 November 2017 Share



The machine bombards sculptures with helium and hydrogen atoms

Light Sources

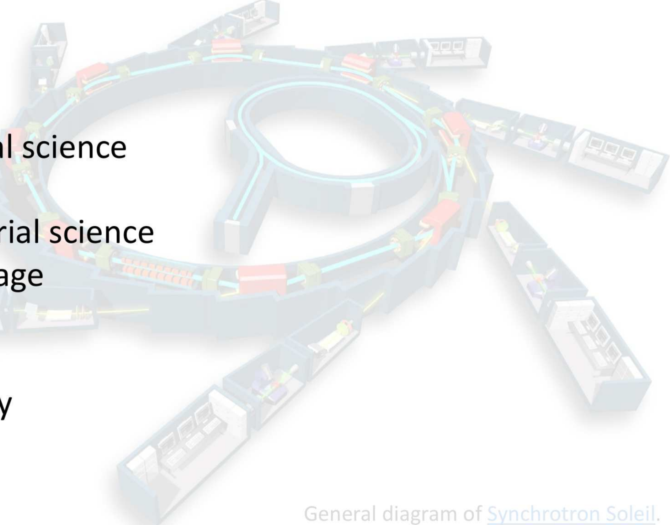


General diagram of Synchrotron Soleil.

Light Sources

Facilitate many types of research:

- Chemistry
- Earth Science
- Engineering
- Environmental science
- Life science
- Physics/material science
- Cultural heritage
- Forensics
- Food science
- Oceanography



General diagram of Synchrotron Soleil.

Accelerator research

Accelerator research

NETWORKING IN THE IMMUNE SYSTEM • NANOTECH BATTERIES

CERN Accelerating science

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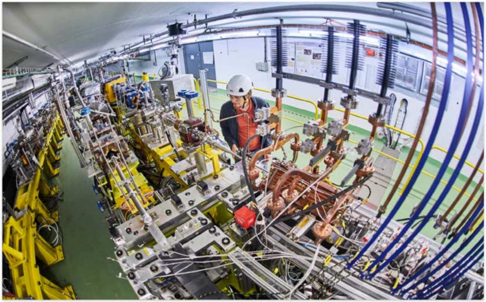
Voir en français

CLEAR prospects for accelerator research

A new user facility, the CERN Linear Electron Accelerator for Research (CLEAR), hosts accelerator research and development projects

1 NOVEMBER, 2017 | By Matthew Chalmers



The CERN Linear Electron Accelerator for Research (CLEAR) will enhance and complement the existing accelerator R&D programme at CERN. (Image: Julien Ordan/CERN)

A new user facility for accelerator R&D, the CERN Linear Electron Accelerator for Research (CLEAR), started

Accelerator research

NETWORKING IN THE IMMUNE SYSTEM • NANOTECH BATTERIES

CERN Accelerating science

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Fermilab news Search

Upcoming events

JUL 01 Mon — Pride celebration with Spectrum
Wilson Hall Atrium
9:00 am

JUL 01 Mon — Pride in STEM: PFLAG Panel
DIR/ One West-WH1W – Wilson Hall 1st fl West
12:00 pm

JUL 01 — Get To Know Fermilab Public Tour

Work at the Fermilab Integrable Optics Test Accelerator

April 2, 2019 | Giulio Stancari

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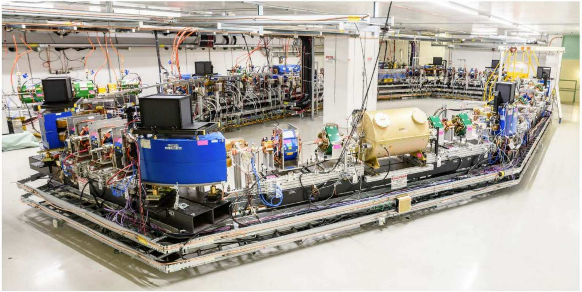
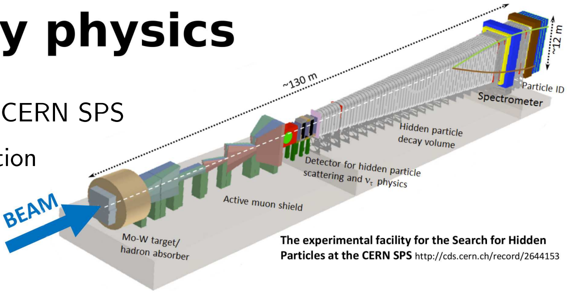


(1/2) After the first electron beam was circulated in August 2018, the experimental program at the Fermilab Integrable Optics Test Accelerator (IOTA) continues with commissioning of machine and diagnostics and with the first beam-physics experiments. This view of IOTA was taken in November 2018. Photo: Giulio Stancari

High energy physics

Fixed target e.g. SHIP @ CERN SPS

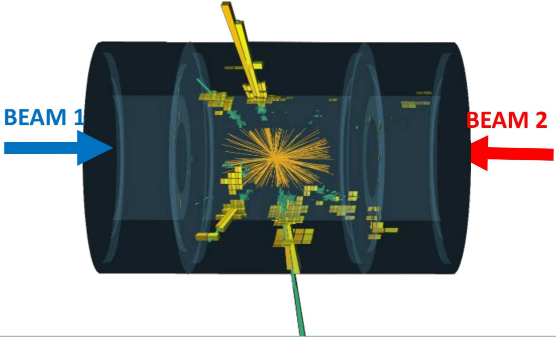
- Simpler design/implementation
  → **cost!**
- Potential for very high intensity beams & large numbers of collissions



The experimental facility for the Search for Hidden Particles at the CERN SPS http://cds.cern.ch/record/2644153

Collider e.g. LHC @ CERN

- More complex design
  + many extra challenges
- **LAB frame = CM frame**
  → maximum energy available for new particle creation



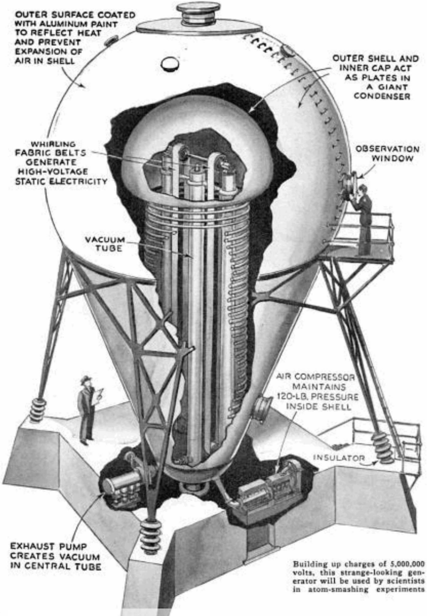
Key Points

- **Accelerators aren't just for HEP**
- **advantages / disadvantages of a beam collider vs fixed target experiment**

Accelerators for HEP

For historical development of particle accelerators see, e.g.

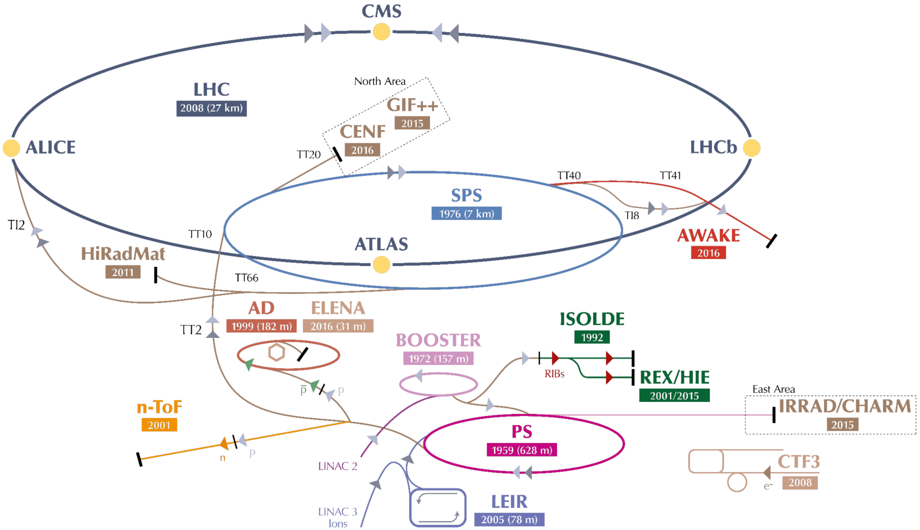
P.J. Bryant, *A brief history and review of accelerators*,
CERN Accelerator School: 5th General Accelerator Physics Course,
Jyväskylä, Finland, Sep 1992 https://cds.cern.ch/record/261062/



Westinghouse Atom Smasher, 5MeV
1937 – 1958, Pennsylvania, USA

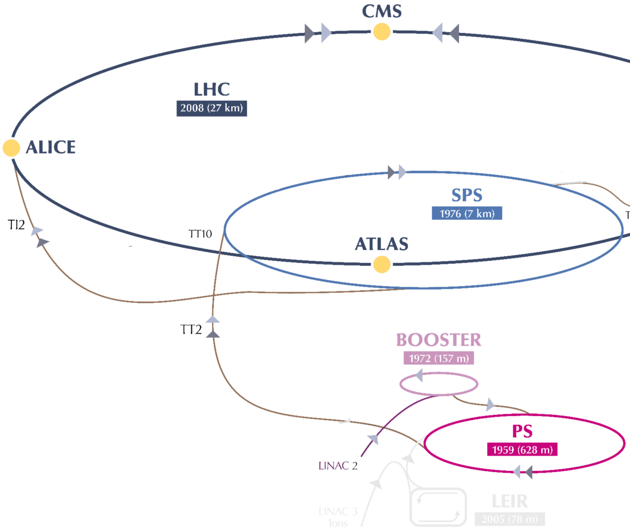
Accelerators for HEP

- **CERN accelerator complex**



Accelerators for HEP

- **LHC injector chain (protons)**



Beam energy (extraction)	**pre-LIU** ($\leq$ 2018)
Linac 2	50 MeV
PSB	1.4 GeV
PS	25 GeV
SPS	450 GeV
LHC	6.5 TeV

Accelerators for HEP

Linear Accelerator $\rightarrow$'Linac'

- **Single pass accelerator**
  $\rightarrow$ beam goes through once
  $\rightarrow$ not always straight e.g. SLC

- **Energy $\propto$ Length**

For HEP 2 main applications:

- **Low energy protons**
- **High energy e^{-} or e^{+} collider**
  e.g. Stanford Linear Collider (1987-1998, 3 $\mathrm{km}/0.09\mathrm{TeV}$)
  e.g. next-gen lepton colliders: ILC (50 km / $1\mathrm{TeV}$)
  e.g. next-gen lepton colliders: CLIC (50 km / $3\mathrm{TeV}$)

Accelerators for HEP

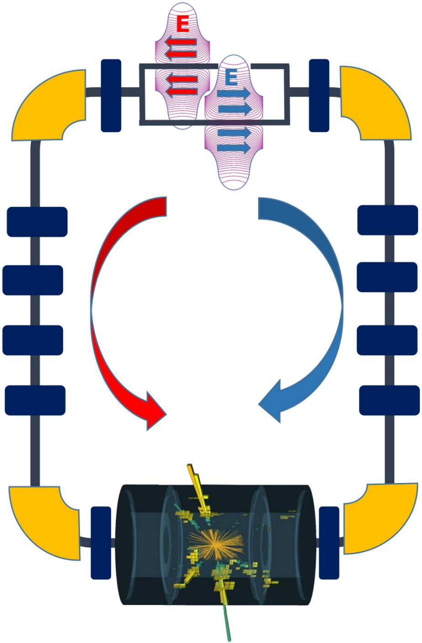
Synchrotron

→ *'circular accelerator'*, *'collider ring'* (doesn't actually need to be a circle)

→ e.g. **LHC**, LEP, Tevatron, RHIC, HERA, SPS, PS, ISR...

- **Repeated passage around the accelerator ring → great for HEP!**
  - → re-use accelerating structures
  - → collide same beams over & over

- **During acceleration guiding magnetic fields increase to keep the beam on the same (∼) orbit**



Acceleration

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

- To accelerate charged particle do work via Lorentz force

$$\Delta W = \int_{s_1}^{s_2} \boldsymbol{F}.\mathrm{d}\boldsymbol{s} = \int_{s_1}^{s_2} \mathrm{q}\vec{E}.\mathrm{d}\vec{s}$$

- Magnetic field does no work $\vec{s}\ .\ (\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \times \vec{B}) = 0$

$$\vec{E} = -\nabla\phi - \frac{\partial \vec{A}}{\partial t}$$

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$$\oint \nabla\phi.\mathrm{d}\vec{s} = 0$$

- **Electrostatic** e.g. Cockcroft Walton, Van-de-Graff...
- **Limited by DC breakdown**
- **No use for acceleration around a closed loop!** e.g. synchrotron

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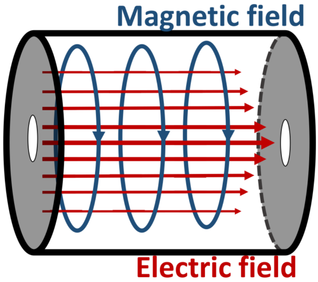
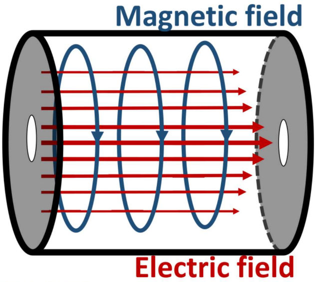
$$\vec{E} = -\nabla\phi - \frac{\partial \vec{A}}{\partial t}$$

$$\nabla \times \vec{E} = -\frac{\partial}{\partial t}\vec{B}$$

- Acceleration by time-varying fields
  $\rightarrow$ all high-energy accelerators
- **'Radiofrequency technology'** or **'RF'**



- Conducting cavity enforces boundary conditions which have solution with accelerating mode
- $H_\phi = -ie^{-i\omega t}\frac{E_0}{\eta}J_1\left(2.405\rho/R\right) \quad E_z = e^{-i\omega t}E_0 J_0\left(2.405\rho/R\right)$
- Resonant frequency (accelerating mode) should be harmonic of f_{rev}



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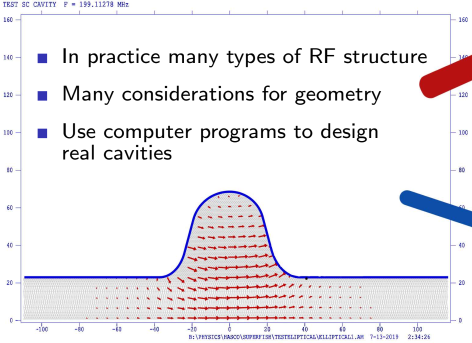
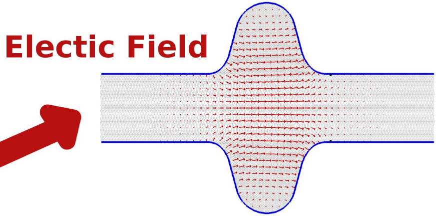
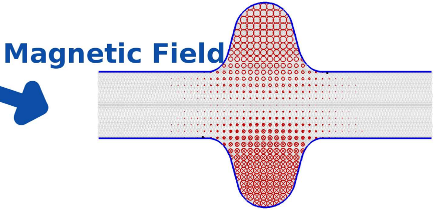
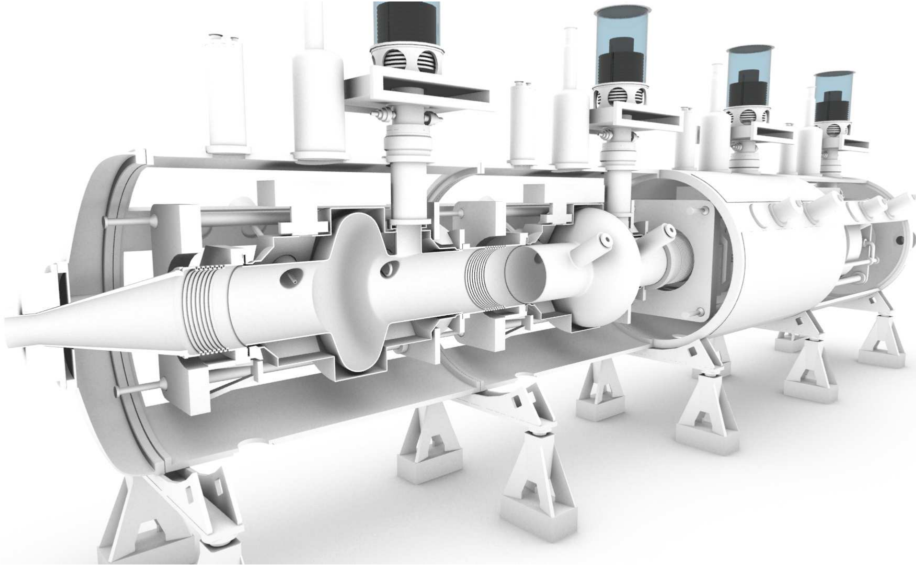


- In practice many types of RF structure
- Many considerations for geometry
- Use computer programs to design real cavities

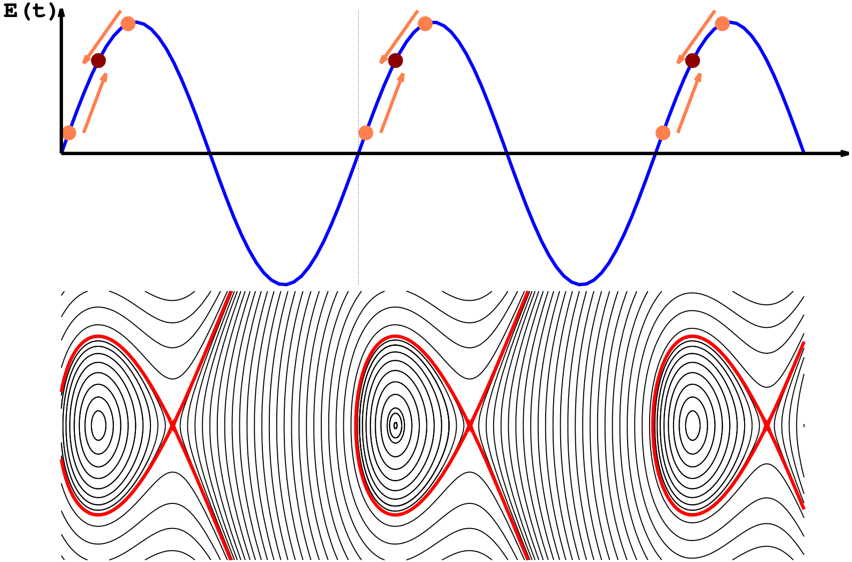




Superconducting 400 MHz LHC RF cavity



Particles come in bunches!



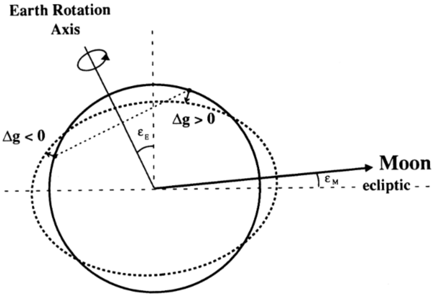
But what about the moon?

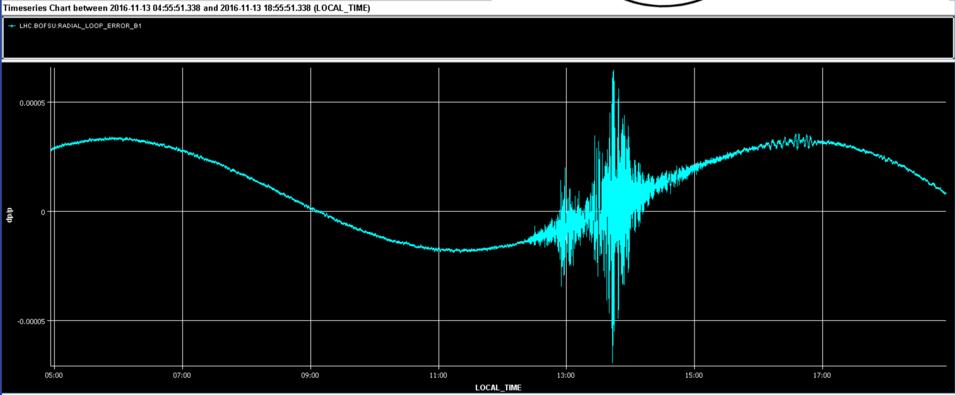
Credit: NASA/Goddard Space Flight Center/Arizona State University

Tidal deformation of earths crust changes the LHC circumference

→ **If uncorrected this causes a drift in the beam energy**

Effect of terrestrial tides on the LEP beam energy
L. Arnaudon et al. CERN SL/94-07 http://cds.cern.ch/record/260368

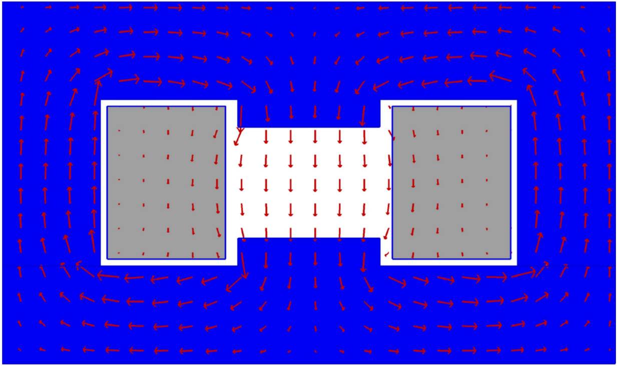




Bending

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

- **Use Lorentz force to bend bunches around the synchrotron ring**
- **Use dipole magnets**



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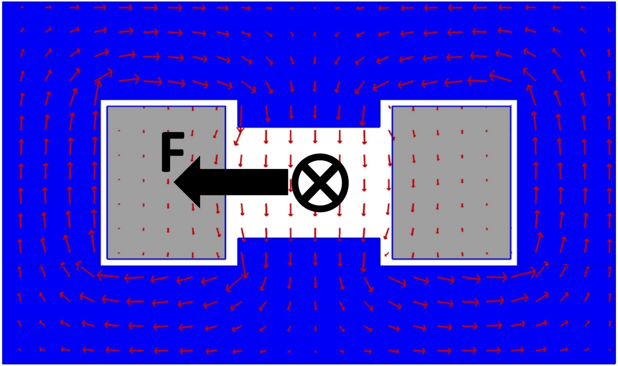
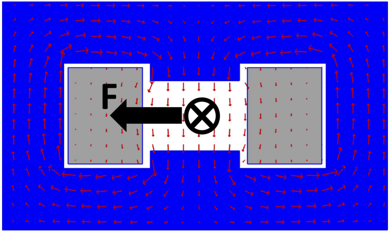
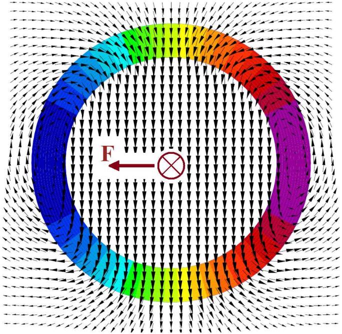


- Conventional dipole field defined by core
- Conventional dipoles limited to $\sim 2\,\mathrm{T}$ by saturation of core



- $> 2\,\mathrm{T}$ need very large current $\rightarrow$ superconductors!!!!
- Field defined by coil geometry $\rightarrow$ $I \propto \cos\Theta$



For discussion of magnet design: **S.Russenschuck**, **Design of accelerator magnets**, CERN accelerator school, Loutraki, Greece, Oct' 2000 https://cds.cern.ch/record/865932

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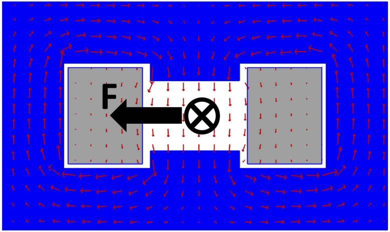

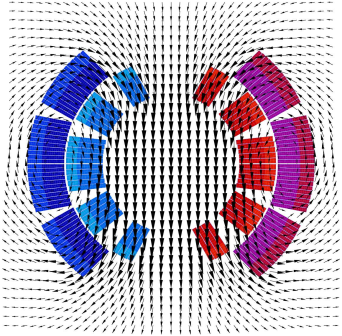

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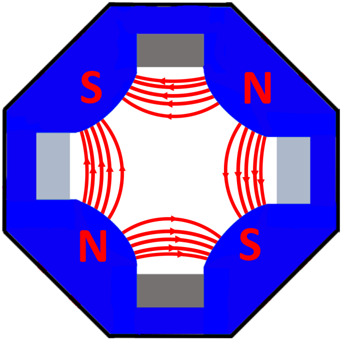
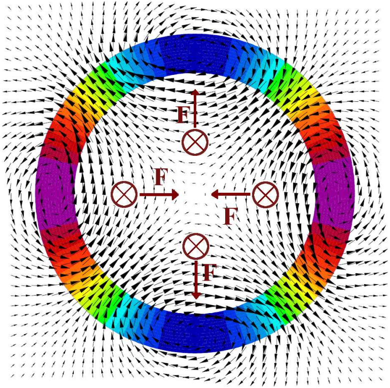
Focusing

- **Use quadrupole fields to focus particle beams**
  - $\rightarrow F \propto$ displacement from center
  - $\rightarrow I \propto \cos 2\Theta$





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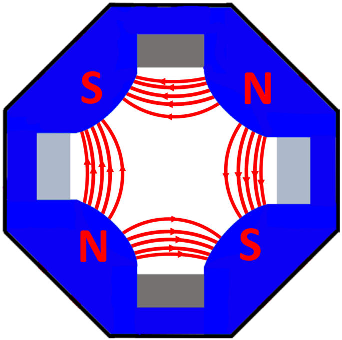

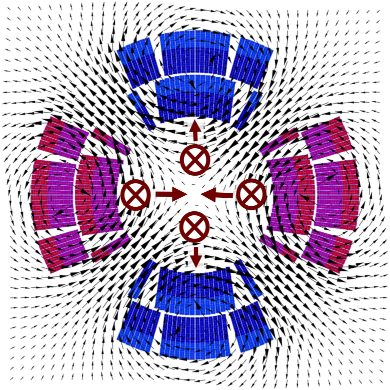

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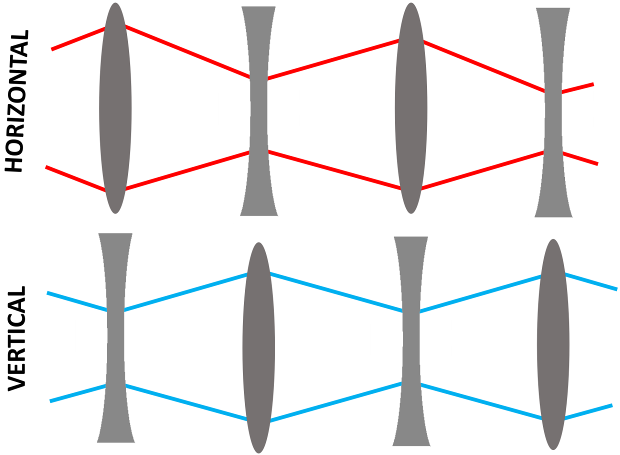
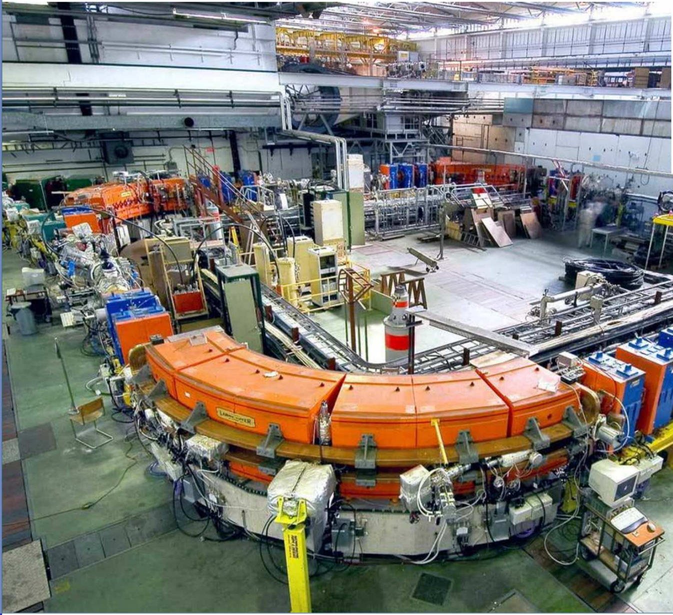
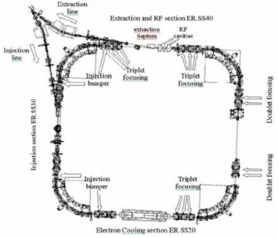
Focusing

- **Single quadrupole can focus in either H or V. Not both.**
- **Use repeating lattice of alternate focusing/defocusing quads**



Accelerators for HEP

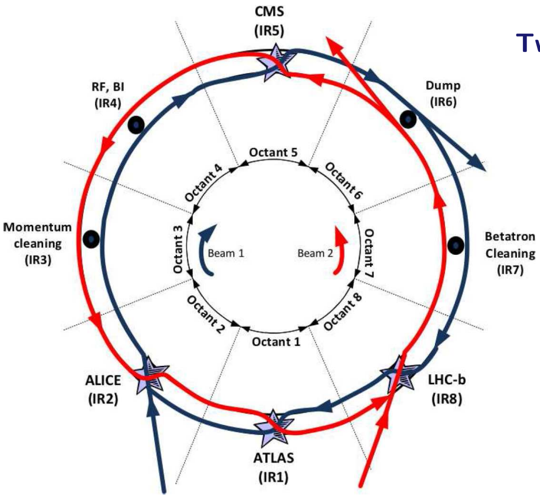




Key Points

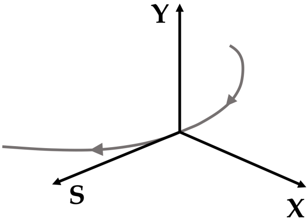
- The LHC injector chain
- What is a synchrotron?
- How do we accelerate?
  $\rightarrow$ Particles come in bunches
- Dipoles and quadrupoles to bend/focus

The Large Hadron Collider (LHC)



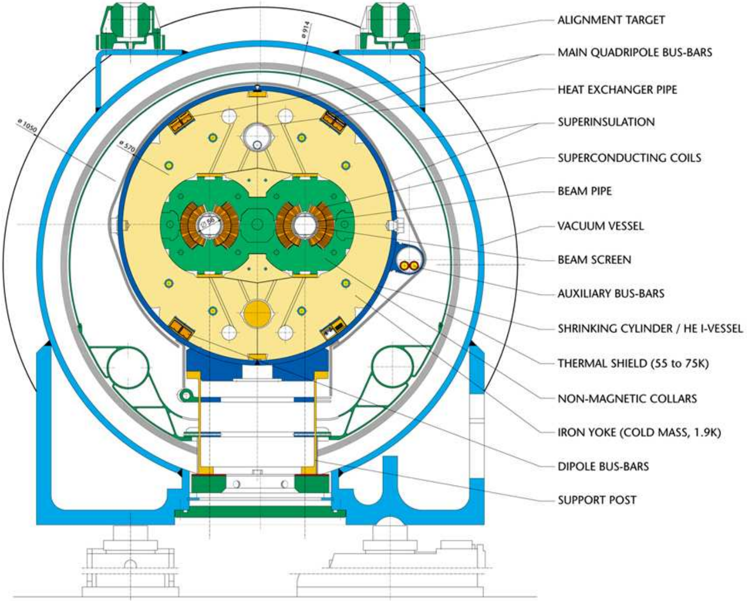
Twin-ring synchrotron collider

- **Collides** p, $^{208}Pb^{82+}$, $^{129}Xe^{54+}$
- **2 counter-rotating beams**
- **Curvilinear coordinate system**

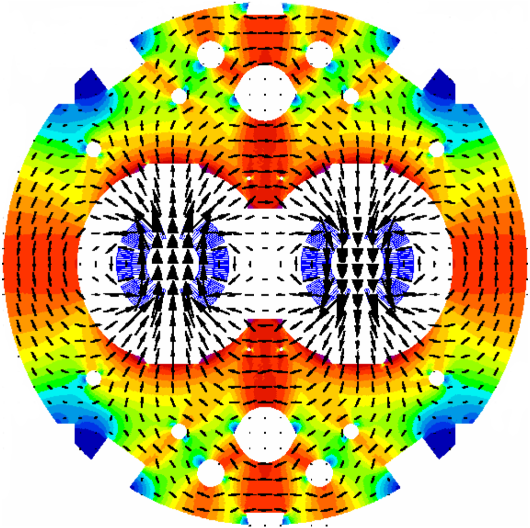


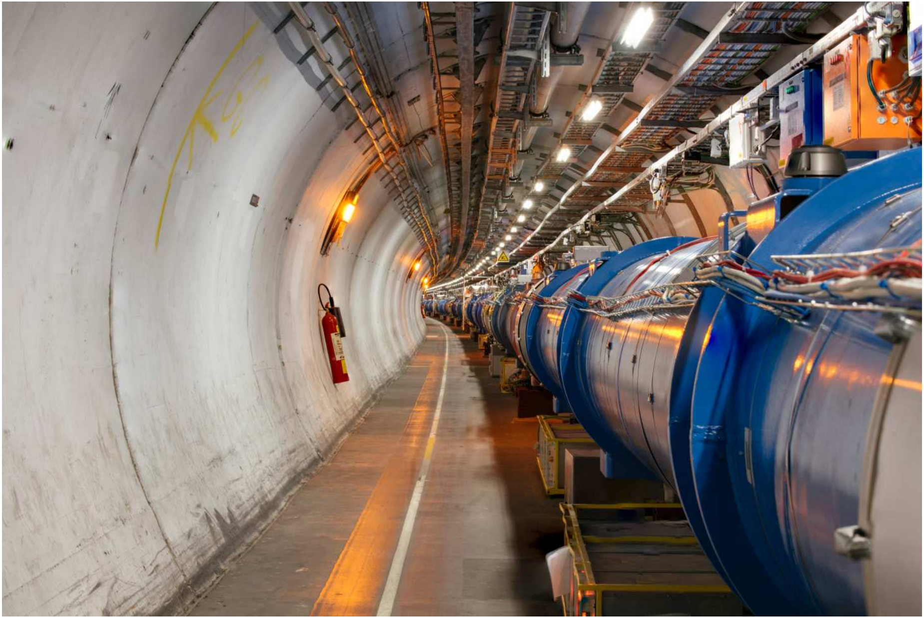
- **8 straight insertion regions** (IRs) **& 8 bending Arcs** *'A12 → A81'*

Arcs utilize superconducting 8.3 T dual bore dipoles



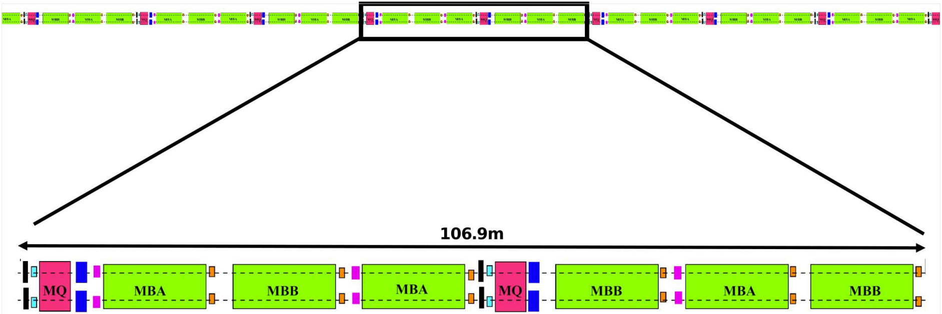
Arcs utilize superconducting 8.3 T dual bore dipoles





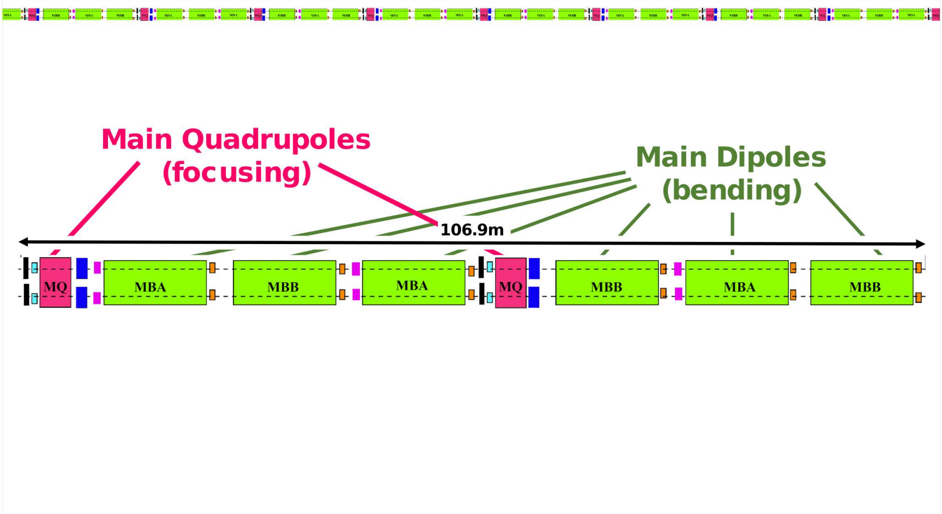
Arcs have repeating pattern ('lattice') of magnets

23 repeating 'cells' per Arc



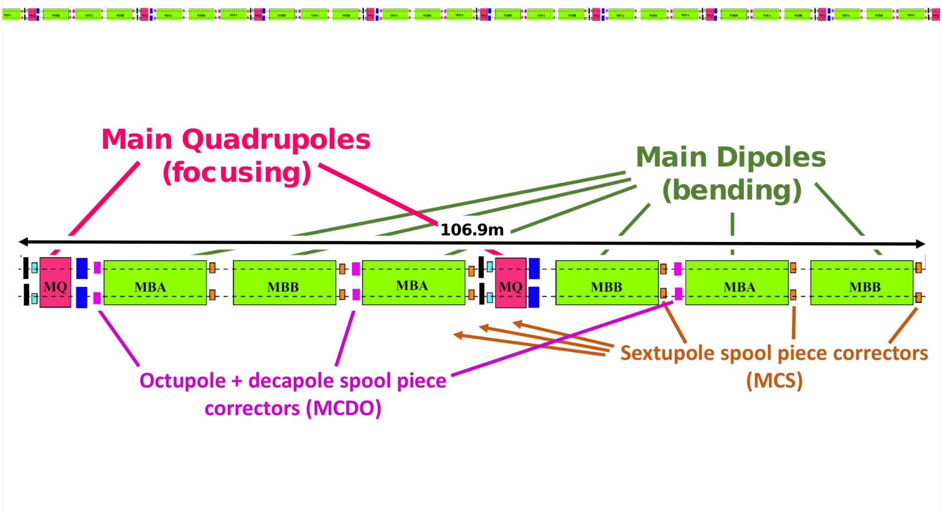
Magnets powered in series (arc-by-arc or families)

23 repeating 'cells' per Arc



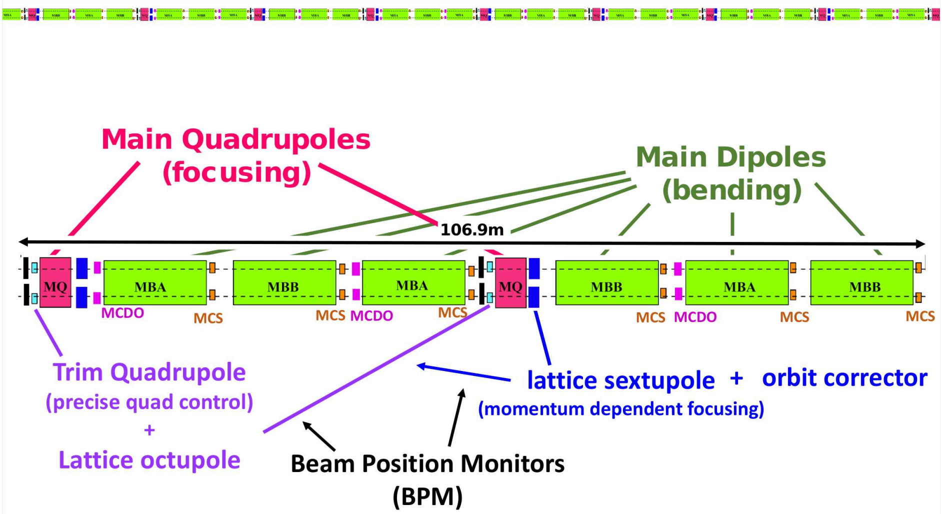
Most space occpied by dipoles and main quadrupoles

23 repeating ‘cells’ per Arc



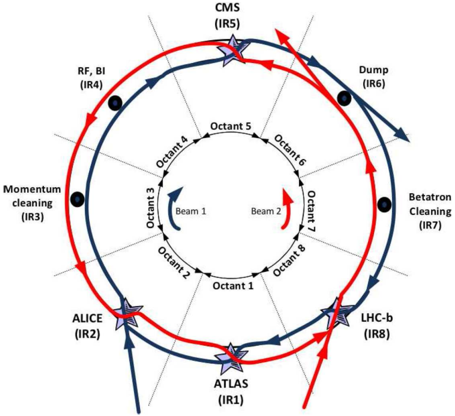
Higher order magnets correct field imperfections in main dipoles

23 repeating ‘cells’ per Arc



Need room for beam instrumentation & magnet connections

The Large Hadron Collider (LHC)



8 insertions:

- **IR2:** LHC B1 injection + HEP (ALICE)
- **IR8:** LHC B2 injection + HEP (LHCb)

- **IR1:** HEP (ATLAS)
- **IR5:** HEP (CMS)

- **IR3:** COLLIMATION (momentum)
- **IR7:** COLLIMATION (transverse)

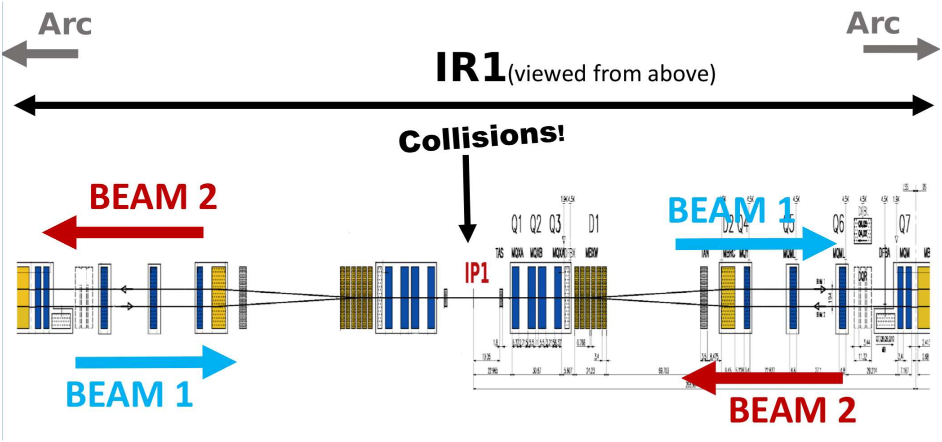
- **IR4:** Acceleration + instrumentation

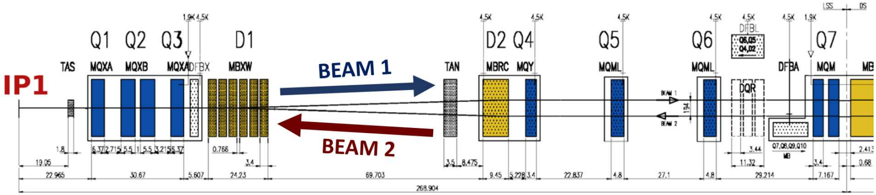
- **IR6:** LHC B1+B2 BEAM DUMP

Structure of a HEP insertion:

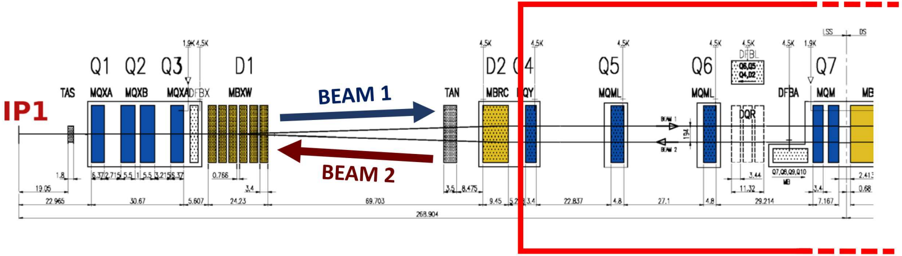
→ e.g. **Insertion Region 1 (IR1)** hosting the ATLAS experiment

→ Beams collide at the **Interaction Point (IP1)**



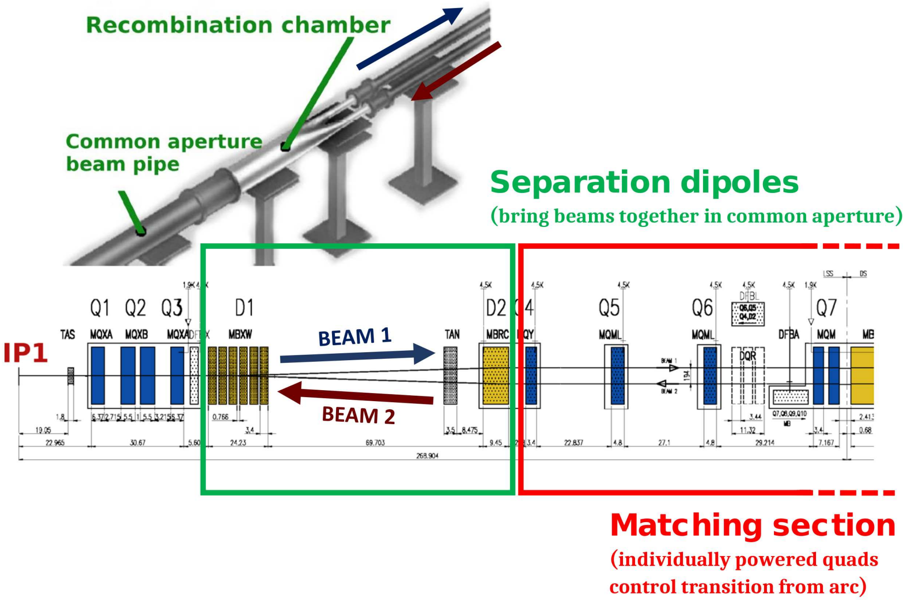


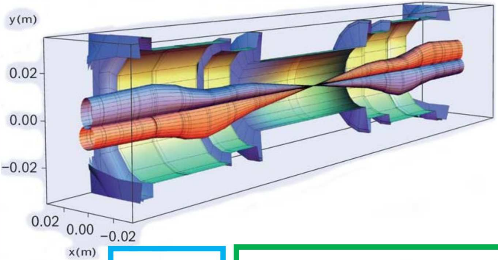
Right side of IR1, viewed from above



Matching section

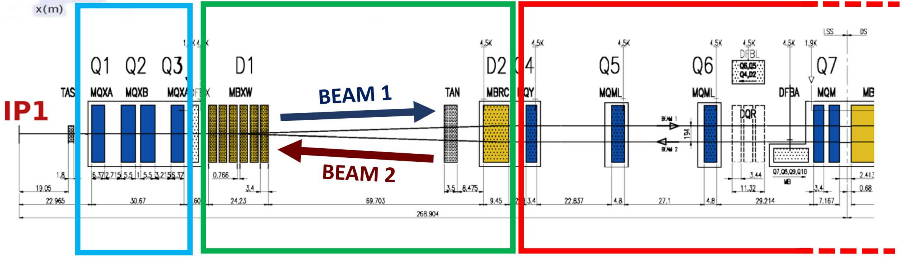
(individually powered quads control transition from arc)


Recombination chamber
Common aperture beam pipe
Separation dipoles
(bring beams together in common aperture)
IP1
Q1 Q2 Q3
D1
D2
Q4
Q5
Q6
Q7
TAS
MQXA
MQXB
MBXW
TAN
MBRC
MQY
MQML
DFBA
MQM
BEAM 1
BEAM 2
Matching section
(individually powered quads control transition from arc)



Separation dipoles

(bring beams together in common aperture)



Quadrupole triplets

Squeeze beam from ~1mm in Arc to ~10um at IP

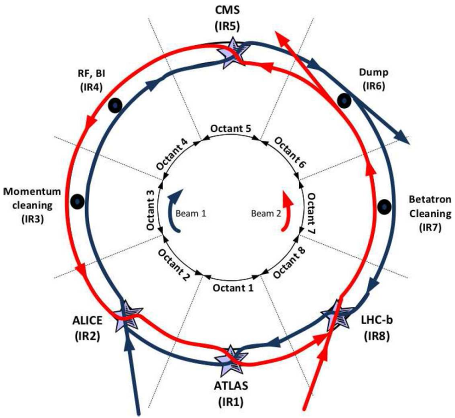
Matching section

(individually powered quads control transition from arc)

Also corrector magnets

(coupling, sextupole, octupole, dodecapole)

The Large Hadron Collider (LHC)



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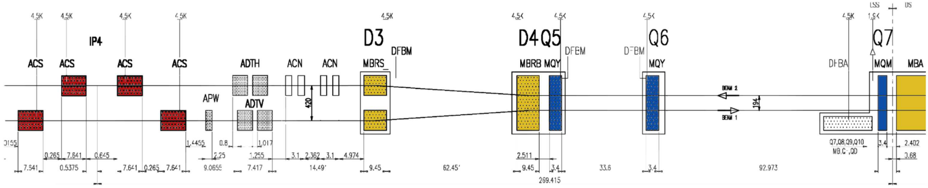
- **IR4:** Acceleration + instrumentation

- **IR6:** LHC B1+B2 BEAM DUMP

- **IR design varies with function**

e.g. IR4 (BI/RF)
(right side viewed from above)



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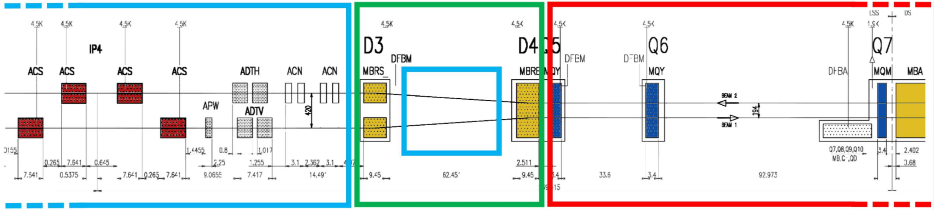
Matching section



Accelerating cavities & Beam instrumentation

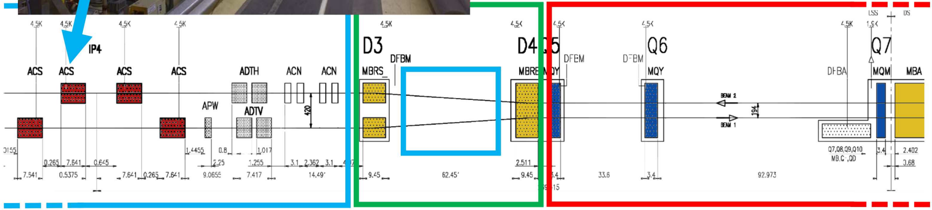
Dipoles (increase beam separation to give space for accelerating cavities)

- **IR design varies with function**

e.g. IR4 (BI/RF)

(right side viewed from above)

Matching section



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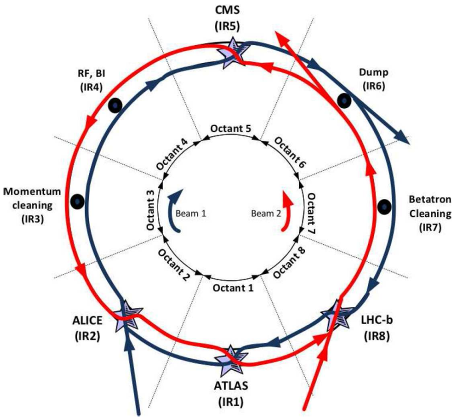

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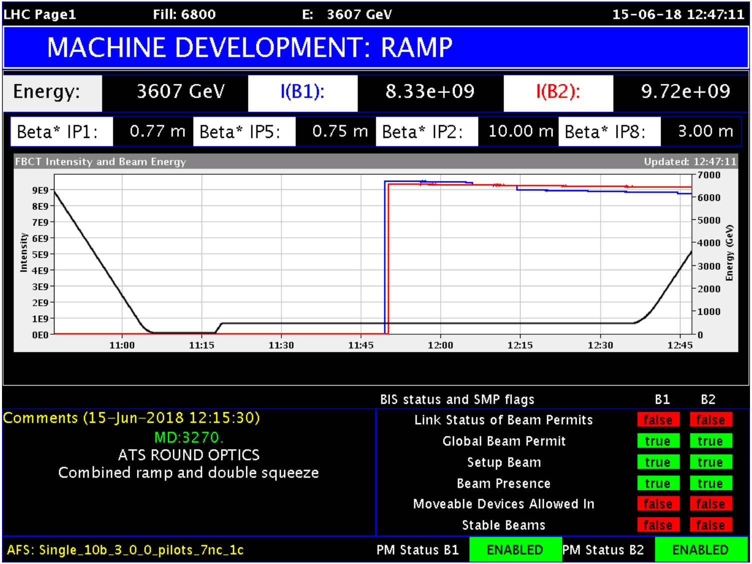
- **IR6:** LHC B1+B2 BEAM DUMP

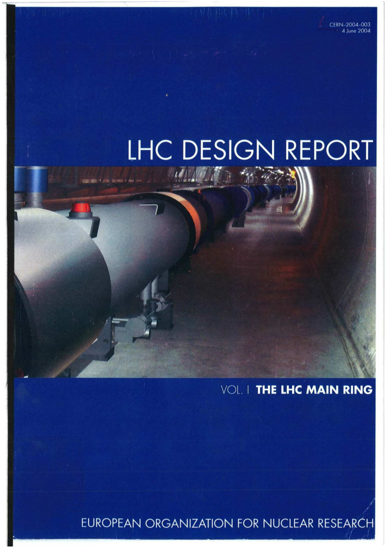
Day to day operation of the CERN accelerators handled by the operations group, from the CERN Control Center (CCC)

LHC page 1: machine status & OP comments

https://op-webtools.web.cern.ch/vistar/vistars.php



For general questions about LHC one commonly used resource is the LHC Design Report



LHC Design Report, v.1 : the LHC Main Ring
http://cds.cern.ch/record/782076/

LHC Design Report, v.2 : the LHC Infrastructure and General Services
http://cds.cern.ch/record/815187

LHC Design Report, v.3 : the LHC Injector Chain http://cds.cern.ch/record/823808

BE CAREFUL: some parameters may be out of date
$\rightarrow$ **LHC has already exceeded its design performance in many ways!**

Key Points

- **Coordinate scheme for accelerators**
- **Overall structure of LHC**

  → 8 Arcs - this is where the beams are bent around the ring

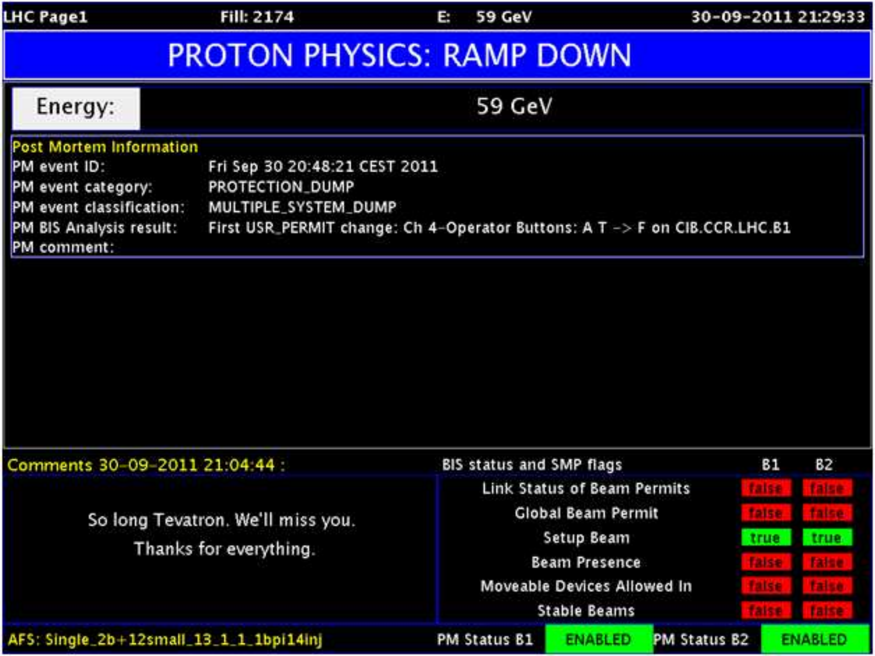
  → 8 IRs - various functions
- **Repeating lattice in the arcs → the LHC arc cell**

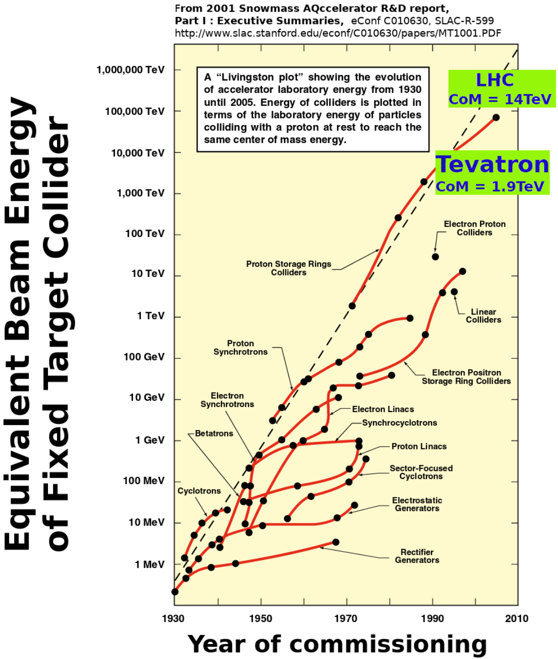
  → can't fill the arc completely with dipoles!

  → also quadrupoles for focusing, nonlinear magnets, instrumentation...
- **Typical layout of an insertion region**

What do particle physicists care about??

Energy

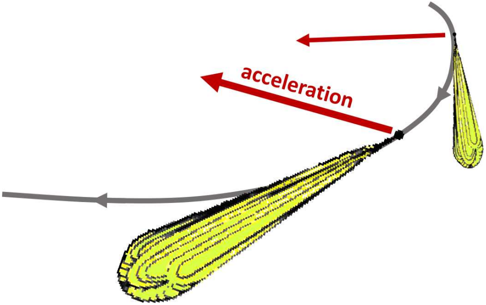

LHC Page1
Fill: 2174
E: 59 GeV
30-09-2011 21:29:33
PROTON PHYSICS: RAMP DOWN
Energy:
59 GeV
Post Mortem Information
PM event ID: Fri Sep 30 20:48:21 CEST 2011
PM event category: PROTECTION_DUMP
PM event classification: MULTIPLE_SYSTEM_DUMP
PM BIS Analysis result: First USR_PERMIT change: Ch 4-Operator Buttons: A T -> F on CIB.CCR.LHC.B1
PM comment:
Comments 30-09-2011 21:04:44 :
So long Tevatron. We'll miss you.
Thanks for everything.
BIS status and SMP flags B1 B2
Link Status of Beam Permits false false
Global Beam Permit false false
Setup Beam true true
Beam Presence false false
Moveable Devices Allowed In false false
Stable Beams false false
AFS: Single_2b+12small_13_1_1_1bpi14inj
PM Status B1 ENABLED
PM Status B2 ENABLED


From 2001 Snowmass AQccelerator R&D report,
Part I : Executive Summaries, eConf C010630, SLAC-R-599
http://www.slac.stanford.edu/econf/C010630/papers/MT1001.PDF
A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.
Equivalent Beam Energy of Fixed Target Collider
1,000,000 TeV
100,000 TeV
10,000 TeV
1,000 TeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
1930
1950
1970
1990
2010
Year of commissioning
LHC
CoM = 14TeV
Tevatron
CoM = 1.9TeV
Electron Proton Colliders
Proton Storage Rings Colliders
Linear Colliders
Proton Synchrotrons
Electron Positron Storage Ring Colliders
Electron Synchrotrons
Electron Linacs
Synchrocyclotrons
Betatrons
Proton Linacs
Sector-Focused Cyclotrons
Cyclotrons
Electrostatic Generators
Rectifier Generators

Limiting factor for circular e^+ / e^- accelerators:

$\rightarrow$ particles emit **synchrotron radiation** as they are bent around ring

$$\Delta E/\mathrm{turn} \propto \frac{(\beta_{rel}\gamma_{rel})^4}{\rho}$$



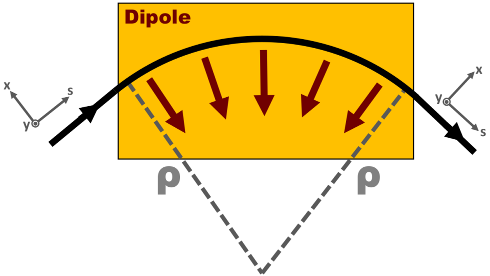
- **LEP** (e) **energy loss:** $\sim 3\,\mathrm{GeV/turn}$ (@ $101\,\mathrm{GeV}$)
- **LHC** (p) **energy loss:** $\sim 5\,\mathrm{keV/turn}$ (@ $6.5\,\mathrm{TeV}$)

Limiting factor for circular hadron collider:

$\rightarrow$ **High Energy = high magnetic ridiidity**

$$F_{Lorentz} = F_{centrip}$$

$$F_{Lorentz} = q(\vec{E} + \vec{v} \times \vec{B})$$



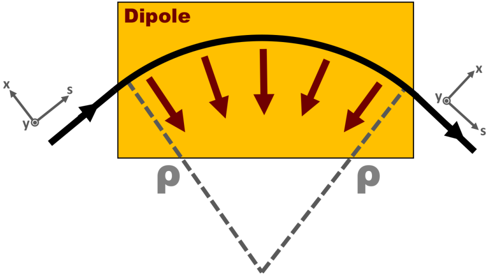
- consider proton $(\mathrm{q/A} = 1)$
- assume pure dipole fields
- $(v_x, v_y) << v_s$

Limiting factor for circular hadron collider:

$\rightarrow$ **High Energy = high magnetic ridAfter**

$$F_{Lorentz} = F_{centrip}$$

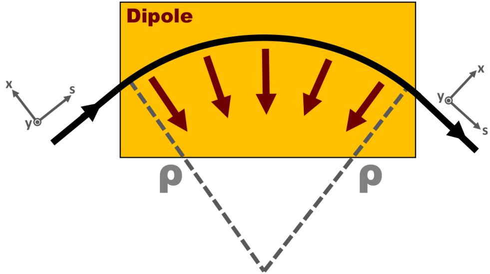
$$F_{Lorentz} = q(\vec{E} + \vec{v} \times \vec{B})$$
$$= evB_{dipole}$$



Limiting factor for circular hadron collider:

→ **High Energy = high magnetic ridAfter**

$$F_{centrip} = \frac{\mathrm{d}p}{\mathrm{d}t}$$



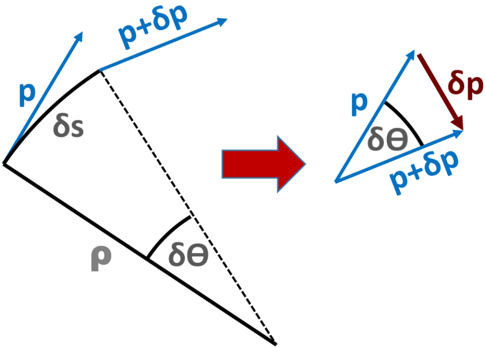
Limiting factor for circular hadron collider:

$\rightarrow$ **High Energy = high magnetic rididity**

$$\mathrm{d}p = p\mathrm{d}\theta$$

$$\mathrm{d}s = \rho\mathrm{d}\theta$$

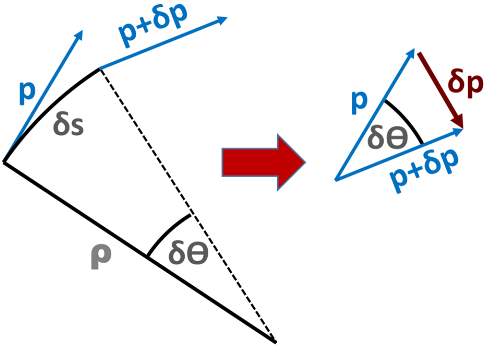
$$p = \gamma_{rel} m_{rest} v$$



Limiting factor for circular hadron collider:

$\rightarrow$ **High Energy = high magnetic ridAnd**

$$F_{centrip} = \frac{\mathrm{d}p}{\mathrm{d}t} = p\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{p}{\rho}\frac{\mathrm{d}s}{\mathrm{d}t} = \frac{pv}{\rho} = \frac{\gamma m_0 v^2}{\rho}$$



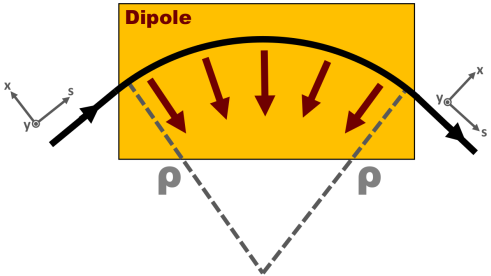
Limiting factor for circular hadron collider:

$\rightarrow$ **High Energy = high magnetic rididity**

$$F_{Lorentz} = F_{centrip}$$

$$evB = \frac{\gamma m_0 v^2}{\rho} = \frac{pv}{\rho}$$

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

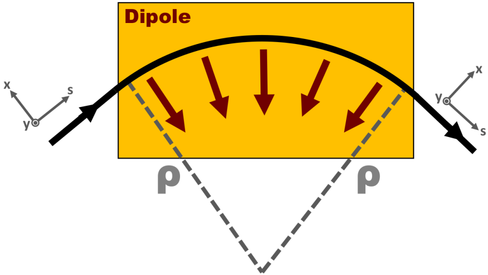


Limiting factor for circular hadron collider:

$\rightarrow$ **High Energy = high magnetic ridiity**

$B\rho$ is *'Magnetic Rigidity'*

$$B\rho \ \ [\mathrm{Tm}] = \frac{p \ \ [\mathrm{kgms^{-1}}]}{e \ \ [\mathrm{C}]}$$



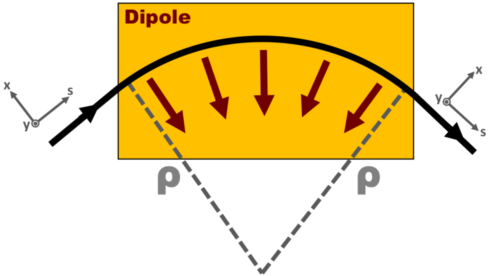
- Not so convenient units

Limiting factor for circular hadron collider:

$\rightarrow$ **High Energy = high magnetic rididity**

$B\rho$ is *'Magnetic Rigidity'*

$$B\rho \ \ [\mathrm{Tm}] = \frac{10}{2.998} p \ \ [GeV/c]$$



Magnetic rigidity defines the maximum energy you can reach for a given dipole field in a given tunnel geometry

The Future of laboratory based HEP?

$$\Delta E/\mathrm{turn} \propto \frac{(\beta_{rel}\gamma_{rel})^4}{\rho}$$

$$B\rho \;\; [\mathrm{Tm}] = \frac{10}{2.998}\, p \;\; [GeV/c]$$

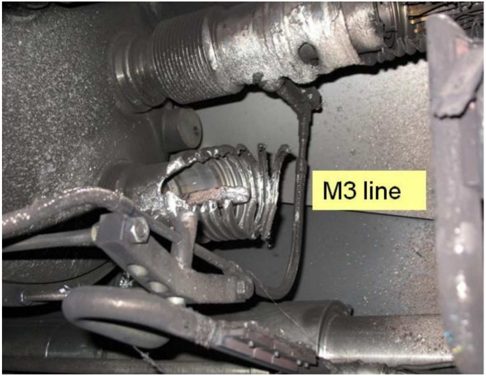
- **linear e/e colliders (ILC/CLIC)**
- $100\,\mathrm{km}$ **e/e collider ring (FCC-ee,CEPC)**
- **New magnets in LHC tunnel (HE-LHC)**
- $100\,\mathrm{km}$ **hadron collider (FCC-hh,SppC)**
- **Something new?**

LHC main dipole designed for $8.327\,\mathrm{T}$

→ **allows $7.0\,\mathrm{TeV/beam}$ (protons)**

→ **In practice LHC still not reached design energy**

→ **Report of the Task Force on the Incident of 19th September 2008 at the LHC, CERN-LHC-PROJECT-Report-1168** https://cds.cern.ch/record/1168025/



"The dipole bus bar at the location of the arc was vaporized, as well as the M3 line bellows around it, thus breaking open the helium enclosure..."

"The force was applied to the external support jacks, displacing the cryomagnets from them and in some cases, rupturing their ground anchors or the concrete in the tunnel floor."

To ensure machine protection the LHC operated at lower energy until upgrades performed

LHC main dipole designed for $8.327\,\mathrm{T}$

$\rightarrow$ **allows** $7.0\,\mathrm{TeV/beam}$ **(protons)**

Year	mode	Beam energy [*TeV*]	n-n CoM [TeV]
2010-2011	pp	3.5	7.0
2012	pp	4.0	8.0
2015-2018	pp	6.5	13.0
≥2021	pp	7.0?	14.0?

WATCH OUT: HEP normally discuss CoM → ABP may use alternative definition of energy! e.g. energy/nucleon or beam energy (E*Z/A)

Ultimate energy of LHC is still unclear!

$\rightarrow$ **Main dipoles may be able to exceed their nominal value**

$\rightarrow$ $7.0\,\mathrm{TeV} - 7.5\,\mathrm{TeV}$ **(protons)**

New High Luminosity LHC Baseline and Performance at Ultimate Energy, CERN-ACC-2018-069

Key Points

- **Accelerator physicists don't always talk about CoM - watch out!**
- **Different limitations on beam-energy for $e^{\pm}$ and hadron accelerators**
- **What is magnetic rigidity & where does it come from?**

  $\rightarrow$ the future of hadron colliders?

What do particle physicists care about???

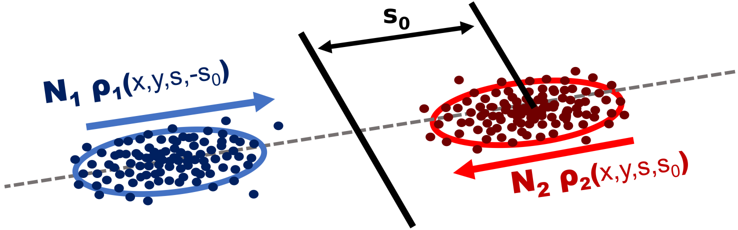
$\rightarrow$ How much data (how many collisions) are generated?

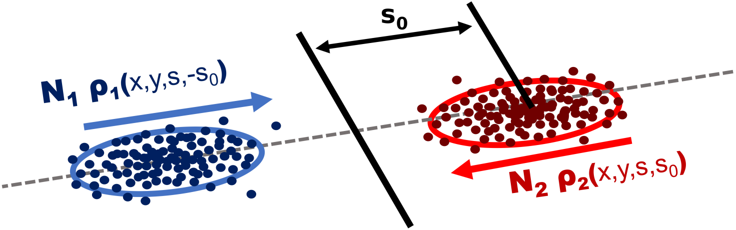
Luminosity

Event rate for a HEP interaction:

$$R = L \times \sigma$$

- *R*: *Event Rate* $[\mathrm{s}^{-1}]$
- σ: *Cross Section* $[\mathrm{barn} = \mathbf{10}^{-34}\mathrm{cm}^2]$
  property of the HEP interaction
- *L*: *Luminosity* **[inverse barn / s]**
  property of the collider





$$L = f\sqrt{(\bar{v}_1-\bar{v}_2)^2-(\bar{v}_1\times\bar{v}_2)^2\ /\ c^2}\ N_1 N_2 \iiiint_{-\infty}^{+\infty} \rho_1(x,y,s,-s_0)\rho_2(x,y,s,s_0)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}s\,\mathrm{d}s_0$$

M.A. Furman, *The Møller Luminosity Factor*, LBNL-53553,CBP Note-543, September 24, 2003
W.Herr & B.Muratori, *Concept of Luminosity*, CERN Accelerator School, Zeuthen, Germany, 15 - 26 Sep 2003

with some approximation:

$$L = \frac{\left(f_{rev} n_{coll}\right) \; N_1 N_2}{2\pi \sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)} \sqrt{\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}}$$

Assume:

- **uncorrellated gaussian bunch profiles in x,y,s**
- **head-on colinear collission of equal/opposite velocity beams**
- **equal bunch lengths** $\sigma_{s,1} \approx \sigma_{s,2}$
- **revolution frequency of 2 beams are in sync**
- n_{coll} **colliding bunches are all described by similar** $N_{1,2}, \sigma$

$$\boldsymbol{L} = \frac{\left(f_{rev}\, n_{coll}\right)\ N_1 N_2}{2\pi\sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)}\sqrt{\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}}$$

- n_{coll}: **Number of colliding bunches**

How many bunches can we fit in the LHC?

- **LHC revolution frequency** $\approx 11.245\,\mathrm{kHz}$

  $\rightarrow$ **revolution period** $\approx 89\,\mu\mathrm{s}$

- **Minimum separation of bunches defined by RF system of the injector chain**

  $\rightarrow$ **25** ns bunch spacing

soooo.... 3564 bunches?

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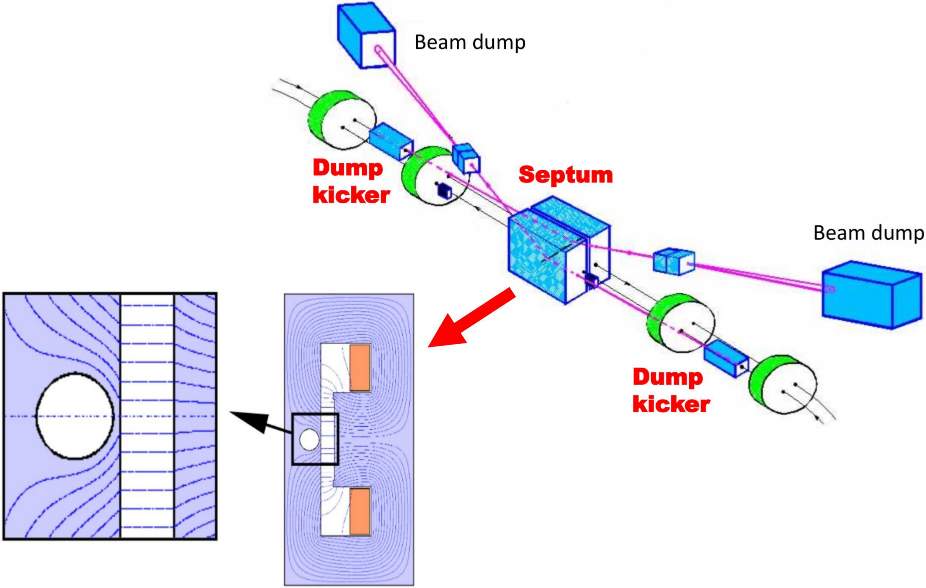
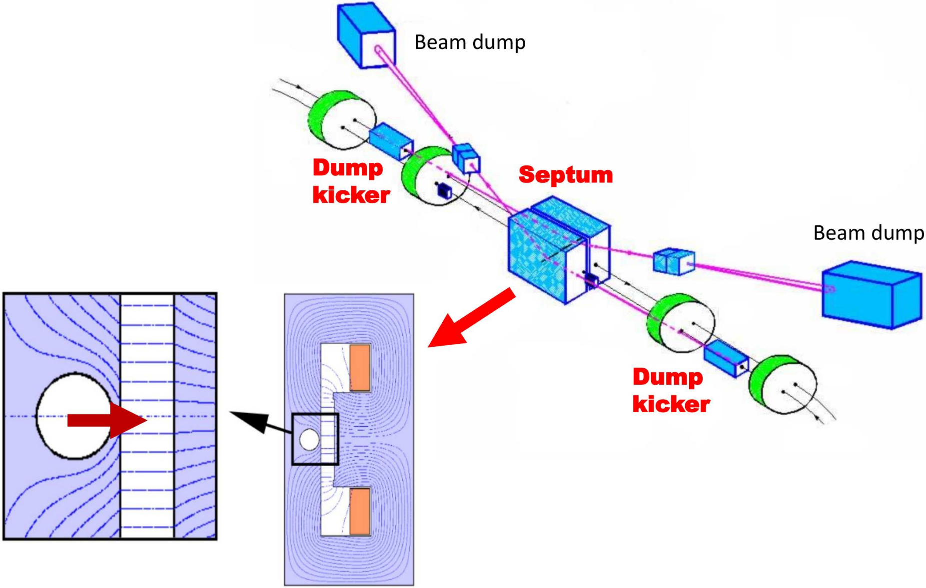
soooo.... 3564 bunches?

NO!

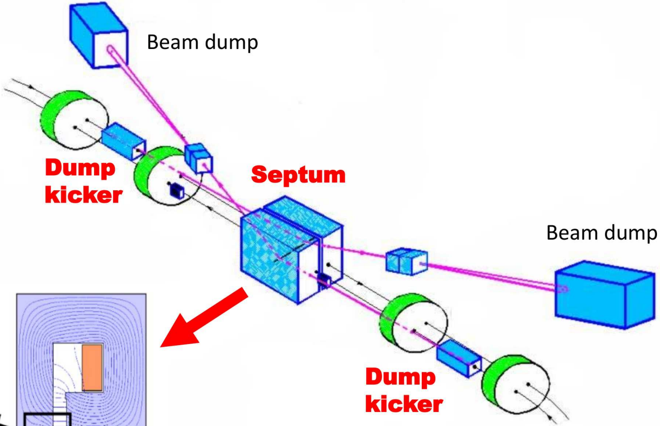
Also need time to dump / inject beams

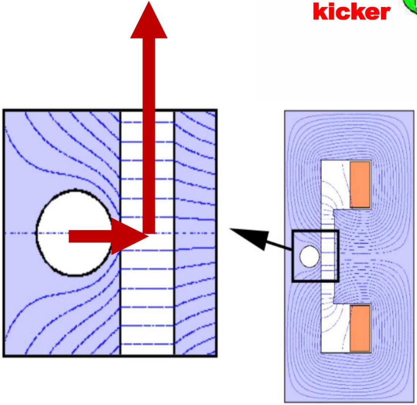


Also need time to dump / inject beams



Also need time to dump / inject beams

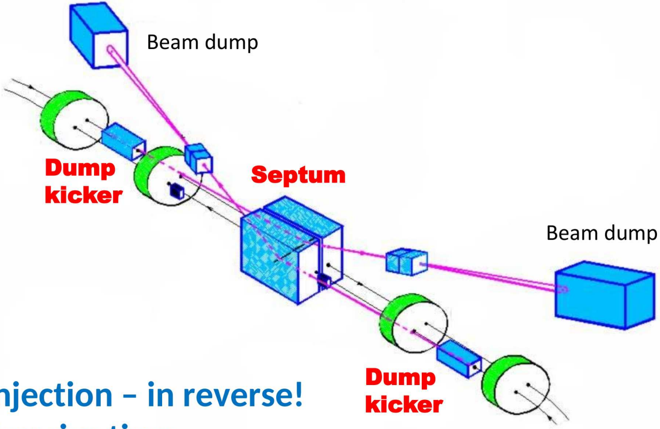




Takes 3us for dump kicker to reach required field

Need an `abort gap' without beam

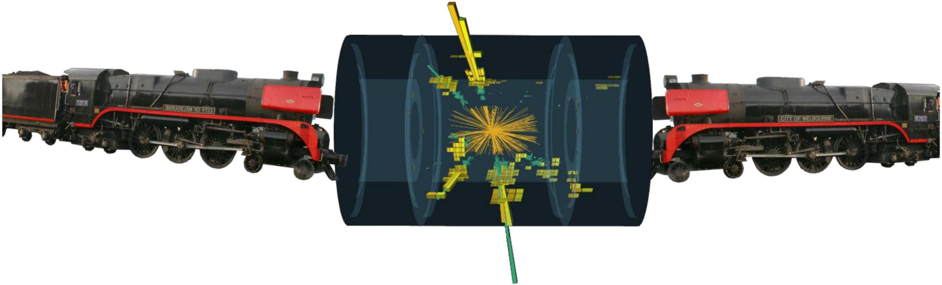
Also need time to dump / inject beams



Similar issue at injection – in reverse!
1us injection kicker rise time

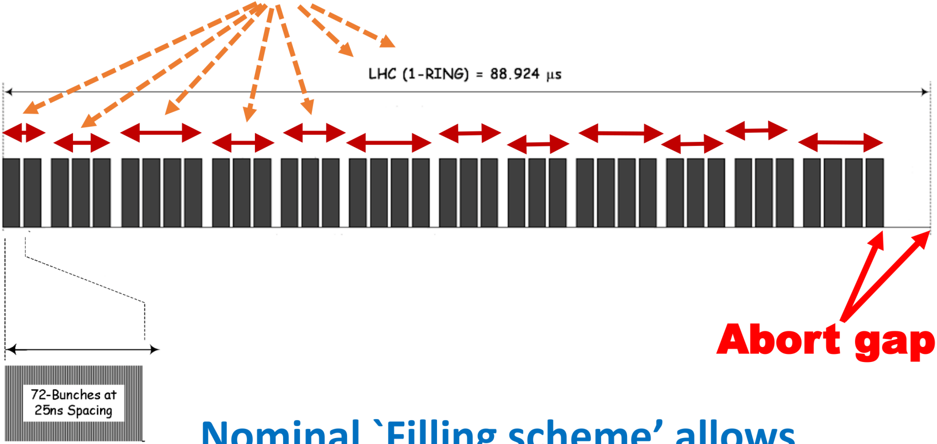
Not practical to inject bunches one at a time!

Increase luminosity by colliding trains



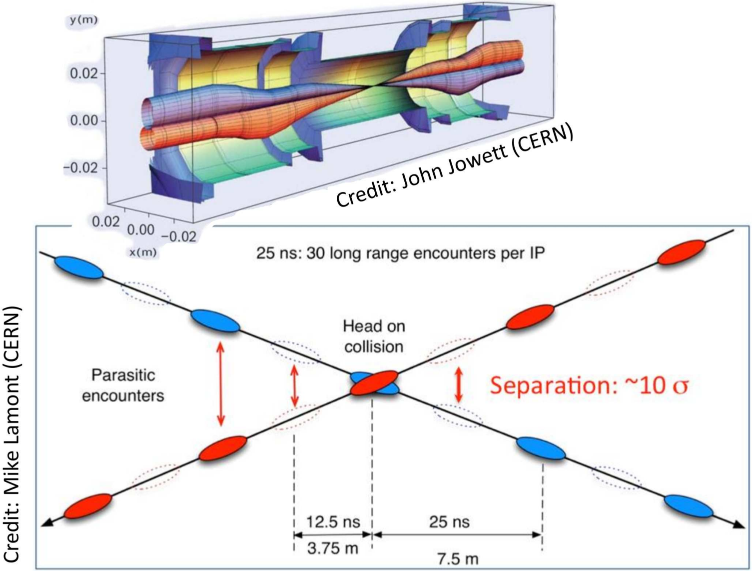
Increase luminosity by colliding trains

Accumulate *`trains'* of bunches in SPS & inject 1 train at a time



Nominal `Filling scheme' allows 2808 bunches in each ring

Introduce *'crossing angle'* to prevent parasitic collisions either side of the IP



Crossing angles reduce the luminosity

$$\boldsymbol{L} = \frac{\left(f_{rev}\, n_{coll}\right)\ N_1 N_2}{2\pi\sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)}\sqrt{\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}} \times S$$

- **Exact value of S depends on operating conditions**
- **Very approximately $S \approx 0.8$**

$$\boldsymbol{L} = \frac{\left(f_{rev}\, n_{coll}\right)\ N_1 N_2}{2\pi\sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)}\sqrt{\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}}$$

Beamsize:

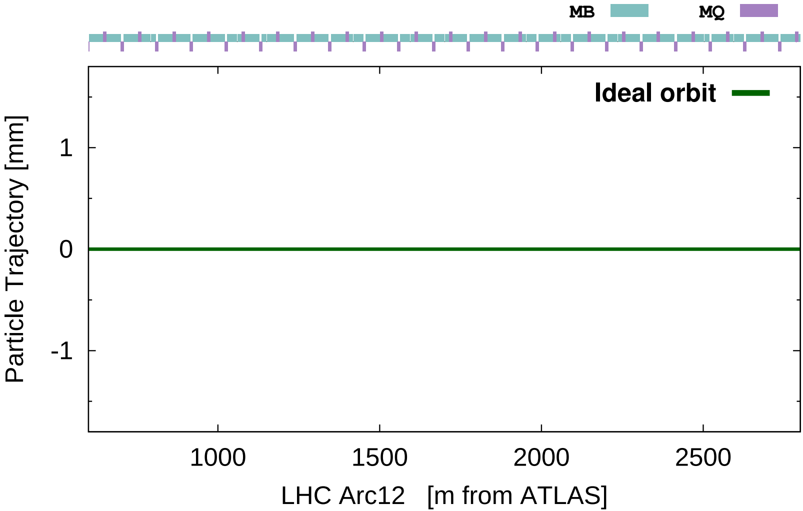
$$\boldsymbol{\sigma_{x,y}} = \sqrt{\boldsymbol{\beta_{x,y}(s)\ \epsilon_{x,y}}}$$

- $\boldsymbol{\beta(s)}$: *'beta-function'* [m]
  - → **Property of the magnetic lattice**
  - → **varies around the ring**
- $\boldsymbol{\epsilon}$: *'emittance'* [μm]
  - → **Property of the particle bunch**
  - → **Invariant around the ring**

$$\sigma_{x,y} = \sqrt{\beta_{x,y}(s)\ \epsilon_{x,y}}$$

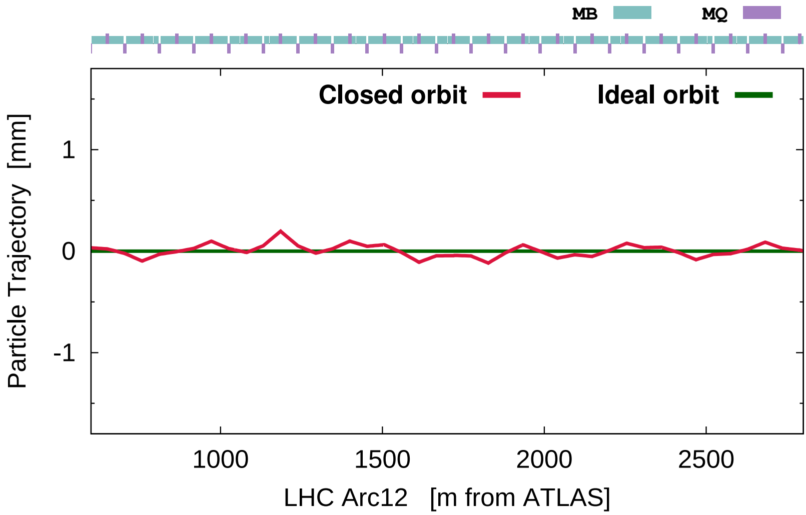
center of a bunch follows closed orbit (CO)

→ orbit closes upon itself after 1 turn

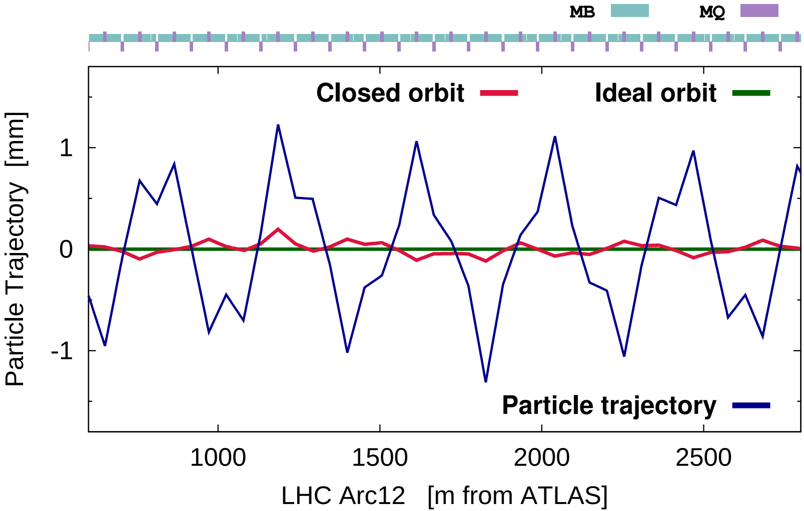


center of a bunch follows closed orbit (CO)

→ dipole imperfections distort CO (but still closes)



Individual particles oscillate about bunch center / CO
$\rightarrow$ caused by restoring forces from quadrupoles

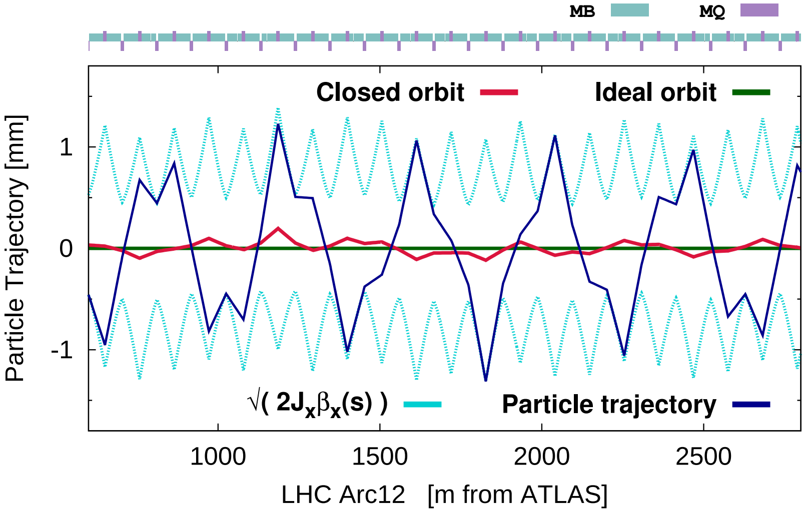


- Restoring force from quadrupoles changes with location
- Restoring force is periodic: $K(s+L) = K(s)$
- Particle motion about CO described by **Hill's equation:**

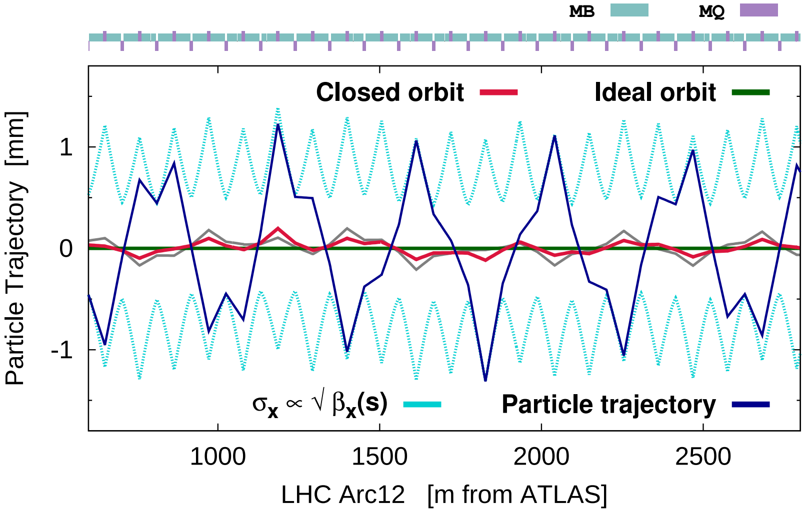
$$\frac{\mathrm{d}^2 x}{\mathrm{d}s^2} - K(s)x = 0$$

$$x = \sqrt{2J_x\beta_x(s)}\cos\left(\phi_x(s) + \phi_0\right) \qquad \phi(s) = \int_0^s \frac{\mathrm{d}s}{\beta(s)}$$

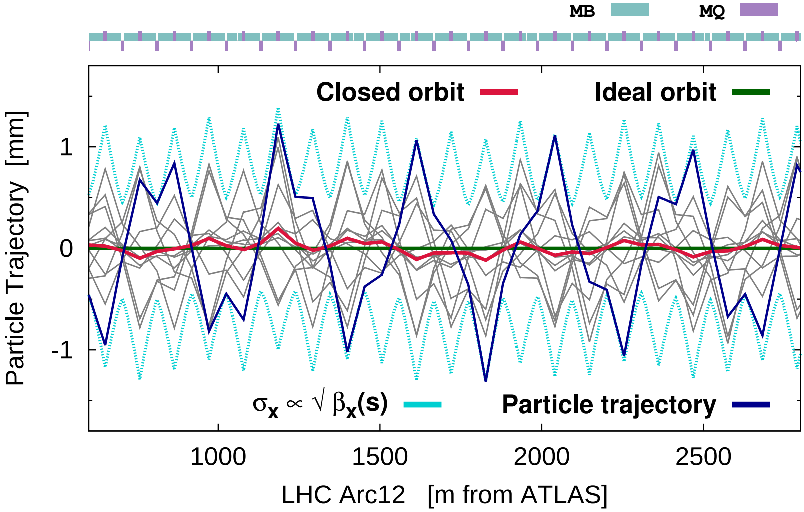
β-function describes evelope of particle oscillations around the closed-orbit



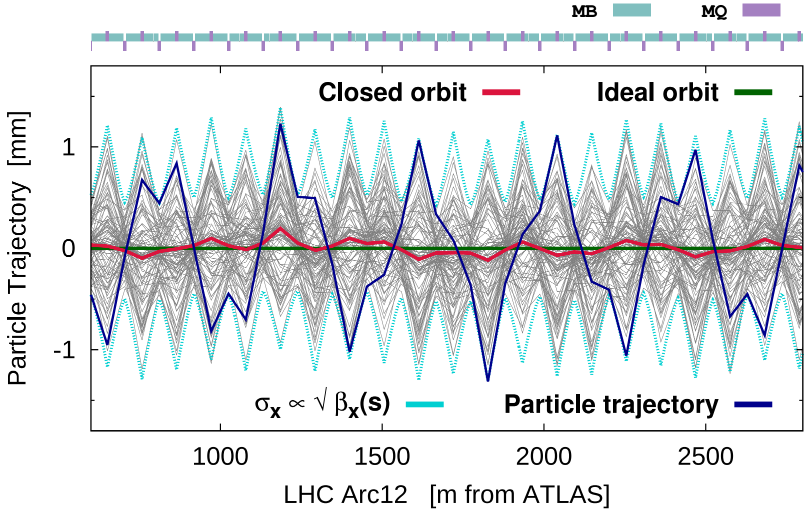
β-function describes evelope of particle oscillations around the closed-orbit



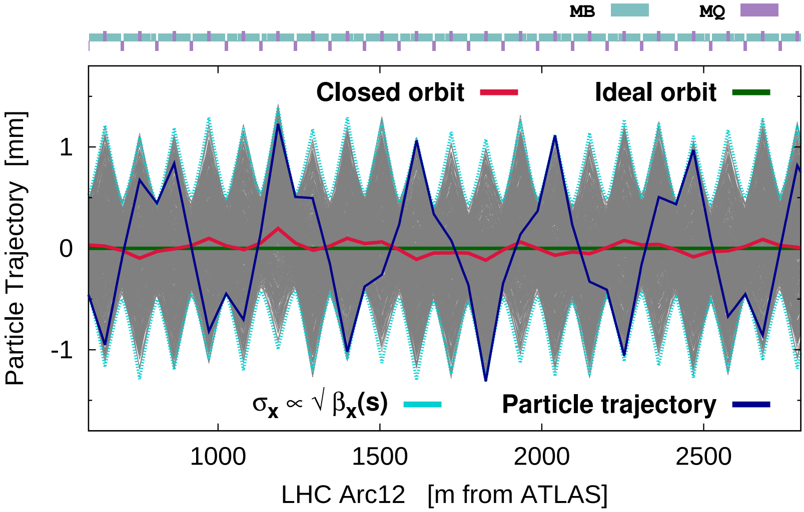
β-function describes evelope of particle oscillations around the closed-orbit



β-function describes evelope of particle oscillations around the closed-orbit

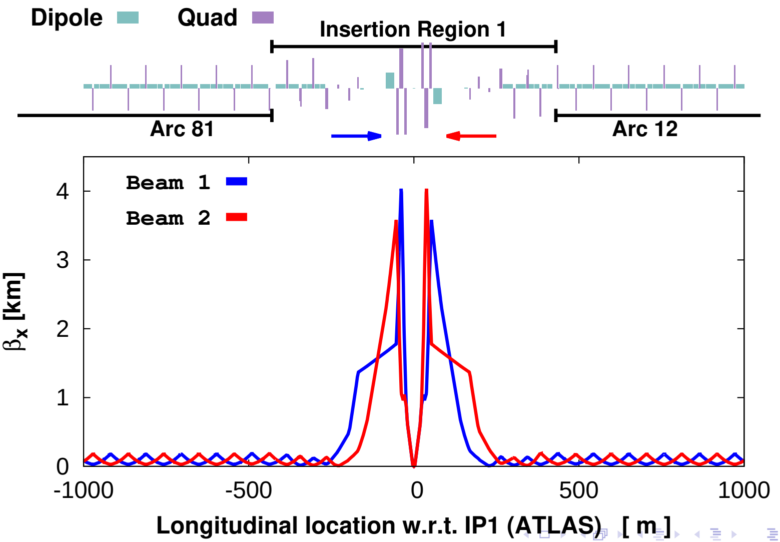


β-function describes evelope of particle oscillations around the closed-orbit



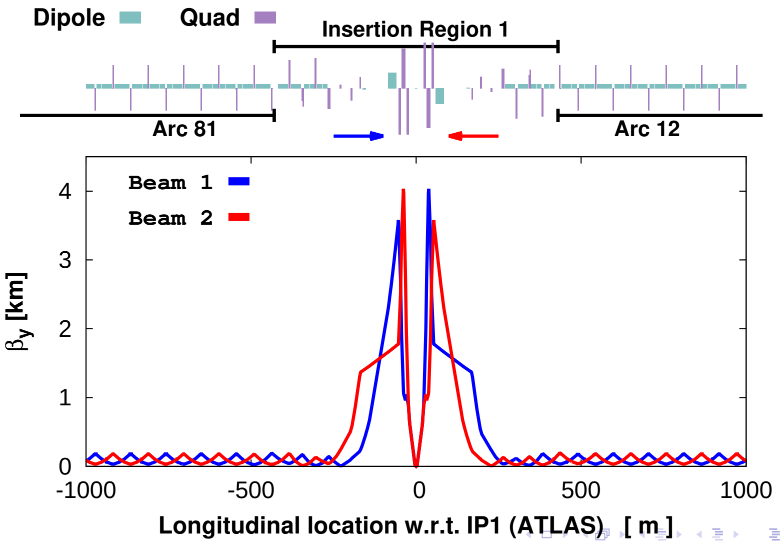
Triplet quadrupoles in experimental IRs squeeze $\beta_{x,y}$

$\rightarrow \beta^{*} = $ minimum β in the IR $\approx 25\,\mathrm{cm}$



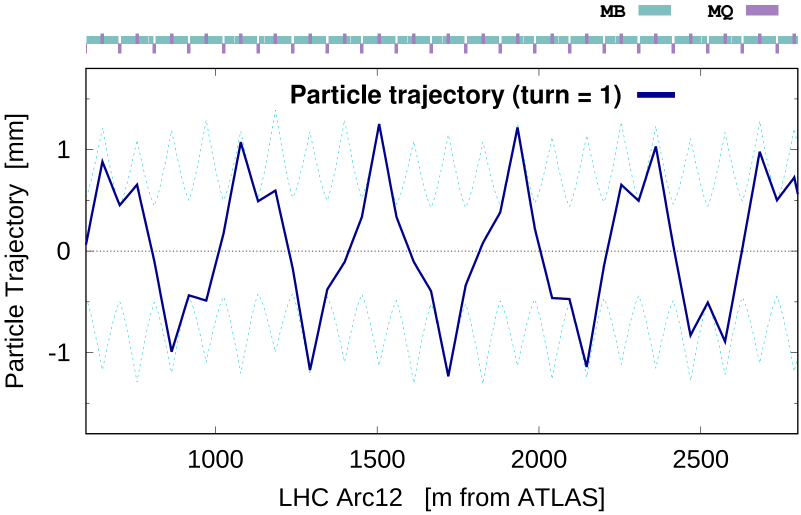
Triplet quadrupoles in experimental IRs squeeze $\beta_{x,y}$

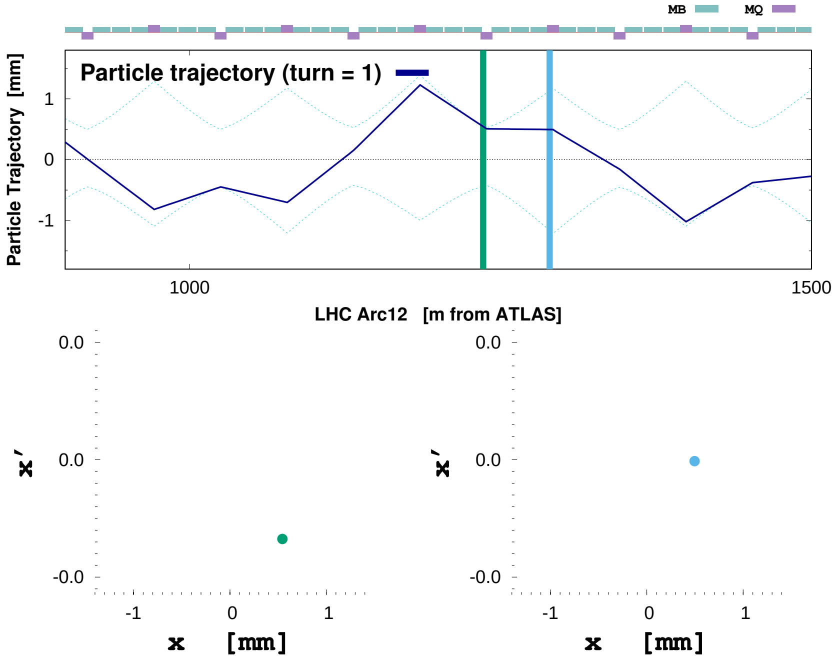
$\rightarrow \boldsymbol{\beta^*} = \text{minimum } \beta \text{ in the IR} \approx 25\,\text{cm}$

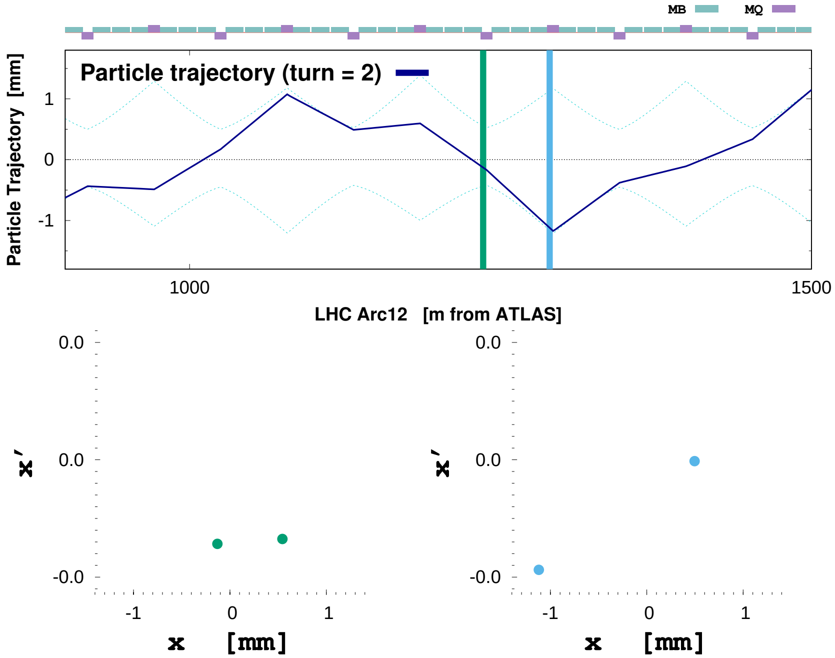


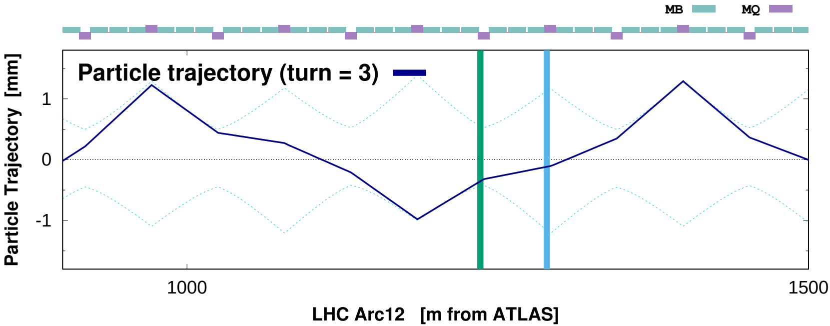
$$\sigma_{x,y} = \sqrt{\beta_{x,y}(s)\ \epsilon_{x,y}}$$

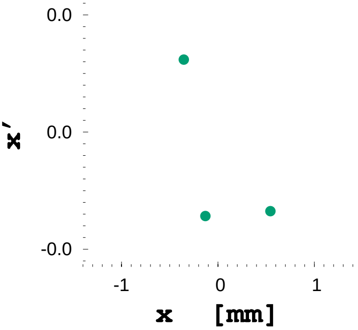
Characterise a particle's trajectory: position (x) and divergent angle ($x' = \frac{\mathrm{d}x}{\mathrm{d}s}$)

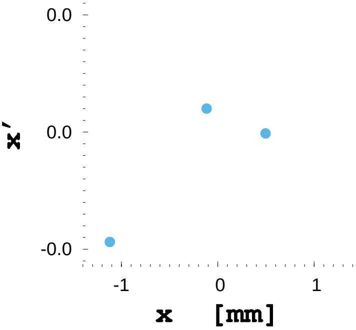


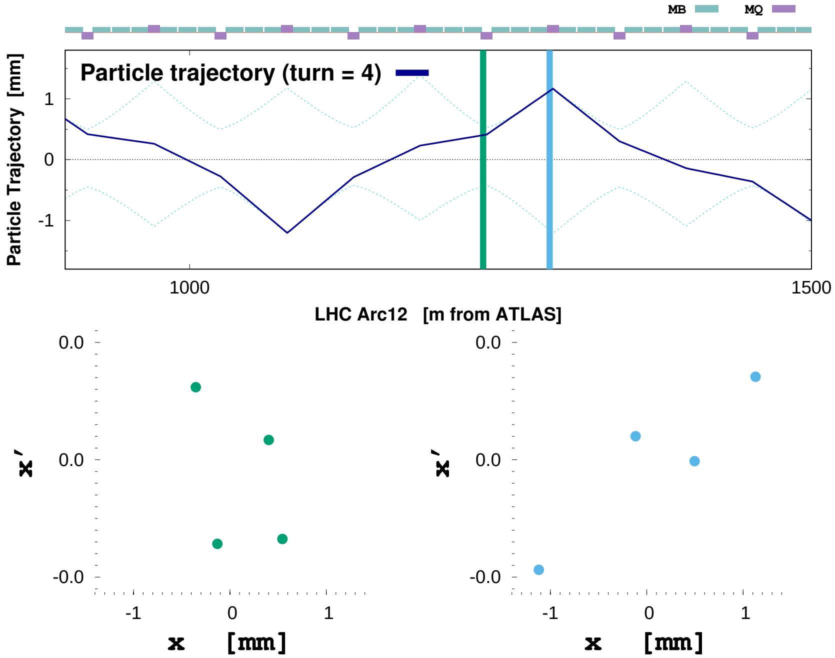

MB
MQ
Particle trajectory (turn = 1)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
x'
0.0
0.0
-0.0
-1
0
1
x [mm]
x'
0.0
0.0
-0.0
-1
0
1
x [mm]

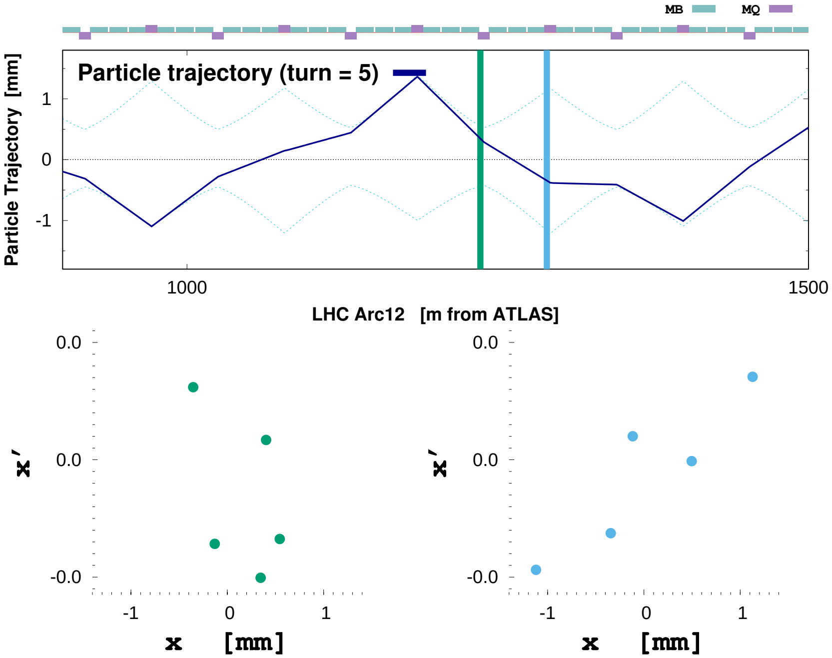

MB
MQ
Particle trajectory (turn = 2)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]

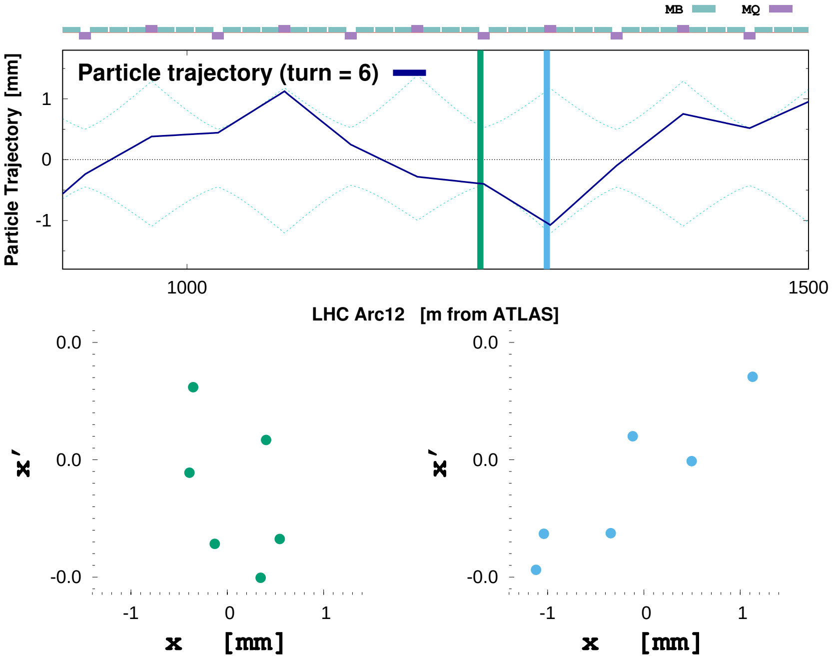

MB
MQ
Particle trajectory (turn = 3)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]

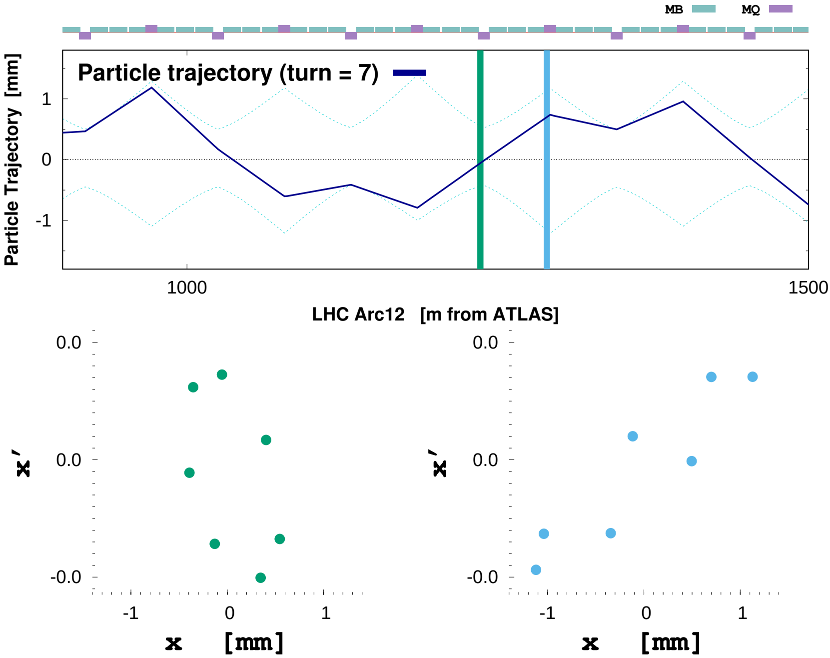

0.0
0.0
-0.0
x′
-1
0
1
x [mm]

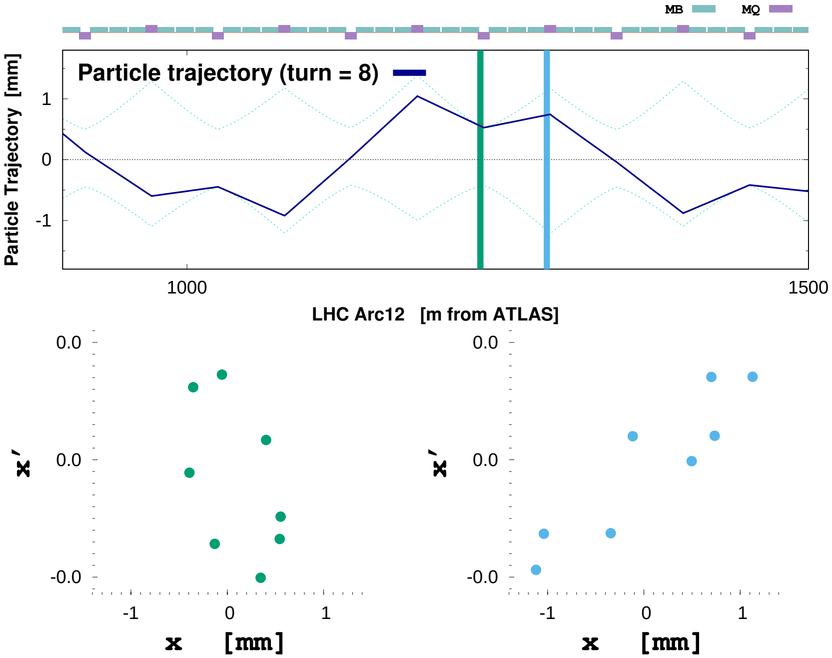

0.0
0.0
-0.0
x′
-1
0
1
x [mm]

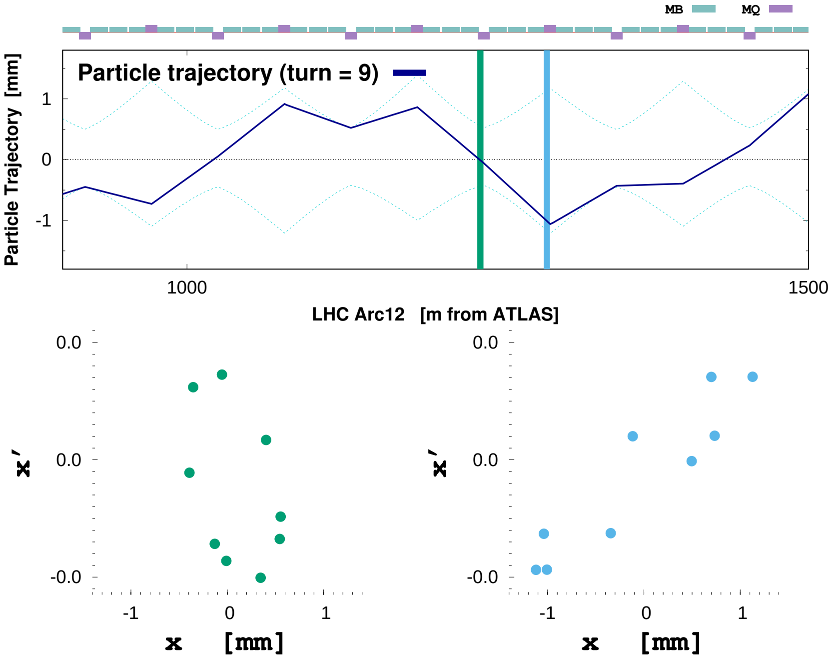

MB
MQ
Particle trajectory (turn = 4)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]

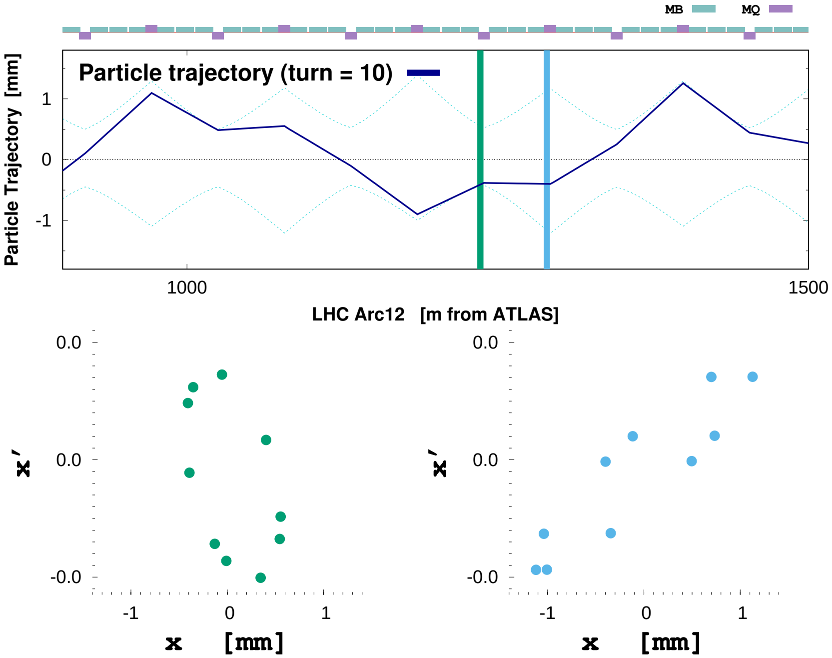

MB
MQ
Particle trajectory (turn = 5)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]


MB
MQ
Particle trajectory (turn = 6)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]


MB
MQ
Particle trajectory (turn = 7)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
x′
0.0
-0.0
-1
0
1
x [mm]
0.0
x′
0.0
-0.0
-1
0
1
x [mm]

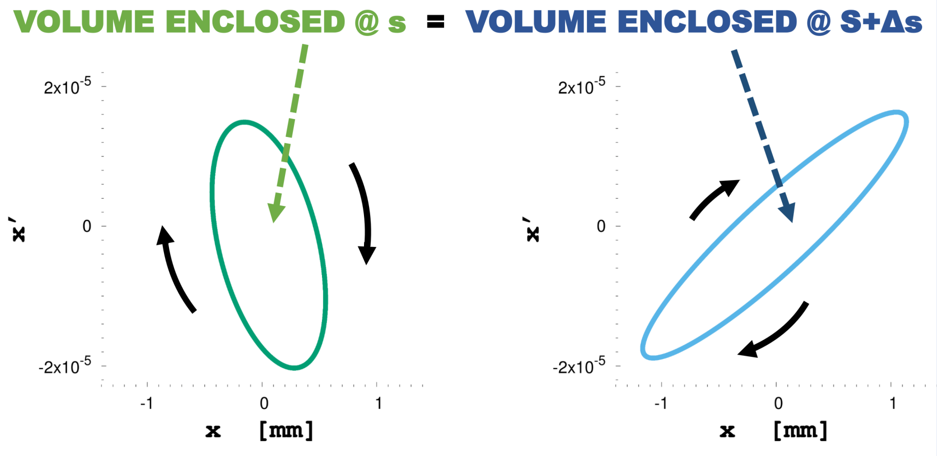

MB
MQ
Particle trajectory (turn = 8)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
0.0
-0.0
x′
-1
0
1
x [mm]
0.0
0.0
-0.0
x′
-1
0
1
x [mm]


MB
MQ
Particle trajectory (turn = 9)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]
0.0
0.0
-0.0
x'
-1
0
1
x [mm]


MB
MQ
Particle trajectory (turn = 10)
Particle Trajectory [mm]
1
0
-1
1000
1500
LHC Arc12 [m from ATLAS]
0.0
0.0
-0.0
x′
-1
0
1
x [mm]
0.0
0.0
-0.0
x′
-1
0
1
x [mm]

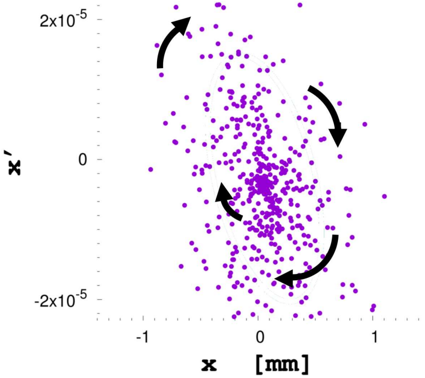
Particles trace out eliptical paths in (x,x') phase space

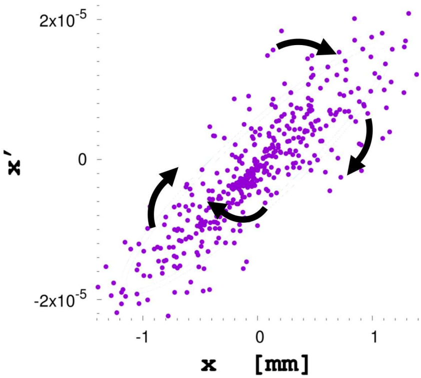
- shape changes around the ring
- **Area of ellipse is invariant** (for constant energy)



Particles trace out eliptical paths in (x,x') phase space

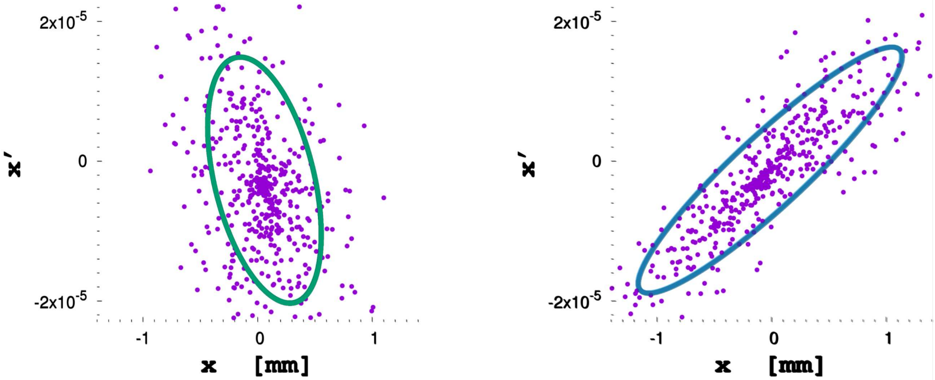
- in practice have many particles
- all follow similar eliptical trajectories (linear approximation)





Particles trace out eliptical paths in (x,x') phase space

- '**beam emittance**' is area/π of elipse enclosing 1σ of the particles in the bunch



$$\sigma_{x,y} = \sqrt{\beta_{x,y}(s)\ \epsilon_{x,y}}$$

What about the real world?

Emittance conserved providing particle's energy is constant

Acceleration

Define *'normalized emittance'* which is invariant with the beam energy

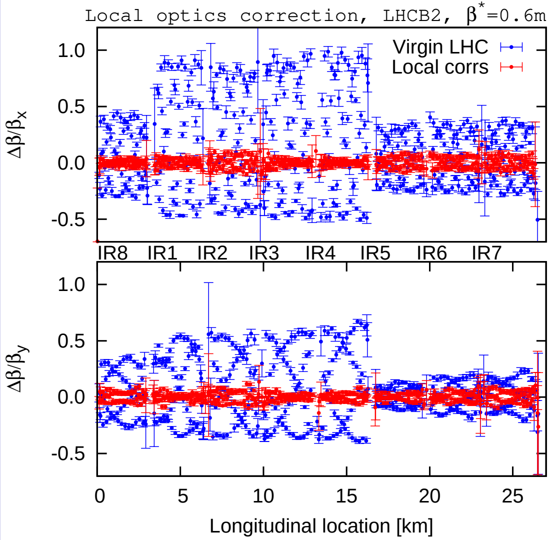
$$\epsilon^* = \beta_{rel}\gamma_{rel}\epsilon$$

In practice many effects can change or dilute emittance

- **Injection errors**
- **Synchrotron radiation**
- **IntraBeam Scattering**
- **Emittance evolution in LHC still not fully undersood!**

What about the real world?

→ Characterize optics quality by **'beta-beating'**



$$\frac{\Delta\beta}{\beta} = \frac{\beta_{meas} - \beta_{nominal}}{\beta_{nominal}}$$

Beam-based correction of LHC optics is essential to operation

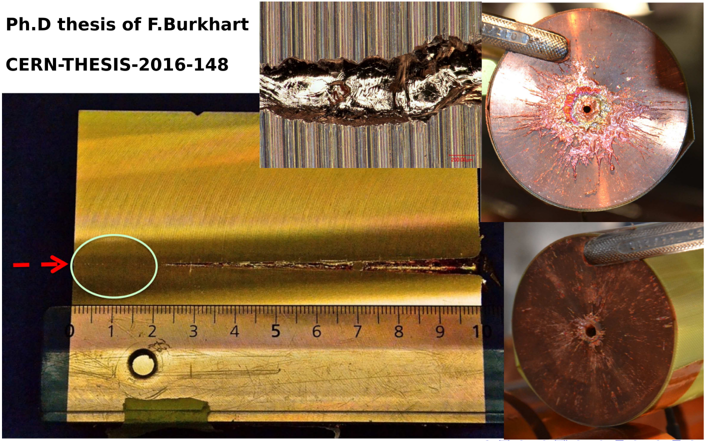
- Optics errors can reduce data delivered to HEP experiments
- Create Luminosity imbalance between HEP experiments

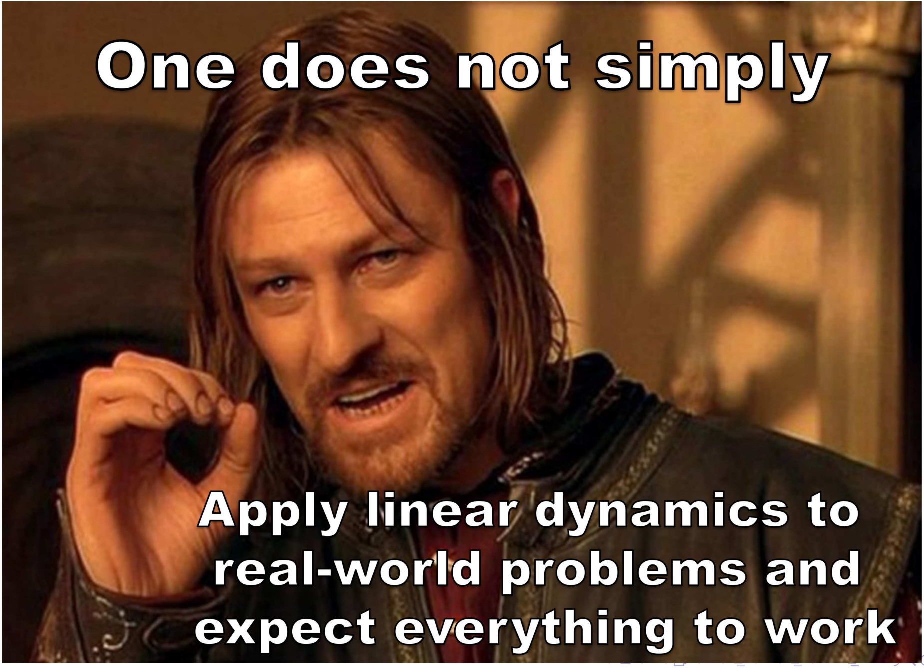
$\rightarrow$ **Aim for β^*-beat $\leq 1\,\%$**

- MACHINE PROTECTION $\rightarrow$ **require beta-beat $\leq 18\,\%$**

Ph.D thesis of F.Burkhart

CERN-THESIS-2016-148

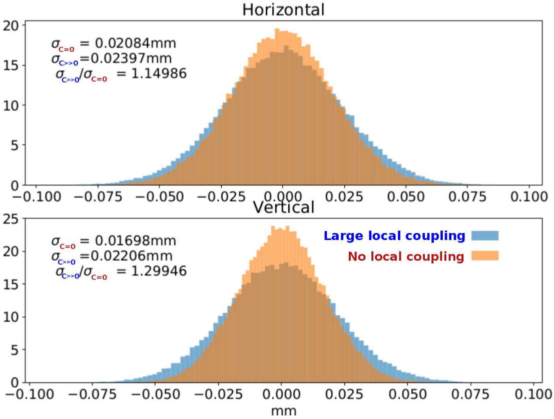



One does not simply
Apply linear dynamics to
real-world problems and
expect everything to work

A more accurate description of beam-size considers coupled 4D phase space

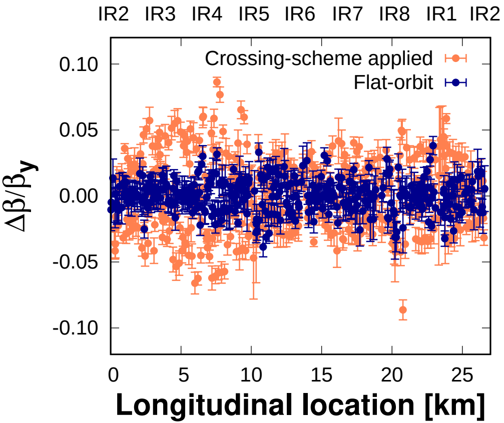
$$\Sigma_x^2 = \beta_{11}\epsilon_1 + \beta_{12}\epsilon_2$$
$$\Sigma_y^2 = \beta_{21}\epsilon_1 + \beta_{22}\epsilon_2$$

Betartron motion with coupling of horizontal and vertical degrees of freedom V.A.Lebedev, S.A.Bogacz FERMILAB-PUB-10-383-AD



Poor local coupling correction in IR2 during 2018 Pb/Pb run caused 50 % reduction to Luminosity delivered to ALICE until diagnosed & corrected

Nonlinear magnetic (sextupole,octupole) fields create orbit dependent perturbations of the beam size



2017 optics related lumi-imbalance without nonlinear correction:

$$\frac{L_{\mathrm{CMS}}}{L_{\mathrm{ATLAS}}} = 0.974 \pm 0.004$$

2017 optics related lumi-imbalance with nonlinear correction:

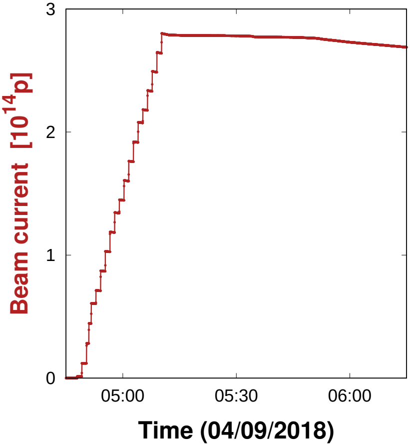
$$\frac{L_{\mathrm{CMS}}}{L_{\mathrm{ATLAS}}} = 1.003 \pm 0.004$$

Also ignored momentum dependent effects.

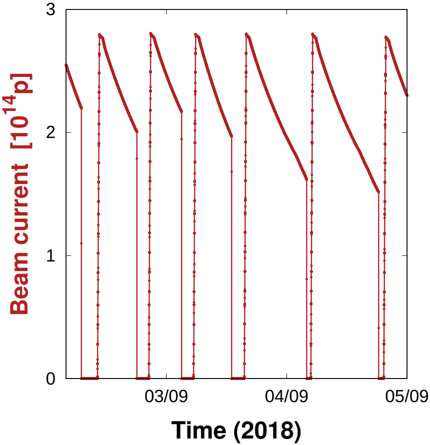
$$\boldsymbol{L} = \frac{\left(f_{rev}\, n_{coll}\right)\ N_1 N_2}{2\pi\sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)}\sqrt{\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}}$$

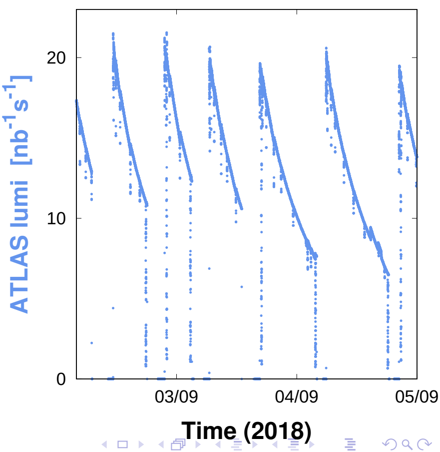
- $N_{1,2}$: **Number of particles per bunch**

- **Accumulate bunch trains in the LHC ring at 450GeV**
- **Accelerate to 6.5TeV**
- **Bring bunches into collision & store for several hours**
- **Dump / Repeat**

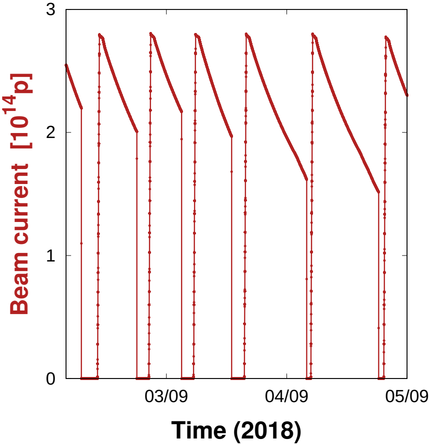


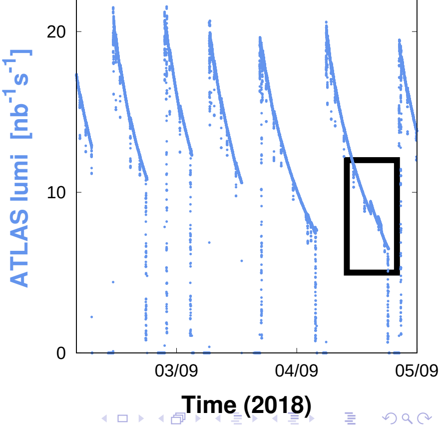
- Beam intensity decays during a fill
- Show a corresponding reduction in instantaneous luminosity
- Bulk of decay (LHC ideal conditions) is losses of particles which are colliding at the IPs ‘burnoff’



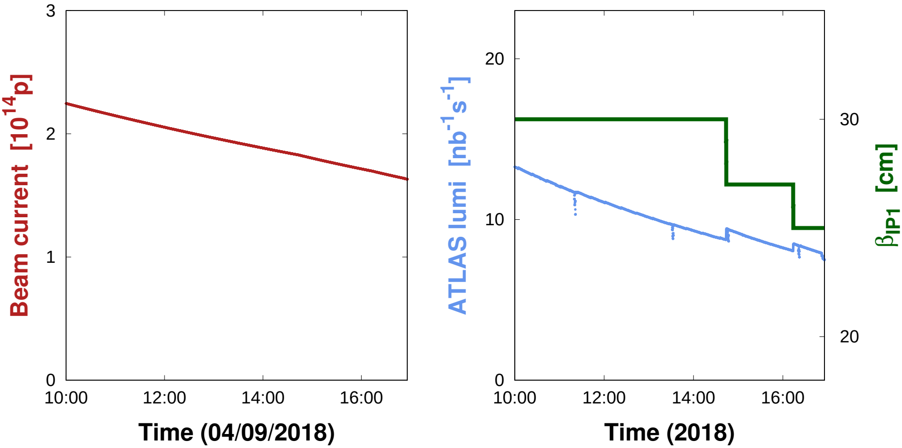


- **Beam intensity decays during a fill**
- **Show a corresponding reduction in instantaneous luminosity**
- **Bulk of decay (LHC ideal conditions) is losses of particles which are colliding at the IPs 'burnoff'**

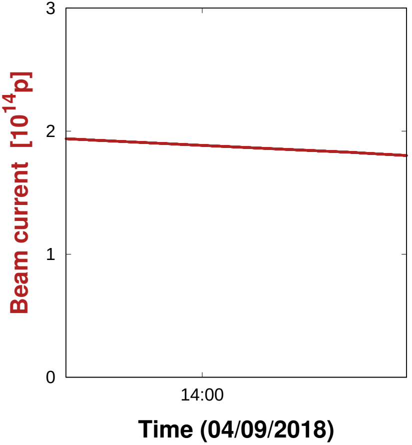


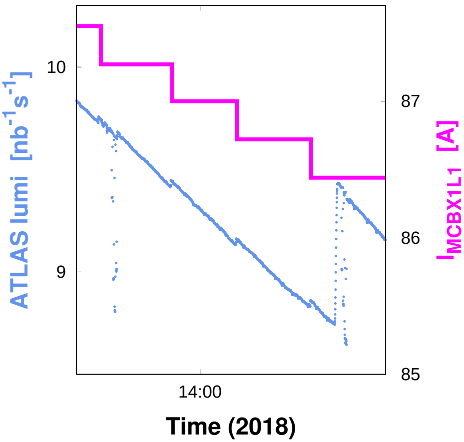


- **Can try to maintain luminosity while $N_{1,2}$ decays by changing other accelerator parameters which influence luminosity**
- '**Luminosity levelling**' $\rightarrow$ e.g. β^*-levelling

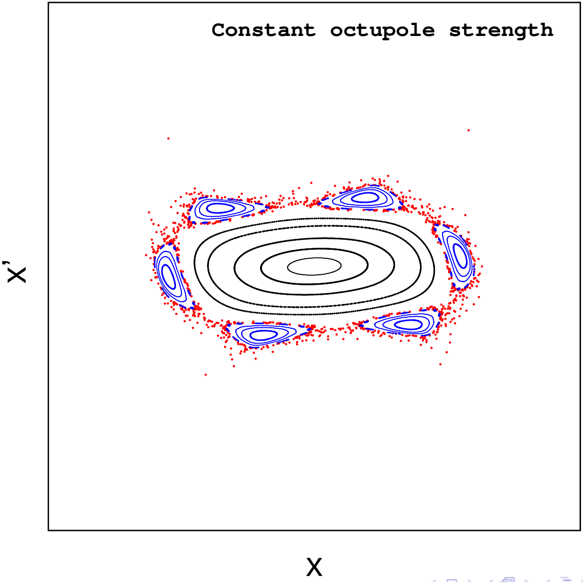


- **Can try to maintain luminosity while $N_{1,2}$ decays by changing other accelerator parameters which influence luminosity**
- '**Luminosity levelling**' → e.g. crossing-angle levelling

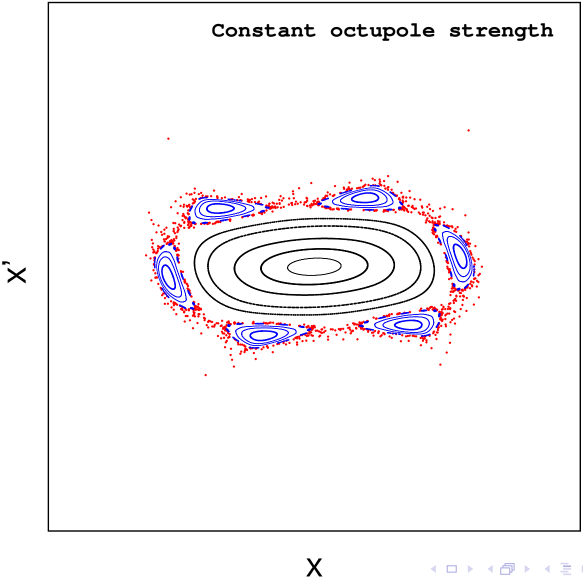




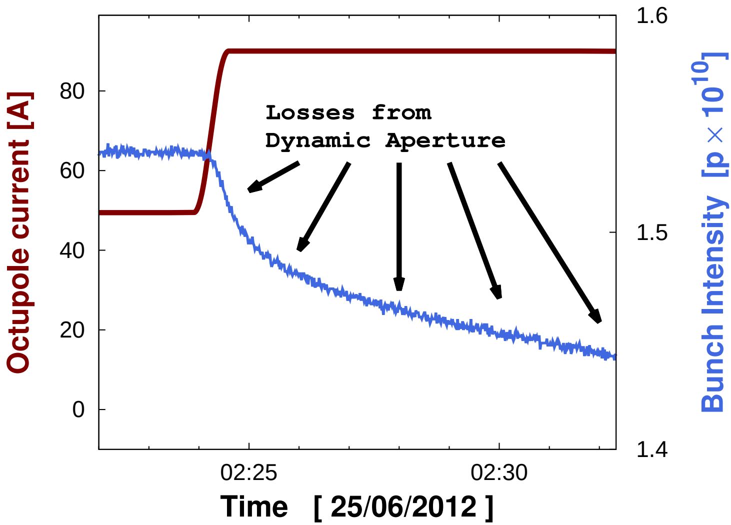
What about the particles that don't collide?



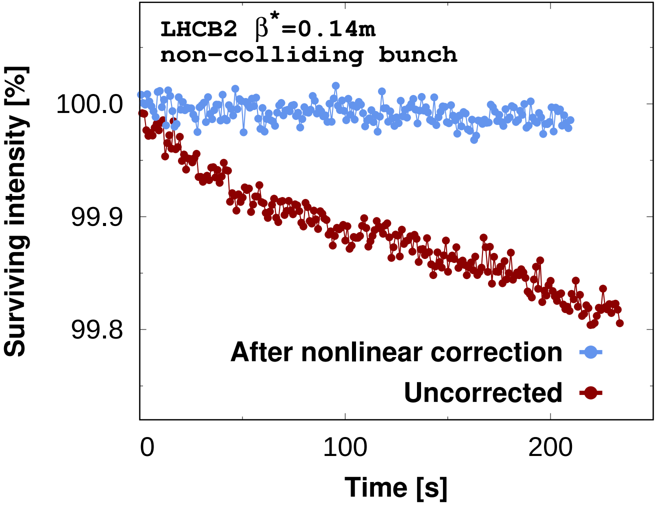
Large amplitude particles' motion can become chaotic & unstable → '**Dynamic aperture**'



The more nonlinear the beam dynamics becomes the smaller the dynamic aperture



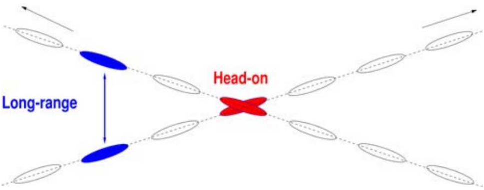
Can use sextupole, octupole, decapole & dodecapole magnets to correct nonlinear dynamics in LHC



Beams themselves can introduce large nonlinearities into the dynamics e.g.

Beam-Beam

- Force exerted on a particle by the fields of bunches in the other beam
- **A major limitation to LHC performance**



Collective effects have a big influence on LHC performance!

'Intensity Limitations in Particle Beams' CERN Accelerator School, 2-11 Nov 2015, Geneva, Switzerland https://cds.cern.ch/record/865932

Key Points

- **What is luminosity?**
- **What are its main dependencies?**
- **There are many real world complications which affect the luminosity!**

Event rate for a HEP interaction:

$$R = L \times \sigma$$

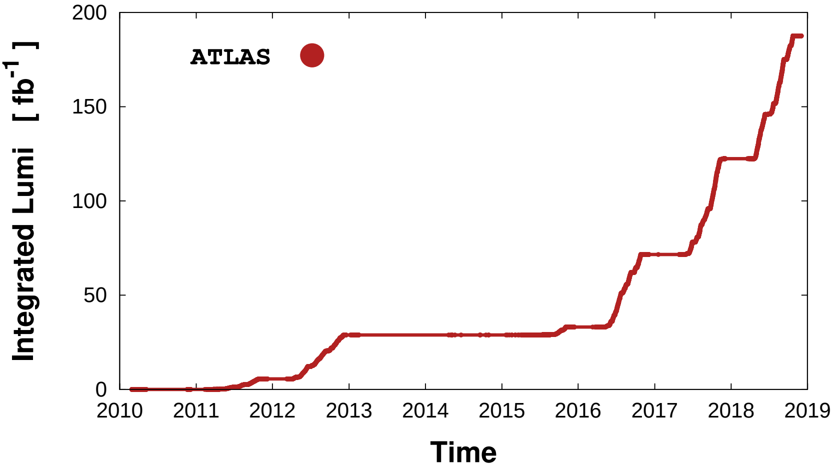
- R: *Event Rate* $[\mathrm{s}^{-1}]$
- σ: *Cross Section* $[\mathrm{barn} = 10^{-34}\mathrm{cm}^2]$
  property of the HEP interaction
- L: *Luminosity* **[inverse barn / s]**
  property of the collider

Total number of interactions defined by the Integrated Luminosity [inverse femto-barn]

$$N = \left(\int L(t)\mathrm{d}t\right) \times \sigma$$

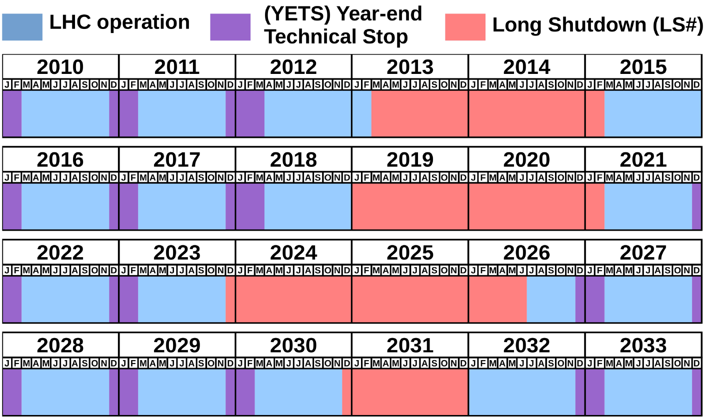
Integrated Luminosity is key figure of merit for collider like LHC

→ significant factor is how much time spent on luminosity production



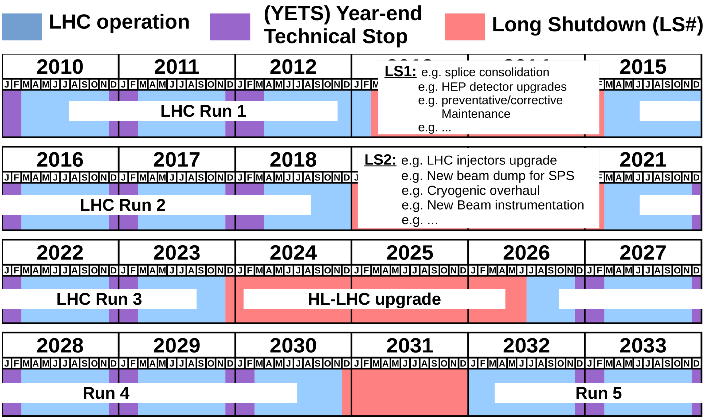
https://lhc-statistics.web.cern.ch/LHC-Statistics/

Approximate schedule for LHC lifetime (accurate up to 2019)



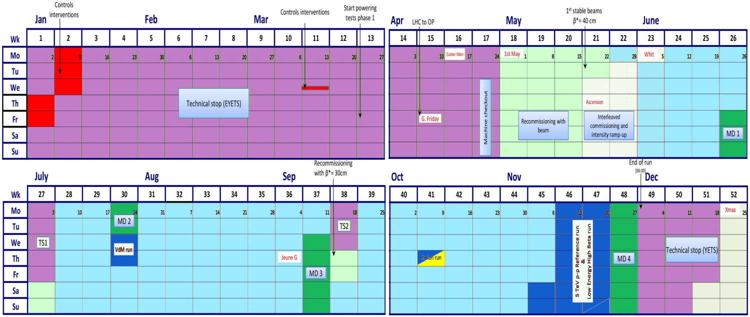
- LHC operation is interspersed with regular **shutdown** periods for maintenance and upgrades

Approximate schedule for LHC lifetime (accurate up to 2019)



- LHC operation is interspersed with regular **shutdown** periods for maintenance and upgrades

LHC schedule over 1 year (2017)

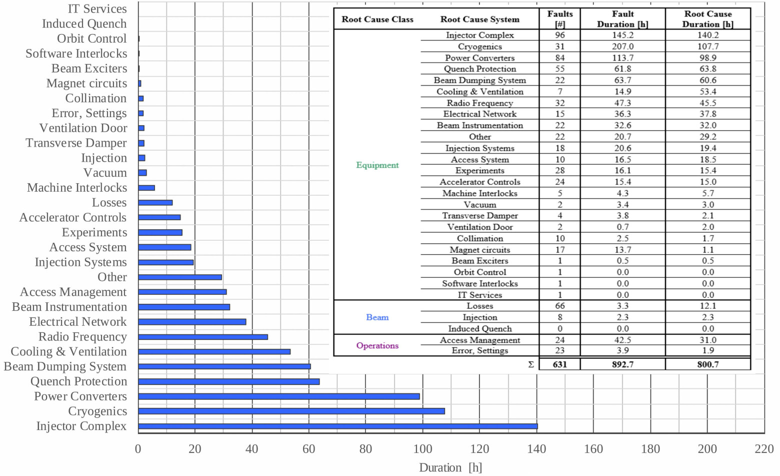


Many types of activities during 1 year of LHC operation

- Technical Stop (YETS + regular breaks)
- Accelerator commissioning
- Accelerator physics/technology studies
- Luminosity production proton-proton and special runs

LHC is an extremely complicated system

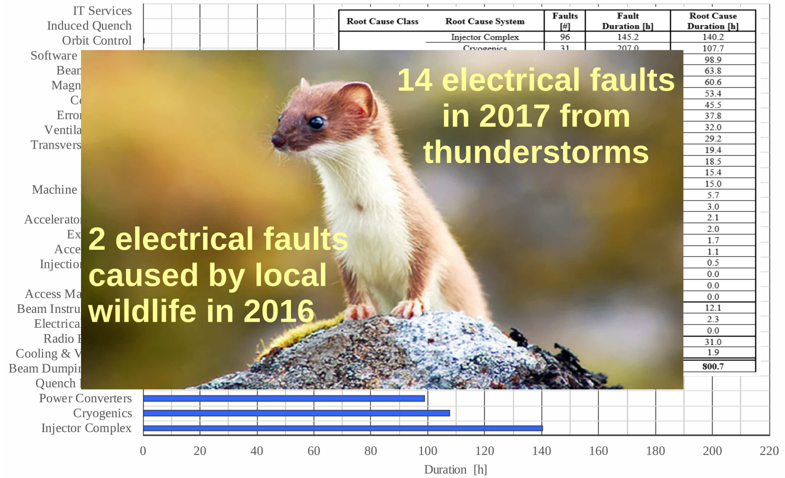
- Even small technical problems add up over 1 year
- Statistics for LHC availabitity/faults monitored by *availability working group*, e.g. 2017:



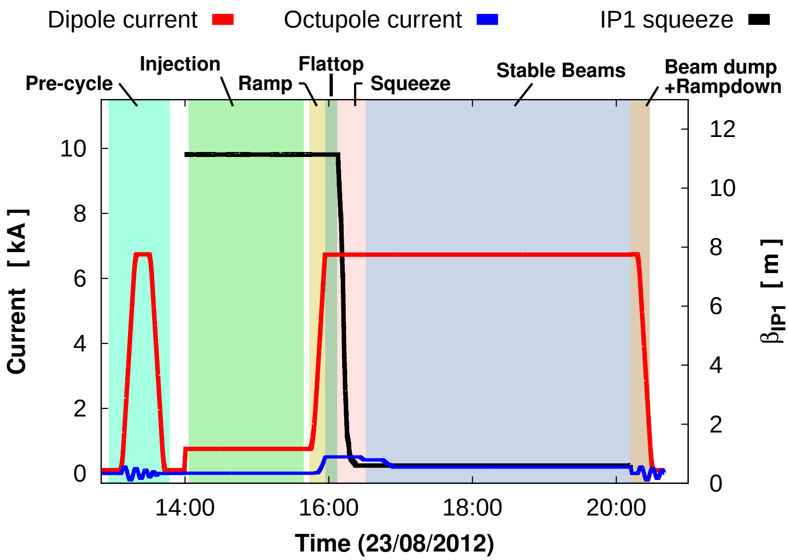
Root Cause Class	Root Cause System	Faults [#]	Fault Duration [h]	Root Cause Duration [h]
Equipment	Injector Complex	96	145.2	140.2
	Cryogenics	31	207.0	107.7
	Power Converters	84	113.7	98.9
	Quench Protection	55	61.8	63.8
	Beam Dumping System	22	63.7	60.6
	Cooling & Ventilation	7	14.9	53.4
	Radio Frequency	32	47.3	45.5
	Electrical Network	15	36.3	37.8
	Beam Instrumentation	22	32.6	32.0
	Other	22	20.7	29.2
	Injection Systems	18	20.6	19.4
	Access System	10	16.5	18.5
	Experiments	28	16.1	15.4
	Accelerator Controls	24	15.4	15.0
	Machine Interlocks	5	4.3	5.7
	Vacuum	2	3.4	3.0
	Transverse Damper	4	3.8	2.1
	Ventilation Door	2	0.7	2.0
	Collimation	10	2.5	1.7
	Magnet circuits	17	13.7	1.1
	Beam Exciters	1	0.5	0.5
	Orbit Control	1	0.0	0.0
	Software Interlocks	1	0.0	0.0
	IT Services	1	0.0	0.0
Beam	Losses	66	3.3	12.1
	Injection	8	2.3	2.3
	Induced Quench	0	0.0	0.0
Operations	Access Management	24	42.5	31.0
	Error, Settings	23	3.9	1.9
	Σ	631	892.7	800.7

LHC is an extremely complicated system

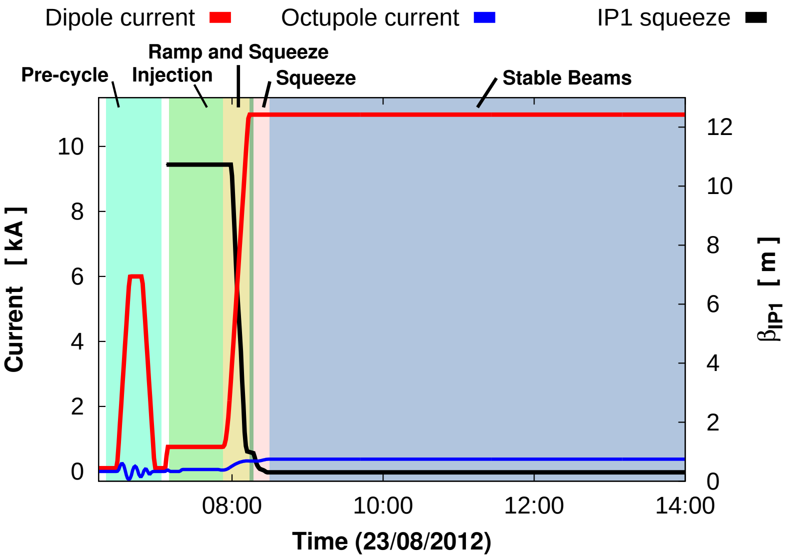
- Even small technical problems add up over 1 year
- Statistics for LHC availabitity/faults monitored by *availability working group*, e.g. 2017:



Not all time during operation spent colliding beams: **LHC cycle (2012)**



Reduced turn-around-time inceases integrated lumi: **LHC cycle (2018)**

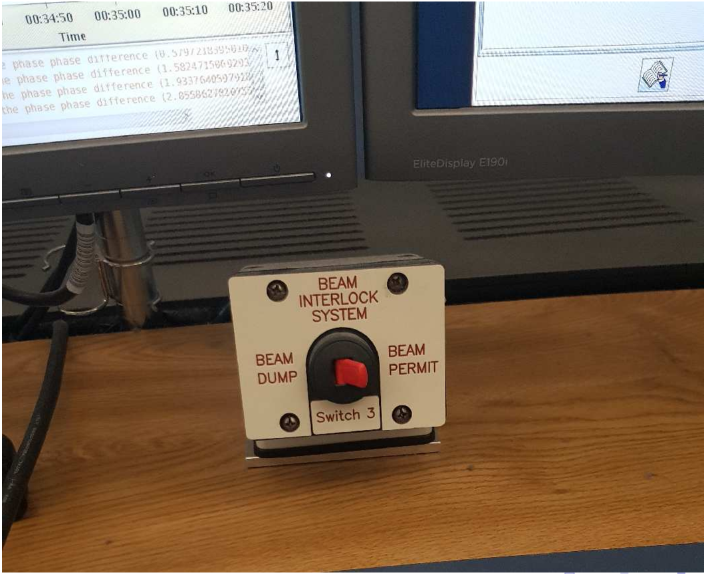


Gain 6 day/year from combined Ramp/Squeeze & precyle optimization

Key Points

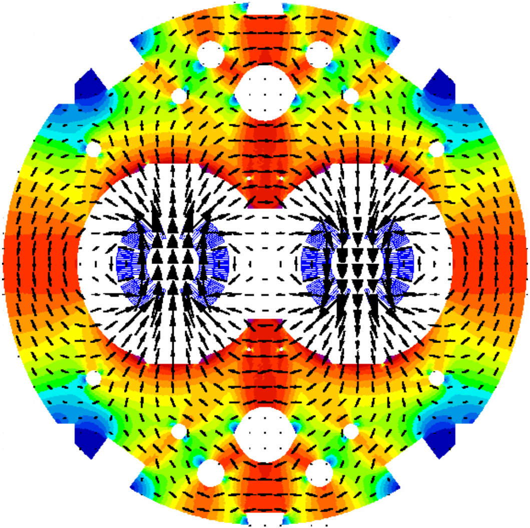
- Integrated luminosity is the key figure of merit for a collider like the LHC
- How much time is actually spent colliding beams together?
- What are we doing the rest of the time?

Many thanks for your attention!



Reserve

Arcs utilize superconducting 8.3 T dual bore dipoles



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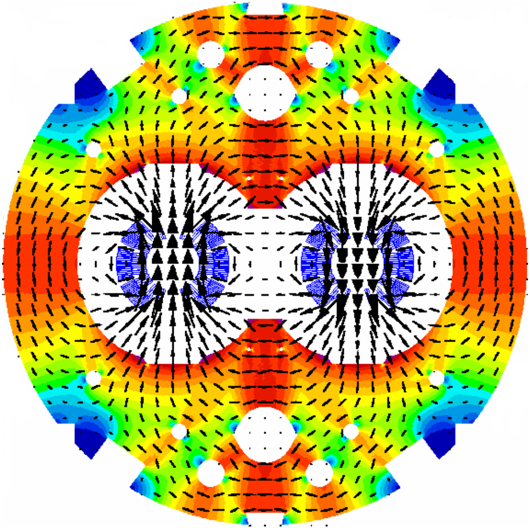

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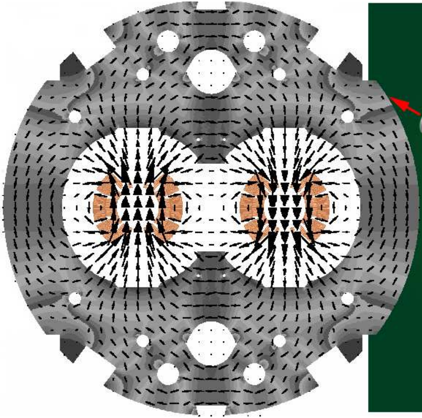
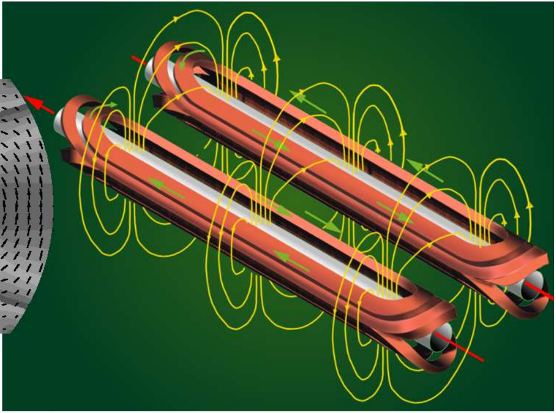
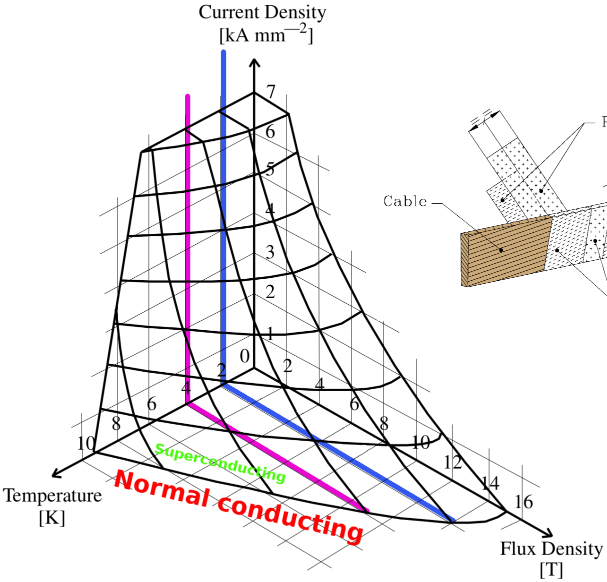
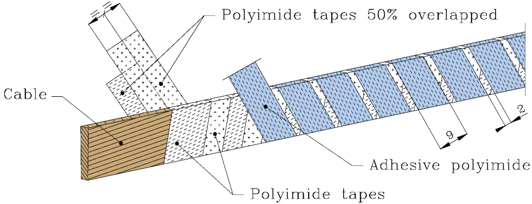




NbTi coils cooled to $1.9\,\mathrm{K}$ with superfluid helium





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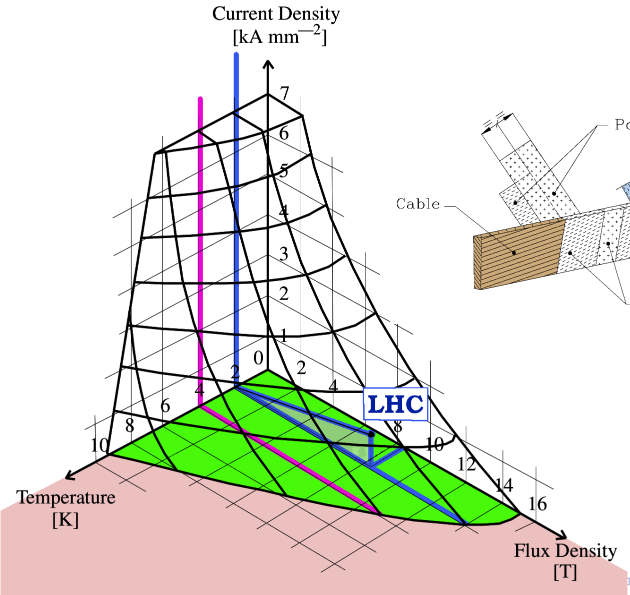

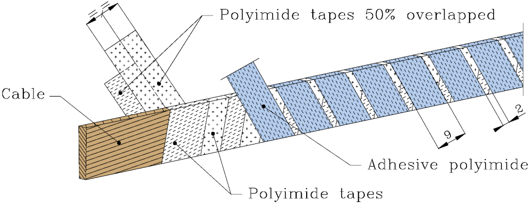

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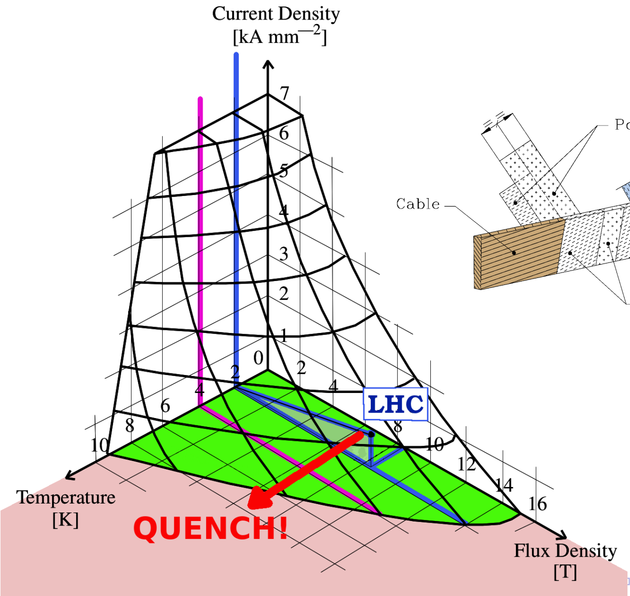
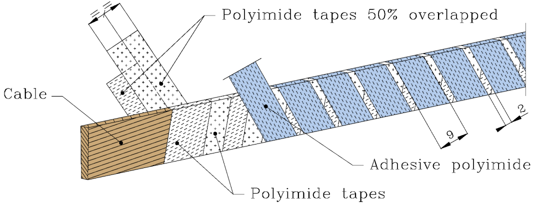


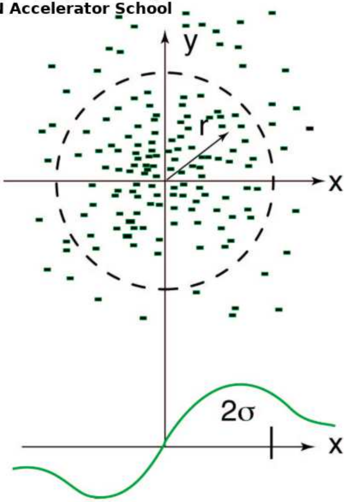


Beams themselves can introduce large nonlinearities into the dynamics e.g.

Direct Space Charge

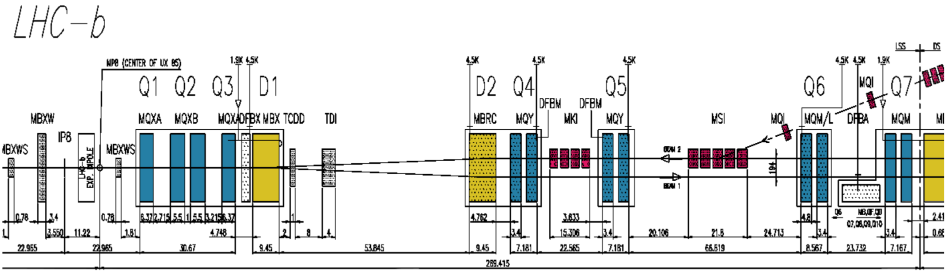
- Repulsive (defocusing) force on a particle due to the field of all other particles in the bunch
- **A big challenge at low energy in injector chain**

K.Schind, `Space Charge'
CERN Accelerator School



Similar problem at injection

IR8 (LHCb / beam2 injection)
Right side viewed from above



Injection kickers have rise time of ~1us