Unit 2

Magnets for circular accelerators: the interaction regions

Ezio Todesco
European Organization for Nuclear Research (CERN)

Lectures based on USPAS courses in 2009-2015 with P. Ferracin, H. Felice, S. Prestemon
and on University of Milano Bicocca courses in 2016-2018
Thanks to L. Bottura and G. de Rijk for proposing and supporting this initiative

All the units will use International System (meter, kilo, second, ampere) unless specified

PLAN OF THE LECTURES

- Part 1 – From beam dynamics to magnet specifications
  - Unit 1: the energy of a synchrotron and the magnets in the arcs
  - Unit 2: the luminosity in a collider and the interaction region magnets – will be mostly focused on the LHC case
- Part 2 – Principles of electromagnets
- Part 3 – Basics of superconductivity
- Part 4 – Magnet design
  - Each unit lasting approximately 90 minutes
  - Additional units with exercises could be envisaged

TENTATIVE RULES OF THE LECTURES

- Lectures are carried out in the early European morning to allow participation from Eurasia
- Please register yourself for each unit, so we have an idea of the attendance
  - Put also your institute
- When entering vidyo, please use your name and surname
  - Please, not email of initials …
- During the lecture mute the microphone
- Questions (please ask !)
  - I will stop from time to time to open for questions
  - Otherwise please use the dialog box
  - When you make questions, please switch camera on, and tell your name and institute
- Lectures will be registered, but this should not limit the possibility to put questions (even naïve, wrong, or stupid) – we are here to learn

CONTENTS

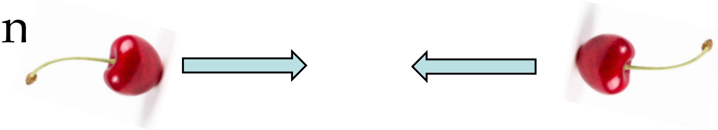
- Equation for luminosity
- A few words about detector magnet size
- The interaction regions: low-beta magnet specifications
  - How to squeeze the beam to get more collisions
  - Gradient and aperture requirements for low-beta quadrupoles

LUMINOSITY

- After the energy, the luminosity is the other main characteristic of an accelerator
  - Related to the quantity of collisions per second
- The property of the accelerator is the rate of collisions divided by the cross section: this is the luminosity *L*
  - Expressed in $\mathrm{cm^{-2}\,s^{-1}}$ (CGS units)
- Luminosity multiplied by the cross section gives the rate of collisions
- Cross-sections usually given in barn
  - 1 barn = $10^{-28}\ \mathrm{m^2} = 10^{-24}\ \mathrm{cm^2}$

This is not a barn

- Order of magnitudes for the LHC
  - Nominal luminosity is $10^{34}\ \mathrm{cm^{-2}\,s^{-1}}$
  - Cross-section for proton-proton is abut 100 mbarn, 1 billion events per second
  - If the LHC were colliding cherries (1 $\mathrm{cm^2}$ of area) we would have 10^{34} collisions per secon



LUMINOSITY

- Equation for the luminosity, and LHC design parameters

$$L = \frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F = \frac{c}{4\pi}\frac{\gamma}{l}N_b^2 n_b\frac{1}{\varepsilon_n\beta^*}F$$

Accelerator features

Energy of the machine 7 TeV

Length of the machine 27 km

Beam intensity features

N_b Number of particles per bunch 1.15×10^{11}

n_b Number of bunches ~2808

Beam geometry features

ε_n Size of the beam from injectors: 3.75×10^{-6} m

β^* Squeeze of the beam in IP (LHC optics): 55 cm

F: geometry reduction factor: 0.84

Nominal luminosity: 10^{34} cm^{-2} s^{-1}

(considered very challenging in the 90's,
this parameter was pushed up to compete with SSC)

LUMINOSITY

- Equation for the luminosity

$$L=\frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F=\frac{c}{4\pi}\frac{\gamma}{l}N_b^2 n_b\frac{1}{\varepsilon_n\beta^*}F$$

- We will outline some of the limits to getting large luminosities
  - Beam beam (limit on N_b/ε_n)
  - Parasitic beam-beam and the crossing angle
  - Electron cloud (limit on n_b)
  - Squeeze (limit on $\beta^* \varepsilon_n$)
  - Injectors (limit on N_b, n_b, ε_n)

LIMITS TO LUMINOSITY
HEAD ON BEAM-BEAM

- The beam-beam limit (Coulomb)

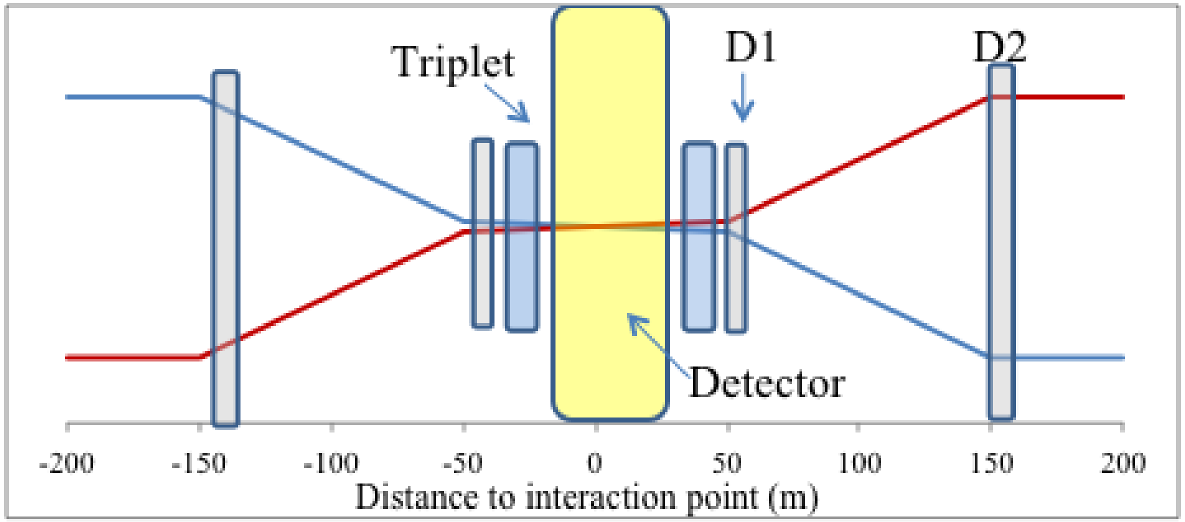
$$L = \frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F = \boxed{\frac{N_b}{\varepsilon_n}} N_b n_b \frac{f_{rev}\gamma}{4\pi\beta^*}F$$

$$\xi = n_{IP}\frac{r_p}{4\pi}\frac{N_b}{\varepsilon_n} < 0.01?$$

  - N_b Number of particles per bunch ε_n transverse size of beam
  - One cannot put too many particles in a "small space" (brightness)
    - Otherwise the Coulomb interaction seen by a single particle when collides against the other bunch creates instabilities (tune-shift)
  - This is an empirical limit, of the order of 0.01
    - Very low nonlinearities → larger limits
    - LHC design assumed a conservative value of 0.007
    - LHC behaves better than expected and can operate with a beam-beam of 0.02
    - This allows to fill a smaller space with more particles, i.e. collide beams with smaller emittance and larger beam intensity than initially foreseen

LIMITS TO LUMINOSITY: PARASITIC BEAM-BEAM AND X-ANGLE

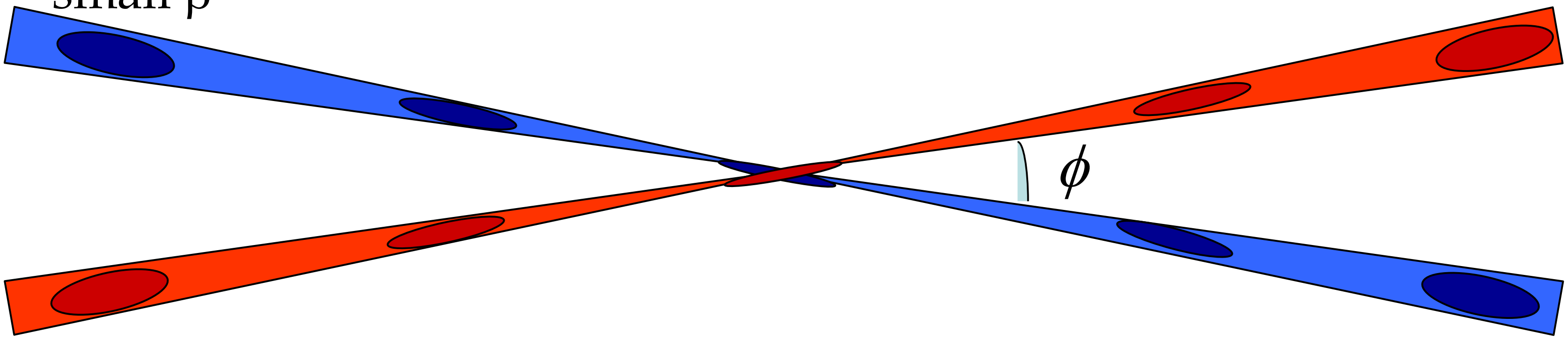
- The parasitic beam-beam and crossing angle
  - In the LHC bunch spacing is 25 ns = 7.5 m
  - Since experiments are about 50 m long, one had several collisions, not only in the detector centre
  - One has to open a crossing angle to avoid collisions inside the detector – this sets a limit to the increase for small β*
  - Parasitic beam beam is the Coulomb interaction between non colliding bunches that are separated through the crossing angle



Layout around the detectors ATLAS and CMS in the LHC

LIMITS TO LUMINOSITY: PARASITIC BEAM-BEAM AND X-ANGLE

- The parasitic beam-beam and crossing angle
  - One has to open a crossing angle to avoid collisions inside the detector, but not at the centre – this sets a limit to the increase for small β*



Detail of beam crossing in the detectors with non zero crossing angle

- One can prove that in a free space beam size is shrinking linearly up to a minimum β* the interaction point
  - The non orthogonal collision gives a luminosity loss *F*

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

- *F* is the geometric reduction factor due to the crossing angle ϕ

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi\varepsilon_n \beta^*} \boxed{F}$$

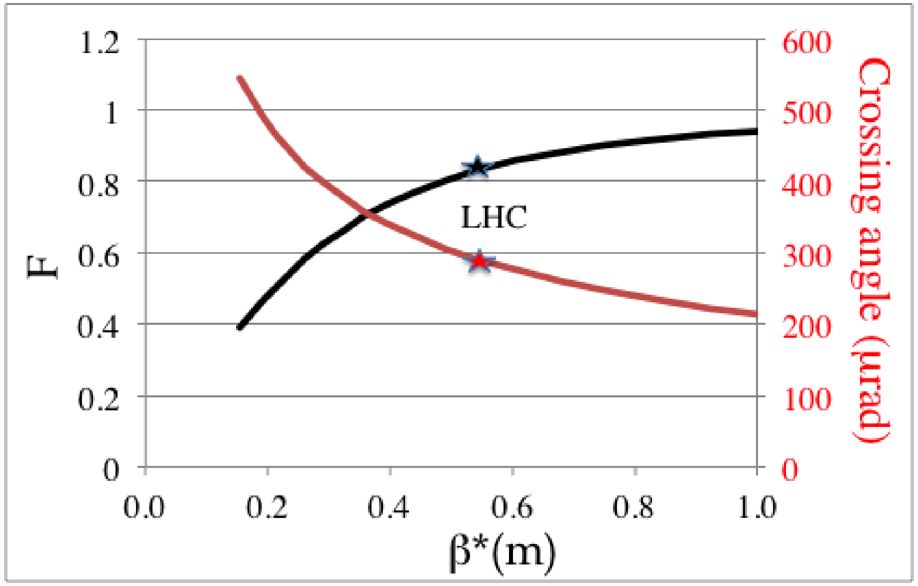
$$F(\phi) = \sqrt{\frac{1}{1-\left(\frac{\sigma_z}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

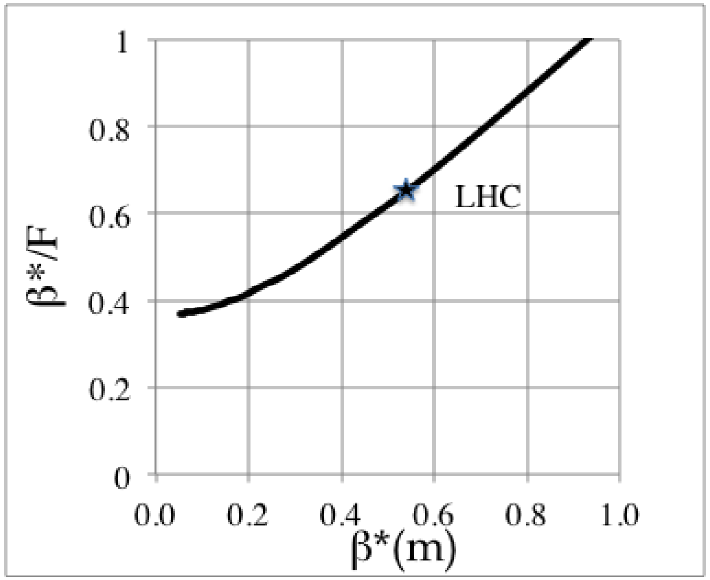
LIMITS TO LUMINOSITY:
PARASITIC BEAM-BEAM AND X-ANGLE

- LHC case, design value
  - Crossing angle is of the order of 200 μrad
  - β*=55 cm, F=0.86 – 14% lost !
  - Non negligible, and get worse with smaller beta

$$F(\phi)=\sqrt{\frac{1}{1-\left(\frac{\sigma_z}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

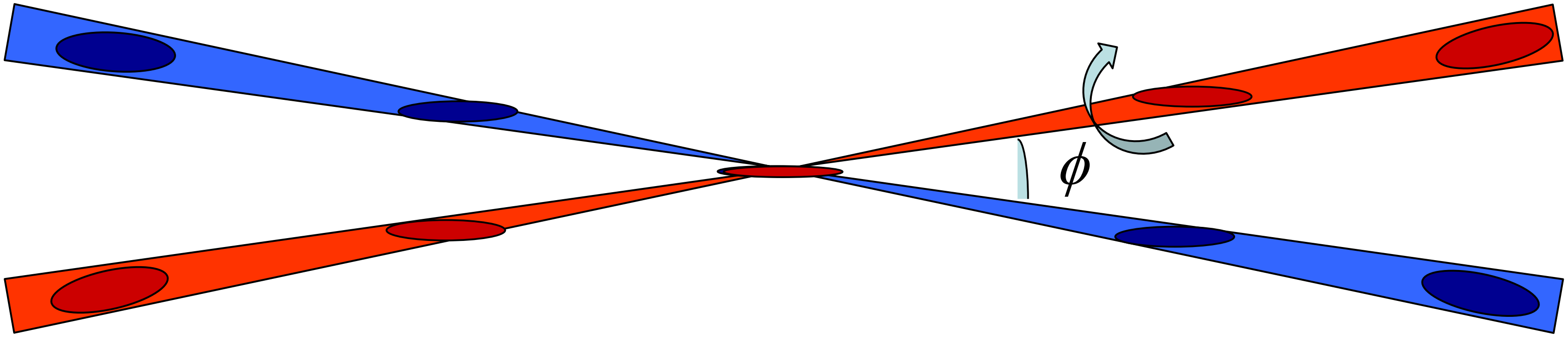
$$\phi(\beta^*)\propto\sqrt{\frac{1}{\beta^*}}$$





LIMITS TO LUMINOSITY: PARASITIC BEAM-BEAM AND X-ANGLE

- Crab cavities are a device that allow to avoid this reduction
  - Rotates the bunch like a crab
  - F stay equal to one with this rotation: no loss!



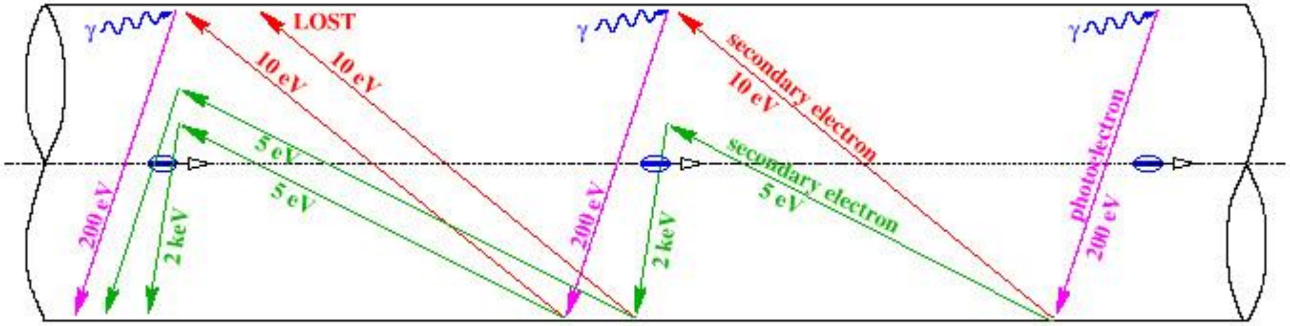
Detail of beam crossing in the detectors with non zero crossing angle and crab cavities

  - They are one of the enabling technologies of the upgrade in luminosity of the LHC (HL-LHC project, lead by L. Rossi)
  - Were used in electron machines (KEK, Japan) and tested successfully in the SPS at CERN with protons

LIMITS TO LUMINOSITY: THE ELECTRON CLOUD

- The electron cloud

$$L=\frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F=\frac{c}{4\pi}\gamma\frac{1}{L}N_b^2\boxed{n_b}\frac{1}{\varepsilon_n\beta^*}F$$



Mechanism of electron cloud formation [F. Ruggiero]

- This is related to the extraction of electrons in the vacuum chamber from the beam
- A critical parameter is the spacing of the bunches: smaller spacing larger electron cloud – threshold effect
  - So this effect pushes for 50 ns w.r.t. 25 ns
- Spacing (length) ↔ spacing (time) ↔ number of bunches n_b

  7.5 m ↔ 25 ns ↔ 3560 free bunches (2808 used)

LIMITS TO LUMINOSITY: PARASITIC BEAM-BEAM AND X-ANGLE

- Electron cloud in the LHC has been observed where expected in RunI during 50 ns ramp up
  - Was cured by scrubbing of surface with intense beam
  - In RunI we operated in a reliable way with 1300 bunches at 50 ns

- In LHC RunII we used 25 ns
  - After initial run at 50 ns, scrubbing allowed a ramp up of bunch number to about nominal value
  - Scrubbing run lasts few weeks – beam operation also cleans the beampipe

LIMITS TO LUMINOSITY: THE OPTICS IN THE INTERACTION REGIONS

- Optics: squeezing the beam

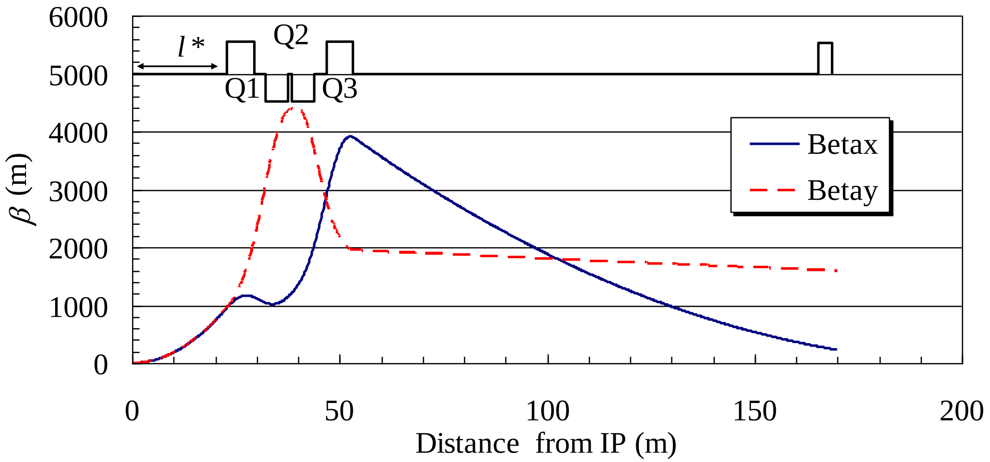
$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi\varepsilon_n \beta^*} F = \frac{c}{4\pi}\gamma \frac{1}{L} N_b^2 n_b \frac{1}{\varepsilon_n \boxed{\beta^*}} F$$

  - Size of the beam in a magnetic lattice
  - Luminosity is inverse prop to ε and β*

$$|x(s)| = \sqrt{\frac{\varepsilon\beta(s)}{\gamma_r}}$$

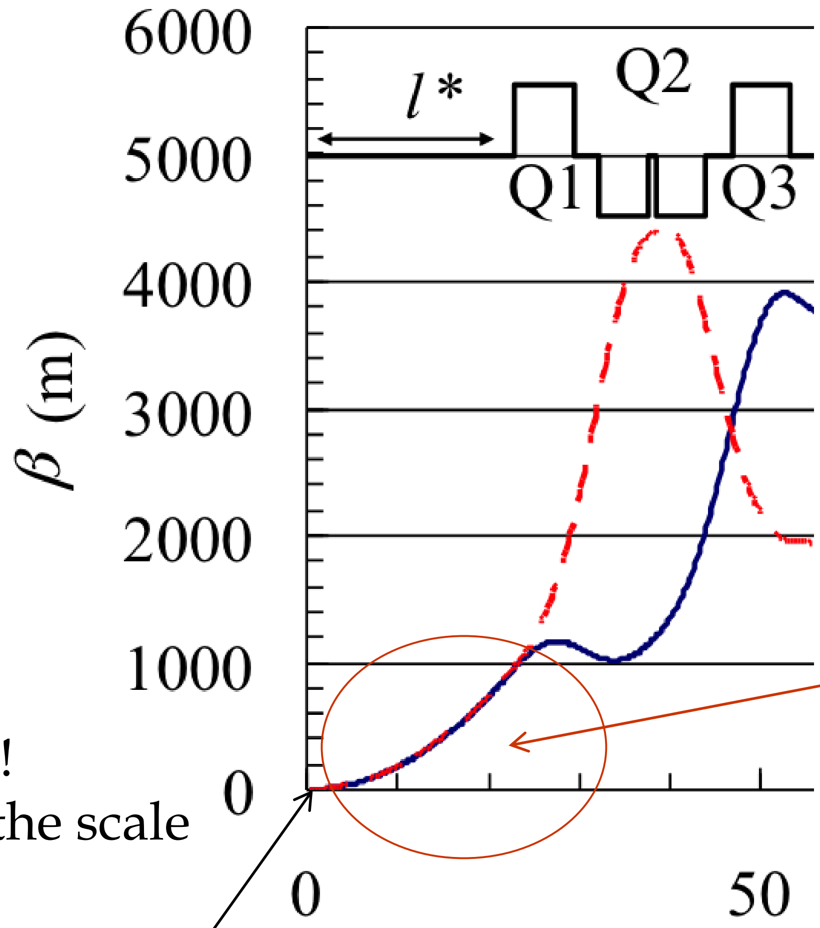
- In the free path (no accelerator magnets) around the experiment, the *β** has a nasty dependence with *s* distance to IP

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \approx \frac{s^2}{\beta^*}$$



- The limit to the squeeze is the magnet aperture
  - Key word for reducing β*: not stronger magnets but larger magnets

LIMITS TO LUMINOSITY: THE OPTICS IN THE INTERACTION REGIONS



$$\beta(s) = \beta^* + \frac{s^2}{\beta^*} \approx \frac{s^2}{\beta^*}$$

Looks zero, but it is not!
It is 0.5 m, invisible in the scale

$$b(0) = b^*$$

LIMITS TO LUMINOSITY: THE OPTICS IN THE INTERACTION REGIONS

- Optics: squeezing the beam

$$L=\frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F=\frac{c}{4\pi}\gamma\frac{1}{L}N_b^2 n_b\frac{1}{\boxed{\varepsilon_n\beta^*}}F$$

  - Size of the beam in a magnetic lattice

$$|x(s)|=\sqrt{\frac{\varepsilon\beta(s)}{\gamma_r}}$$

- LHC was designed to reach $\beta^* = 50$ cm with 70 mm aperture IR quads
  - In RunI 60 cm were reached
  - In Run II 25 cm were reached, thanks to a much lower emittance than nominal ($\varepsilon = 2.2\times10^{-6}$ m instead of 3.75×10^{-6} m)

(see Evian workshop 2019 for a complete outlook, introductory talk from R. Steerenberg)

The HL-LHC aims at reducing β* to 15 cm though larger aperture magnets (see O. Bruning, L. Rossi Eds. "The high luminosity large hadron collider" World Scientific)

LIMITS TO LUMINOSITY: THE BEAM FROM THE INJECTORS

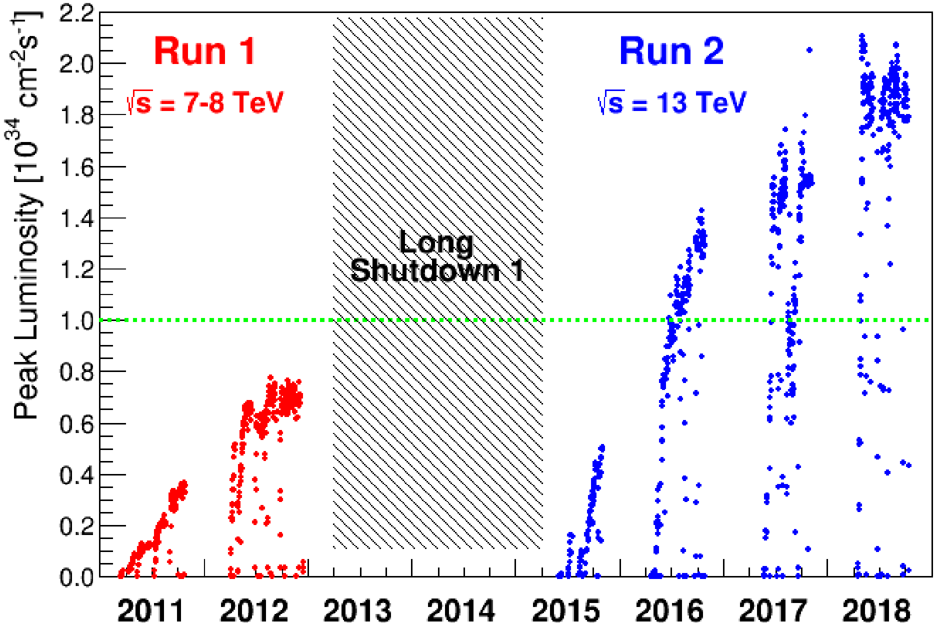
- The injector chain limits

$$L=\frac{N_b^2 n_b f_{rev}\gamma}{4\pi\varepsilon_n\beta^*}F=\frac{c}{4\pi}\gamma\frac{1}{L}\boxed{N_b^2 n_b}\frac{1}{\varepsilon_n\beta^*}F$$

  - The emittance ε_n is a linear invariant so if the accelerator chain is totally linear this quantity is preserved
    - But there are nonlinearities and optics mismatch that can increase emittance
  - The beam intensity N_b is preserved is there are no beam losses
    - But there are nonlinearities that may provoke particle loss
  - There are different limits on the emittance/beam intensity that can be provided by the injectors, in any of the accelerating rings
- LIU (LHC Injector Upgrade) R. Garoby, M. Meddahi, see Technical Design Report I: protons, CERN-ACC-2014-0337
  - Project to improve the performance of the injectors to match the requirements of the upgrade of the LHC
  - Bring the N_b to 2.2×10^{11} protons with an ε_n of 2.5×10^{-6} m

LUMINOSITY

- The ramp up to LHC performance
  - Notwithstanding a very challenging target, nominal value was reached, and doubled - close to what in the design report was indicated as ultimate peak luminosity



LHC luminosity ramp up in the 10’s (M. Lamont, J. Wenninger, and many many others)

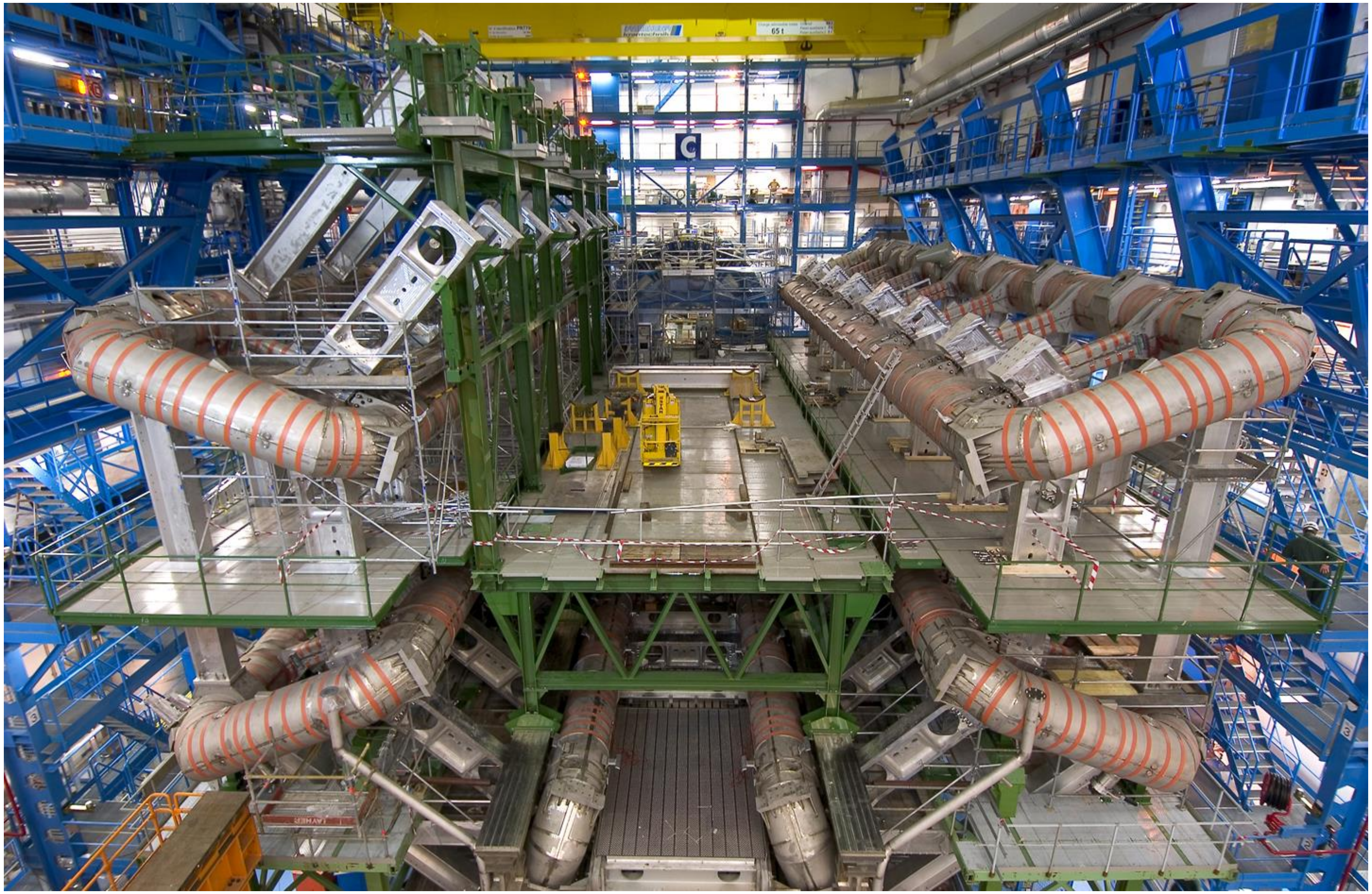
  - No visible bottlenecks in magnet operation due to 6.5 TeV

CONTENTS

- Equation for luminosity
- A few words about detector magnet size
- The interaction regions: low-beta magnet specifications
  - How to squeeze the beam
  - Gradient and aperture requirements for low-beta quadrupoles

THE INTERACTION REGIONS: DETECTORS

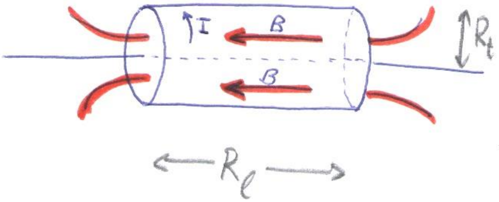
- The beam is small … why are detectors so large ?



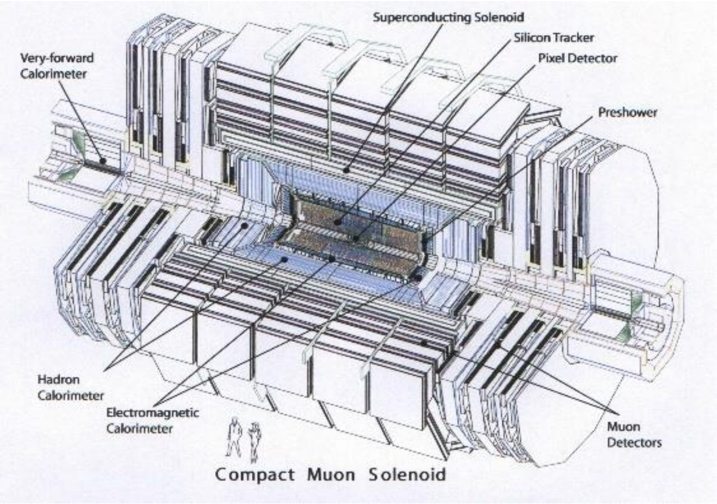
The toroidal coils of ATLAS experiment

THE INTERACTION REGIONS: DETECTORS

- Detector magnets provide a field to bend the particles generated by collisions (not the particles of the beam !)
  - The measurement of the bending radius gives an estimate of the charge and energy of the particle
- Different lay-outs
  - A solenoid providing a field parallel to the beam direction (example: LHC CMS, LEP ALEPH, Tevatron CDF)
    - Field lines perpendicular to *(x,y)*



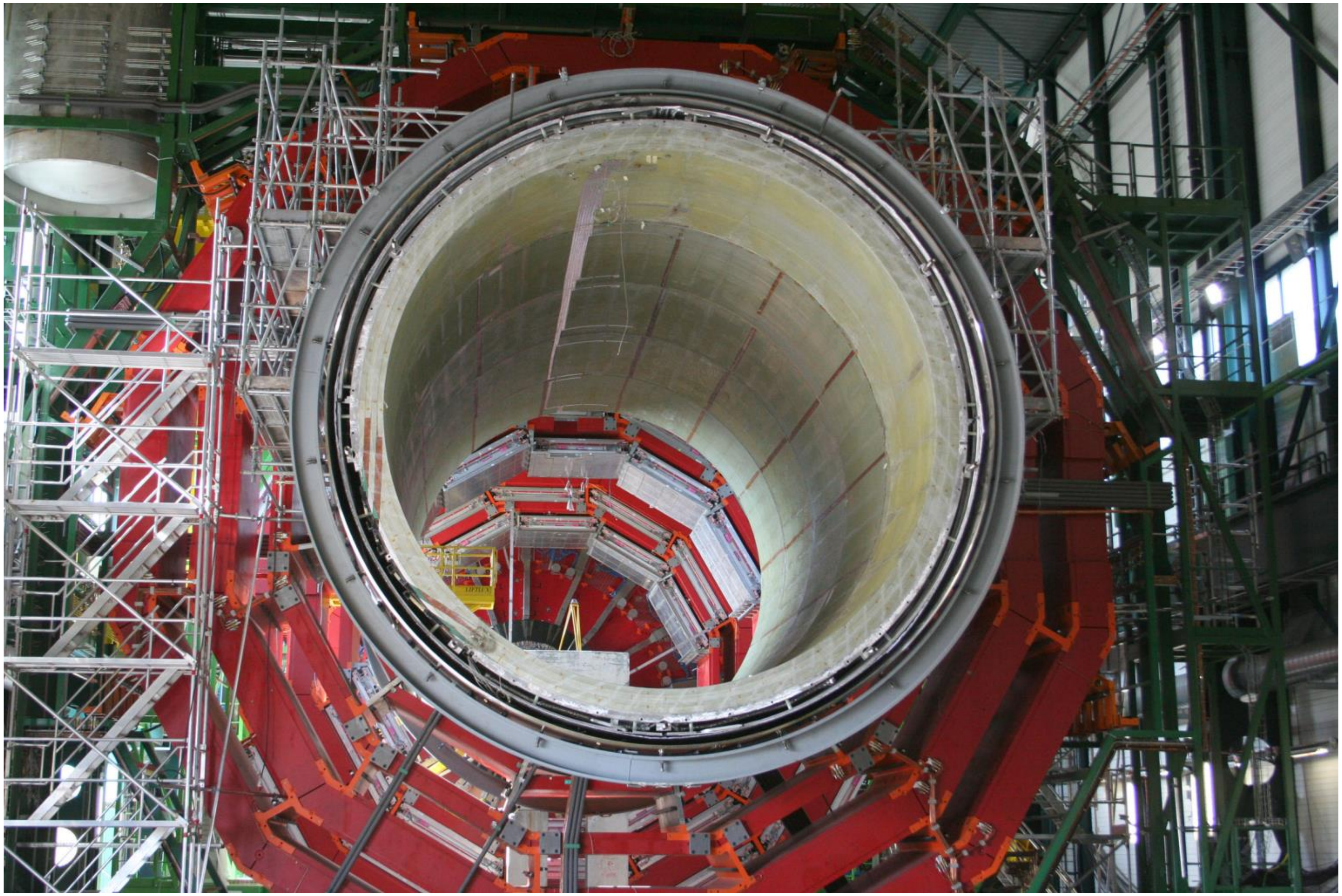
Sketch of a detector based on a solenoid



Sketch of the CMS detector in the LHC

  - A series of toroidal coils to provide a circular field around the beam (example: LHC ATLAS)
    - Field lines of circular shape in the *(x,y)* plane

THE INTERACTION REGIONS: DETECTORS

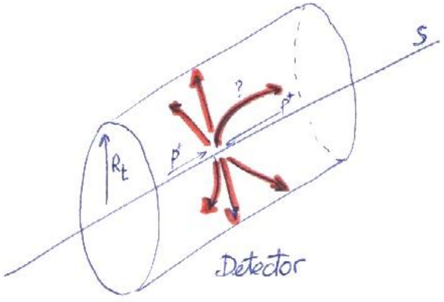


The solenoid of CMS experiment

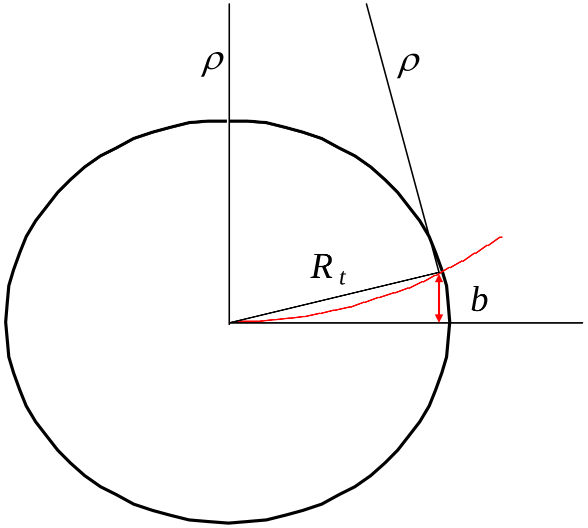
THE INTERACTION REGIONS: DETECTORS

- Detector transverse size
  - The particle is bent with a curvature radius

$$E = eB\rho$$



  - B is the field in the detector magnet
  - R_t is the transverse radius of the detector magnet
  - The precision in the measurements is related to the parameter b
  - A bit of trigonometry gives



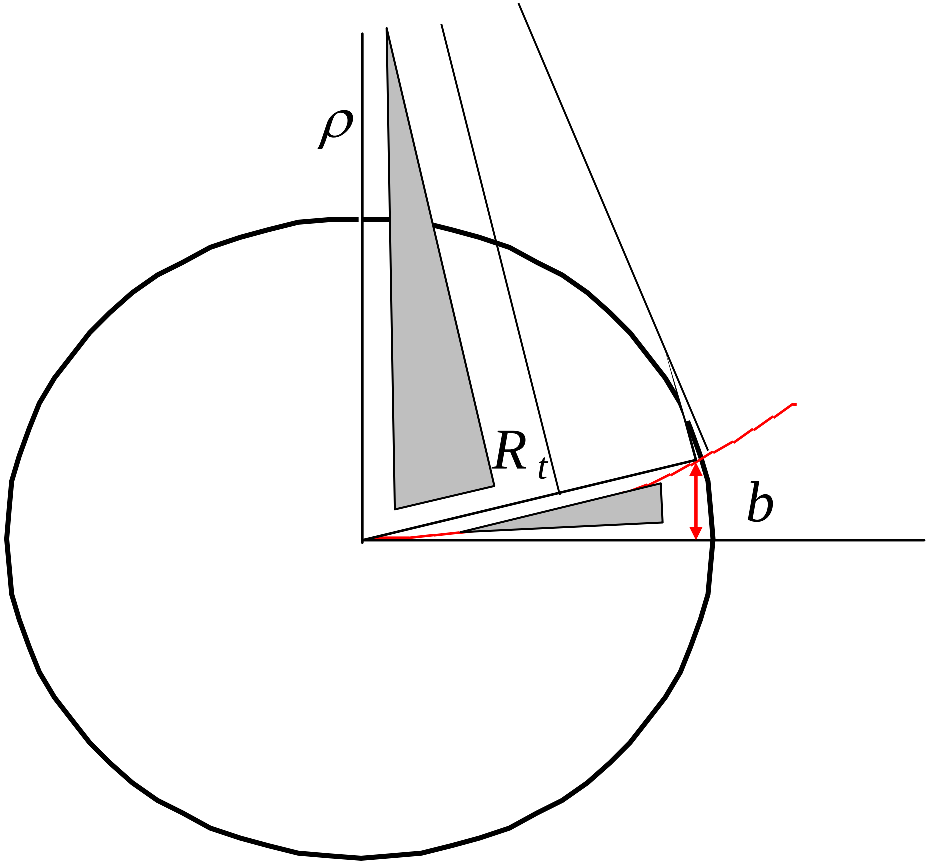
$$b = \frac{R_t^2}{2\rho} = \frac{e}{2}\frac{R_t^2 B}{E}$$

THE INTERACTION REGIONS: DETECTORS

- Explication – the shadowed triangles are similar

$$\frac{b}{R_t} = \frac{R_t}{2r}$$

$$b = \frac{R_t^2}{2\rho} = \frac{e}{2}\frac{R_t^2 B}{E}$$



THE INTERACTION REGIONS: DETECTORS

- Detector transverse size
  - B is the field in the detector magnet
  - R_t is the transverse radius of the detector magnet
  - The precision in the measurements is $\propto 1/b$

$$b = \frac{R_t^2}{2\rho} = \frac{e}{2}\frac{R_t^2 B}{E}$$

$$b \sim 0.15 \frac{R_t^2 B}{E[\mathrm{GeV}]}$$

- Examples
  - LEP ALEPH: E=100 GeV, B=1.5 T, R_l=6.5 m, R_t=2.65 m, b=16 mm
    - that's why we need sizes of meters and not centimeters !

- The magnetic field is limited by technology
  - But fields are not so high as for accelerator dipoles (4T instead of 8 T)
  - Note that the precision with BR_t^2 – better large than high field …

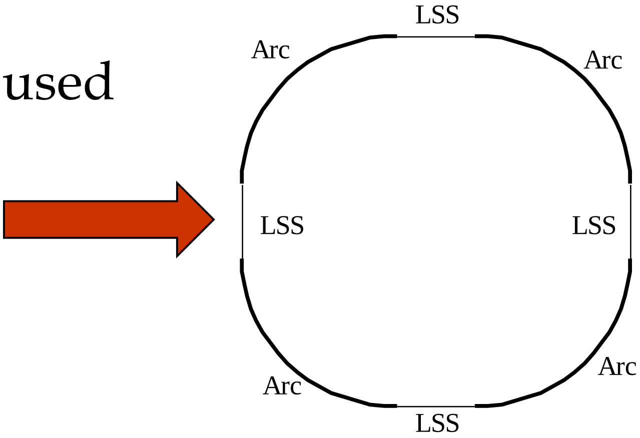
- Detector longitudinal size
  - At first order the same scaling can be assumed to preserve the overall shape

CONTENTS

- Equation for luminosity
- A few words about detector magnet size
- The interaction regions: low-beta magnet specifications
    - How to squeeze the beam
    - Gradient and aperture requirements for low-beta quadrupoles

THE INTERACTION REGIONS: LOW-BETA MAGNET SPECIFICATIONS

- We are now in the straight sections of the machine
  - There are no dipoles
  - Only quadrupoles to keep the beam focused

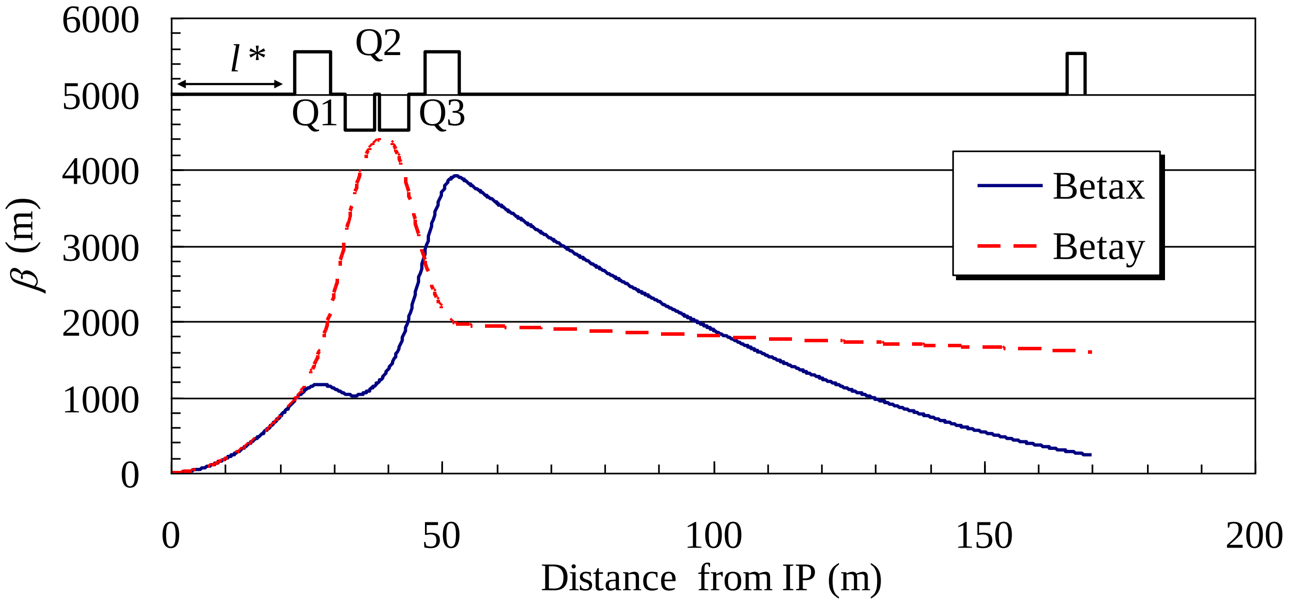


- In the middle of the straight section one has a free space for the experiment, with the interaction point (IP) where beams collide
  - Around the experiment the optics must keep two distinct aims
    - Keep the beam focused
    - Reduce the size of the beam in the interaction point (IP) to increase the rate of collisions (luminosity) → reduce β

$$\sigma = \sqrt{\frac{\beta\varepsilon}{\gamma}}$$

THE INTERACTION REGIONS: LOW-BETA MAGNET SPECIFICATIONS

- The focusing system in the LHC
  - A system of quadrupoles is used to reach a very low beta function, called β^*, in the IP (LHC: 0.55 m instead of the 30-200 m in the arcs)
  - Physical constraint: empty space around the IP – distance of the first magnet to the IP, called l^*, (LHC: 23 m) – needed for the detectors !



The lay-out of quadrupoles close to the interaction point in the LHC, and the beta functions

THE INTERACTION REGIONS: LOW-BETA MAGNET SPECIFICATIONS

- Drawback: beta function gets huge in the quadrupoles !
  - But this happens only in collision, where the beam is smaller

$$\sigma = \sqrt{\frac{\beta\varepsilon}{\gamma}}$$

  - In free space around IP (s=0), one has $\beta(s) = \beta^* + \frac{s^2}{\beta^*}$
  - At the entrance of the triplet one has $\beta(l^*) = \beta^* + \frac{l^{*2}}{\beta^*} \approx \frac{l^{*2}}{\beta^*}$
  - And the beta function grows by a factor r within the triplet, depending on its length
  - For instance in the LHC l_t=23 m, l^*=23 m, β_m =4400 m, about 4.5 times larger than

$$\beta(l^*) \approx \frac{l^{*2}}{\beta^*} = \frac{23^2}{0.55} = 960\ \mathrm{m}$$

THE INTERACTION REGIONS: LOW-BETA MAGNET SPECIFICATIONS

- The integrated gradient of the triplet
  - Triplet is like an optical system, where the strength is the inverse of the focal length
  - One can take the focal length as the distance of the triplet midpoint to the IP

$$G l_t \sim \kappa \frac{E}{l^* + \frac{l_t + l_g}{2}}$$

    - If the required gradient is not reached, we have to reduce the energy since the position is fixed
    - Remember: β* is not inverse proportional to the gradient, but to the aperture
- Integrated gradient is limited by the magnet technology
  - The quadrupole gradient over an aperture ϕ is limited by the maximum field B_m imposed by the technology
    - About 2 T for resistive, 8 T for Nb-Ti, 16 T for Nb_3Sn
  - So to get a larger aperture one needs either to make much longer triplet (does it fit? Larger new infrastructure?), or go for more challenging technologies

THE INTERACTION REGIONS: LOW-BETA MAGNET SPECIFICATIONS

- Example: the LHC interaction regions
  - Nb-Ti quadrupoles, 200 T/m, 70 mm aperture, β^* =0.55 m, total length of the quadrupole is 23 m (peak field around 8.5 T)
- Example: the HL-LHC interaction regions
  - Nb_3Sn quadrupoles, 132 T/m, 150 mm aperture, β^* =0.15 m, total length of the quadrupole is 30 m (peak field around 11.5 T)

- Note that the first superconducting magnets (based on Nb-Ti) used in a particle accelerator were the 8 quadrupoles for the triplet of ISR (J. Billan et al, CERN yellow report 76-16)

- Then Tevatron came with a massive (700) production of 4.3 T dipoles, setting the standard for the magnet technology for the next 30 years

TOWARDS HIGH LUMINOSITY IN THE LHC

- After the LHC construction, CERN has launched two projects
  - LIU: injector upgrade
    - Aiming at removing all bottlenecks in injectors to have a bunch intensity of 2.2×10^{11} protons with small emittance
    - The project is now in the installation phase, to be commissioned next year

R. Garoby, M. Meddahi, see Technical Design Report I: protons, CERN-ACC-2014-0337

TOWARDS HIGH LUMINOSITY IN THE LHC

- After the LHC construction, CERN has launched two projects
  - HL-LHC: upgrade of the LHC
    - To remove the bottleneck in the beam squeeze (larger aperture triplets)
    - To install additional collimators to reduce beam losses through a higher field 11 T dipole in Nb_3Sn
    - To install use crab cavities to remove the reduction of luminosity due to the factor *F* (crossing angle)
    - As to superconducting technology, magnets will be powered through a MgB_2 superconducting link, whose superconductive properties were discovered only in recent times (2001)

O. Bruning, L. Rossi Eds. "The high luminosity large hadron collider" World Scientific

- LHC has the triplet built as special contribution from US and Japan
  - HL-LHC as well (and more) relies on several contributions of international collaborations: US, Japan, Russia, China, … and many member states as UK, Spain, Italy, Sweden…

SUMMARY

- Luminosity is a measure of the quantity of data provided by the accelerator per second
  - It has a complex equation that mainly tells you
  - More fuel, more luminosity
  - More focused beam, more luminosity
- There are four limitations to luminosity
  - Beam-beam (Coulomb interaction)
  - Crossing angle
  - Electron cloud (beam pipe cleanliness)
  - Optics (magnets)
  - Injected beam (injectors)
- Experimental magnets are large since the resolution power is proportional to the square of the size and only to B

SUMMARY

- To reduce the beam size in the interaction, the beam becomes very large just outside the experiments
  - Beta function grows quadratically, beam size grows linearly
  - The experiment are large (order of 50 m), so the beam size grows a lot until the first quadrupole
  - An optical system as a telescope is used to reduce the beam size:a sequence of 3 quadrupoles in the LHC (triplet)
    - Then another sequence of quadrupoles (matching section quadrupoles) match the beam siz to the arcs
  - The larger is the triplet quadrupole aperture, the smaller the beam can be made
- Putting together unit 1 and unit 2, magnets are an enabling technology for the accelerator performance
  - Both in terms of energy (yesterday) and of data quantity (today)
  - It is time to enter this domain … next units