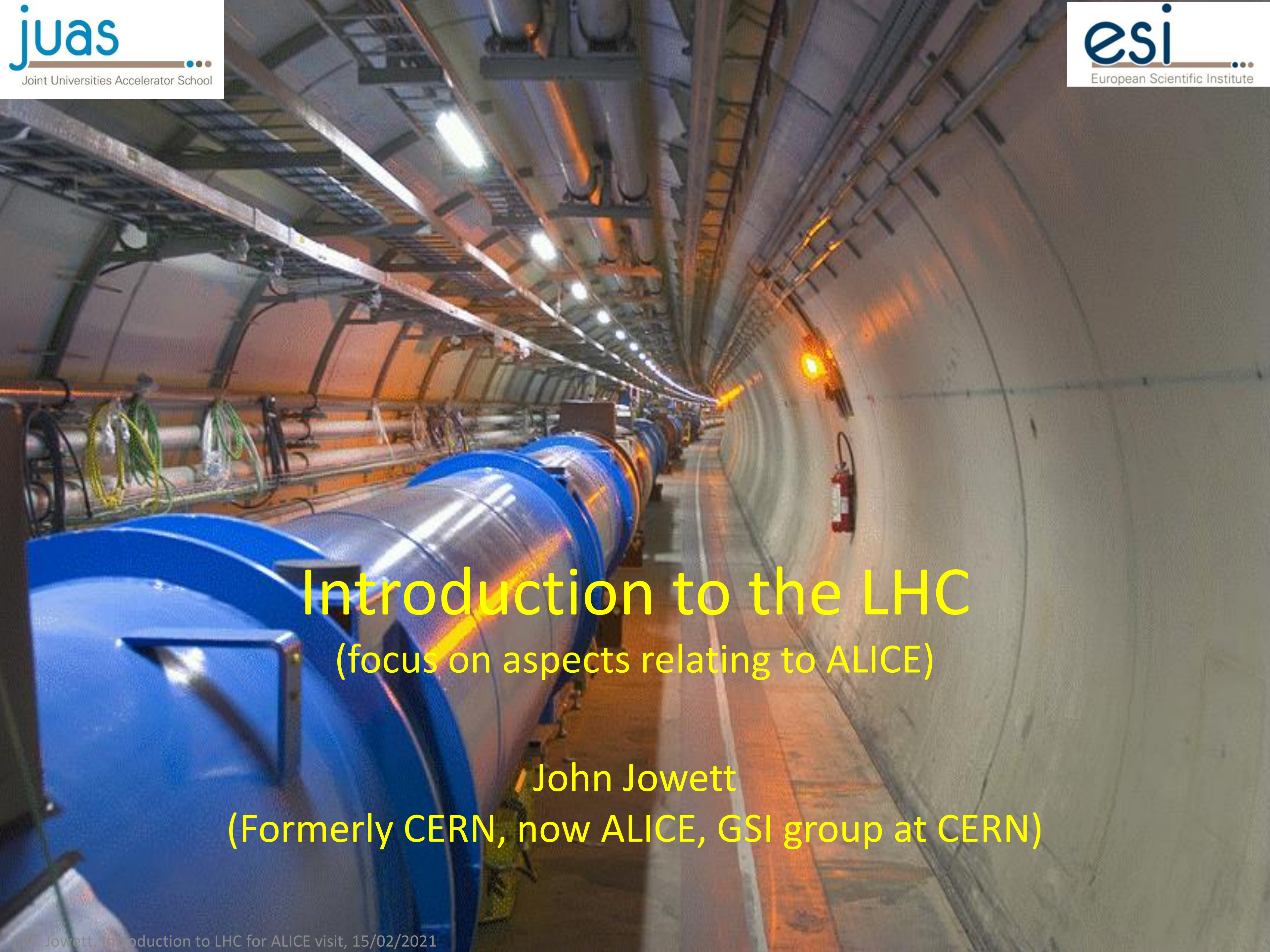


Joint Universities Accelerator School

European Scientific Institute

Introduction to the LHC

(focus on aspects relating to ALICE)

John Jowett
(Formerly CERN, now ALICE, GSI group at CERN)

Goals of a collider

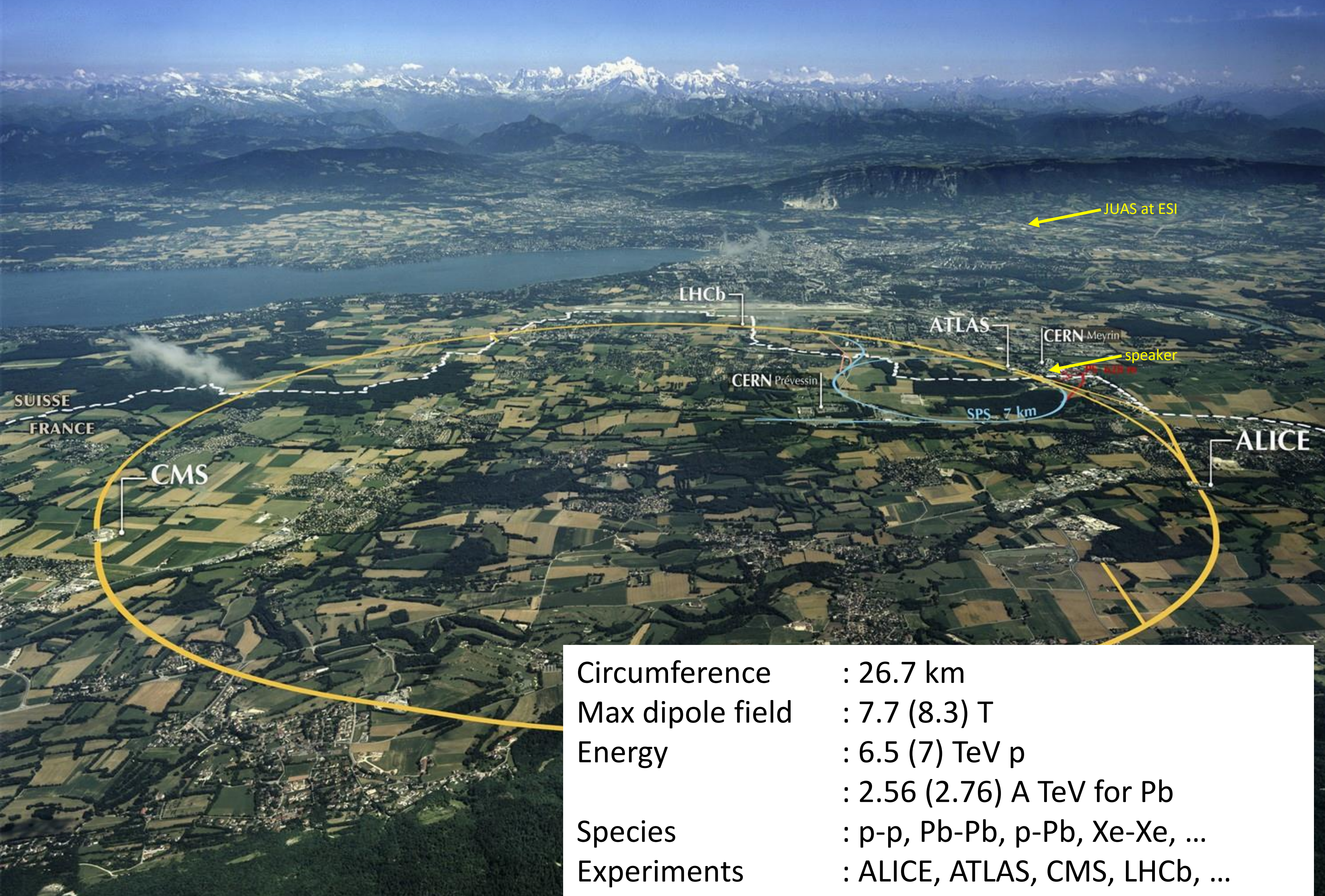
- High collision energy: LHC has provided
  - 13 TeV total energy in pp collisions
  - 1 PeV total (or 5.02 TeV per colliding nucleon pair) in Pb-Pb collisions
- High (time-averaged) collision rate for processes of interest

$$R = L\sigma$$

where σ (units of area) is the fundamental cross section for an interaction of interest and L is the luminosity, a quantity characterising the collider's performance

- More details in future lectures and seminars in JUAS Course 1
- Today, we try to relate the ALICE visit to the courses on transverse beam dynamics (and MAD-X)

LHC at CERN, Geneva area



Circumference	: 26.7 km
Max dipole field	: 7.7 (8.3) T
Energy	: 6.5 (7) TeV p
	: 2.56 (2.76) A TeV for Pb
Species	: p-p, Pb-Pb, p-Pb, Xe-Xe, …
Experiments	: ALICE, ATLAS, CMS, LHCb, …

Hot and dense matter in Pb-Pb collisions at LHC

Quark Gluon Plasma (QGP) created in Pb-Pb collisions.

Nuclear fusion temperature at core of sun $T_{\text{sun}} = 1.6 \times 10^7$ K

Temperature of QGP (thermal photon spectrum measured by ALICE, the highest temperature ever measured in a lab):

$T_{\text{ALICE}} = 304$ MeV / $k_B = 3.5 \times 10^{12}$ K=200,000 T_{sun}

Energy density in QGP: u_{QGP} □ 15 GeV/fm^3

Exercise: check all these numbers

Total electrical energy generated in Europe in a year: $U_{\text{Ey}} = 3.6 \times 10^{12}$ kWh

Imagine pumping all that energy into as sphere of radius r and calculate the value of r needed to achieve the same energy density

$\frac{U_{\text{Ey}}}{(4/3)\pi r^3} = u_{\text{QGP}} \Rightarrow r = 1.1\ \mu\text{m}$, a speck of very fine dust, mass 140 kg

Density = $10^{15} \times$(density of metallic Pb)

World annual electrical energy production ~ 1 mole of LHC Pb-Pb collisions

LHC is an extraordinary concentrator of energy.

Luminosity of a hadron collider

$$L = \frac{N^2 k_c f}{4\pi\sigma_x\sigma_y} F = \frac{N^2 k_c f_0 \gamma}{4\pi\,\varepsilon_n \beta^*} F(\theta_c)$$

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

- Parameters in luminosity
  - No. of particles per bunch N
  - No. of bunches per beam k_b
  - No. of bunches collliding at IP k_c
    - $(k_c < k_b)$
  - Relativistic factor γ
  - Normalised emittance ε_n
  - Beta function at the IP β^*
  - Crossing angle factor F
    - Full crossing angle θ_c
    - Bunch length σ_z
    - Transverse beam size at the IP σ^*

Equal amplitude functions:

$\beta_x^* = \beta_y^* = \beta^*$,

Geometric and normalised emittance:

$$\varepsilon_x^* = \varepsilon_y^* = \varepsilon^* = \frac{\varepsilon_n}{\sqrt{\gamma^2 - 1}}$$

$\Rightarrow$ Round beams at IP:

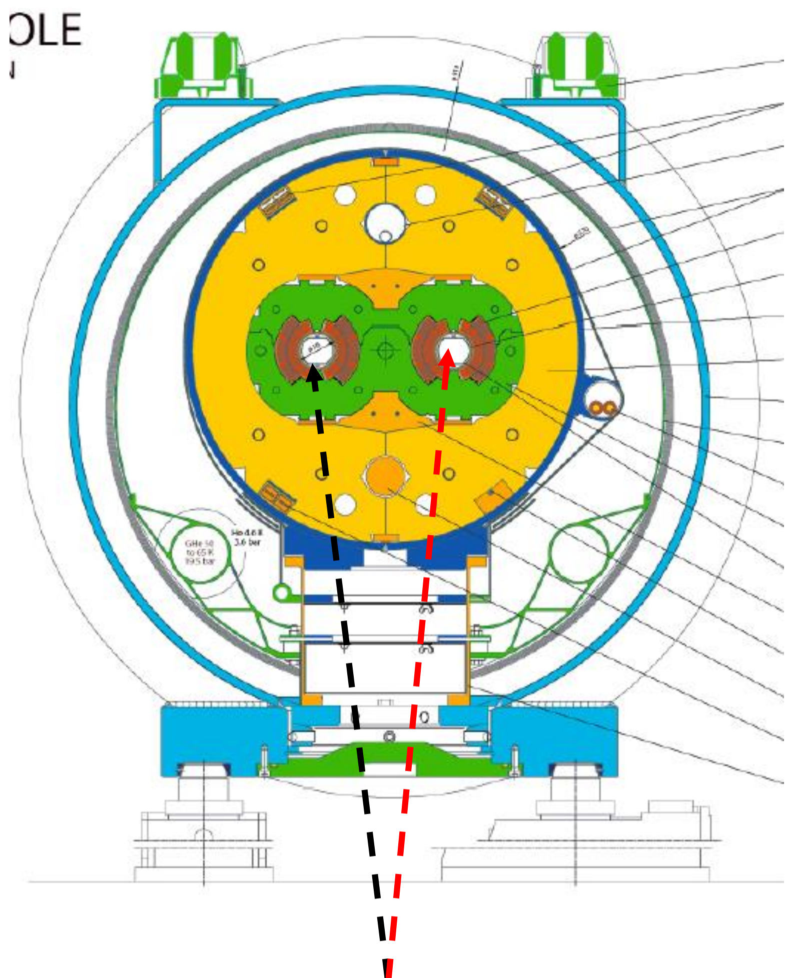
$$\sigma_x^* = \sigma_y^* = \sigma^* \approx \sqrt{\frac{\beta^* \varepsilon_n}{\gamma}}$$

(N.B. LHC uses RMS emittances.)

IP = "interaction point"

The two-in-one dipole magnet of LHC

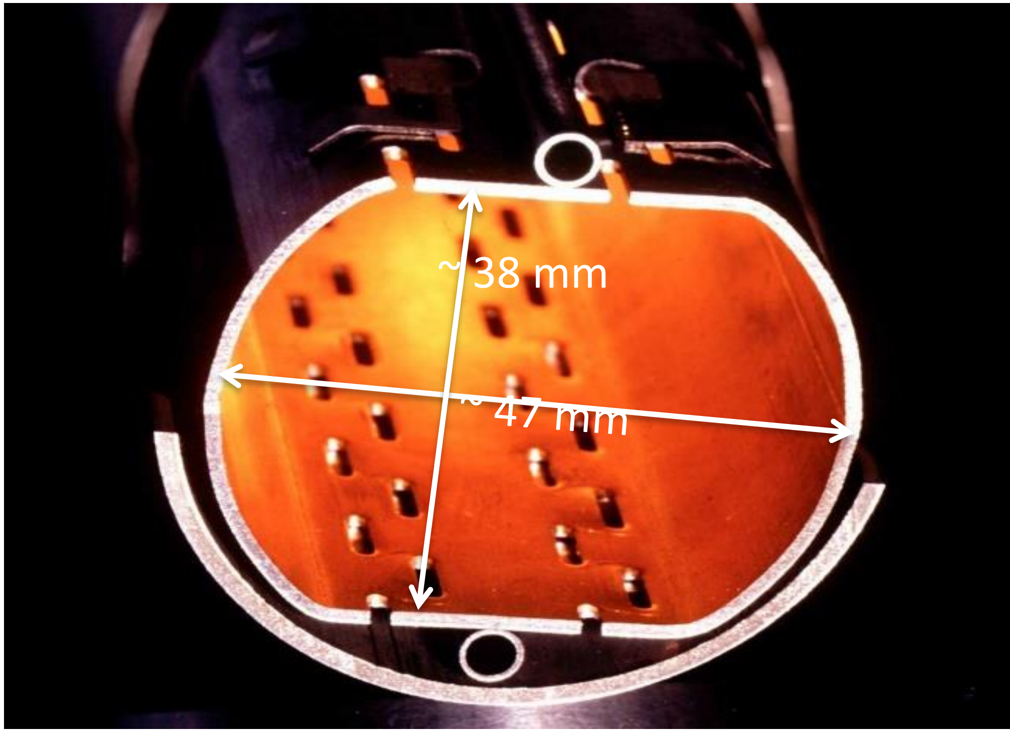
- Superconducting dipole magnet (8 T) with twin apertures, opposite fields fills most of arcs
- Coils at 1.9 K
- Also superconducting quadrupoles, higher multipoles, RF system
- Many other systems, eg, beam collimation
- More in seminars later (and in Course 2 for magnet technology)



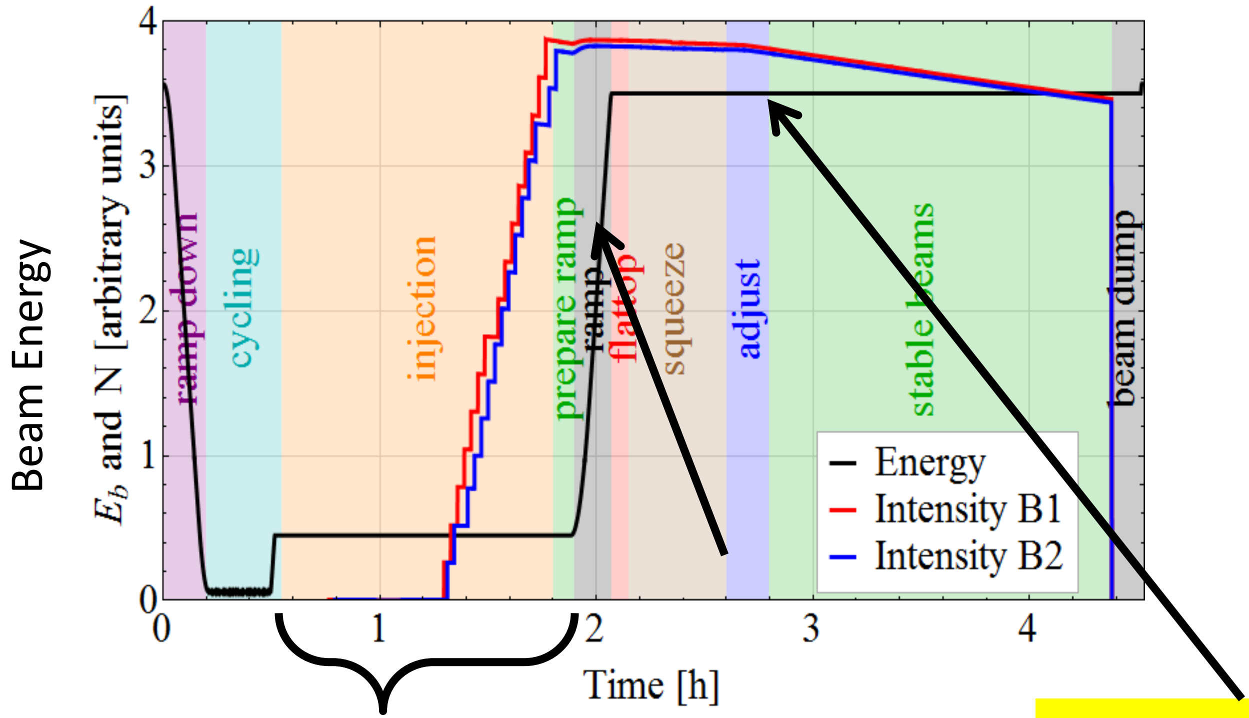
LHC: Identical magnitude bending field in both apertures of two-in-one dipole (but opposite sign).
Arc quadrupoles are similar.

LHC beam pipe

- LHC cryogenic vacuum
- Beam screen 20 K, see JUAS Course 2 on vacuum technology
- Impedance of this and other elements closest to beam, Course 1
- Beam confined to centre by collimation system to prevent uncontrolled beam losses and potential damage
- LHC machine protection



LHC Accelerator Cycle (Fill) schematic



Low energy injection plateau:
Accumulation of beam

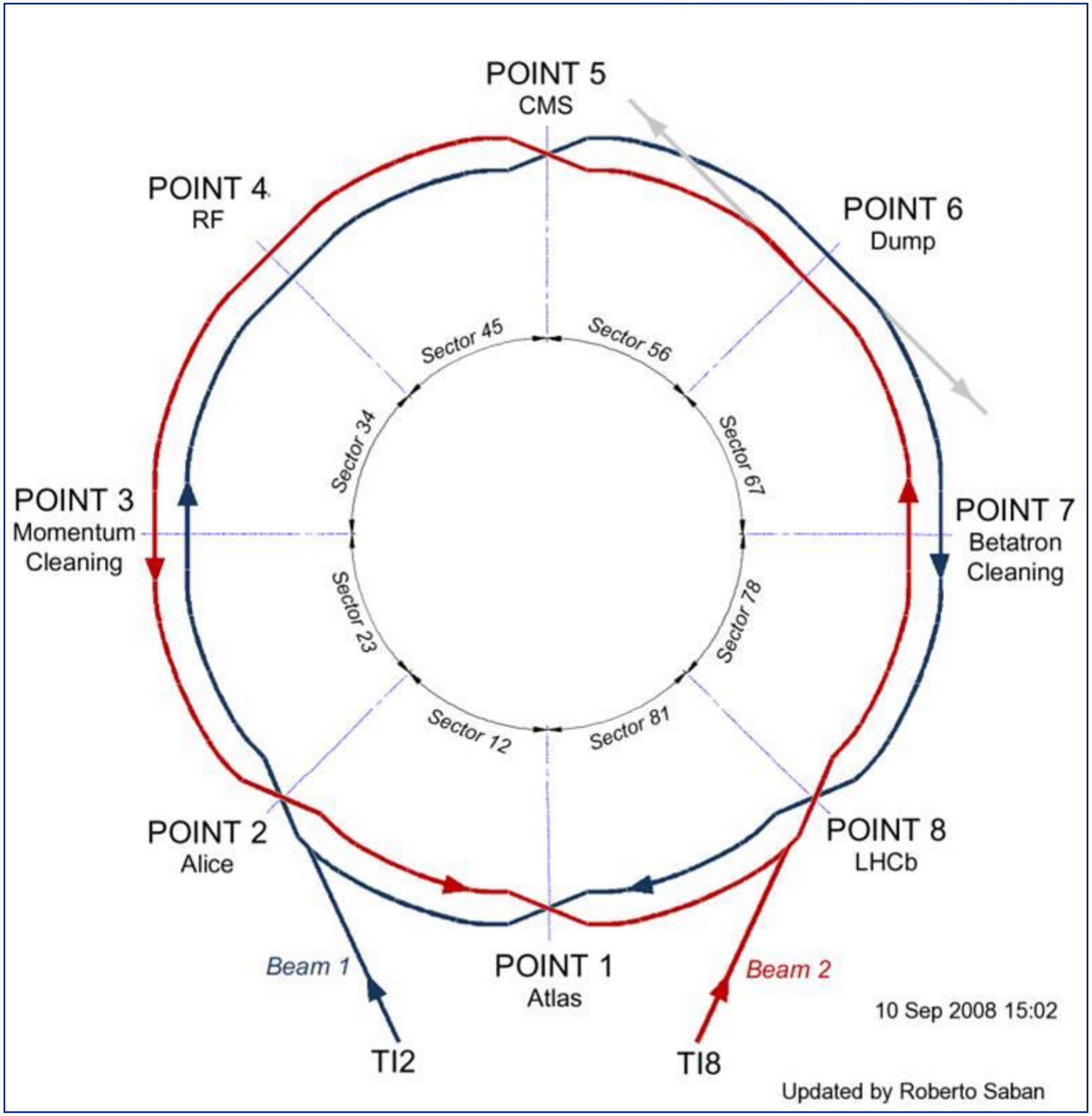
Acceleration

Top (max) Energy:
Store & Collide (LHC)

Injector cycles (e.g. PS or SPS) are analogous except that, after the ramp, beams are immediately extracted into a transfer line to the next machine rather than being collided.

A machine which ramps its magnetic fields in synchronism with a change of the RF frequency like this is called a *synchrotron*.

LHC orientation – schematic (1)



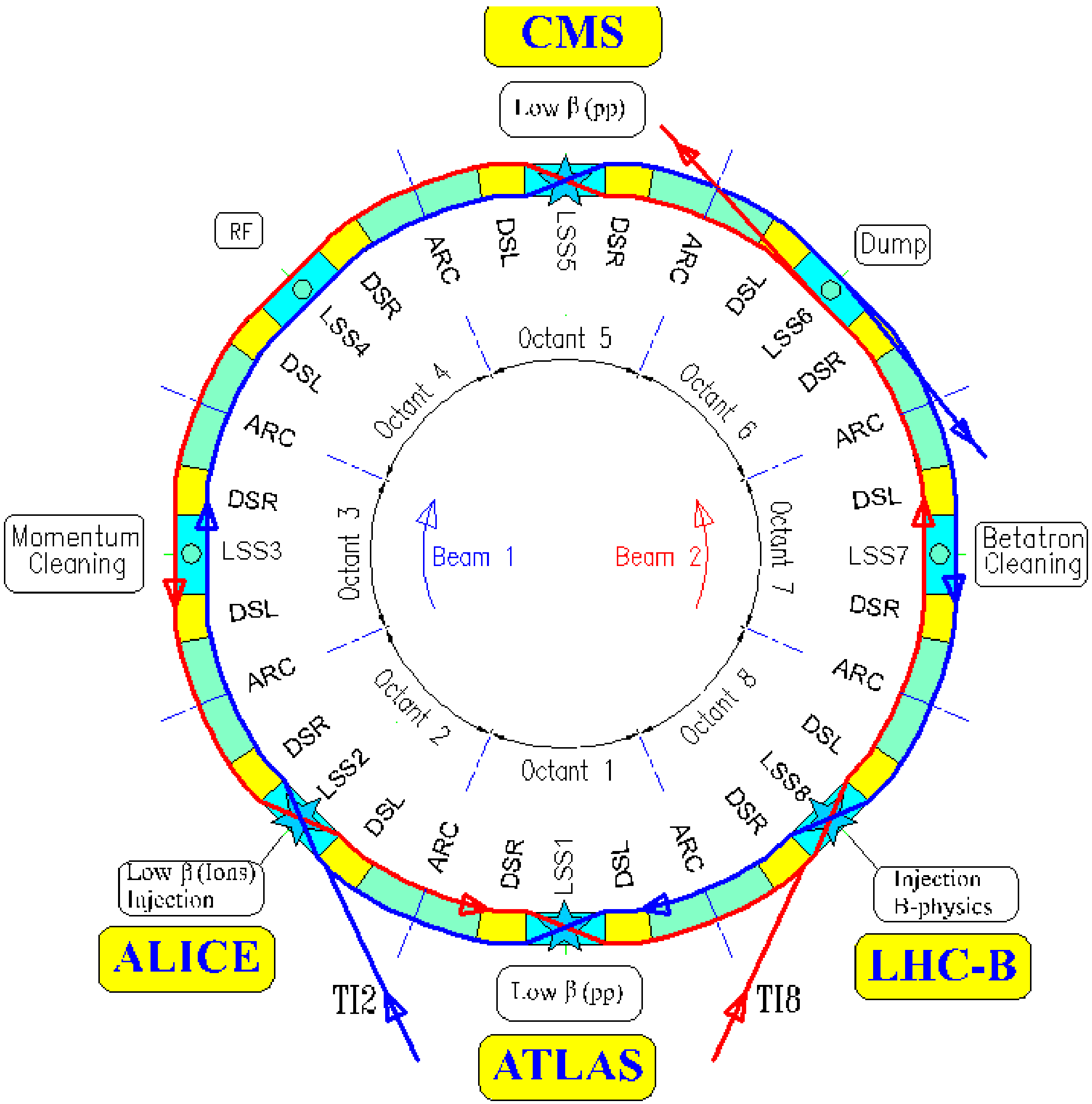
Four large and highly capable physics experiments:
ALICE, CMS, ATLAS, LHCb.
Beams circulate in independent beam pipes over most of circumference

Each beam has its own reference orbit in the twin-aperture magnets of the arcs but the beam pipes merge and orbits are common in interaction regions.

Interaction regions:

- IR1 (ATLAS ± 145 m)
- **IR2 (ALICE ± 117 m)**
- IR5 (CMS ± 145 m)
- IR8 (LHC-B ± 80 m)

LHC orientation – schematic (2)



s coordinate along each beam's central orbit, clockwise from IP1

$s_1(\text{IP1}) = s_2(\text{IP1}) = 0$ (ATLAS) for both beams by convention

Inner and outer arc lengths are slightly different so
$s_1(\text{IP2}) = 3332.436$ m
$s_2(\text{IP2}) = 3332.284$ m

Exercise: estimate the distance between the centres of the two magnet apertures

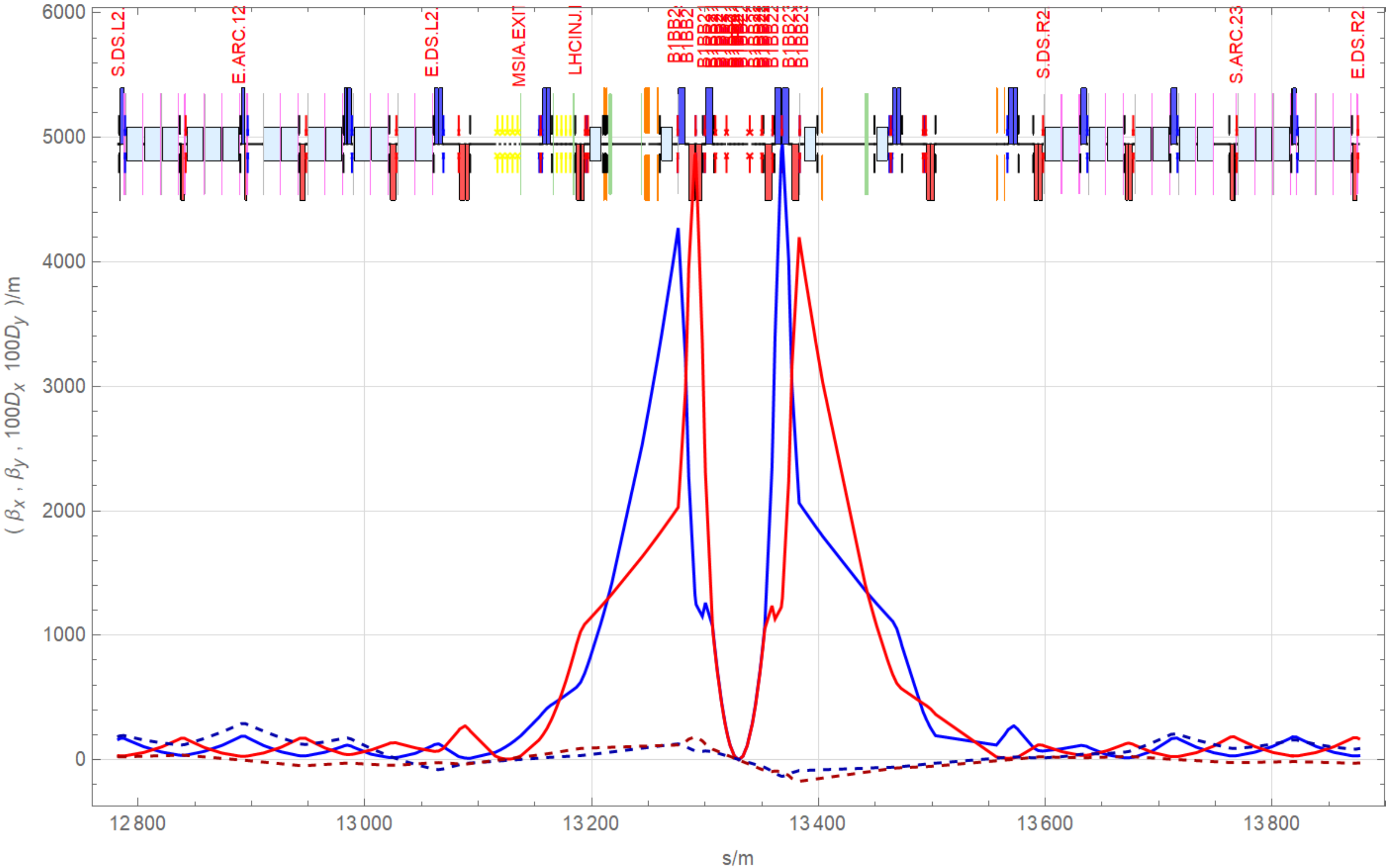
Magnet polarities in the ARCS of the LHC

- The two-in-one magnet design provides opposite sign fields in the two apertures
- LHC beams have the same (positive) charge but are travelling in opposite directions so the bending force is always towards the centre of the ring
- Similarly a horizontally focusing (F) arc quadrupole for Beam 1 (clockwise) will be a horizontally defocusing (D) quadrupole for Beam 2
- So the FODO cells of the arcs will essentially have the horizontal and vertical orbits switched

Magnet polarities in the interaction regions of the LHC

- In the common interaction regions, beams pass through the same quadrupoles (~no bends)
- LHC beams have the same (positive) charge but are travelling in opposite directions so a horizontally focusing (F) arc quadrupole for Beam 1 (clockwise) will be a horizontally defocusing (D) quadrupole for Beam 2
- The optics cannot be the same for the two beams
- Matching the optics is more complicated as it has to be done for the two beams with the same variables (quadrupole strengths)
- To first approximation, the IR optics are symmetric under the interchange of x and y AND left to right of the IP

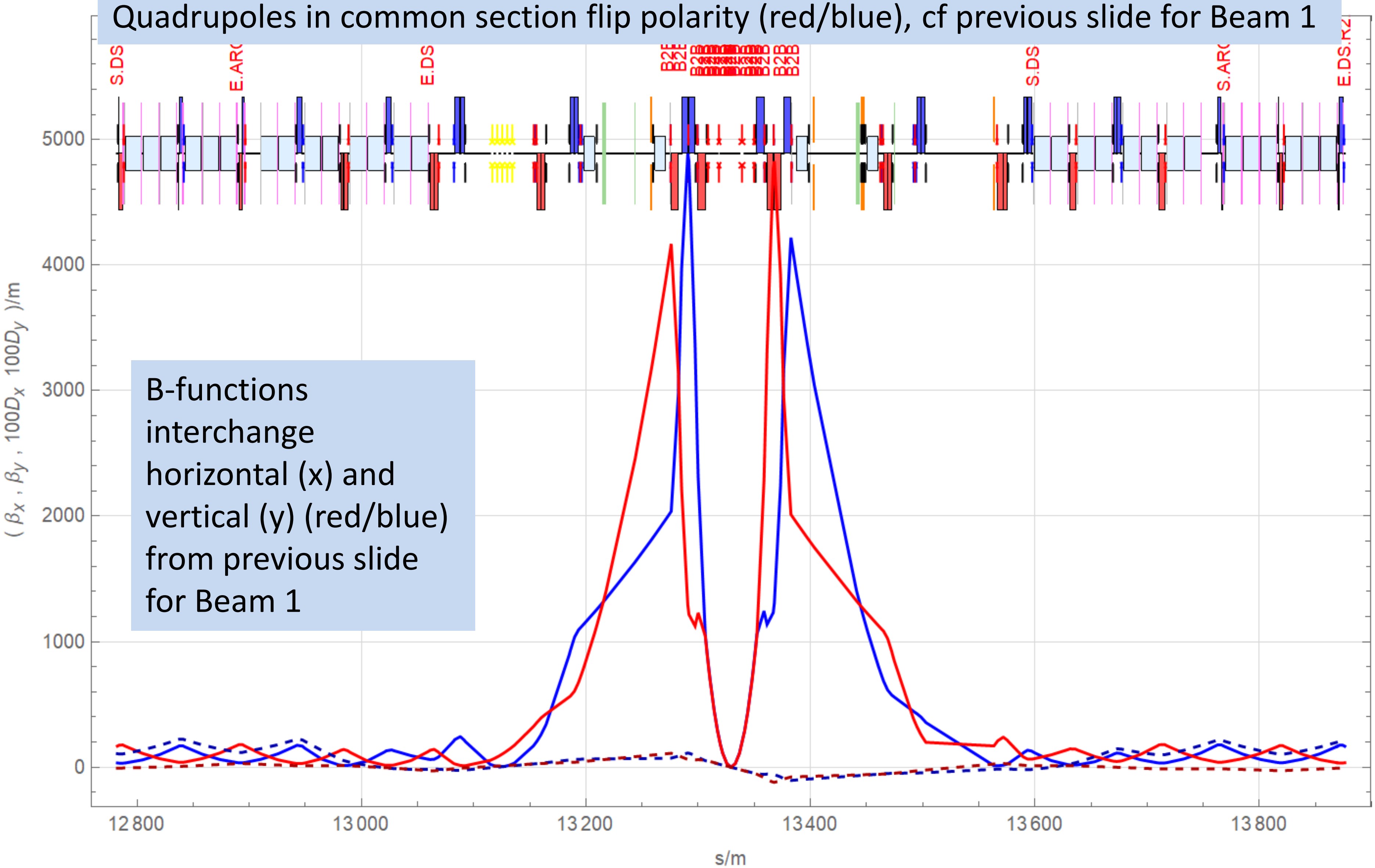
Optical functions for Beam 1 in LHC IR2, 2018 pb-Pb run



Some common quadrupoles focus/defocus Beam 1/Beam 2.

Optical functions or Beam 2 in LHC IR2, 2018

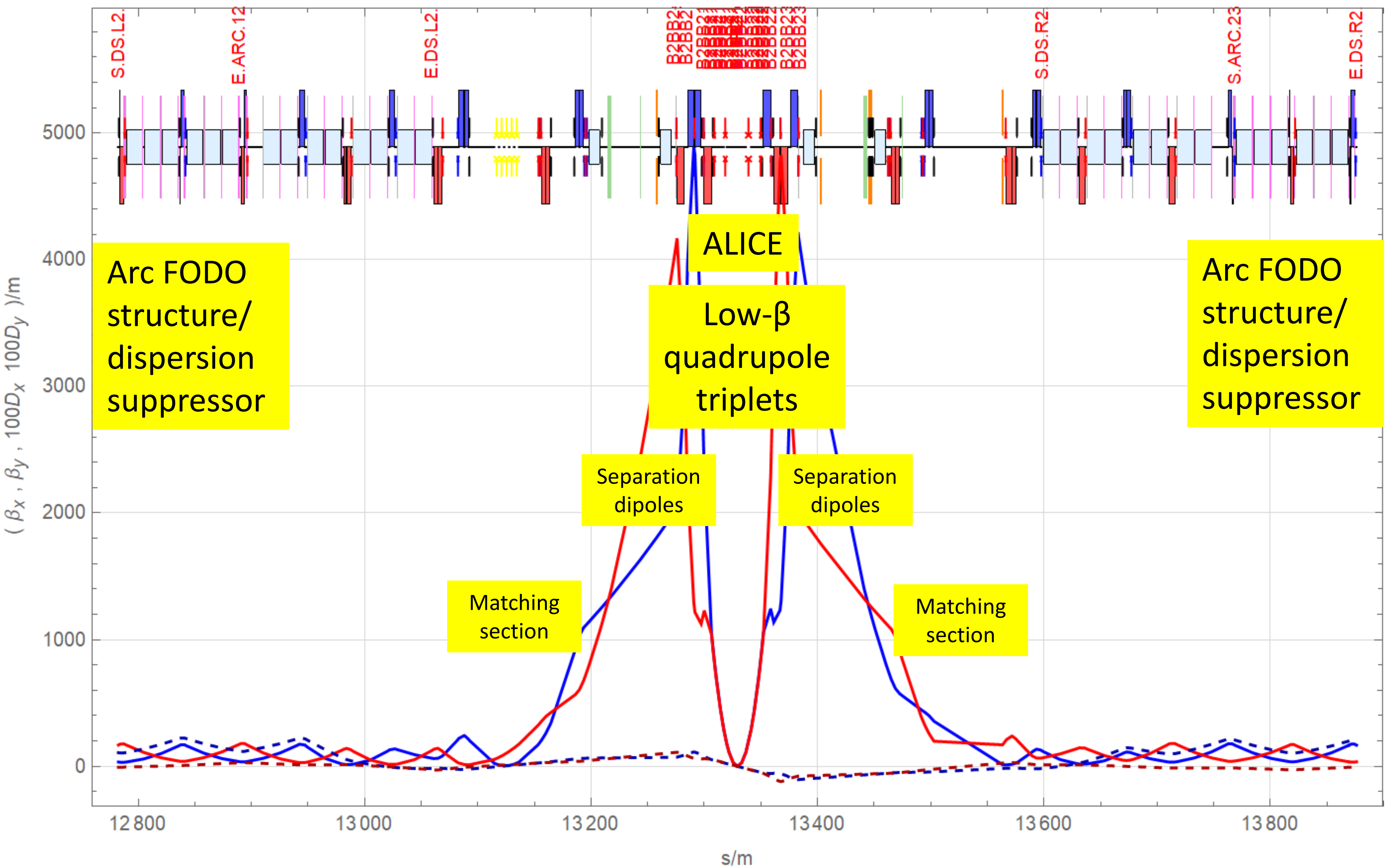
Quadrupoles in common section flip polarity (red/blue), cf previous slide for Beam 1



B-functions interchange horizontal (x) and vertical (y) (red/blue) from previous slide for Beam 1

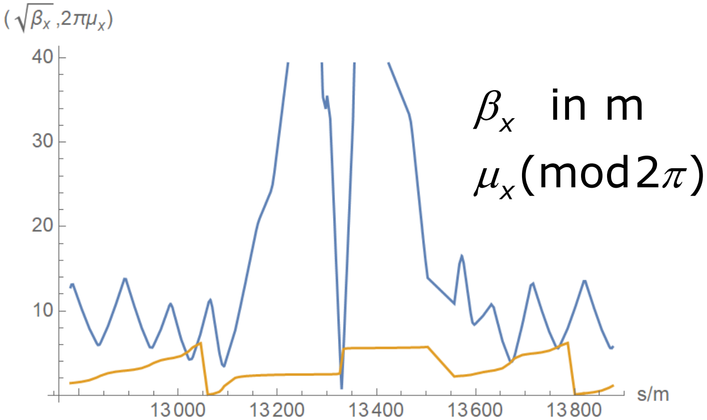
Approximate symmetry with Beam 1 under Left <->Right and x <-> y

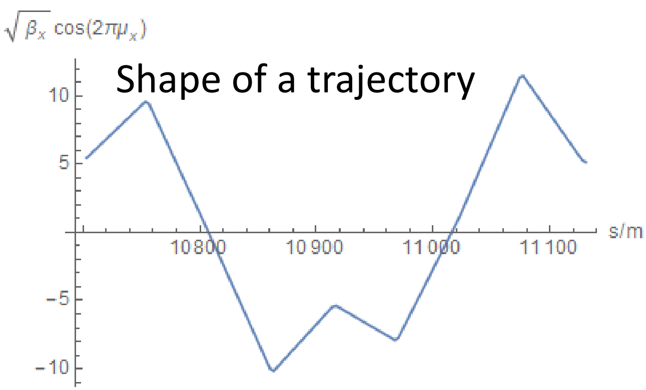
Optics modules in LHC IR2

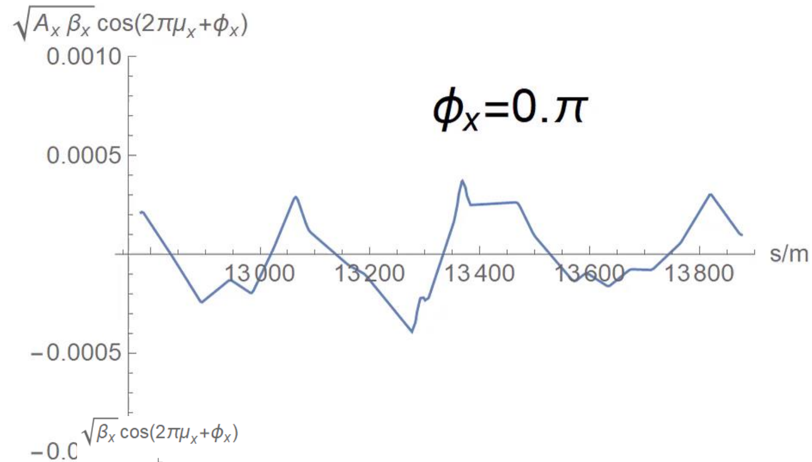


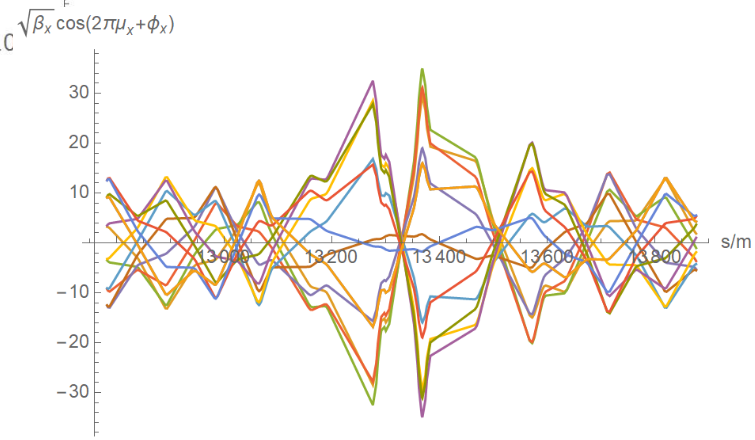
Beam1 is also injected into IR2 so there are a number of special elements for that

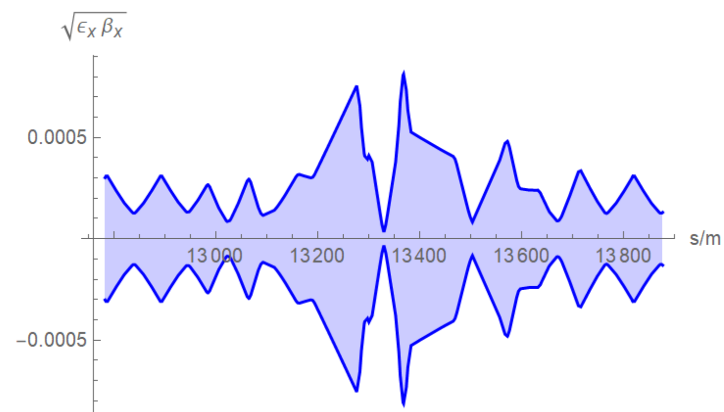
Optical functions and beam envelope in IR2



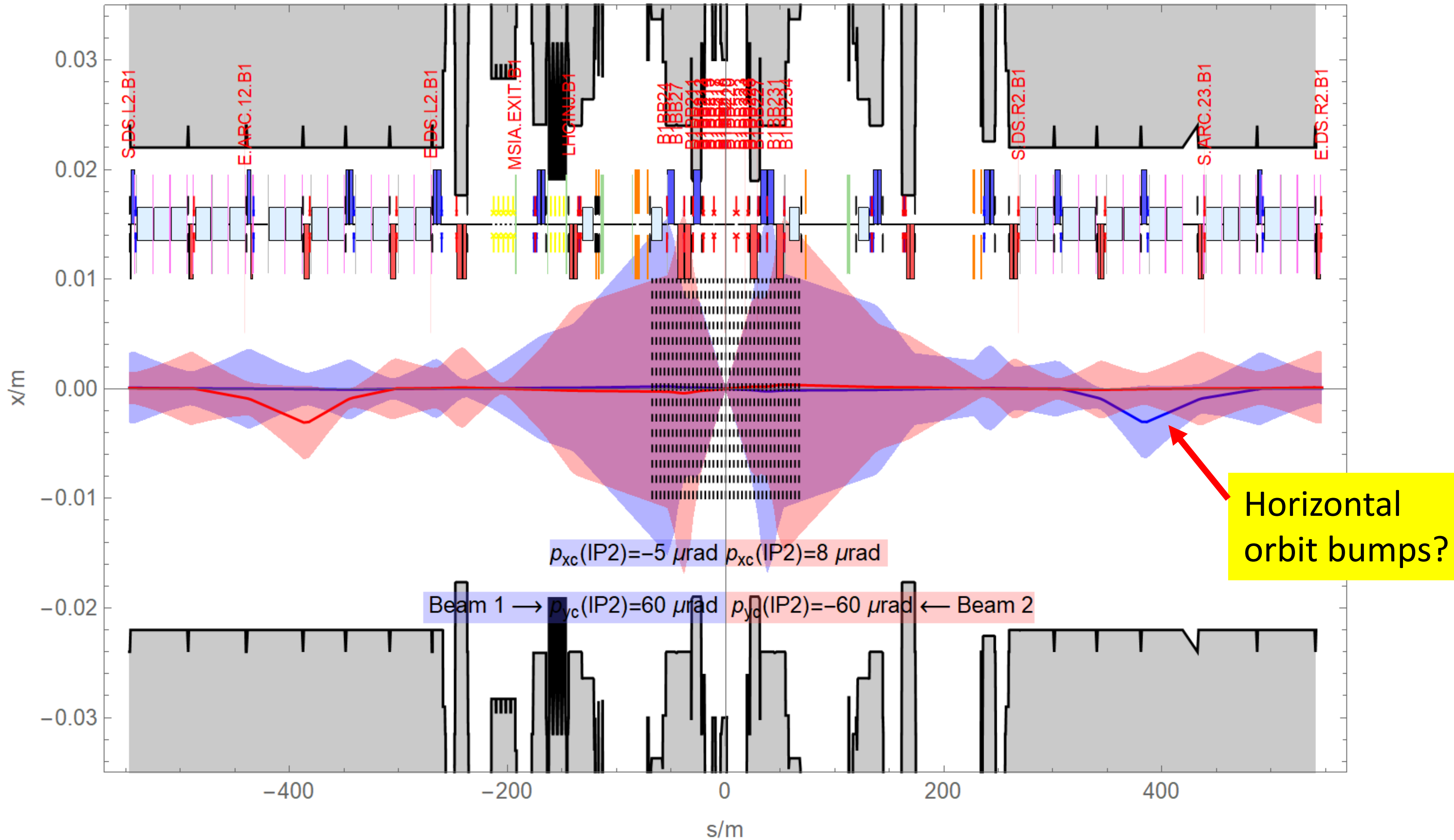








Collision conditions in LHC, IR2 horizontal plane 2018

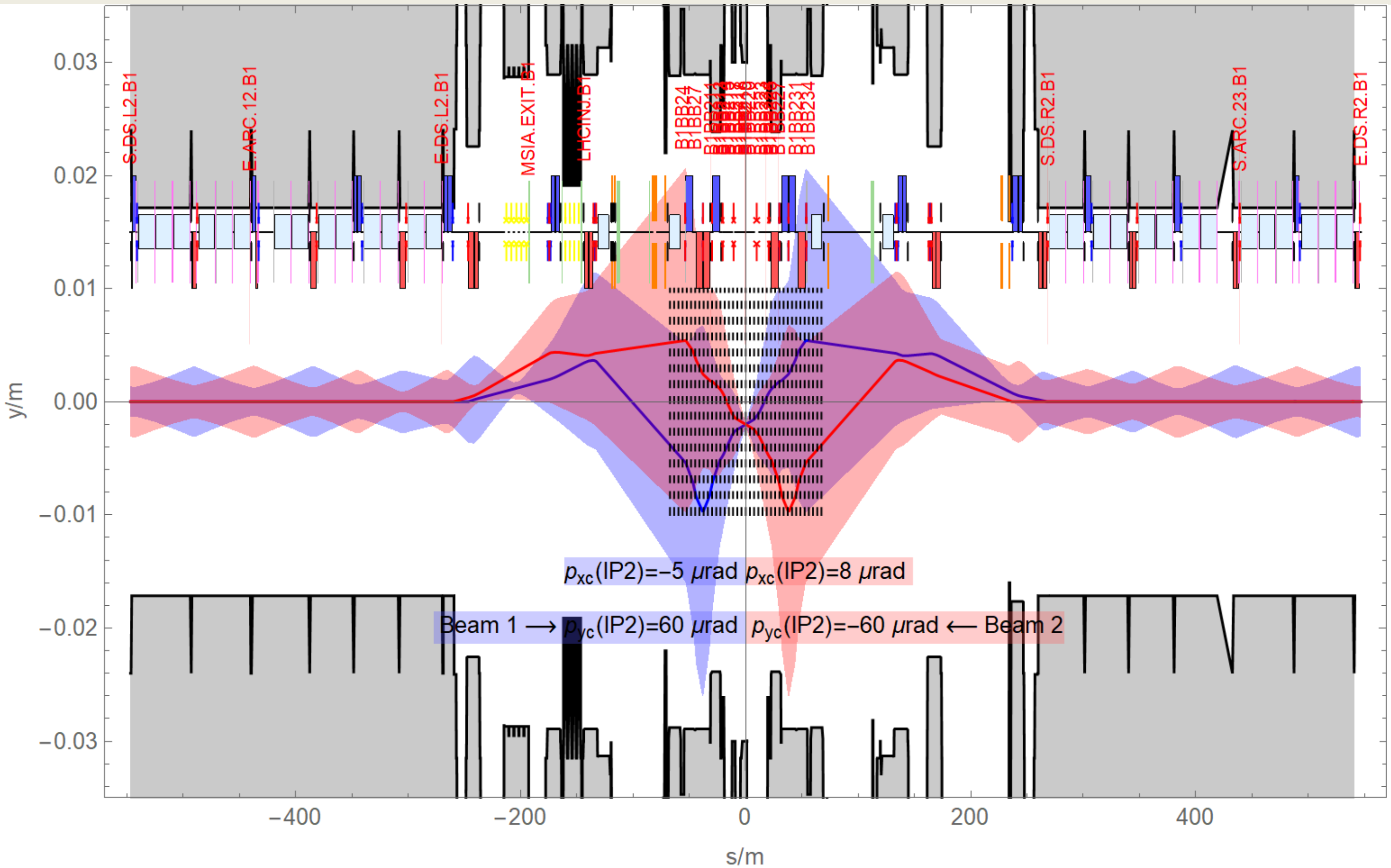


Aim for small β-functions at IP (called β* by convention).

Gives small beams, higher luminosity and collision rate.

Keep beam envelopes sufficiently well within beam pipe (aperture, shown in grey).

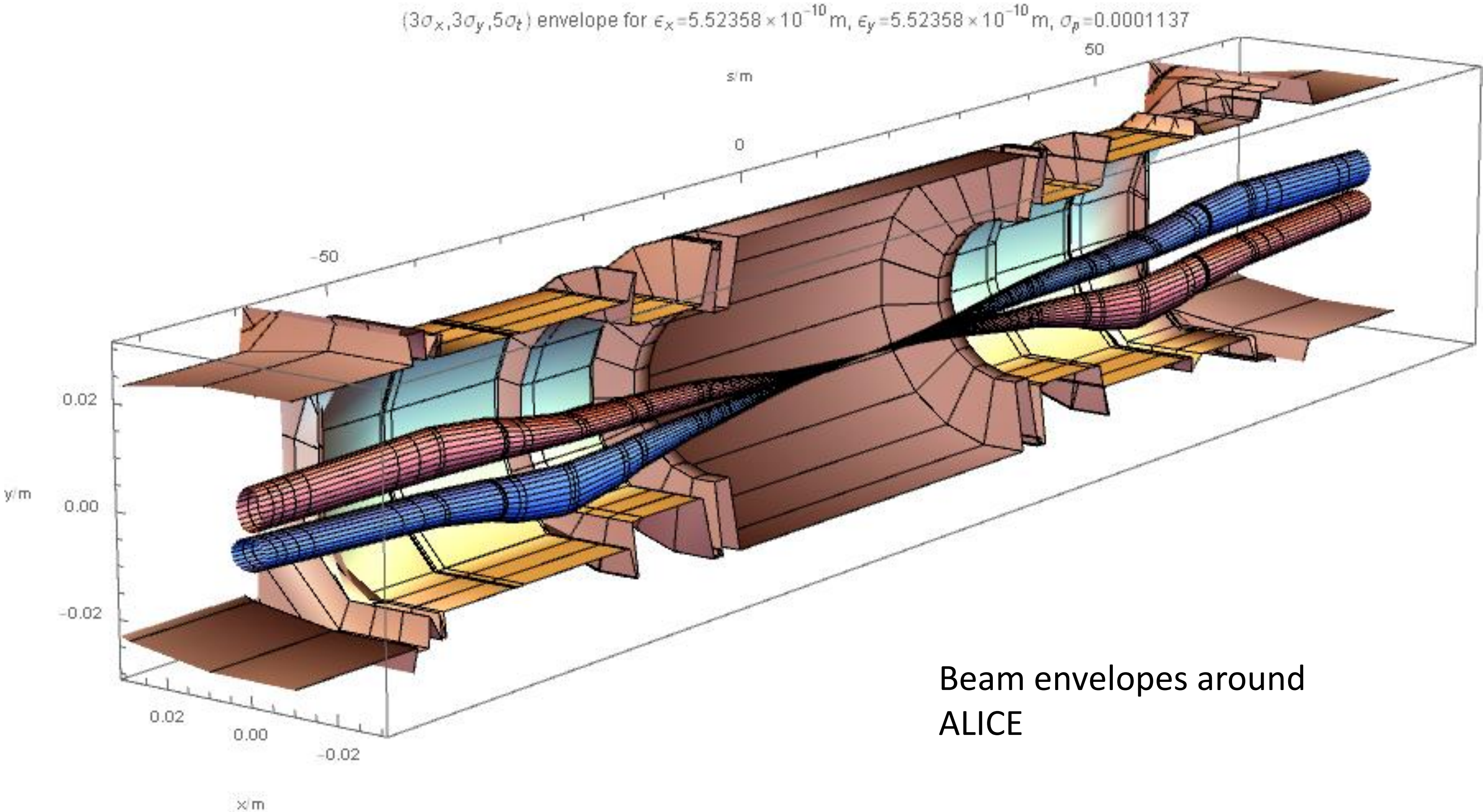
Collision conditions in LHC, IR2 vertical plane 2018



Combination of three orbit bumps (displacement from reference orbit by "small" dipole magnets called correctors, see Imperfections course later):

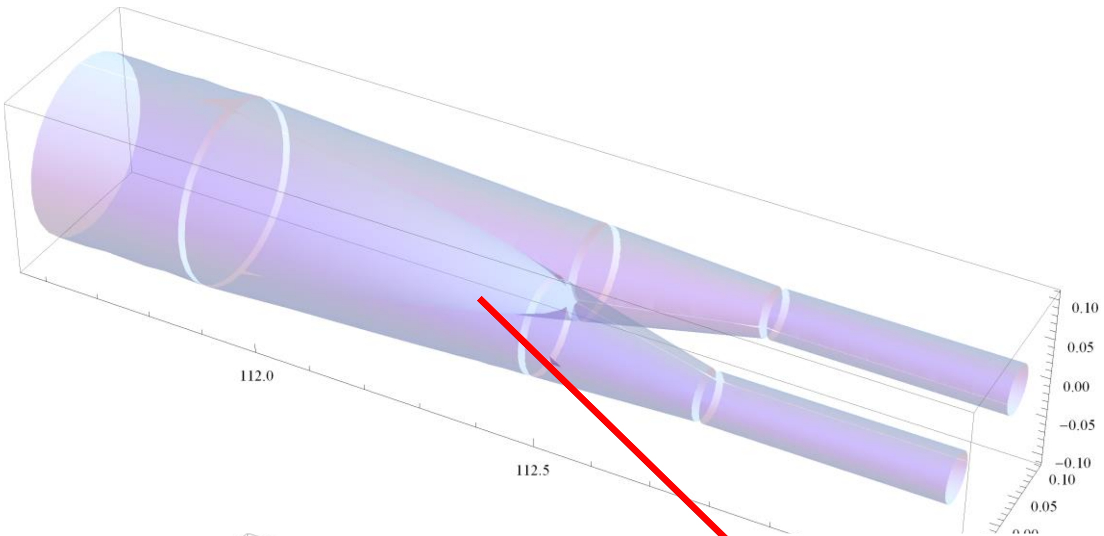
1. Compensate magnetic field of ALICE experiment spectrometer magnet
2. Arrange for vertical crossing angle of beams (avoid unwanted encounters)
3. Lower collision point by 2 mm (the experiment sank …)

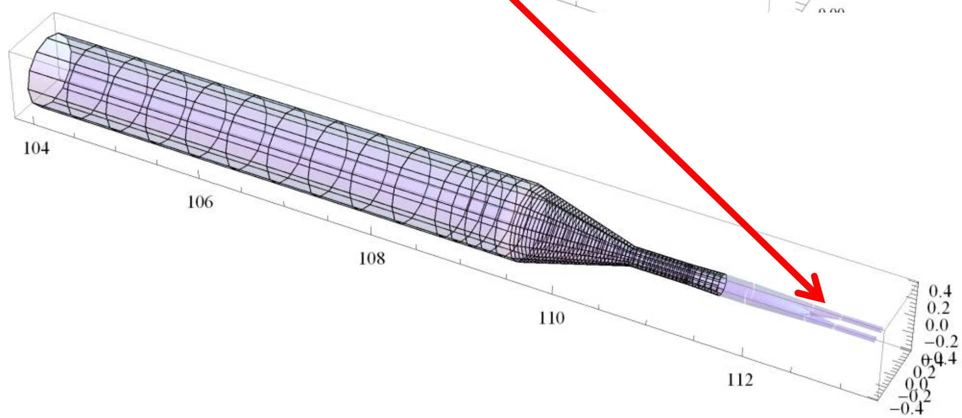
Optics for Pb-Pb collisions in ALICE



Beam envelopes around ALICE

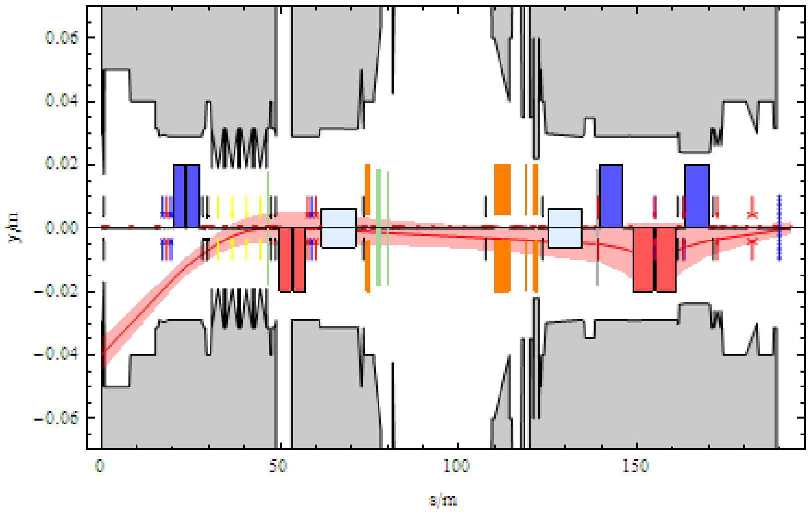
Y-chamber and combined chambers in 3D





Injected beams

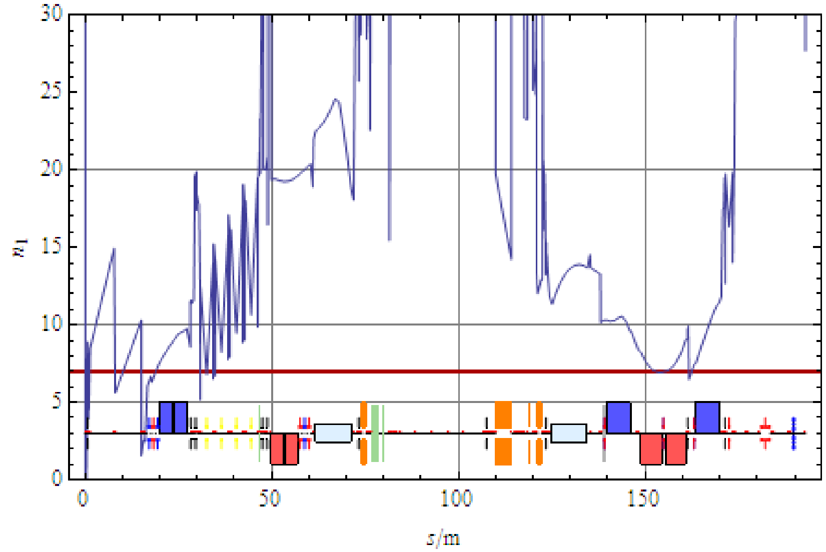
Moved vacuum chamber, injected beam with MKI working, 4 mm mechanical tolerance



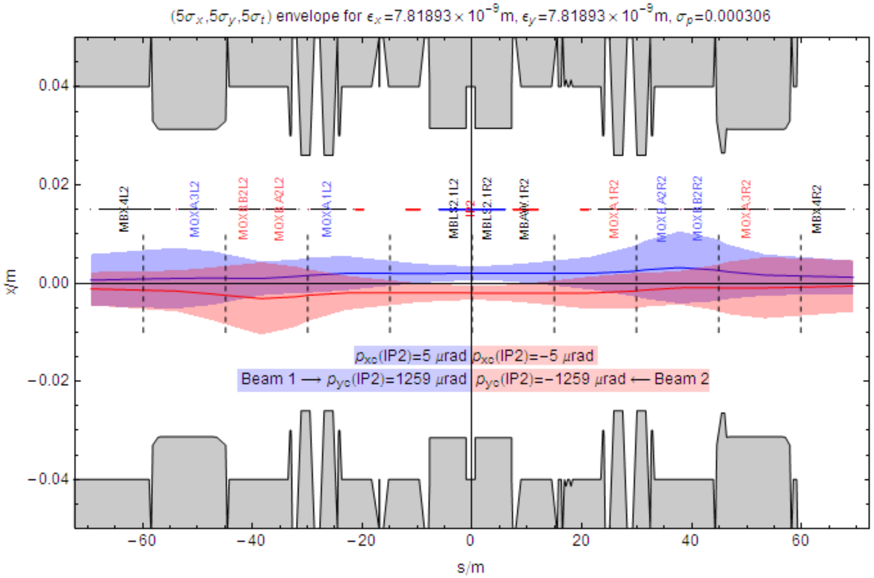
Care must be taken to design the beam optics and the vacuum chamber to provide adequate clearance not only for circulating beams but also injected beams and various failure scenarios – protection of the LHC is a major concern.

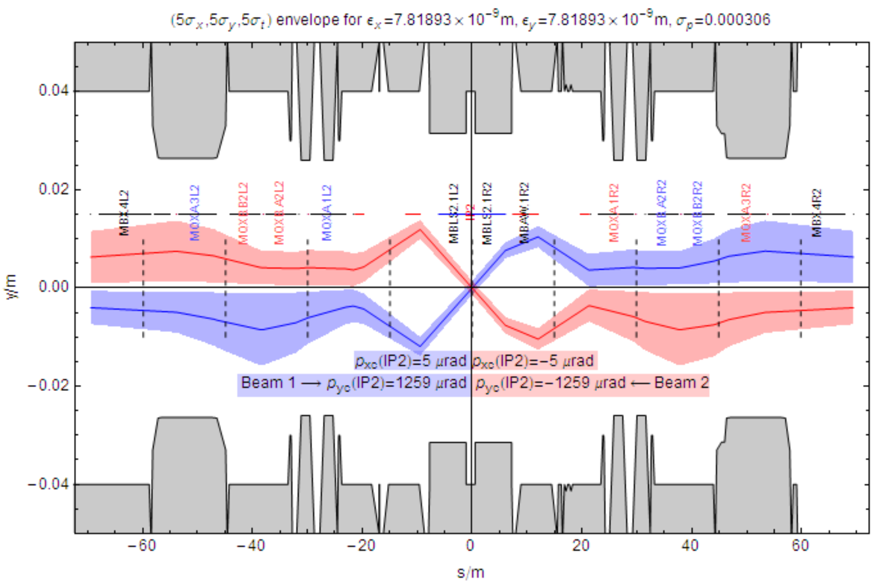
Aperture at critical chamber markers

	n_1
VCTYD.4L2.D.B1	15.4677



ALICE – Separation at injection, circulating beams



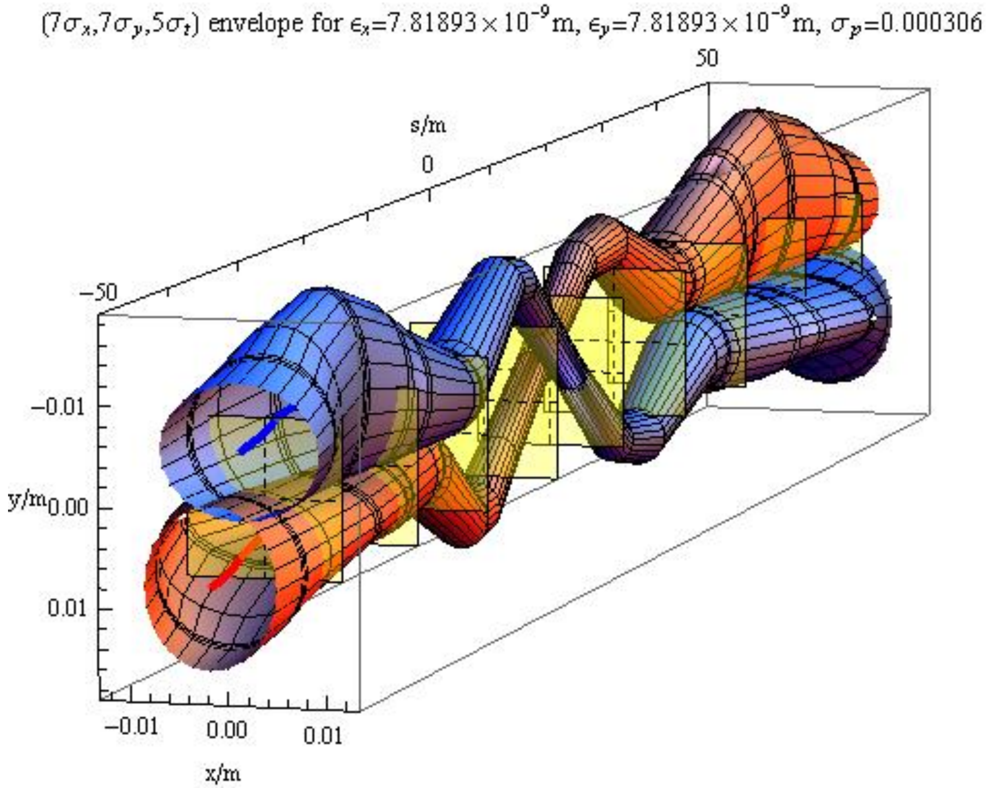


Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (as also in physics).
Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.

Beams are larger in arcs (larger geometrical emittance) but β-functions are smaller in triplets (since β*=10 m at injection).

Other experiments have different separation schemes.

Beam envelopes around ALICE at injection



Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (also in physics).
Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.
Other experiments have different separation schemes …

The "ramp and squeeze" is the process of going from the injection optics at 0.45 *Z* TeV to the collision optics at 6.5 *Z* TeV through a series of matched intermediate optics).

Summary

- With a quick tour of the LHC, and the ALICE interaction region in particular, we have tried to show how the concepts from the transverse beam dynamics and optics courses give you the concepts and tools to understand a real-world hadron collider.

BACKUP SLIDES

History of hadron colliders in the 20th century

- 1970s:
  - First hadron collider, the ISR at CERN operated
    - Mainly p-p collisions, but also first ppbar, d and α (just a few days)
  - Construction of larger pp collider ISABELLE started in USABut growing conviction that linear e+e- colliders were the future …
- 1980s:
  - Two ppbar colliders, SppS and Tevatron, major discoveries
  - ISABELLE abandoned
  - LHC pp collider feasibility study (1983-4) for late 1990s …
  - UNK pp collider construction (21 km tunnel completed)
  - SSC pp collider, 80 km tunnel construction started in USA
- 1990s:
  - UNK abandoned
  - first ep collider HERA operated
  - SSC abandoned
  - RHIC construction in ISABELLE tunnel
  - LHC pp collider approved, including mention of Pb+Pb for ALICE, CMS experiments

History of hadron colliders in the 21st century

- 2000:
  - RHIC collider at Brookhaven, in ISABELLE tunnel, collides first heavy ions Au+Au, then polarized p+p, many other species, outpouring of discoveries in heavy-ion physics
- 2009-11:
  - LHC first p+p and Pb+Pb collisions …
  - Tevatron closed down
  - Higgs discovery in 2012 at LHC
- Now:
  - All (both) hadron colliders in the world have substantial heavy-ion programmes
  - All hadron collider experiments in the world study heavy-ion collisions, transition to precision physics
- Future:
  - Electron-ion collider in USA (the next collider – seminar later)
  - pp and heavy-ion collisions at HL-LHC, possibly SppC or FCC