

Introduction to ALICE in the LHC

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ALICE

Pb-Pb 5.36 TeV

LHC22s period

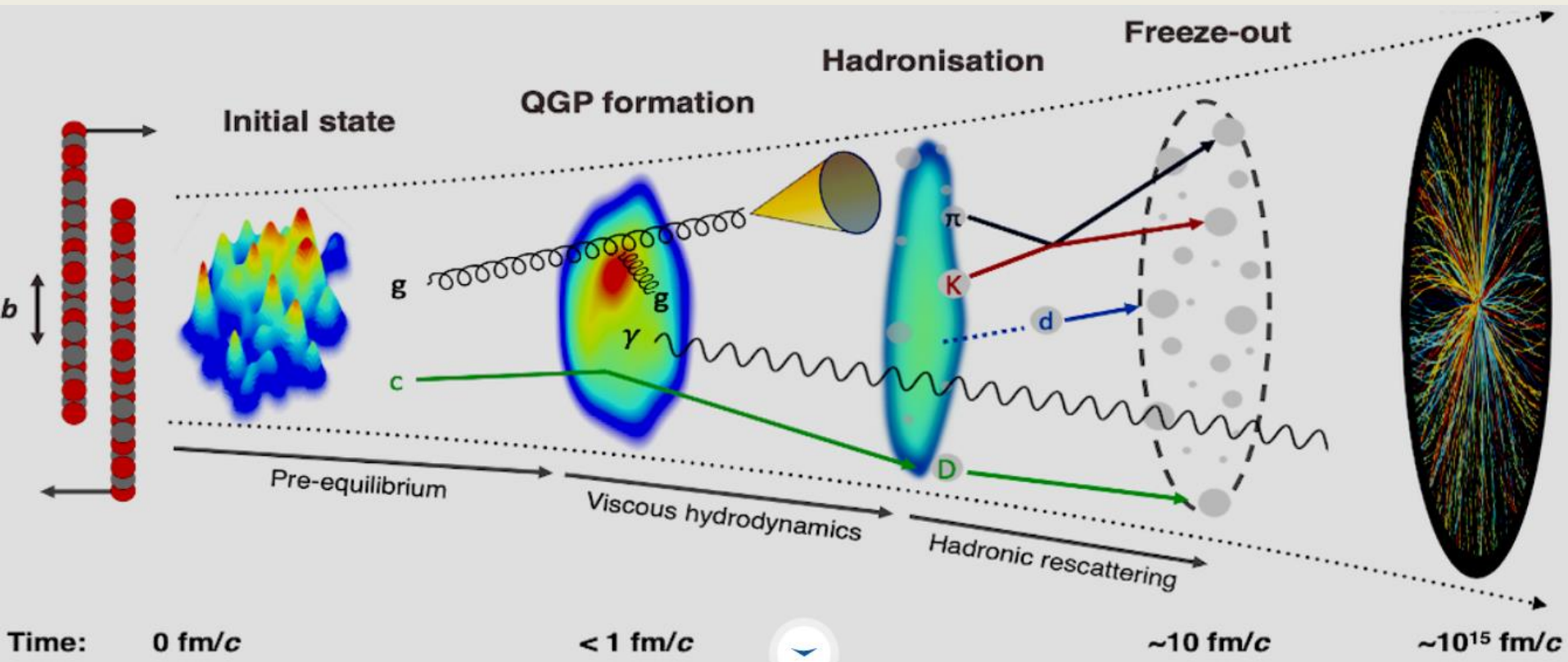
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The Experiment

- The collision of single lead-lead nuclei at LHC energies produces several tens of thousands of particles.
- ALICE detectors measure the basic information about the majority of these particles: information on the number of particles as well as the type, mass, energy, and direction of each of the particles.
- Many different subdetectors are used, each providing a separate piece of information.
- From this, we can infer the existence and properties of matter under the extreme conditions created during the collision. ALICE also takes data with proton-proton, proton-lead, and collisions of other intermediate nuclei.

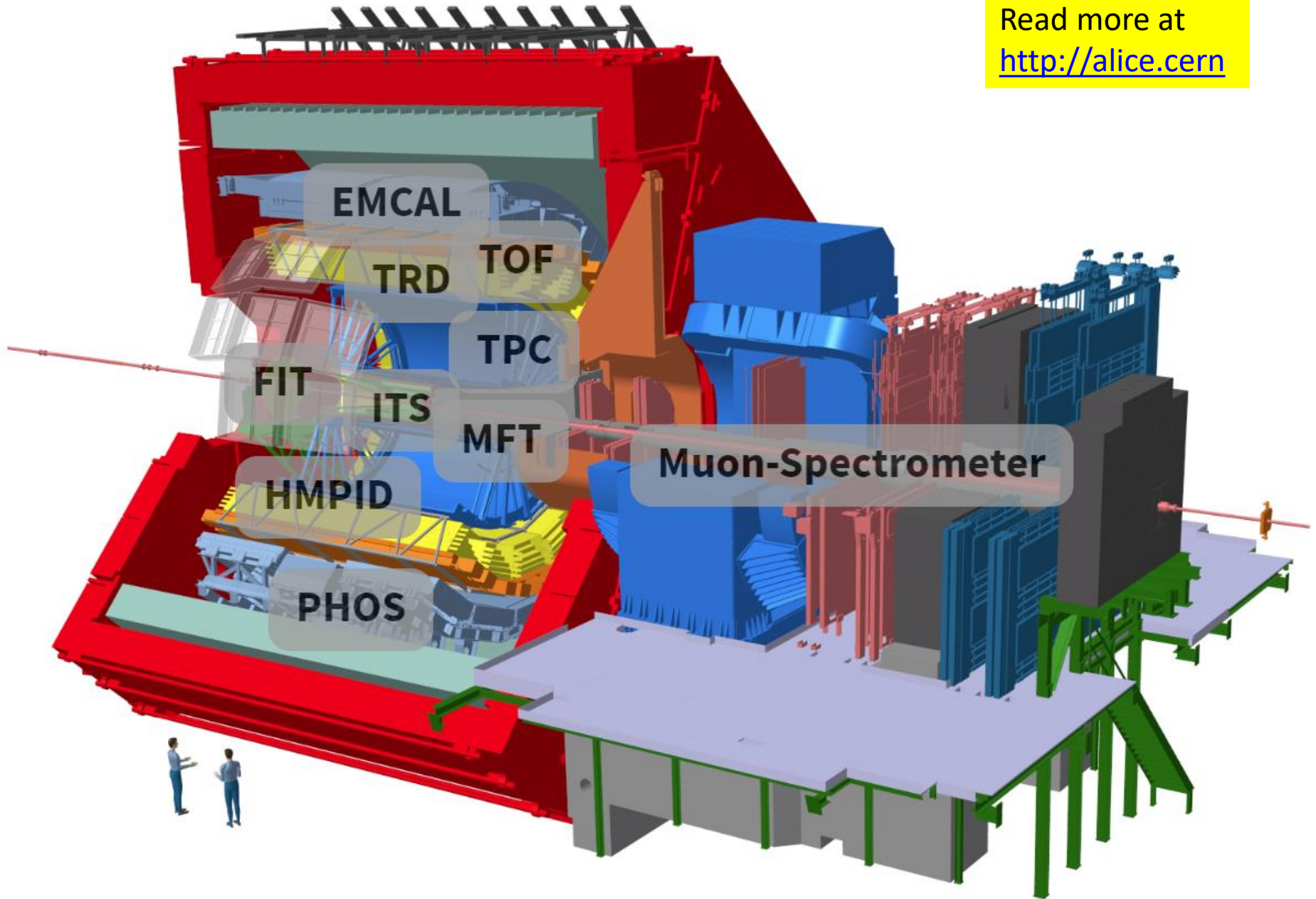
Physics of nucleus-nucleus collision



ALICE is designed to study the physics of strongly interacting matter at extreme conditions of high temperature and energy density, where a phase of matter called the quark-gluon plasma (QGP) forms. The characterization of the QGP matter require creating a sufficiently large volume of hot and dense matter and is therefore pursued in collisions of heavy nuclei at the highest possible energies at the CERN LHC. Very rich physics, eg, the QGP is the most perfect liquid in Nature.

Under normal conditions, quarks are bound ('confined') into composite objects called baryons (bound states of three quarks, eg proton and neutron) and mesons (bound states of a quark and antiquark pair). Quantum Chromodynamics (QCD) predicts that at high energy density a transition occurs from ordinary nuclear matter to a plasma of free ('deconfined') quarks and gluons – a state of matter that existed in the early Universe

Read more at
<http://alice.cern>



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, ...

Goals of a collider

- High collision energy: since 2015 LHC has provided
 - > 13 TeV total energy in pp collisions
 - > 1 PeV total (or 5. TeV per colliding nucleon pair) in Pb-Pb collisions, also p-Pb and Xe-Xe 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)

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 $T_{\text{sun}} = 1.6 \times 10^7 \text{ K}$

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

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

Energy density in QGP: $u_{\text{QGP}} \approx 15 \text{ GeV/fm}^3$

Exercise: check all these numbers

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

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

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

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

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

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

- Parameters in luminosity

- No. of particles per bunch N
- No. of bunches per beam k_b
- No. of bunches colliding 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:

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

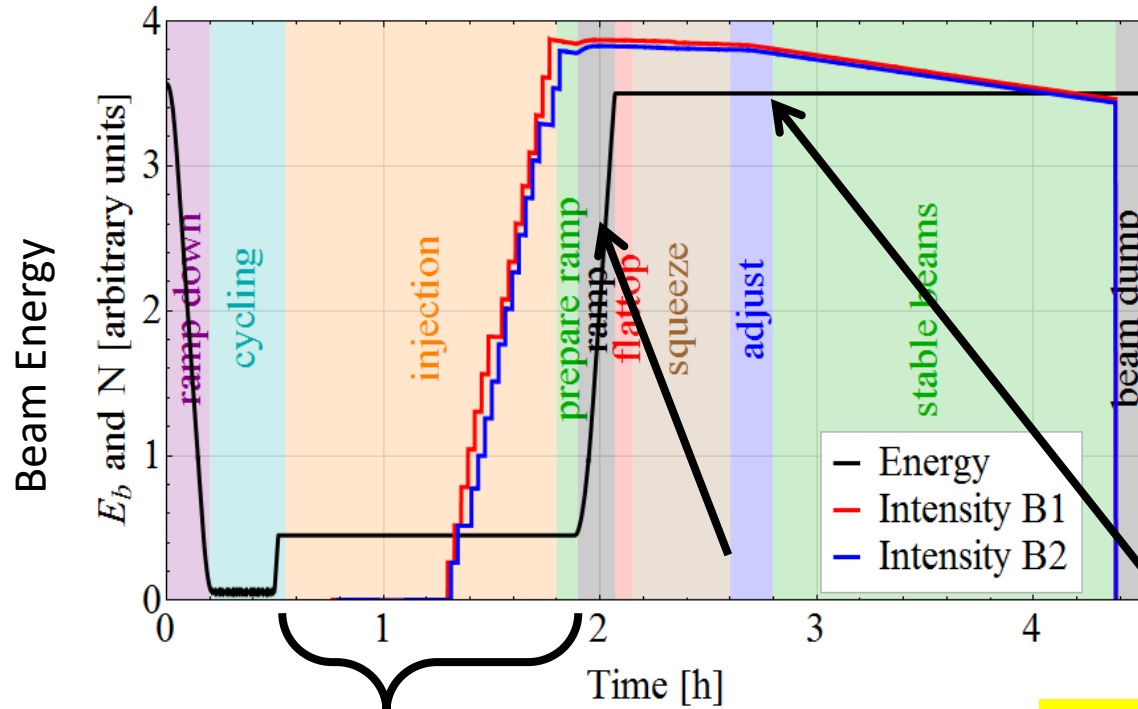
⇒ Round beams at IP:

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

(N.B. LHC uses RMS emittances.)

IP = “interaction point”

LHC Accelerator Cycle (Fill) schematic



Low energy injection plateau:
Accumulation of beam

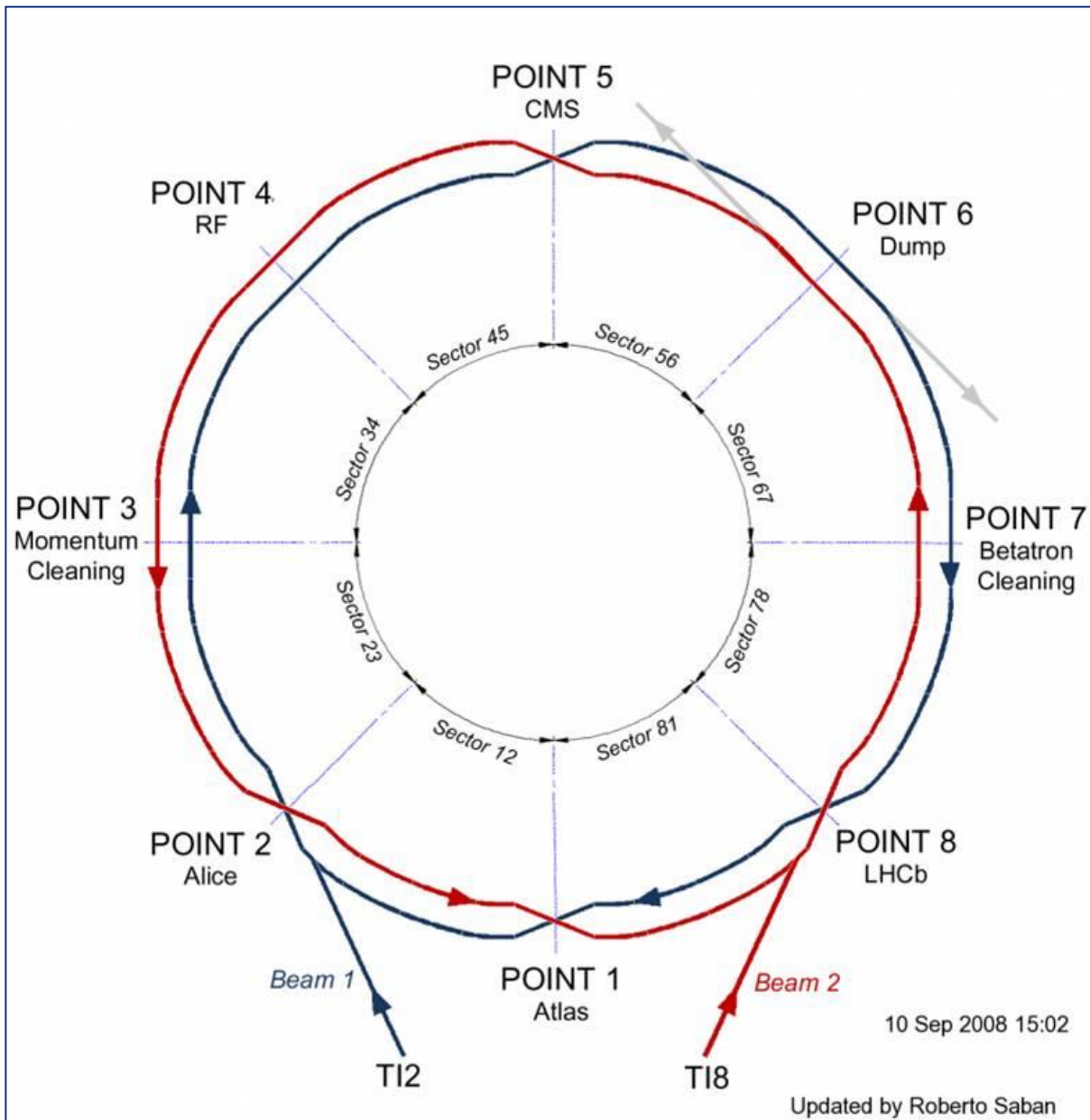
Acceleration

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 \pm 145 m)

IR2 (ALICE \pm 117 m)

IR5 (CMS \pm 145 m)

IR8 (LHC-B \pm 80 m)

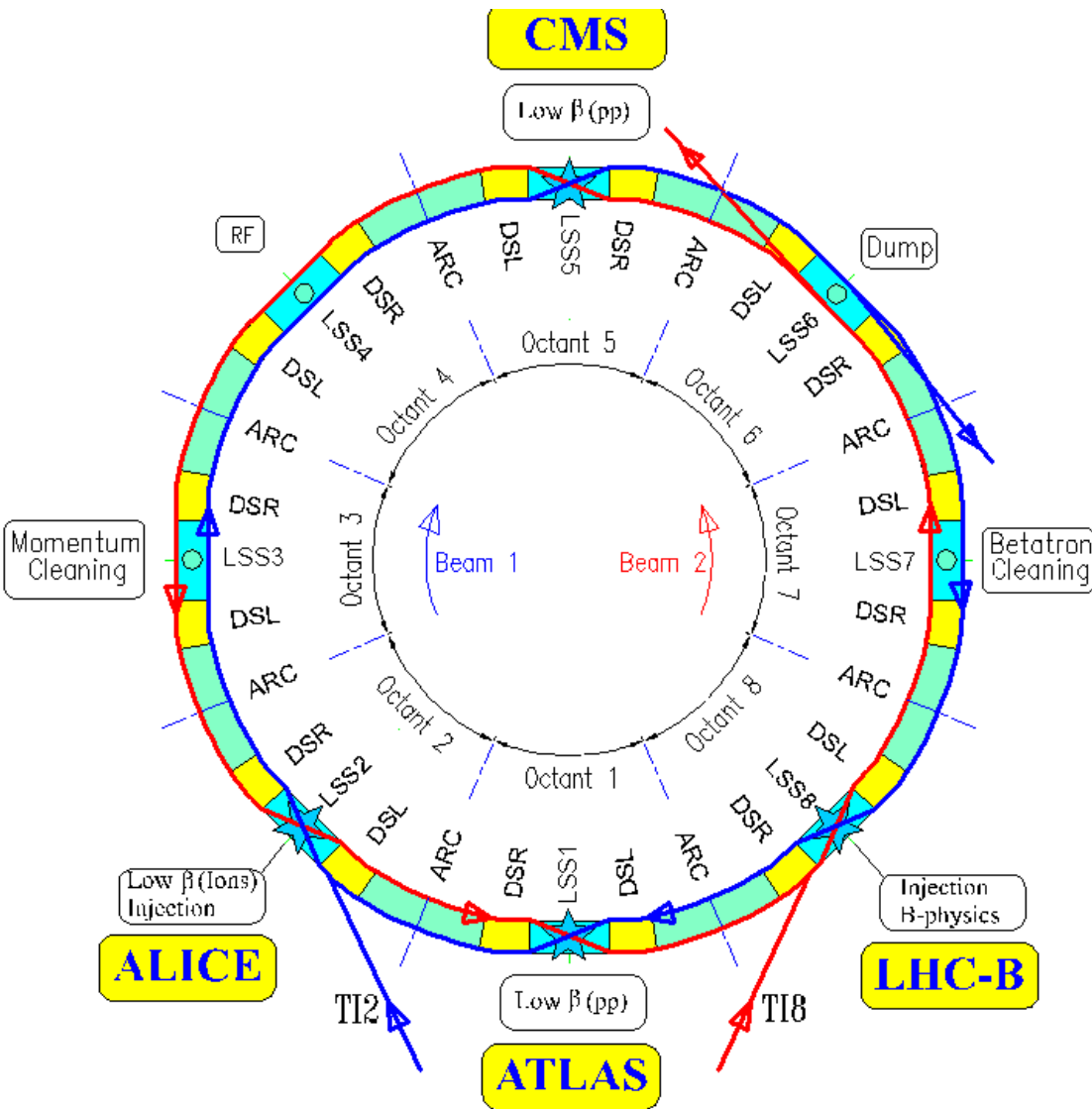
LHC orientation – schematic (2)

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



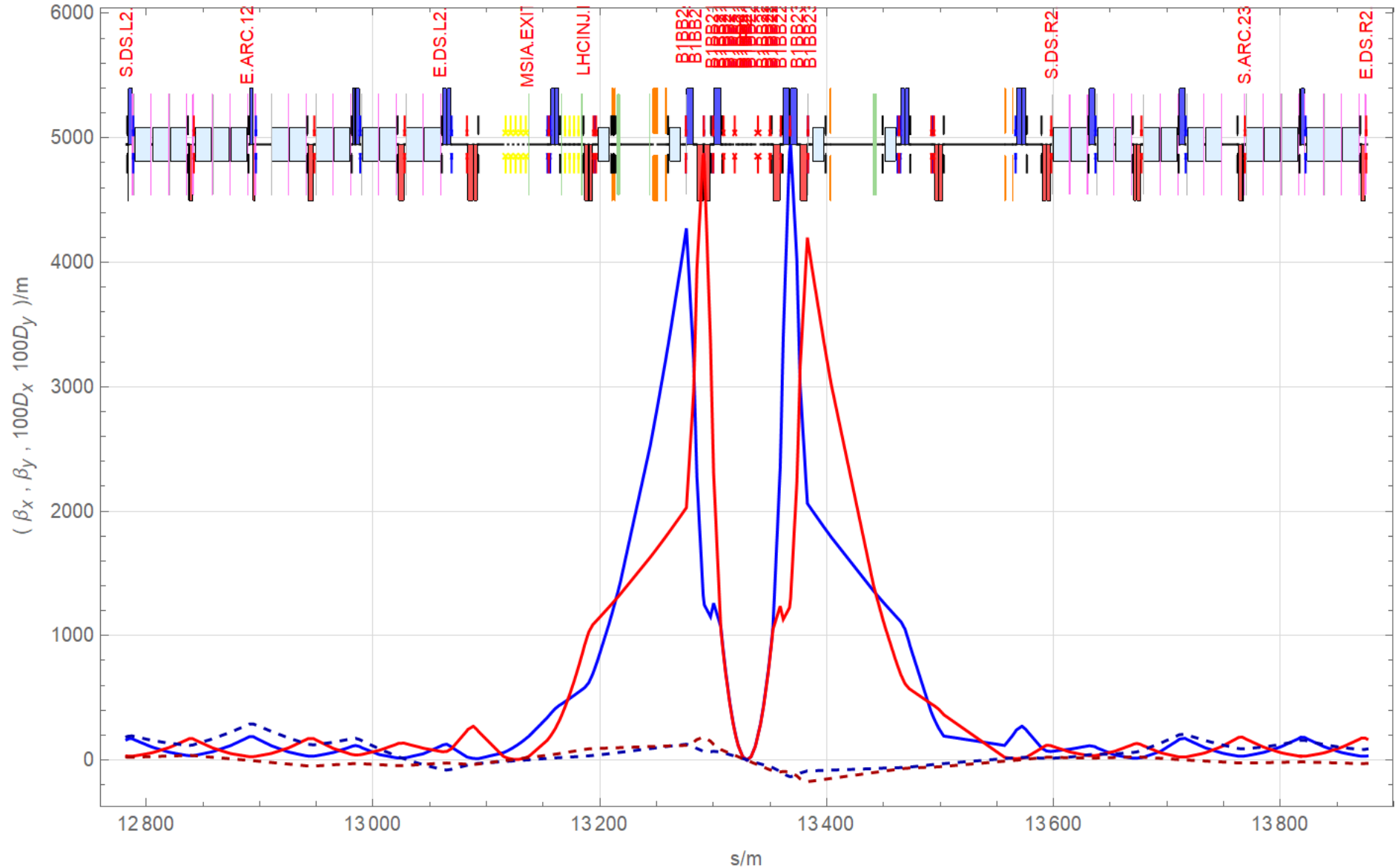
Magnet polarities in the ARCS of the LHC

- 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 optics 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 using the same variables (strengths of common quadrupoles)
- To first approximation, the IR optics are symmetric under the interchange of x and y AND left to right of the IP

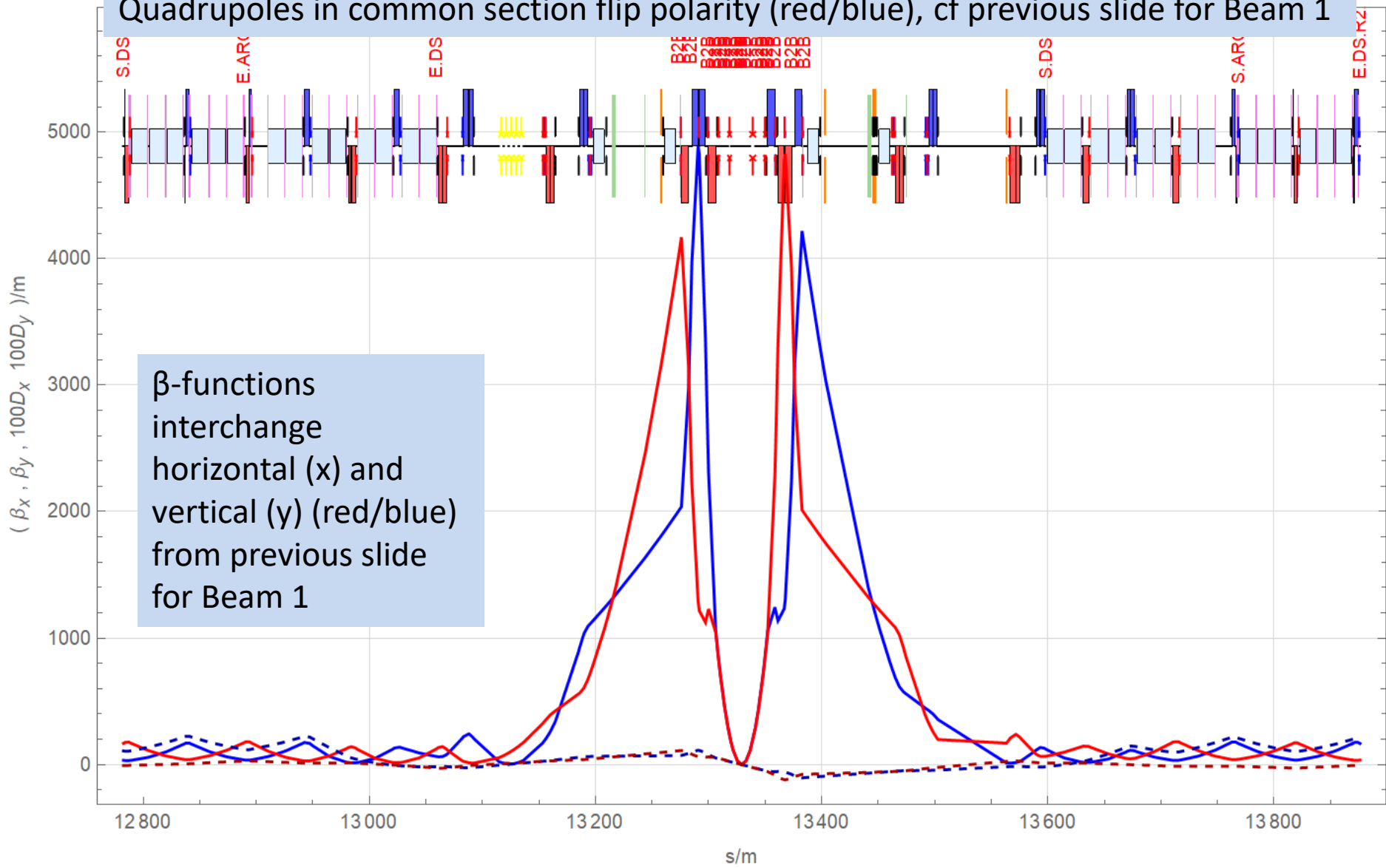
Optical functions for Beam 1 in LHC IR2, 2018 Pb-Pb run



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

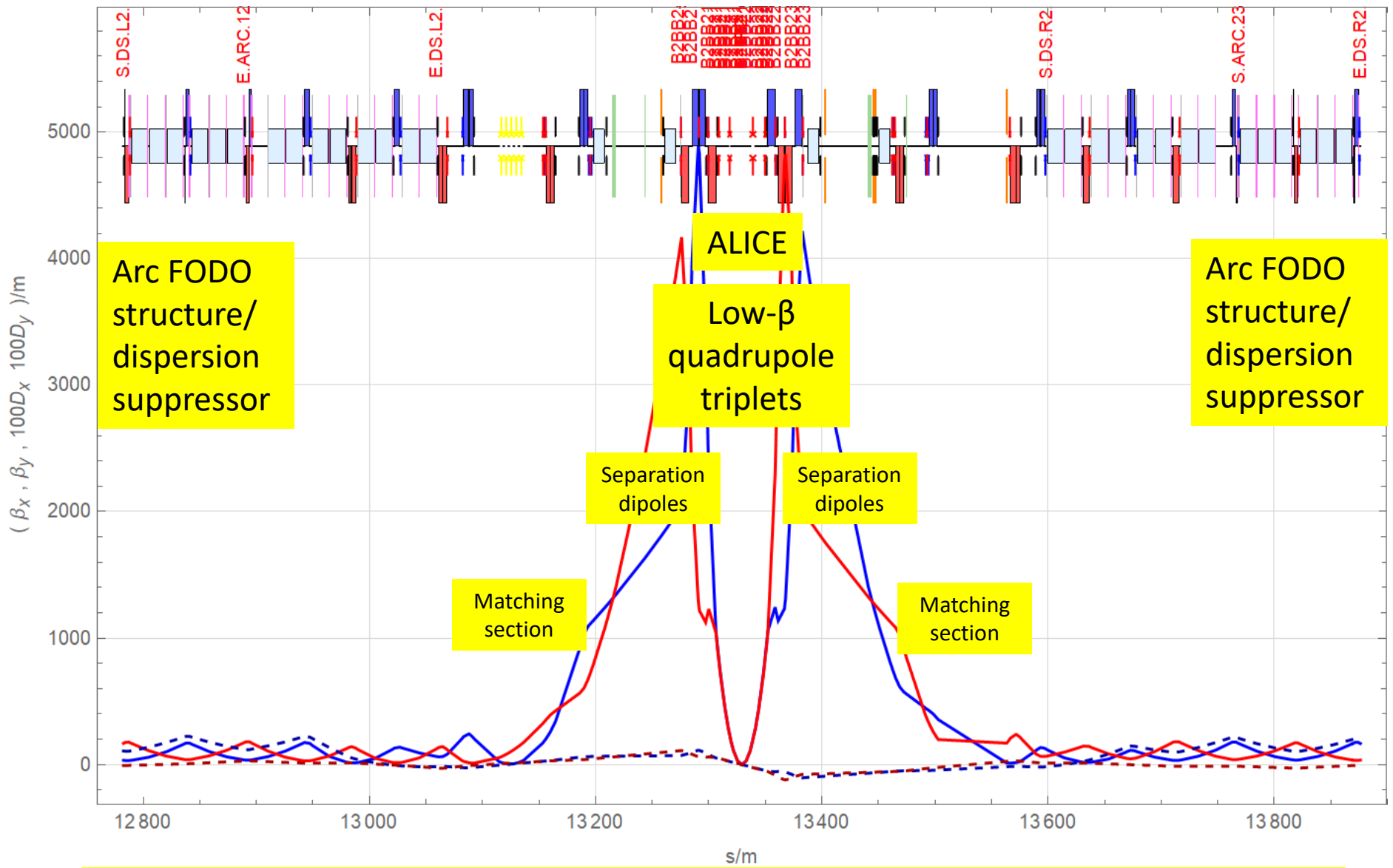
Optical functions or Beam 2 in LHC IR2, 2018

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



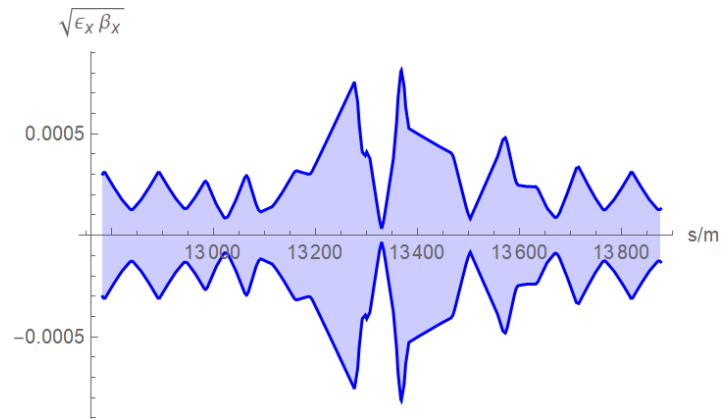
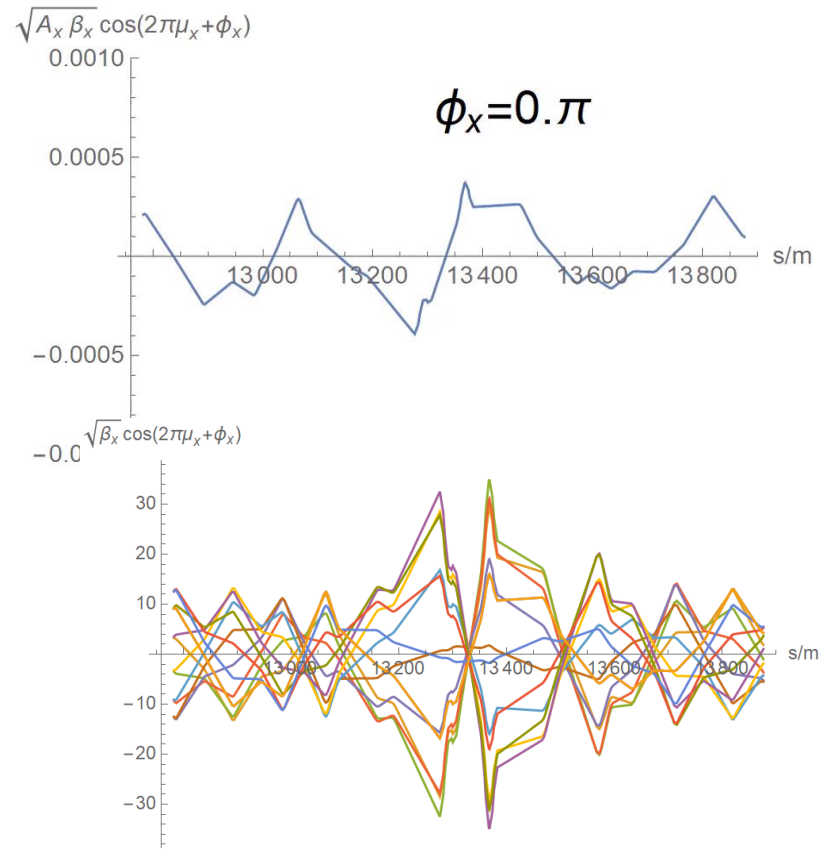
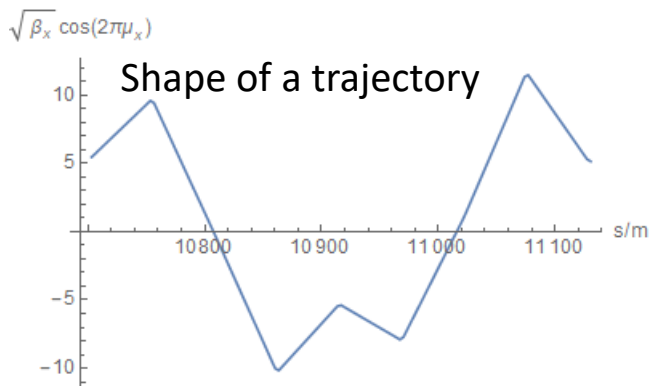
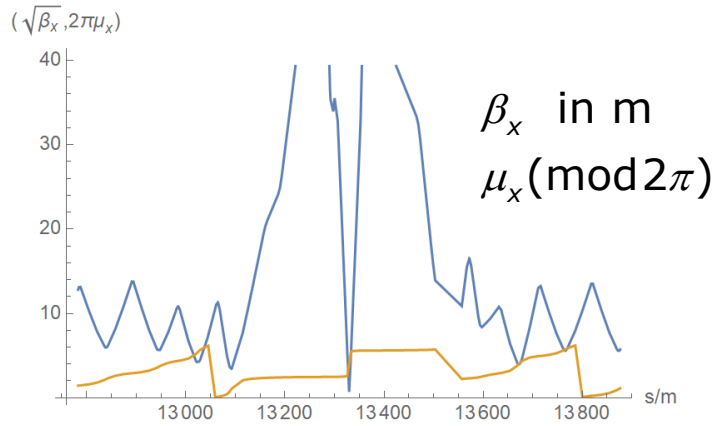
Approximate symmetry with Beam 1 under Left \leftrightarrow Right and x \leftrightarrow y

Optics modules in LHC IR2

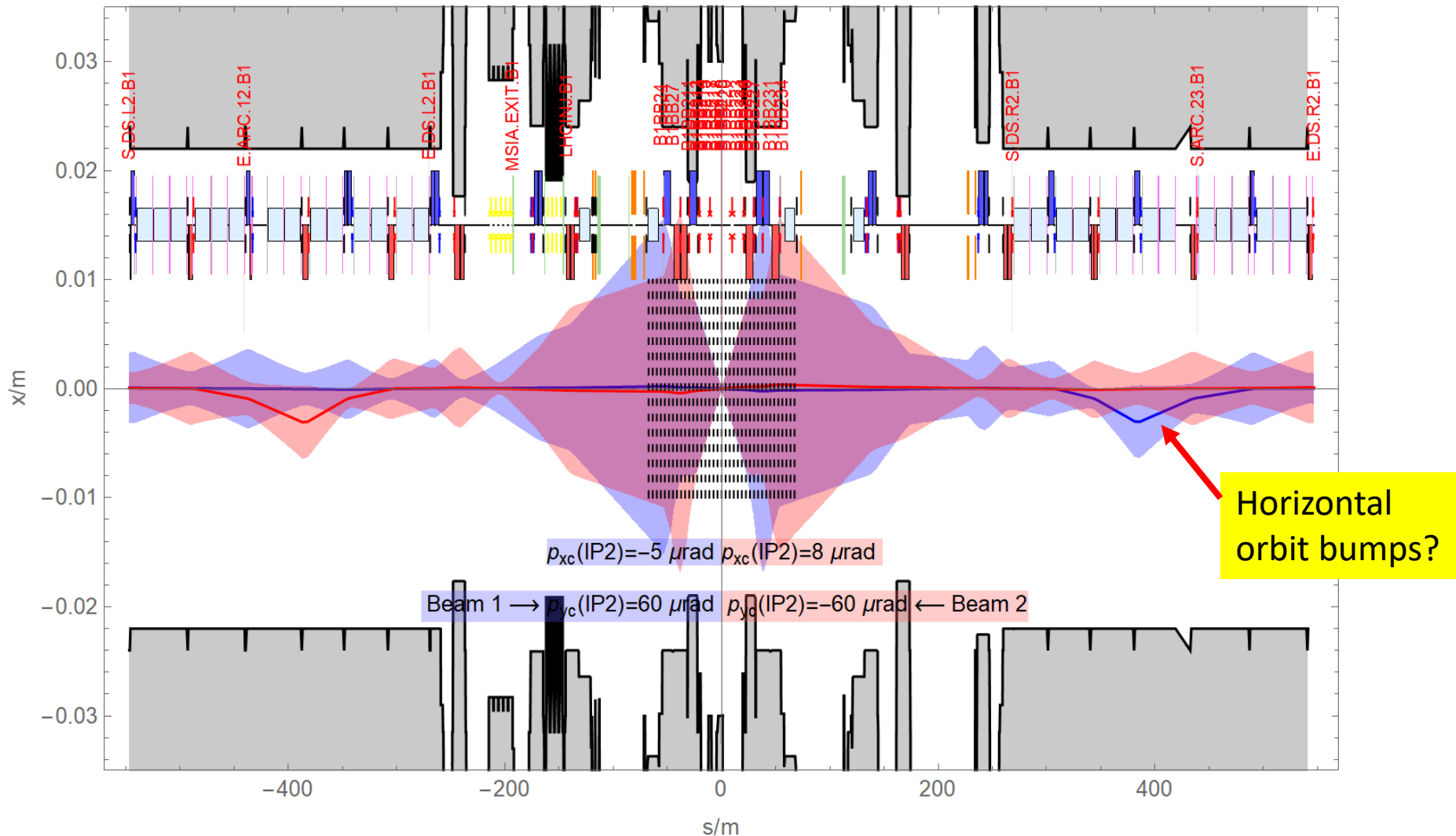


Beam1 is also injected into IR2 so there are a number of special elements for that

Optical functions and beam envelope in IR2



Collision conditions in LHC, IR2 horizontal plane 2018

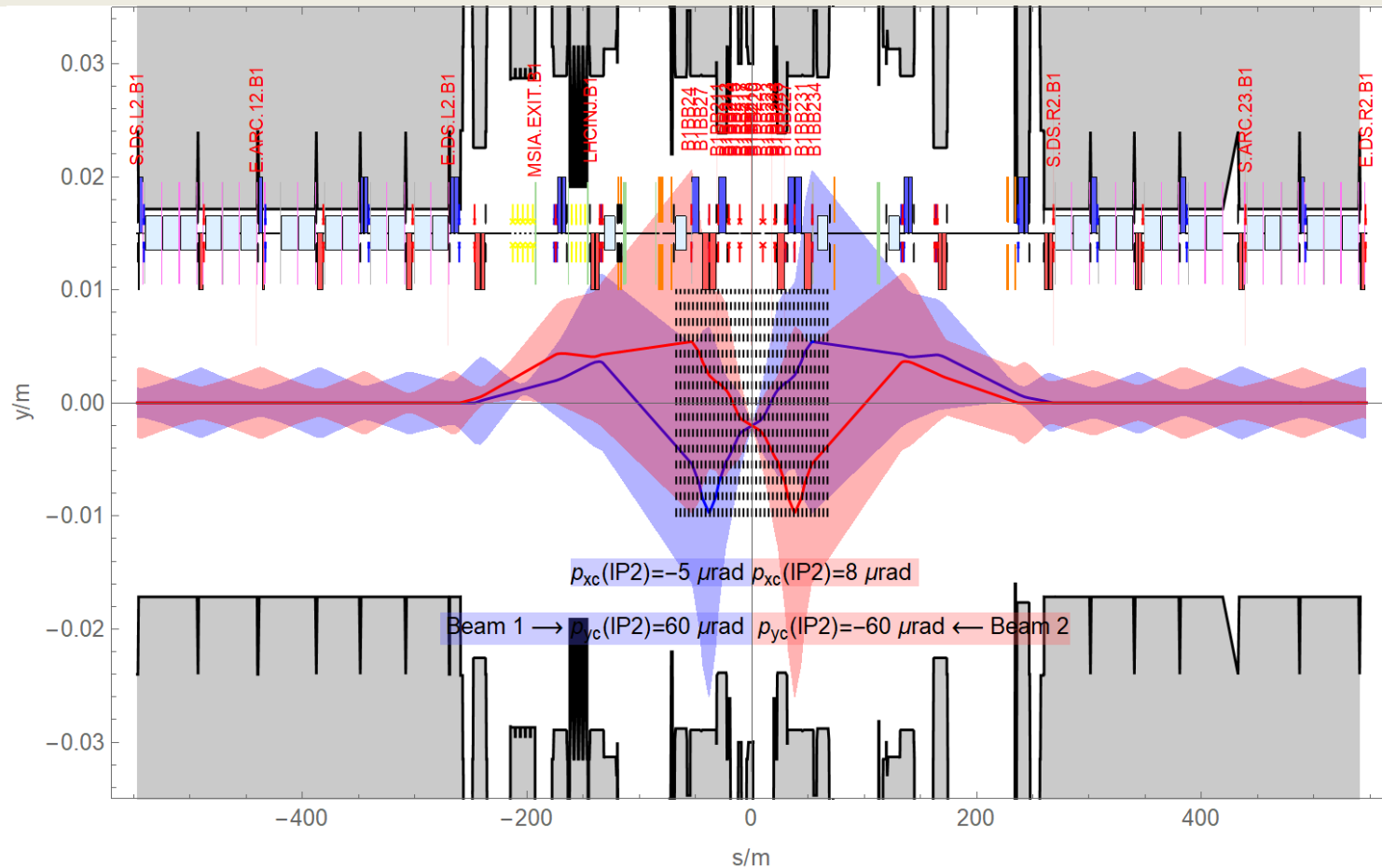


Aim for small β -functions at IP (called β^* by convention).

Gives small beams, higher luminosity and collision rate.

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

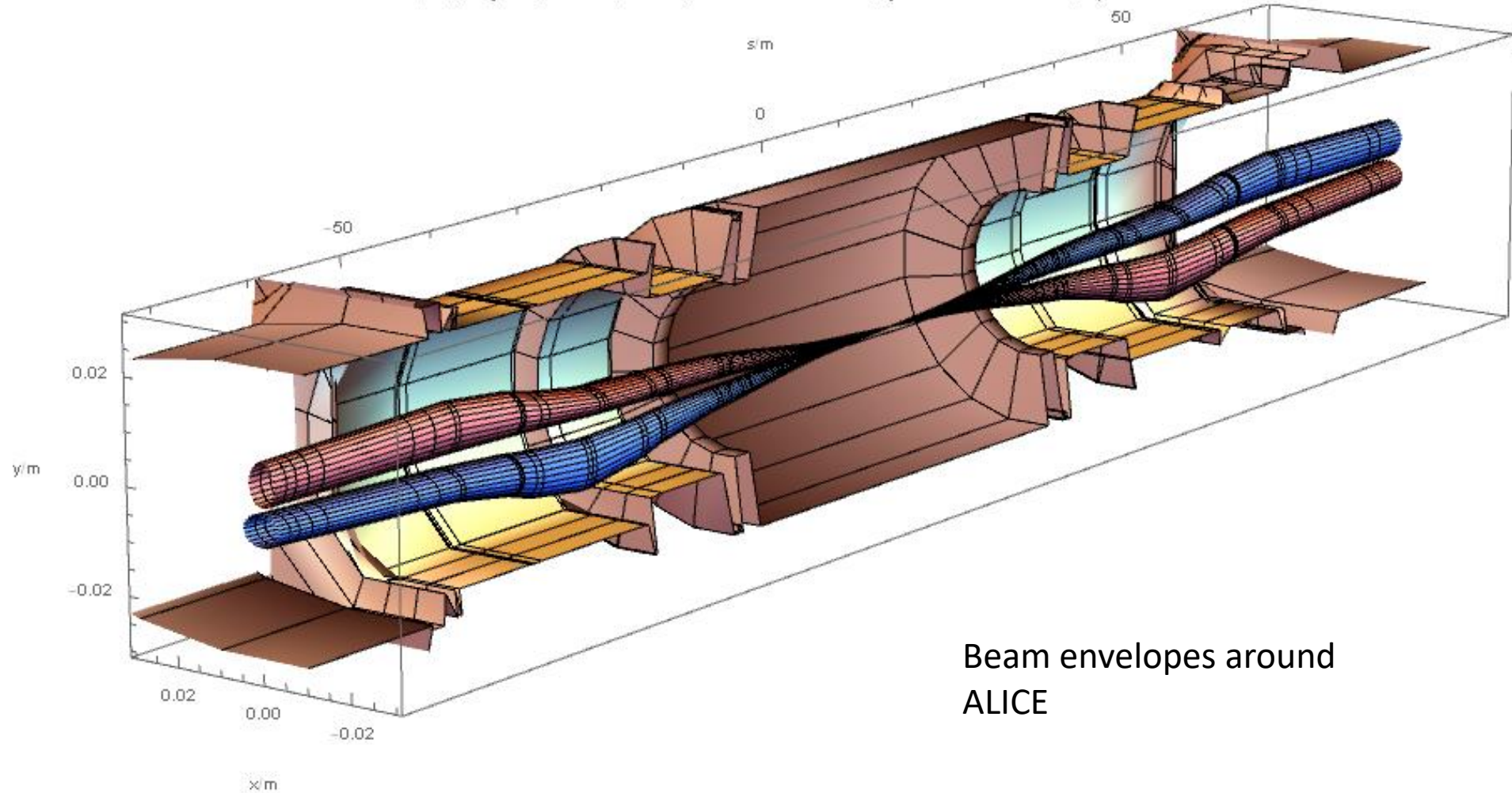
Collision conditions in LHC, IR2 vertical plane 2018



- 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 ...)

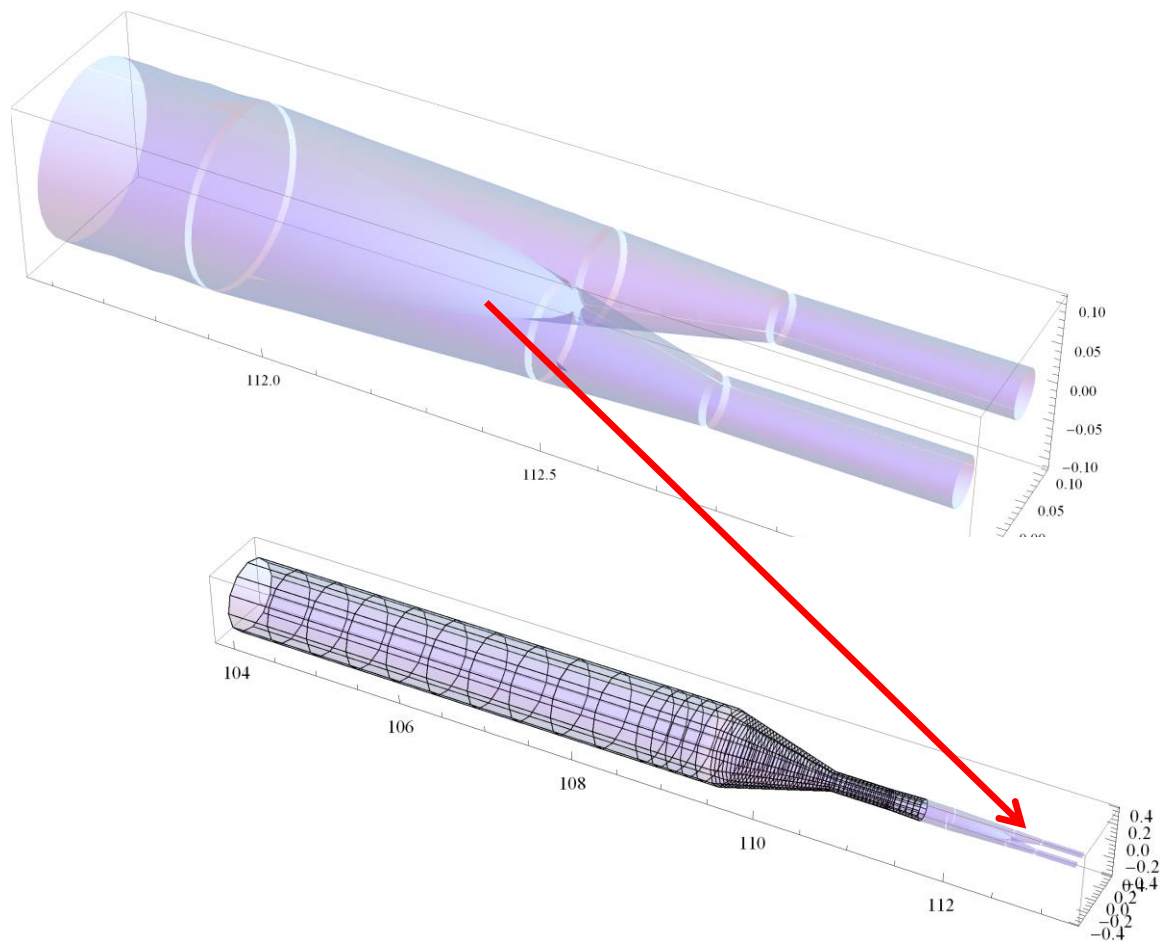
Optics for Pb-Pb collisions in ALICE

$(3\sigma_x, 3\sigma_y, 5\sigma_z)$ envelope for $\epsilon_x = 5.52358 \times 10^{-10} \text{ m}$, $\epsilon_y = 5.52358 \times 10^{-10} \text{ m}$, $\sigma_p = 0.0001137$



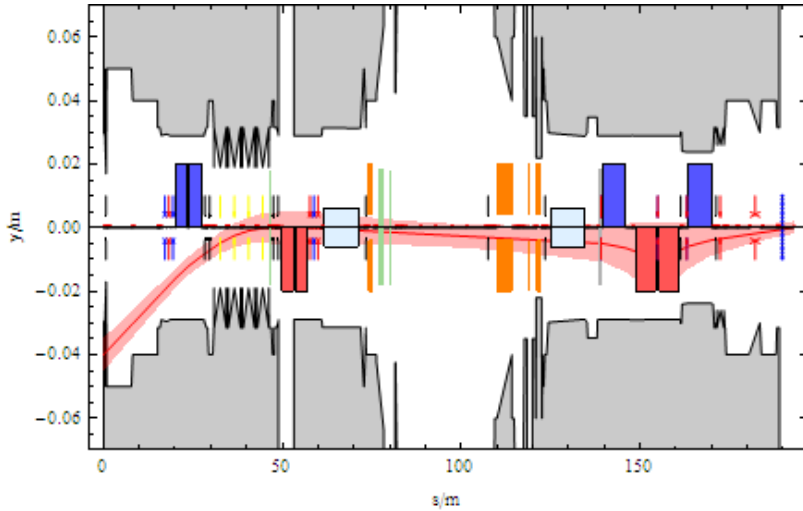
Beam envelopes around
ALICE

Y-chamber and combined chambers in 3D



Injected beams

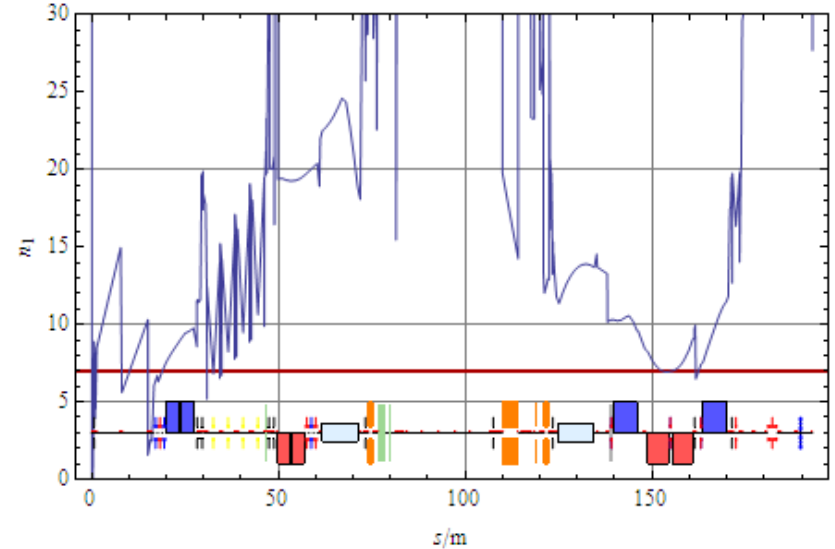
Moved vacuum chamber, injected beam with MKI working, 4 mm mechanical tolerance



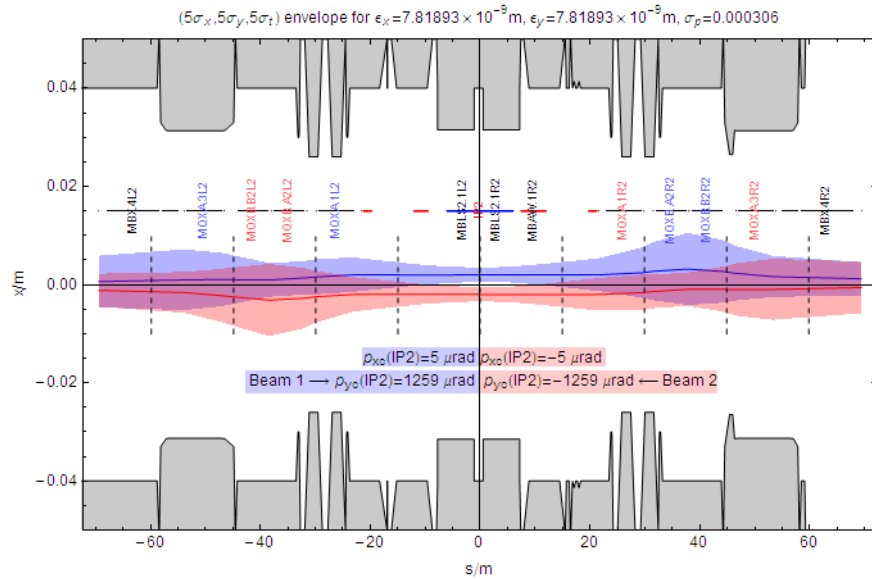
Care must be taken to design the beam optics and the vacuum chamber to provide adequate clearance not only for circulating beams but also injected beams and various failure scenarios – protection of the LHC is a major concern.

Aperture at critical chamber markers

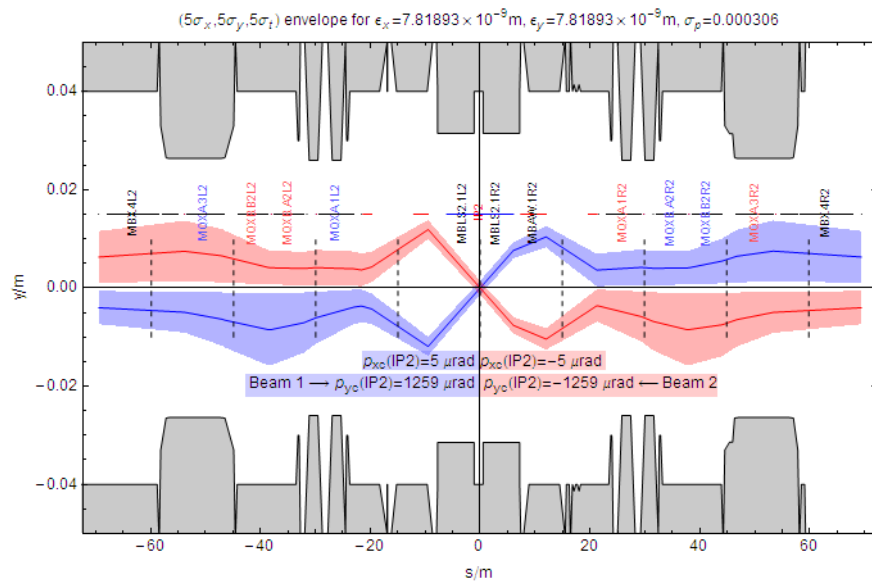
	n_1
VCTYD.4L2.D.B1	15.4677



ALICE – Separation at injection, circulating beams



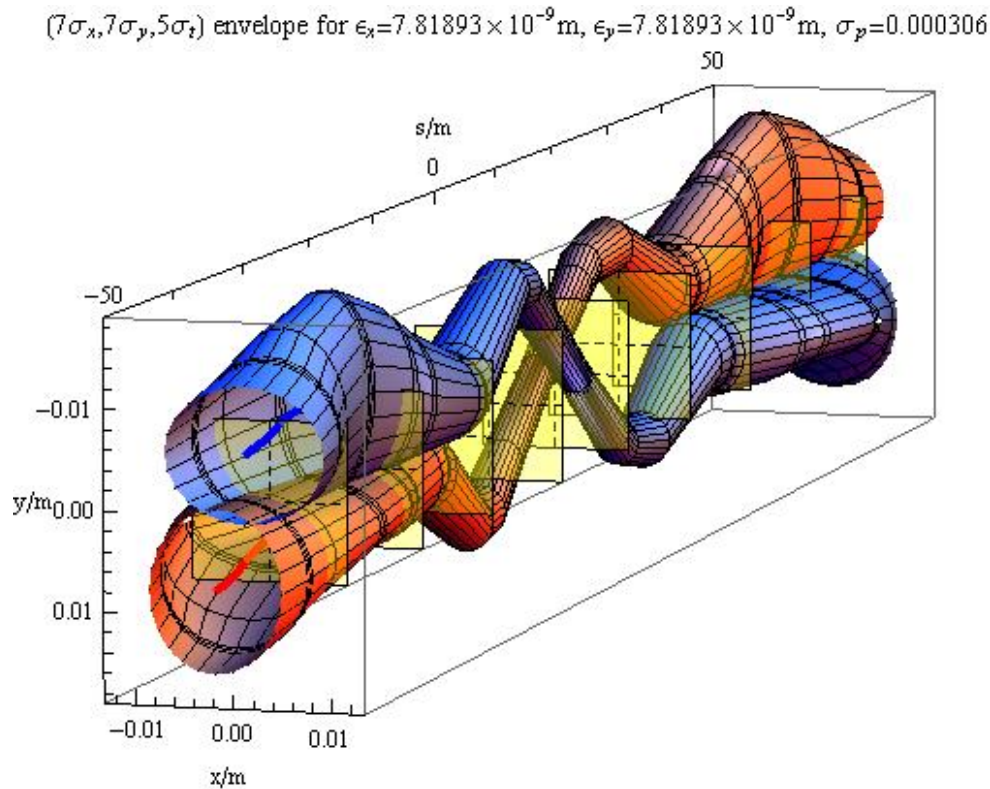
Crossing angle from spectrometer and external bump separates beams vertically everywhere except at IP (as also in physics). Parallel separation also separates beams horizontally at the IP during injection, ramp, squeeze.



Beams are larger in arcs (larger geometrical emittance) but β -functions are smaller in triplets (since $\beta^* = 10$ 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).

ALICE LS3 upgrades and ALICE 3

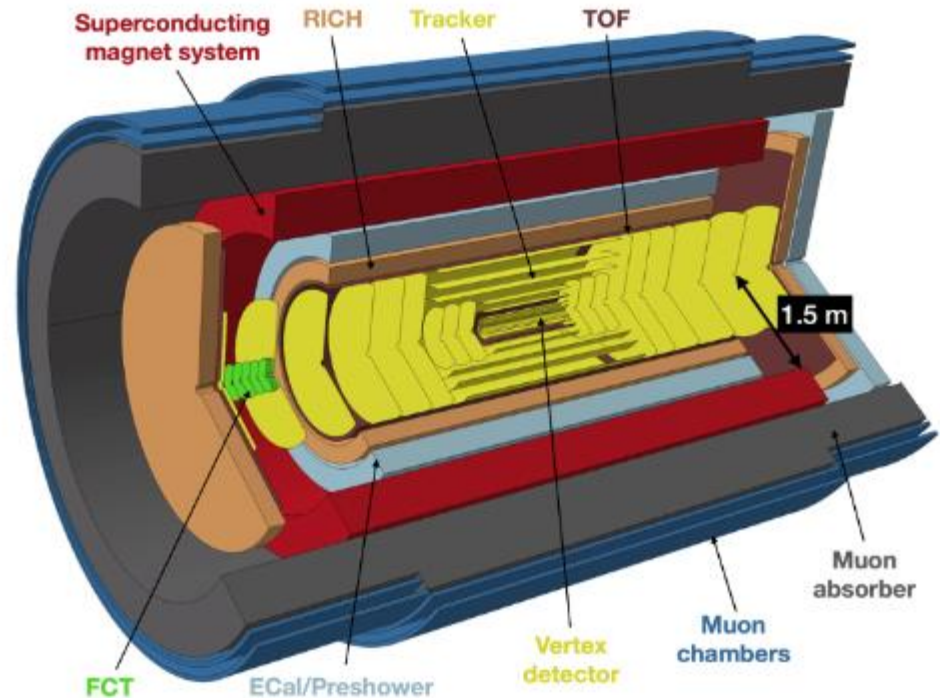
ALICE is set to be upgraded and even evolved into a new experiment, exploiting new technologies.

For the LHC Run 4 starting in the year 2029: two upgrade projects are being undertaken:

ALICE:

- A new Inner Tracking System (ITS3)
- A Forward Calorimeter: FoCal

Beyond that, ALICE 3 is the next-heavy-ion experiment for Run 5 of the LHC and beyond.



ALICE 3: a roadmap to exciting heavy-ion physics in LHC Runs 5 and 6.

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.
- Much more about the LHC and other colliders in seminars tomorrow.

BACKUP SLIDES