Introduction to the LHC

John Jowett (GSI, CERN)

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
  - But 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
- 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)
  - Heavy-ion (and p+p) collisions at HL-LHC, SppC and FCC

Hot and dense matter in Pb-Pb collisions at LHC

Exercise: check all these numbers

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

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

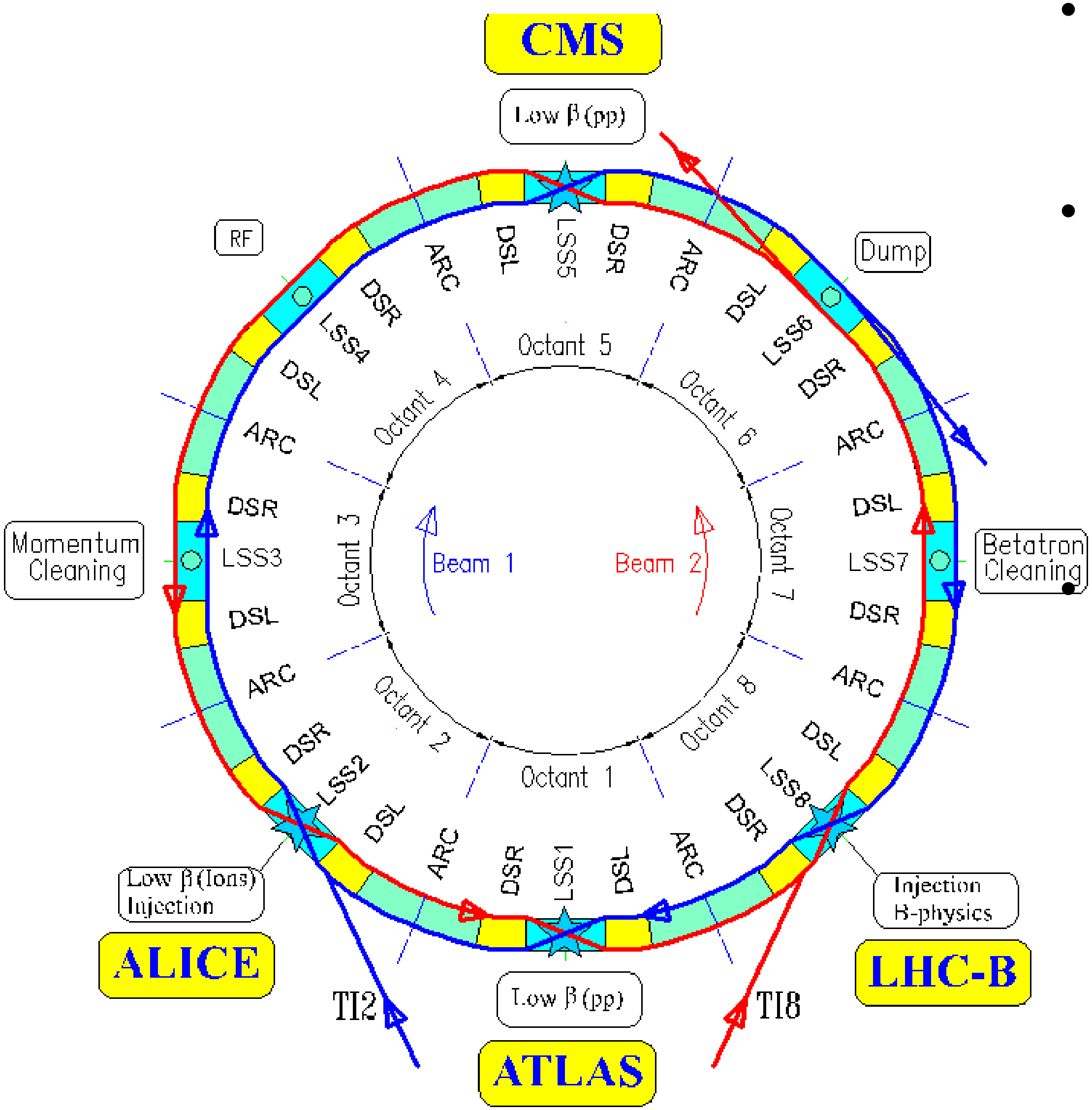
$$\frac{U_{\text{Ey}}}{(4/3)\pi r^3} = u_{\text{QGP}} \Rightarrow r = 1.1\ \mu\text{m}$$, a speck of very fine dust, mass 140 kg

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.

LHC Layout



- Beams circulate in independent beam pipes over most of circumference
- Except in:
  - IR1 (ATLAS ± 145 m)
  - IR2 (ALICE ± 117 m)
  - IR5 (CMS ± 145 m)
  - IR8 (LHC-B ± 80 m)

ALICE, ATLAS, CMS may take heavy-ion (and p-A) collisions

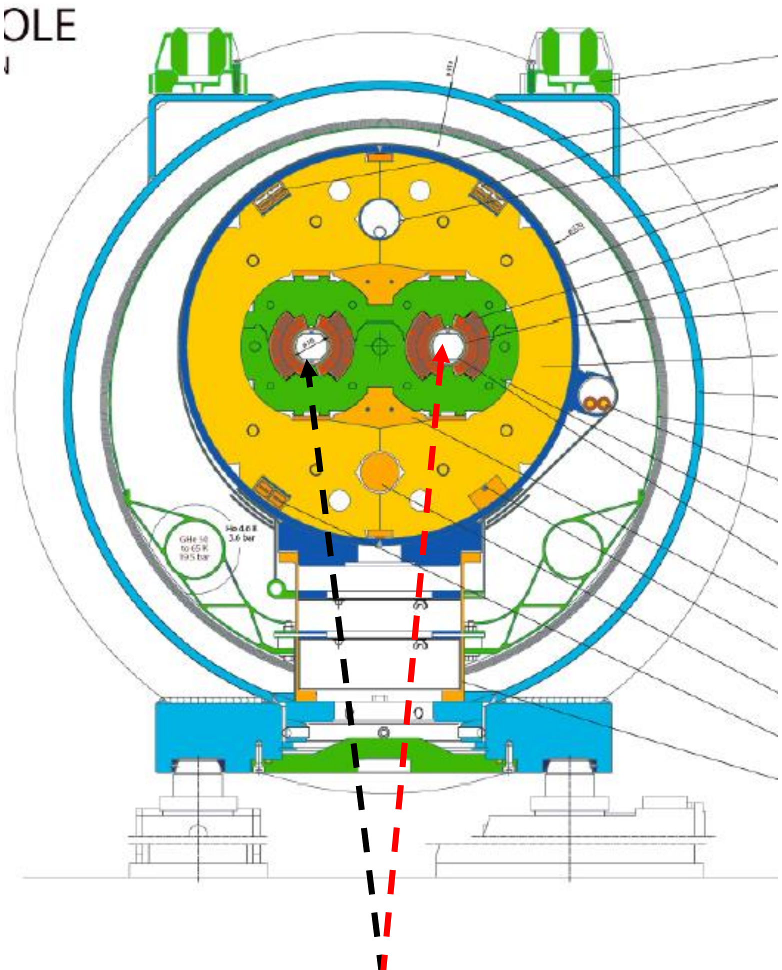
s coordinate along each beam's central orbit, clockwise from IP1

Long bunch trains up to ~2800 bunches around most of circumference

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

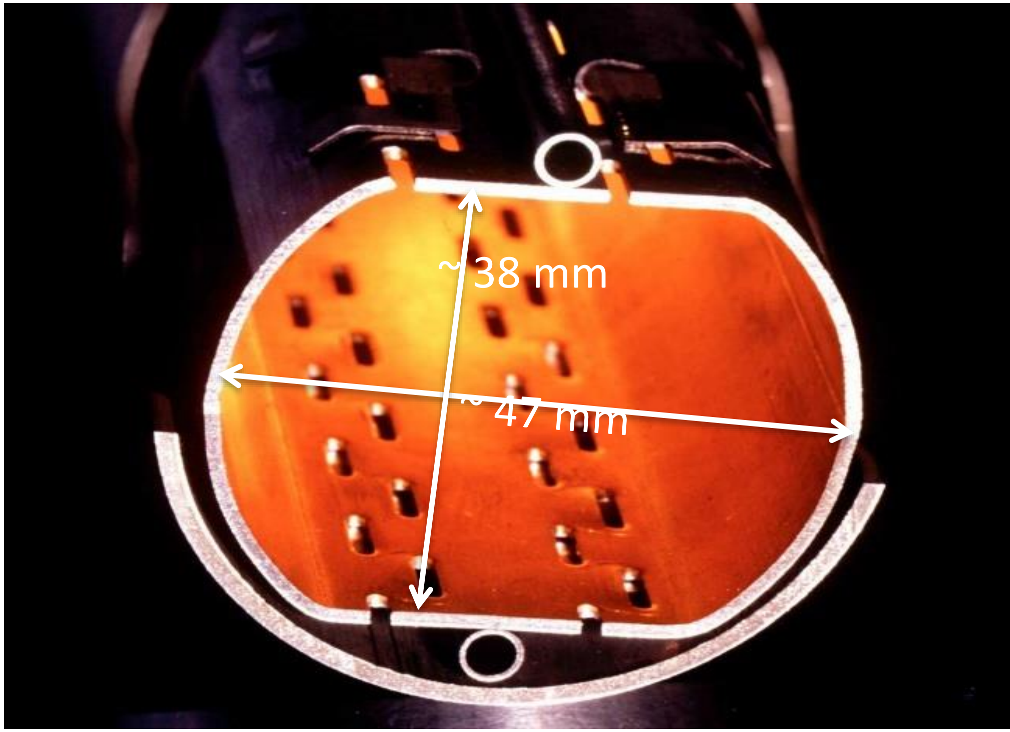
- Many other system, eg, beam collimation
- More in seminar by O. Bruning later (and in Course 2 for technology)



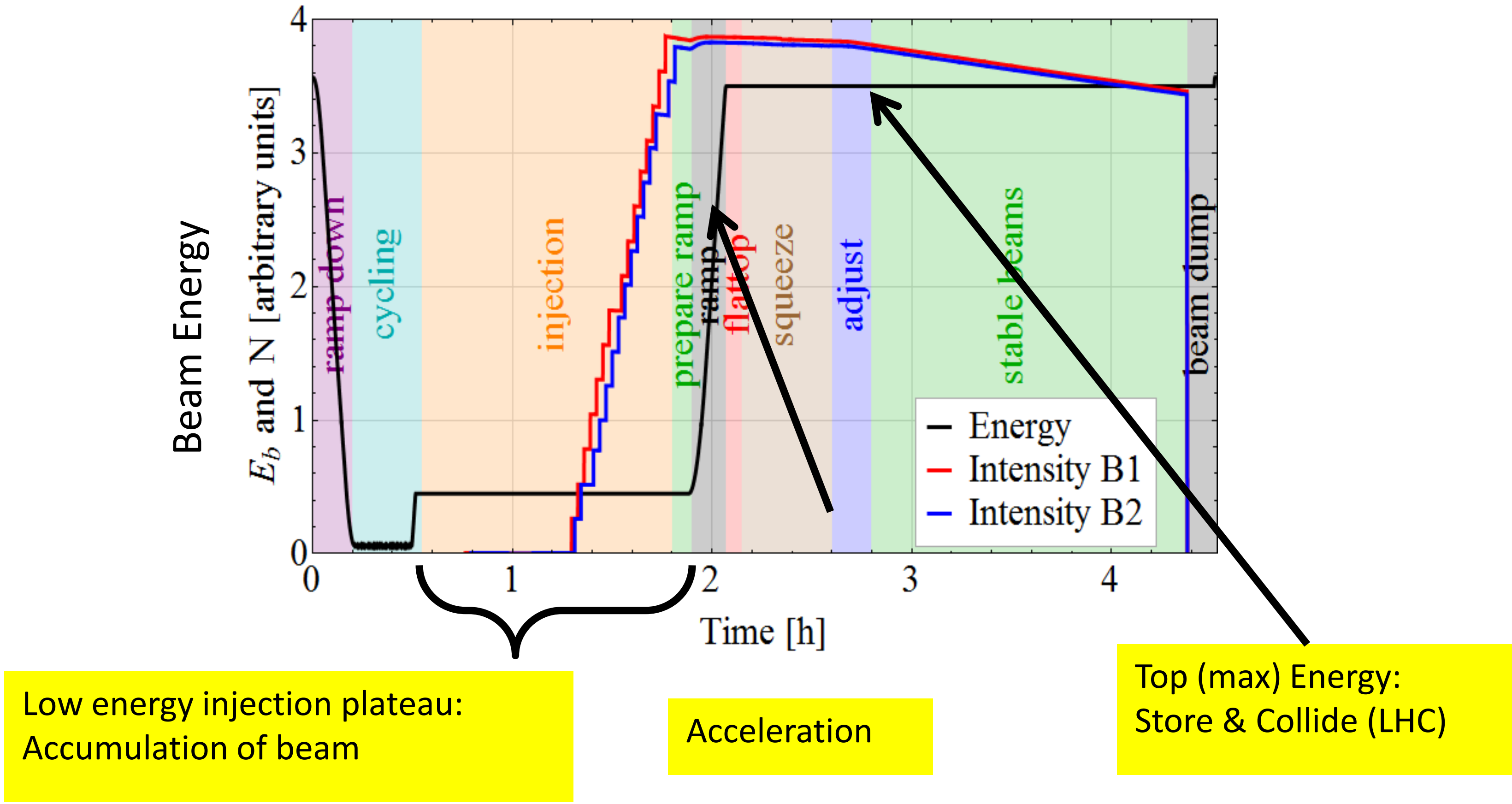
LHC: Identical bending field in both apertures of
two-in-one dipole – no choice

LHC beam pipe

- LHC cryogenic vacuum
- Beam screen 20 KJUAS 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



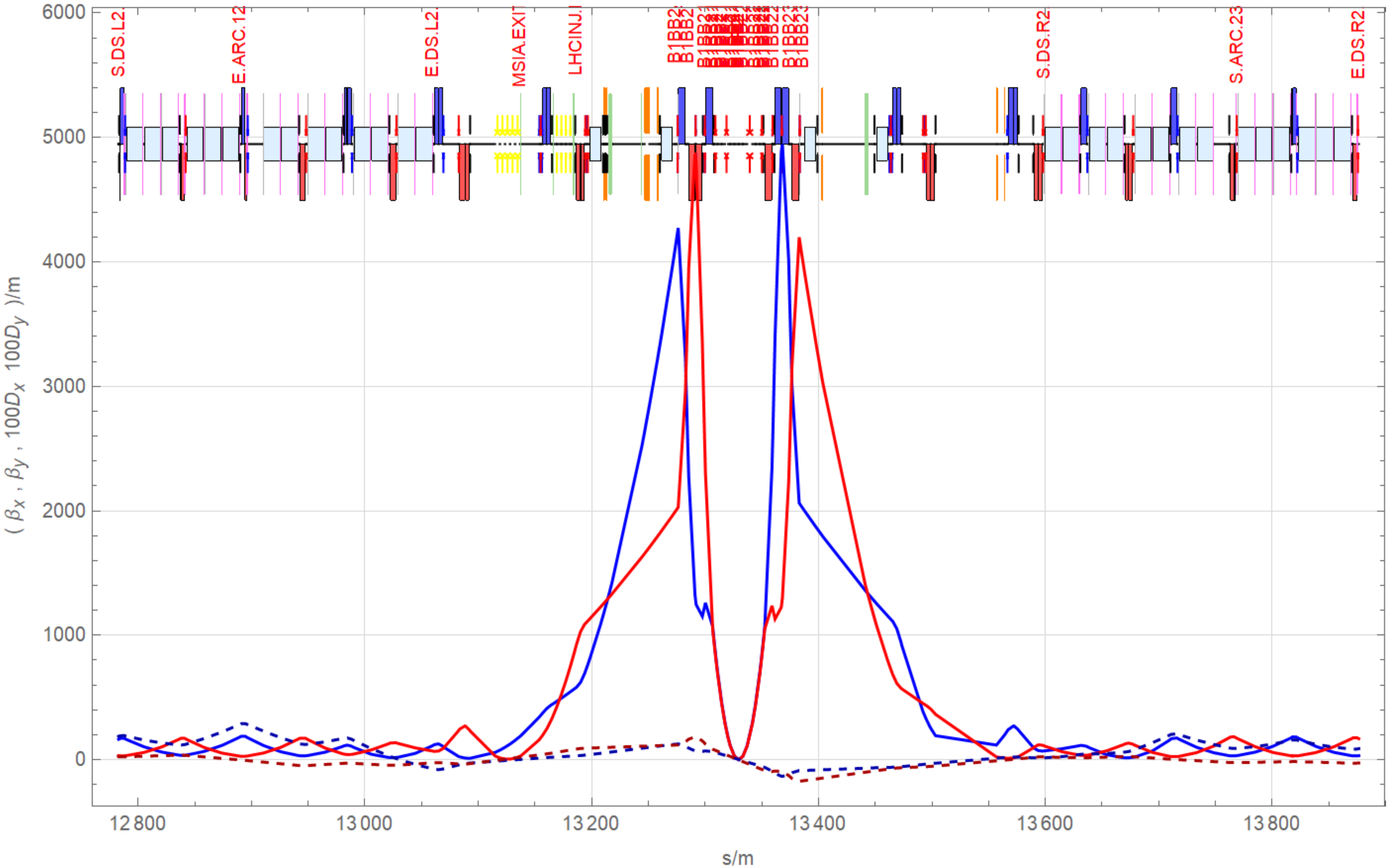
LHC Accelerator Cycle (Fill) schematic



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.

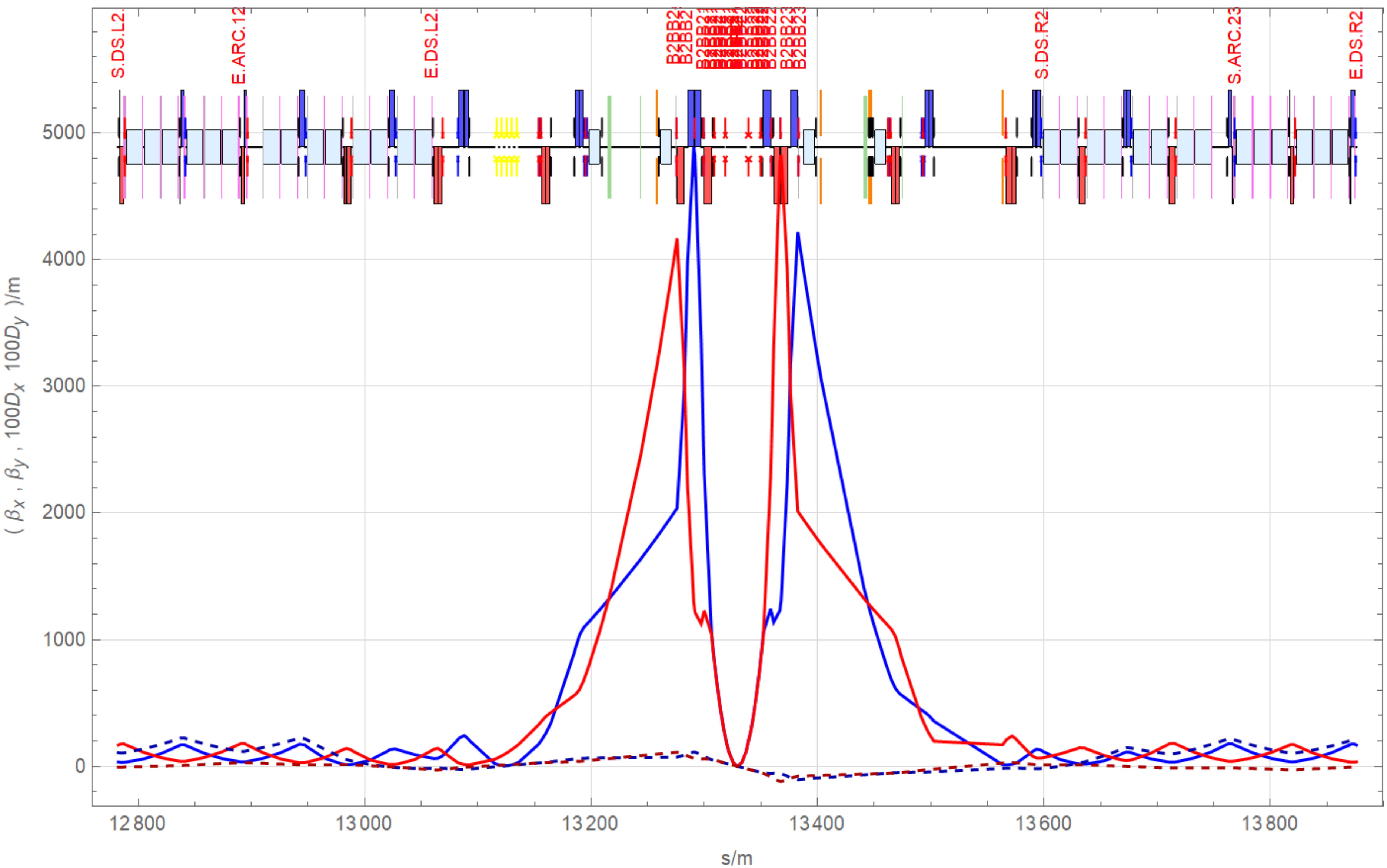
A machine which ramps its magnetic fields in synchronism with a change of the RF frequency like this is called a *synchrotron*.

Optical functions for Beam 1 in LHC IR2, 2018



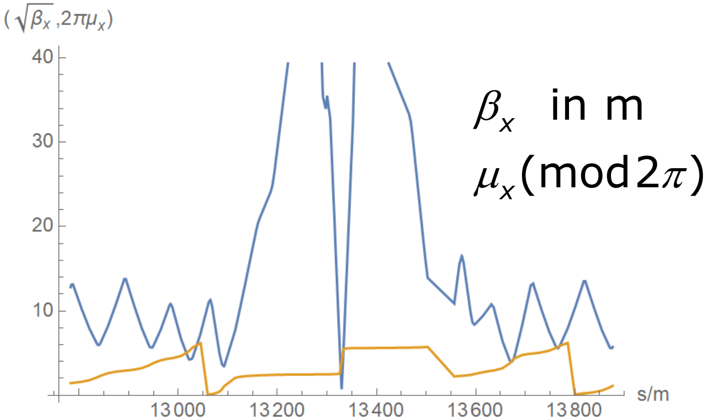
Optics solutions must be found for each beam with these constraints.

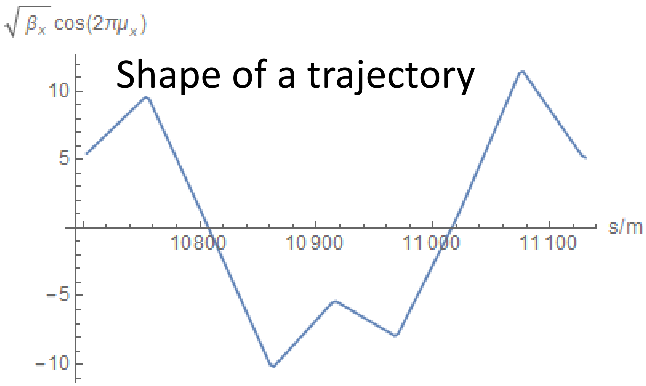
Optical functions or Beam 2 in LHC IR2, 2018

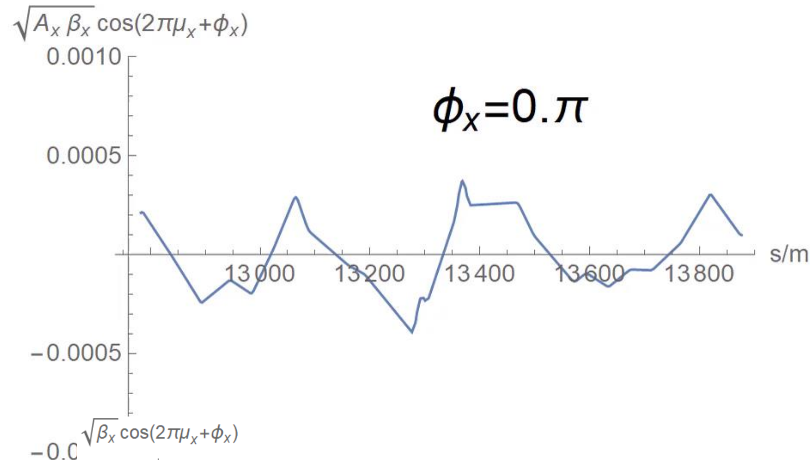


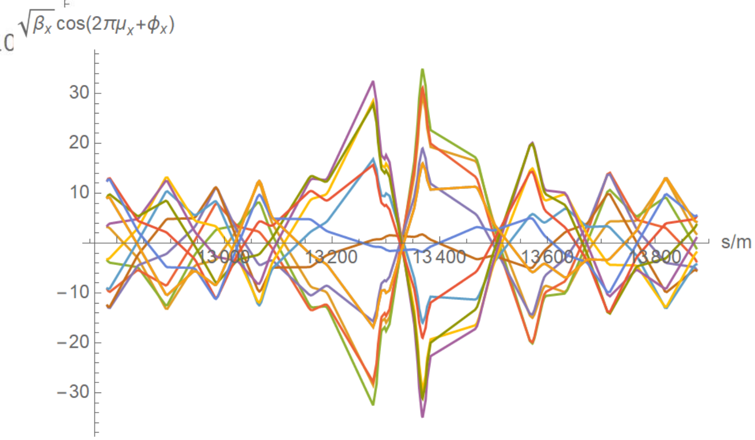
Approximate symmetry with Beam 1 under Left <->Right and x <-> y

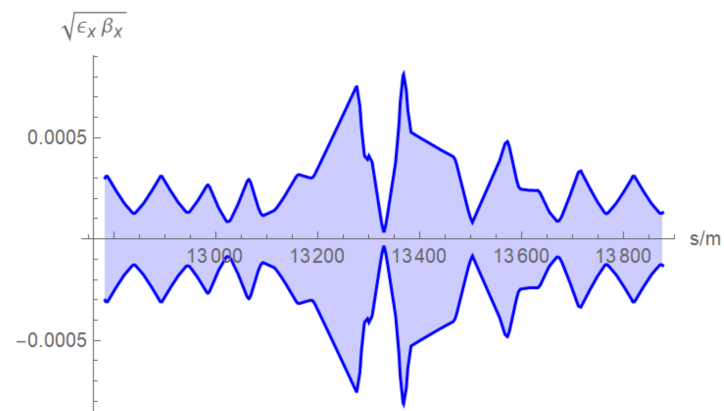
Optical functions and beam envelope in IR2



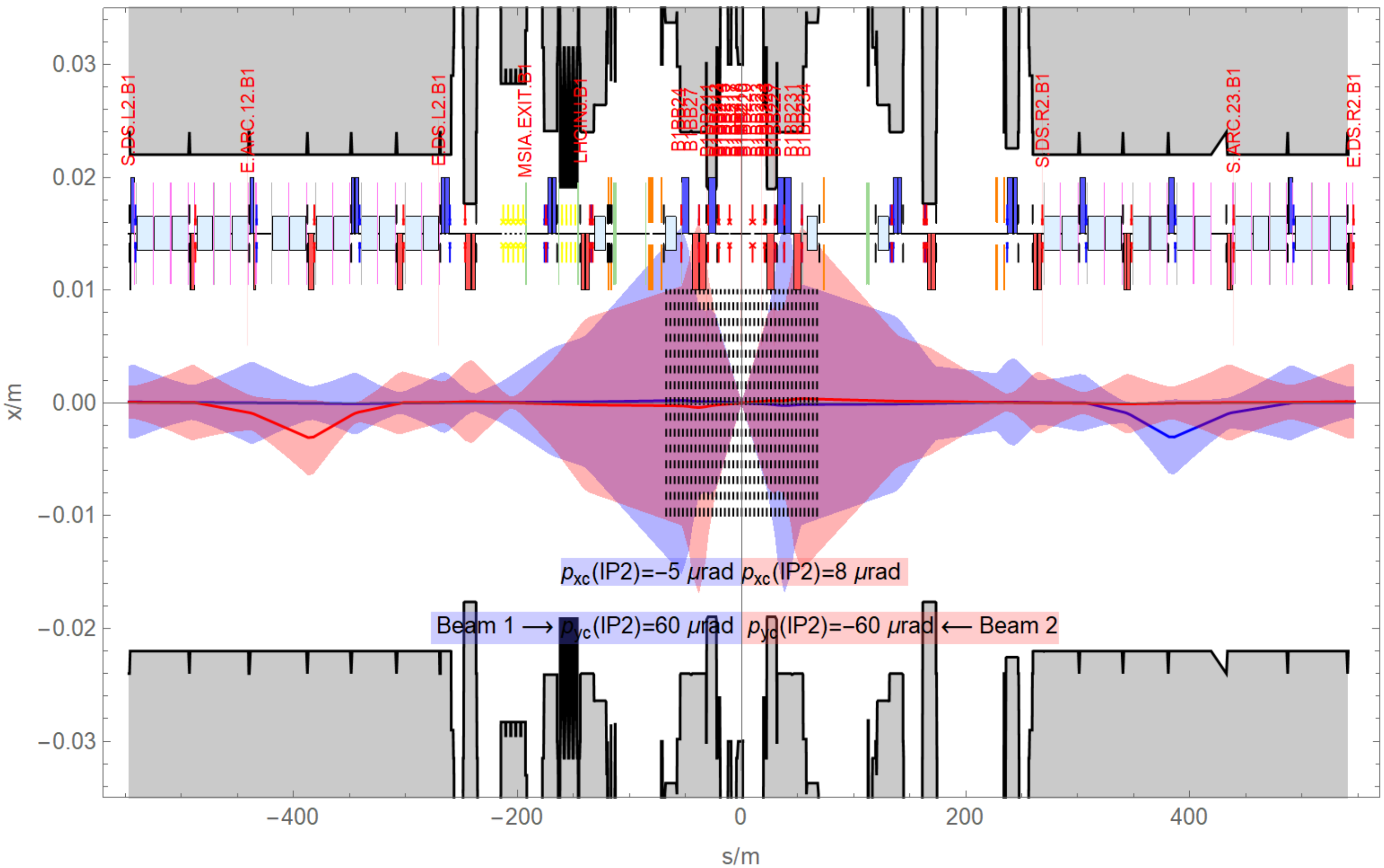






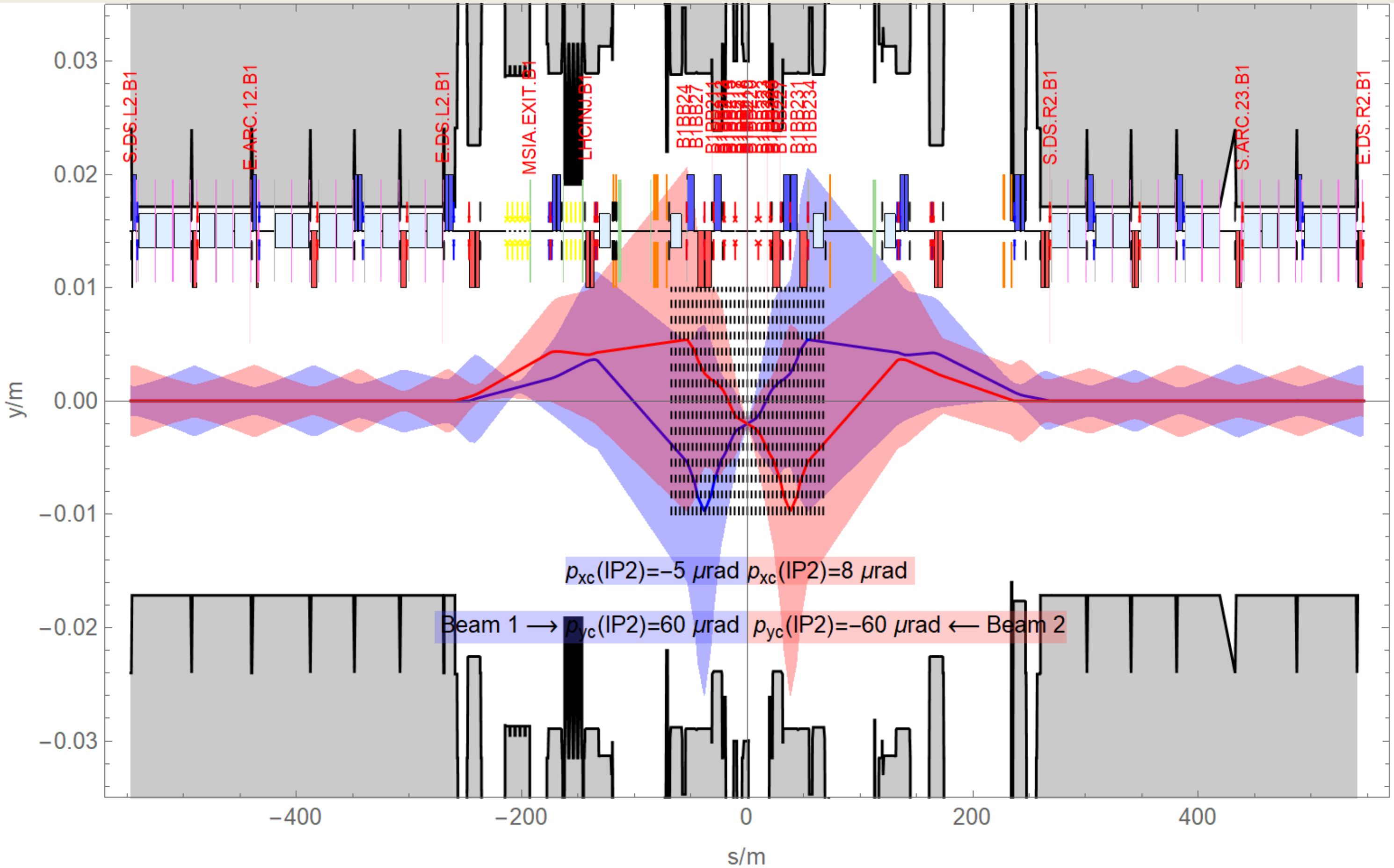


Collision conditions in LHC, IR2 horizontal plane 2018



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).

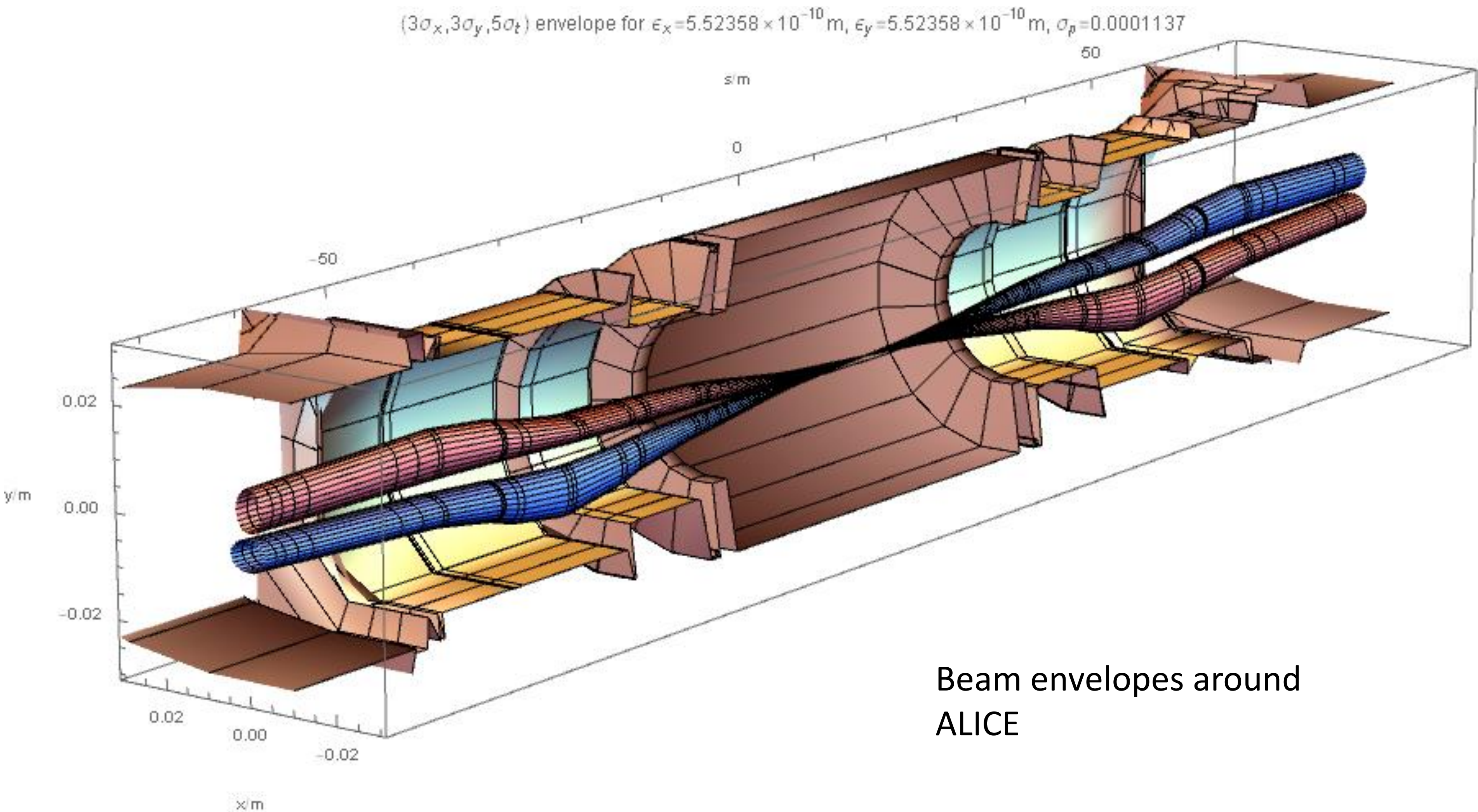
Collision conditions in LHC, IR2 vertical plane 2016



Combination of three orbit bumps (displacement from reference orbit by small dipole magnets called correctors):

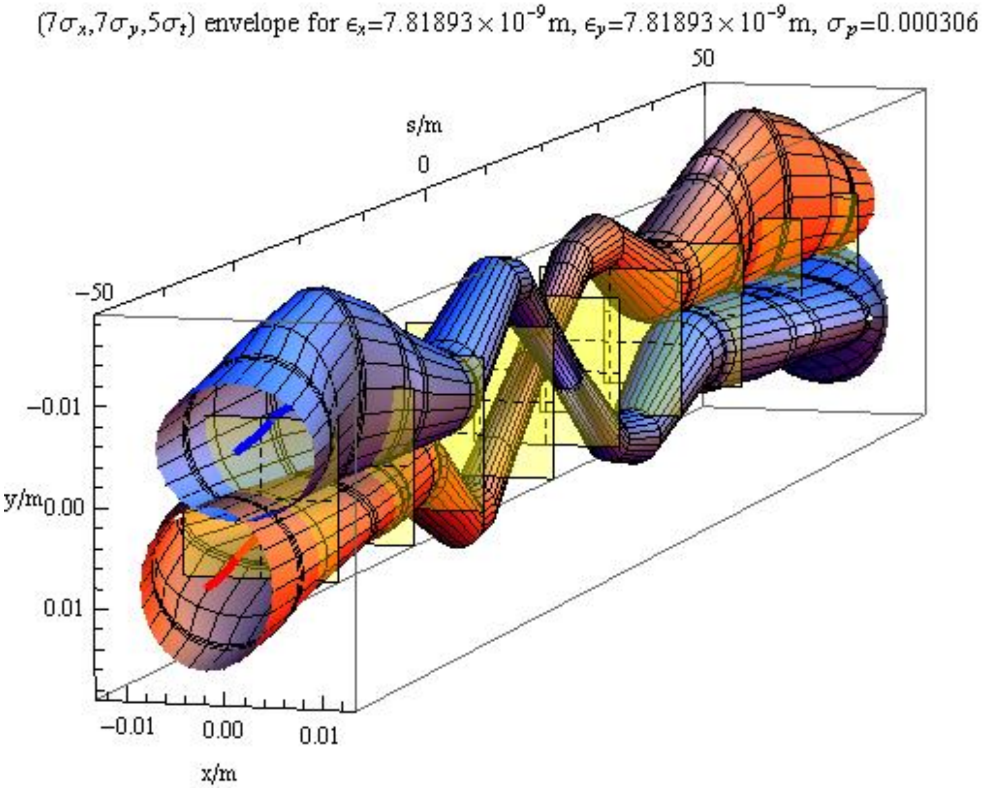
1. Compensate magnetic field of ALICE experiment spectrometer magnet
2. Arrange for vertical crossing angle of beams (avoid unwanted encounters)
3. Lower collision point by 2 mm (the experiment sank …)

Optics for Pb-Pb collisions in ALICE



Beam envelopes around ALICE

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 …

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

- 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.)

BACKUP SLIDES