John Adams Institute for Accelerator Science Lecture Series

Oxford, 21st March 2013

Crab-waist collisions. From lepton to hadron colliders

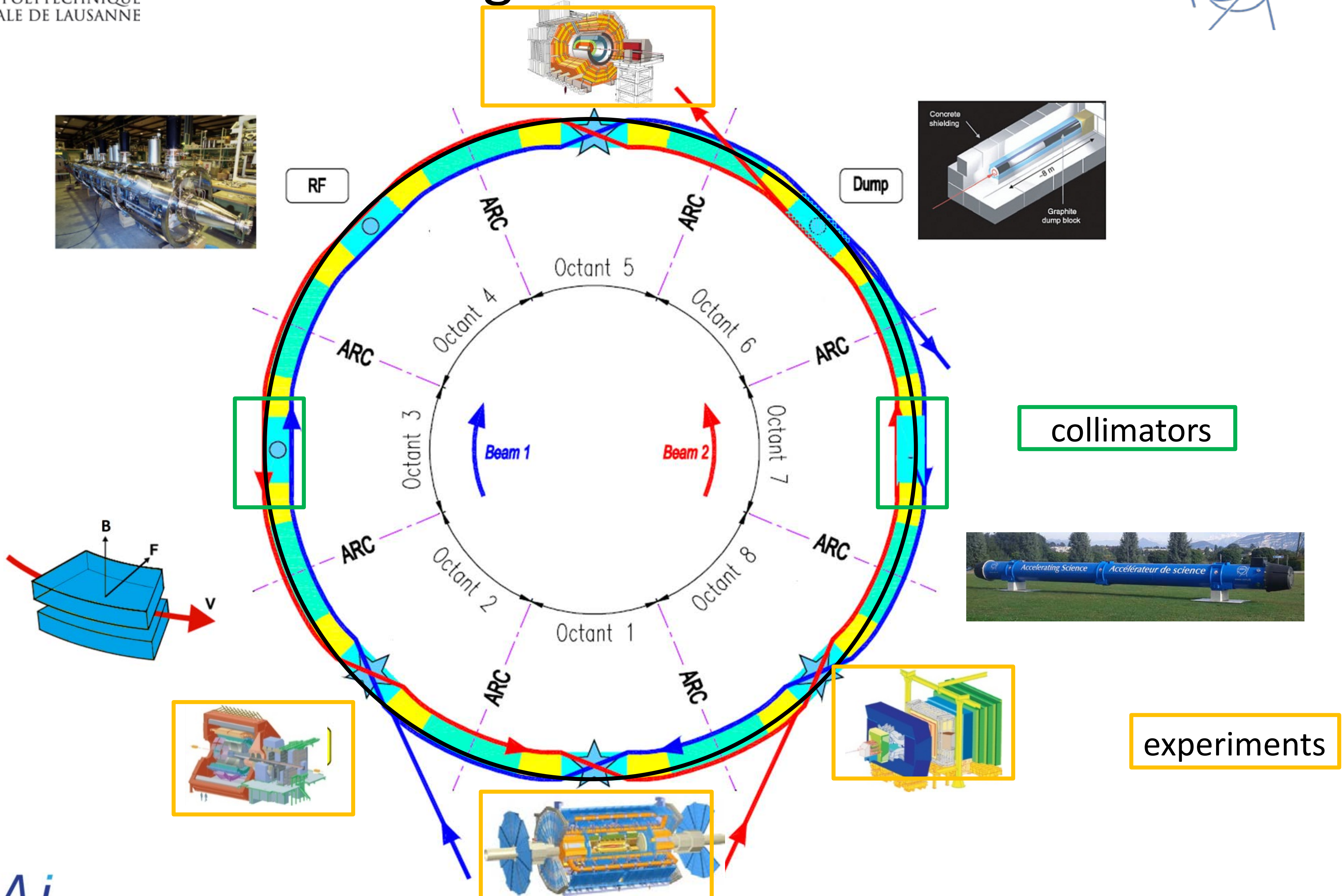
José L. Abelleira, PhD candidate.
École Polytechnique Fédérale de Lausanne (EPFL)

Thanks to: R. de Maria, S.Russenschuck, F. Zimmermann (CERN), D.Shatilov (BINP SB RAS,Novosibirsk), C. Milardi, M. Zobov (INFN/LNF, Frascati (Roma))

Contents

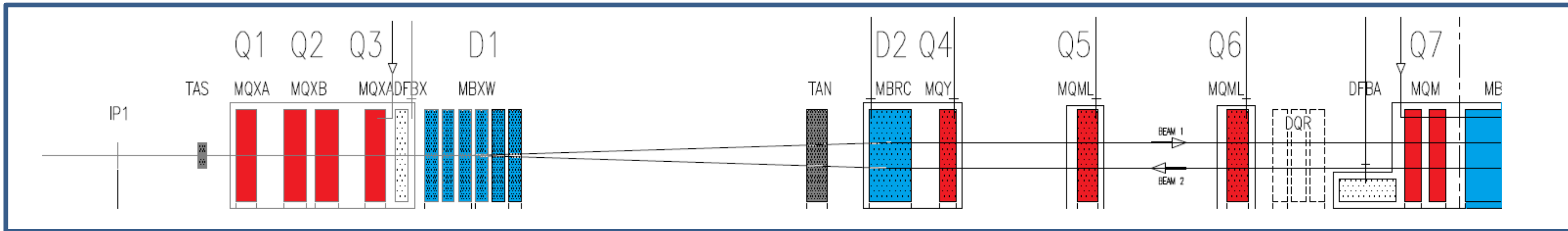
- The LHC
- Flat beams
- Crab-waists collisions concept
- Crab-waist in DAΦNE
- A new IR for LHC

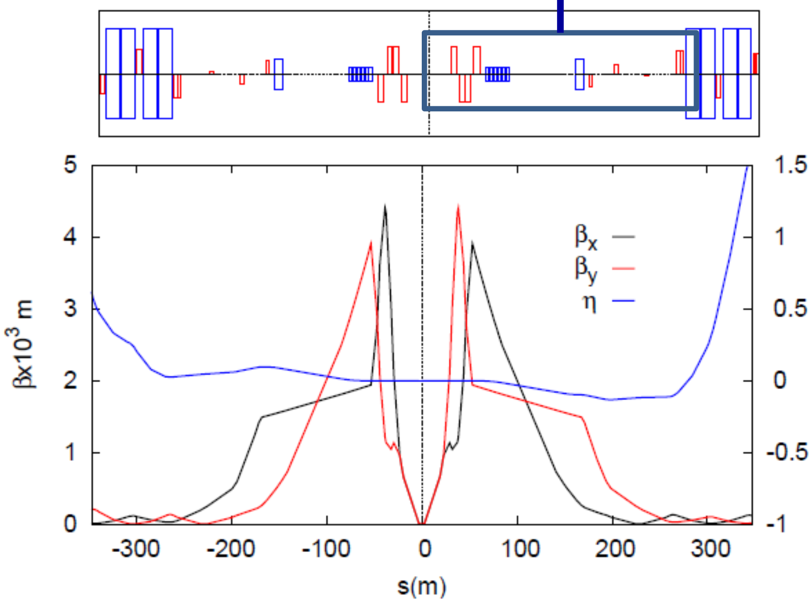
The Large Hadron Collider



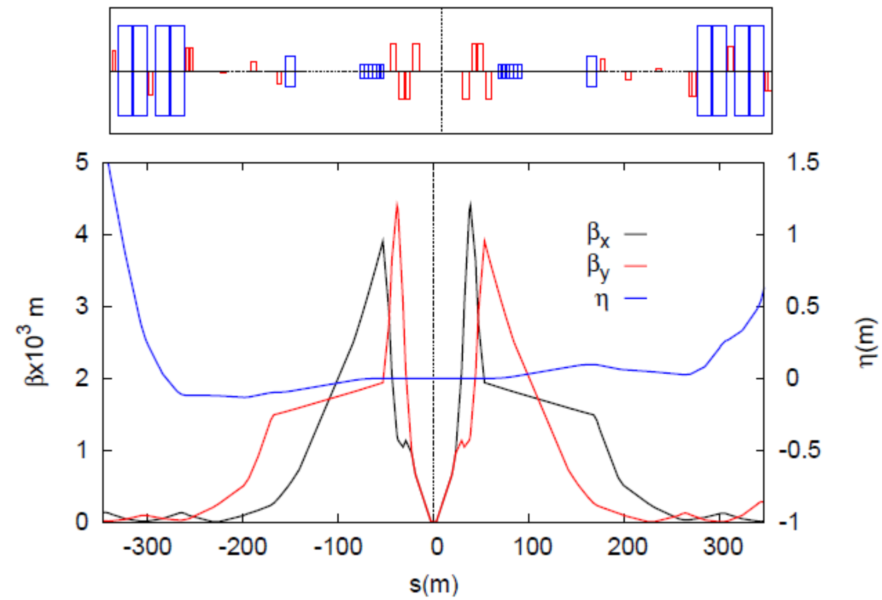
John Adams Institute for Accelerator Science

LHC final focus system





Beam 1



Beam2

Antisymmetric optics due to the opposite direction of the beams

Luminosity

The event rate for a process (number of collisions) is given by the cross section of the process times the luminosity.

$$\frac{dR}{dt} = L\sigma_p$$

Luminosity depends on by the beam parameters as follows.

$$L = \frac{N^2 n_b f}{4\pi\sigma^*{}_x\sigma^*{}_y}\frac{1}{\sqrt{1+\Phi^2}} \qquad \Phi = \frac{\theta\sigma_z}{2\sigma_x{}^*}$$

Piwinski angle

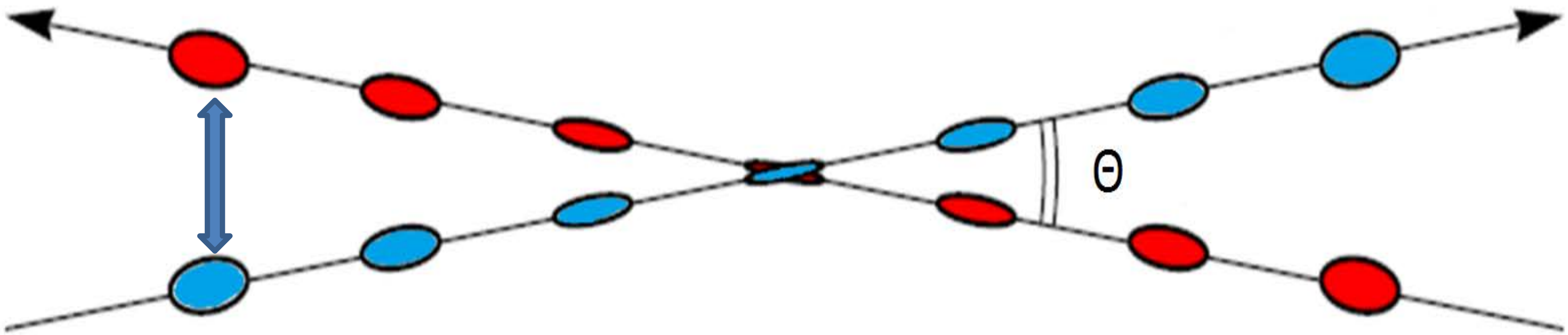
The values for nominal LHC are given

N	Particles per bunch.	$1.15\text{x}10^{11}$
n_b	Number of bunches.	2808
f	Revolution frequency	11.245 kHz
$\sigma_{x,y}{}^*$	Hor/vert beam size at IP*	16.7 µm
$\sigma_z{}^*$	bunch length	7.55 cm
θ	Crossing angle*	285 µm
Φ	Piwinski angle*	0.64
L	Luminosity*	10^{34} cm^{-2} s^{-1}

*For the experiments at IP1 and IP5.

Normalized separation

A crossing angle is introduced to avoid parasitic collisions



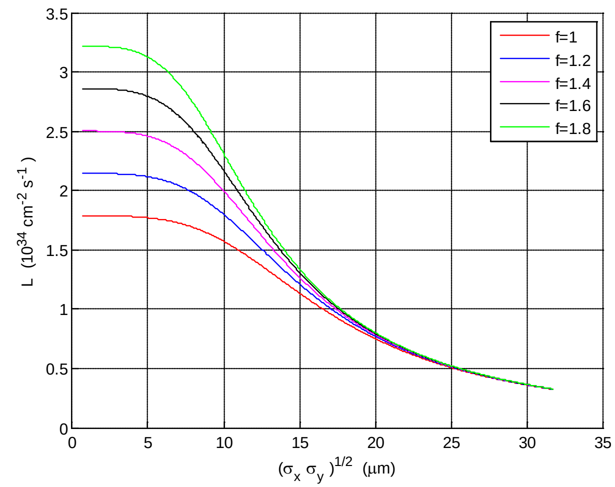
Even thought there are collisions only in the IP, there are long range interactions between the two beams.
A measure of the interaction between the beams is the normalized separation.

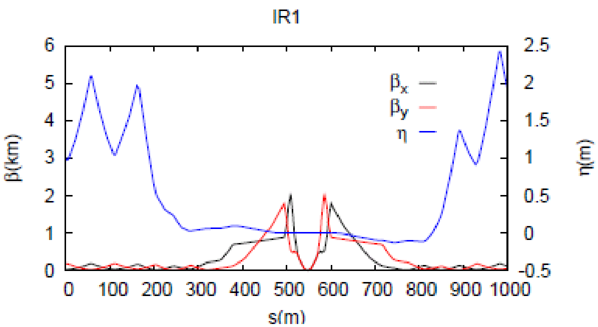
$$\Delta_{sep} = \frac{d_{sep}}{\sigma_x} \approx \frac{\theta}{\sigma_x{}'}$$

Flat beams

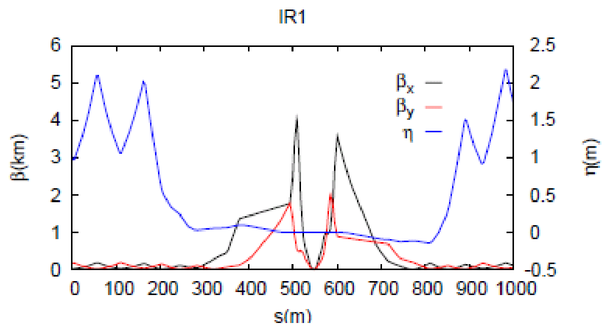
$$\Delta_{sep} \approx \frac{\theta}{\sigma_{x'}} = \frac{\theta}{\sqrt{\varepsilon/\beta^*_x}}$$

For the same section area $\sigma_x\sigma_y$
Flat beams increase Δ_{sep}, for a given θ
Less θ for the same Δ_{sep}

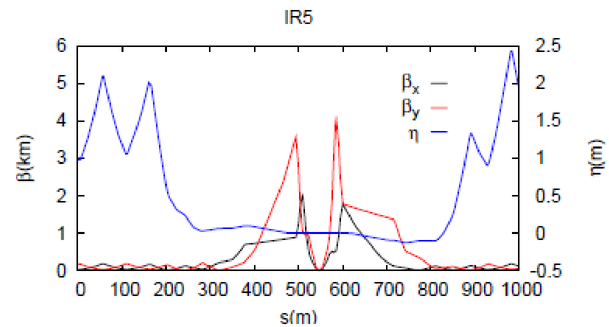




$\beta_x = 1.20$ m
$\beta_y = 1.20$ m



$\beta_x = 0.60$ m
$\beta_y = 1.20$ m



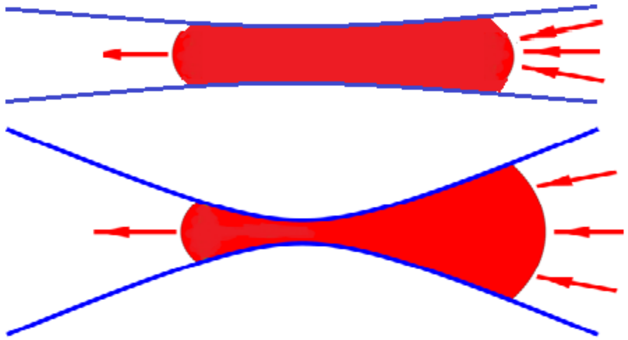
$\beta_x = 1.20$ m
$\beta_y = 0.60$ m

R. De Maria

Hourglass effect

Beam size is given as $\sigma = \sqrt{\varepsilon\beta.}$

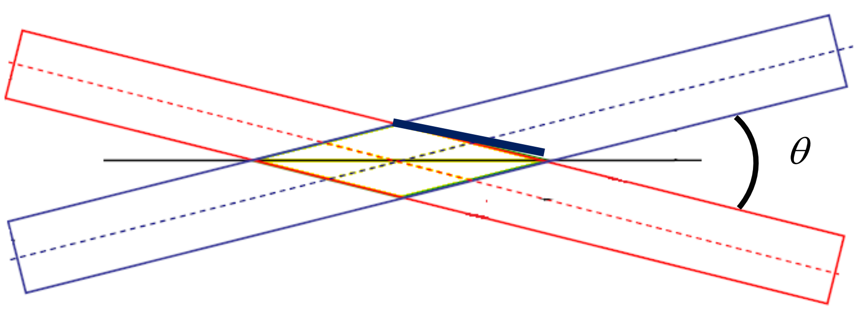
$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$



Especially important when the β function at the IP approaches the bunch length.

What is important is the length of the collision section.

Length of the Collision section



With Head-on collisions or small ϕ

$$l_{OA} \approx \sigma_z$$

But in Large Piwikinsi Angle (LPA) regime

$$l_{OA} \approx \frac{2\sigma_x}{\theta}$$

Crab-waist collisions

An important limitation in hadron machines is beam-beam tune shift

$$L \propto \frac{N\xi_y}{\beta_y}; \quad \xi_y \propto \frac{N\beta_y}{\sigma_x\sigma_y\sqrt{1+\phi^2}}; \quad \xi_x \propto \frac{N}{\varepsilon_x(1+\phi^2)}; \quad \phi = \frac{\theta\sigma_z}{2\sigma_x}$$

A **Large Piwinski Angle** Φ (LPA)

reduces tune shift, allowing N↑

reduces the length of the collision section, allowing β_y↓

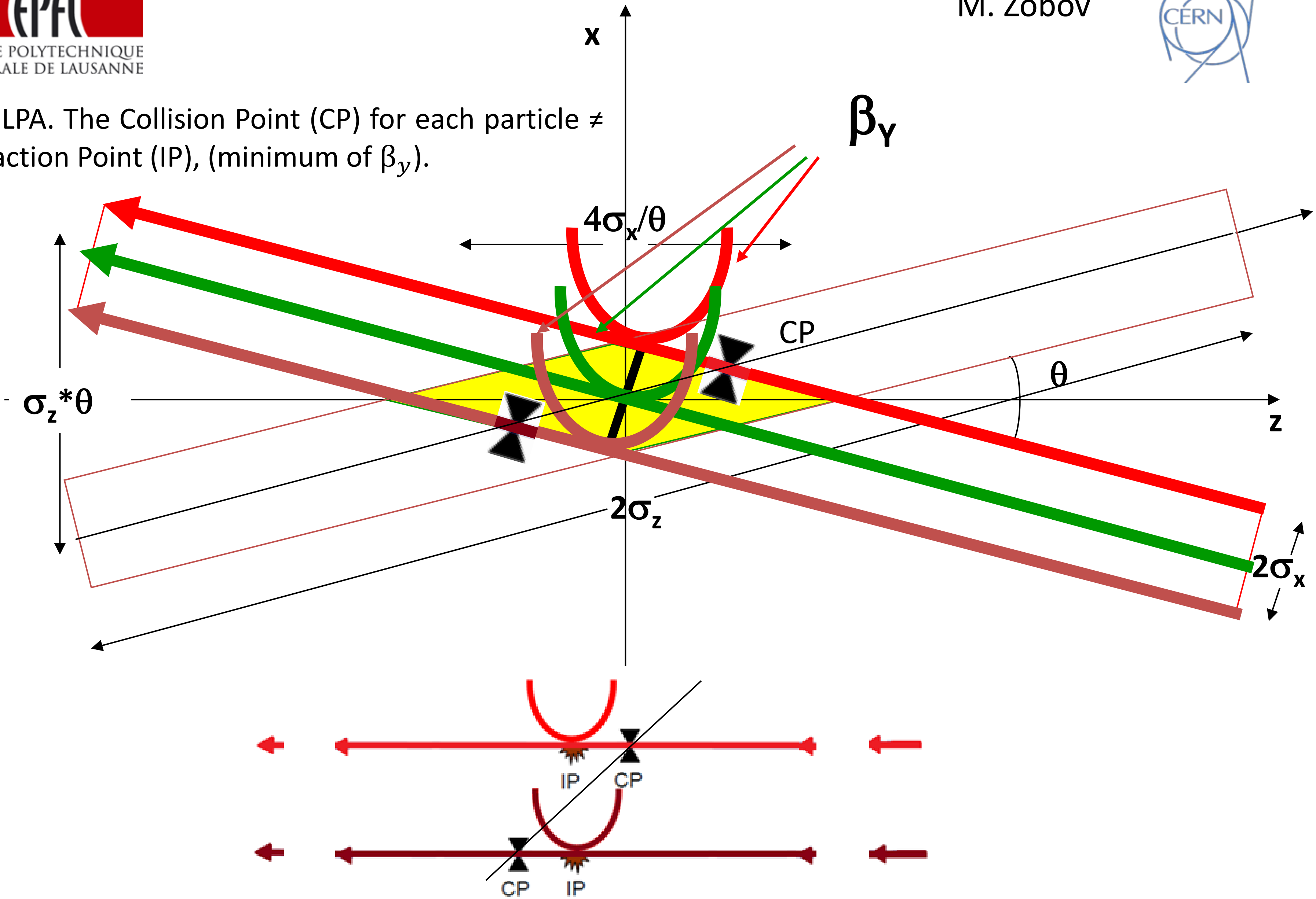
} More luminosity

On the other hand, a LPA induces strong X-Y resonances

Suppressed by crab-waist scheme

M. Zobov

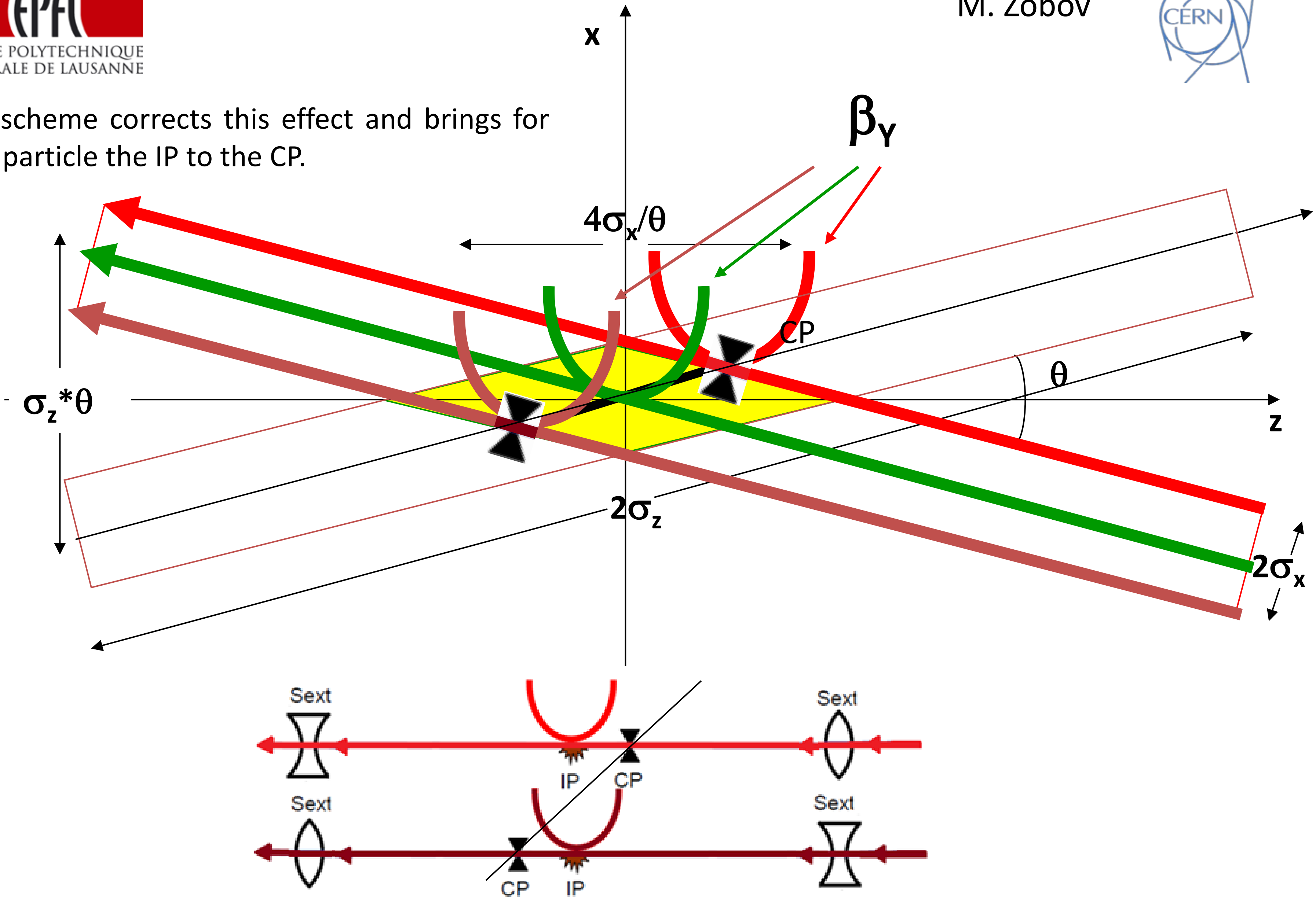
With LPA. The Collision Point (CP) for each particle ≠ Interaction Point (IP), (minimum of β_y).



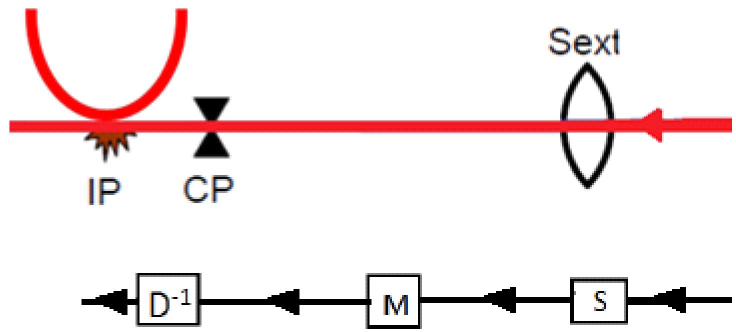
John Adams Institute for Accelerator Science

M. Zobov

C-W scheme corrects this effect and brings for each particle the IP to the CP.



Crab-waist collisions



$$\hat{M}_y = D^{-1} M_y S = \begin{pmatrix} 1 & \Delta l \\ 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} \pm \alpha_{CP} \sqrt{\frac{\beta_y^*}{\beta_{y,cs}}} & \pm \sqrt{\beta_{y,cs} \beta_y^*} \\ \mp \frac{1}{\sqrt{\beta_{y,cs} \beta_y^*}} & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$

$$\Delta l = \frac{x_{IP}}{\theta} \qquad f = \frac{1}{k_{sl} x_{cs}}$$

Crab-waist collisions

Conditions for the crab-waist sextupole

$$\Delta\mu_x = \pi m$$
$$\Delta\mu_y = \frac{\pi}{2}(2n+1)$$

Sextupole strength

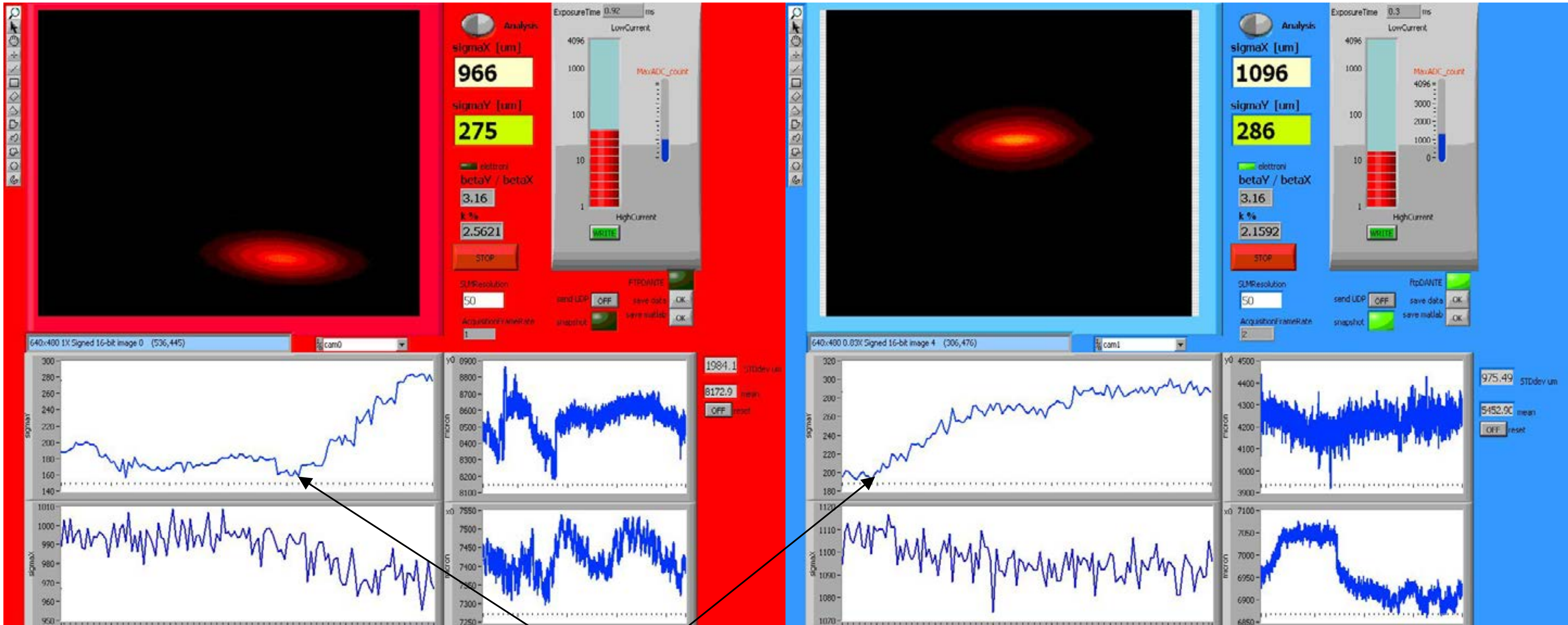
$$kl_s = \frac{\sqrt{\beta_x^* / \beta_x}}{\theta \beta_y^* \beta_y}$$

$\sigma_x^*/\sigma_y^* \geq 10$ $\xrightarrow[\varepsilon_x = \varepsilon_y]{}$ $\beta_x^*/\beta_y^* \geq 100$

Suitable for lepton machines ($\varepsilon_x \neq \varepsilon_y$)

More challenging for hadron colliders

Crab waist collisions in DAΦNE



Start of switching off the CW sextupoles in both rings: 200 A → 0 A

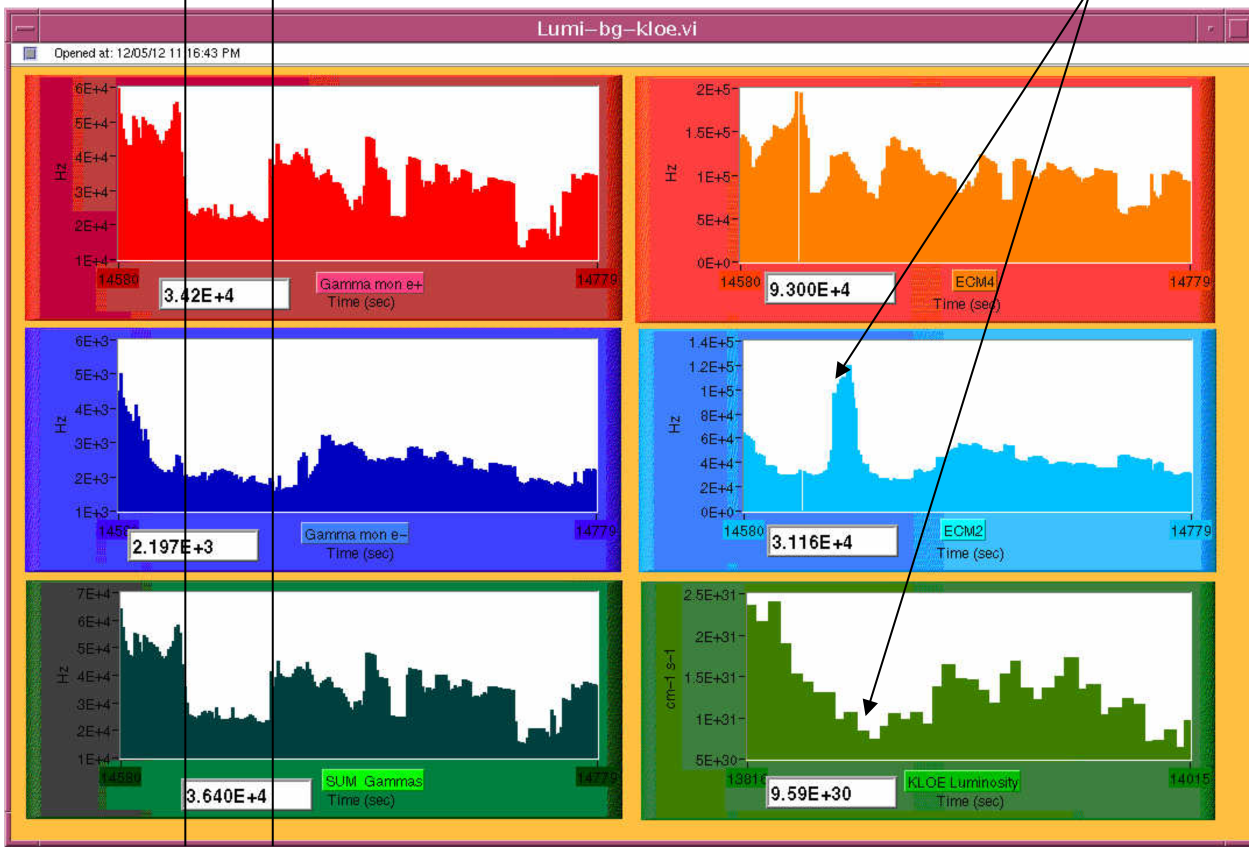
900 mA x 500 mA

C. Milardi
M. Zobov

Crab waist collisions in DAΦNE

OFF ON

Minimum luminosity, highest background when the sextupoles are OFF



KLOE background

KLOE luminosity monitor

DAFNE luminosity monitor

C. Milardi
M. Zobov

C-W collisions for hadron colliders

There are several facts that make difficult the implementation of crab-waist collisions in LHC:

- Same charge of particles
- Large L*
- Large energy
- Same emittance in the two planes

A new IR for HL-LHC is presented with the following ingredients:

- Large Piwinski Angle
- Flat beams
- Local chromatic correction **?**
- Crab-waists

A new IR for LHC

β_x^*=1.5 m
β_y^*=1.5 cm

Phase advance from IP

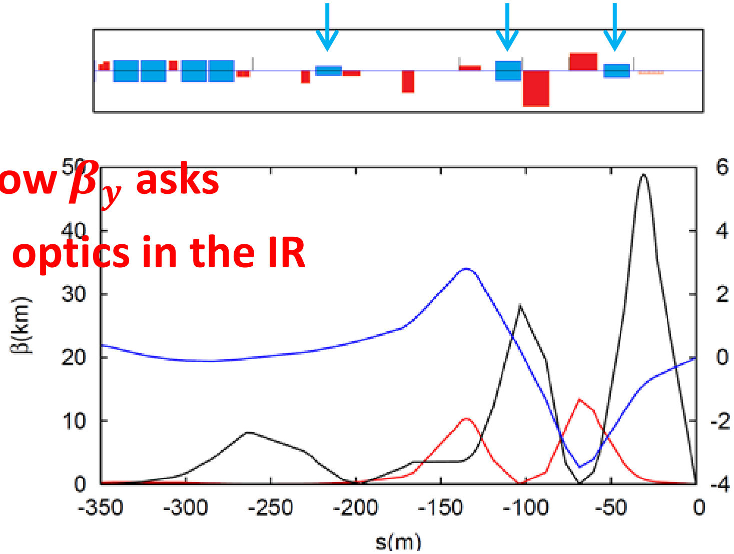
	$\Delta\mu_x$	$\Delta\mu_y$
sext1	$\pi/2$	$\pi/2$
sext2	$\pi/2$	$\pi/2$
sext3	$3\pi/2$	$3\pi/2$
sext4	$3\pi/2$	$3\pi/2$
sext5	2π	$5\pi/2$

Local chromatic correction in both planes + crab-waist collisions

Chromatic correction

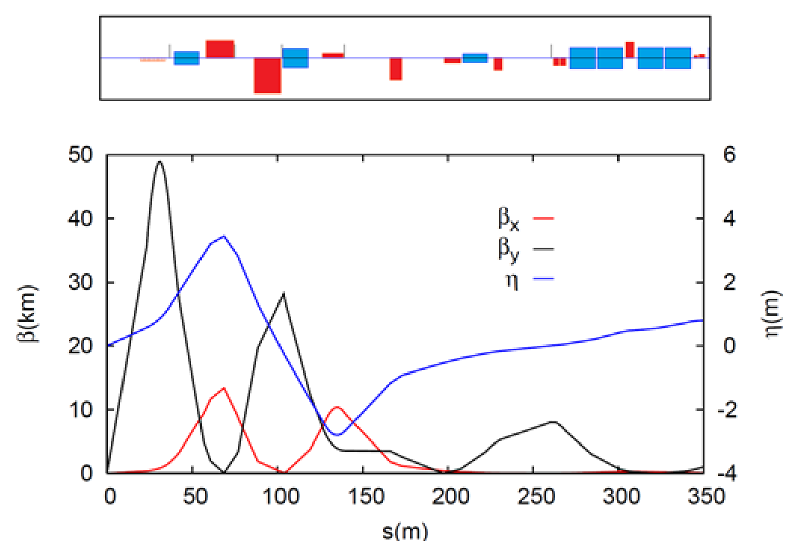
CRAB-WAIST SEXTUPOLE

Separation magnets



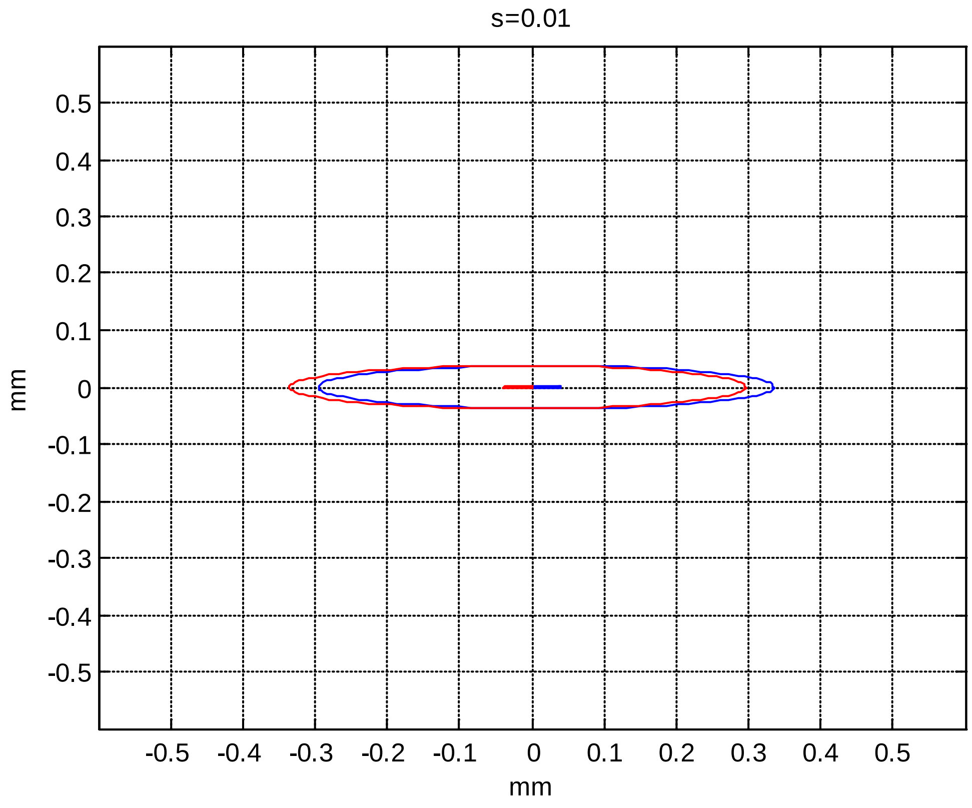
The extremely low β_y asks for a symmetric optics in the IR

sext1 sext3
sext2 sext4
sext5

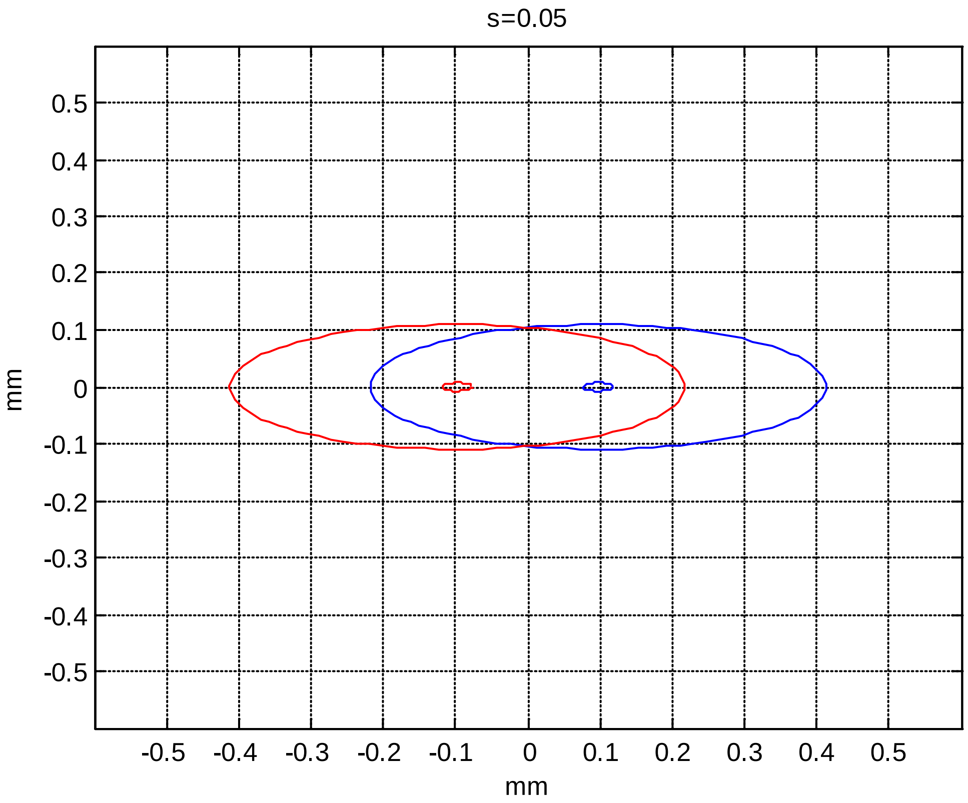


José L. Abelleira

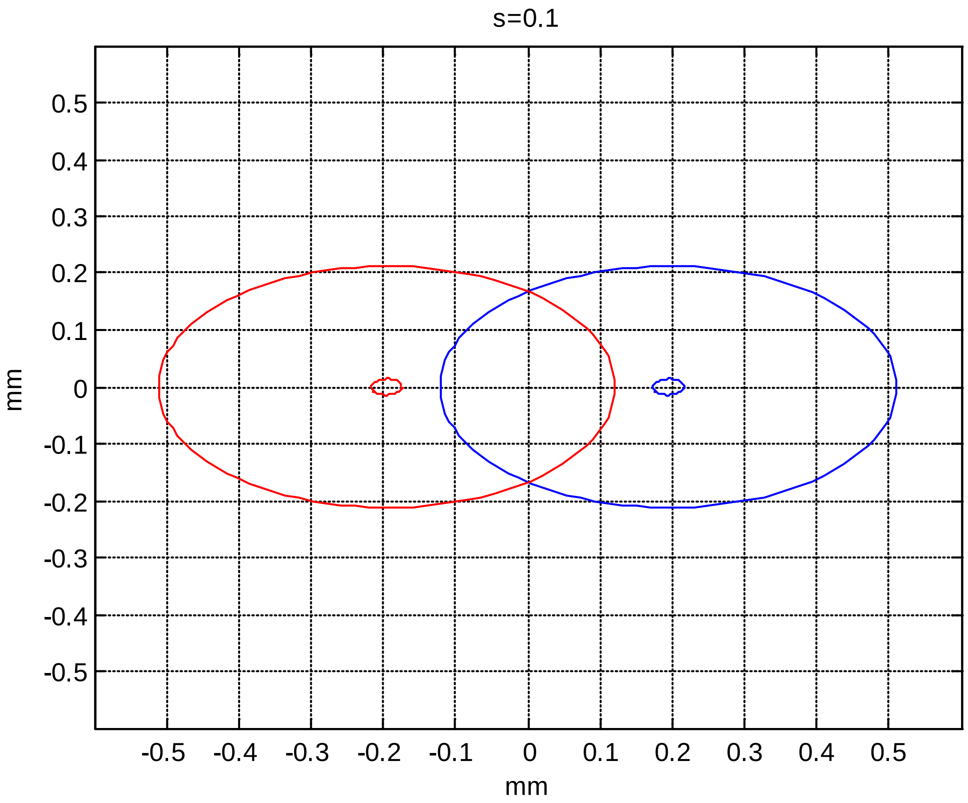
A new IR for LHC



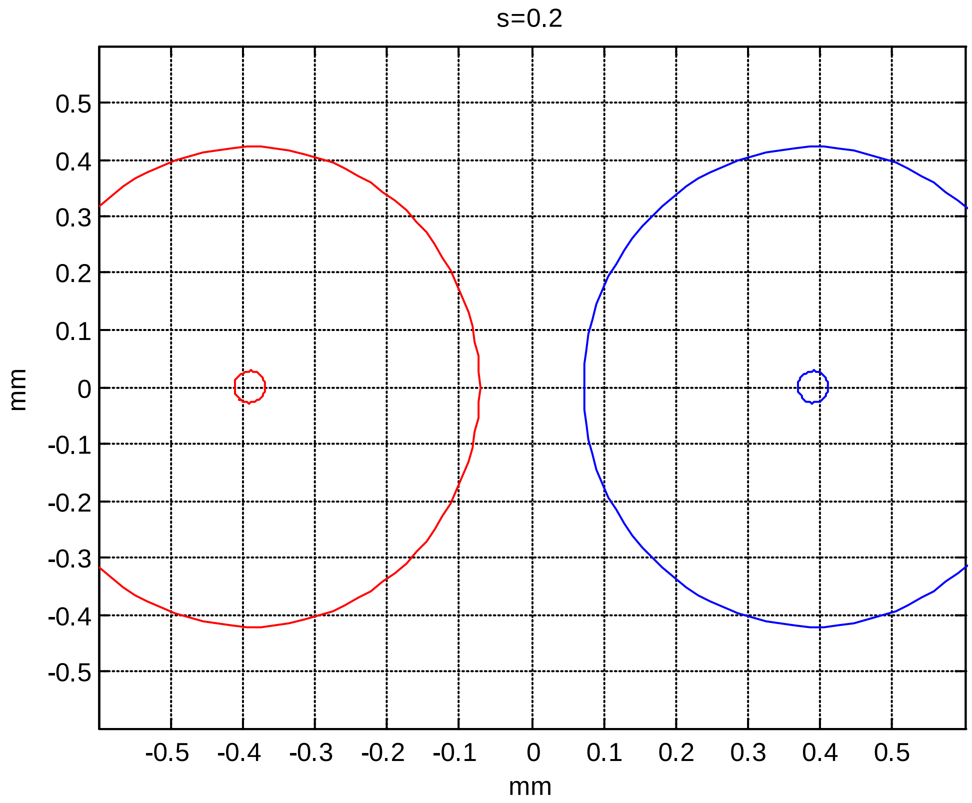
A new IR for LHC



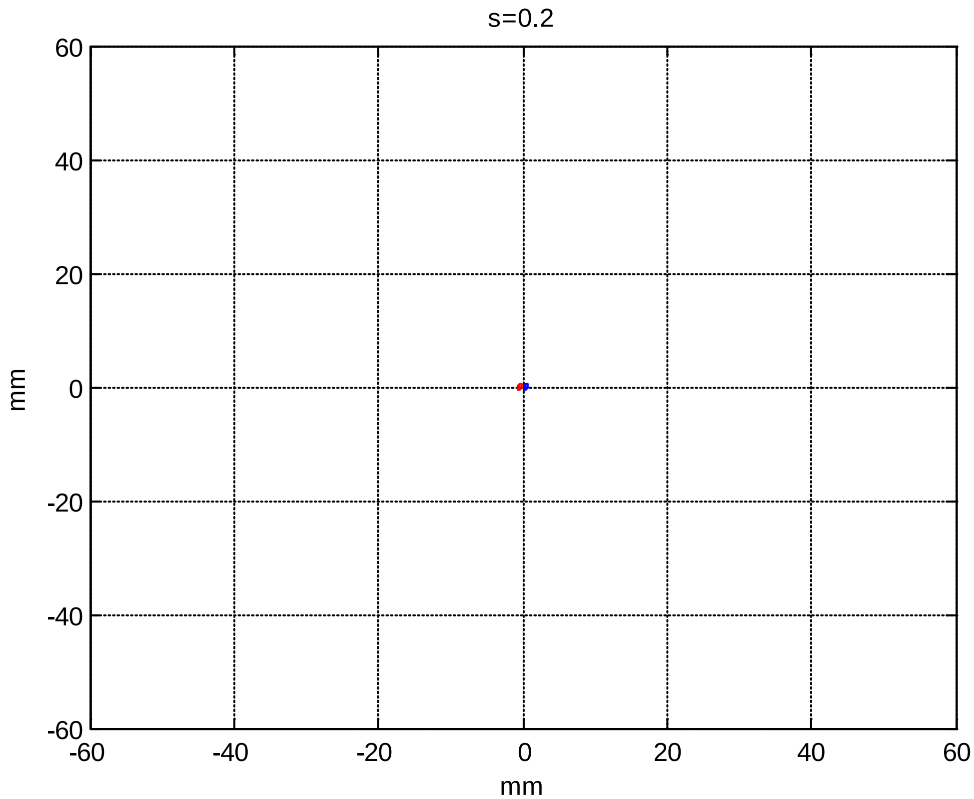
A new IR for LHC



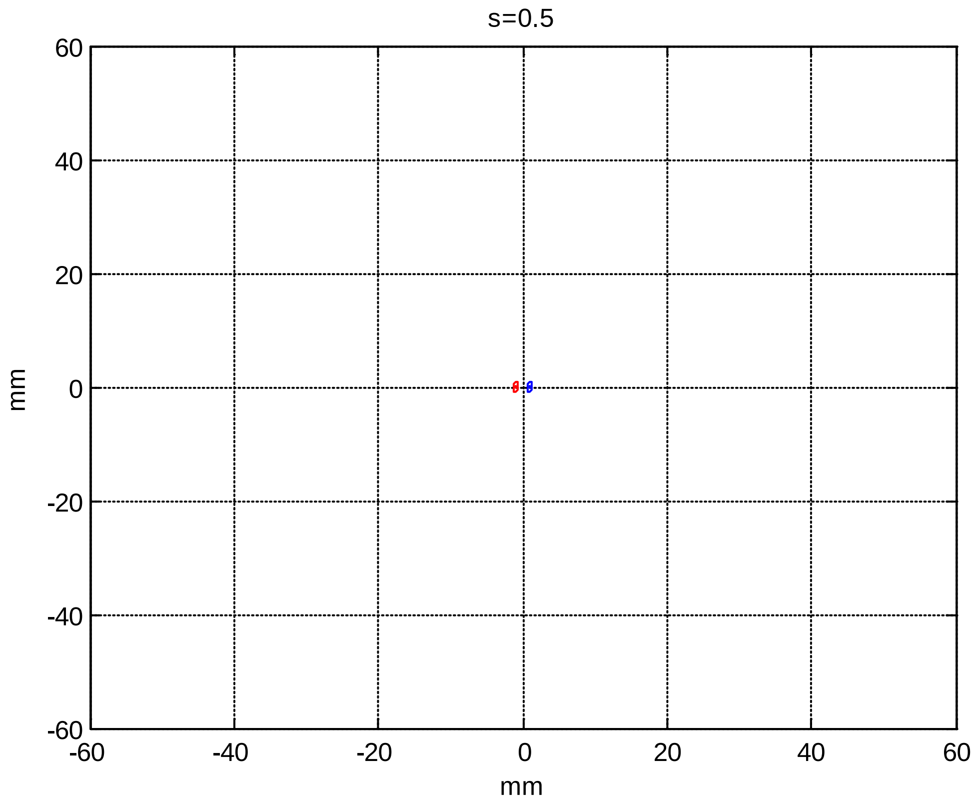
A new IR for LHC



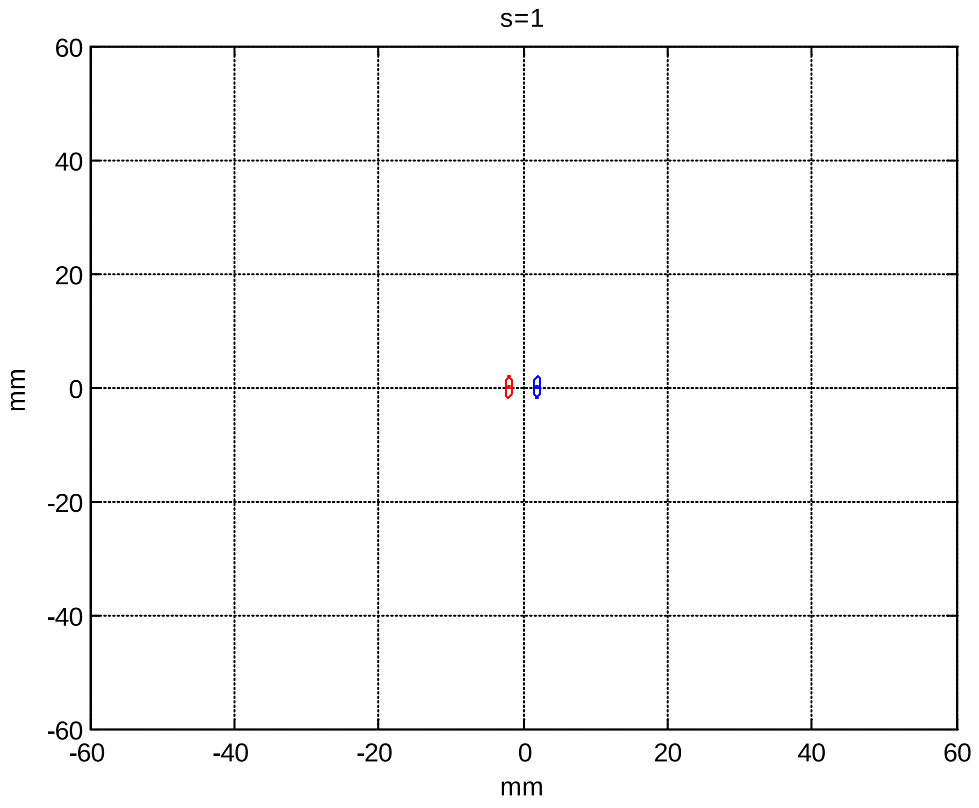
A new IR for LHC



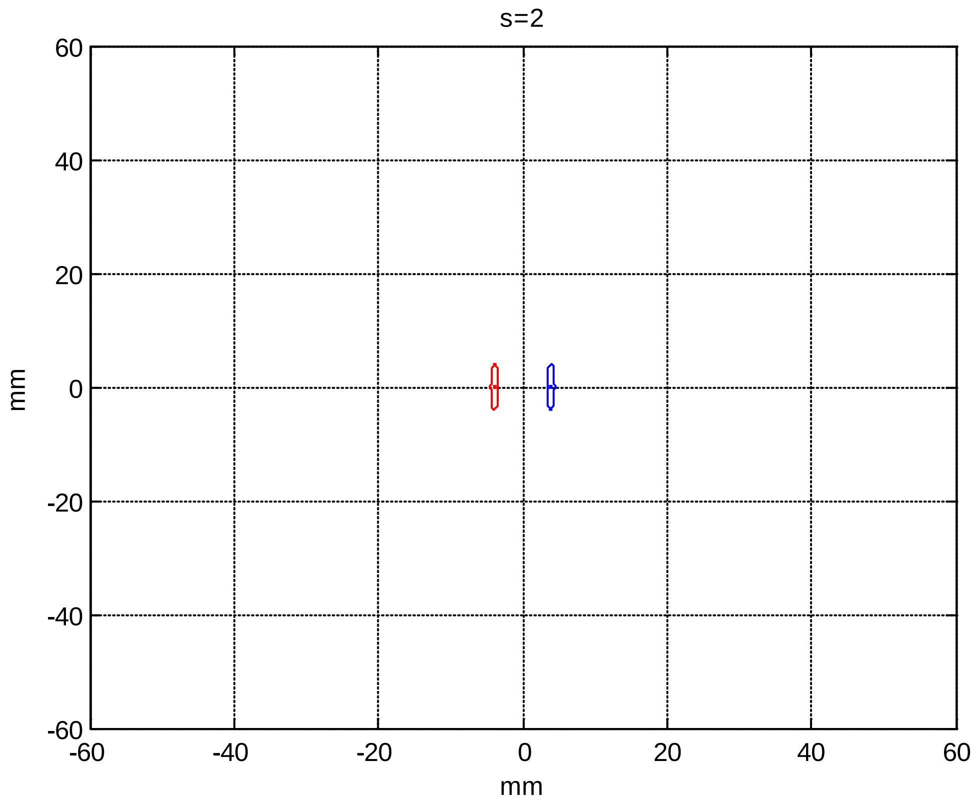
A new IR for LHC



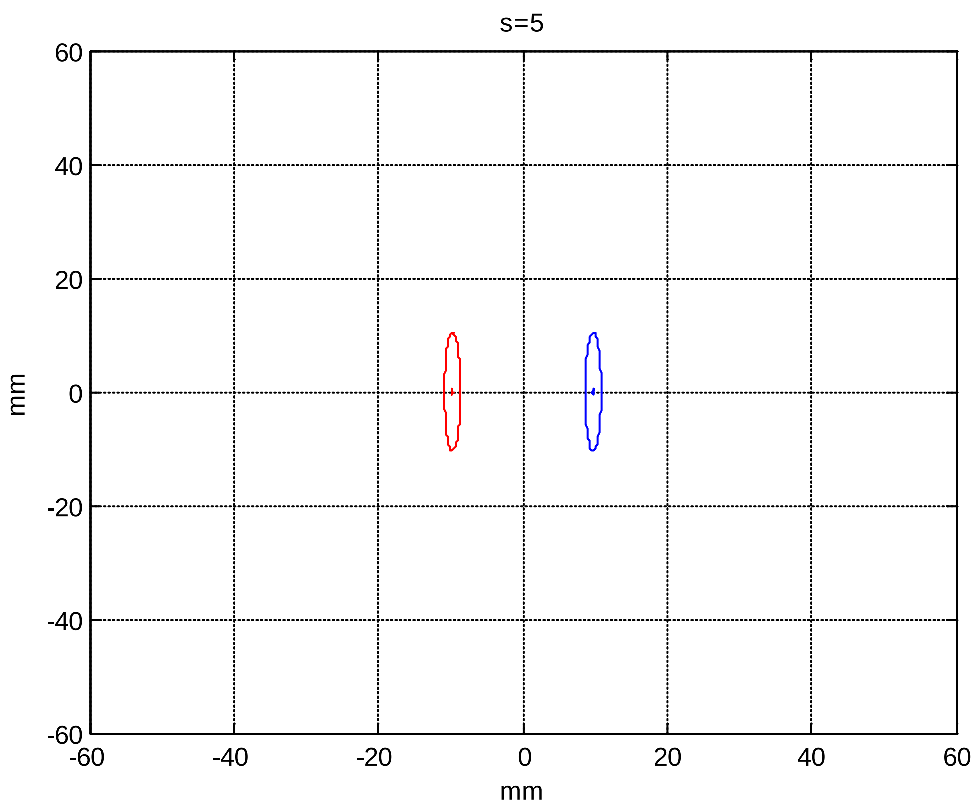
A new IR for LHC



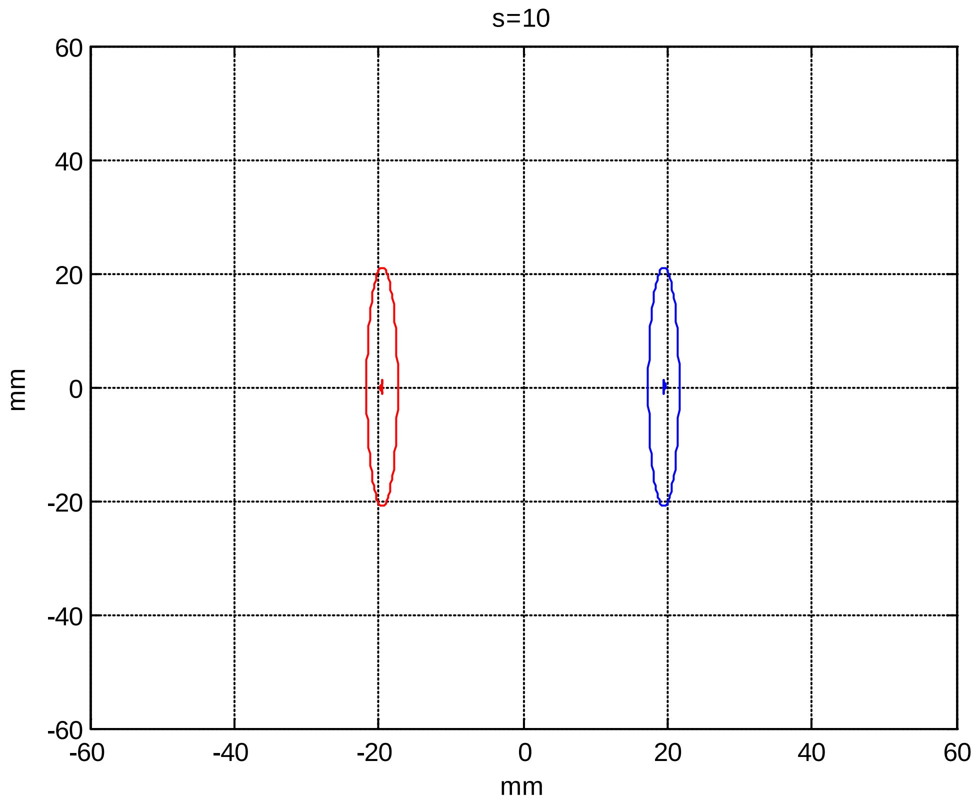
A new IR for LHC



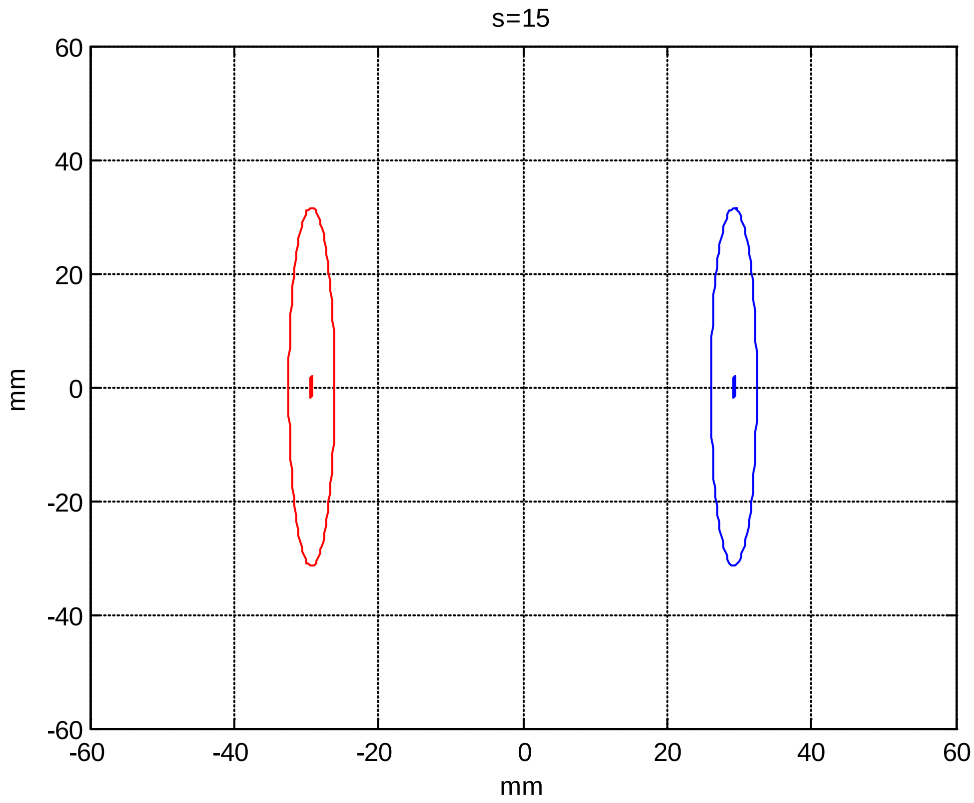
A new IR for LHC



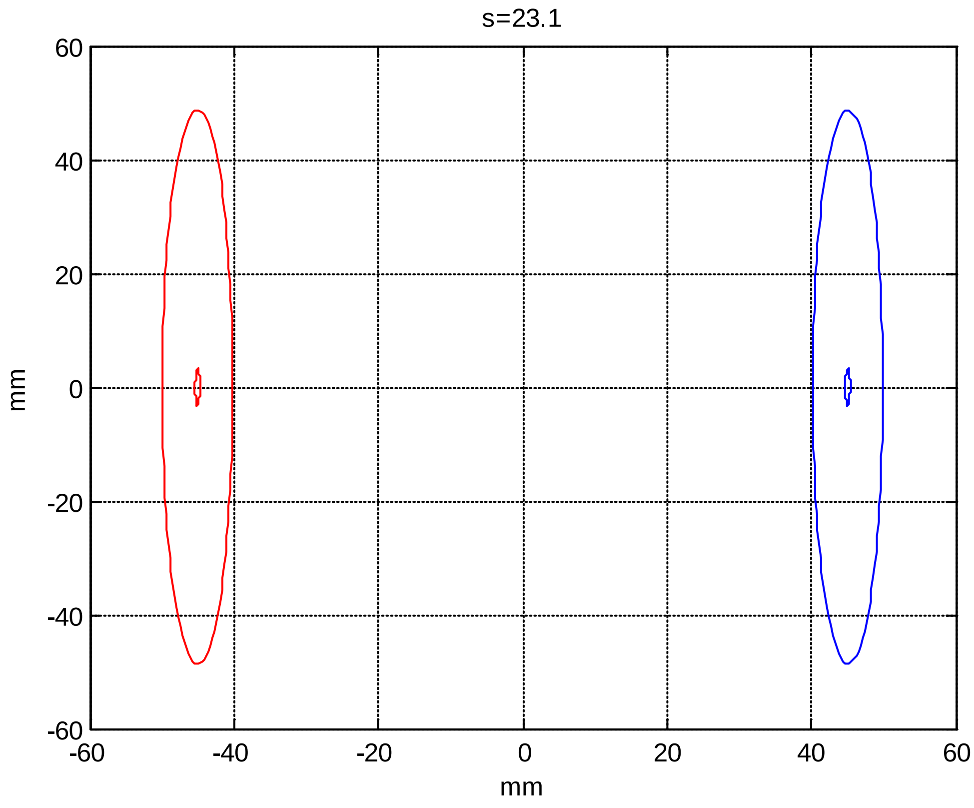
A new IR for LHC



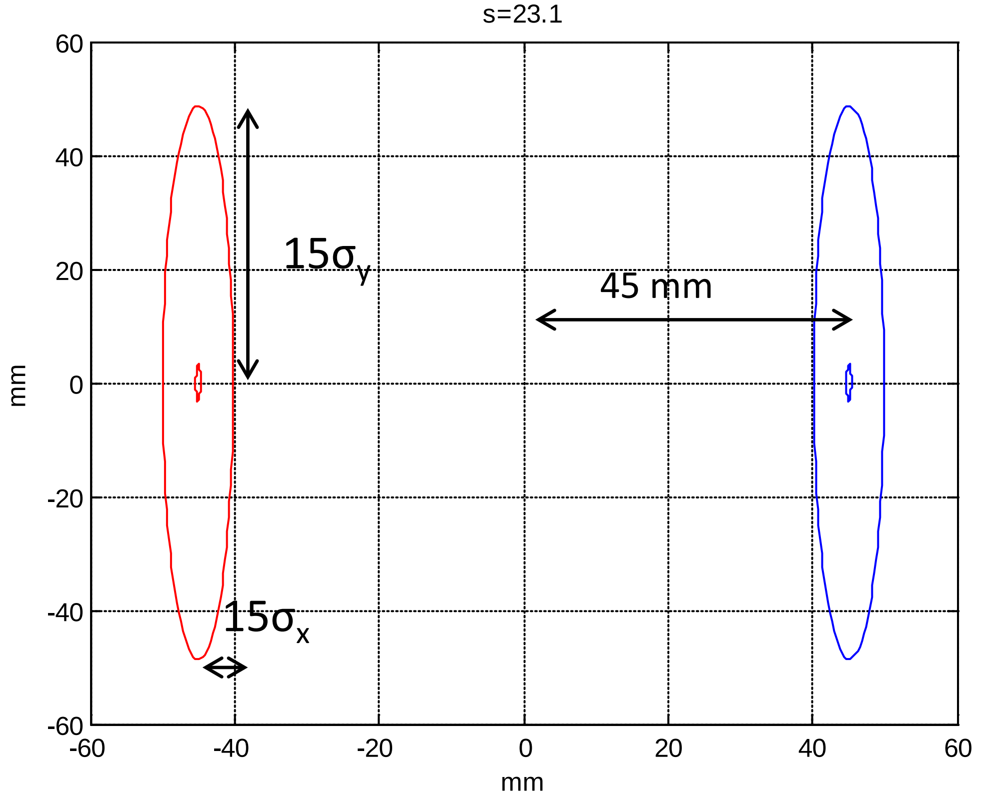
A new IR for LHC

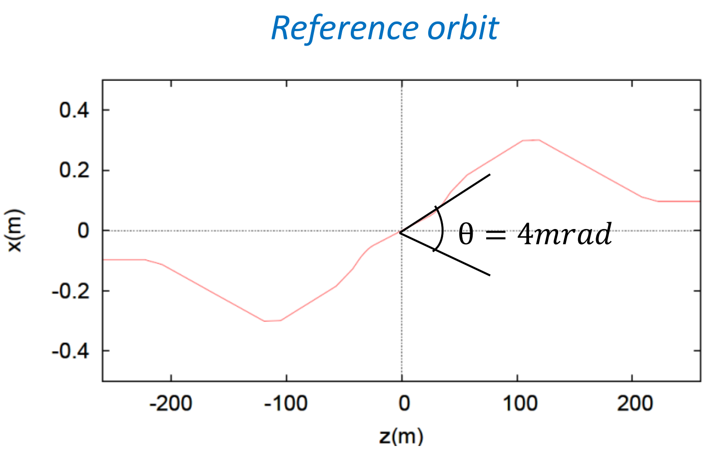


A new IR for LHC



A new IR for LHC

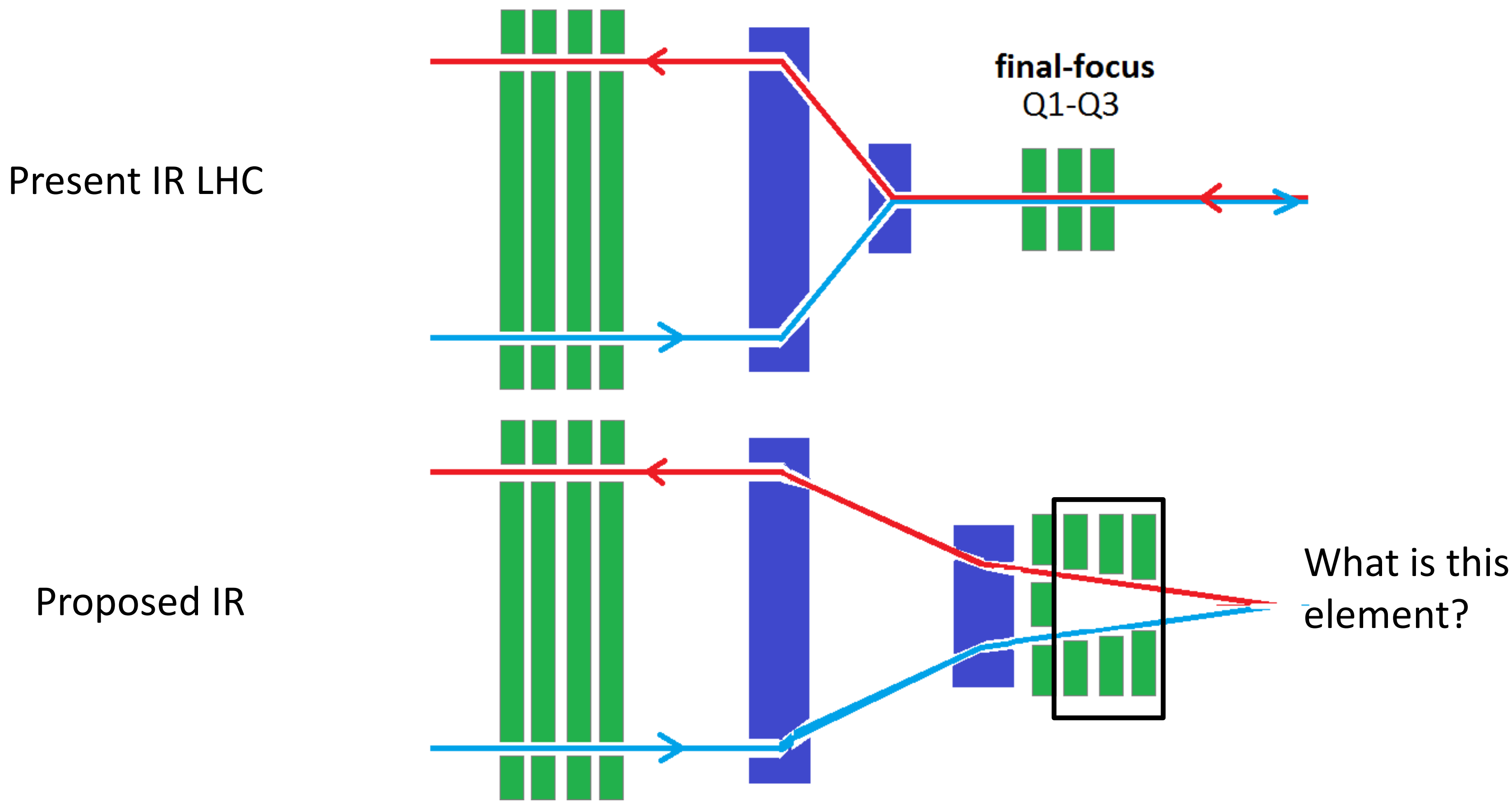




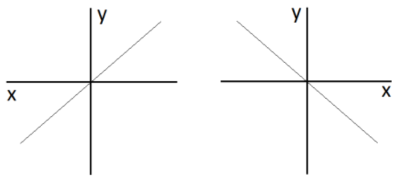
$\sigma^*_x / \sigma^*_y = 10$

Minimum required according to beam-beam simulations.

A new IR for LHC

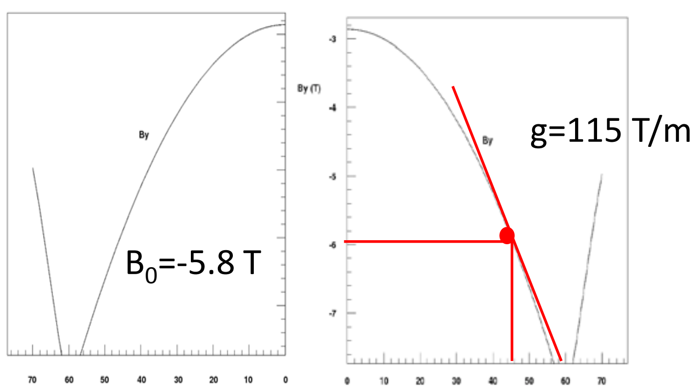


Last quadrupole



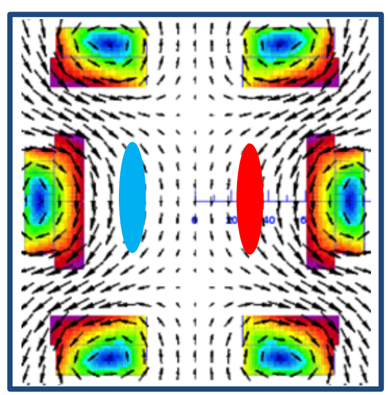
$B_y(x)$

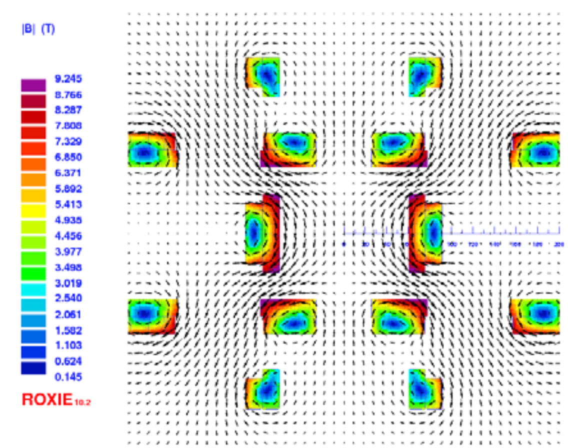
solution to have diff quadrupole sign for the 2 beams in the same aperture



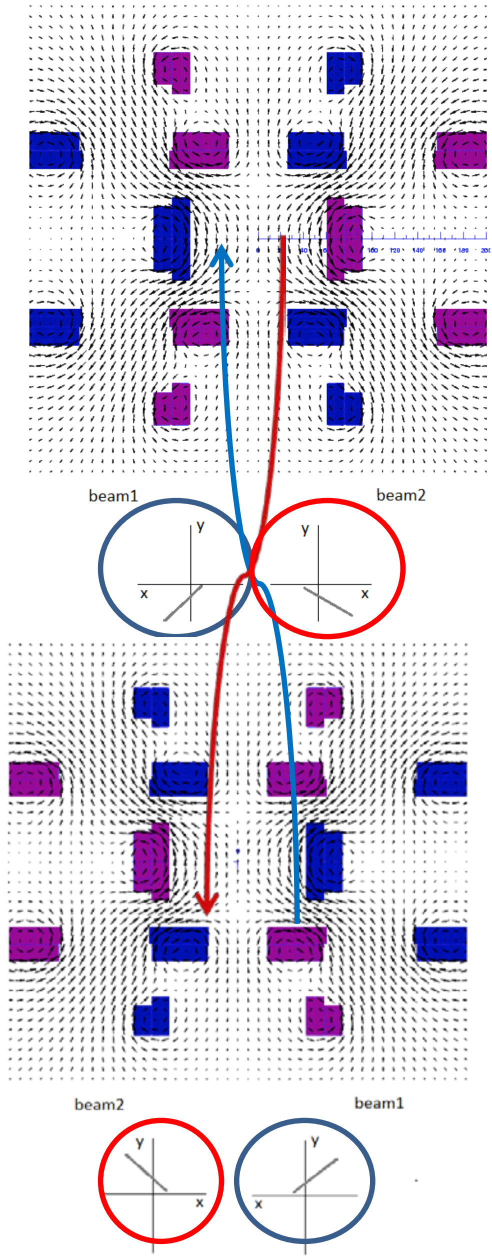
Dipolar component and sextupolar component

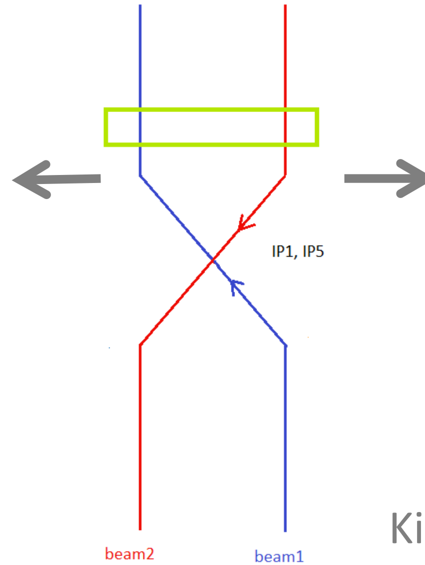
Double half quadrupole

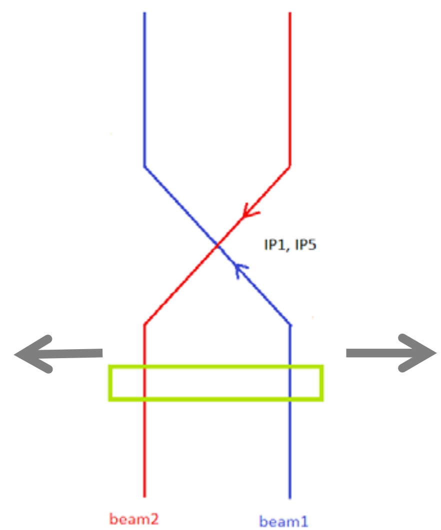




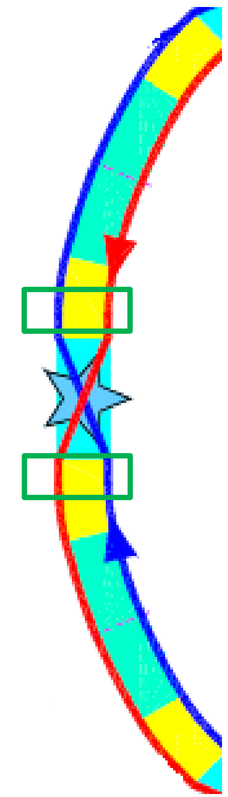
S. Russenchuck







Kick due to the dipolar term

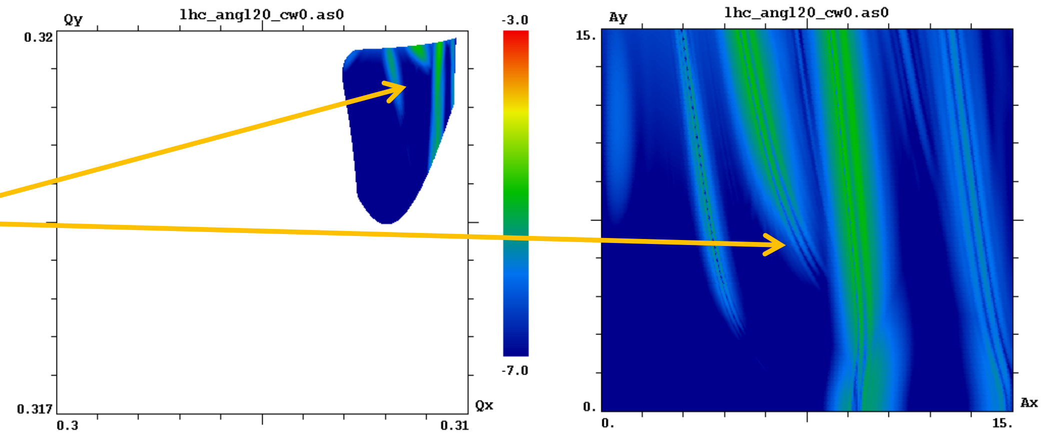


ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Crab-waist simulations

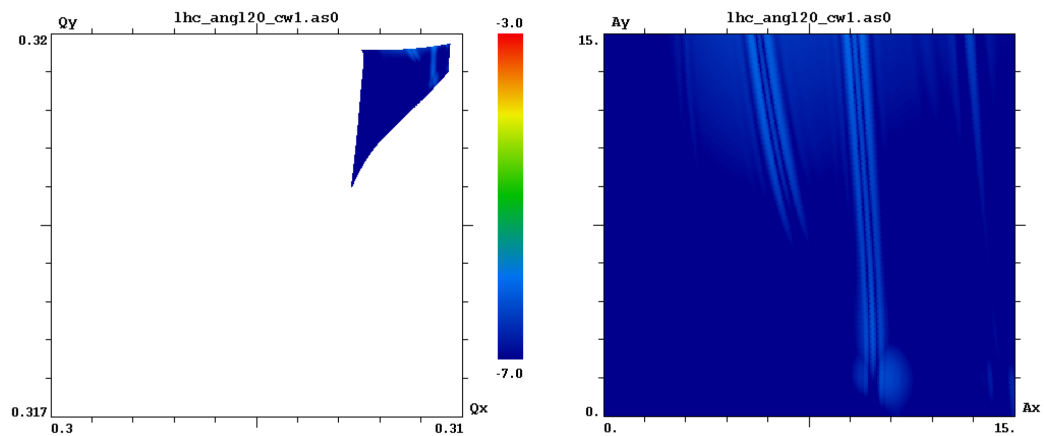
CW = 0

Resonances



CW = 0.5

Resonances suppressed



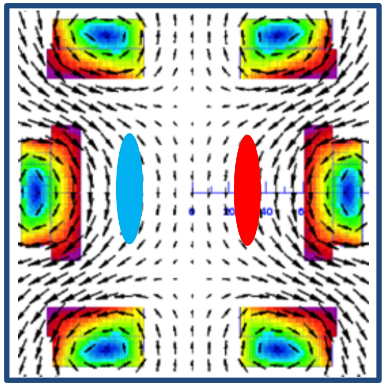
Frequency Map Analysis (FMA)
Effective for the beam-beam resonance suppression.
Plot shown for $\theta_c = 1.5$ mrad

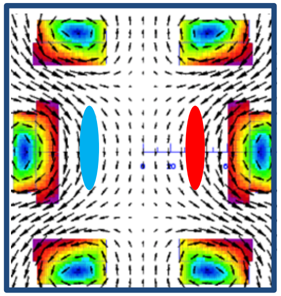
Dmitry Shatilov
Mikhail Zobov

John Adams Institute for Accelerator Science

Work on progress

- Chromatic correction and sextupole compensation
- Plan B





β_x^*=1.5 m
β_y^*=1.5 cm
θ = 4 mrad

β_x^*=3.5 m
β_y^*=3.5 cm
θ = 2.6 mrad

Conclusions

- An extremely-flat beam optics (β_y^*/β_y^*=100) is conceptual possible for LHC and HELHC
  - Large Piwinski angle, to reduce the collision area and allow for a lower β_y^*
  - Local chromatic correction
  - Possibility to have crab waist collisions that can increase luminosity and suppress resonances
  - Can accept higher brightness.

Bibliography

- W. Herr and B. Muratori. *Concept of luminosity*.
- P. Raimondi[1], D. Shatilov, M. Zobov, *Beam-beam issues for colliding schemes with large Piwinski angle and crabbed waist* .
- J.L. Abelleira, *et. al.* ”Local Chromatic Correction Scheme and Crab-Waist Collisions for an Ultra-low beta* at the LHC”, *Proc. of the 2012 International Particle Accelerator Conference, New Orleans, USA,* p. 118 (2012).
- J.L. Abelleira,”Flat beam IR optics”, *Joint Snowmass-EUCARD/AccNet-HiLumi LHC meeting Frontier capabilities for Hadron colliders. February 22-23; 2013, CERN, Switzerland*
- J.L. Abelleira, ”Towards an extremely-flat beam optics with large crossing angle for the LHC”, *EUCARD Annual Meeting, April 25-27, 2012, Warsaw, Poland.*

Thank you…

…For your attention