Circular Modes and Flat Beams for LHC

Alexey Burov, Alexander Valishev

FNAL-LARP

Special thanks to
Slava Danilov, ORNL/SNS
Ya. S. Derbenev, JLab,
Elias Metral, CERN

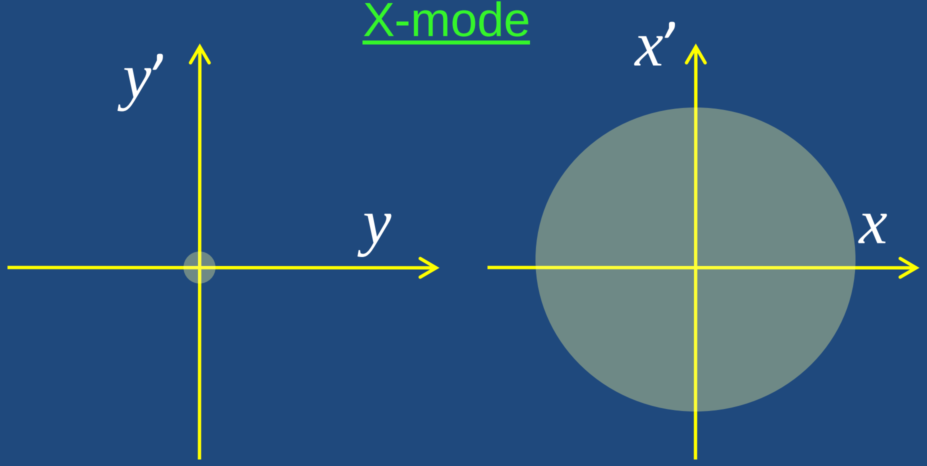
CERN AP Forum, Oct 1, 2012

Can coupling be useful?

- Normally we are talking about uncoupled X and Y betatron oscillations, considering coupling as small/unwanted.

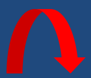
- However, coupling can be beneficial in some cases - e. g. for electron and ionization cooling. Can coupled optics be helpful for the LHC complex?

- Conventional X/Y betatron oscillations can be referred to as a planar optics.



Circular Optics

- An interesting special case of coupling is circular optics.

- Instead of  and  eigenmodes, we may have clockwise / counter-clockwise optical modes:  /  .

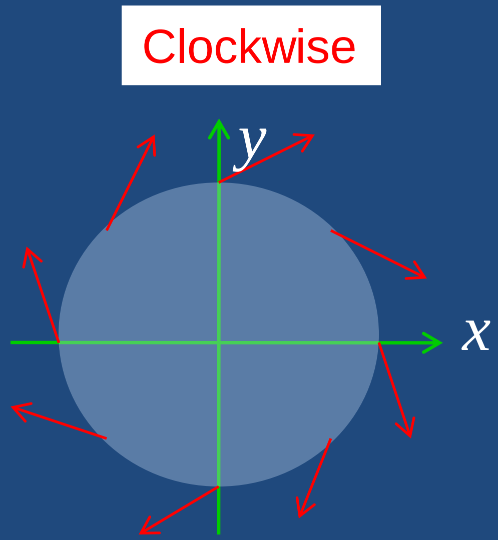
- In fact, circular vs planar betatron modes are similar to circular vs planar light polarization. In both cases the true eigenfunctions are determined by the optical symmetry.

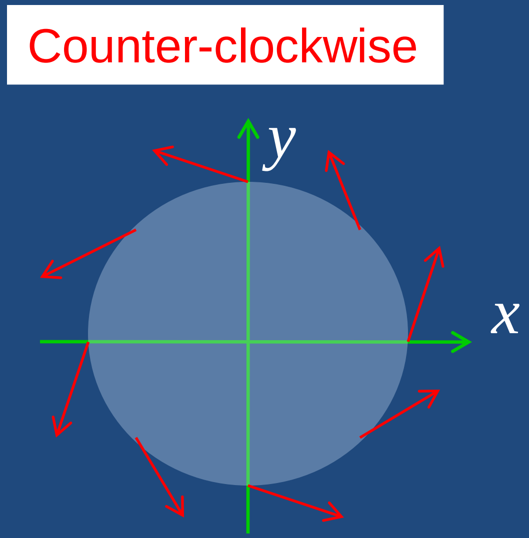
- To have circular optics, focusing has to be rotationally invariant in the transverse plane. This is provided by solenoids as focusing elements and bending magnets with the field index

$$-\frac{dB_y}{dx}\frac{\rho}{B_y}=\frac{1}{2}$$

- With skew quads, optics could be approximately circular.

Circular emittances





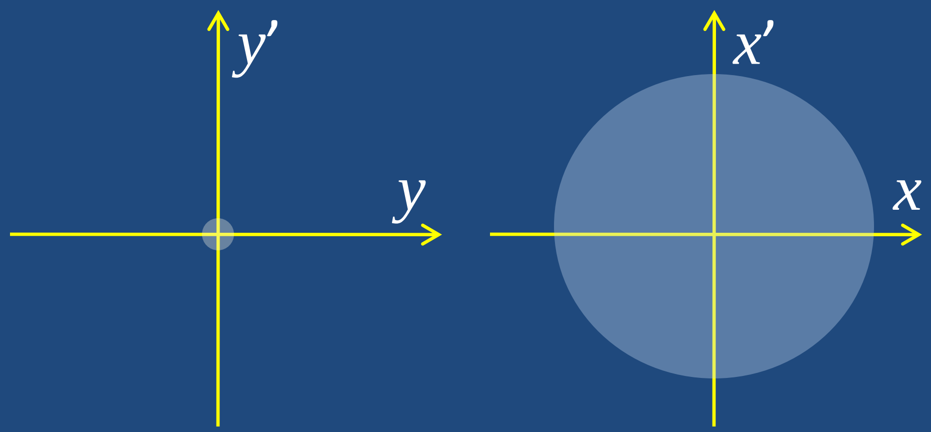
In general, emittances are beam-averages of the 4D phase space Courant-Snyder invariants (4D quadratic forms).

For the circular modes, the beam angular momentum is their difference:

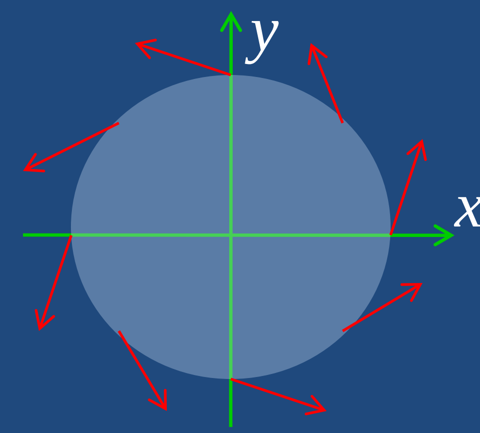
$$M = \varepsilon_+ - \varepsilon_-$$

Planar-Circular transformation (Derbenev)

X-mode

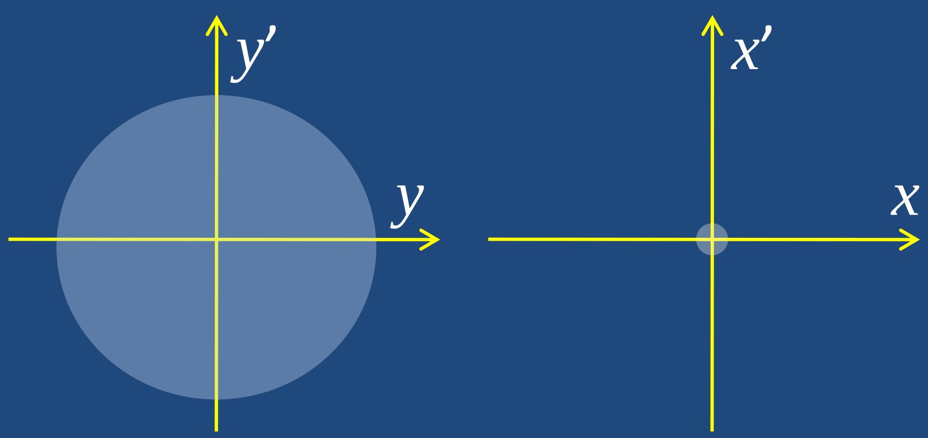


Counter-clockwise

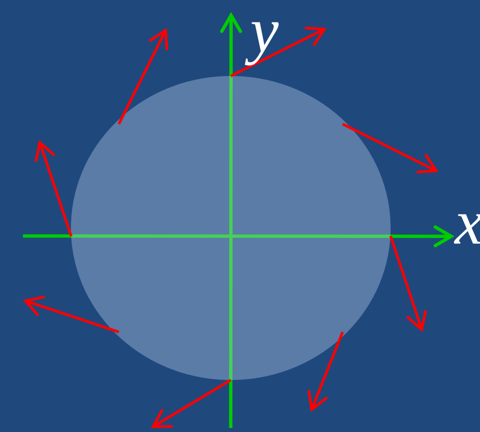


$\Leftrightarrow$

Y-mode



Clockwise



$$\varepsilon_x = \varepsilon_+$$

$$\varepsilon_y = \varepsilon_-$$

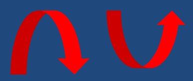
Emittance preservation

- Thus, beams can be linearly transformed from planar to circular states and back.

- Under these transformations, *both* emittances are preserved:

$$\varepsilon_x = \varepsilon_+ = \varepsilon_1$$
$$\varepsilon_y = \varepsilon_- = \varepsilon_2$$

- This transformation normally require 3 skew quads.

Space charge suppression for 

- Let the two emittances be significantly different: $\varepsilon_1 \gg \varepsilon_2$. For planar modes, the maximal space charge tune shift is determined by their geometric average, preventing the smaller emittance to be too small:

$$\Delta Q_y \propto \frac{1}{\sqrt{\varepsilon_x \varepsilon_y}} \to \infty \Big|_{\varepsilon_y \to 0} .$$

- For the circular modes, it is not so: the SC tune shift is determined by the maximal emittance, being independent of the minimal one!

$$\Delta Q_{\pm} \propto \frac{1}{\varepsilon_1} \to \mathrm{const} \Big|_{\varepsilon_2 \to 0} .$$

- The reason is simple: in the circular case, the beam cross-section is a circle, which radius is determined by the maximal emittance.

Flat beams and luminosity gain for 

- For circular optics, the smaller emittance is not limited by the space charge tune shift! At least in that direct way…

- With a proper painting injection, with a pencil-beam linac, the beam can be injected into one of the modes, when the emittance ratio can be as small as the ring acceptance to the pencil beam emittance (V. Danilov et al., EPAC 2004)

- After acceleration, the beam can be transferred into the planar state, becoming flat.

- For colliders, this gives high luminosity:

$$\mathcal{L} \propto \frac{1}{\sqrt{\varepsilon_2}} \to \infty \Big|_{\varepsilon_2 \to 0}$$

BB effects and leveling

- For flat beams, the 2D net of resonances degenerates into 1D only, thus allowing much higher long-range and head-on beam-beam tune shifts, having smaller separation without detrimental effects.

- Crab cavity is not needed.

- Similar to electron beams, luminosity leveling can be achieved by means of the horizontal (larger emittance) beta-function, making it high at the beginning, and then gradually squeezing.

- Required triplet aperture is reduced.

Coherent Stability

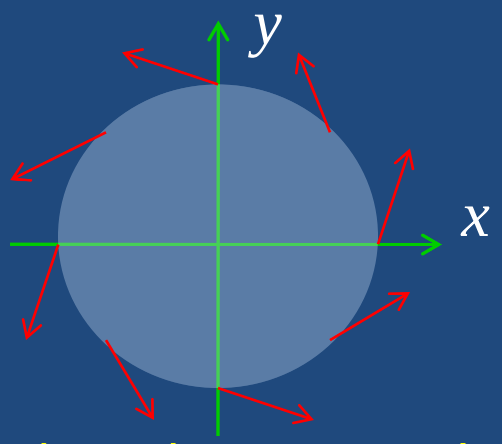
- Absolute value of the octupole nonlinearity is about the same, but the x/y signs are opposite. Squeeze at collisions could be a must. Analysis of the current instabilities will shed more light.

- Due to high beam-beam tune shift, more than one bunch-by-bunch dampers may be needed.

What limits the minimal emittance?

- Finite linac emittance and injection process. Pencil beam is required.

- Mismatch due to SC defocusing in the synchrotron. In a ‘careless’ case, this limits the emittance ratio by $\Delta Q_{sc} / Q \simeq 0.1$. A solution to have it much lower (Danilov et al, EPAC 2004; J. Holmes et al, HB 2006) –
  - homogeneous vortex painting to -



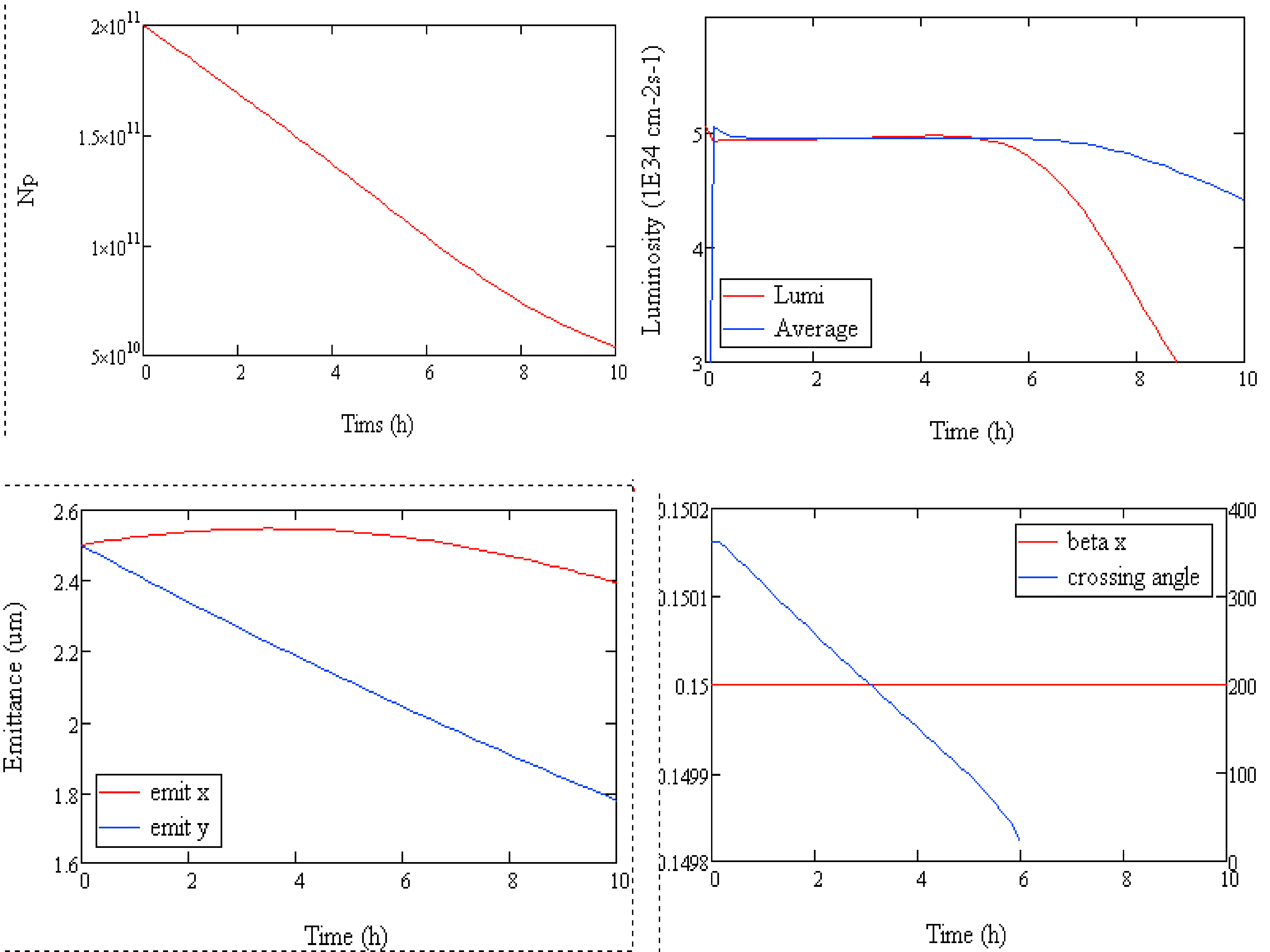
  - Induction synchrotron (K. Takayama et al, PRL 2007)

- IBS and gas scattering in the collider.

	LHC nominal	HL-LHC 25 ns	HL-LHC Flat
# Bunches	2808	2808	2808
p/bunch [10^{11}]	1.15 (0.58A)	**2.0 (1.01 A)**	**2.0 (1.01 A)**
ε_L [eV.s]	2.5	2.5	2.5
σ_z [cm]	7.5	7.5	7.5
$\sigma_{\delta p/p}$ [10^{-3}]	0.1	0.1	0.1
$\gamma\varepsilon_{x,y}$ [μm]	3.75	**2.5**	**4.0, 0.4**
β^* [cm] (baseline)	55	**15**	**55, 15**
X-angle [μrad]	285	**590 (12.5 σ)**	**318 (10 σ)**
Lumi loss factor	0.84	0.30	0.85
Peak lumi [10^{34}]	1.0	6.0	19.3
Virtual lumi [10^{34}]	1.2	20.0	22.8
$T_{leveling}$ [h] @ 5E34	n/a	**7.8**	**8**

Nominal Luminosity Scenario

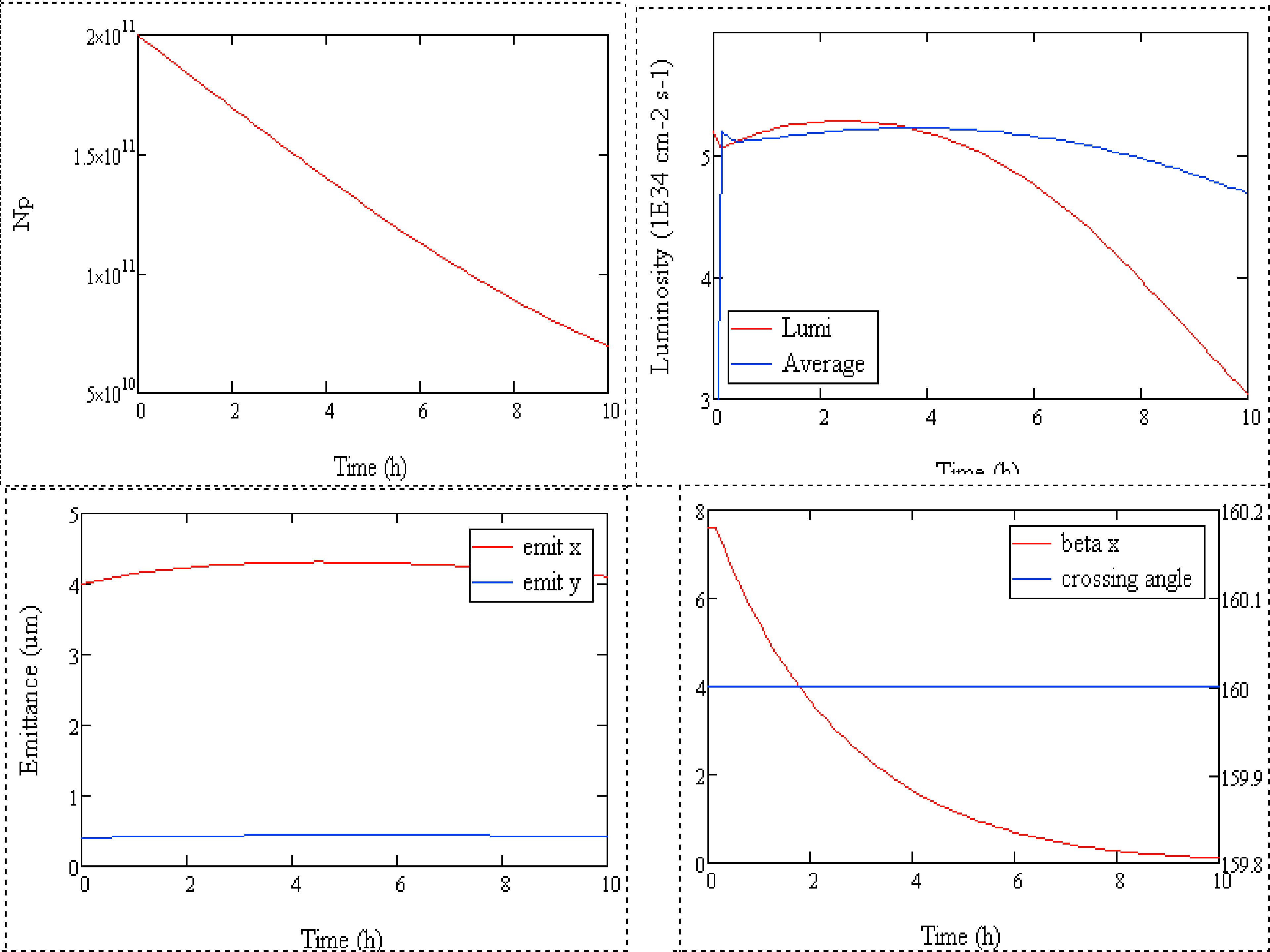
- Assuming betatron coupling κ=0.1
  - tx_{IBS}=20 h
  - ty_{IBS}=180 h
  - tz_{IBS}=12 h
- tx_{SR}=26 h, quantum fluctuations negligible
- Luminosity evolution is dominated by particle burn in collisions.



Np
2×10^11
1.5×10^11
1×10^11
5×10^10
0
2
4
6
8
10
Tims (h)
Luminosity (1E34 cm-2s-1)
5
4
3
Lumi
Average
Time (h)
Emittance (um)
2.6
2.4
2.2
2
1.8
1.6
emit x
emit y
Time (h)
0.1502
0.1501
0.15
0.1499
0.1498
400
300
200
100
0
beta x
crossing angle
Time (h)

Flat Beams Luminosity Scenario

- Assuming betatron coupling κ=0.1
  - tx_{IBS}=12 h
  - ty_{IBS}=10 h
  - tz_{IBS}= 5 h
- tx_{SR}=26 h, quantum fluctuations negligible
- How big is the effect of IBS on luminosity evolution compared to particle burn in collisions?


Np
2x10^11
1.5x10^11
1x10^11
5x10^10
0 2 4 6 8 10
Time (h)
Luminosity (1E34 cm-2 s-1)
5
4
3
Lumi
Average
0 2 4 6 8 10
Time (h)
Emittance (um)
5 4 3 2 1 0
emit x
emit y
0 2 4 6 8 10
Time (h)
8 6 4 2 0
160.2
160.1
160
159.9
159.8
beta x
crossing angle
0 2 4 6 8 10
Time (h)

Flat Beam Results

- Luminosity leveling with horizontal β*. Begin with 7.6 m, end with 0.28 m (after 8 hours)
- Crossing angle of 320 μrad and NO crab cavity
- IBS growth rate in V plane (determined by coupling) does not affect luminosity life time

Beam-beam effects

- Head-on beam-beam parameter
  - ξ_x=0.011 ξ_y=0.015 per IP
- Long-range separation with βx=0.55m, βy=0.15m
  - A_x=10 σ_x A_y=13.7 σ_y

- Simplified machine model -> 1E6 turn 6D DA with $\Delta p/p$=2.7E-4
  - Linear arcs
  - 2 main IPs
  - 18 LR collision points on each side
  - DA > 6 sigma even at L=1.8E35 !

Summary

- Circular optics in the injectors in principle allows to have flat beams in the LHC, thus increasing luminosity and letting to have smaller separation.

- Perhaps, the space charge tune shift, together with the head-on and long-range beam-beam effects all could be excluded as practical limitations for the luminosity.

- However, to see the real potential of this scheme, special research is needed.

- Limitations on the smaller emittance have to be found for the injection process, for the SC mismatch at acceleration, optics, diffusion and the entire scenario in the collider.

- So far, this circular-flat scheme looks very promising, suggesting a new exciting vision for the long-term future of the LHC.

References

1. A. Burov, Ya. Derbenev, S. Nagaitsev, “Circular modes, beam adapters and their applications”, PRE, **66**, 016503 (2002).
2. V. Danilov, S. Cousineau, S. Henderson, J. Holmes, “Self-consistent space charge 2D and 3D distributions”, PRST-AB **6**, 094202 (2003)
3. V. Danilov, S. Cousineau, S. Henderson, J. Holmes, M. Plum “Injection schemes for self-consistent space charge distributions”, Proc. EPAC 2004.
4. J. Holmes, S. Cousineau, V. Danilov, A. Shishlo, “RF barrier cavity for SNS”, HB 2006.
5. A. Burov, Ya. Derbenev, “Space charge suppression for uneven emittances”, Fermilab-PUB-09-392-AD, 2009.
6. A. Burov, “Circular modes for flat beams in LHC”, Proc. High Brightness 2012, Beijing.

Thanks for your attention!