Circular Modes and Flat Beams for LHC

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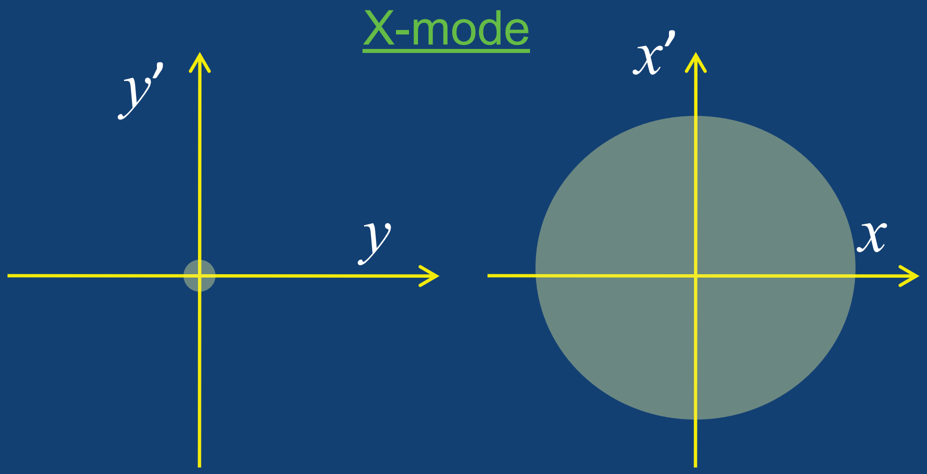
Conventional Planar Optics

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

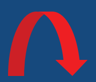
- However, coupled modes could be an optimal solution for a particular case. It is so for e. g. electron and ionization cooling. Can they be effectively applied for the LHC complex?

- 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:  /  .

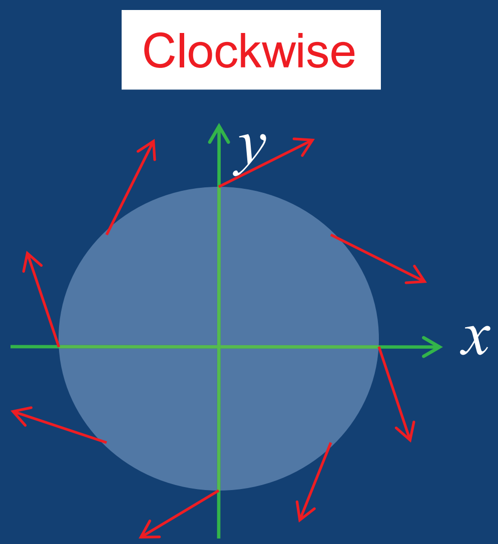
- In fact, circular vs planar betatron modes are similar to circular vs planar light polarization. In both cases the true eigenfunctions are determined by the optical symmetry.

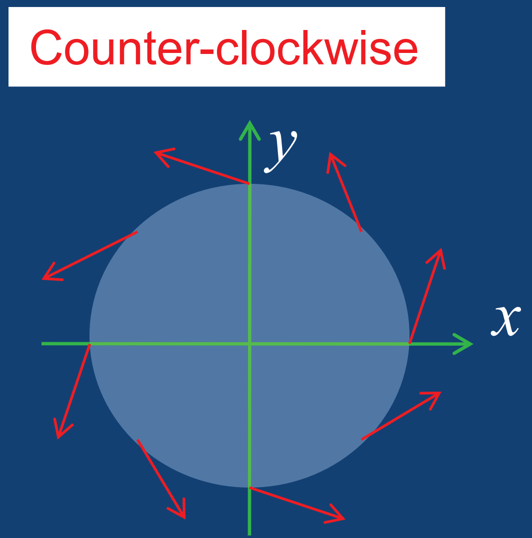
- To have circular optics, focusing has to be rotationally invariant in the transverse plane. Exactly, this is provided by solenoids as focusing elements and gradient bending magnets with index

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

- With skew quads, optics could be approximately circular.

How do they look like





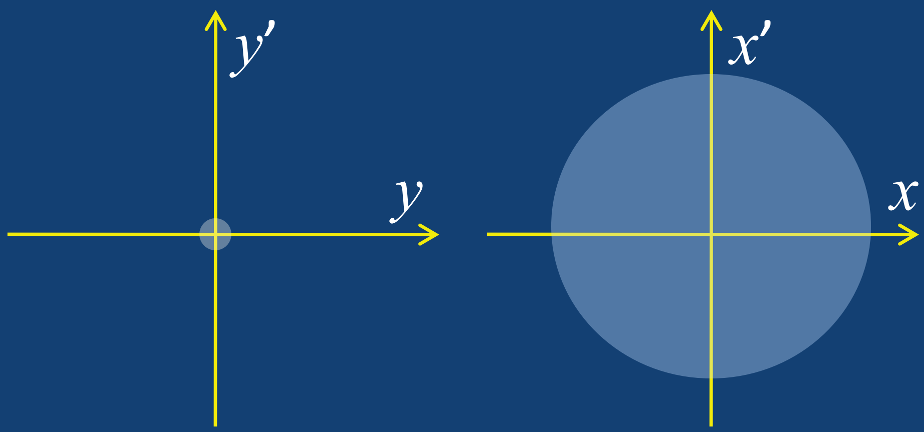
In general, emittances are beam-averages of the 4D phase space Courant-Snyder invariants.

For the circular modes, emittances are nothing else as rms angular momentums for each of the modes. Thus, the beam angular momentum is their difference:

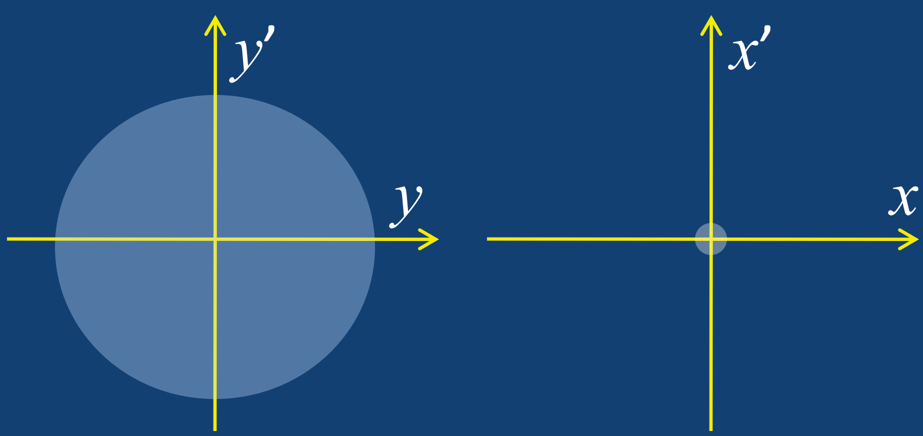
$$M = \varepsilon_+ - \varepsilon_-$$

Planar-Circular transformation (Derbenev)

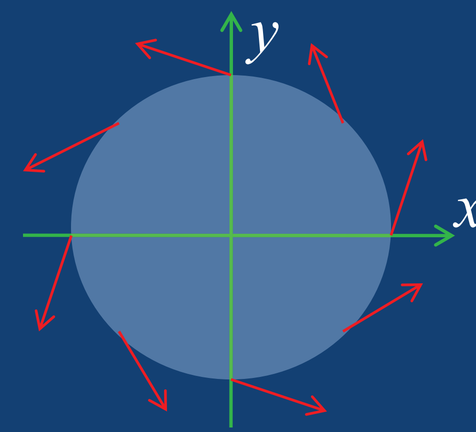
X-mode



Y-mode



Counter-clockwise



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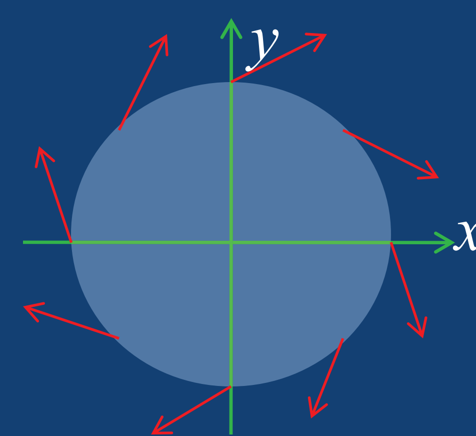
Clockwise



$$\varepsilon_x = \varepsilon_+$$

$$\varepsilon_y = \varepsilon_-$$

Planar-Circular mode transformation

- 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.

What is good for  ?

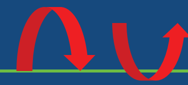
- Let the two emittances be significantly different: $\varepsilon_1 \gg \varepsilon_2$. For planar modes, the maximal space charge tune shift is determined by their geometric average, preventing the smaller emittance to be too small:

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

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

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

- The reason is simple: in the circular case, the beam size is determined by the maximal emittance.

What is good 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 (S. Danilov, J. Holmes, S. Cousinou, EPAC 2004)
- After acceleration, the beam can be transferred into the planar state, becoming flat.
- For colliders, this gives high luminosity:

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

BB effects for flat beams

- Flat beams in the collider not only directly contribute to the luminosity.

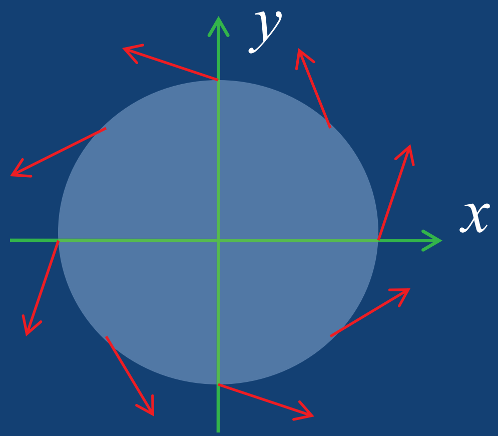
- For flat beams, the 2D net of resonances degenerates into 1D only, thus allowing much higher long-range and head-on beam-beam tune shifts, having smaller separation without detrimental effects.

- In Frascatti, as high BB tune shift as 0.2 was reached.

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 ~0.1-0.2. Perfect solution to have it much lower (Danilov, Holmes, Cousinou) –
  - homogeneous vortex painting to -



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

- IBS and gas scattering in the collider.

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, for IBS and diffusion 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

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Thanks for your attention!