Space charge limitation for bunch compression in synchrotrons

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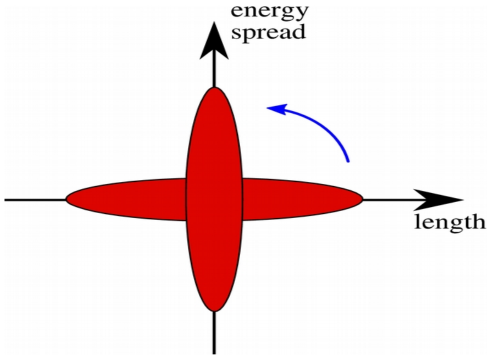
Introduction

- What problem to be solved: intensity limitation due to space charge during bunch compression
  1. Bunch compression has many applications (plasma physics, spallation neutron sources...)
  2. A well-accepted method for bunch compression is a fast 90° longitudinal bunch rotation.
- Why?

  During bunch compression, space charge will be enhanced and leads to resonance crossing and emittance growth— **space charge limitation**



- Which methods:
  1. PIC simulations
  2. Combined envelope approach
- Results

  (1) One major space charge limitation is the fourth order particle resonance, which dominates over the envelope instability;

  (2) Another limitation the recently-discovered dispersion-induced instability is observed, which could be another intensity limitation.

Coupled envelope system

- The transverse motion **is coupled** with longitudinal motion **by space charge and dispersion**.

$$\left\{\begin{aligned} & z_m'' + \kappa_{z0} z_m - \frac{K_L}{z_m^2} - \frac{\varepsilon_L^2}{z_m^3} = 0 \\ & \sigma_x'' + \left[\kappa_{x0}(s) - \frac{K_{sc}}{2X(X+Y)}\right]\sigma_x - \frac{\varepsilon_{dx}^2}{\sigma_x^3} = 0 \\ & \sigma_y'' + \left[\kappa_{y0}(s) - \frac{K_{sc}}{2Y(X+Y)}\right]\sigma_y - \frac{\varepsilon_{dy}^2}{\sigma_y^3} = 0 \\ & D_x'' + \left[\kappa_{x0}(s) - \frac{K_{sc}}{2X(X+Y)}\right]D_x = \frac{1}{\rho(s)} \end{aligned}\right.$$

With the coupling relation:

$$\sigma_\delta = \sqrt{\left(\frac{\sigma_z'}{\eta}\right)^2 + \left(\frac{\varepsilon_z}{\eta\sigma_z}\right)^2} \qquad X = \sqrt{\sigma_x^2 + \sigma_\delta^2 D_x^2}$$

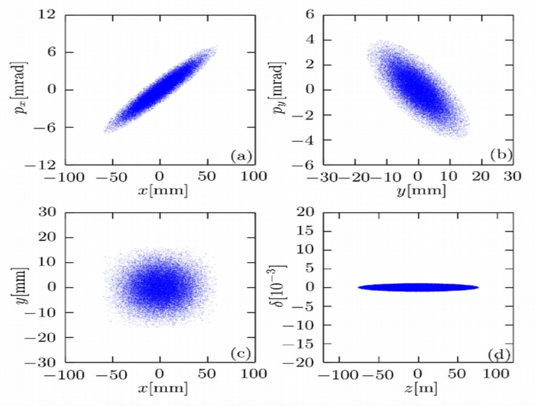
$\sigma_{x,y}$	rms beam sizes without dispersion
X	rms *total* beam size with dispersion
D_x	space-charge modified dispersion
ϵ_{dx}	generalized transverse emittance with dispersion
z_m	half bunch length
K_{sc}	space charge perveance

J. A. Holmes, *et.al*, PRSTAB 2, 114202 (1999).

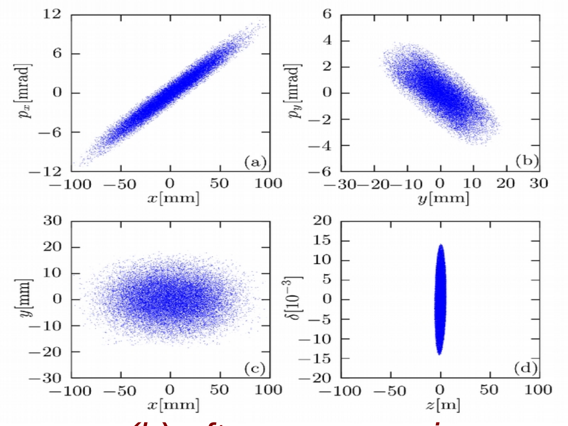
M. Venturini and M. Reiser, PRL. 81, 96 (1998).

Bunch compression in SIS-18 at GSI

- PIC simulations (pyORBIT)



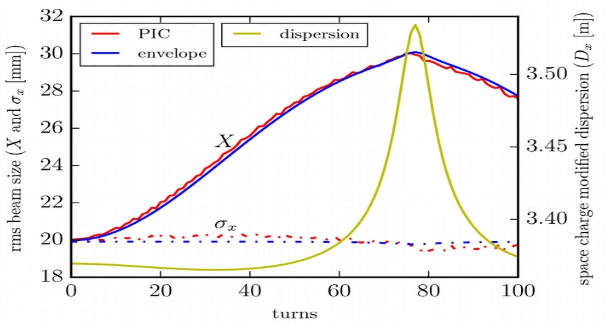
(a) before compression



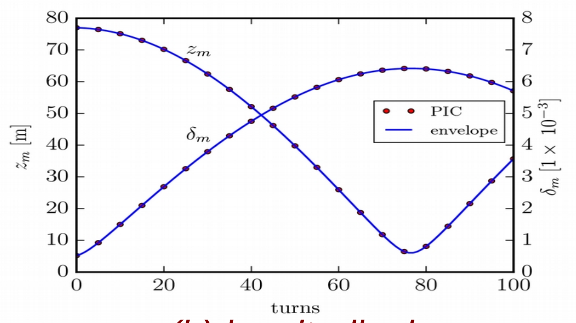
(b) after compression

Parameters [unit]	Value
Circumference [m]	216
Kinetic energy [GeV/u]	0.295
Particle number	1×10^{11}
Initial half bunch length [ns]	395
Final half bunch length [ns]	30
Rf voltage [kV]	31
Required turns	75
Periodic phase advance	128,104

- Coupled envelope equations



(a) transverse



(b) longitudinal

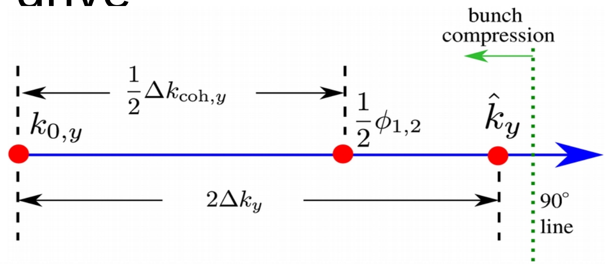
- Good agreement between two methods
- **Space-charge modified dispersion** (yellow) & transverse beam size (blue) is increasing because of dispersion, transverse beam size remains constant.

90° fourth-order particle resonance

Ref. I. Hofmann et.al., PRL. 115, 204802 (2015).
D. Jeon, et. al., PRSTAB 12, 054204 (2009).

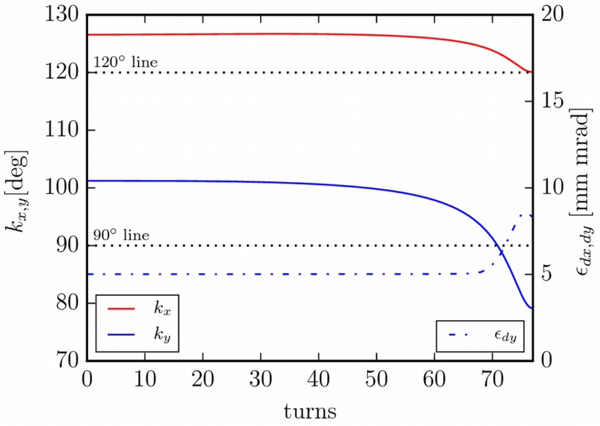
- During bunch compression, enhanced space charge could drive
  (1) Fourth order particle resonance
  $$4k_y = 360^\circ$$
  (2) Envelope instability
  $$2k_{0,y} - \Delta k_{coh,y} = \frac{1}{2}360^\circ$$

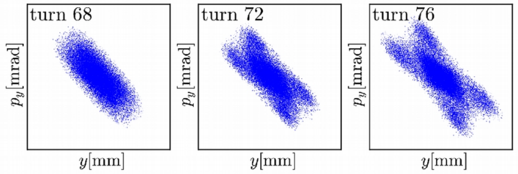
  With overlapped stop band of 90°



- For bunch compression in SIS-18, with doubled intensity, depressed phase advance crosses 90°
- Simulation show only fourth order resonance

  ➡ Incoherent effect dominates over coherent ones





- Competition mechanism
  During bunch compression, ky will first reach the 90 deg line and trigger the fourth order resonance, preventing the envelope instability

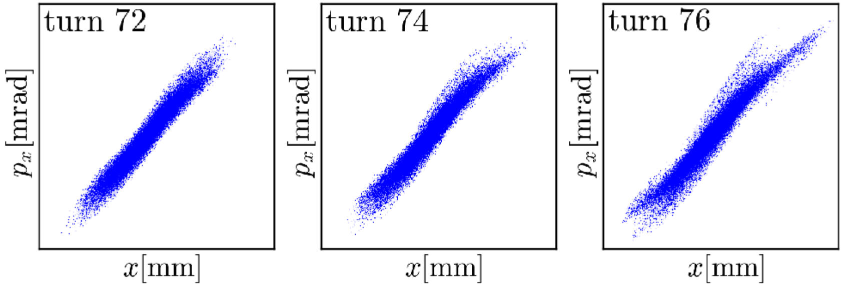
120° dispersion-induced instability

- The recently discovered dispersion-induced instability exists in synchrotrons with phase advance larger than 120 deg, with the criteria

$$k_{0,x} > 120^\circ \qquad \phi_1 + \phi_d = 360^\circ$$

(Here, Φ1 is the envelope mode, Φd is the dispersion

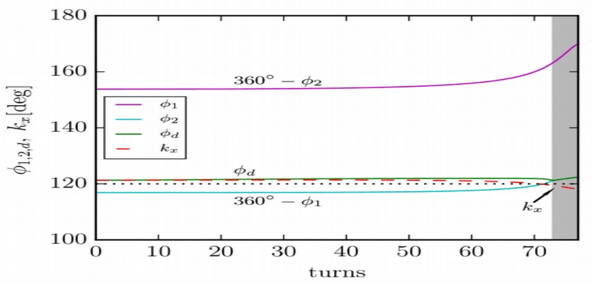
Ref. Y. S. Yuan, et. al., PRL 118, 154801 (2017)



Dispersion-induced instability during bunch compression

- During bunch compression in SIS-18, the dispersion-induced instability can be triggered with $k_{0,x} = 122^\circ$

Coherent effect is not inhibited
in the absence of incoherent effect



The confluence of dispersion mode and envelope modes

- Onset mechanism: Compared to the case of 90° crossing, there's no obvious single particle resonance, which exists earlier and can prevent the instability.