Ion Instability in the HEPS Storage Ring

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Outline

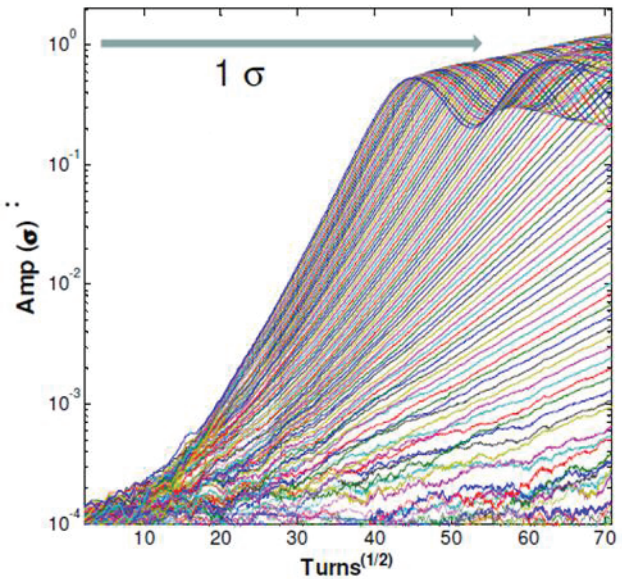
Ions related instabilities

- Ion instabilities include conventional ion trapping instability and fast beam-ion instability.
- In the case of storage rings, ions are generated not only by collisional ionization from the beam, but also by synchrotron radiation. Ions generated by synchrotron radiation are far outside the beam area and are equally distributed between the beam and the chamber wall. The density of the radiation-generated ions is low compared with the density of ions generated by collisional ionization, they can be ignored.
- These ions in the beam result in beam emittance growth, beam size blow-up, additional tune shifts etc.

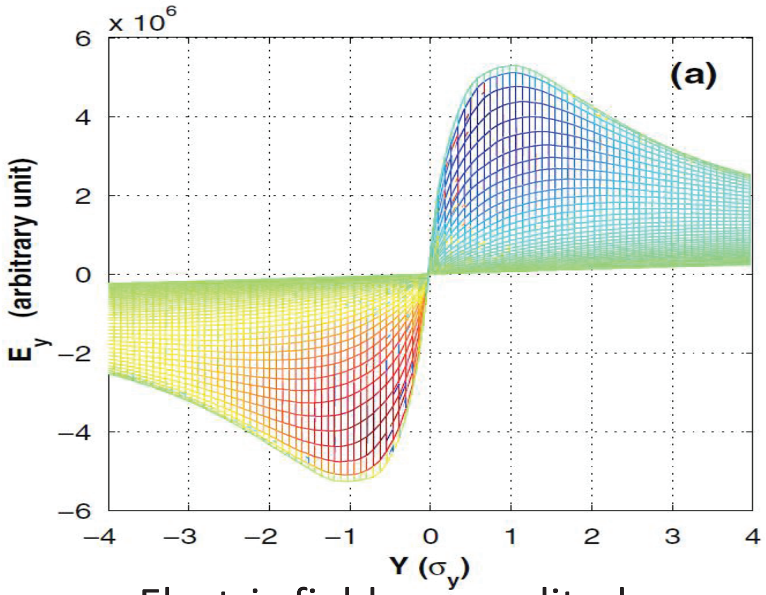
Fast beam-ion instability. I. Linear theory and simulations

Ions related instabilities

- Different from other instabilities, ions related instability rarely causes beam loss. When the bunches' amplitude is larger (compare with beam size),the nonlinear force automatically slow down the instability.



vertical oscillation amplitude of different bunches

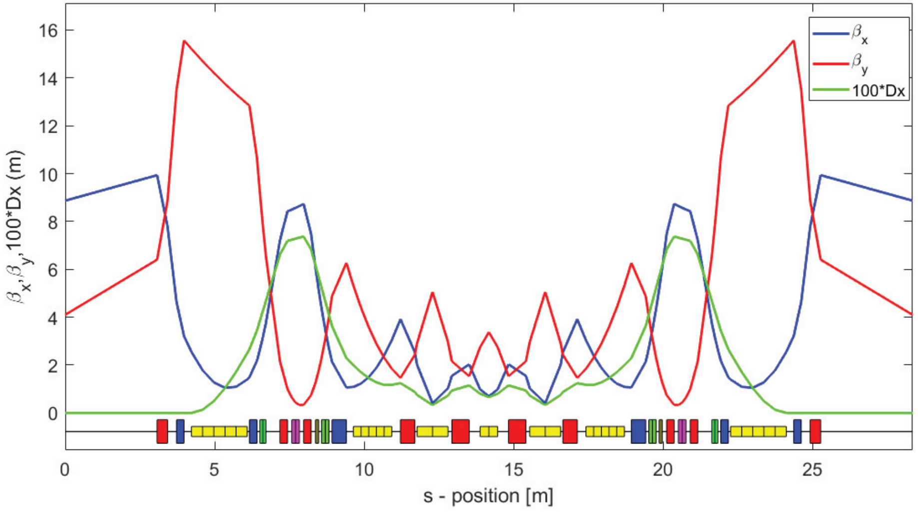


Electric field vs. amplitude

Beam-ion Instabilities in SPEAR3
Suppression of beam-ion instability in electron rings with multi bunch train beam filling

HEPS Lattice Design Parameters

•A reference design of the 7BA lattice for the HEPS main ring



- 48 identical hybrid 7BAs, with a cell length of about 28m
- 48 dispersion-free 6.15-m straight sections, with beta functions of 8.9/4.1 m.
- 4 outer dipoles with longitudinal gradients; 3 inner dipoles with defocusing gradients.
- Two filling patterns
  - Brightness mode → 680 bunches (1.3nC, 0.3mA),
  - Timing mode→ 63 bunches （14.4nC, 3.2mA）

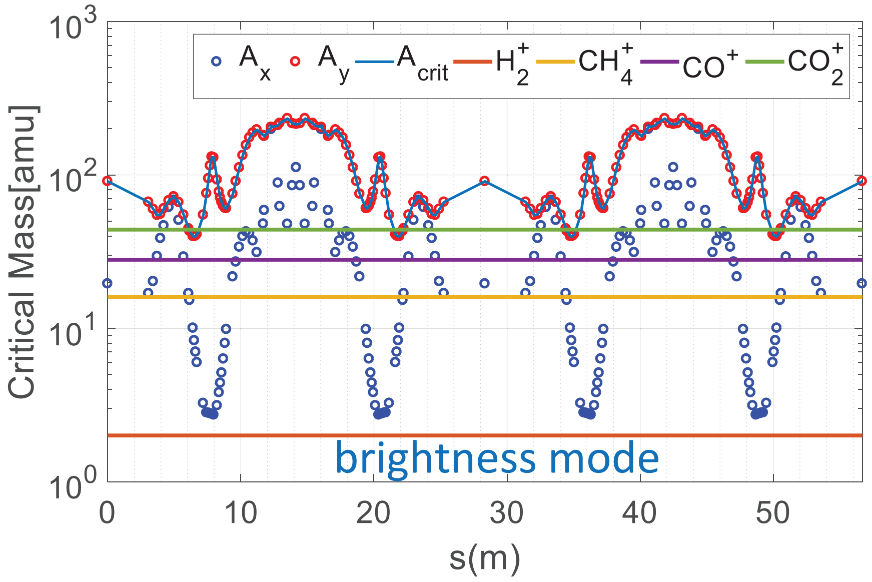
Parameter	Value	Unit
Beam energy	6	GeV
Beam current	200	mA
Circumference	1360.4	m
Partition number $J_x/J_y/J_z$	1.51/1.0/1.49	
Horizontal natural emittance	58.4	pm·rad
Transverse tune (x/y)	107.37/82.43	
Natural chromaticity (x/y)	-214/-133	
Corrected chromaticity (x/y)	+5/+5	
No. of cell / long straight section	48/48	
Length of LSS	6.15	m
Beta function @ mid-LSS (x/y)	8.9/4.1	m
Damping time (x/y/z)	18.3/27.8/18.7	ms
U_0 per turn (w/o ID)	1.959	MeV
Natural energy spread	8.20×10^{-4}	
RF frequency	166.6/499.8	MHz
RF voltage (swap-out injection)	2.65/0.575	MV
Harmonic number	756	
Bunch length with 3rd harm. cavity	31.6	mm

Ion trapping

- Trapped ions could pose a serious threat to beam stability.
- Ions with mass numbers larger than the "critical mass" A will be trapped, while lighter ions will not! Trapping condition must be fulfilled in both x and y.
- The critical mass will vary along the ring：
  - **Trapping condition depends on emittance ratio （coupling factor κ)**
  - **A given ion may be trapped in some parts of the lattice, but not in others**
- Consider brightness mode filling(κ =10%),the minimum critical mass is ~40, so only CO_2^+ can be trapped.
- No trapping is expected in timing mode

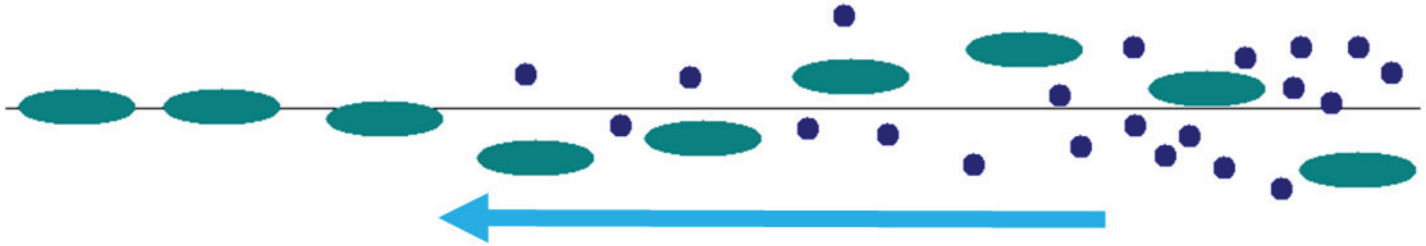
$$A_{x,y}(s) = \frac{N_e r_p L_{sep}}{2\left(\sigma_x(s)+\sigma_y(s)\right)\sigma_{x,y}},$$

$$A_{crit}(s) = \frac{N_e r_p L_{sep}}{2\min\left(\sigma_x(s),\sigma_y(s)\right)\left(\sigma_x(s)+\sigma_y(s)\right)}.$$



The stability of ions in bunched beam machines

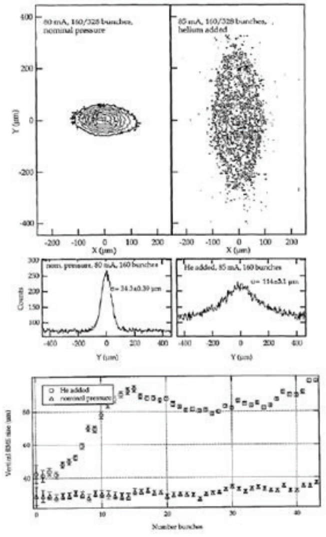
Fast beam-ion instability (FBII)



A multi-bunch effect for electron beams, Seminal paper by T. O. Raubenheimer, et al (Linear theory of FBII)
FBII has been confirmed experimentally in many facilities.

Characteristics of FII

- The residual can be ionized by the single passage of a bunch train, FBII is a single pass instability.
- Beam bunches' motion couple the ions' motion, the interaction drives transverse oscillations
- FBII can arise in storage rings, linacs, and beam transport line. For ultra low emittance accelerator, the growth rate of this instability is high



ALS (1997)

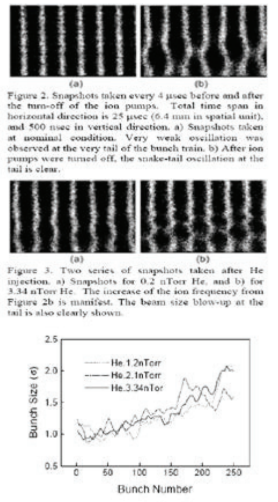
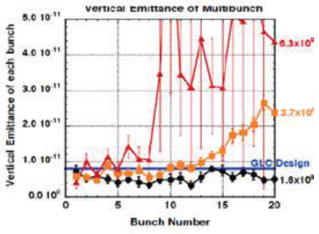


Figure 5. Bunch size measured along the bunch train for three different cases of 1.2 nTorr, 2.1 nTorr, and 3.34 nTorr showing the same growth pattern. Bunch sizes are normalized to the initial bunch size.

PLS (1998)



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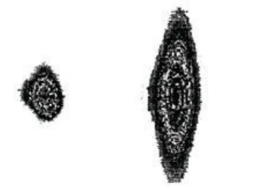

Figure 4. Synchrotron radiation profile just before and after the vertical beam blow-up threshold.

ELETTRA

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Fast beam-ion instability (FBII)

Some formulas in used:

The ion line density at the tail of the bunch train:

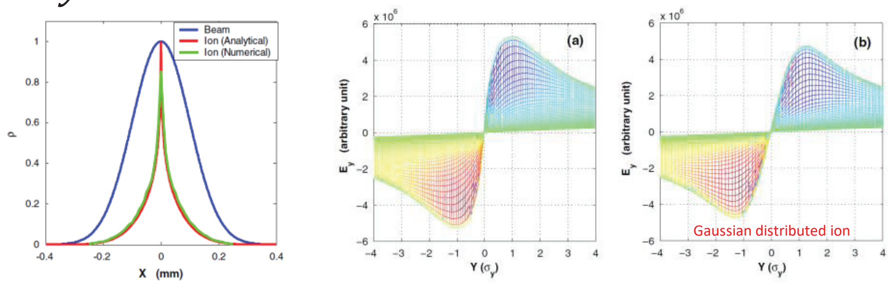
$$\lambda_i = \sigma_{ion} \frac{P}{kT} N_e n_b$$

The effective ion density is:

$$\rho_{i,eff} = \frac{\lambda_i}{k_y \sigma_y (\sigma_y + \sigma_x)}$$

k_y represents the dependence on the ion's distribution

The transverse distribution of ions is not Gaussian, but the electric field of the ion cloud closely approximates that of a Gaussian distribution with $\sigma_i^2 \approx \sigma_e^2/2$,in this case $k_y \sim 3/2$



Vertical electric field of a ion cloud and a Gaussian distributed ion cloud with $\sigma_i^2 \approx \sigma_e^2/2$

If mini-train is introduced in the fill pattern, the diffusion of the ions during the gaps causes a larger size of ion cloud and a lower ion density. In order to evaluate the effects of gaps, an Ion-density Reduction Factor is defined as：

$$IRF = \frac{1}{N_{train}} \frac{1}{1 - \exp(-\tau_{gap}/\tau_{ions})}$$

Ion oscillation frequency：

$$f_i = \frac{c}{\pi} \sqrt{\frac{Q N_e r_p}{3 A L_{sep} \sigma_y (\sigma_x + \sigma_y)}}$$

The FBII arises when the ions are trapped between bunches：

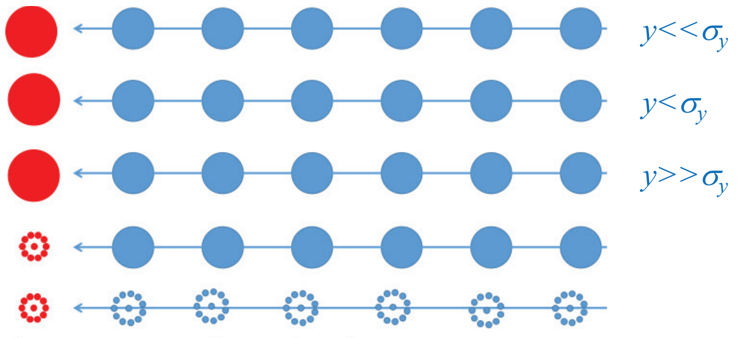
$$4 L_{sep} f_i / c \leq 1$$

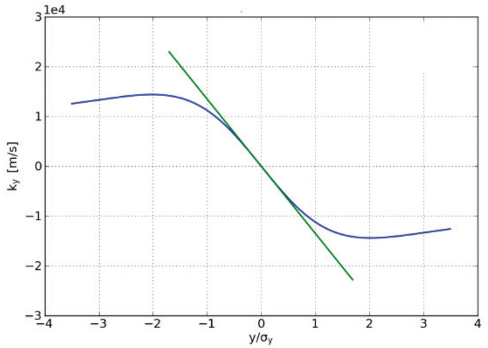
Suppression of beam-ion instability in electron rings with multi-bunch train beam fillings

Fast beam-ion instability (FBII)

Models of the Ion Instability：

1. Bunch and ion cloud are expressed using one macro particle each. The interaction force between the beam and the ion is linear. $(y<<\sigma_y)$
2. Bunch and ion cloud are expressed using one macro particle each. The interaction force between the beam and the ion is linear, but the ion oscillation damps with a Q value.$(y<\sigma_y)$
3. Bunch and ion cloud are expressed using one macro particle each. The interaction force between the beam and the ion is nonlinear. $(y>>\sigma_y)$
4. A bunch is represented using a macro particle, while the ion cloud is represented by many macro particles
5. Both the bunch and the ion cloud are represented by many macro particles





Simulations on the Fast-Ion Instability in the International Linear Collider Damping Rings

Fast beam-ion instability (FBII)

Rise time prediction

Model 1:Simple linear treatment for small amplitude ($y<<\sigma_y$)
An initial perturbation ŷ increase quasi-exponentially as:

$$y = \hat{y}\frac{1}{2\sqrt{2\pi}(t/\tau_c)^{1/4}}exp\left(\sqrt{t/\tau_c}\right)$$

with a characteristic time

$$\frac{1}{\tau_c} = \frac{4d_{gas}\sigma_{ion}\beta N_e^{3/2}n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{3\sqrt{3}\gamma\sigma_y^{3/2}(\sigma_y+\sigma_x)^{3/2}A^{1/2}}$$

Model 2:Include ion decoherence and ion frequency spread
Oscillation increases exponentially as:

$$y\sim exp(t/\tau_e)$$

with an e-folding time of:

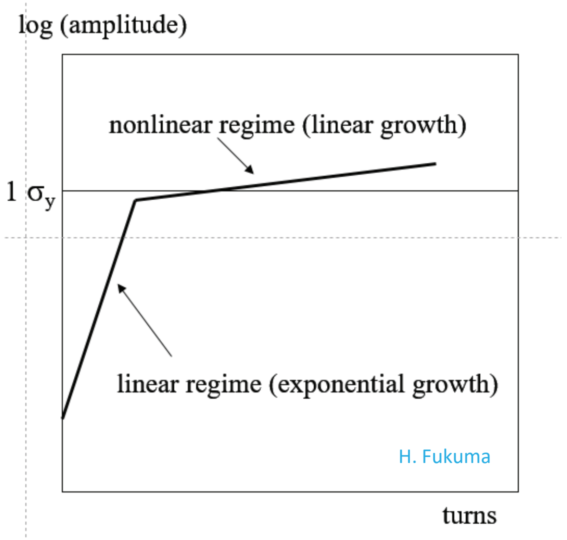
$$\frac{1}{\tau_e} \approx \frac{1}{\tau_c}\frac{c}{4\sqrt{2}\pi L_{sep} n_b a_{bt} f_i}$$

Model 3:For very large oscillation amplitudes (y>>σy)
a linear growth expected:

$$y\sim\sigma_y\frac{t}{\tau_H}$$

with a time constant:

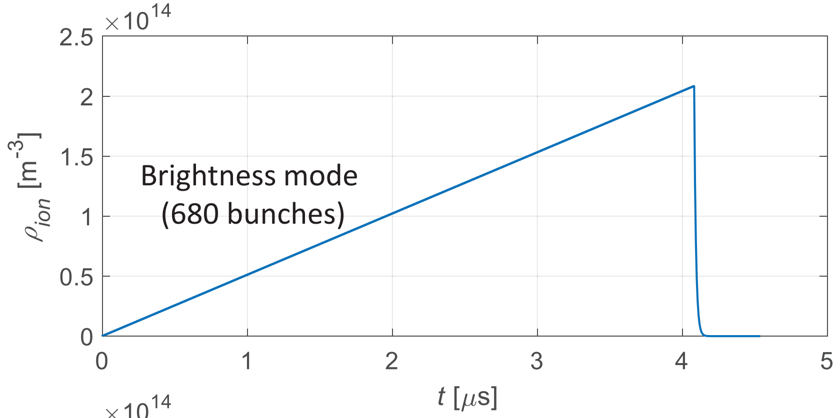
$$\frac{1}{\tau_H} \approx \frac{1}{\tau_c}\frac{c}{2\pi f_i L_{sep} n_b^{3/2}}$$

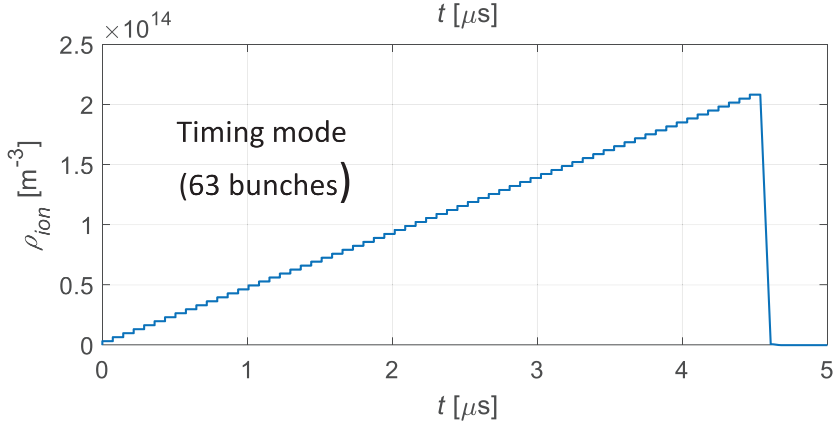


Fast beam-ion instability (FBII)

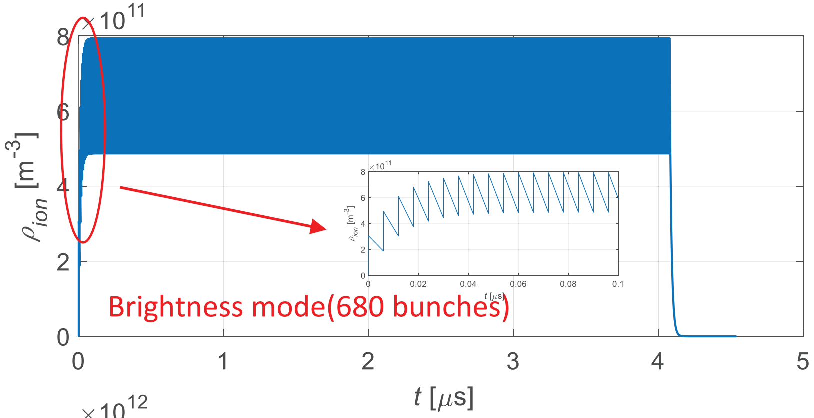
Single bunch train beam filling

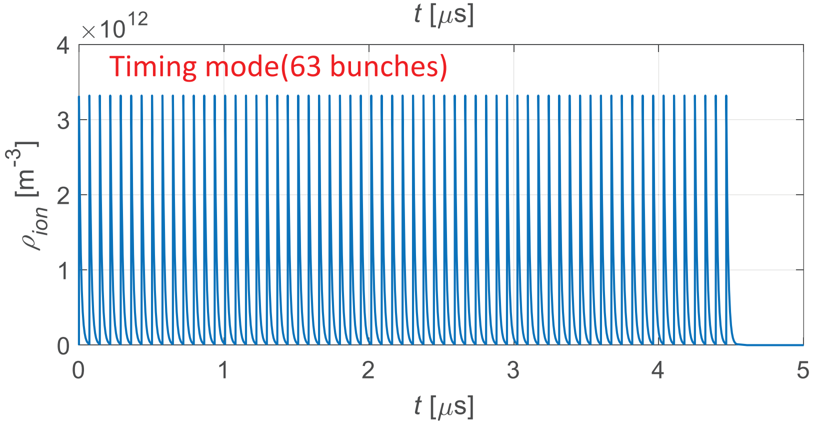
The ion density increases at every bucket.
Without density reduction between bunches, the ion density will increases linearly:





During the bucket, the ion density decay exponentially with a decay time order of the ion's oscillation period. For one bunch train, consider density reduction between bunches:





Fast beam-ion instability (FBII)

Accelerators	HEPS (nb=680)	HEPS (nb=63)	HEPS (nb=680)	HEPS (nb=63)	HEPS (nb=680)	HEPS (nb=63)
E [GeV]	6		6		6	
C [m]	1360.4		1360.4		1360.4	
β_x/β_y [m]	4.4/5.9		4.4/5.9		4.4/5.9	
L_{sep} [m]	1.8	21.6	1.8	21.6	1.8	21.6
N_e [10^{10}]	0.83	9.0	0.83	9.0	0.83	9.0
σ_x [μm]	15.3		282.4	334.9	282.4	334.9
σ_y [μm]	5.4		100.4	119.1	100.4	119.1
P [nTorr]	1		1		1	
$\rho_{i,eff}$ [10^{13} m^{-3}]	21.5	21.6	0.063	0.045	0.063	0.045
f_i [MHz]	78.4	78.5	4.2	3.6	4.2	3.6
$4L_{sep}f_i/c$	2.1	22.6	0.1	1.0	0.1	1.0
τ_c [μs]	0.005	0.005	31.0	51.3	31.0	51.3
τ_e [ms]	**0.03**	**0.03**	**10.6**	**14.8**	**3.4**	**4.2**
τ_H [ms]	0.3	0.09	97.5	41.6	97.5	41.6

CO is assumed.
Beta function is the average beta function.

$a_{bt}=1$

$a_{bt}=0.28$

Fast beam-ion instability (FBII)

Simulation model of FBII(K. Ohmi):

- based on weak-strong model
- e- beam: rigid Gaussian
- ion: macro particles(The number of ions increase)
- the interaction between them is based on Bassetti-Erskine formula
- 2 -D code (Ions move only transversely and exist only outside of magnets. The effect of bunch length and the synchrotron motion are not considered)
- one collision point in the ring.

Numerical study for the two-beam instability due to ions in electron-storage rings

Fast beam-ion instability (FBII)

Kicks between electrons and ions (based on Bassetti-Erskine formula)
The velocity change of an ion is:

$$\Delta y_i' + i\Delta x_i' = -2N_b r_e c \frac{m_e}{M_i} f(x_{ie}, y_{ie})$$

$$f(x,y) = -\sqrt{\frac{\pi}{2(\sigma_x^2 - \sigma_y^2)}} \left[w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) w\left(\frac{x\frac{\sigma_y}{\sigma_x}+iy\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right)\right]$$

$$w(z) = \exp(-z^2)[1 - erf(-iz)]$$

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-x^2)\, dx$$

The ions drift in the space between adjacent bunches linearly:

$$x = x_0 + v_x \frac{L_{sep}}{c} \quad ; \quad y = y_0 + v_y \frac{L_{sep}}{c}$$

Summing for all the ions, the kick to the rigid electron by ion:

$$\Delta y_e' + i\Delta x_e' = \frac{2N_e r_e}{\gamma} \sum_i f(x_{ie}, y_{ie})$$

Beam motion between ionization points can be linked via linear optics:

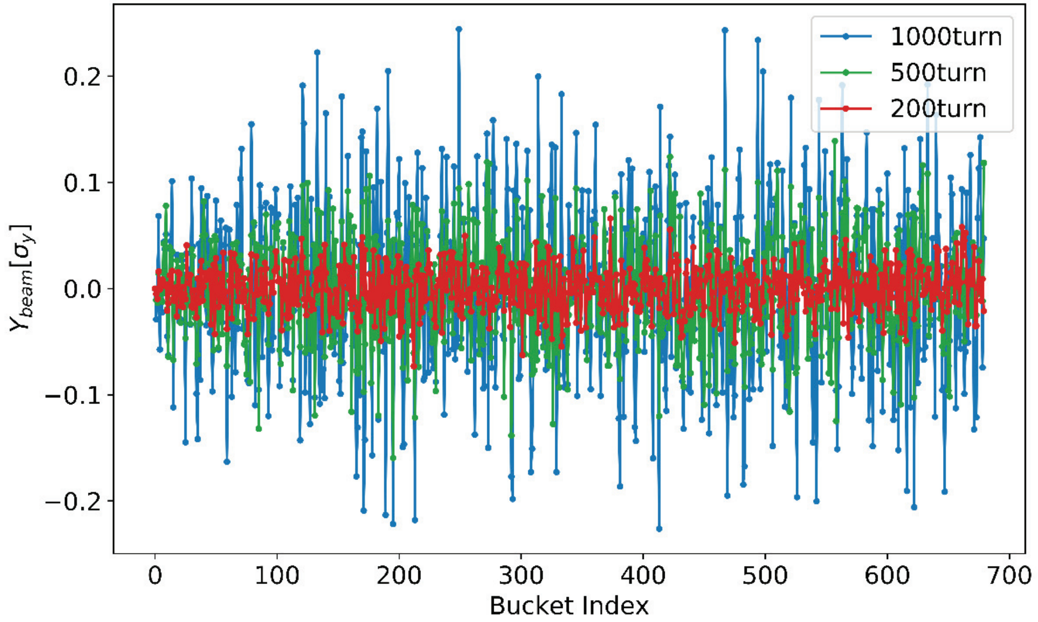
$$\begin{pmatrix} z_2 \\ z_2' \end{pmatrix} = \begin{bmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\psi + \alpha_1 \sin\psi) & \sqrt{\beta_2\beta_1}\sin\psi \\ \frac{\alpha_1 - \alpha_2}{\sqrt{\beta_2\beta_1}}\cos\psi - \frac{1+\alpha_1\alpha_2}{\sqrt{\beta_2\beta_1}}\sin\psi & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\psi + \alpha_2\sin\psi) \end{bmatrix} \begin{pmatrix} z_1 \\ z_1' \end{pmatrix}$$

$$z = (x, y)$$

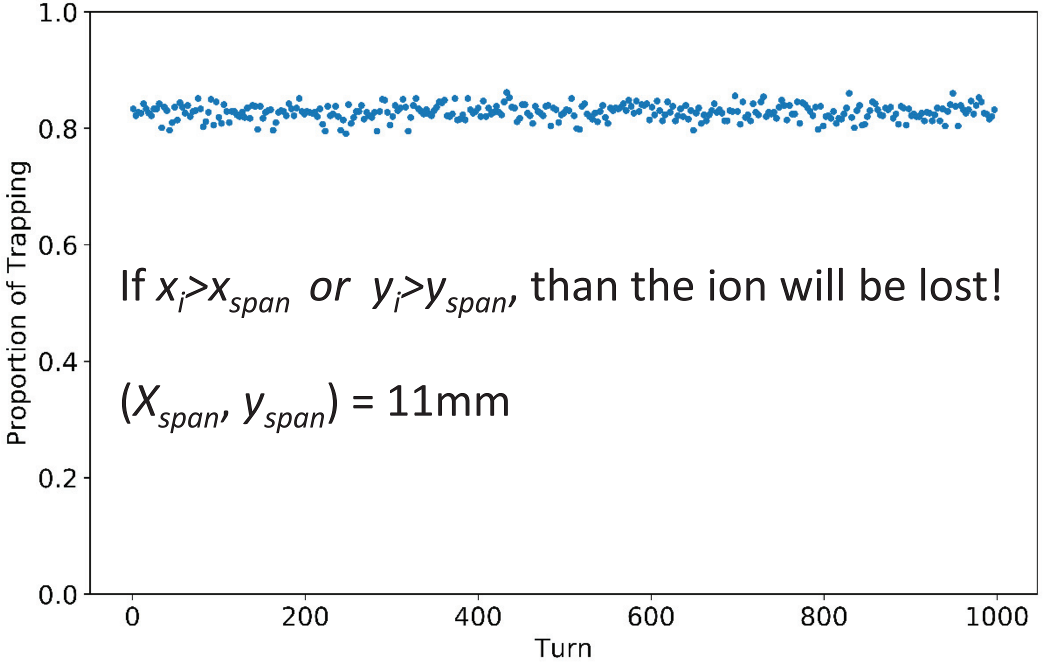
Closed expression for the electrical field of a two-dimensional Gaussian charge

Fast beam-ion instability (FBII)

Some results(Brightness mode)：



The amplitude of the beam oscillations due to the interaction with the ions versus the bucket index



The proportion of ions survived every turn

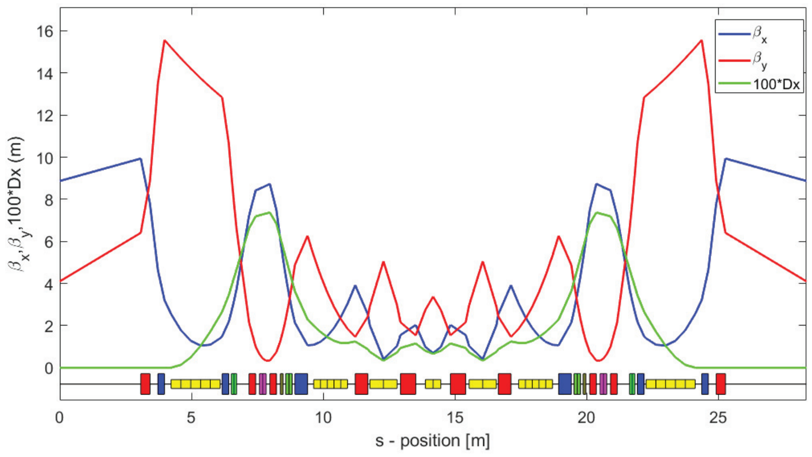
Partial pressure of CO: 1nTorr

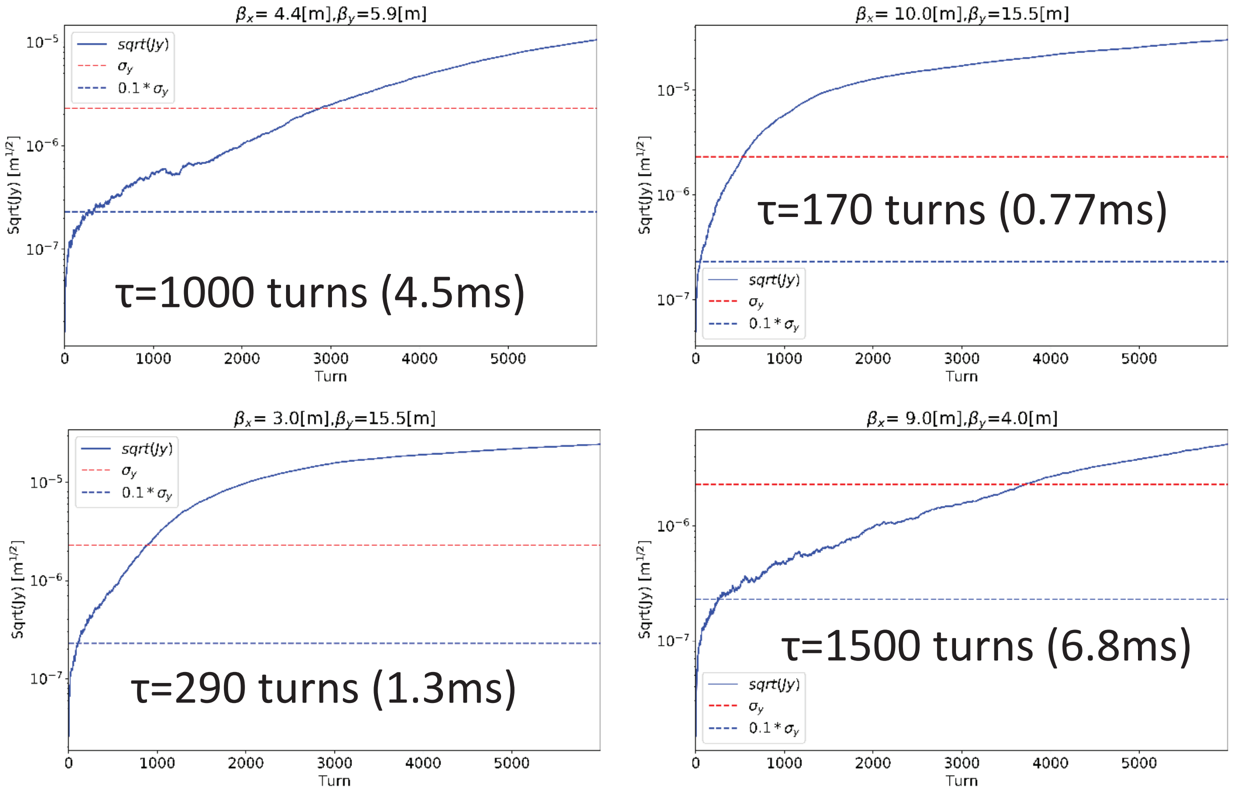
Fast beam-ion instability (FBII)

Some results(Brightness mode)：

Case	β_x[m]	β_y[m]	τ_e[ms]
Case1	4.4	5.9	4.5
Case2	10	15.5	0.77
Case3	3	15.5	1.3
Case4	9	4	6.8

different β function selected for simulation





The vertical action of the bunch centroid:

$$J_y = \frac{1+\alpha^2}{\beta} y^2 + 2\alpha y y' + \beta (y')^2$$

Partial pressure of CO: 1nTorr

Summary

- Fast ion instability is still one of critical issues for diffraction limited storage ring.
- Both analytical calculation and weak-strong simulation show a growth time of around a few millisecond.it shows that this instability is within control with transverse feedback system(need further check).
- Further simulations need to be performed(filling pattern, mixed gas, feedback system) and strong-strong simulation will be also performed to predict blow-up of beam emittance.

Thank you for your attentions!