Update on Ion Studies

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Outline

- Ions production
- Ion trapping instability
- Fast ion instability
- Fill patterns
- Simulation study of FII
- Summary

Ions production

- Sources of ions production
  - The main source of ions comes from the inelastic collisions of the electron beam with the molecules of residual gas in vacuum chamber
  - Tunneling ionization due to the collective electric field of the bunch
  - Compton scattering of the synchrotron radiation on the electrons of residual gas molecules

Ions production

The cross section of the collisional ionization,

$$\sigma_i = 4\pi \left(\frac{\hbar}{mc} \right)^2 \left[C_1 \left(\frac{1}{\beta^2} \ln(\frac{\beta^2}{1-\beta^2}) - 1 \right) + \frac{C_2}{\beta^2} \right]$$

the molecular density

$$n_m = 3.22 \times 10^{22} P_m$$

And the time it takes for one circulating particle to create one ion is given by

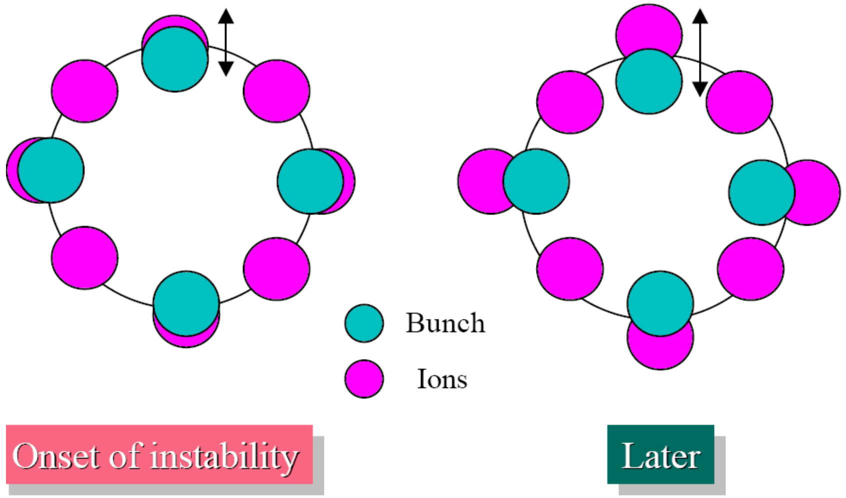
$$\tau_{col} = \frac{1}{n_m c \beta \sigma_i}$$

Cross sections of collision ionization for ILC damping rings
(nominal beam energy:5GeV)

Molecule	A	C_1	C_2	σ_i [10^{-22}m^2]	P_m [10^{-9} Torr]	n_m [10^{12}m^3]	τ_m [sec]
H_2	2	0.50	8.1	0.31	0.75	24.15	4.39
CO	28	3.70	35.1	1.86	0.14	4.51	3.97
CO_2	44	5.75	55.9	2.92	0.07	2.25	5.06
CH_4	16	4.23	41.85	2.16	0.04	1.29	11.97

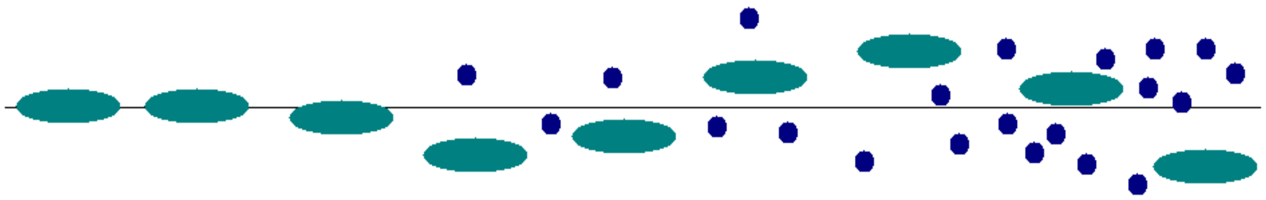
Ion trapping instability

- Ion effects will arise when ions are trapped turns by turn in the potential well of the beam
- Ions accumulate until stabilized by neutralization, second ionization, etc
- The adverse effects of ions include beam emittance growth, beam lifetime reduction, tune shift and tune spread etc
- These were already observed in many existing machines (PLS,KEK-PF,SRRC,NSLS-VUV, PEPII, BEPC etc.)



Fast ion instability

- In high current storage rings or linacs with long bunch trains, the ions accumulation during the passage of a single bunch train is significant
- This leads to fast ion instability (FII), which is noticeable in the ultra-low emittance (2pm) damping ring for the International Linear Collider (ILC)
- Linear theory of FII was developed by Raubenheimer, Zimmermann, Stupakov, etc
- This instability has been confirmed experimentally in some facilities such as ALS, TRISTAN AR, PLS, Spring-8, KEKB HER, ATF DR etc.



Fast ion instability

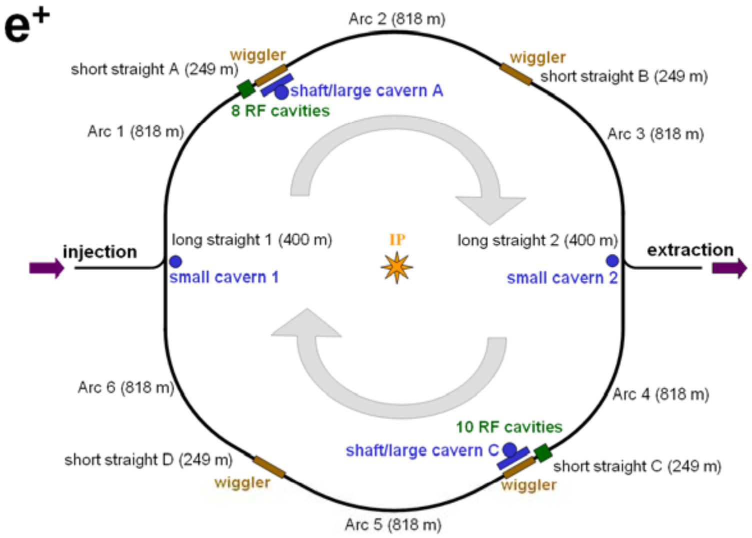
FII characteristics:

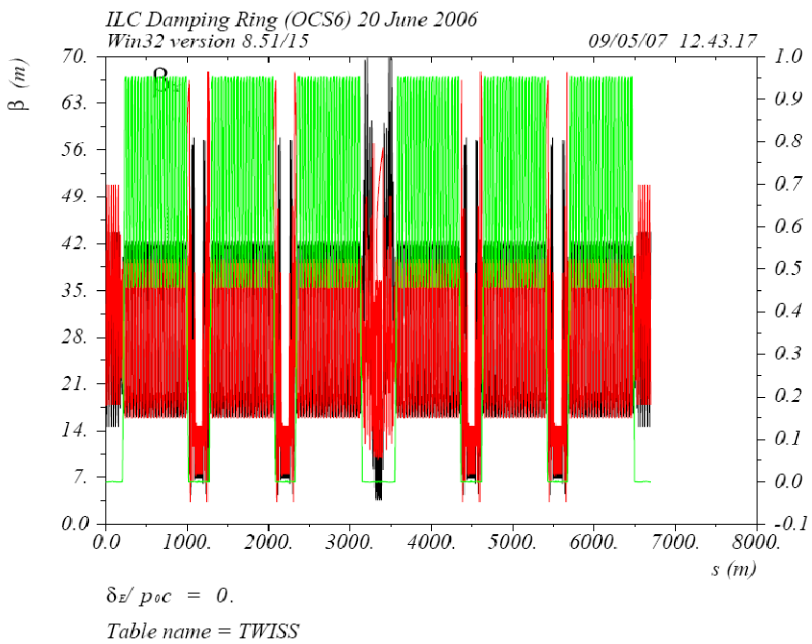
- FII is due to residual gas ionization
- Beam bunches' motion couple the ions' motion
- FII is a single pass instability like BBU, unlike the classical trapped-ion instability
- FII can arise in storage ring, linacs, and beam transport line.
- It can cause coupled bunch instability, beam size blow-up, emittance growth and tune shifts etc

Potential cures:

- Upgrade the vacuum condition
- Increase the ion frequencies spread using an optical lattice, so that the ion frequencies varies significantly with the time, and no coherent oscillation can therefore develop
- Introduce the gap in the bunch trains in order to clear the ions or make ions unstable
- Bunch by bunch feedback system to realign the trailing bunch

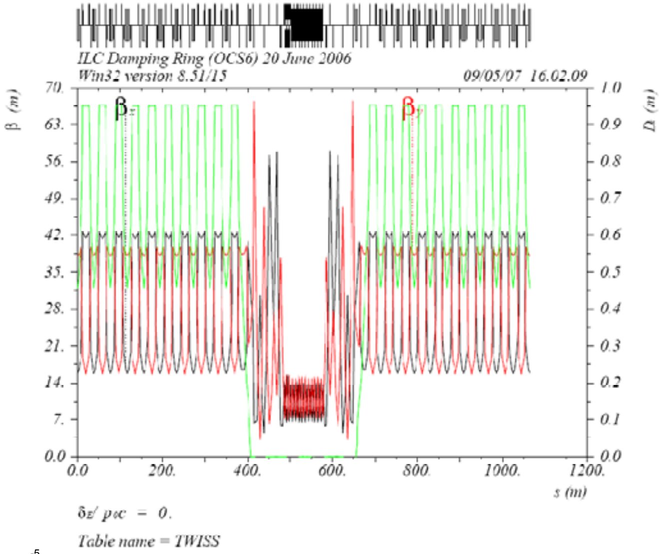
OCS6

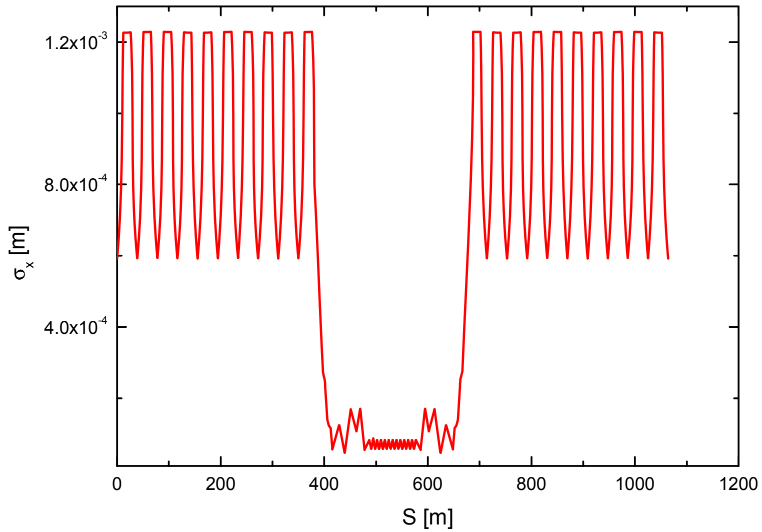


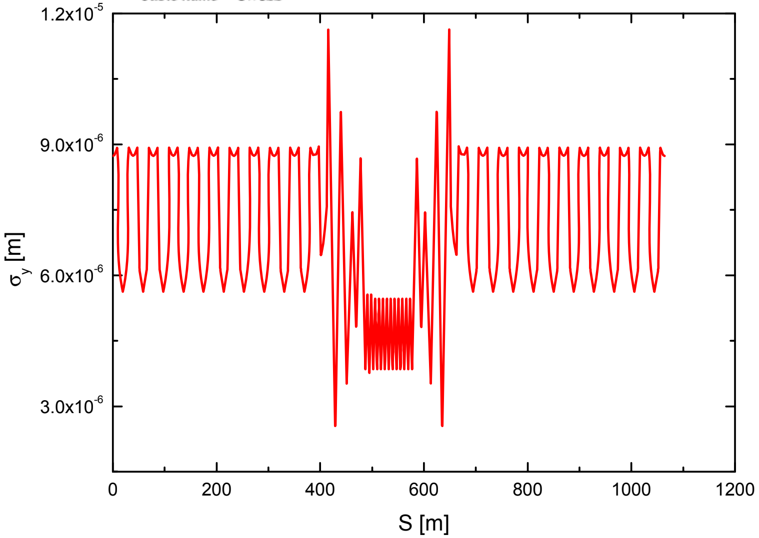


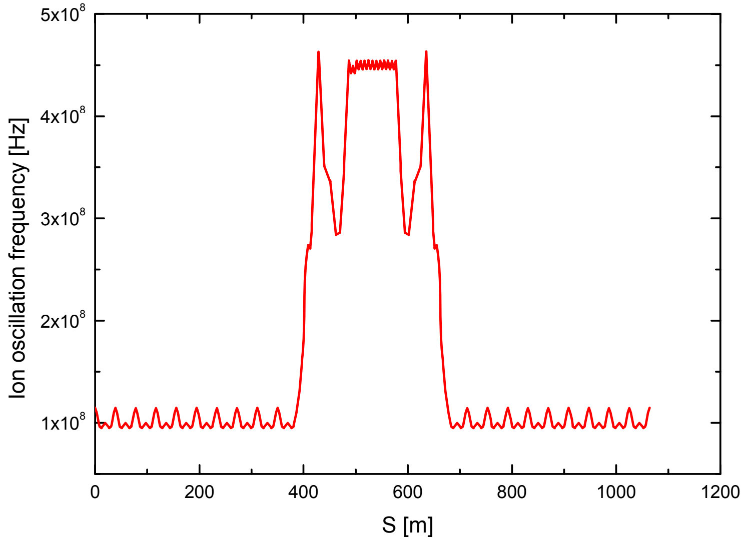
Parameters	Value
Energy [GeV]	5.0
Circumference [km]	6.695
Nominal # of bunches	2625
Nominal bunch population	2.0×10^{10}
Maximum # of bunches	5534
Bunch population at max # of bunches	1.0×10^{10}
Average current [A]	0.40
Energy loss per turn [MeV]	8.7
Beam power [MW]	3.5
Nominal bunch current [mA]	0.14
RF frequency [MHz]	650
RF bucket height [%]	1.5
Injected beam emittance, A_x+A_y [m.rad]	0.09
Equilibrium γεx [μm.rad]	5.0
Chromaticity,Ξ_x/Ξ_y	-63/-62
Partition numbers, $Jx/Jy/J_E$	0.9998/1.0000/2.0002
Harmonic number h	14,516
Synchrotron tune ν_s	0.067
Momentum compaction factor α_c	4.2×10^{-4}
Tunes ν_x/ν_y	52.40/49.31
Bunch length [mm]	9.0
Momentum spread σ_p/p	1.28×10^{-3}
Transverse damping time τ_x [ms]	25.7
Longitudinal damping time [ms]	12.9

One sextant of the ring





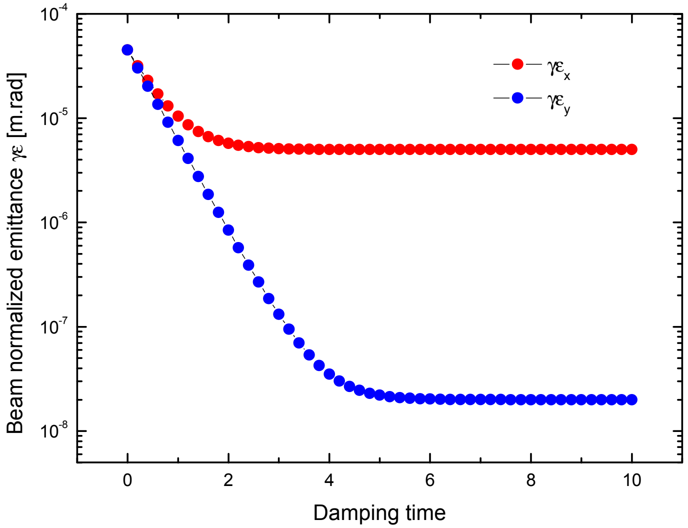


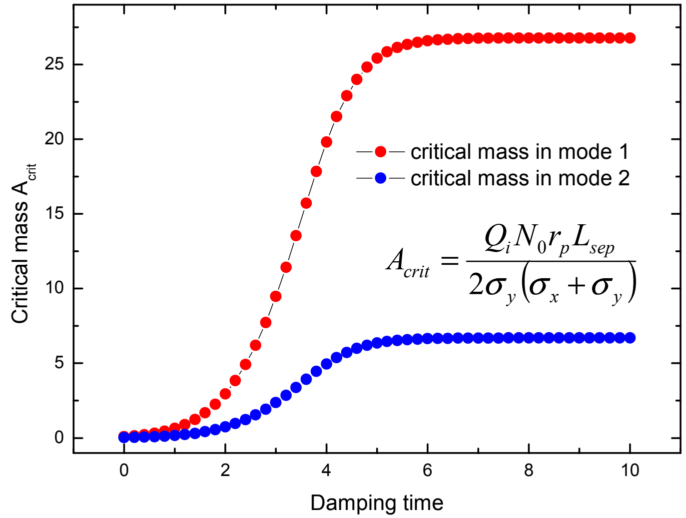


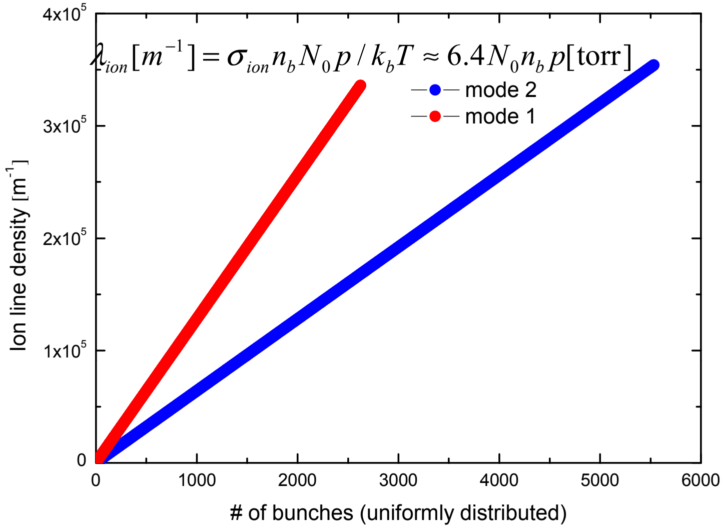
Simulation result shows the ion oscillation frequency spread ≈ 30%

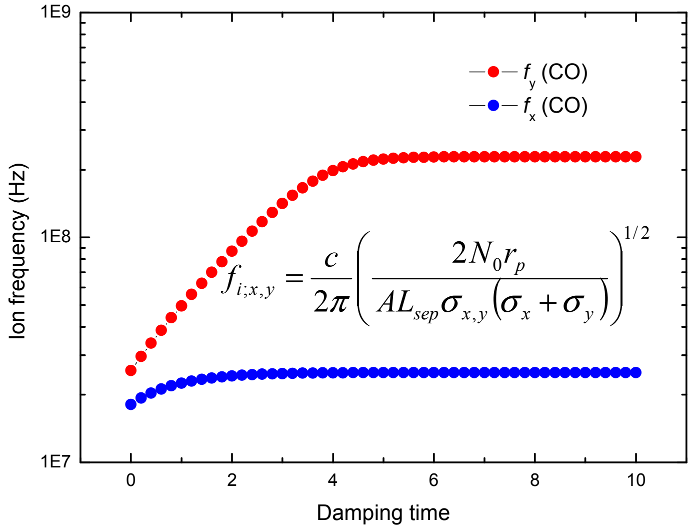
FII characteristics

- Emittance, critical mass, ion line density, ion frequency vs. damping time, # of bunches

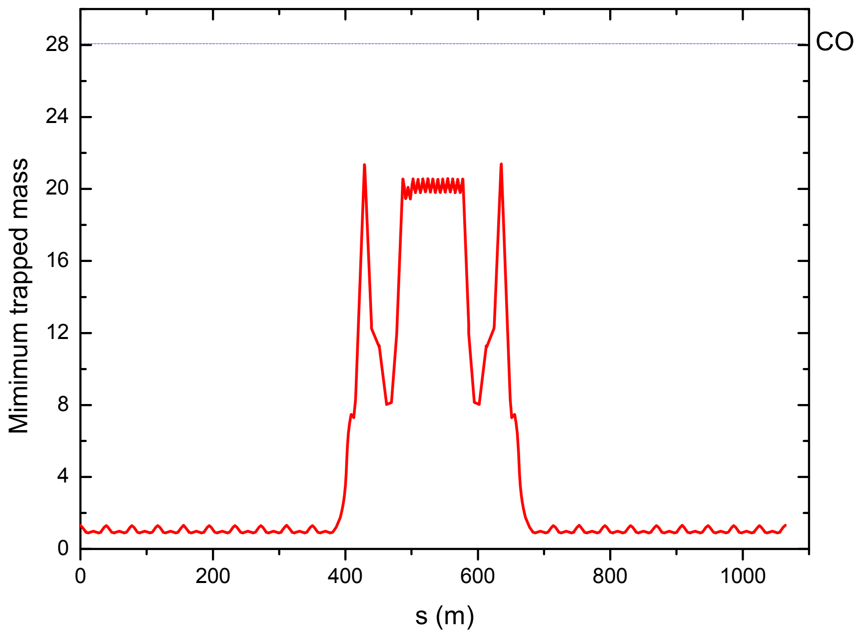


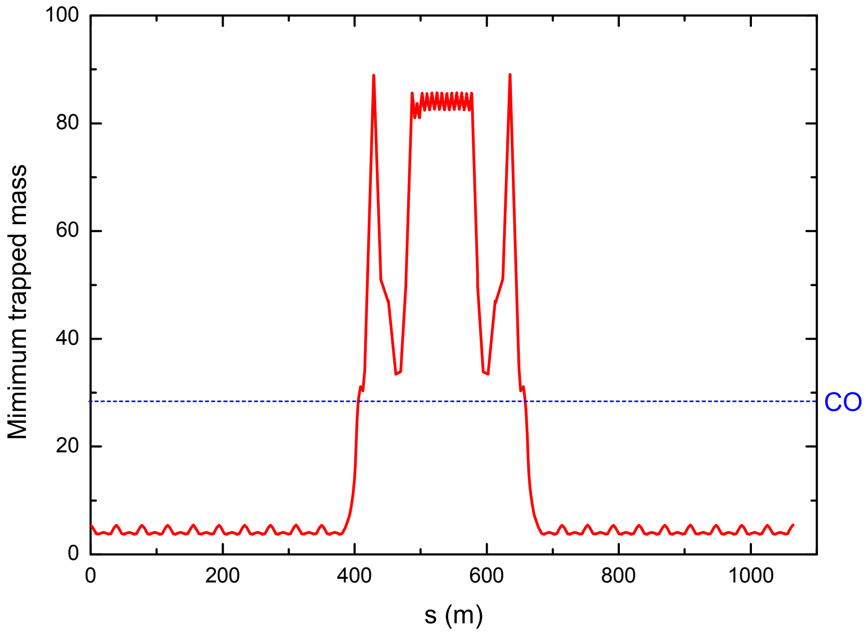






Critical mass





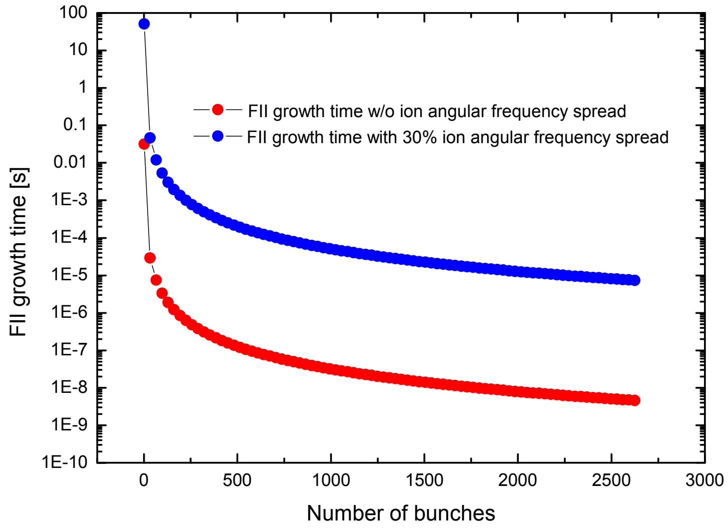
Critical mass of ions for fill pattern case A. nb=5782, N0=0.97E10, Ntrain=118. Bunch spacing =2 RF buckets=3.08 ns

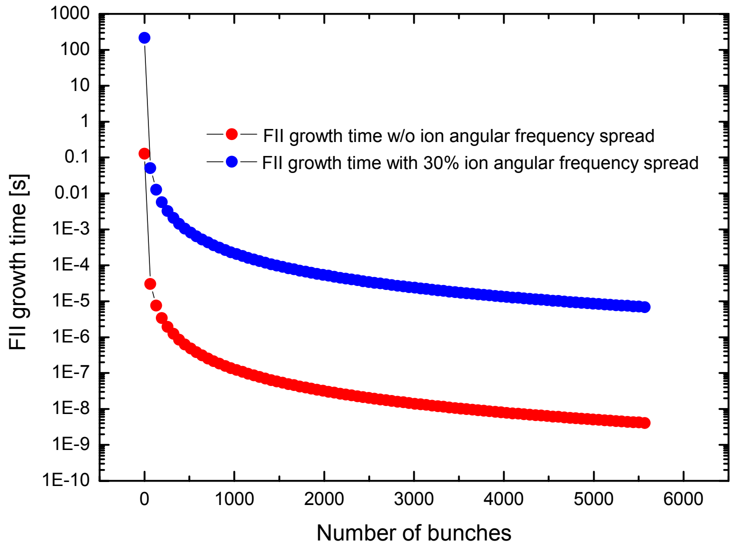
Critical mass of ions for fill pattern case E. nb=2767, N0=2.02E10, Ntrain=61. Bunch spacing =4RF buckets=6.16 ns.

All the CO ions will be trapped in the beam in case A

FII growth time

- FII growth time as a function of bunch number in mode 1 and mode 2 for CO partial pressure of 1 nTorr





$$\tau_e^{-1}[s^{-1}] = \frac{1}{\tau_c}\frac{c}{2\sqrt{2}l_{train}\left(\Delta\omega_i\right)_{rms}}$$

$$\omega_i = \left(\frac{4N_0 r_p c^2}{3AL_{sep}\sigma_y\left(\sigma_x+\sigma_y\right)}\right)^{1/2}$$

$$\tau_c^{-1}(s^{-1}) = 5p[Torr]\frac{N_0^{3/2}n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{\gamma\sigma_y^{3/2}\left(\sigma_x+\sigma_y\right)^{3/2}A^{1/2}\omega_\beta}$$

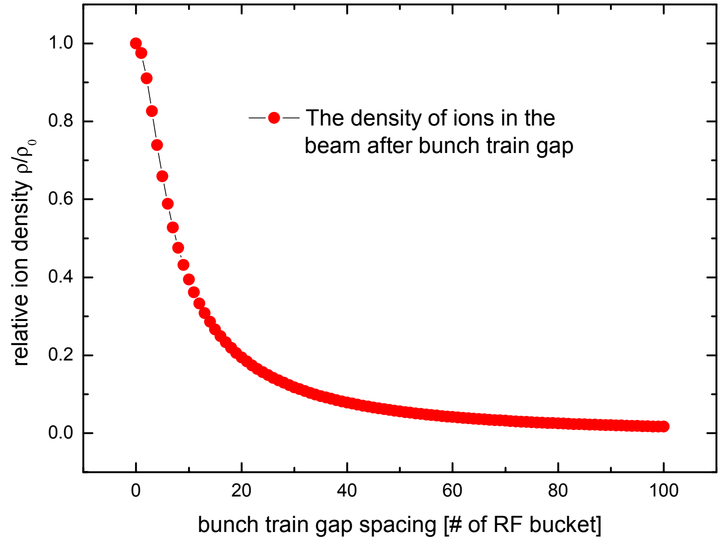
$$\Delta Q_{x,y;coh} = \frac{\beta_{x,y} r_e \lambda_{ion} C}{\gamma 4\pi\sigma_{x,y}\left(\sigma_x+\sigma_y\right)}$$

Gap effects

- If a gap is introduced in the bunch train, one can estimate the density of the residual ions in the beam after the clearing gap

$$\rho \approx \frac{\rho_0}{\sqrt{\left(1 + L_{gap}^2 \omega_x^2\right)\left(1 + L_{gap}^2 \omega_y^2\right)}}$$

$$\omega_{x,y}^2 = \frac{2 N_0 r_p}{L_{sep} A \sigma_{x,y} \left(\sigma_x + \sigma_y\right)}$$



The density of the residual ions in the beam after the clearing gap

where ρ is the ion density at the end of the bunch train and $\omega_{x,y}$ are the ion oscillation frequencies

If the gap length is more than 30 RF buckets, the ion density does not change so much !

Fill patterns

- Ion line density for a bunch train is

$$\lambda_{ion} = \sigma_{ion} p N_0 n_b / (k_B T)$$

- 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*

$$IRF = \frac{\lambda_{ion}(\tau_{gap})}{\lambda_{ion,1}} \approx \frac{1}{N_{train}} \frac{1}{1-\exp\left(-\tau_{gap}/\tau_{ion}\right)}$$

here, τ_{ion} is the diffusion time of ion cloud. IRF is the ratio of the ion density with gaps and without gaps.

$$\tau_{ion} \sim \frac{2\pi}{c}\left(\frac{\sigma_y\left(\sigma_x+\sigma_y\right)}{4N_0 r_p}\right)$$

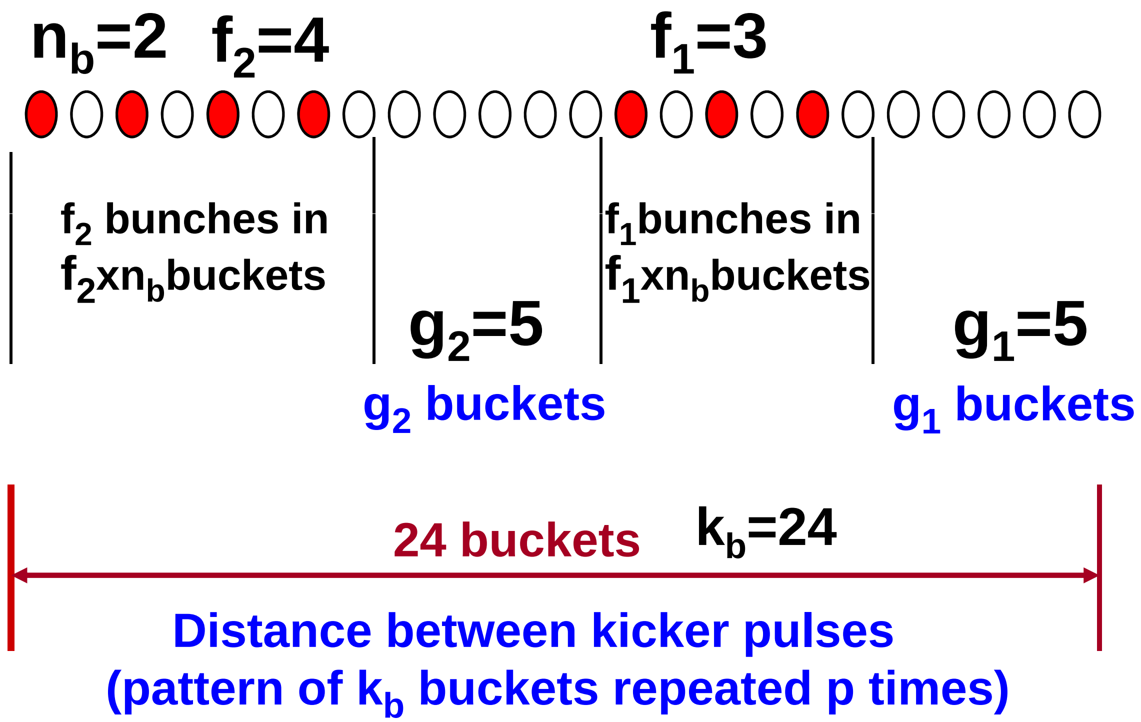
- So the fill pattern can be optimized in terms of obtain the smallest possible IRF (this work is ongoing)

* See L. Wang, WEPCH103, EPAC06

Fill patterns

Fill patterns	*A*	*B*	*C*	*D*	*E*
Number of bunches, n_b	5782	5658	4346	3646	2767
Particles per bunch, N_0 [10^{10}]	0.97	0.99	1.29	1.54	2.02
Average linac current [mA]	8.2	8.7	7.6	7.9	8.9
Machine pulse length, τ_{beam} [ms]	1.09	1.03	1.18	1.14	1.00
i	1	2	1	1	4
Bunch spacing, n_b [bucket]	2	2	2	3	4
k_b	123	118	177	203	236
Number of trains, p	118	123	82	71	61
Bunches per train, f_2 [bucket]	0	0	0	26	23
Gap between trains, g_2 [bucket]	0	0	0	25	28
Bunches per train, f_1 [bucket]	49	46	53	25	22
Gap between trains, g_1 [bucket]	25	26	71	25	28
Partial CO pressure [nTorr]	**1**				
FII characteristic growth time at bunch train end [10^{-9} s]	**3.922**	**3.973**	**4.527**	**4.026**	**4.030**
FII growth time at bunch train with 30% ion frequency spread [10^{-6} s]	**6.889**	**6.898**	**6.892**	**6.882**	**6.913**
Incoherent tune shift at train end ΔQ_y	**0.325**	**0.325**	**0.325**	**0.326**	**0.324**

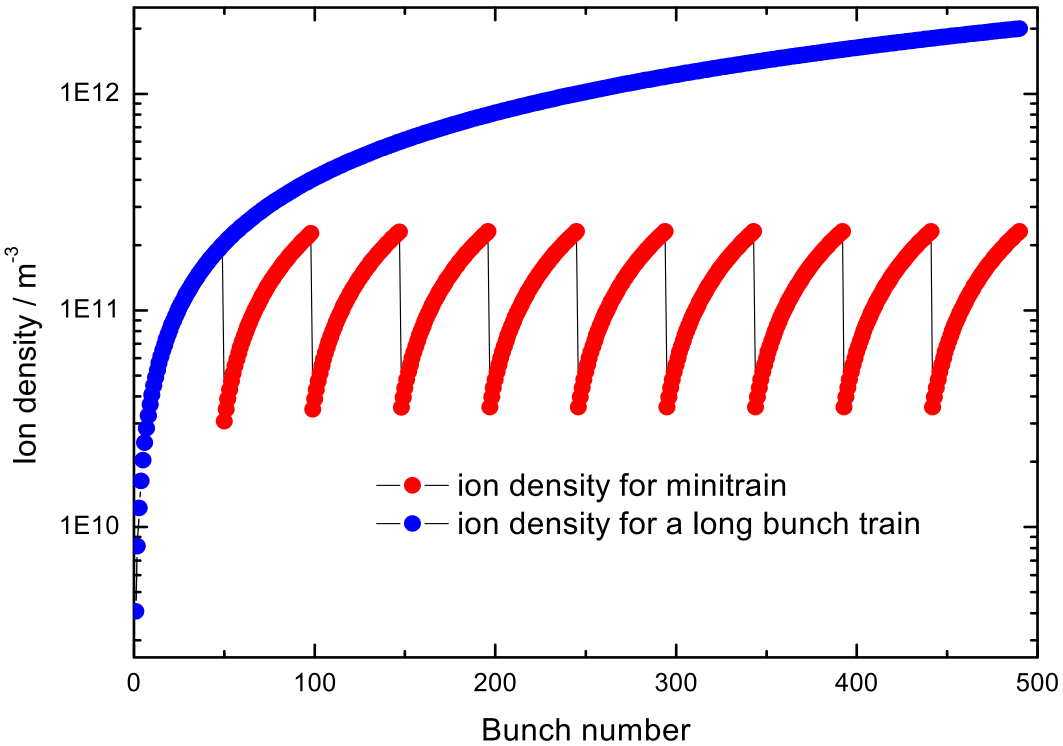
A fill pattern case



p=1

Fill patterns

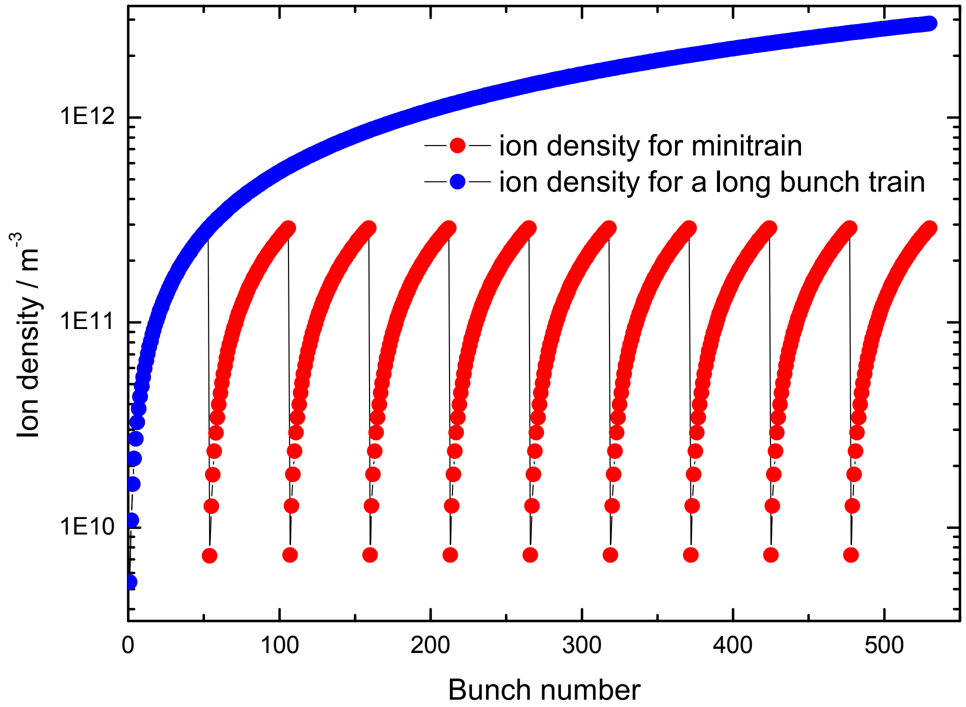
- For case A, the ion density like this



Ion density for 10 bunch trains for case A. n_b= 5782, N_0= 0.97E10, N_{train}= 118. There are 49 bunches per train. Bunch spacing = 2 RF buckets= 3.08 ns,gaps between trains=25 RF buckets, partial gas pressure of CO is 1 nTorr

Fill patterns

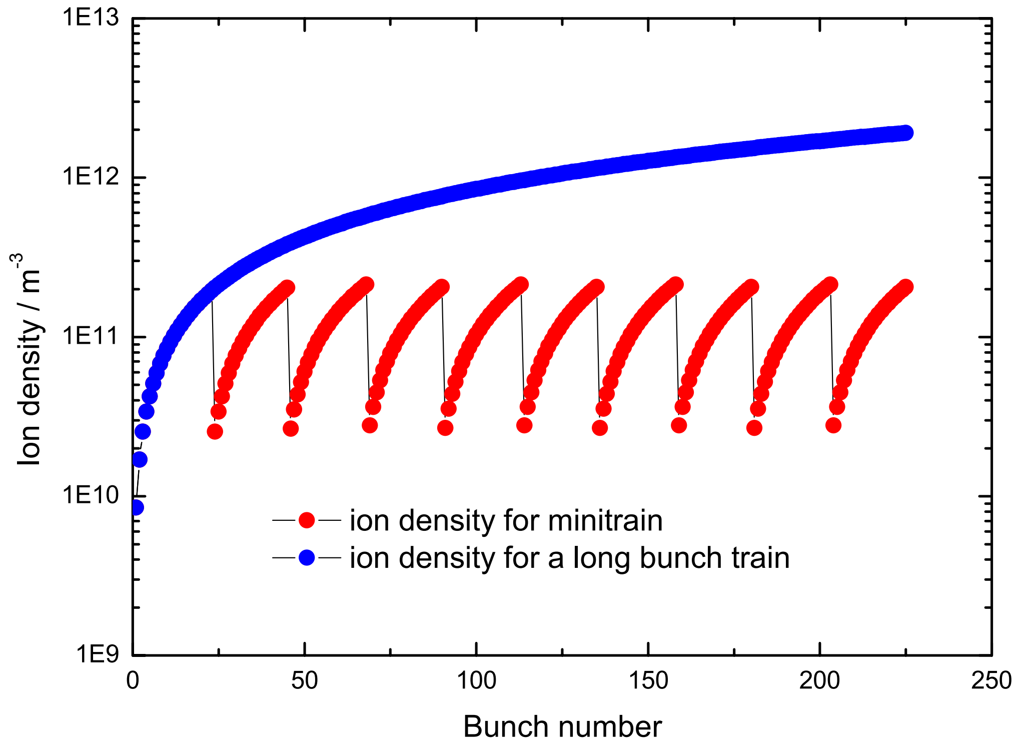
- For case C, the ion density like this



Ion density for 10 bunch trains for case C. n_b= 4346, N_0= 1.29E10, N_{train}= 82. There are 53 bunches per train. Bunch spacing =2 RF buckets= 3.08 ns. Gap between trains= 71 RF buckets. Partial pressure of CO is 1 ntorr.

Fill patterns

- For case E, the ion density like this

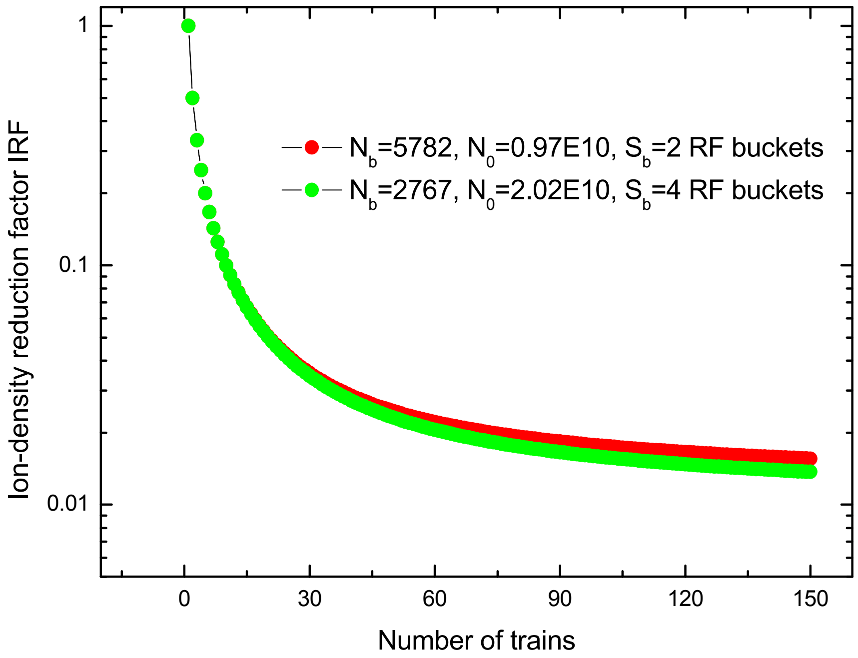


Ion density for 5 bunch trains for case E. n_b= 2767, N_0= 2.02E10, N_{train}=61. There are 45 bunches per train (23 bunches+28 RF buckets+22 bunches). Bunch spacing = 4 RF buckets= 6.16 ns. Gap between trains=28 RF buckets. Partial pressure of CO is 1 ntorr.

Fill patterns

$$IRF = \frac{\lambda_{ion}(\tau_{gap})}{\lambda_{ion,1}} \approx \frac{1}{N_{train}} \frac{1}{1-\exp\left(-\tau_{gap}/\tau_{ion}\right)}$$

The fill pattern can be optimized in terms of obtain the smallest possible IRF (this work is ongoing)

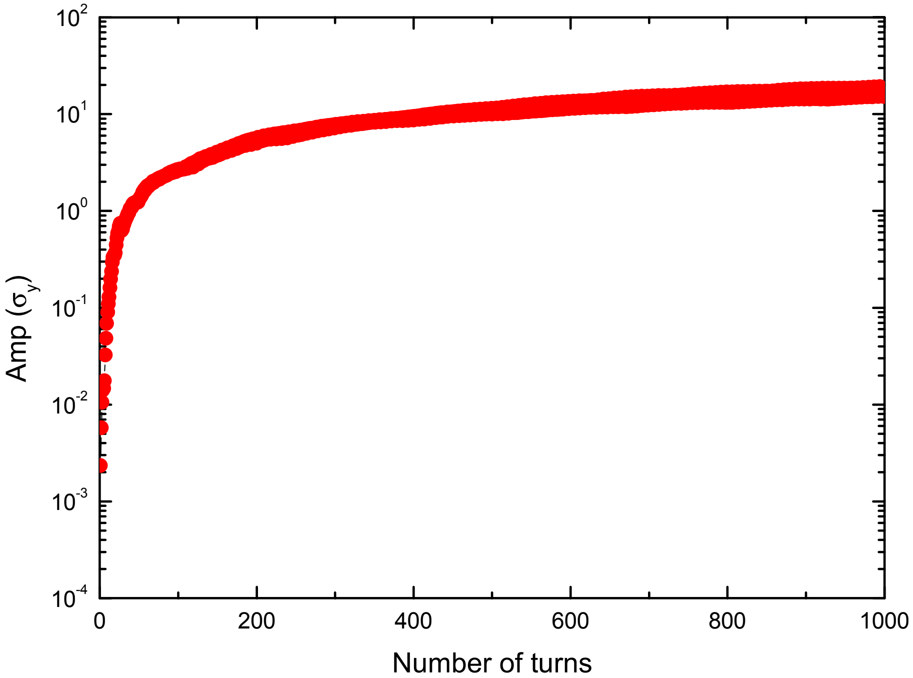


IRF factor versus number of trains in OCS6 damping ring (for low Q case and nominal operation---two extreme cases in the fill pattern)

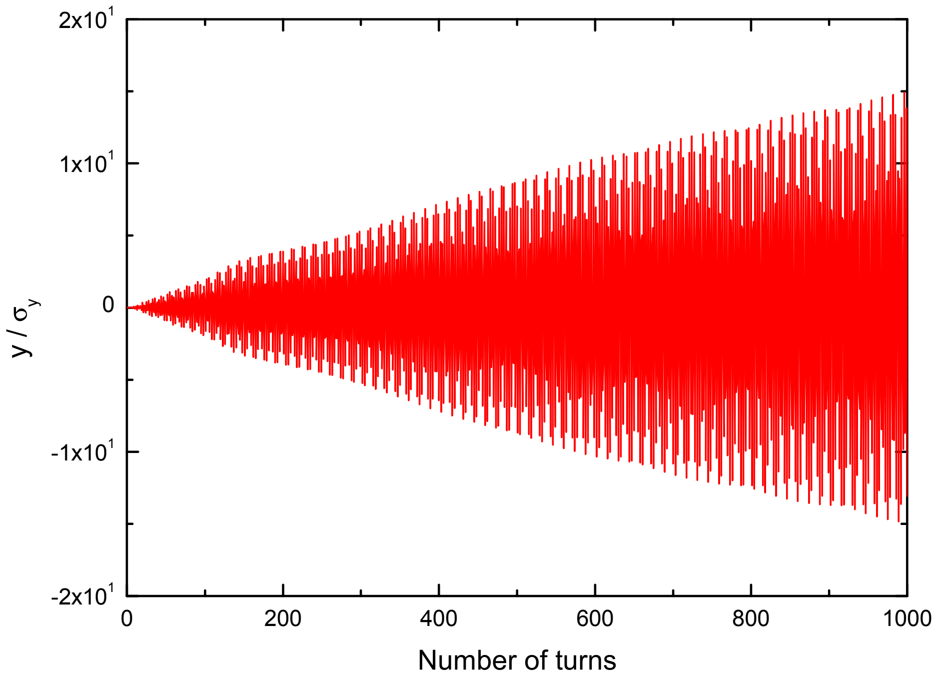
Simulation study of FII

- A weak-strong code is developed
- Electron bunch is a rigid Gaussian beam
- Ions are regarded as marco-particles
- The interaction of ions and beam particles is based on Bassetti-Erskine formula
- Beam motion between ionization points can be linked *via* linear optics
- A few interaction points are chosen in the ring

Simulation study of FII



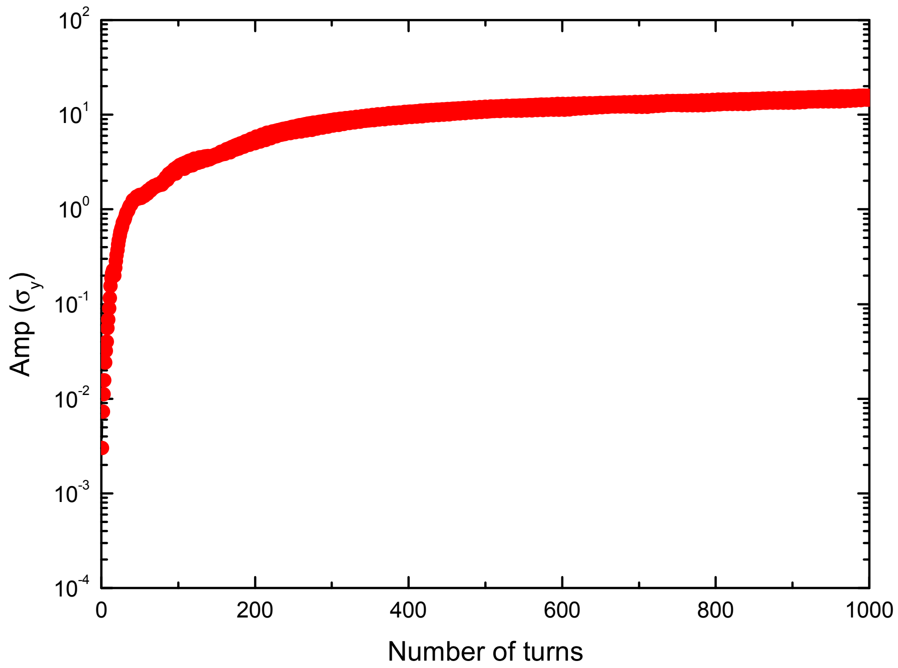
Growth of maximum vertical oscillation amplitude for the 2767th bunch

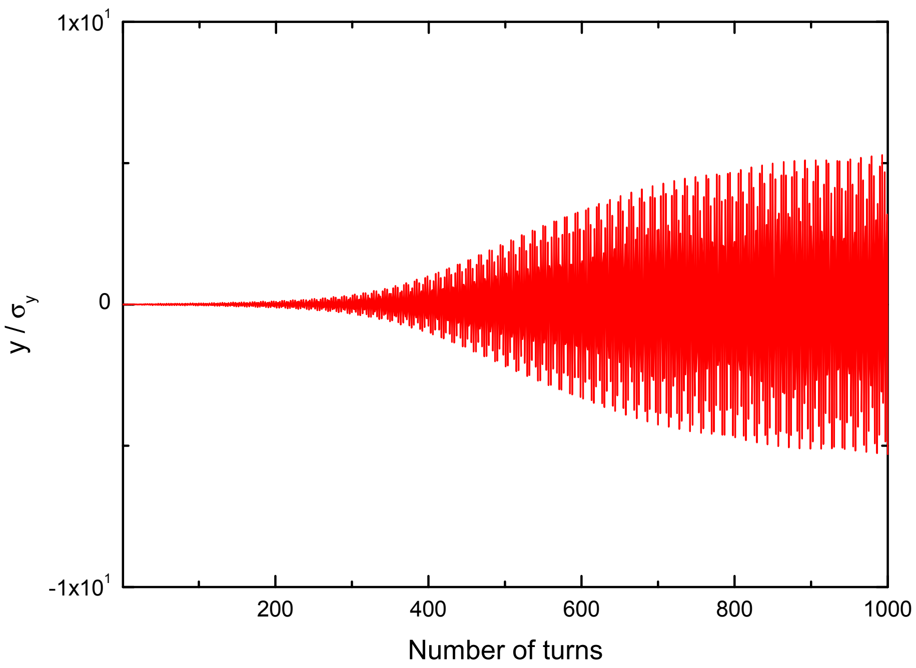


Bunch centroid oscillation

test9.dat (5 interaction points)

Simulation study of FII





Growth of maximum vertical oscillation amplitude for the 5782th bunch

Bunch centroid oscillation

test11.dat (5 interaction points)

Summary

- For CO partial pressure of 1ntorr, the FII growth time is very fast for one long train in linear theory
- If the gap length is larger than 30 RF buckets, the ion density will not change a lot
- Gaps between bunch trains can significantly lower the ion density.
- 60~120 bunch trains can reduce the ion density by a factor of ~ 100 comparing to one long bunch train
- Simulation on mini-train effect is ongoing
- FII experimental study is foreseen in ATF by the end of this year

Thank you!

Recent FII study in ATFDR *

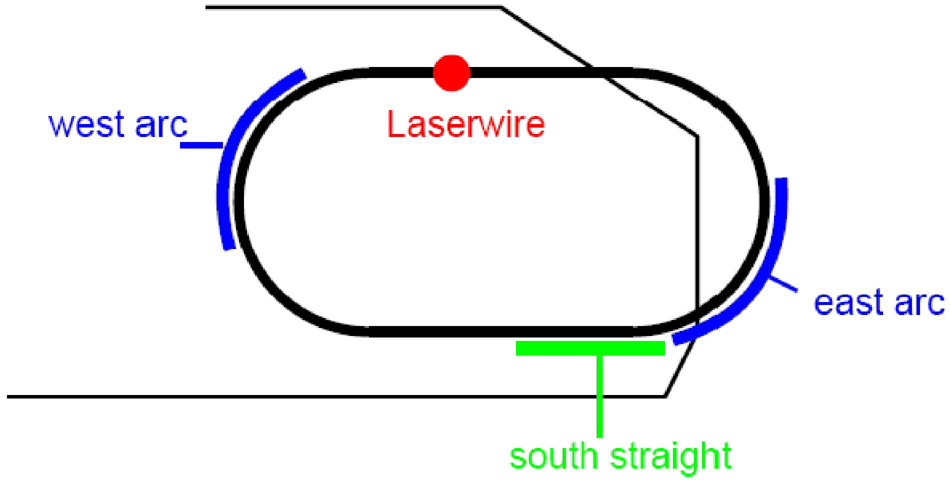


Table 1: vacuum pressure in the measurements

ion pump status	5mA	10mA	20mA
normal	4.6×10^{-7} Pa	5.9×10^{-7} Pa	1.0×10^{-6} Pa
south straight OFF	2.0×10^{-6} Pa	2.7×10^{-6} Pa	5.5×10^{-6} Pa
both arcs and south straight OFF	3.4×10^{-6} Pa	5.2×10^{-6} Pa	

Switch off the ion pumps around the ring in south straight, east arc and west arc sections, try to elevate vacuum pressure to some extent (one order of magnitude change).

* M. Fukuda's report on beam size measurement on 2007.3/13,14

Experimental results*

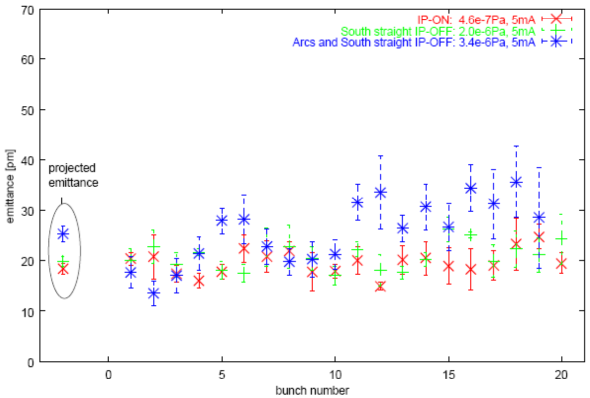


Figure 7: emittance of multi-bunch beam at 5mA/20bunches

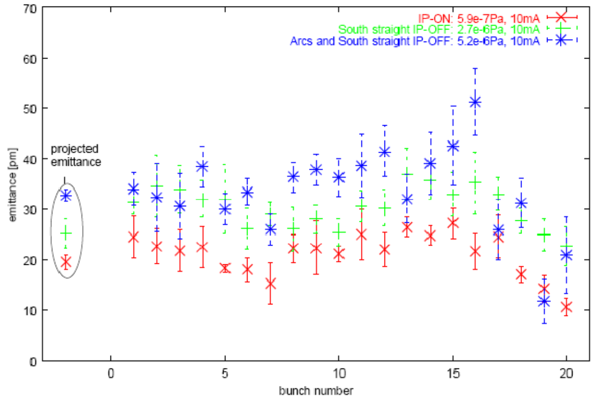


Figure 8: emittance of multi-bunch beam at 10mA/20bunches

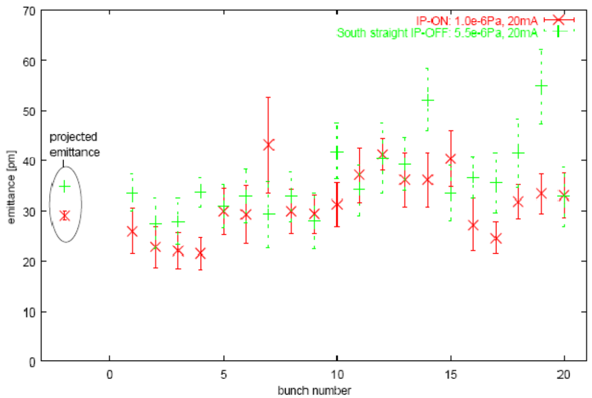


Figure 9: emittance of multi-bunch beam at 20mA/20bunches

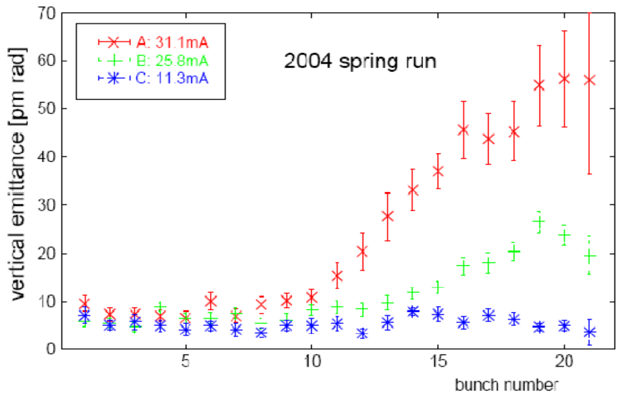


Figure 10: data taken in 2004

* M. Fukuda's report on beam size measurement on 2007.3/13,14

Conclusion from this experiment

- There is no clear emittance blow-up along the bunch train (20 bunches in one train)
- Probably it is because beam initial emittance is quite different. (on 3/14 experiment, the initial emittance is 30 pm, while in the year 2004, the initial emittance is about 5 pm)
- From FII theory, it really reveals to us that the emittance affects this instability very much, as can be seen from Lanfa's Frascati talk.
- In ILCDR, the vertical emittance is extremely small (2pm) and bunch intensity and bunch number are large, so this instability will be somewhat severe
- Additional experiments are needed to further understanding this instability
- A gas injection system is planned to start from October this year in ATF DR; hopefully the residual gas species can be analyzed via RGAs then. The different ion species effect on FII can be investigated.
- The detailed experiment will be carried out in Nov. 2007 (joint experiment with SLAC, DESY, KEK, Cockcroft Inst. PAL, etc)