Lattices and Multi-Particle Effects in ILC Damping Rings

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November 12 , 2005

Electron cloud- K. Ohmi and M. Pivi
Fast Ion- L. Wang

Super B-Factories 2005 workshop, November 11-12, 2005, Frascati, Italy

Motivations and Challenges

PEP-II:
Emittance: 50 nm
Beam current: 3 A
Damping time: 50 ms

ILC damping rings:
Emittance: 0.5 nm
Beam current: < 1 A
Damping time: 20 ms

Super-B rings:
Emittance: 0.5 nm
Beam current: 4 A
Damping time: 1.5 ms

How to Obtain Ultr-Low Emitance

Horizontal equilibrium emittance due to dipole magnet with bending angle: ϕ_d in arc can be written as

$$\varepsilon_{arc} = C_q F_c \gamma^2 \phi_d^3 / J_x$$

- Reduce energy
- Increase number of cell
- Choose a better cell
- Make dipole longer

$$C_q = 55\hbar c / 32\sqrt{3} mc^2$$

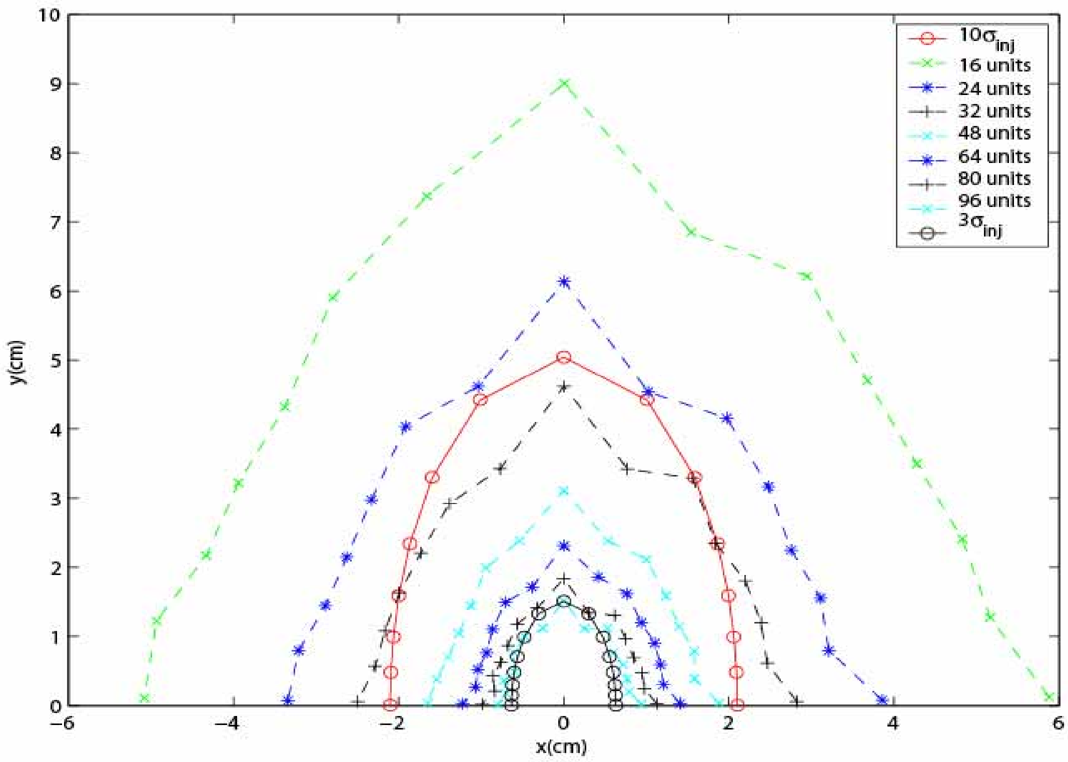
γ - Lorentz factor

J_x - Partition number ~ 1

F_c - Cell factor: how dipole and quadrupole magnets are arranged its theoretical minimum value $1/12\sqrt{15}$

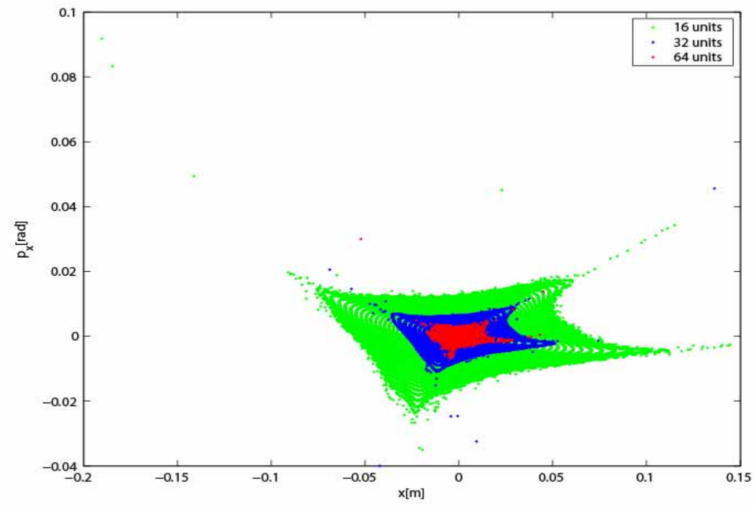
$$F_c^{FODO} = \frac{1}{\sin\mu} \frac{5 + 3\cos\mu}{1 - \cos\mu} \frac{L_c}{l_d}$$

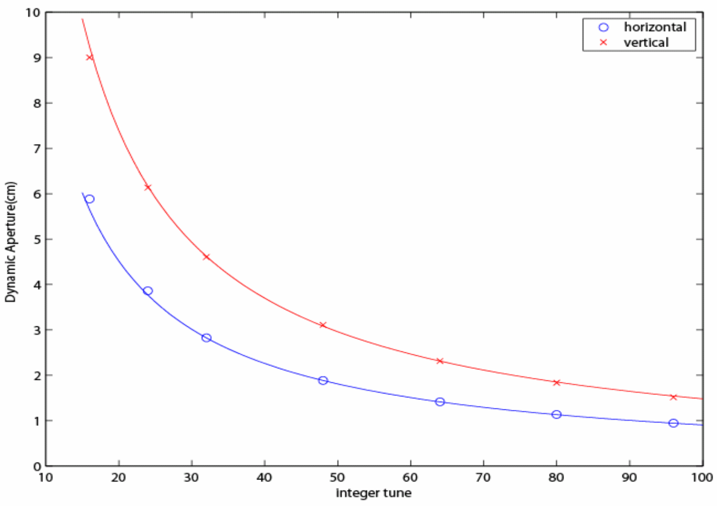
Dynamic Aperture v.s. Strength of Sextupoles in 5-Gev Ring



Dynamic aperture scales inversely proportional to the strength of the sextupoles! It is not so bad and it can be worse.

Scaling of Dynamic Aperture





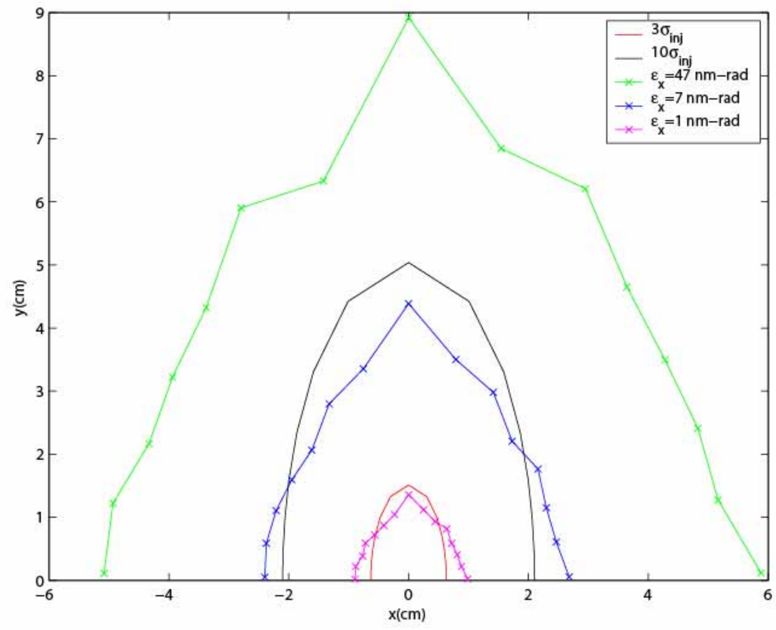
scaling of phase space

solid lines are inverse curves

Dynamic aperture is determined by the location of fix points In phase space when a single resonance dominates the system. Perturbation theory can be used to explain this scaling property of the dynamic aperture.

Reduce Emittance by Enlarging the Ring While Keeping the Cell Structure

Simulation of actual lattices:



40 cells -> 80 cells -> 160 cells,
ε_x=47 nm -> 7 nm -> 1 nm
C=960 m -> 1560 m -> 2760 m

Scaling properties:

$$\varepsilon_x \rightarrow \varepsilon_x / 10$$

$$\theta_{dip} \rightarrow \theta_{dip} / \sqrt[3]{10} = \theta_{dip} / 2.15$$

$$N_c \rightarrow 2.15 N_c$$

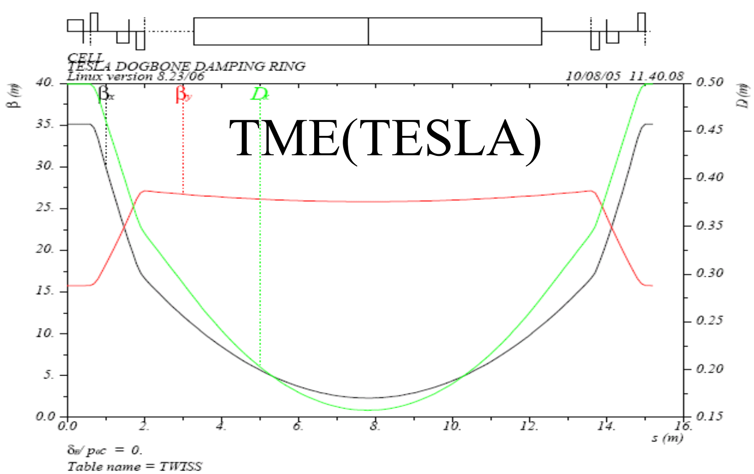
$$\rho_{dip \rightarrow} 2.15 \rho_{dip}$$

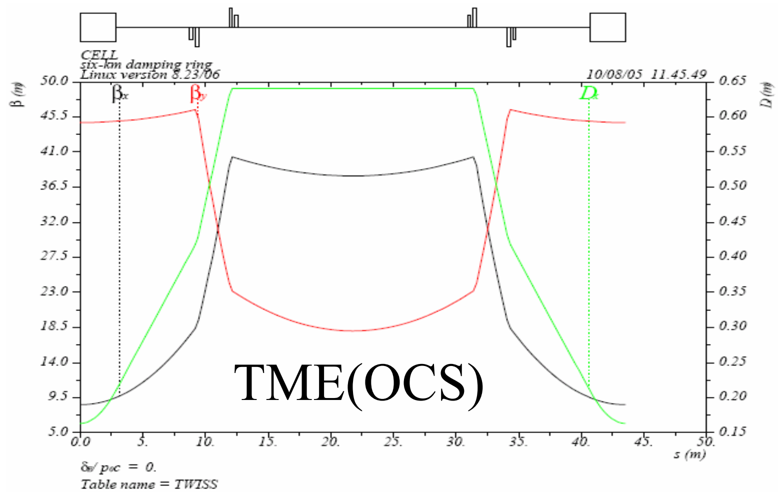
$$\eta_x \rightarrow \eta_x / 2.15$$

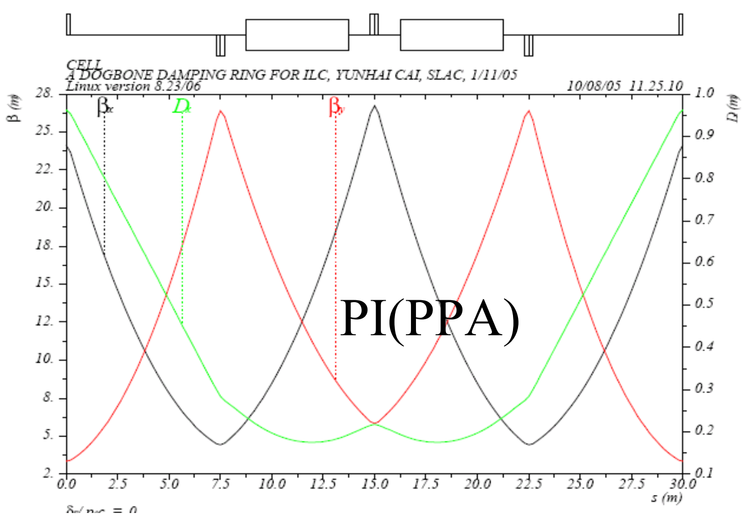
$$SF, SD \rightarrow 2.15(SF, SD)$$

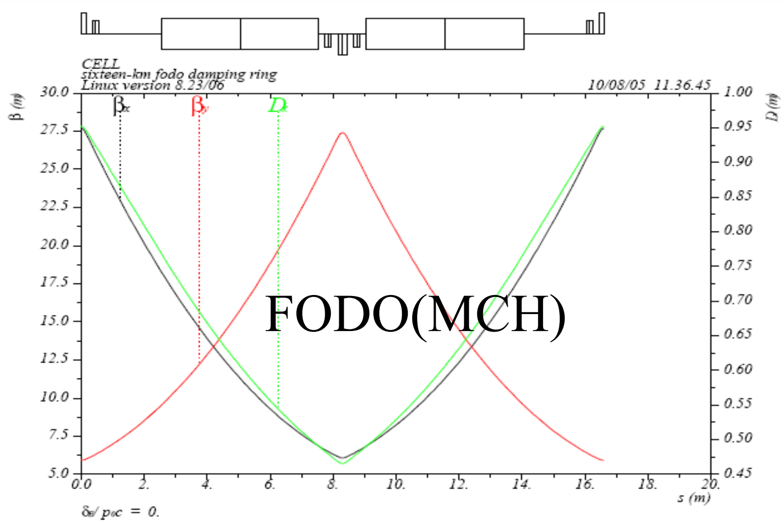
$$DA \rightarrow DA / 2.15$$

Cells Used in ILC Damping Rings



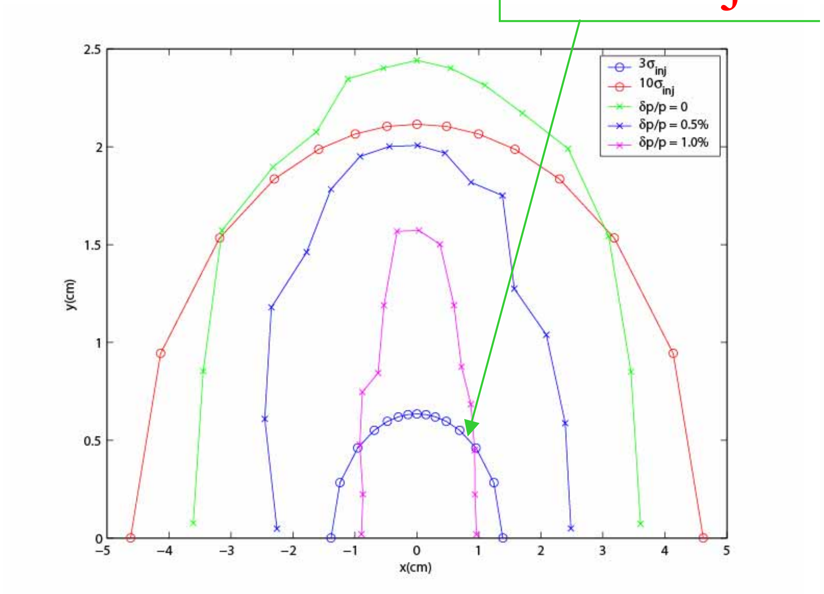




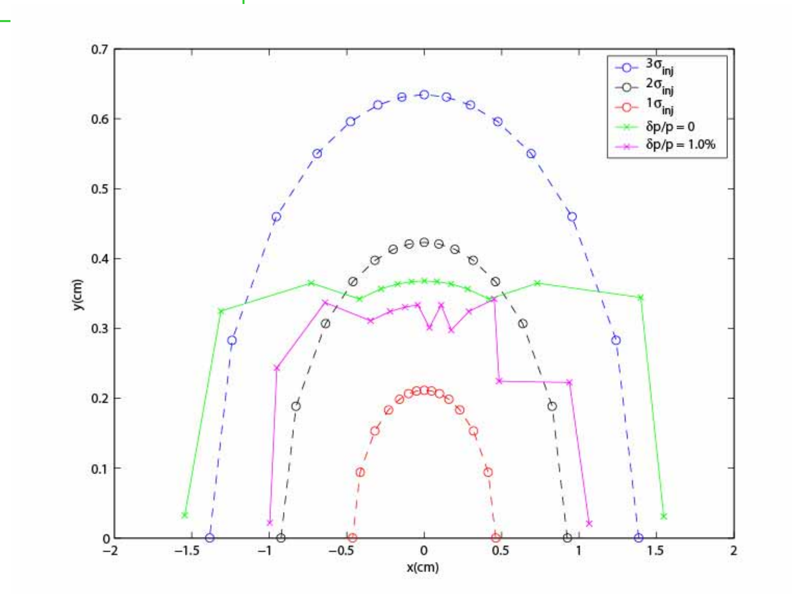


Dynamic Aperture of PPA with Permanent-Magnet Wigglers

3σ of injected beam



Linear wiggler



Full nonlinear wiggler

Dynamic aperture is entirely dominated by 24 wigglers in the lattice. They act like physical scrappers.

Tunes vs. Amplitudes (PPA)

Calculated with nonlinear map and normal form using LEGO & LIELIB:

	Linear Wiggler	Single-Mode Wiggler
$\frac{\partial \nu_x}{\partial \varepsilon_x}$	-4903	-4903
$\frac{\partial \nu_x}{\partial \varepsilon_y}, \frac{\partial \nu_y}{\partial \varepsilon_x}$	-616	-616
$\frac{\partial \nu_y}{\partial \varepsilon_y}$	-1153	-410

For single-mode wiggler:

$$\frac{d\nu_y}{ds} = \frac{\sin^2 k_w s}{4\pi(1+\delta)\rho_0^2}[\beta_y(s) + k_w^2 \beta_y^2(s) J_y + \ldots]$$

Main Parameters of ILC Damping Rings

Parameters	PPA	OCS	TESLA	MCH
Energy E(Gev)	5	5	5	5
Circumference (m)	2824	6114	17,000	15,815
Horizontal emittance (nm)	0.433	0.56	0.50	0.68
Damping time (ms)	20	22	28	27
Tunes, n_x,n_y,n_s	47.81, 47.68, 0.027	50.4, 40.80, 0.038	76.31, 41.18, 0.071	75.78, 76.41, 0.19
Momentum compaction a_c	2.83×10^{-4}	1.62×10^{-4}	1.22×10^{-4}	4.74×10^{-4}
Bunch length s_z (mm)	6.00	6.00	6.04	9.0
Energy spread s_e/E	1.27×10^{-3}	1.29×10^{-3}	1.29×10^{-3}	1.40×10^{-3}
Chromaticity x_x, x_y	-63,-60	-65,-53	-125,-62.5	-90.98, -94.86
Energy loss per turn (Mev)	4.7	9.33	20.4	19.75
RF Frequency (MHz)	500	650	500	650
RF Voltage (MVolt)	17.76	19.27	50	66

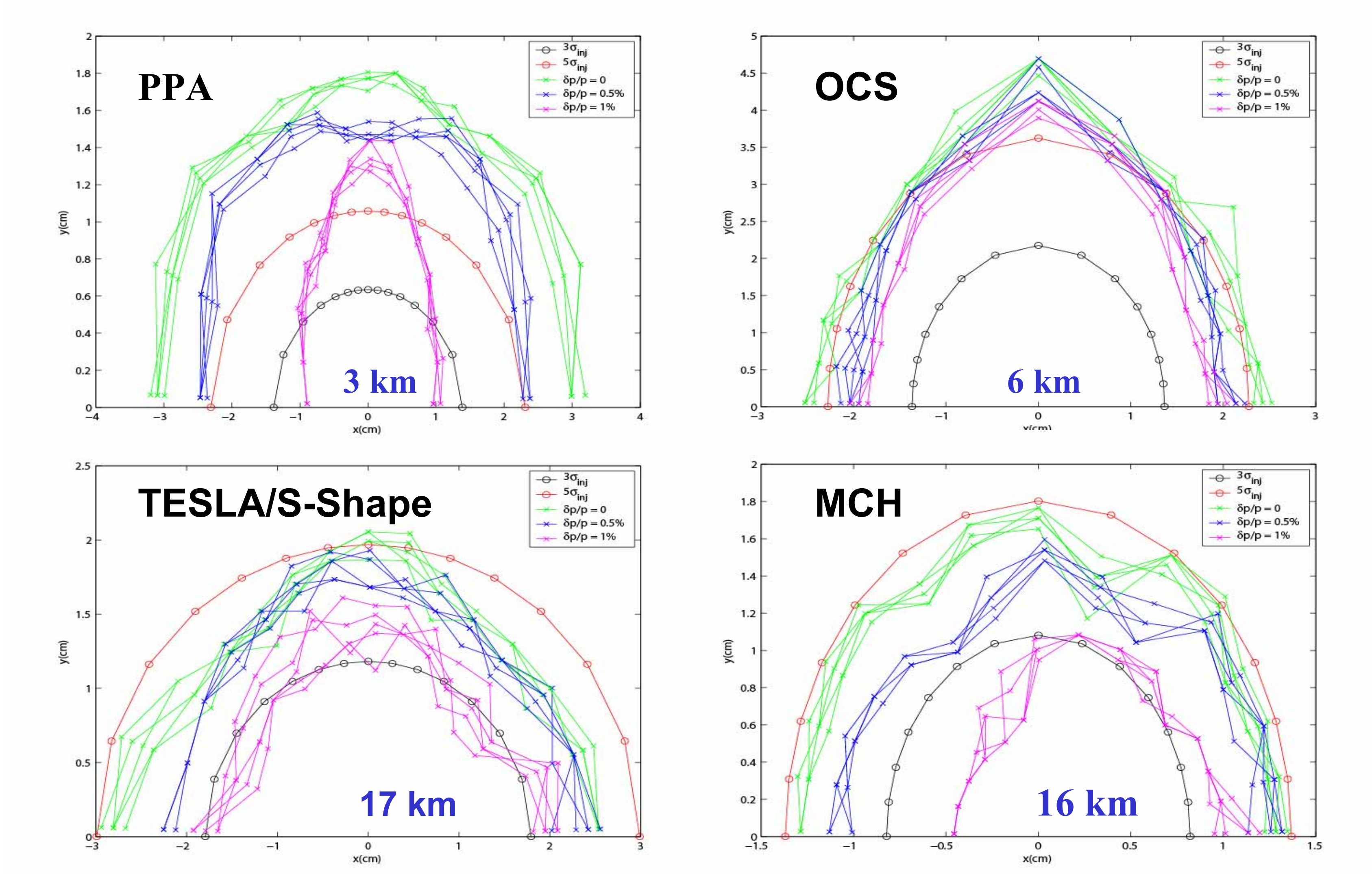
Tune vs. Amplitude and Energy Deviation

NAME	$\frac{\partial \nu_x}{\partial \varepsilon_x}$	$\frac{\partial \nu_y}{\partial \varepsilon_y}$	$\frac{\partial \nu_x}{\partial \varepsilon_y}, \frac{\partial \nu_y}{\partial \varepsilon_x}$	$\frac{\partial^2 \nu_x}{\partial \delta^2}$	$\frac{\partial^3 \nu_x}{\partial \delta^3}$	$\frac{\partial^2 \nu_y}{\partial \delta^2}$	$\frac{\partial^3 \nu_y}{\partial \delta^3}$
PPA	-4903	-1153	-616	233	5713	112	8912
OCS	-5938	982	-5593	-18	-270	2	42
TESLA	-7929	-2772	1917	318	12219	-68	2566
MCH	-712	-1130	-4008	-78	3825	-128	3337

Clearly, the OCS lattice has the best chromatic properties.

Dynamic Aperture with Mutilpole Errors and Single-Mode Wigglers

(Injected Positron Beam $\gamma\varepsilon_x$=0.01m-rad)



Conclusion of Acceptance Study

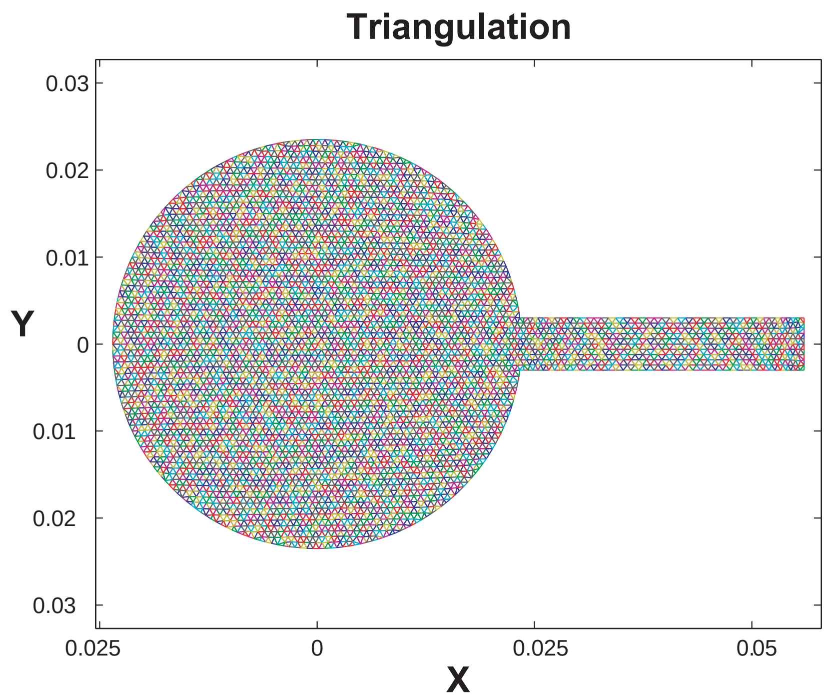
- Well optimized wigglers do not cause much degradation of dynamic aperture
- It is challenge but achievable to design a lattice with adequate dynamic aperture for a very large injected positron beam. More attention has to be paid to the energy acceptance
- Lattice with many super periods has advantage in terms of acceptance
- Type of cell is a determinant factor for large acceptance

Issues Due to Electron Clouds

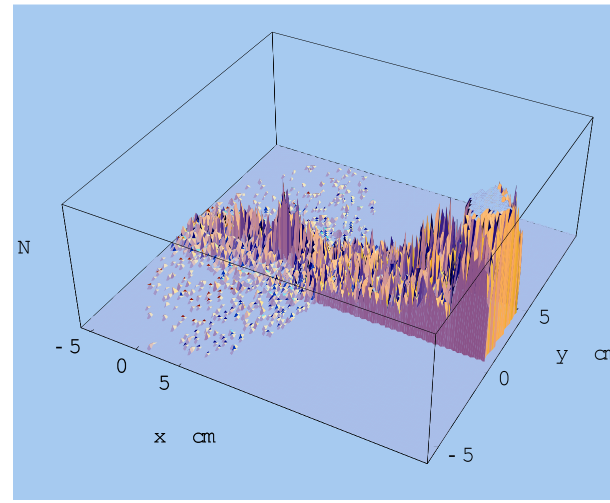
- How electron clouds are generated?
  - Photoelectron build-up
    - Synchrotron radiation
    - Geometry of bending
    - Antechamber
    - Reflectivity
    - Secondary eletrcon yield (SEY)
  - Multipacting of electrons
    - Solenoid wining in straight sections
- What are the effects on the positron beam?
  - Coupled bunch instability
    - Transverse bunch-by-bunch feedback system
  - Single bunch instability
    - Growth of beam size especially in the vertical plane

Poisson solver with the Finite Element Method

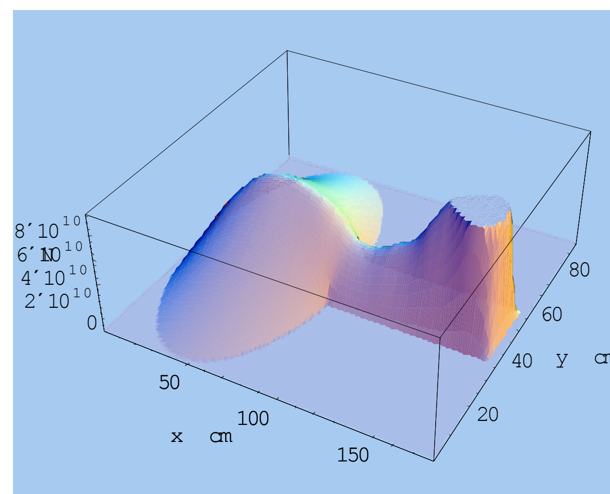
- Mesh



ρ_e

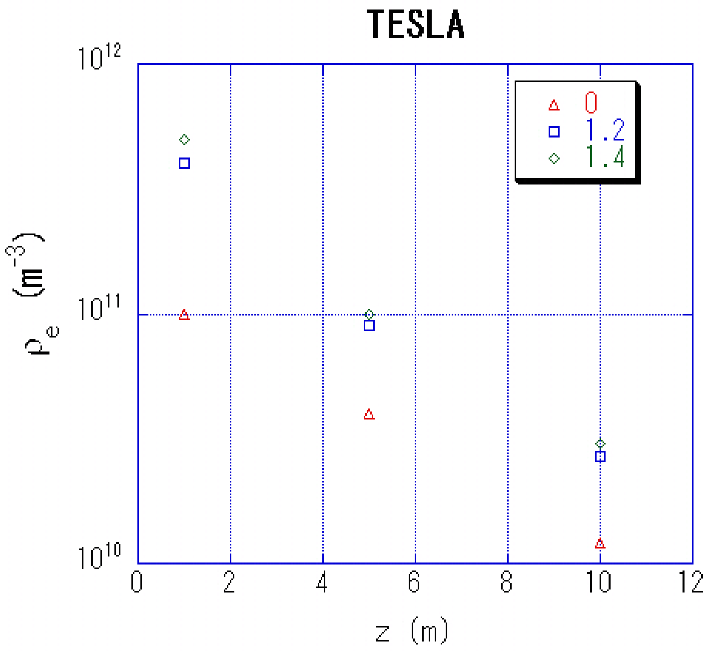


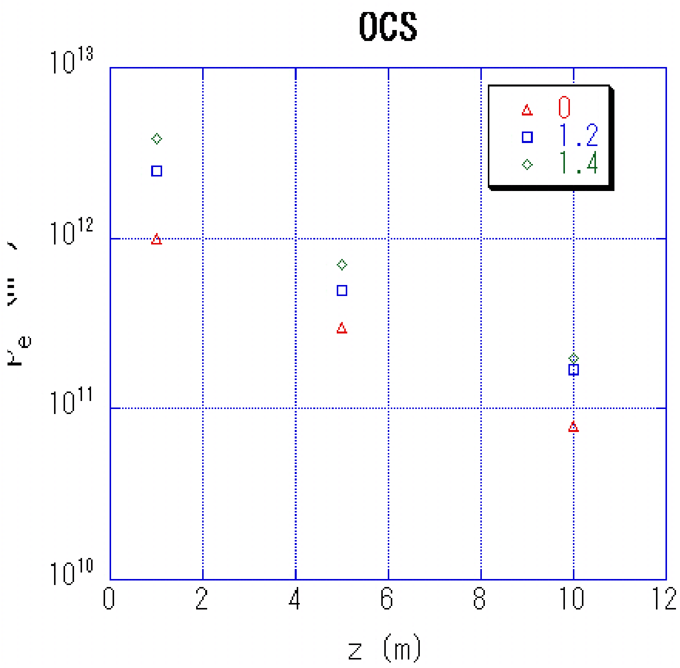
ϕ_{cloud}



Antechamber suppress the cloud line density to a few percent level (5-10m downstream), if multipacting can be avoided.

Density of Electron Cloud in Arcs

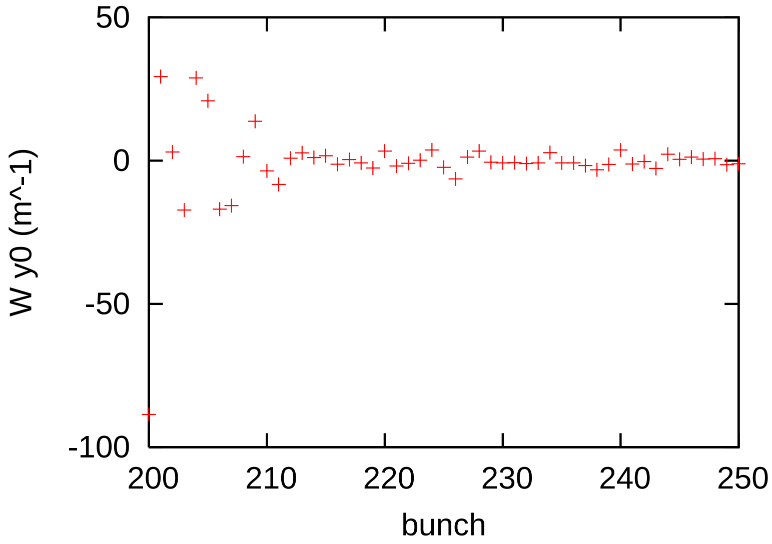


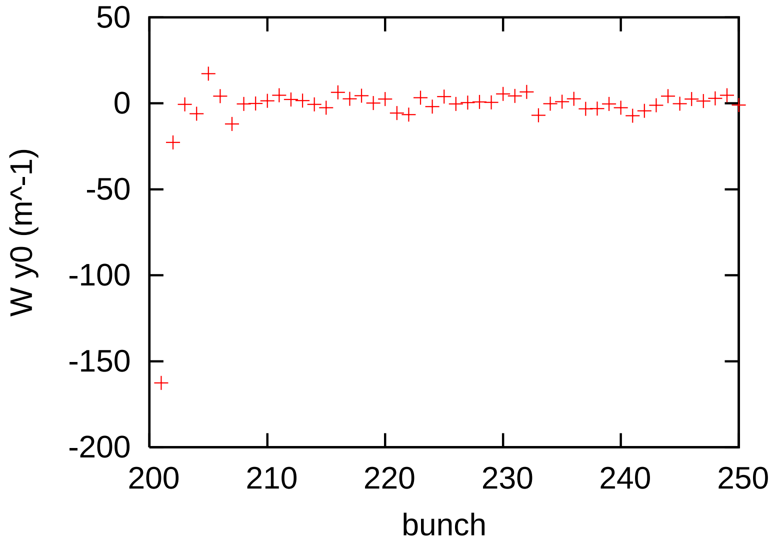


r =1 mm as a function of z.

Coupled Bunch Instability

- Wake force induced by electron cloud
- λ_e=7x 10^7 m^{-1} (OTW)   5x10^7 m^{-1} (OCS)
- This line density corresponds to that at 10 m down stream.
- The wake is 5 times stronger at 5 m downstream.
- At Injection, the wake is 10-20 times stronger.

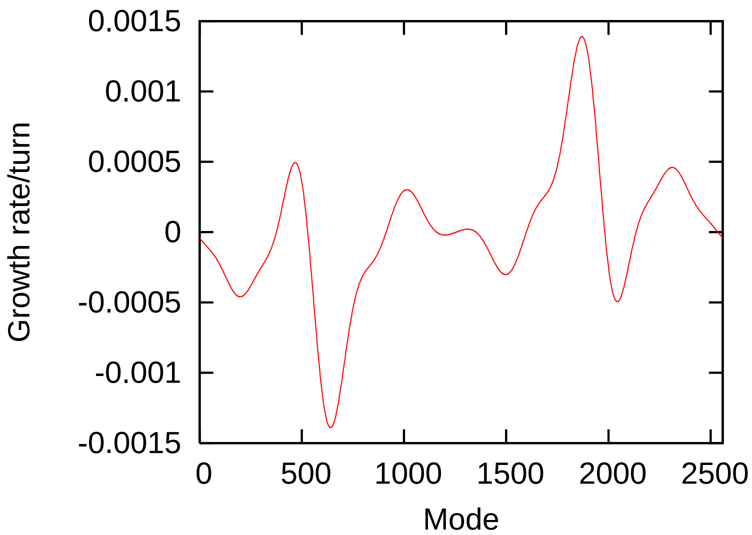




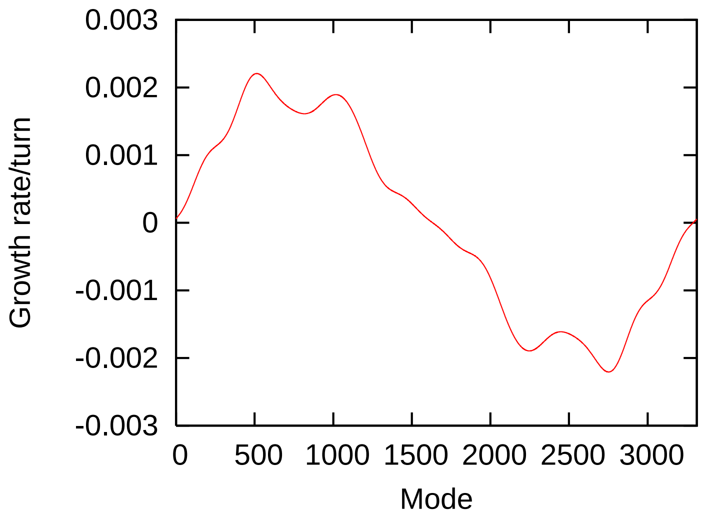
Growth rate of the coupled bunch instability

- Slow growth rate (τ~1000 turn), if the conditions (average density =10m down stream) are kept.
- At injection, growth rate increases 10-20 times, (τ~50-100 turn)

OTW



OCS



Single Bunch Instability Based on Linear Theory

- Electrons oscillate in a bunch with a frequency, ω_e.

$$\omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$$

- $\omega_e \sigma_z / c > 1$ for vertical.
- Vertical wake force with ω_e was induced by the electron cloud causes strong head-tail instability, with the result that emittance growth occurs.

- Threshold of the instability based of linear theory

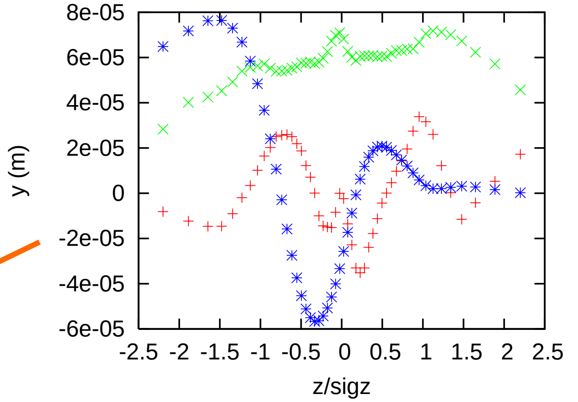
$$\rho_{e,th} = \frac{2\gamma \nu_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_0 \beta L}$$

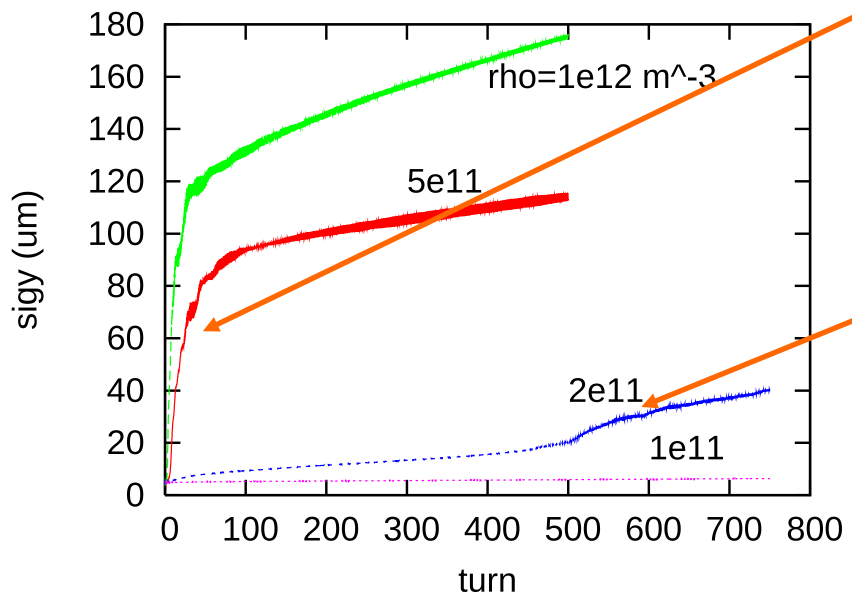
- Q=min(Q_{nl}, $\omega_e \sigma_z / c$)
  Q_{nl}=5-10? Depending on the nonlinear interaction
- K~3 Cloud size effect.
- $\omega_e \sigma_z / c$~12-15 for damping rings.

Simulation for OCS Lattice

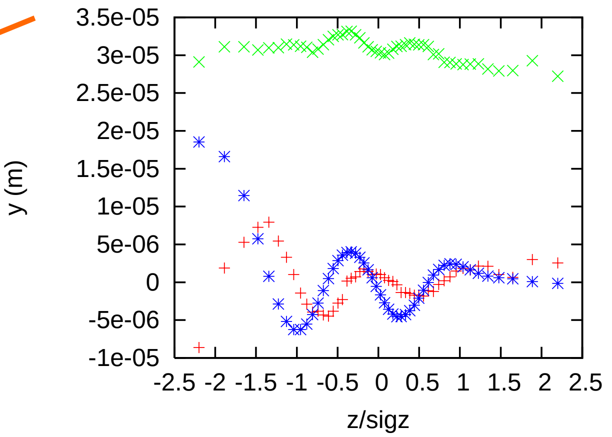
- Clear head-tail signal was observed ρ_e=2x10^{11} m^{-3} and more.
- Threshold $\rho_{e,th}$=2x10^{11} m^{-3}

ρ_e=5x10^{11} m^{-3}

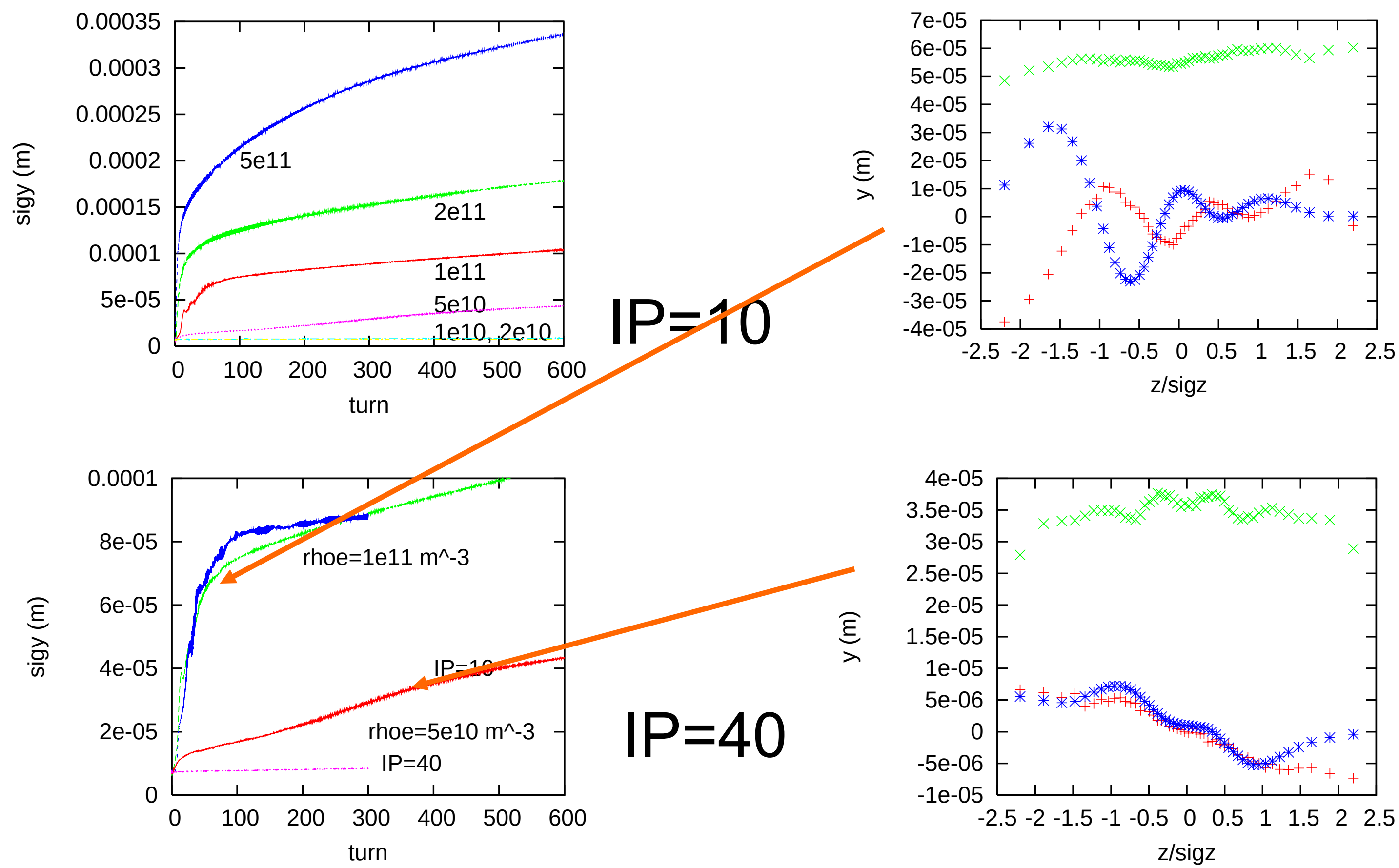




ρ_e=2x10^{11} m^{-3}



Simulation for TESLA Lattice



- Threshold $\rho_{e,th}=1\times10^{11}\ m^{-3}$

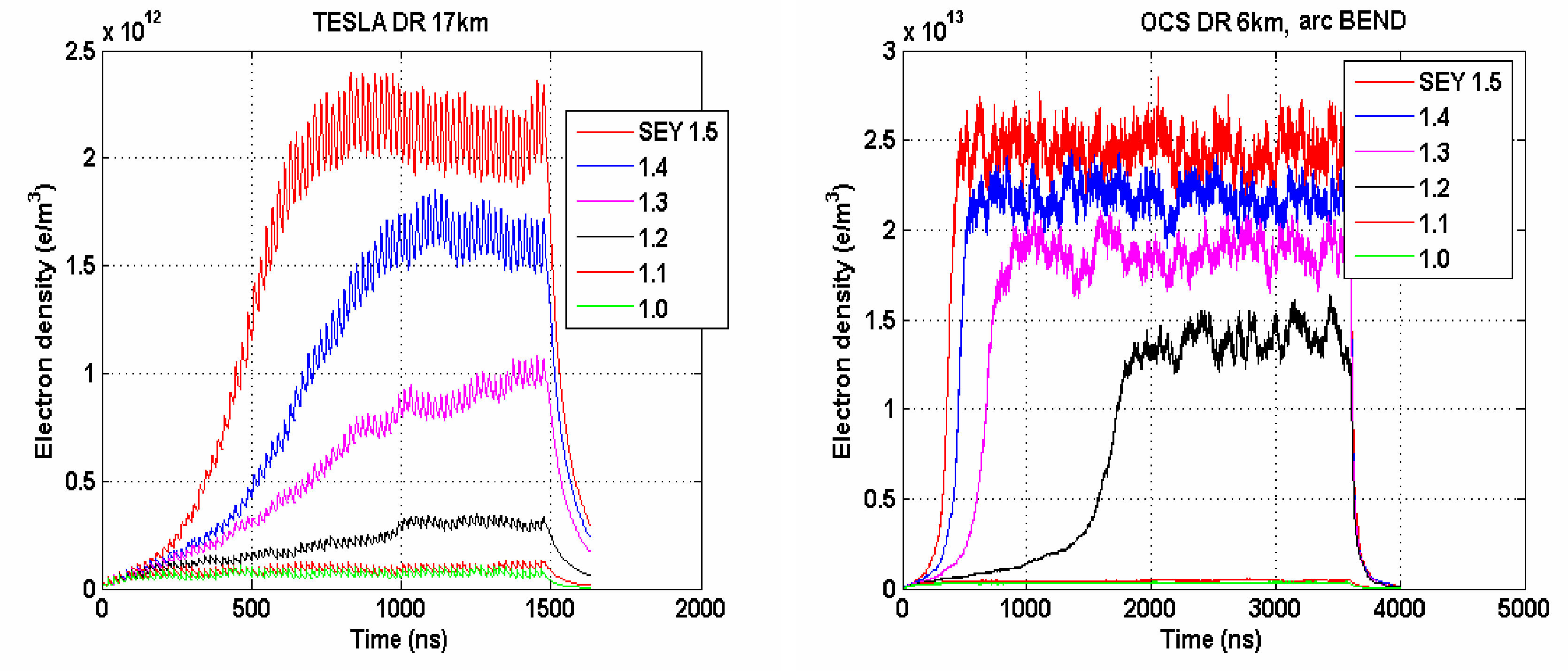
Simulation vs. Linear Theory?

- The threshold density

	simulation	linear theory
OTW	$\rho_{e,th}=5\times10^{11}\ m^{-3}$	(1.8×10^{12})
OCS	$=2\times10^{11}\ m^{-3}$	(7.4×10^{11})
TESLA	$=1\times10^{11}\ m^{-3}$	(4.5×10^{12})

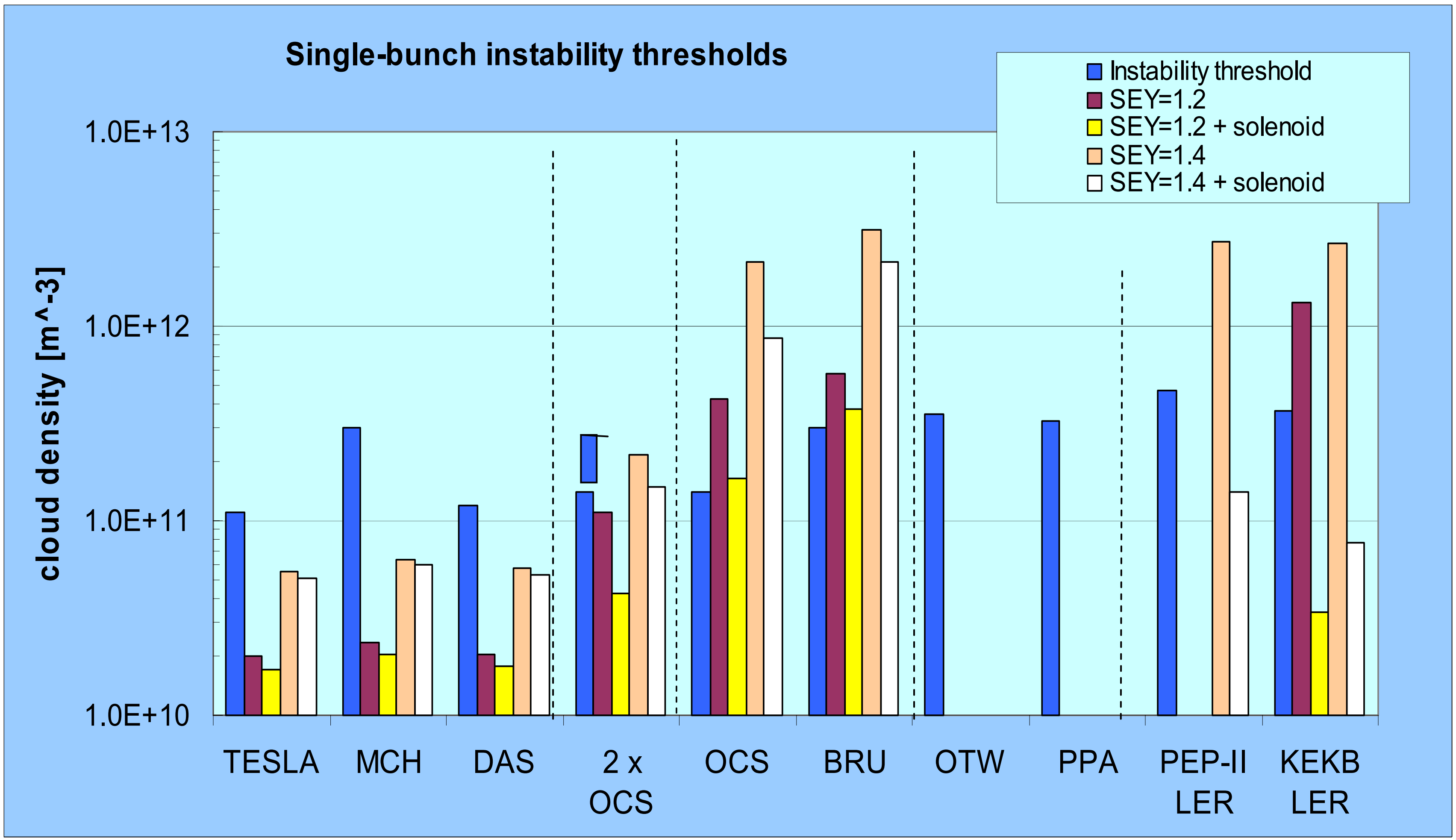
- The systematic difference (3-4x) between simulation and linear theory may be due to the cloud pinching.
- Simulations are accurate because the pinching is taken into account.
- To make lower density, multipacting should be avoided.
- Cloud density has been estimated with considering photoelectron production and antechamber geometry.

Production of Electron Cloud in Bending Magnets



OCS has a factor of 10 more electron density than the TESLA dogbone ring. We expect a factor of 3 simply based on the argument of neutralization density.

Threshold of Single Bunch Instability for ILC Damping Ring



Conclusion of Electron Cloud Study

- The growth time for coupled bunch instability could be 50 turns at the injection due to the large positron beam size. However, the instability could be easily control by a bunch-by-bunch feedback system.
- For single bunch instability, linear theory predicts a higher threshold than by the strong-strong simulation.
- Using the tighter threshold, OCS lattice is very likely to have this instability given a reasonably achievable secondary electron yield between 1.2~1.4.

Linear Theory

T. Ranbenheimer, F. Zimmerman, G. Stupakov

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

$$\frac{1}{\tau_e} = \frac{1}{\tau_c} \cdot \frac{c}{2\sqrt{2}\, l_{train} \Delta\omega_i^{rms}}$$

where

$$\frac{1}{\tau_c} = \sqrt{\frac{2m_e}{m_N}} \, \frac{\beta_y L_{sep}^{1/2}}{c\gamma} \, \frac{n_g \sigma_i}{\sqrt{A}} \, \frac{2 r_e z N}{3\sigma_y \sigma_x}^{3/2} n^2$$

$$\frac{1}{\tau_{eff}} = \sum_i \frac{1}{\tau_i} w_i$$

Here,

- m_e, m_N=electron and nucleon masses
- β_y=average beta-function
- γ=gamma factor
- r_e=classical electron radius
- z, A=electrovalence and mass number of ion
- n=number of bunches
- n_g=residual gas density
- σ_i=ionization cross-section
- l_{train}=length of a bunch train
- $\Delta\omega_i$=spread in ion frequency

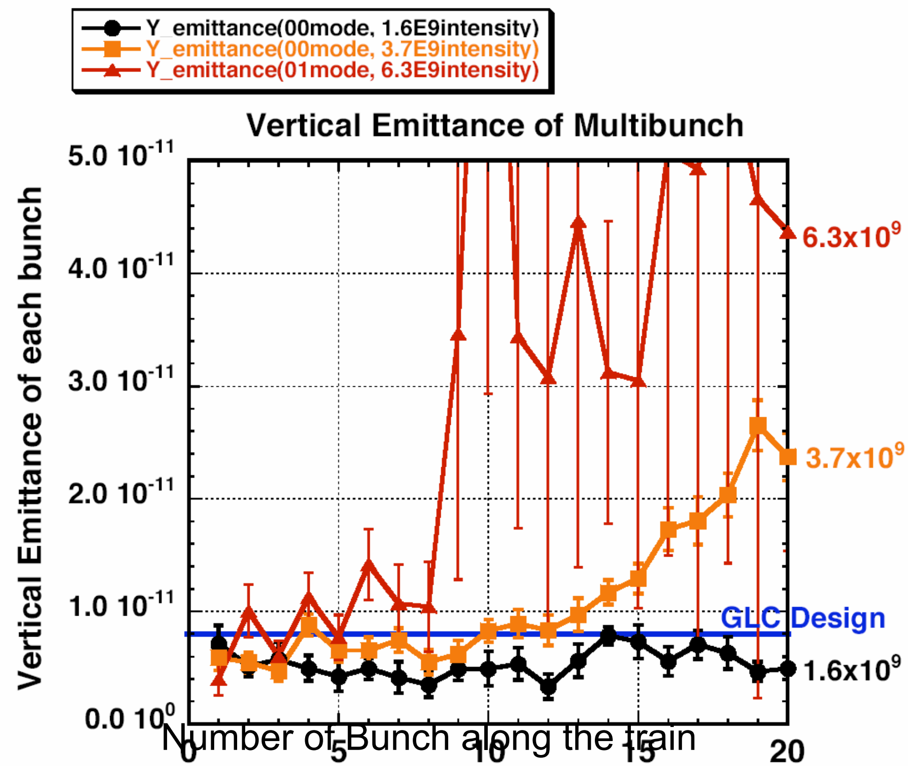
coherent tune-shift due to ions:

$$\Delta \upsilon_y = \frac{r_e \lambda_{ion}}{4\pi\gamma} \int_{trapped\ region} \frac{\beta_y}{\sigma_y^{ion} \left(\sigma_x^{ion} + \sigma_y^{ion}\right)} ds$$

$$\sigma_{ion} = \sigma_{electron} / \sqrt{2}$$

ATF Measurement, Simulation, and Calculation

Radiation damping time is about 30ms



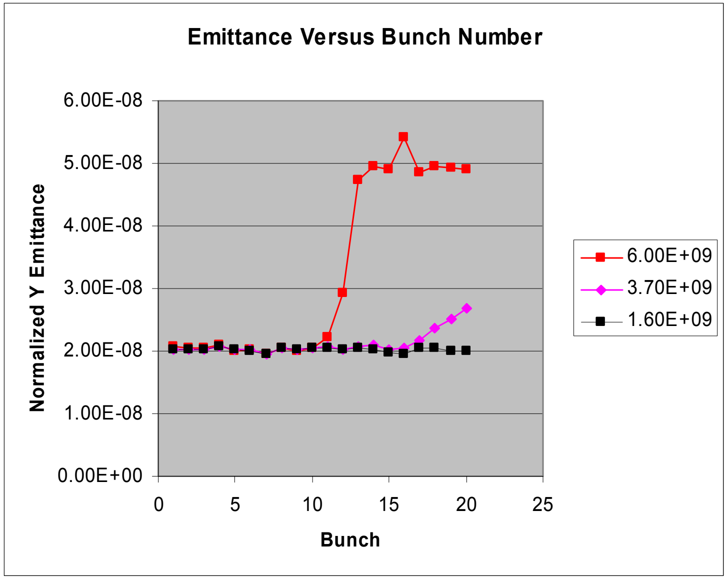
Beam size blow-up at ATF (experiment)

Nbunch=20, P=10nTorr

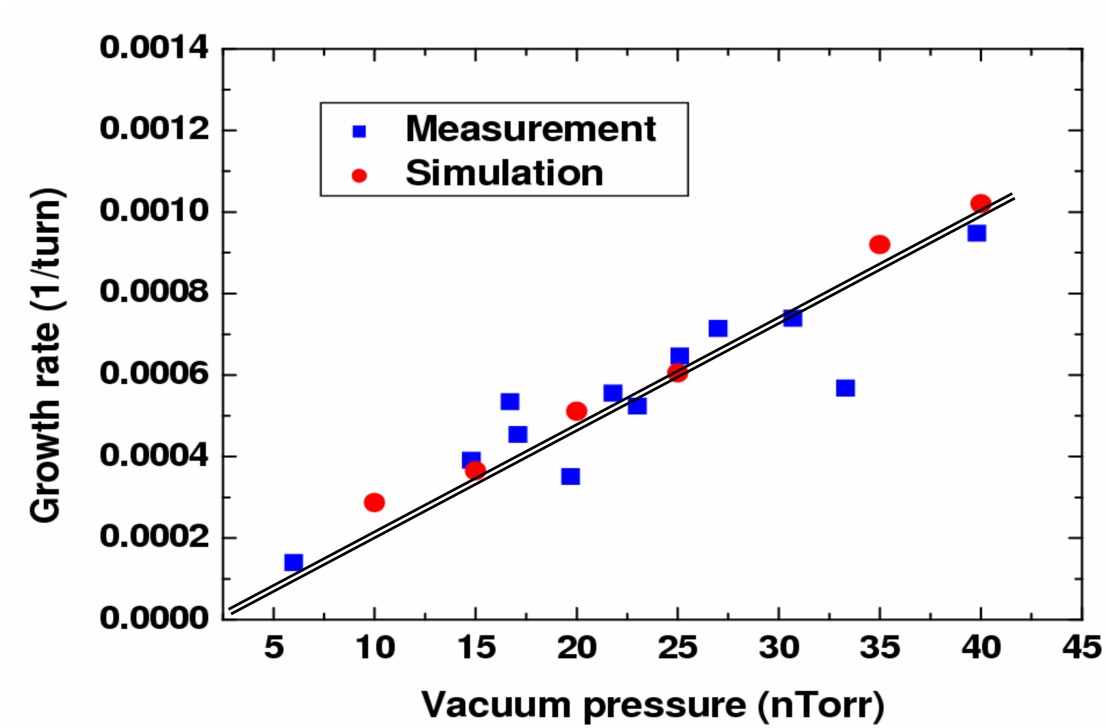
Calculated Growth time and Tune-shift

(20% is CO+)

Bunch intensity	Growth time (ms)	Tune shift
0.16E10	27	3.4324e-006
0.37E10	12	7.9375e-006
0.63E10	6.7	1.3030e-005



Comparison of measured and simulation growth rates at Pohang Light Source Eun-San Kim, PAC2005



Good agreement with experiment and simulation

Electron Ring in B-factories

KEKB(P=1nTorr)

- Energy 8.0GeV
- Lsep=2.4m
- εx=24nm
- εy=0.4nm
- $N=5.6\times10^{10}$
- Nbunch=1389
- $\tau_{feedback}$=0.5ms

Assuming 20% is CO+

$\tau_{calculated}$=1.8ms, ΔQ_{cal}=0.001;

PEPII(P=1nTorr)

- Energy 9.0GeV
- Lsep=1.26m
- εx=50nm
- εy=1nm
- $N=4.6\times10^{10}$
- Nbunch=1732

$\tau_{calculated}$=1.15ms, ΔQ_{cal}=0.0008;

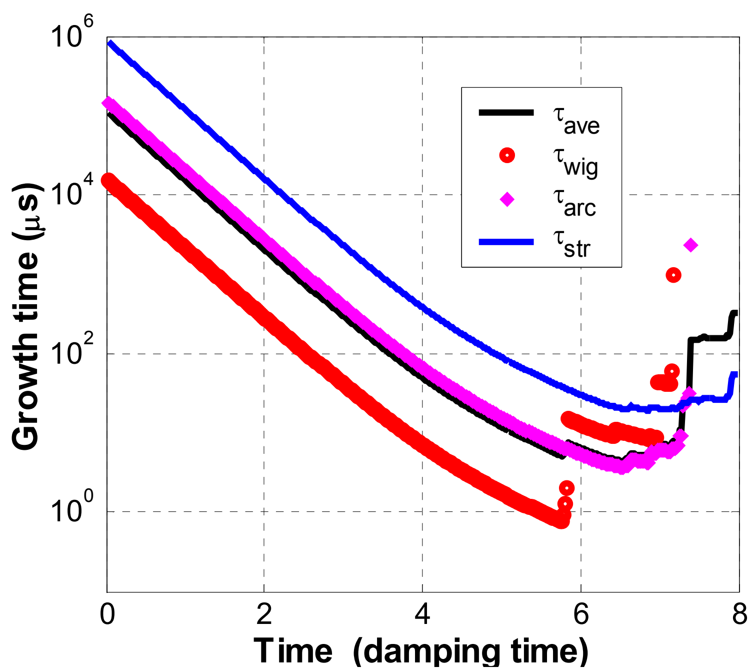
Fast Ion Instability

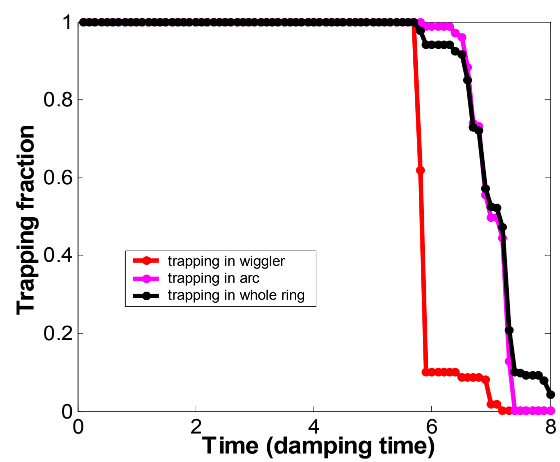
- Assuming there are different pressure at different section:

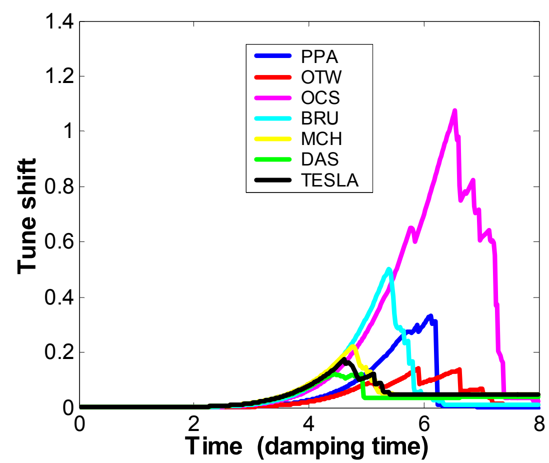
  Pwiggler=2nTorr; P_long_straight =0.1nTorr & P_arc=0.5nTorr

- Assuiming a tune spread of 0.3[G.V. Stupakov, Proc. Int. Workshop on Collective Effects and Impedance for B-Factories KEK Proc. 96-6 (1996) p243.]
- The growth rate has been estimated at each element and the effective growth rate at each section and the whole ring are calculated
- The trapping condition is considered when the growth time is calculated at each element.
- Coupling bump is applied in the long straight section
- The growth rate has been estimated during the whole damping time

Growth Time and Tune Shift for 6-km Damping Ring (OCS)







Comparison of Damping Rings

Ring	PPA	OTW	OCS	2OCS	BRU	MCH	DAS	TESLA
$\tau_{wiggler}$ (μs)	0.6	0.8	0.8	1.6	0.7	1.75	2.67	2.4
τ_{arc} (μs)	25	4.2	3.6	6.9	3.56	9.43	12.7	13.5
$\tau_{straight}$ (μs)		43	19	38	46	821(52)	929(54)	844(53)
τ_{ring} (μs)	2.6	8.7	4.4	8.3	3.2	20.8(20.5)	40.5(40.2)	44.3(43)
τ_{ring} in turns	0.28	0.81	0.22	0.2	0.15	0.39	0.71	0.76
Tune shift	0.33	0.2	1.05	1.0	0.5	0.22(0.69)	0.12(0.72)	0.17(0.9)

- Dependency on the circumference is not consistent
- Ring that has longer arcs is worse
- Ring that has larger beta function is worse

How Long for an Effective Ion Gap?

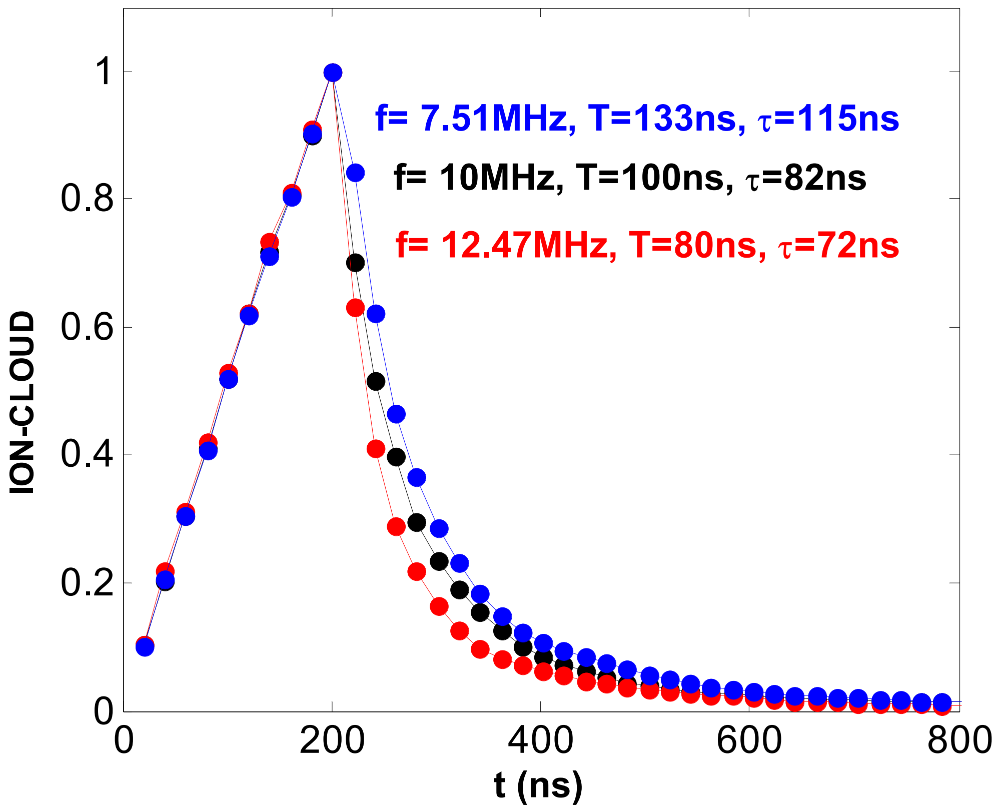
The diffusion time of ion-cloud is about 1 times of the ion oscillation period:

Wiggler section need a short gap

Light ion need a short gap.

Gap in PEPII HER:
40m(130ns) /2

(T_{co+}=110ns; T_{H+}=30ns)



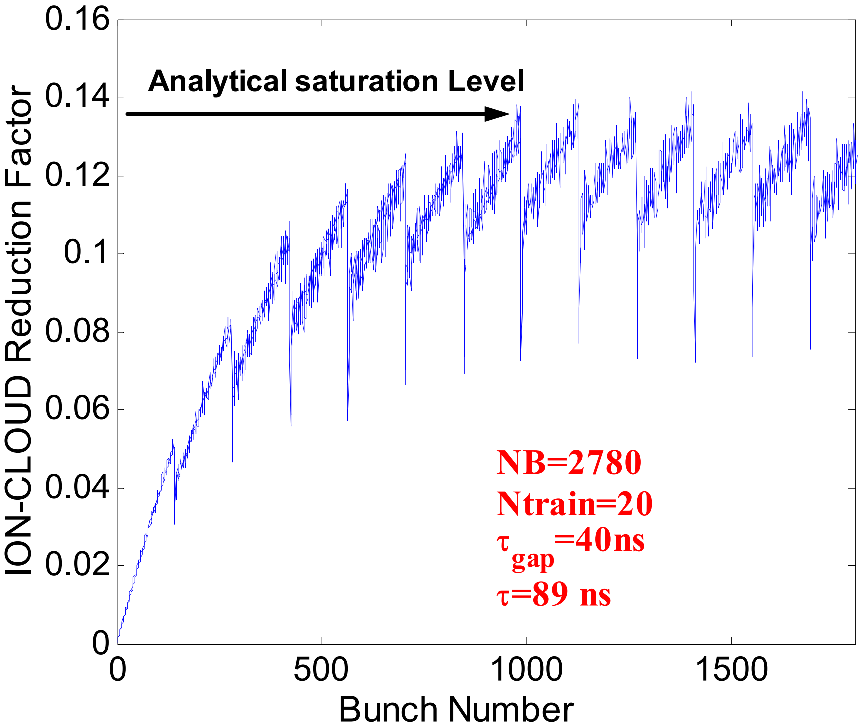
Build of Ions with Mini Bunch Train (20)

- A factor of 7.2 improvement with **20 mini-train**;

- More train will get more improvement

$$IRF \propto \frac{1}{Ntrain} \quad \text{(for fixed gap length)}$$

Just a sample! Every ring can has its different fill pattern!



Accumulation of Ion-cloud with mini-gaps

Conclusion of Fast Ion Instability

- Application of the linear theory to the existing rings (ATF, PLS, KEKB, PEP-II) shows a reasonable agreement between the theory and observation.
- The effects depend on the bunch spacing and detail of the optics. In general longer arcs or higher beta function is worse.
- Mini-gaps is very helpful to reduce the growth time and tune shift. Number of bunches reduced due to the gaps is at a few percent level.
- Transverse feedback is necessary even with mini-gaps to control the instability.