Lattices and Multi-Particle Effects in ILC Damping Rings

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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

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

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

γ - Lorentz factor

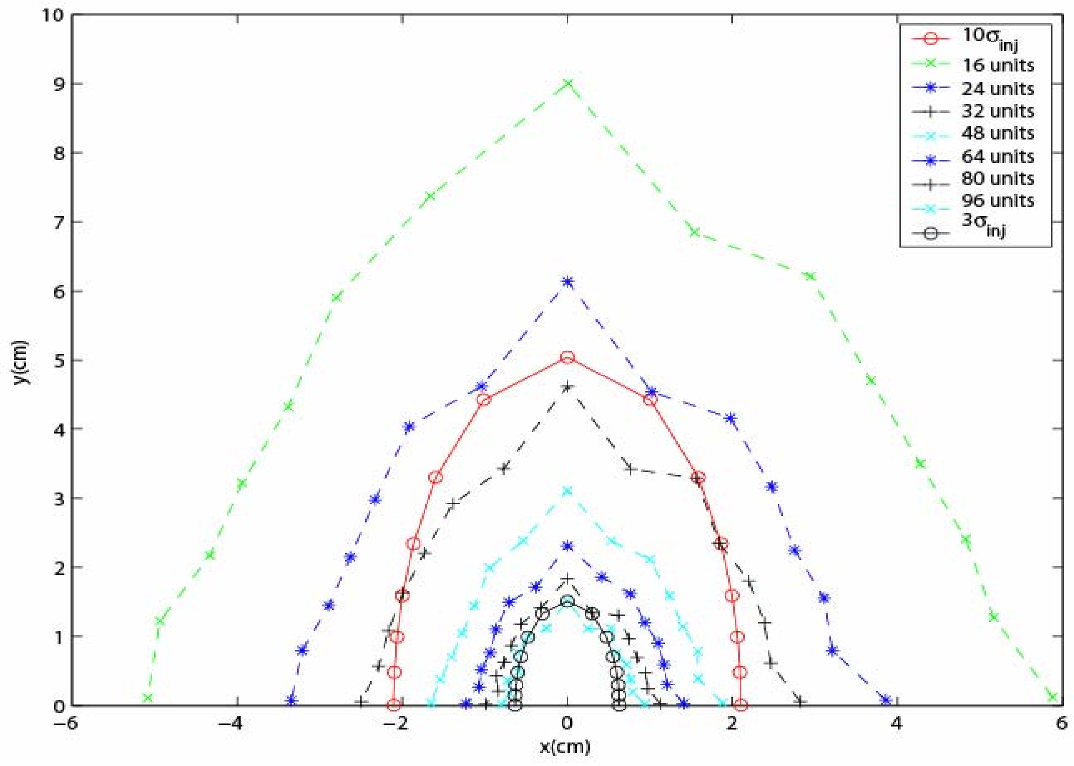
J_x - Partition number ~ 1

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

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

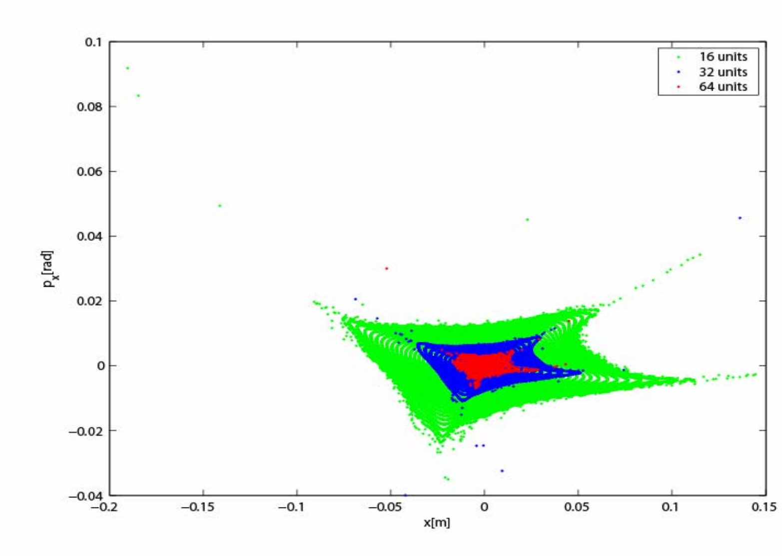
- Reduce energy
- Increase number of cell
- Choose a better cell
- Make dipole longer

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

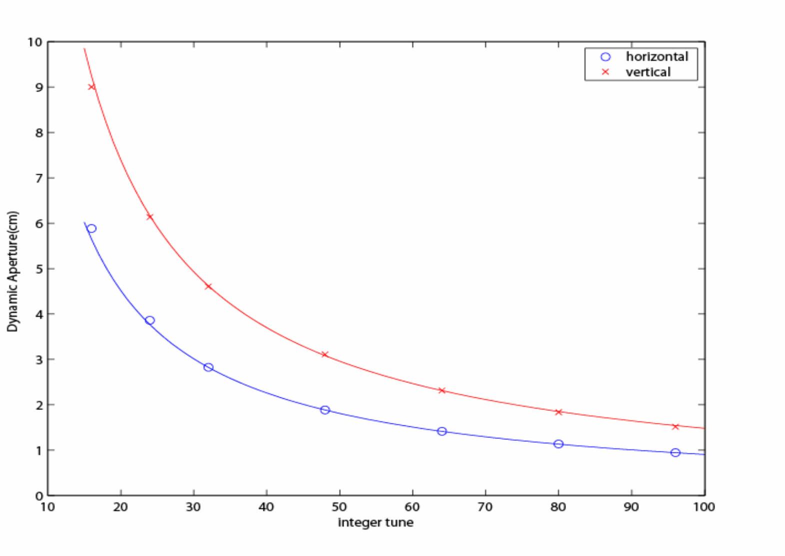


Dynamic aperture scales inversely proportional to the strength of the sextupoles! It is not so bad and it can be worse.

Scaling of Dynamic Aperture



scaling of phase space

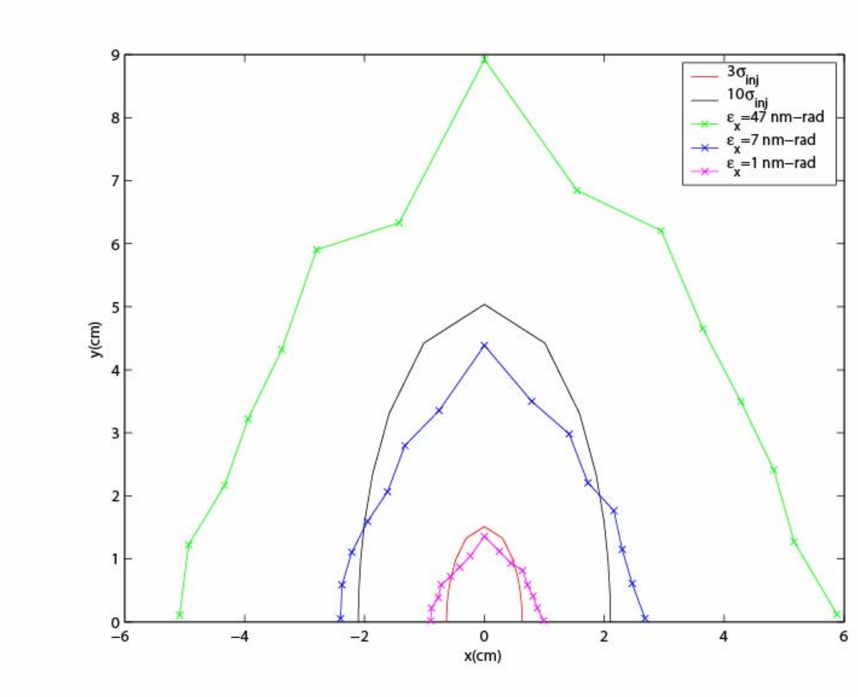


solid lines are inverse curves

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:

$$\varepsilon_x \to \varepsilon_x / 10$$

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

$$N_c \to 2.15 N_c$$

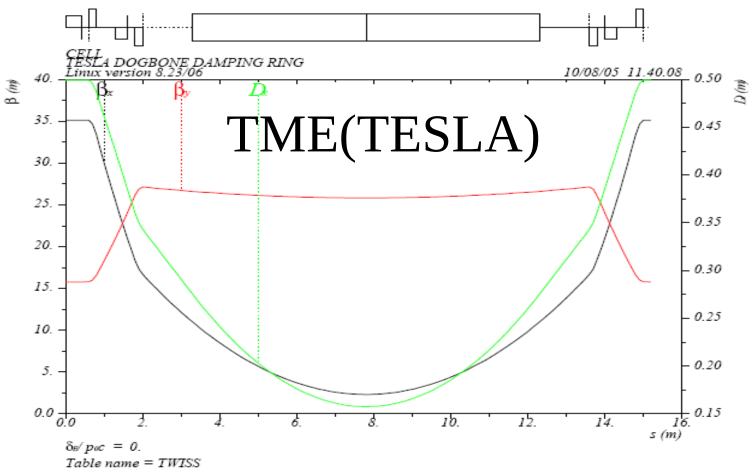
$$\rho_{dip\to} 2.15 \rho_{dip}$$

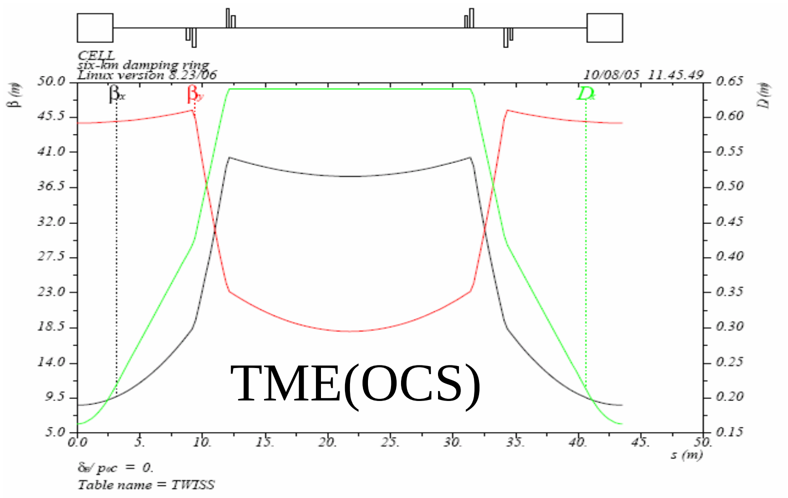
$$\eta_x \to \eta_x / 2.15$$

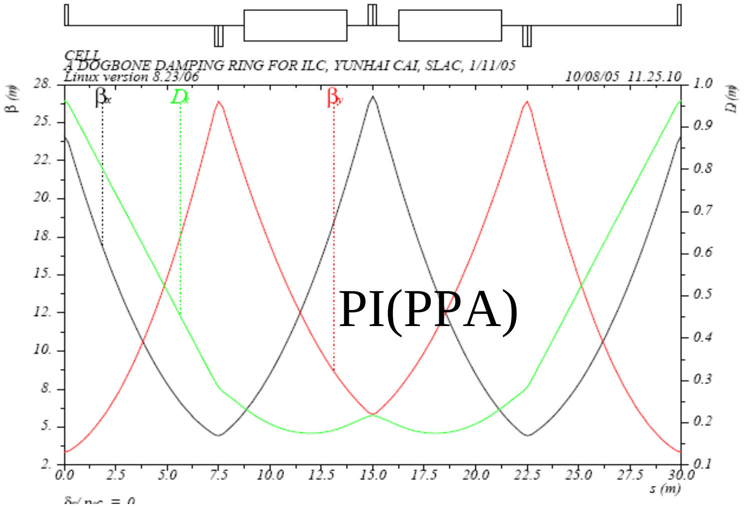
$$SF, SD \to 2.15(SF, SD)$$

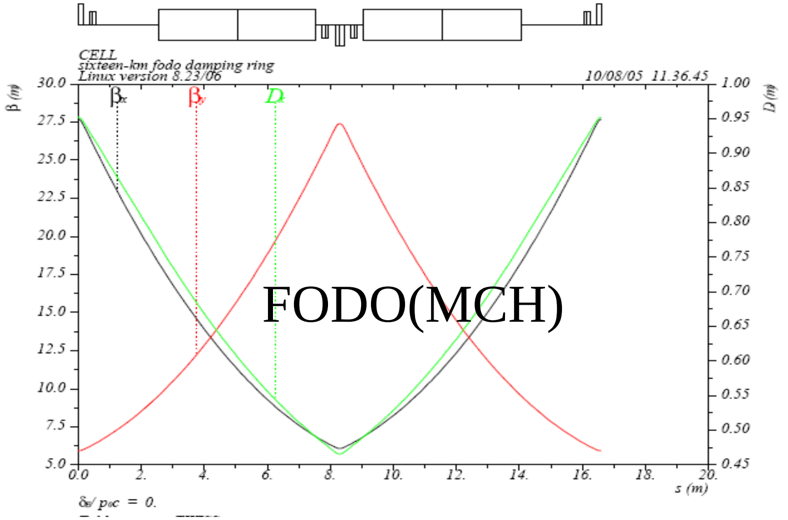
$$DA \to DA / 2.15$$

Cells Used in ILC Damping Rings


TME(TESLA)

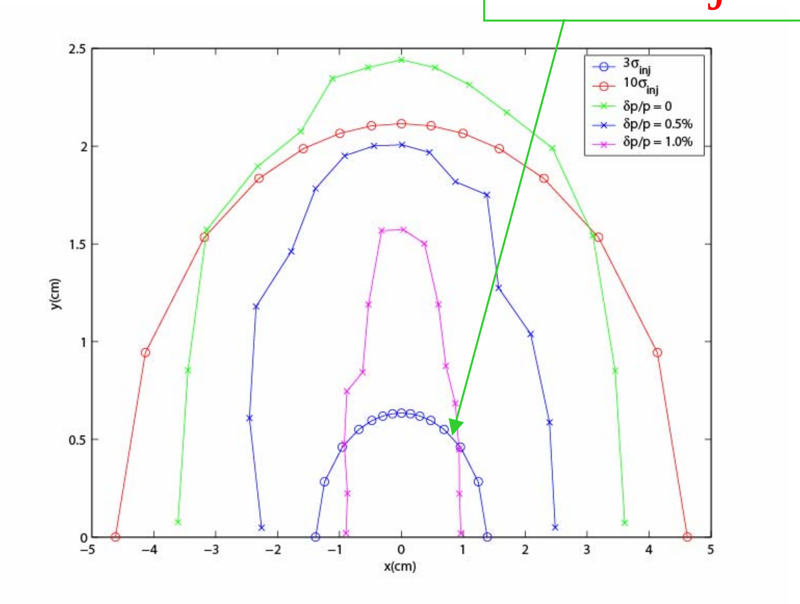

TME(OCS)


PI(PPA)

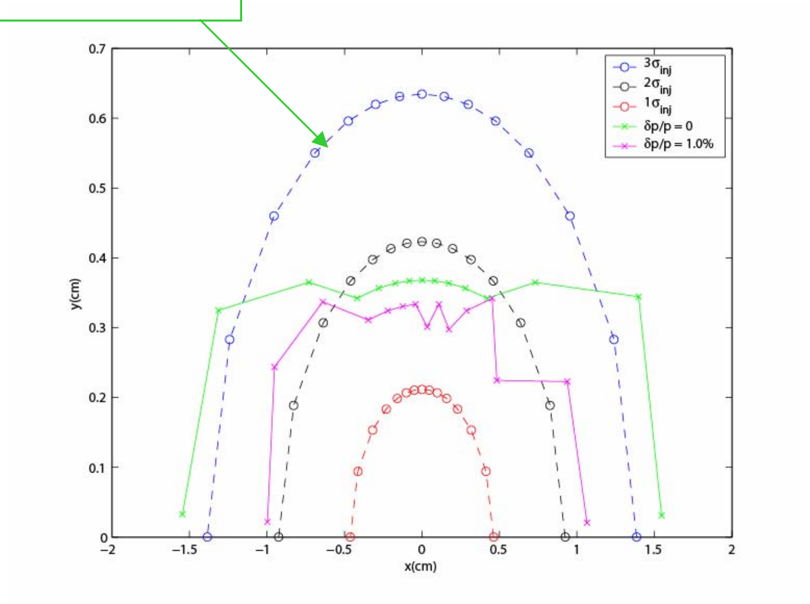

FODO(MCH)

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:

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

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D.O.E.

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

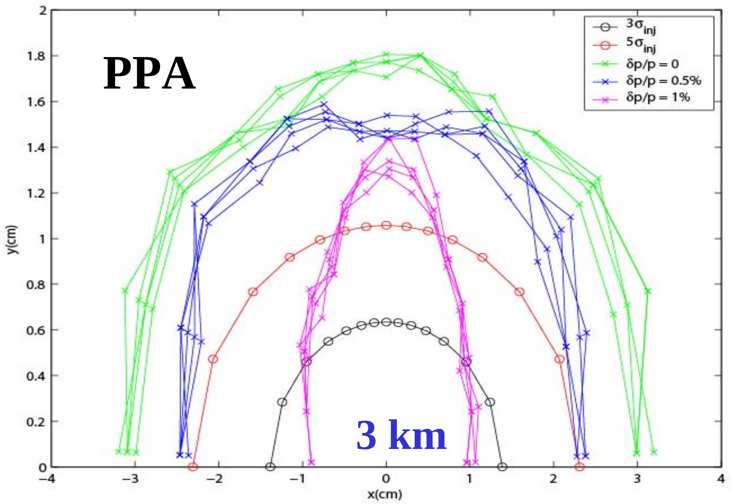
Tune vs. Amplitude and Energy Deviation

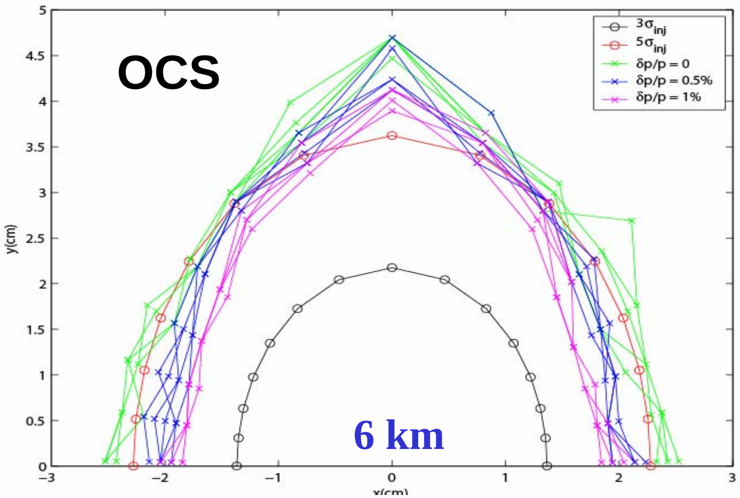
NAME	$\frac{\partial\nu_x}{\partial\varepsilon_x}$	$\frac{\partial\nu_y}{\partial\varepsilon_y}$	$\frac{\partial\nu_x}{\partial\varepsilon_y},\frac{\partial\nu_y}{\partial\varepsilon_x}$	$\frac{\partial^2\nu_x}{\partial\delta^2}$	$\frac{\partial^3\nu_x}{\partial\delta^3}$	$\frac{\partial^2\nu_y}{\partial\delta^2}$	$\frac{\partial^3\nu_y}{\partial\delta^3}$
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

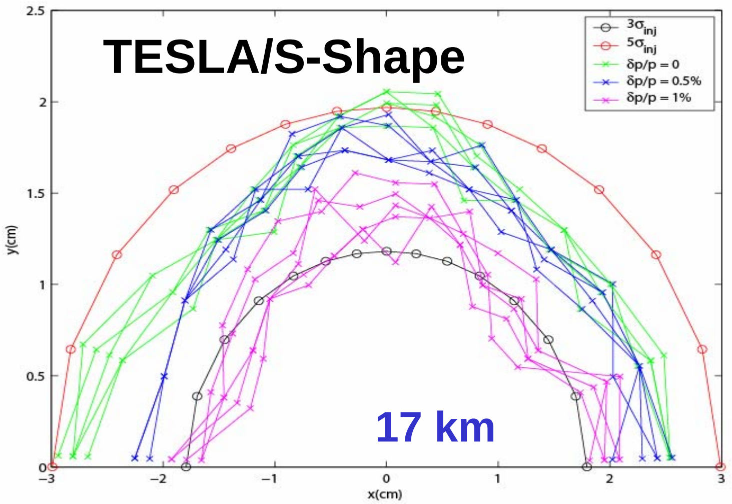
Clearly, the OCS lattice has the best chromatic properties.

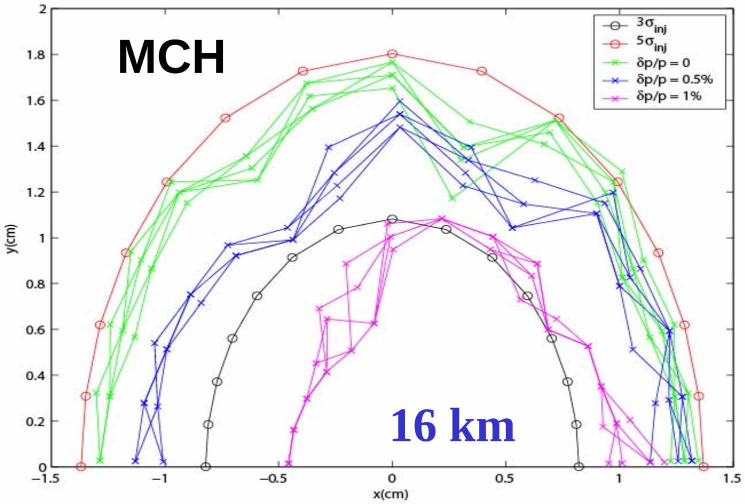
Dynamic Aperture with Mutilpole Errors and Single-Mode Wigglers

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









Conclusion of Acceptance Study

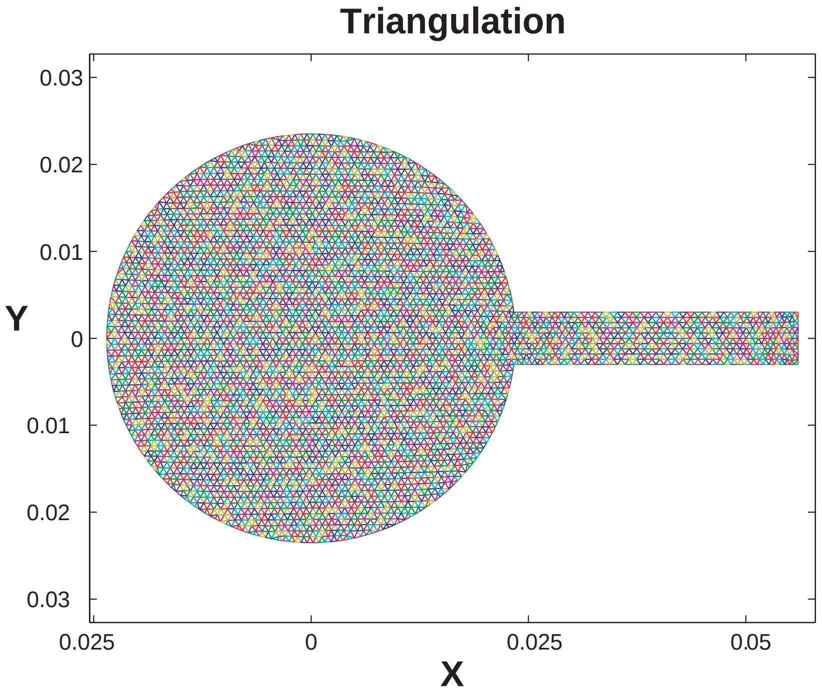
- Well optimized wigglers do not cause much degradation of dynamic aperture
- It is challenge but achievable to design a lattice with adequate dynamic aperture for a very large injected positron beam. More attention has to be paid to the energy acceptance
- Lattice with many super periods has advantage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

Issues Due to Electron Clouds

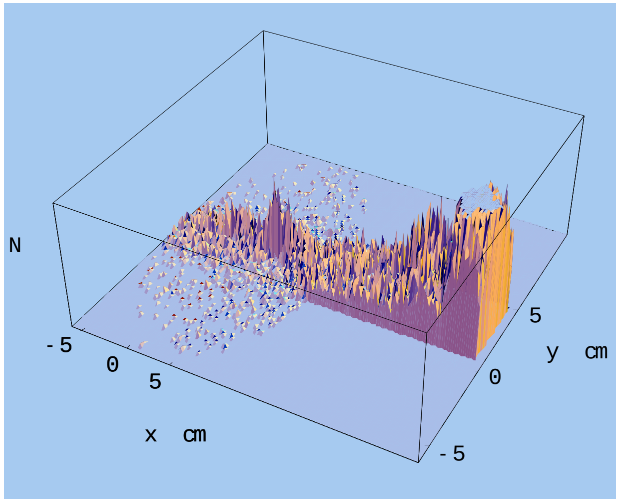
- How electron clouds are generated?
  - Photoelectron build-up
    - Synchrotron radiation
    - Geometry of bending
    - Antechamber
    - Reflectivity
    - Secondary eletrcon yield (SEY)
  - Multipacting of electrons
    - Solenoid wining in straight sections
- What are the effects on the positron 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

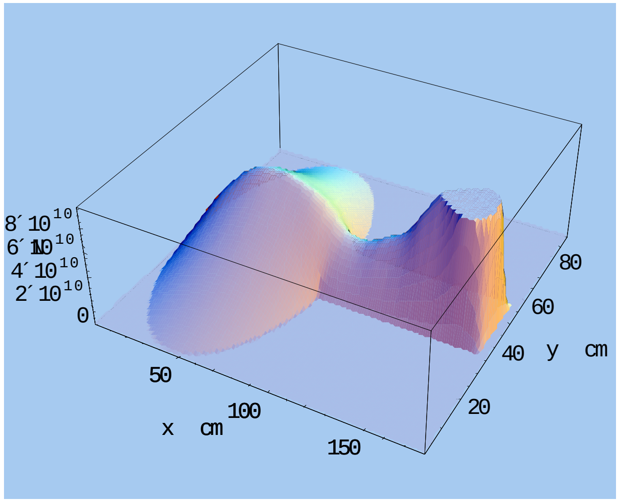
- Mesh



ρ_e

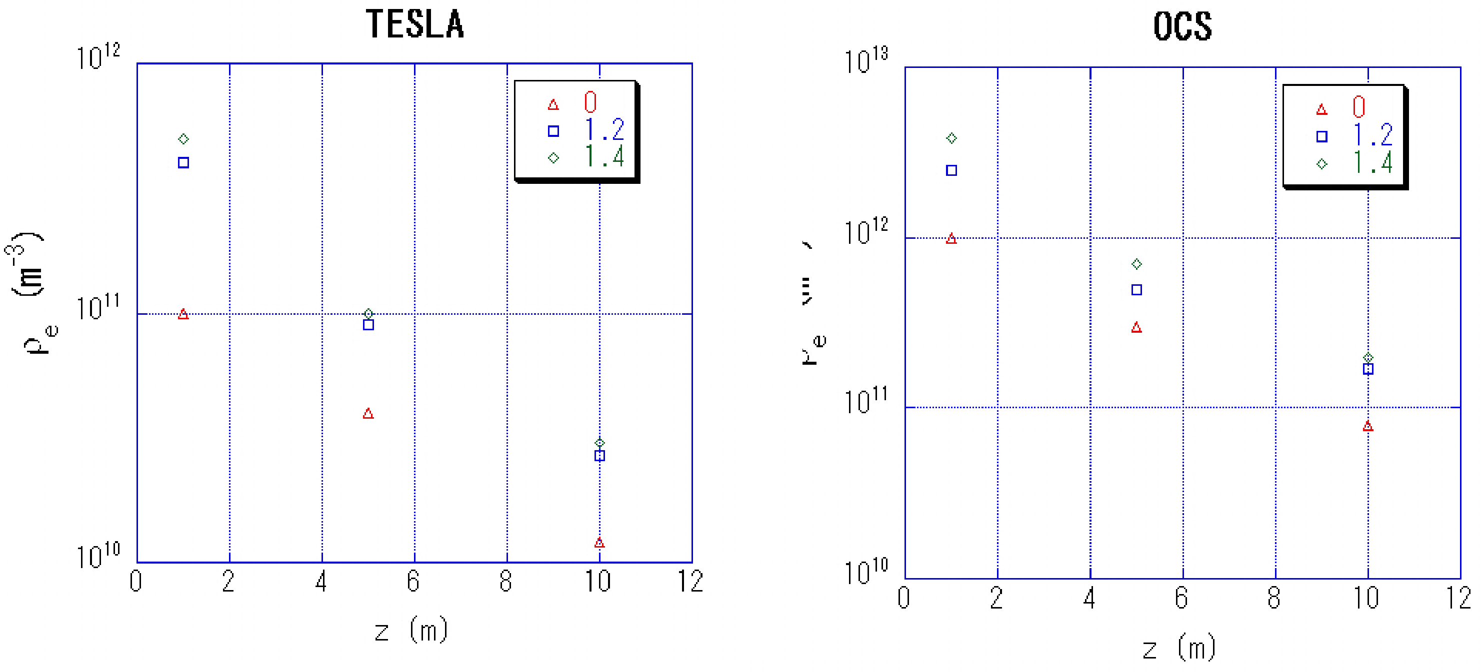


ϕ_{cloud}



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

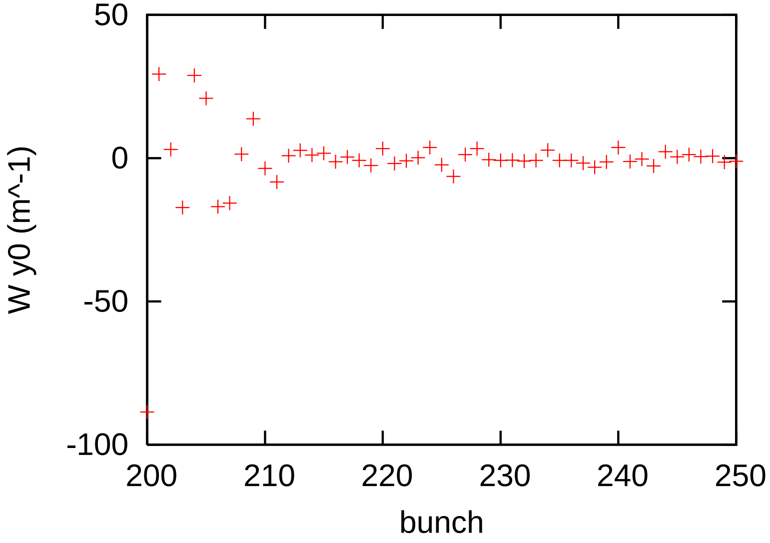
Density of Electron Cloud in Arcs

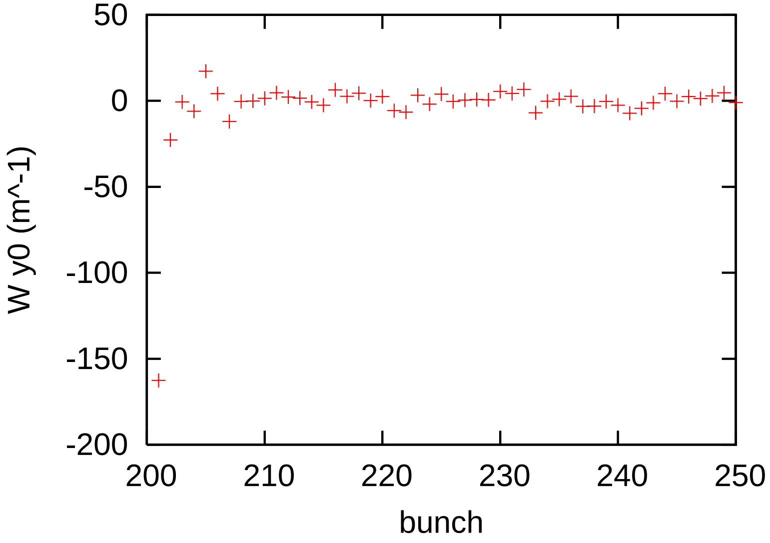


r =1 mm as a function of z.

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.

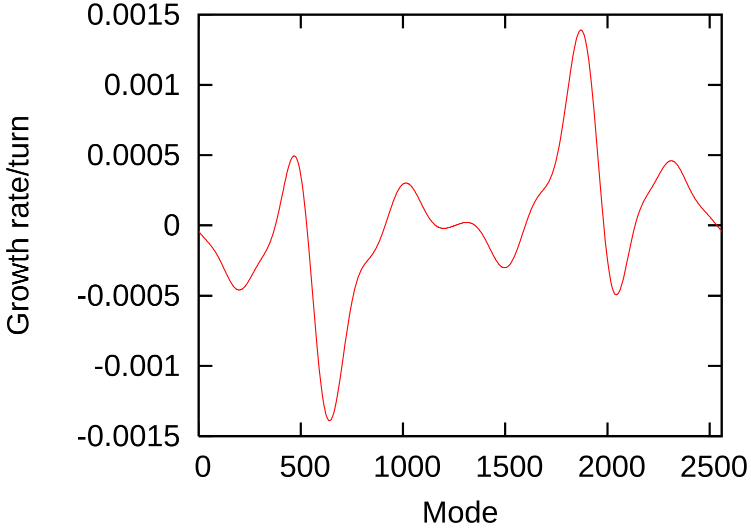




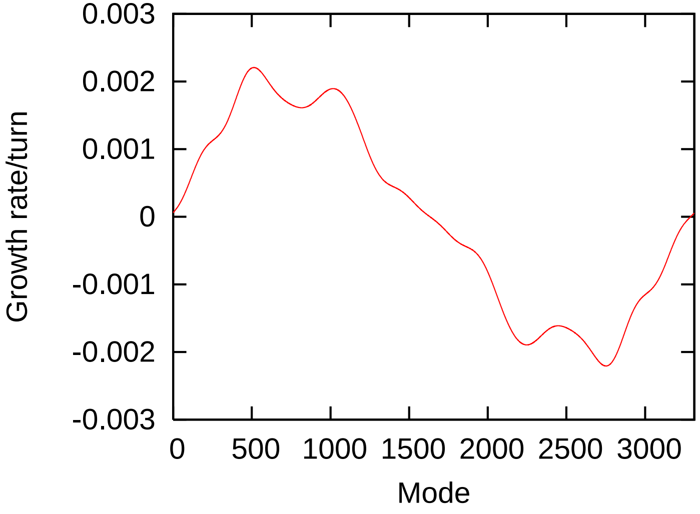
Growth rate of the coupled bunch instability

- 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.

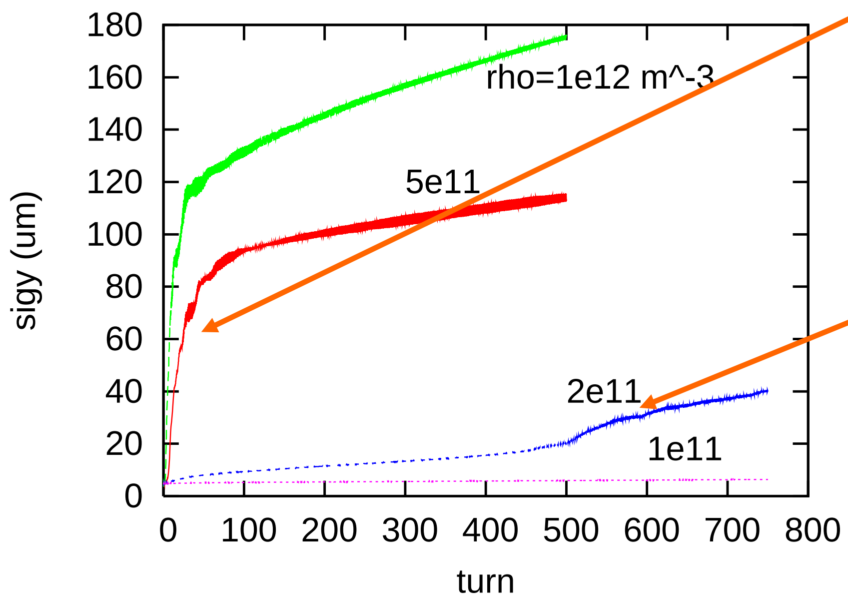
- Threshold of the instability based of linear theory

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

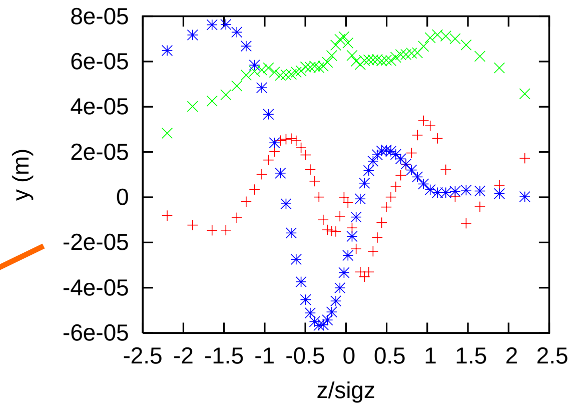
- Q=min(Q_{nl}, $\omega_e \sigma_z/c$)
  Q_{nl}=5-10? Depending on the nonlinear interaction
- K~3 Cloud size effect.
- $\omega_e \sigma_z/c$~12-15 for damping rings.

Simulation for OCS Lattice

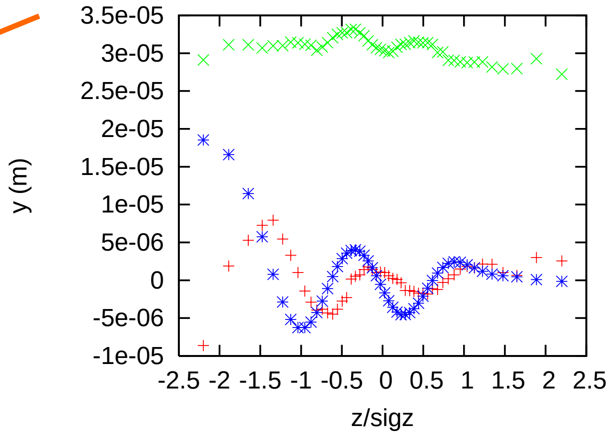
- Clear head-tail signal was observed ρ_e=$2x10^{11}$ m^{-3} and more.
- Threshold $\rho_{e,th}$=$2x10^{11}$ m^{-3}



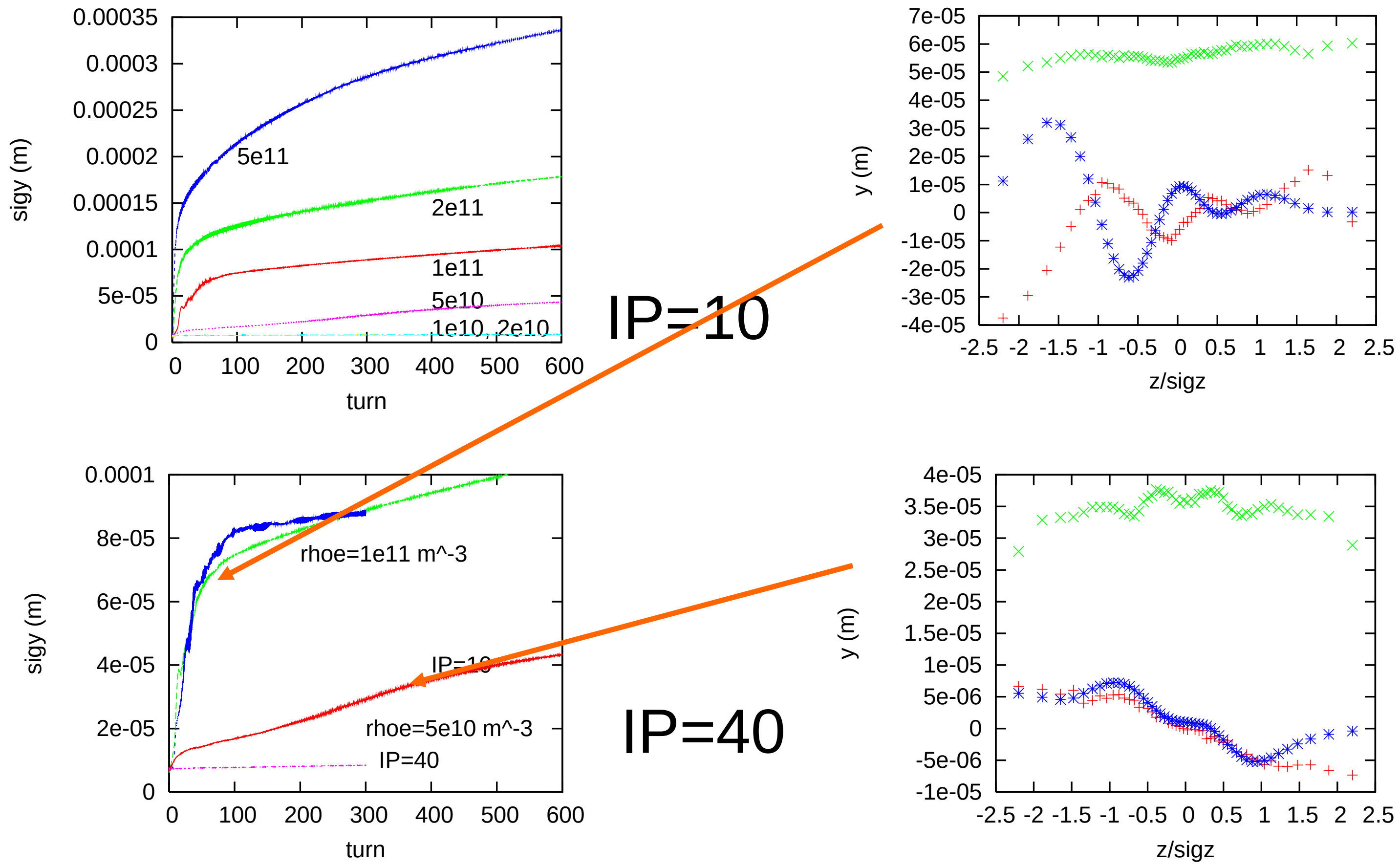
ρ_e=$5x10^{11}$ m^{-3}



ρ_e=$2x10^{11}$ m^{-3}



Simulation for TESLA Lattice



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

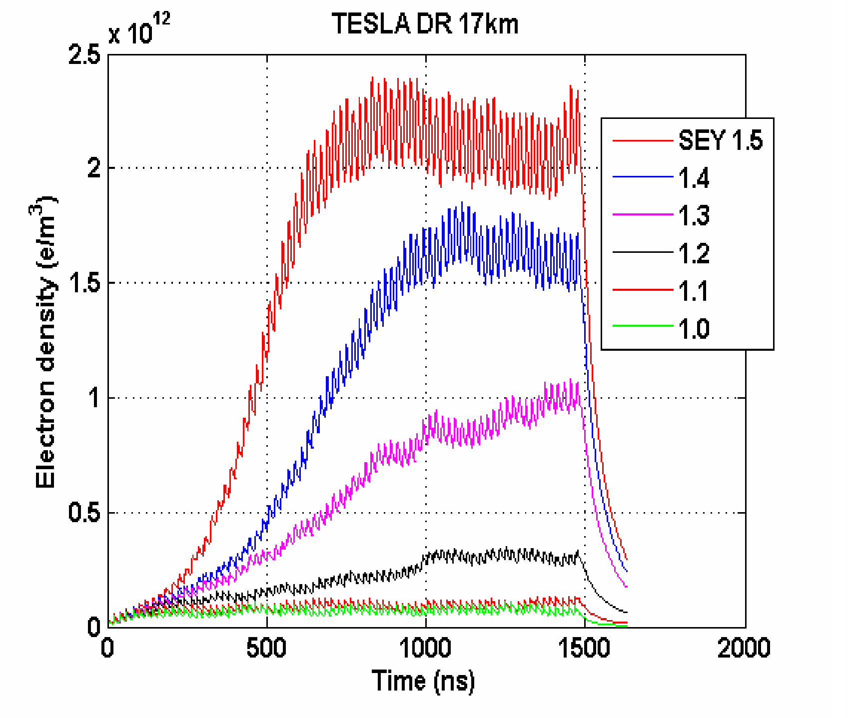
Simulation vs. Linear Theory?

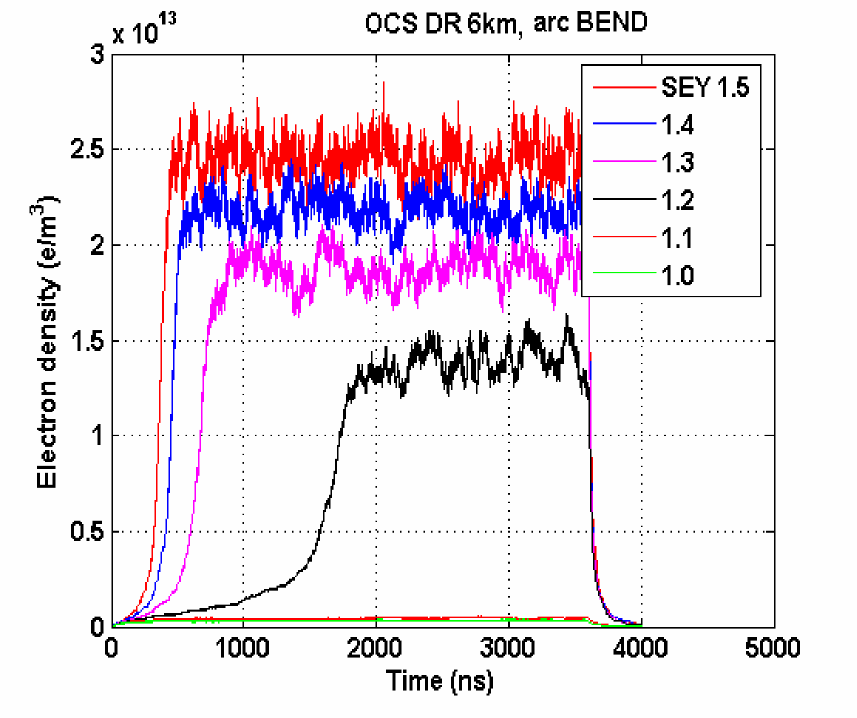
- The threshold density

	simulation	linear theory
OTW	$\rho_{e,th}$=5x10^{11} m^{-3}	(1.8x10^{12})
OCS	=2x10^{11} m^{-3}	(7.4x10^{11})
TESLA	=1x10^{11} m^{-3}	(4.5x10^{11})

- 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.

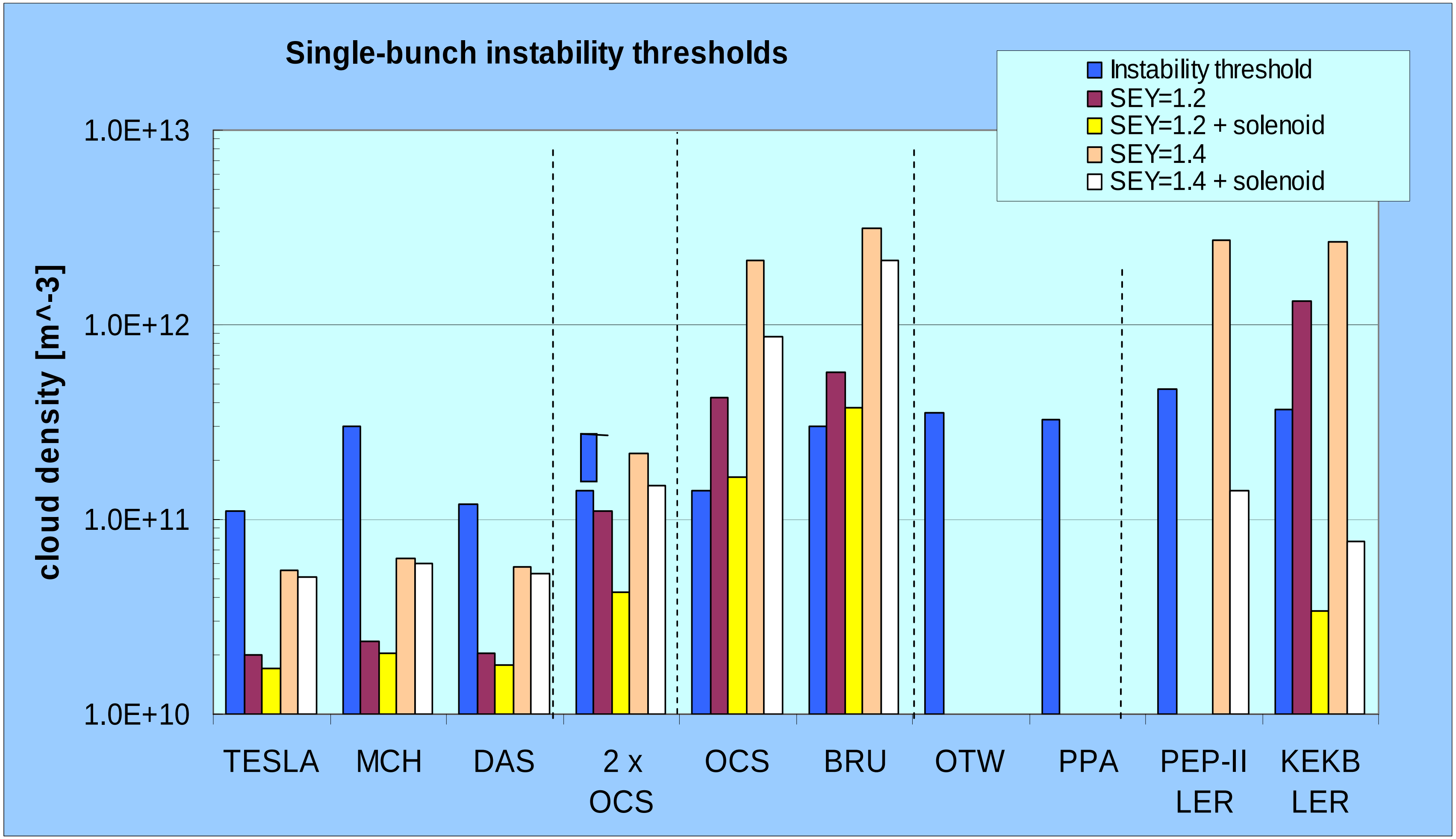
Production of Electron Cloud in Bending Magnets


TESLA DR 17km


OCS DR 6km, arc BEND

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

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

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

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

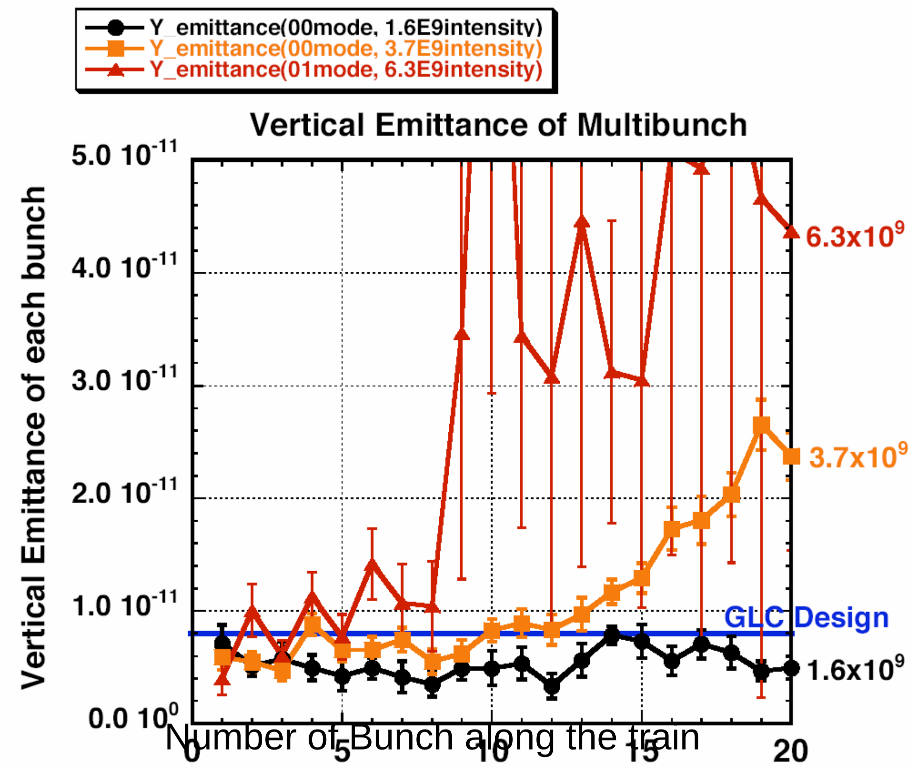
coherent tune-shift due to ions:

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

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

ATF Measurement, Simulation, and Calculation

Radiation damping time is about 30ms



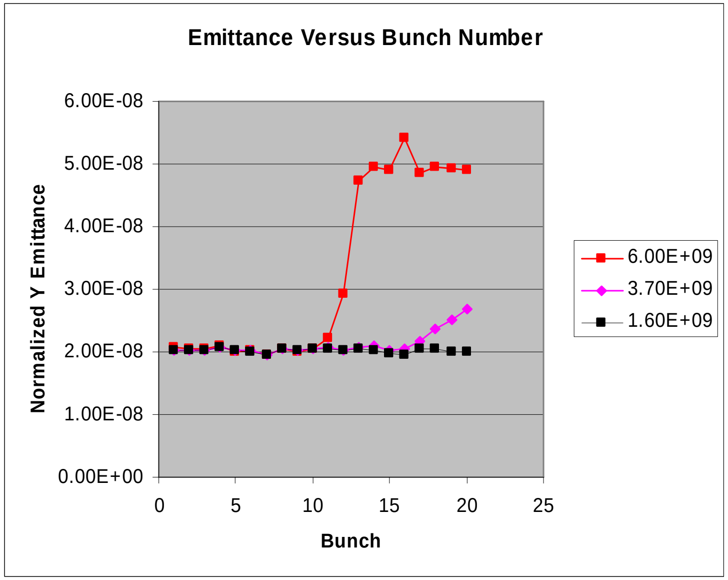
Beam size blow-up at ATF (experiment)

Nbunch=20, P=10nTorr

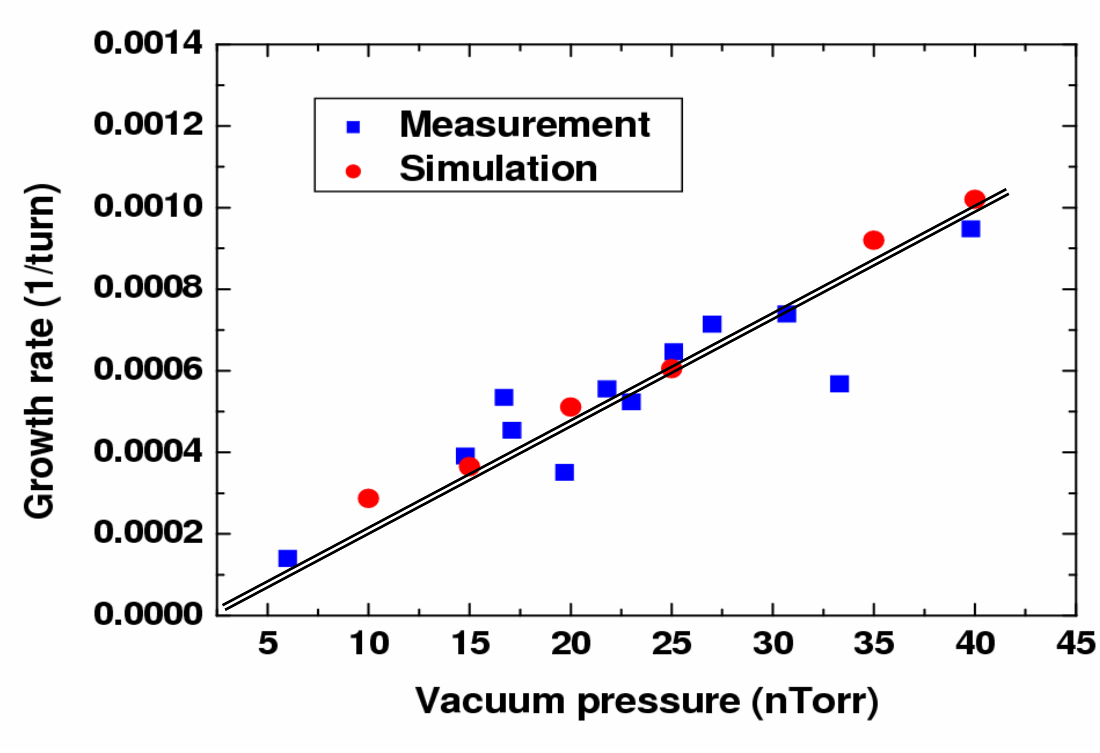
Calculated Growth time and Tune-shift

(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



T_{exp}=98.2 μs

T_{simu}=91 μs

$T_{calcuated}$=98 μs

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

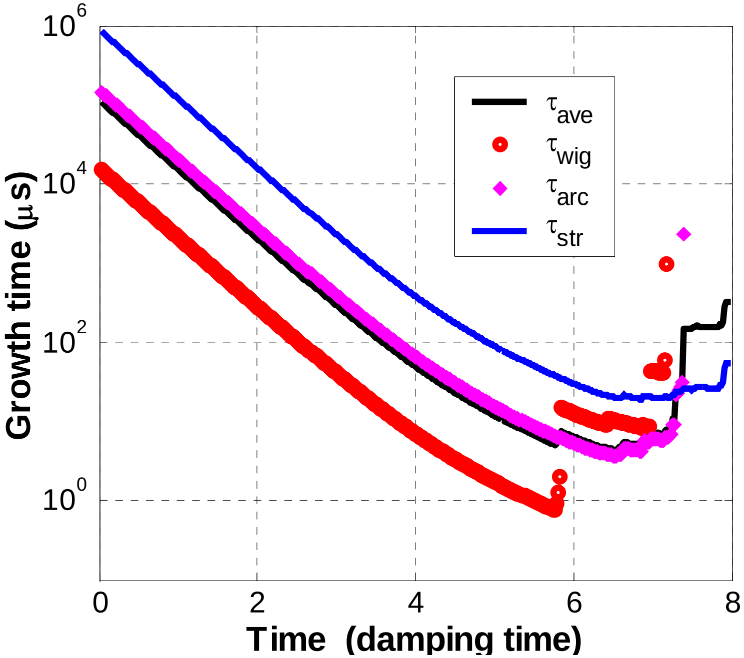
$\tau_{calculated}$=1.15ms, ΔQ_{cal}=0.0008;

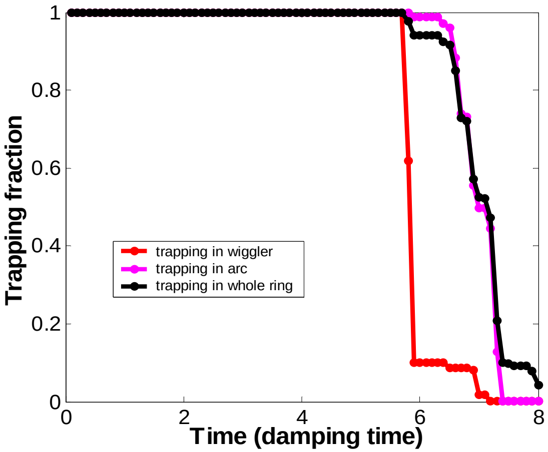
Fast Ion Instability

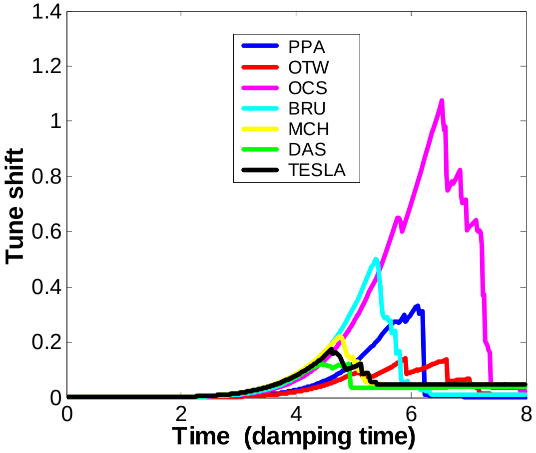
- Assuming there are different pressure at different section:

  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	2OC S	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:

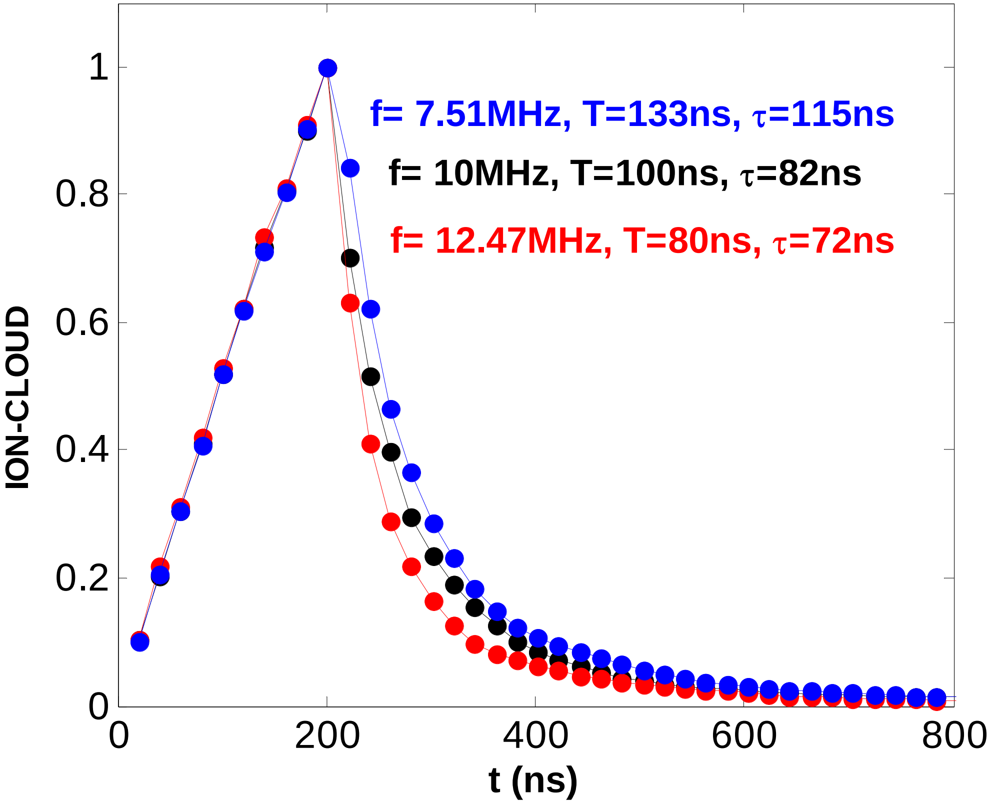
Wiggler section need a short gap

Light ion need a short gap.

Gap in PEPII HER:

40m(130ns) /2

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



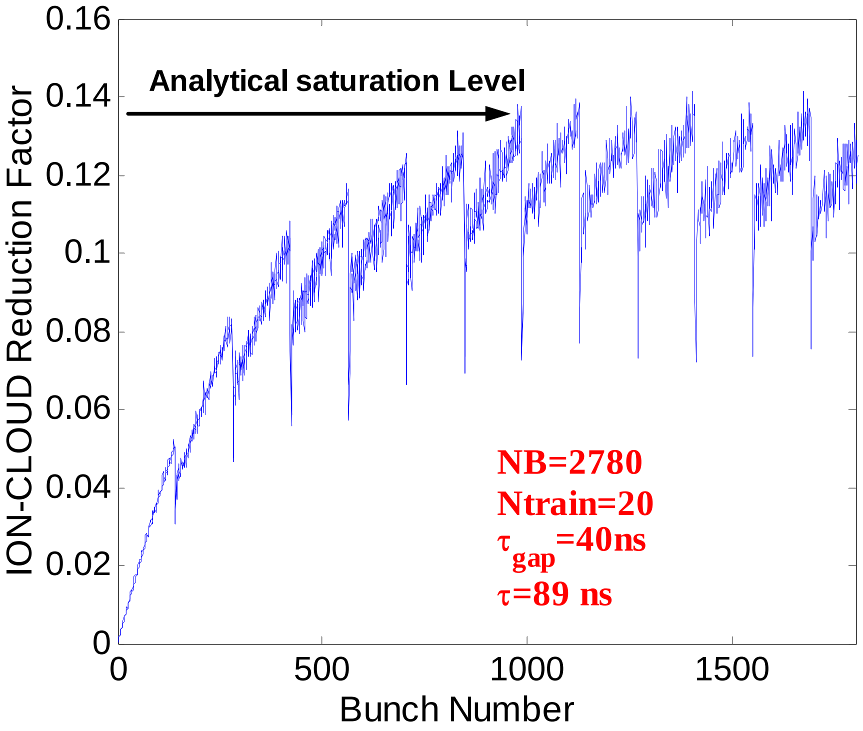
Build of Ions with Mini Bunch Train (20)

- 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.

Low-Emittance Beams and Collective Effects in the ILC Damping Rings

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Super-B Factory Meeting,
Laboratori Nazionali di Frascati

November 12, 2005

Comparison of parameters

	ILC Damping Rings	Super B-Factory
Circumference	3 km – 17 km	2.2 km
Beam energy	5 GeV	3.5 GeV
Horizontal emittance	0.8 nm	0.1 nm
Vertical emittance	2 pm	1 pm
Bunch length	6 mm	2 mm
Bunch charge e^+ / e^-	2×10^{10} / 2×10^{10}	4×10^{10} / 8×10^{10}

Notes:

Super B-Factory parameters from P. Raimondi, “Exotic approach to a Super B-Factory,” presented at Super B-Factory Workshop, Hawaii, April 2005.

Parameters are for the flat-beam case, $L = 10^{36}$ cm^{-2}s^{-1}

Bunch length 2 mm (in the ring) assumes factor 20 compression between ring and IP.

There are several common issues and concerns, including:

Tuning for low vertical emittance

- Best achieved vertical emittance is ~ 4 pm (at KEK-ATF).
- ILC DR's require 2 pm, Super B-Factory parameters assume 1 pm.

Intrabeam scattering

- IBS causes emittance growth; growth rates scale strongly with energy, linearly with bunch charge, and inversely with beam sizes and bunch length.

Touschek lifetime

Space-charge tune shifts

- Can cause emittance growth and particle loss.

Microwave instability

Coupled-bunch instabilities

- Can be suppressed using bunch-by-bunch feedback systems.

Electron cloud, ion effects

- - see Yunhai's talk.

Damping ring configuration options

Studies of a number of different damping ring configuration options have been performed over the past several months.

The configuration studies have focused on beam dynamics issues in seven “representative” lattice designs:

Lattice Name	Energy [GeV]	Circumference [m]	Cell Type
PPA	5.0	2824	PI
OTW	5.0	3223	TME
OCS	5.0	6114	TME
BRU	3.7	6333	FODO
MCH	5.0	15935	FODO
DAS	5.0	17014	PI
TESLA	5.0	17000	TME

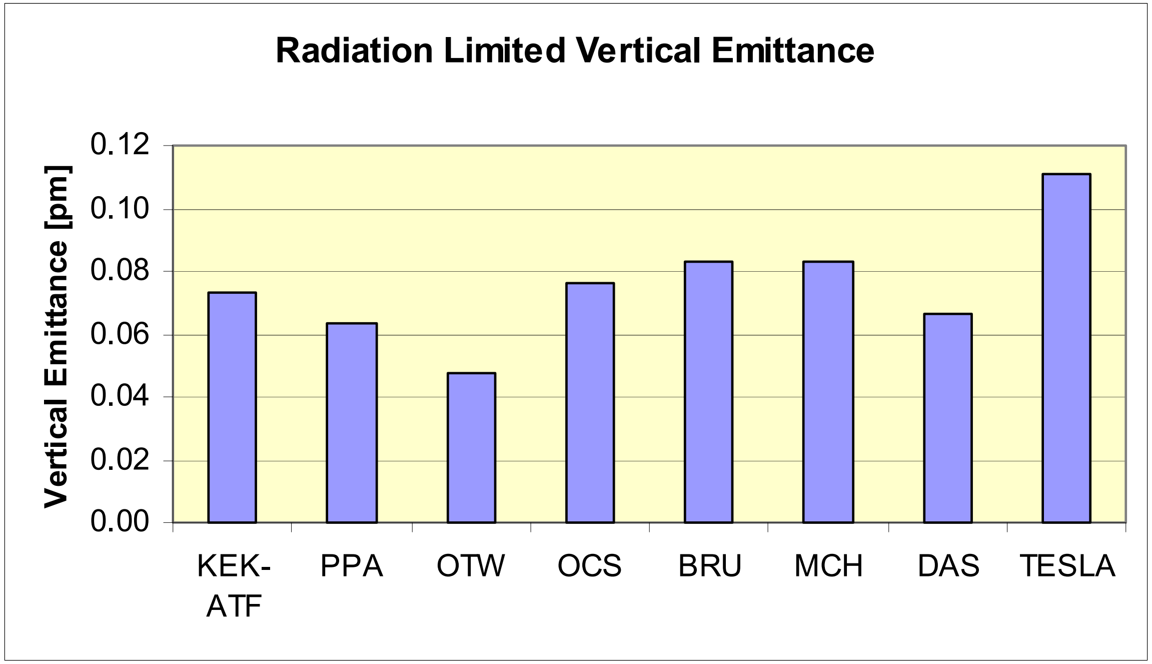
Vertical emittance has a fundamental limit from SR

Vertical opening angle of the synchrotron radiation places a fundamental lower limit on the vertical emittance.

The fundamental limit depends on lattice design, and not on beam energy.

In the ILC damping rings, the lower limit is of order 0.1 pm

- 1 pm looks ok from point of view of fundamental limits



$$\varepsilon_{y,SR} = \frac{13}{55}\frac{C_q}{J_y I_2}\oint \frac{\beta_y}{|\rho|^3} ds$$

Vertical emittance is mostly generated by alignment errors

Vertical emittance is generated by vertical dispersion and betatron coupling

Dominant sources are:

- vertical beam offset in sextupoles
- quadrupole tilts about the beam axis

We can characterize the sensitivity of a lattice to magnet alignment errors, as the magnet misalignment, starting from a perfect machine, that will generate the nominal vertical emittance.

Larger values are better (indicate a lower sensitivity to magnet misalignments)

Sensitivity estimates do not take into account tuning and coupling correction.

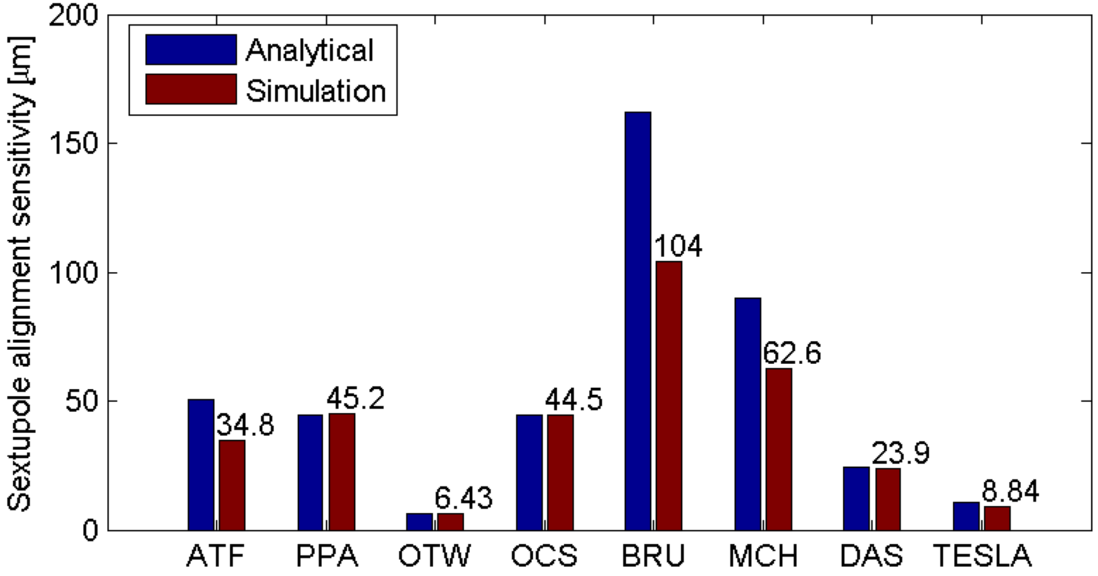
Sensitivity values should not be interpreted as tolerances on survey alignment.

These sensitivity values simply indicate the likely difficulty of achieving a given emittance, and the frequency with which tuning will need to be performed.

Damping Ring sensitivity to sextupole misalignments

$$\frac{\varepsilon_y}{\langle Y_{sext}^2 \rangle} \approx \underbrace{\frac{J_x\left[1-\cos(2\pi\nu_x)\cos(2\pi\nu_y)\right]}{4J_y\left[\cos(2\pi\nu_x)-\cos(2\pi\nu_y)\right]^2}\Sigma_{2C}\varepsilon_x}_{\text{coupling}} + \underbrace{\frac{J_z\sigma_\delta^2}{4\sin^2(\pi\nu_y)}\Sigma_{2D}}_{\text{dispersion}}$$

$$\Sigma_{2C} = \sum_{sexts} \beta_x\beta_y(k_2L)^2 \qquad \Sigma_{2D} = \sum_{sexts} \beta_y\eta_x^2(k_2L)^2$$



Sensitivities are typically of the order of a few tens of microns.

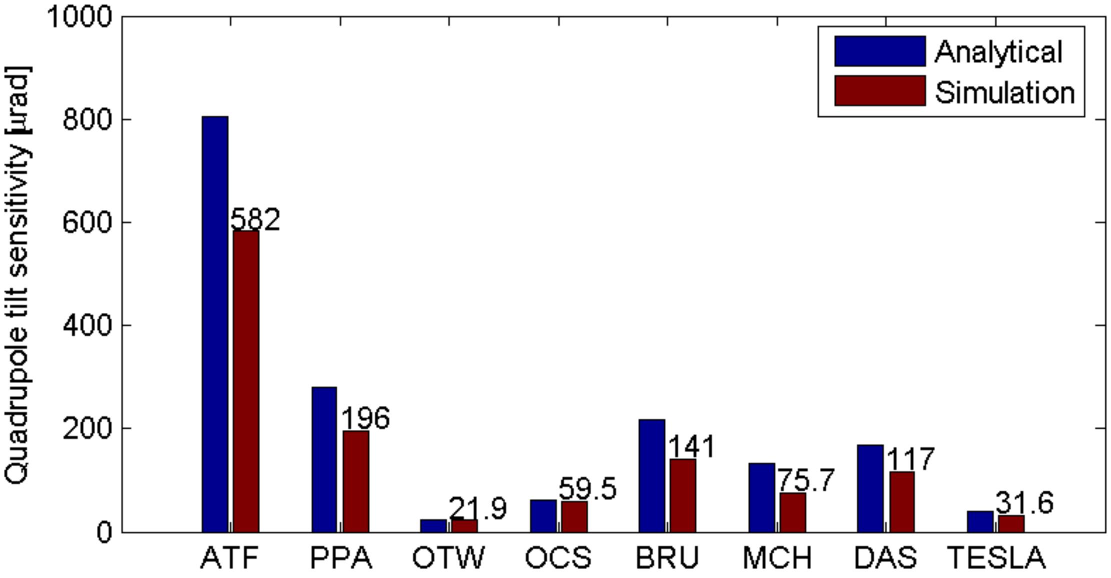
Note:

Horizontal emittance in Super-B Factory is 8 times lower than in damping rings, so a Super-B Factory could be less sensitive to sextupole misalignment than the damping rings.

Damping Ring sensitivity to quadrupole tilts

$$\frac{\varepsilon_y}{\left\langle \Theta_{quad}^2 \right\rangle} \approx \underset{\text{coupling}}{\boxed{\frac{J_x\left[1-\cos(2\pi\nu_x)\cos(2\pi\nu_y)\right]}{4J_y\left[\cos(2\pi\nu_x)-\cos(2\pi\nu_y)\right]^2}\Sigma_{1C}\varepsilon_x}} + \underset{\text{dispersion}}{\boxed{\frac{J_z\sigma_\delta^2}{4\sin^2(\pi\nu_y)}\Sigma_{1D}}}$$

$$\Sigma_{1C} = \sum_{quads}\beta_x\beta_y(k_1L)^2 \qquad \Sigma_{1D} = \sum_{quads}\beta_y\eta_x^2(k_1L)^2$$



Sensitivities are typically of the order of 100 µrad.

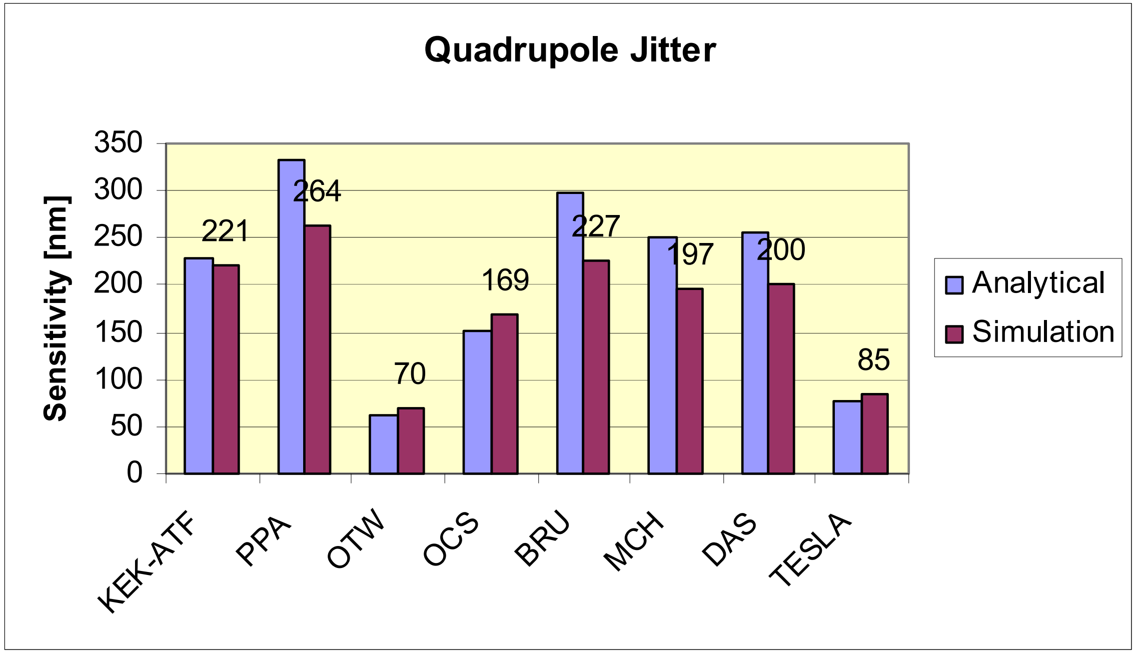
Note:

Horizontal emittance in Super-B Factory is 8 times lower than in damping rings, so a Super-B Factory could be less sensitive to sextupole misalignment than the damping rings.

Orbit jitter is also a concern

Quadrupole jitter sensitivity is the rms quadrupole misalignment that will generate an orbit distortion equal to the beam size.

$$\text{amplification factor} \approx \sqrt{\frac{\langle \beta_y \rangle \Sigma_{1O}}{8 \sin^2(\pi \nu_y)}} \qquad \Sigma_{1O} = \sum_{quads} \beta_y (k_1 L)^2$$



Sensitivities are typically of the order of 200 nm.

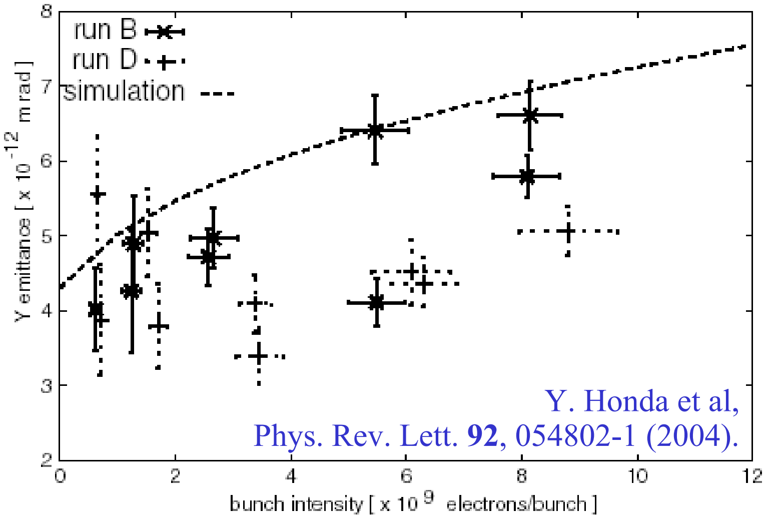
IBS increases the emittance with increasing bunch charge

Intrabeam scattering (IBS) can be a strong effect in low-emittance machines at low energy and high bunch charge.

Measurements from KEK-ATF have been used to benchmark the theories.

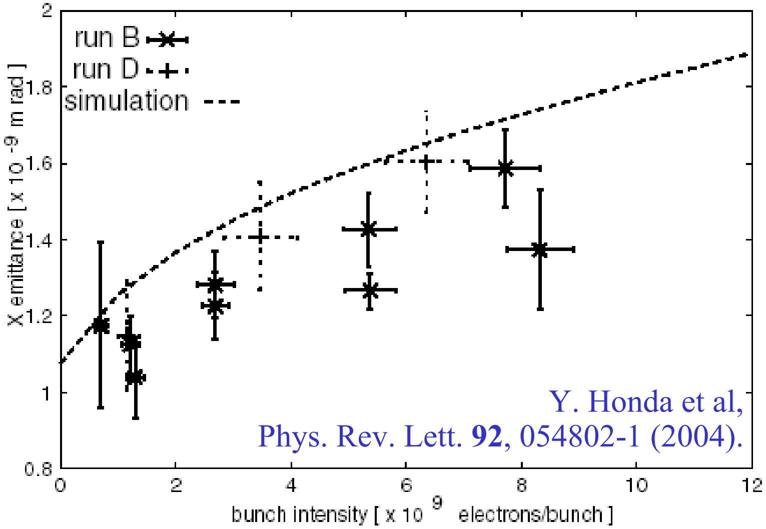
Accurate measurements with beam sizes ~ few μm are hard to make.

- Beam size at 4.5 pm is around 5 μm, and comparable to the size of the laser-wire itself.
- Measurements do not allow for beam jitter, but this should be small.



Y. Honda et al,
Phys. Rev. Lett. **92**, 054802-1 (2004).

FIG. 2. Current dependence of the vertical emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

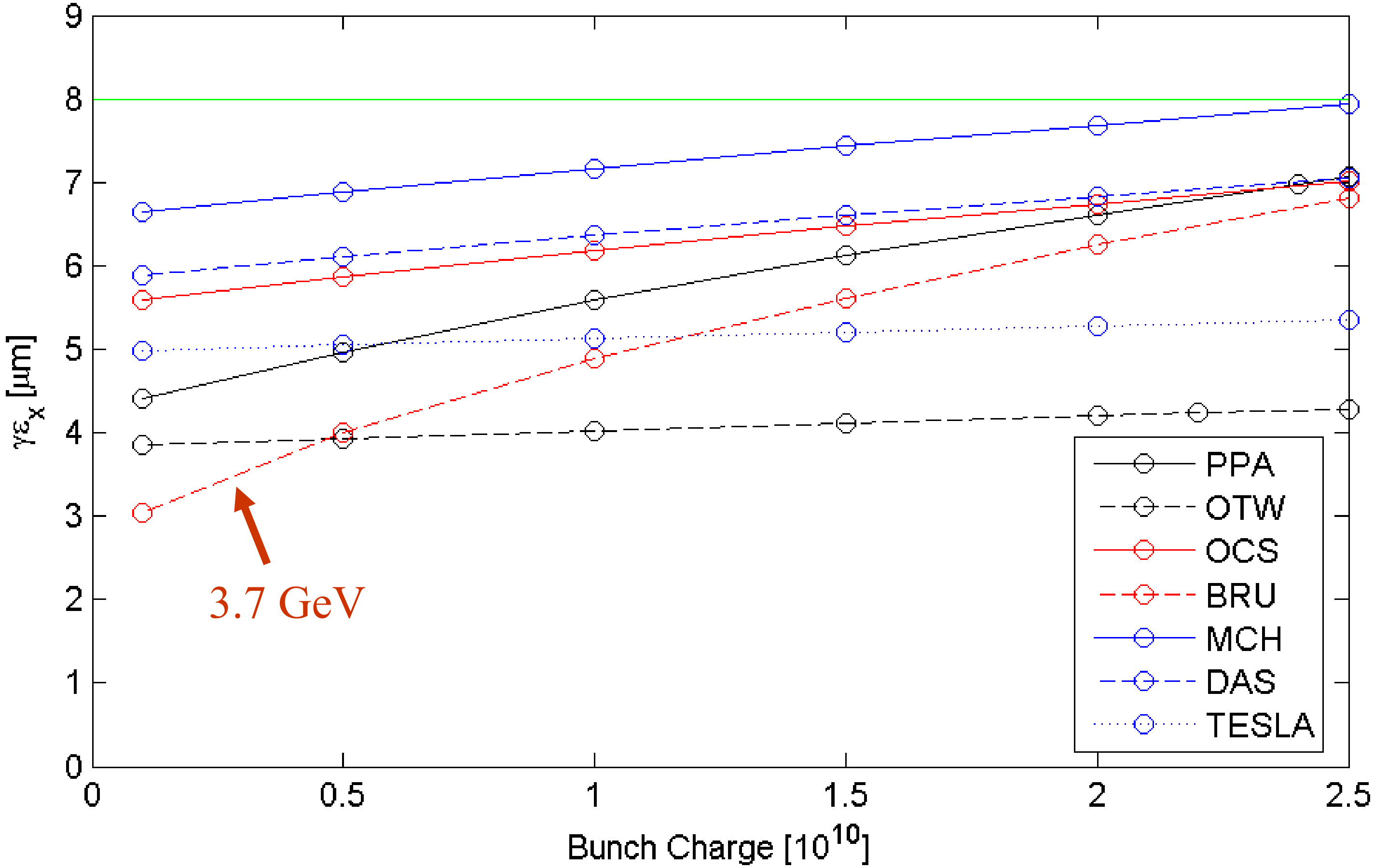


Y. Honda et al,
Phys. Rev. Lett. **92**, 054802-1 (2004).

FIG. 3. Current dependence of the horizontal emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

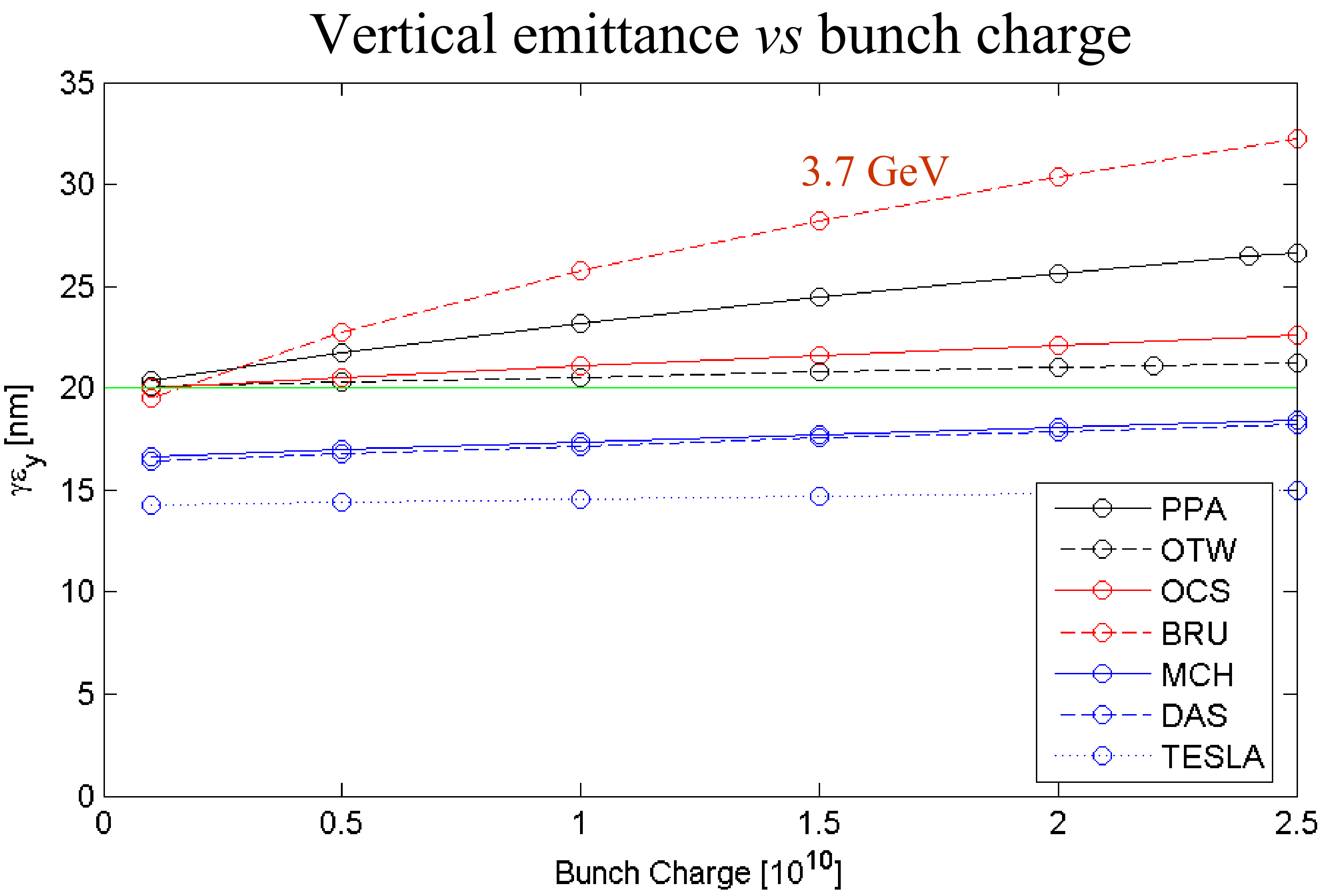
IBS will increase emittance in the ILC damping rings

Horizontal emittance *vs* bunch charge

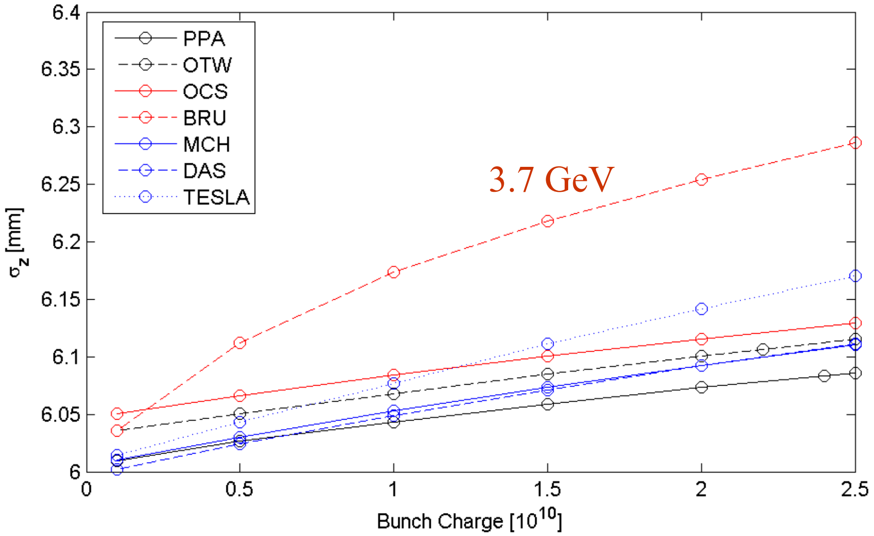


3.7 GeV

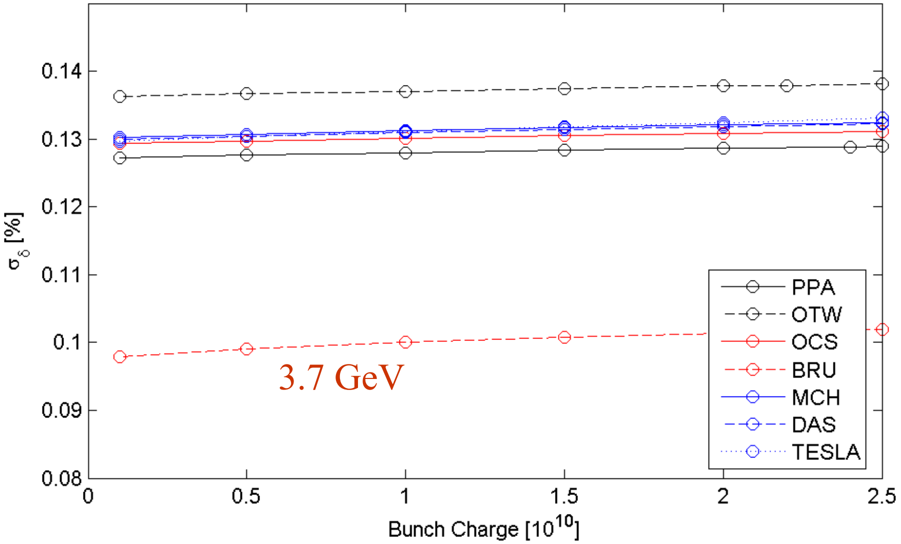
IBS will increase emittance in the ILC damping rings



IBS growth is less severe longitudinally than transversely



Bunch length *vs* bunch charge



Energy spread *vs* bunch charge

Intrabeam scattering scales strongly with energy

Emittance growth is largest in horizontal plane

Growth mechanism is analogous to quantum excitation: energy change resulting from particle scattering at locations of high dispersion leads to large betatron oscillations.

Growth rates ~ $1/E^6$ (for fixed bunch length and vertical emittance):

$$\frac{1}{T_\delta} \approx \frac{r_0 c^2 N(\log)}{16\gamma^3 \left(\varepsilon_x \varepsilon_y\right)^{3/4} \sigma_z \sigma_\delta^2} \left\langle \frac{\sigma_H}{\sigma_\delta} g\left(\sqrt{\frac{\beta_x \varepsilon_y}{\beta_y \varepsilon_x}} \right) \left(\beta_x \beta_y\right)^{-1/4} \right\rangle$$

$$\frac{1}{T_{x,y}} \approx \frac{\sigma_\delta^2}{\varepsilon_x} \left\langle H_{x,y} \right\rangle \frac{1}{T_\delta}$$

IBS could make it very difficult to achieve 0.1 nm horizontal emittance with high bunch charge, low vertical emittance and short bunch length.

IBS effects in the ILC damping rings are suppressed to some extent by relatively fast radiation damping.

Touschek lifetime can be expected to be short (~ ½ hour)

A rigorous calculation of the Touschek lifetime requires a detailed model of the energy acceptance at every point around the lattice.

We can make a simple estimate, assuming a fixed energy acceptance of 1%.

Touschek lifetime scales as the square of the energy acceptance.

Using the formulae from Wiedemann (“Particle Accelerator Physics II”):

$$\frac{1}{\tau} = \frac{r_e^2 c N_0 \delta_{\max}^3}{8\pi\gamma^2\sigma_x\sigma_y\sigma_z} D(\varepsilon)$$

$$D(\varepsilon) = \sqrt{\varepsilon}\left[-\tfrac{3}{2}e^{-\varepsilon} + \tfrac{1}{2}\varepsilon\int_\varepsilon^\infty \frac{\ln u}{u}e^{-u}du + \tfrac{1}{2}(3\varepsilon - \varepsilon\ln\varepsilon + 2)\int_\varepsilon^\infty \frac{e^{-u}}{u}du\right]$$

$$\varepsilon = \left(\frac{\beta_x\delta_{\max}}{\gamma^2 mc\sigma_x}\right)^2$$

	PPA	OTW	OCS	BRU	MCH	DAS	TESLA
Lifetime [min]	16	17	33	18	68	44	50

$\underbrace{\text{MCH} \quad \text{DAS} \quad \text{TESLA}}$

dogbone lattices have large
beam sizes in the long straights

Space-charge tune shifts are large in the dogbone rings

We can estimate the incoherent space-charge tune shift using a simple linear-focusing approximation:

$$\Delta\nu_y = -\frac{r_e N_0}{(2\pi)^{\frac{3}{2}}\sigma_z\gamma^3}\oint\frac{\beta_y}{\sigma_y(\sigma_x+\sigma_y)}ds$$

	PPA	OTW	OCS	BRU	MCH	DAS	TESLA
C [m]	2824	3223	6114	6333	15935	17014	17000
γ	9785	9785	9914	7319	9785	9785	9785
ε_y [pm]	2.04	2.04	2.00	2.52	1.69	1.67	1.45
σ_z [mm]	6	6	6	9	9	6	6
N_0 [10^{10}]	2.4	2.2	2	2	2	2	2
$\Delta\nu_y$	-0.026	-0.064	-0.056	-0.12	-0.17	-0.30	-0.37

Studies for the TESLA TDR suggested significant emittance growth from particles crossing resonance lines in the tune plane.

- Coupling bumps in the long straights were proposed as a solution.

More detailed studies to understand the full impact of space-charge effects are in progress.

Space-charge effects may also be large for Super B-Factory

We can estimate the incoherent space-charge tune shift using a simple linear-focusing approximation:

$$\Delta\nu_y = -\frac{r_e N_0}{(2\pi)^{\frac{3}{2}}\sigma_z\gamma^3}\oint\frac{\beta_y}{\sigma_y(\sigma_x+\sigma_y)}ds$$

Circumference	2.2 km
Number of particles, N_0	4×10^{10}
Bunch length, σ_z	2 mm
Beam energy, γ	6850 (3.5 GeV)
Horizontal emittance, ε_x	0.1 nm
Vertical emittance, ε_y	10 pm
Horizontal beta function, β_x	50 m
Vertical beta function, β_y	50 m
Incoherent tune shift, $\Delta\nu_y$	-0.59

In general, tune shifts should be kept below ~ 0.1

A very simple estimate for the microwave threshold…

We can use the Keill-Schnell-Boussard criterion to estimate the impedance (Z/n) at which we expect to see an instability:

$$\frac{Z}{n} = Z_0 \sqrt{\frac{\pi}{2}} \frac{\gamma \alpha_p \sigma_\delta^2 \sigma_z}{N_0 r_e}$$

	PPA	OTW	OCS	BRU	MCH	DAS	TESLA
γ	9785	9785	9914	7319	9785	9785	9785
α_p [10^{-4}]	2.83	3.62	1.62	11.9	4.09	1.14	1.22
σ_δ [10^{-3}]	1.27	1.36	1.29	0.973	1.30	1.30	1.29
σ_z [mm]	6	6	6	9	9	6	6
N_0 [10^{10}]	2.4	2.2	2	2	2	2	2
Z/n [mΩ]	187	299	134	622	510	94.8	100

Compare with measured values:

APS: measured Z/n ~ 500 mΩ (240 mΩ from impedance model)

Y.-C. Chae et al, "Broadband Model Impedance for the APS Storage Ring," PAC 2001.

DAΦNE: measured Z/n ~ 530 mΩ in electron ring (260 mΩ from impedance model), and Z/n ~ 1100 mΩ in positron ring

A. Ghigo et al, "DAΦNE Broadband Impedance," EPAC 2002.

Comments on microwave threshold

Z/n is a very crude characterization of the impedance.

Much more detailed analysis is needed to understand the instabilities properly.

The impedance found from beam-based measurements in a storage ring are often several times larger than the impedance expected from a model of the individual components.

A significant safety margin is highly advisable between the nominal working point and the point at which instabilities are expected to occur.

Z/n for KEK-B is of the order 100 mΩ or less, but still several times larger than that expected from the design model.

SLC experience suggests that very small effects in the damping rings, which may not be any real concern to other machines, could have a significant impact on ILC operation and performance.

Feedbacks will be needed to suppress multibunch instabilities

We can make an estimate of the growth rates from the resistive-wall impedance.

A number of assumptions are needed:

- Uniformly filled ring
- Homogeneous lattice (i.e. constant beta function around ring)
- Uniform circular aperture for the vacuum chamber

Time domain simulations show that these assumptions are good, even in the dogbone damping rings.

> *"Simulations of Resistive-Wall Instability in the ILC Damping Rings"*, A.Wolski, J.Byrd, D.Bates (PAC 2005).

For our calculations, we assume an aluminum vacuum chamber, with radius:

- 20 mm in the arcs
- 49 mm in the long straights
- 8 mm in the wigglers

We also assume a uniform fill with the nominal bunch charge.

Resistive-wall growth times are fast

$$\Gamma = \frac{4\pi}{Z_0 c} A \frac{\beta_y c}{4\gamma} \frac{\langle I \rangle}{I_A} \frac{1}{\sqrt{C\left(1 - \mathrm{frac}(\nu_y)\right)}}$$

$$A = \frac{2}{\pi} \left\langle \frac{1}{b^3} \right\rangle C \sqrt{\frac{Z_0 c}{4\pi} \frac{c}{\sigma}}$$

Lattice	Shortest growth time	
	Chamber 40/16/100	Chamber 50/32/100
PPA	65	155
OTW	21	82
OCS	12	29
BRU	6	23
MCH	6	21
DAS	6	21
TESLA	9	32

Note: chamber sizes are diameters in arcs/wigglers/straights

Feedback systems look challenging in some cases. Growth times of 20 turns are state-of-the-art.

There is a potential concern with bunch-to-bunch jitter that can be induced on the beam from the feedback system, because of limited pick-up resolution.

Higher-order modes in the RF cavities, and other long-range wakes, will contribute to the growth rates, and make the feedback systems still more challenging.

Summary and Conclusions – for Super-B and ILC DRs

Super-B Factory parameters could be more challenging than the ILC damping rings

Tuning for low vertical emittance ~ 1 pm will be difficult

- Best achieved so far is ~ 4 pm at KEK-ATF.
- Vertical emittance will likely **not** be limited by synchrotron radiation opening angle.
- Vertical emittance will be sensitive to sextupole motion at the level of ~ 10 μm.

Orbit stability will be important

- Quadrupole jitter should be kept < 100 nm.

Collective effects look particularly challenging

- All get worse at lower energy and higher bunch charge.
- Variety of symptoms can be expected: emittance growth; coherent single-bunch and coupled-bunch modes; particle loss…

Summary and Conclusions: Collective Effects

Intrabeam scattering

Could be a limiting effect on low emittance (horizontal and vertical) at high bunch charge.

IBS growth rates scale strongly with energy.

Touschek lifetime

Could be as short as ½ hour.

A lattice with a large energy acceptance will help.

Space-charge tune shifts

Large tune shifts are expected, because of high charge, short bunch and low emittance.

Tracking studies are needed to see if space-charge is really a problem.

Microwave threshold

As always, very careful design and construction of vacuum chamber will be needed to keep impedance as low as possible.

Coupled-bunch instabilities

Bunch-by-bunch feedbacks will almost certainly be needed.

Increasing the chamber aperture helps a lot with the resistive-wall impedance.

The bottom line: maybe not impossible – but very challenging.