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

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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

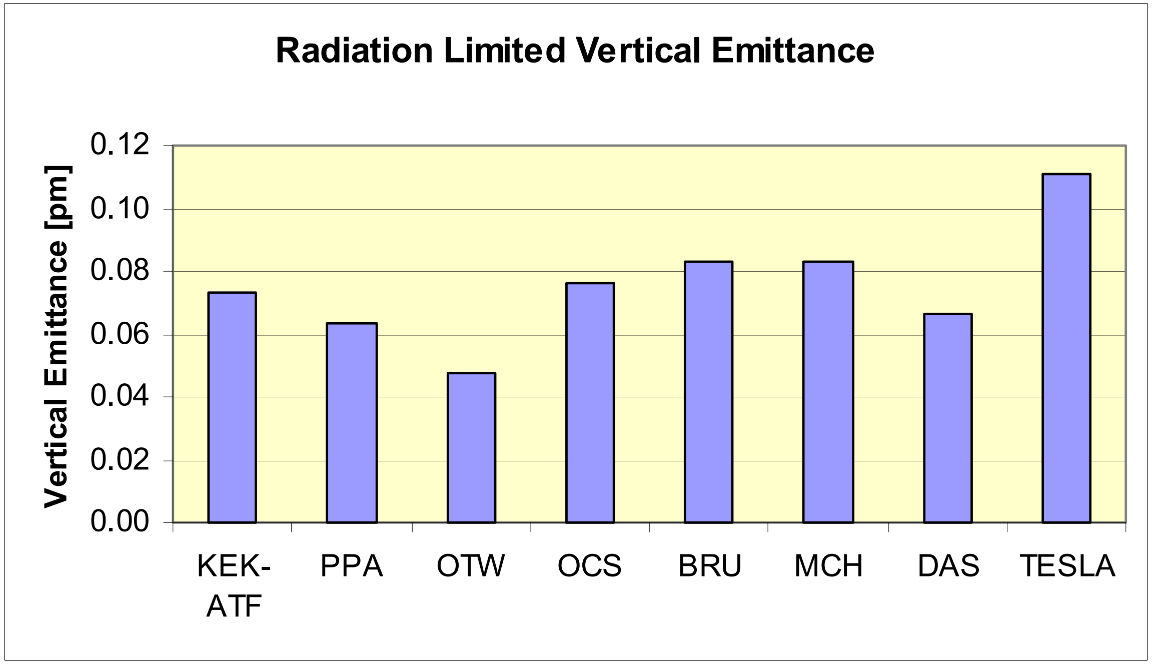
Vertical emittance has a fundamental limit from SR

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.

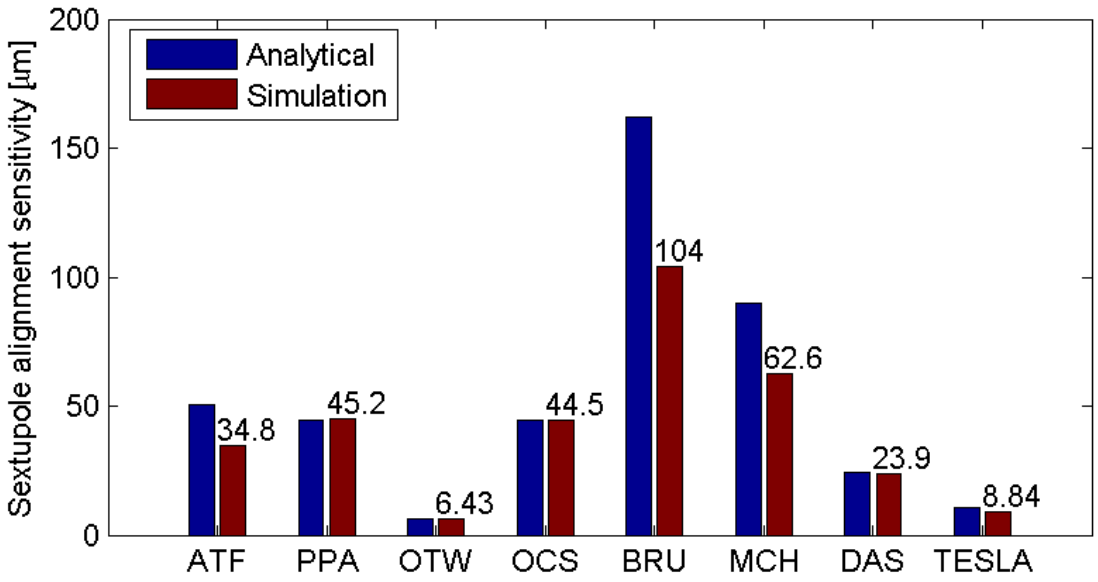
These sensitivity values simply indicate the likely difficulty of achieving a given emittance, and the frequency with which tuning will need to be performed.

Damping Ring sensitivity to sextupole misalignments

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

coupling　　　　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:

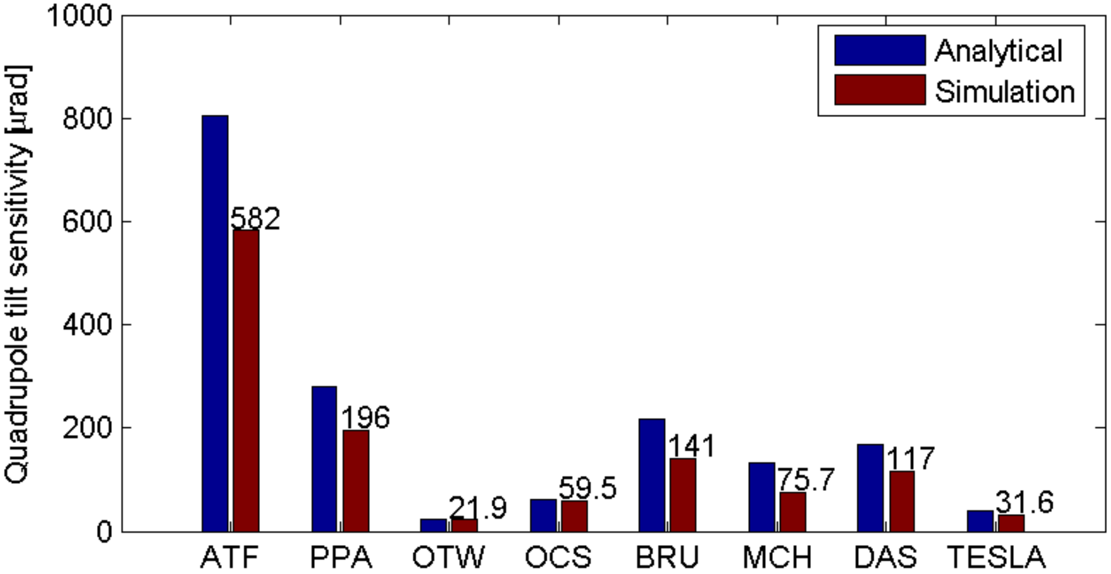
Horizontal emittance in Super-B Factory is 8 times lower than in damping rings, so a Super-B Factory could be less sensitive to sextupole misalignment than the damping rings.

Damping Ring sensitivity to quadrupole tilts

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

coupling — dispersion

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



Sensitivities are typically of the order of 100 µrad.

Note:

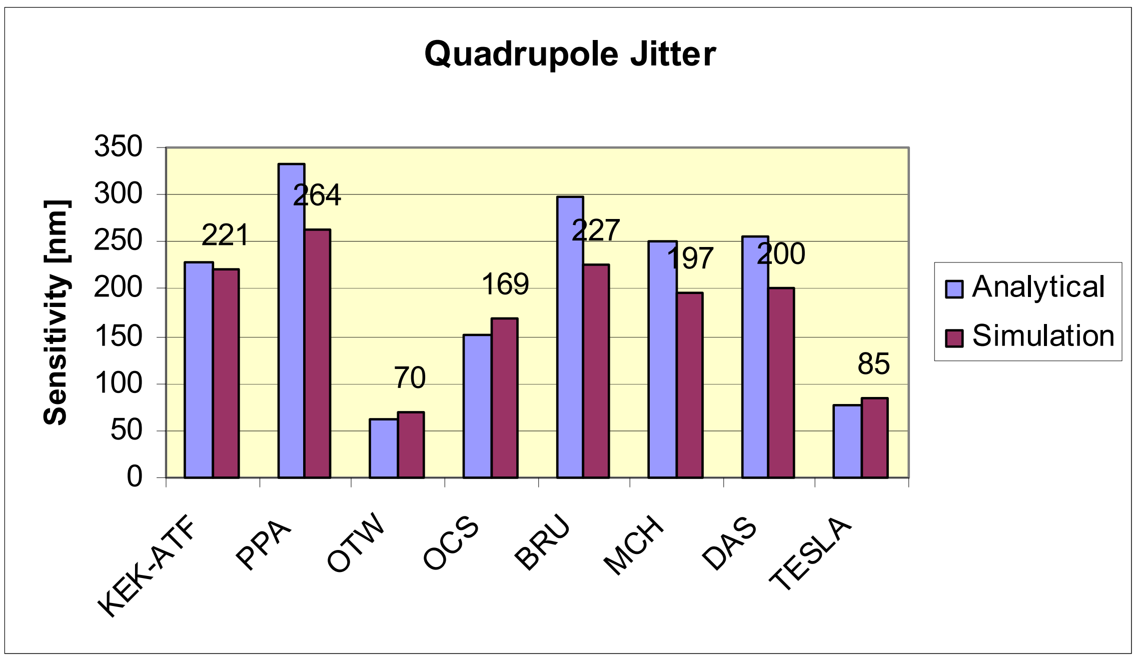
Horizontal emittance in Super-B Factory is 8 times lower than in damping rings, so a Super-B Factory could be less sensitive to sextupole misalignment than the damping rings.

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.

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

$$\Sigma_{1O} = \sum_{quads} \beta_y (k_1 L)^2$$



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.

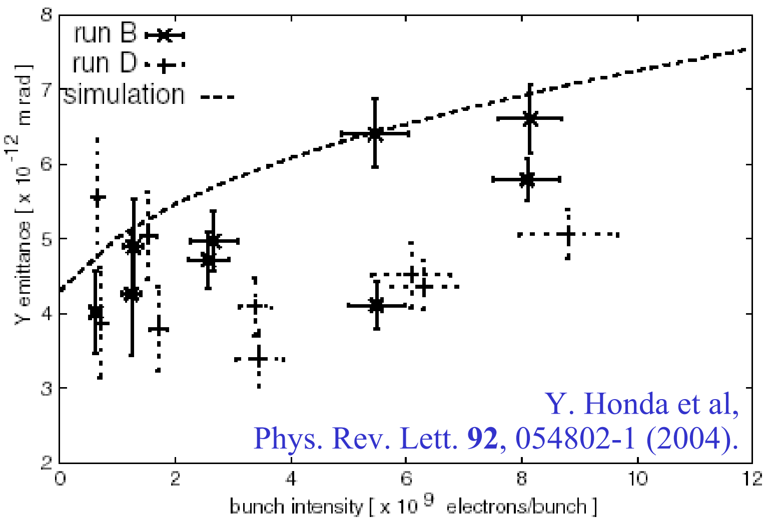


FIG. 2. Current dependence of the vertical emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

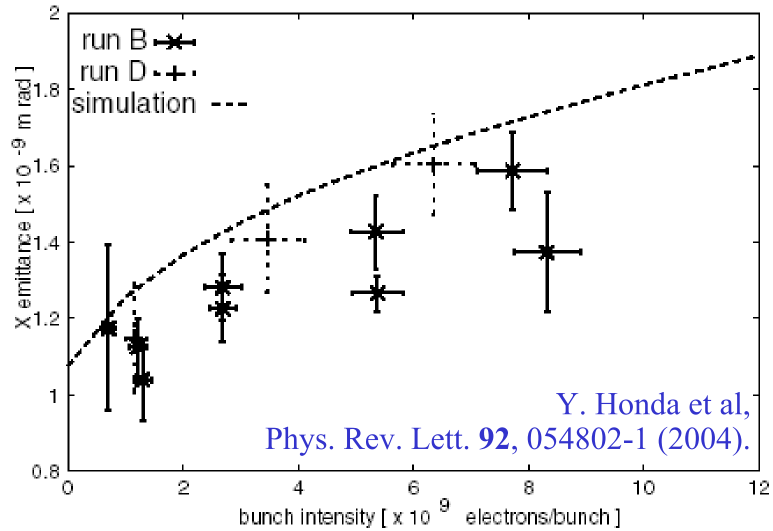
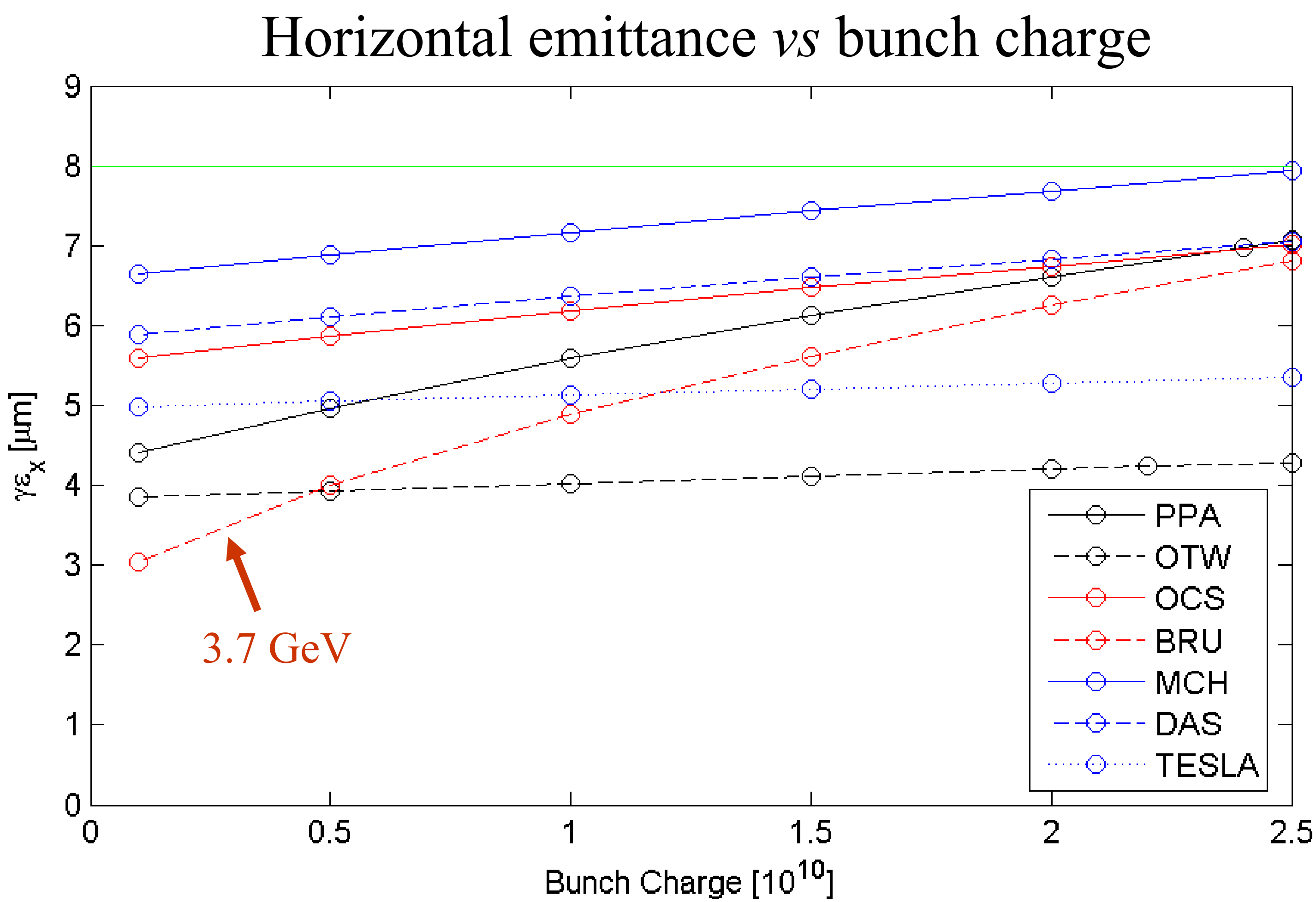


FIG. 3. Current dependence of the horizontal emittance: Data for the smallest emittance cases (runs B and D) are shown. The result of a SAD simulation for 0.4% coupling is superimposed.

IBS will increase emittance in the ILC damping rings



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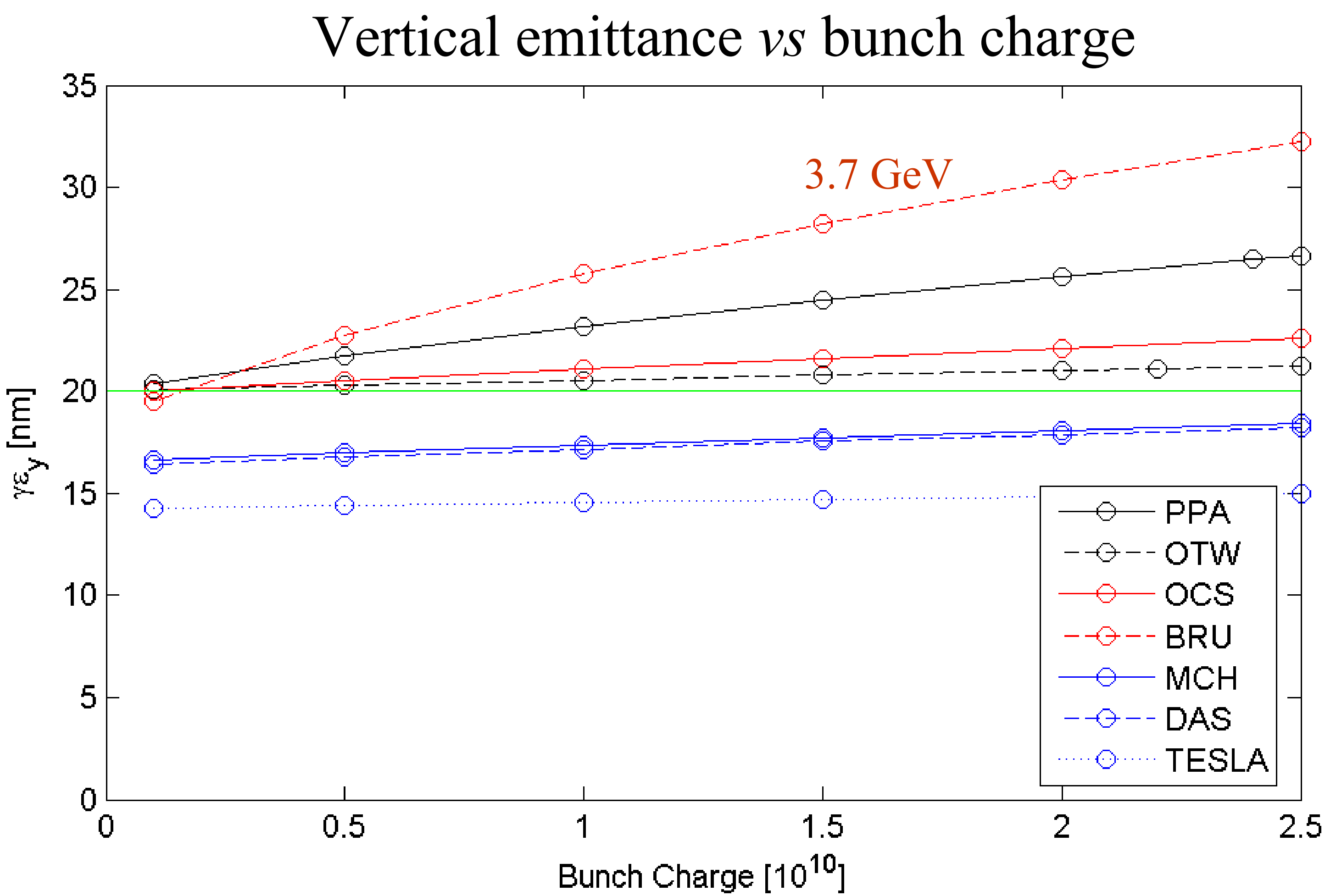
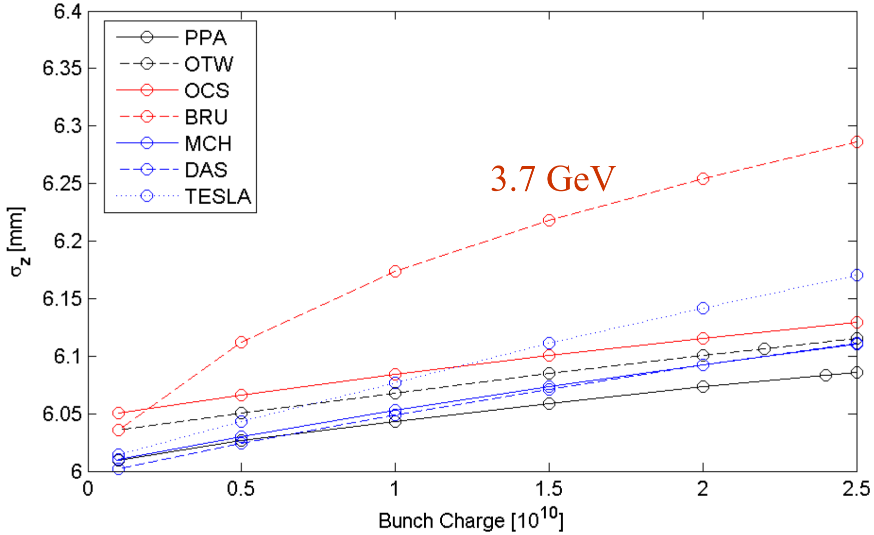
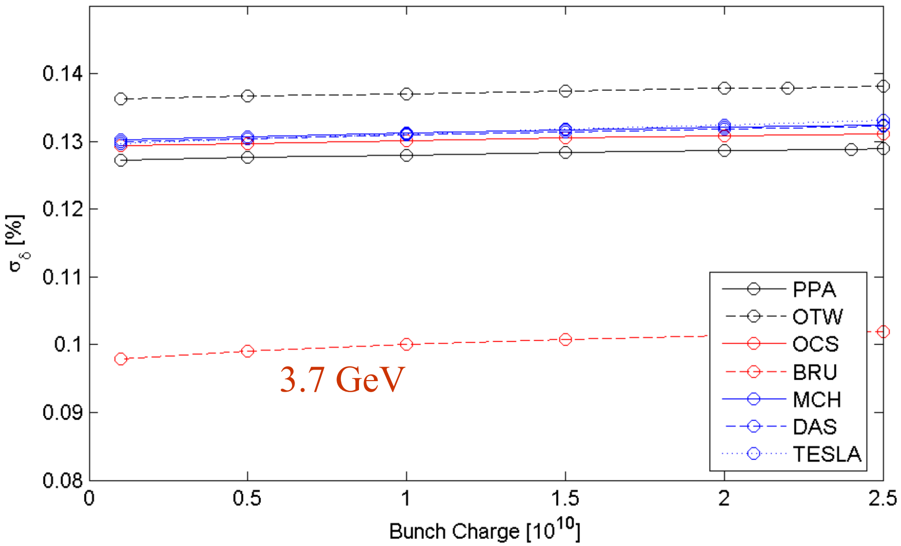


IBS growth is less severe longitudinally than transversely



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

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.