Collective Effects in ILC Damping Rings

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Aim: compare collective effects in three damping ring designs

- Calculations based on existing lattice designs:
  - 17 km (DESY - TESLA TDR)
  - 6 km (FNAL)
  - 3 km (LBNL)
- We look at a range of potential performance limitations:
  - Microwave instability
  - Coherent synchrotron radiation (CSR) instability
  - Space-charge tune shift
  - Resistive-wall instability
  - Fast-ion instability
  - Electron-cloud instability
  - Touschek lifetime
  - Intrabeam scattering
- Use simple estimates only: no detailed simulations at present.
- Use same assumptions and formulae as far as possible.
  - Coupling bumps used in 17 km lattice throughout (except for IBS).
- There are others collective effects to worry about…

A few parameters are needed for the calculations

Circumference	**C**	**17.0 km**	**6.114 km**	**3.043 km**
Energy	E_0	5.0 GeV	5.066 GeV	5 GeV
Bunch charge	N_0	2×10^{10}	2×10^{10}	2×10^{10}
Normalized x emittance	$\gamma\varepsilon_x$	4.96 μm	5.48 μm	6.03 μm
Normalized y emittance	$\gamma\varepsilon_y$	0.02 μm	0.02 μm	0.02 μm
Bunch length	σ_z	6.0 mm	6.0 mm	6.0 mm
Energy spread	σ_δ	1.29×10^{-3}	1.51×10^{-3}	1.16×10^{-3}
Momentum compaction	α_p	1.22×10^{-4}	1.42×10^{-4}	2.88×10^{-4}
Horizontal tune	ν_x	76.320	56.584	51.280
Vertical tune	ν_y	41.192	41.618	31.590
Mean vertical beta function	$\langle\beta_y\rangle$	121 m	28.7 m	25.8 m
Synchrotron tune	ν_s	0.0707	0.0345	0.0269
Transverse damping times	$\tau_{x,y}$	27.9 ms	26.8 ms	19.0 ms
Longitudinal damping time	τ_s	14.0 ms	13.4 ms	9.5 ms
Bunch spacing	$\Delta\tau_b$	20 ns	6 ns	3.077 ns
Bunches per train	n_{train}	2820	47	94
‘Bunches’ per gap		0	11	16

Microwave instability

- We use the Keill-Schnell-Boussard criterion.
- Instability occurs with impedance greater than:

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

Lattice		Instability threshold	
17 km	Arcs (2 km)	100 mΩ	660 mΩ
	Straights (15 km)		25 mΩ
6 km		163 mΩ	
3 km		191 mΩ	

- Estimated impedance in KEK-B ~ 70 mΩ.
- More careful analysis required, using realistic wake fields.
- Transverse instability has much higher threshold.

Coherent synchrotron radiation

- Bunch interacts with long-wavelength coherent synchrotron radiation from dipoles and wigglers.
- Instability occurs with bunch charge greater than*:

$$N_{0,th} = 3.6 \frac{C}{4\pi \langle b \rangle} \frac{\gamma \alpha_p \sigma_\delta^2 \sigma_z}{r_e}$$

Lattice	Beam-pipe radius $\langle b \rangle$	Instability threshold
17 km	25 mm	8.3×10^{11}
6 km	25 mm	4.9×10^{11}
3 km	25 mm	2.9×10^{11}

- Safety margin appears to be ~ an order of magnitude.
- Again, more careful analysis is required to improve confidence.

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* M. Venturini, “Longitudinal Single-Bunch Instabilities in the NLC Main Damping Rings”, LBNL-55103 (May 2004).

Space-charge tune shift

- Defocusing force from beam potential gives coherent and incoherent tune shifts.
- Effects are much larger in the vertical plane than the horizontal, because of the smaller vertical beam size.
- For the 17 km lattice, we approximate the effects of the coupling bumps by using $\varepsilon_x = \varepsilon_y = \frac{1}{2}\,\varepsilon_0$ in the straights.
- The incoherent tune shift (tune spread) is given by:

$$\Delta\nu_y = \frac{N_0 r_e}{(2\pi)^{\frac{3}{2}}\gamma^3\sigma_z}\int_0^C \frac{\beta_y}{\sigma_y(\sigma_x+\sigma_y)}\mathrm{ds}$$

Lattice	Incoherent vertical tune shift
17 km	0.056
6 km	0.070
3 km	0.052

- Possible emittance growth and particle loss: tracking studies needed.

Resistive wall instability: formulae

- Resistive wall impedance drives coupled bunch instability.
- Higher order modes from the RF cavities can also contribute, but are not included at this time.
- We use the standard expressions (e.g. from A. Chao, “Physics of Collective Beam Instabilities”):

Resistive wall impedance:

$$Z_\perp(\omega) = \left(1 - \operatorname{sgn}(\omega)\,\mathrm{i}\right) Z_0 \frac{C}{2\pi\langle b\rangle^3}\,\delta_{skin}(\omega)$$

Skin depth:

$$\delta_{skin}(\omega) = \sqrt{\frac{2}{\sigma_c \mu_c \omega}}$$

Growth rate (mode *m*):

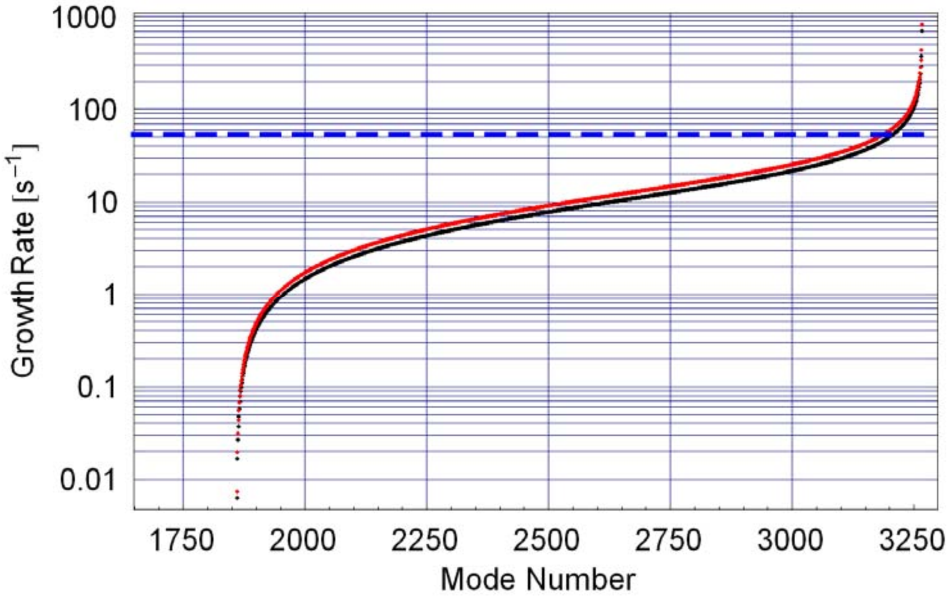
$$\frac{1}{\tau_m} = -\frac{c\langle I\rangle}{4\pi\nu_y E/e}\,\mathrm{Re}\sum_{p=-\infty}^{\infty} Z_\perp\left(\left(\nu_y + n_b p + m\right)\omega_0\right)$$

Lattice	*C*	17 km	6 km	3 km
Beam-pipe radius	<*b*>	37 mm	25 mm	25 mm
Number of bunches in a ‘complete fill’	n_b	2820	3399	3299
Average current (uniform fill, nominal N_0)	<*I*>	159 mA	534 mA	1041 mA
Revolution frequency	ω_0	1.11×10^5 s^{-1}	3.08×10^5 s^{-1}	6.19×10^5 s^{-1}

Note: We assume all vacuum chambers are circular aluminum pipe, conductivity $\sigma_c = 3.8\times10^7\ \Omega^{-1}\mathrm{m}^{-1}$

Resistive wall instability: growth rates

- Example: 3km lattice.
- Black points: uniform fill at nominal average current.
- Red points: uniform fill at nominal bunch charge.
- Blue line: synchrotron radiation damping rate.

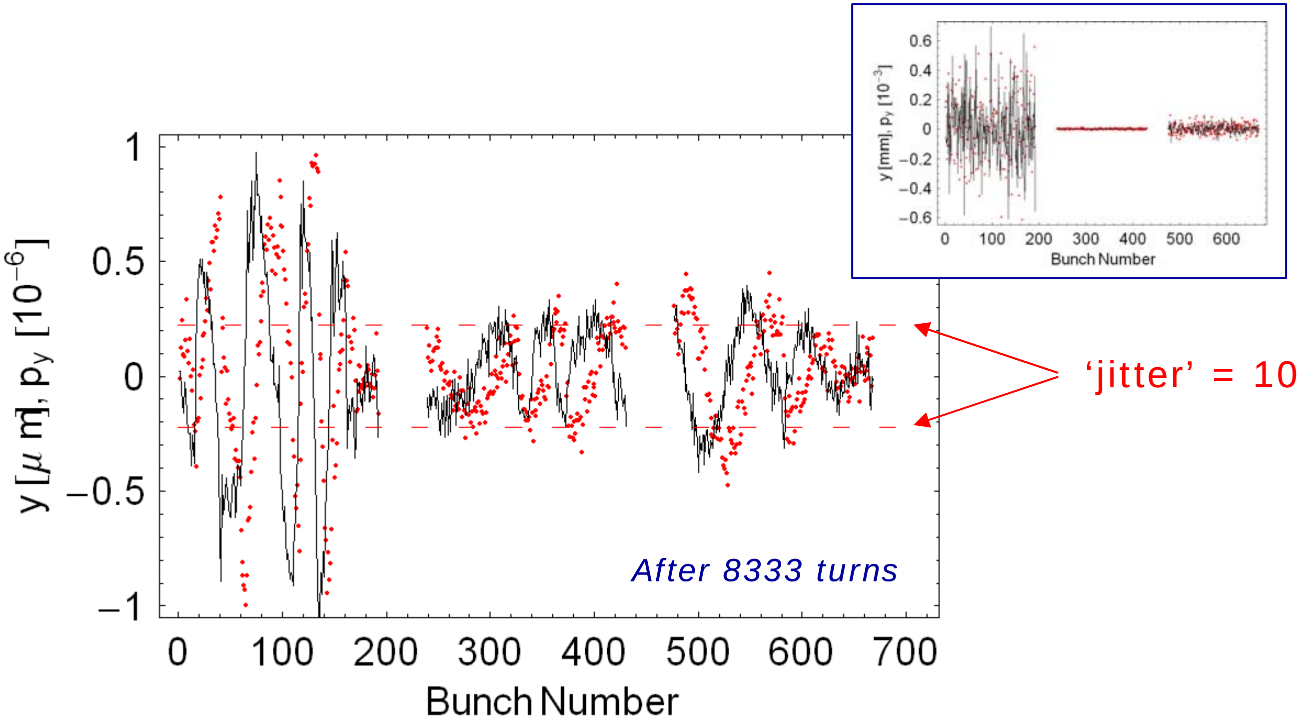


Lattice	Shortest growth time
17 km	69 turns
6 km	57 turns
3 km	121 turns

- Bunch-by-bunch feedback system will be needed in all cases.
- Beam jitter introduced by feedback system is a concern.

Resistive wall instability: feeback-induced jitter

- Simulation studies were carried out for NLC damping ring, including:
  - transverse dynamics with real lattice functions
  - nominal fill with three trains of 192 bunches
  - radiation damping
  - feedback system with 5 μm resolution on the pick-up
- Shortest growth times to be damped were ~ 1000 turns.
- Bunch-to-bunch jitter on extraction was barely within specification.



Initial conditions

‘jitter’ = 10% of beam size

After 8333 turns

Fast-ion instability: formulae

- We use the Raubenheimer-Zimmermann theory.
- We assume a residual gas pressure 0.1 ntorr, CO (*A*=28) the dominant species.
- We assume the ionization cross-section is σ_{ion} = 2 Mb.

Ion line-density at end of bunch train:

$$\lambda_{ion} = N_0 n_{train} \frac{p_0}{kT} \sigma_{ion}$$

Beam focusing from ions:

$$K_y = \frac{\lambda_{ion} r_e}{\gamma \sigma_y (\sigma_x + \sigma_y)}$$

Ion oscillation frequency in beam potential:

$$\frac{\omega_{ion}^2}{c^2} = \frac{\bar{\lambda}_{beam} r_p}{A \sigma_y (\sigma_x + \sigma_y)}$$

Incoherent tune shift:

$$\Delta \nu_y = \frac{1}{2\pi} \int_0^C K_y \beta_y \,\mathrm{d}s$$

Instability exponential growth rate:

$$\frac{1}{\tau} = \frac{1}{4\sqrt{2}} \frac{c}{\sigma_\omega} \frac{1}{C} \int_0^C \omega_{ion} K_y \beta_y \,\mathrm{d}s$$

Fast-ion instability: parameters and results

Lattice	**C**	**17 km**	**17 km**	**6 km**	**3 km**
Number of bunches per train	n_{train}	2820	94	47	94
Mean beam density [×10^9 m^{-1}]	$\bar{\lambda}_{beam}$	3.34	3.34	11.1	21.7
Ion density at end of train [m^{-1}]	λ_{ion}	36,000	1200	605	1210
Mean ion oscillation frequency [m^{-1}]	$\langle\omega_{\mathrm{ion}}\rangle/c$	0.114	0.114	0.615	1.08
StDev ion oscillation frequency [m^{-1}]	σ_{ω}/c	0.157	0.157	0.313	0.21
Incoherent vertical tune shift [m^{-1}]	$\Delta\nu_y$	**0.15**	**0.0049**	**0.0032**	**0.0046**
Exponential growth time [turns]	τ	**2.6**	**78**	**111**	**35**

- Coupling bump included in 17 km lattice.
- Simulation studies are needed to confirm results.
- Experimental studies are needed to confirm theory and benchmark simulations.
  - Simulations for KEK-ATF already show excellent agreement with experiment.

Electron-cloud instability: formulae

- We assume that the electron cloud density reaches the neutralization level (indicated by simulations of build-up).
- We consider the single-bunch instability, treating the electron cloud as a transverse impedance.
  - K. Ohmi and F. Zimmermann, “Study of Head-Tail Effect Caused by Electron Cloud”, Proceedings of EPAC 2000.
- Cloud frequency is large compared to bunch length, so we use a coasting-beam instability model.

Cloud oscillation frequency in beam potential:

$$\frac{\omega_{cloud}^2}{c^2} = \frac{\hat{\lambda}_{beam} r_e}{\sigma_y(\sigma_x + \sigma_y)}$$

Transverse impedance from electron cloud:

$$Z_\perp = Z_0 C \frac{\hat{\rho}_{cloud}}{2\hat{\lambda}_{beam}}$$

Instability impedance threshold:

$$Z_{\perp,th} = Z_0 \frac{\gamma \alpha_p \sigma_\delta \nu_y}{N_0 r_e} \frac{\omega_{cloud} \sigma_z}{c}$$

Instability mean-cloud-density threshold:

$$\hat{\rho}_{cloud} = \sqrt{\frac{2}{\pi}} \frac{\gamma \alpha_p \sigma_\delta}{r_e} \frac{\nu_y}{C} \frac{\omega_{cloud}}{c}$$

Electron-cloud instability: parameters and results

Lattice	**C**	**17 km**	**6 km**	**3 km**
Peak beam density	$\hat{\lambda}_{beam}$	1.33×10^{12} m^{-1}	1.33×10^{12} m^{-1}	1.33×10^{12} m^{-1}
Cloud oscillation frequency	$\omega_{\mathrm{cloud}}/c$	517 m^{-1}	1518 m^{-1}	1920 m^{-1}
Cloud oscillations per bunch	$\omega_{\mathrm{cloud}}\sigma_z/c$	3.1	9.2	11.5
Instability impedance threshold	$Z_{\perp,\mathrm{th}}$	1.33 MΩ/m	5.44 MΩ/m	7.97 MΩ/m
Neutralization density	ρ_{neut}	**0.78×10^{12} m^{-3}**	**5.76×10^{12} m^{-3}**	**11.8×10^{12} m^{-3}**
Instability cloud-density threshold	$\hat{\rho}_{cloud}$	**0.55×10^{12} m^{-3}**	**6.23×10^{12} m^{-3}**	**18.5×10^{12} m^{-3}**

- Neutralization density scales as: $\rho_{\mathrm{neut}} \sim 1/C\langle b\rangle^2$
- Instability impedance threshold scales as: $Z_{\perp,\mathrm{th}} \sim \alpha_p\sigma_\delta\omega_{\mathrm{cloud}}/\langle\beta_y\rangle$
- Instability cloud-density threshold scales as: $\rho_{\mathrm{cloud}} \sim Z_{\perp,\mathrm{th}}C$

- Sensitivity to instability *decreases* as circumference *decreases.*
- There are many other effects of electron cloud to consider.

Touschek lifetime

- Large-angle scattering within bunch leads to particle loss because of limited momentum acceptance.
- Main lifetime limitation in 3rd generation synchrotron light sources.
  - Generally operate with emittance ratio 1% or more to achieve lifetime of several hours
  - Lifetime falls to a few minutes with very low coupling in low energy machines
  - Strongly dependent on momentum acceptance (limited by dynamics or RF voltage)
- An issue for damping rings during commissioning and tuning

$$\frac{1}{\tau} = \frac{r_e^2 c N_0}{8\pi\gamma^2 \delta_{\max}^3 \sigma_z} \int_0^C \frac{D(\varepsilon)}{\sigma_x \sigma_y} \mathrm{d}s \qquad \varepsilon = \left(\frac{\delta_{\max} \beta_x}{\gamma \sigma_\delta} \right)^2$$

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

Lattice	Touschek lifetime ($\delta_{\max}$ = 1.5%)
17 km	319 minutes
6 km	82 minutes
3 km	63 minutes

Intrabeam scattering: formulae

- Small-angle scattering within a bunch causes emittance growth.
- We use Bane's approximation to the Bjorken-Mtingwa formulae.

Longitudinal growth rate:

$$\frac{1}{T_p} = \frac{r_e^2 c N_0}{16\gamma^3 \sqrt{\beta_x \varepsilon_x^3 \beta_y \varepsilon_y^3}\,\sigma_z \sigma_\delta^3} \ln\left(\frac{\sqrt{\beta_y \varepsilon_y}\,\gamma^2 \varepsilon_x}{r_e \beta_x} \right) g\left(\sqrt{\frac{\beta_x \varepsilon_y}{\beta_y \varepsilon_x}} \right) \cdot \left(\frac{1}{\sigma_\delta^2} + \frac{H_x}{\varepsilon_x} + \frac{H_y}{\varepsilon_y} \right)^{-\frac{1}{2}}$$

$$g(\alpha) = \alpha^{0.021 - 0.044 \ln \alpha} \qquad \alpha \le 1 \qquad\qquad g(\alpha) = g(1/\alpha) \qquad \alpha > 1$$

Dispersion H-functions:

$$H_x = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2$$

$$\varepsilon_y = C_q \gamma^2 \left\langle H_y \right\rangle \frac{I_3}{I_2}$$

Transverse growth rates:

$$\frac{1}{T_{x(y)}} = \sigma_\delta^2 \frac{H_{x(y)}}{\varepsilon_{x(y)}} \frac{1}{T_p}$$

Equilibrium emittances:

$$\varepsilon_{x(y),N} = \frac{T_{x(y)}}{T_{x(y)} - \tau_{x(y)}} \varepsilon_{x(y),0} \qquad \sigma_{\delta,N} = \frac{T_p}{T_p - \tau_p} \sigma_{\delta,0}$$

Intrabeam scattering: results

- We find the average growth rates by integrating around the lattice.
- The equilibrium emittances are found by iteration.
  - IBS growth rates depend on the emittances.
  - Emittances depend on the IBS growth rates.
- Assuming all the vertical emittance is generated by vertical dispersion:

Lattice	***C***	**17 km ***	**6 km**	**3 km**
Horizontal growth time	T_x	0.532 s	0.169 s	0.109 s
Vertical growth time	T_y	1.65 s	2.00 s	1.88 s
Longitudinal growth time	T_p	0.838 s	1.01 s	0.483 s
Horizontal emittance growth	$\varepsilon_{x,N} / \varepsilon_{x,0} - 1$	**5.5%**	**19%**	**21%**
Vertical emittance growth	$\varepsilon_{y,N} / \varepsilon_{y,0} - 1$	**1.8%**	**1.4%**	**1.9%**
Energy spread growth	$\sigma_{\delta,N} / \sigma_{\delta,0} - 1$	**1.7%**	**1.4%**	**1.9%**

** No coupling bumps*

- If all the vertical emittance is generated by betatron coupling, then: relative vertical emittance growth = relative horizontal emittance growth
- IBS emittance growth is not strong, but is not negligible either.

Summary (Conclusions on next - final - slide)

Lattice	**C**	**17 km**	**6 km**	**3 km**
Microwave threshold	Z/n	**660mΩ/25mΩ**	163 mΩ	**191 mΩ**
CSR threshold	$N_{0,\mathrm{th}}/N_{0,\mathrm{nominal}}$	**42**	25	15
Space-charge tune shift	$\Delta\nu_y$	0.056	0.070	**0.052**
Resistive-wall instability	τ_{min}	69 turns	57 turns	**121 turns**
Fast-ion instability	$\Delta\nu_y$	0.0049	**0.0032**	0.0046
Fast-ion instability	τ_{min}	78 turns	**110 turns**	35 turns
Electron-cloud instability	$\rho_{\mathrm{neut}}/\ \rho_{\mathrm{th}}$	1.4	0.92	**0.64**
Touschek lifetime	τ	**319 min**	82 min	63 min
IBS emittance growth	$\varepsilon_{x,N}/\varepsilon_{x,0}$ - 1	**5.5%**	19%	21%

🟩 Best 🟦 Intermediate 🟥 Worst

Conclusion: All lattices are (almost) the same

- Microwave instability
  - Impedance requirements look challenging, but possible
  - Detailed studies needed using ‘real’ wakefields for the various components
- Coherent synchrotron radiation
  - Appears to be a safe margin
  - More precise studies needed to state the threshold with confidence
- Space-charge tune shift
  - Coupling bumps bring tune-shift within probable safe limits in 17 km lattice
  - Tracking studies needed to investigate emittance growth and particle loss
- Resistive-wall instability
  - Growth rates are fast: bunch-by-bunch feedback will be needed
  - Jitter induced by feedback system is a concern, needs simulation studies
- Fast-ion instability
  - Growth rates are fast, even at 0.1 ntorr
  - Detailed studies are needed, including vacuum design and feedback design
- Electron-cloud instability
  - Close to (if not above) threshold for single-bunch transverse instability
  - Measures must be taken to suppress cloud build-up
- Touschek lifetime
  - Sufficient for commissioning and tuning
- IBS emittance growth
  - Should be tolerable (20% in horizontal plane, less in vertical plane).