Classical Instabilities in the ILC Damping Rings

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DR instabilities were a major issue for SLC

Instability History

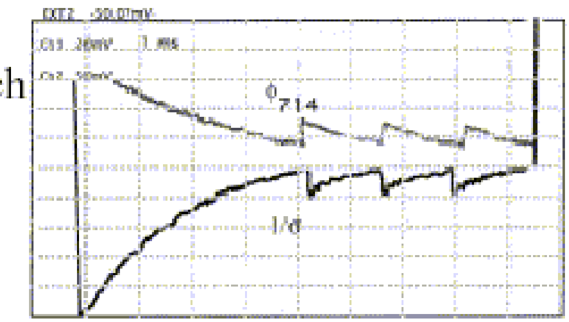
- 1992

  Attempt to raise current above 3×10^{10}/bunch

  Severe single bunch longitudinal instability

  Transient, "Saw-tooth" behavior

  Inability to operate the linac



P. Krejcik et. al., PAC-93

- 1993

  Solution - vacuum chamber replacement. Total inductance was reduced by a factor of 5.

  Simulations predicted threshold of 5×10^{10}/bunch

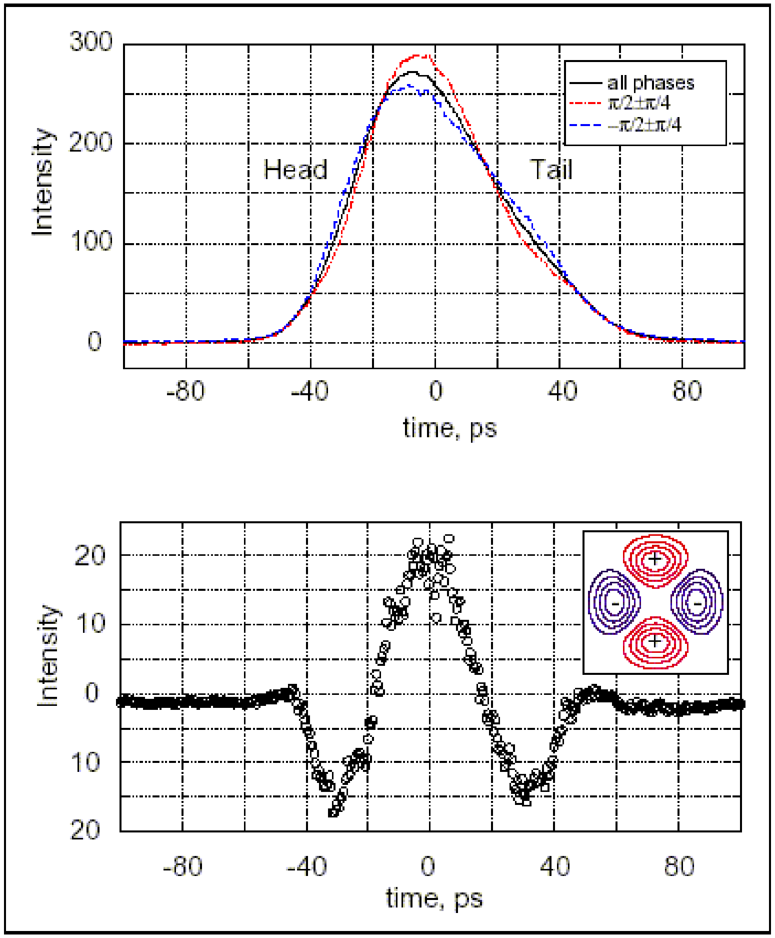
- 1994-1998

  The actual threshold went down ~2×10^{10}/bunch

  Instability less severe. Saturates at lower level. It is no longer the main limiting factor for the SLC

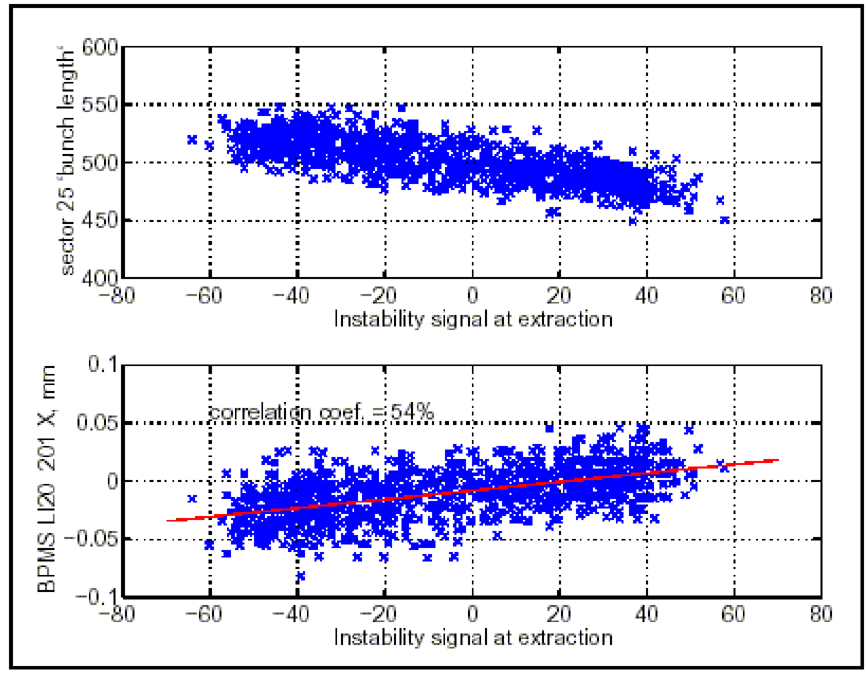
B. Podobedov, "Longitudinal Dynamics in the SLC Damping Rings"
http://www.slac.stanford.edu/pubs/slacwps/wp04/slac-wp-016-ch02-Podobedov.pdf

Small effects in DRs get amplified downstream



Unstable mode contains ~3% of beam

Correlating Instability Signal at Extraction with Linac Bunch Length and Trajectory



- Instability contributes to the transverse jitter in the linac
- We estimate that about 40% of the jitter power is caused by the instability
- This effect could be a problem for NLC

B. Podobedov, "Longitudinal Dynamics in the SLC Damping Rings"
http://www.slac.stanford.edu/pubs/slacwps/wp04/slac-wp-016-ch02-Podobedov.pdf

Points emphasized in the ILC-TRC 2nd report

"The SLC experience emphasized the importance of low particle losses and the suppression of collective instabilities. Based on the SLC experience, particle losses and extracted beam stability are likely to be more important for integrated luminosity than extracted emittance.

Excessive loss leads to radiation damage and downtime for the replacement or repair of damaged components. Beam instability and jitter can lead to severe instantaneous luminosity reduction, and can cause fluctuating backgrounds which make the machine inoperable."

(p.304)

ILC will likely be more sensitive to unstable beam than SLC

Compared to SLC:

- Vertical emittance in ILC will be smaller by 2-3 orders of magnitude.
- Bunch trains will be ~ few thousand bunches in ILC.
- Bunch length in ILC will be smaller by factor ~ 4, leading to a higher peak current.

These effects will more than offset the advantages of ILC:

- Bunch charge in ILC will be smaller by factor ~ 2.
- Beam energy out of damping rings will be larger by a factor ~ 4.

Luminosity upgrades for ILC will likely put even more pressure on beam stability in the damping rings.

ILC damping rings must be designed with as much safety margin as possible with respect to collective effects.

There are many collective effects to worry about

Single-bunch effects:

- ➡ Microwave instability
- Head-tail or transverse mode coupling instability
- ➡ Space-charge tune shifts
- Electron-cloud instabilities
- ➡ Intrabeam scattering
- ➡ Touschek effect

Multi-bunch effects:

- ➡ Resistive-wall instability
- Higher-order modes
- Electron-cloud instabilities
- Ion instabilities

All these effects deserve detailed study and analysis…

See other talks in the workshop.

…however in some cases, we can make simple order-of-magnitude estimates.

A 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.

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

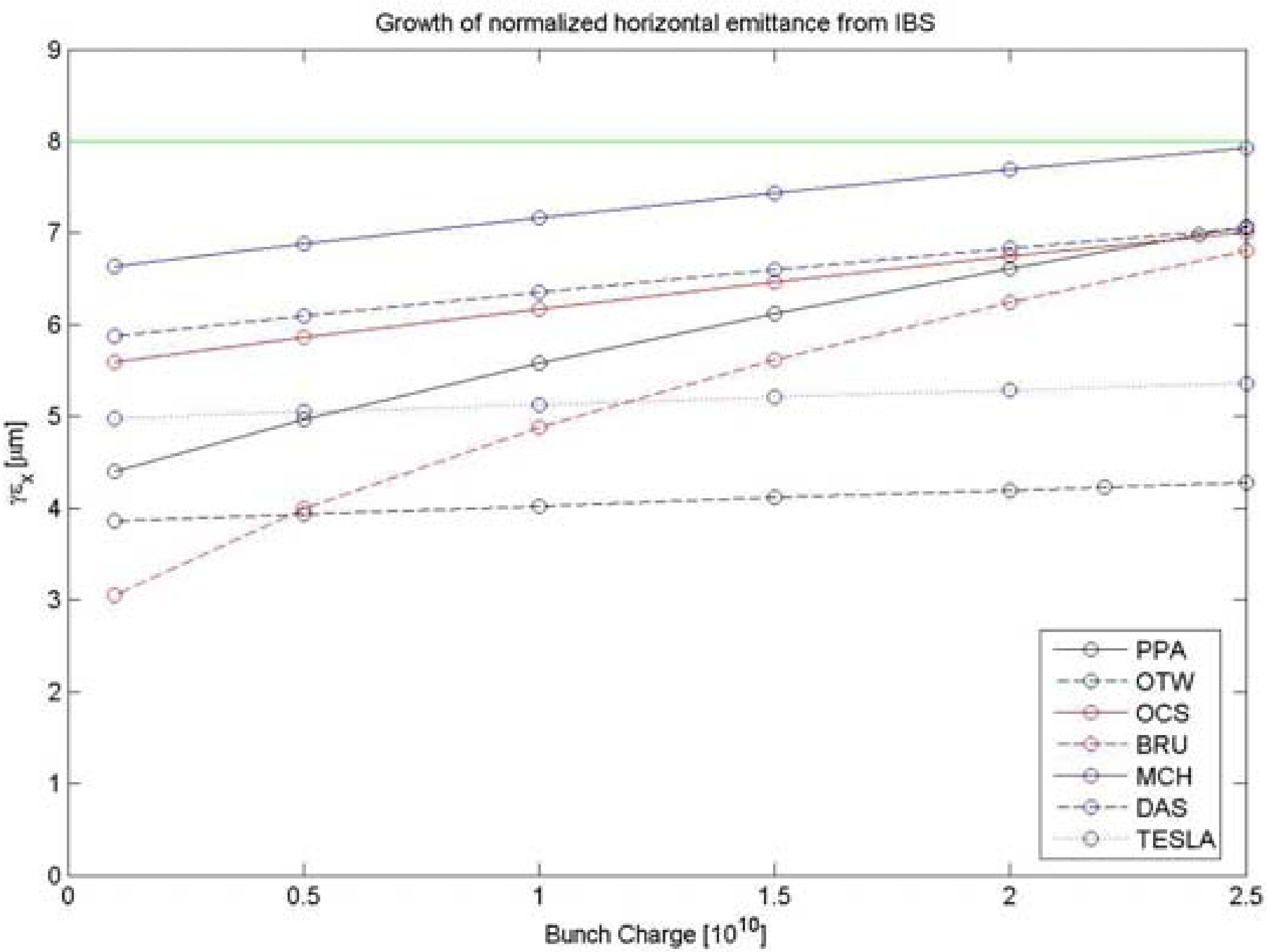
Studies for the TESLA TDR suggested significant emittance growth from particles crossing resonance lines in the tune plane.

- 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.

Intrabeam scattering can increase the equilibrium emittances

http://www.desy.de/~awolski/ILCDR/USTeleconference_files/2005-07-13/05-07-13-IBS-ILCDR.pdf



IBS effects are strongest in the transverse planes

Lattice	PPA	OTW	OCS	BRU	MCH	DAS	TESLA
Beam Energy, E_0 [GeV]	5.0	5.0	5.066	3.74	5.0	5.0	5.0
Bunch Charge, N_0 [10^{10}]	2.4	2.2	2.0	2.0	2.0	2.0	2.0
$1/\langle T_x^{-1} \rangle$ [ms]	51.1	1291	122	45.4	185	180	456
$1/\langle T_y^{-1} \rangle$ [ms]	6520	1880	5270	2400	2180	1975	1167
$1/\langle T_p^{-1} \rangle$ [ms]	759	487	967	31.9	923	848	632
$\Delta\gamma\varepsilon_x/\gamma\varepsilon_x$	64%	11%	22%	126%	17%	14%	7.1%
$\Delta\gamma\varepsilon_y/\gamma\varepsilon_y$	32%	5.5%	11%	65%	8.9%	9.8%	4.5%
$\Delta\sigma_z/\sigma_z$	1.4%	1.8%	1.9%	4.2%	1.5%	1.5%	2.4%
$\Delta\sigma_\delta/\sigma_\delta$	1.4%	1.4%	1.4%	4.2%	1.6%	1.4%	2.7%
$\gamma\varepsilon_x(N_0)$ [μm]	6.97	4.23	6.74	6.25	7.69	6.84	5.28
$\gamma\varepsilon_y(N_0)$ [nm]	26.4	21.1	22.1	30.3	18.1	17.9	14.8

Touschek lifetime looks reasonable in most cases

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"):

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

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

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

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

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.

RW growth times are of the order 10 - 100 turns

$$\frac{1}{\tau^{(\mu)}} = -\frac{ec\langle I \rangle}{4\pi \nu E_0} \mathrm{Re} \sum_{p=-\infty}^{+\infty} Z_1((\nu + pn_b + \mu)\omega_0)$$

$$Z_1(\omega) = (1 - i\,\mathrm{sgn}(\omega)) \frac{Z_0 c}{2\pi b^3} \sqrt{\frac{2c}{Z_0 \sigma |\omega|}}$$

	PPA	OTW	OCS	BRU	MCH	DAS	TESLA
τ_{min} [μs]	964	1150	380	1150	3720	1570	3860
τ_{min} [turns]	102	107	19	54	70	28	68

Feedback systems look challenging in some cases.

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.

Conclusions

Instabilities are hard to predict.

The consequences of an instability can be severe.

The damping rings must be designed with as much safety margin as possible with respect to collective effects.