Collective Effects Study for the Diamond-II Storage Ring

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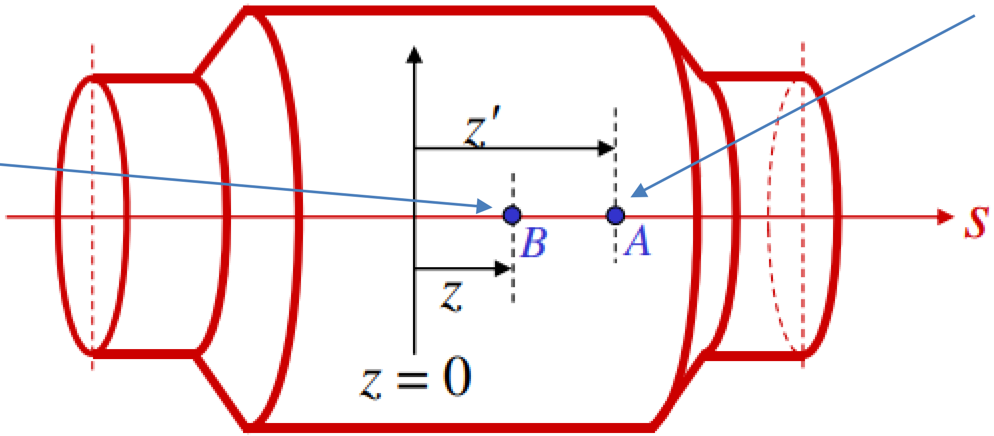
Collective Effects in Storage Rings

- Beam in an accelerator interacts with its surroundings:
  - Interacting with the vacuum chambers via electromagnetic fields: resistive-wall effects, geometric effects. (wake and impedance)
  - Interacting with other particles within one bunch-> intra-bunch scattering (IBS)
  - Interacting with positively charged ions due to ionisation of residual gases.

- Coupling between bunches:
  - Single-bunch instabilities. (Short-range instability)
  - Coupled-bunch instabilities. (Long-range instability)

Wake and Impedance



Particles exciting electromagnetic fields:

- A bunch: wake fields
- A delta-function bunch: wake function

- The electromagnetic fields generated by a particle or a bunch of particles, The frequency domain counterpart of the wake function is the impedance $Z(f)$

$$V_{\parallel,\perp}(t) = \int_{-\infty}^{t} W_{\parallel,\perp}(t-\tau)\rho(\tau)d\tau \,, Z_{\parallel,\perp}(f) = \int_{-\infty}^{\infty} W_{\parallel,\perp}(t)\exp(-2\pi i f t)\, dt$$

- Tracking implementation in ELEGANT
  - One-turn map element, including longitudinal and transverse oscillation
  - Time domain (using wake function): convolution of the bunch distribution and the wake function.
  - Frequency domain (using impedance): IFFT(FFT(bunch distribution)×impedance)

Motivation

- The impact of resistive-wall and geometric impedance on storage rings
  - Short-range effects:
    - Longitudinal: bunch lengthening, microwave instability, synchronous phase shift.
    - Transverse: transverse mode coupling instability (TMCI), head-tail instability.
  - Long-range effects:
    - Driven by transverse resistive-wall wake, cavity higher order modes (HOMs)
    - Affect multi-bunch train motion. (Also coupled-bunch instability)
- Study of the instability in the storage ring design phase
  - Different instability thresholds.
  - Potential cure of instability
    - Positive chromaticity to damp the TMCI.
    - Bunch-by-bunch feedback system to stabilise the coupled-bunch beam motion.
    - Bunch lengthening using harmonic cavities.

Some Results of Collective Instability Study for Diamond-II

More details: R. Fielder, H.-C. Chao and S. Wang,
"Single Bunch Instability Studies with a new Impedance database for Diamond-II",
IPAC2022, Bangkok, Thailand, WEPOMS011

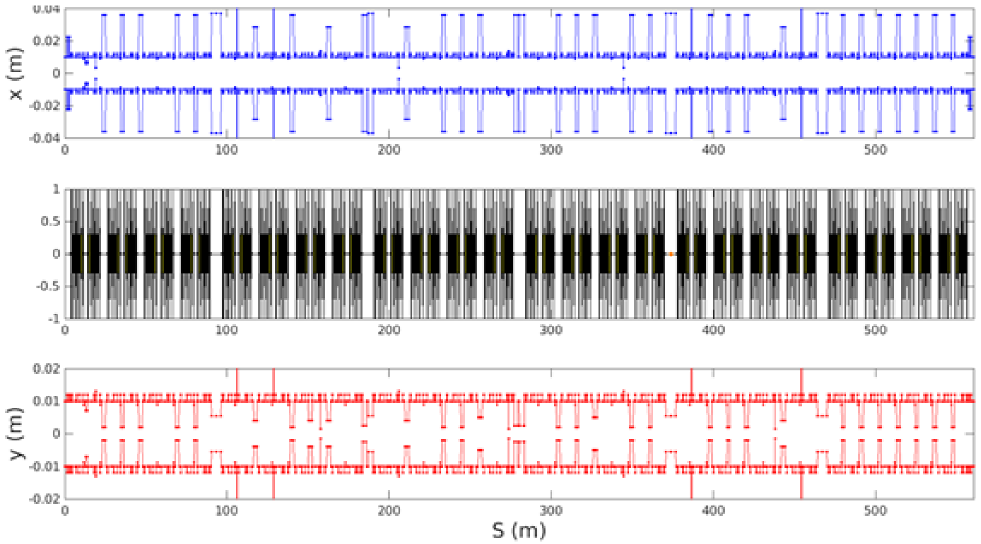
S. Wang, H.-C. Chao, R. Fielder, I. P. S. Martin and T. Olsson,
"Studies of Transverse Coupled-Bunch Instabilities from Resistive-Wall and Cavity Higher Order Modes for Diamond-II",
IPAC2022, Bangkok, Thailand, WEPOMS010

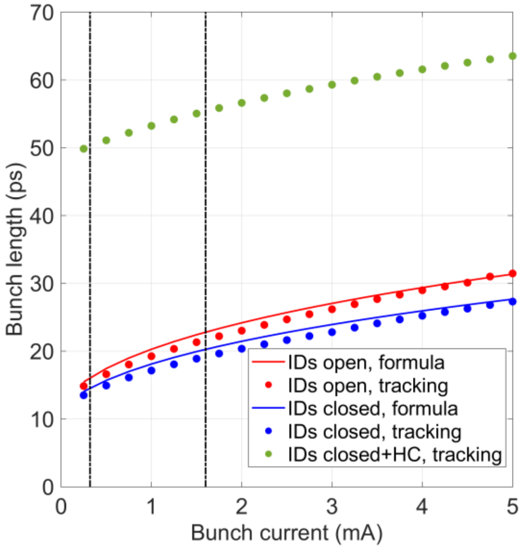
Single-bunch instability

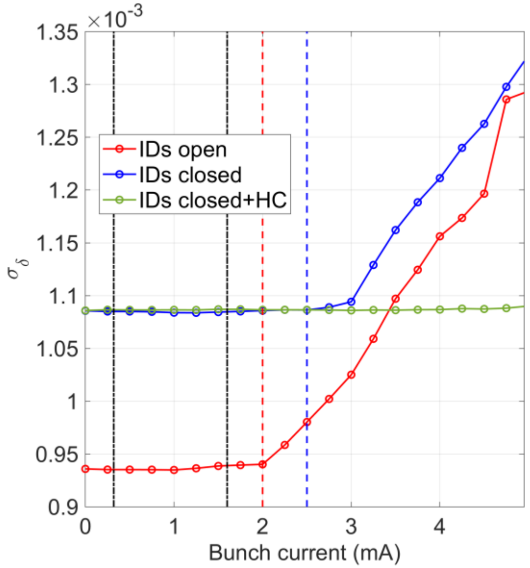
Courtesy of Richard Fielder

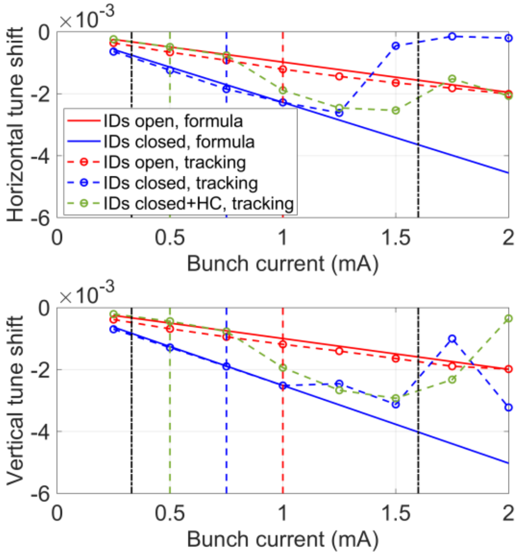
- All impedance information stored in an impedance lattice (Accelerator Toolbox structure)
  - Resistive-wall impedance calculated using ImpedanceWake2D
  - Geometric impedance simulated with CST.
- Simulation using ELEGANT, 0.25mA step
  - Bunch lengthening, synchrotron phase shift, Microwave instability threshold.
  - Transverse mode coupling instability (TMCI) and head-tail instability threshold.

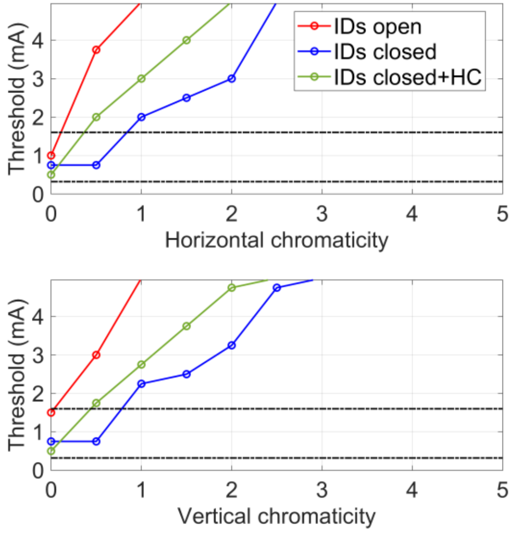
Apertures with closed collimators and in-vacuum IDs











Coupled-bunch Instability

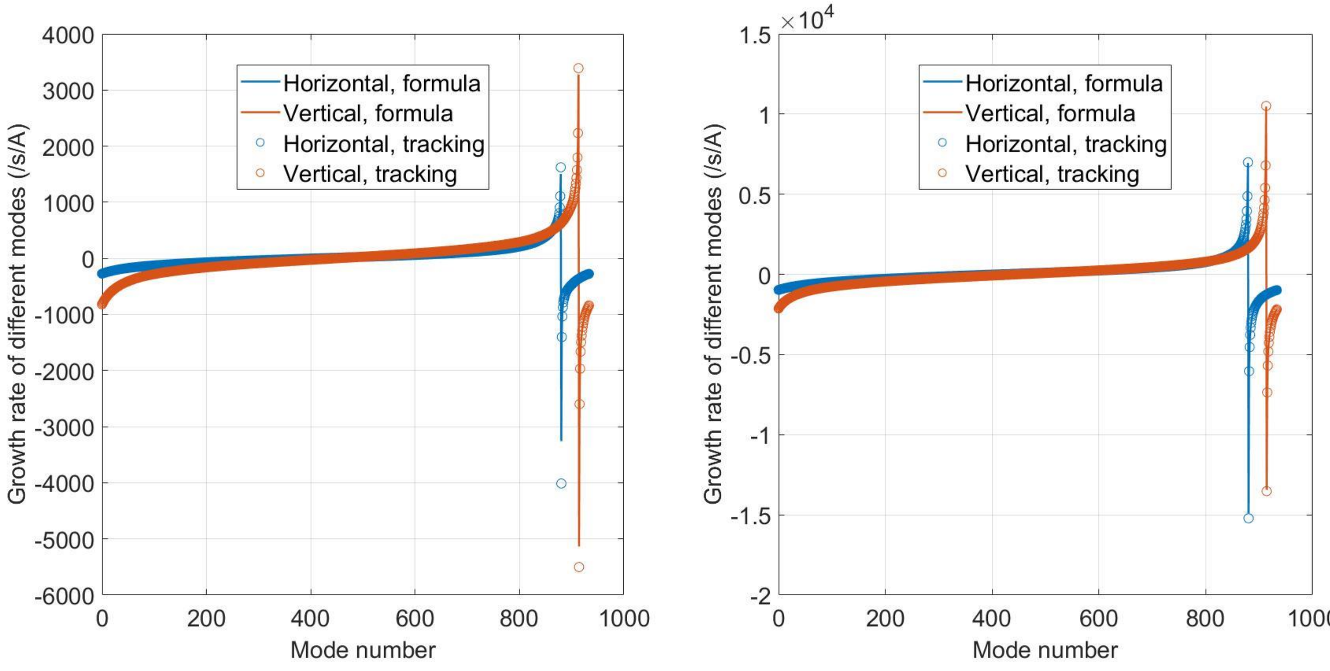
- Tracking with one particle representing one bunch. Discrete Fourier Transform on every turn to get the coupled-bunch modes.

- Good agreement between tracking and analytic formula for uniform fill pattern with chromaticity 0.

$$\Omega_\mu - \omega_\beta = -i\frac{ecI_0}{4\pi E_0 \nu_\beta}\sum_p Z_\perp(\omega_p)$$

Ω_μ is the complex frequency of mode μ.

- Estimated thresholds from largest growth rate mode agree with tracking including radiation damping.

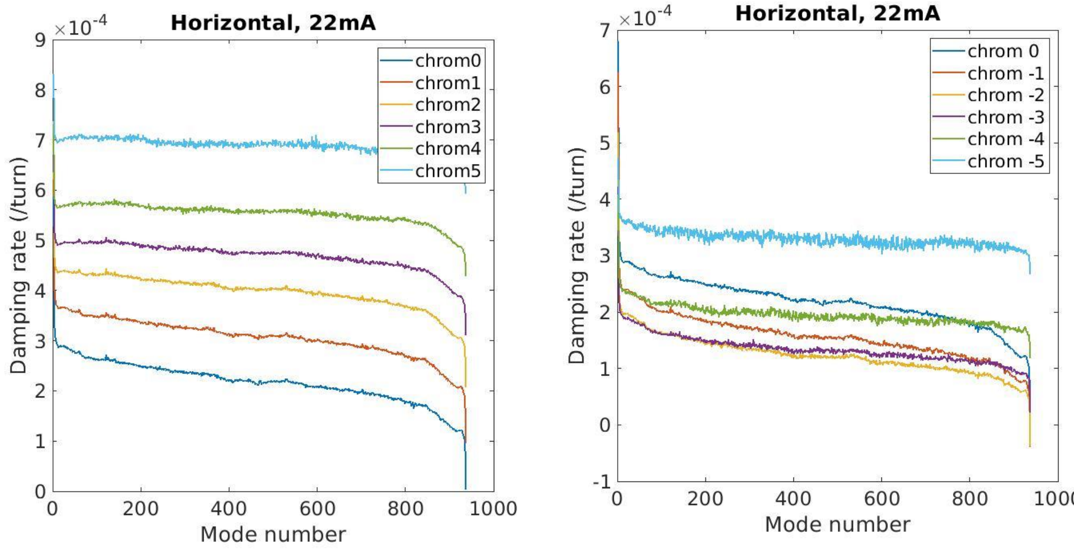


Open IDs	Closed IDs

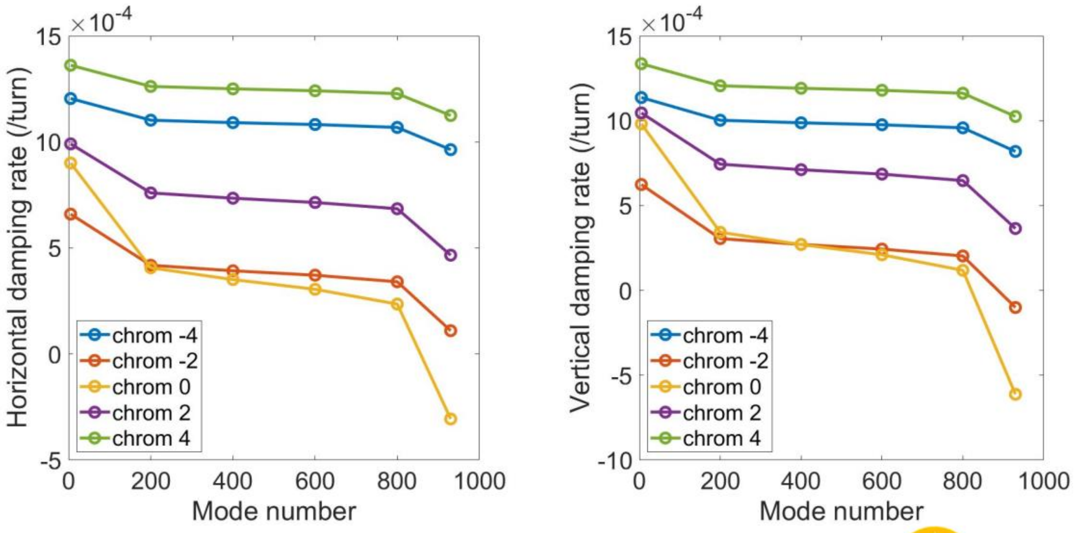
Growth Rate with Chromaticity

- Drive/damp measurement in existing ring
  - Drive the beam with specific mode frequency and measure natural damping
  - Damping rate fitted from IQ data.
  - Shift of curve with chromaticity. Different behaviour for positive and negative chromaticity.
- Simulation with Diamond-II impedance model
  - Including long + short wake + radiation damping, uniform fill pattern, 100mA
  - Similar trend as the experiment.
- Initial observations:
  - Long range wake: shrink of curve vs chromaticity
  - Radiation: larger damping rate for higher absolute value of chromaticity
  - Short range wake: Difference between positive and negative chromaticity

Measurement at Diamond-I



Simulation for Diamond-II



diamond

Conclusions

- Single-bunch instability threshold below different operation modes for the Diamond-II storage ring.

Fill pattern mode	Bunch current requirement (mA)
Uniform	0.32
Standard	0.33
Hybrid	1.6

	Microwave	Transverse (chromaticity 2)	
		Horizontal	Vertical
Open IDs	2 mA	> 5 mA	> 5 mA
All IDs closed	2.5 mA	3 mA	3.25 mA
All IDs closed + FP HC	> 5 mA	> 5 mA	4.75 mA

- Coupled-bunch instability threshold very low at chromaticity 0 (300mA beam current).
  - Bunch-by-bunch feedback system required to stabilise the beam.
  - Harmonic cavity and chromaticity can help reduce the largest growth rate.

		SR damping time (ms)	Largest growth rate (/A/s)	Threshold (mA)
Open ID	Horizontal	9.66	1622	63.8
	Vertical	18.1	3390	16.3
Closed ID	Horizontal	5.66	6993	25.3
	Vertical	7.78	10505	12.2

Thanks