Collective Effects in the Diamond-II Storage Ring

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on behalf of the Diamond-II team

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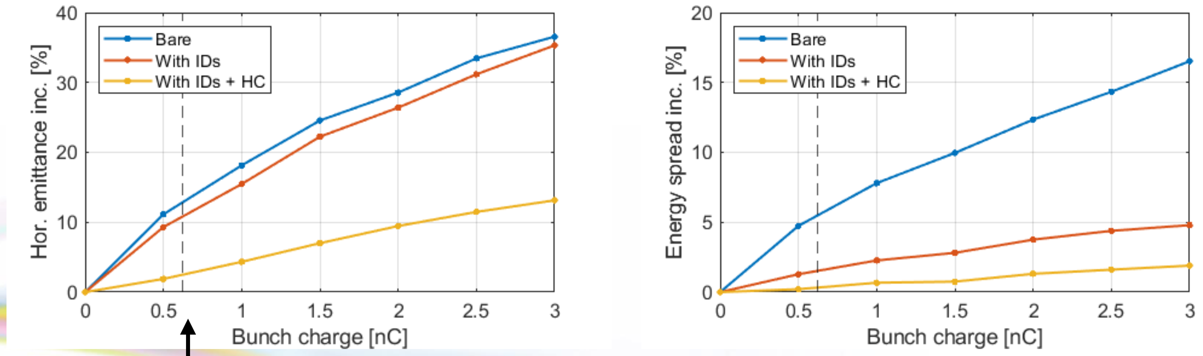
Lattice Parameters

Diamond-II Storage Ring

- The machine will operate at 300 mA as the existing ring.
- The ring includes 30+ insertion devices → significant change of the lattice parameters between fully opened and fully closed.
- The ring will operate with harmonic cavity to:
  - Increase Touschek lifetime
  - Reduce intra-beam scattering
  - Mitigate instabilities

Effect of intra-beam scattering



Nominal bunch charge (≈ 0.6 nC) HC according to flat potential conditions

	Open IDs	All IDs closed
Energy [GeV]	3.5	
Circumference [m]	560.561	
Harmonic number	934	
RF frequency [MHz]	499.511	
Tune (h/v)	54.15/20.27	
Chromaticity	2.0/2.3	
Momentum compaction	$1.04 \cdot 10^{-4}$	
Nominal current [mA]	300	
RF voltage [MV]	1.42	2.53
Equilibrium emittance [pm rad]	**161.7**	**121**
Energy spread [%]	0.094	0.11
Energy loss/turn [MeV]	0.723	1.68
Damping times (h/v/l) [ms]	**9.7/18.1/16.0**	**5.7/7.8/4.8**
Nominal bunch length [ps]	12.5 ps	11.7 ps
Lifetime [h] (0.6 nC, nat. bunch length, 8 pm vertical emittance, after simulated commissioning corrections)	2.15 ± 0.1	2.33 ± 0.1

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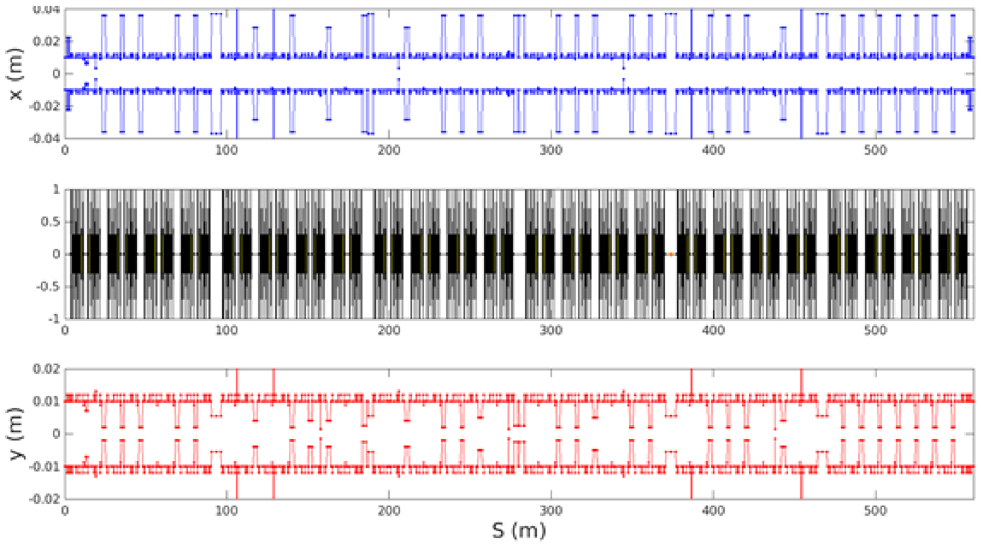
Impedance Database

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

Organisation and Simulations

- All impedance information stored in an impedance lattice (Accelerator Toolbox structure)
  - Apertures, materials, paths to files etc.

Apertures with closed collimators and fully closed in-vacuum IDs



- Tracking simulations in Elegant to include as many effects as possible self-consistently
  - Lumped impedance at 1 point except for injection tracking → 24 points.
  - Interface to generate input files from impedance lattice with normalisation with local beta in transverse planes.
  - Intra-beam scattering not included self-consistently yet.

Impedance Contributions

Courtesy of Richard Fielder

Resistive-wall:

- Majority NEG coated (1 µm, 1e5 S/m as worst case).
- Dipole vessel for photon extraction of aluminium with ante-chamber design.
- Impedance calculated with ImpedanceWake2D. Rectangular Yokoya factors used for ID chambers.

Material	Length (m)	Conductivity (S/m)
Steel	42.02	1.35 e6
Copper	51.85	5.96 e7
Aluminium	96.00	3.77 e7
NEG-coated copper	336.36	1.00 e5, 5.96 e7
NEG-coated aluminium	31.73	1.00 e5, 3.77 e7
Ti-coated alumina	2.60	2.38 e6, 0.00
Total	560.56	

Geometric:

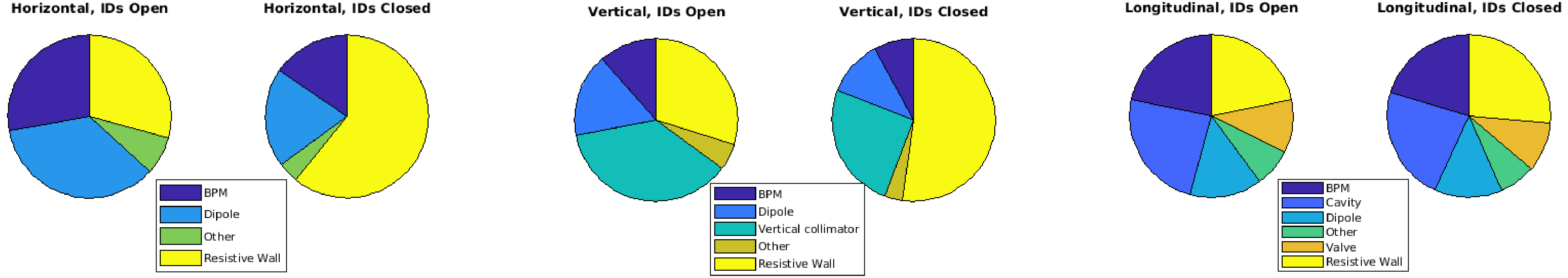
- Simulations in CST using PEC. So far with 3 mm bunch length, but in progress to reduce to 1 mm.
- Main RF cavities NC instead of SC as in existing ring → EU HOM damped.
- Total 252 BPMs (one included in dipole vessel) with updated design.
- New flange design using copper gasket to avoid gap.
- Six collimators: horizontal gap: 7 mm, vertical gap: 3 mm.
- Updated design of transverse multibunch feedback (TMBF) striplines.

Component	Number in ring	Loss factor (V/pC)	Hor. kick factor (V/pC/mm)	Ver. kick factor (V/pC/mm)
BPM1 assembly	48	0.0806	-0.0298	-0.0127
BPM2 assembly	48	0.0210	-0.0046	-0.0050
BPM4 assembly	48	0.0383	-0.0109	-0.0125
BPM5 assembly	12	0.0690	-0.0304	-0.0058
BPM6 assembly	48	0.0414	-0.0118	-0.0119
Dipole vessel	47	0.117	-0.195	-0.0301
Visible Light Extraction	1	0.176	-0.322	-0.0356
Flange	492	0.00003	0.0001	-0.0002
Main RF cavity	8	1.186	0.0011	-0.0001
Hor. TMBF stripline	1	0.0821	-0.0056	-0.0126
Ver. TMBF stripline	1	0.0821	-0.0126	-0.0056
Valve	96	0.0427	-0.0012	-0.0059
Screen	2	0.023	-0.0027	-0.0029
Ver. collimator	3	0.2843	-0.1991	-1.0070
Hor. collimator	3	0.2679	-0.2095	-0.0580
Injection stripline	4	0.2463	-0.0173	-0.1008
Total		21.222	-14.324	-7.976

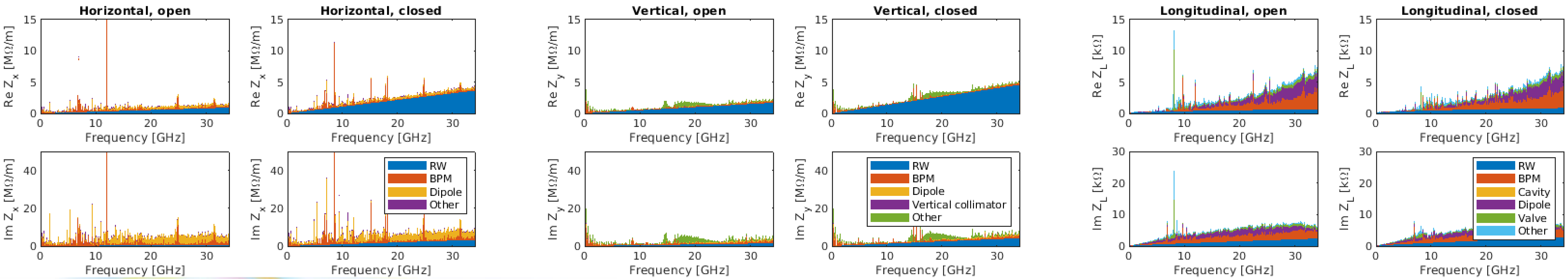
Total Impedance

Courtesy of Richard Fielder

Contribution to kick/loss factors



Beta-weighted impedance



Harmonic Cavity

Harmonic Cavity Choice

- Different choices considered but need to choose existing design due to human resources and time constraints.
- Third order cavity chosen because of availability of 1500 MHz cavities and good bunch lengthening.

- **Passive NC**: Unstable unless low total R/Q → no suitable cavity design for Diamond-II parameters.

- **Passive SC** (CEA Super-3HC): sufficiently low total R/Q to avoid instabilities + lengthening at lower currents too.

- **Active NC** (ALBA cavity): unstable unless high power coupling (β > 10) → high power consumption. Still does not solve problem with transient beam loading.
  Reason: main cavities have significant contribution to transient beam loading due to large total R/Q.

→ **Passive superconducting cavity of the CEA Super-3HC type**

Requirements for flat potential conditions at 300 mA for third order HC

	Open IDs	All IDs closed
RF voltage [MV]	1.42	2.53
Harmonic voltage [kV]	398.270	597.665
Tuning angle [°]	-103.124	-110.608
Shunt impedance [MΩ]	**3.26**	**3.14**
Bunch lengthening for uniform fill (RMS) [times]	3.9	4.2

Cavity parameters

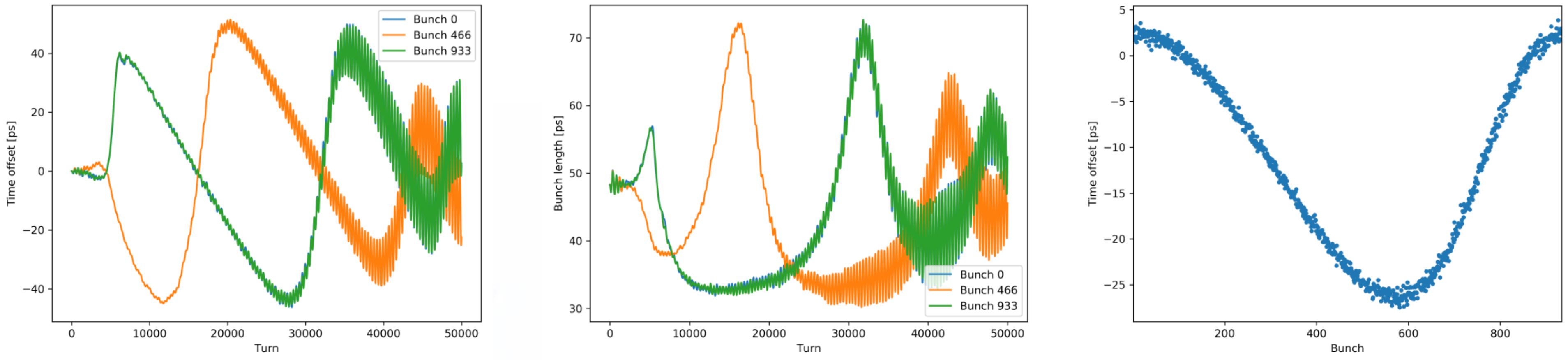
	Main	Harmonic
Type	EU HOM damped	CEA Super-3HC
Number of cavities	8	1
Cavity harmonic	1	3
Shunt impedance [Ω]	$3.94 \cdot 10^6$	$1.77 \cdot 10^{10}$
Q factor	33 000	$2 \cdot 10^8$
R/Q per cavity	119.5	88.4
Total R/Q [Ω]	**956**	**88.4**

Periodic Transient Beam Loading

- Beam loading does not reach steady-state even for uniform fill but periodic variations in centroid and length with time.
- Behaviour described for HALF also seen in simulations for Diamond-II
  - Centroid distribution presents as longitudinal coupled-bunch mode 1
  - Can be very long period (tracking of millions of turns might be required)
  - Independent of radiation damping
  - Mitigated by lower HC R/Q, higher RF voltage or tuning the HC further out
  - Impedance helps to stabilise the beam so the HC can be tuned in further
- Efforts to maximise bunch lengthening (close to uniform fill, small charge variation, tuning cavity beyond flat potential etc.) increases risk of PTBL → for Diamond-II more often limitation rather than Robinson instability.
- Seen for both passive NC and passive SC HC but higher threshold for SC case due to lower total R/Q.

He, Li, Bai and Wang,
"Periodic transient beam loading effect with passive harmonic cavities in electron storage rings",
Phys. Rev. Accel. Beams 25, 024401 (2022)

Example for uniform fill:



Fill Patterns

More details: T. Olsson and H.-C. Chao,
“Fill Pattern for Reducing Transient Beam Loading and Ion-Trapping in the Diamond-II Storage Ring ”,
IPAC2022, Bangkok, Thailand, TUPOMS031

Fill Pattern Requirements

- Standard mode: 300 mA
  - Requirements only given by machine: **transient beam loading + ion instabilities**
  - Existing ring operate with 900 bunches + single gap of 74 ns → bad for transient beam loading
  - Avoid increasing the bunch charge too much since affects lifetime → rules out uniform fills → need to operate with bunch trains with gaps between.

- Hybrid mode: 300 mA
  - Users request hybrid mode similar to operated in existing machine for timing experiments: **3 nC hybrid bunch in middle of long gap**
  - Transient beam loading major concern → other options to increase lifetime might have to be considered, e.g. increasing vertical emittance or reducing current.
  - Also looking at other options than hybrid mode:
    - Pulse Picking by Resonant Excitation (PPRE)
    - Pseudo Single Bunch (PSB)
    - Transverse Resonance Island Buckets (TRIBs)

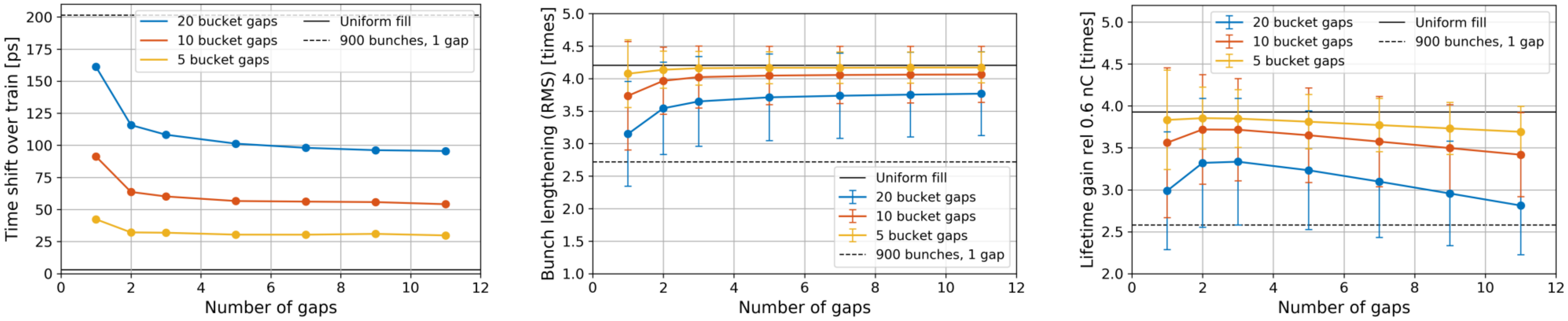
Current gap requirements

Beamline	Gap requirement around hybrid bunch
1	250 ns before and after
2	70 ns before, unspecified after
3	150 ns before and after for Dectris detector 20 ns before and after for Timepix or Tristan

Transient Beam Loading

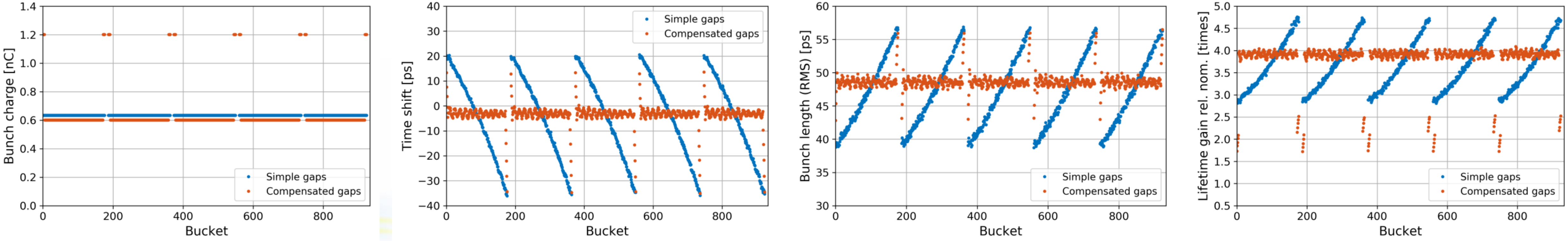
- Additional gaps helps up to the point where the bunch length no longer increases → lifetime gain decreases due to higher bunch charge.

Simulations for all IDs closed including 8 NC MCs with RF feedback, SC HC and longitudinal impedance.



- Future option to add guard bunches/compensated gaps but not included so far in favour of less complex fill pattern.

Example with 5 gaps of 10 buckets



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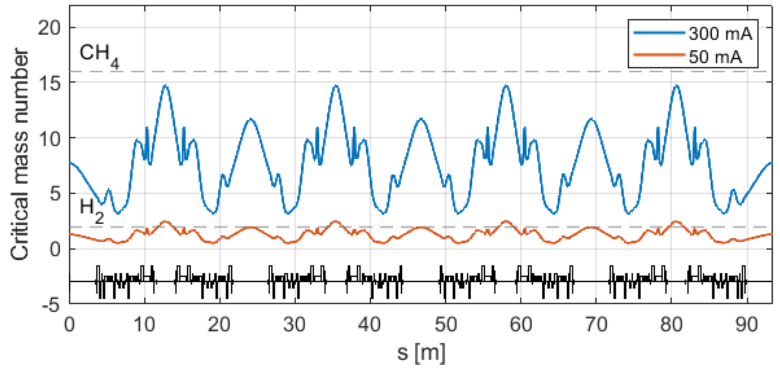
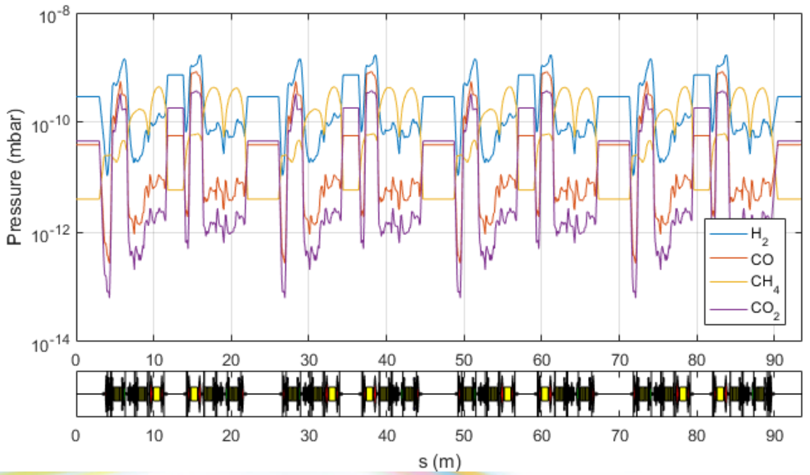
Ion Instabilities

- Critical mass number: where ions trapped for uniform fill.
- CO, CH_4, CO_2 trapped at 300 mA, H_2 trapped below 50 mA.

Critical mass number for 8 pm vertical emittance



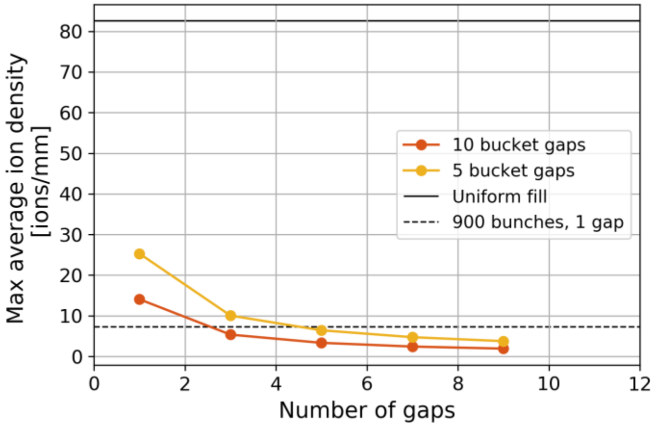
Distributed pressure profile

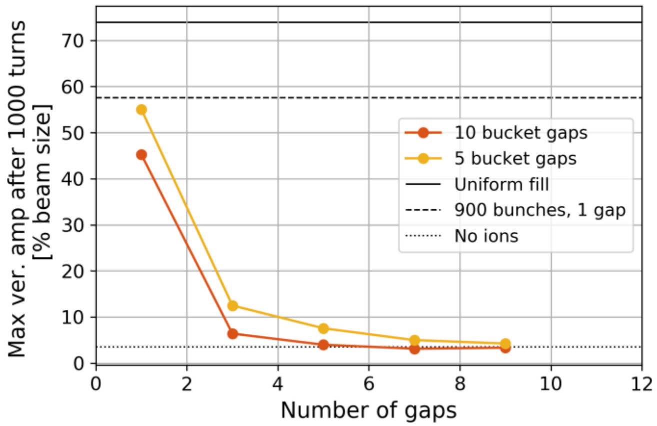


Simulation setup:

- Electrons: macroparticles tracked in 6D along lattice.
- Ions: macroions generated at specified interaction points representing line density between points
- 97 interaction points based on critical mass number
- Distributed pressure profile for 100 Ah conditioning with unsaturated NEG.
- So far Gaussian distribution assumed for both electron and ions when calculating the kicks.

All IDs closed, 8 pm vertical emittance



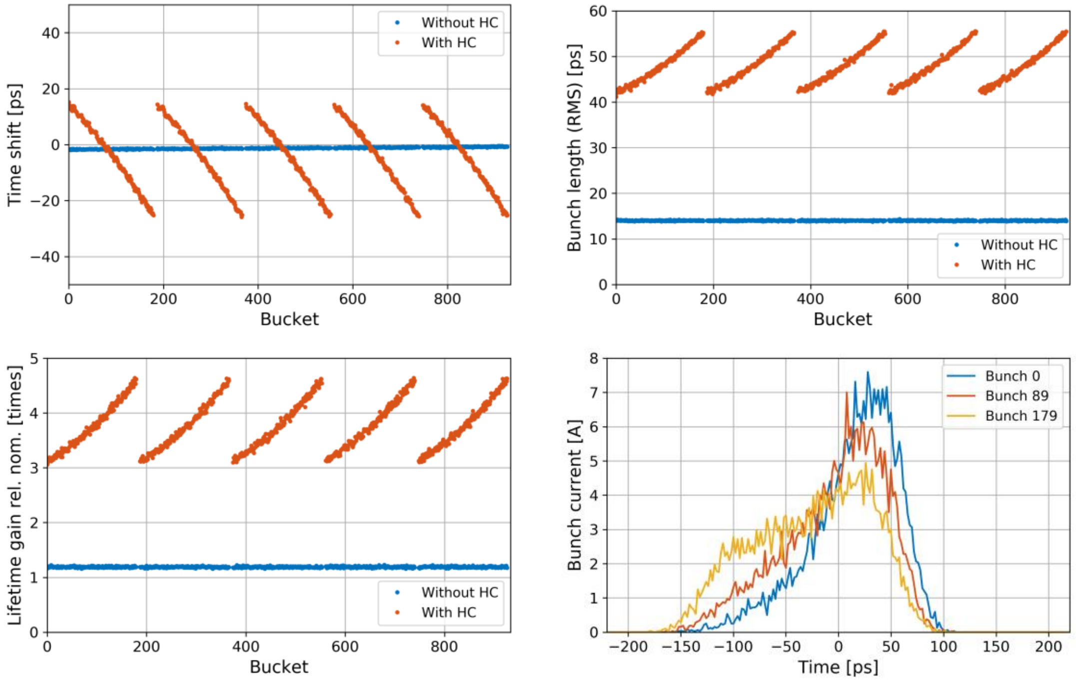


- For same number of bunches better ion-clearing with several short gaps instead of single long one → better to operate with several short bunch trains.
- Next steps: include charge variation, transverse impedance, multiple ionisations and multibunch feedback.

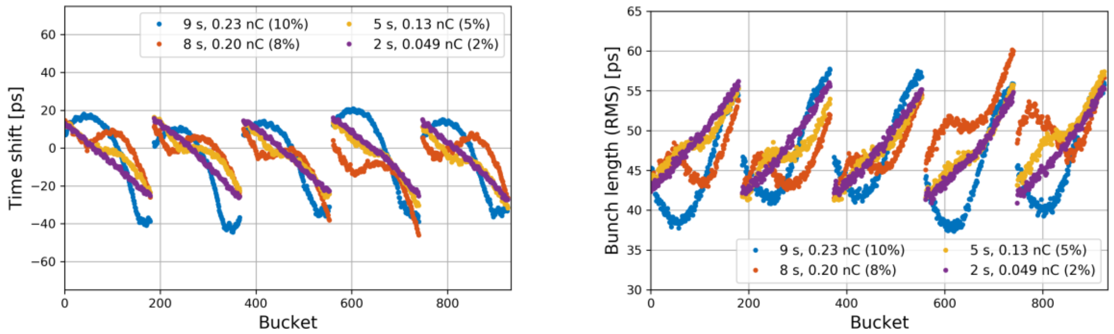
Standard Mode

- Fill pattern with 5 gaps of 7 buckets chosen → fits well with maximum train from booster if using multibunch injection.

All IDs closed



Variation at different top-up conditions (time between injections, charge per shot)

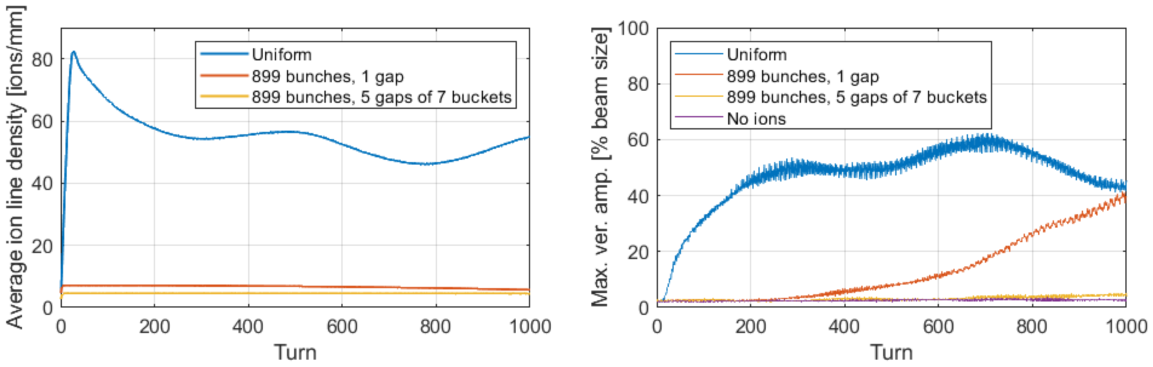


Charge variation below 5% preferable.

Statistics at nominal HC detuning

	Open IDs	All IDs closed
Total time/phase shift [ps/°]	55.7/10.0	41.0/7.4
Bunch length (RMS) [ps]	48.4 ± 3.2	48.0 ± 3.9
Lifetime gain rel. nom. [times]	**3.7 ± 0.4**	**3.8 ± 0.4**

Ion instabilities



Ion instability growth rate within expected magnitude possible to damp with feedback.

Instabilities

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

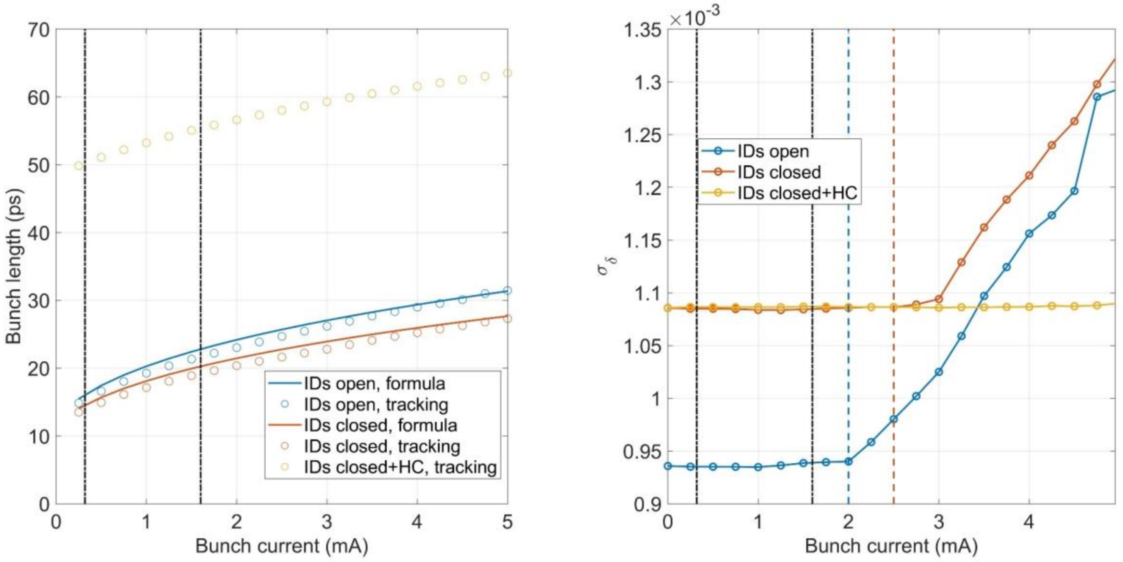
S. Wang, H.-C. Chao, R. Fielder, I. P. S. Martin and T. Olsson,
“Studies of Transverse Coupled-Bunch Instabilities from Resistive-Wall and Cavity Higher Order Modes for Diamond-II”,
IPAC2022, Bangkok, Thailand, WEPOMS010

Single Bunch Thresholds

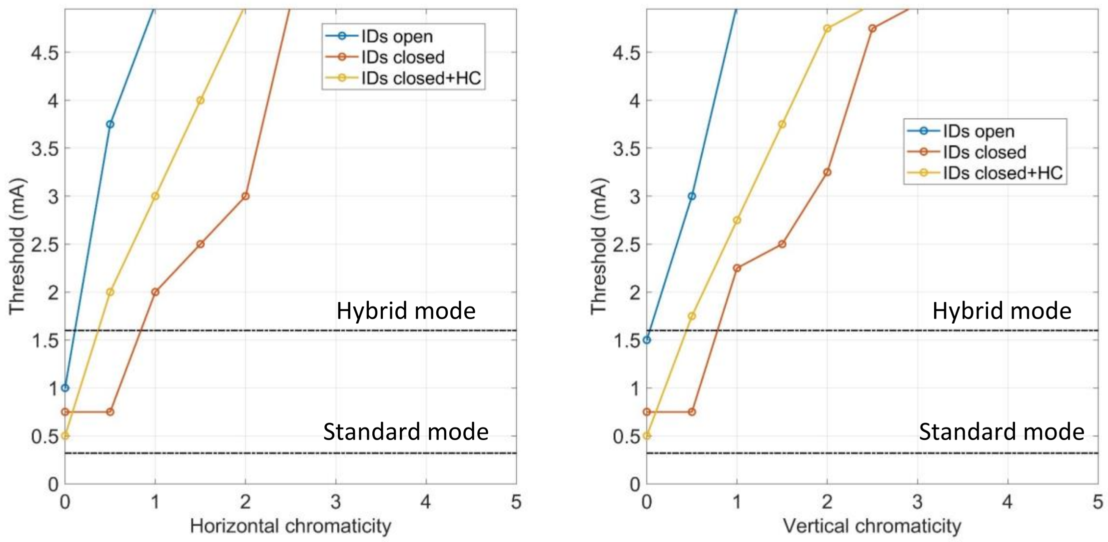
Courtesy of Siwei Wang

- Tracking results benchmarked against analytic formulas with good agreement.
- Harmonic cavity included as flat potential to be able to scan the current.

Longitudinal



Transverse



Standard mode bunch current = **0.33 mA**
Hybrid bunch aim = **1.6 mA**

Green = okay for both modes
Red = not okay for hybrid mode

	Microwave	TMCI (chromaticity 0)		Head-tail at chromaticity +2	
		Horizontal	Vertical	Horizontal	Vertical
Open IDs	2 mA	1.0 mA	1.5 mA	> 5 mA	> 5 mA
All IDs closed	2.5 mA	0.75 mA	0.75 mA	3 mA	3.25 mA
All IDs closed + FP HC	> 5 mA	0.5 mA	0.5 mA	> 5 mA	4.75 mA

Coupled-Bunch Instabilities

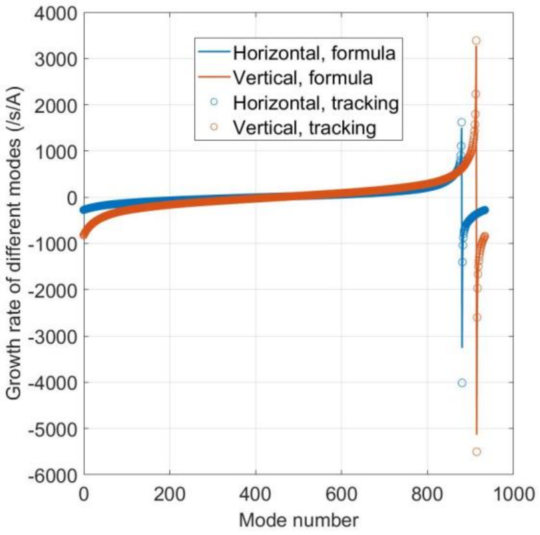
Courtesy of Siwei Wang

- Transverse resistive-wall instability expected to be strongest coupled bunch instability.
- Studies of growth rates to understand behaviour and impact of different parts of the impedance.

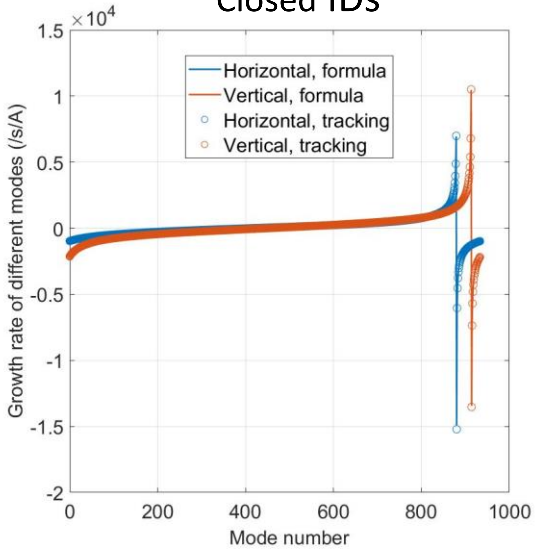
- Good agreement between tracking and analytic formula for uniform fill with chromaticity 0.
- Estimated thresholds from growth rate agree with tracking including radiation damping.

Uniform fill

Open IDs



Closed IDs



Uniform fill, chromaticity 0, long range impedance only		Radiation damping rate (/s)	Largest growth rate (/A/s)	Estimated threshold (mA)
Open IDs	Horizontal	103.5	1622	**63.8**
	Vertical	55.2	3390	**16.3**
Closed IDs	Horizontal	176.7	6993	**25.3**
	Vertical	128.5	10505	**12.2**

Growth Rate with Chromaticity

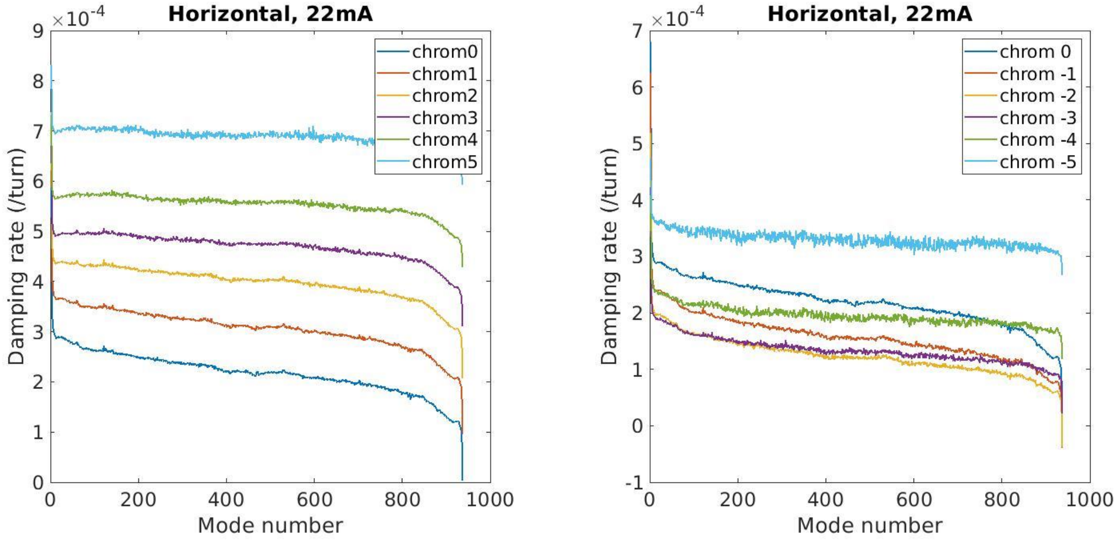
Courtesy of Siwei Wang

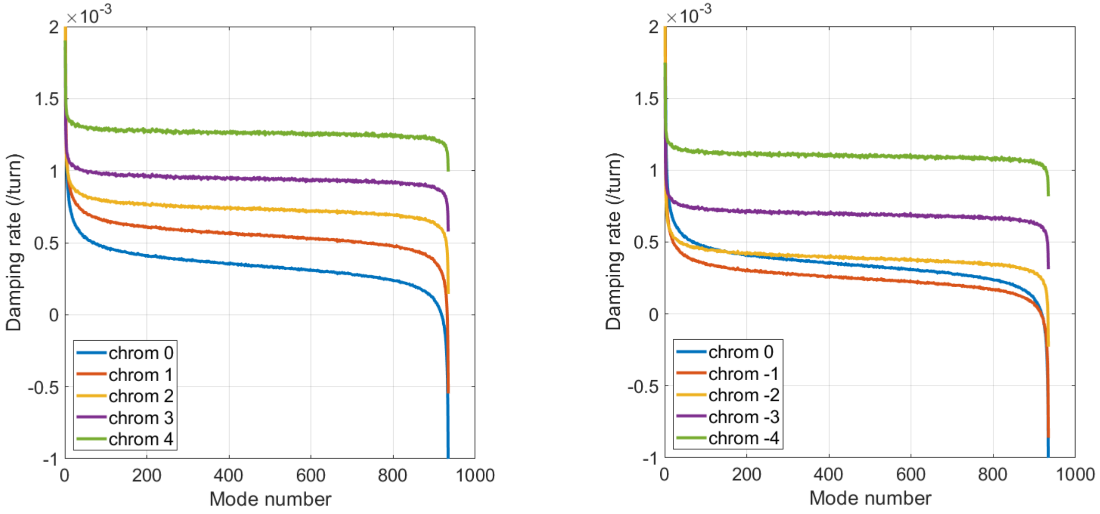
- Drive/damp measurement in existing ring
  - Drive the beam with specific mode frequency and measure natural damping.
  - Damping rate fitted from IQ data.
  - Shift of curve with chromaticity. Different behaviour for positive and negative chromaticity.

- Simulation with Diamond-II impedance model
  - Including long + short wake + radiation damping.
  - 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 in existing ring





Diamond-II: 100 mA, closed IDs, uniform fill, long + short range wake + radiation damping

Emittance Feedback

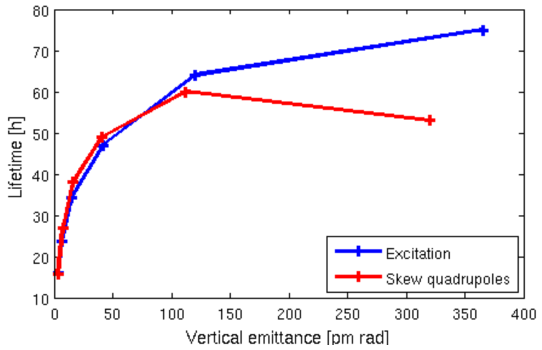
More details: S. Preston, T. Olsson and B. Singh,
"Emittance Feedback for the Diamond-II Storage Ring Using Resonant Excitation",
IPAC2022, Bangkok, Thailand, TUPOMS035

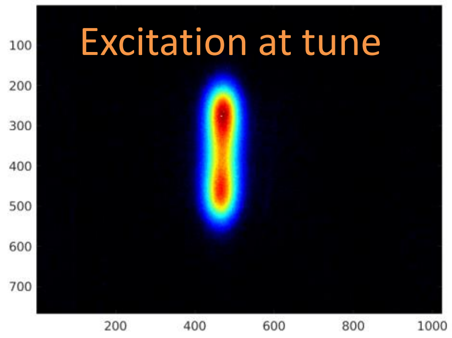
Emittance Feedback

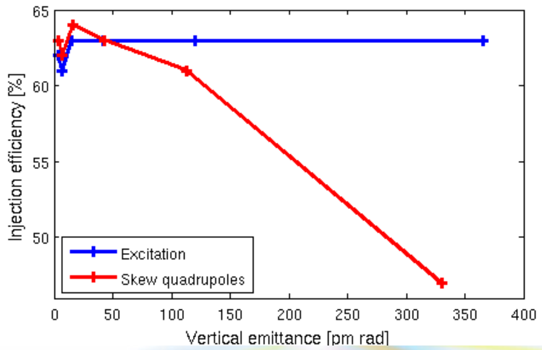
- Existing ring has vertical emittance feedback based on skew quadrupoles → affects injection efficiency and lifetime.
- New feedback based on exciting the beam at a synchrotron sideband → idea from PPRE.
- Tests are ongoing in existing ring together with benchmarking against simulations.

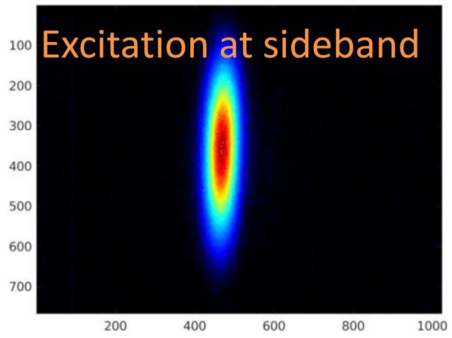
Courtesy of Shaun Preston

Measurements at existing ring

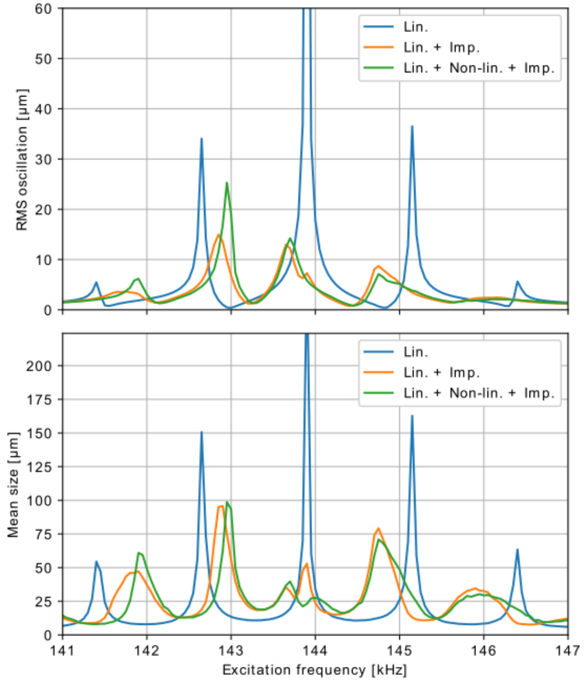


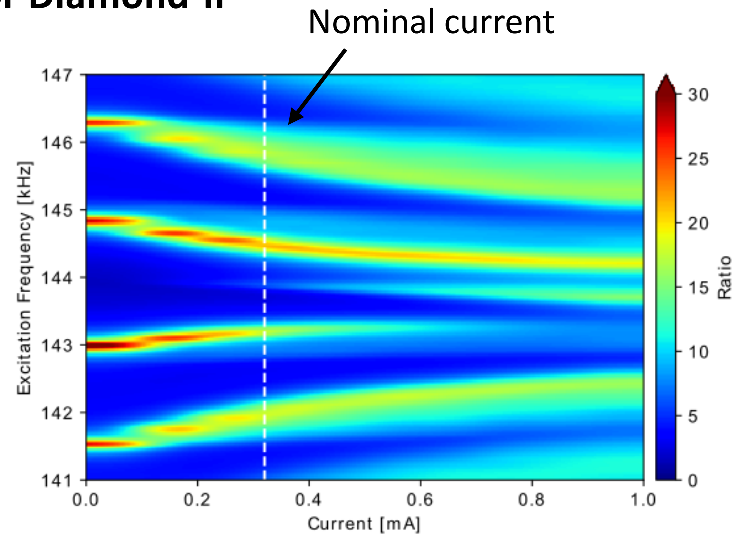






Simulations for Diamond-II





Conclusion: important to include impedance in simulation.
Best excitation frequency: large ratio between size and oscillation → upper sideband.

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Lessons Learned

Lessons Learned

- Increasing demand on computer resources for collective effects simulations
  - Impedance calculations with short bunch length (high frequency content) + long wake (narrow resonators)
  - Injection tracking more important → distributed impedance + element-by-element tracking + different error seeds
  - Self-consistent simulations of instabilities including harmonic cavity
  - Ion instabilities (very resource demanding!)

  Diamond: 960 cores only for the AP group + extra cluster resources at RAL but still often bottleneck when simultaneously high demand for single-particle tracking → code development needed to push the execution time.

- "Periodic transient beam loading" instability must be better understood → currently limiting the use of normal conducting harmonic cavities.
- New ways must be developed to serve timing users → hybrid modes are no longer feasible without compromises to the machine performance.
- The new machines offer better opportunities for benchmarking between simulations and measurements due to better developed impedance models.

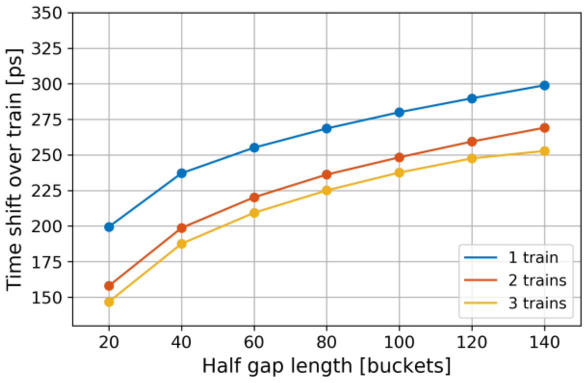
Thank you!

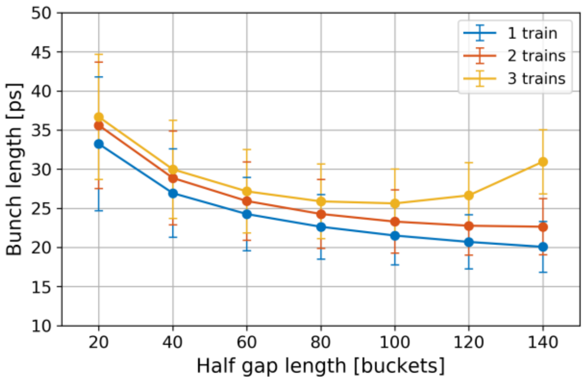
Backup slides

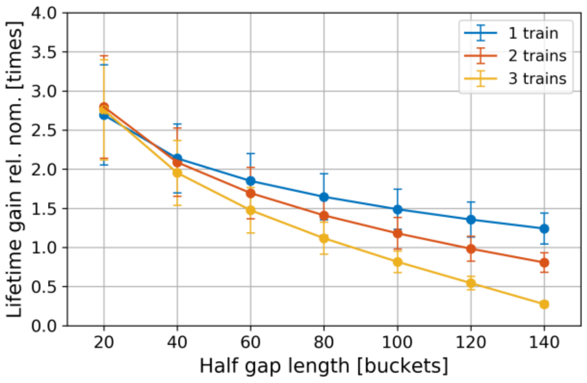
Hybrid Mode

- Depending on gap length it might be favourable to operate with several multibunch trains.
- For long gaps no lifetime gain by tuning in HC more → better to operate less tuned in.

All IDs closed, nominal HC detuning







All IDs closed, 1 multibunch train