Emittance Control for Diamond-II

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Talk Outline

Introduction to Diamond-II

- Lattice details
- Target emittance (horizontal and vertical)
- Impact of IDs (max/min/variation)

Vertical Dispersion and Coupling Control using Skew Quadrupoles

- Method
- Impact on dynamic aperture

Emittance Excitation using the Transverse Multi-bunch Feedback (TMBF)

- Method
- Simulation results for Diamond-II
- Experimental tests on Diamond

Diamond-II Lattice

Modified Hybrid 6-Bend Achromat (M-H6BA) for low emittance

Number of insertion straights increased from 24 to 48

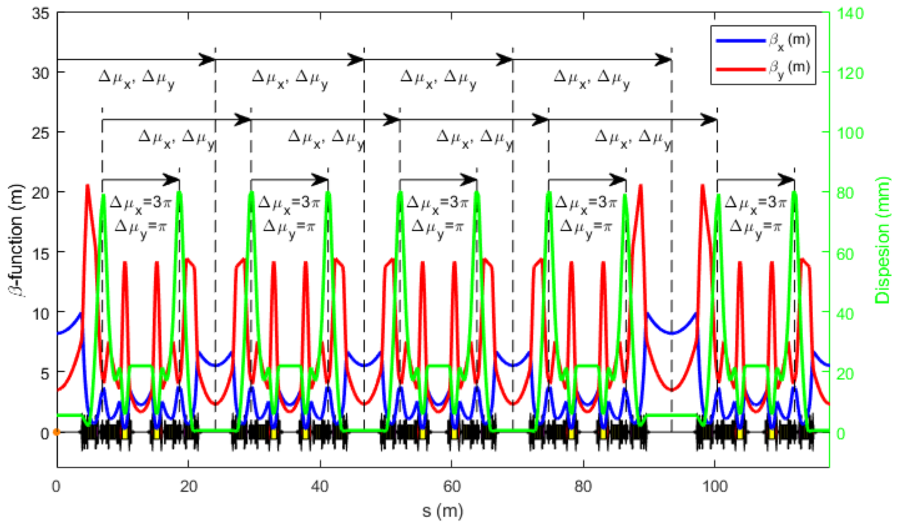
- ➢ Long straights: 7.54 m
- ➢ Standard straights: 5.06 m
- ➢ Mid straights: 2.92 m

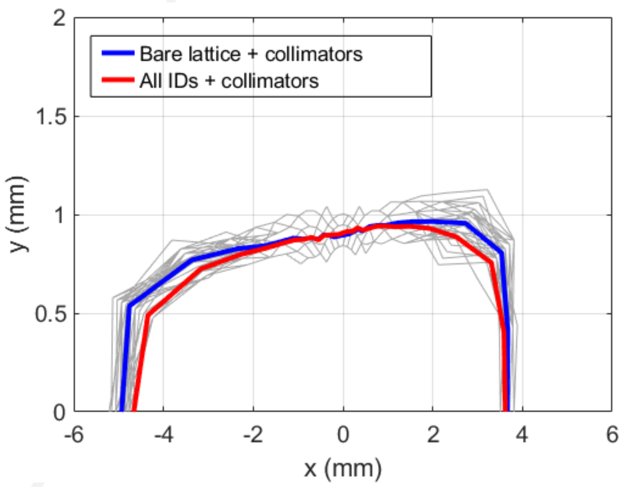
Off-axis injection for beam accumulation

'-I' transformer plus const. cell phase for nonlinear dynamics

Passive SC harmonic cavity for lifetime / beam stability / IBS

Parameter	Units	Diamond	Diamond-II
Energy	**GeV**	**3.0**	**3.5**
Circumference	M	560.6	560.560944
Harmonic Number	-	936	934
RF Frequency	MHz	499.654	499.511
Positive Bending Angle	deg	360.0	374.4
Reverse Bending Angle	deg	0.0	14.4
Total Bending Angle	deg	360.0	388.8
Betatron Tunes	-	[27.21, 12.36]	[54.14, 20.24]
Natural Chromaticity	-	[-79.0, -35.6]	[-68.2, -89.1]
Corrected Chromaticity	-	[1.7, 2.2]	[2.6, 2.6]
Mom. Compaction Factor	$\times 10^{-4}$	1.70	1.03
Natural Emittance	**pm.rad**	**2729**	**162**
Energy Spread	%	0.096	0.094
Energy Loss per Turn	MeV	1.01	0.724
Natural Bunch Length	ps	11.4@2.4 MV	12.4@1.4 MV
Horizontal Damping Partition	-	1.00	1.88
Horizontal Damping Time	ms	11.1	9.4
Vertical Damping Time	ms	11.2	18.1
Longitudinal Damping Time	ms	5.6	16.1





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Target Emittance for Diamond-II

Emittance control will be required for Diamond-II.

User requirements:

1) stable conditions
2) aim for $\varepsilon_y < 10$ pm (diffraction limit at 10 keV)

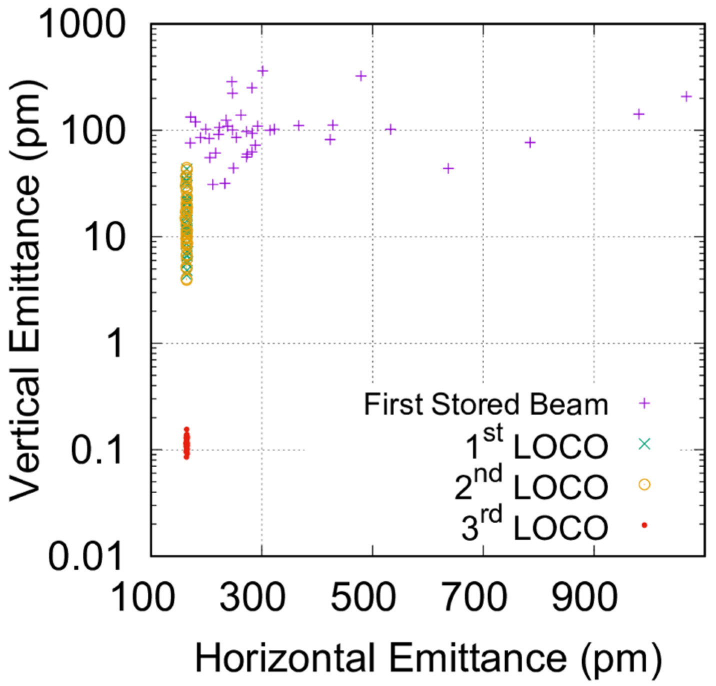
Horizontal emittance can vary between 115 pm and 178 pm depending on ID conditions

Simulated commissioning simulations suggest $\varepsilon_y < 1$ pm after optics and coupling correction

Lifetime favours larger ε_y (targeting τ ~8 h with harmonic cavity)

Target emittance (stabilised):

- $\varepsilon_y = 8$ pm (same as current Diamond storage ring)
- $\varepsilon_x \sim 140$ pm (TBD, depending on operational experience)



Machine Condition	Emittance
Bare lattice	162 pm
All mid-straight IDs (9 devices)	178 pm
All standard straight IDs (18 devices)	115 pm
All long straight IDs (7 devices)	145 pm
All IDs (34 devices)	121 pm

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Vertical Dispersion and Coupling Control using Skew Quads

Method:

1) Apply LOCO to correct η_y and betatron coupling
2) Analytically calculate vector of skew quadrupoles to drive η_y wave without exciting betatron coupling*
    1) Use skew-quads at high η_x point to drive η_y wave
    2) Use skew-quads at zero η_x point to correct betatron coupling in the straights without altering η_y
3) Use feedback to adjust amplitude of skew vector to maintain constant measured vertical emittance

Change in vertical dispersion at BPM #k due to skew quadrupole #j:

$$\Delta\eta_{y,k} = -(\Delta a_2 L)_j \eta_{x,j} \frac{\sqrt{\beta_{y,j}\beta_{y,k}}}{2\sin(\pi Q_y)} \cos(\mu_{y,j\to k} - \pi Q_y)$$

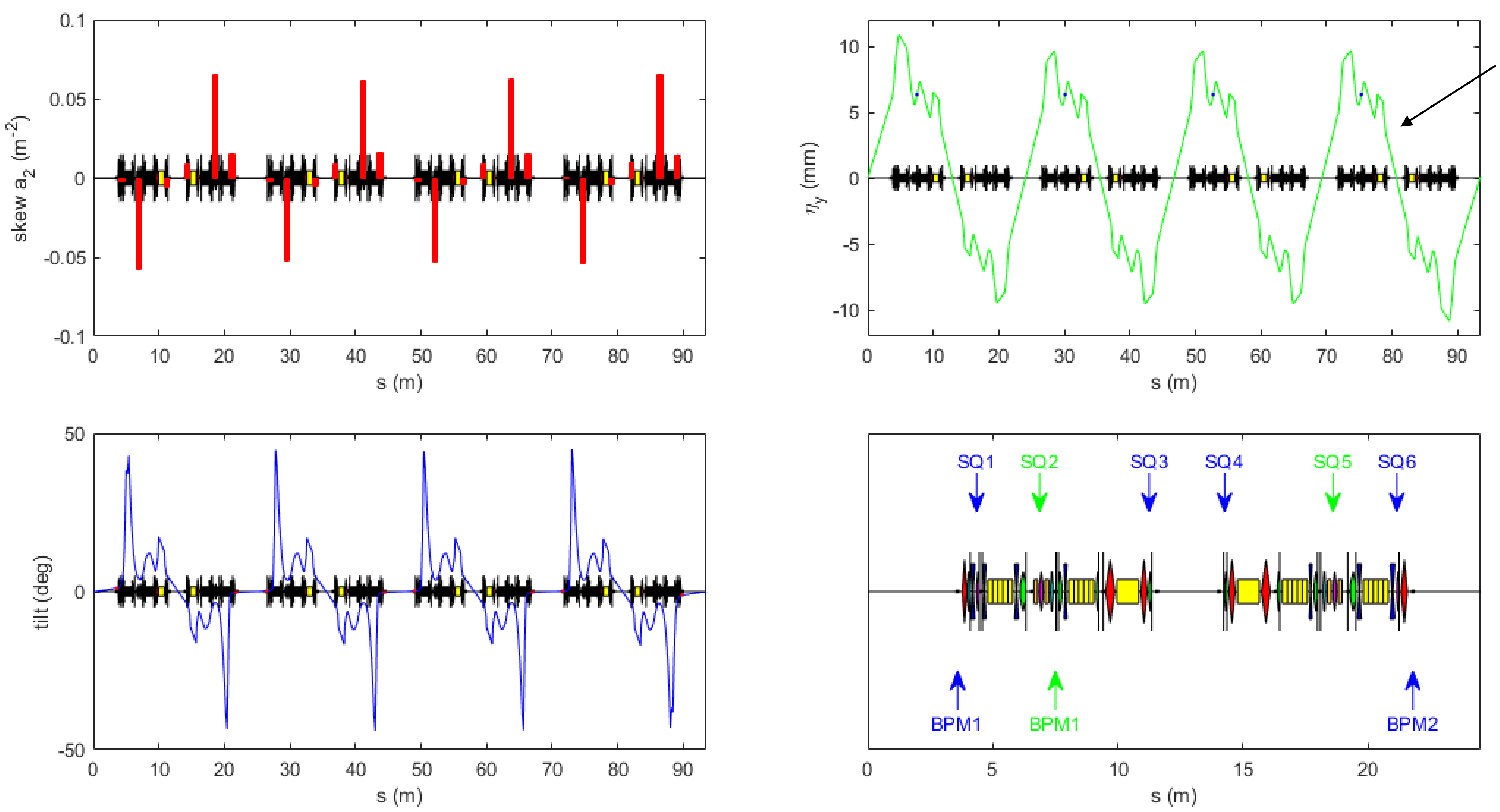
J. Bengtsson, NSLS-II Tech Note 007, July 2007

Change in off-diagonal orbit response matrix element for corrector #i due to skew quadrupole #j:

$$\frac{\partial y_k}{\partial \theta_{x,i}} = -(\Delta a_2 L)_j \frac{\sqrt{\beta_{x,i}\beta_{x,j}\beta_{y,j}\beta_{y,k}}}{4\sin(\pi Q_x)\sin(\pi Q_y)} \cos(\mu_{x,i\to j} - \pi Q_x)\cos(\mu_{y,j\to k} - \pi Q_y)$$

$$\frac{\partial x_k}{\partial \theta_{x,i}} = -(\Delta a_2 L)_j \frac{\sqrt{\beta_{y,i}\beta_{y,j}\beta_{x,j}\beta_{x,k}}}{4\sin(\pi Q_x)\sin(\pi Q_y)} \cos(\mu_{y,i\to j} - \pi Q_y)\cos(\mu_{x,j\to k} - \pi Q_x)$$

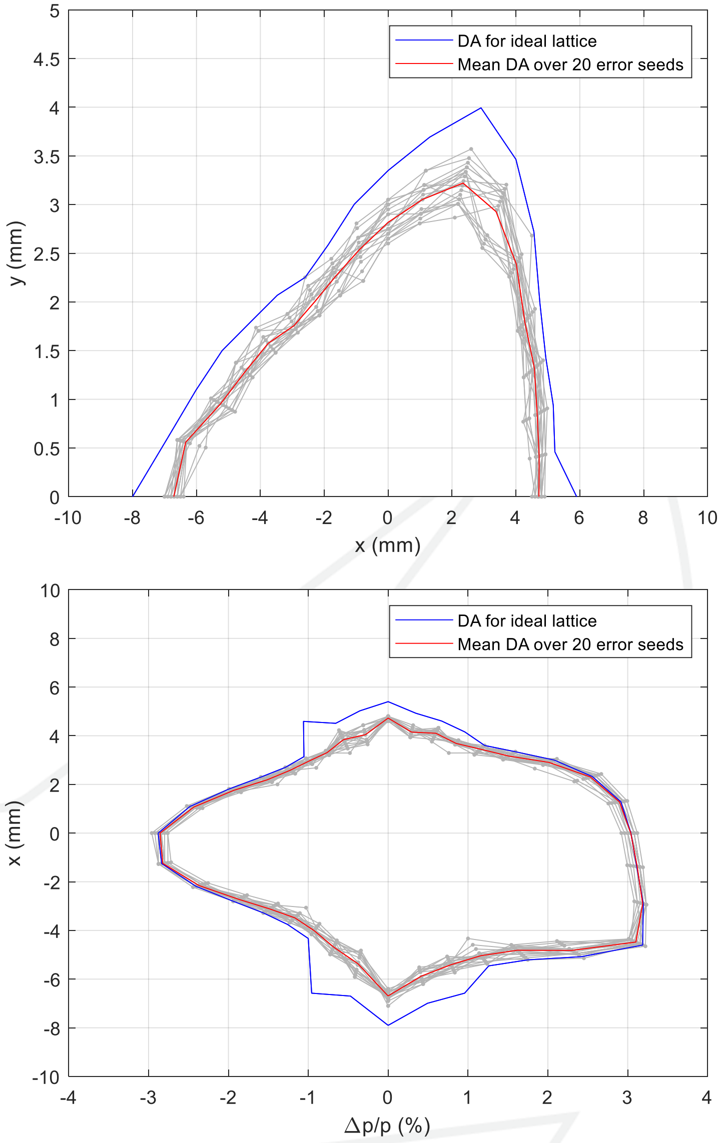
Vertical Dispersion and Coupling Control using Skew Quads



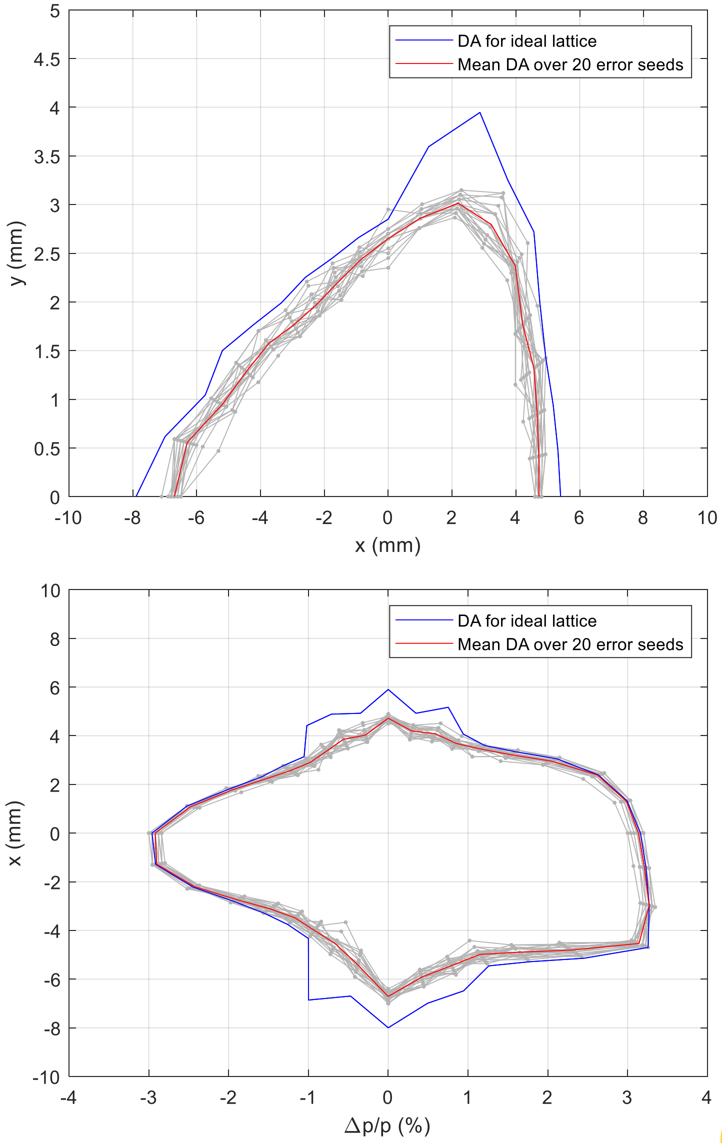
η_y wave for $\varepsilon_y = 8$ pm

Vertical Dispersion and Coupling Control using Skew Quads

$\varepsilon_y = 1$ pm



$\varepsilon_y = 8$ pm



Vertical Dispersion and Coupling Control using Skew Quads

Seems to work.

<u>Pros:</u>

- Straightforward to implement
- In operation at Diamond for >10 years

<u>Cons:</u>

- Small reduction in dynamic aperture
- Suffers from hysteresis; performance degrades over time
- Can impact off-axis injection if aperture restrictions occur where betatron coupling not controlled
- Cannot stabilise horizontal and vertical emittance simultaneously (due to e.g. ID gap changes)

Emittance Excitation using MBF

Alternative method under investigation using transverse multi-bunch feedback (TMBF) to excite the beam at a synchrotron sideband of the betatron tune

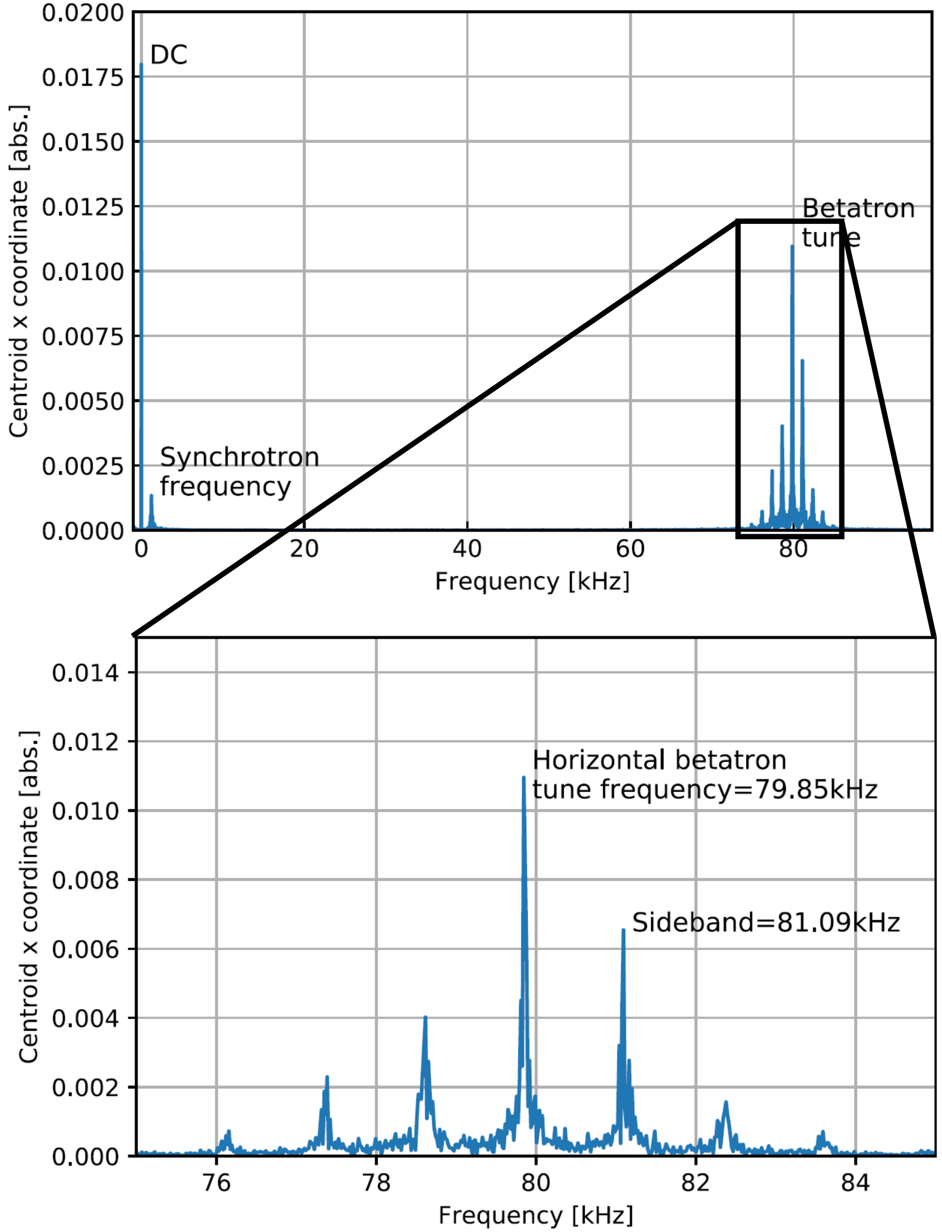
Based on Pulse-Picking by Resonant Excitation (PPRE) method developed at BESSY-II*

- ➢ Drives increase in beam size
- ➢ Minimises centroid motion

Simulation method for Diamond-II (ELEGANT):

- ➢ ILMATRIX + RF cavity + radiation + TMBF kicker
- ➢ (tune-shifts with amplitude)
- ➢ (higher-order chromaticity)
- ➢ (Impedance)
- ➢ (Harmonic cavity)

**K Holldack et al., Nature Communications, 5, 4010, (2014)*



Emittance Excitation for Diamond-II

Linear motion only: Non-zero chromaticity is required to generate the required synchro-betatron coupling

Chromaticity = 0: no increase in vertical beam size. Centroid motion only

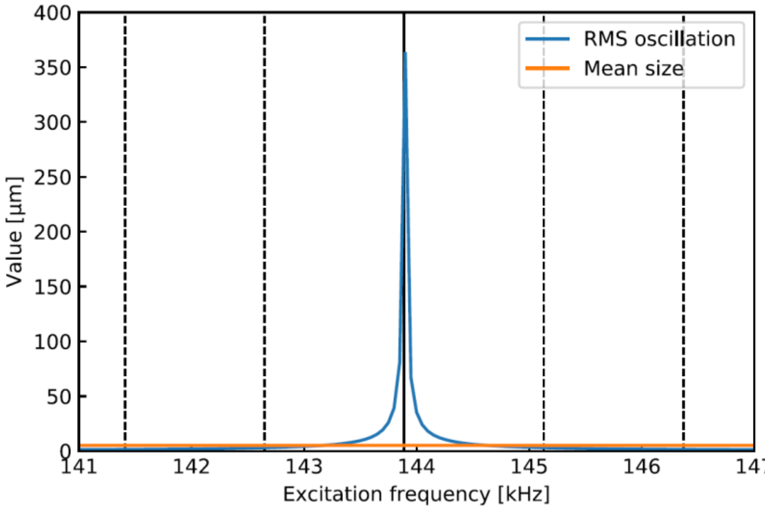
Chromaticity = 1: increase in beam size at side-band with small centroid motion

Chromaticity = 2.3: ratio of beam size growth to centroid motion at sidebands improves

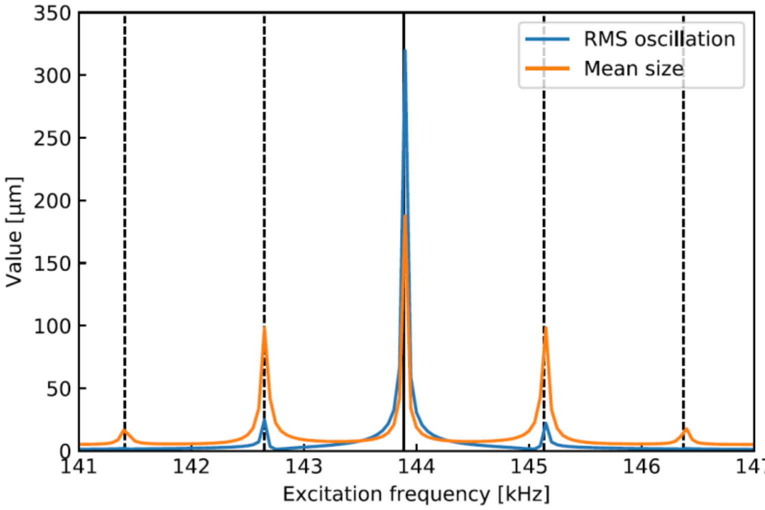
Synchrotron sidebands remain fixed in frequency

Symmetric behaviour for positive and negative sidebands

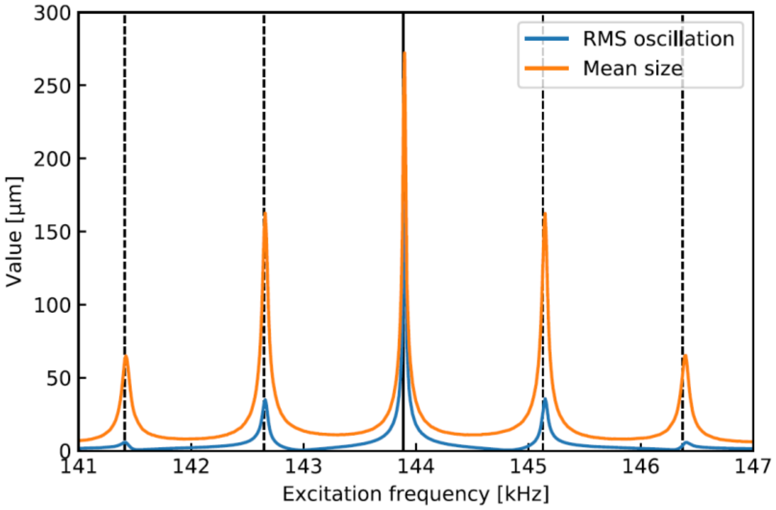
Chromaticity = 0



Chromaticity = 1



Chromaticity = 2.3



Emittance Excitation for Diamond-II

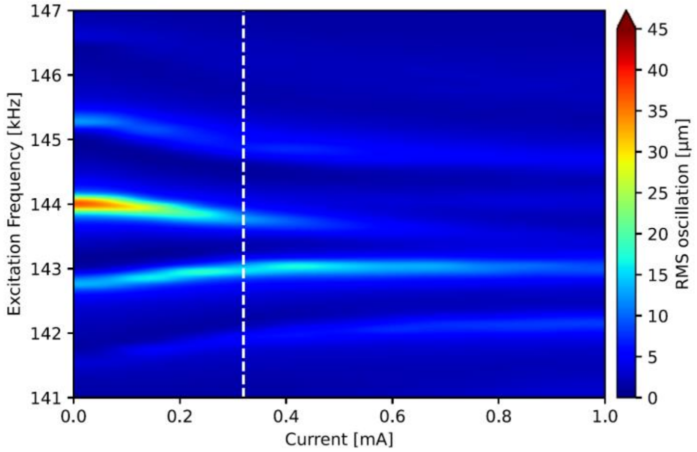
<u>Combined effects</u>:

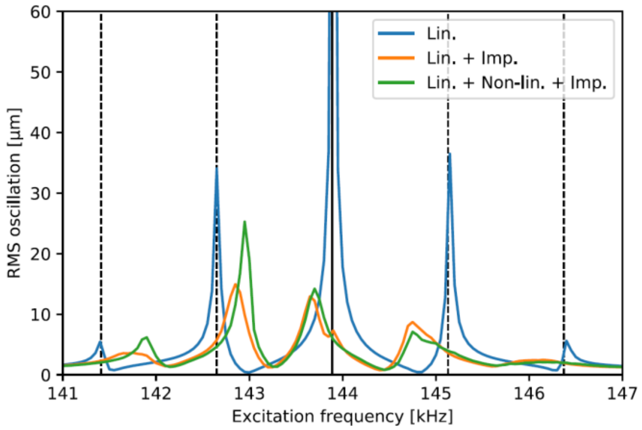
- Tune shift with amplitude
- Higher order chromaticity
- Transverse impedance
- Longitudinal impedance

Overall impact:

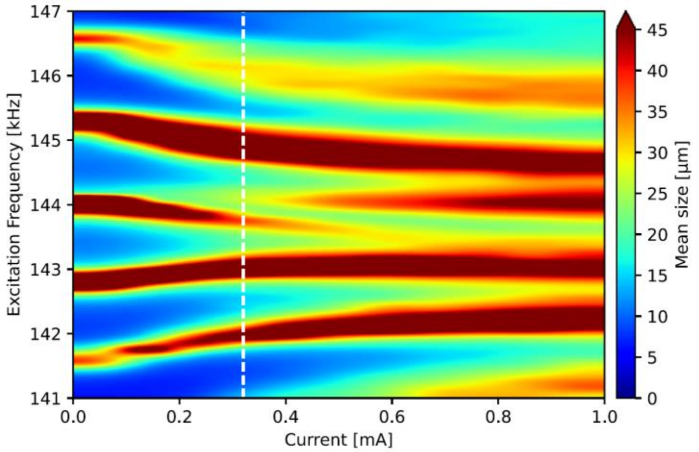
- Ratio of vertical beam size to centroid motion is reduced, but generally more favourable for upper sidebands
- Upper sidebands: broader and shallower
- Lower sidebands: narrower and taller

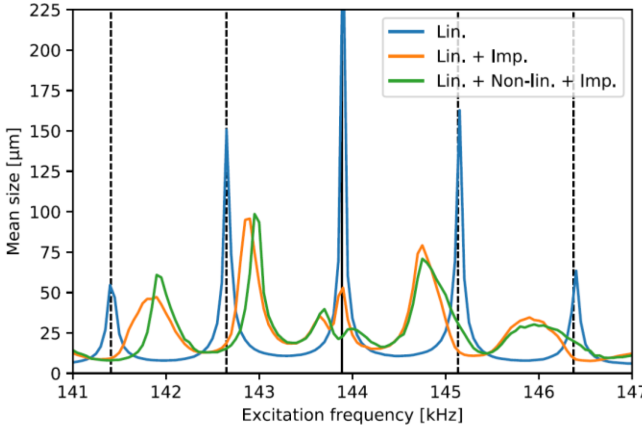
<u>Centroid</u>





<u>Vertical Beam Size</u>





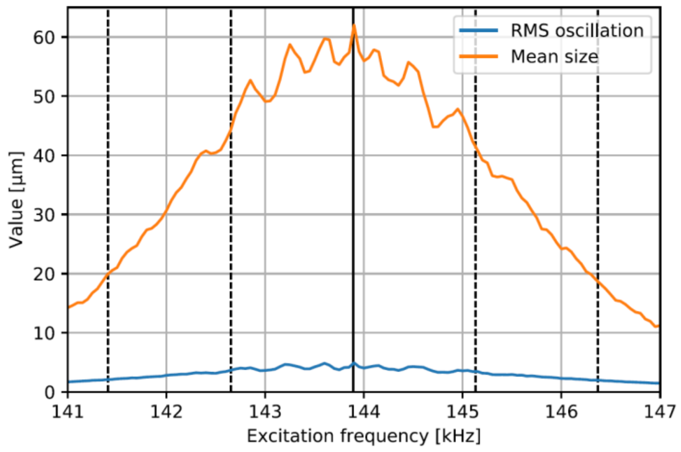
Emittance Excitation for Diamond-II

Harmonic cavity set for flat-potential conditions

Impact on bunch motion including all effects:

- Synchrotron sidebands broaden and overlap
- Peaks no-longer well-defined
- Achieving exact excitation frequency no longer as significant

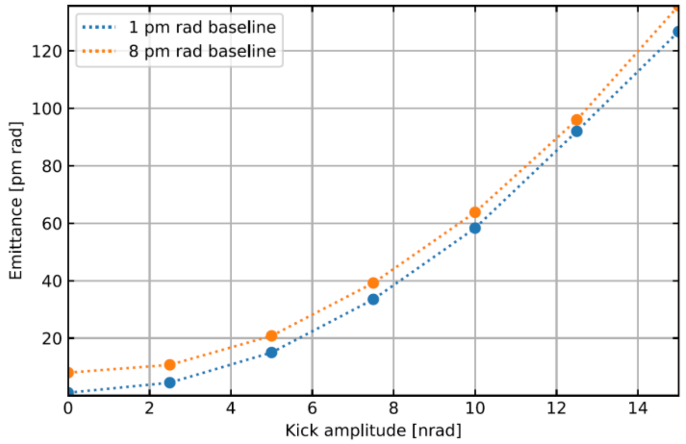
Beam size and centroid motion including harmonic cavity



Kick strength

- Quadratic growth in amplitude at small excitation
- Growth becomes more linear and eventually saturates at large excitation due to detuning of the oscillation with amplitude

Vertical emittance vs kick strength



Assuming ~1 pm vertical emittance after LOCO, ~3-4 nrad kicks at the first upper sideband look sufficient to reach target value of 8 pm at standard bunch current (0.3 mA)

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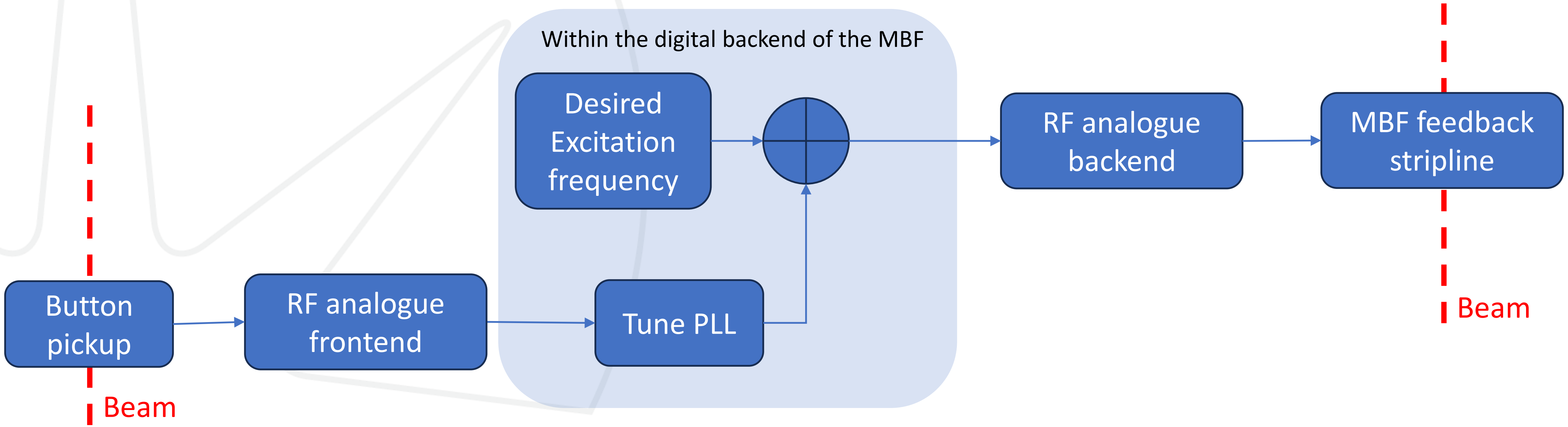
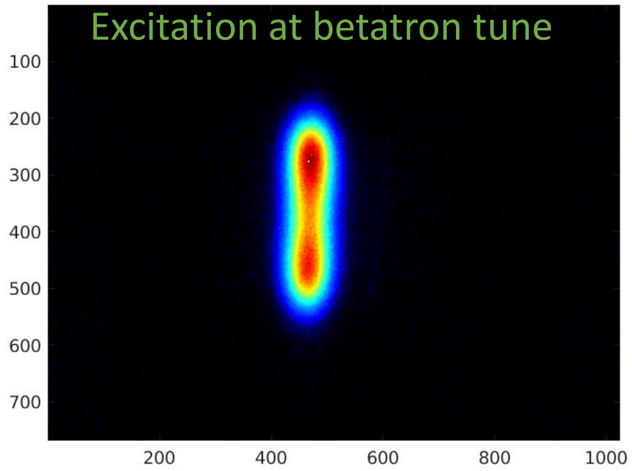
Experimental tests on Diamond

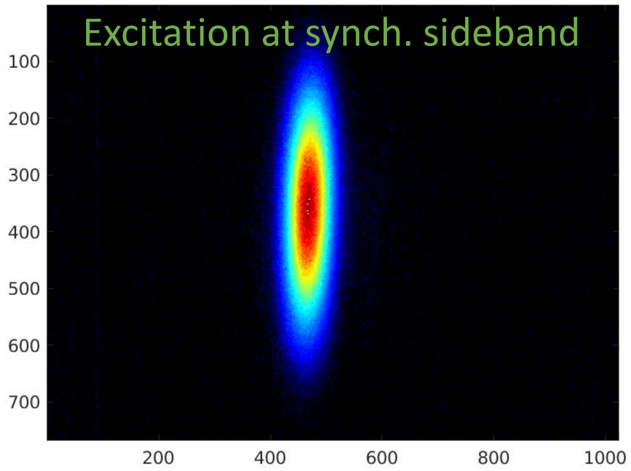
- The excitation is generated using a crystal oscillator at a user defined frequency.
- Phase-locked loop required to track jitter and/or drift in the betatron tune (and hence the sidebands)
  - Keeps excitation at a fixed point of the curve to stabilise excitation amplitude
- Excitation frequency and amplitude can be adjusted to probe the problem space and find optimal settings.
- Excitation can be combined with the signals for standard multi bunch feedback to allow simultaneous use.



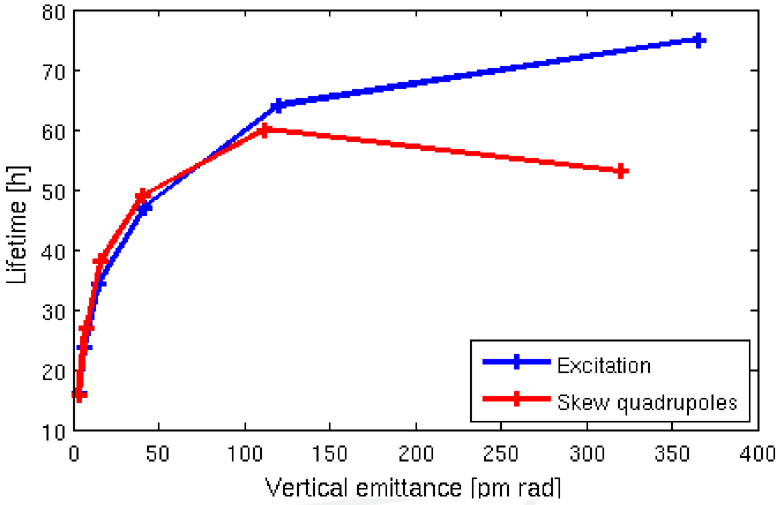
Experimental tests on Diamond

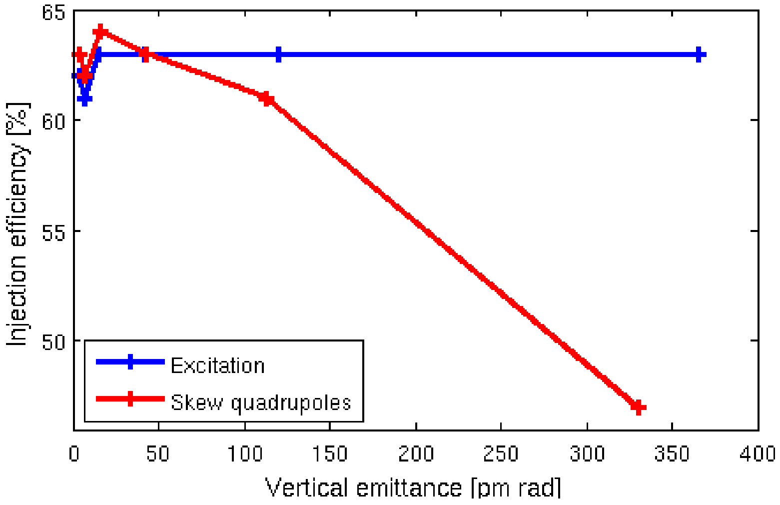
Comparison of beam size using TMBF method: at the betatron tune vs. sideband excitation





Comparison of lifetime and injection efficiency for different schemes:





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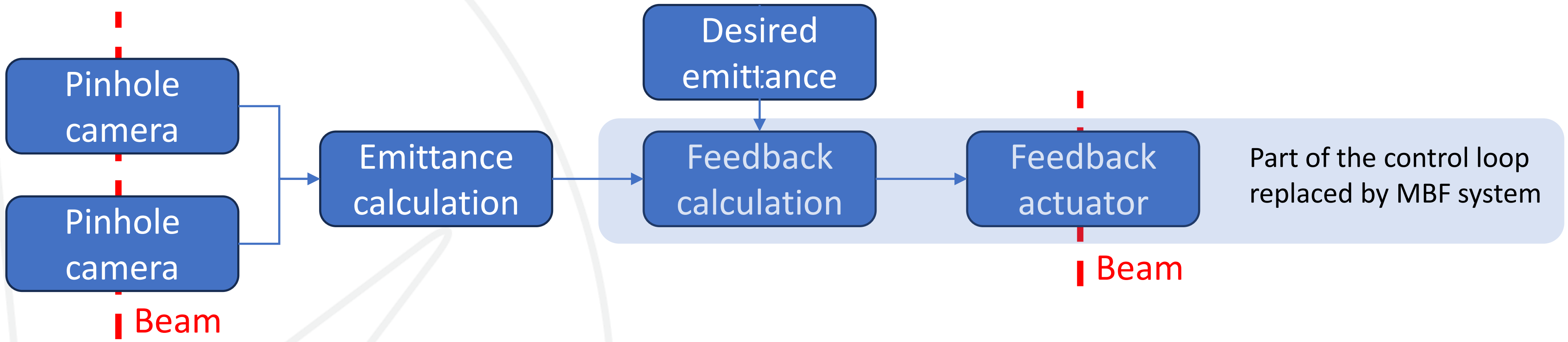
Experimental tests on Diamond

- Initial studies on using the TMBF to allow emittance control and stabilisation have been successfully trialled.
- Further work is underway to improve the response of the control loop to insertion device gap changes.



- The emittance was successfully set in both planes and held at user defined values over several hours.
- There are some differences in behaviour which need to be accounted for before it can be used in operation:
  - When feedback switched off, need to leave the machine in the last set state.
  - Control loop needs optimising to account for logarithmic output and excitation step-size

Note: Although the MBF system is faster than using skew-quadrupoles, the overall system response is dominated by the frequency of the camera used to capture the beam sizes.

Conclusions and Future Work

- MBF excitation offers method to control horizontal and vertical emittances independently
- MBF can be controlled to give different excitation to different bunches:
  - how to measure? control bunch lifetime rather than vertical emittance?
- Skew quadrupoles offer alternative method:
  - horizontal and vertical emittances are not independent
  - suffers from magnet hysteresis
  - underlying correction can drift with time affecting off-axis injection

<u>Outstanding questions</u>

1) What to do about the hybrid bunch?
   - Response changes with bunch currents due to machine impedance
2) Do long range wakes have significant impact on vertical emittance excitation?
3) Can MBF effectively suppress residual centroid oscillations?
4) What is optimum way of operating with passive harmonic cavity and self-consistent bunch distributions?

Extra Slides

Emittance Excitation for Diamond-II

Adding tune-shift with amplitude (NUY1AY):

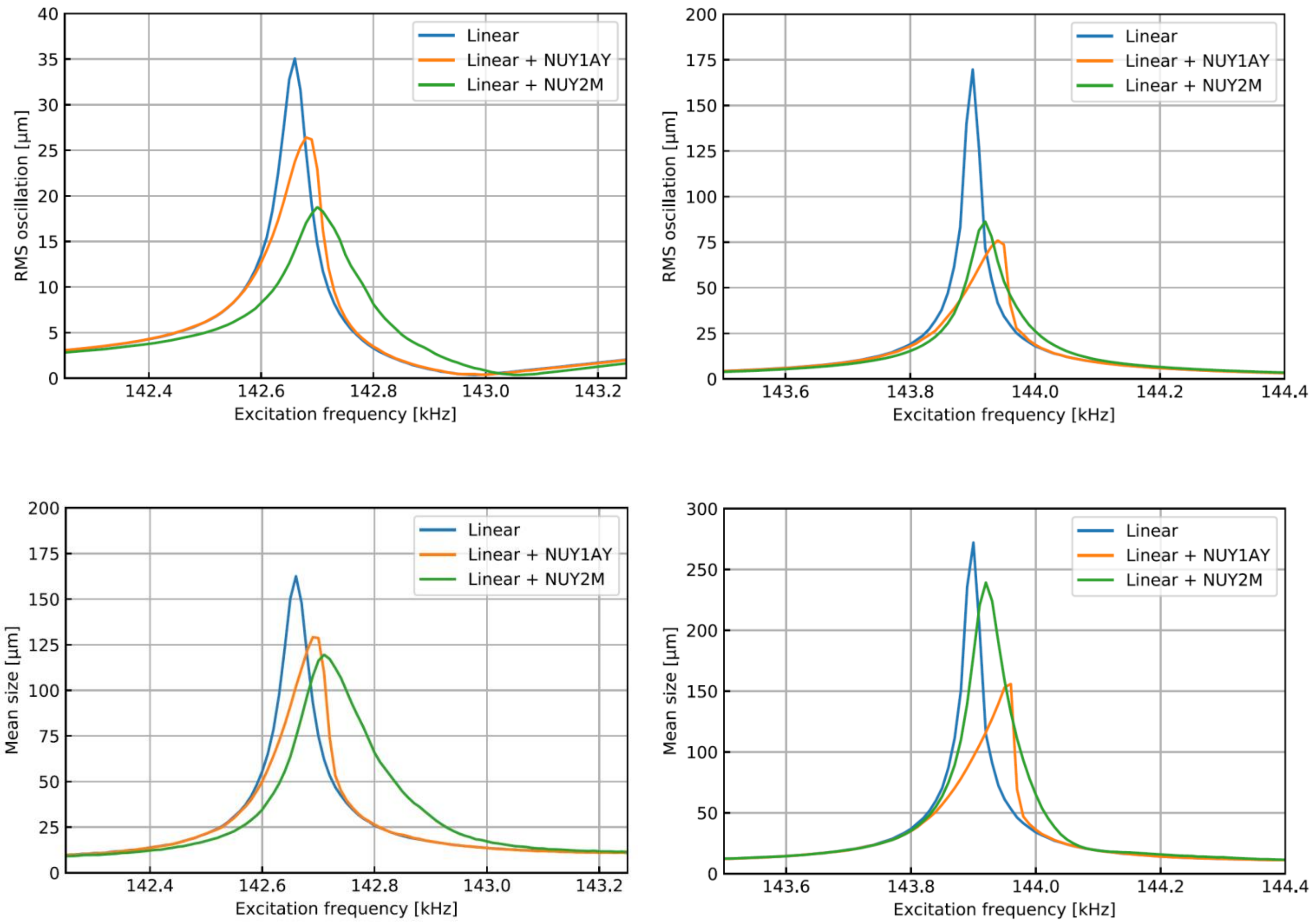
- Stronger impact on betatron tune peak (where centroid motion is largest)
- Peaks reduce in amplitude, distort, and shift in frequency
- Detuning causes saturation for large excitation amplitudes

Adding higher-order chromaticity (NUY2M):

- Stronger impact on sidebands
- Peaks reduce in amplitude, broaden, and shift in frequency

Lower sideband

Tune peak



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Emittance Excitation for Diamond-II

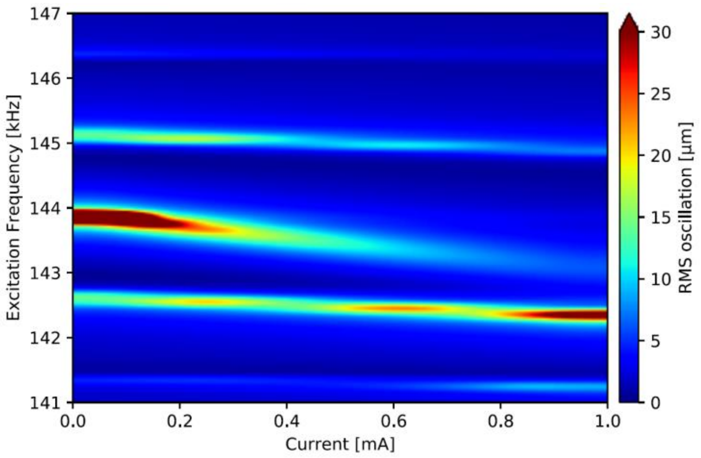
Impact of transverse impedance:

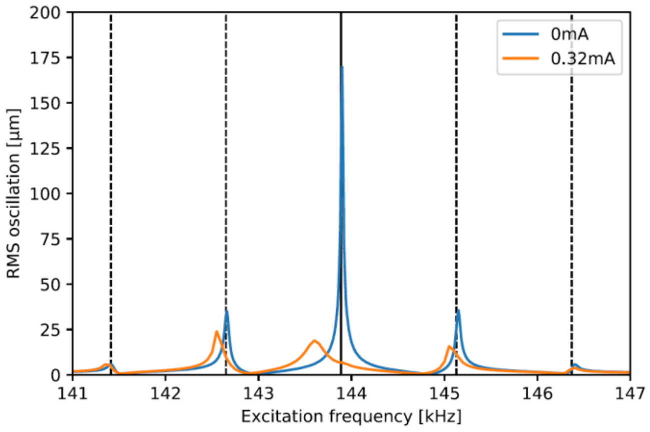
- Amplitudes and widths of peaks shift with bunch current
- Peaks grow with current for lower sidebands and reduce with current for upper sidebands
- Tune peak shifts to lower frequencies
- Peaks at betatron tune are suppressed

Ratio of beam size increase to centroid motion:

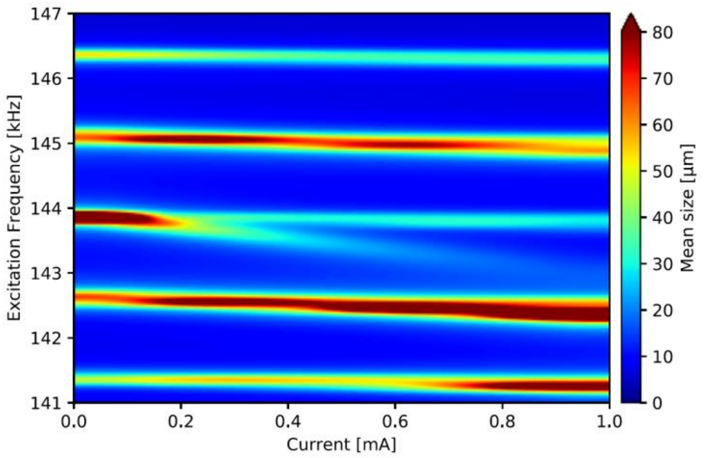
- larger for upper sidebands
- reduces with current

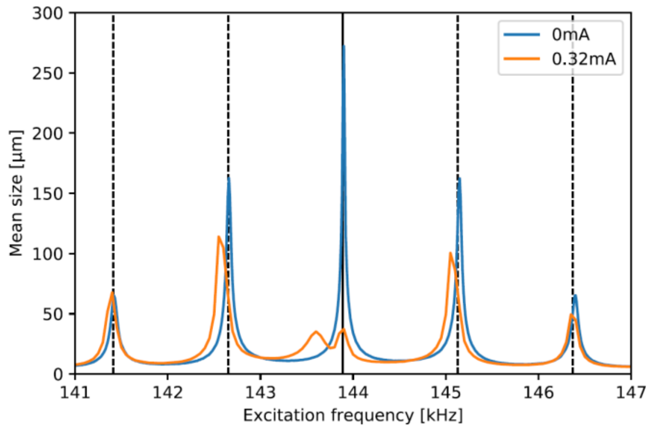
Centroid





Beam Size





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Emittance Excitation for Diamond-II

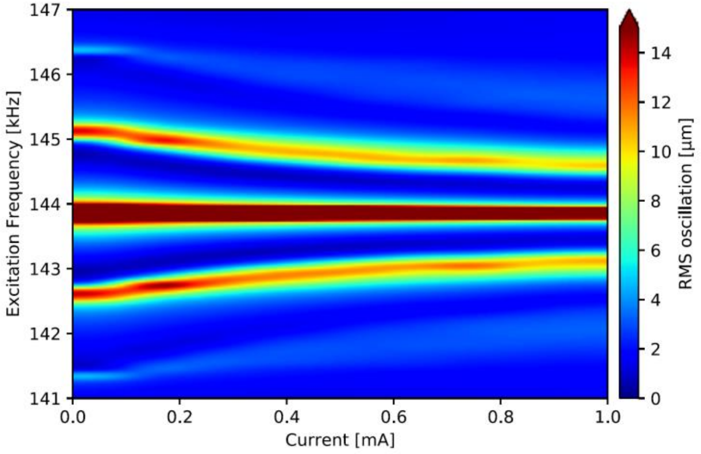
Impact of <u>longitudinal impedance</u>:

- ➢ Sidebands shift towards the tune frequency
- ➢ Symmetric behaviour for upper and lower sidebands

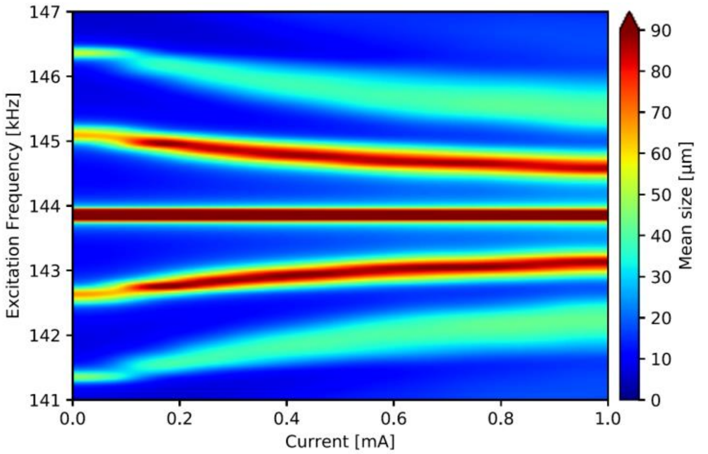
Change with bunch current:

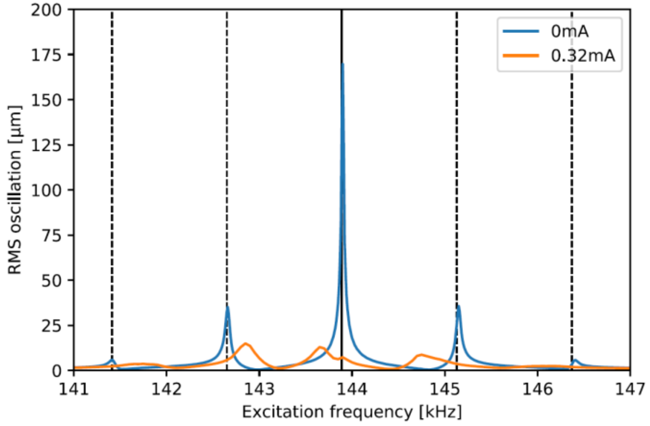
- ➢ Growth in beam size
- ➢ Reduction in centroid motion

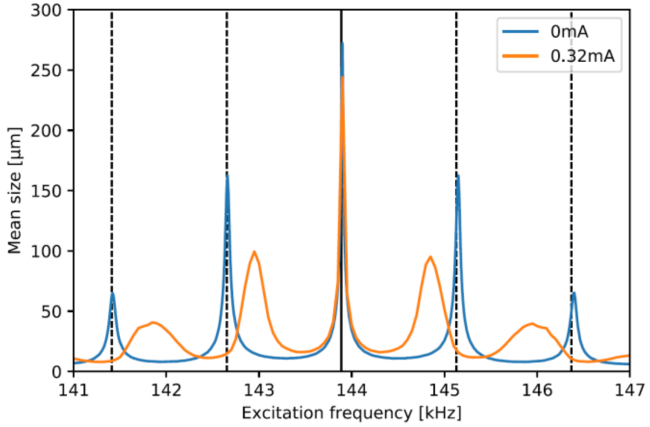
<u>Centroid</u>



<u>Beam Size</u>







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