Intensity Limits with Space Charge and Round Beams

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Low Emittance Ring Workshop, DESY, Hamburg
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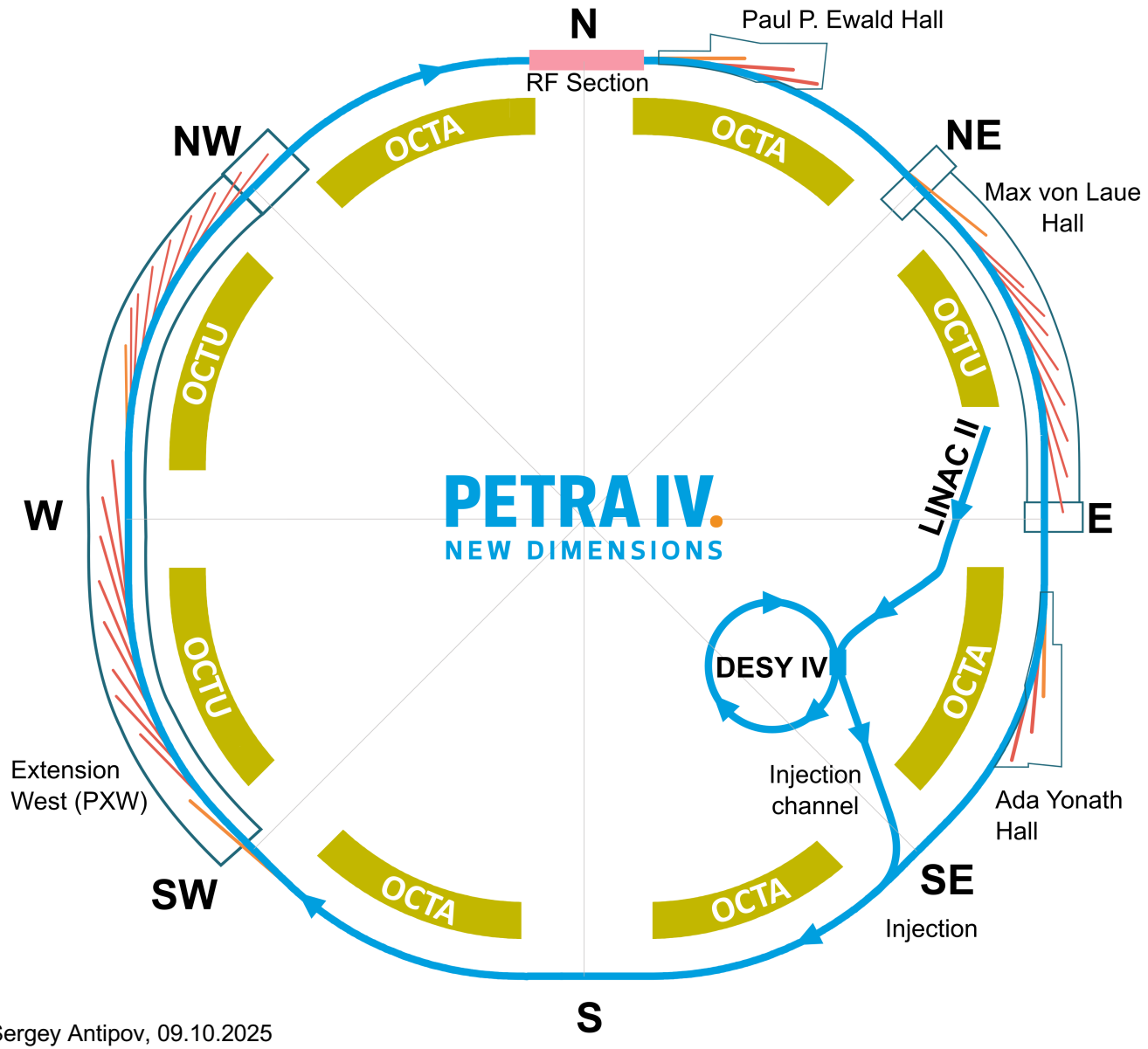
HELMHOLTZ

DESY.

PETRA IV: Germany's future flagship light source

6 GeV, 2.3 km, 20 pm



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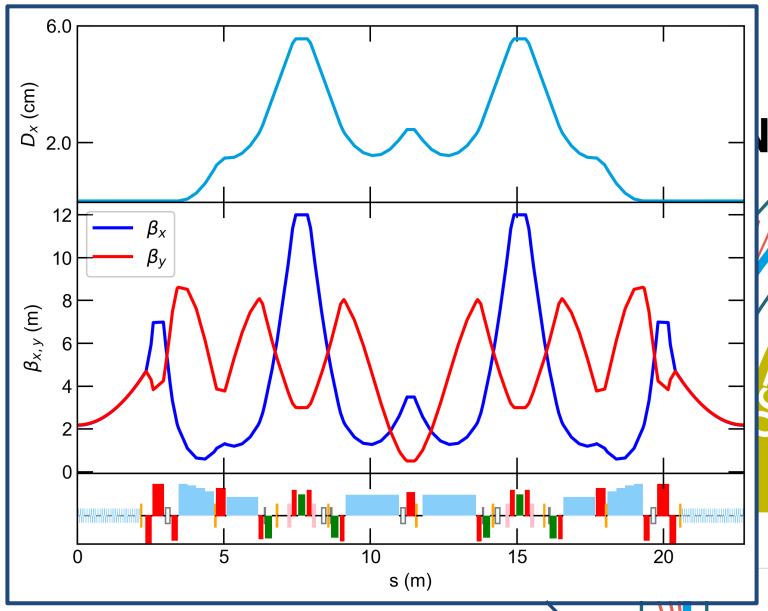
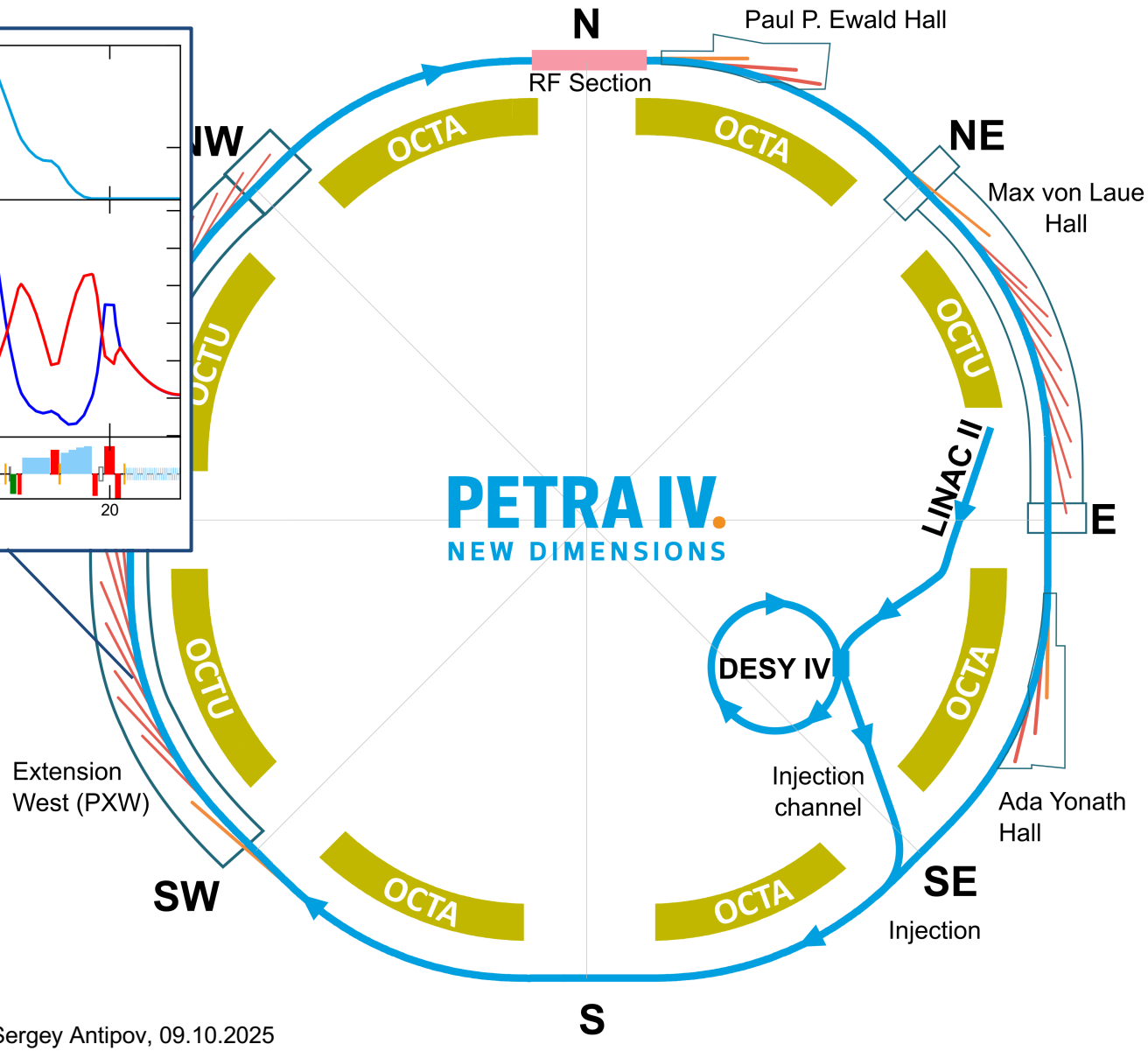


H6BA cell



PETRA IV: Germany's future flagship light source

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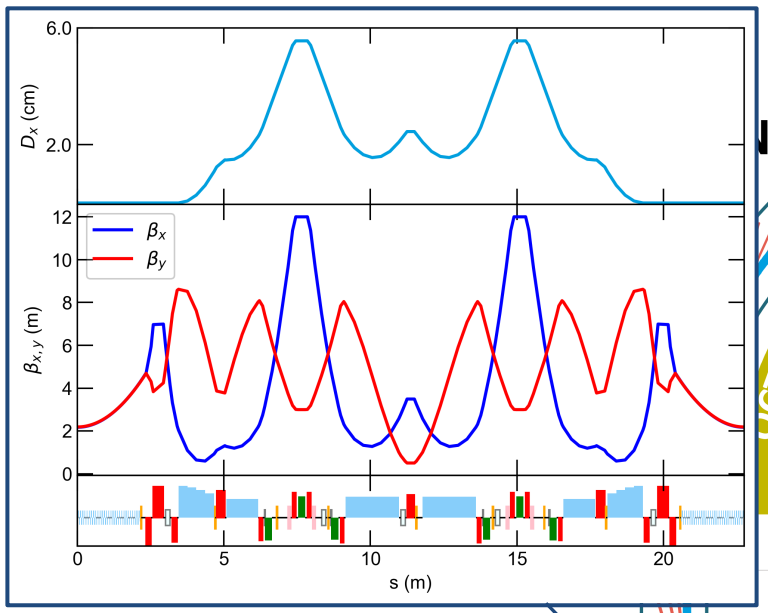

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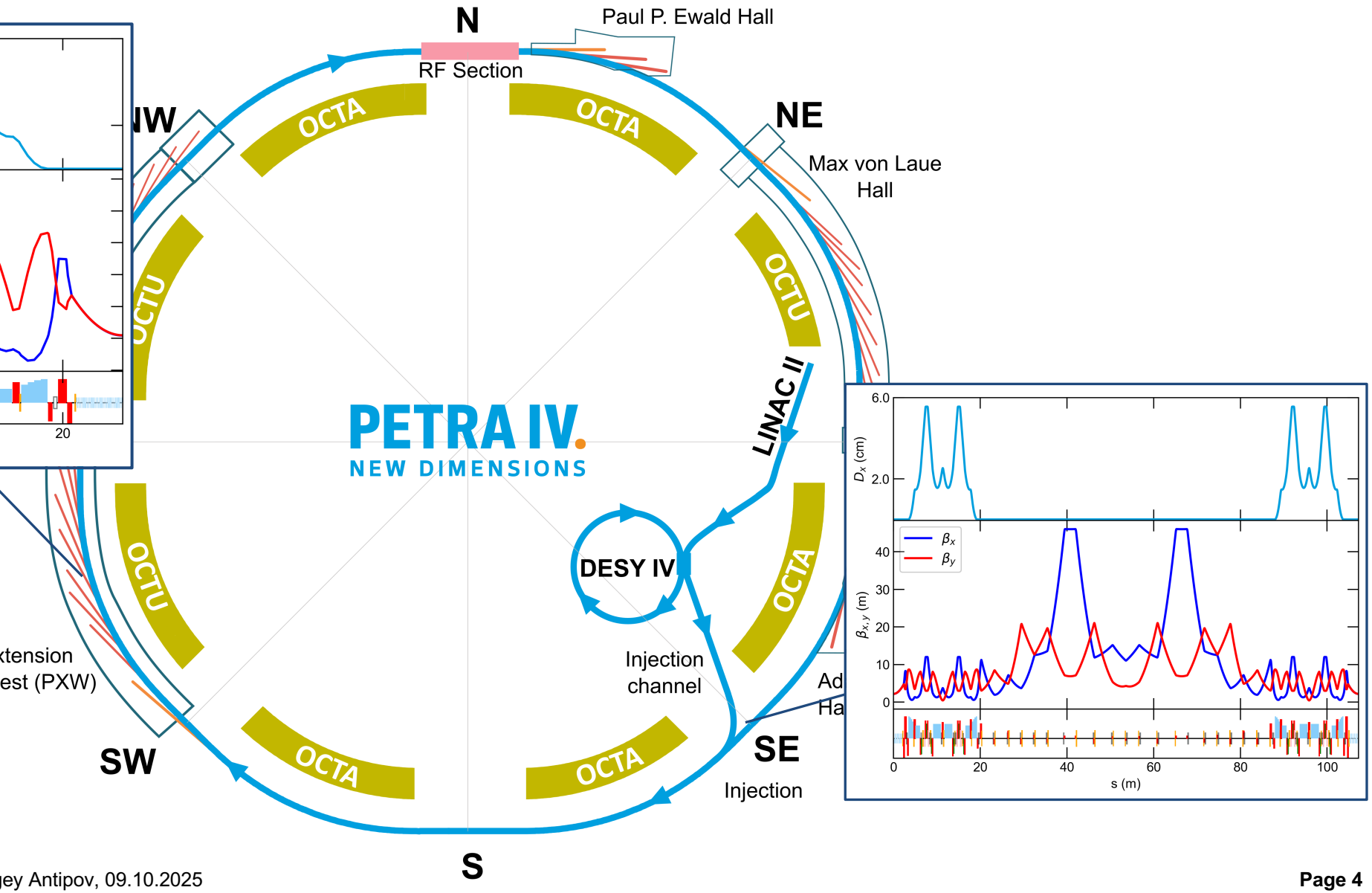
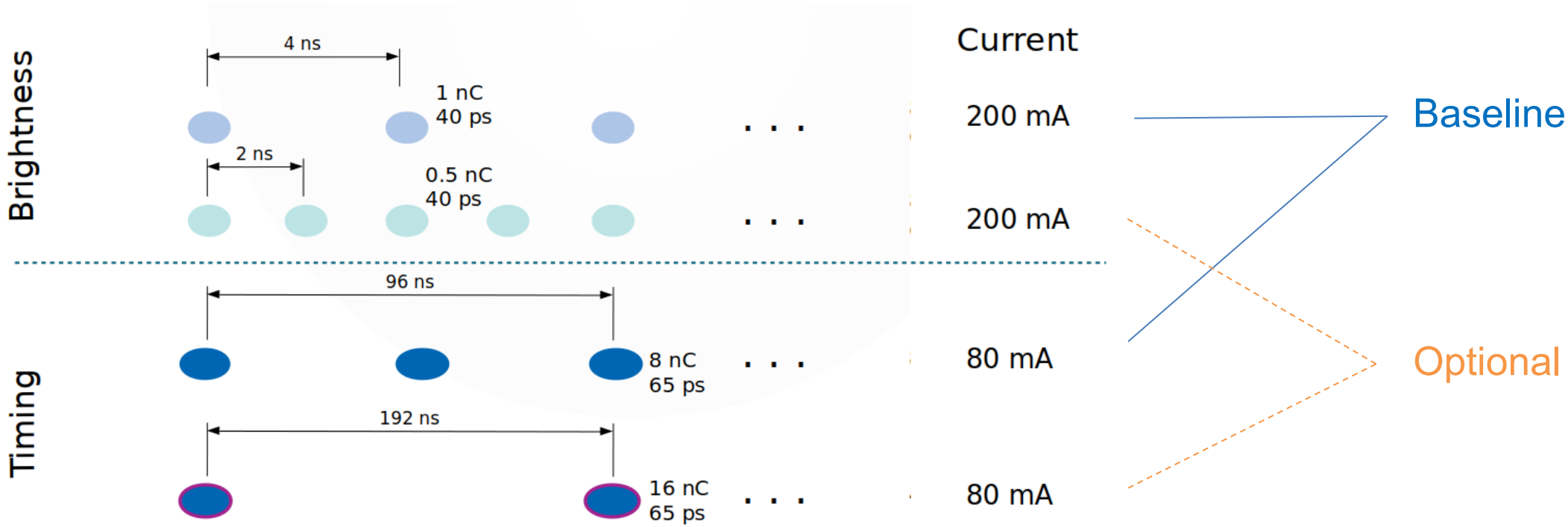


PETRA IV offers a variety of operation modes

Do collective effects at injection pose any limitation?



Potential Hybrid filling patterns have interest for Timing community and are presently being discussed

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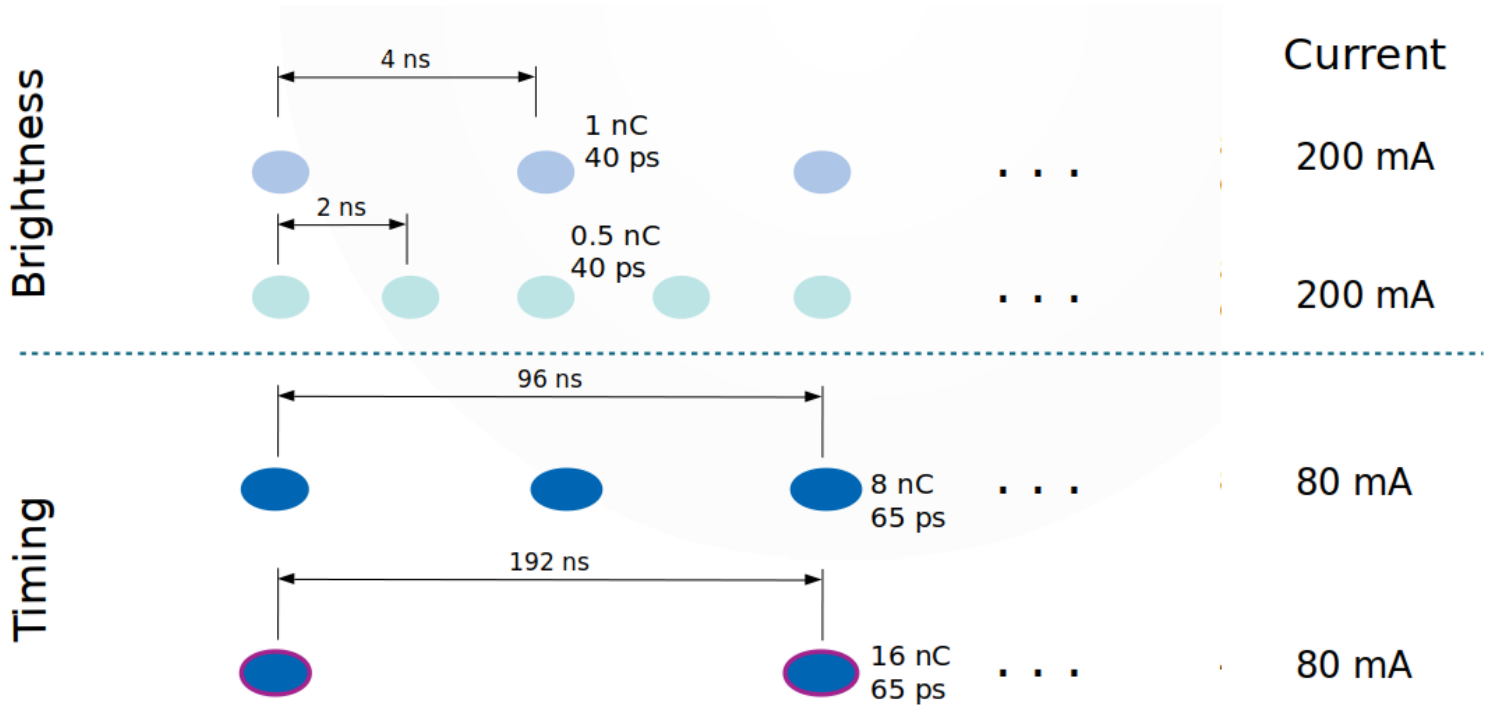


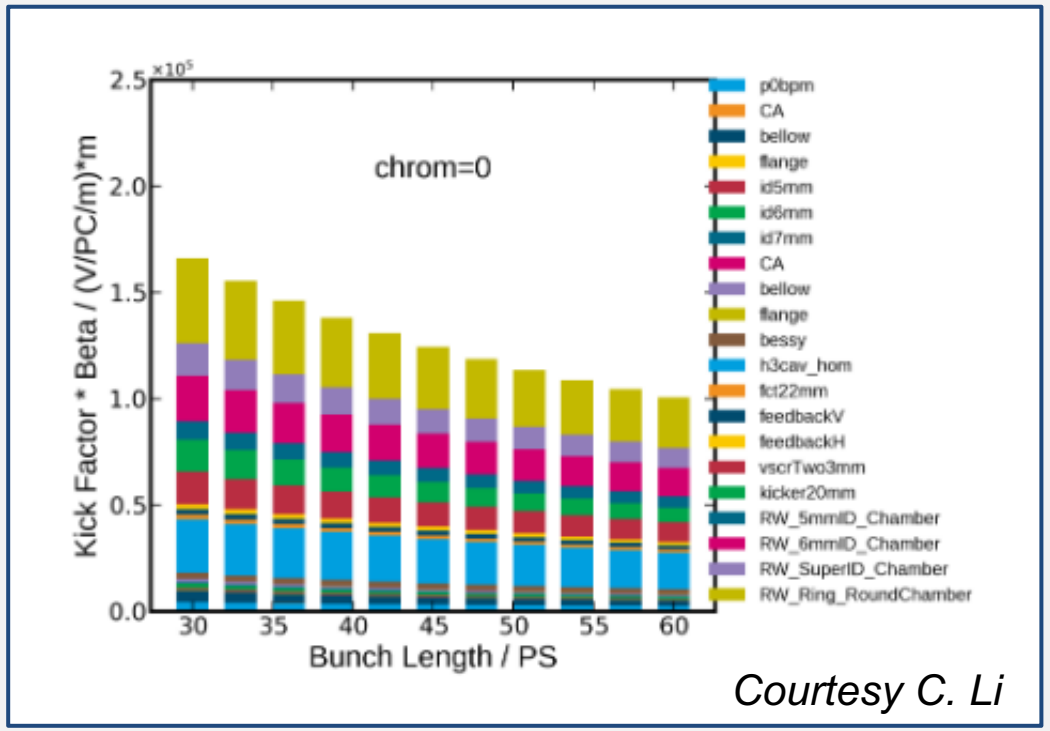
6D element-by-element tracking

- Main & 3rd harmonic RF
- SR damping
- Optics errors
- Real physical aperture
- Long & transverse wakefields
- Intrabeam scattering, non-selfconsistent
- *Space charge*

Potential Hybrid filling patterns have interest for Timing community and are presently being discussed

Impedance model: RW dominates

Mainly due to tight undulator gaps



Courtesy C. Li

All key hardware included

RW simulated with I2DW

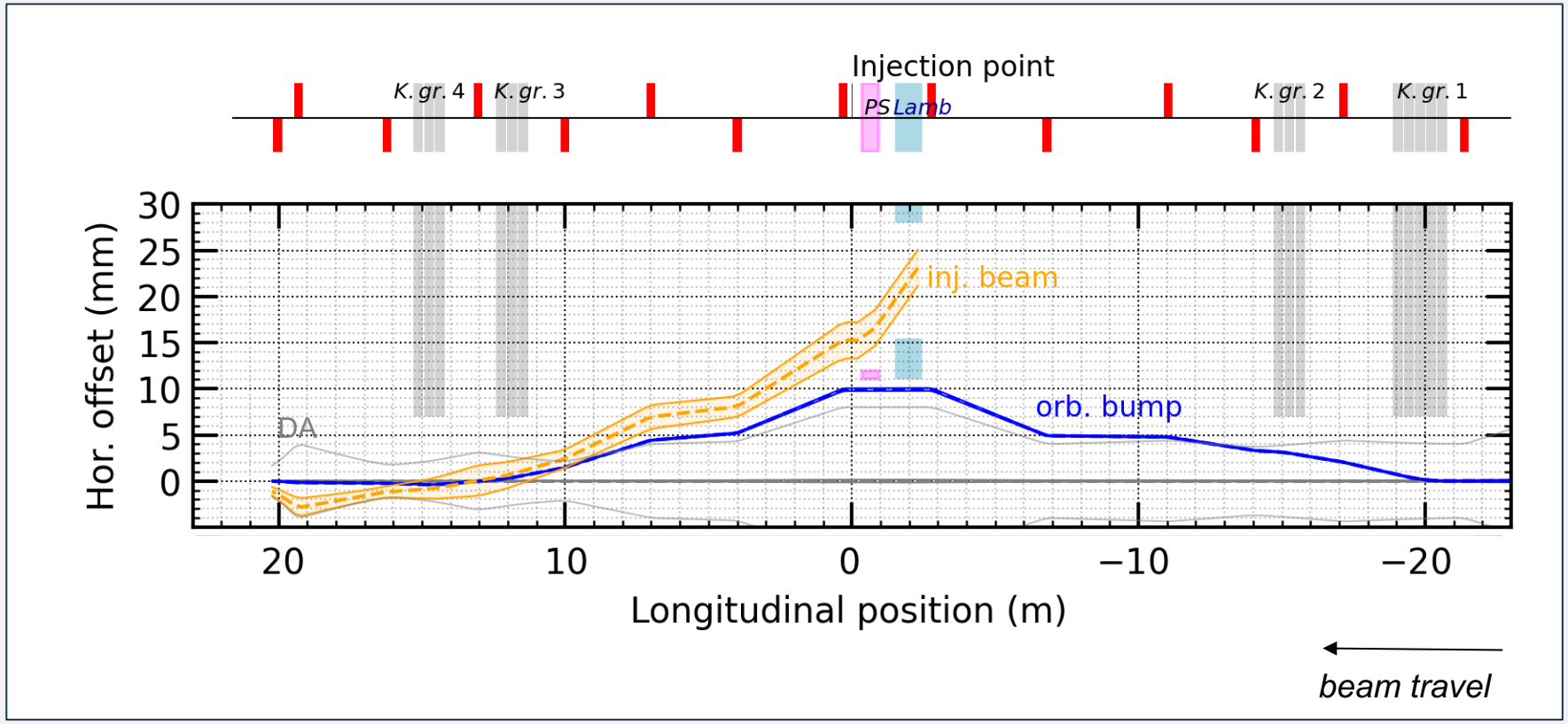
- NEG coating included, based on measured resistivity

Geometric simulated up to 100 GHz

- Including hardware as it is being designed
- Some still as broadband contributions

Top-up injection in PETRA IV

Topping up any of 3840 RF buckets with minimal perturbations to the stored beam



4 kicker bump + pulsed septum

Fast orbit bump

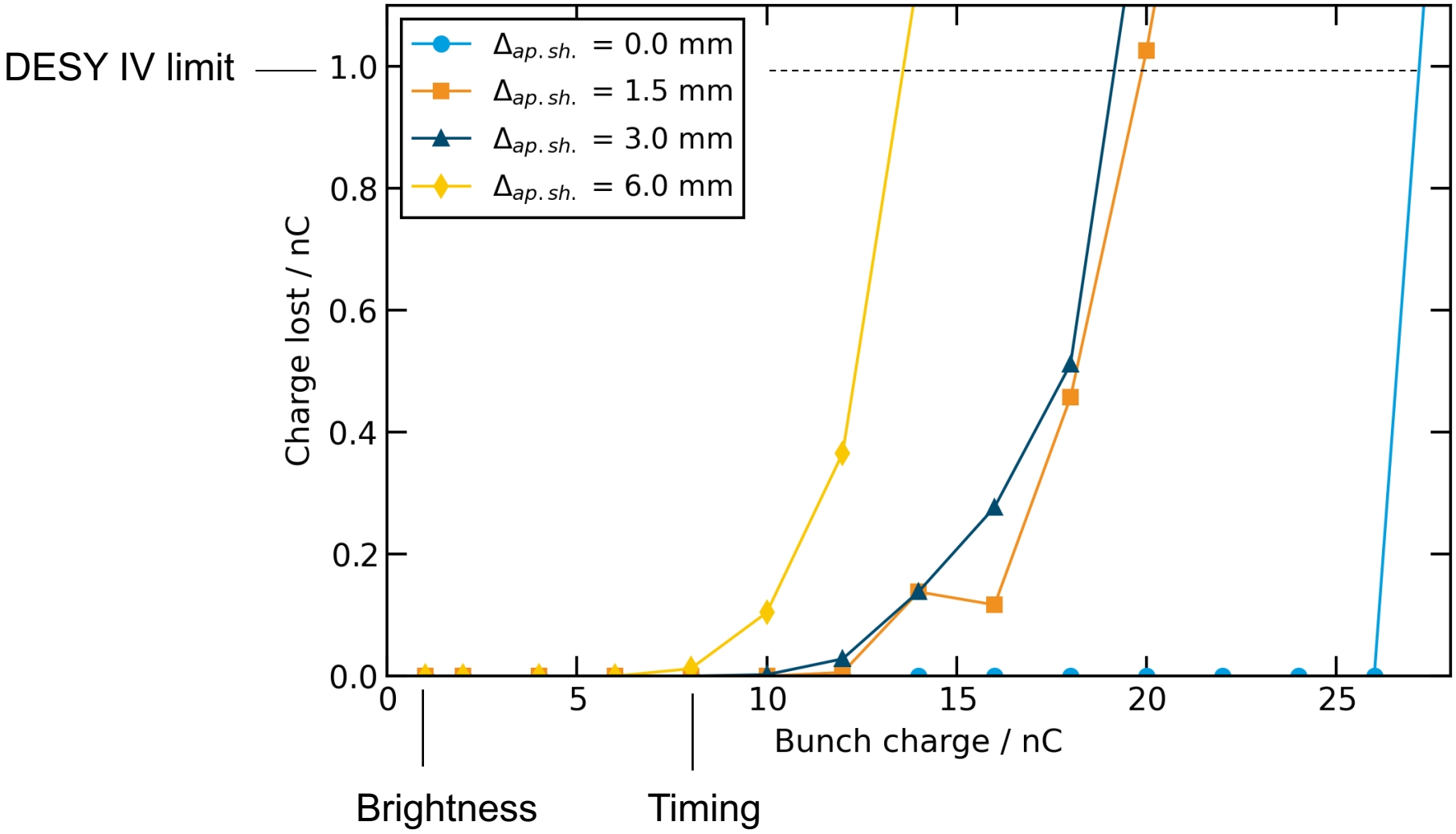
- 2 ns stripline kickers
- On axis injection also possible

Thin pulsed septum

- 1 mm thickness
- DC Lambertson pre-septum

Accumulation limit

Theoretical limit is reached when lost charge = injected charge



Average of 20 error seeds

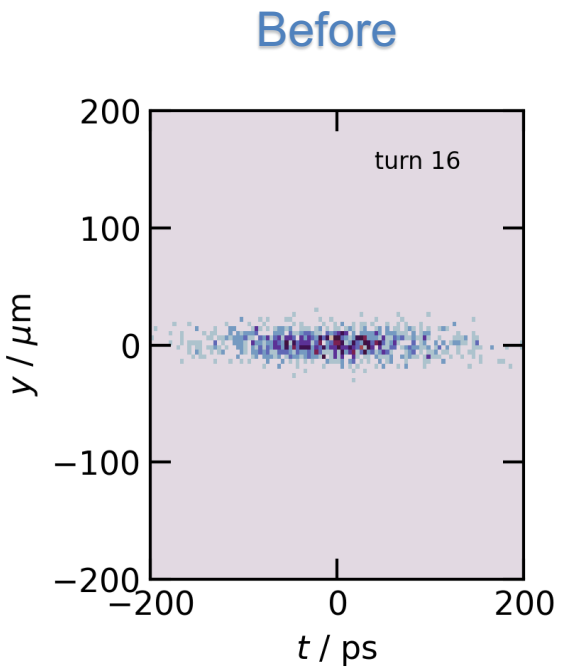
- Each with 5% rms beta-beating

Most losses happen in the stored bunch

- Y.-C. Chae, *IPAC'07*
- S. Antipov, *LER'24*

Instability at high intensities

Leads to blow-up of the transverse beam size in ~1000 turns

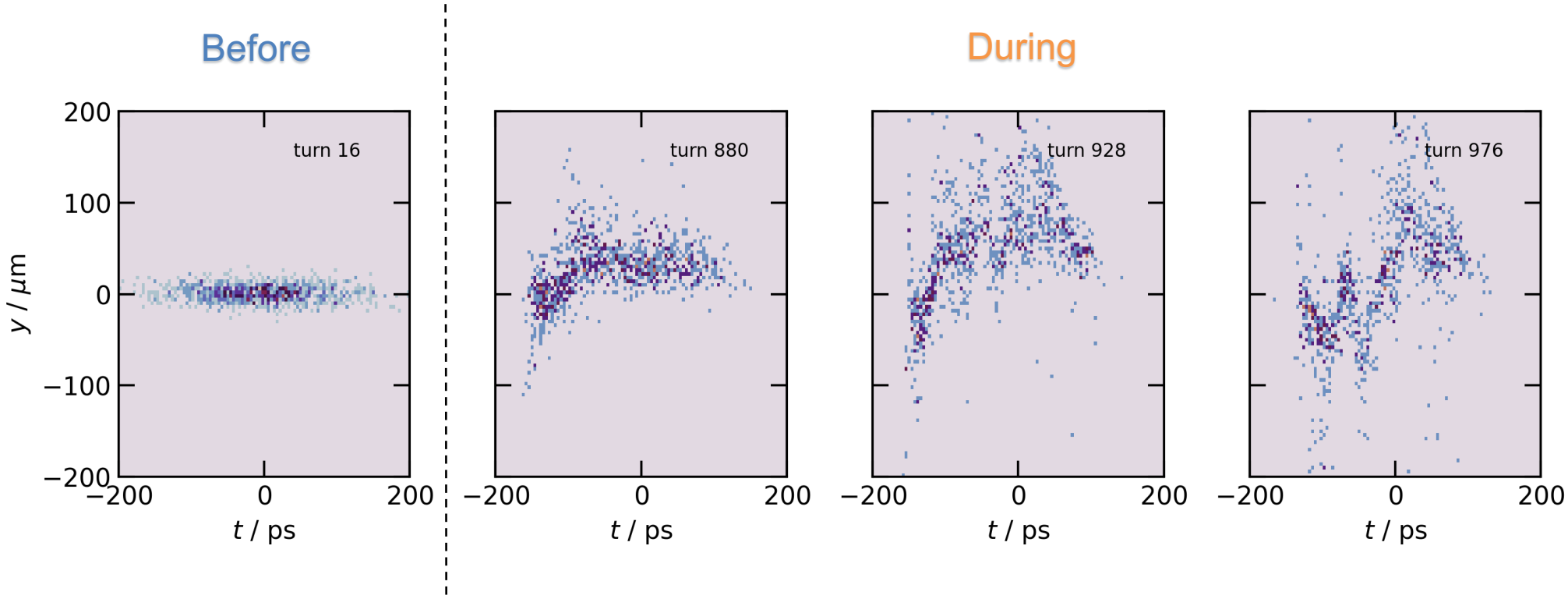


High-charge Timing mode

- 14 nC in the stored bunch
- No apeture sharing (starts from noise)
- Chromaticity 5

Instability at high intensities

Leads to blow-up of the transverse beam size in ~1000 turns



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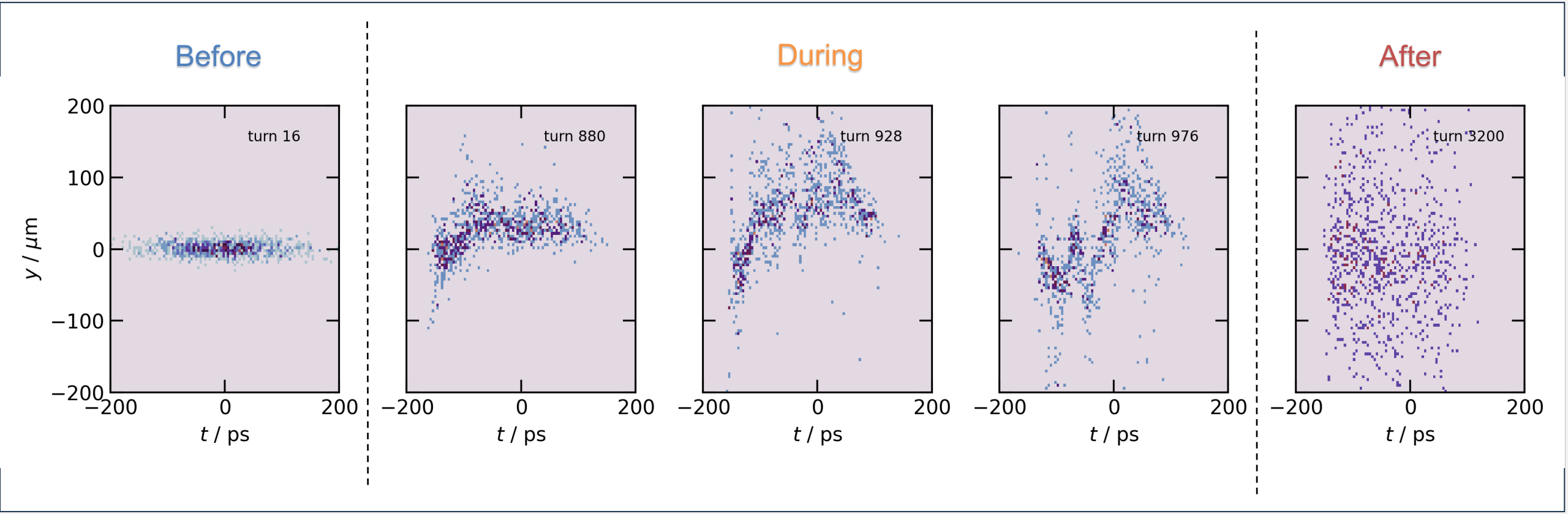
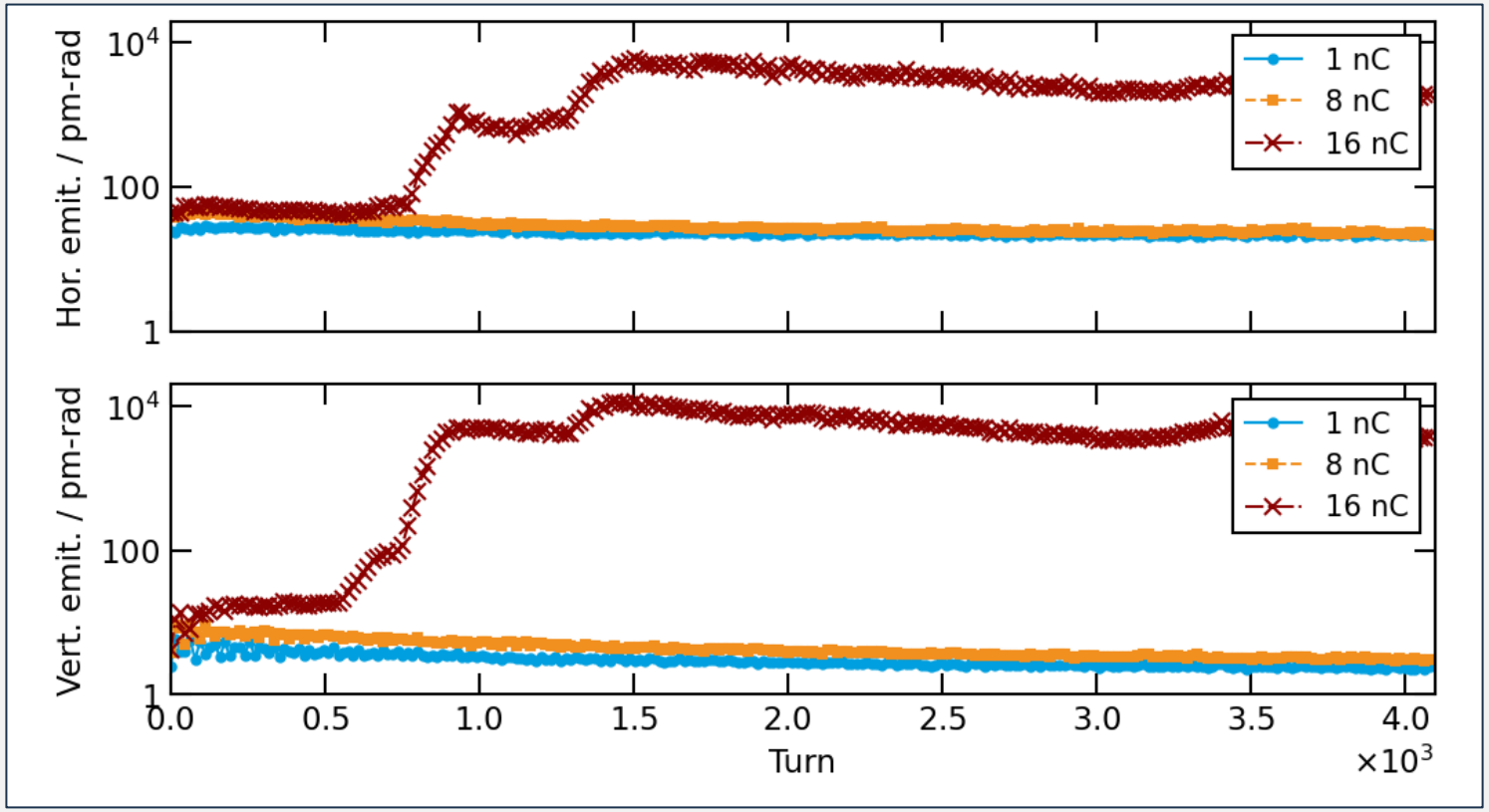


Emittance might blow up to nm scale for high charge modes

Blow-up happens on time scales of ~1000 turns

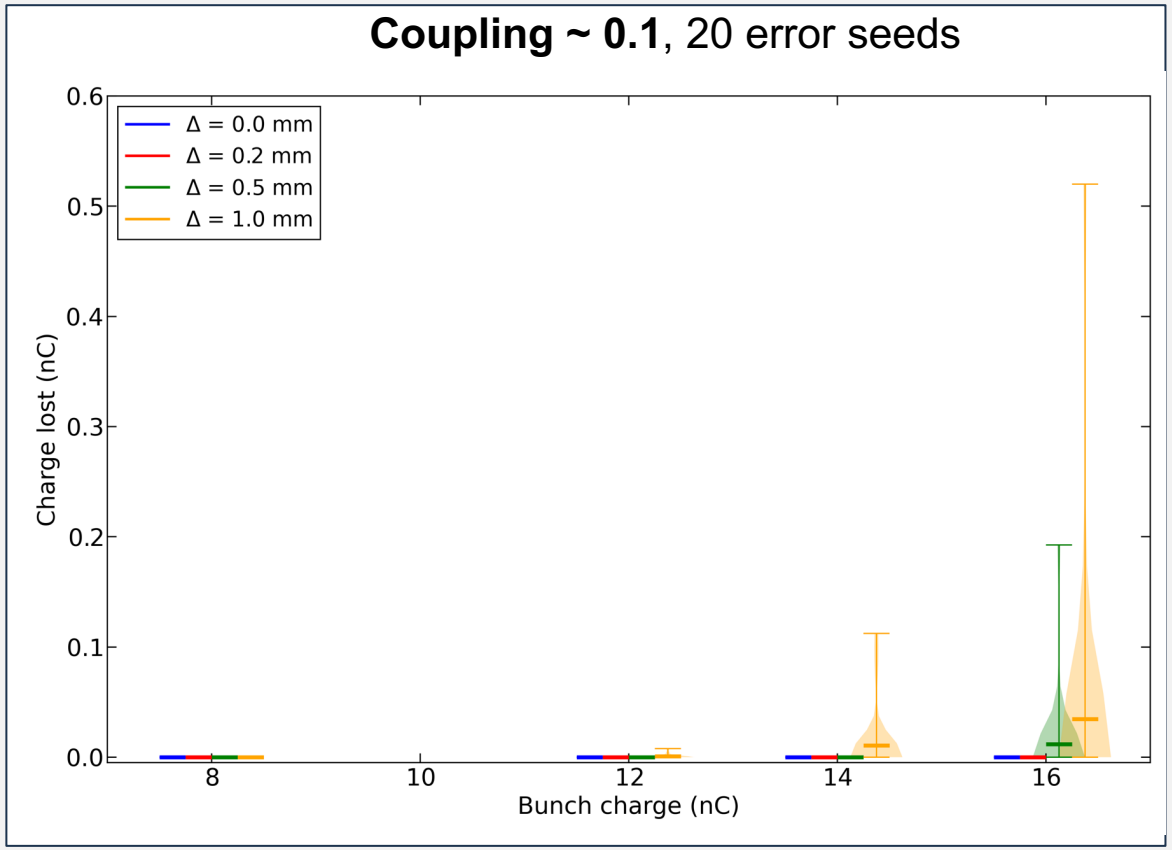


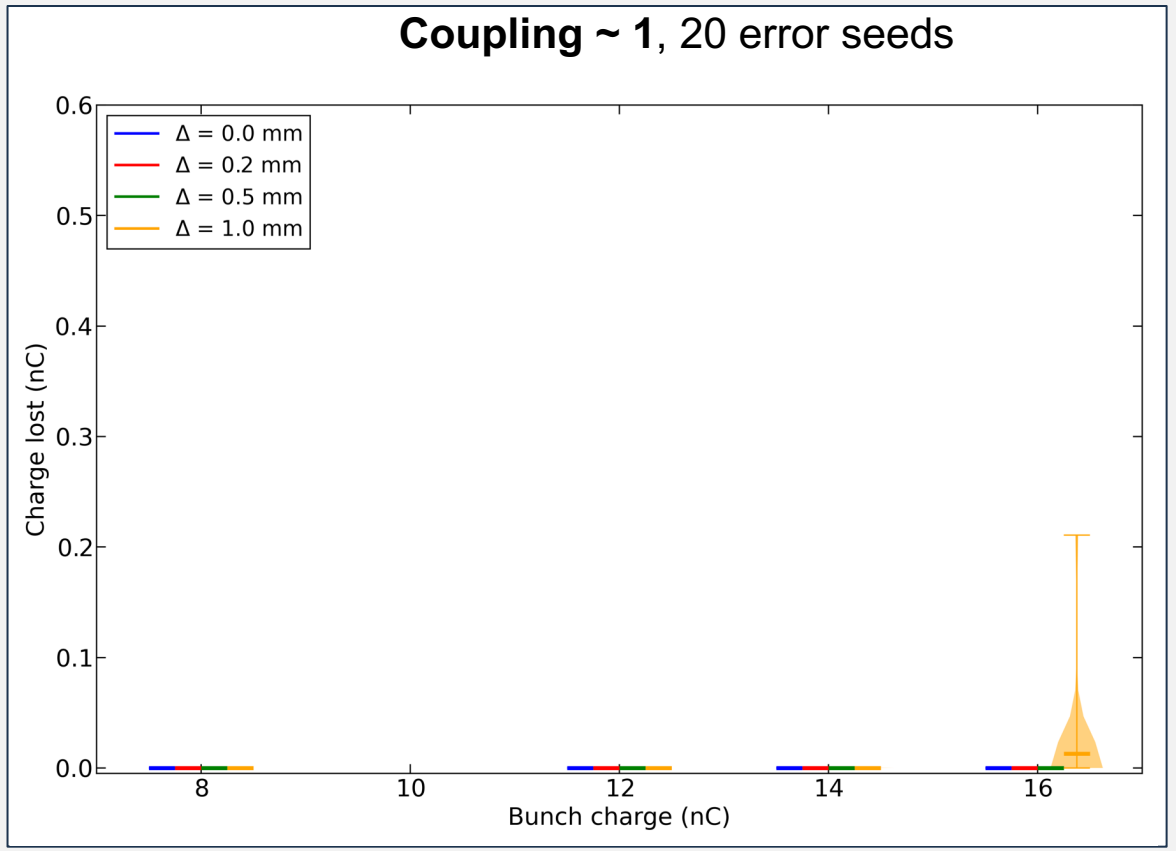
- Chromaticity 5
- Multi-bunch FB not included

Higher coupling – lower losses

Sharing of impedance between the transverse planes likely helps

→ R.R. Lindberg, *IPAC'21*





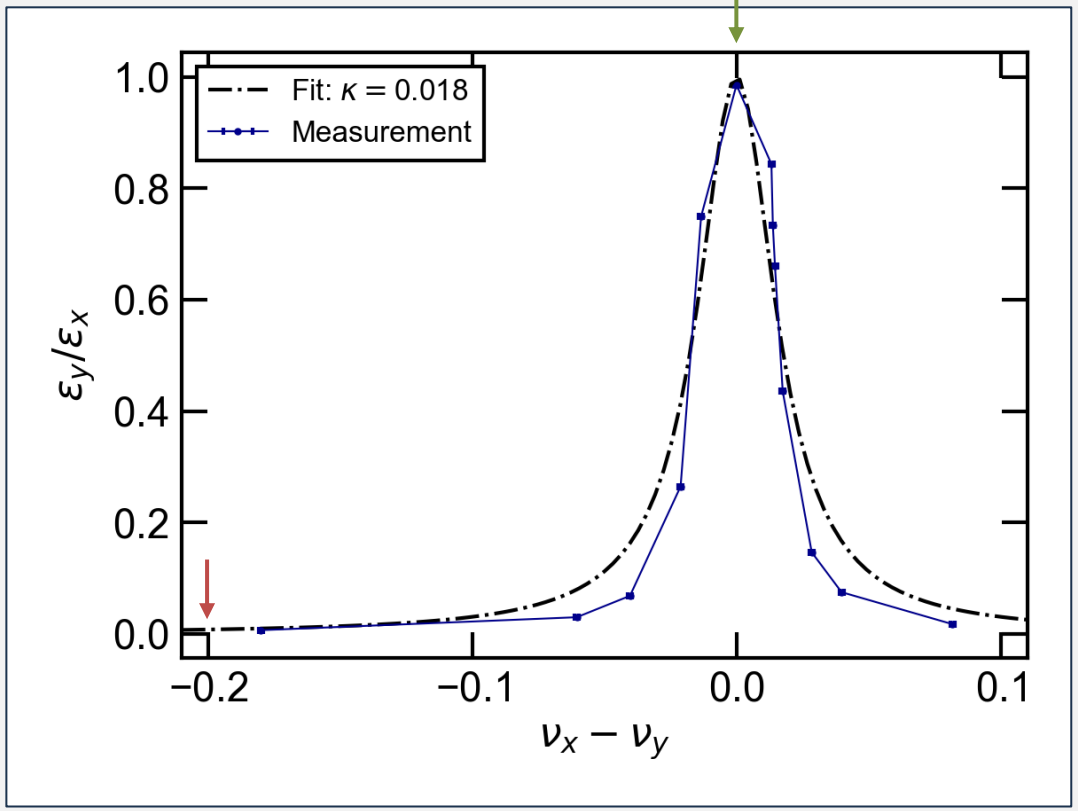
S. Antipov, *LER'24*

High coupling helps accumulate more charge in experiment

Measurable increase confirmed at ESRF-EBS

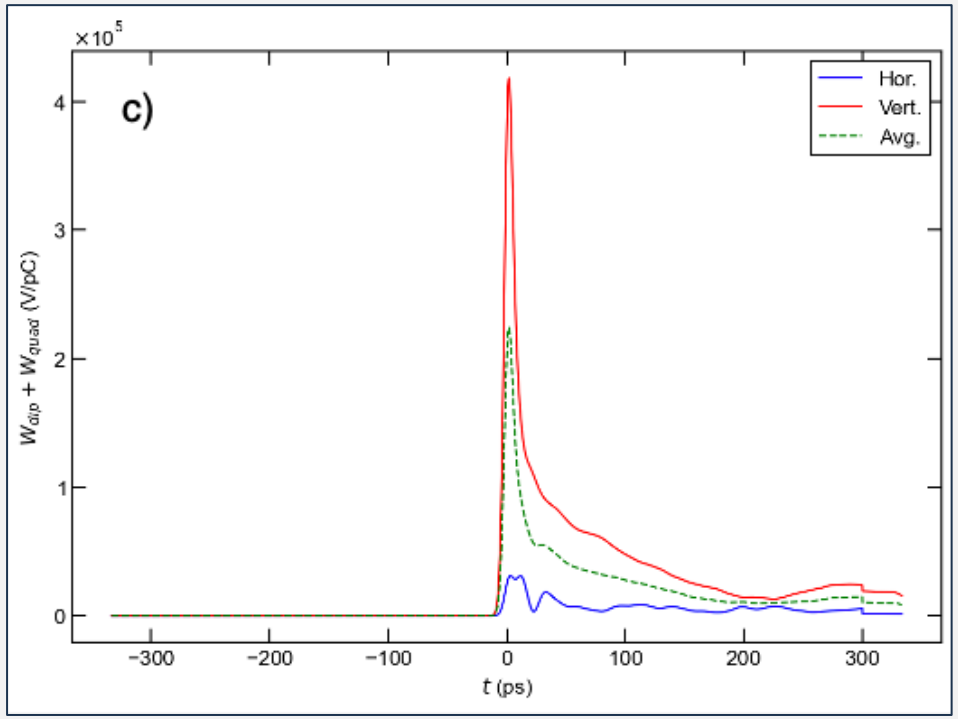
R.R. Lindberg, *IPAC'21:*

$$W_{eff} = [1+|\cos(2\Theta)|]W_y/2+[1-|\cos(2\Theta)|]W_x/2,$$



ESRF-EBS short-range wakefield model

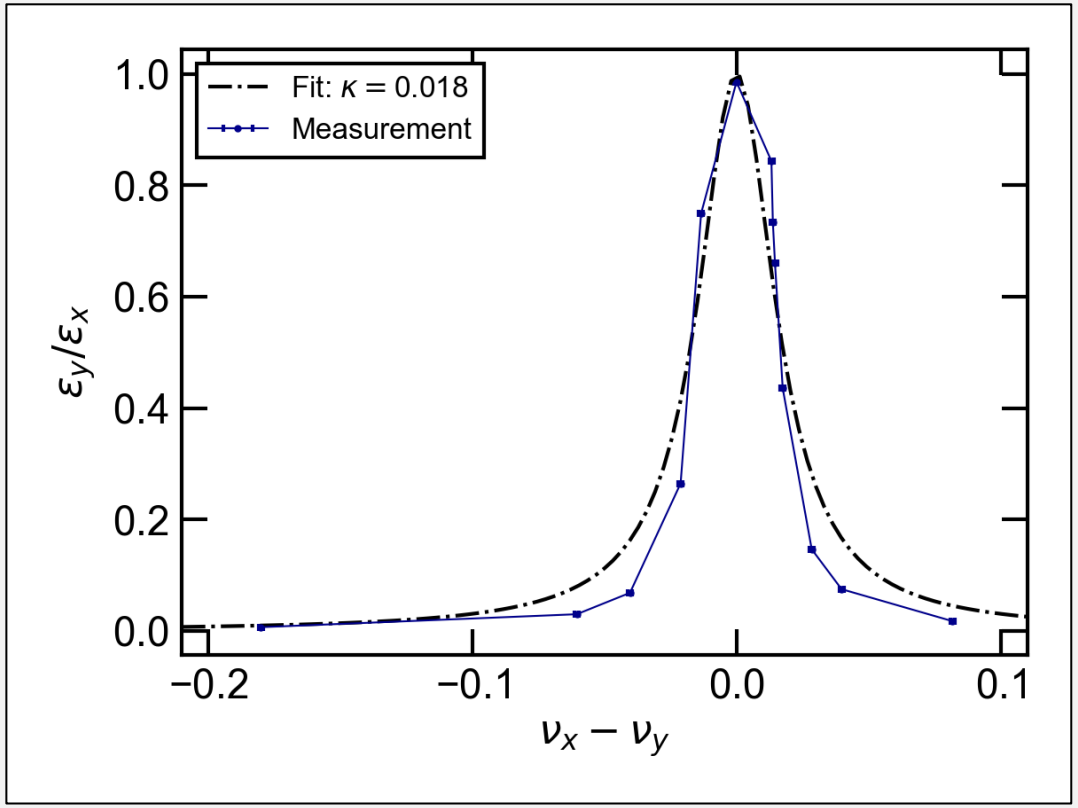
- Verified by beam-based measurements
- L. Carver *et al.*, *PRAB* **26**, 044402 (2023)



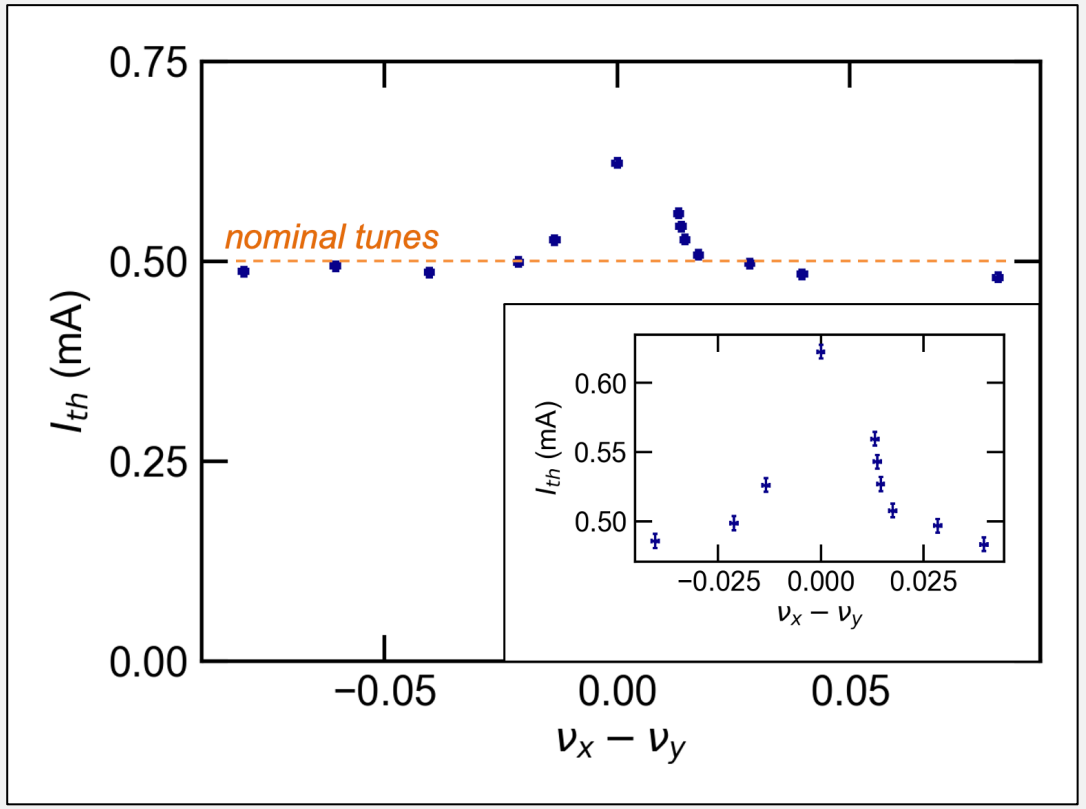
S. Antipov, L. Carver *et al.*, *IPAC'25*

High coupling helps increase accumulation limit in experiment

Measurable increase confirmed at ESRF-EBS



+ 20% at Q' = 0

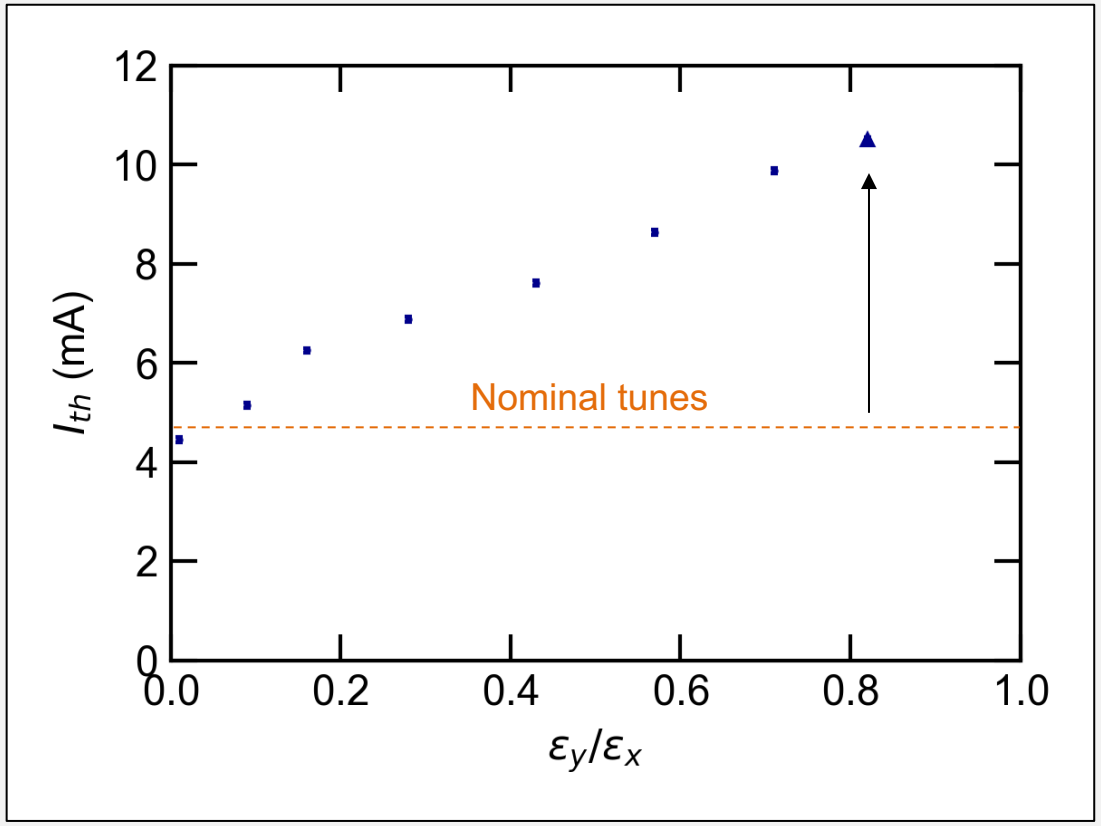


S. Antipov, L. Carver *et al.*, *IPAC'25*

High coupling helps increase accumulation limit in experiment

Measurable increase confirmed at ESRF-EBS

+ 100% at Q' = 5



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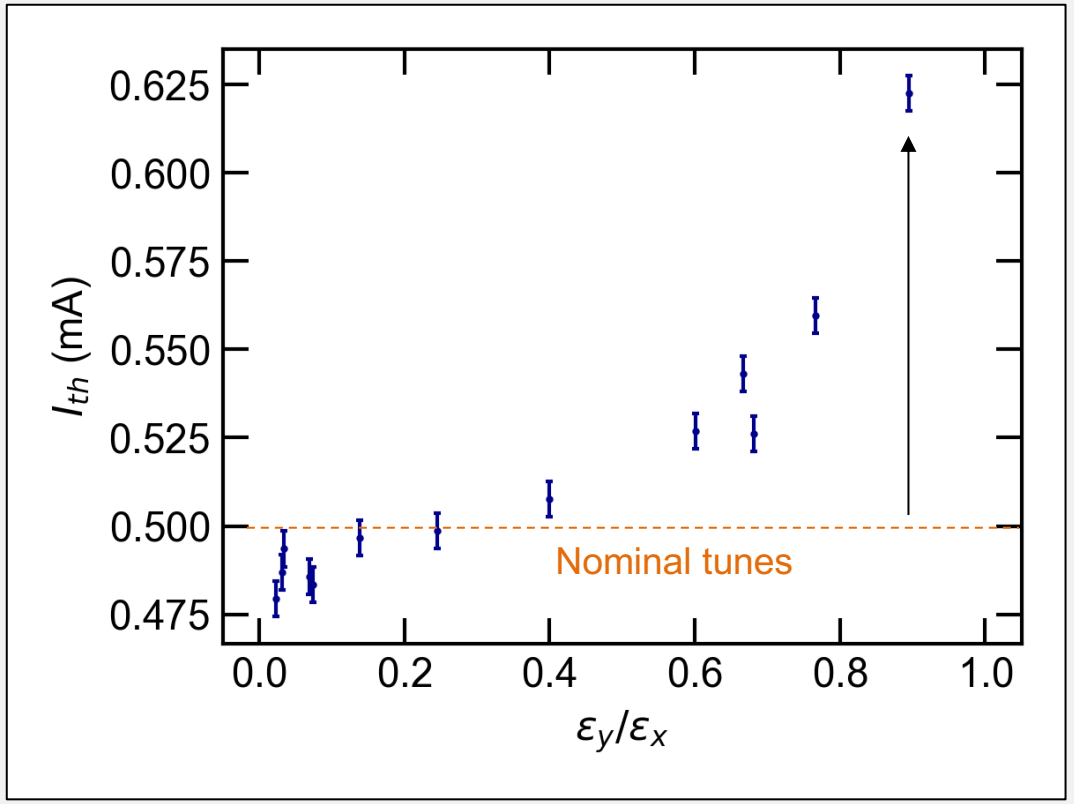
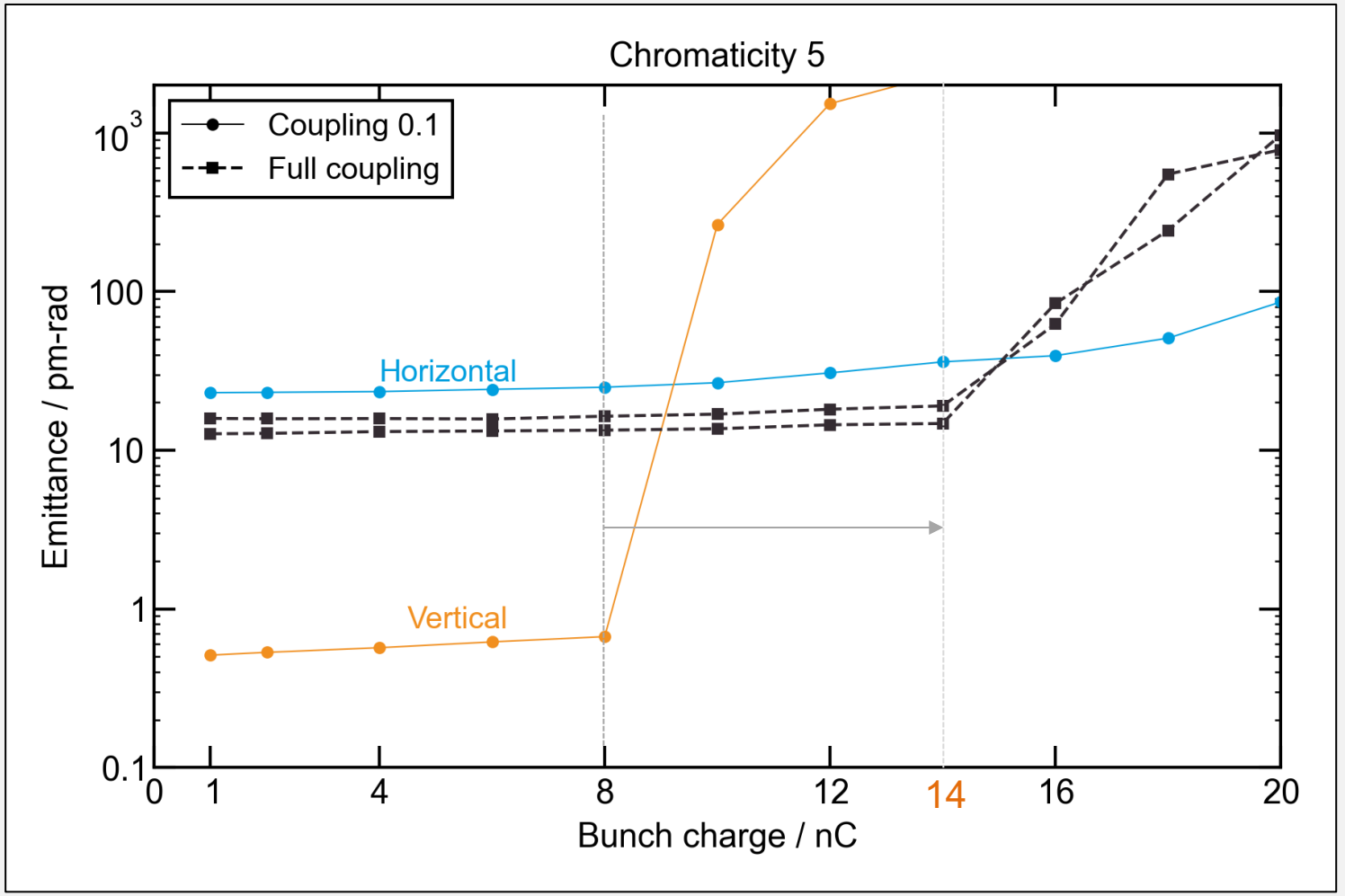


S. Antipov, L. Carver *et al.*, *IPAC'25*

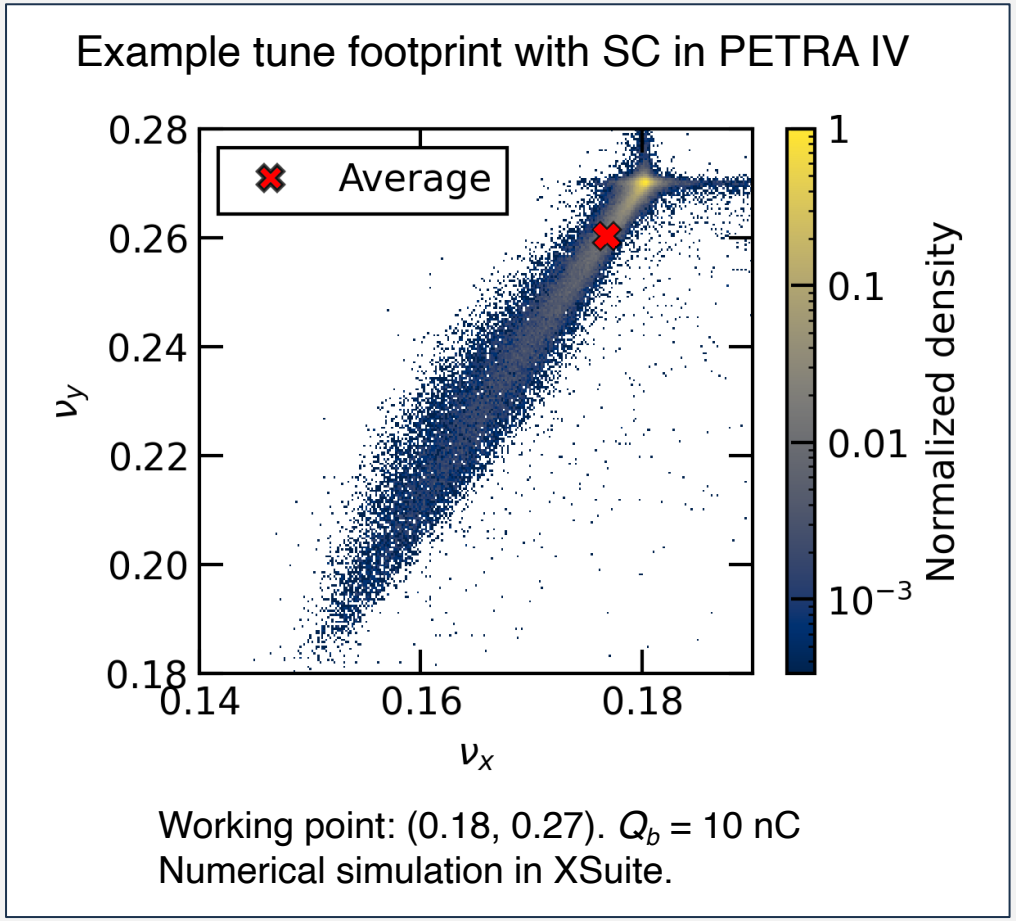
High coupling increases accumulation limit in PETRA IV

+75% at Q' = 5



Space charge starts playing a role in 4th Gen light sources

Sharing of impedance between the transverse planes likely helps



Working point: (0.18, 0.27). Q_b = 10 nC
Numerical simulation in XSuite.

$$\Delta\nu_{x,y}^{SC} = -\frac{Nr_eC}{(2\pi)^{3/2}\gamma^3\sigma_z}\left\langle \frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x+\sigma_y)} \right\rangle$$

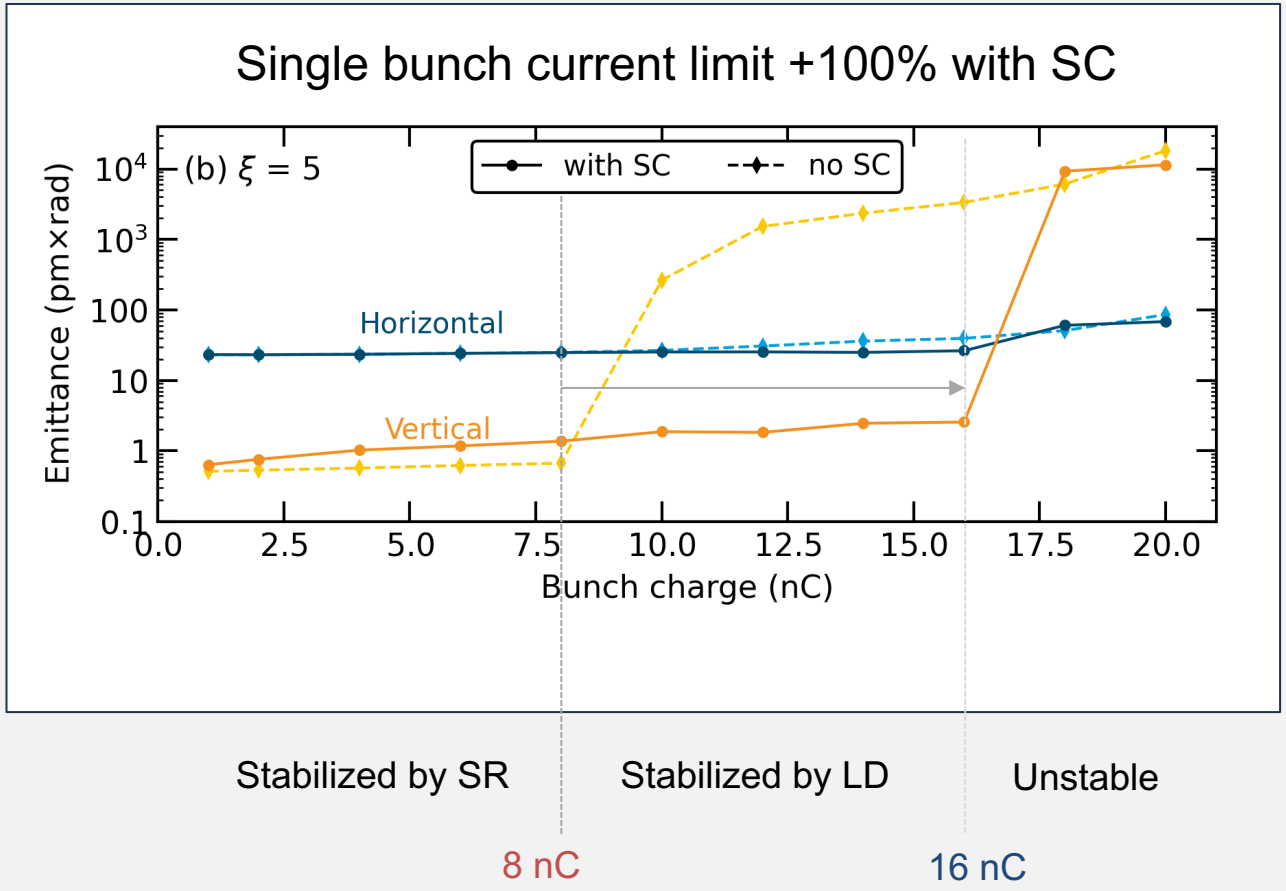
TABLE II. Estimated SC tune shifts in PETRA IV (PIV) and SOLEIL II (SII)

	Q_b	w/ harm cav		w/o harm cav	
	(nC)	$\Delta\nu_x$	$\Delta\nu_y$	$\Delta\nu_x$	$\Delta\nu_y$
PIV	1	-2.8×10^{-3}	-1.0×10^{-2}	-7.6×10^{-3}	-2.7×10^{-2}
	8	-1.2×10^{-2}	-4.1×10^{-2}	-2.2×10^{-2}	-7.7×10^{-2}
SII	1.4	-3.1×10^{-3}	-6.2×10^{-3}	-8.8×10^{-3}	-1.8×10^{-2}
	7.4	-1.4×10^{-2}	-2.9×10^{-2}	-2.7×10^{-2}	-5.4×10^{-2}

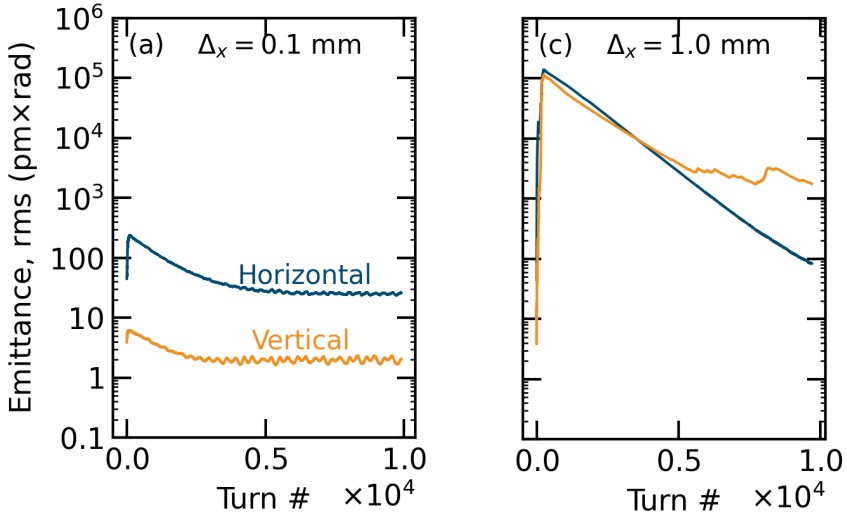
S. Antipov, V. Gubaidulin *et al., PRAB* **28**, 024401 (2025)

Space charge mitigates the head-tail instability

But the second equilibrium is a fragile one



Strong injection perturbation may destabilize the bunch that has been kept stable by SC



Bunch charge 12 nC, chromaticity 5

S. Antipov, V. Gubaidulin *et al.*, *PRAB* **28**, 024401 (2025)

Baseline operation modes of PETRA IV are safe

No significant losses even for high degrees of amplitude sharing

High coupling can help push the single bunch thresholds further

- Simulated and demonstrated in an experiment

Space charge is also beneficial

- The equilibrium is fragile, can be broken by injection oscillations

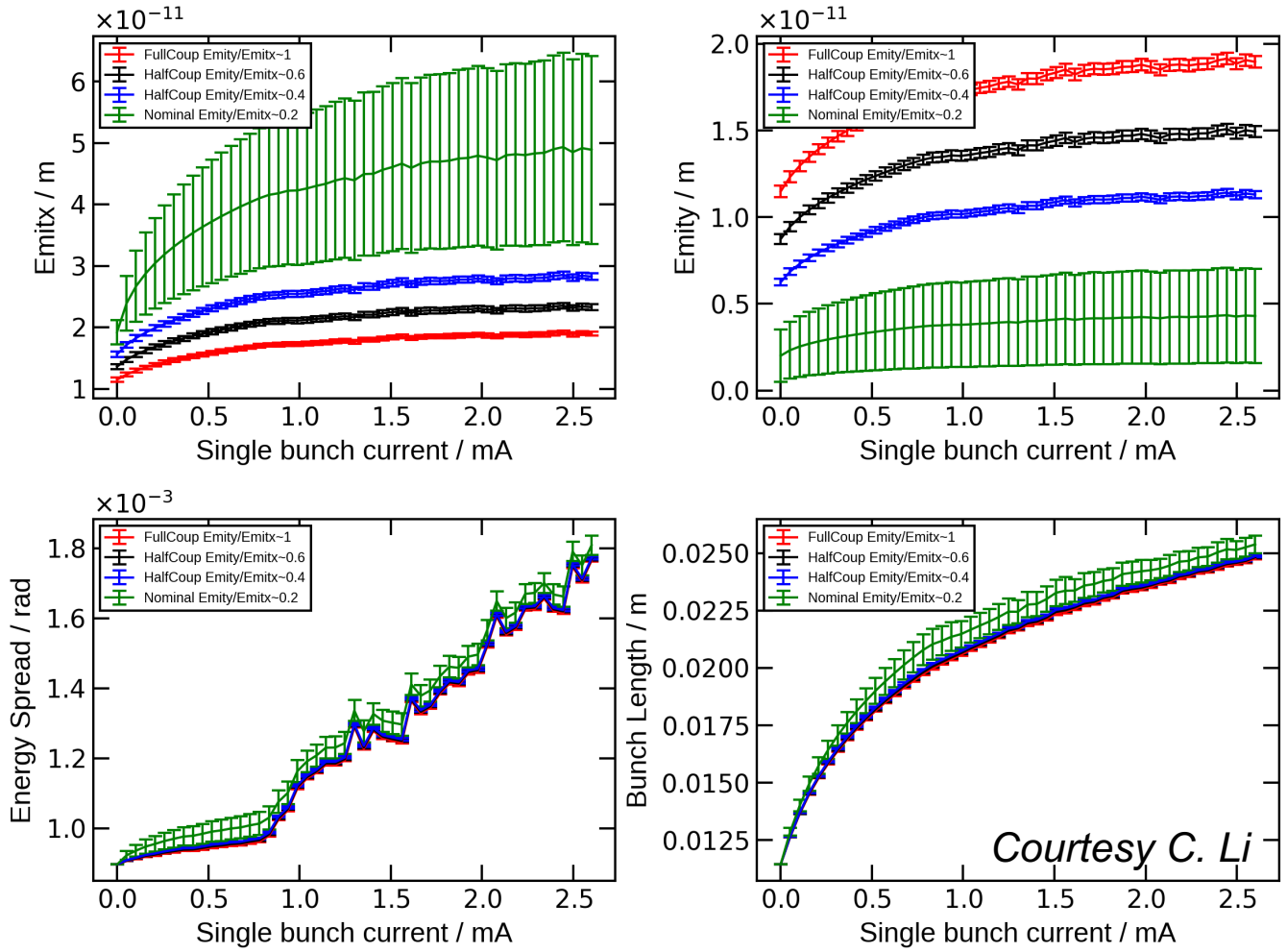
What is next?

- Space charge + high coupling
- Sharing of wakes, chromaticities, Landau damping

Thank you

Initial conditions

Average stationary beam distributions among multiple error seeds



IBS and wakefields taken into account

RW simulated with I2DW

- NEG coating included, based on measured resistivity

Geometric simulated up to 100 GHz

- Including hardware as it is being designed
- Some still as broadband contributions

Generating errors seeds

Automated procedure in Elegant

Apply misalignments

- All quadrupoles
- All sextupoles

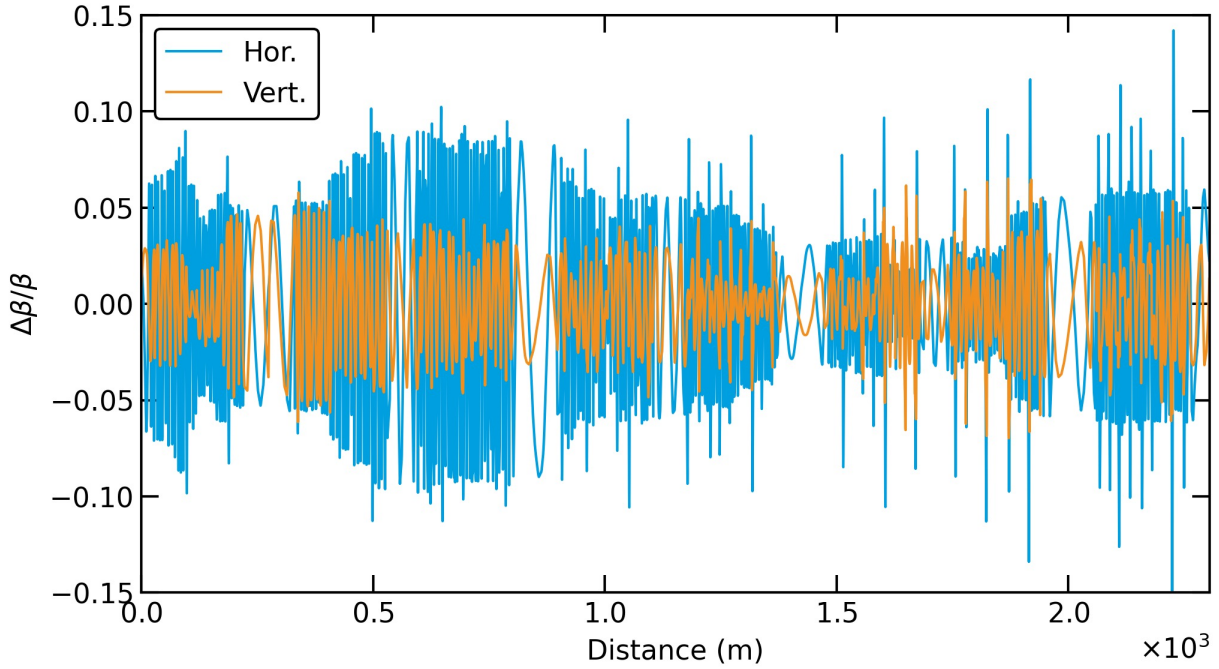
Turn SR off

- Avoid confusion between orbit correction & SR decay
- In real machine: adjust BPM offsets

10 iterations of correction

- Orbit
- Tunes
- Chromaticity

rms β-beating: 5%

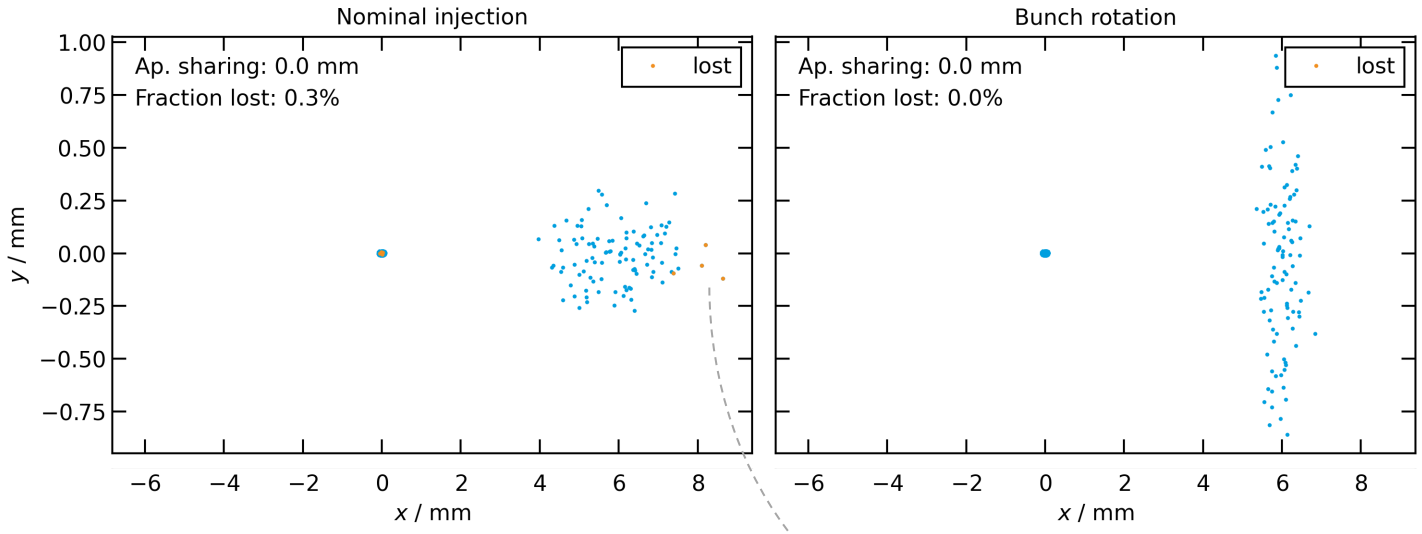


Automated procedure developed C. García Cortéz

Losses happen mainly in the circulating beam

Can simulate 1 beam instead of 2

→ Y.-C. Chae, IPAC'07



a few losses on horizontal collimators

Numerical example:

- 16 nC in the stored bunch
- 800 pC in the injected bunch
- Beam separation 6 mm
- 200 000 macroparticles

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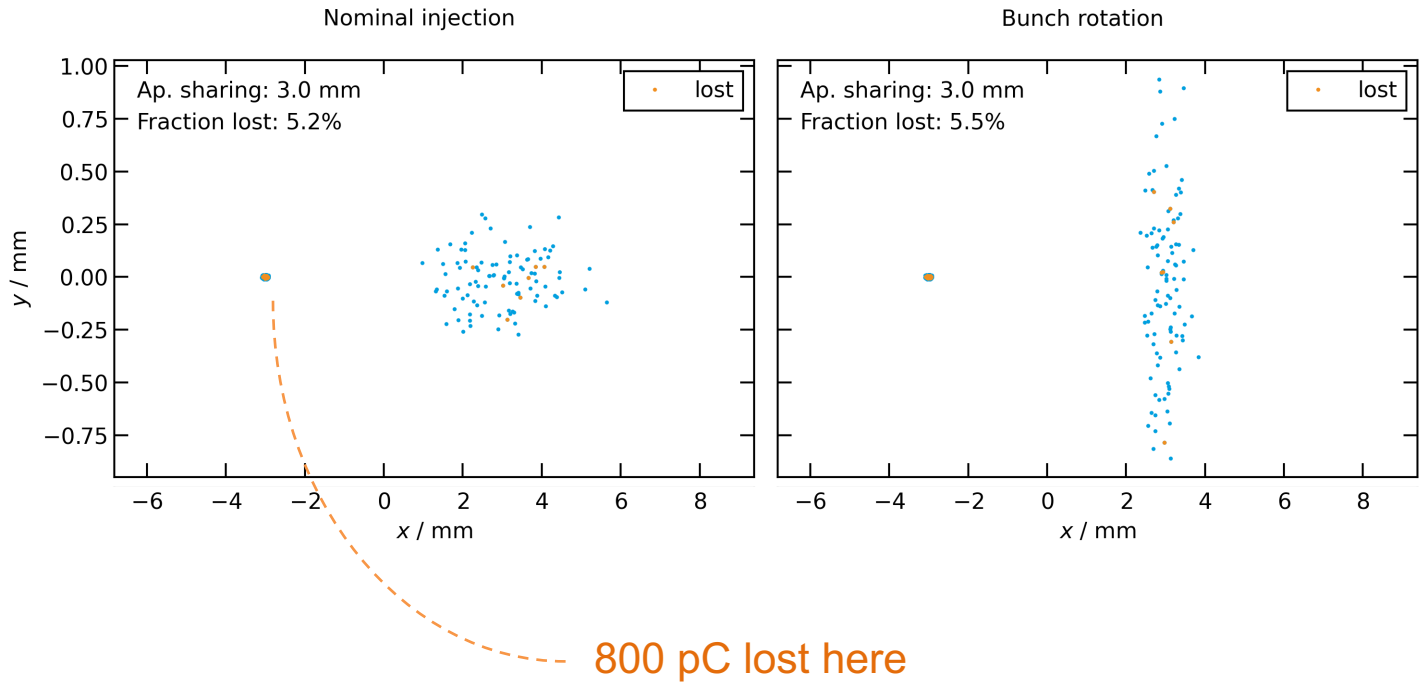

Numerical example:

- 16 nC in the stored bunch
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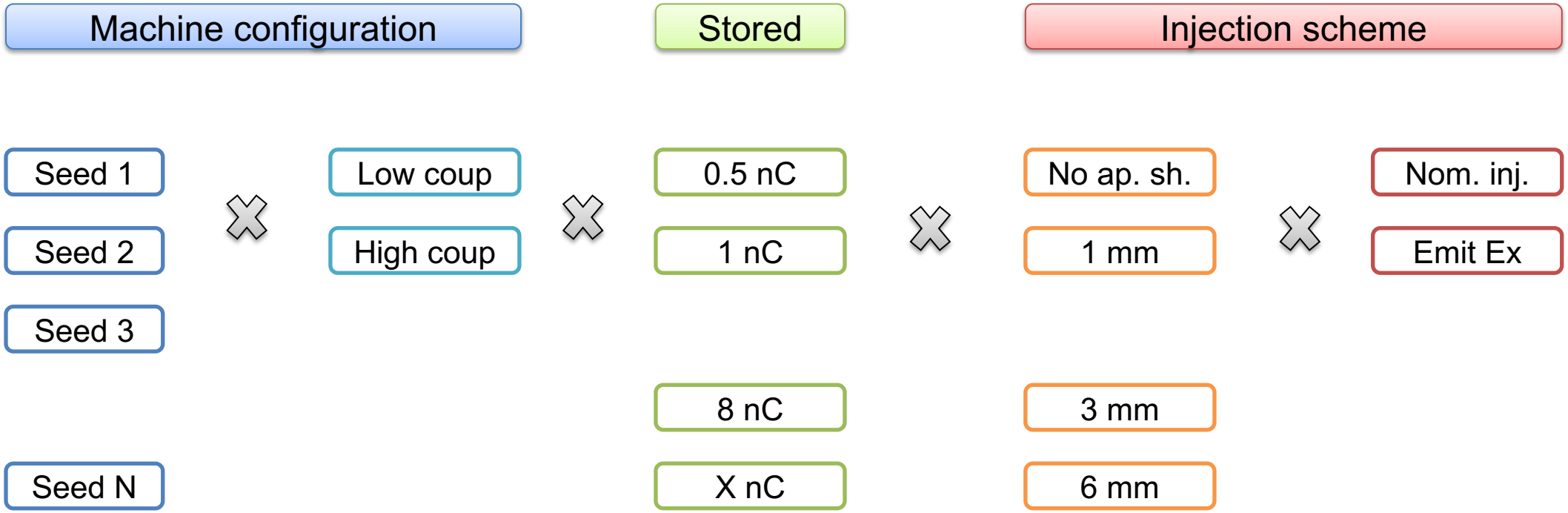
Parameter space to cover

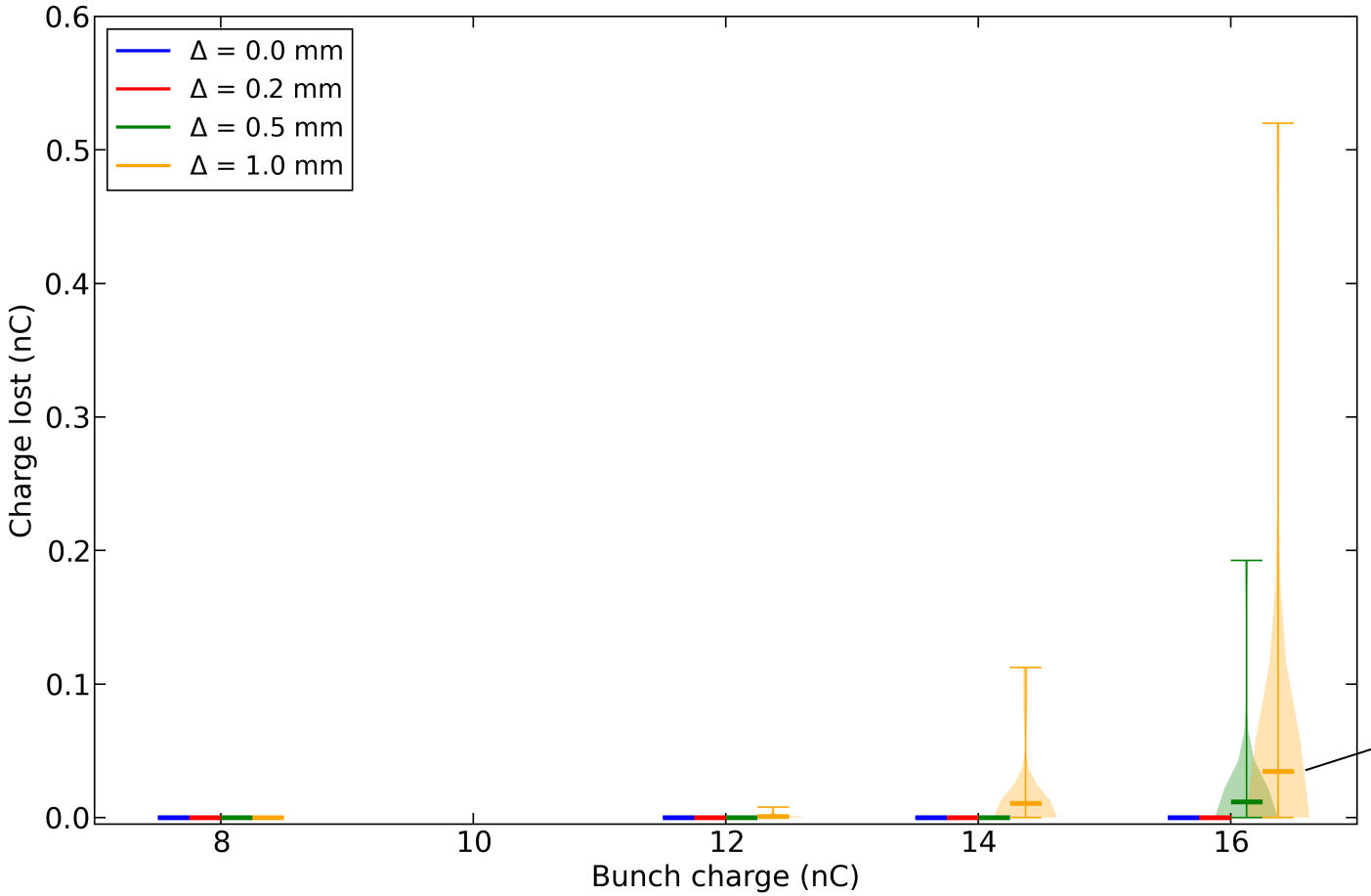
1 point = 2 node*days on DESY's HPC cluster



Many thanks to the Maxwell computing cluster for providing the computing infrastructure

Large variation of losses observed between error seeds

‘Average’ is not ‘most likely’



20 random error seeds

- Each with 5% rms beta-beating

Need a more realistic set of error seeds

- Based on commissioning simulations
- Work in progress

Use ‘average’ seed for analysis