Injection Efficiency and Accumulation Limit in PETRA IV

Sergey Antipov, Ilya Agapov, Yong-Chul Chae, Christopher Cortes, Marc Jebramcik, Joachim Keil, Chao Li, Lukas Malina

Low Emittance Ring Workshop, CERN, Geneva

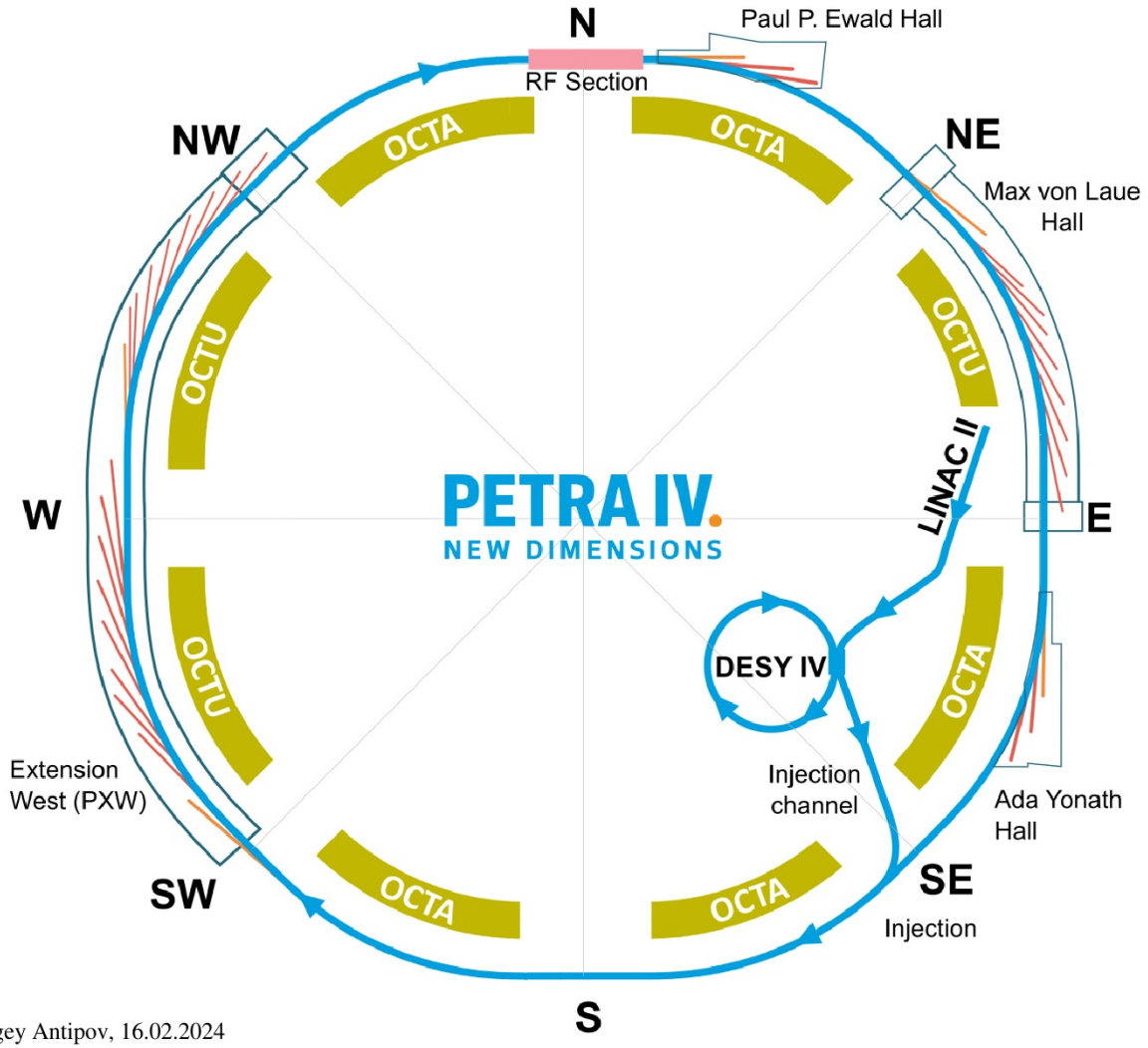
February 16, 2024

HELMHOLTZ

DESY.

PETRA IV: Germany's future flagship light source

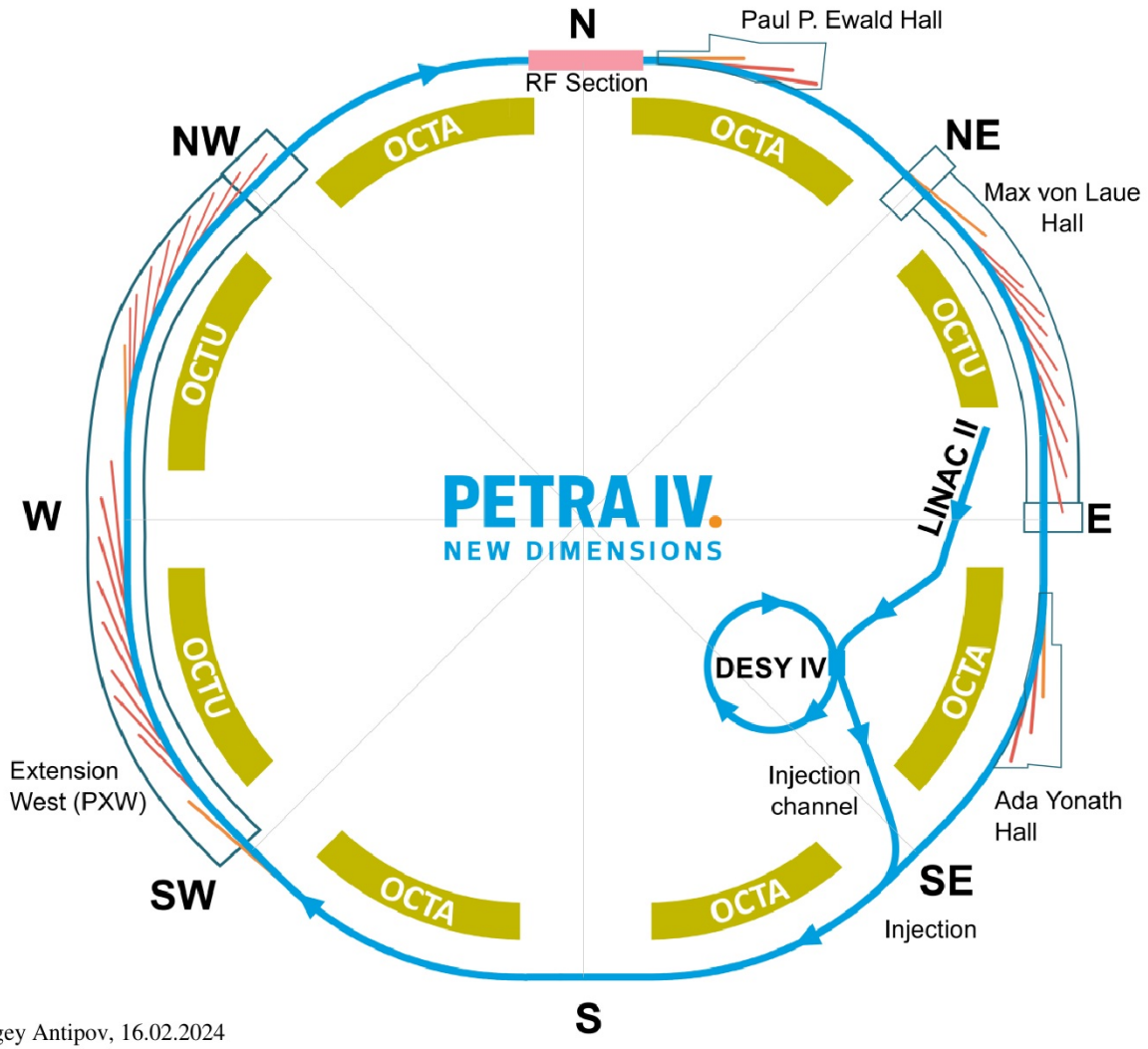
6 GeV, 2.3 km, 20 pm



PETRA IV: Germany's future flagship light source

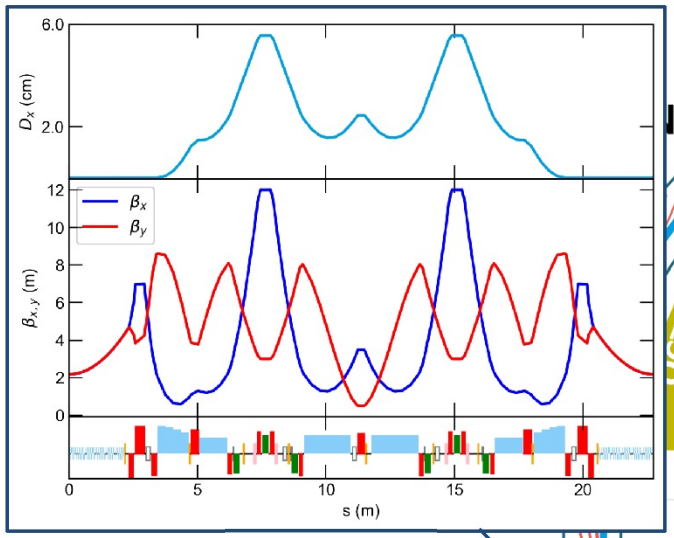
6 GeV, 2.3 km, 20 pm

Gluons discovered here in 1979

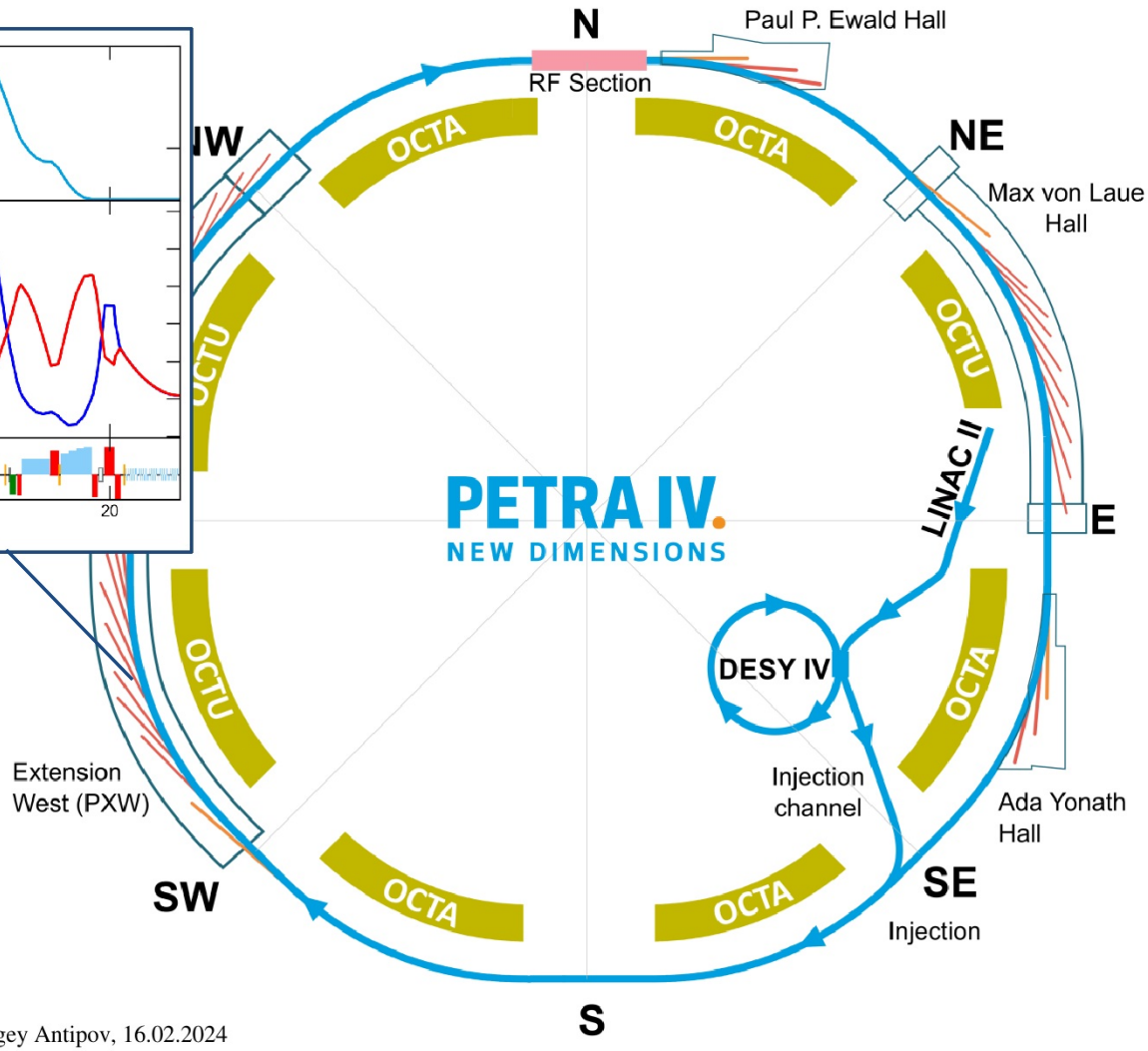


PETRA IV: Germany's future flagship light source

6 GeV, 2.3 km, 20 pm

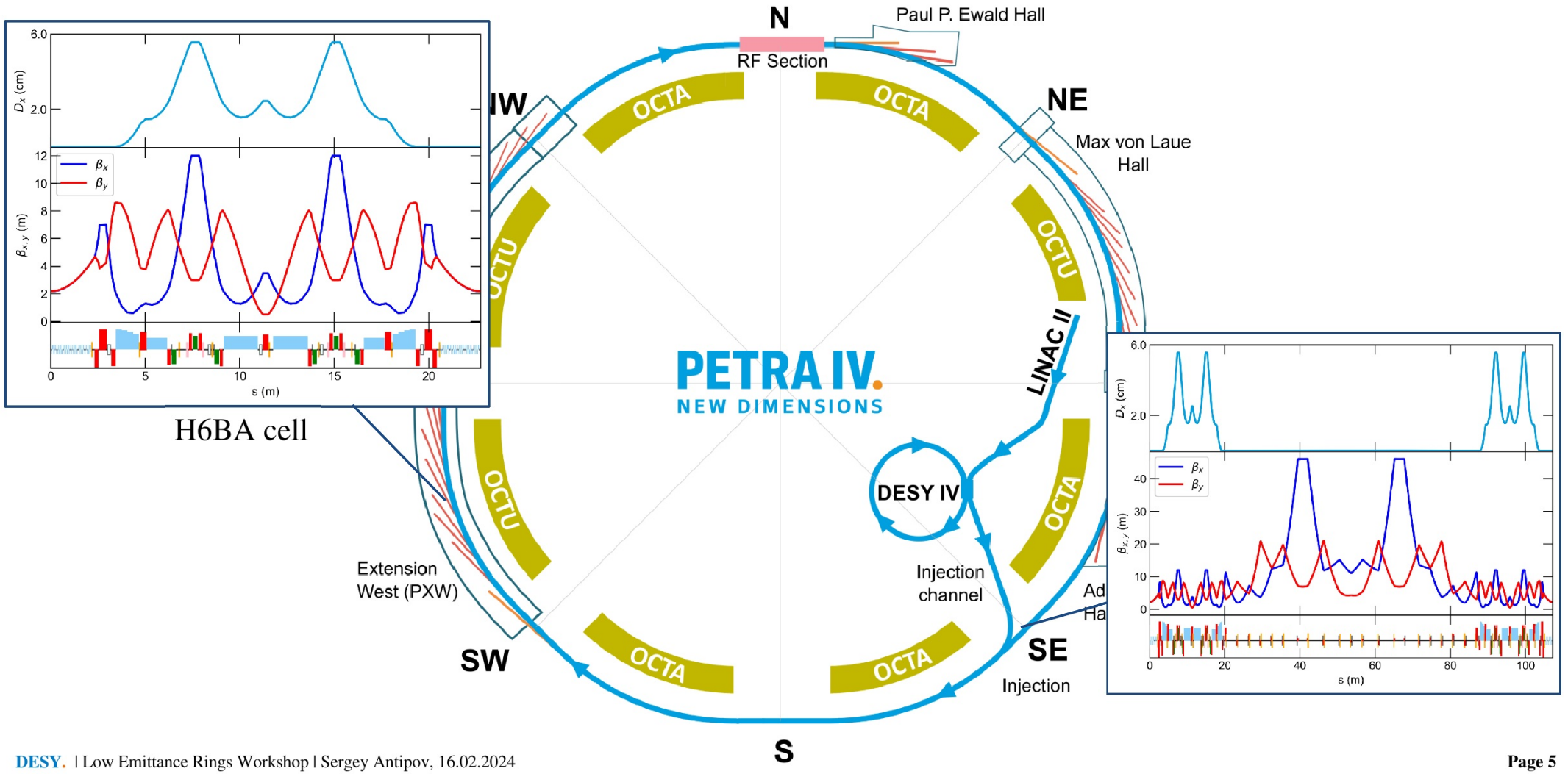


H6BA cell



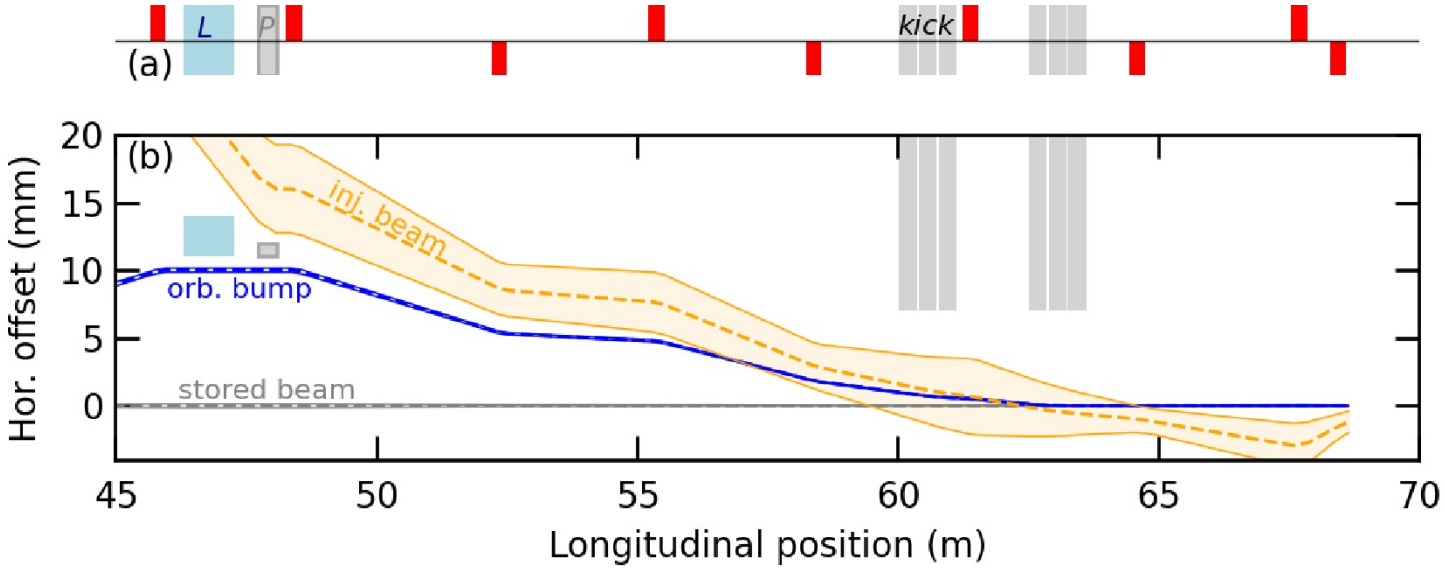
PETRA IV: Germany's future flagship light source

6 GeV, 2.3 km, 20 pm



Injection section layout

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

Scheme also works for LPA injector

PAUL SCHERRER INSTITUT

Where are we going?

Kicker-bump injection	Multipole/Nonlinear kicker	Swap-out	Short pulse kicker (Aperture sharing, Long. Inj.)
			
Most 3GLS ESRF-EBS ELETTRA II etc.	MAX IV Sirius Soleil II etc.	ALS-U APS-U HEPS etc.	SLS 2.0 Diamond II PETRA IV etc.

The optimum injection scheme may depend on each storage ring as well as the demands of the beamline users

* Free images from pixabay.com

M. Aiba, "A Review on Injection Schemes", FLS'23, Lucerne, 2023

PAUL SCHERRER INSTITUT

Where are we going?

Kicker-bump injection

Most 3GLS
ESRF-EBS
ELETTRA II
etc.

Multipole/Nonlinear kicker

MAX IV
Sirius
Soleil II
etc.

Swap-out

ALS-U
APS-U
HEPS
etc.

Short pulse kicker
(Aperture sharing, Long. Inj.)

SLS 2.0
Diamond II
PETRA IV
etc.

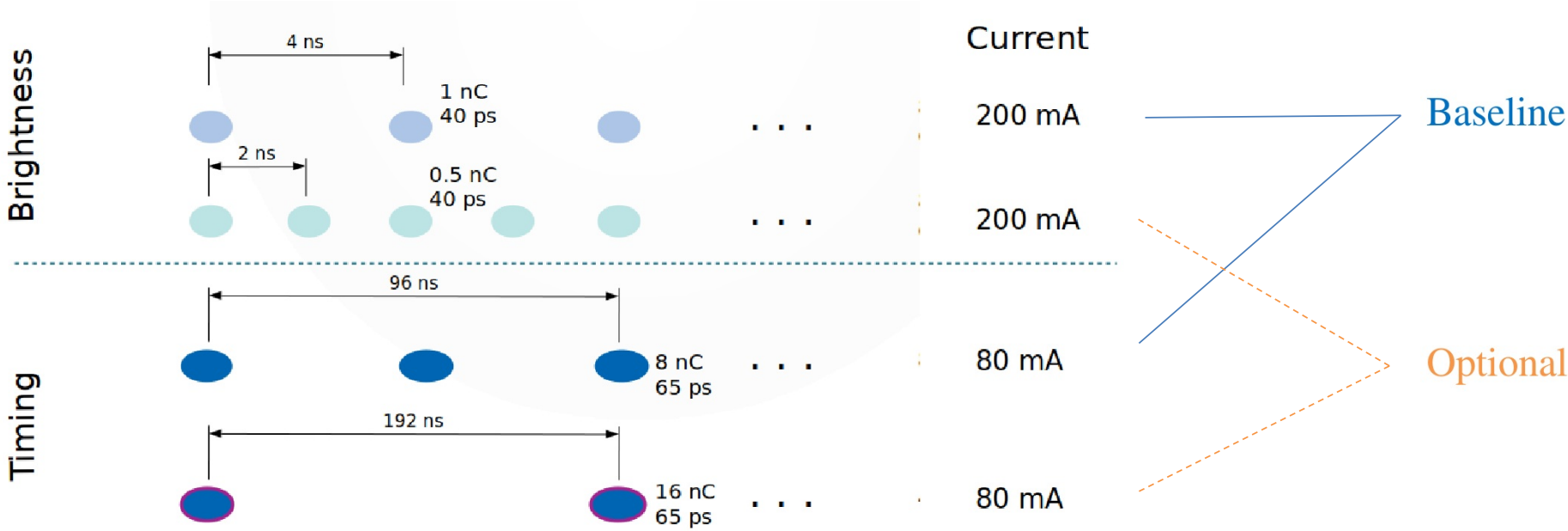
The optimum injection scheme may depend on each storage ring as well as the demands of the beamline users

* Free images from pixabay.com

M. Aiba, "A Review on Injection Schemes", FLS'23, Lucerne, 2023

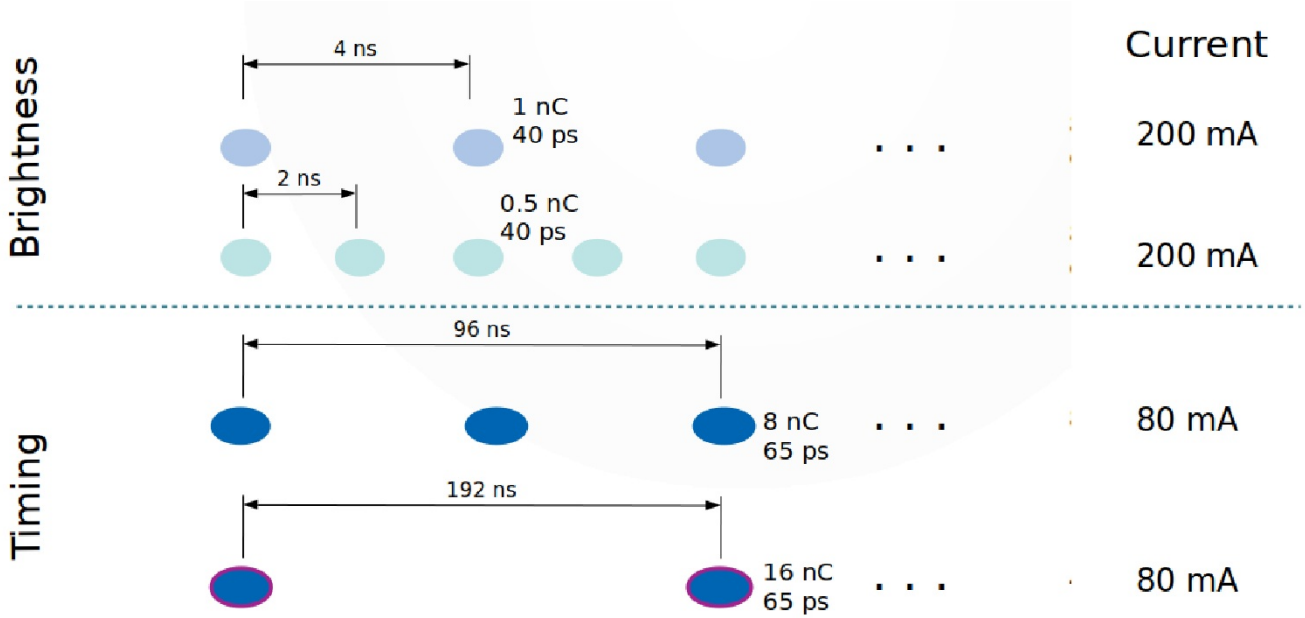
PETRA IV supports a variety of operation modes

Do collective effects at injection pose any limitation?



PETRA IV supports a variety of operation modes

Do collective effects at injection pose any limitation?

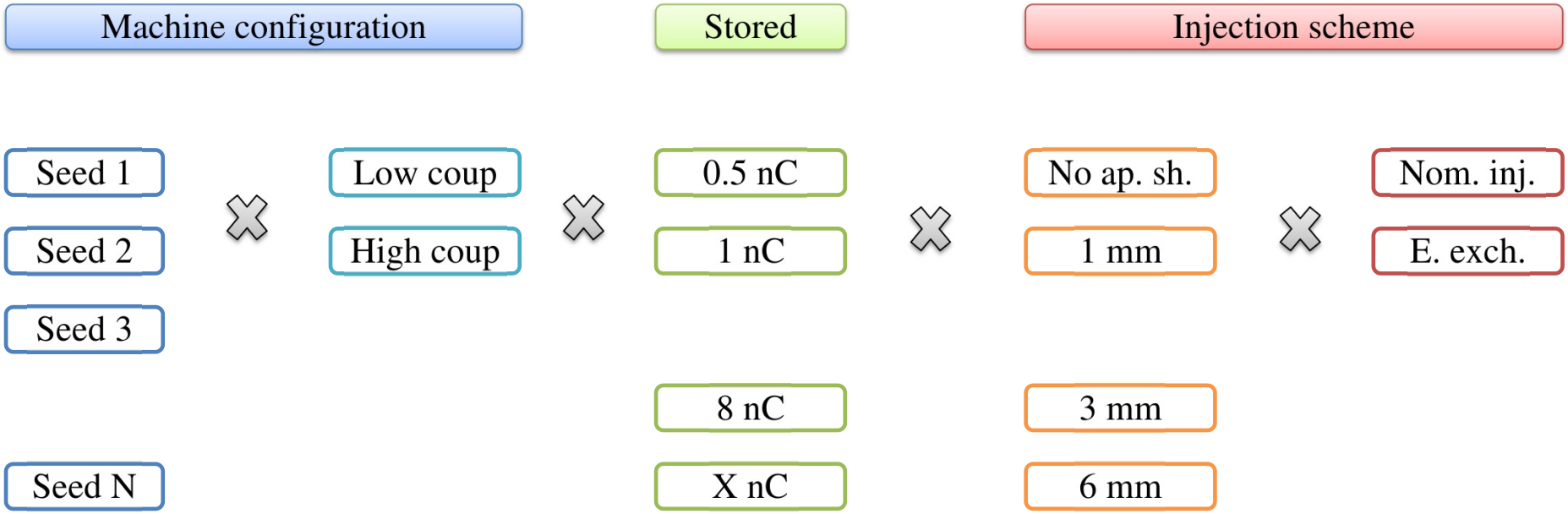


6D element-by-element tracking

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

Parameter space to cover

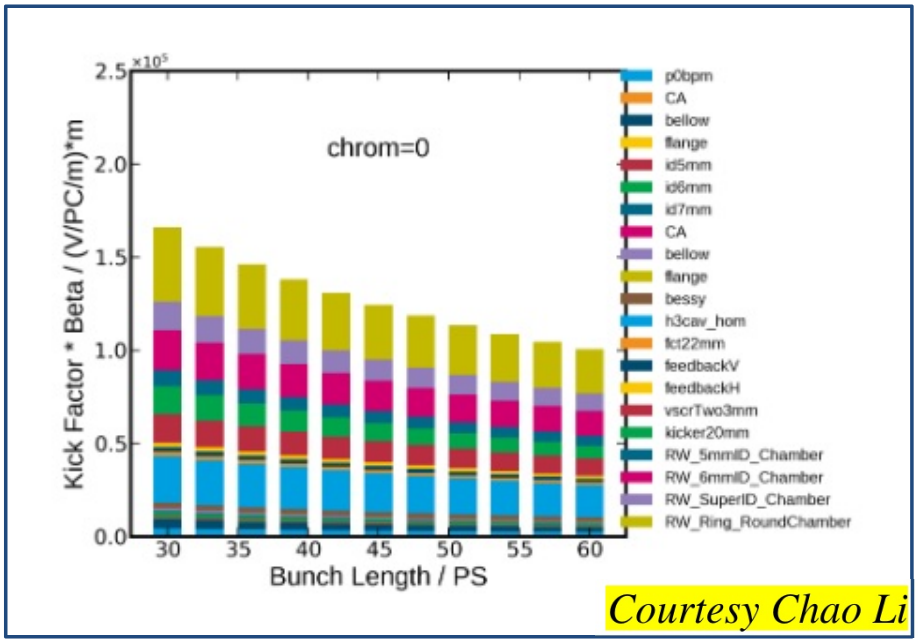
1 point = 2 node*days on DESY's HPC cluster



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

Impedance model: RW dominates

Mainly due to tight undulator gaps



Courtesy Chao Li

All key hardware included

RW simulated with I2DW

- NEG coating included, based on measured resistivity

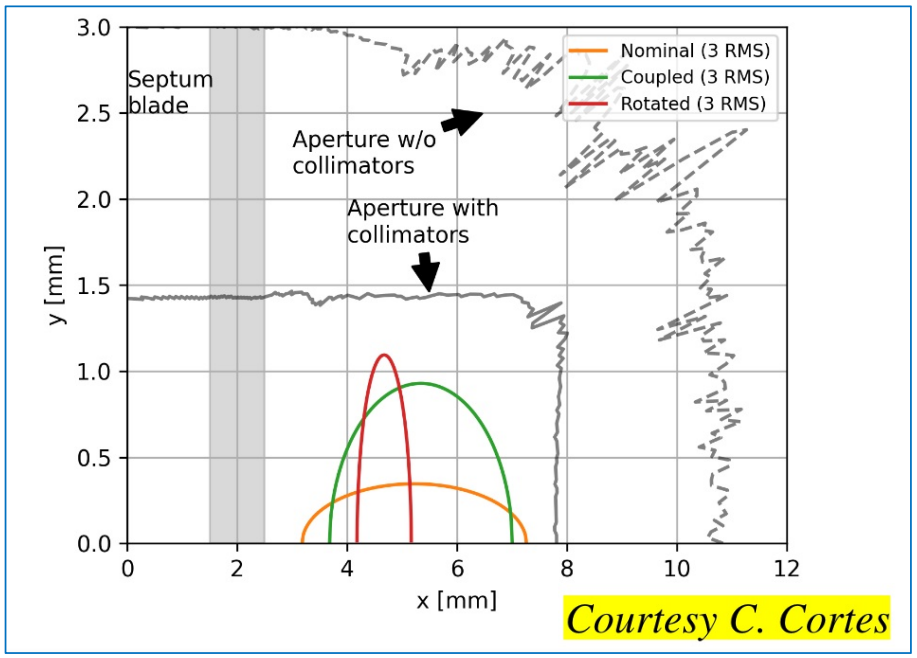
Geometric simulated up to 100 GHz

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

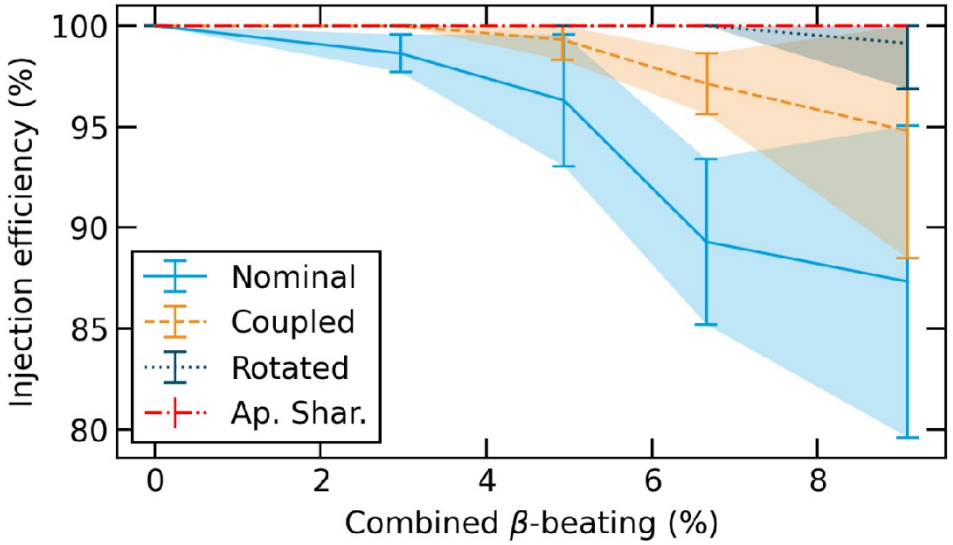
Space is tight for the booster beam

Can do phase space manipulation to improve injection efficiency

DESY IV booster emittance: **20, 2 nm**



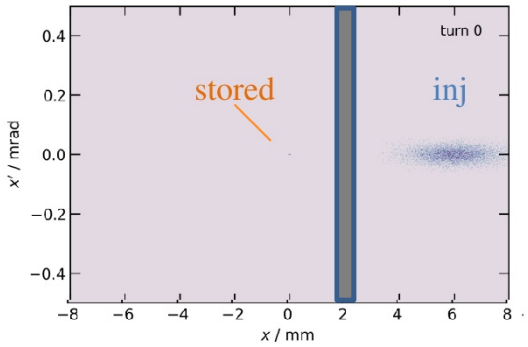
Courtesy C. Cortes



Simulation by M. Jebramcik

Injected beam decoheres in several turns

No perturbation of the stored bunch observed

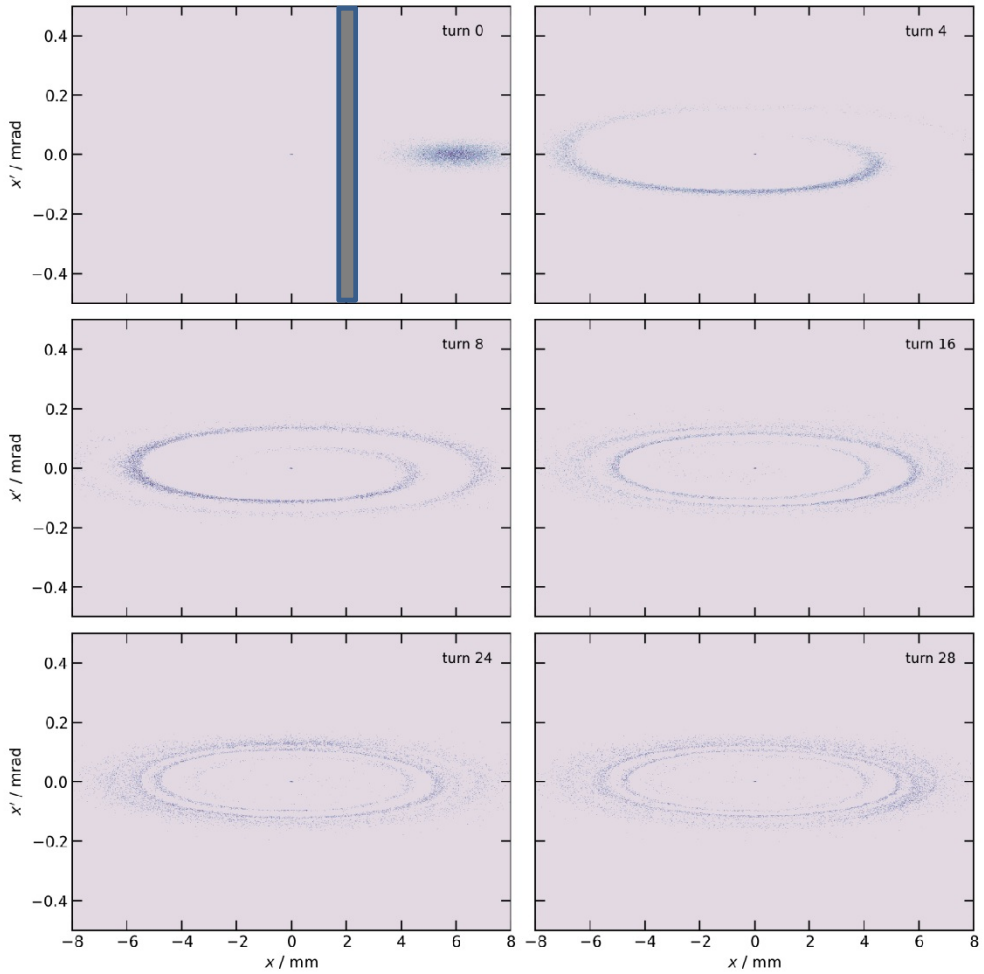


Timing mode example

- 8 nC in the stored bunch: 20, 2 pm
- 800 pC in the injected bunch: 20, 2 nm

Injected beam decoheres in several turns

No perturbation of the stored bunch observed



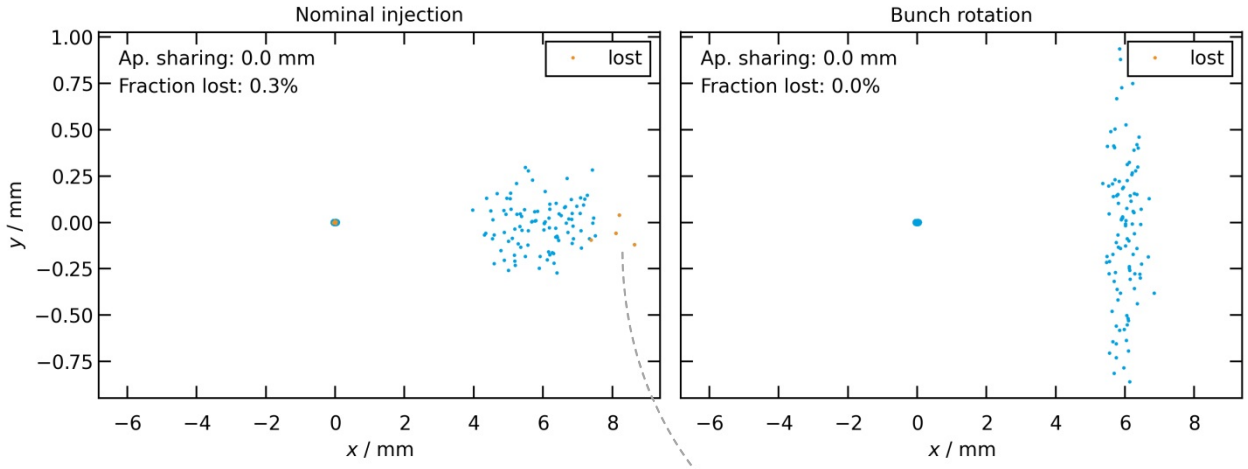
Timing mode example

- 8 nC in the stored bunch: 20, 2 pm
- 800 pC in the injected bunch: 20, 2 nm

Losses happen mainly in the circulating beam

Can simulate 1 beam instead of 2

→ Y.-C. Chae, IPAC'07



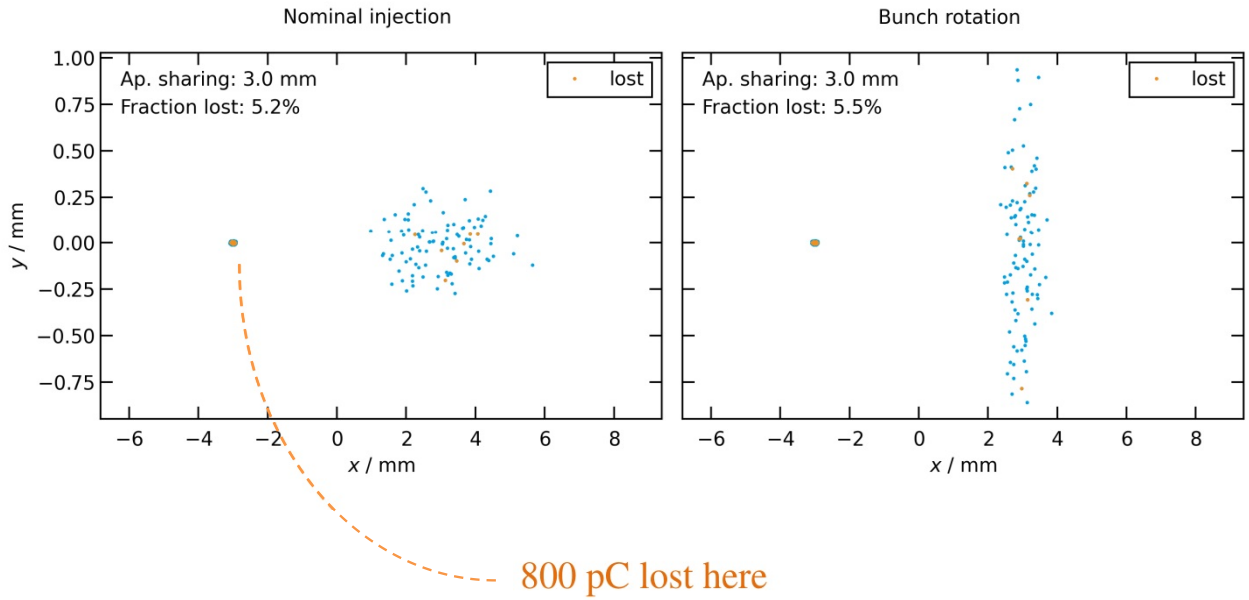
Numerical example:

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

Losses happen mainly in the circulating beam

Can simulate 1 beam instead of 2

→ Y.-C. Chae, IPAC'07

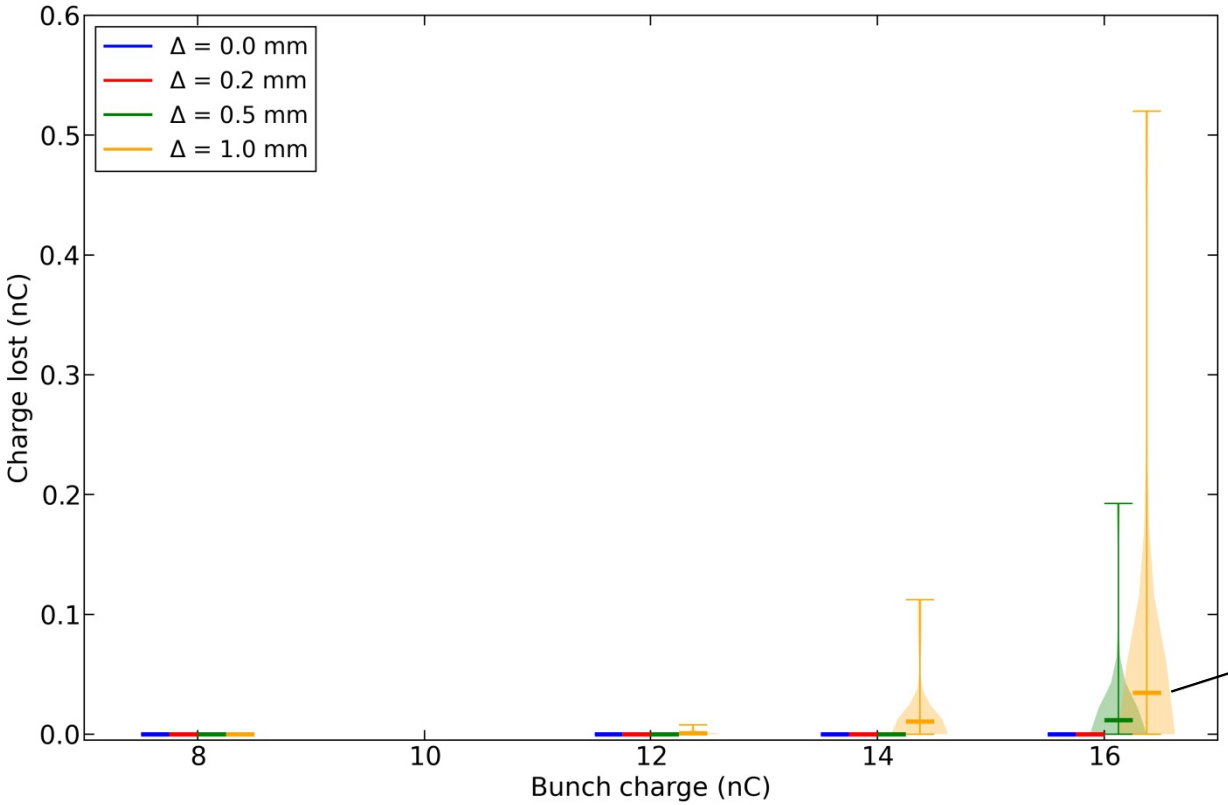


Numerical example:

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

Large variation of losses observed between error seeds

‘Average’ is not ‘most likely’



20 random error seeds

- Each with 5% rms beta-beating

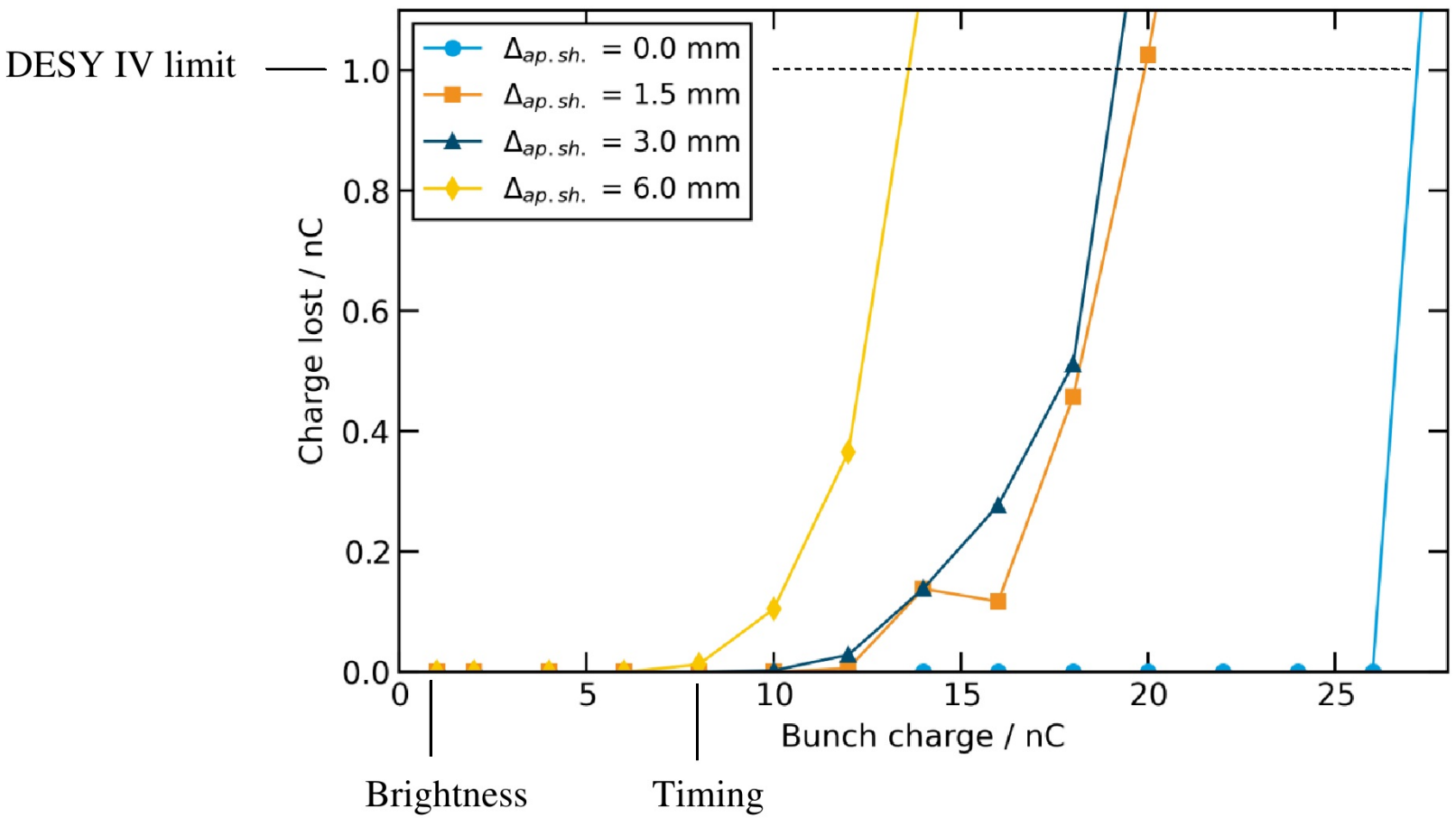
Need a more realistic set of error seeds

- Based on commissioning simulations
- Work in progress

Use ‘average’ seed for analysis

Accumulation limit

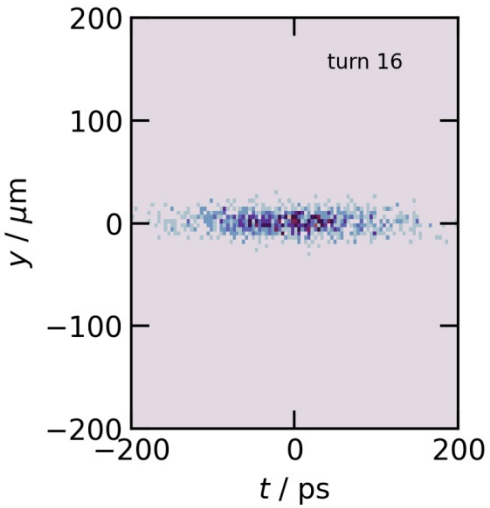
Theoretical limit is reached when lost charge = injected charge



Instability at high intensities

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

Before

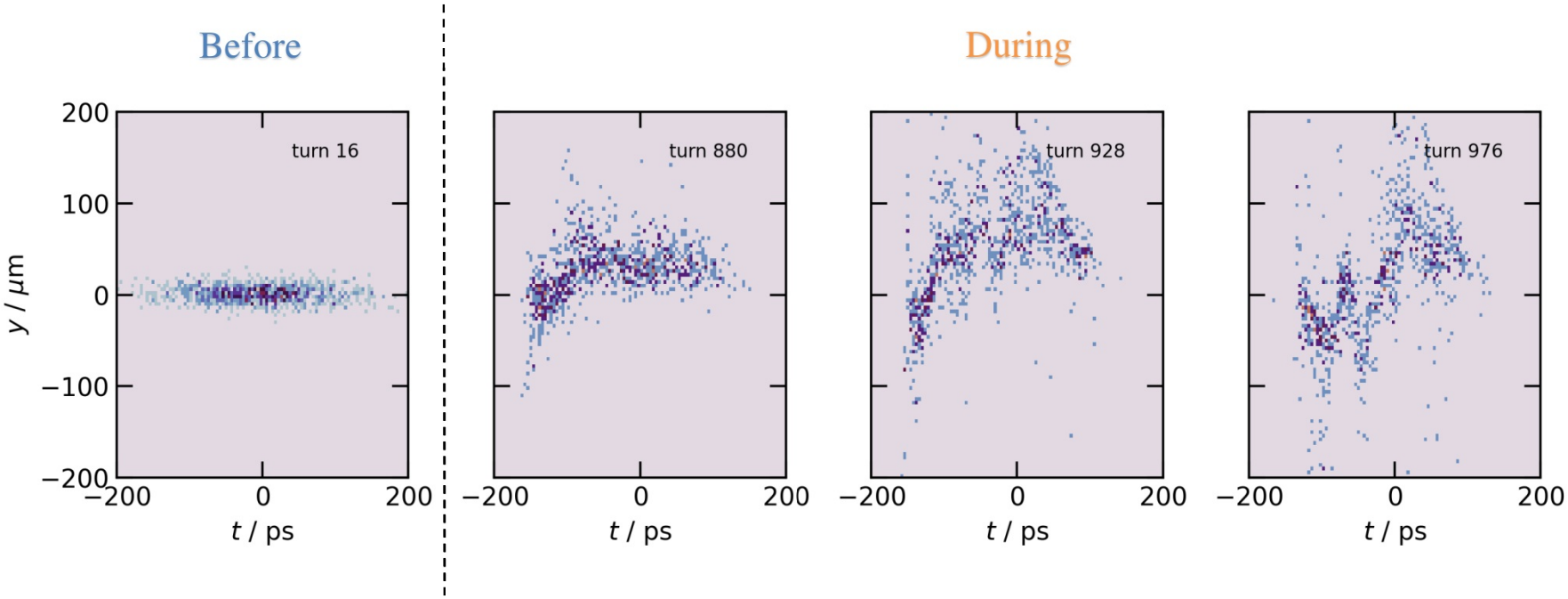


High-charge Timing mode

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

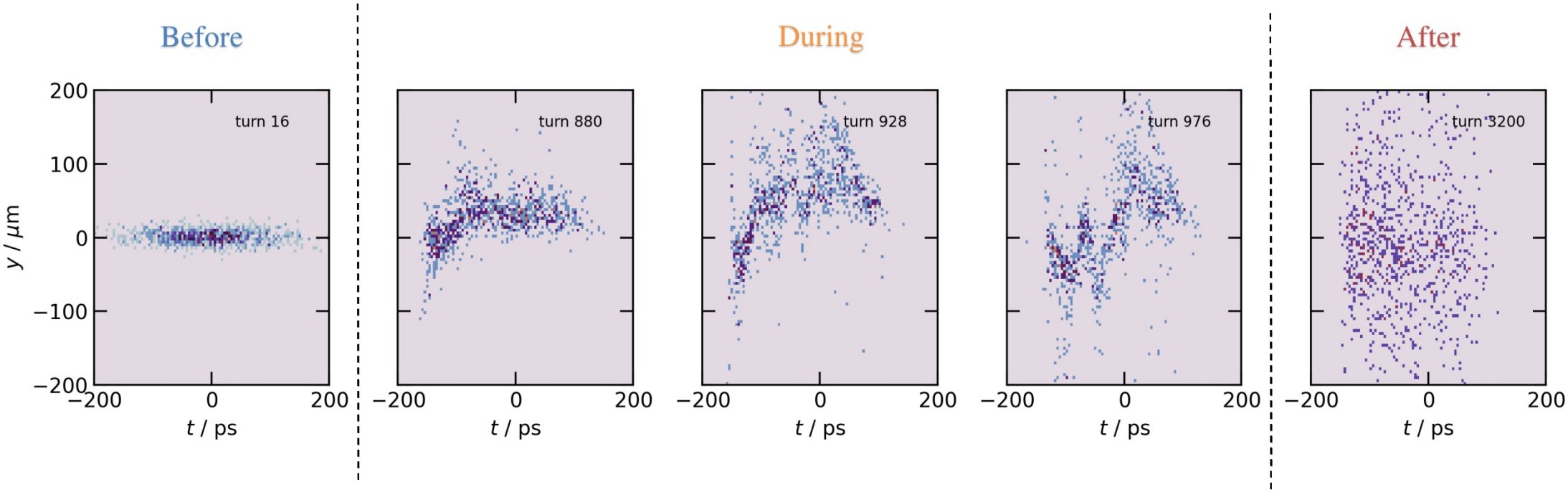
Instability at high intensities

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



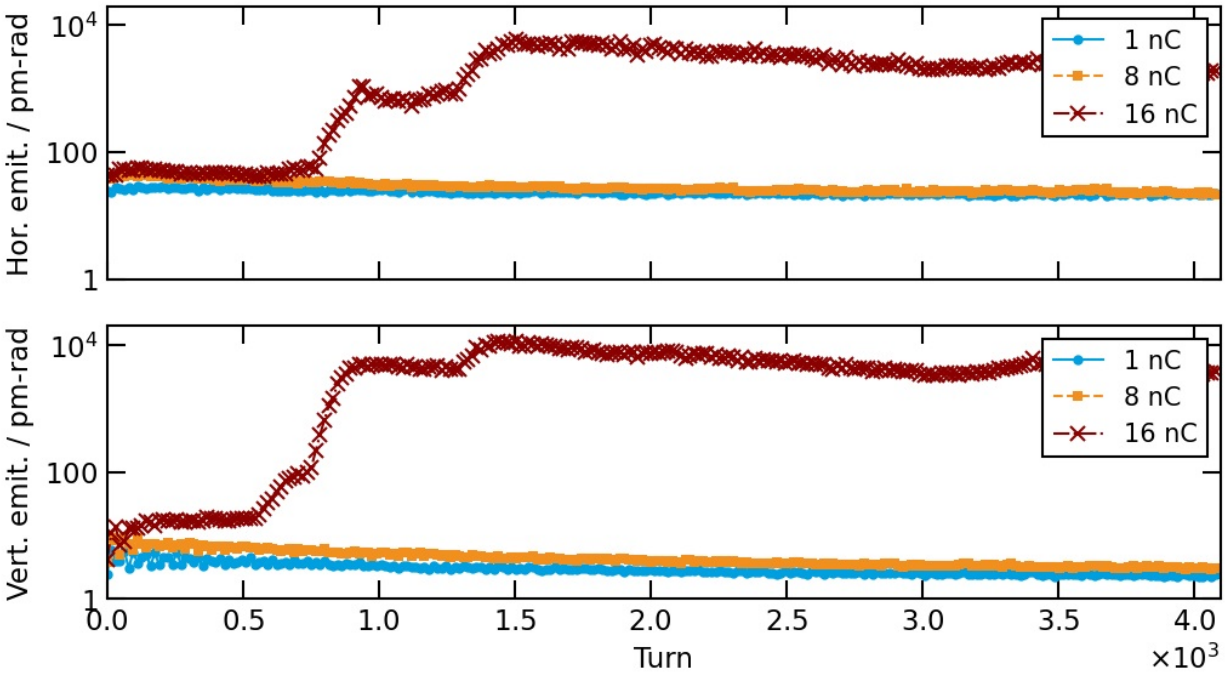
Instability at high intensities

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



Emittance might blow up to nm scale for high charge modes

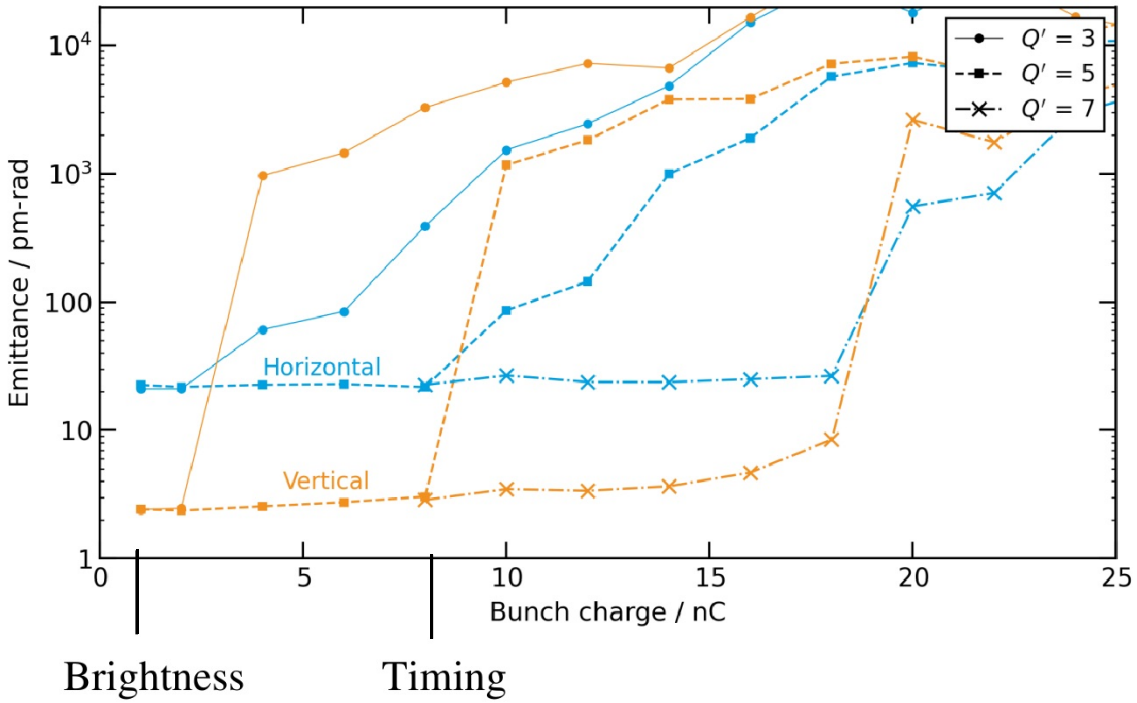
Blow-up happens on time scales of ~1000 turns



- Chromaticity 5
- Multi-bunch FB not included

Emittance might up to nm scale for high charge operation modes

Higher chromaticity helps



Nonlinear amplitude detuning stabilizes

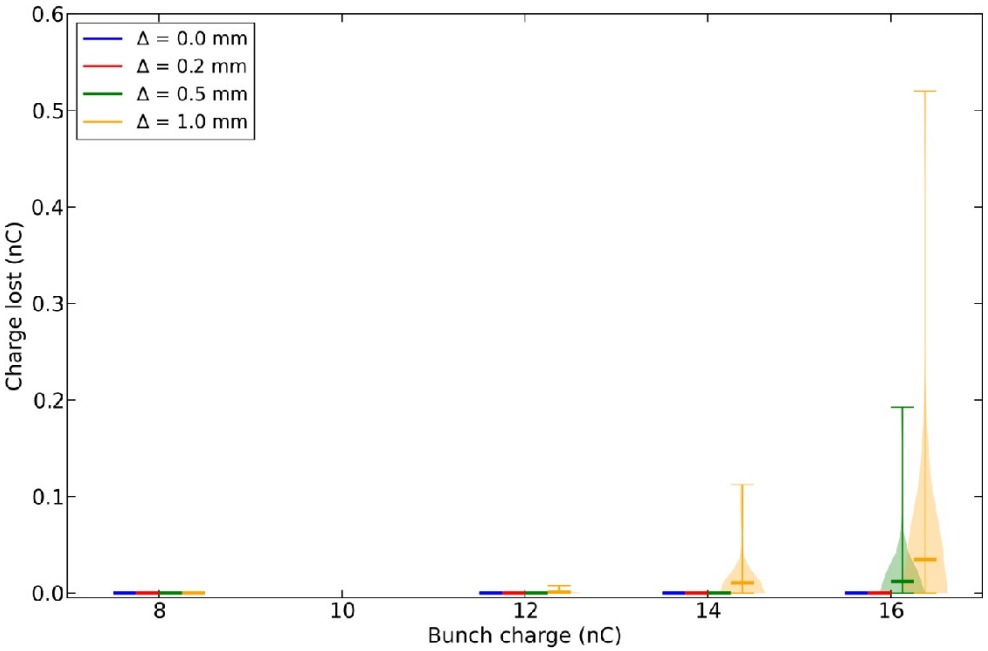
- Detuning with action: dQ/dJ ~ 5×10^5 m
- Landau damping: G ~ 2π dQ ~ 1/300 turn^{-1}

Higher coupling – lower losses

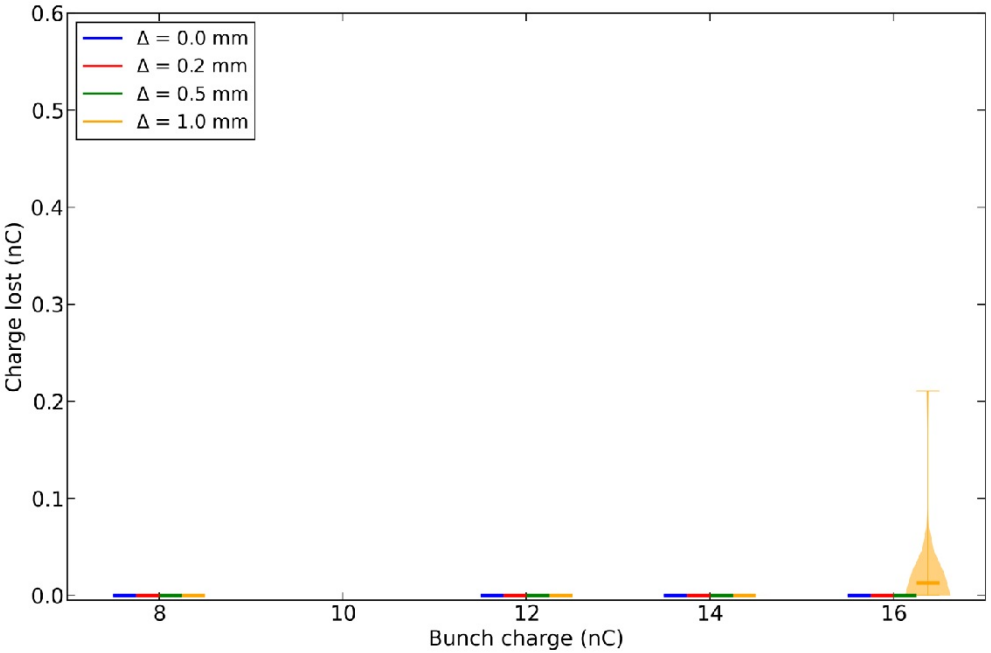
Sharing of impedance between the transverse planes likely helps

→ R.R. Lindberg, IPAC'21

Coupling ~ 0.1, 20 error seeds



Coupling ~ 1, 20 error seeds



Baseline operation modes of PETRA IV are safe

No significant losses even for high degrees of amplitude sharing

High charge Timing modes could be challenging

- Require little to no aperture sharing
- Even if no losses happen, beam emittance may be strongly degraded at high bunch charges

During top-up most beam losses happen in the stored beam

- Can simulate one beam instead of two and capture most of the dynamics

There may be significant differences between error seeds

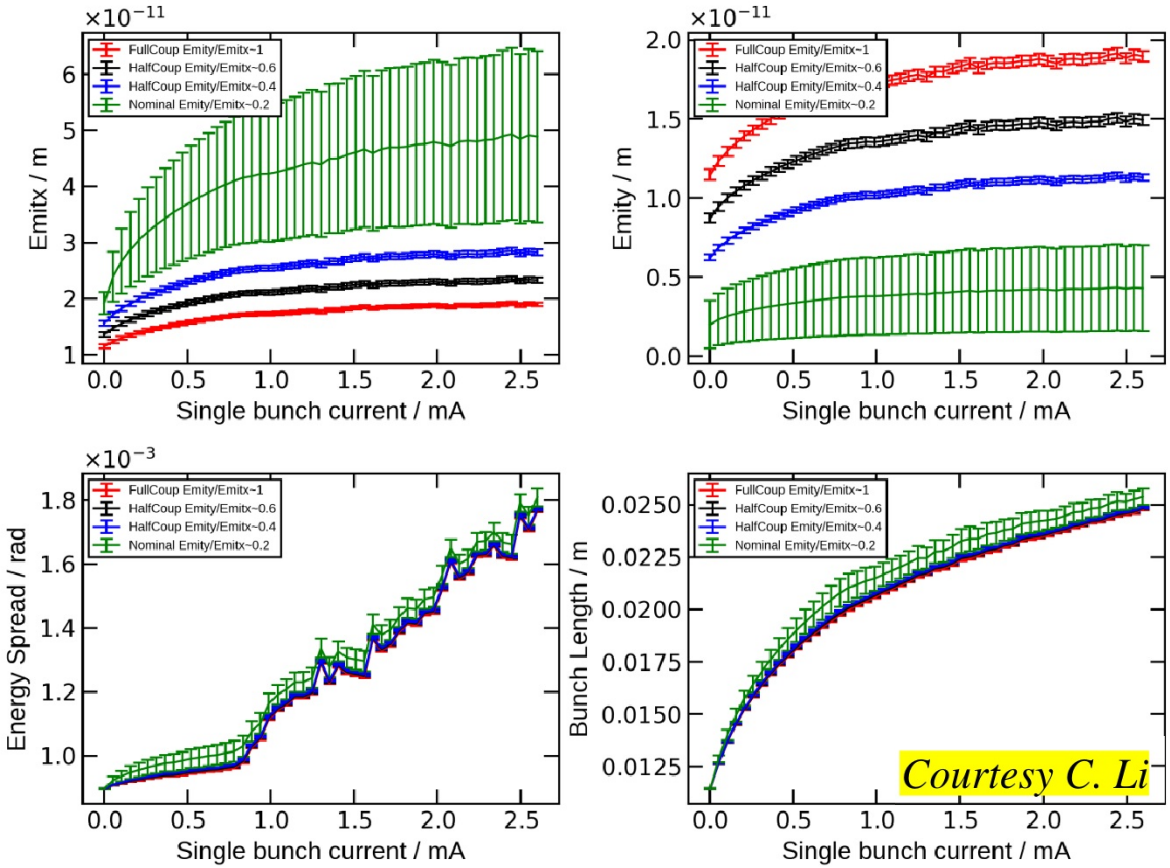
- Need the results of commissioning simualtions to produce a more realistic set of error seeds

High coupling seems beneficial for raising the accumulation limit

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

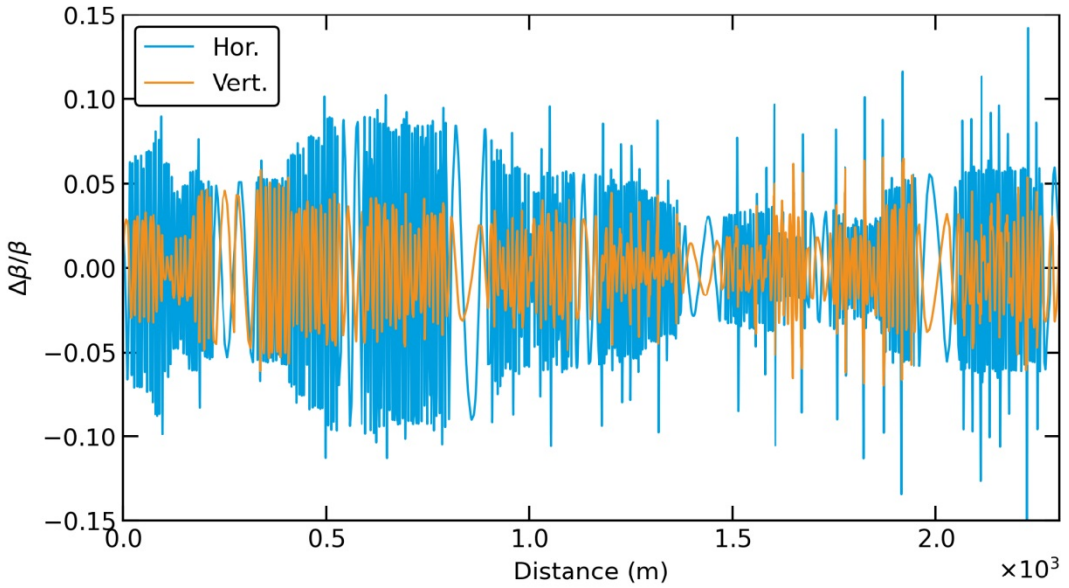
Turn SR off

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

10 iterations of correction

- Orbit
- Tunes
- Chromaticity

rms β-beating 5%

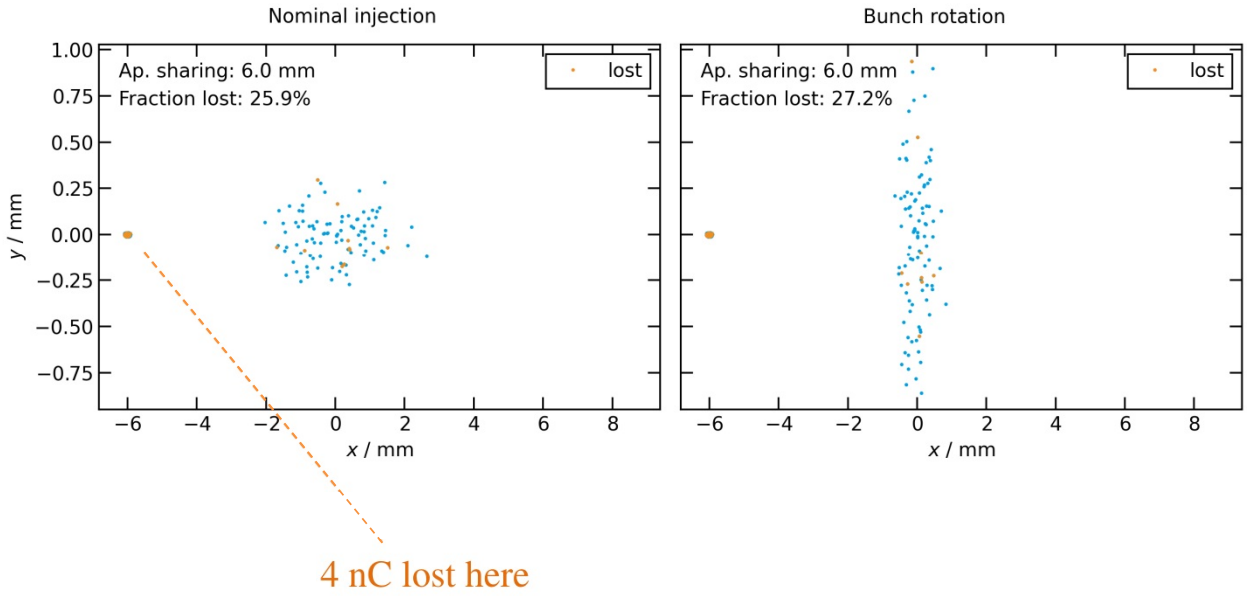


Automated procedure developed C. Cortez

Losses happen mainly in the circulating beam

Can simulate 1 beam instead of 2

→ Y.-C. Chae, IPAC'07



Numerical example:

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

Accumulation limit for the ‘median seed’

Theoretical limit is reached when lost charge = injected charge