FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

FUTURE CIRCULAR COLLIDER

Existing and possible synergies with light sources on performance enabling technologies

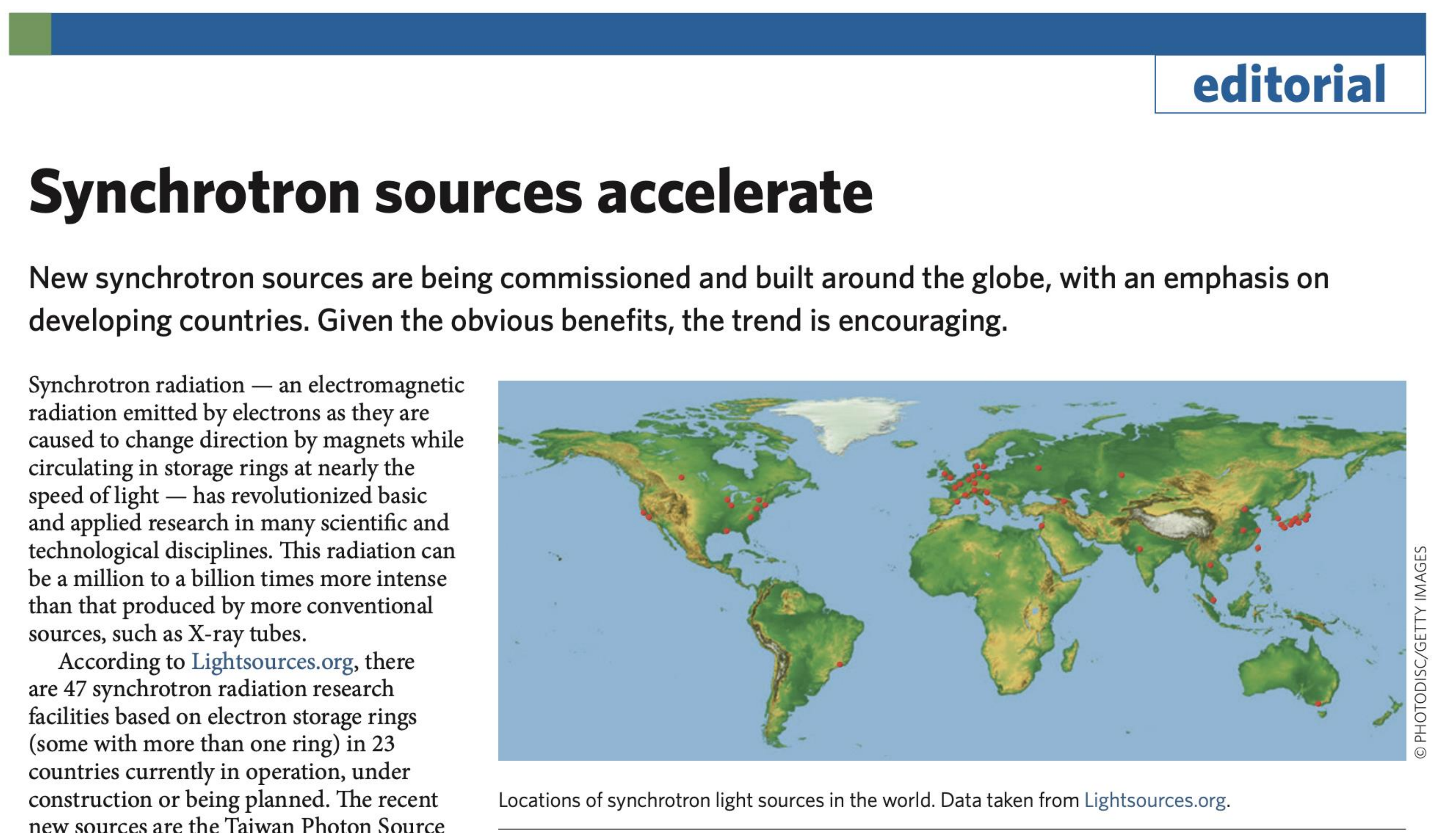
I. Agapov, FCCIS workshop Nov 2023

Content

- Light source/FCC synergies: where we are
- Some techniques and technologies of potential interest being developed at light sources (in random order)
  - Girders
  - Vibrations, beam stability analysis, ground motion
  - Diagnostics
  - pyAT/pySC/tuning studies
  - LPA injector
  - Collimation
  - Bunch manipulation with dielectric structures

Light source synergies

2015 - first 4th generation light source MAX IV


editorial

Synchrotron sources accelerate

New synchrotron sources are being commissioned and built around the globe, with an emphasis on developing countries. Given the obvious benefits, the trend is encouraging.

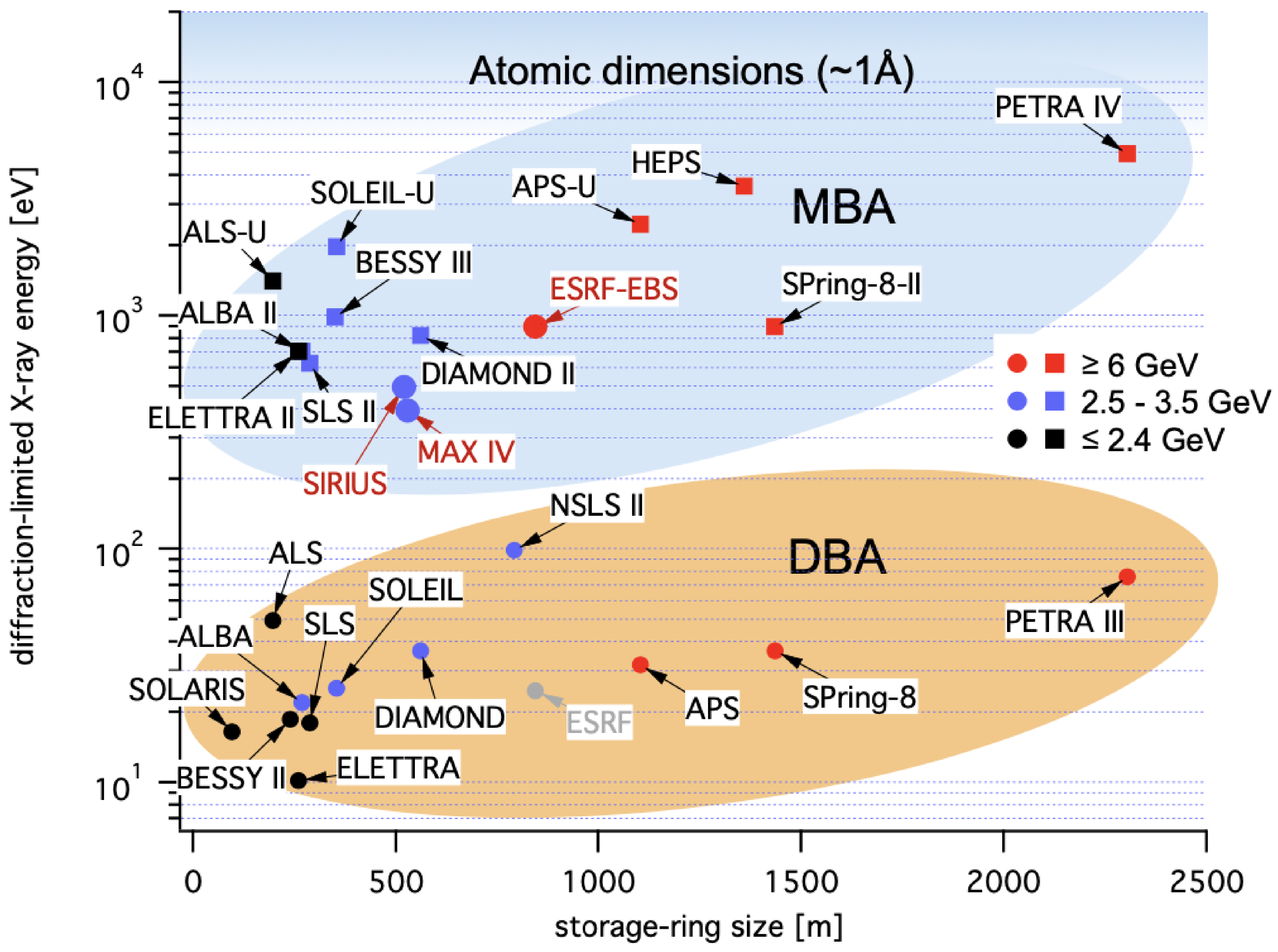
Synchrotron radiation — an electromagnetic radiation emitted by electrons as they are caused to change direction by magnets while circulating in storage rings at nearly the speed of light — has revolutionized basic and applied research in many scientific and technological disciplines. This radiation can be a million to a billion times more intense than that produced by more conventional sources, such as X-ray tubes.

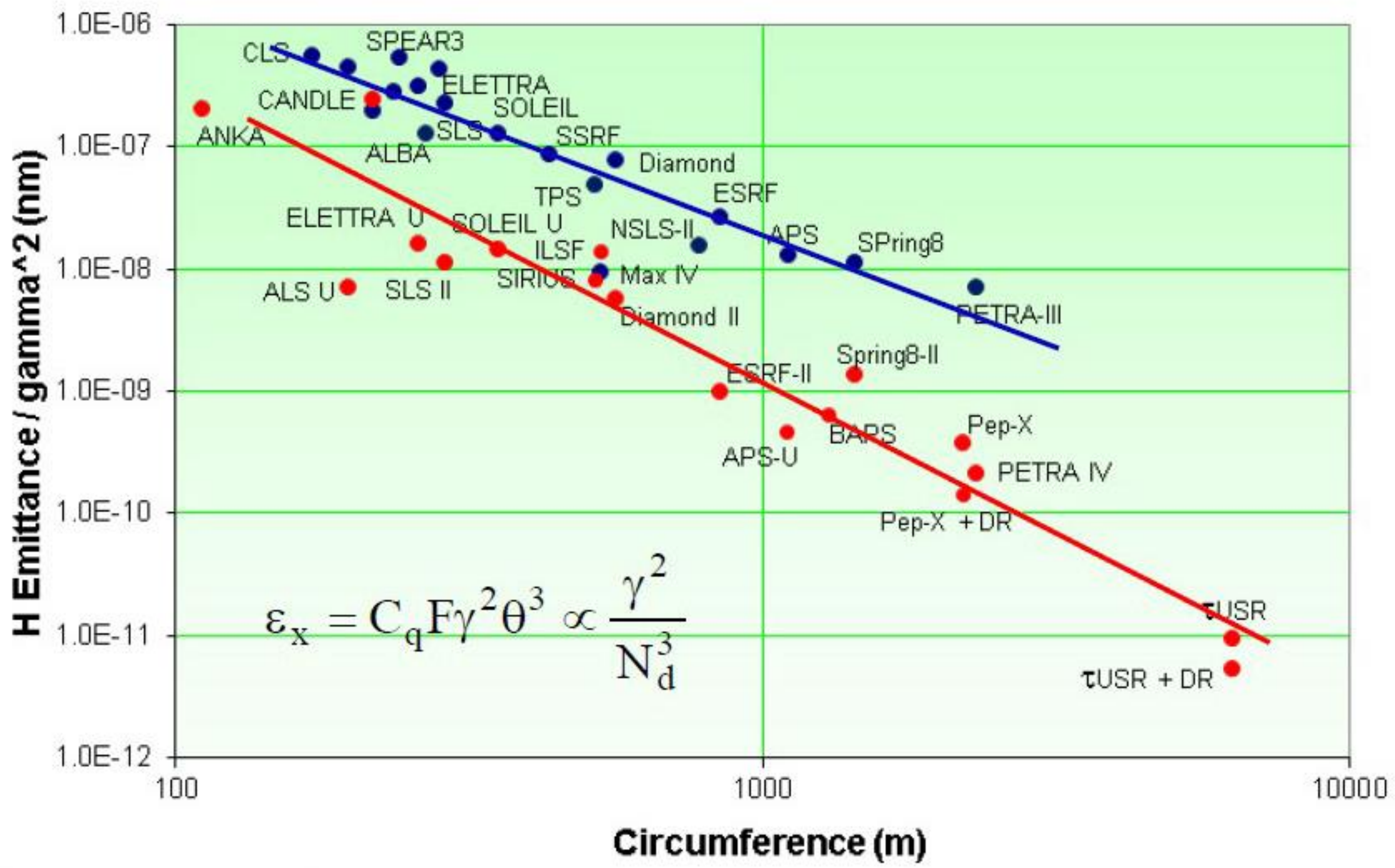
According to Lightsources.org, there are 47 synchrotron radiation research facilities based on electron storage rings (some with more than one ring) in 23 countries currently in operation, under construction or being planned. The recent new sources are the Taiwan Photon Source

Locations of synchrotron light sources in the world. Data taken from Lightsources.org.

© PHOTODISC/GETTY IMAGES

- The last decade saw boom in 4th generation light source development
- Several facilities are already operational, and the majority of the projects are in construction phase or moving there
- Most of the designs are finalized, key technologies in place. By the end of this decade all upgrades are expected to be complete.
- Certain techniques are being more aggressively pursued in newer projects (e.g. permanent magnets, harmonic cavities)





Light source synergies

- Within FCCIS, light source community is strongly involved from the beginning
- Common challenges:
  - Precise diagnostics
  - Optics correction procedures
  - Impedance and collective instabilities
  - Collimation
- Wrt. several techniques, differences are noticeable
  - IR design and alignment
  - Alignment
  - Performance evaluation taking beam-beam interaction/beamstrahlung
- Some prominent developments probably cannot be capitalized on, such as PM technologies
- In general, synergies and technologies should be further exploited
- In the following, I present some techniques/development mostly on the example of PETRA (with some ESRF-EBS input)

DESY.

Campus Bahrenfeld

Accelerator-based photon sources

European XFEL

X-Ray Free-Electron Laser

fs dynamics of complex matter on the atomic scale

PETRA IV: project to upgrade the SR source PETRA III

Parameter	Brightness mode	Timing mode
total current (mA)	200	80
bunch current I_b (mA)	0.125	1.0
arc ID β_x/β_y(m)	3.6/2.2	3.6/2.2
flagship ID β_x/β_y(m)	4.0/4.0	4.0/4.0
hor. emittance ϵ_x (pm rad)	14.2	22.9
vert. emittance ϵ_y (pm rad)	2.84	4.60
bunch length σ_z (mm)	13.58	19.96
bunch length σ_t (ps)	45.7	64.3
energy spread σ_p (10^{-3})	0.988	1.436
Touschek lifetime τ (h)	8.5	2.1

PETRA III
Ada Yonath Hall

CHyN

HARBOR

MPI-SD

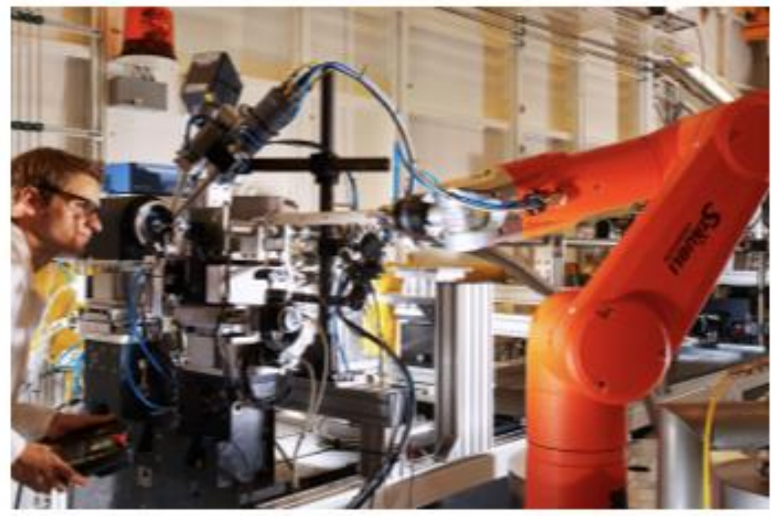
Cooperation partners

UHH · MPG · EMBL · HZG

CSSB partner institutes

Sweden · India · CENSORED

PETRA III
Paul Peter Ewald Hall

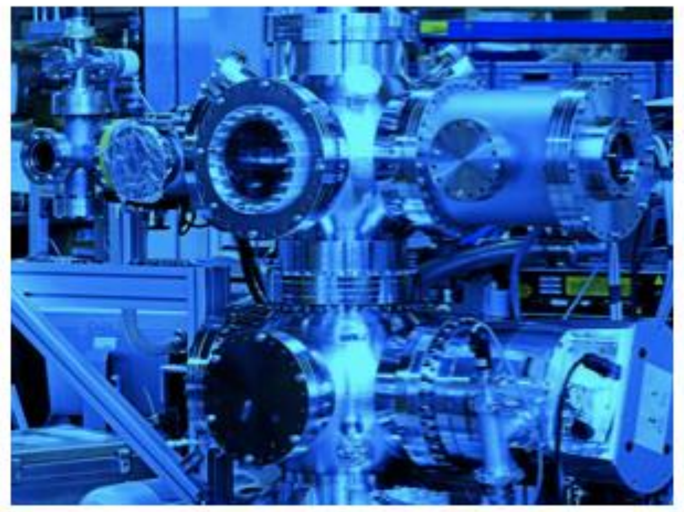


PETRA III

Synchrotron Radiation of Highest Brightness

atomic structure of complex matter

CFEL SCIENCE



FLASH

VUV & Soft X-ray Free-Electron Laser

fs dynamics of complex matter (spectroscopy)

Girders

N. Koldrack

- ‘Bionic girder’ designed and produced as an R&D project
- Work on topology-optimized girder including installation constraints, movers, etc. has been completed
- First eigenmode at 42 Hz
- Demonstrator girder ordered Sept 2023

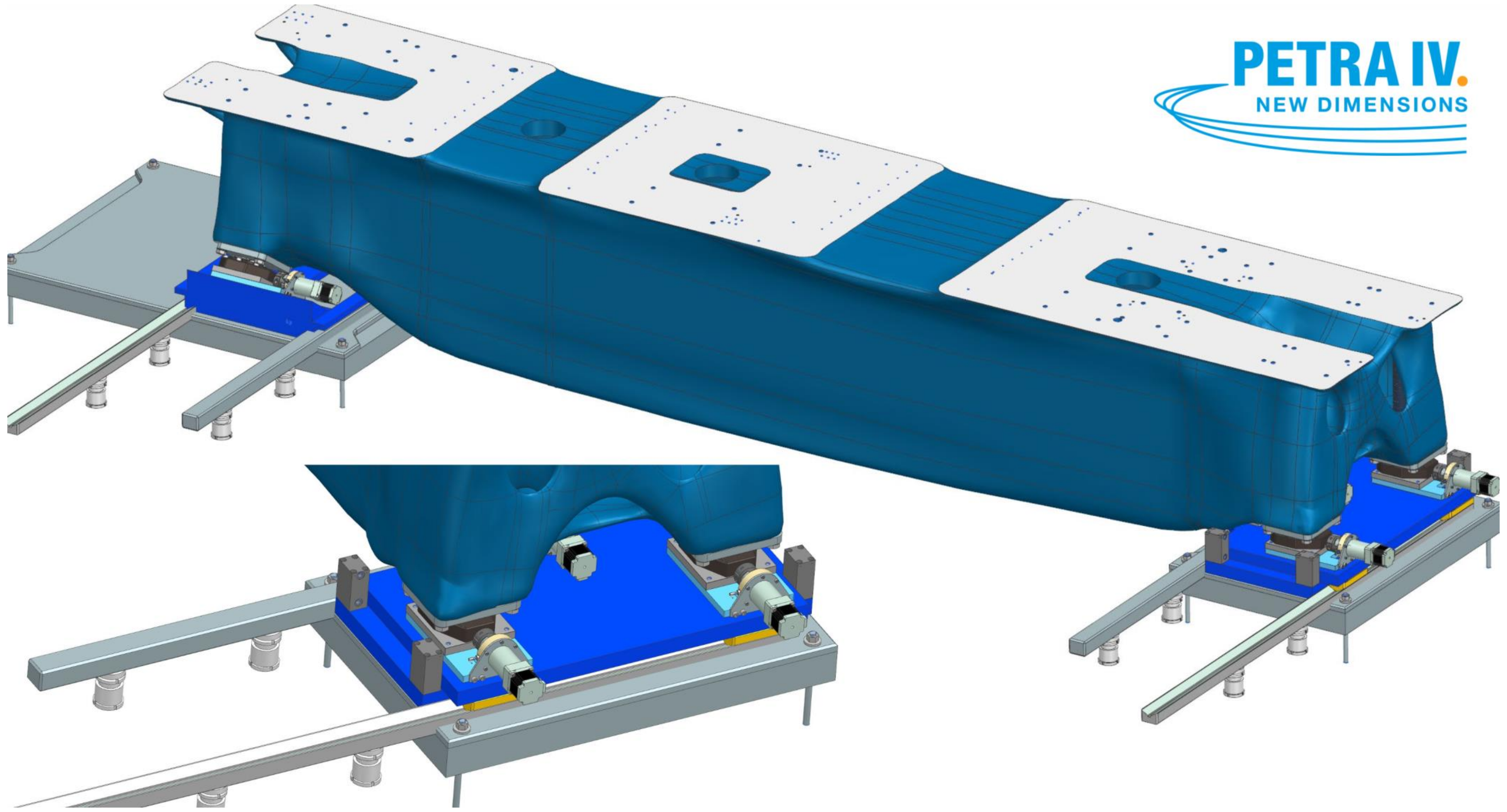
Journal of Bionic Engineering (2023) 20:1996–2017
https://doi.org/10.1007/s42235-023-00373-7
RESEARCH ARTICLE

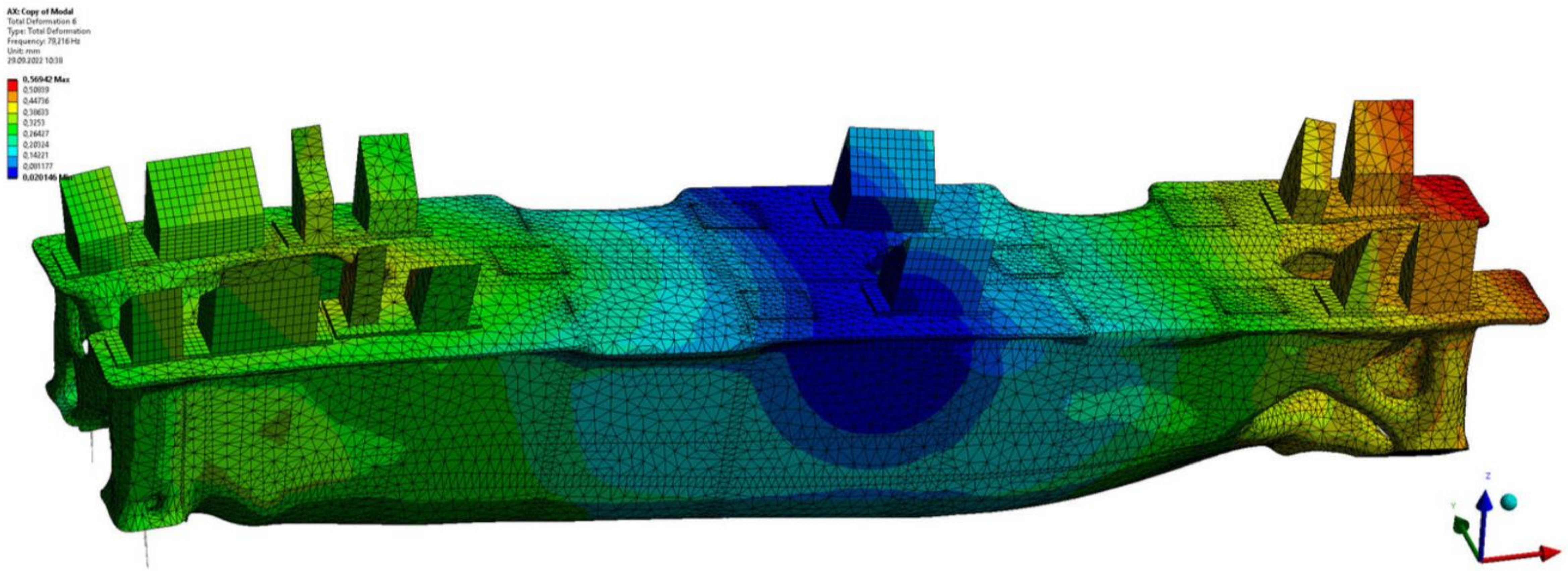
Biologically Inspired Girder Structure for the Synchrotron Radiation Facility PETRA IV

Simone Andresen[1] · Norbert Meyners[2] · Daniel Thoden[2] · Markus Körfer[2] · Christian Hamm[1]

R&D bionic

PETRA IV production





Vibrations: impact of construction site

M. Schaumann

Roller Mode at 32 Hz clearly visible

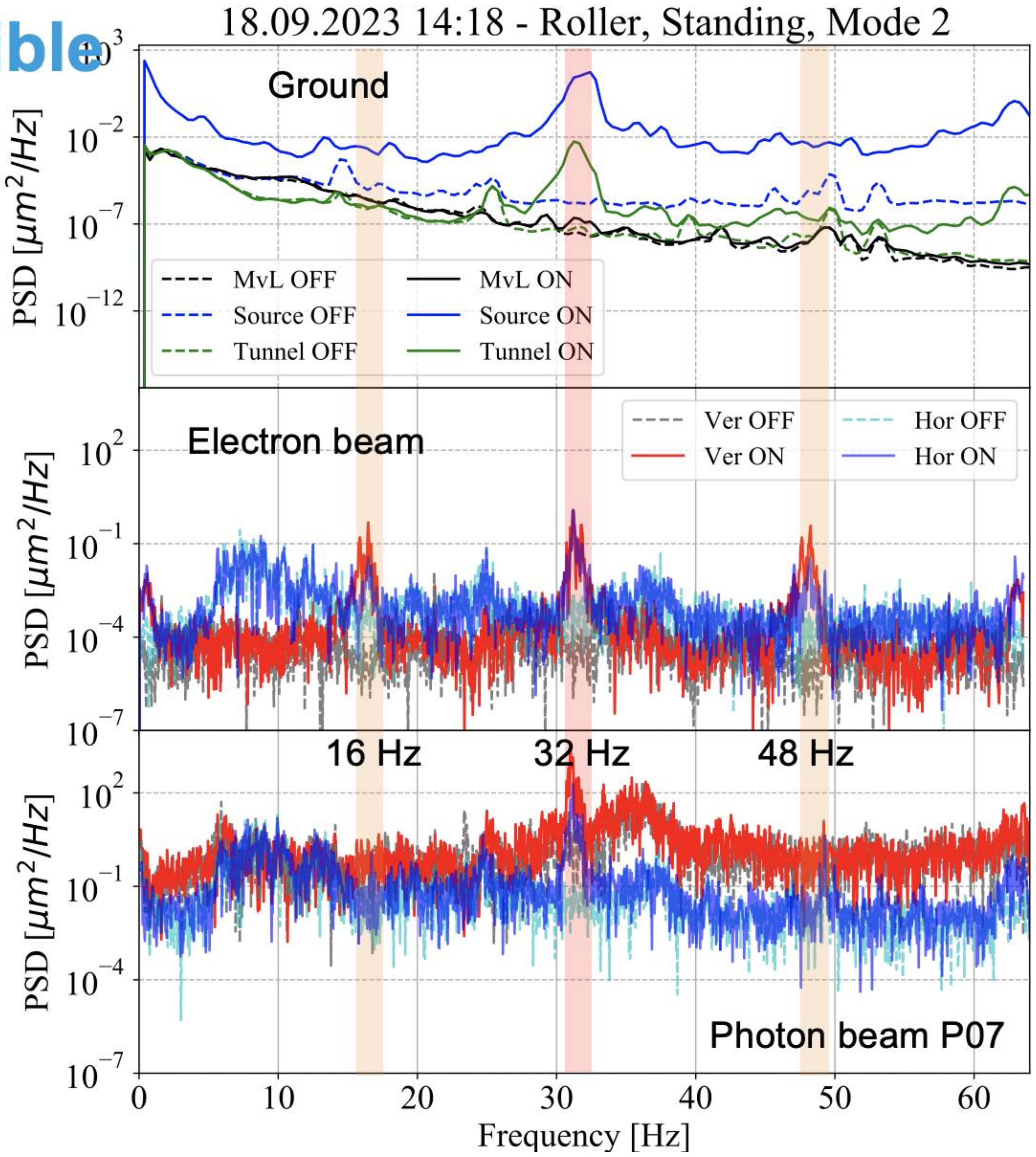
Strong 16 Hz sidebands in vertical plane

<u>Example Event</u>
Vibrating Roller: Standing Mode 2
Location: WEST Right

Main frequency induced by the **roller is ~32 Hz**, clearly visible ground, electron and photon beam spectra

Localized excitation: Ground vibration in Max von Laue hall is negligible

Vibrating Roller: Standing Mode 2
Location: WEST Right



Reducing corrector strength with girders (PETRAIV sim.)

Sajjad Hussain Mirza

Tikhonov regularization for Girder ORM inverse

Random Girder misalignments of start and end points = $\sigma = 150\ \mu m$ cut at 2σ

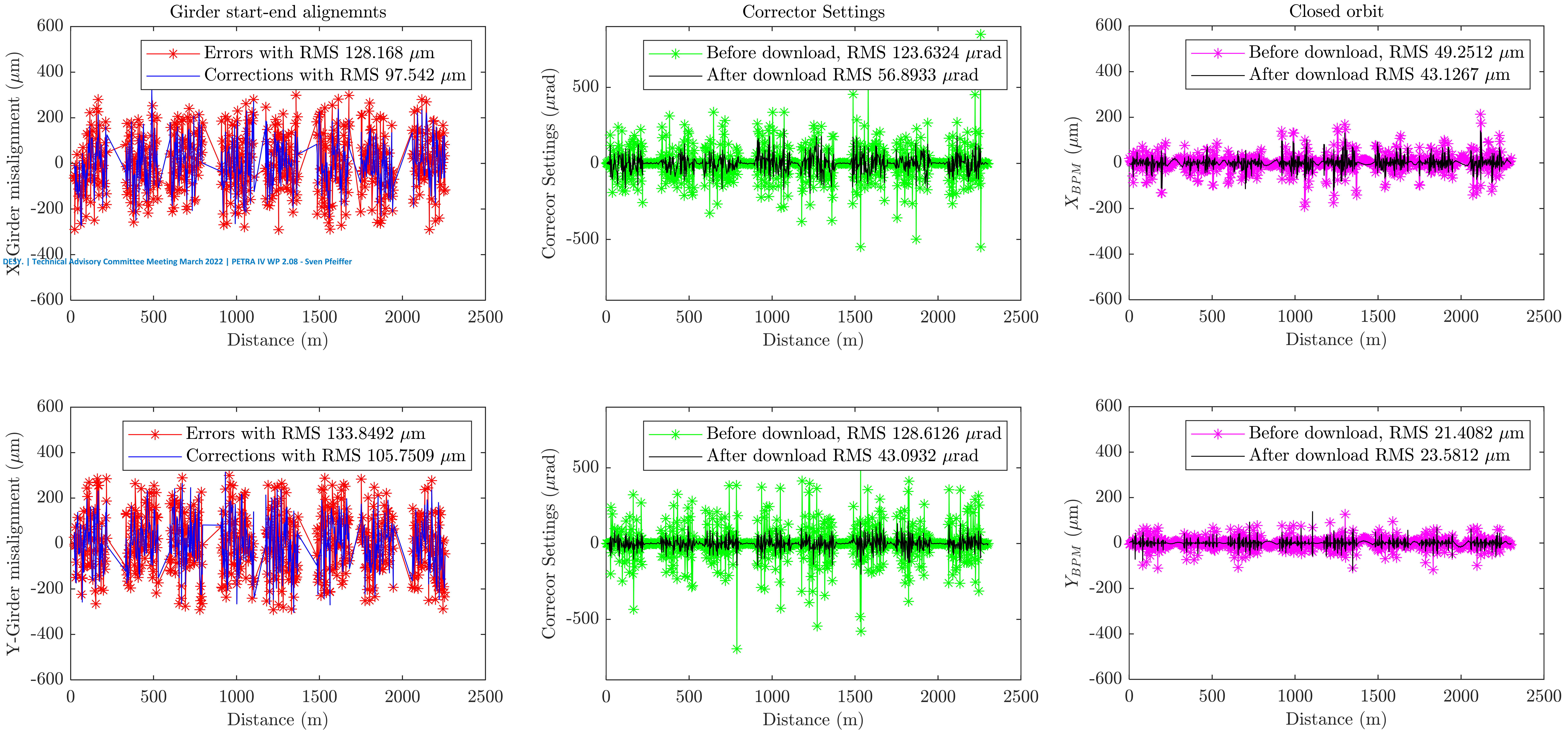
Random BPM offset= $\sigma = 20\ \mu m$

Random Magnet misalignments = $\sigma = 30 \mu m$ cut at 2σ

Corrector calibration errors = 0.02%

BPM calibration errors = 0.02%

$\mu_x = 1, \mu_y = 1$



Sajjad Hussain Mirza

Random Girder misalignments of start and end points = $\sigma = 150\ \mu m$ cut at 2σ

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Tikhonov regularization for Girder ORM inverse

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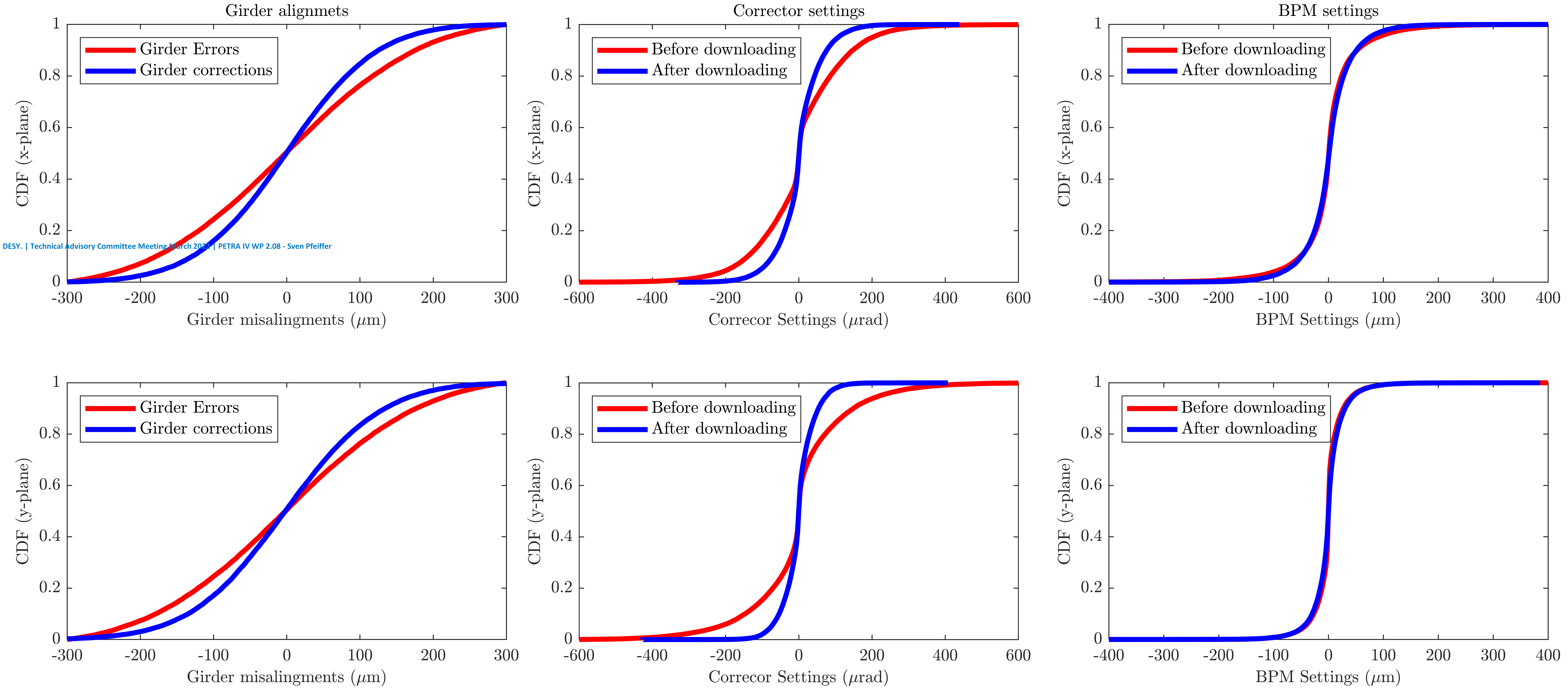
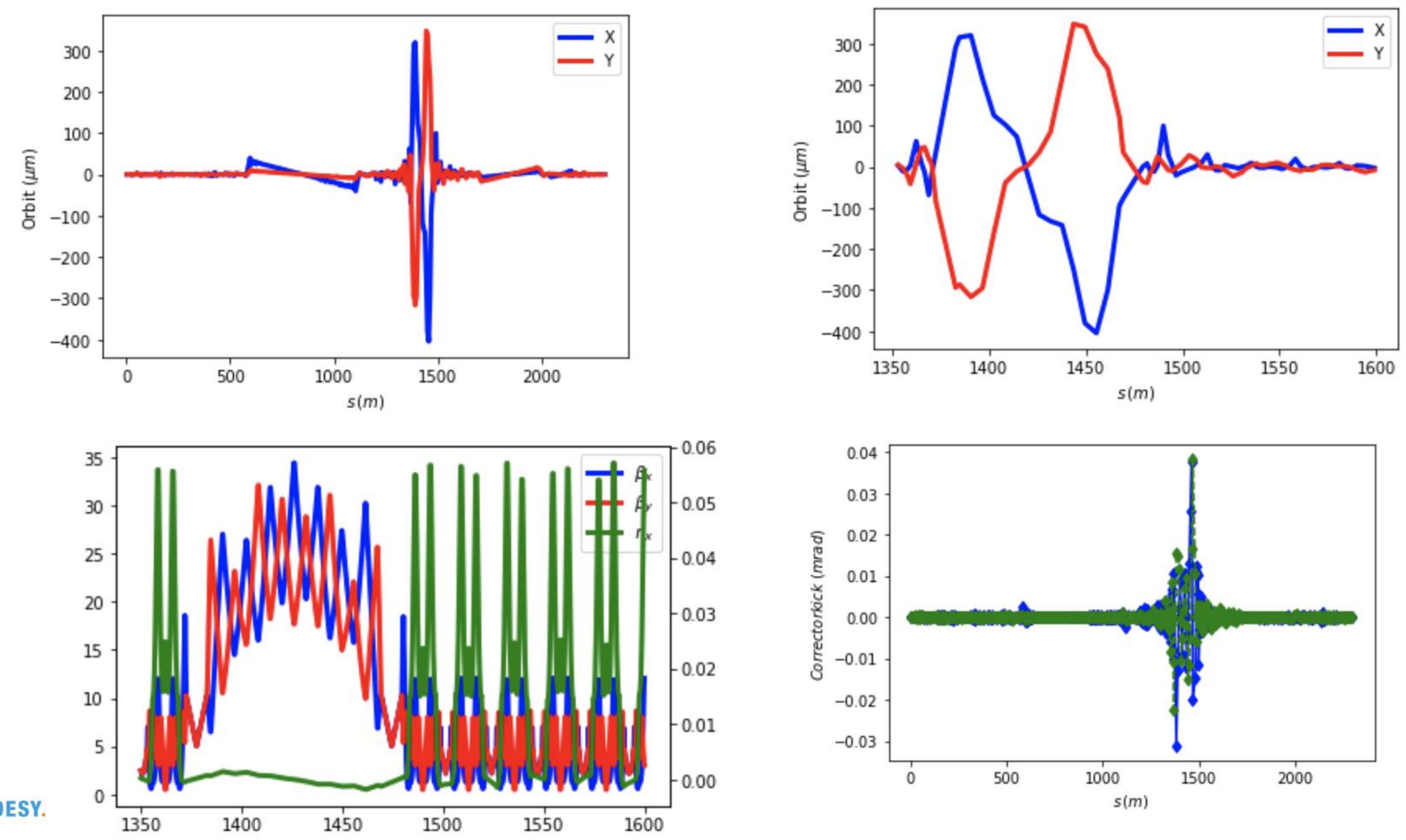
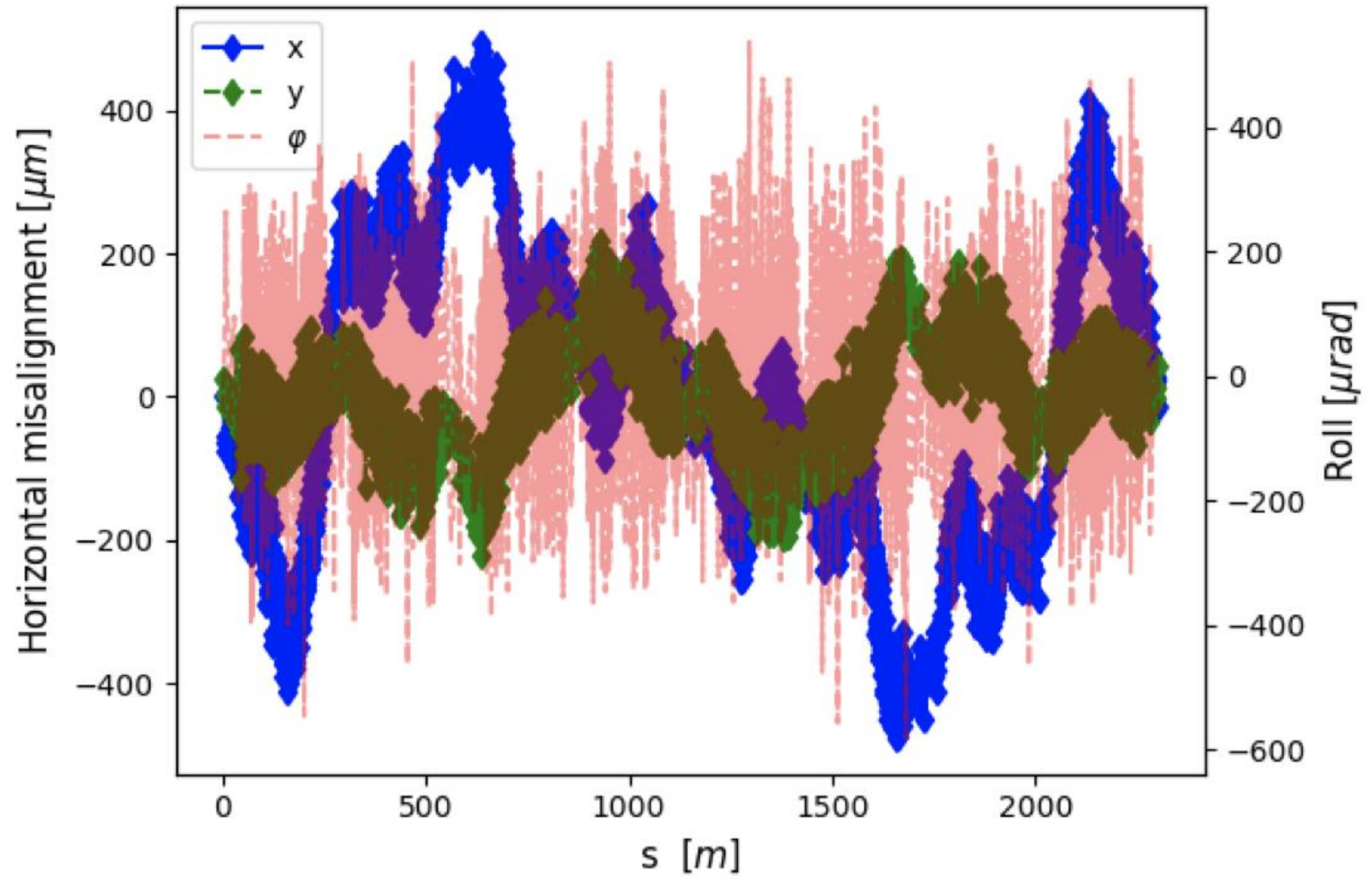


Ground motion model for PETRA IV

- Beam dynamics model can include alignment model based on:
  - Coordinates of floor segments and expected floor motion (partially based on measurements)
  - Model of long-range ground motion
  - Random magnet and girder offsets
- For PETRA IV, magnet-to-magnet offsets and extreme floor motion define stability





$$\Delta_{X,Y} = \xi_{X,Y}(s) + \zeta_{X,Y}(s) + \sum_{k=1}^{N_h} \frac{A_{X,Y,k}}{k^{\alpha}} \sin\left(\frac{2\pi k s}{L}\right)$$

Diagnostics

G. Kube

Beam Position Monitor (BPM) System for PETRA IV

Readout Electronics

PETRA IV. NEW DIMENSIONS

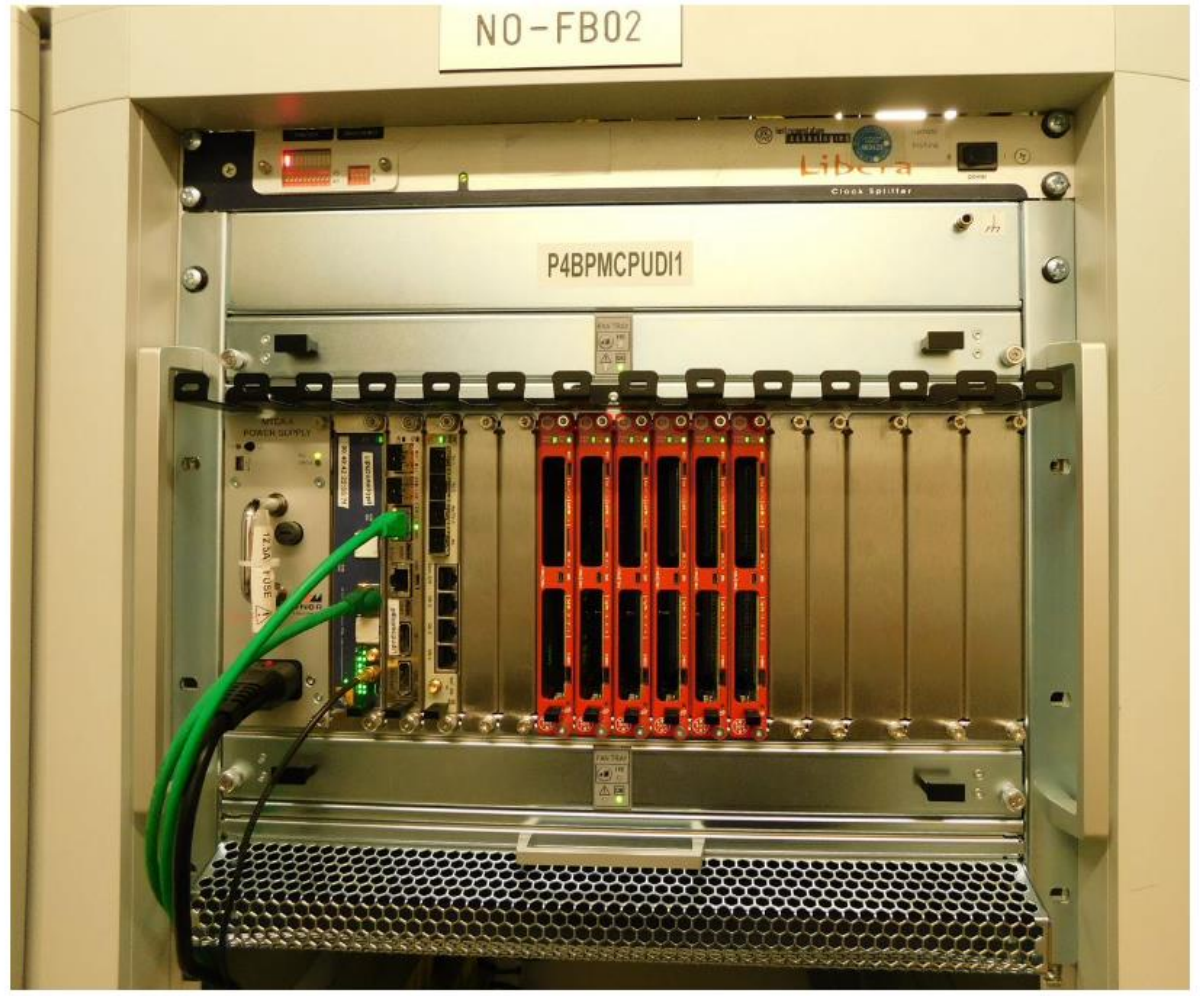
DESY Strategy

INSTRUMENTATION TECHNOLOGIES

- prototype development of MTCA.4 based BPM system with industrial partner
- long term stabilization scheme including cable paths (external crossbar switching concept)

Status

- prototype MTCA-based system installed at PETRA III
  - possibility to operate 12 BPMs
    → in parallel with existing Libera Brilliance system
  - so far 8 BPMs connected
- systematic studies since spring 2023
  - supported by bachelor student
- encountered problems with beam stability (see next slide)
  - since 09/2023: studies with only 1 BPM



Diagnostics: focus on BPM resolution

G. Kube

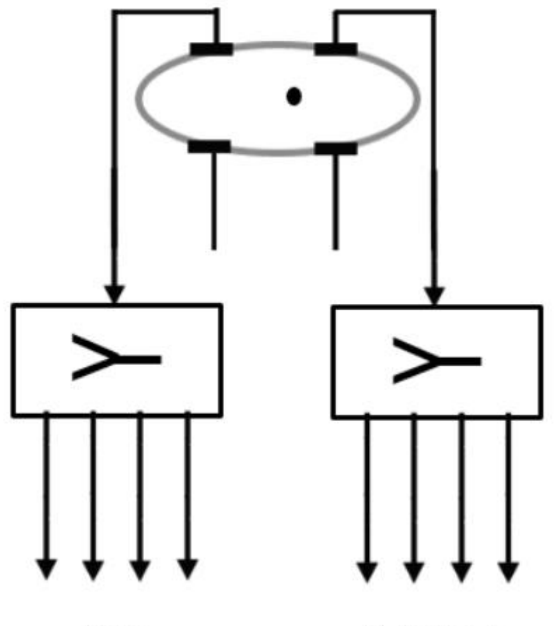
BPM Studies at PETRA III

Remedies

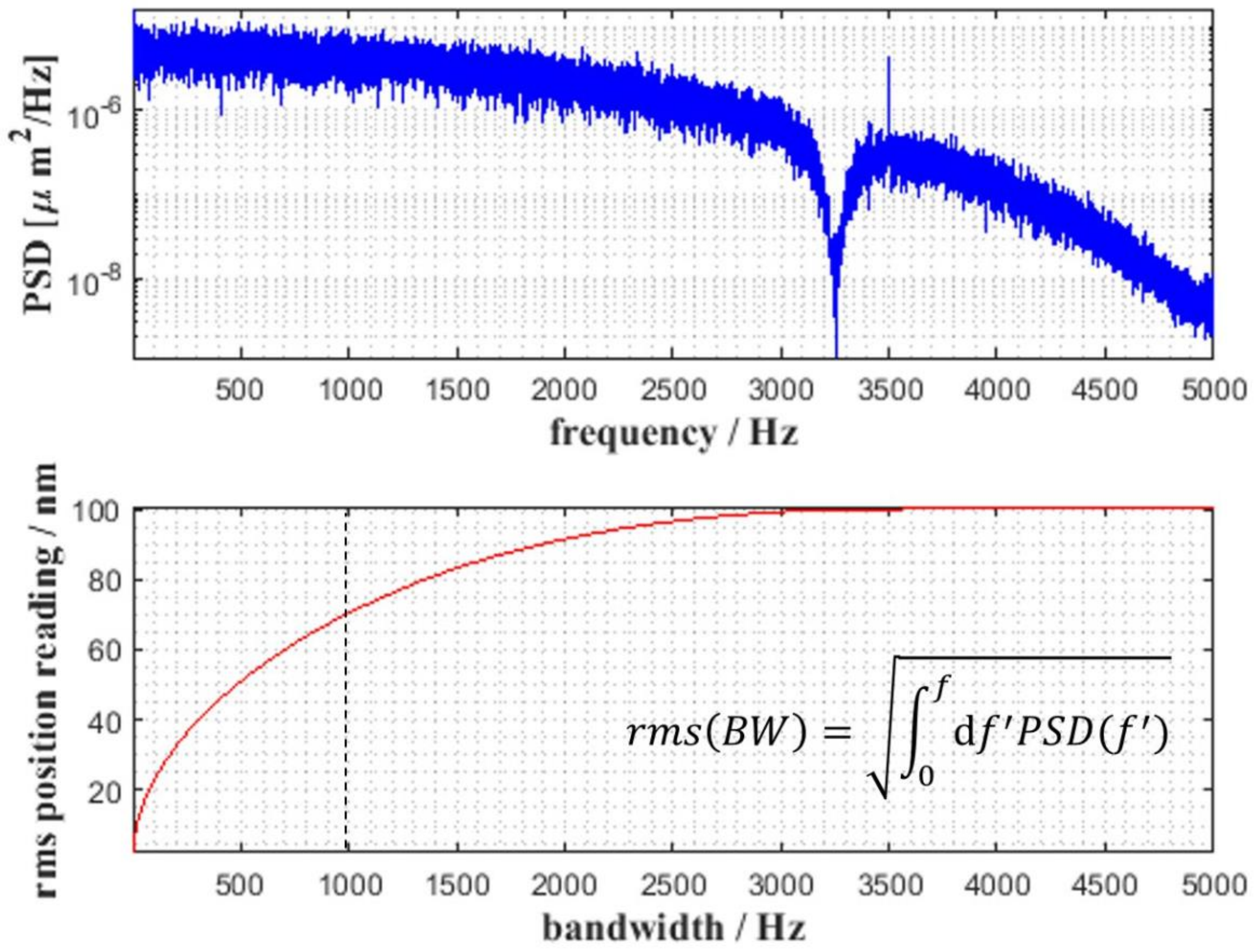
PETRA IV. NEW DIMENSIONS

Influence of Beam Motion

- much stronger than expected
  - mimicking / hiding electronics noise
    → has to be eliminated
- install 4-way splitter in signal path (09/2023)
  → all spurious lines eliminated
  - disadvantage: no orbit information from BPM
    → studies restricted to single BPM



FA data path, BPM in DBA cell



K_x = 10 mm

rms Resolution

- specification: < 100 nm @ 1 kHz BW
- measurement: **70 nm** @ K = 10 mm
  → PETRA IV: K < 10 mm

Comparison with Libera Brilliance

- TbT data path (f_0 = 130.1 kHz), rms for full BW

120 mA

- Libera Brilliance: rms ≈ 1 μm
- MTCA system: rms ≈ 300 nm

⇨ significant improvement

pyAT/pySC

L. Malina

Python library for commissioning being developed

Bottom-up approach to decrease the failure rate

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 100702 (2019)

Toolkit for simulated commissioning of storage-ring light sources and application to the advanced light source upgrade accumulator

Thorsten Hellert, Philipp Amstutz, Christoph Steier, and Marco Venturini
Lawrence Berkeley National Laboratory, Berkeley 94720, California, USA

(Received 23 July 2019; published 10 October 2019)

PYTHON LIBRARY FOR SIMULATED COMMISSIONING OF STORAGE-RING ACCELERATORS*

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N. Carmignani, L. Carver, L. Hoummi , S.M. Liuzzo, T. Perron and S. White,
ESRF, Grenoble, France
T. Hellert, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

ICALEPCS 2023

Collaboration with ESRF (EURIZON project)

- Switched to **Python** and **pyAT** for beam dynamics
  - Python-based solutions gain momentum and user base
  - Translated the main library (SC) with the help of AI
  - Improved the code maintainability and test coverage

Introducing new methods

- Implementing robust methods for the previously skipped steps in the commissioning chain
  - Trajectory BBA, RF-setup
- Introducing new error sources

Bottom-up approach

- Focus (temporarily) on single cases and fixing them
- Advancing incrementally from the (commissioning) start to its end

- PETRA IV performance previously evaluated based on the MATLAB toolkit version, python version is now in place and being used

pyAT/pySC

L. Malina, T. Hellert

- First turn steering — Done
- Trajectory BBA — Done & New
- Multipole ramp-up — Done
- RF setup — Done & New
- Tune scan — Done
- Orbit BBA
- Orbit correction — Done
- Tune correction
- Optics correction (LOCO and TBT)

In progress

Commissioning simulations: Expanded error sources (rms)

Missing multipole and injection errors

BPM Errors:

- BPM offsets = 500 µm
- BPM noise (TBT) = 50 µm
- BPM noise (CO) = 0.1 µm
- BPM roll = 400 µrad
- BPM calibration = 5%

Magnet Errors:

- Magnet offsets = 30 µm
- Magnet roll = 200 µrad
- Magnet calibration = 0.1%
- Quadrupole calibration = 0.05%

Corrector Errors:

- Corrector roll = 200 µrad
- Corrector calibration = 2%

Girder Errors:

- Girder offsets = 150 µm
- Girder roll = 200 µrad

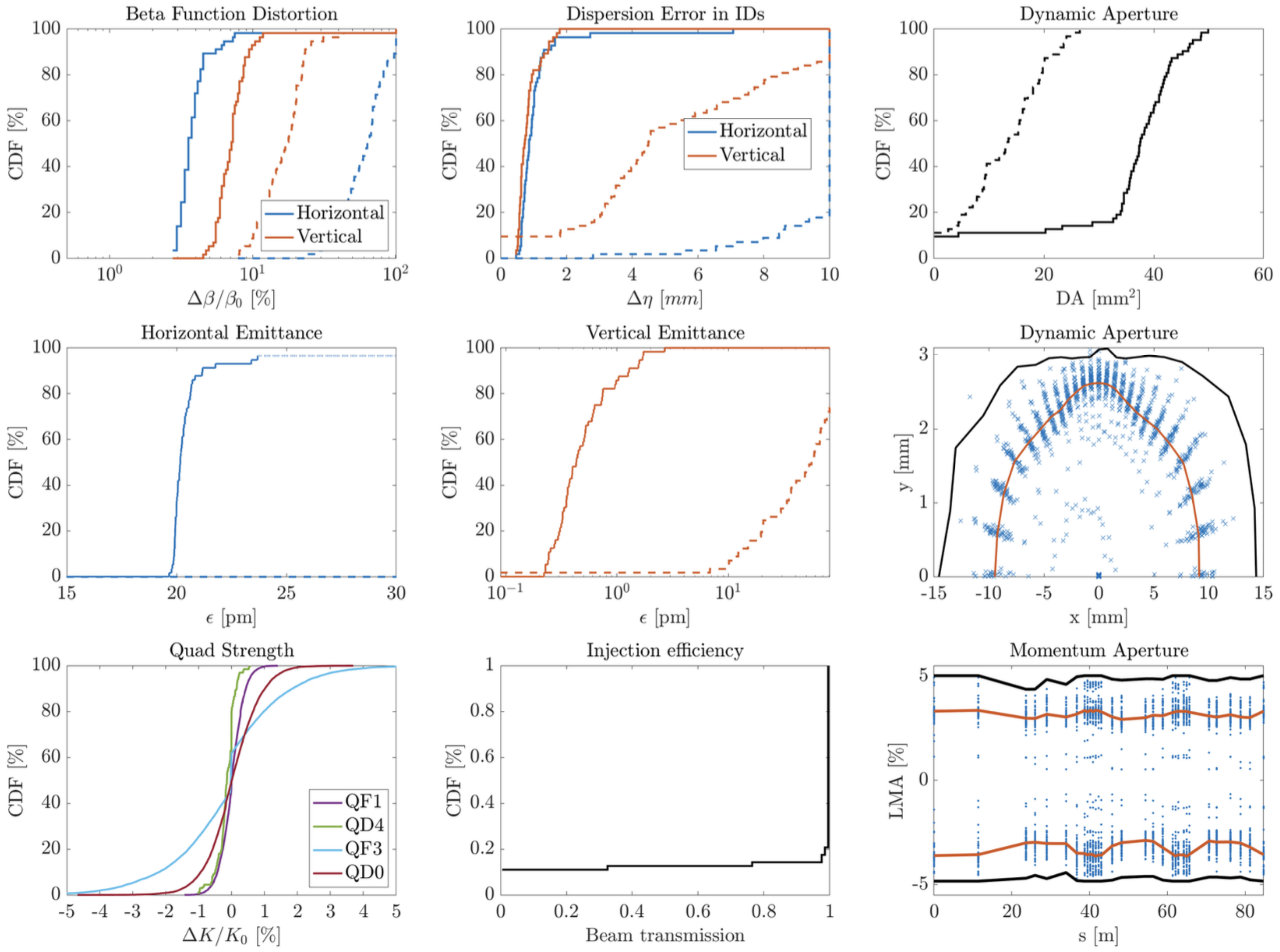
RF errors: New

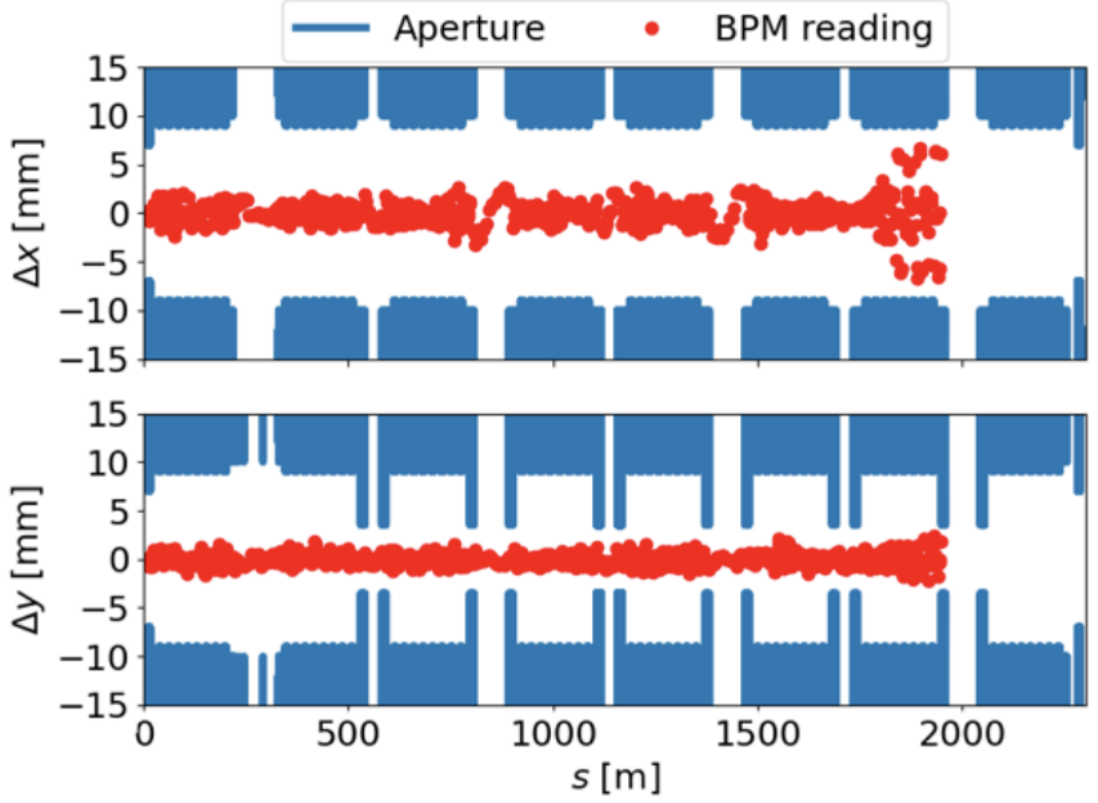
- RF phase is random
- RF frequency = 100 Hz
- RF Voltage = 1 kV
- Relative ring circumference = 10^{-6}

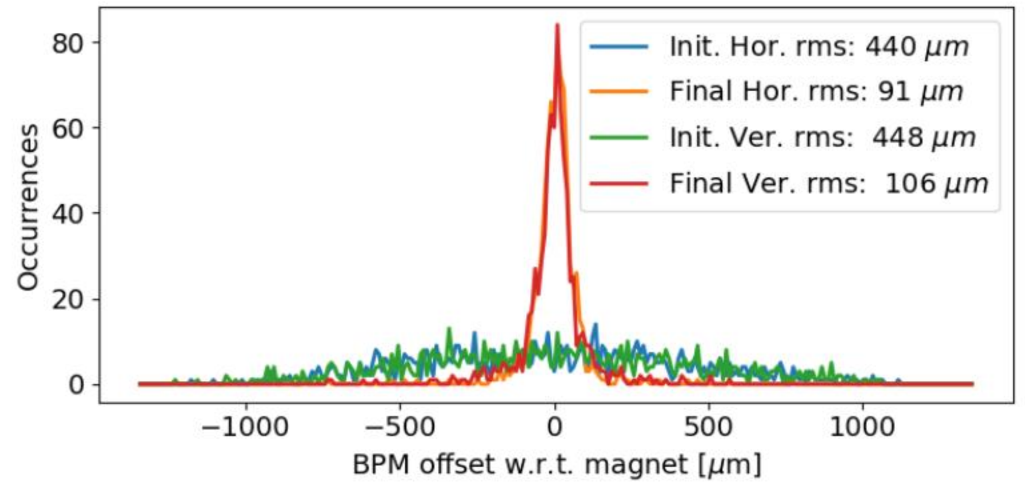
pyAT/pySC

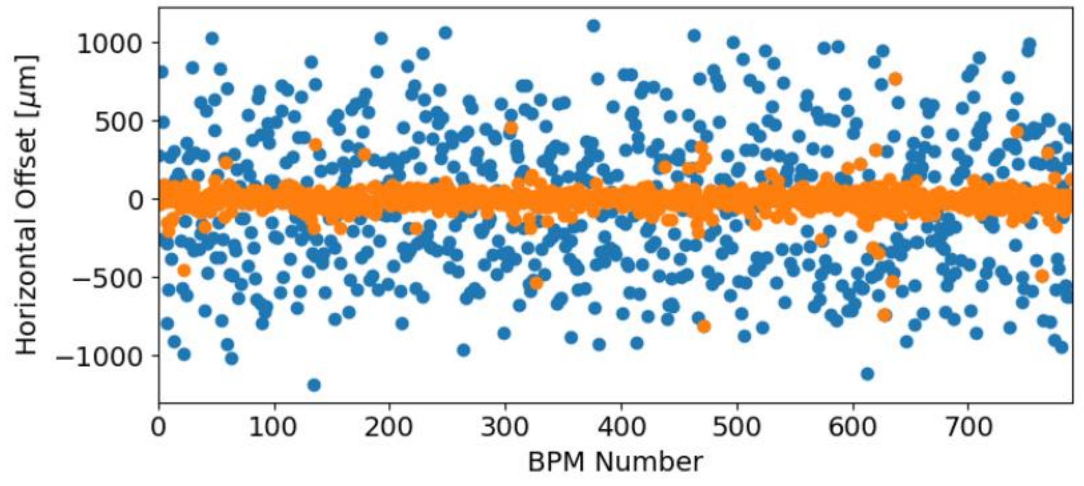
L. Malina, T. Hellert

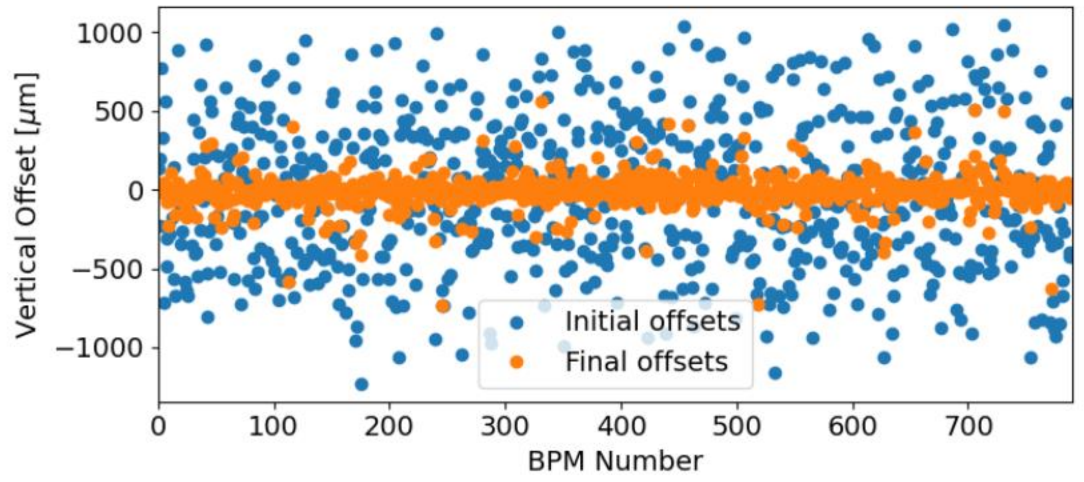
- Mostly works, several aspects are work in progress
- Trajectory BBA procedure is a potential cause of failures in approx. 2% of error seeds.
- For various performance evaluation tasks, we still use a reduced *elegant* model. Conversion should be implemented
- Not all multipole errors are in place (some effects are complicated, such as modelling multi-function magnets with corrector coils)
- Lots of work ahead on common hardware binding (“middle layer”)





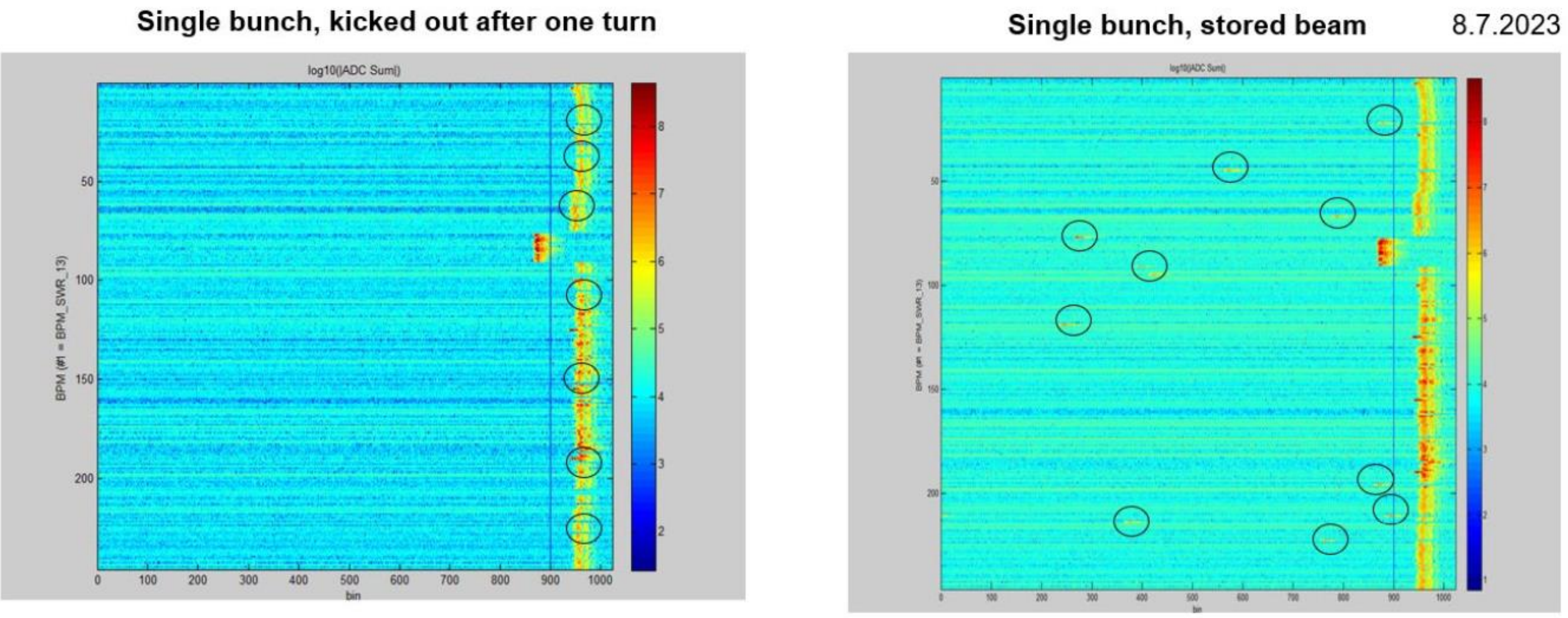






pyAT/pySC beam tests ongoing

- Automatic first-turn steering tested (MATLAB code)
- Problem of not synchronised ADC data
- A couple of injections needed to get first-turn trajectories at all BPMs

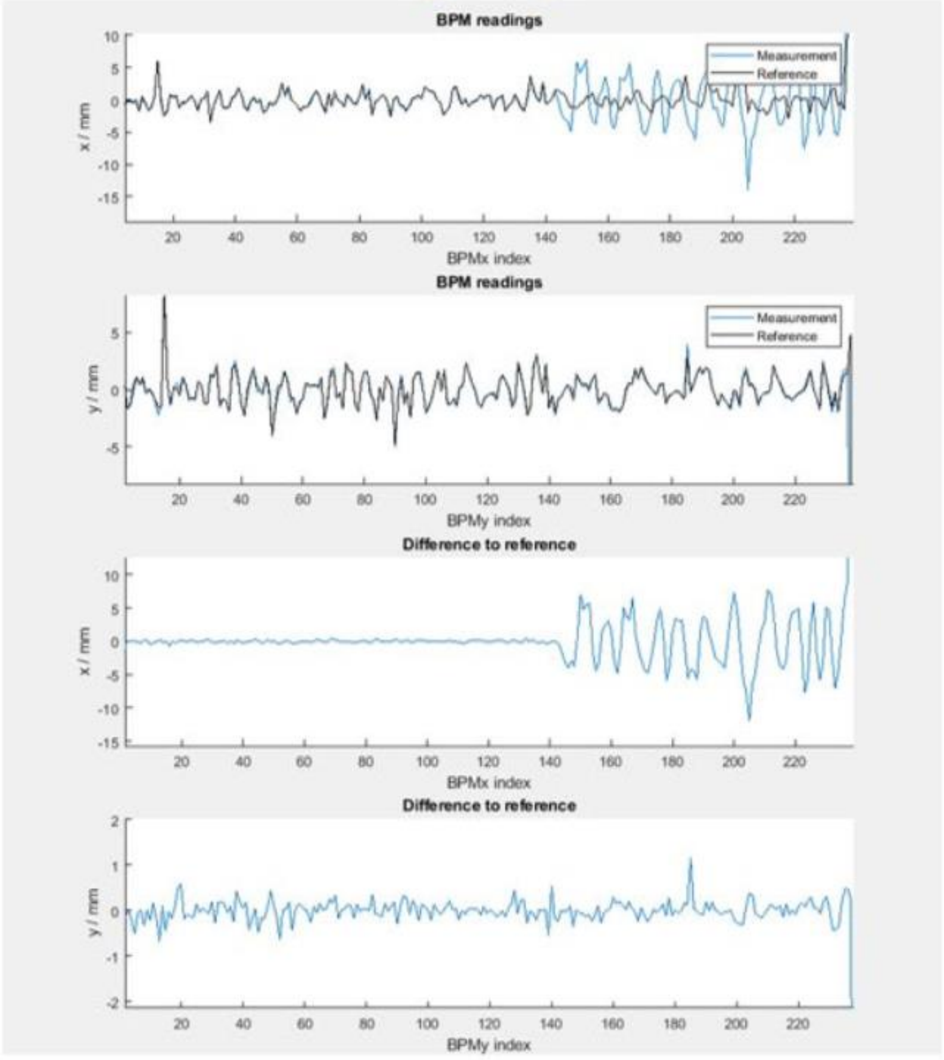


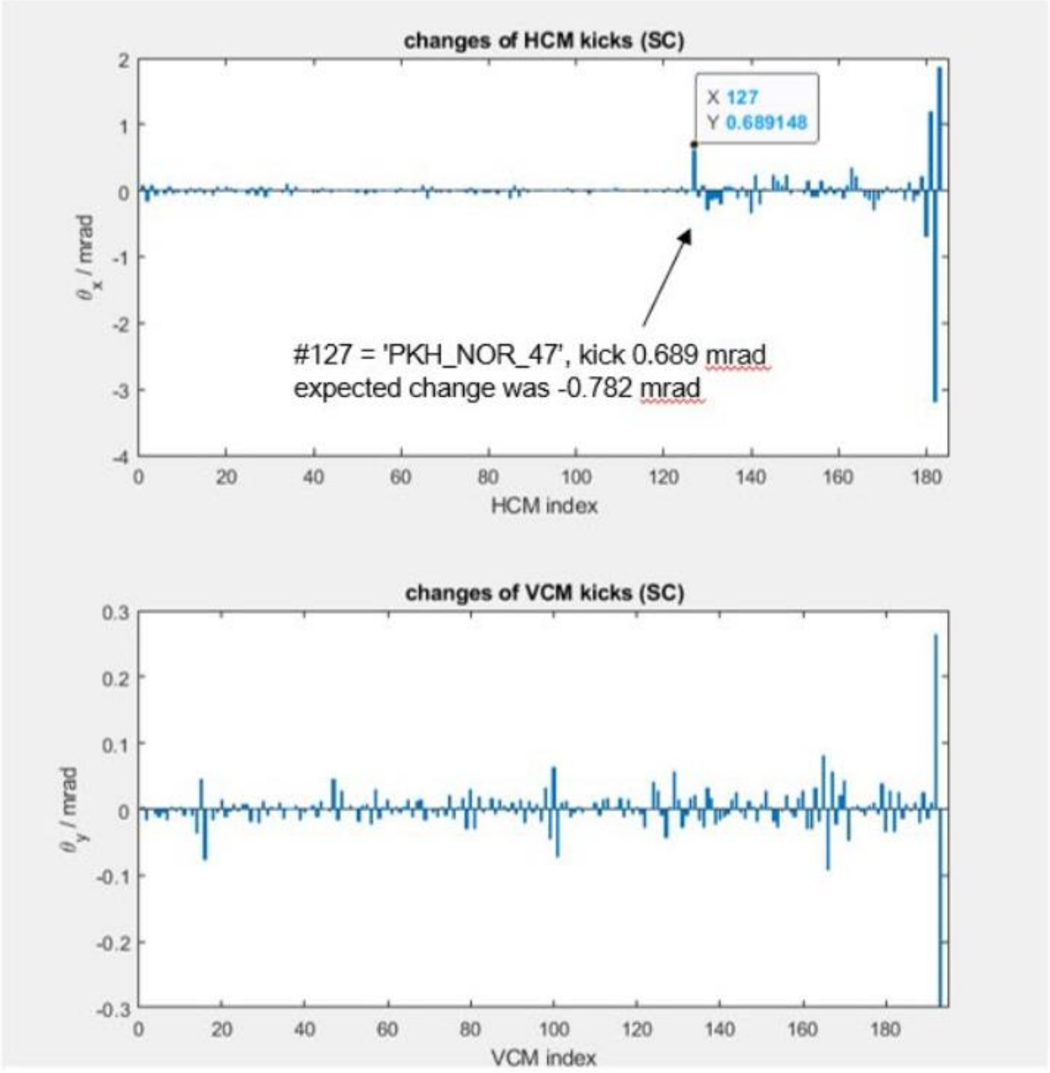
Some BPMs have only noise sum signal in ADC data → filtering out BPMs without sum signal within window

J. Keil

- Modified corrector visibly changes trajectory
- Calculated a correction

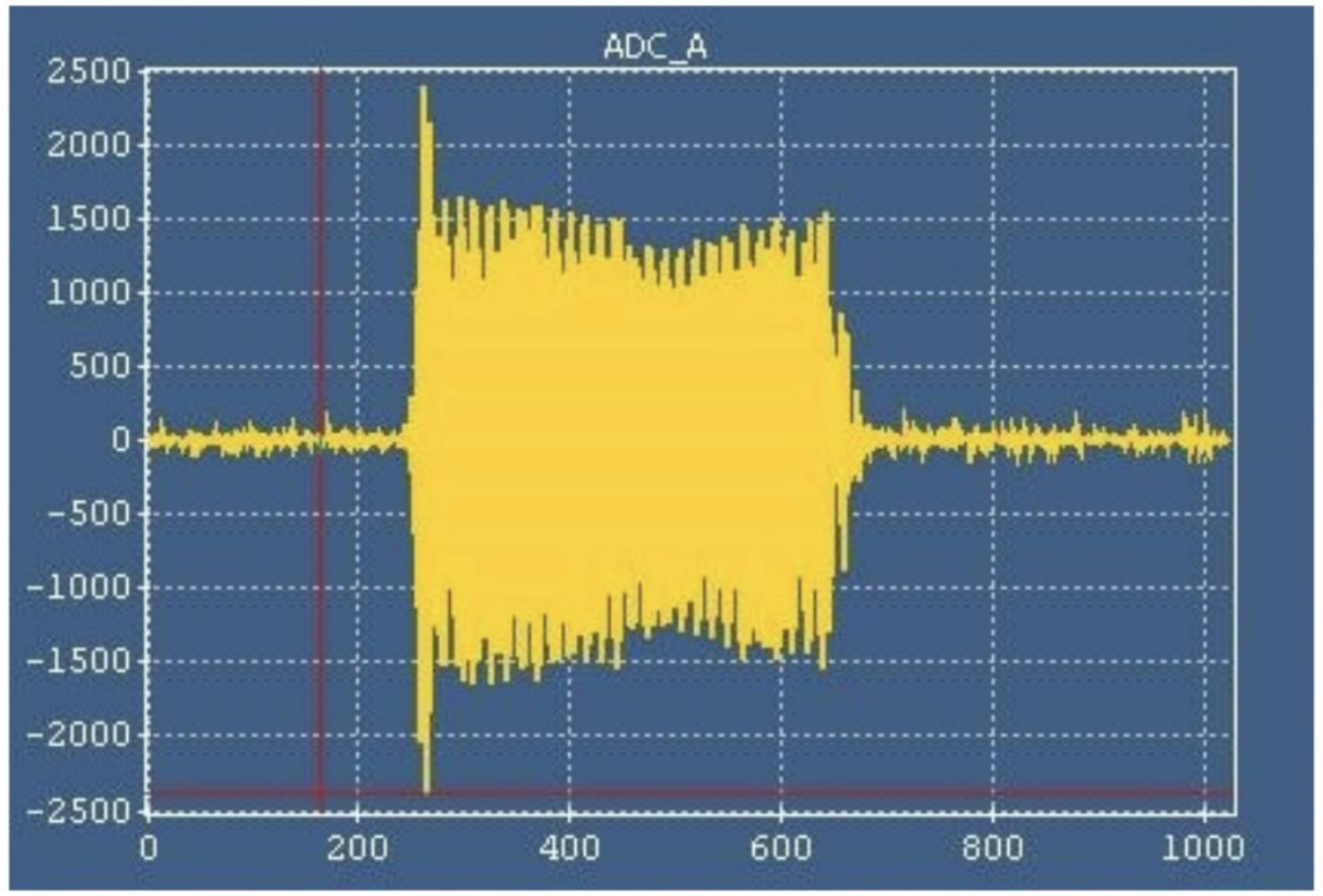
PKH NOR 47 changed by -4.0 A



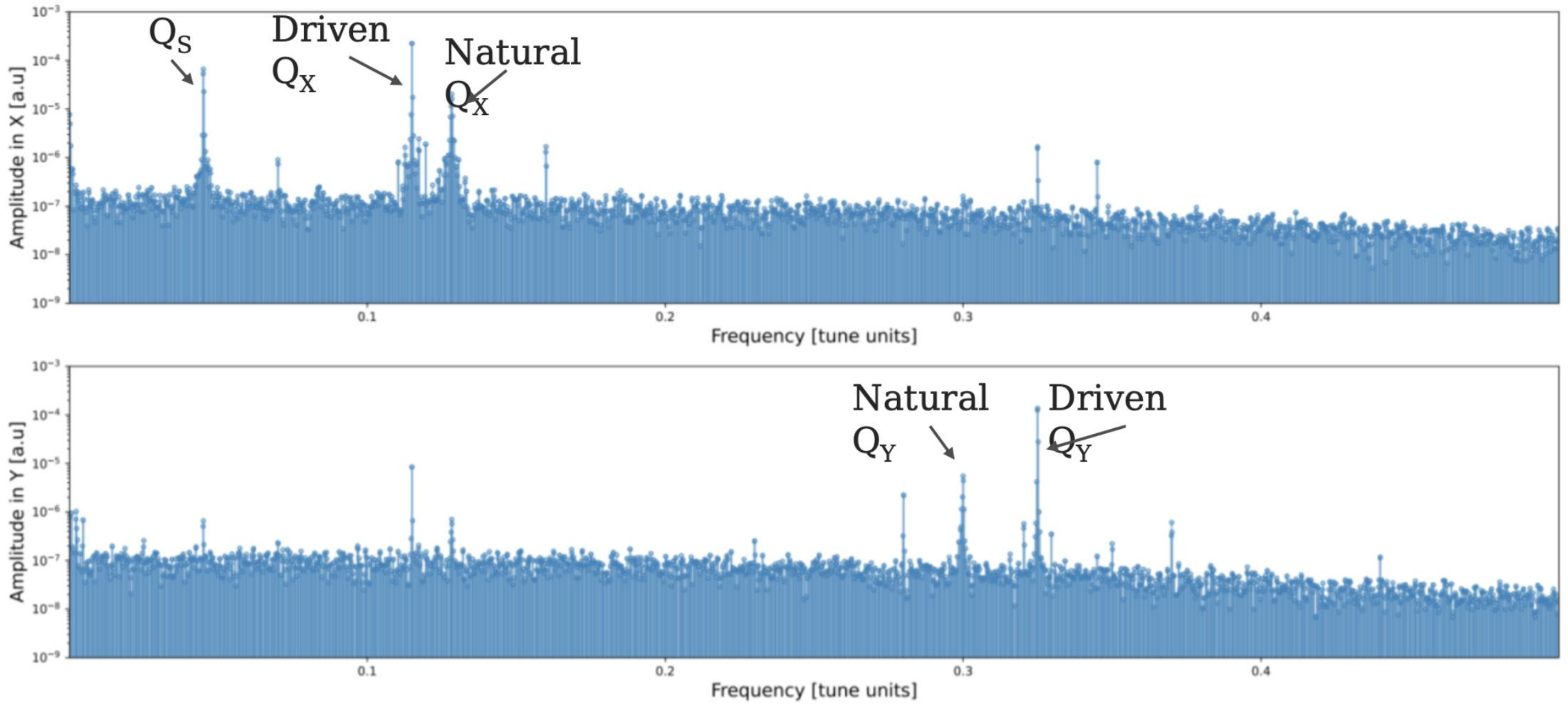


AC dipole

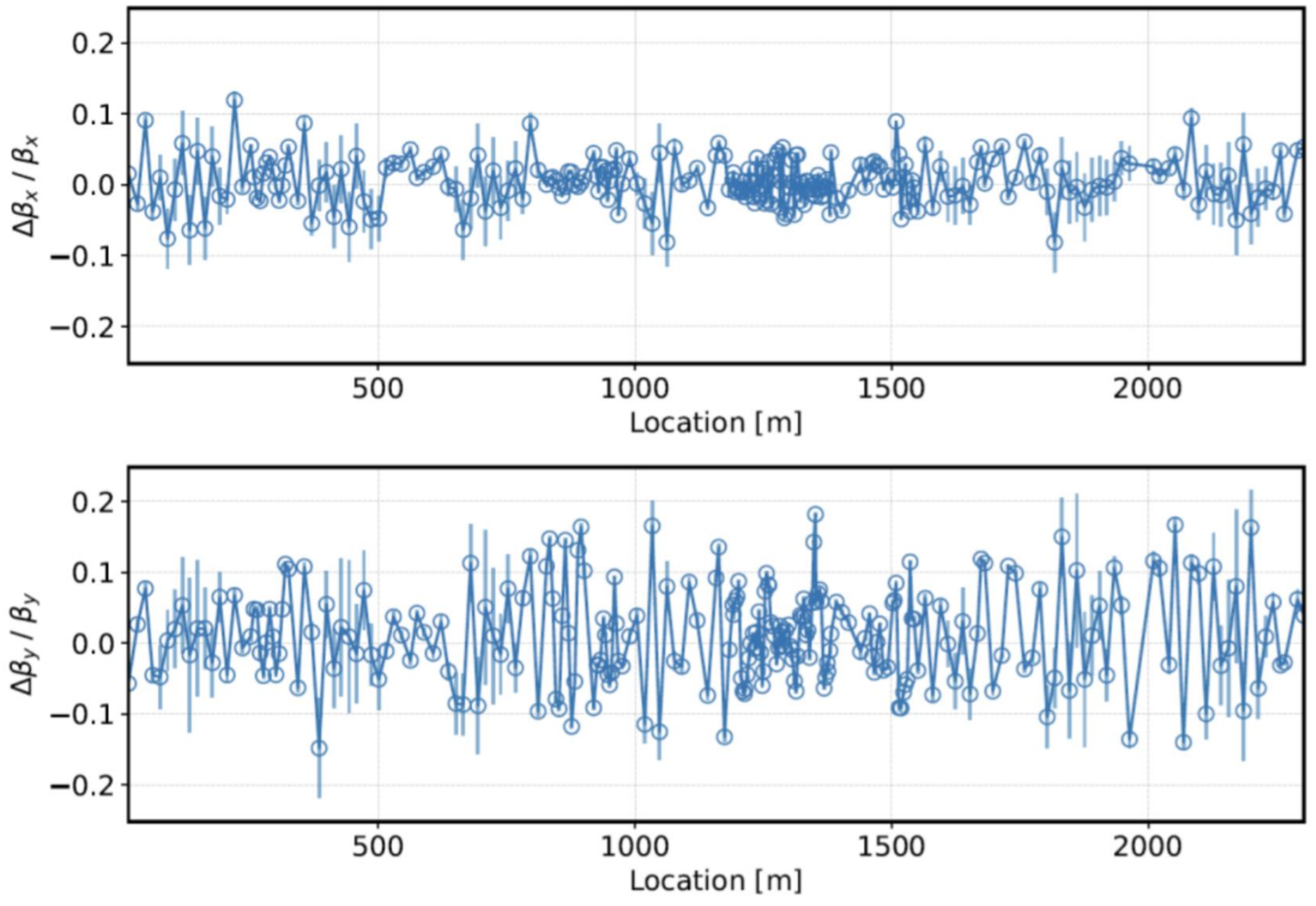
- AC excitation-based optics measurement at PETRA III tested
- Issue: BPM mix several turn data.
  - Solution 1: MAF filter (difficult to set up)
  - Solution 2: No filter, but fill pattern adjusted (40 bunches in one half of the ring)
- Optics measurements done (2022)
- Not in routine operation



PETRA III: Forced 3D excitation



Beta beating (N-BPM method)



Analytical N-BPM method:

- Large error bars come from the estimate of transverse misalignment of sextupoles
- Orbit bumps now taken as uncertainty
- Once included in the model, the errors will

L. Malina

FCC-ee applications of pyAT and tuning tools

- Standard tools (among others) for performance evaluation for FCC-ee
- See talks Elaf Musa, and Simone Liuzzo/Michael Hofer on Wednesday
- Note, that light source tuning tools usually do not address optics “in collision”. This functionality should be ensured by e.g. integrating with other tools

Empirical optimization

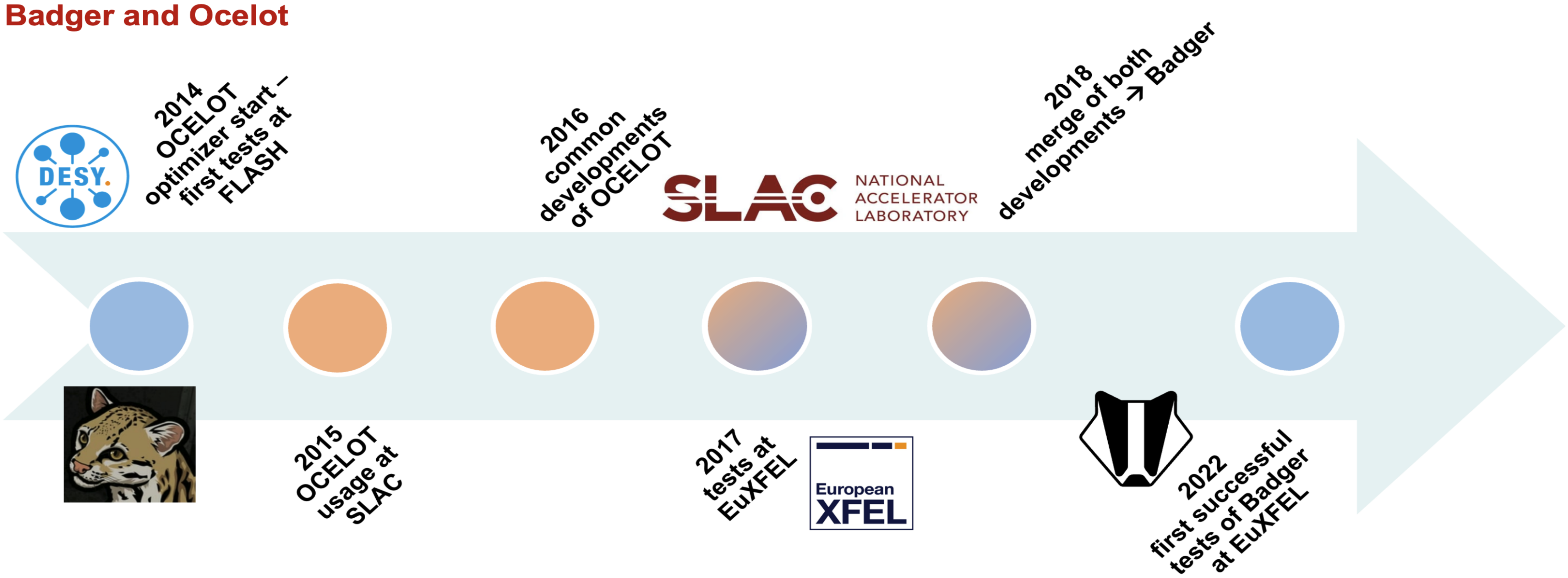
Thanks to Simone Liuzzo et al.

6th International Particle Accelerator Conference IPAC2015, Richmond, VA, USA JACoW Publishing
ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPWA037

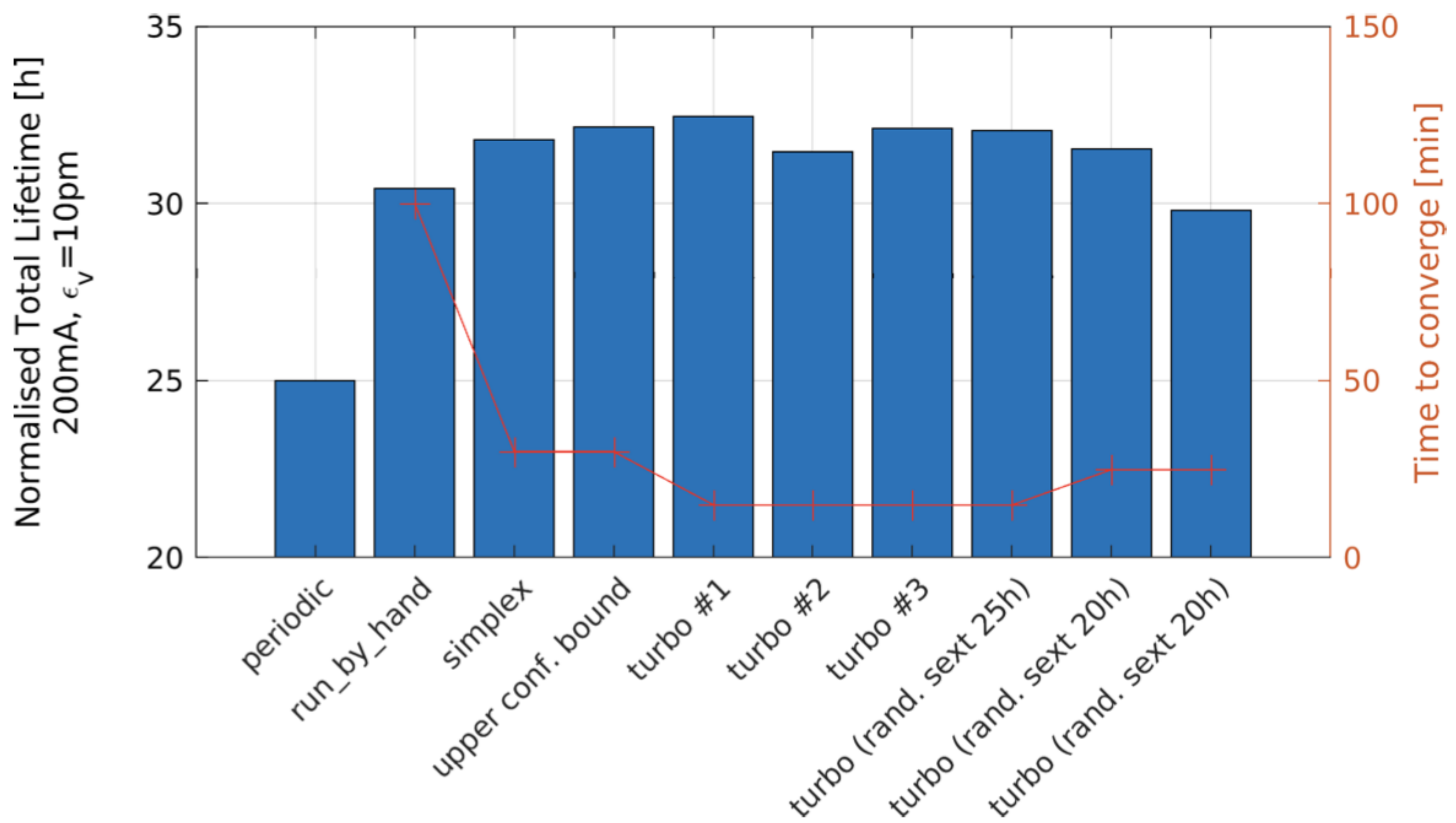
STATISTICAL OPTIMIZATION OF FEL PERFORMANCE

I. Agapov *, G. Geloni, European XFEL GmbH, Hamburg, Germany
I. Zagorodnov, DESY, Hamburg, Germany

Badger and Ocelot



- Routine approach for SASE-FEL optimization
- Recently gaining traction for storage ring light sources
- In operation at ESRF-EBS and PETRA
- Maybe possible approach for luminosity tuning in colliders?

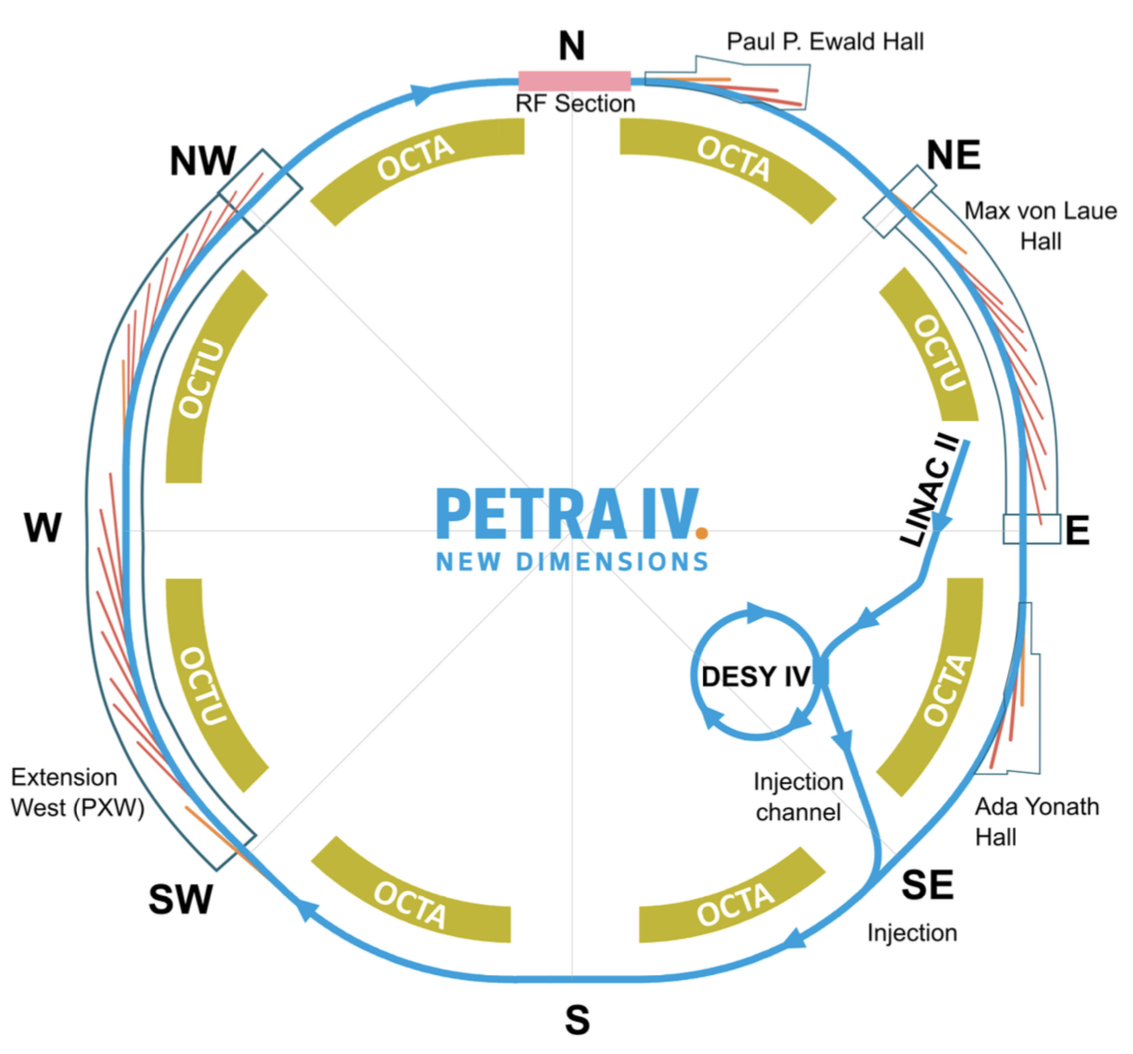


Proceedings of ICALEPCS2023, Cape Town, South Africa - Pre-Press Release 28-October-2023 -

OPTIMISATION OF THE TOUSCHEK LIFETIME IN SYNCHROTRON LIGHT SOURCES USING BADGER*

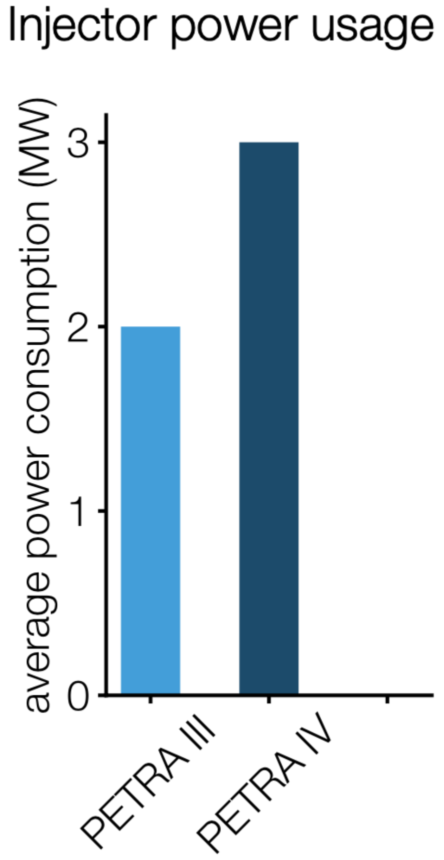
S.M. Liuzzo†, N. Carmignani, L. Carver, L. Hoummi, D. Lacoste, A. Le Meillour, T. Perron, S. White, ESRF, Grenoble, France
I. Agapov, M. Boese, L. Malina, E. Musa, J. Keil, B. Veglia
Deutsches Elektronen-Synchrotron, 22607 Hamburg, Germany
T. Hellert, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
A. Edelen, P. Raimondi, R. Roussel, Z. Zhang, SLAC, Menlo Park, CA, USA

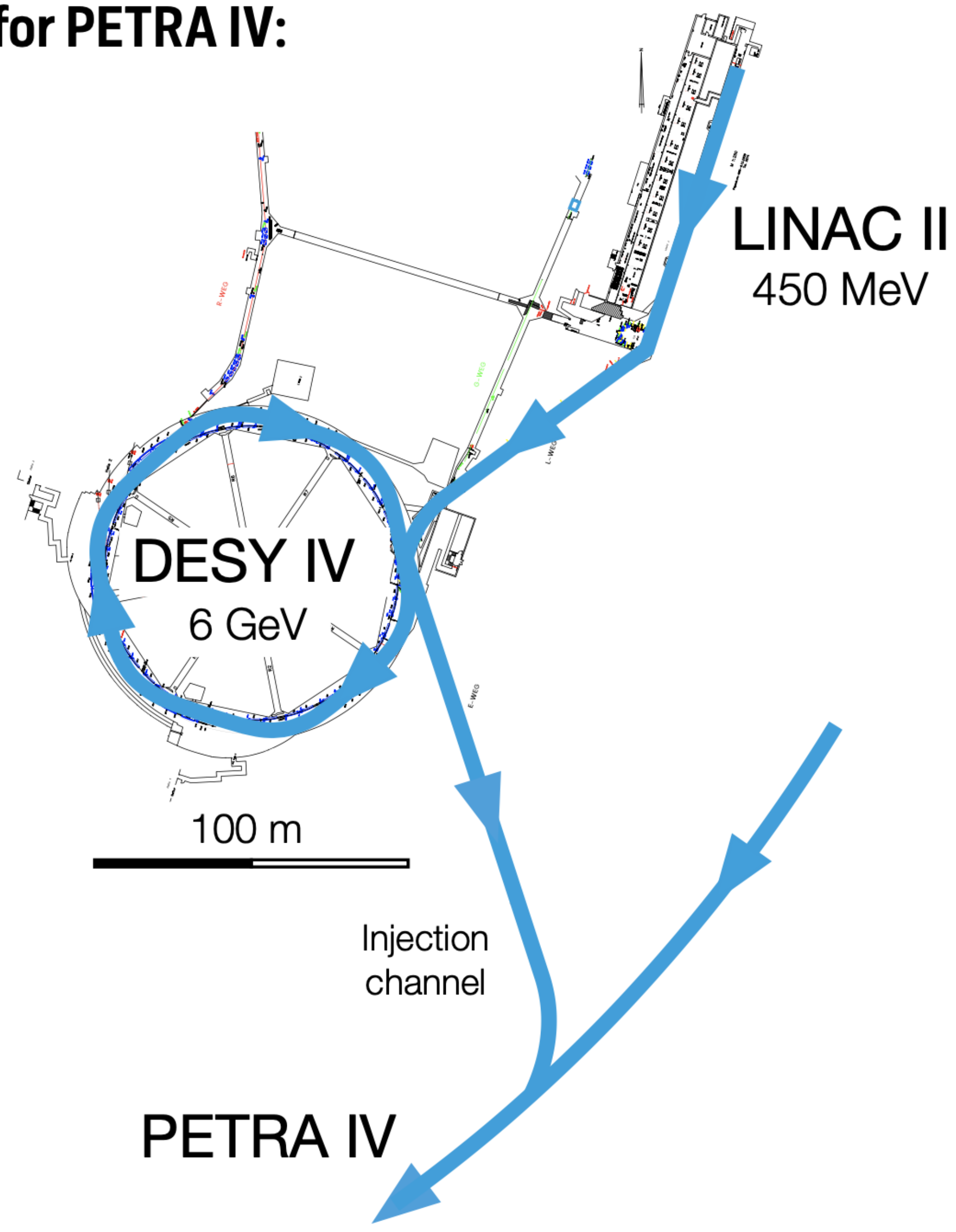
LPA injection



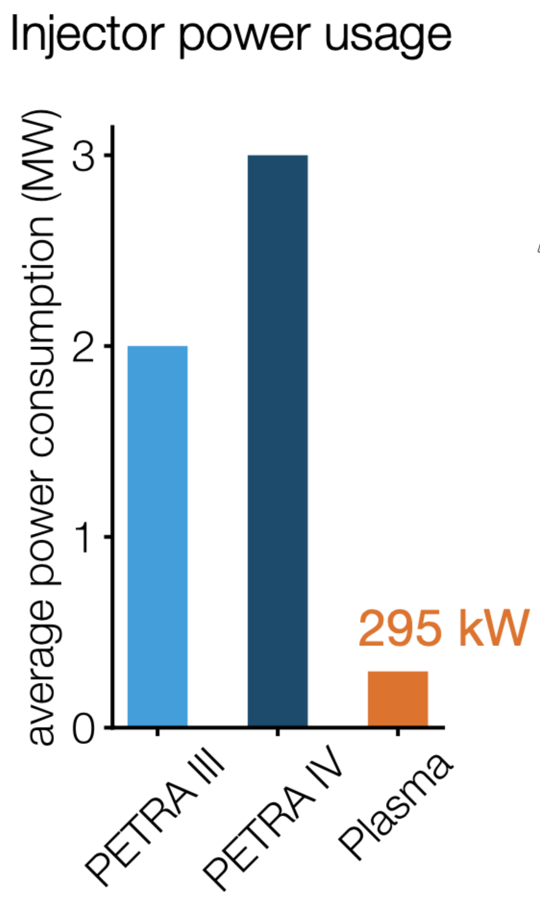
circumference: 2.3 km

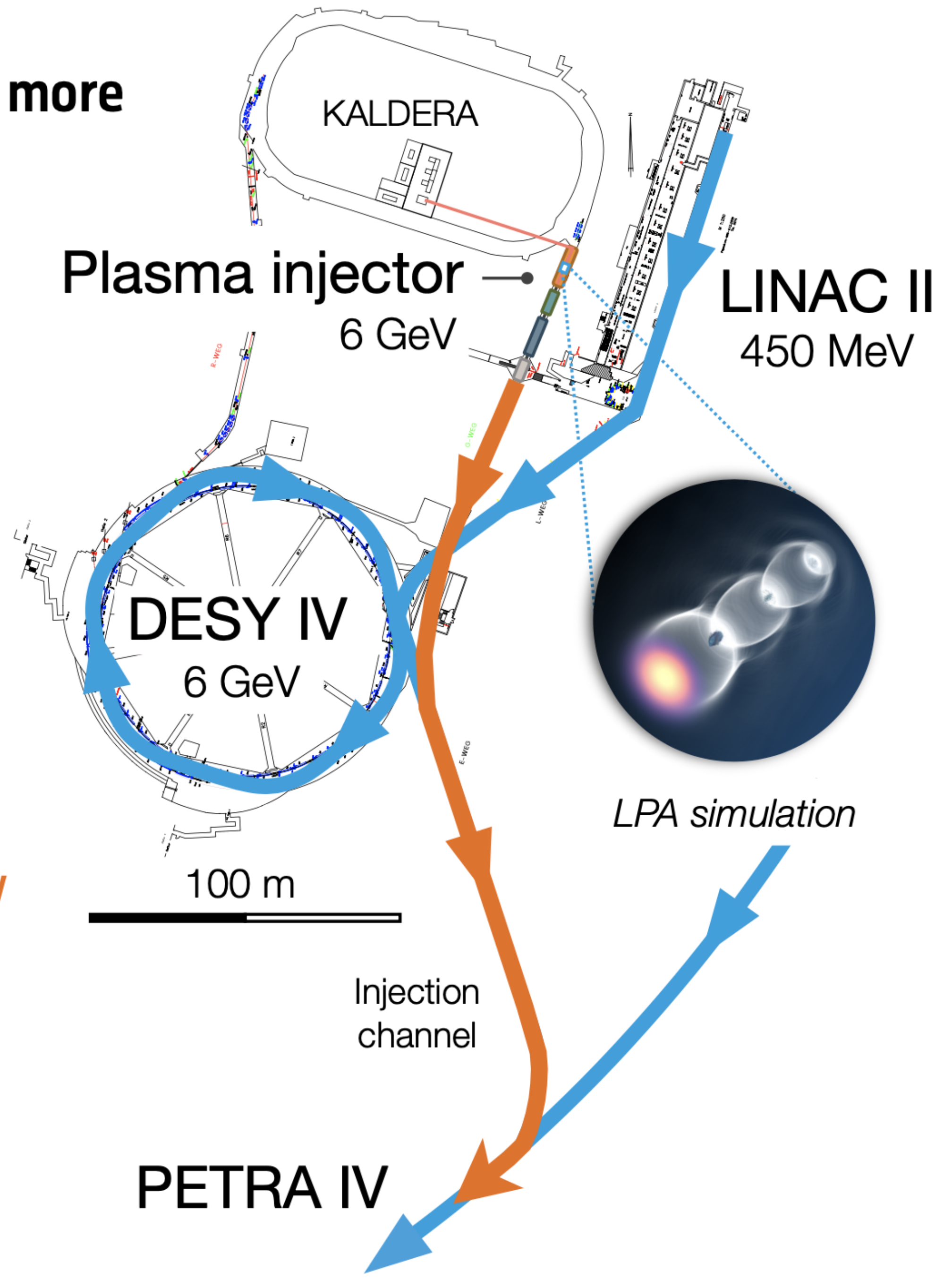
Conventional injector for PETRA IV: LINAC II + DESY IV





In practice, G-Weg is a more convenient location





PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 111301 (2021)

Design of a prototype laser-plasma injector for an electron synchrotron

S. A. Antipov,[1,*] A. Ferran Pousa,[1] I. Agapov,[1] R. Brinkmann,[1] A. R. Maier,[1] S. Jalas,[2] L. Jeppe,[2] M. Kirchen,[2] W. P. Leemans,[1,3] A. Martinez de la Ossa,[1] J. Osterhoff,[1] M. Thévenet,[1] and P. Winkler[1,2]

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(Received 12 July 2021; accepted 15 October 2021; published 9 November 2021)

PHYSICAL REVIEW LETTERS **129**, 094801 (2022)

Energy Compression and Stabilization of Laser-Plasma Accelerators

A. Ferran Pousa,[1,*] I. Agapov,[1] S. A. Antipov,[1] R. W. Assmann,[1,2] R. Brinkmann,[1] S. Jalas,[3] M. Kirchen,[1] W. P. Leemans,[1,3] A. R. Maier,[1] A. Martinez de la Ossa,[1] J. Osterhoff,[1] and M. Thévenet[1]

[1]*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
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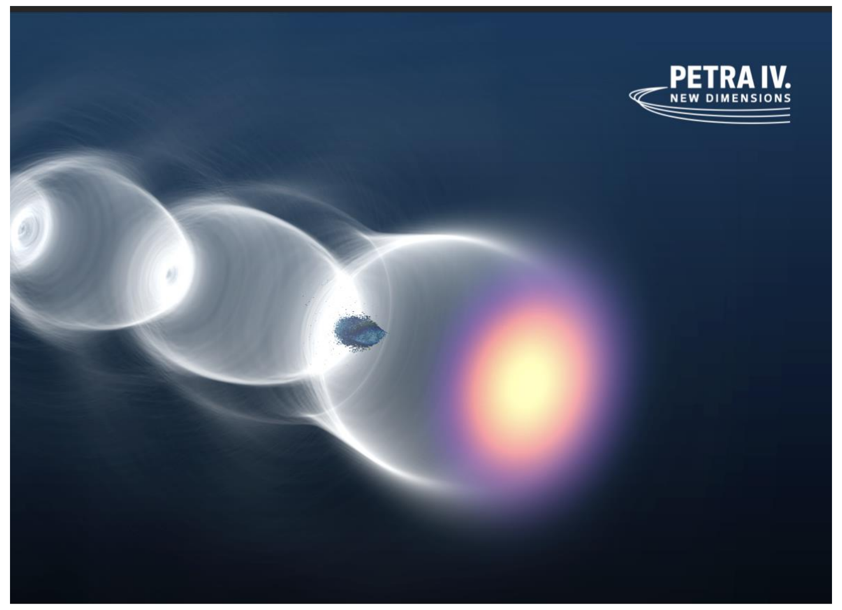
(Received 9 June 2021; revised 6 May 2022; accepted 25 July 2022; published 22 August 2022)



The Plasma Injector for PETRA IV.

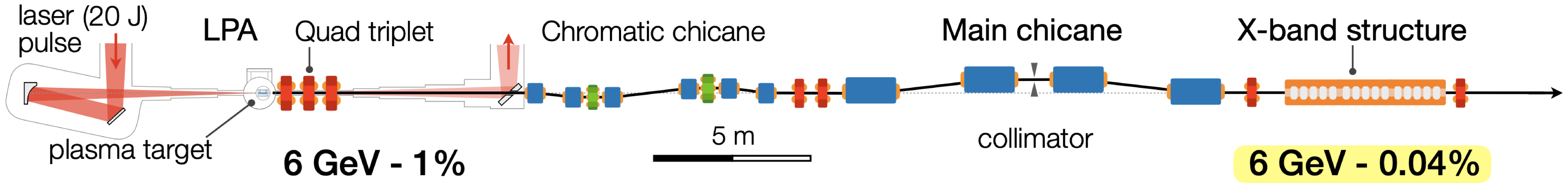
Enabling Plasma Accelerators for Next-generation Light Sources
Conceptual Design Report

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

DESY.

The Plasma Injector for PETRA IV: conceptual design

Maximizes charge injection throughput and stability



Laser Plasma Accelerator (LPA)

- **Drive Laser (Ti:Sa | λ_0=800 nm):** Peak power: ~350 TW, energy: ~20 J.
- **Plasma source (~20 cm):** Controlled injection (LUX). Efficient laser guiding (HOFI).
- **Bayesian optimization:** maximizes the beam spectral density at 6 GeV and minimizes the laser energy.

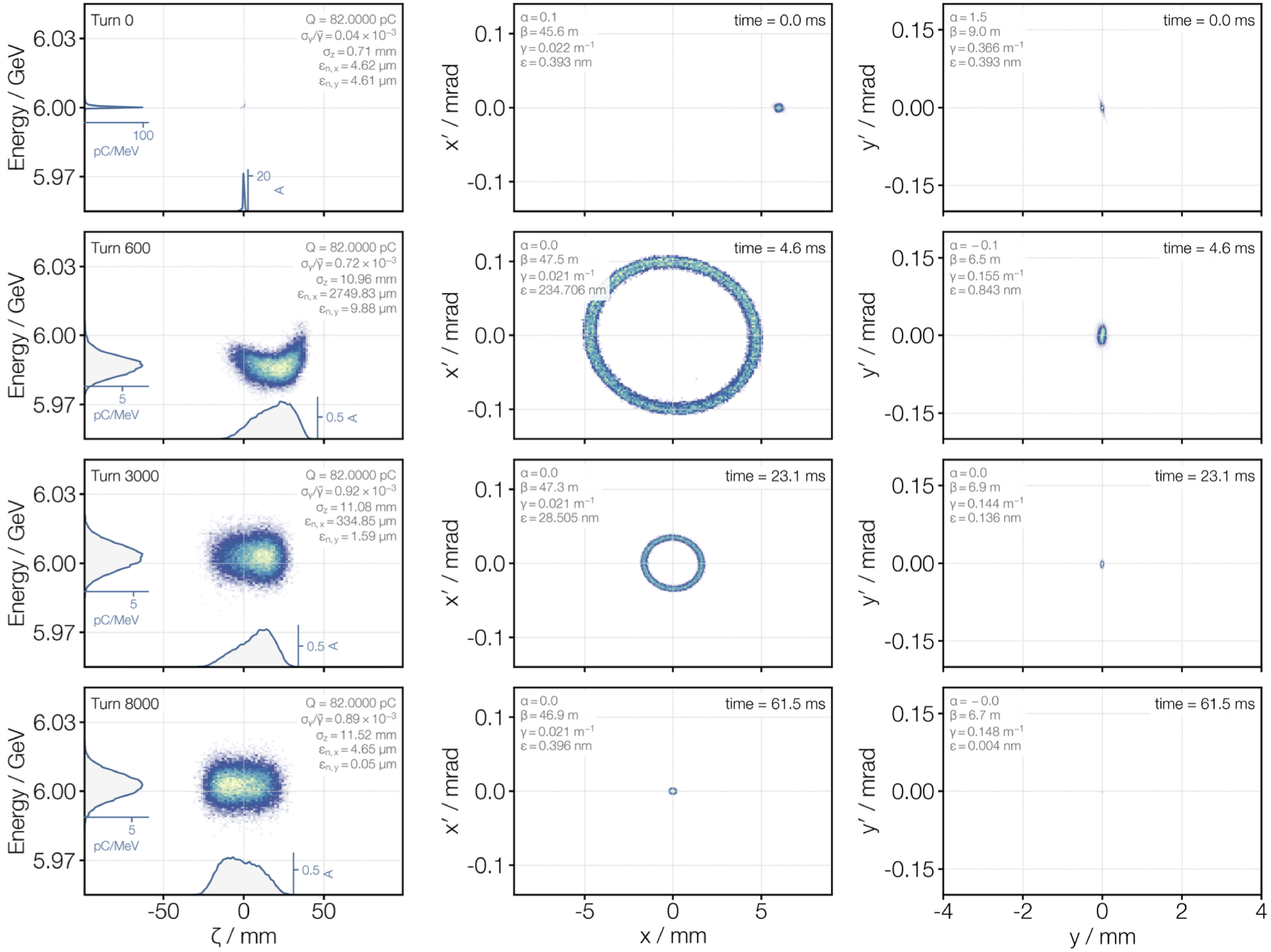
Energy Compression Beamline (ECB)

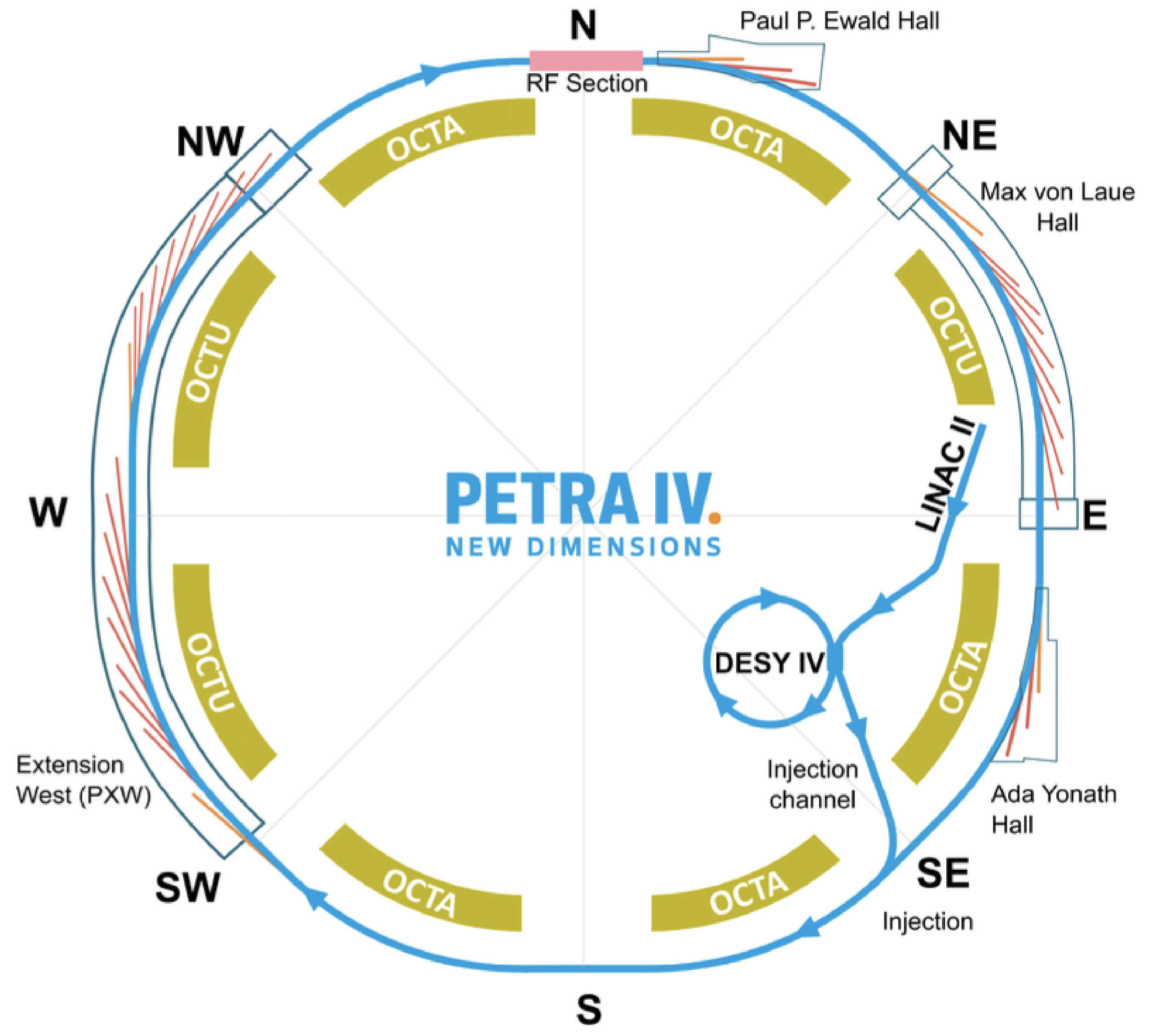
- **Quad triplet:** Beam capturing
- **Chromatic chicane:** pre-stretcher + chromaticity correction (horizontal plane)
- **Main chicane:** beam length decompression
- **X-band structure:** energy compression and stabilization

Enables sub-per-mile level of energy spread and stability

The Plasma Injector: injection into PETRA IV

PETRA IV element-by-element beam tracking with ELEGANT





PETRA IV tracking — ELEGANT

- Simulation run for 8000 turns (3 x damping time)
- No particle losses for beams within the considered jitter.

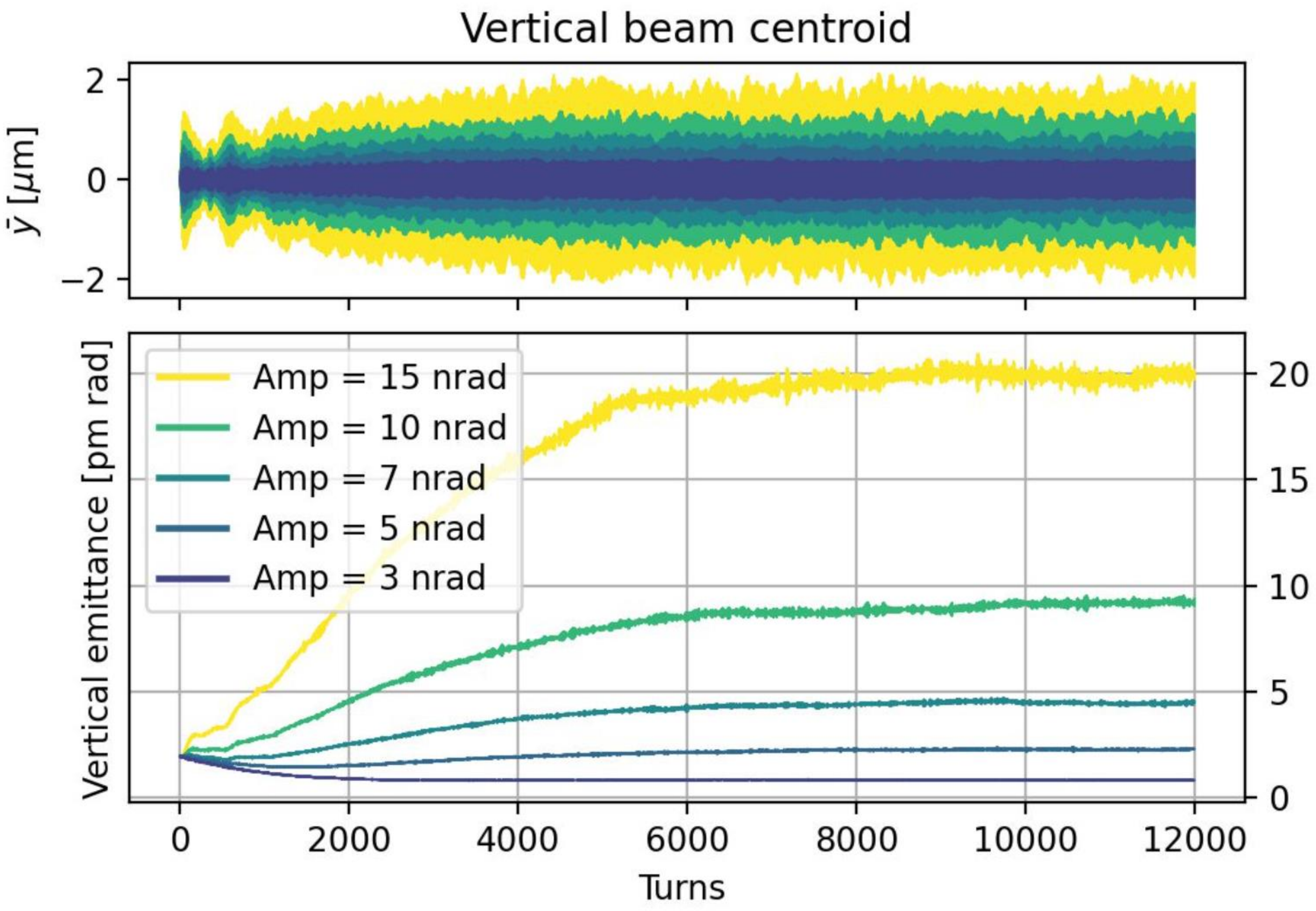
Efficient and clean injection into the PETRA IV storage ring

"Reverse flow": xsuite now used at DESY

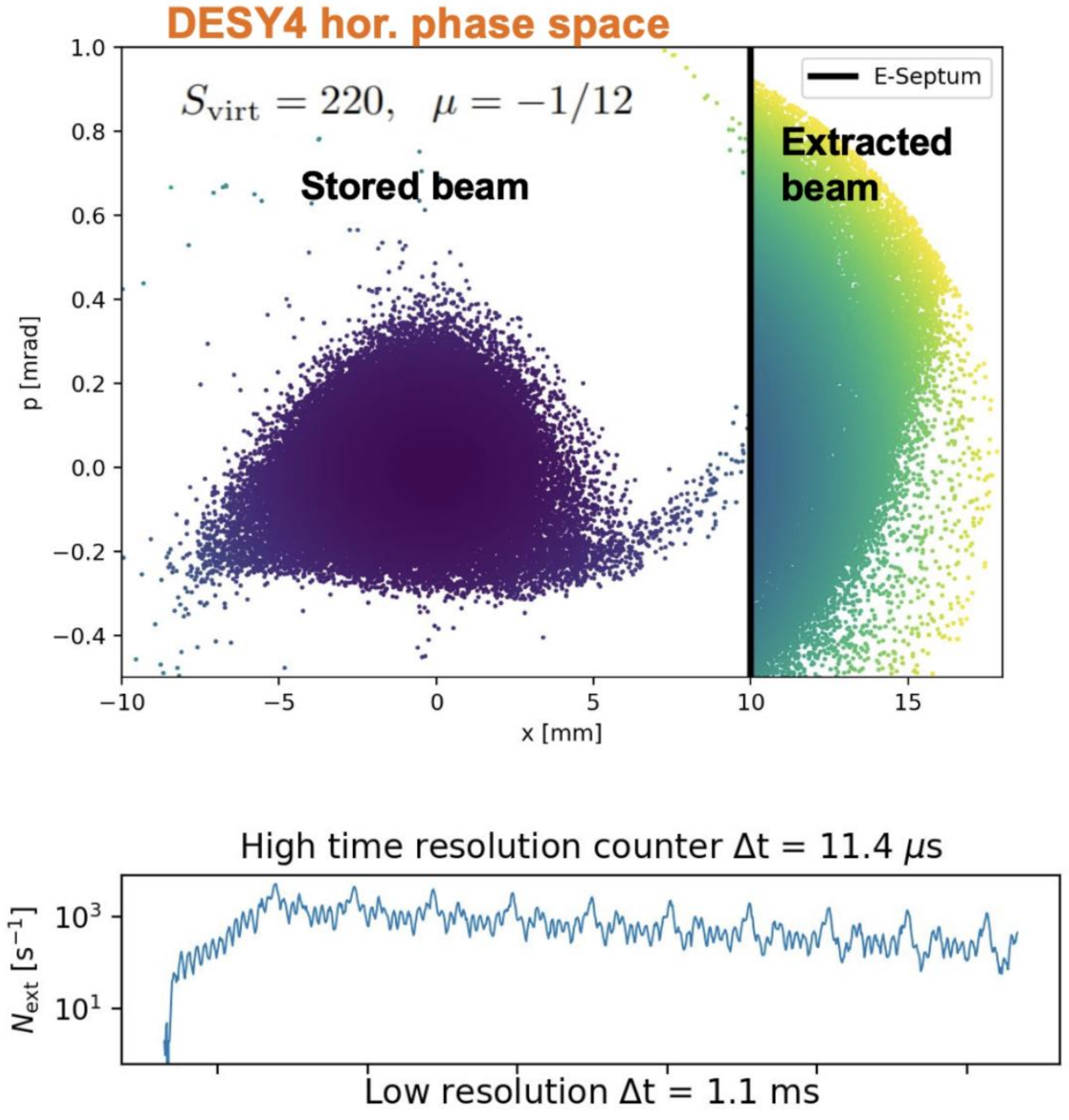
C. Cortes

- Several intensive simulations could be sped up

Emittance control with excitation on the tune frequency



Resonant extraction from the booster

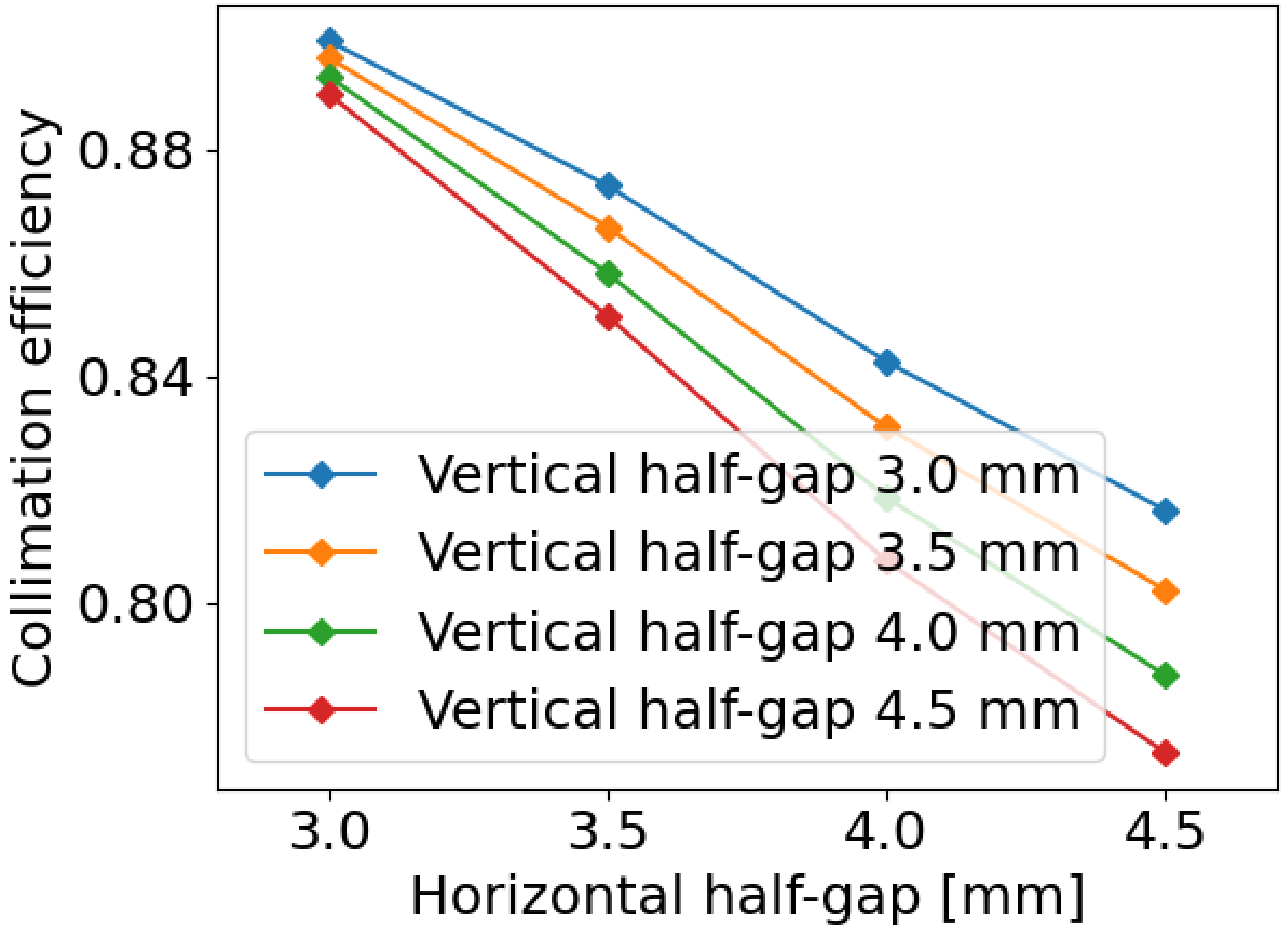


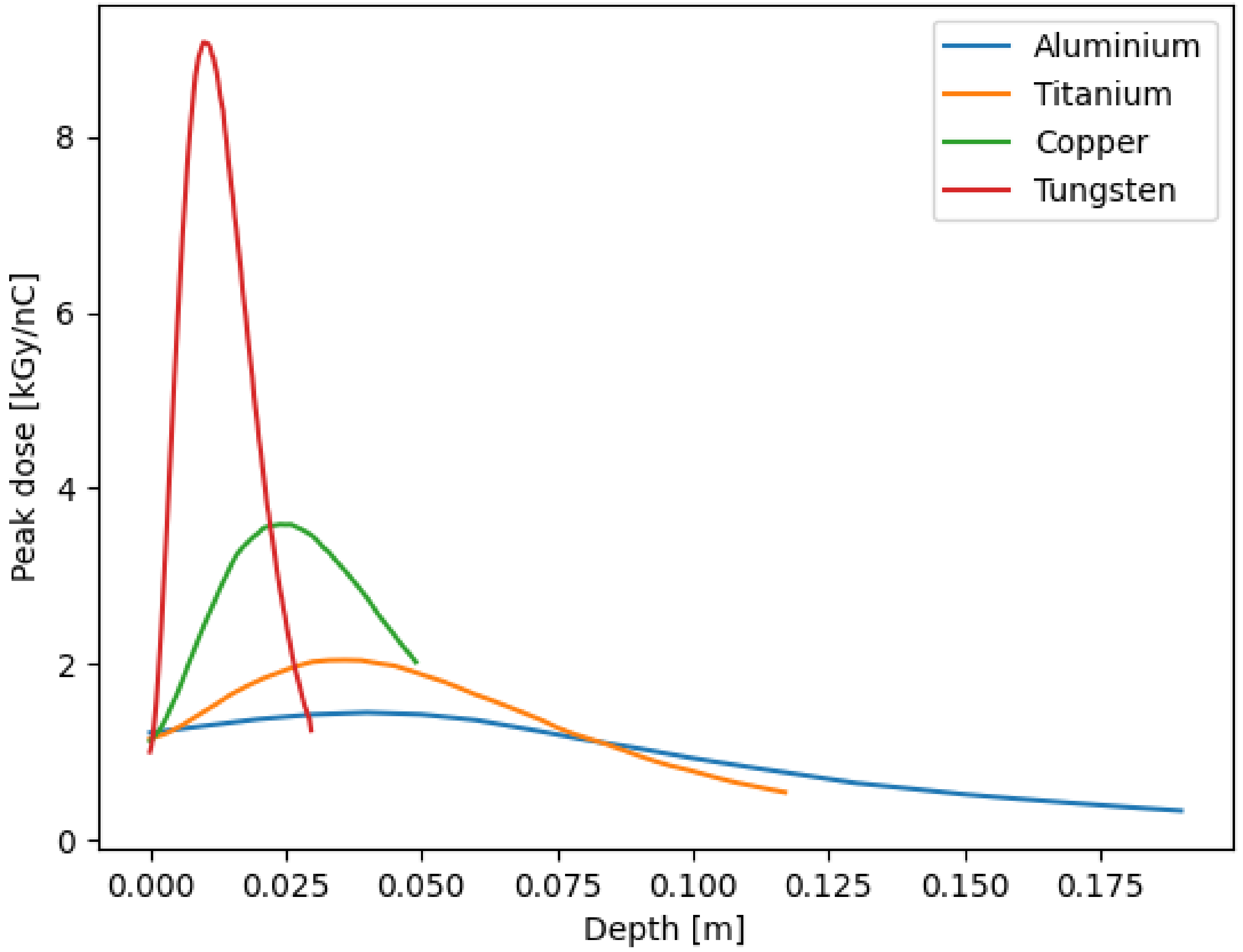
"Reverse flow": BDSIM

L. Malina, S. Strokov

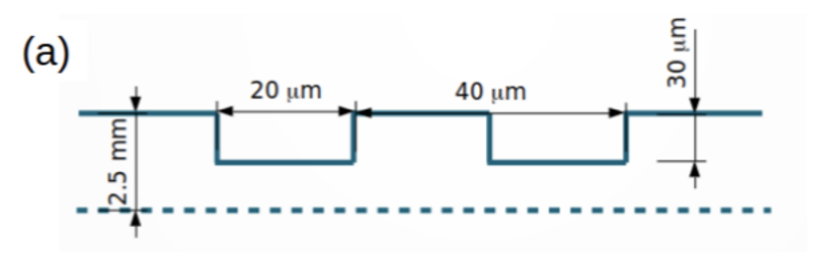
- Collimation and beam abort in a 4th generation light source are challenging, since
  - Limited beam energy but high density due to small emittance
  - For beam lifetime effects (Touschek), collimation challenging due to limited space and relatively small dispersion. 100% efficiency can not be achieved
  - For beam abort, usual way do dump beam on collimators. Additional sweeper required to blow up beam size prior to dump. Material damage possible even for low-Z materials (e.g. Al)
- BDSIM used for energy deposition calculations

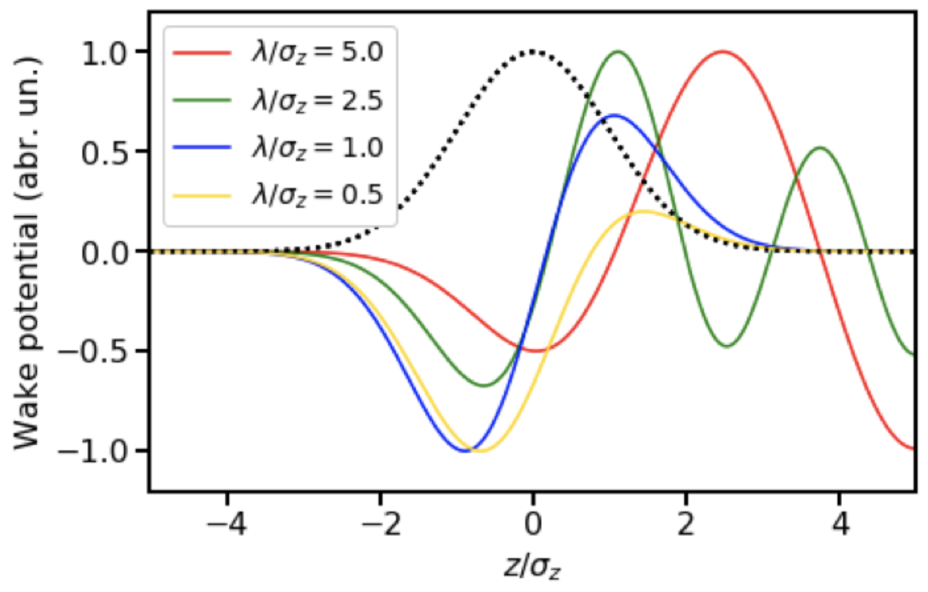
Touschek





Bunch length manipulation with dielectric structures





Adiabatic bunch compression in storage rings from self wakes generated in Cherenkov waveguides

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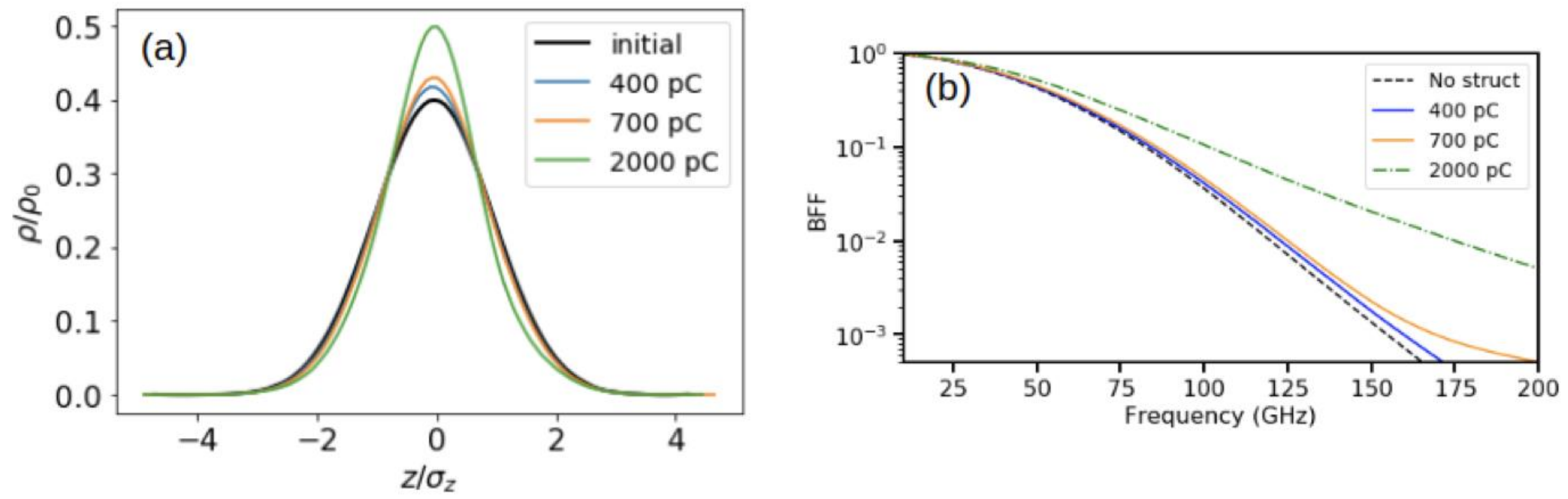

Figure 9. Bunch shortenings that can be obtained with a 30-cm-long 400 GHz corrugated structure in the KARA ring for different bunch charges (a) and the corresponding bunch form factors (b). The initial bunch length is assumed to be 0.9 mm, rms (shown as black lines).

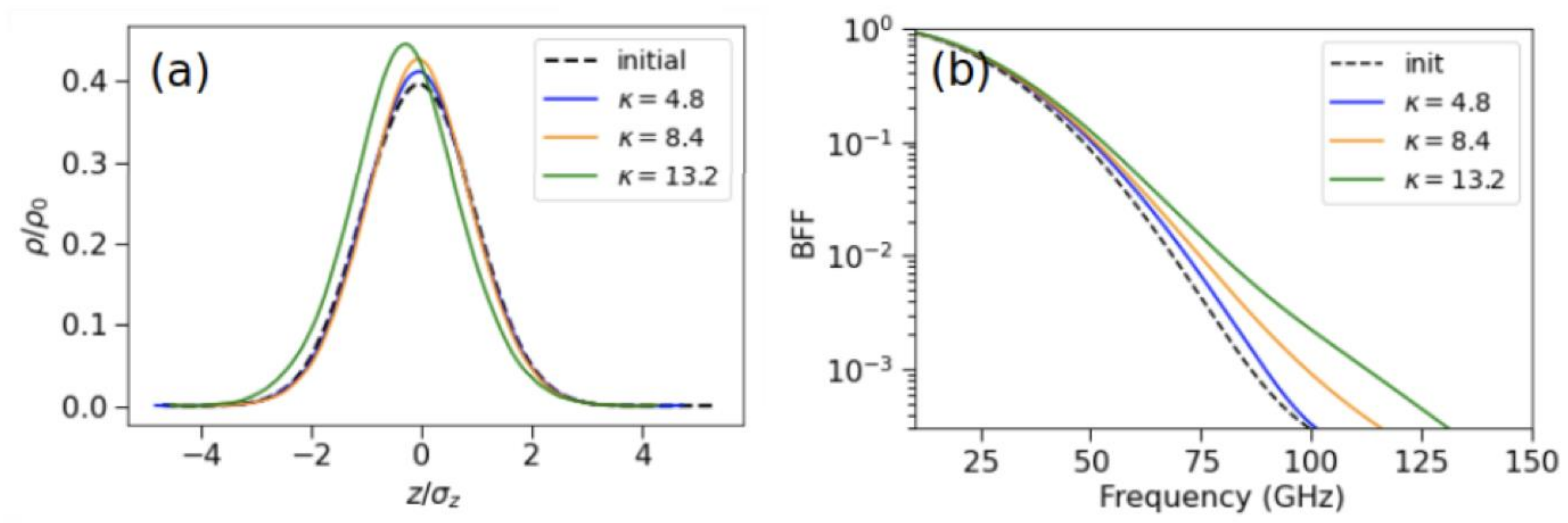

Figure 10. Bunch compression (a) and bunch form factor (b) for different wake strength in PETRA IV.

- Corrugated structures could be used for bunch shortening in electron storage rings
- In a light source, the application could be coherent radiation generation. The reach should be increased (beyond 100 GHz currently) to for more appeal
- Could we use this technique for collider luminosity improvement

Conclusion/summary/outlook

- Some work in light source area has been transferred to FCC-ee
- In particular development of optics tuning software and certain optics measurement and correction techniques as well as experience in operating machines with high sensitivity to optics errors is an important contribution from light source community
- Some FCC developments benefit the light source community (xsuite, bdsim)
- A number of technologies developed at light sources could be additionally considered (LPA, empirical optimization, bunch length manipulation with dielectric structures)

THANK YOU

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