Simulations of the Plasma Injector for PETRA IV

Ilya Agapov, Sergey Antipov, Reinhard Brinkmann, Florian Burkart, Heiko Ehrlichmann, Ángel Ferran Pousa, Sören Jalas, Manuel Kirchen, Wim Leemans, Andreas Maier, Alberto Martinez de la Ossa, Jens Osterhoff, Konstantinos Paraschou, Rob Shalloo, Maxence Thévenet, Paul Winkler

11th Matter & Technologies Annual Meeting, GSI Germany

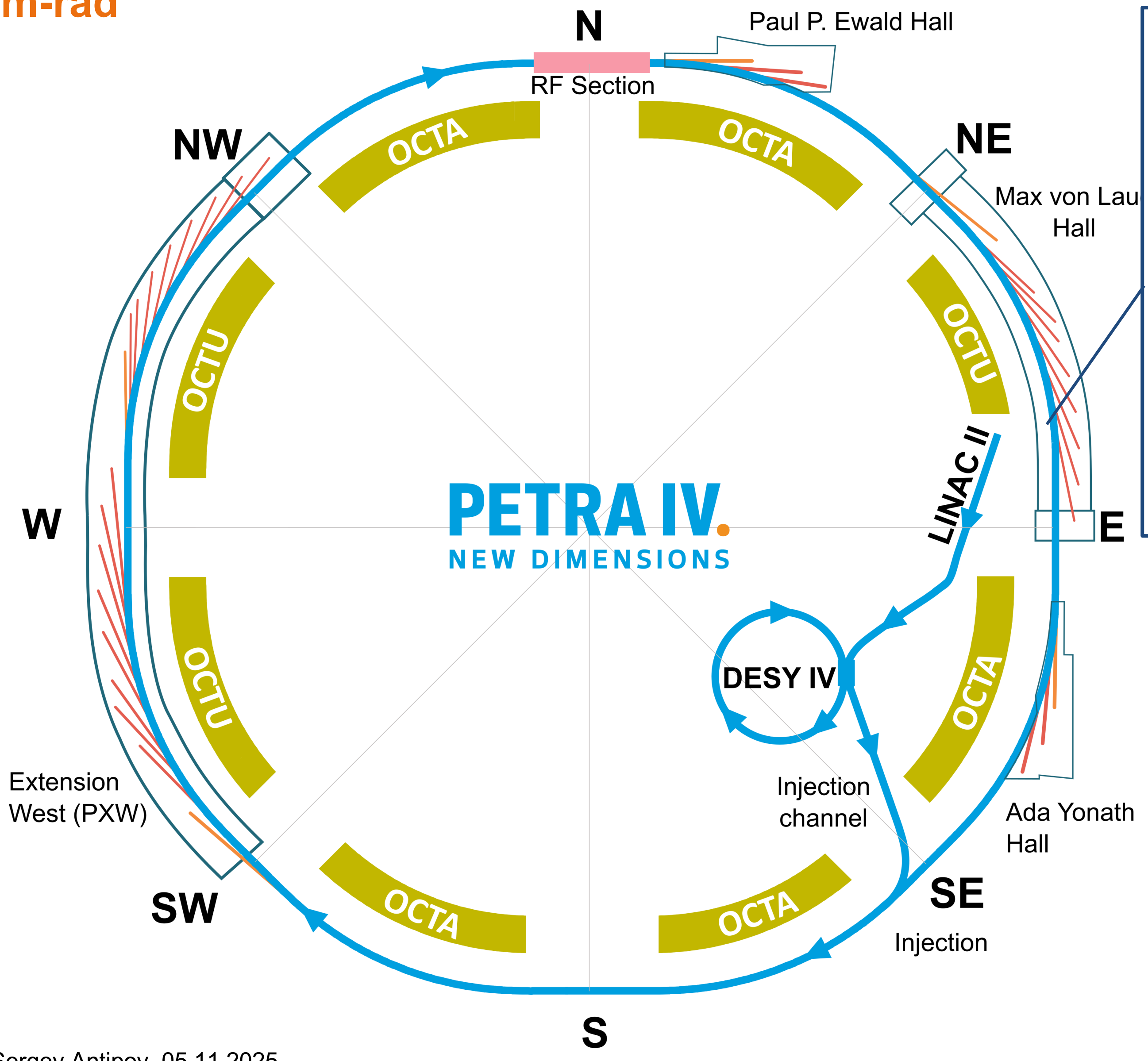
05.11.25

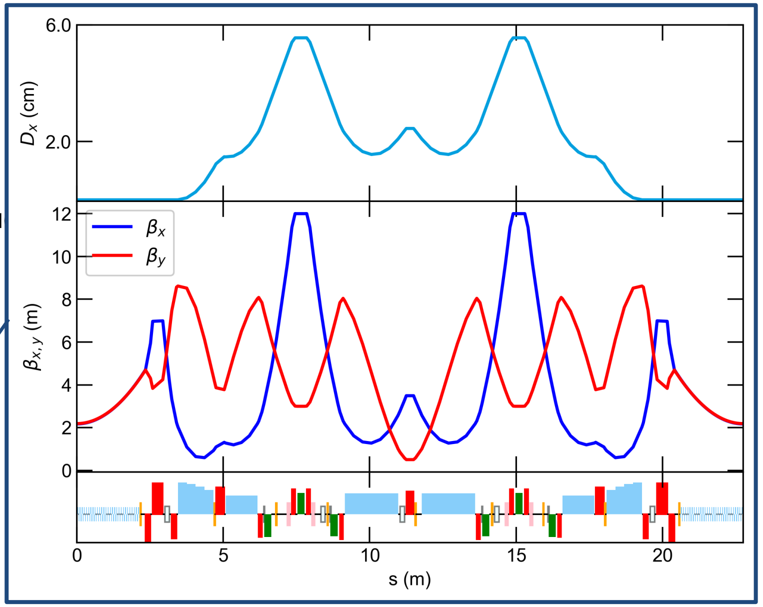
HELMHOLTZ

DESY.

PETRA IV: Germany's future flagship light source

6 GeV, 2.3 km, 20 pm-rad



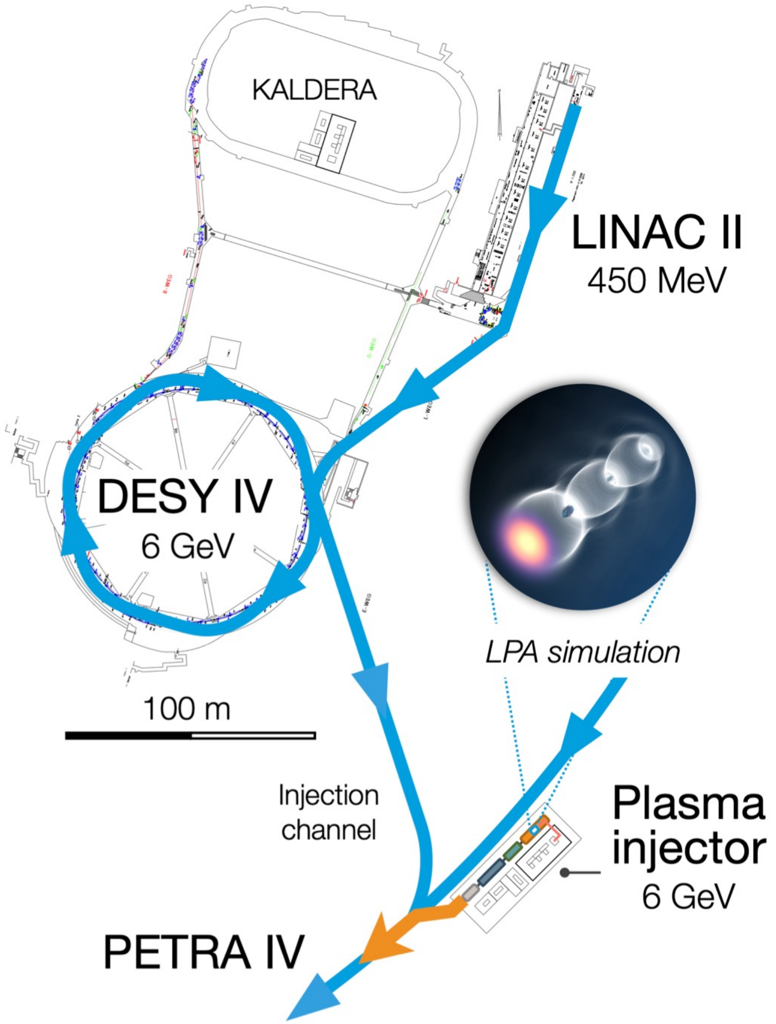


H6BA cell

C. Schroer et al., PETRA IV CDR, 2019

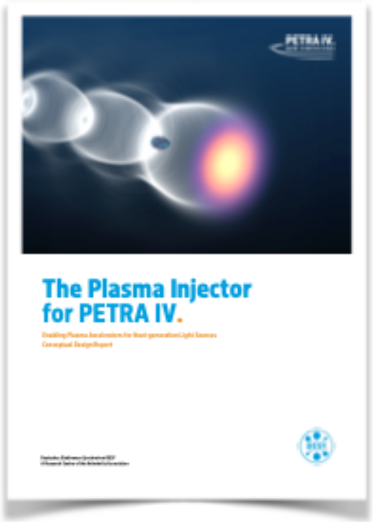
Pursuing an R&D towards an LPA injector

as a compact, cost-effective, competitive alternative



CDR published:

- A. de la Ossa et al, DESY Rep. PUBDB-2024-06078, 2024

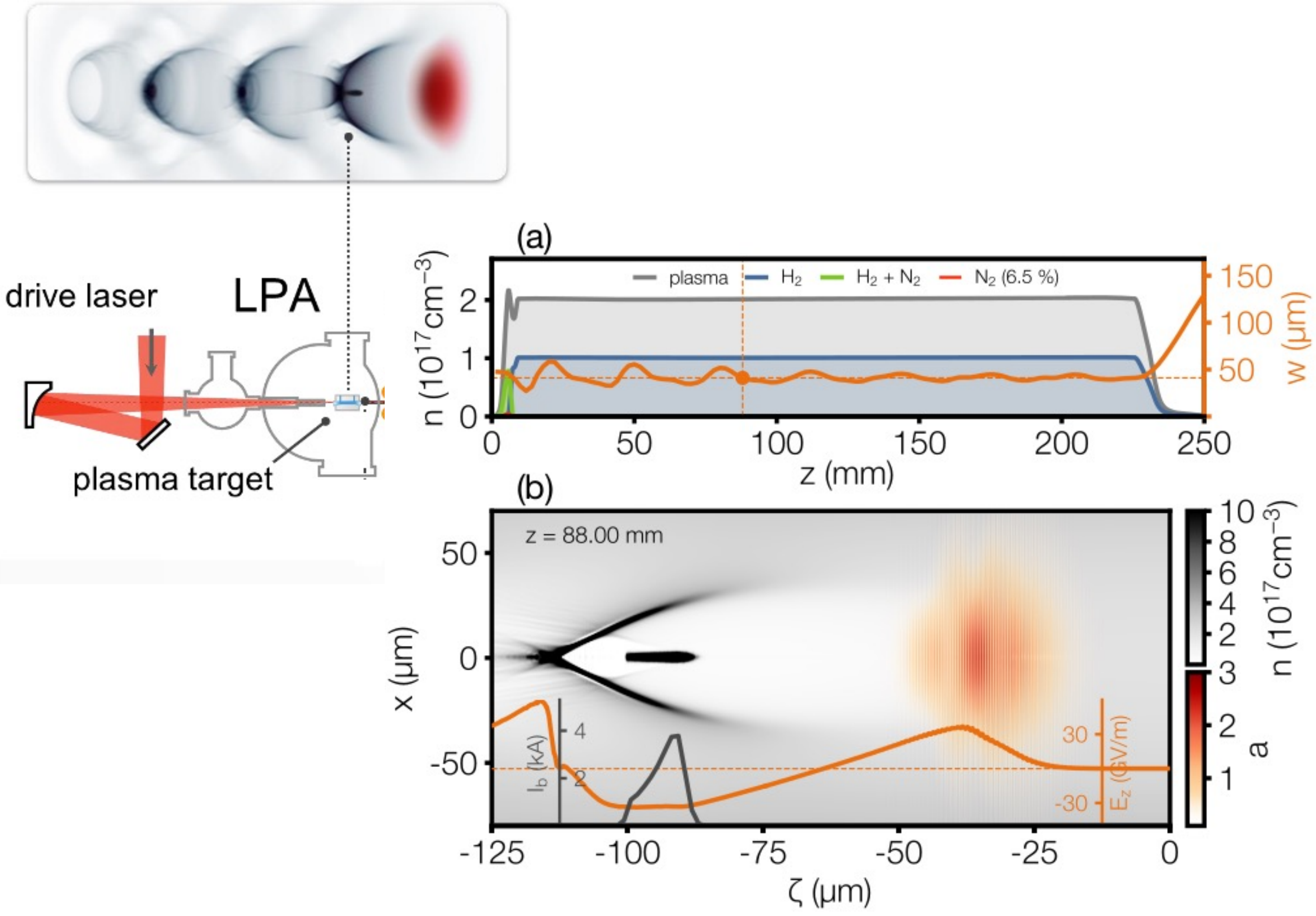


Key figures:

- Energy: 6 GeV
- Charge per shot: 100 pC
- Repetition rate: 30 Hz
- Emittance: ~1 nm-rad
- Energy variation: $< 10^{-3}$

6 GeV LPA injector: the LPA

Achieving ~100 pC bunch charge within a small phase space volume



Á. Ferran Pousa, A. de la Ossa

A single 25-cm-long LPA stage

- Hydrodynamic optical-field-ionized (HOFI) plasma channel
- Driven by a 50 fs-long 20 J Ti:Sa (800 nm) laser pulse
- Bayesian optimization of the working point S. Jalas et al., *Phys. Rev. Lett.* 126 (2021)

optimas

`https://github.com/optimas-org/optimas`

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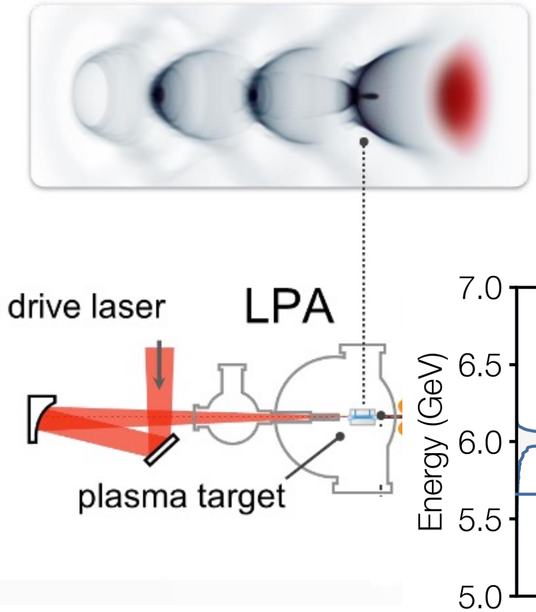

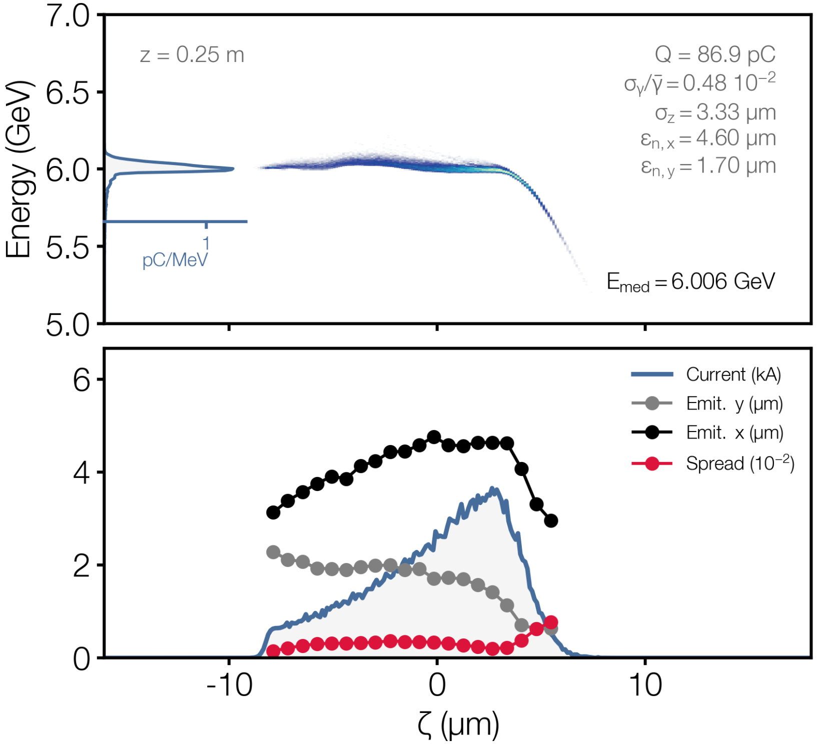

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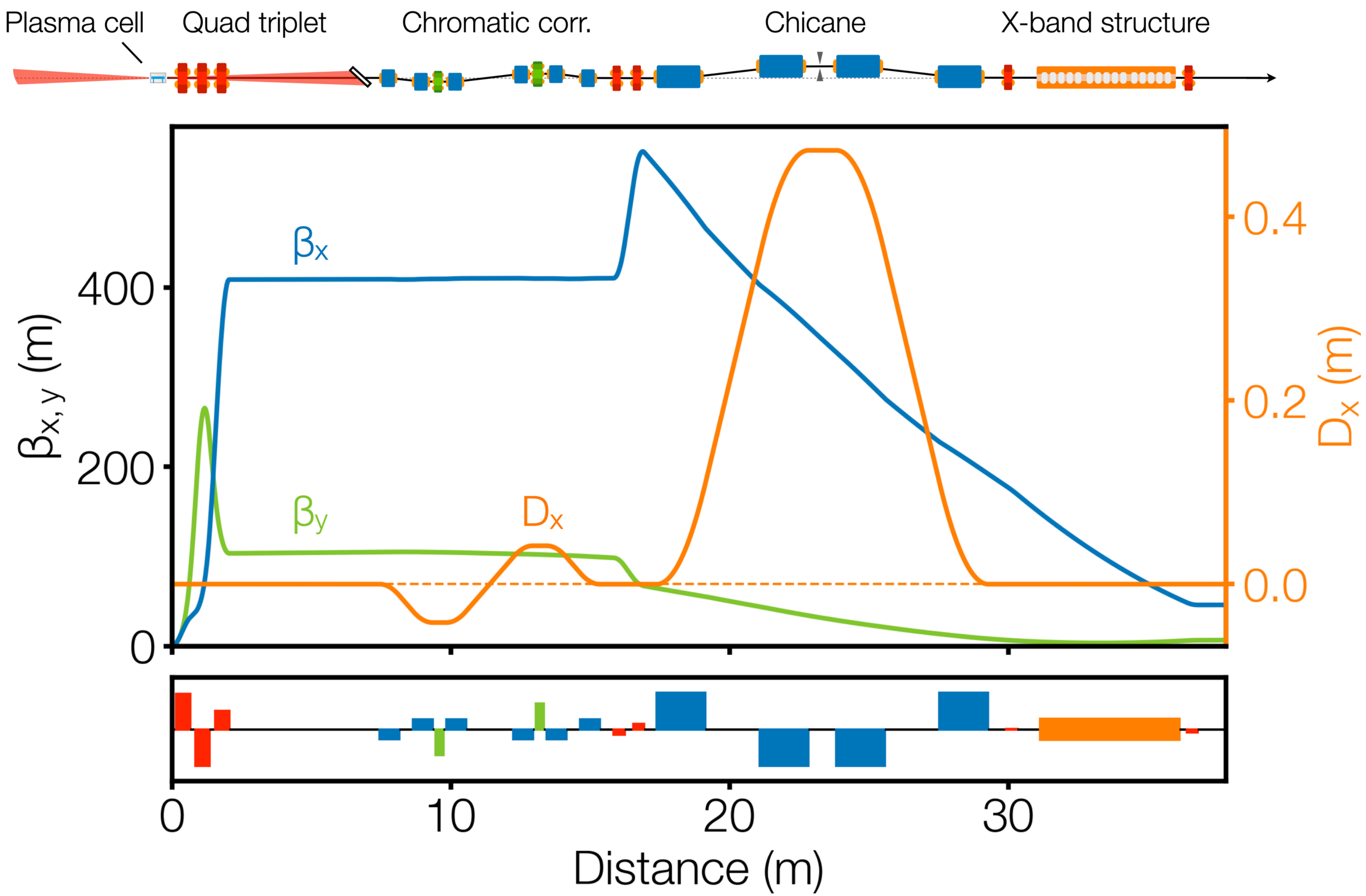
6 GeV beamline with X-band energy compression

Beam capture, chromatic correction, energy compensation



Solely existing, conventional hardware

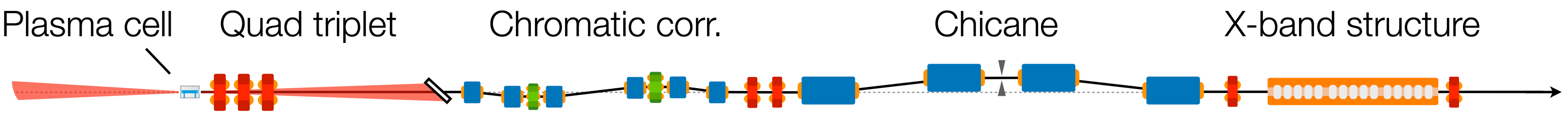
- Magnets – synchronized with the rest of PETRA IV project
- X-band RF – CompactLight design 50 MW, 60 MV/m (W. Wuensch, XLS-Rep.-2021-004)
- S. Antipov et al, PRAB 24 (2021)

An active plasma stage can make it more compact

- A. Ferran Pousa et al, PRL 129 (2022)

Three-stage numerical tracking

Laser to the storage ring



FBPIC

- Laser-plasma interaction
- Wakefields
- Beam loading
- Plasma density downramp assisted ionization injection

`https://github.com/fbpic/fbpic`

Ocelot

- Transport
- RF
- CSR
- Collimation

`https://github.com/ocelot-collab/ocelot`

Elegant

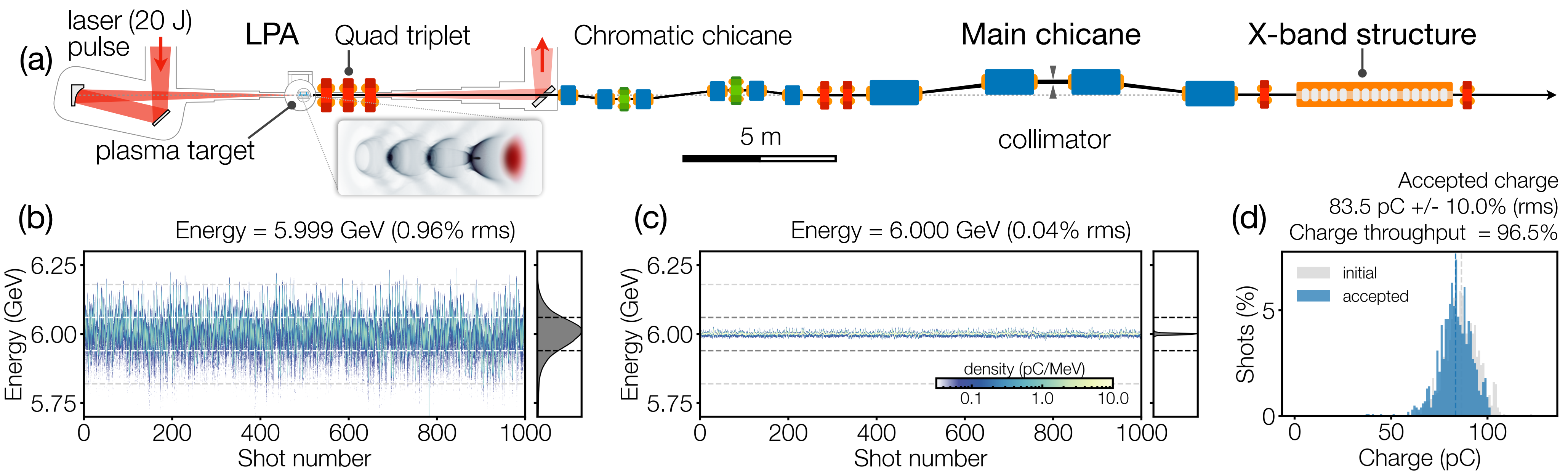
- Lattice errors
- Main & harmonic RF
- Synch rad. damping
- Physical aperture
- Wakefields

`https://www.aps.anl.gov/Accelerator-Operations-Physics/Software`

Streamlined start-to-end procedure developed by A. Ferran Pousa and A. de la Ossa

Start-to-end simulations demonstrate high beam quality

With chromatic correction and energy compression, under realistic jitters



Jitters : {0.75 mm in z_f, 0.75% in E_L , 0.75% in n_p, 0.2 mrad in θx, 0.1 mrad in θy, 100 fs in RF timing}

Courtesy A. de la Ossa

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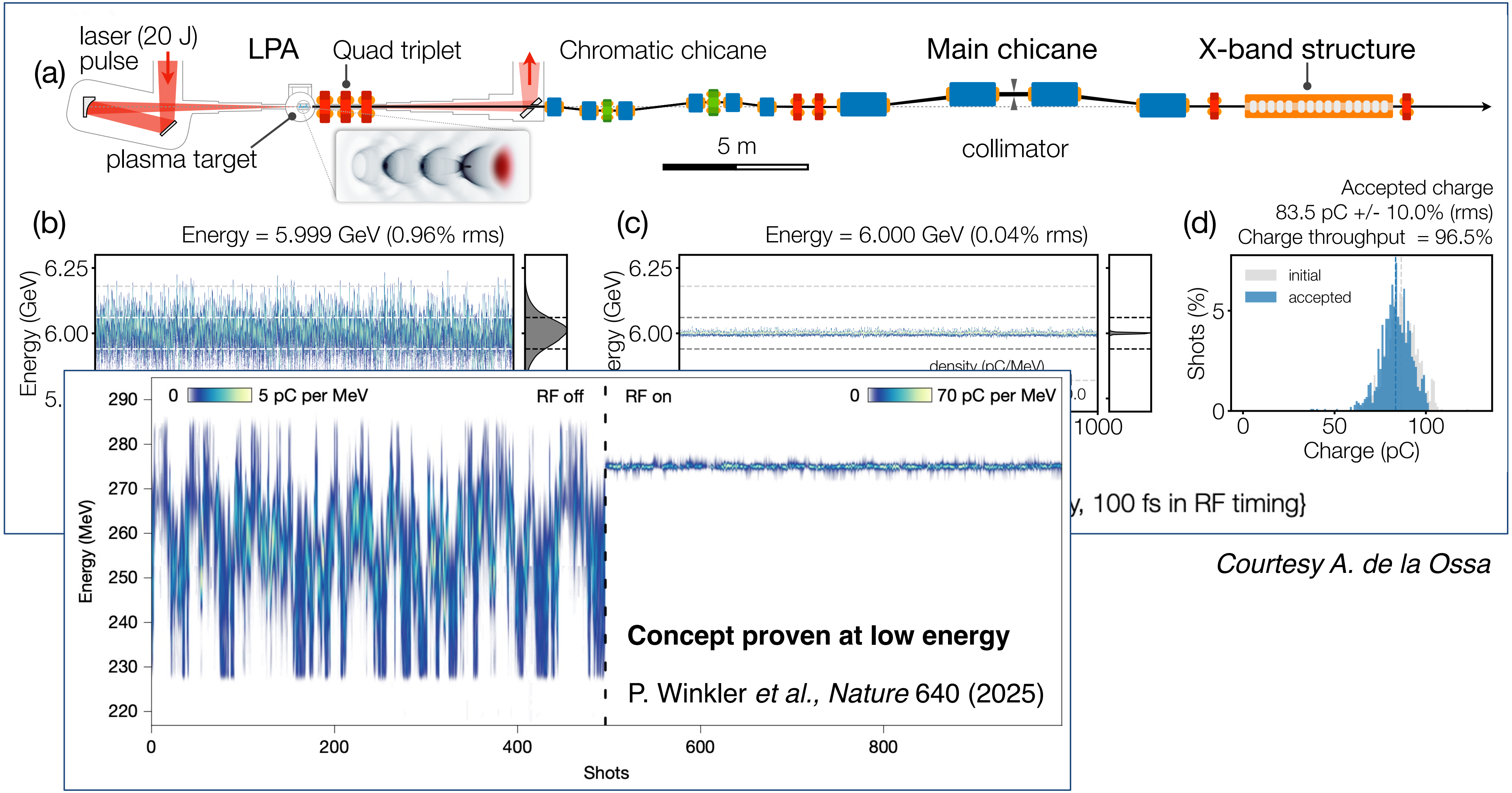

Courtesy A. de la Ossa

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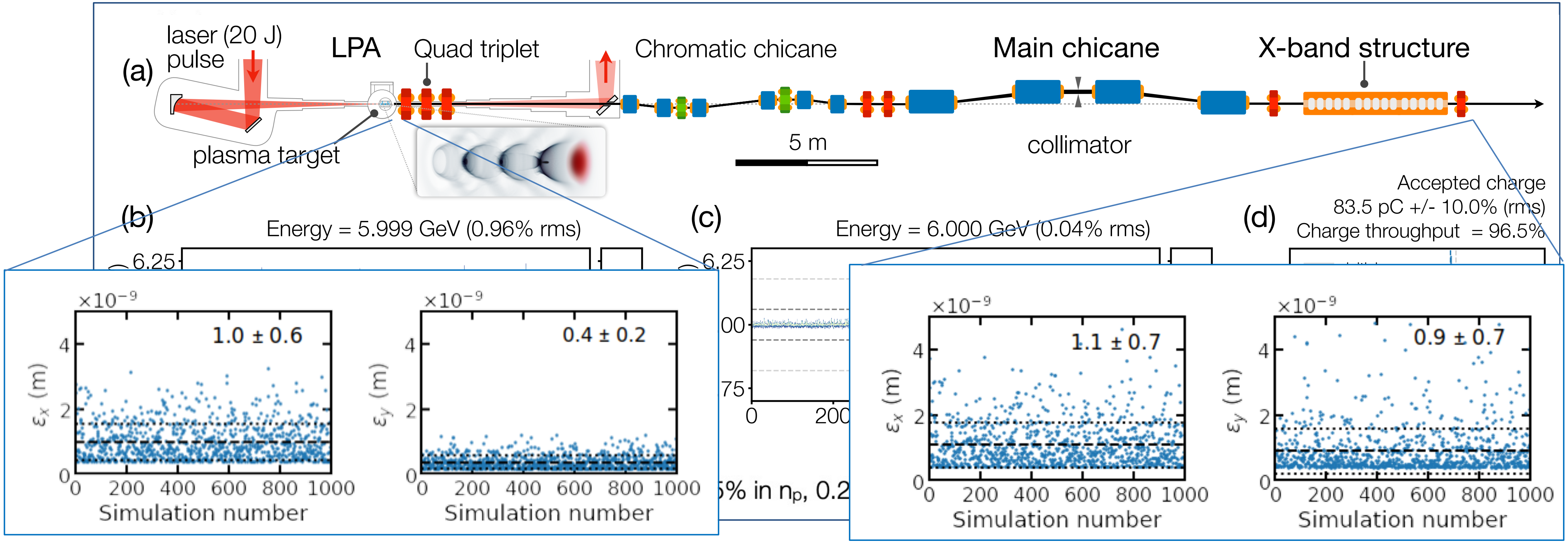


Emittance smaller than from a state-of-the art low-emittance booster synchrotron

- LPA: (1, 1 nm)
- DESY IV: (21, 2 nm)

Are we done?

Not yet

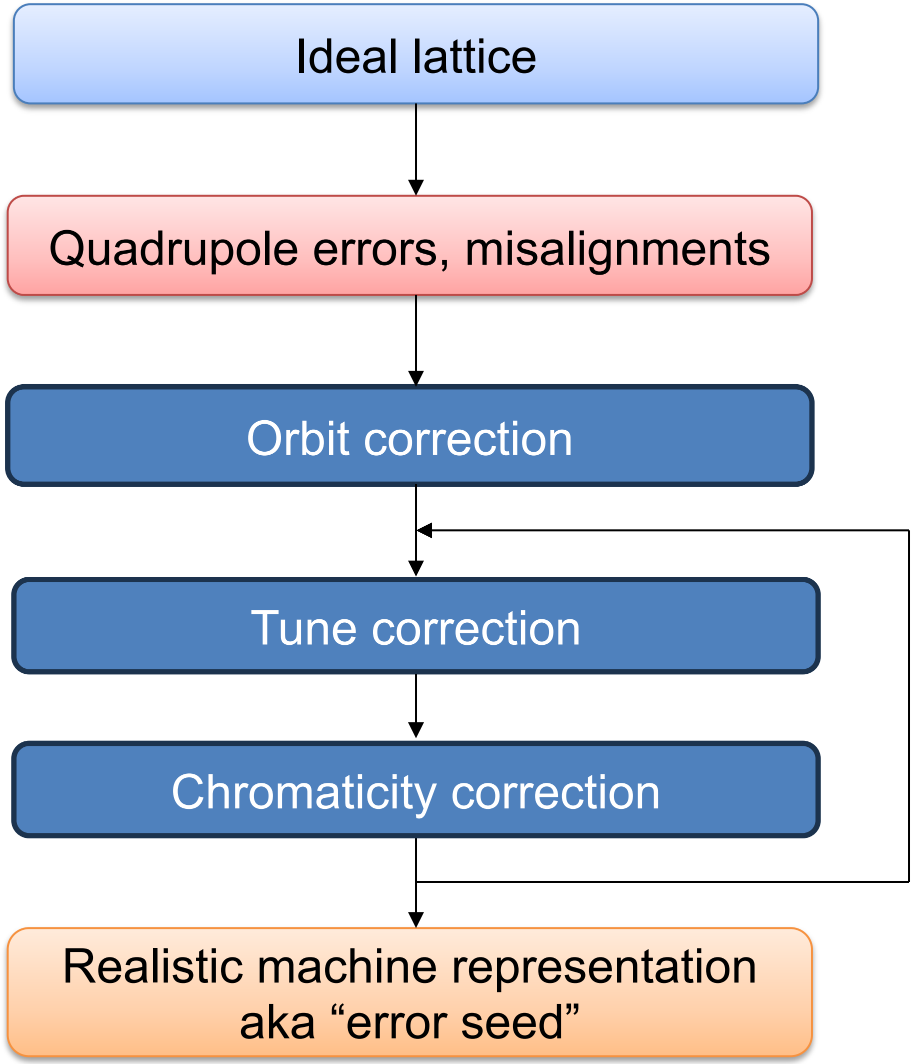
Error studies

A real accelerator is not an ideal model

Realistic machine representations are produced based on assumed errors

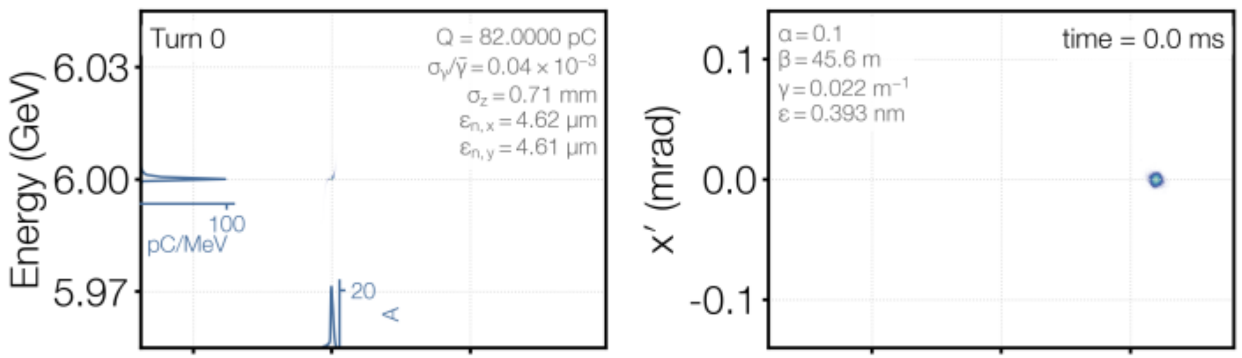
Assumed magnet and diagnostics errors

Error Type	rms value	Error Type	rms value
Girder rolls	200 µrad	BPM offset	500 µm
Girder transverse offset	150 µm	BPM roll	400 µrad
Magnet transverse offset	30 µm	BPM noise (TbT)	50 µm
Magnet rolls	200 µrad	BPM noise (CO)	0.1 µm
Quadrupole calibration	0.05 %	BPM calibration	5 %
Dipole/Sextupole calibration	0.1 %	CM calibration	2 %



Injection into a ring

No losses observed in the injected beam



- Element-by-element simulation in ELEGANT
- 20 realistic error seeds, 5% rms β-beating
- Negligible 10^{-4} losses in one case
- No special beam manipulation (beam rotation or aperture sharing) required

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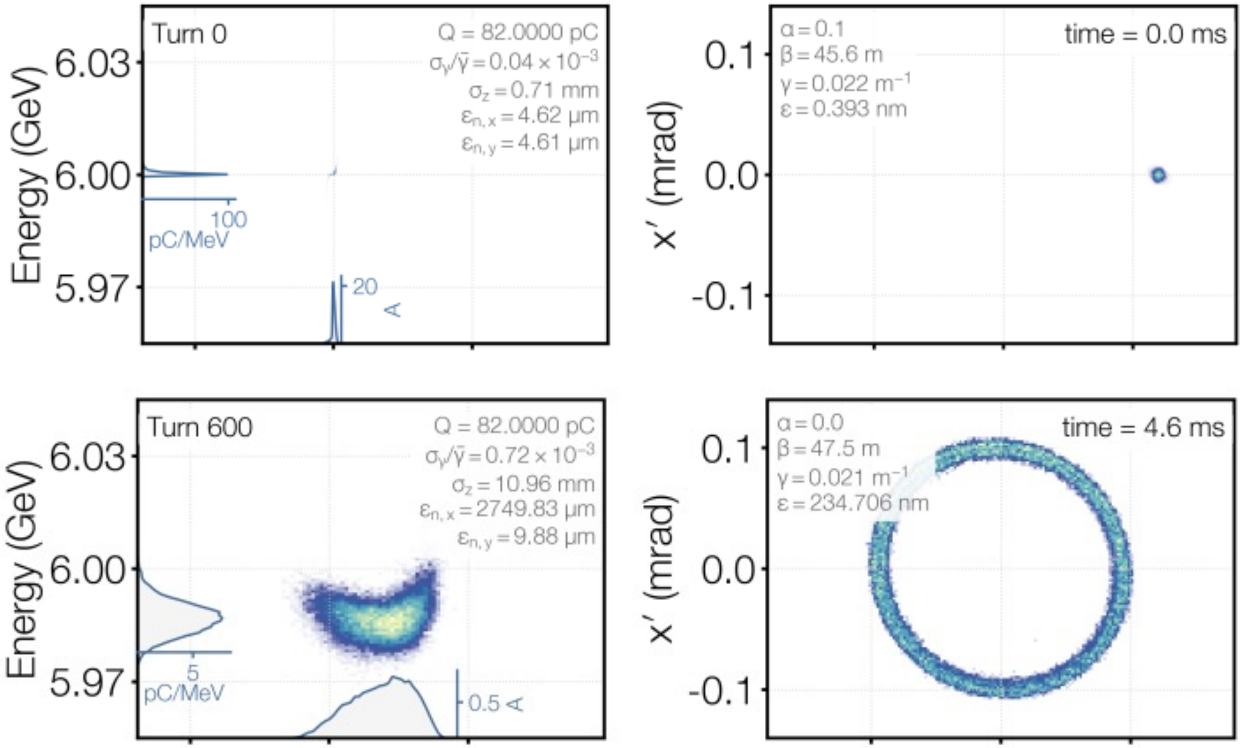

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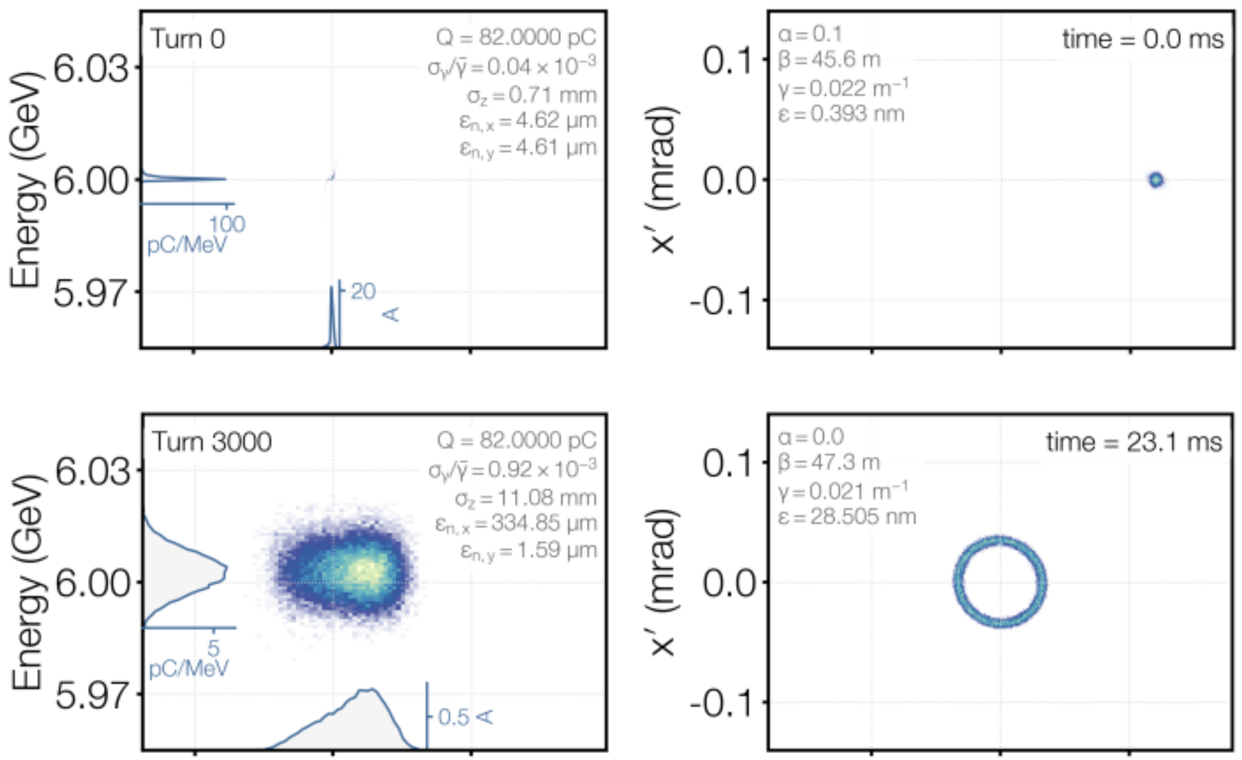

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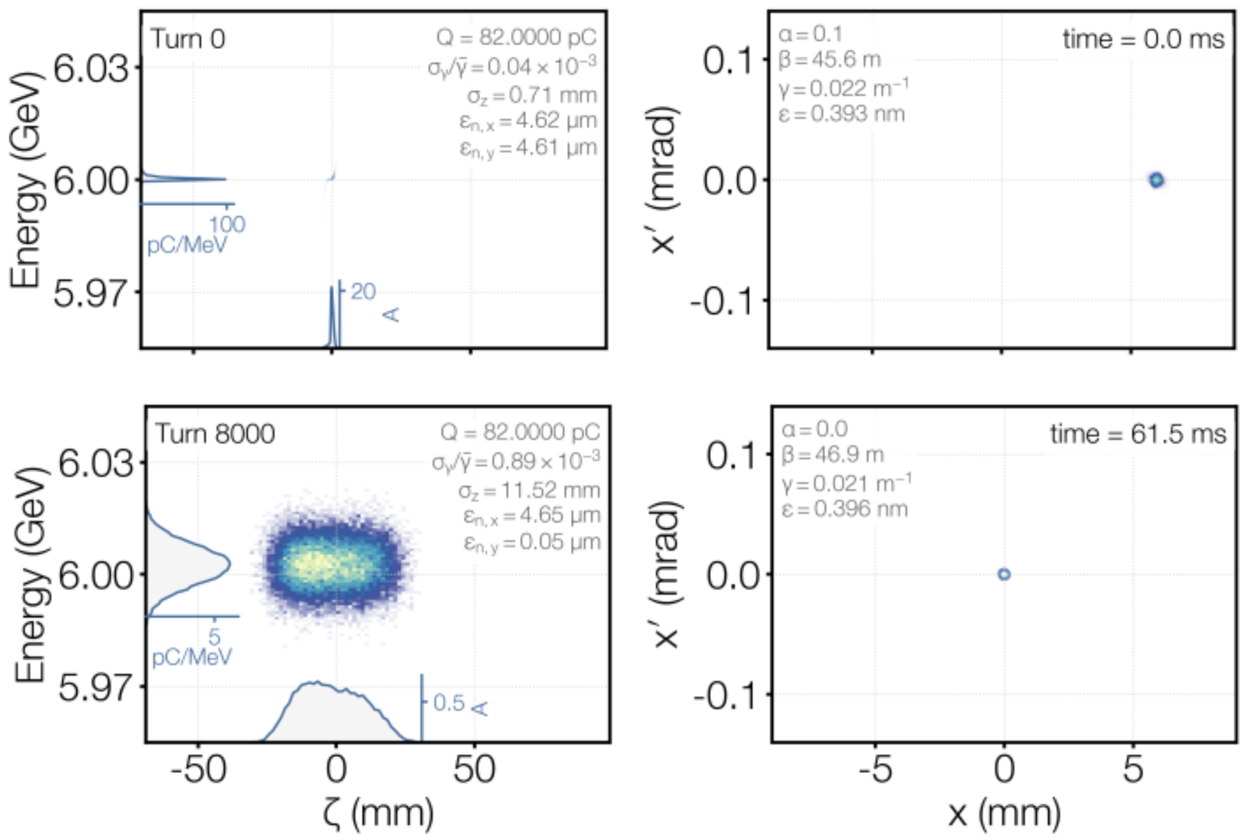

A. de la Ossa et al., PIP IV CDR, 2024

- Element-by-element simulation in ELEGANT
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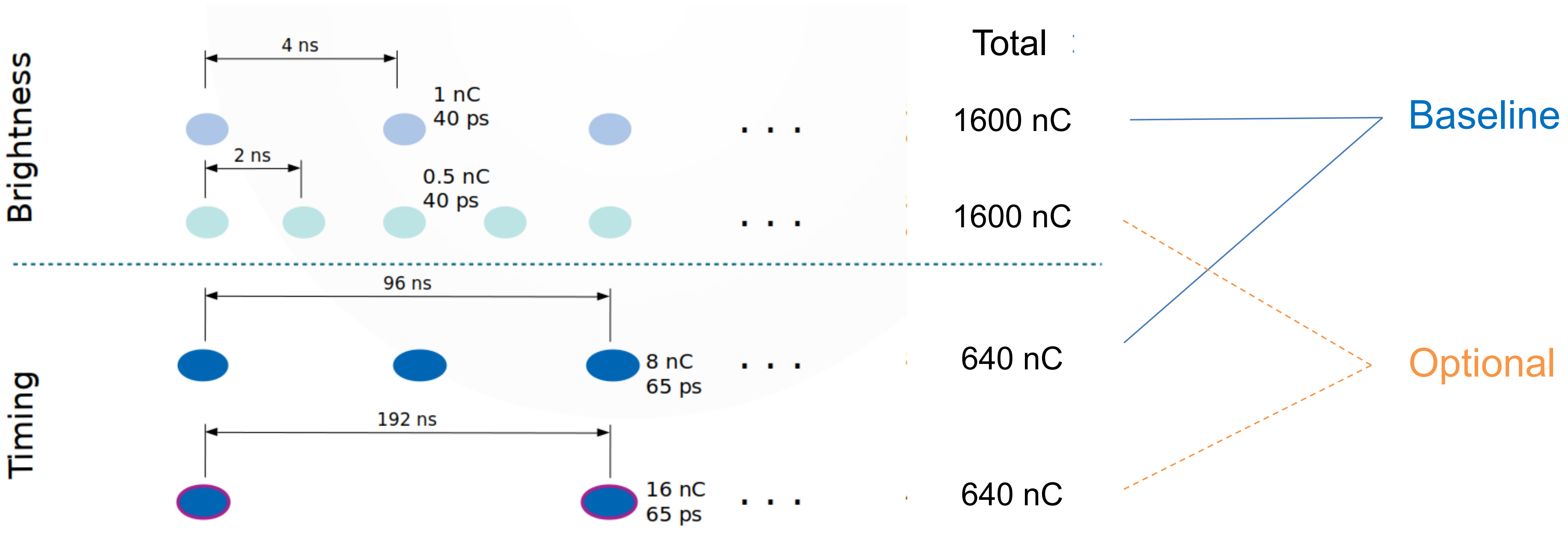
Are we done now?

Getting close…

Charge accumulation in the ring

PETRA IV offers a variety of operation modes

An injector must support all of them



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

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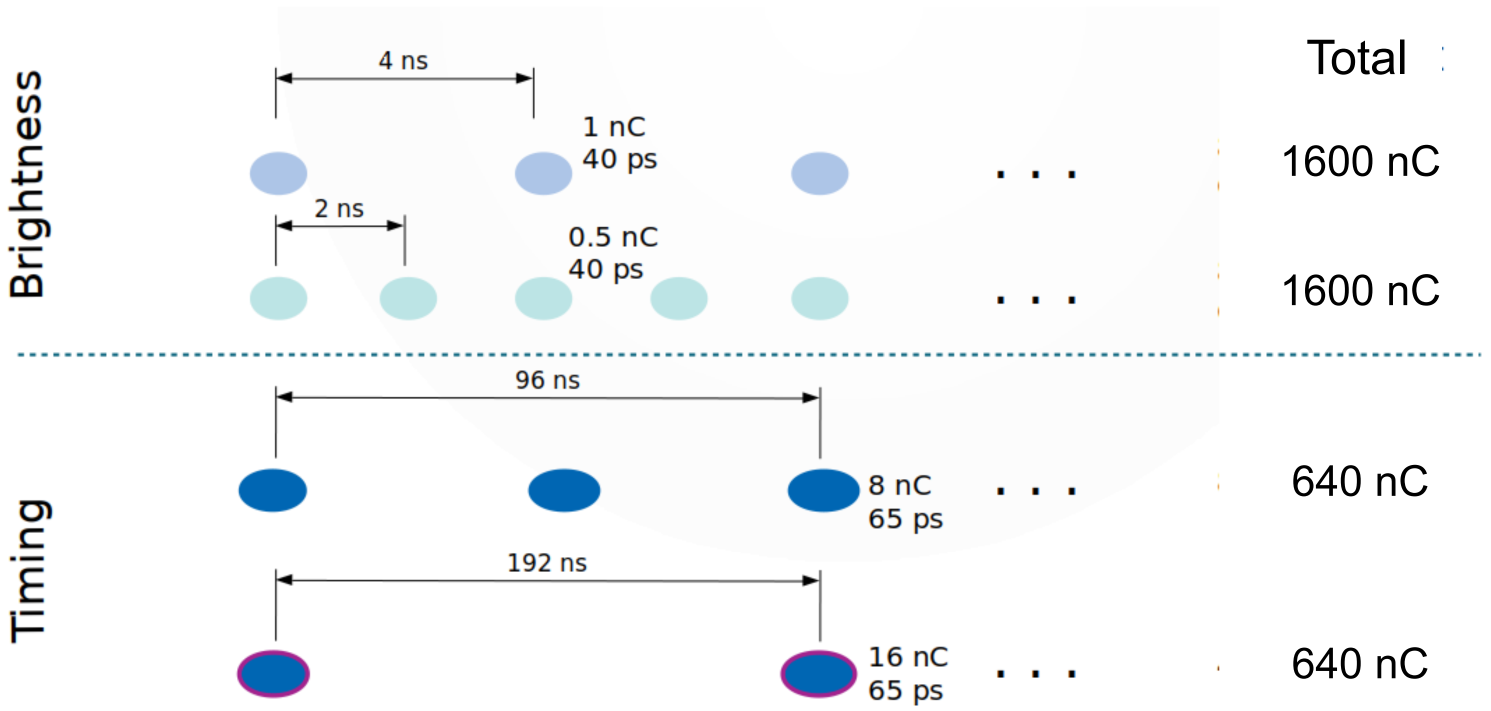


The ring takes care of charge accumulation

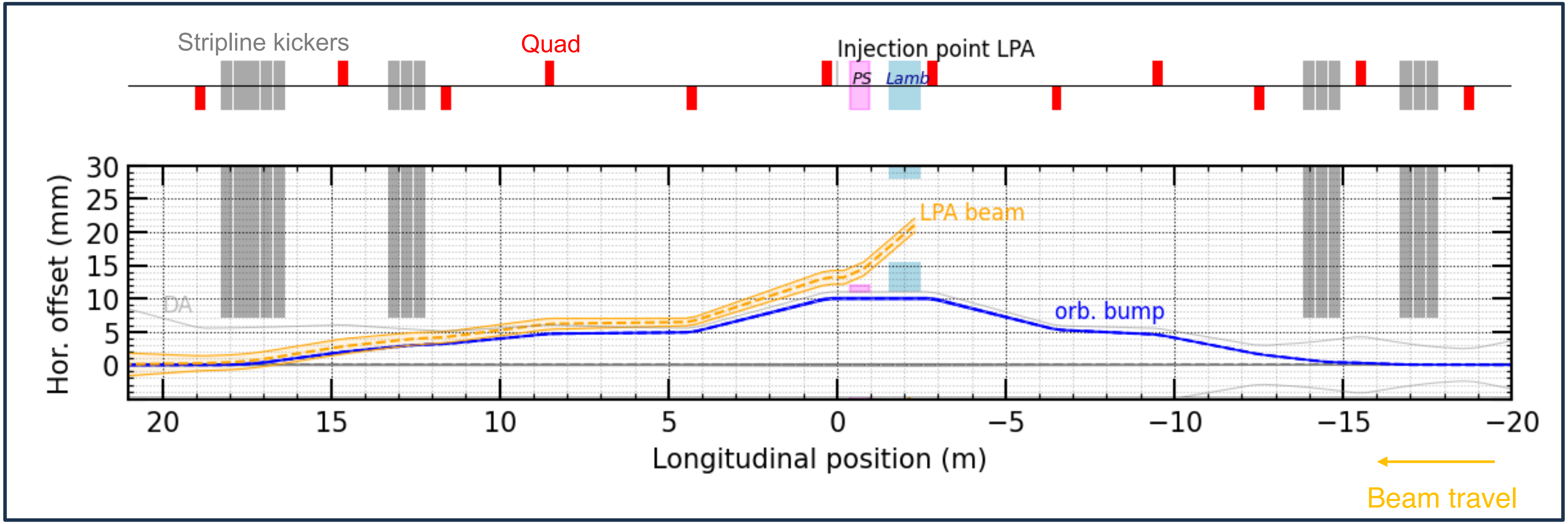
- Large lifetime 10-40 h
- "Top-up" injection scheme

"Just" supply enough charge within the phase space acceptance

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

Top-up injection at PETRA IV

A combination of a fast orbit bump and a thin pulsed septum kick



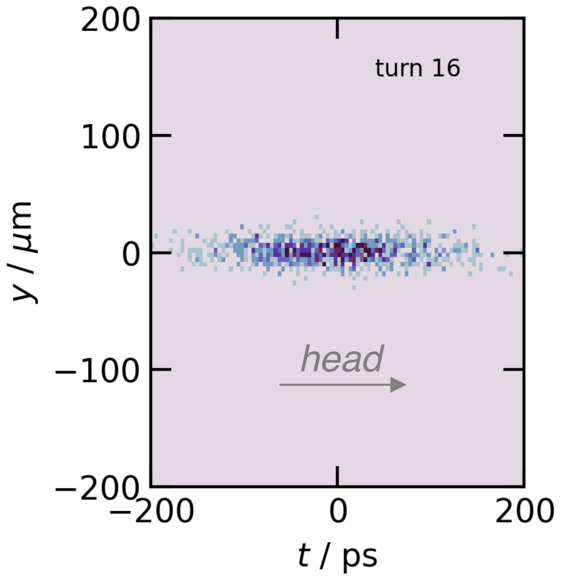
Stored bunch might have residual oscillations after the process

- Parasitic: kicker voltage jitter, optics errors
- Intentional: to provide more room for the injected bunch

Instability at high intensities

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

Before

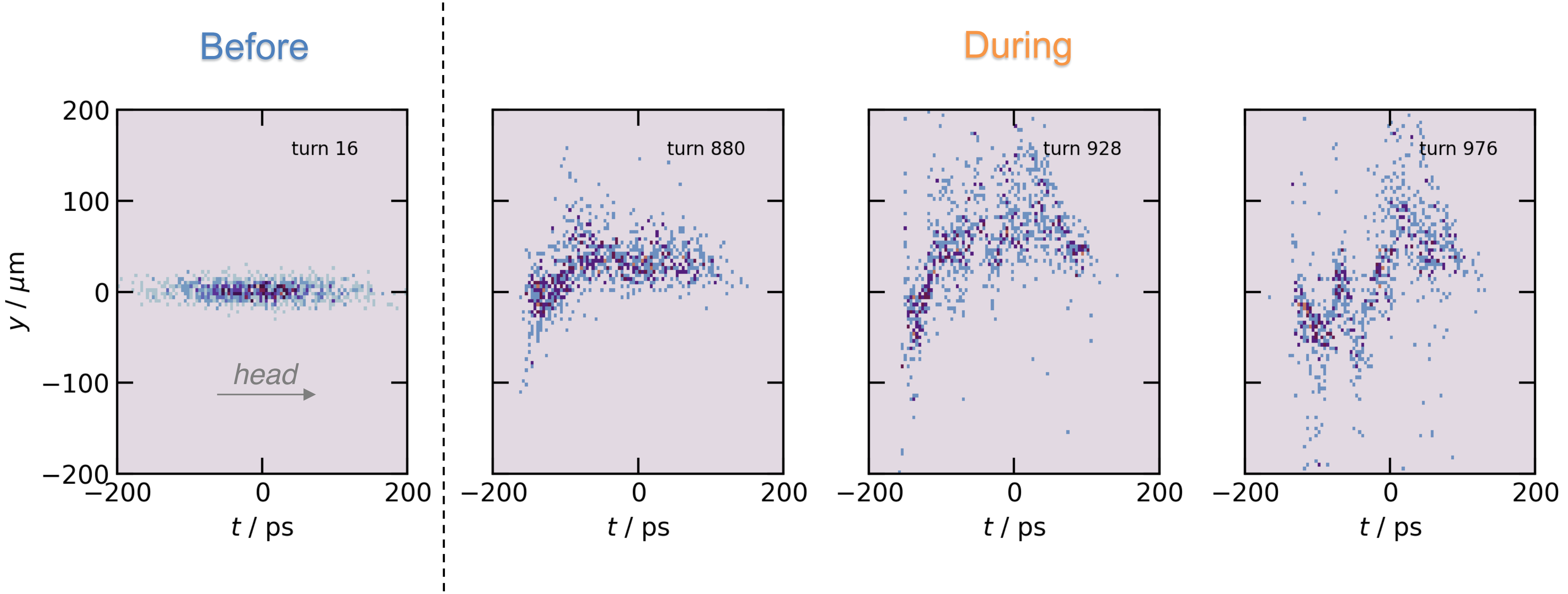


High-charge Timing mode

- 14 nC in the stored bunch
- Starts from jitter

Instability at high intensities

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



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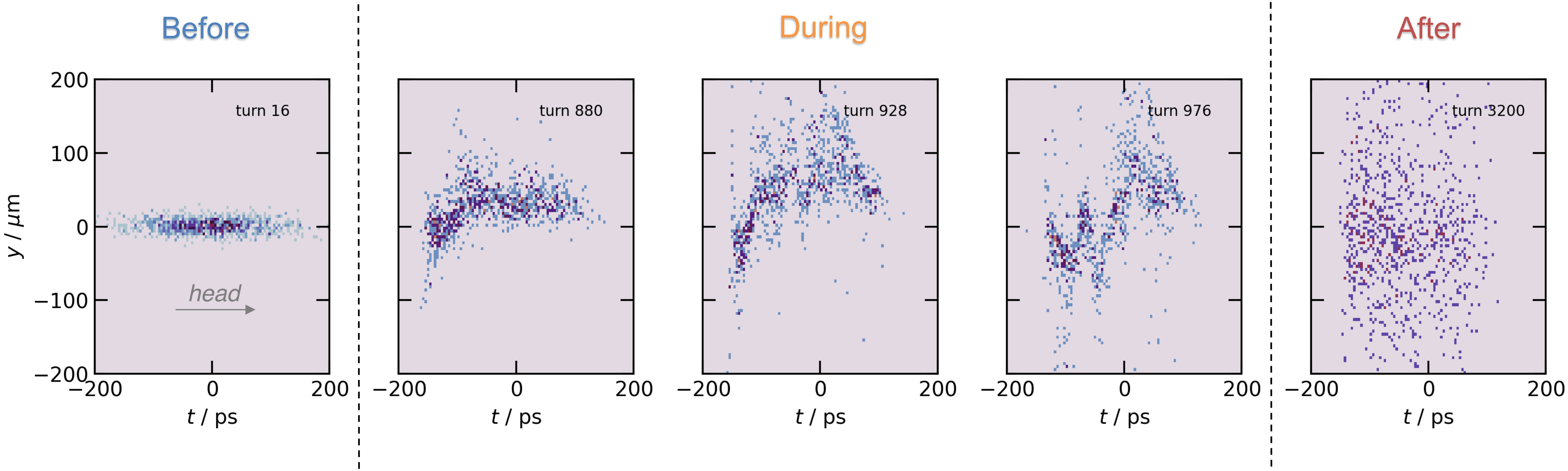


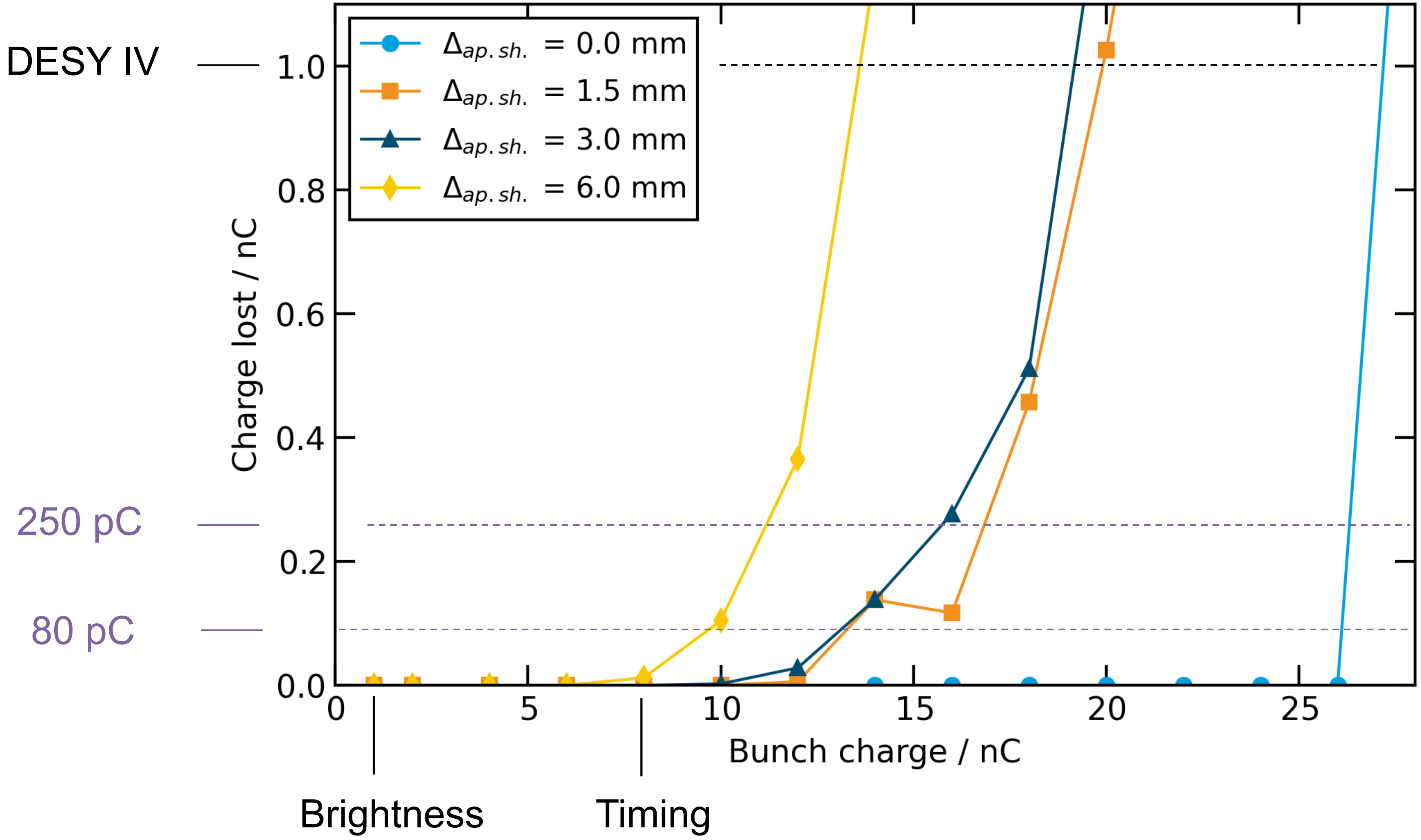
Most charge losses happen in the stored bunch

Y.-C. Chae, IPAC'07, CERN, 2007

S. Antipov, LER'24, CERN, 2024

LPA can accumulate charge for main baseline fill patterns

Theoretical limit is reached when lost charge = injected charge



OK, but now we are finally done, right?

Still not yet

Ring commissioning with LPA beams

LPA beams present a unique challenge for commissioning

Lower charge means worse BPM resolution, critical for establishing the orbit

Threading (1-2 turn store)

Beam-based alignment

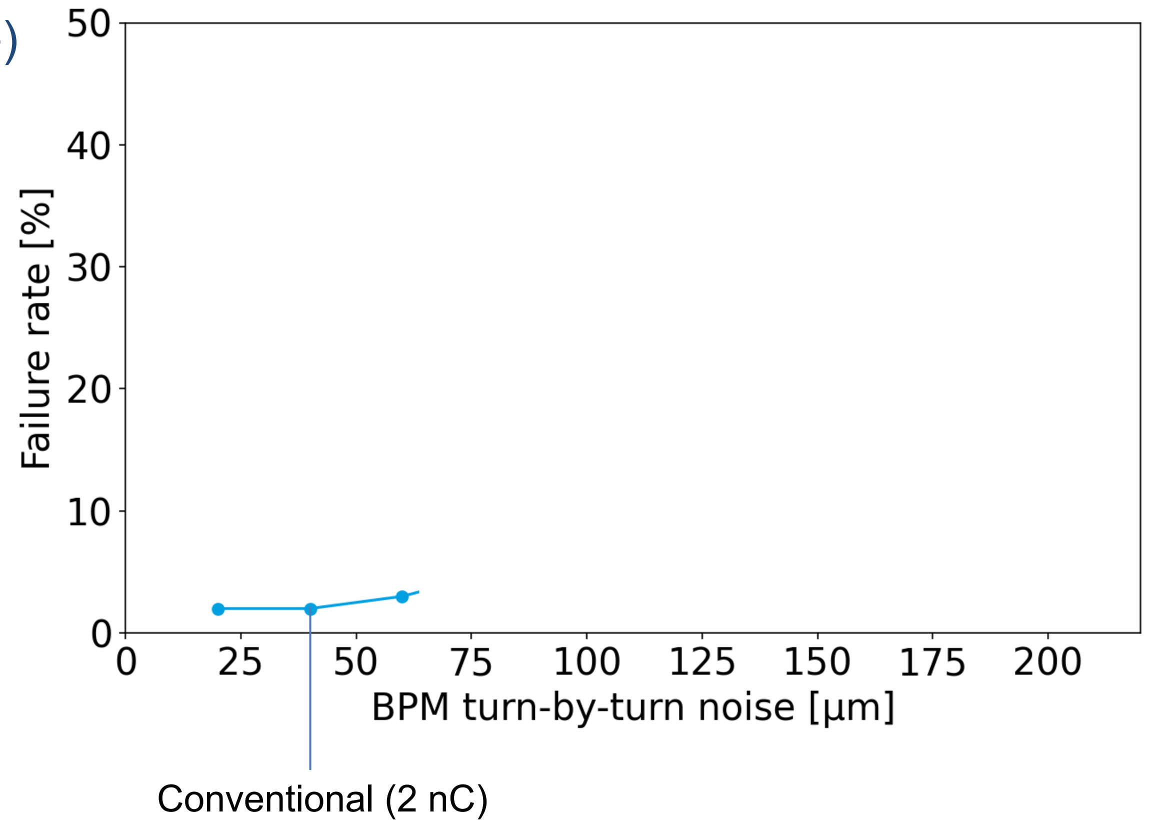
Multipole ramp-up

RF setup

Linear optics correction

ID compensation

Commissioning failure likelihood based on 100 seeds



Courtesy K. Paraschou

https://github.com/lmalina/pySC

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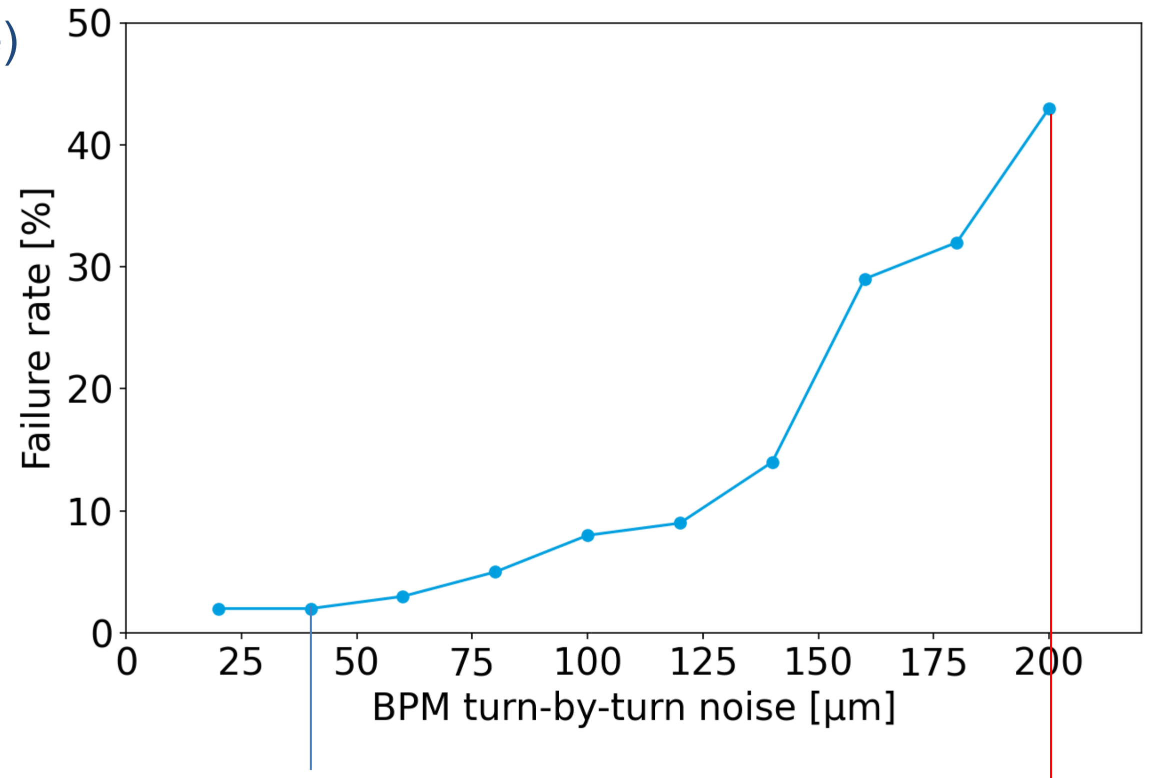


Conventional (2 nC) /

LPA (250 pC)

LPA (80 pC)

Way forward

- Reducing pointing jitter
- Improving BPM resolution
- LPA-beam specific commissioning routines

Courtesy K. Paraschou

Do you have a light source?

Build your own plasma injector

Ring with top-up injection & long lifetime

LPA with low energy spread & divergence

Chromatic correction & energy compression

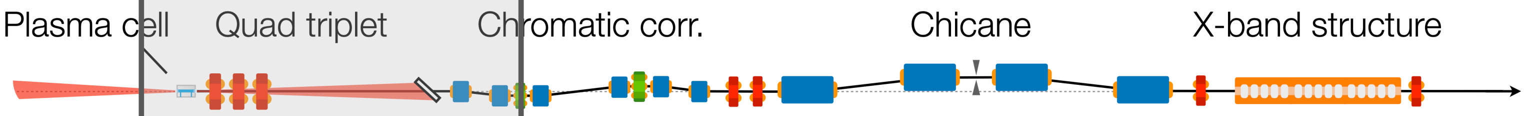
Thank you for your attention

Extras: Beam capture and manipulation

A combination of proven, tested techniques

6 GeV beamline with X-band energy compression

Beam capture, chromatic correction, energy compensation



High-gradient
EM quadrupoles

- Synchrotron light sources
- 120 T/m

A. Aloev et al
IPAC'22

Solely existing, conventional hardware

- Magnets – synchronized
  with the rest of PETRA IV project

- X-band RF – CompactLight design
  50 MW, 60 MV/m
  (W. Wuensch, XLS-Rep.-2021-004)

6 GeV beamline with X-band energy compression

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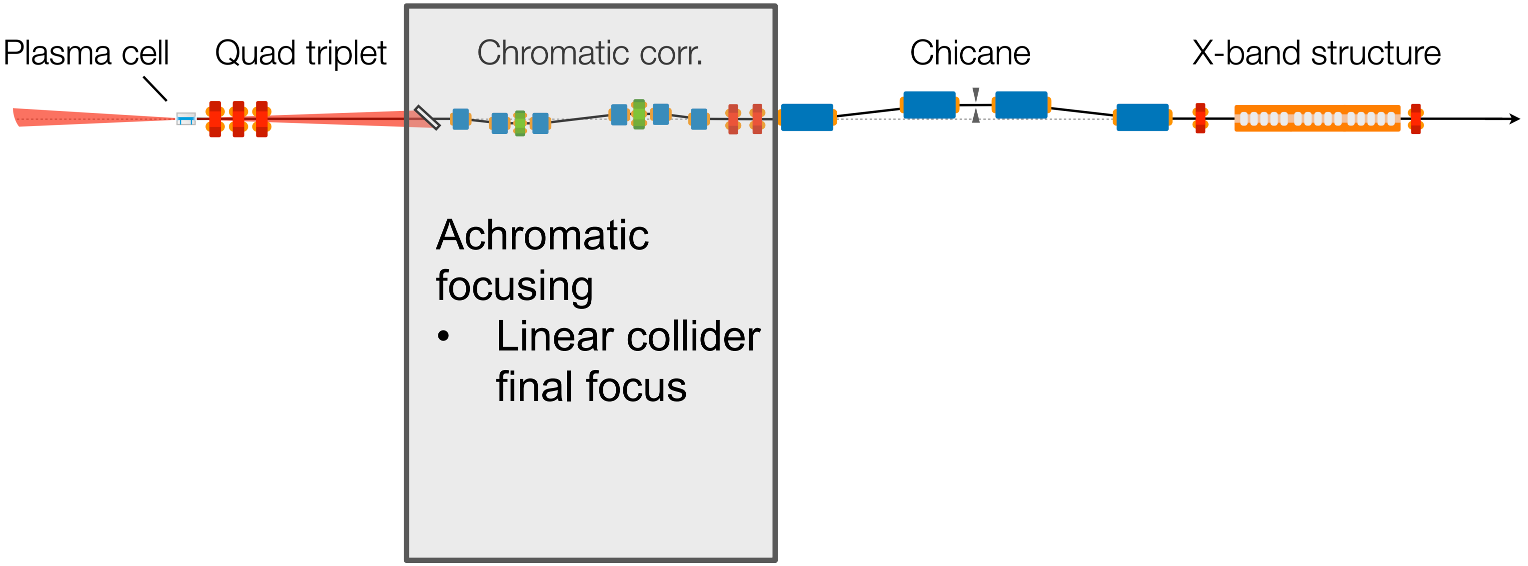

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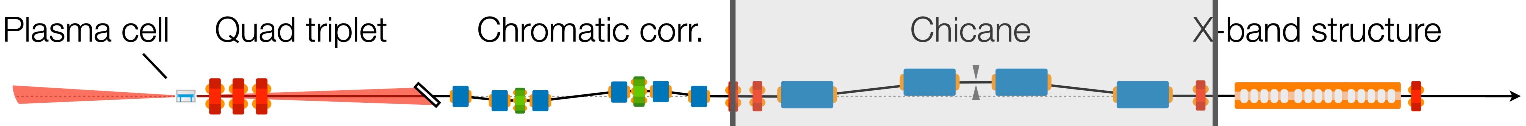

Rotation in phase space

- Free-electron lasers
- Low-energy hadron linacs

Solely existing, conventional hardware

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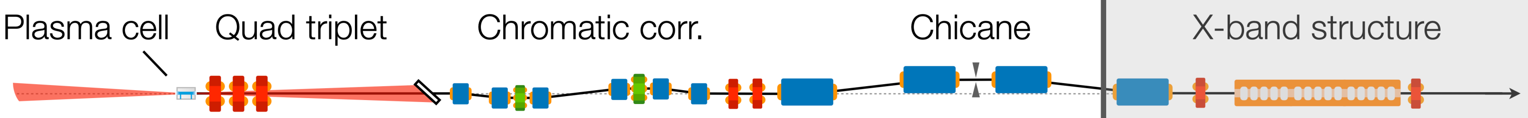
6 GeV beamline with X-band energy compression

Beam capture, chromatic correction, energy compensation



State-of-the-art laser-to-RF synch
- Free-electron lasers
- S. Schulz et al IPAC'25

Solely existing, conventional hardware

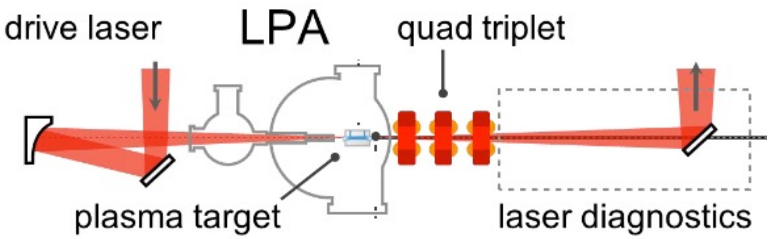
- Magnets – synchronized with the rest of PETRA IV project
- X-band RF – CompactLight design 50 MW, 60 MV/m (W. Wuensch, XLS-Rep.-2021-004)

Extras: Chromaticity correction

Why do we need it?

6 GeV beamline with X-band energy compression:

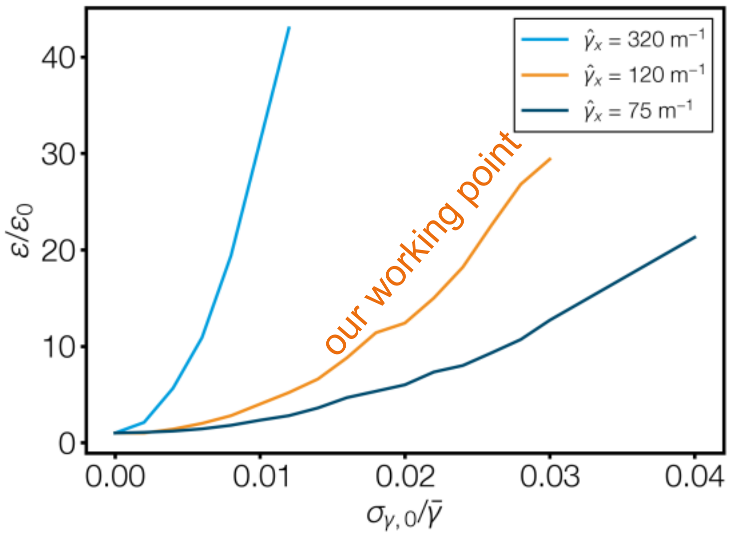
Emittance blows up unless the energy spread is small enough without chromatic correction

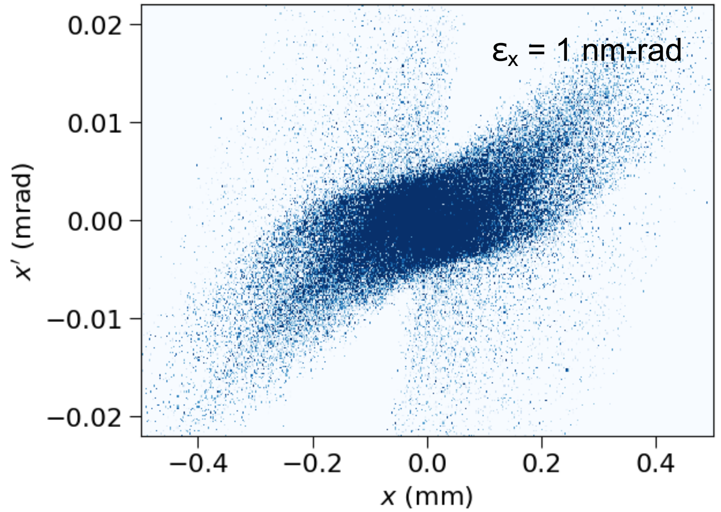


$$\frac{\epsilon^{\mathrm{f}}_{n,x}}{\epsilon_{n,x}} = \sqrt{1+\sigma_\gamma^2\left(1+\frac{L^2}{\hat{\beta}_x^{*2}}\right)} \approx 1 + \frac{1}{2}\sigma_\gamma^2\frac{L^2}{\hat{\beta}_x^{*2}}$$

-> K. Floettmann, PRST AB 6, 034202 (2003)

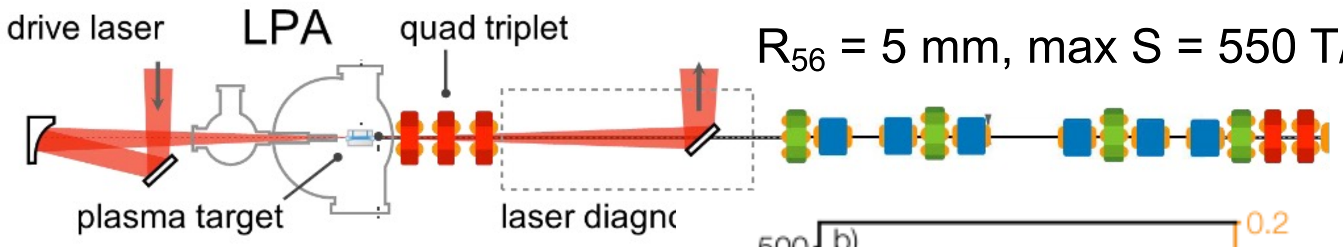
-> M. Migliorati et al., PRST AB 16, 1 (2013)



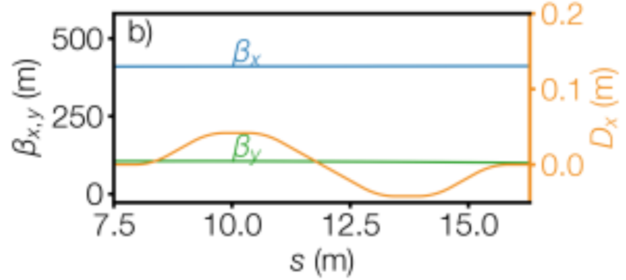


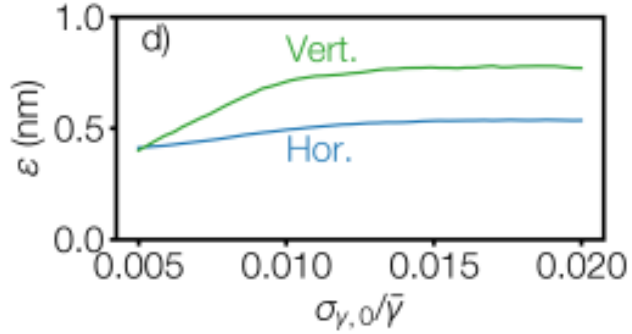
6 GeV beamline with X-band energy compression:

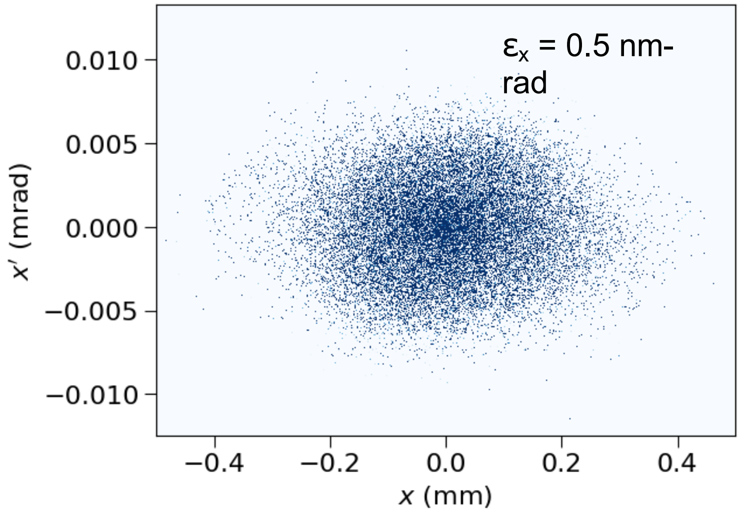
Chromatic correction is crucial for preserving small emittance



R_{56} = 5 mm, max S = 550 T/m^2

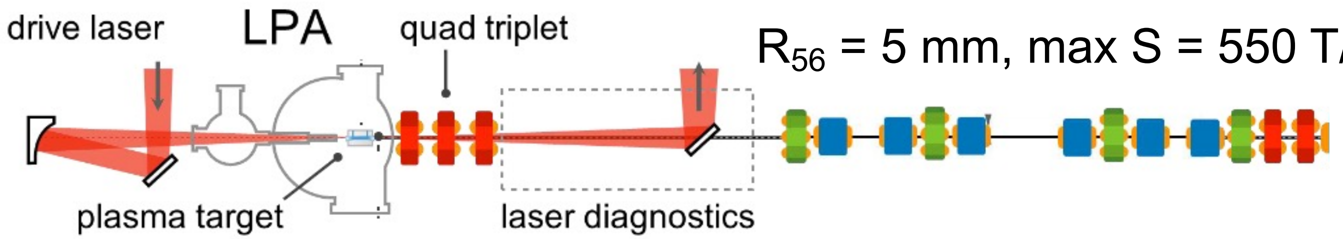






Coherent Synchrotron Radiation

Effect mitigated by the weak chromatic chicane



R_{56} = 5 mm, max S = 550 T/m^2

$$W_{\mathrm{CSR}} = mc^2 N_b r_e \left(\frac{\kappa}{\sigma_z^2}\right)^{2/3}$$

➞ C. Mayes and G. Hoffstaetter, PRST AB 12, 024401 (2009)

Chicane	**Main**	
	No prestr.	**With prestr.**
Bending angle	7.25 deg	
Bending field	1.45 T	
Dipole length	175 cm	
Bunch length, rms	3.2 µm	30 µm
CSR wakefield	2.7 MV/m	0.14 MV/m
CSR kick	**4.7 MeV**	**0.2 MeV**

Extras: Commissioning simulations

Why do we need them?

Error Analysis in Storage Ring Design - Past and Present

- Generate Error Ensembles
  - Gradient errors, misalignments, girders, etc.
- Correct Lattice
  - Closed orbit correction
  - Linear optics correction
- Evaluate Lattice Performance
  - Beta beat, orbit error
  - Injection efficiency, dynamic aperture, lifetime
- Statistical Evaluation
  - Calculate statistics of lattice performance
  - Limit error amplitudes to provide acceptable performance

Aerial view of the present DESY campus
with its PETRA III light source

T. Hellert, FLS Workshop, Lucerne, 2023

Error Analysis in Storage Ring Design - Past and Present

- Generate Error Ensembles
  - Gradient errors, misalignments, girders, etc.
- Correct Lattice
  - ~~Closed orbit correction~~ **No closed orbit!**
  - Linear optics correction
- Evaluate Lattice Performance
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The future 4^{th} generation light source PETRA IV on the DESY campus

T. Hellert, FLS Workshop, Lucerne, 2023

Error Analysis in Storage Ring Design - Past and Present

- Generate Error Ensembles
  - Gradient errors, misalignments, girders, etc.
- Correct Lattice
  - Start to finish commissioning simulation as realistic as possible*
- Evaluate Lattice Performance
  - Beta beat, orbit error
  - Injection efficiency, dynamic aperture, lifetime
- Statistical Evaluation
  - Calculate statistics of lattice performance
  - Limit error amplitudes to provide acceptable performance

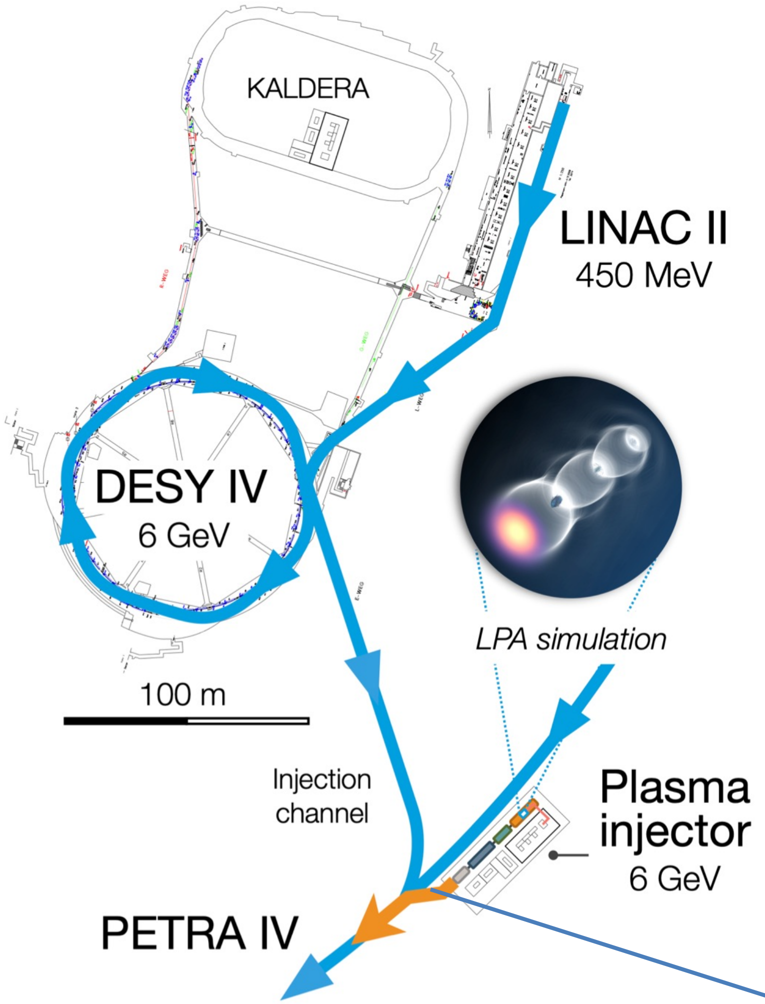
ALS-U SR

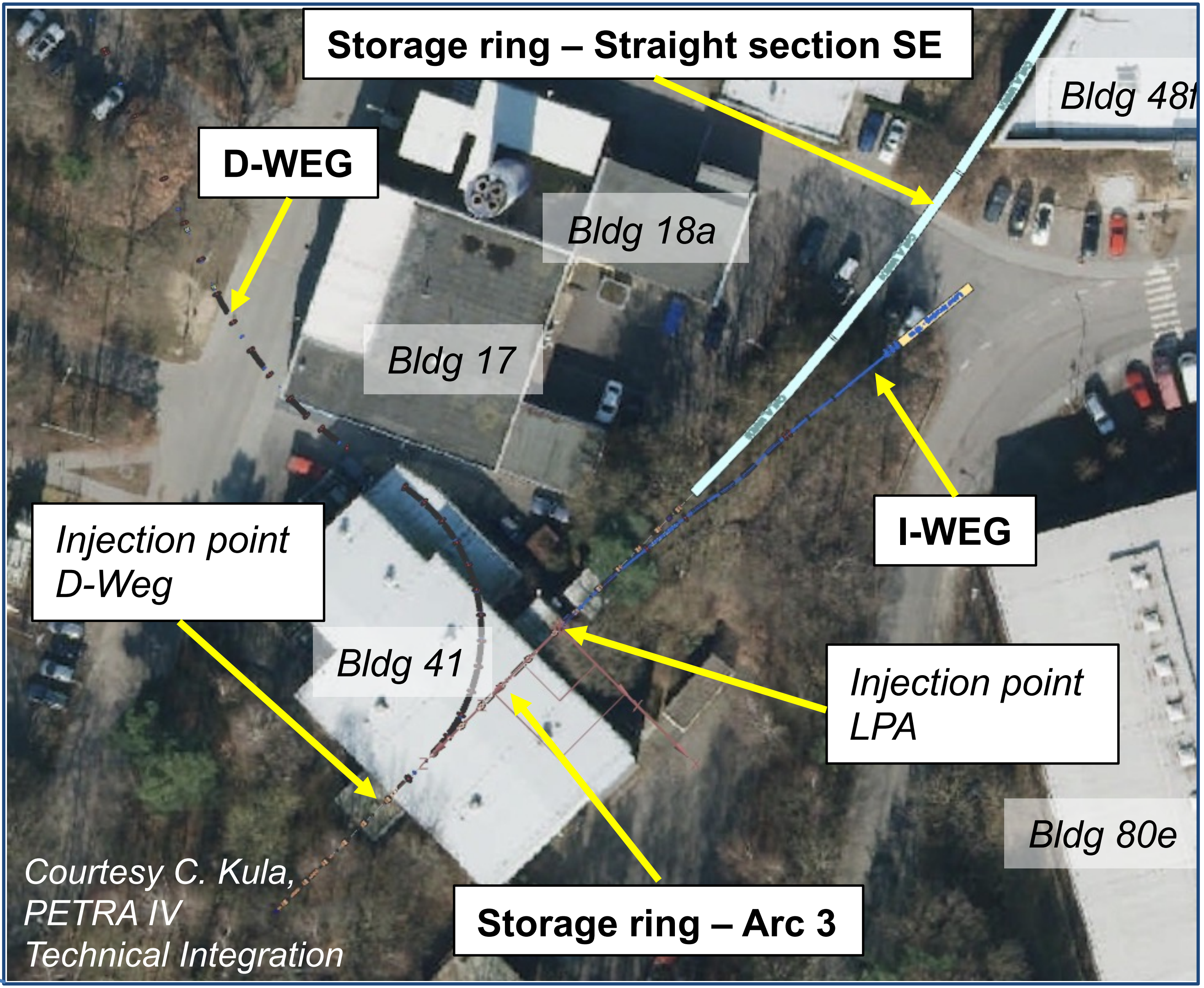
- **Initial Transmission**
  - Achieve first turn transmission
  - 2-turn trajectory correction
- **Multi-Turn Transmission**
  - Trajectory based BBA
  - Static injection error correction
- **Sextupole Ramp-Up**
  - In loop with 2-turn trajectory correction
- **Achieve Beam Capture**
  - RF phase and frequency correction
  - Tune scan
- **Linear Optics Correction**
  - Beam based alignment
  - Closed orbit correction
  - LOCO based optics correction
- **ID Compensation**
  - Close IDs and include kick maps
  - Global optics correction
  - Evaluation of lattice properties

T. Hellert, FLS Workshop, Lucerne, 2023

Extras: Example of layout on the DESY campus

From a concept towards a drawing





Extras: How do we get there?

Step-by-step

Energy compression proof-of-concept	2023-25	Existing LPA infrastructure at LUX Minimum modifications	Demonstrate x10 impovement in energy spread and stability Test synchronization, commissioning
Low energy injector demonstrator	2025-26	Existing ANGUS laser New beamline Existing DESY-II booster	Demonstrate injection around 400 MeV Most technologies in one setup
Full energy injector for PETRA	2027...	Upgraded laser Progress in plasma cells Supporting injection hardware at PETRA	Replace conventional injector chain, ultimately