# 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

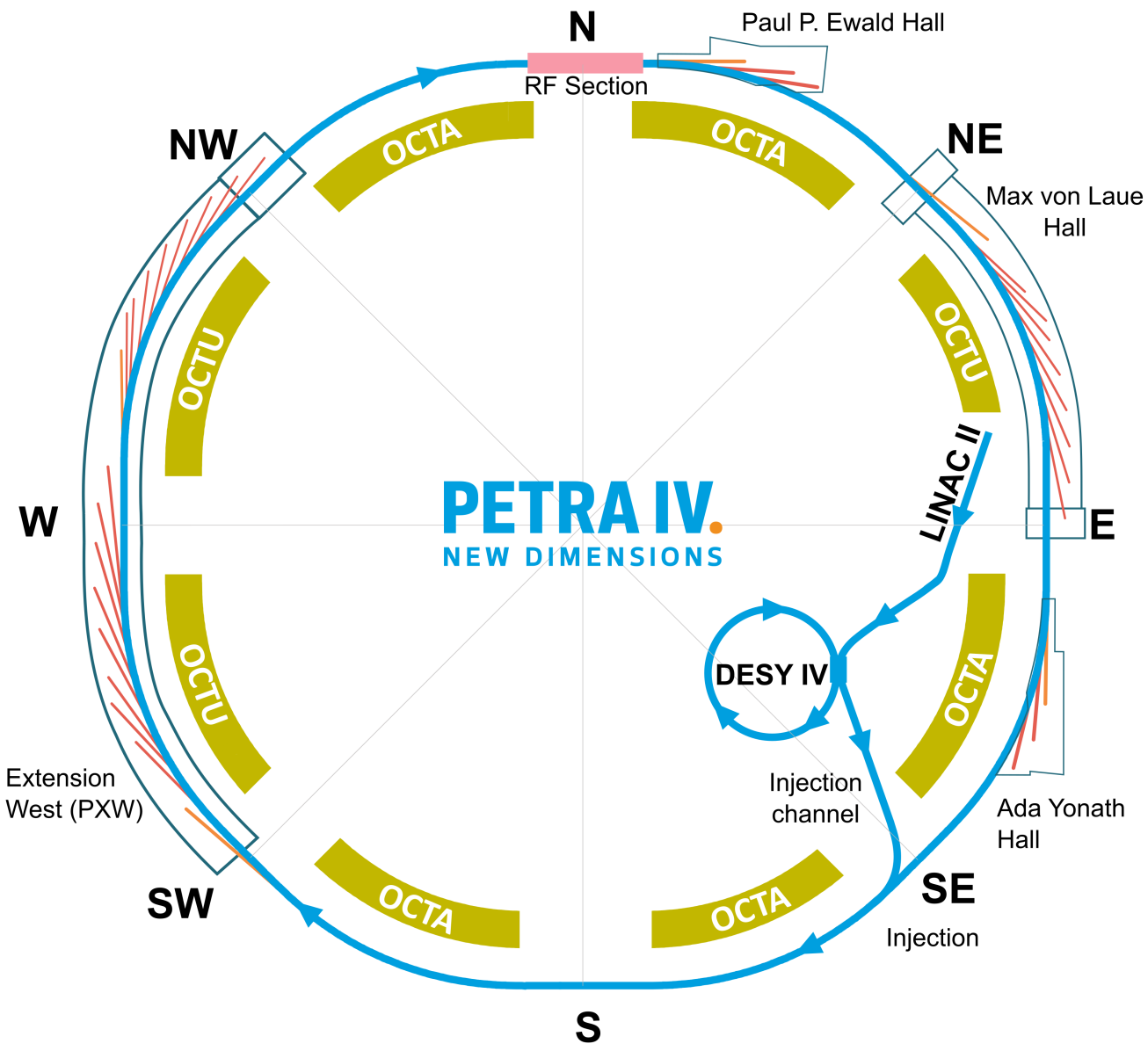
7th European Advanced Accelerator Conference, Isola d'Elba, Italy 26.09.25

HELMHOLTZ

DESY.

# PETRA IV: Germany's future flagship light source

## 6 GeV, 2.3 km, 20 pm-rad



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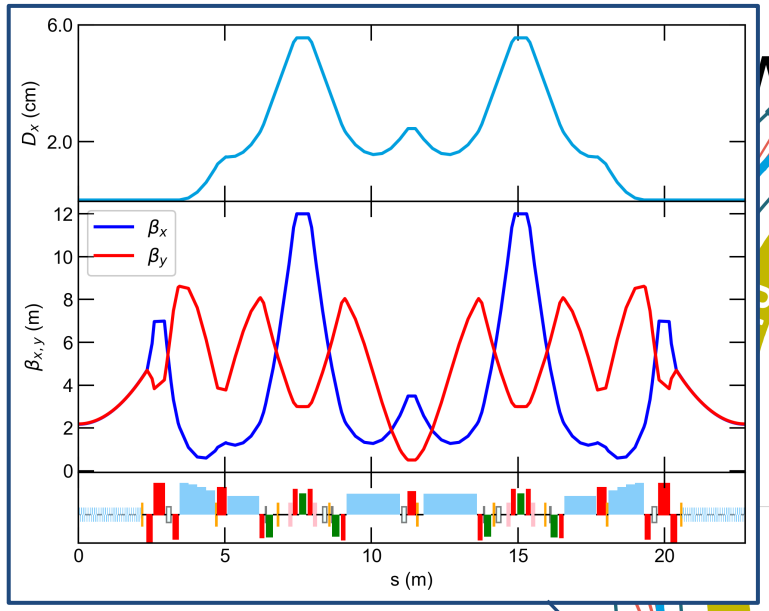
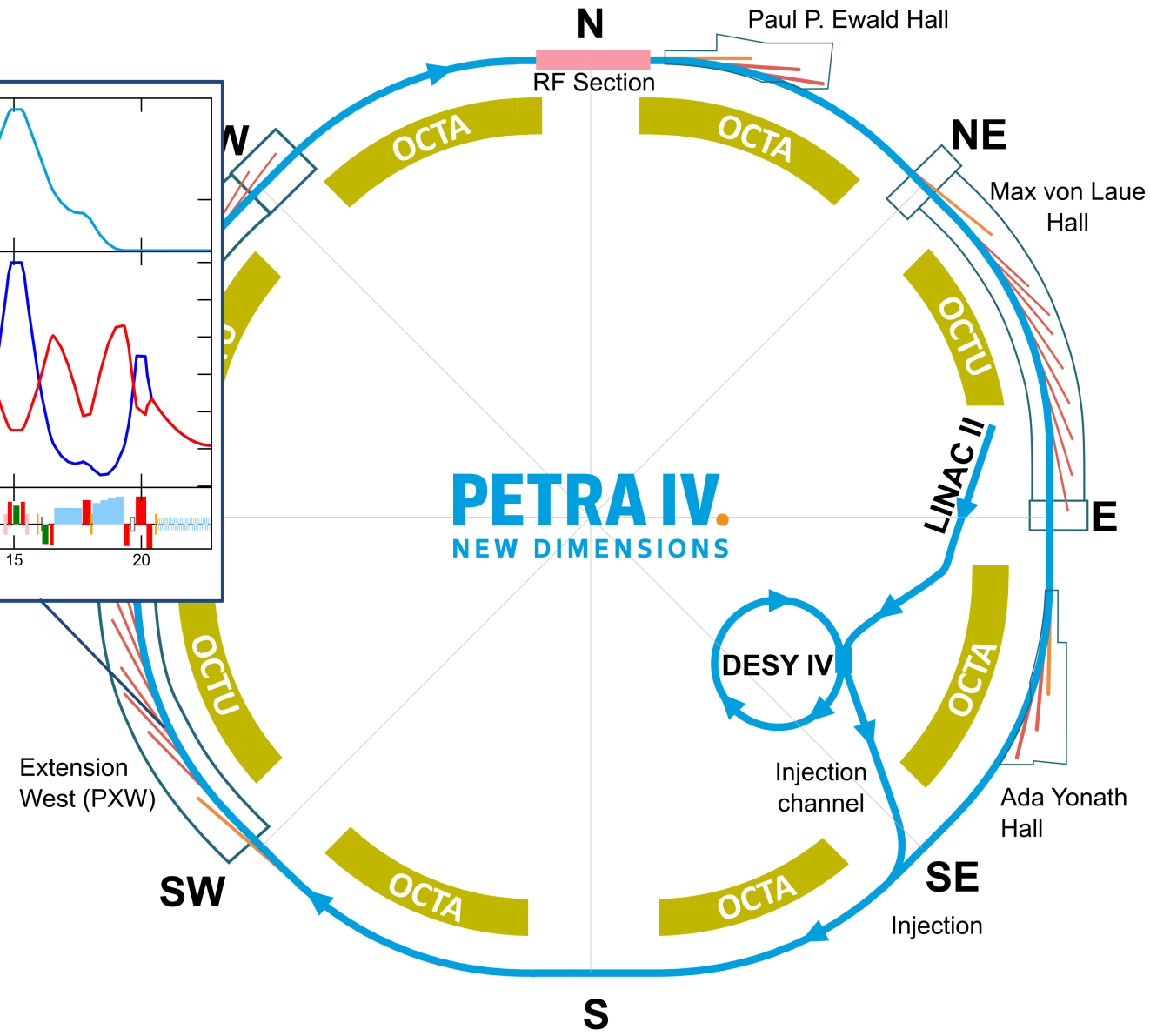
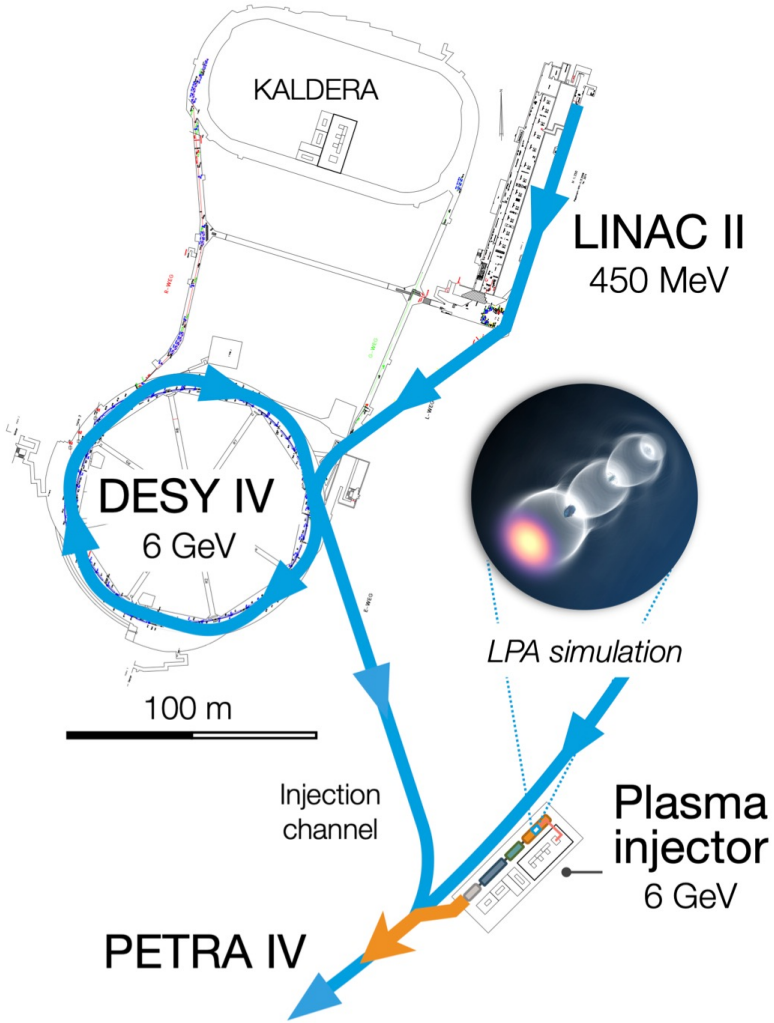



H6BA cell



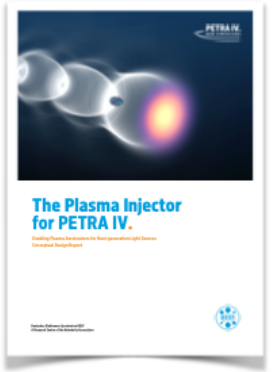
# Pursuing an ambitious LPA injector

## as a compact, cost-effective, competitive alternative




**CDR published:**

- A. de la Ossa et al, DESY Rep. PUBDB-2024-06078, 2024
- A. Maier (Tue 4:20 pm)

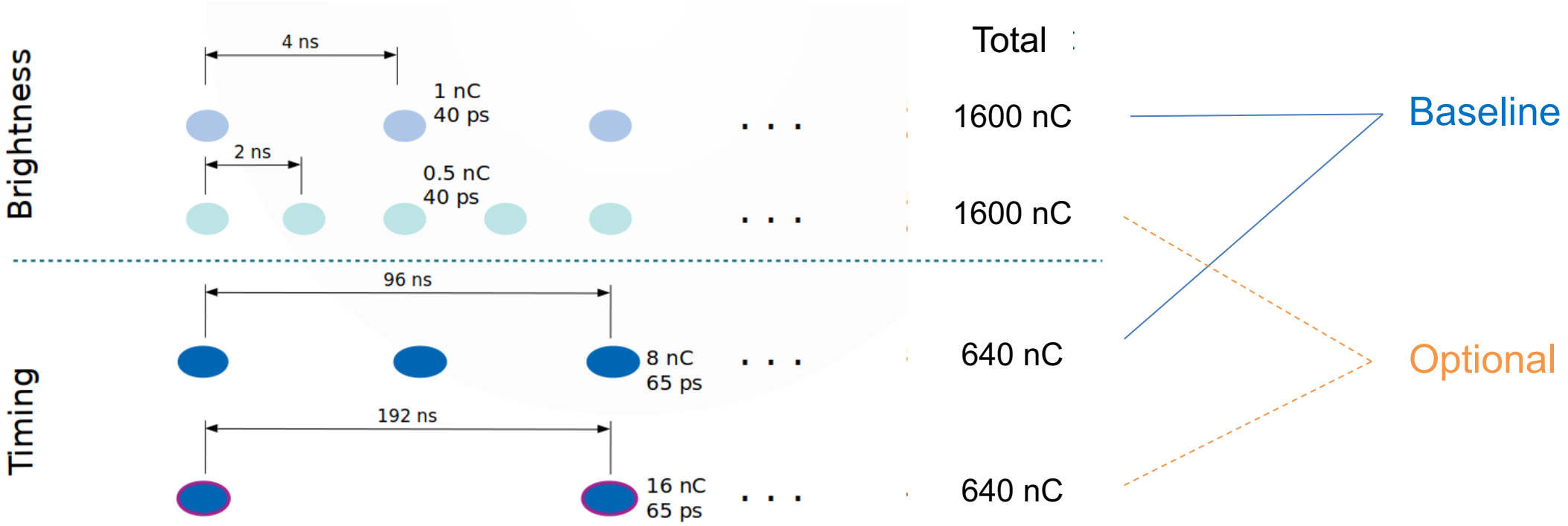



**Key figures:**

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

# 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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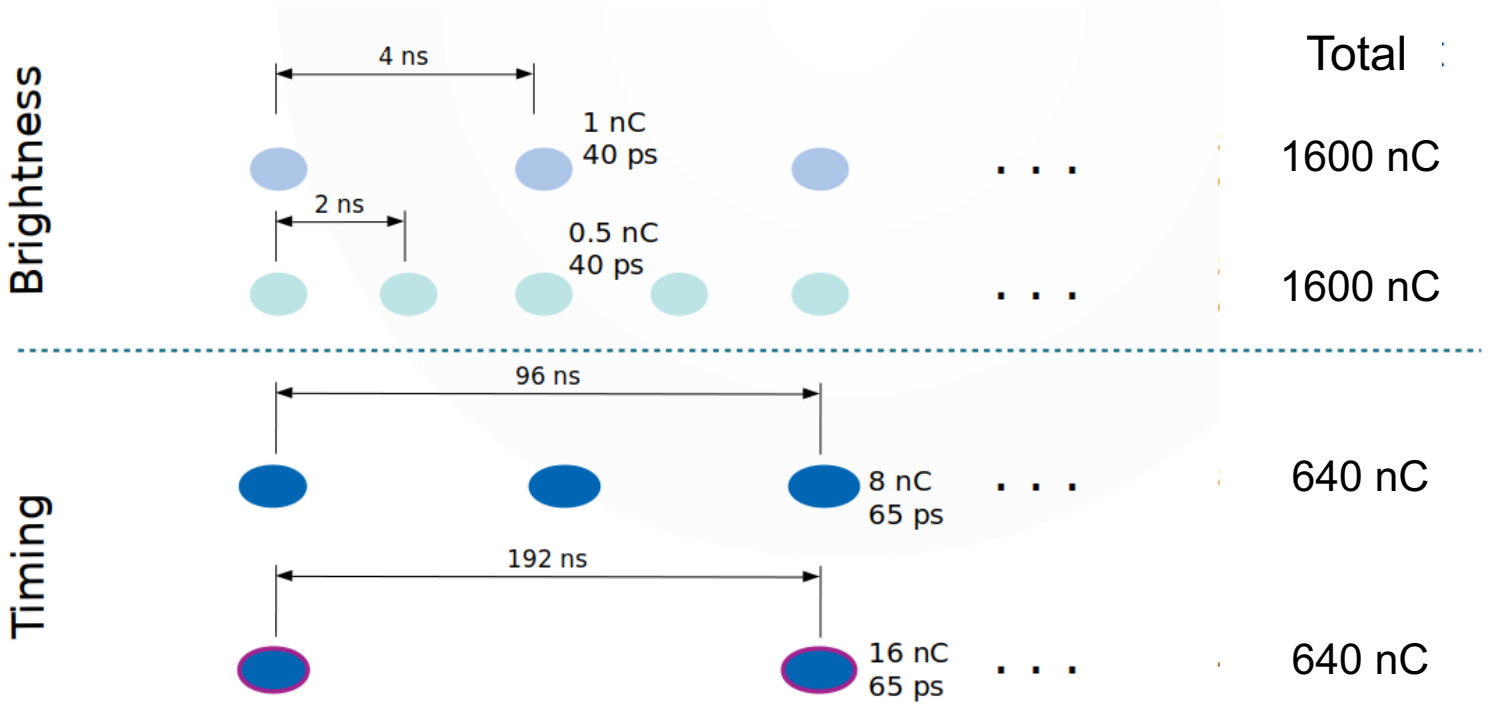



**The ring takes care of charge accumulation**

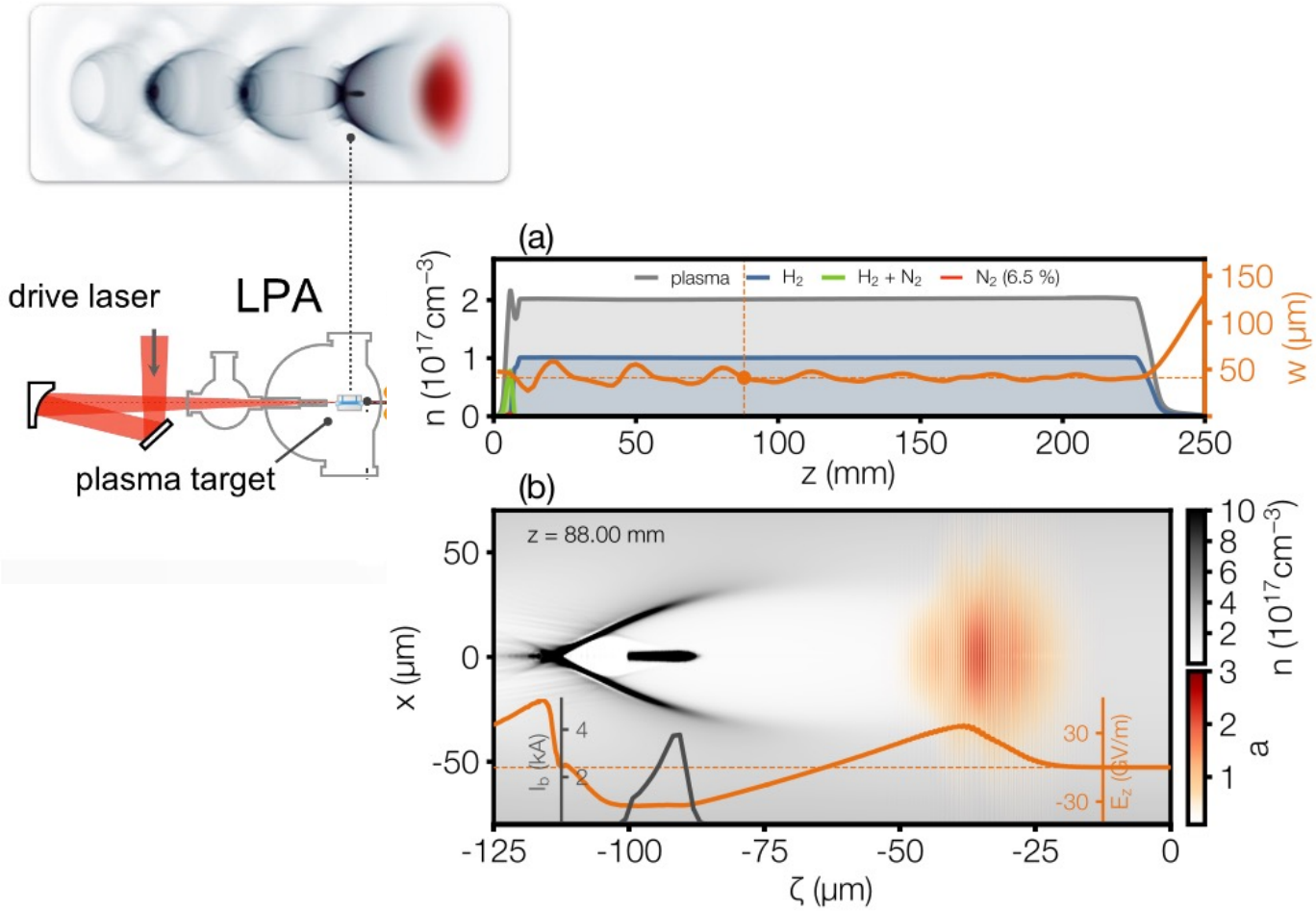
- Large lifetime 10-40 h
- “Top-up” injection scheme

**“Just” supply enough charge within the phase space acceptance**

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

# 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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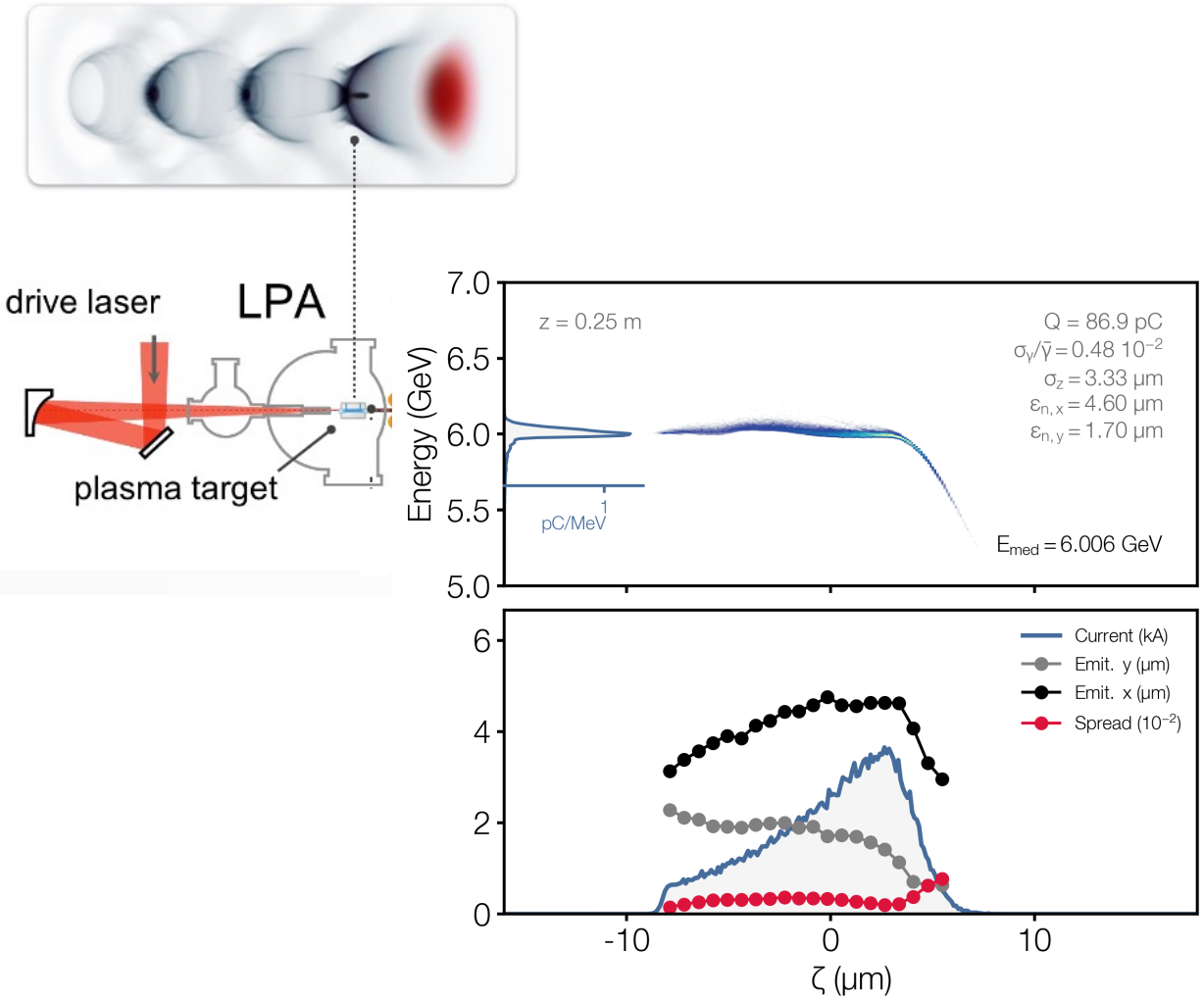


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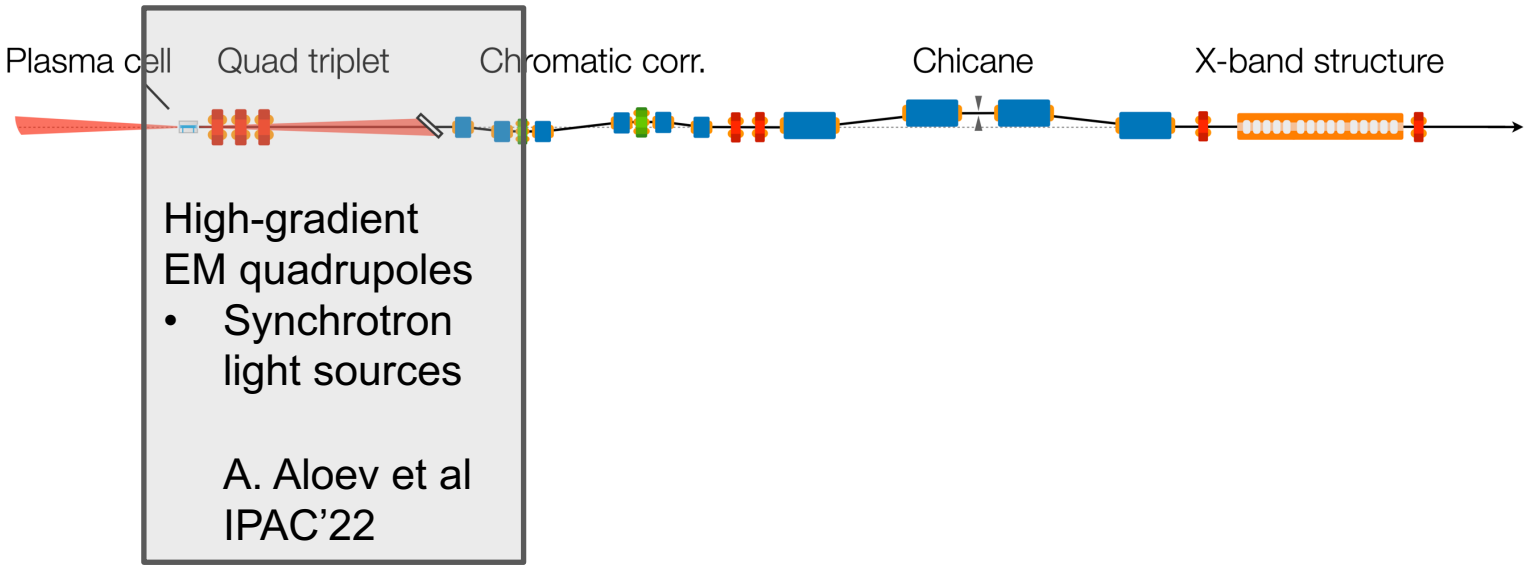
# 6 GeV beamline with X-band energy compression

## Beam capture, chromatic correction, energy compensation




**Solely existing, conventional hardware**

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

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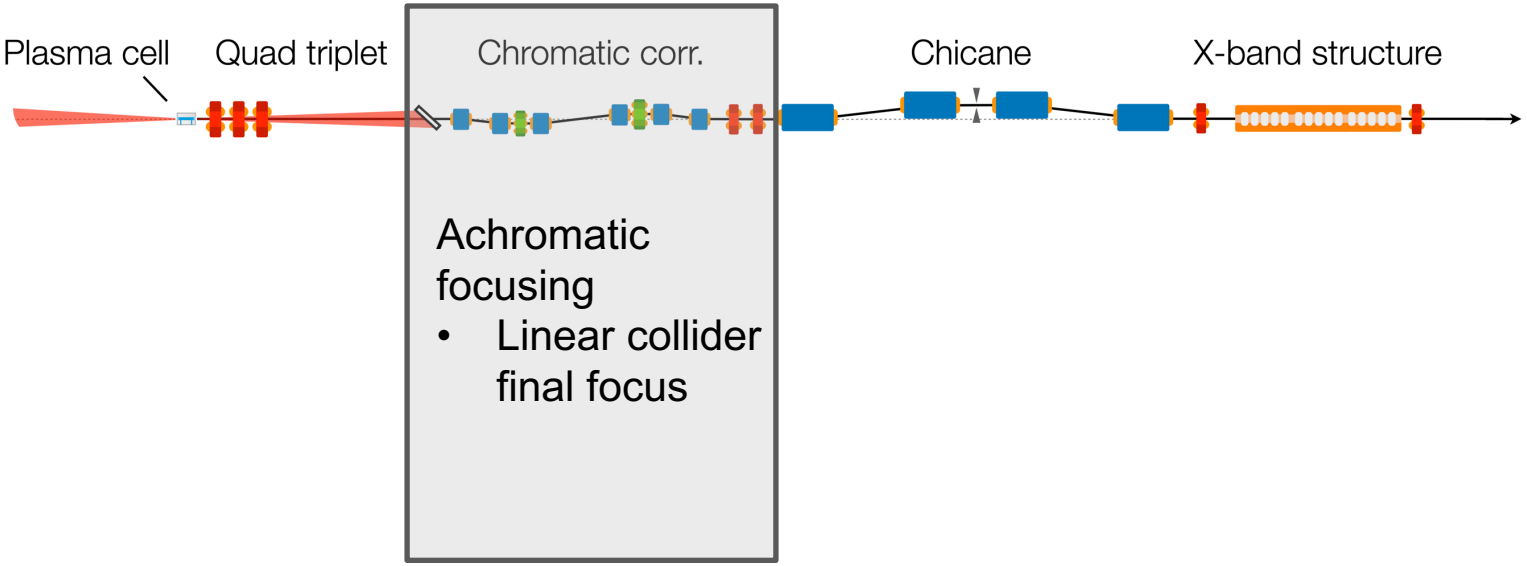


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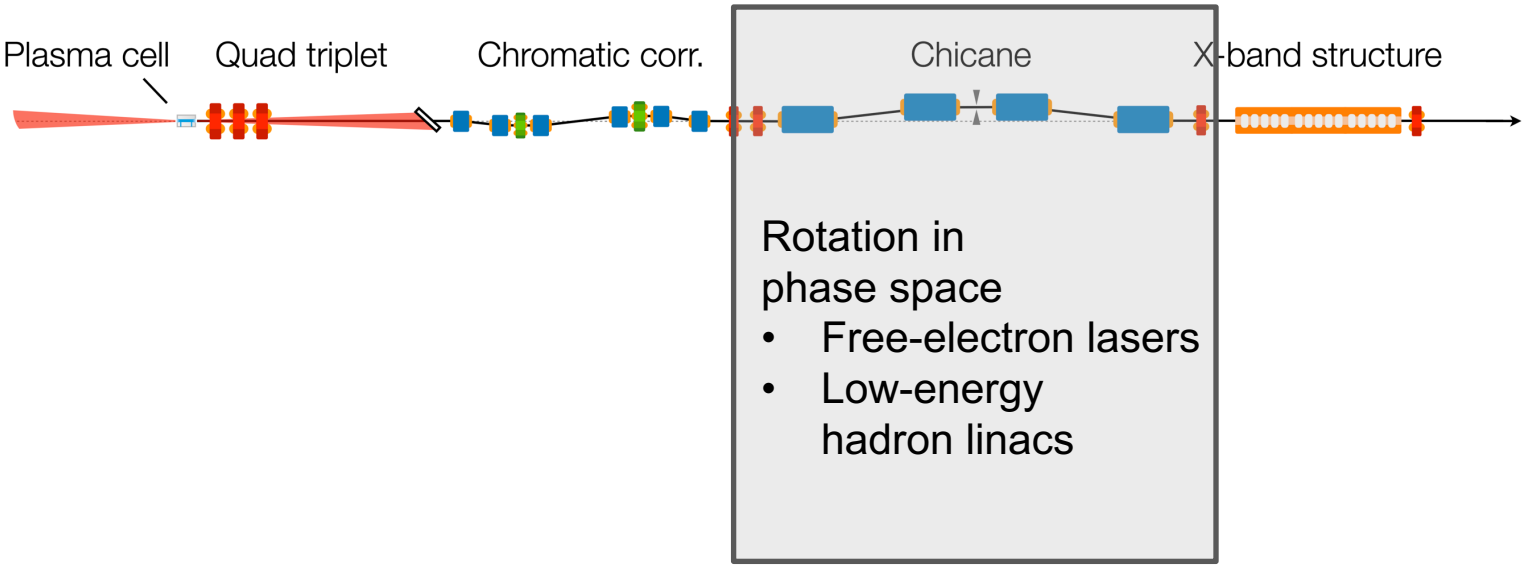


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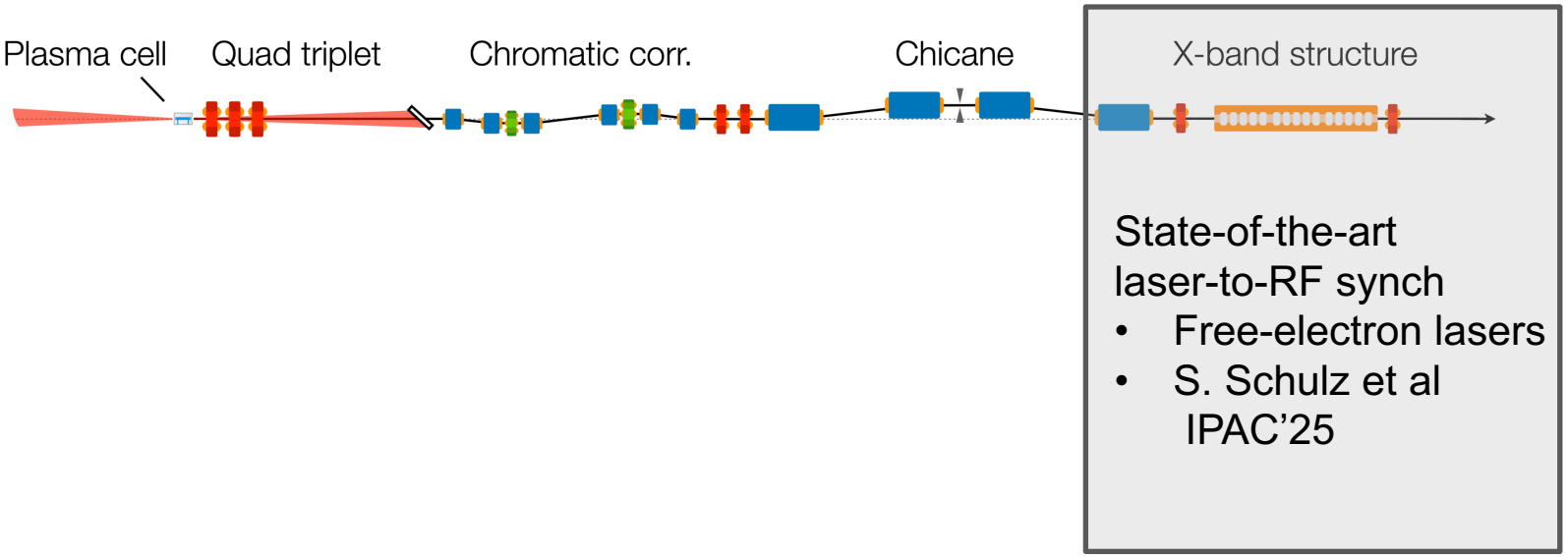


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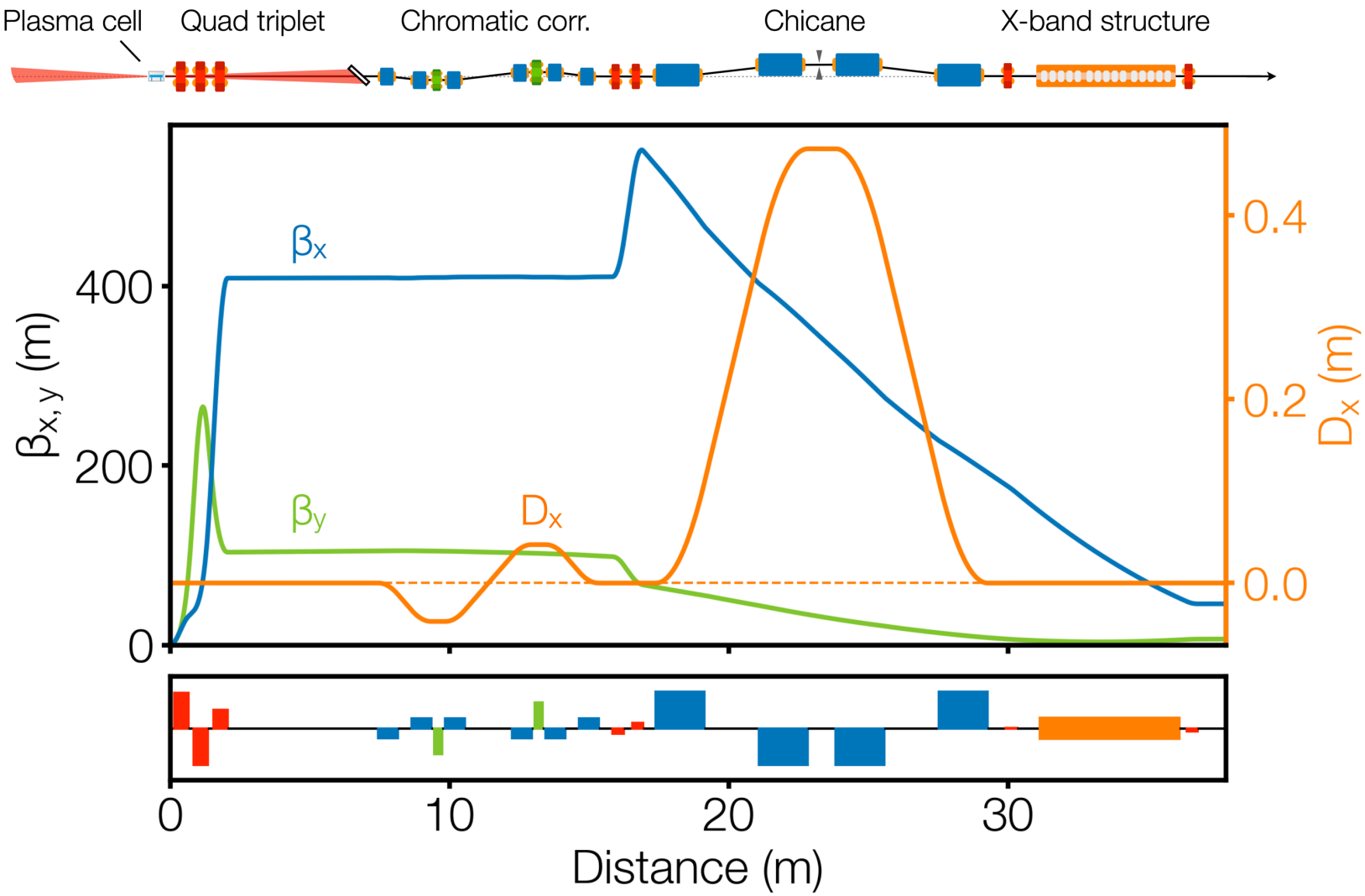


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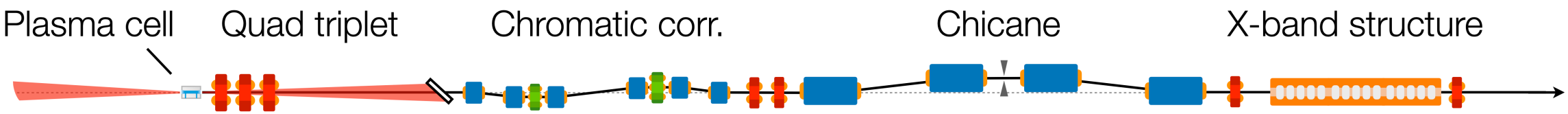
- S. Antipov et al, PRAB 24 (2021)

**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

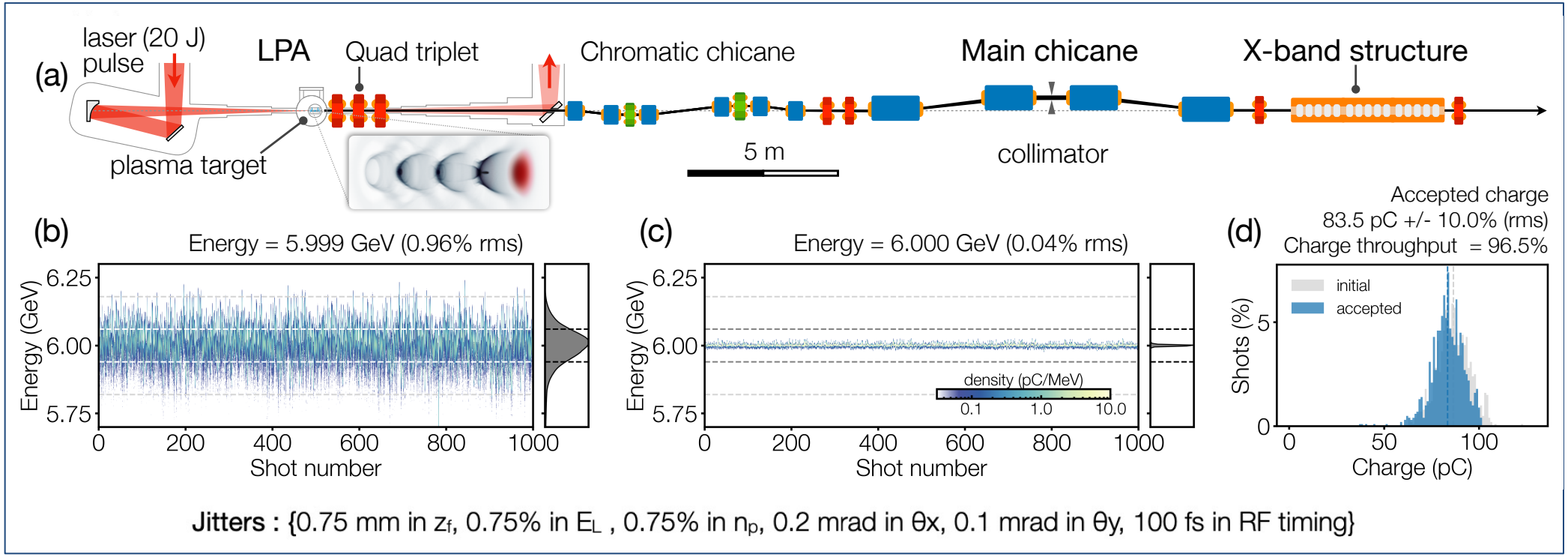
- Lattice errors
- Main & harmonic RF
- Synch rad. damping
- Physical aperture
- Wakefields

`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




*Courtesy A. de la Ossa*

**Concept proven at low energy**

- P. Winkler *et al., Nature* 640 (2025)
- A. Maier (this conference)

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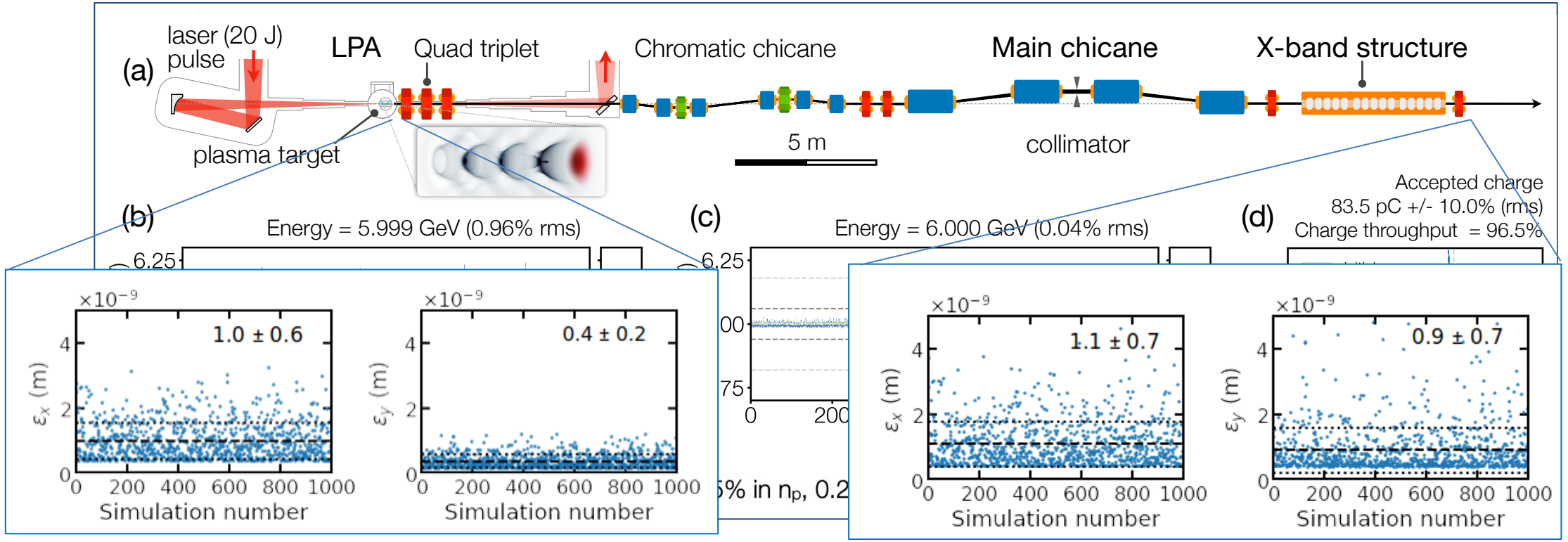



**Emittance smaller than from a state-of-the art low-emittance booster synchrotron**

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

# Are we done?

## Not yet

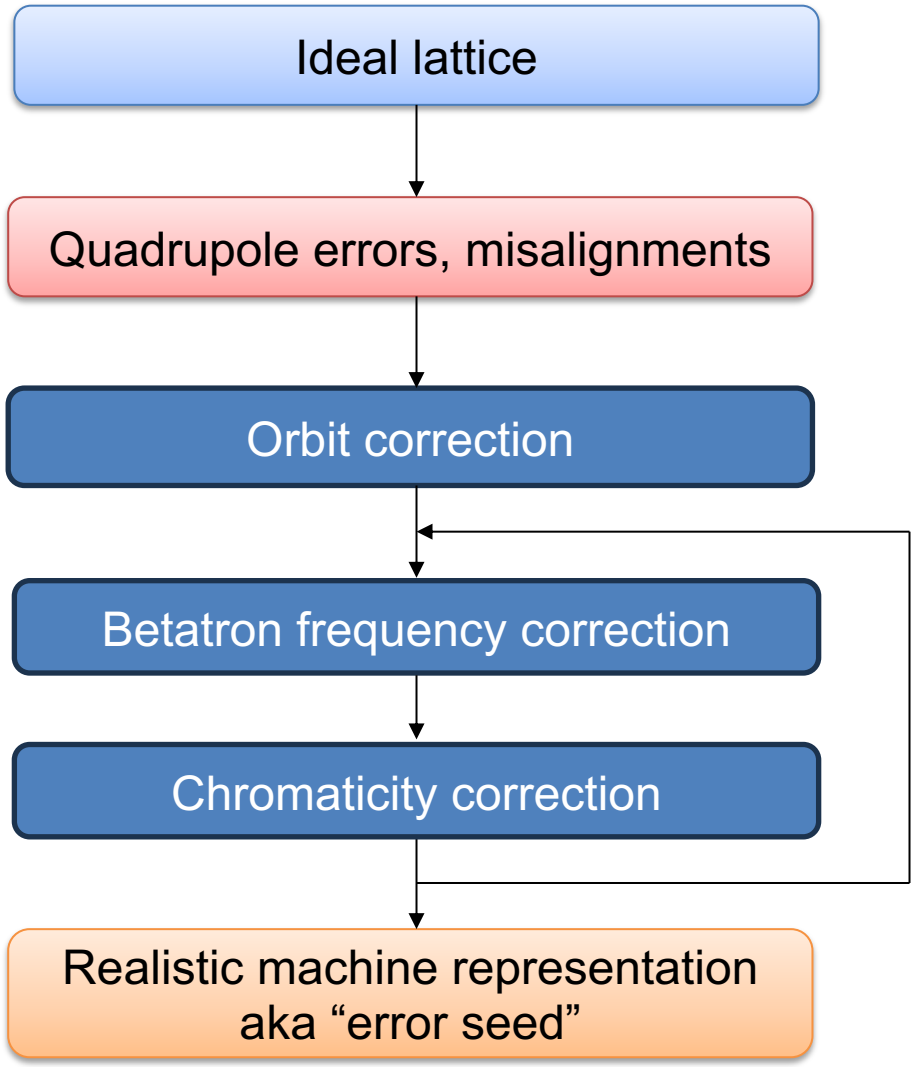
Error studies

# A real accelerator is not an ideal model

## Realistic machine representations are produced based on assumed errors

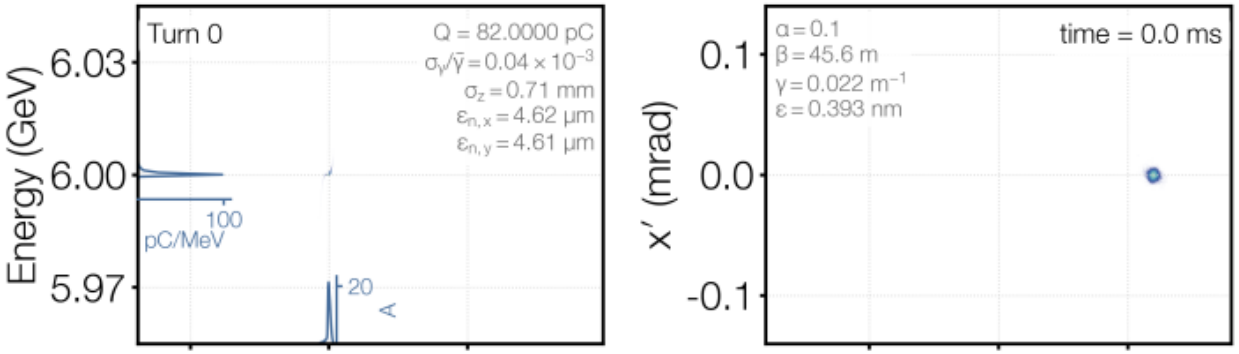
### Assumed magnet and diagnostics errors

| 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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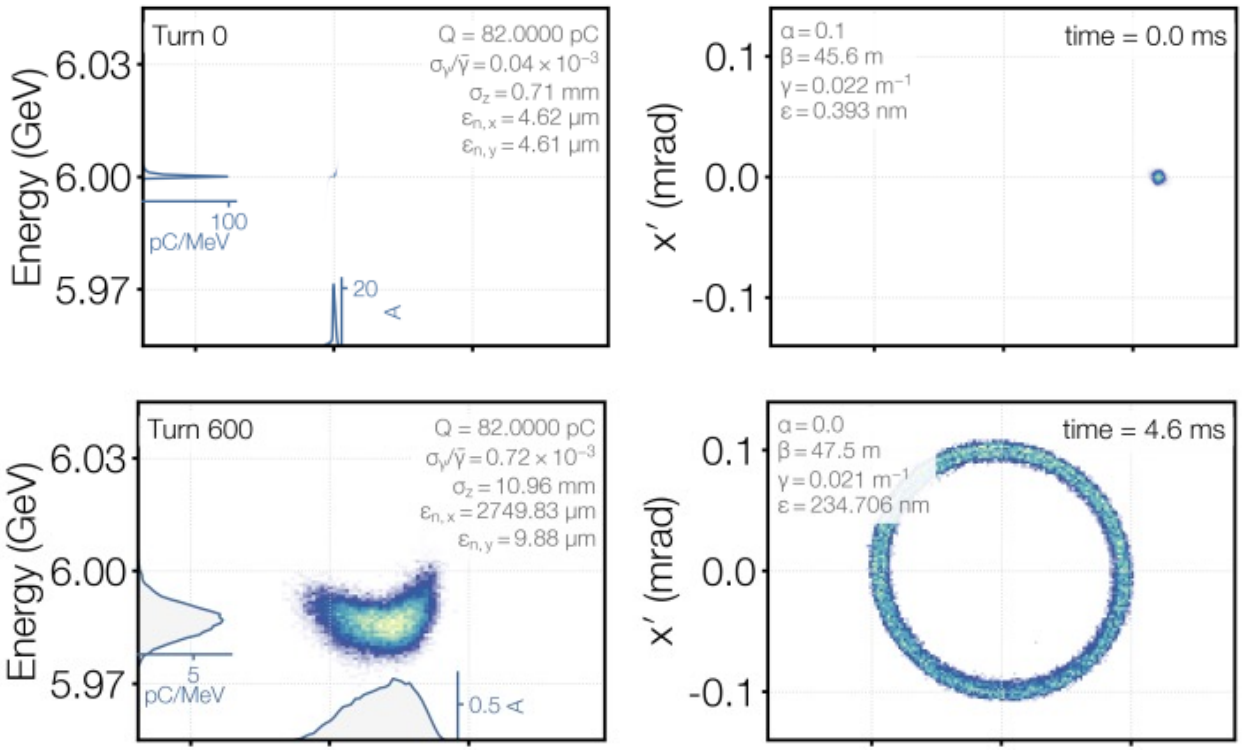


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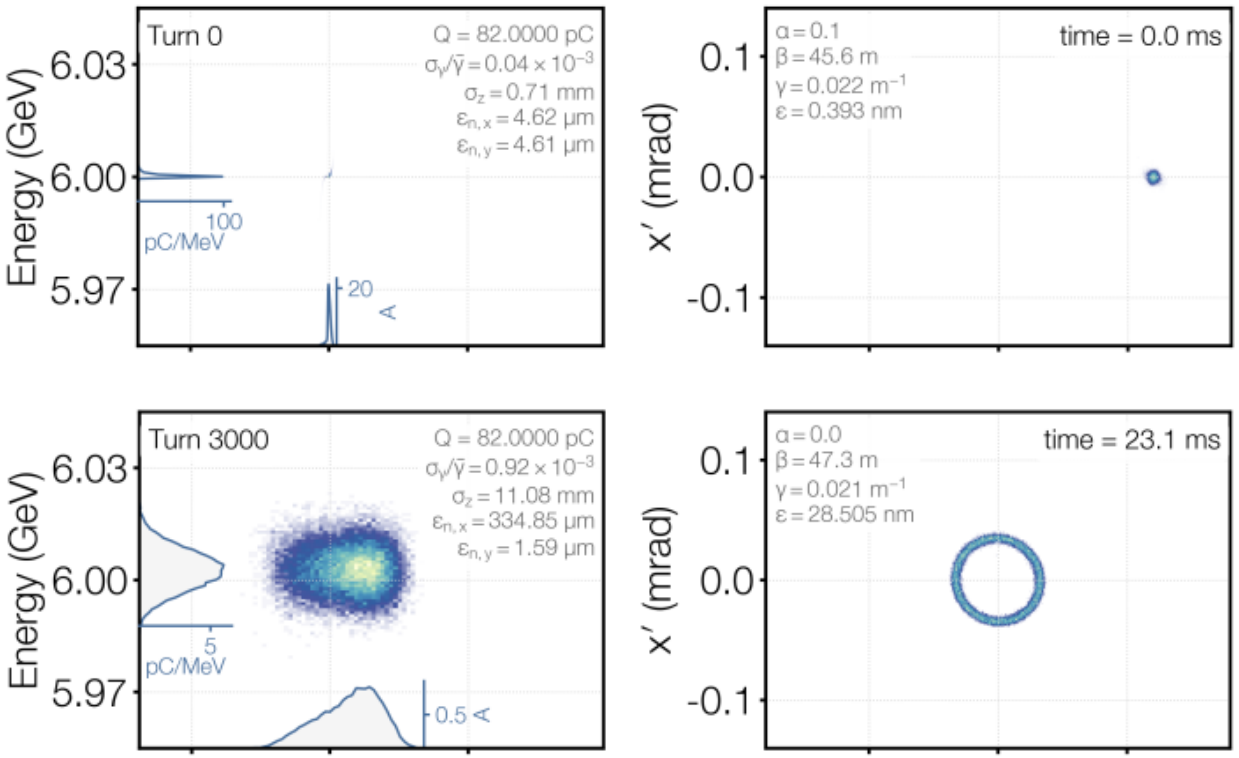


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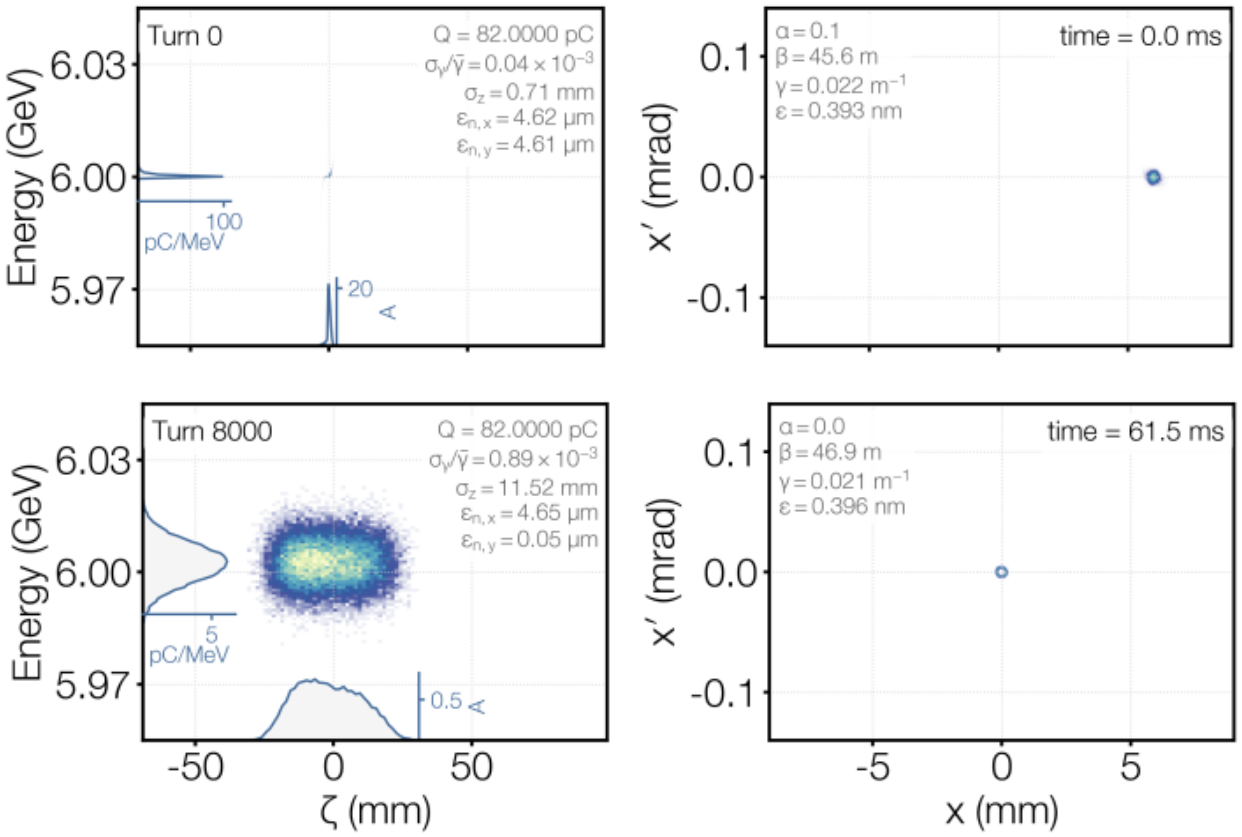


*Numerical tracking by A. de la Ossa, PIP IV CDR*

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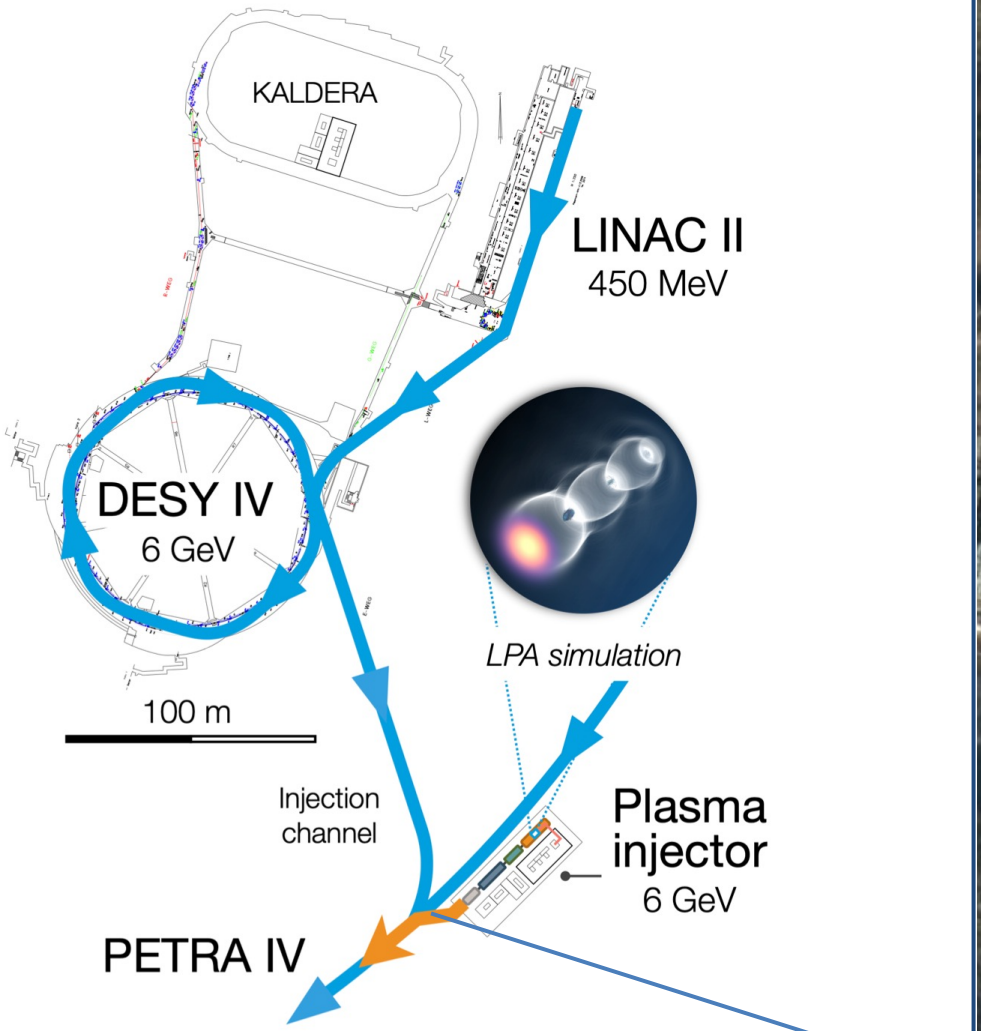
# Are we done now?

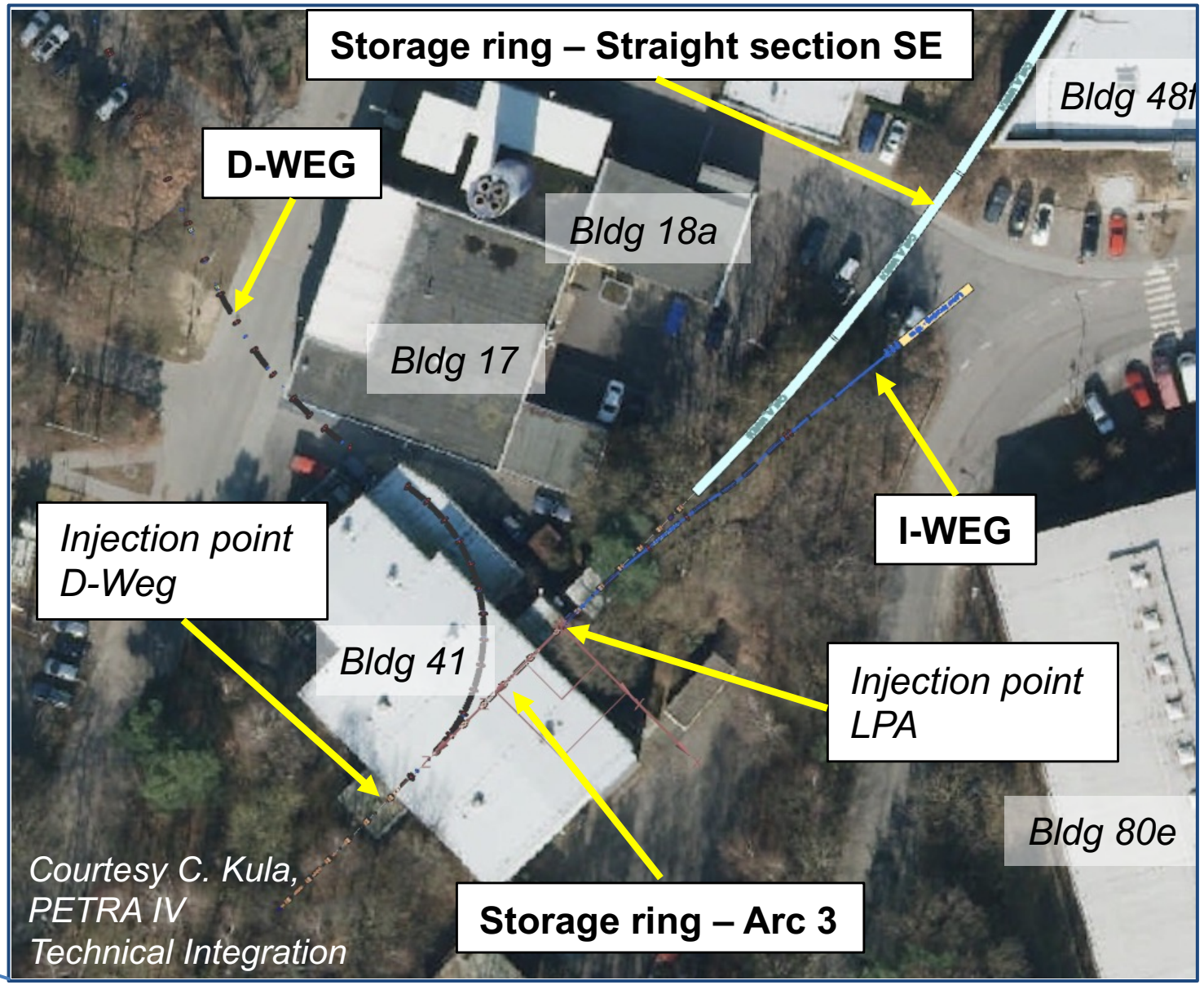
## Getting close…

Charge accumulation in the ring

# Top-up injection at PETRA IV

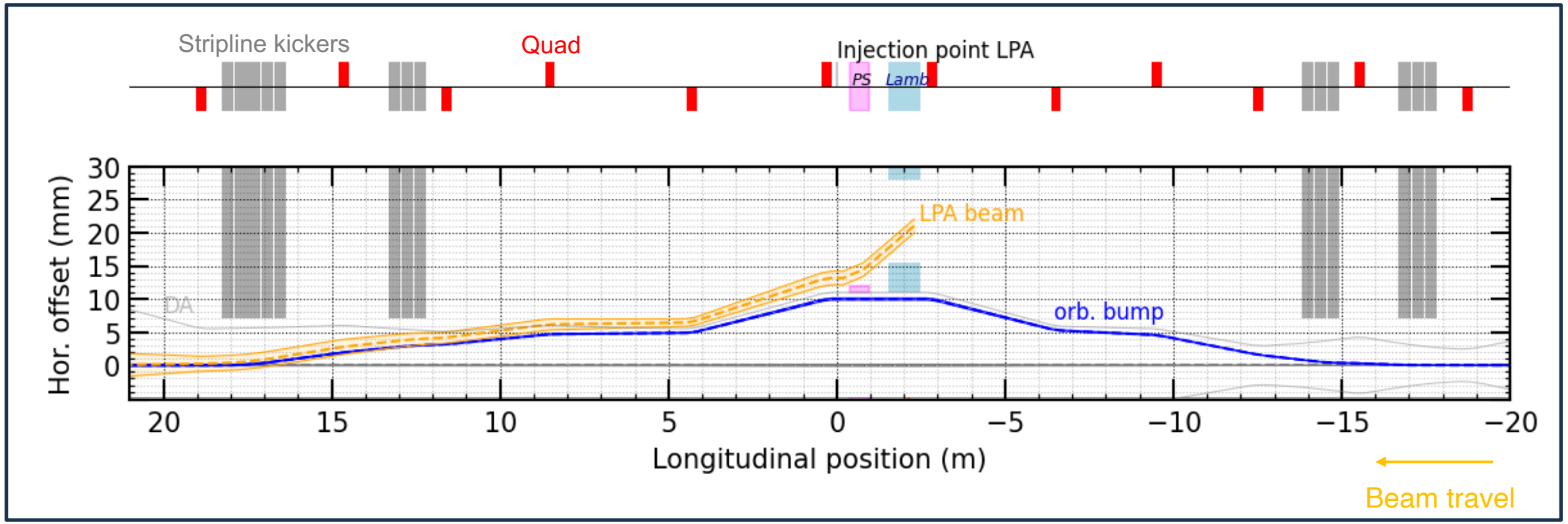
## From a concept towards a drawing



# Top-up injection at PETRA IV

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

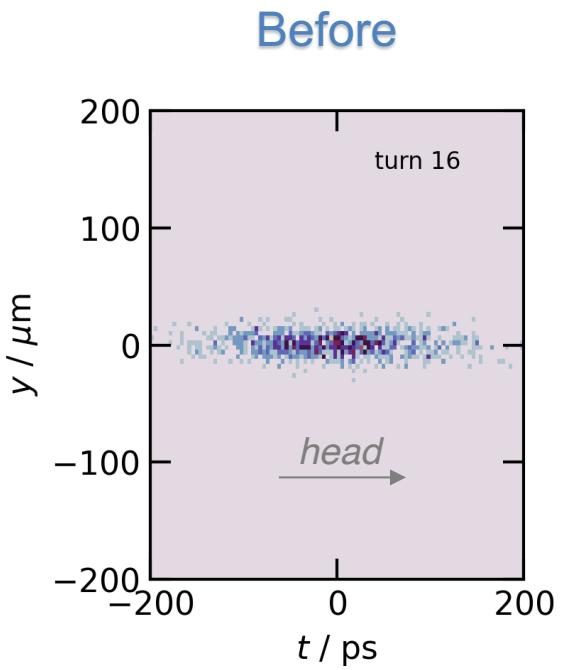



**Stored bunch might have residual oscillations after the process**

- 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




**High-charge Timing mode**

- 14 nC in the stored bunch
- Starts from jitter

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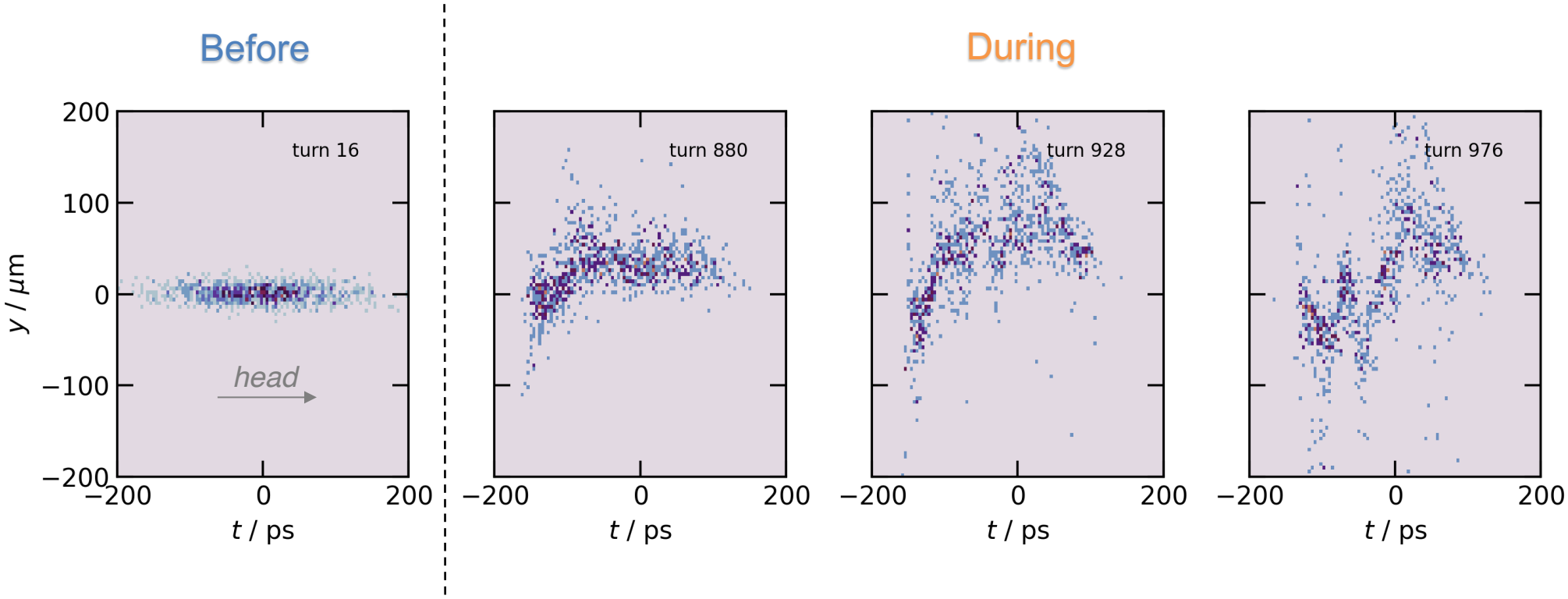

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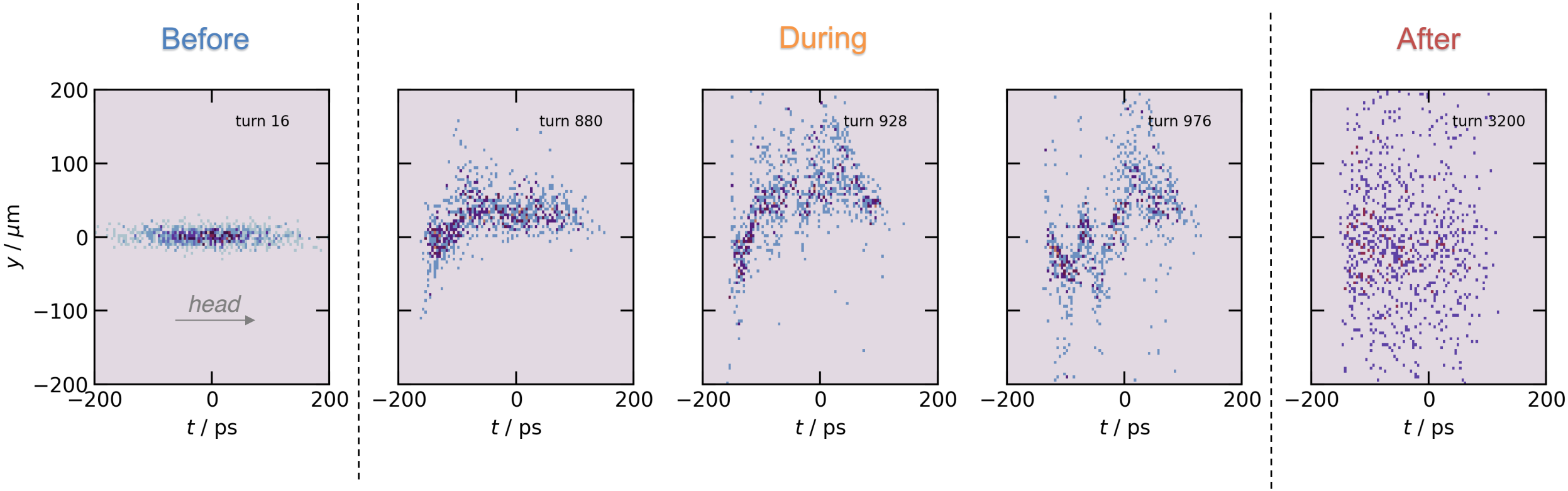


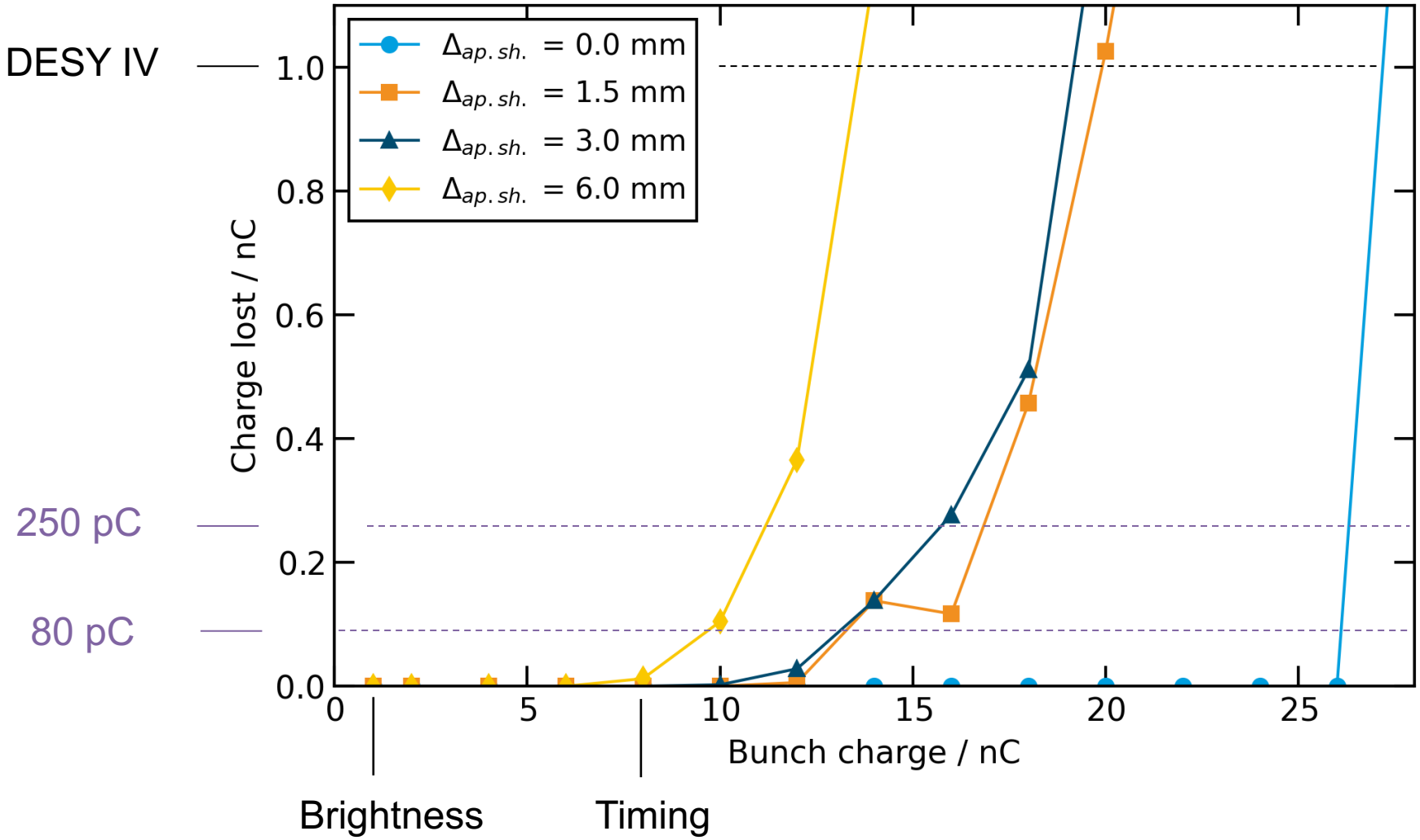

**Most charge losses happen in the stored bunch**

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

*S. Antipov, LER Workshop, 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

# Error Analysis in Storage Ring Design - Past and Present

- Generate Error Ensembles
  - Gradient errors, misalignments, girders, etc.

- Evaluate Lattice Performance
  - Beta beat, orbit error

  - Limit error amplitudes to provide acceptable performance

Construction of the DESY Synchrotron, 1961

*T. Hellert, FLS Workshop, Lucerne, 2023*

# Error Analysis in Storage Ring Design - Past and Present

- Generate Error Ensembles
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- 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
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Aerial view of the present DESY campus with its PETRA III light source

*T. Hellert, FLS Workshop, Lucerne, 2023*

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The future 4th 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
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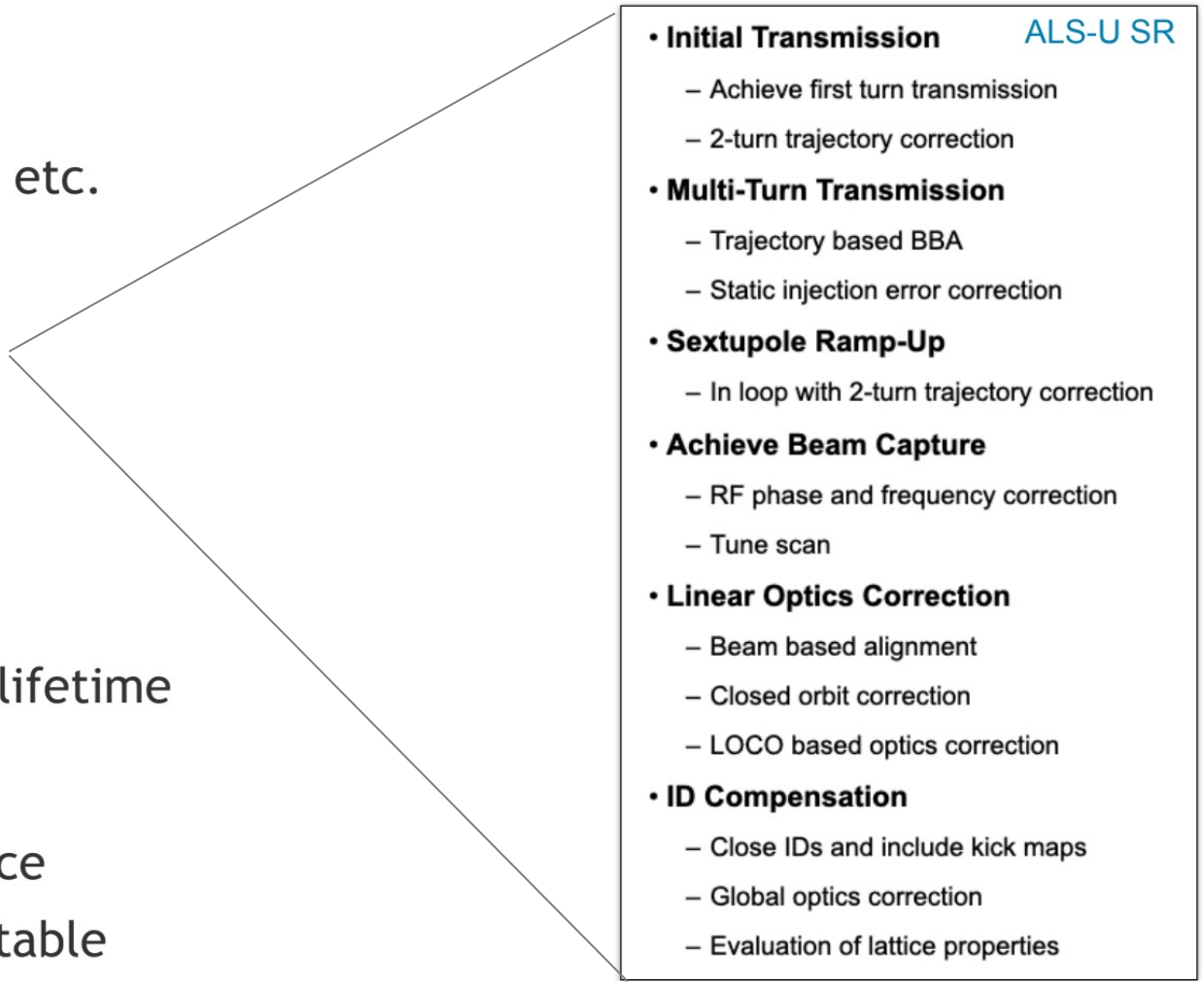
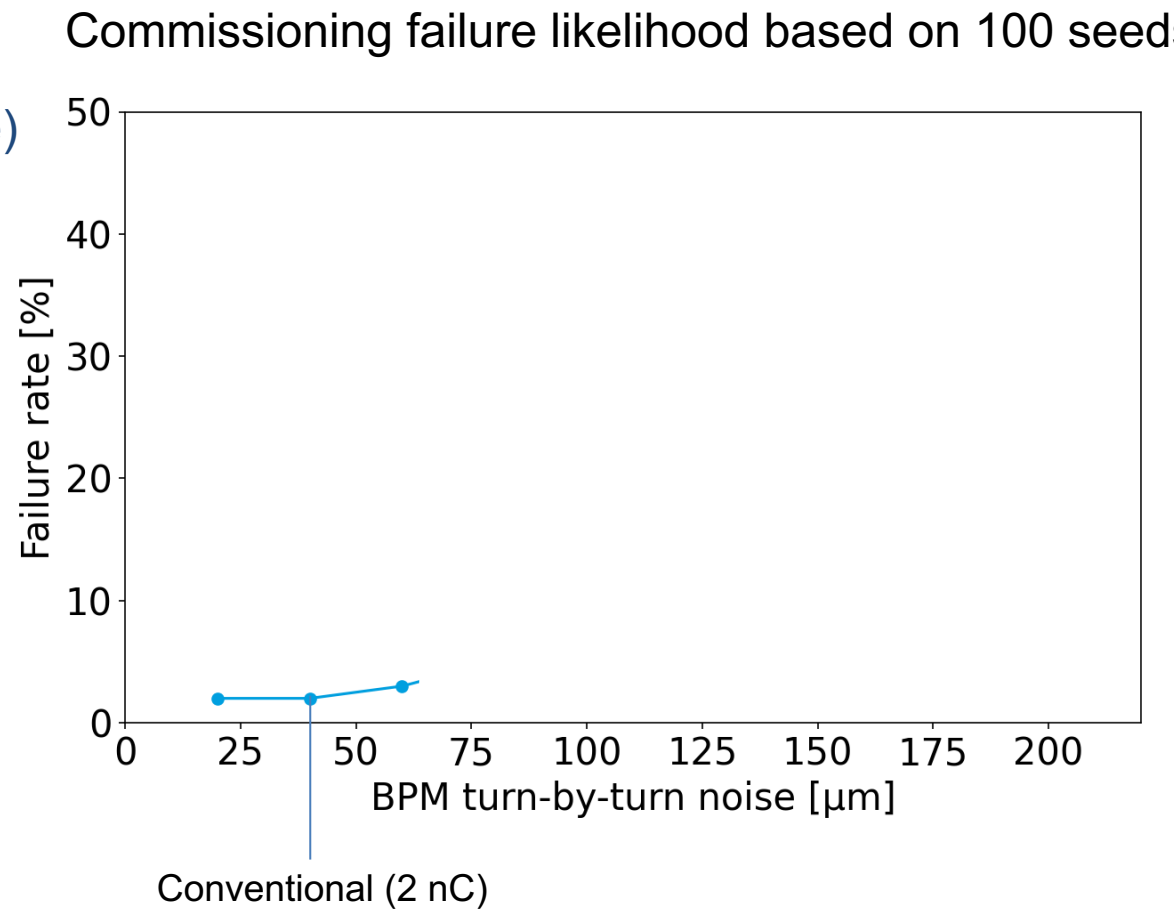



*T. Hellert, FLS Workshop, Lucerne, 2023*

# 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




*Courtesy K. Paraschou*

`https://github.com/lmalina/pySC`

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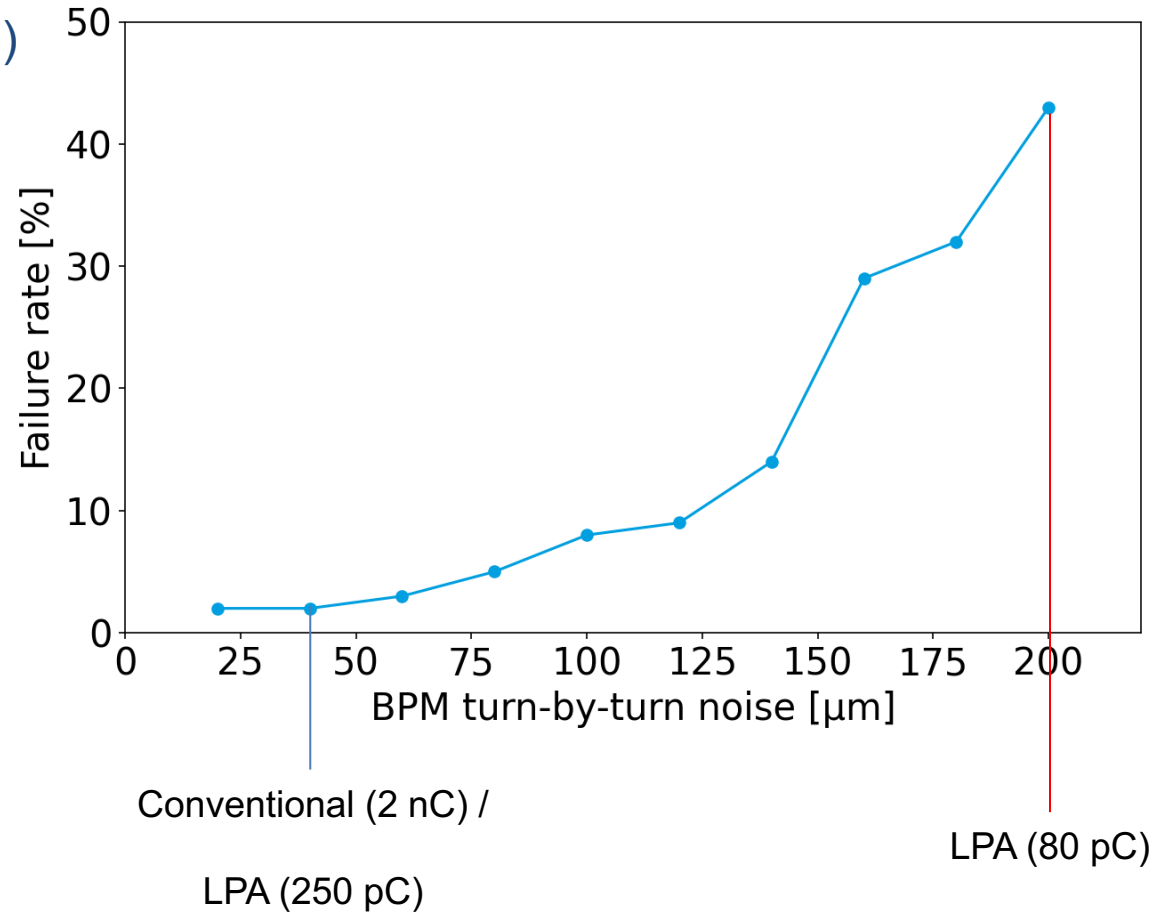
RF setup

Commissioning failure likelihood based on 100 seeds




**Way forward**

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

*Courtesy K. Paraschou*


ONE DOES NOT SIMPLY
INJECT INTO A RING

# How do we get there?

## Step-by-step

| | | | |
|---|---|---|---|
| Energy compression proof-of-concept | 2023-25 | Existing LPA infrastructure at LUX<br><br>Minimum modifications | Demonstrate x10 impovement in energy spread and stability<br><br>Test synchronization, commissioning |
| Low energy injector demonstrator | 2025-26 | Existing ANGUS laser<br><br>New beamline<br><br>Existing DESY-II booster | Demonstrate injection at 300 MeV<br><br>Most technologies in one setup |
| Full energy injector for PETRA | 2027... | Upgraded laser<br><br>Progress in plasma cells<br><br>Supporting injection hardware at PETRA | Replace conventional injector chain, ultimately |

# Make your own plasma injector

## You will need

### Ring

- Top-up injection

### LPA

- Low energy spread
- Low beam divergence

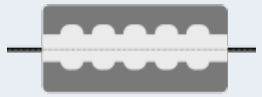
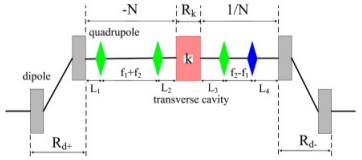
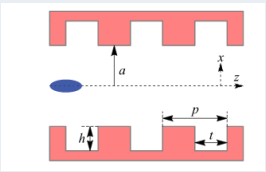
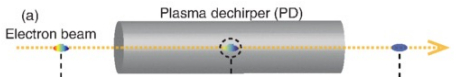
### Beamline

- Chromatic correction
- Energy compression
- Synchronization

# Thank you for your attention

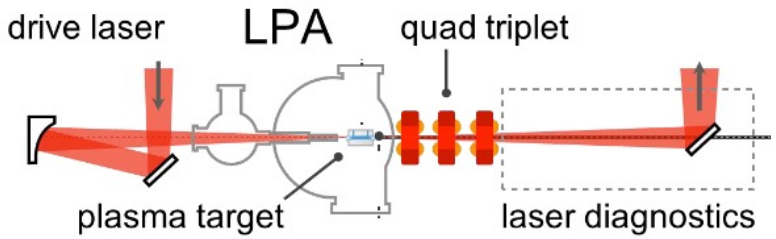
# Reducing the energy spread

## There is more than one way

| | Chicane + ... | Pros | Cons |
|---|---|---|---|
| Active | RF structure  | Readily available<br>Compensates spread & jitter | Power consumption |
| Active | Transverse cavity   | Lower power consumption | More complicated setup<br>Transverse emmittance might become too large |
| Passive | Wakefield structure   | No extra power | Inefficient due to small bunch charge<br>Requires more complicated chicane ($R_{56} > 0$) |
| Passive | Plasma cell   | No extra power<br>The most compact | Need tight re-focusing<br>Degrades emittance |

# 6 GeV beamline with X-band energy compression:

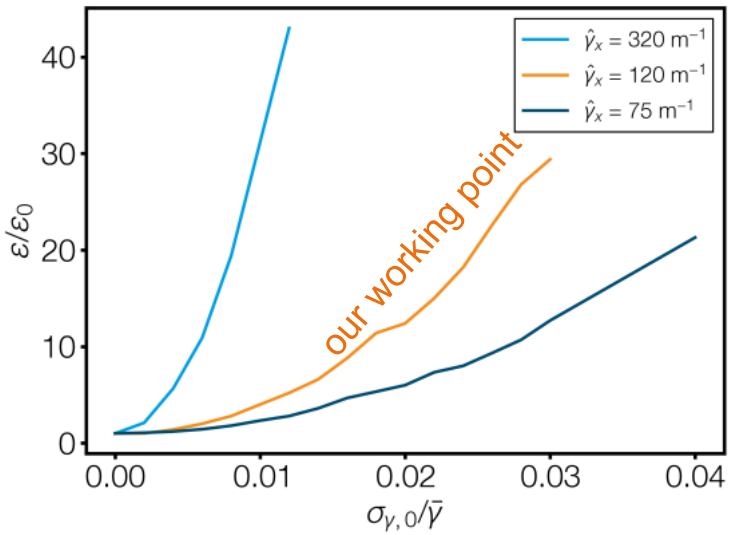
## Emittance blows up unless the energy spread is small enough without chromatic correction

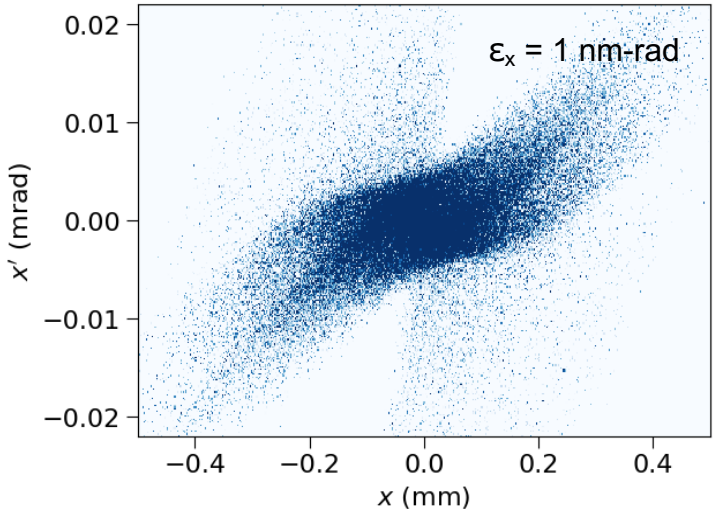



$$\frac{\epsilon^{\mathrm{f}}_{n,x}}{\epsilon_{n,x}} = \sqrt{1+\sigma_\gamma^2\left(1+\frac{L^2}{\hat{\beta}_x^{*2}}\right)} \approx 1+\frac{1}{2}\sigma_\gamma^2\frac{L^2}{\hat{\beta}_x^{*2}}$$

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

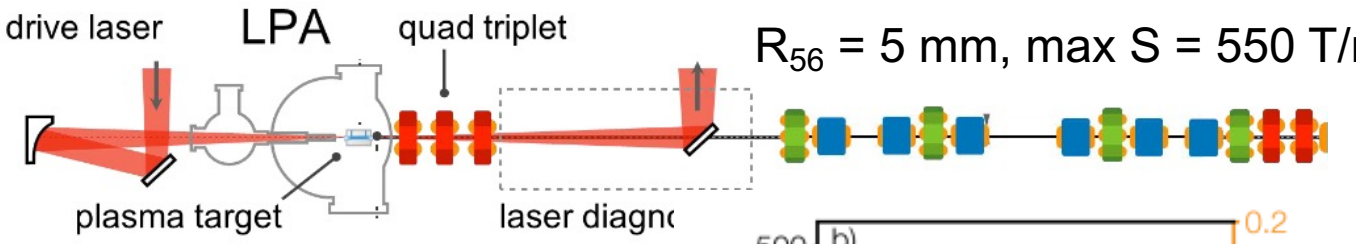
-> M. Migliorati et al., PRST AB 16, 1 (2013)



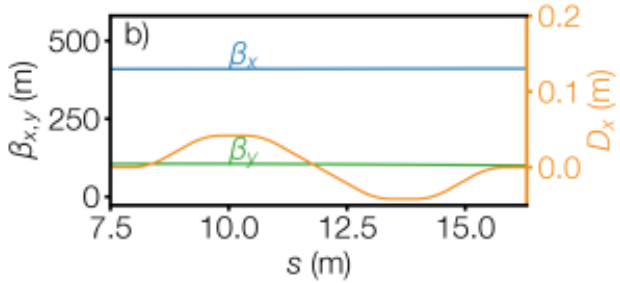



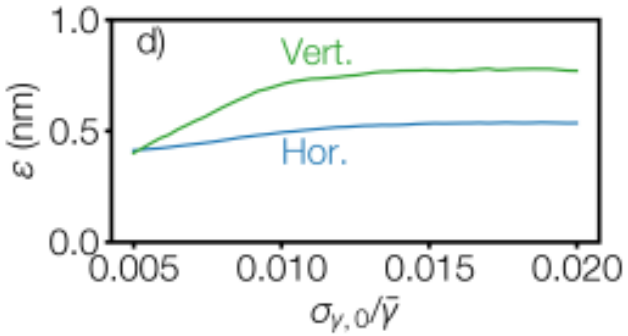
# 6 GeV beamline with X-band energy compression:

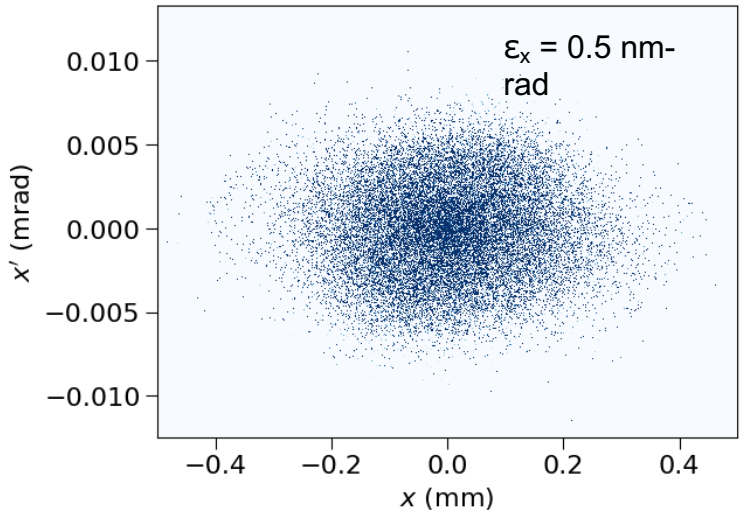
## Chromatic correction is crucial for preserving small emittance




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

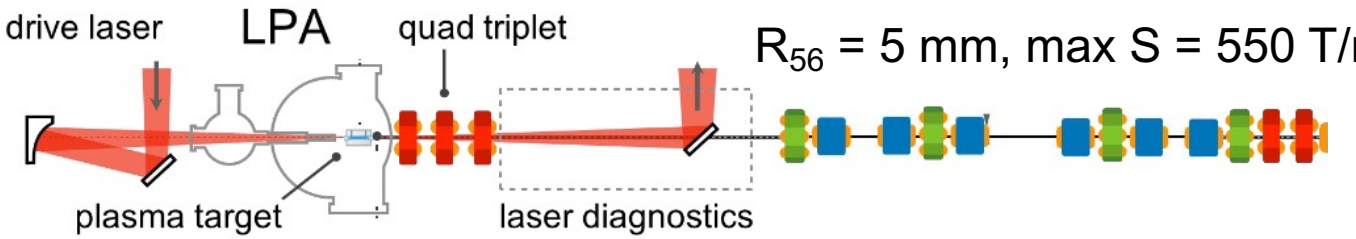


# Coherent Synchrotron Radiation

## 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** |

# Injection efficiency confirmed with comprehensive numerical simulations

## Computing capabilities provided by the DESY Maxwell computing cluster

**6D element-by-element tracking in ELEGANT**

- Main & 3rd harmonic RF systems
- Synch Radiation damping
- Optics errors
- Real physical aperture
- Longitudinal & transverse wakefields
- Intra-beam scattering (non-selfconsistent)

**Parameter space covered**


**1 point = 2 node x days**