PETRA IV.
NEW DIMENSIONS

Pre-accelerator concept for PETRA IV

Sven Sievers
I.FAST Workshop 2024 on Injectors for Storage Ring Based Light Sources
Karlsruhe, March 7th, 2024

HELMHOLTZ

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Agenda

PETRA IV
DESY's bright future

PETRA IV
Facility Layout and injection concepts

DESY IV
A new booster synchrotron for PETRA IV

Plasma Injector for PETRA IV
What about a new concept?

Summary
To make a long story short…

PETRA IV

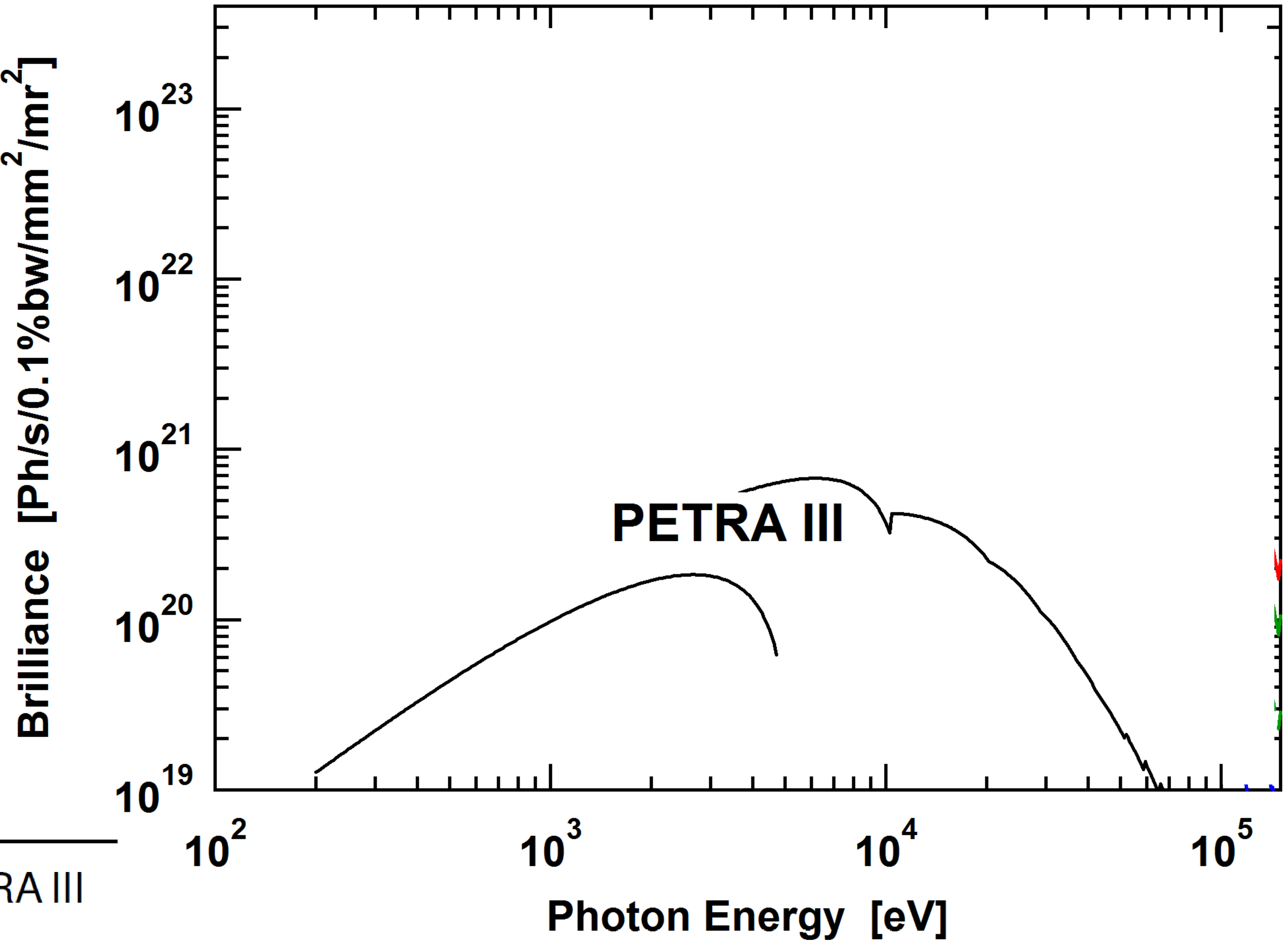
DESY's bright future

PETRA III

... since 2010

Quick Facts

- 2024 PETRA III still up and running...



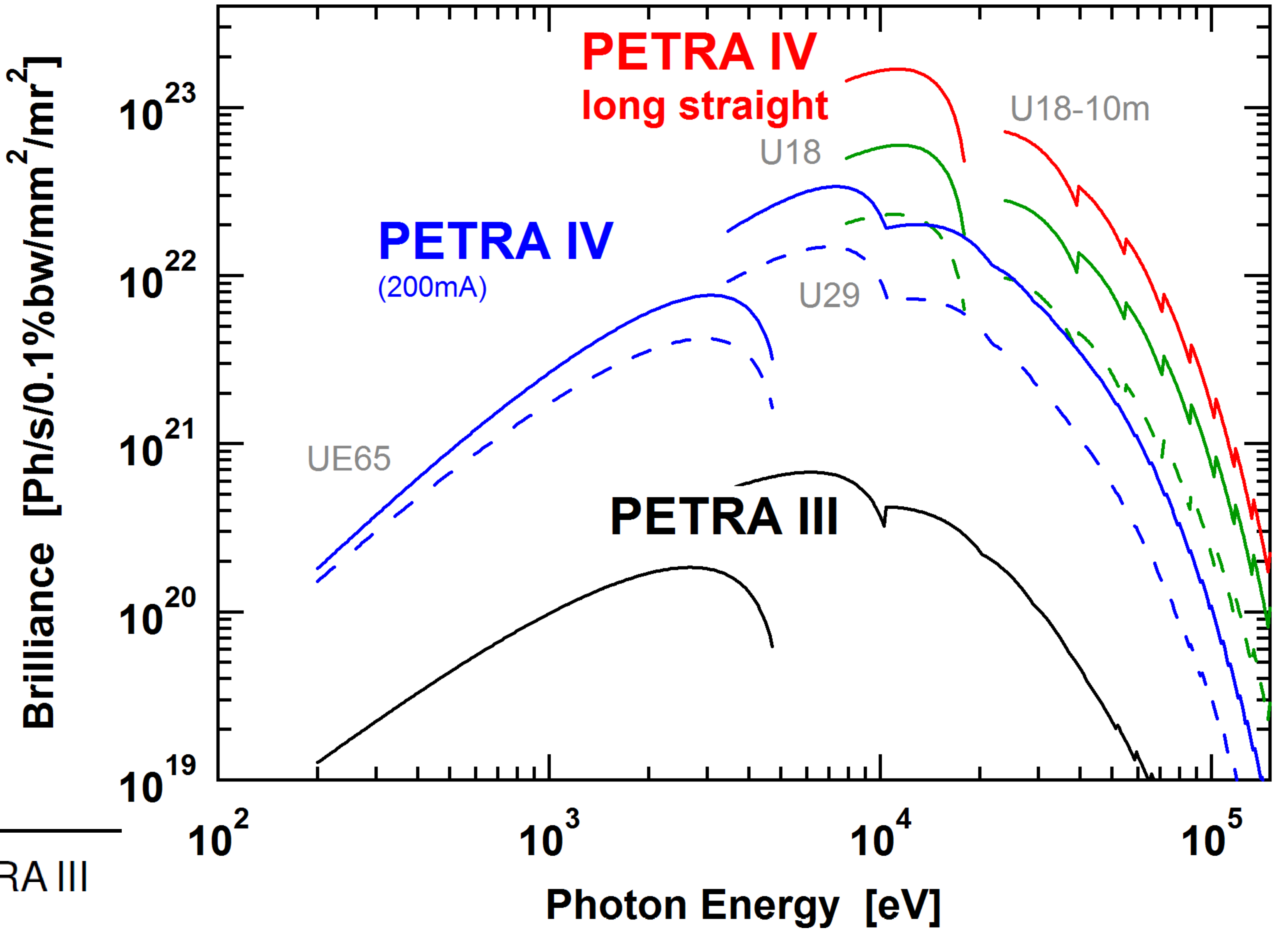
Parameter	PETRA III
Energy / GeV	6
Circumference / m	2304
Total current / mA	100
Number of bunches	40 . . . 960
Emittance	
Horiz. ϵ_x / pm rad	1300
Vert. ϵ_y / pm rad	10
Number of undulator beamlines	21(26)

PETRA IV

… looking into a bright future

Quick Facts

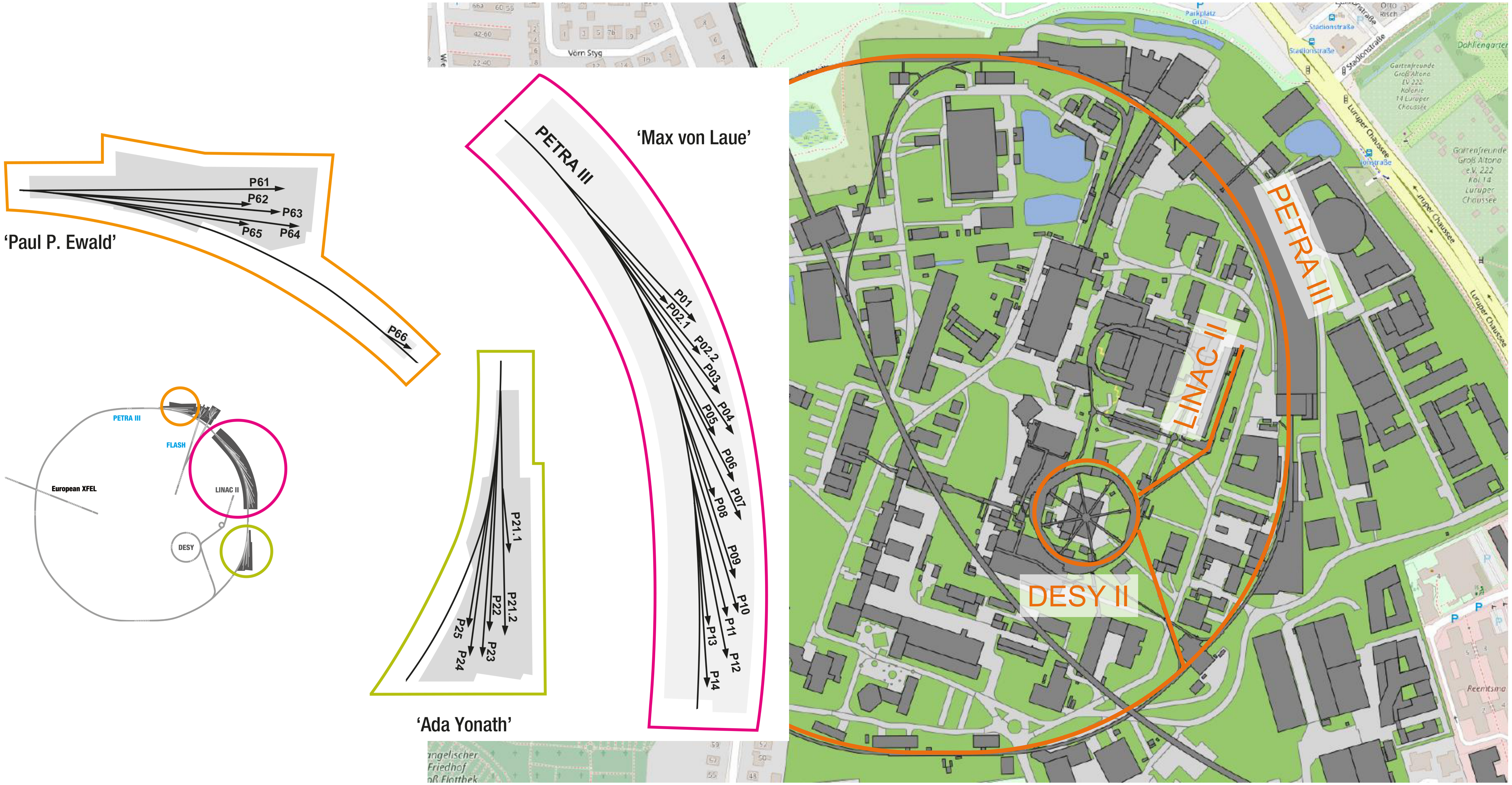
- 2024 PETRA III still up and running…
- … but PETRA IV is on the horizon



Parameter	PETRA IV Brightness mode	PETRA IV Timing mode	PETRA III
Energy / GeV	6	6	6
Circumference / m	2304	2304	2304
Total current / mA	200	80	100
Number of bunches	1600	80	40 . . . 960
Emittance			
Horiz. ϵ_x / pm rad	< 20	< 40	1300
Vert. ϵ_y / pm rad	2 - 10	5 - 20	10
Number of undulator beamlines	30		21(26)

PETRA IV

... looking into a bright future



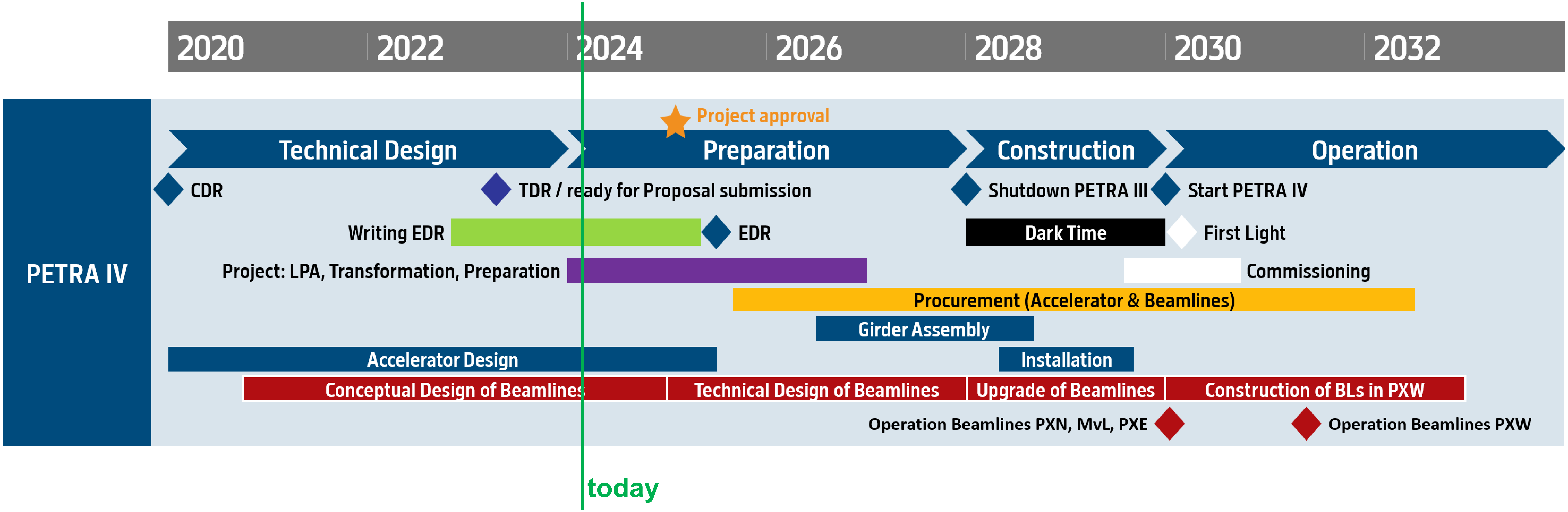
PETRA IV

... looking into a bright future


Phase-I Beamlines
Start Operation in 2030
Phase-II (PXW) Beamlines
Start Operation in late 2031
Paul P. Ewald (PXN) Hall
Max von Laue (MvL) Hall
New PXW Hall
Ada Yonath (PXE) Hall
BL49 Diagnostics Beamline I & II
BL48 Appl. and Analy. XAFS and Q-EXAFS BL
BL47 Free Slot
BL46 SAXSMAT II Beamline
BL45 Powder Diffraction and Total Scattering
BL44 Free Slot
BL43 Free Slot
BL42 Resonant X-ray Scattering Beamline
BL41 ExTReM
BL39 Coherent Applications Beamline
187-m length
BL38 CryoBio Nanoprobe Beamline
150-m length
BL37 Full-Field Imaging for Materials Science (Hereon)
120-m length
BL36 In-Situ/High-Resolution 3D Nanoprobe
BL35 Materials Scanning Nanoscope
BL34 Multiscale Materials Microscope (Hereon/DESY)
BL33 Free Slot
BL32 Free Slot
BL31 HRHS Soft X-ray Beamline
In-Situ Large Volume Press Beamline BL61
Materials Science Lab Beamline (MPG) BL62
X-ray Absorption & Emission Spectroscopy Beamline BL63
Time-Resolved VUV Spectroscopy Beamline BL64
Nuclear Resonance and X-ray Raman Scattering BL01
AdMiNaXS BL02
Hard X-ray Photoelectron Spectromicroscopy BL03
High-Energy Scattering and Diffraction Tomography BL04
High-Energy Materials Science Beamline (Hereon) BL05
Surface and Interface Dynamics Beamline BL06
In-Situ Bragg Microscopy Beamline BL07
High-Throughput MX BL08
BioSAXS (EMBL) BL09
High Performance and Microfocus MX (EMBL) BL10
Bio Diffraction and Imaging (EMBL) BL11
High-Energy Beamline for Physics and Chemistry BL21
Swedish High-Energy Materials Science Beamline (SE) BL22
Hierachical Imaging at Karlsruhe (KIT) BL23
Chemical Crystallography Beamline BL24
5-mrad Canting
Long-Straight Section
Location under consideration
1-mrad Canting
under consideration

PETRA IV –Schedule

Project fixed by (external) boundary conditions

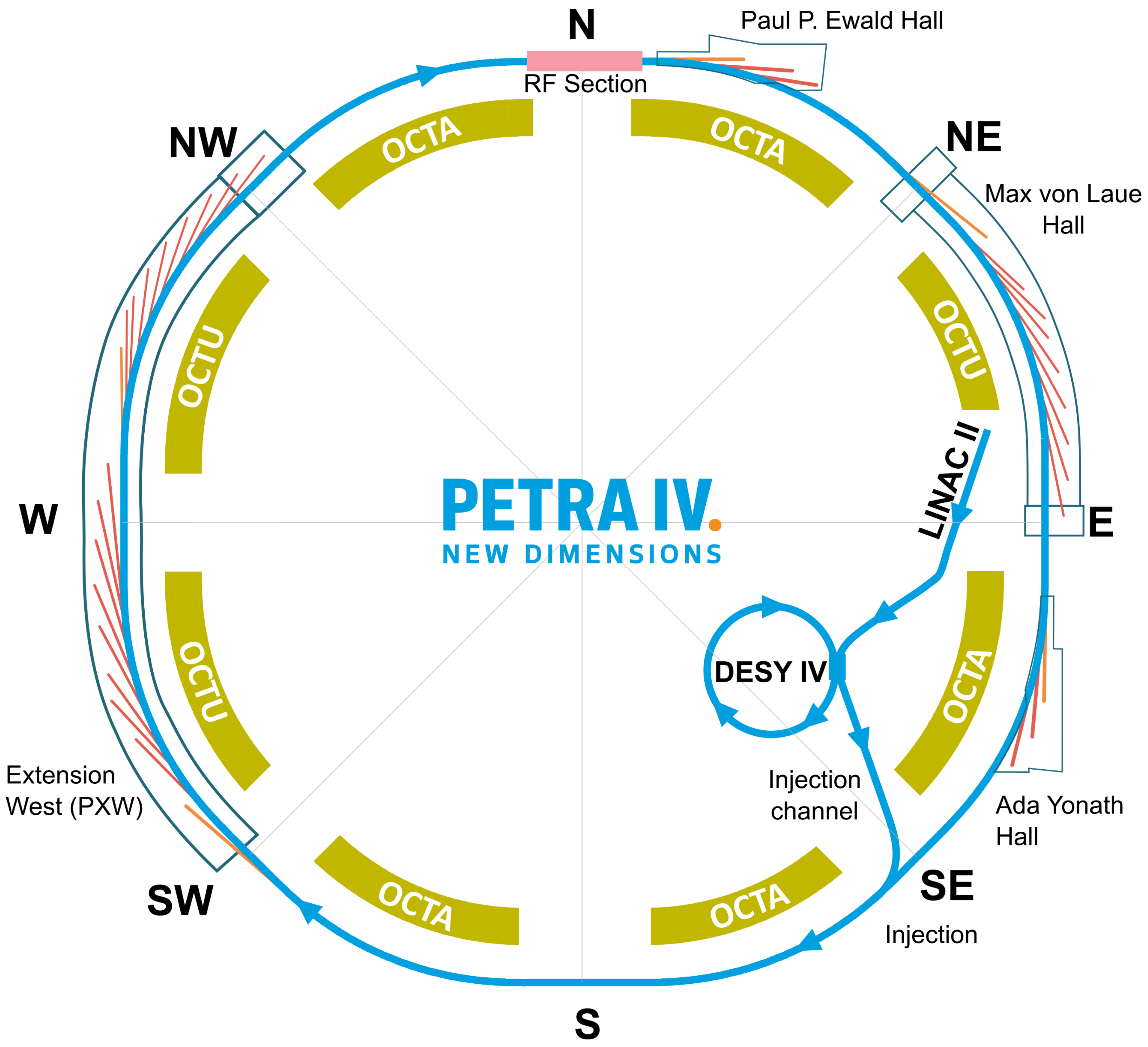


PETRA IV

Facility Layout and injection concepts

PETRA IV facility layout

How will the new facility look like?



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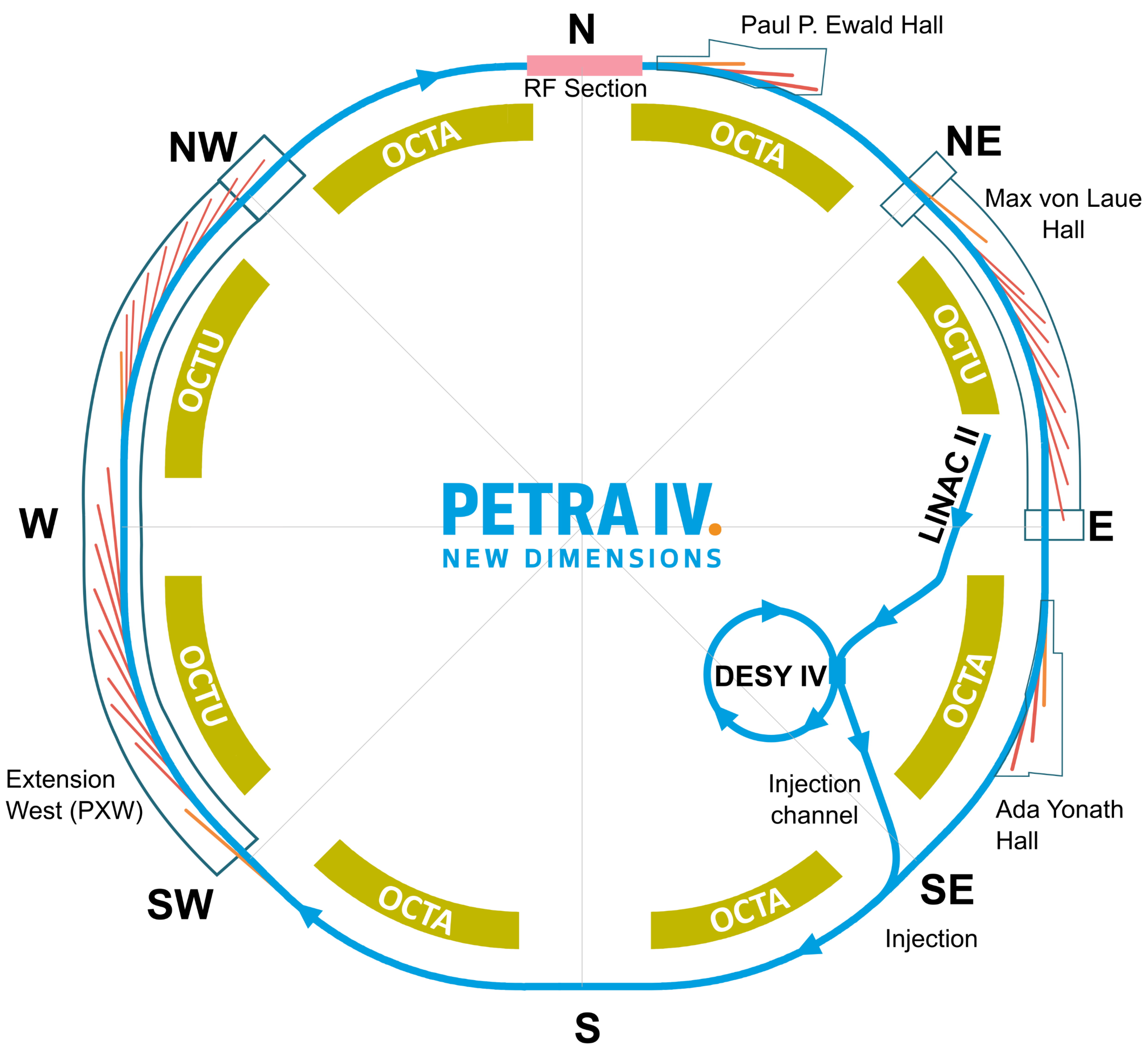
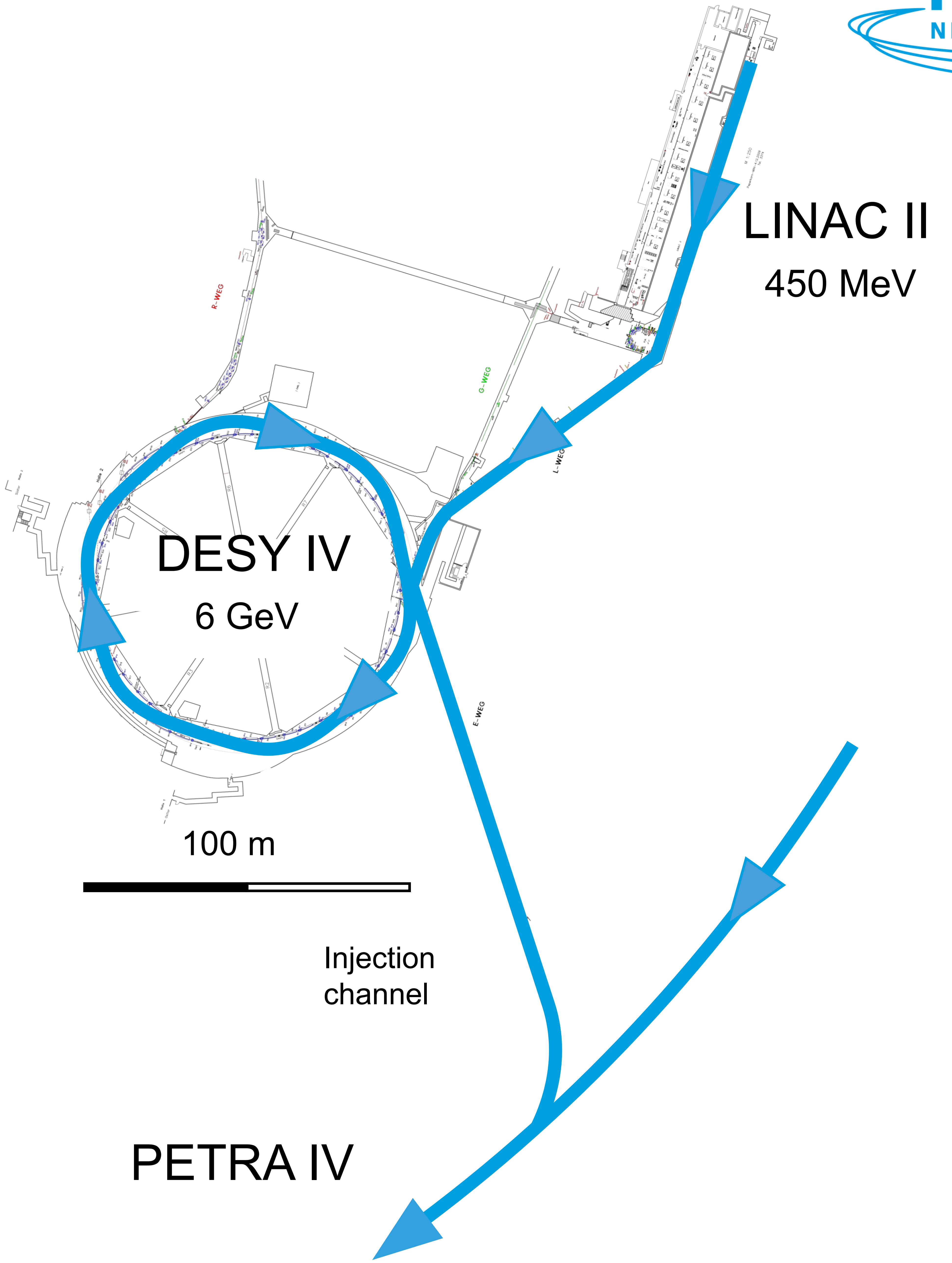
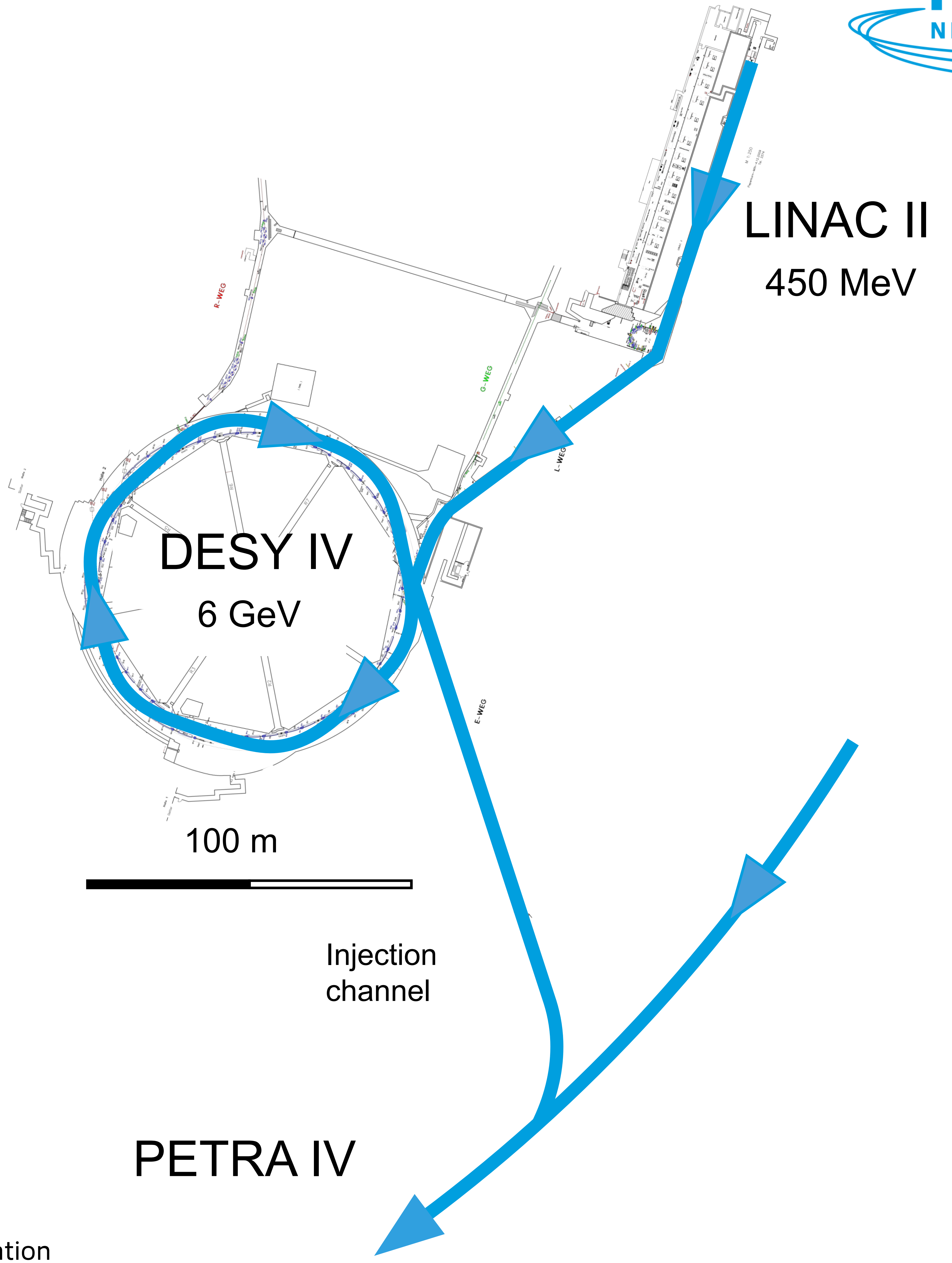




Pre-accelerators for PETRA IV

Two different options

Conventional Pre-accelerator



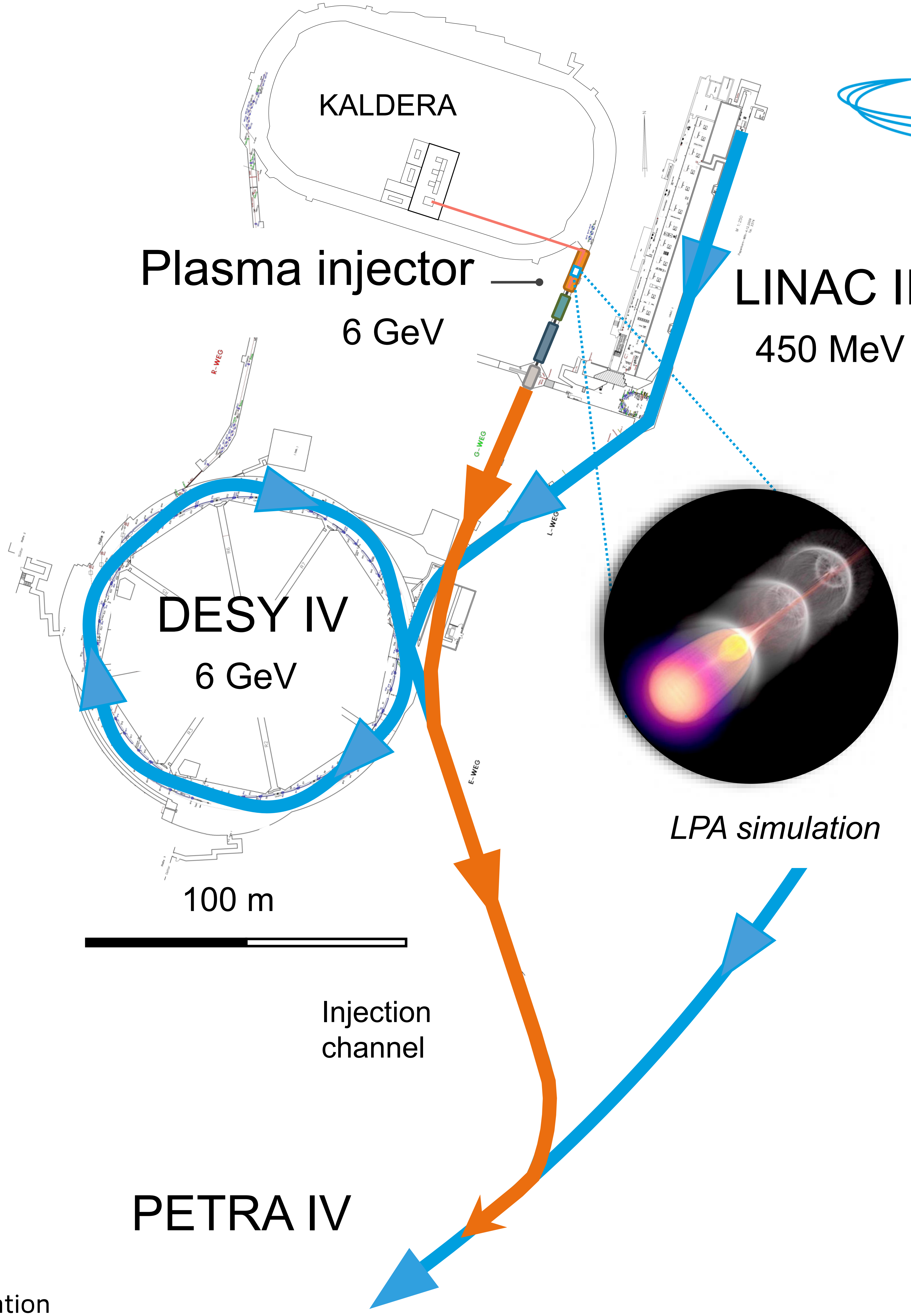
Pre-accelerators for PETRA IV

Two different options

Conventional Pre-accelerator

or

LPA based full energy injector



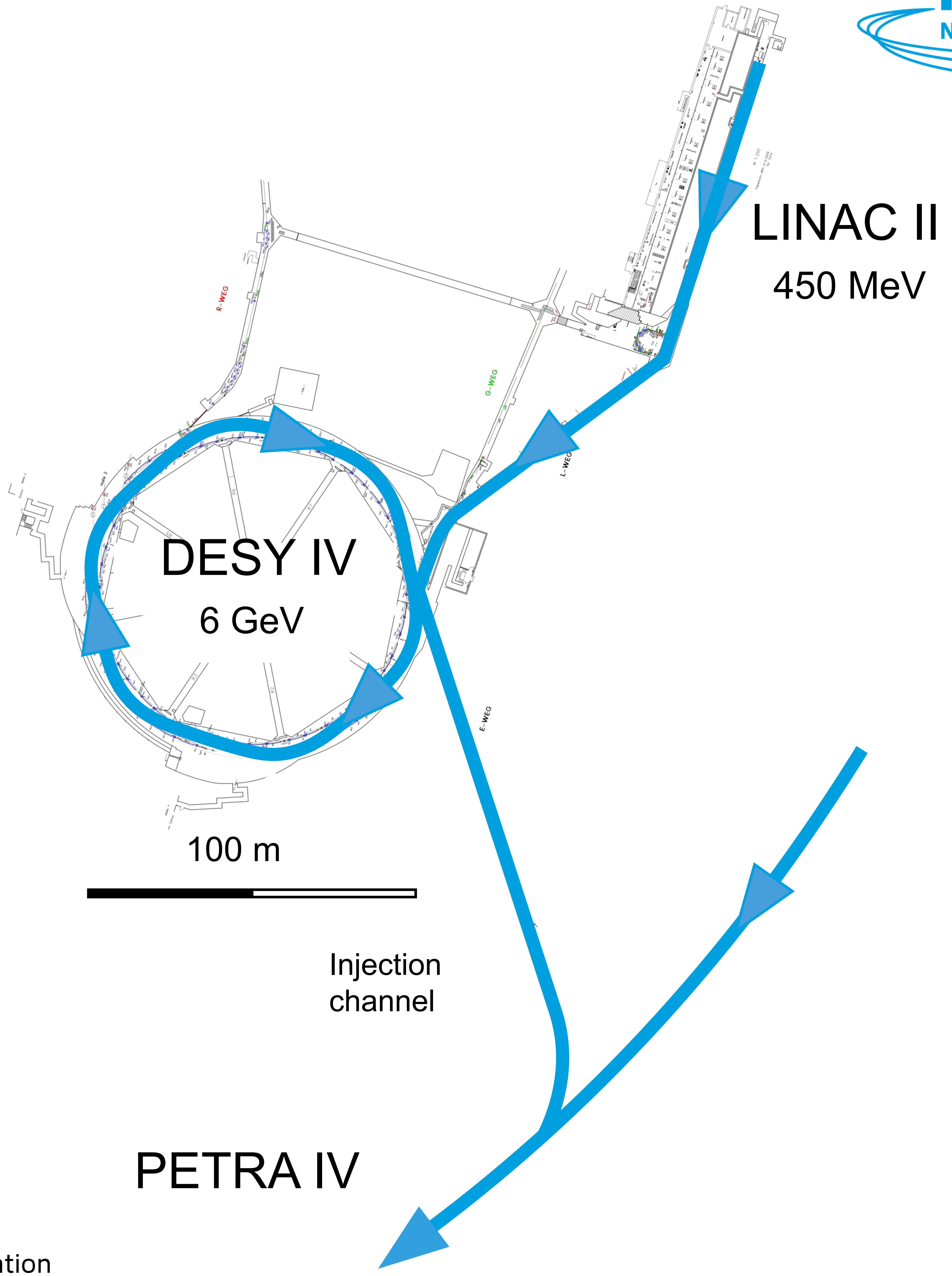
DESY IV

A new booster synchrotron for PETRA IV

PETRA IV - Conventional Injector

Take advantage of the existing facility

Conventional Pre-accelerator



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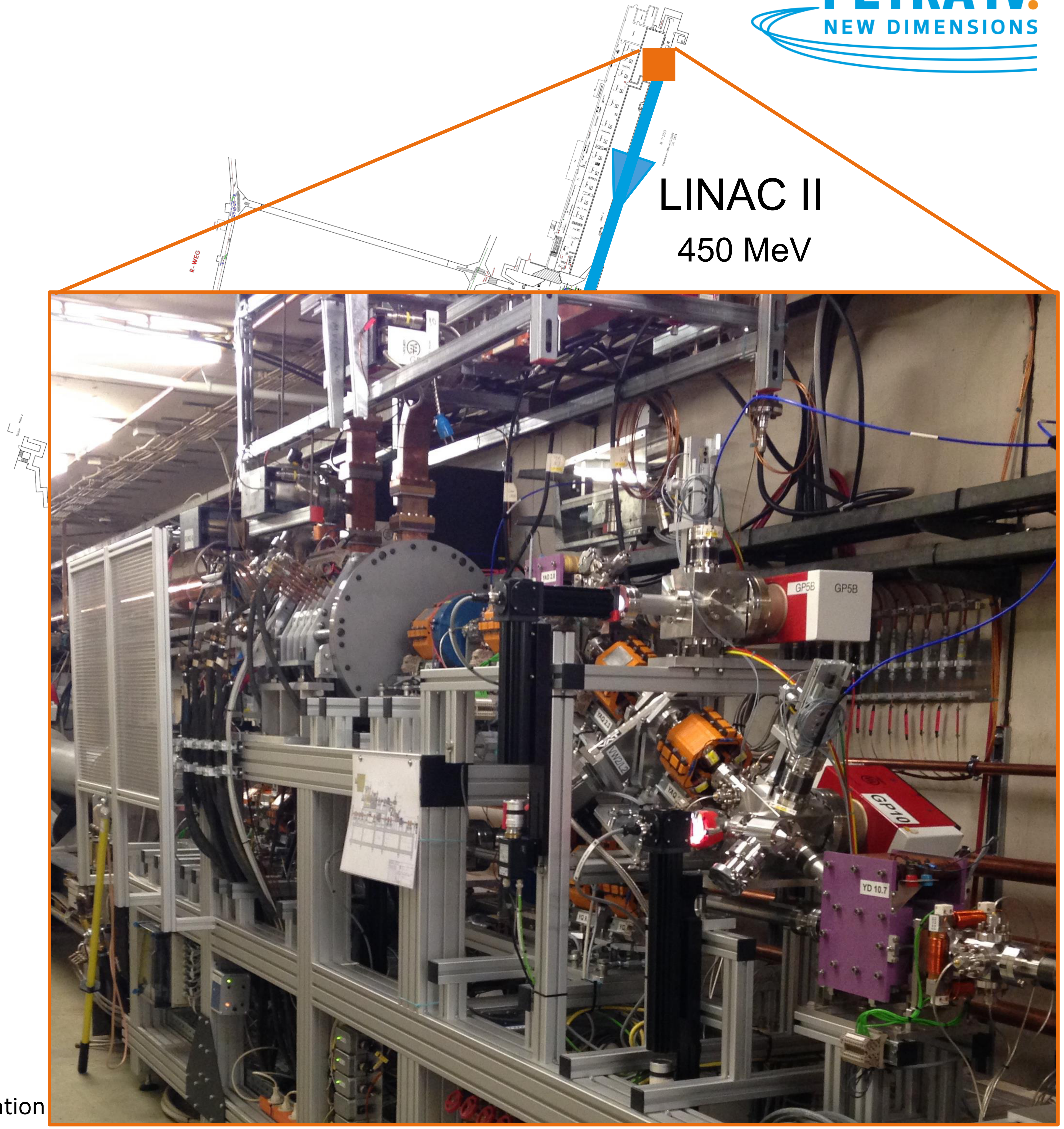
Take advantage of the existing facility

Conventional Pre-accelerator

Thermionic electron source (in operation since 2013)



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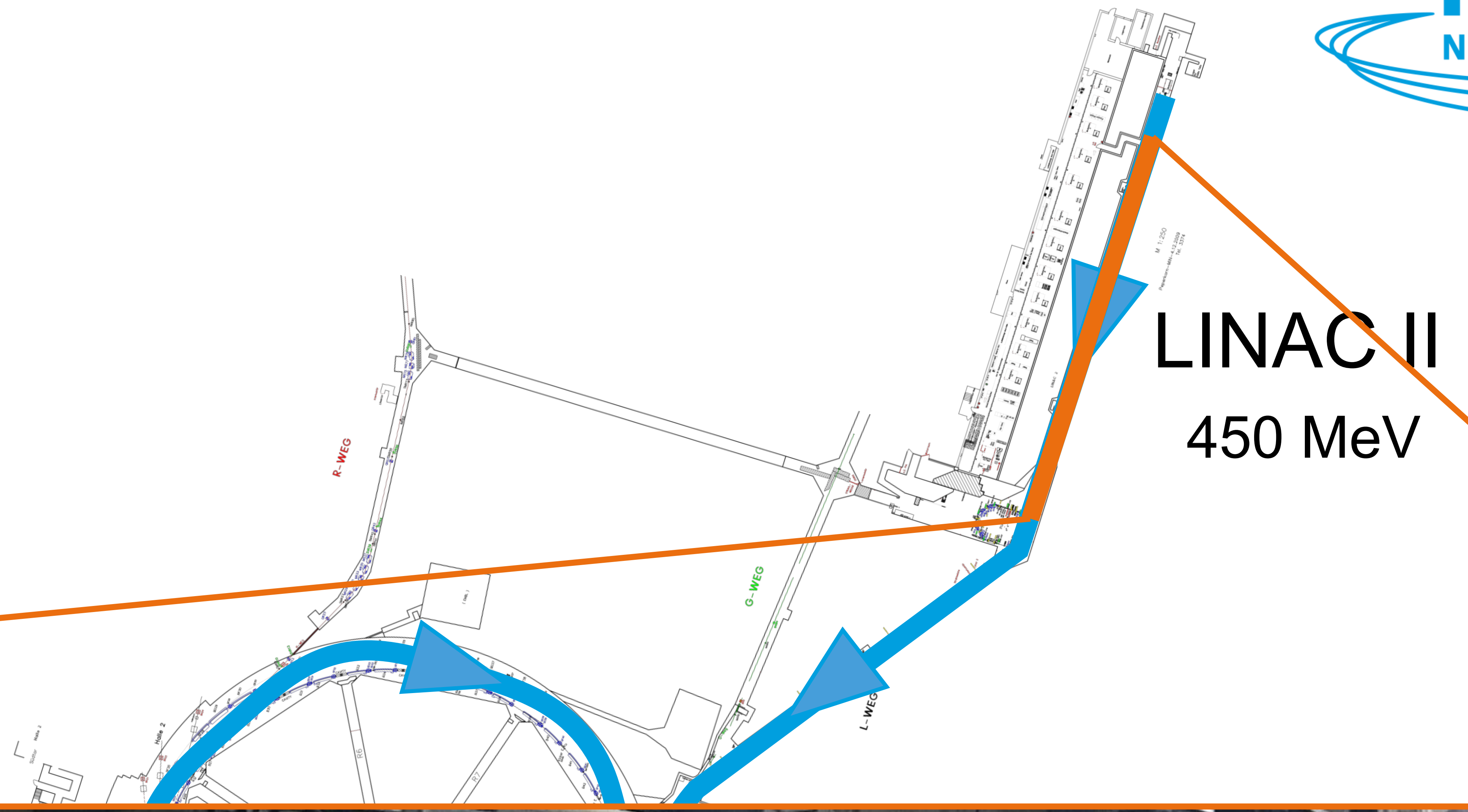
Thermionic electron source (in operation since 2013)

LINAC II   450 MeV S-Band Linac (to be refurbished)



PETRA IV - Conventional Injector

Take advantage of the existing facility

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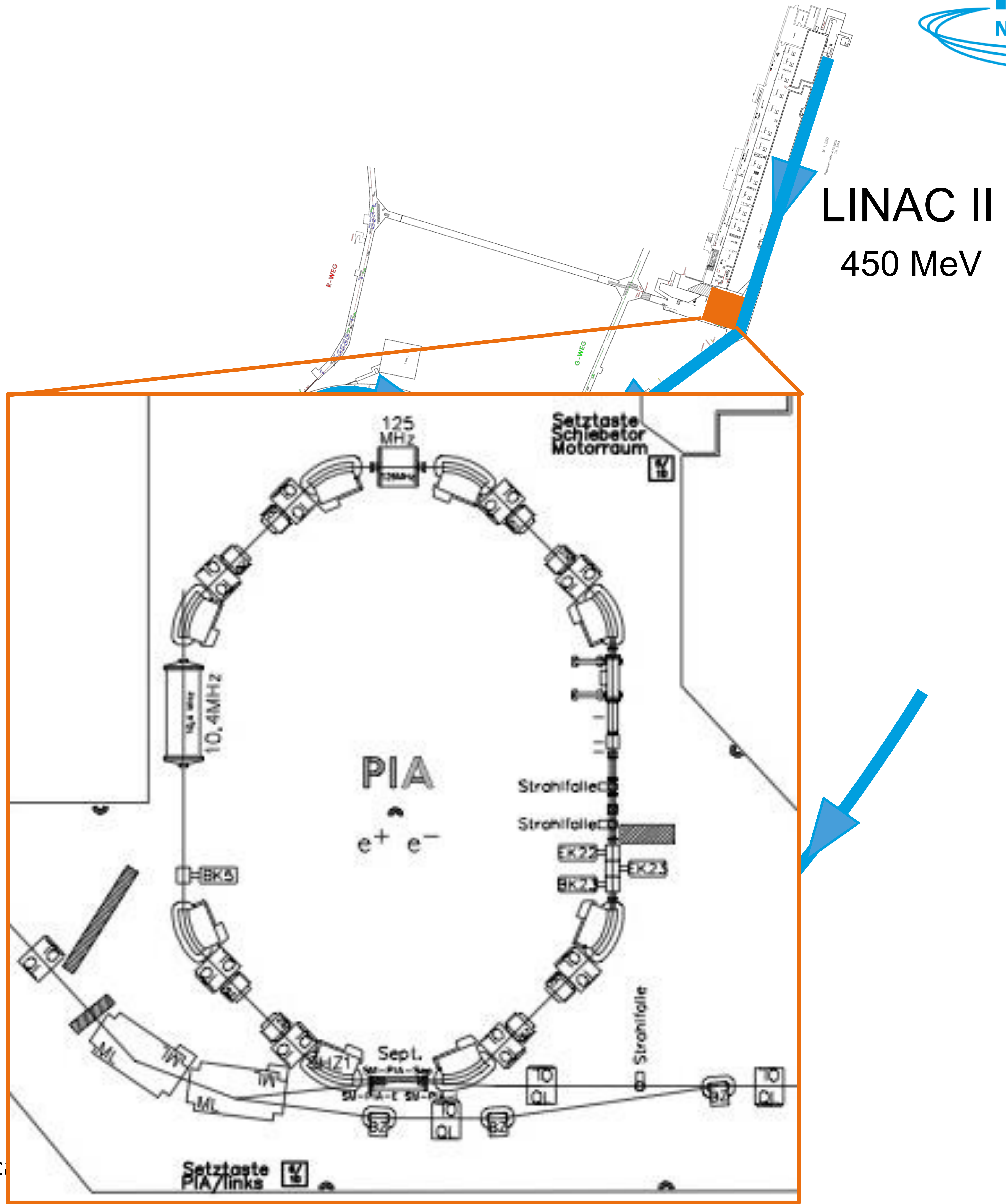
LINAC II   450 MeV S-Band Linac (to be refurbished)

PIA   450 MeV damping ring (to be refurbished)



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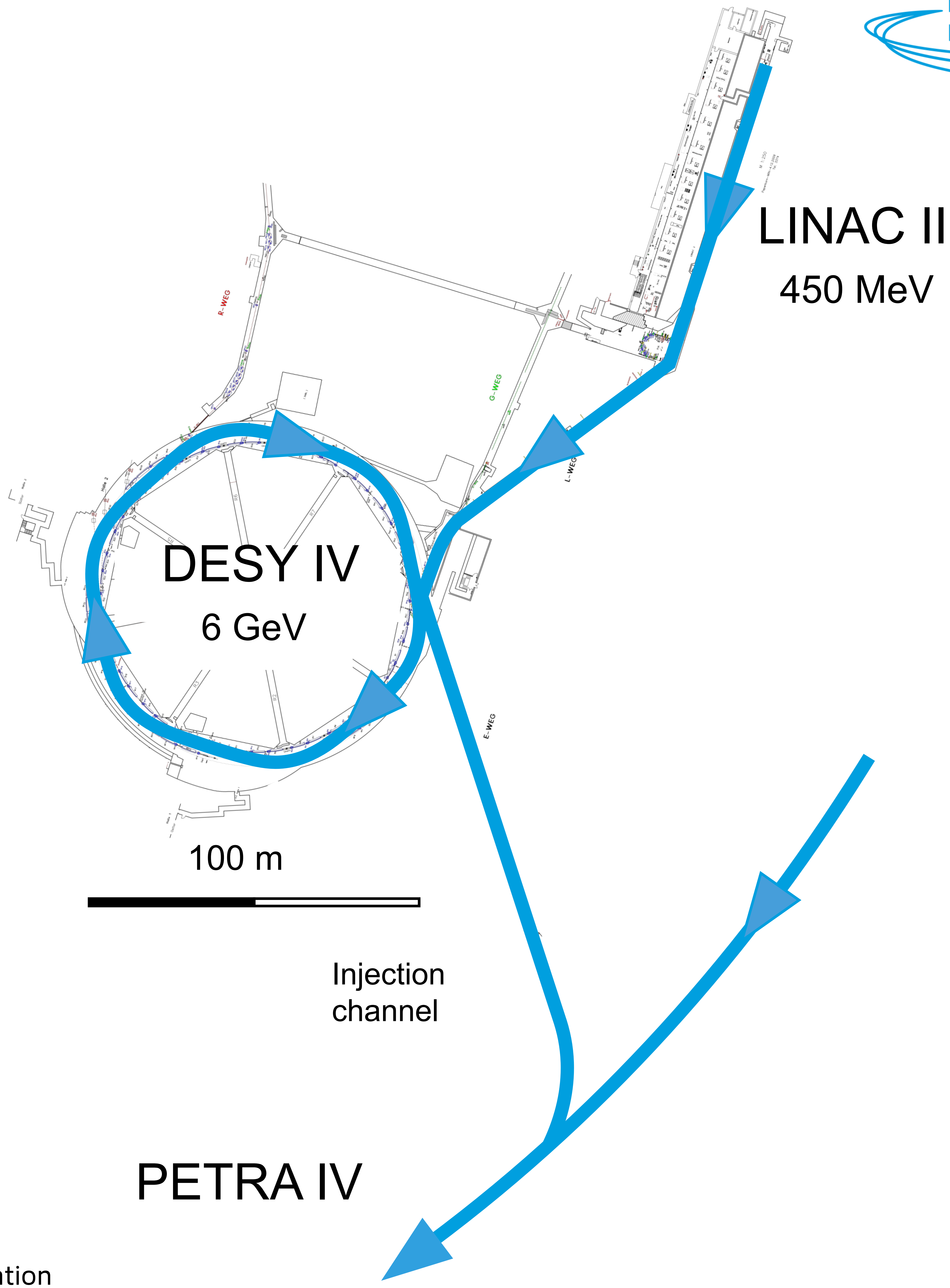
DESY IV   new 6 GeV Booster Synchrotron



PETRA IV - Conventional Injector

Take advantage of the existing facility

Conventional Pre-accelerator

Thermionic electron source (in operation since 2013)

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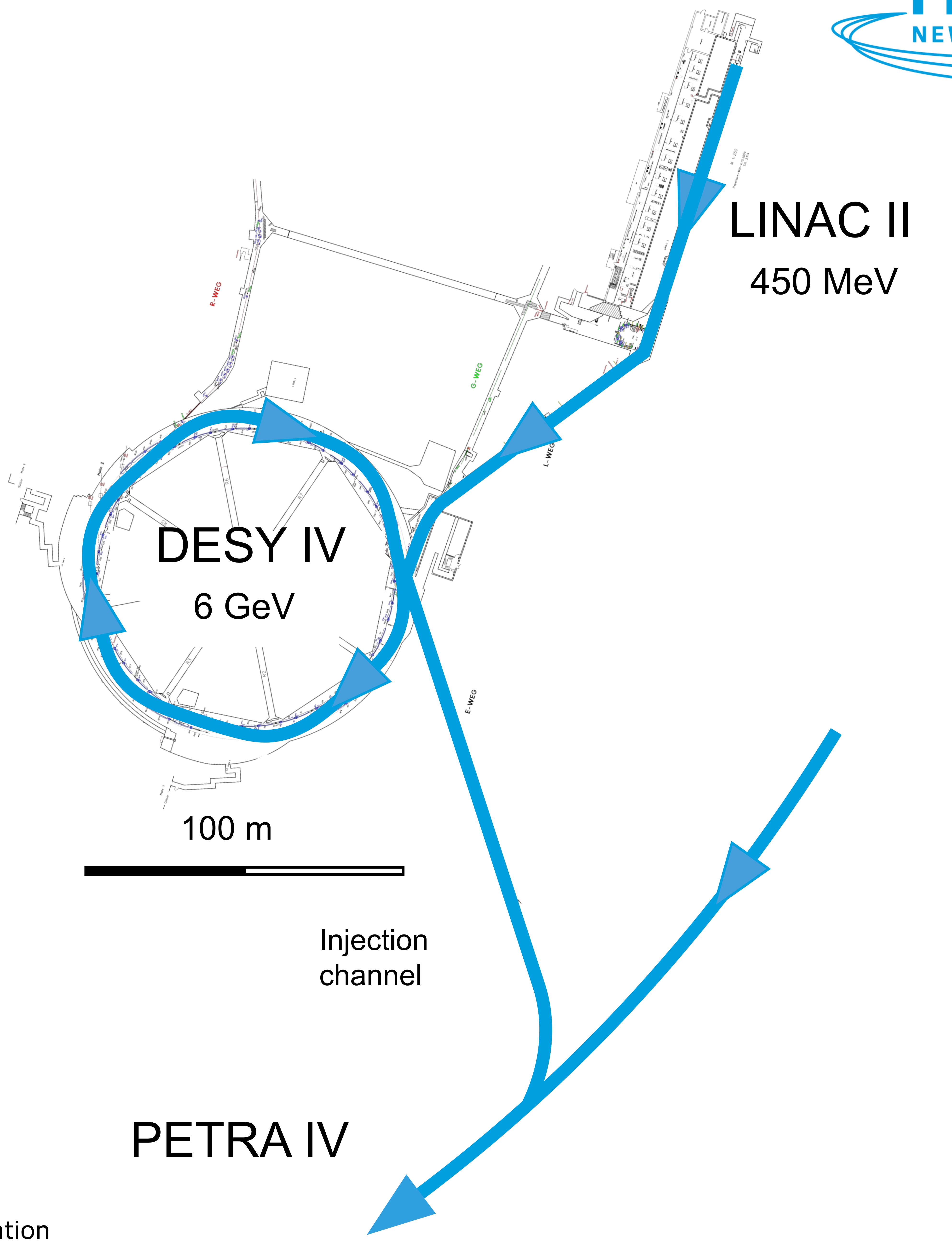
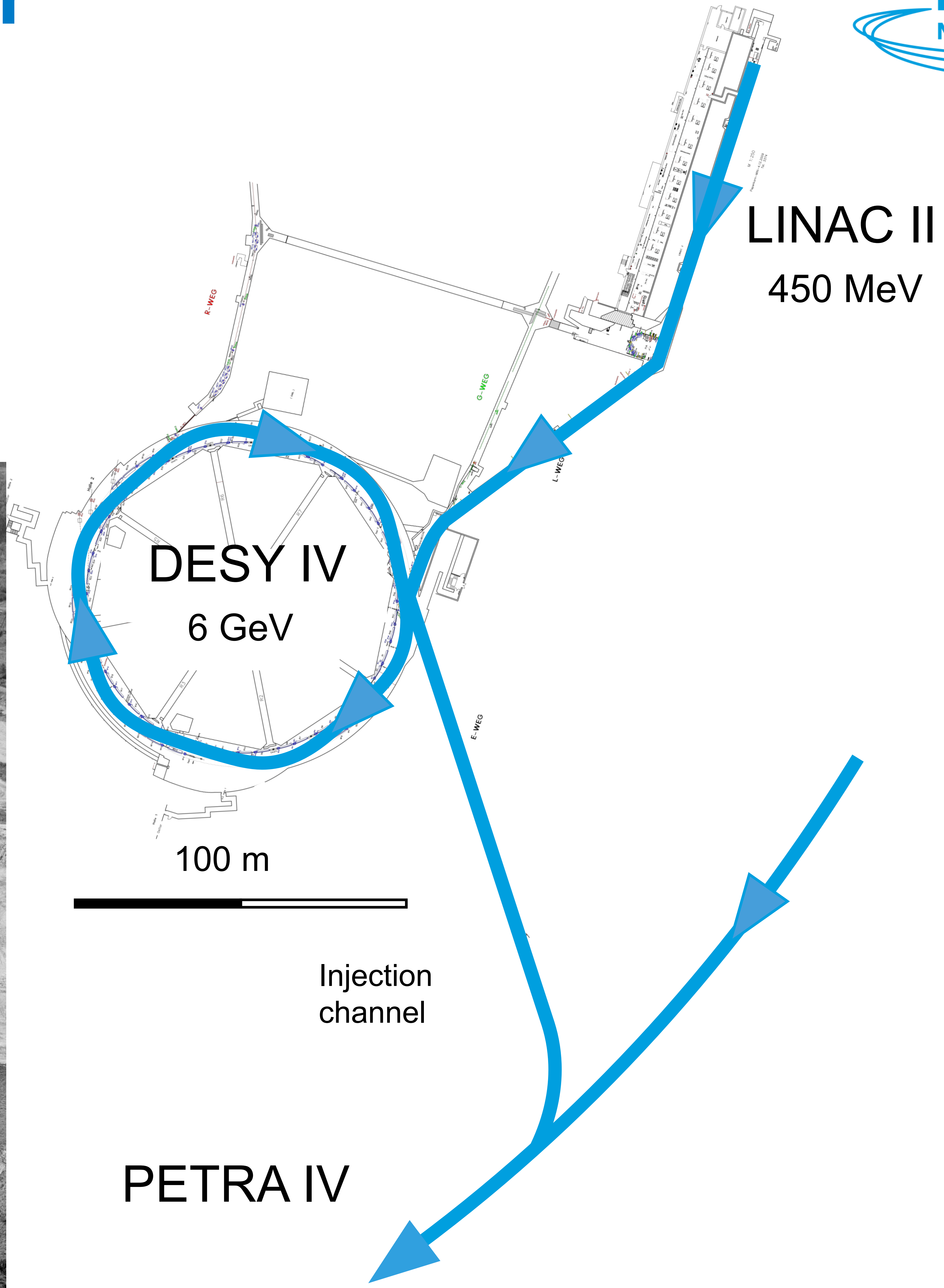
DESY IV new 6 GeV Booster Synchrotron

not trivial to put it in a legacy building



DESY legacy – where to put the booster

Where it all comes from...



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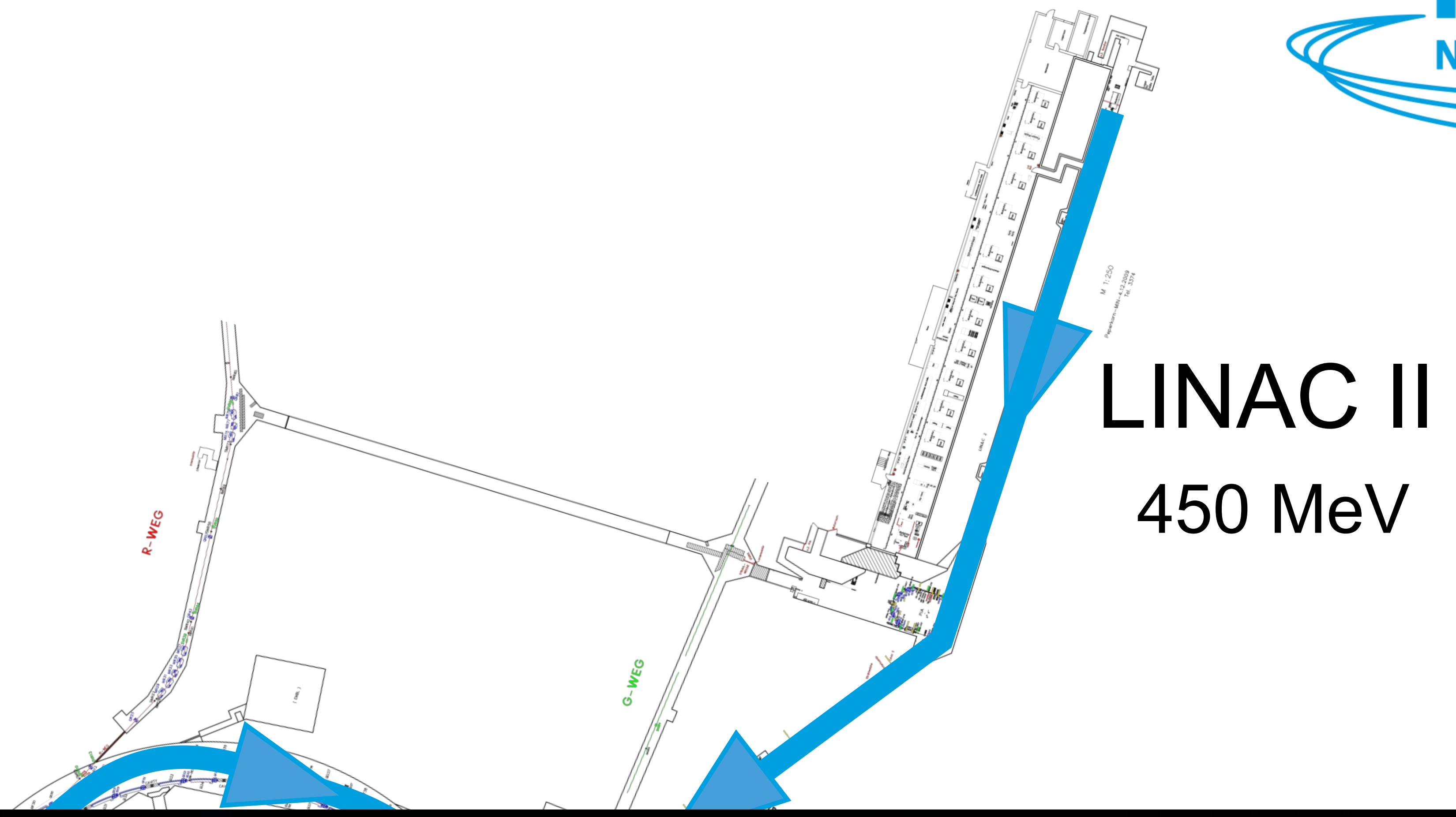
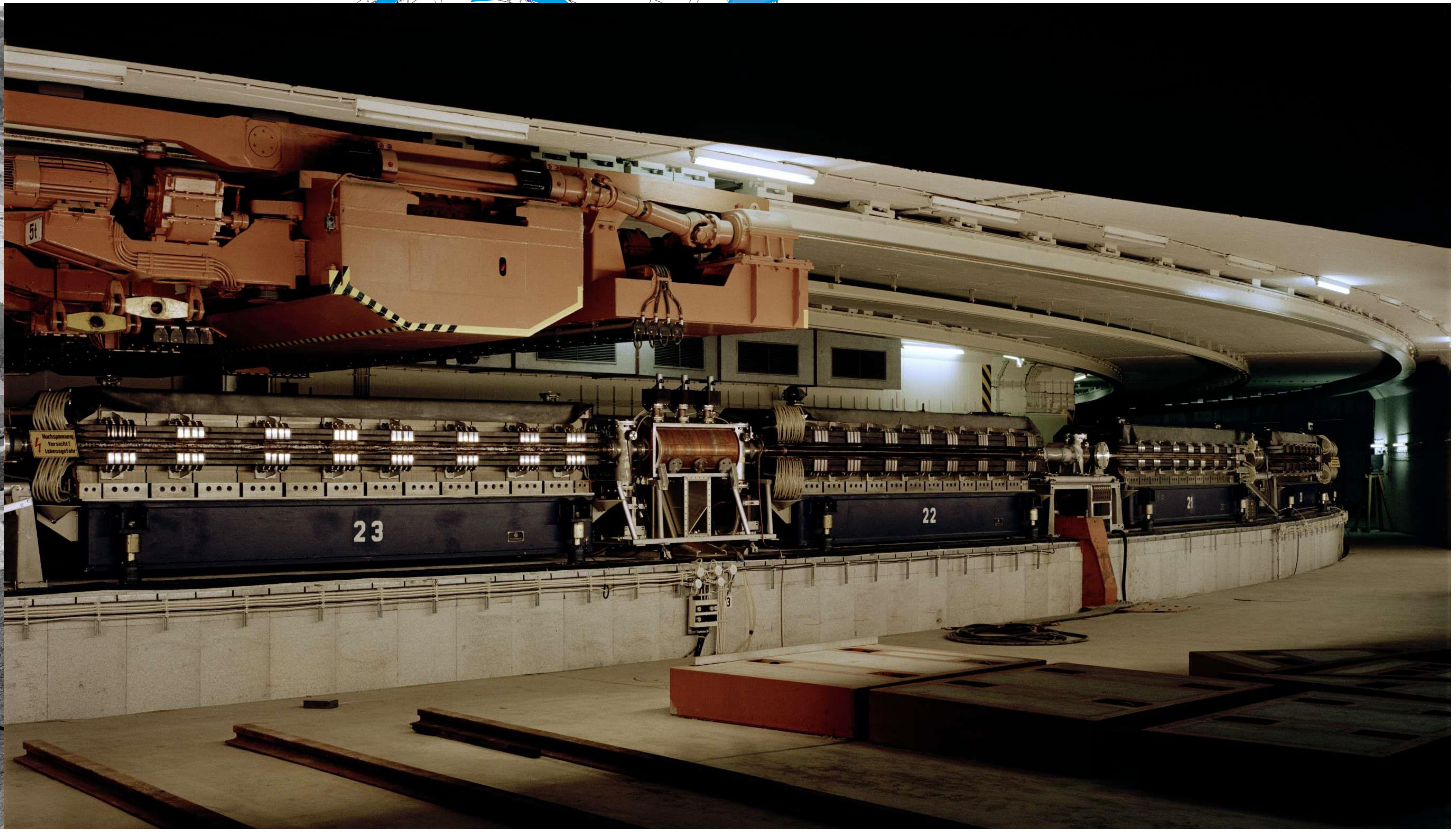
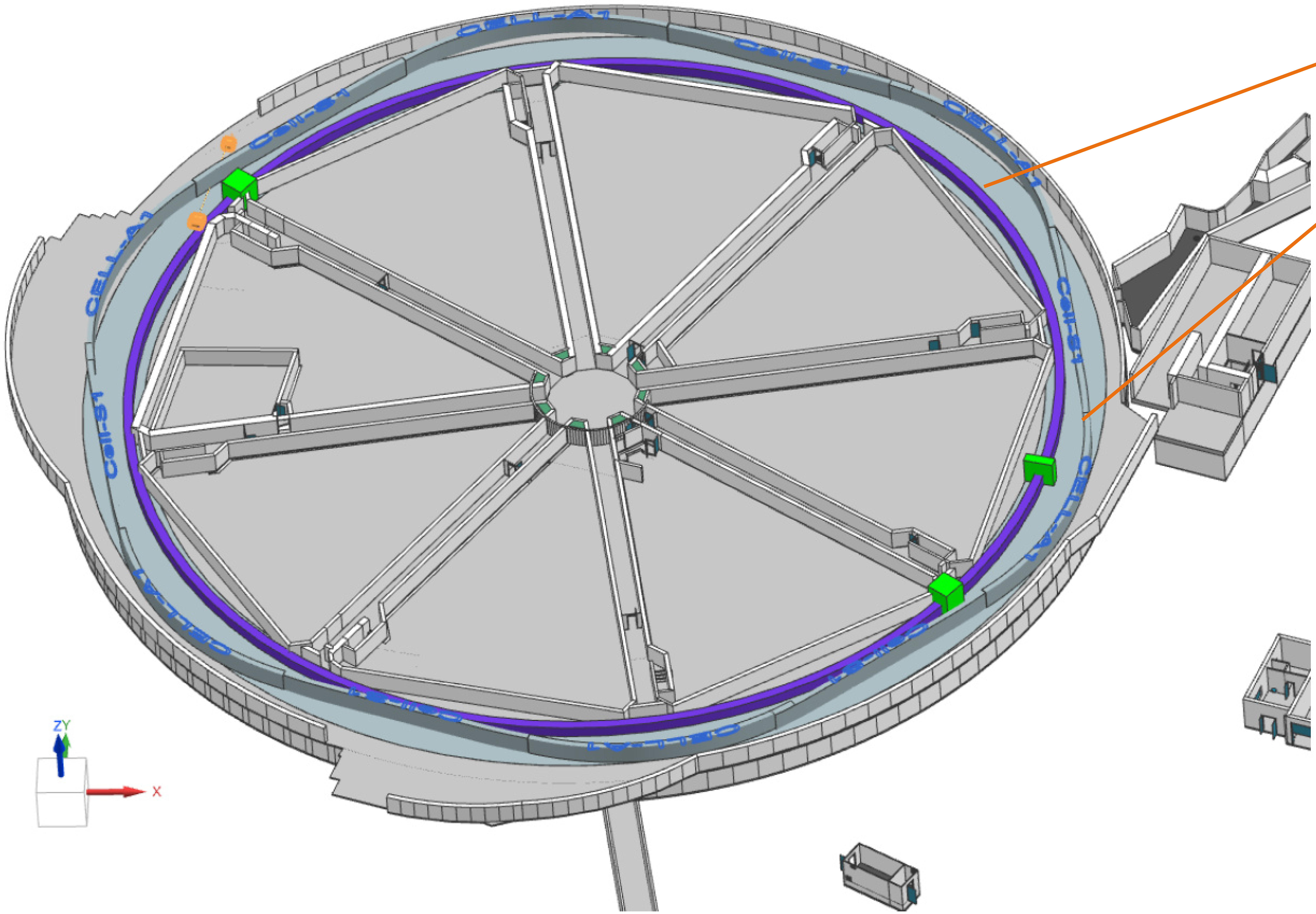




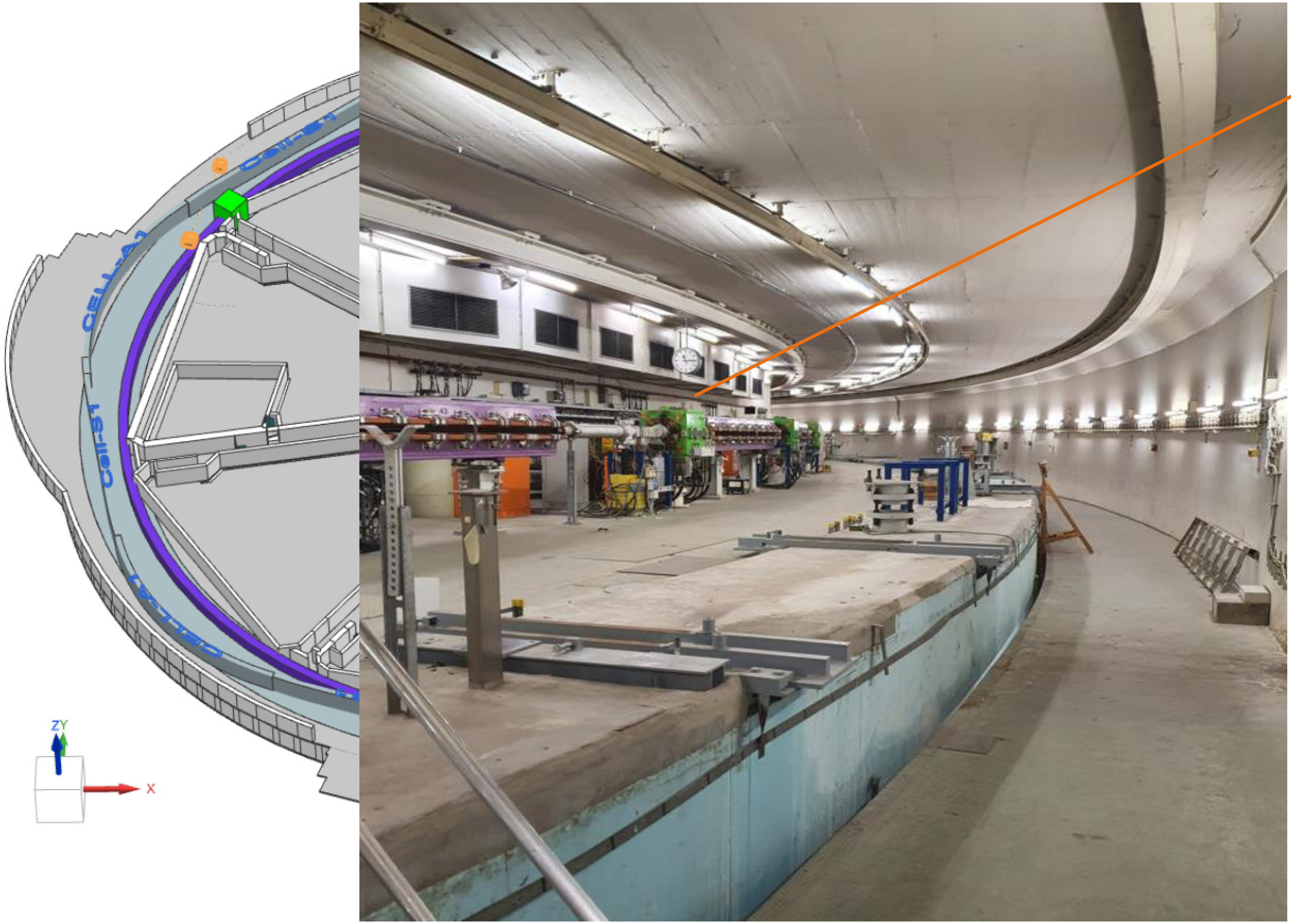
DESY Tunnel Layout

How to treat DESY I Legacy



DESY Tunnel Layout

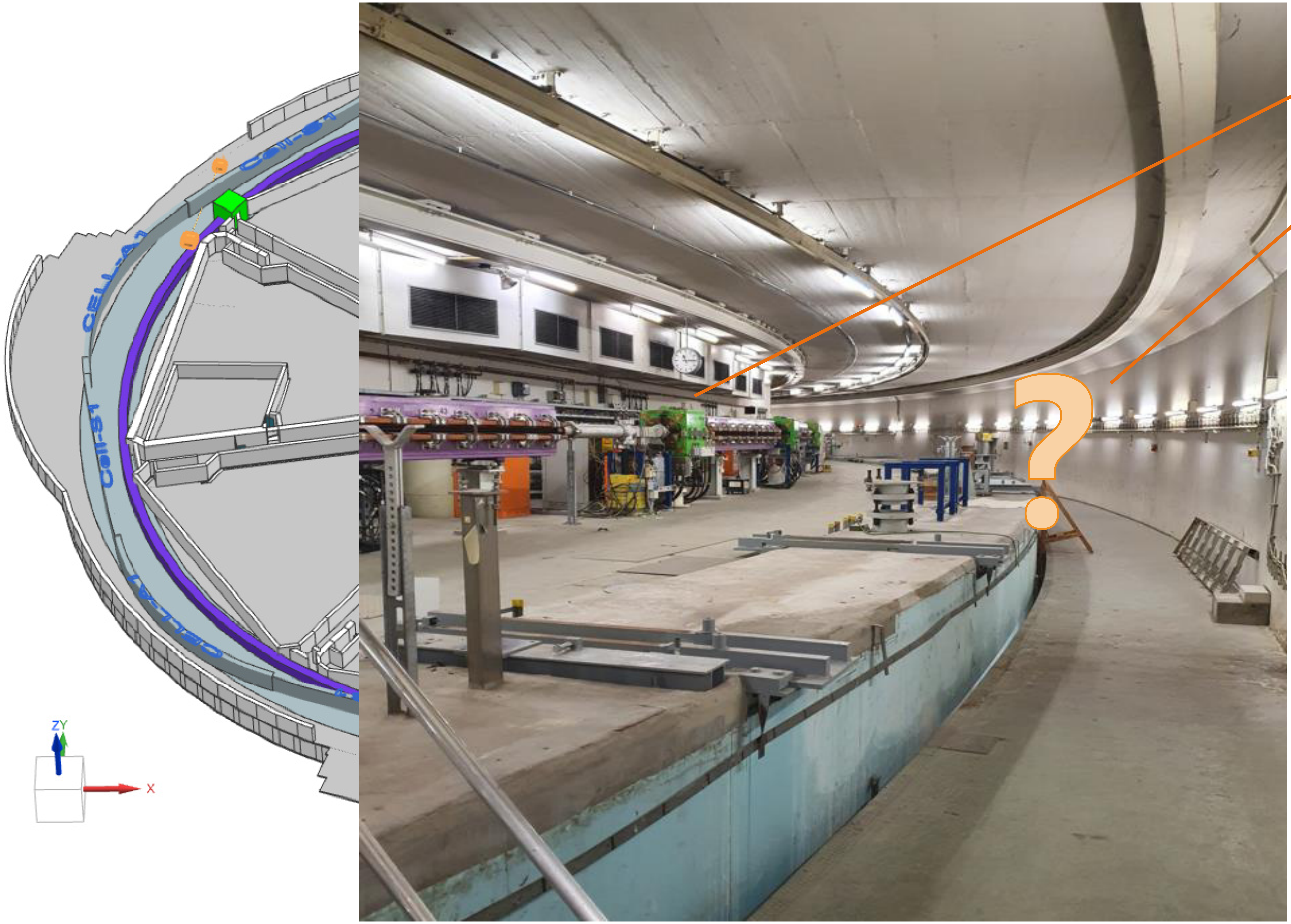
How to treat DESY I Legacy



existing DESY II

DESY Tunnel Layout

How to treat DESY I Legacy



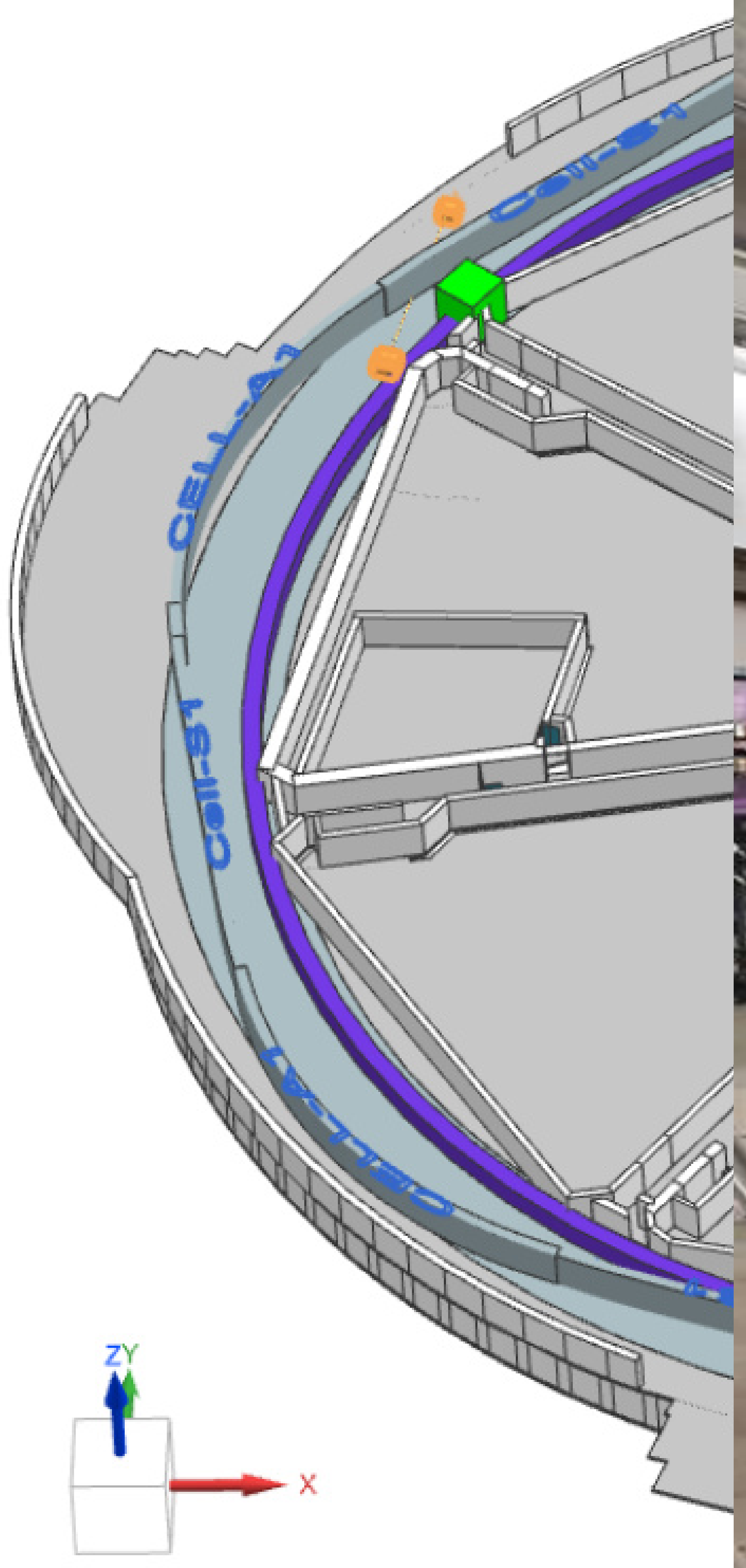
existing DESY II

possible DESY IV layout

But where to put it in the tunnel?

DESY Tunnel Layout

How to treat DESY I Legacy



Maybe on the ceiling?

Redesign of DESY IV Lattice

Installation of booster synchrotron on floor made lattice redesign necessary

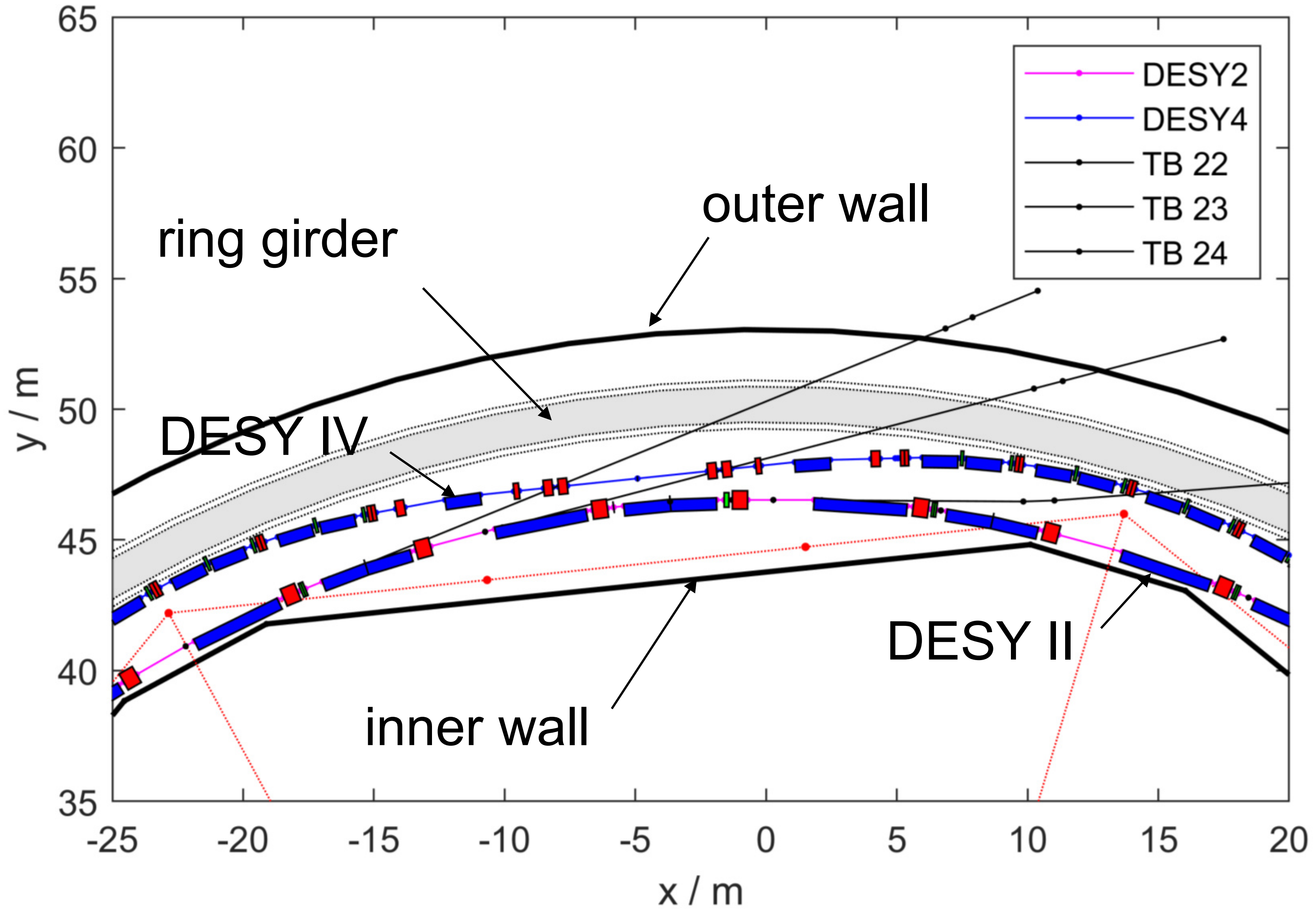
Placement of DESY IV

- Plan was to **install DESY IV on the ceiling**
  - It turned out that the load is near the allowed limit of the ceiling and installation is more complicated and expensive than expected
  - Existing DESY IV lattice had six-fold symmetry; not suitable to be installed on the floor → redesign necessary

- Several lattice options were investigated for the **installation of DESY IV on the floor**:

  1. Near outer wall
  2. On ring girder (DESY III)
  3. Between ring girder and DESY II
  4. Near inner wall (replacing DESY II)

- An 8-fold symmetric lattice adapted to the octagon shape of inner wall of building was selected (position 3)

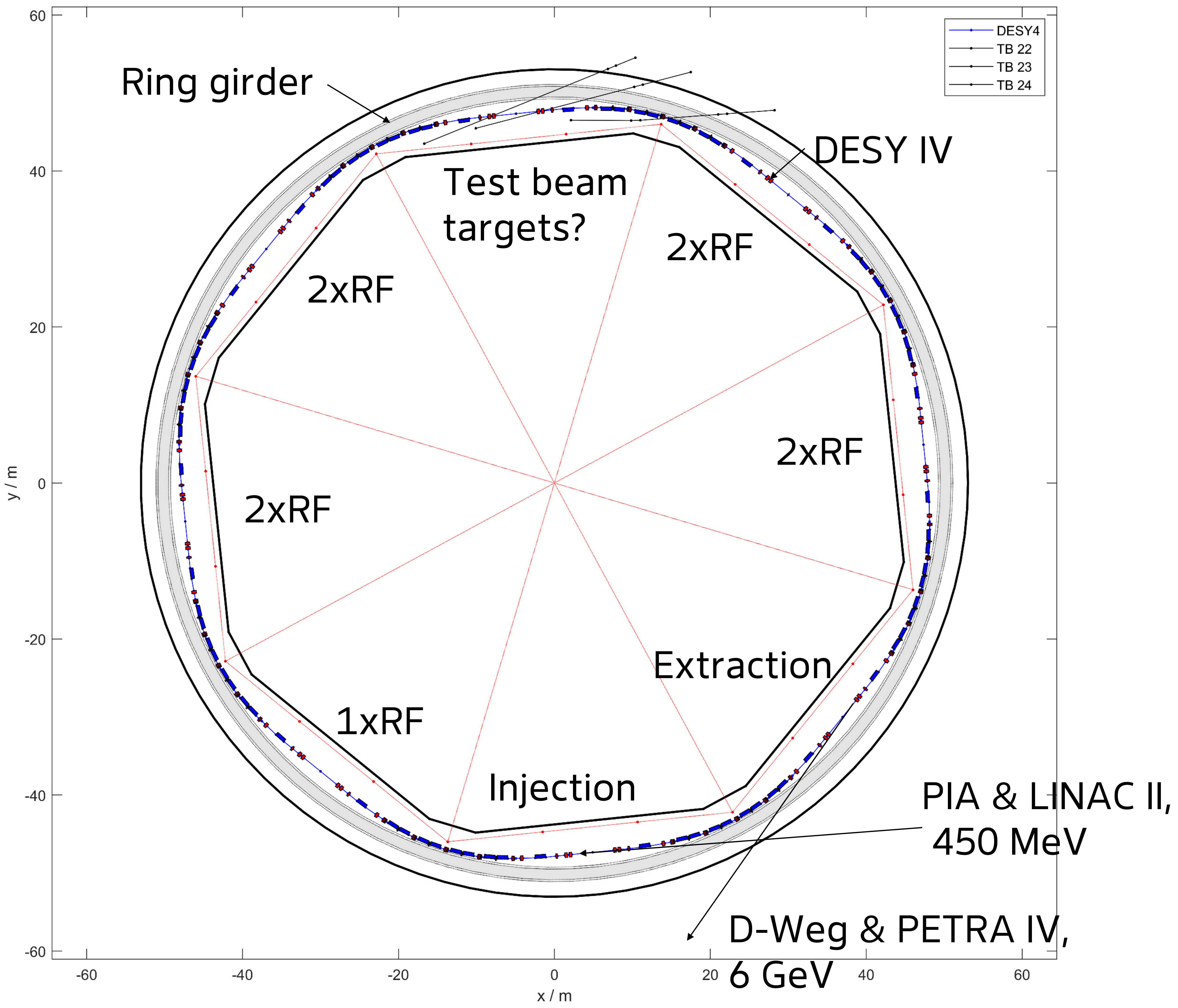


Layout of redesigned DESY IV

Schematic view

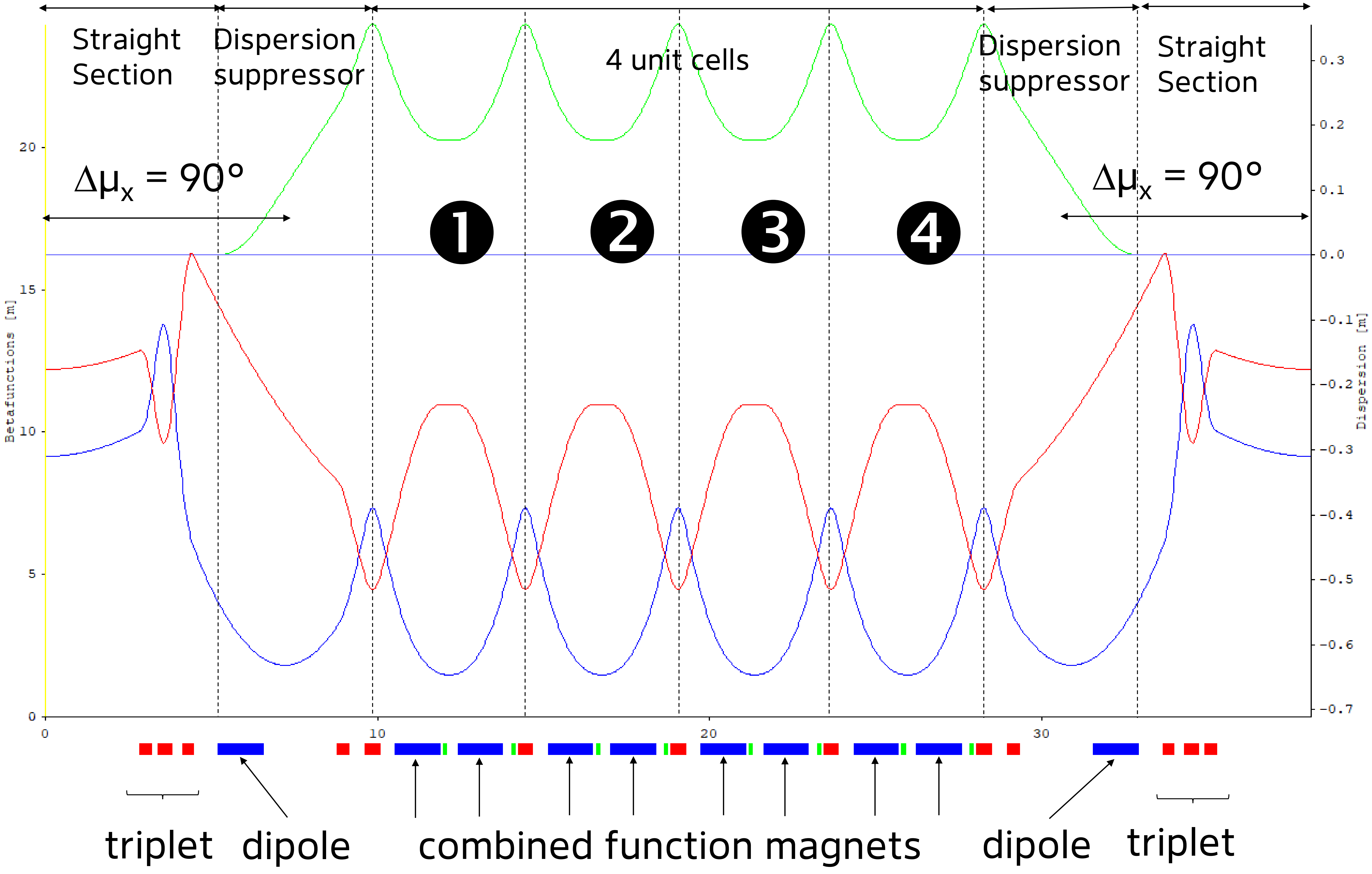
Eight dispersion free straights

- Space reserved for the installation of two PETRA five-cell cavities (2x1.8 m) and tapers
- Five straights with two RF cavities in each straight, 9 (8 for operation and 1 spare) cavities, total voltage 10 MV
- One straight used for horizontal on-axis injection from PIA/LINAC II
- One straight used for horizontal extraction to D-Weg / PETRA IV
- Straight in North could be used for test beam targets



Beam Optics of redesigned DESY IV Lattice

Optics of one super period (8-fold symmetry)



	Installation on ceiling	Installation on floor, (position #3)
Parameter	**DESY IV (3h3l v8)**	**DESY IV (P8 v6.1)**
Energy E	0.45 – 6 GeV	0.45 – 6 GeV
Circumference C	316.8 m	304.8 m
Super periodicity P	3	8
Tune Q	17.37 / 12.15	15.19 / 5.34
Emittance ε_x	19.0 nm·rad	21.1 nm·rad
Damp. part. number J_x	2.56	2.35
Nat. chromaticity ξ	-41.7 / -13.8	-19.2 / -10.5
MCF α	$3.17\cdot10^{-3}$	$3.5\cdot10^{-3}$
Energy loss/turn ΔE	6.55 MeV	6.67 MeV
Rel. energy spread σ_e	$2.6\cdot10^{-3}$	$2.17\cdot10^{-3}$
Damping times τ	0.75, 1.9, 4.4 ms	0.78, 1.8, 2.8 ms

Lattice changes:

- Instead of alternating high / low beta straights only high beta straights; higher periodicity
- 4 unit cells instead of 5 unit cells
- Reduced damping partition number (smaller energy spread but also slightly larger emittance)

The Plasma Injector for PETRA IV

What about a new concept?

The Plasma Injector for PETRA IV

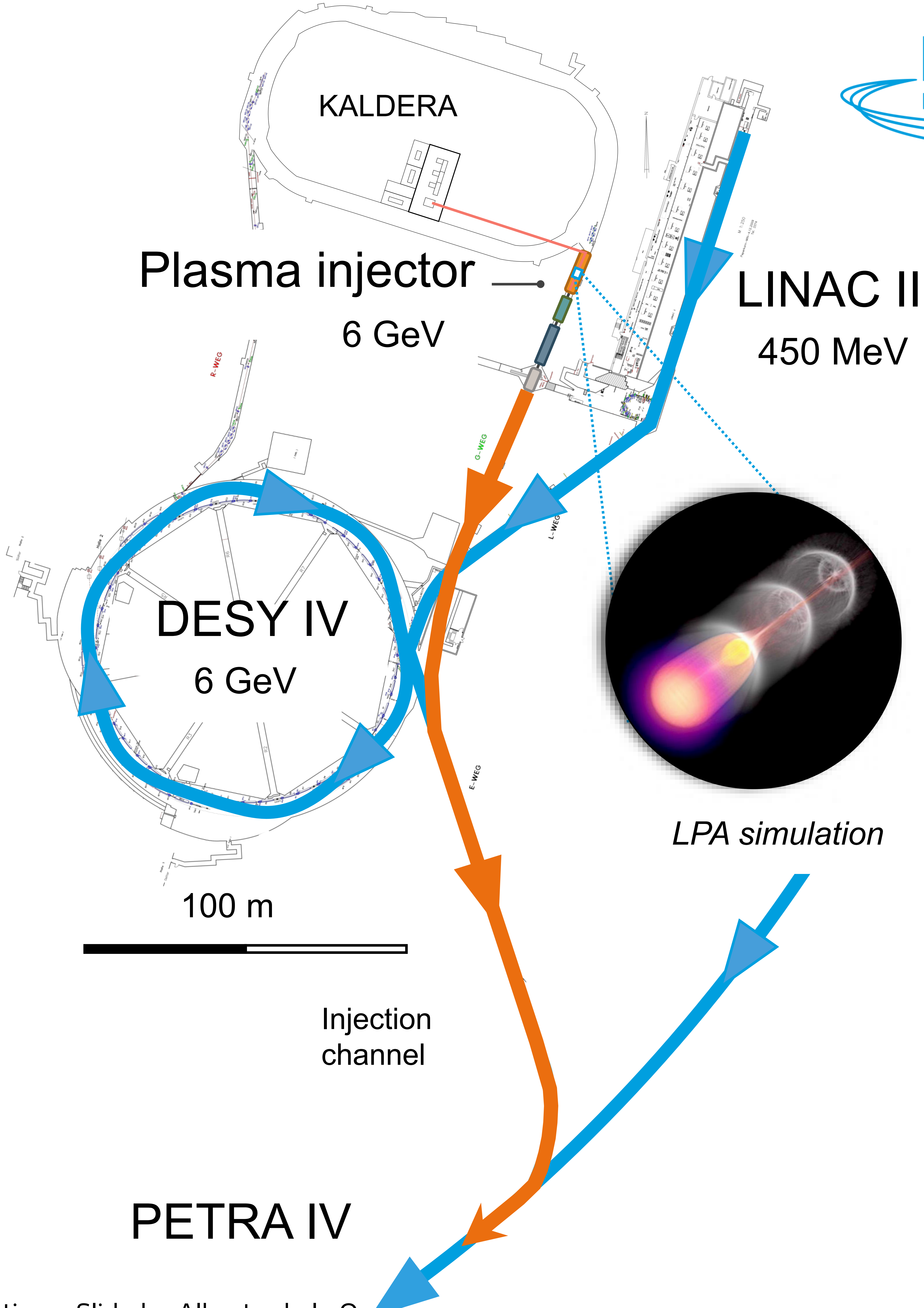
a compact, cost-effective and competitive alternative

- **Compact:** laser-plasma acc. + beamline: < 50 m
- **Cost-effective:** power consumption: < 500 kW
- **Competitive:** full PETRA IV operation (fill + top-up)

Key challenges:

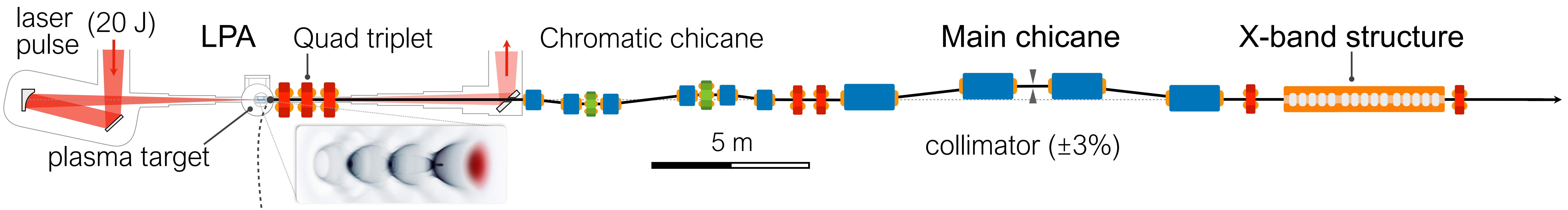
- Energy gain: 6 GeV
- Energy spread and jitter: < 0.3 %
  (to maximize charge throughput and stability)
- Charge injection rate: > 2.6 nC/s
  (to fill the ring in < 10 minutes)
- Availability: > 98% (for the user's satisfaction)

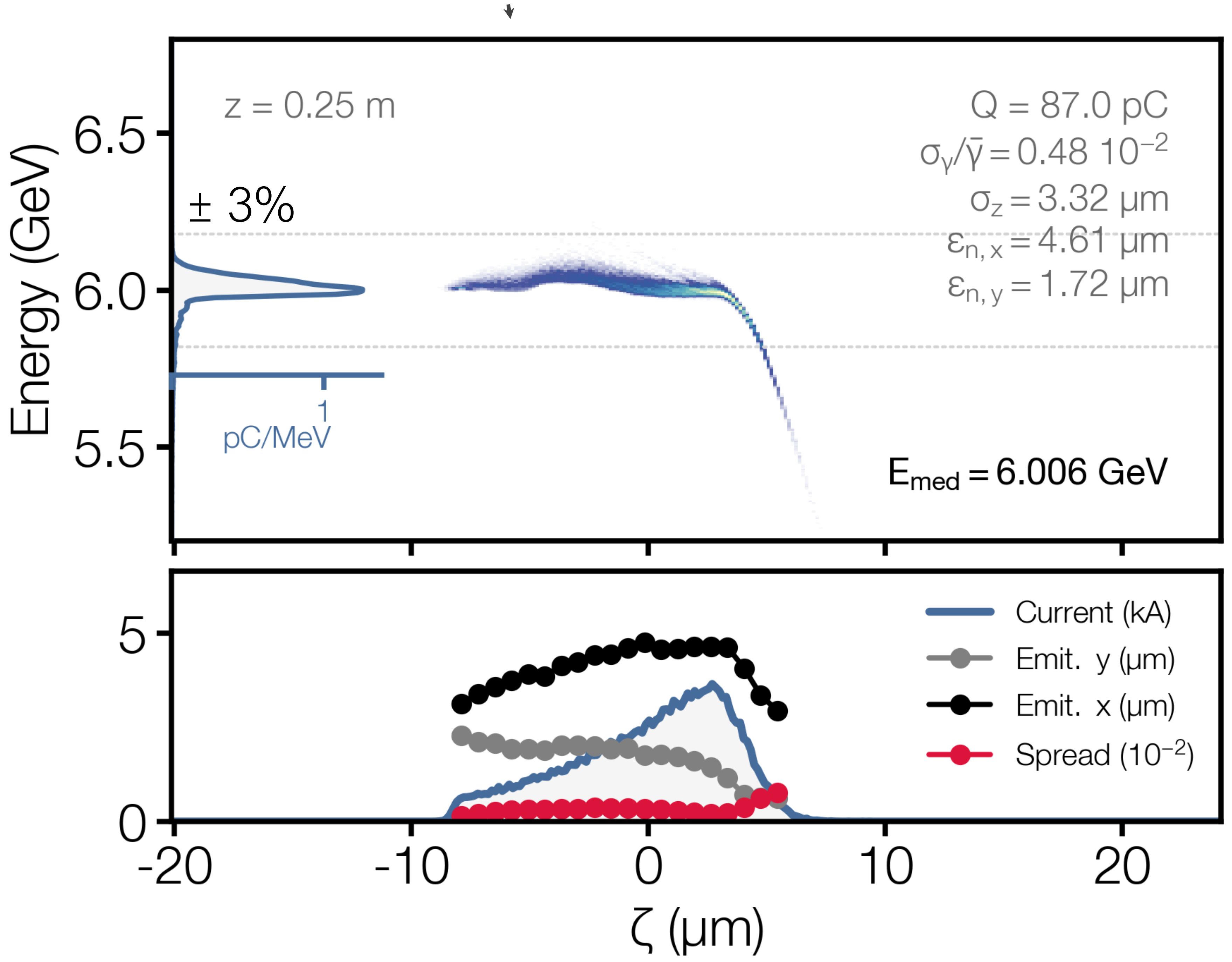
Laser-plasma acceleration technology (LPA) enables a more compact and energy efficient solution



The Plasma Injector: LPA optimization at 6 GeV

Working point 1: optimal case for 50 µm guiding channel



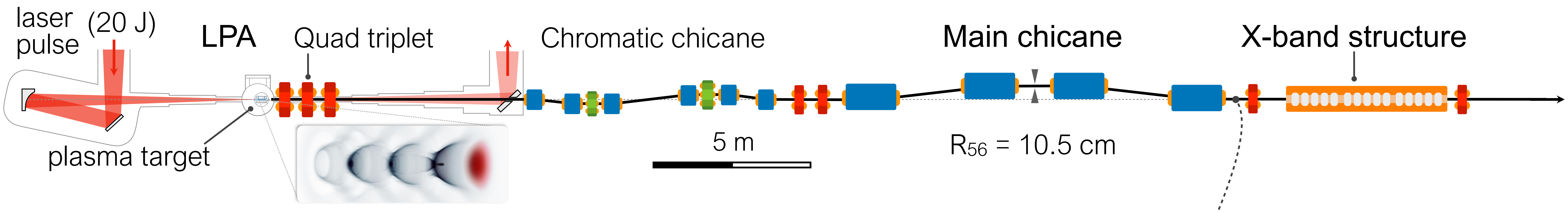


Electron beam (after LPA)

- Optimization: averaged beam-loading.
- Charge: 87 pC, Energy spread: 0.5 %.
- Norm. emittance: 4.6 µm and 1.7 µm.
- Divergence: 0.22 mrad and 0.12 mrad.
- Efficiency: 2.7 %

The Plasma Injector: ECB simulation

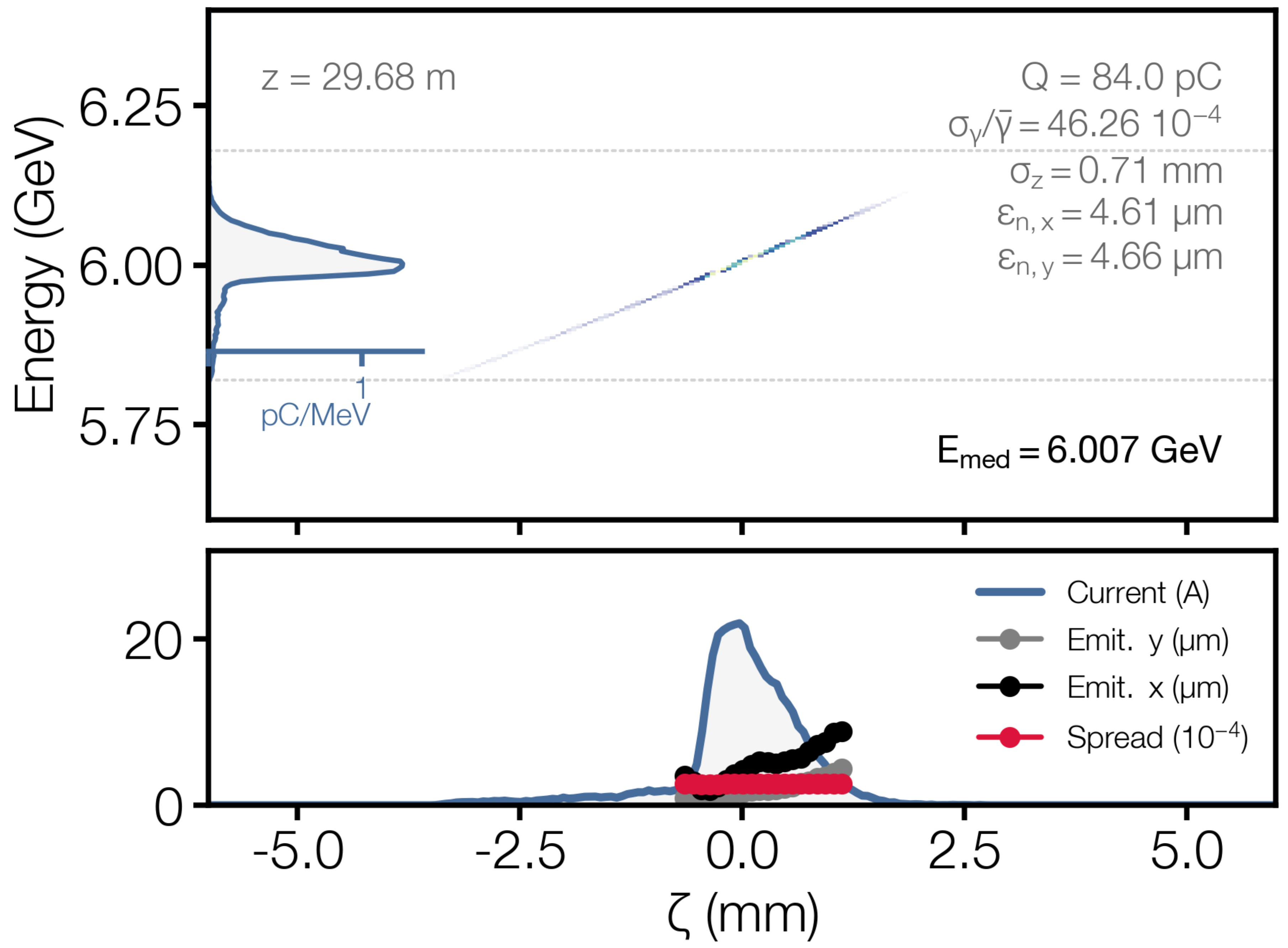
Start-to-end simulation of the optimal case



Electron beam (after chicane)

- Induced energy-time correlation (chirp)

$$\zeta - \zeta_{\mathrm{ref}} = R_{56}\frac{E - E_{\mathrm{ref}}}{E_{\mathrm{ref}}}$$



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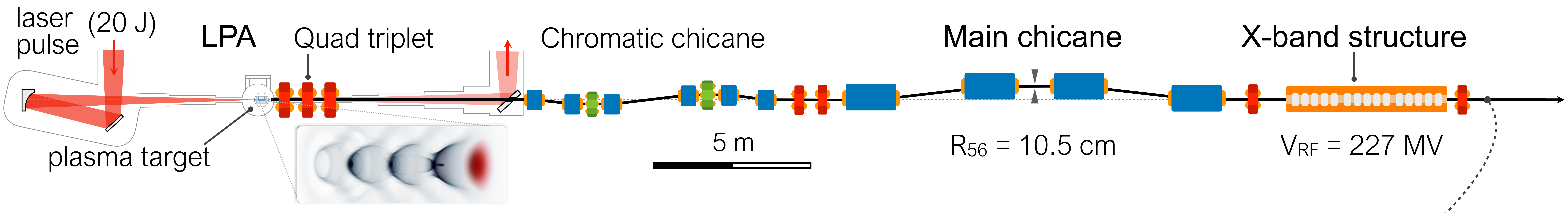

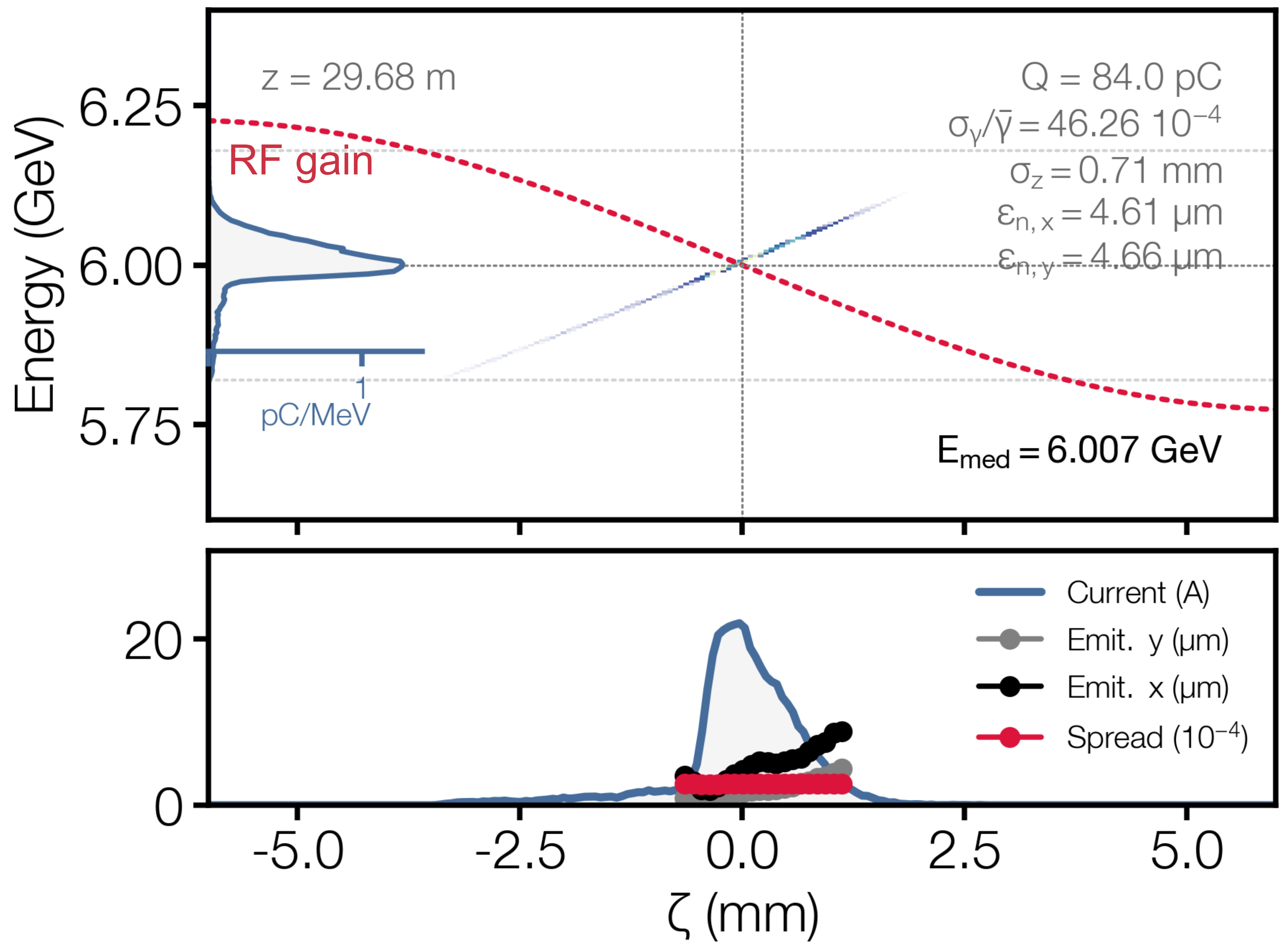

Electron beam (after RF)

- The RF corrects the energy deviations

$$V_{\mathrm{RF}} = V_{\mathrm{RF}}^{0} \sin[k_{\mathrm{RF}}(\zeta - \zeta_{\mathrm{ref}})] \qquad eV_{\mathrm{RF}}^{0} = \frac{E_{\mathrm{ref}}}{k_{\mathrm{RF}} R_{56}}$$

- Final energy spread: $\sigma_{E,\mathrm{rel}} \simeq \dfrac{\sigma_{\zeta,i}}{R_{56}}$

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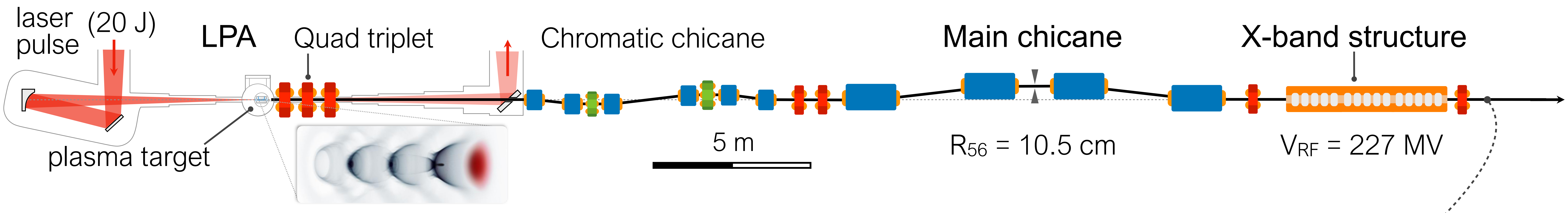

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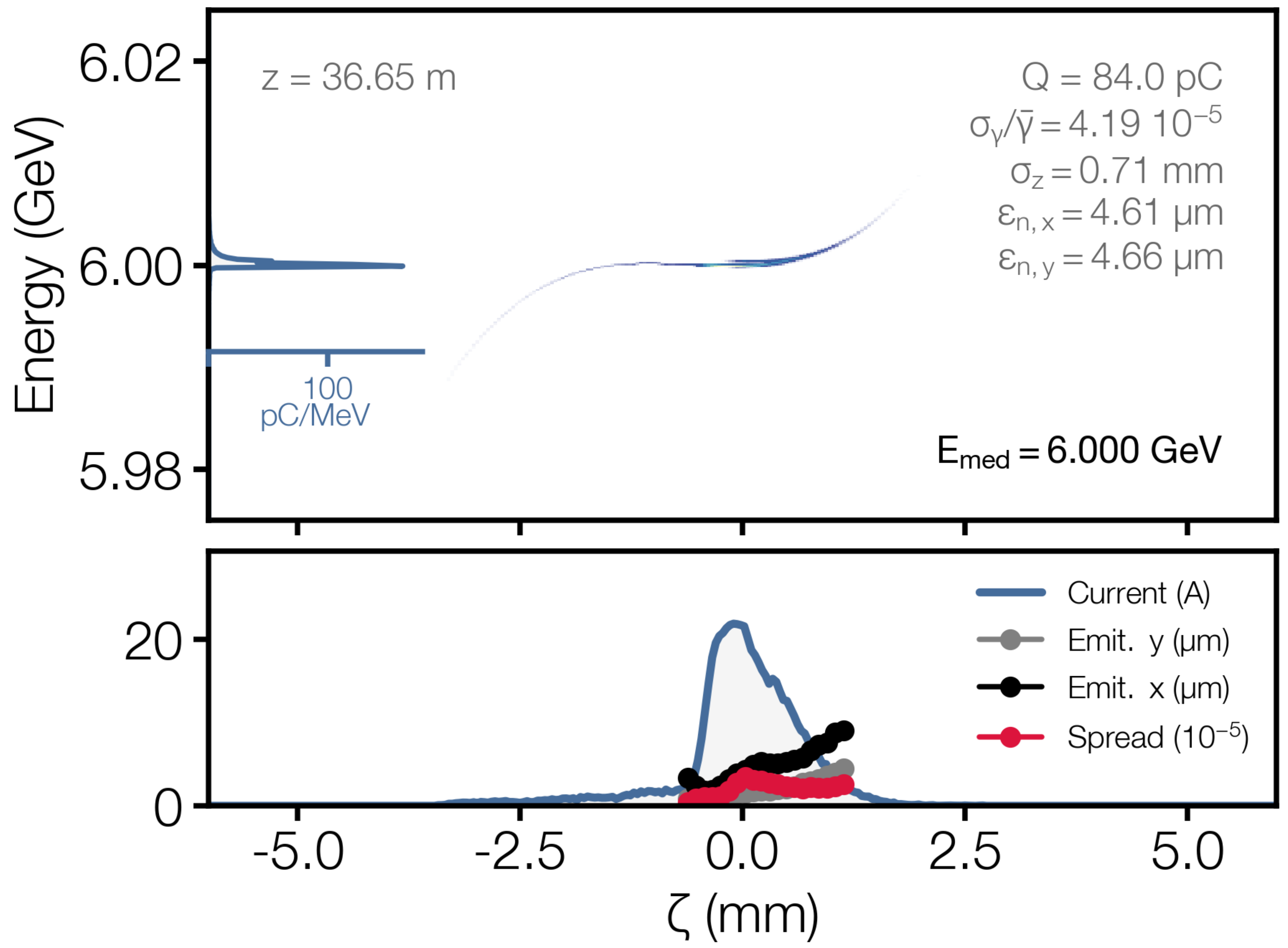
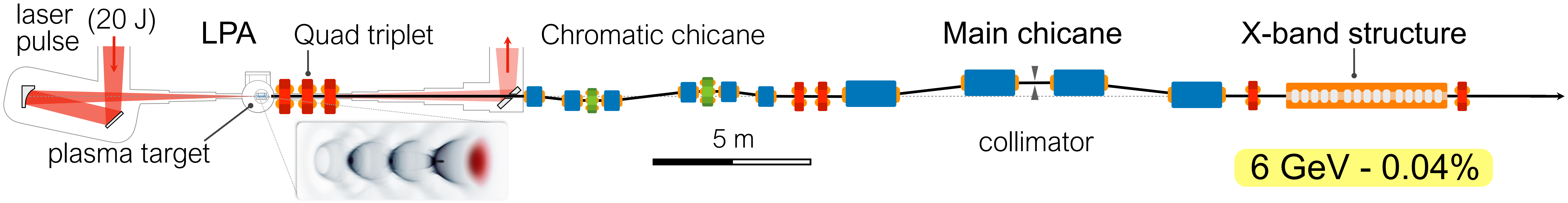
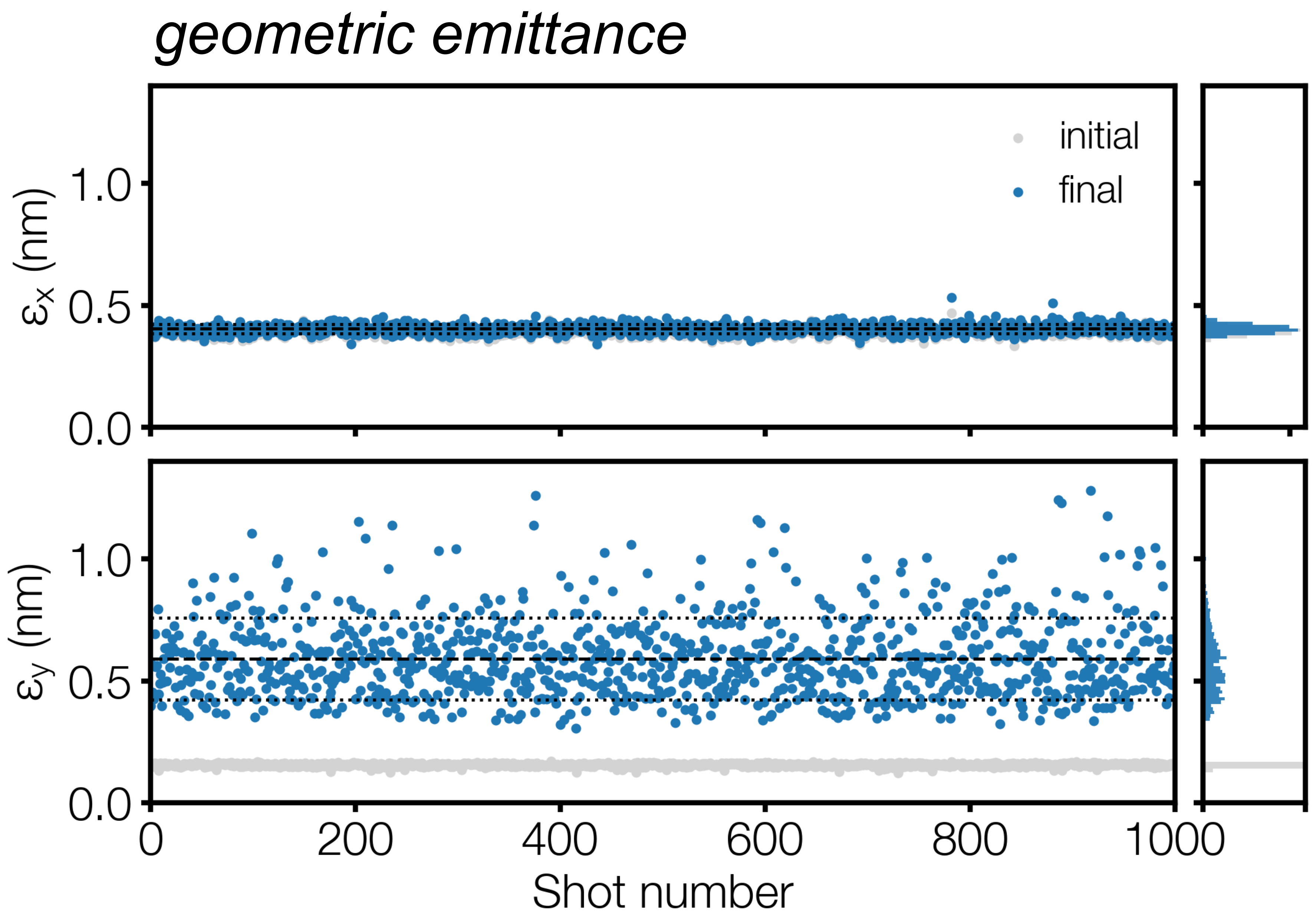


The Plasma Injector: ECB simulation

Start-to-end simulations with realistic jitter





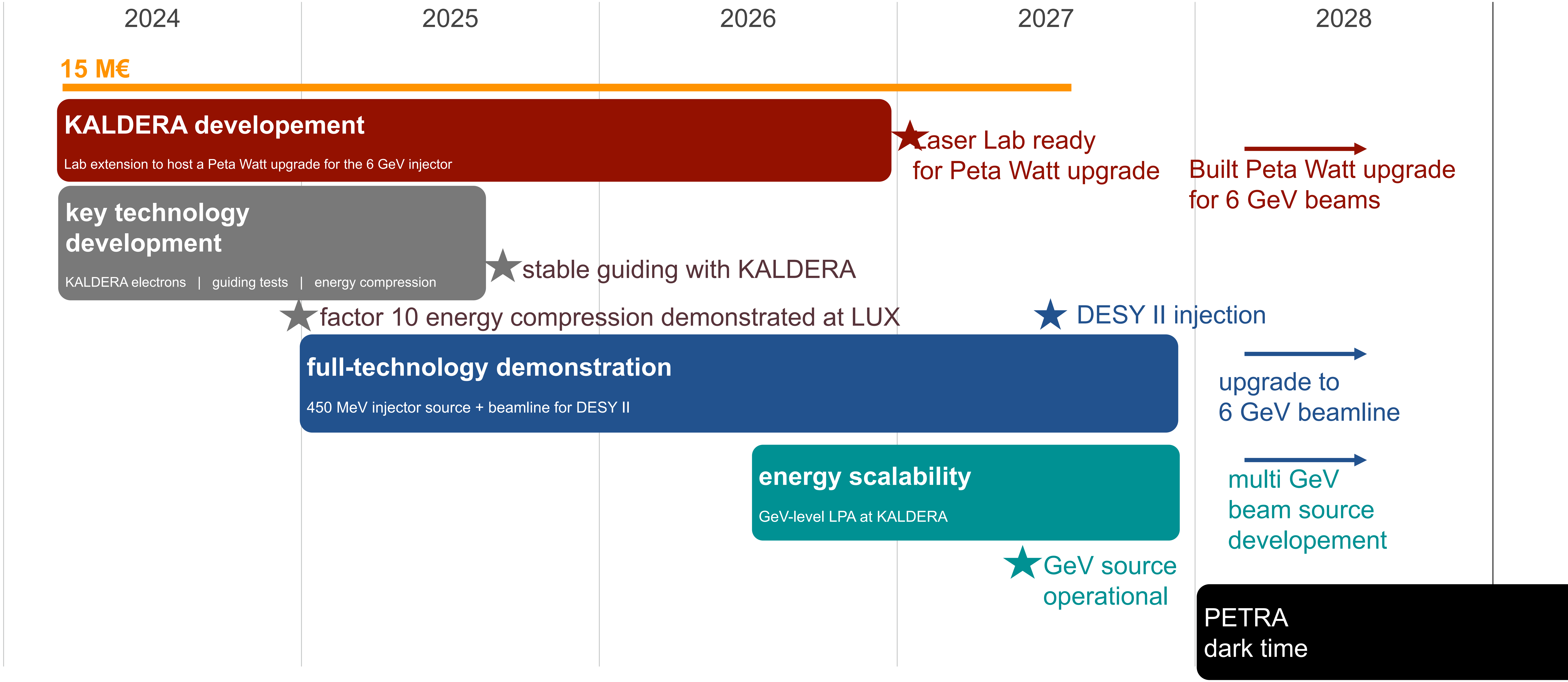
Collective beam parameters

Parameter	After LPA	After ECB
Charge	87 pC	84 pC
Charge spread	9.8 %	10.0 %
Energy	5.999 GeV	6.000 GeV
Energy spread	1.0 %	0.04%
Emittance (x, y)	0.4, 0.2 nm	0.4, 0.6 nm

Emittance is preserved in the horizontal plane

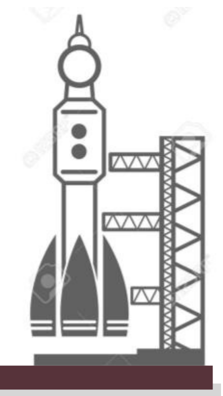
PETRA IV Pre-Project LPA

Demonstrate full-technology chain & asses energy scalability



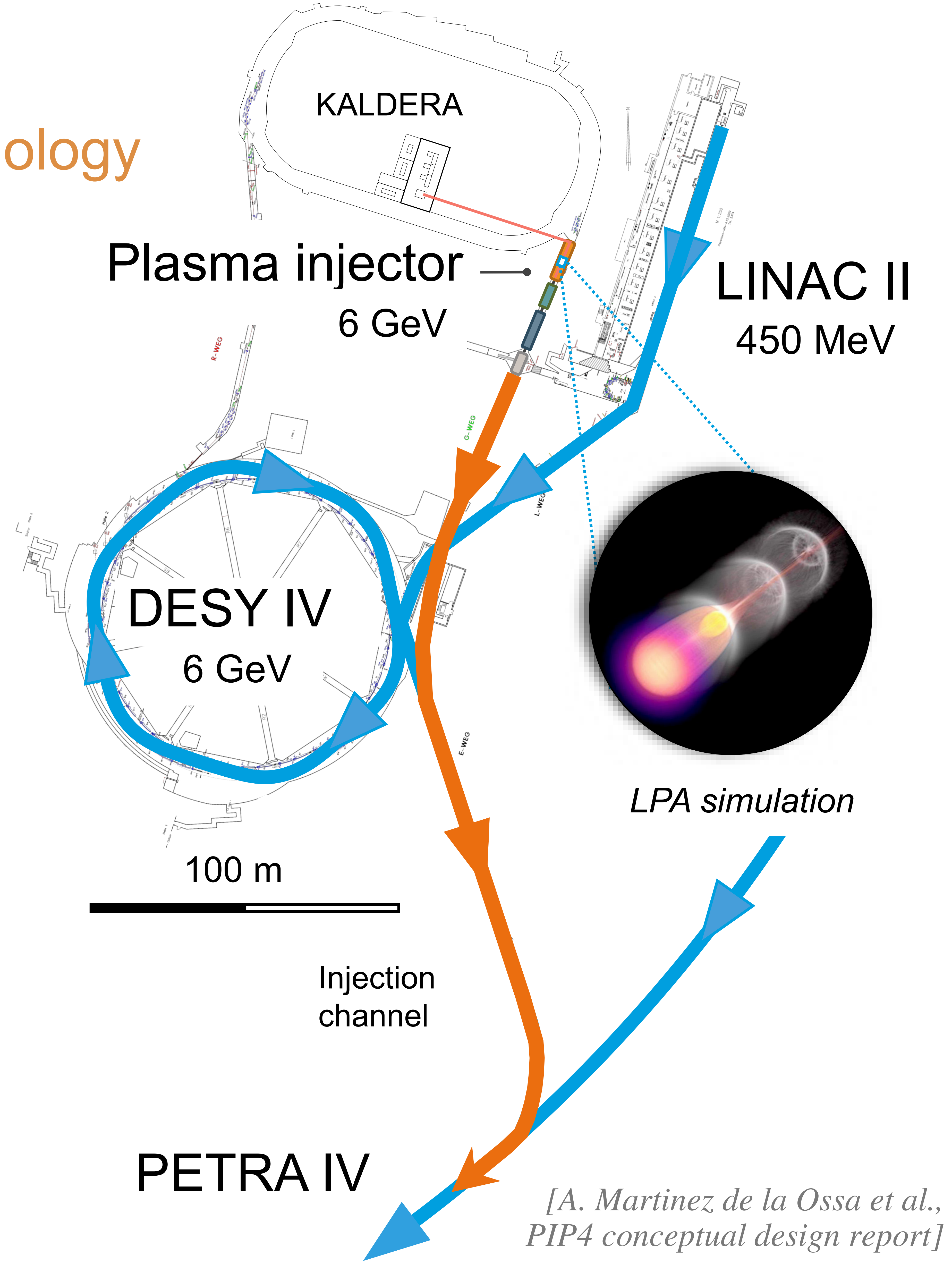
PIP^{IV}: 6 GeV Plasma Injector

Promising a compact and energy efficient injector technology



Success is based on 3 pillars:

efficient high power Lasers & stable high quality electron beams	6 GeV guiding channels	post-plasma energy compression (X-band RF)
KALDERA G. Palmer M. Kirchen et al.	**HOFI** R. Shalloo et al.	**RF Dechirper** P. Winkler, S. Antipov, A. Martinez de la Ossa et al.



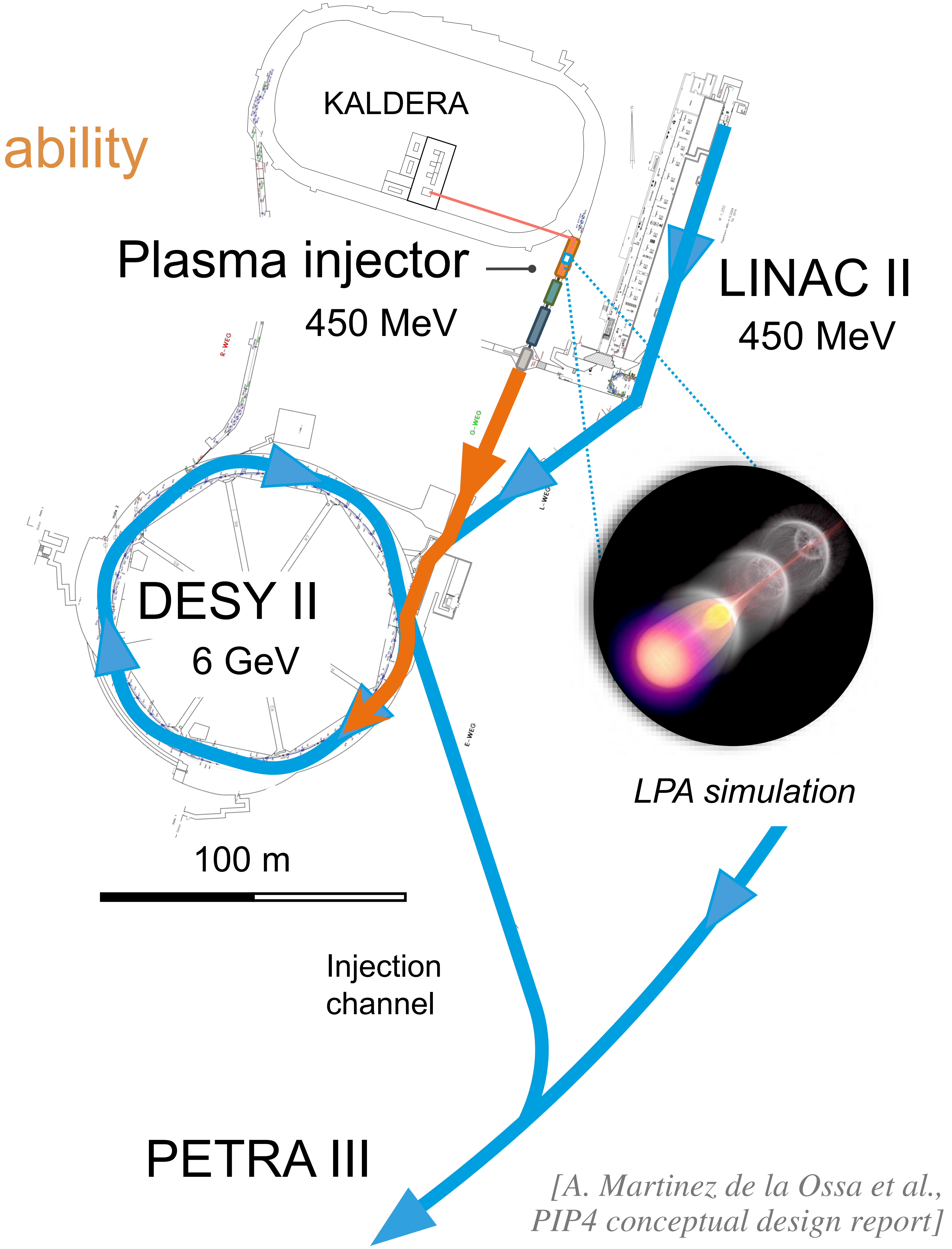
[A. Martinez de la Ossa et al., PIP4 conceptual design report]

PETRA IV Pre-Project LPA

Demonstrate full-technology chain & asses energy scalability

Success is based on 3 pillars:

KALDERA	HOFI	RF Dechirper
efficient high power Lasers & stable high quality electron beams	450 MeV guiding channels	post-plasma energy compression (S-band RF)
G. Palmer, M. Kirchen et al.	R. Shalloo et al.	P. Winkler, S. Antipov, A. Martinez de la Ossa et al.

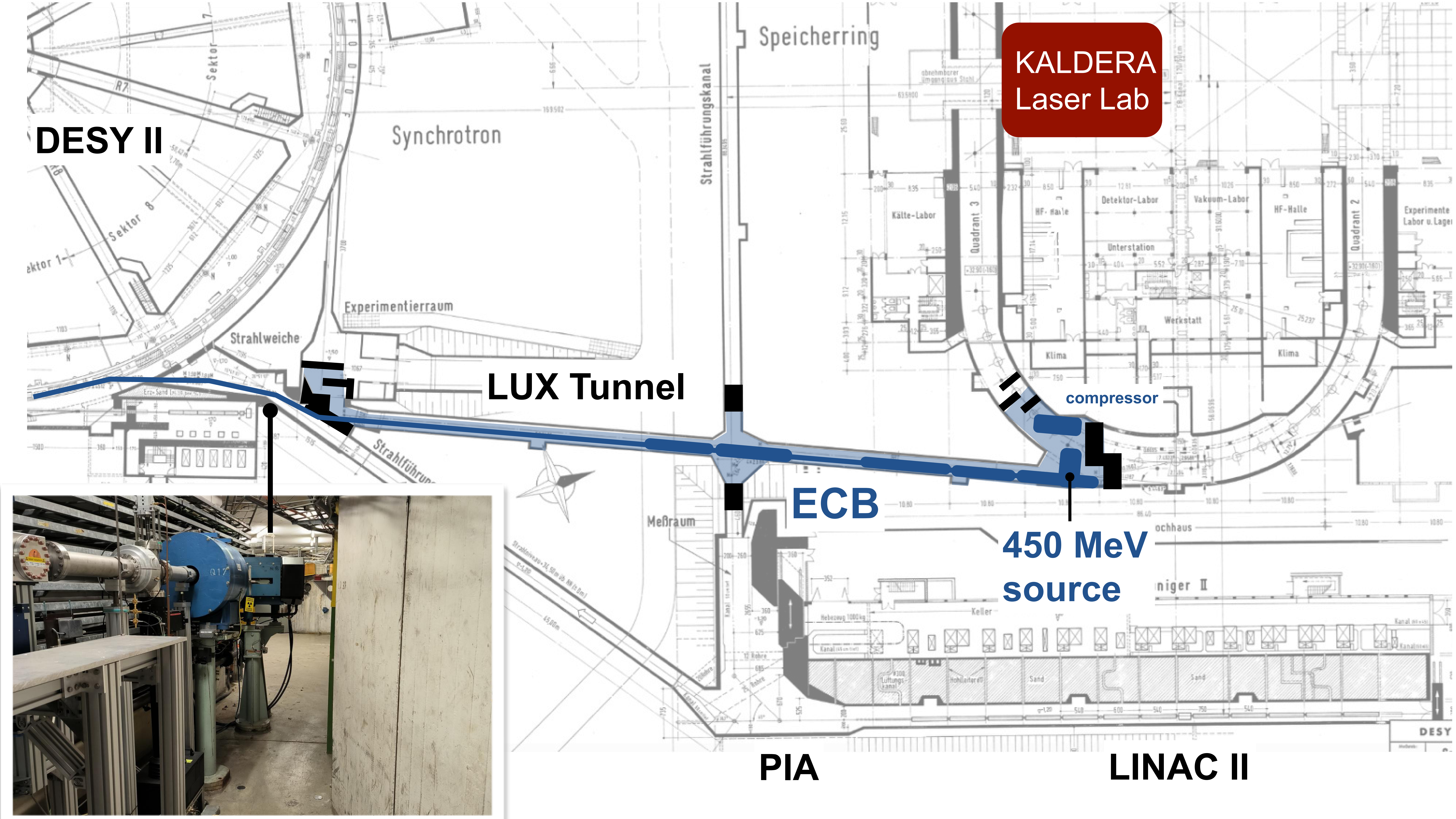


[A. Martinez de la Ossa et al., PIP4 conceptual design report]

PETRA IV Pre-Project LPA

Demonstrate full-technology chain & asses energy scalability

Subject to current planning



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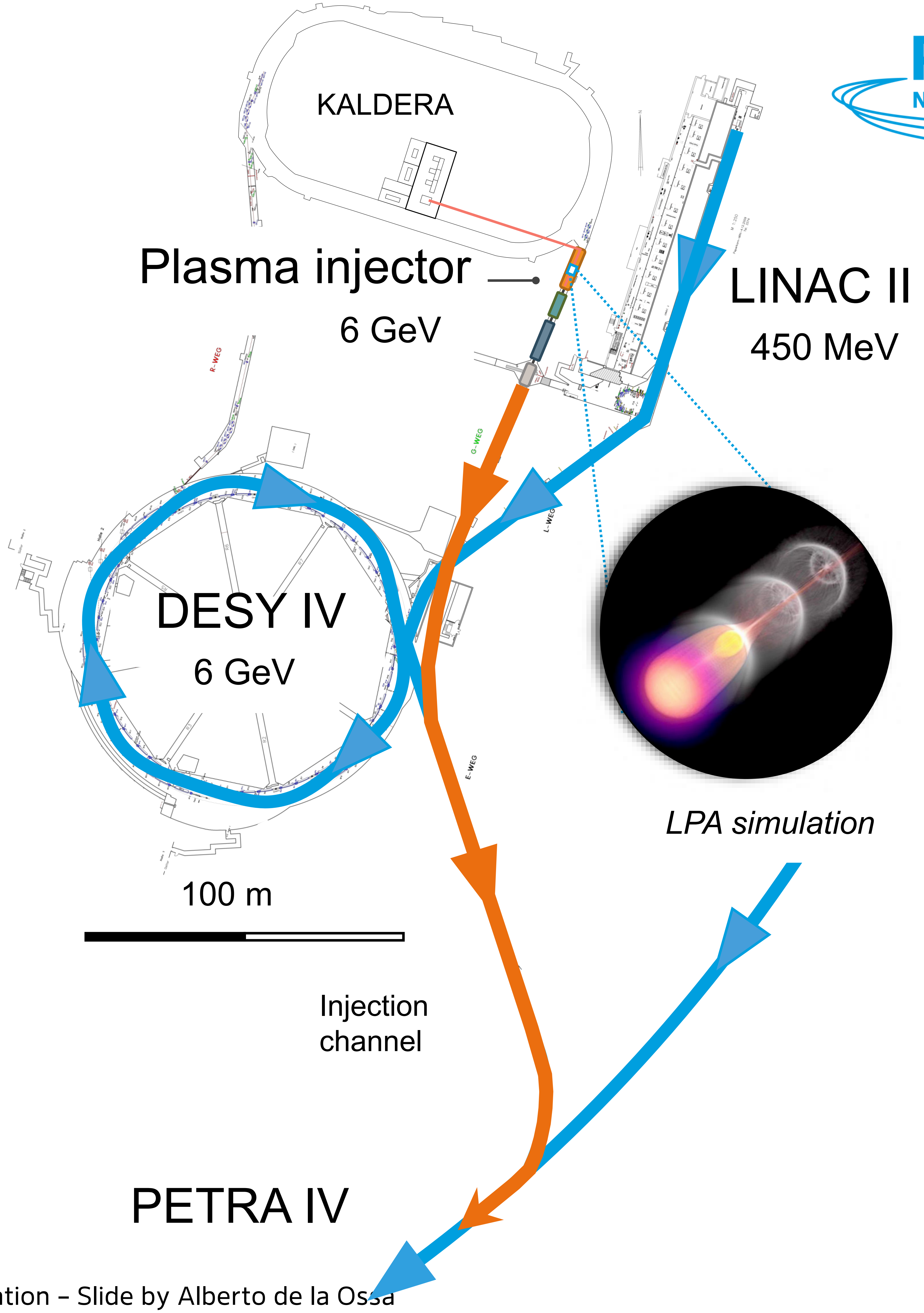


The Plasma Injector for PETRA IV

a compact, cost-effective and competitive alternative

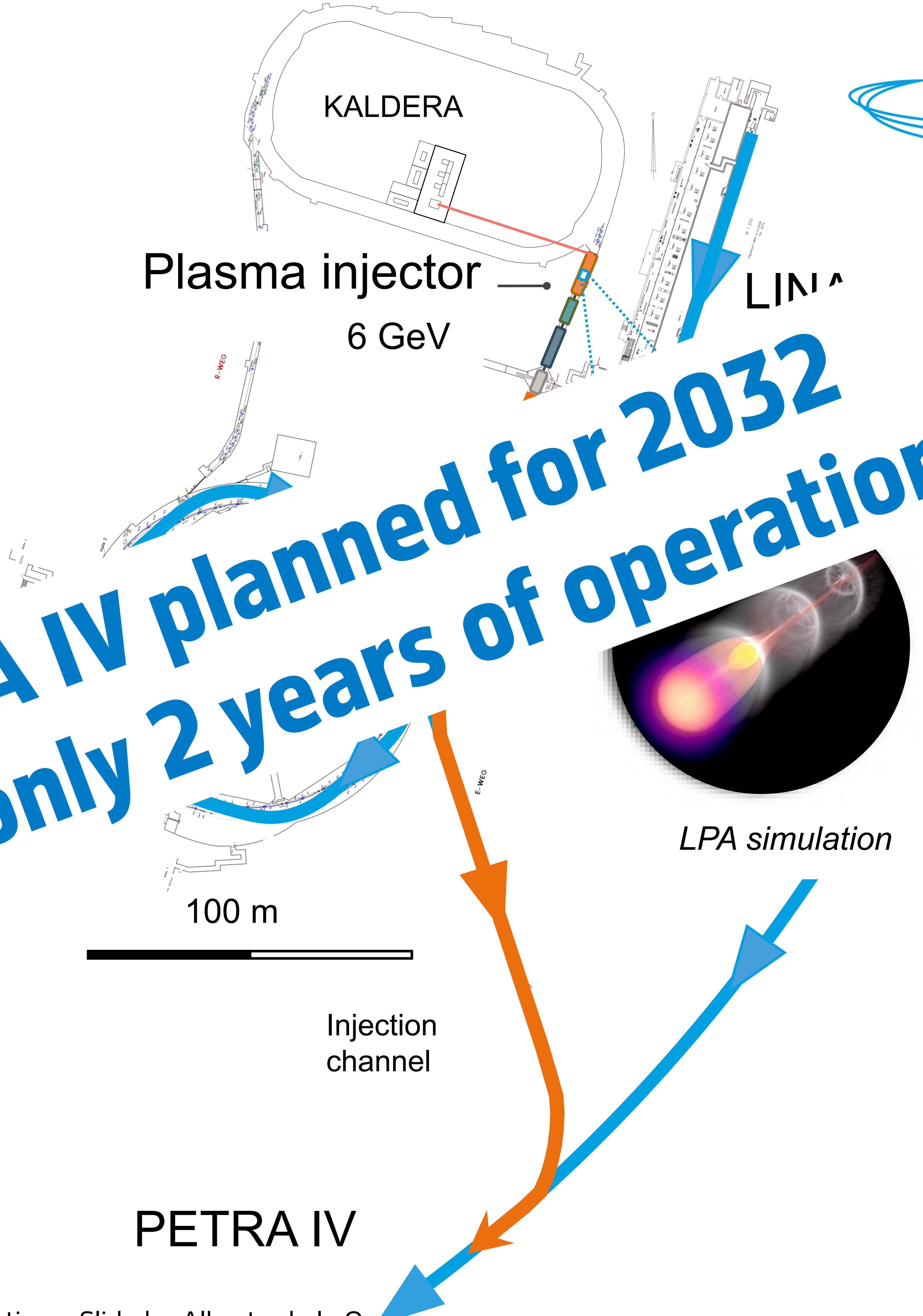
PETRA IV. NEW DIMENSIONS

- **Compact:** laser-plasma acc. + beamline: < 50 m
- **Cost-effective:** power consumption: < 500 kW
- **Competitive:** full PETRA IV operation (fill + top-up)

Key challenges:

- Energy gain: 6 GeV
- Energy spread and jitter: < 0.3 %
  (to maximize charge throughput and st…
- Charge injection rate: > …
  (to fill the ring in < …
- Avail…

…nology (LPA) enables …d energy efficient solution



LPA simulation

First injection in PETRA IV planned for 2032
– so… a new booster for only 2 years of operation?

The Plasma Injector for PETRA IV

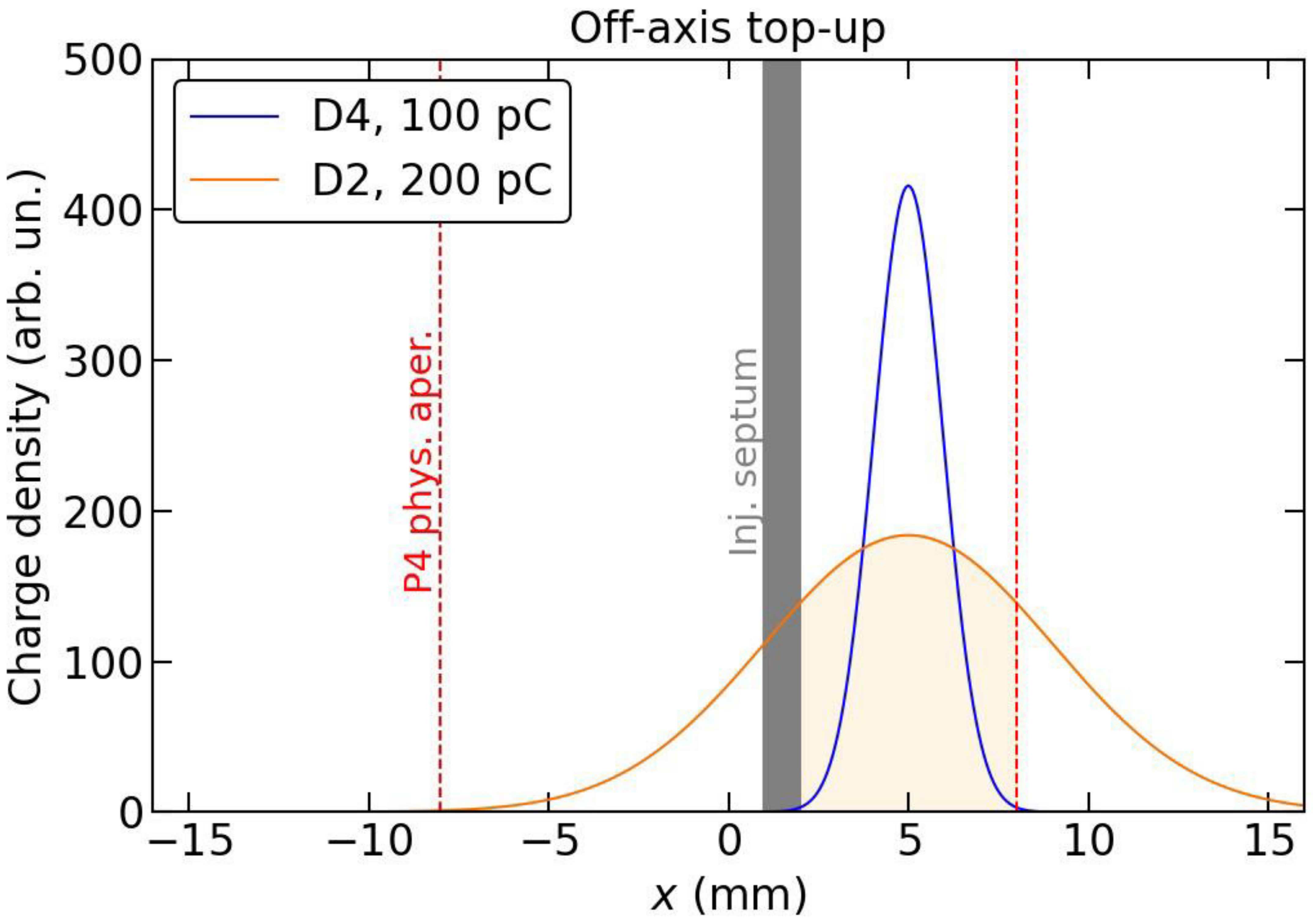
What about a new concept?

LPA for the long run…

Collimation of DESY II beam for the meantime?

How much worse would the injection efficiency be with DESY II?

20 vs 350 nm-rad emittance



[Courtesy S. Antipov]

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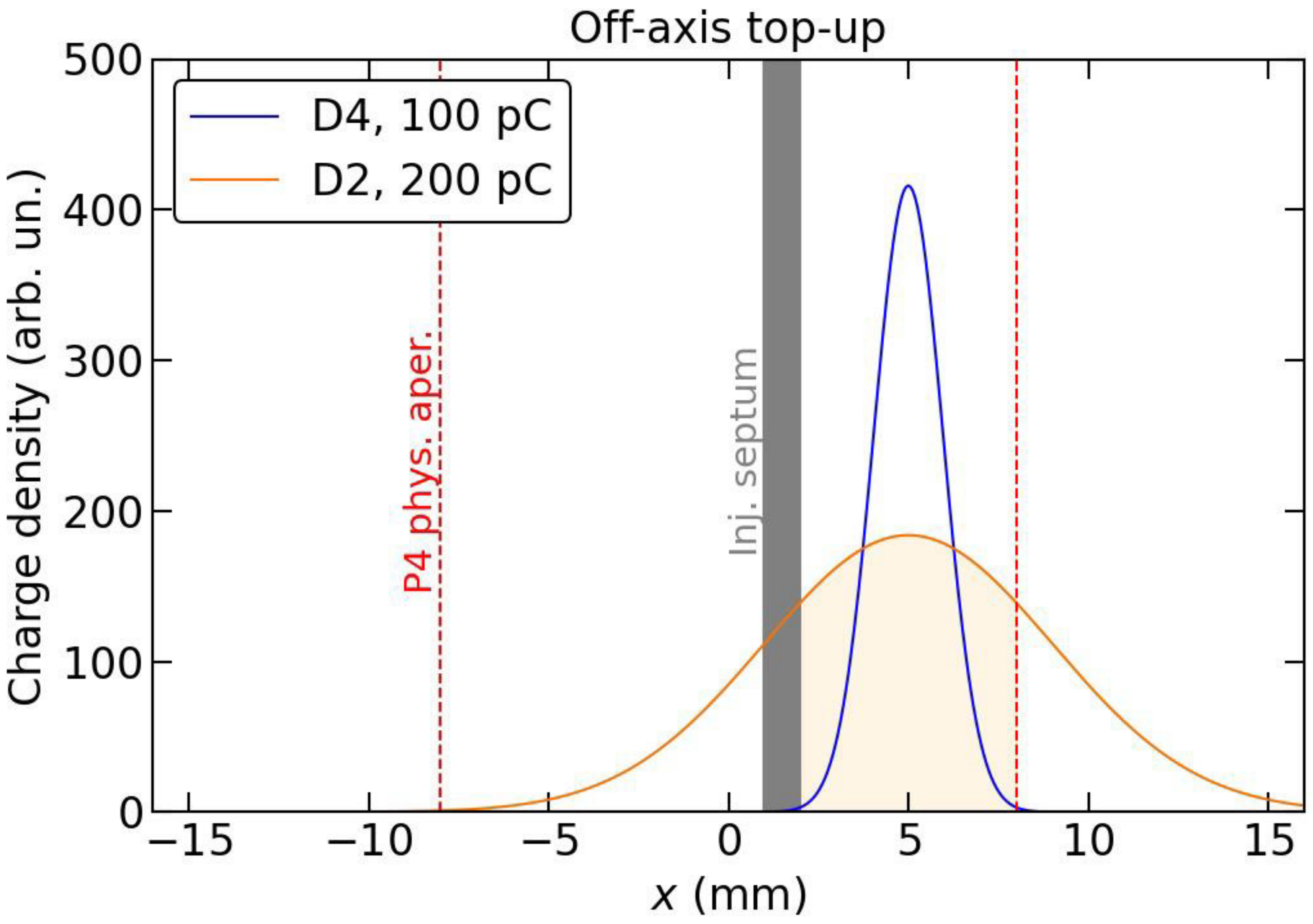

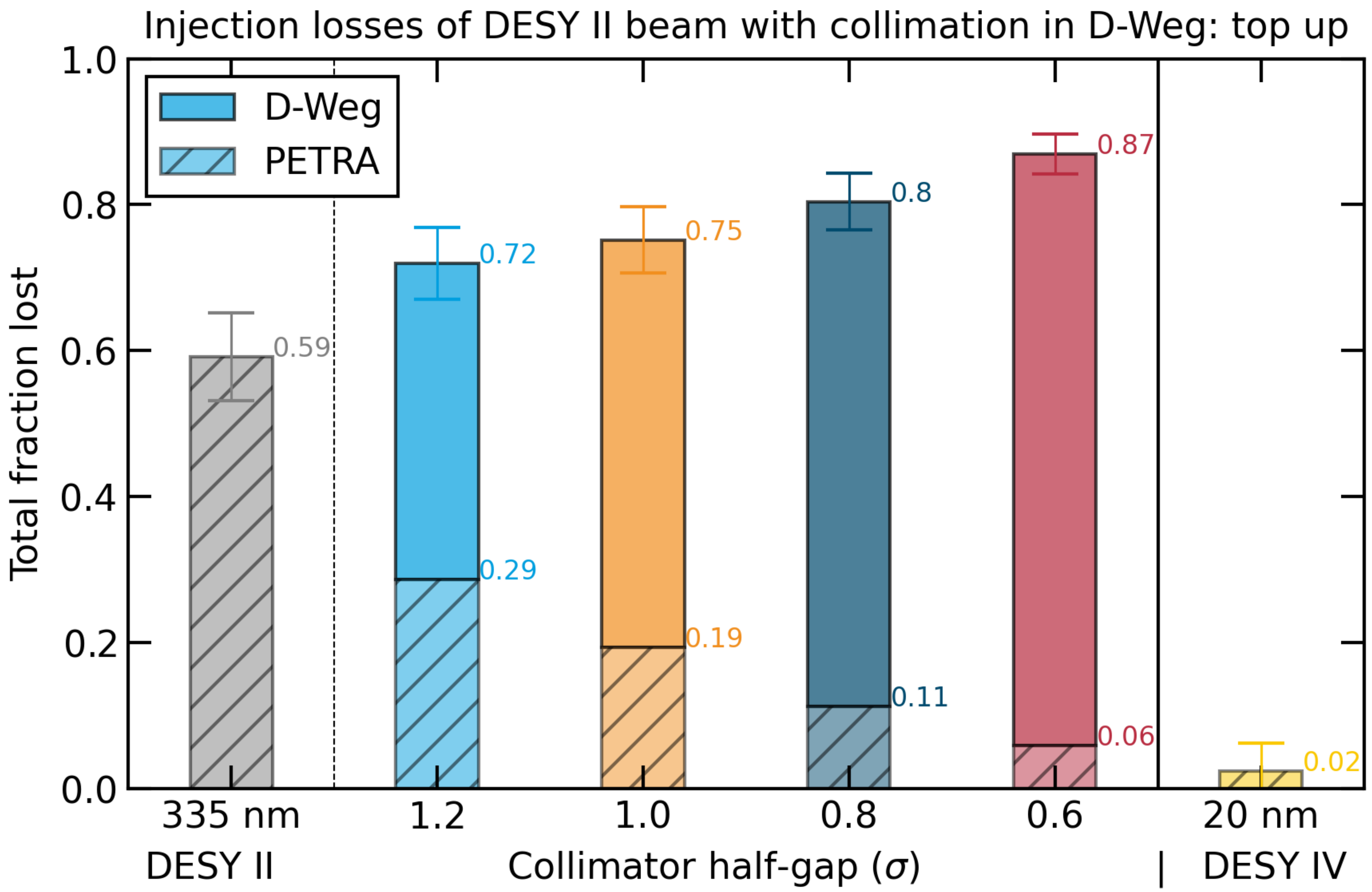

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Summary

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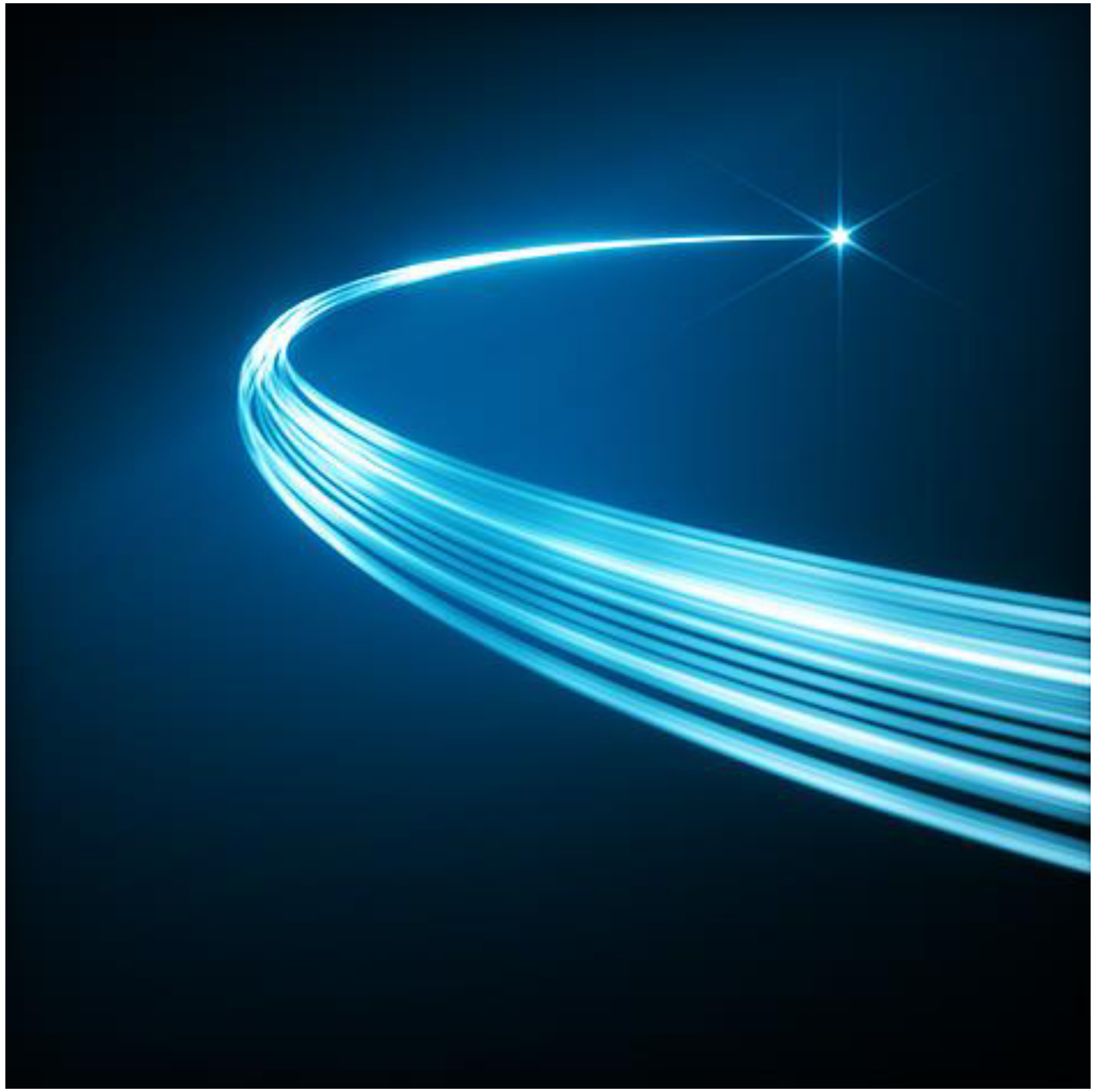
- With PETRA IV DESY aims to build the largest 4^{th} generation light source in the world.
- To benefit from the existing infrastructure many parts of the PETRA III complex will be refurbished and reused.
- However, a new booster synchrotron should be built to meet the requirements of PETRA IV.
- Installing this booster in the existing accelerator tunnel poses some challenges.
- In addition the development of an LPA based full energy injector has started.
- A pre-project with the goal of injecting an LPA beam into DESY II is being prepared.
- Decision on injection concept necessary in about 2 years.



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Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

Sven Sievers
PETRA IV – Technical Coordination
sven.sievers@desy.de
+49 40 8998 2774