PETRA IV.
NEW DIMENSIONS

Design and challenges of PETRA IV

9th General Low-Emittance Rings Workshop

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PETRA IV Machine Project Leader

CERN, Geneva, February 14th, 2024

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outline

PETRA IV. NEW DIMENSIONS

- Description of PETRA IV machine project

- Design challenges
- Highlights of technical subsystems and prototype programme
- Alternatives for the pre-injector

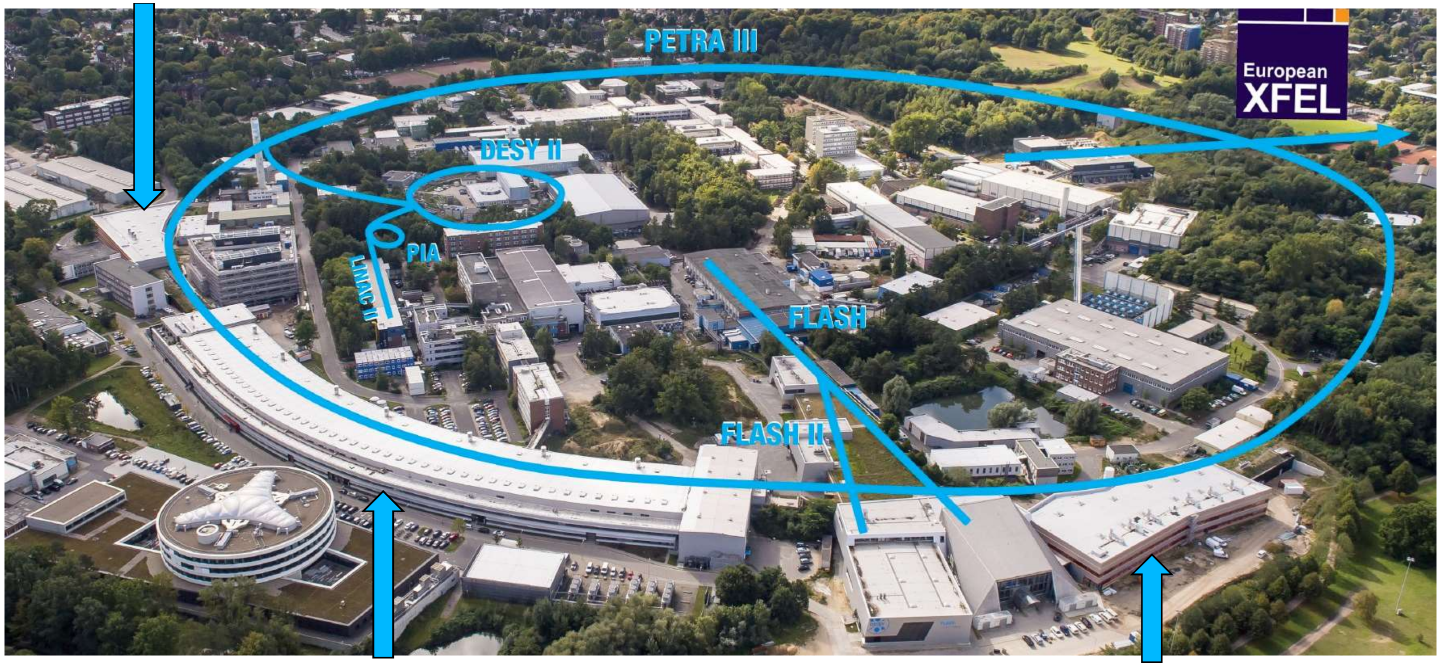
- Conclusions and future work

PETRA III is one of the core facilities at DESY

Each year ~5000h of operation serve more than 3300 users

PETRA IV. NEW DIMENSIONS

Ada Yonath Hall
Extension Hall East



Max von Laue Hall

Paul P. Ewald Hall
Extension Hall North

Parameter	PETRA III
Energy [GeV]	6
Circumference [m]	2304
Emittance (hor./vert.) [nm]	1.3 / 0.013
Total current [mA]	100

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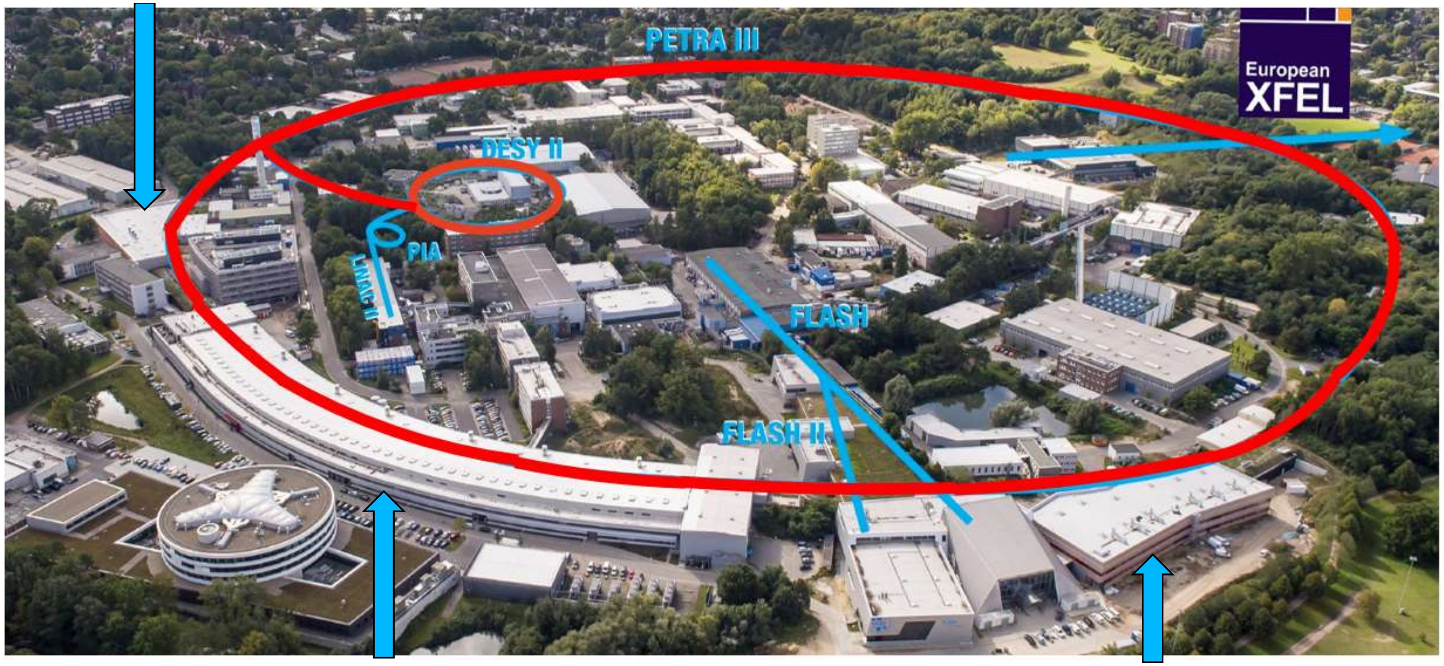

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Energy [GeV]	6
Circumference [m]	2304
Emittance (hor./vert.) [nm]	1.3 / 0.013
Total current [mA]	100

PETRA III emittance 1300 pm

65 times smaller

PETRA IV emittance 20 pm

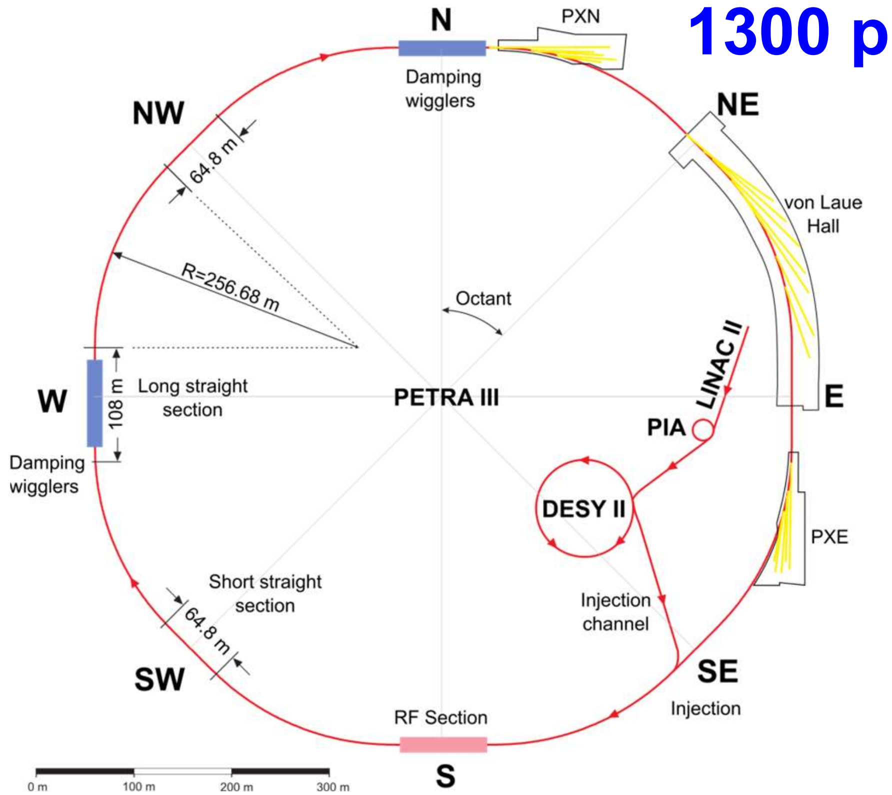
enabling 500 times larger X-ray beams brightness

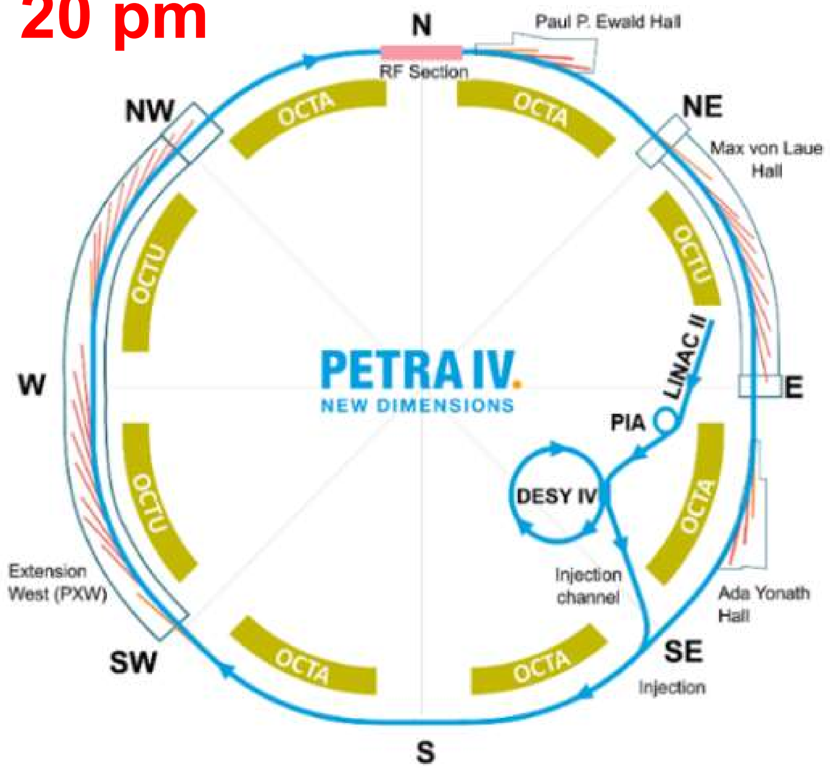
PETRA IV project:

replacing PIII with an ultra-low emittance ring, adding a new Experimental Hall in two more octants, replacing DESY II with a new low emittance booster

from PETRA III to PETRA IV

1300 pm → 20 pm





Eight Arcs (45°), 201.6 m long

One arc build from 9 ***DBA cells*** L_{cell} = 23 m, 5 m ID straight sections

5 pure FODO-arcs + 2 modified FODO arcs with 2 ***DBA cells***

Beamlines

Max von-Laue Hall:14; PXN:5; PXE: 7

Eight Arcs (45°), 201.6 m long

72 cells ***H6BA cells***

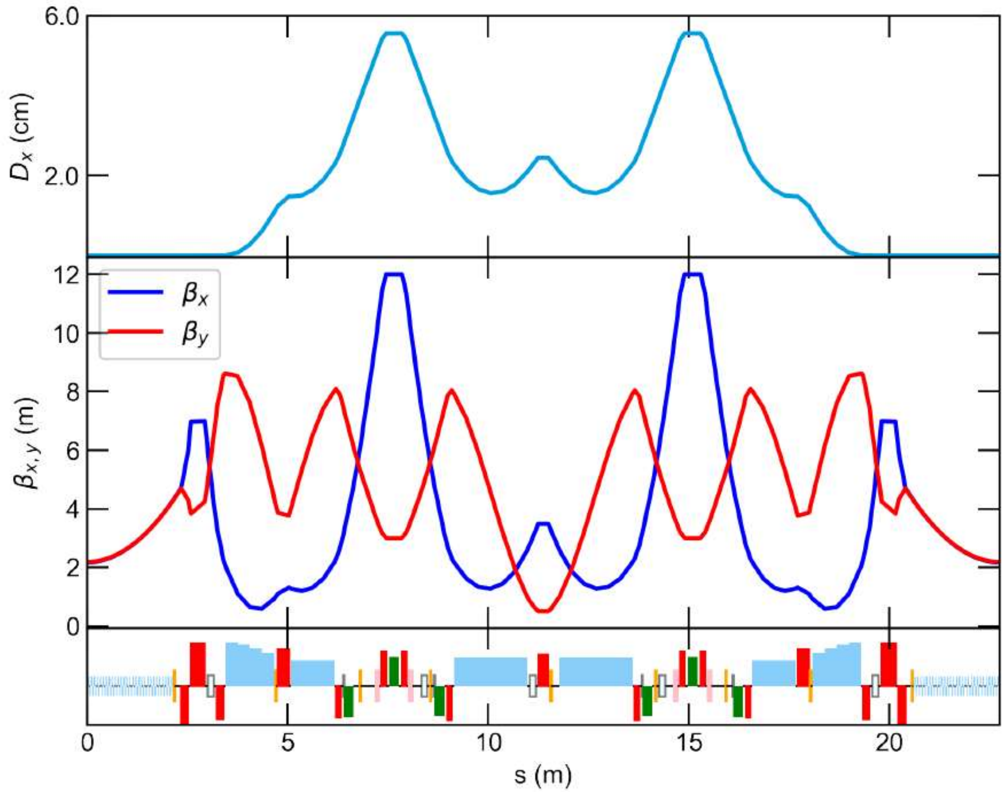
9 cells per arc L_{cell} = 22.75 m, 4.3 (TBC) m ID straight sections

Straights for Beamlines

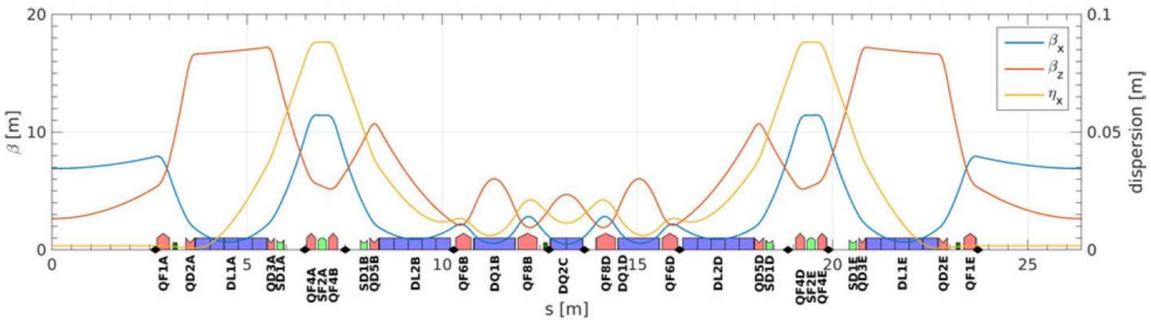
Max von-Laue Hall: 9; PXN: 3; PXE: 3 + New Hall: 9 + 9(8)

The PETRA IV H6BA cell

The lattice is based on a novel cell structure (**H6BA**) that is replicated identical across all octants (72 cells)



The lattice cell is an evolution from the pioneering hybrid multi-bend achromat cell (H7BA) proposed by P. Raimondi



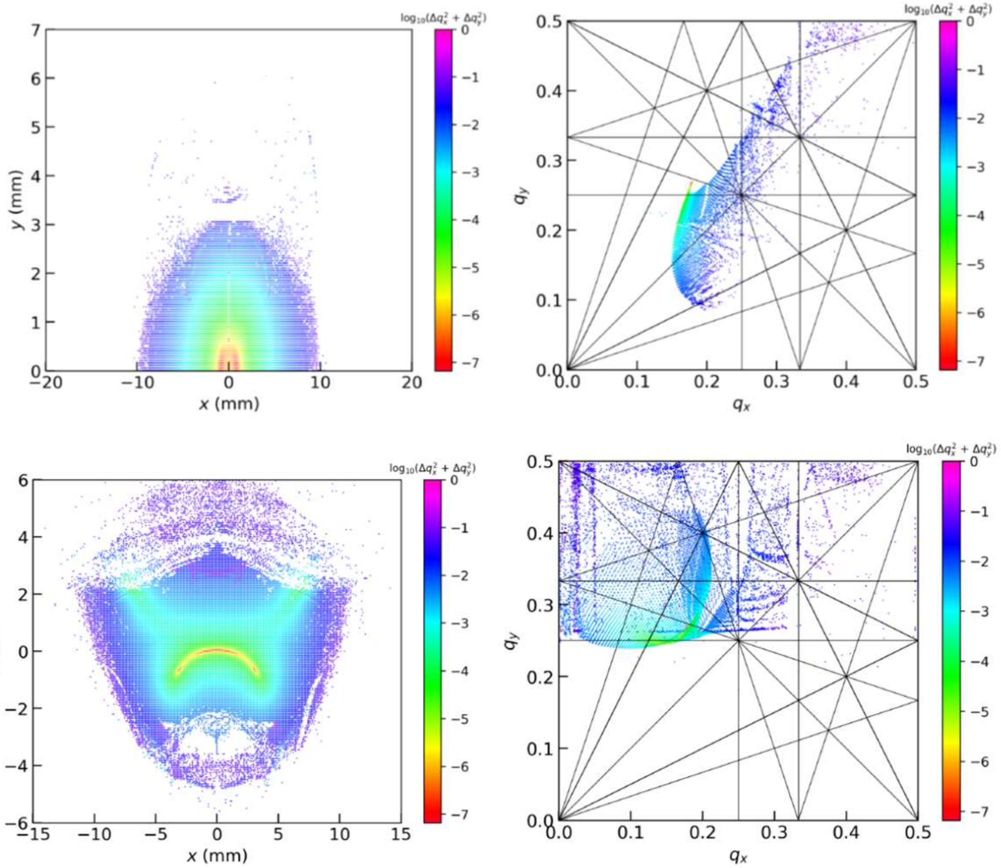
In the H6BA cell, the dispersion bump is increased to compensate for the weaker dipoles (because of the 72 cells/36 cells ratio)

emittance 42 pm decreased to 20 pm with damping wigglers in the straight with no undulators

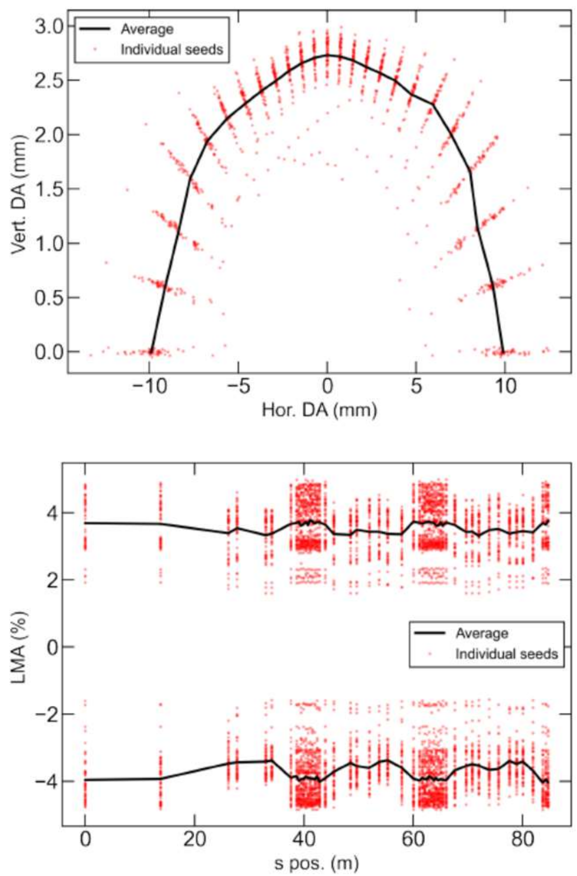
U_0 = 1 Mev/turn → 4 MeV/turn

PETRA IV beam dynamics

FMA shows strong second order chromaticity limits the apertures.
Octupoles have opposite effects on MA and LMA:
a trade off is found



Error analysis supported by extensive
“commissioning simulations”



PIV operating modes: beam parameters at the source point

PETRA IV NEW DIMENSIONS

PETRA IV will operate in two modes

brightness mode: 1900 bunches 4 ns spacing 200 mA (1 nC per bunch)

emittance 20 pm; 20% coupling (17pm/3pm); energy spread 0.1 %

	β_x (m)	β_y (m)	σ_x (μm)	σ_x' (μrad)	σ_y (μm)	σ_y' (μrad)	σ_s (ps)	ε_s (10^{-3})
Standard straights	2.2	2.2	6.1	2.8	2.7	1.2	35	0.96
Long straights	4.0	4.0	8.2	2.0	3.7	0.9	35	0.96
Long straight north	5.0	5.0	9.1	1.8	4.1	0.8	35	0.96

All other optics functions are zero: $\alpha_x = \alpha_y = D_x = D_x' = D_y = D_y' = 0$

timing mode: 80 bunches 96 ns spacing 80 mA (7.8 nC per bunch)

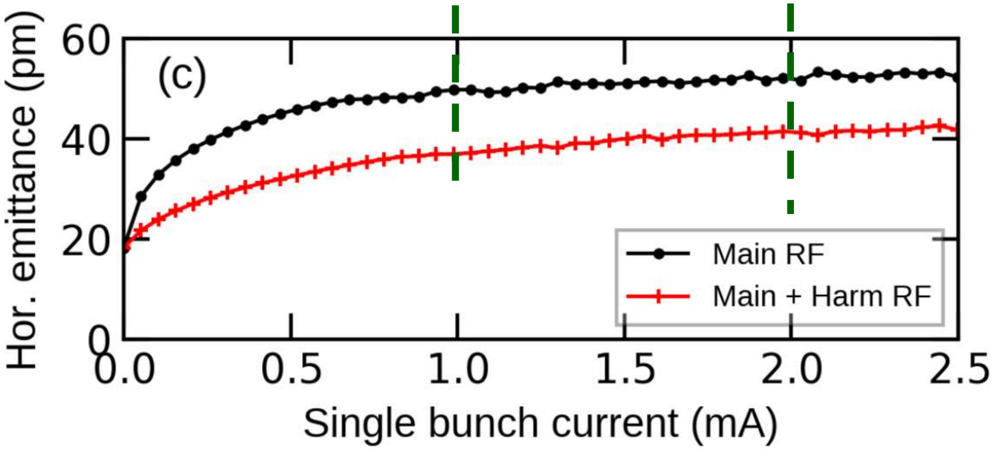
emittance (charge dependent $\rightarrow$ 34pm/7pm); energy spread 0.12 %

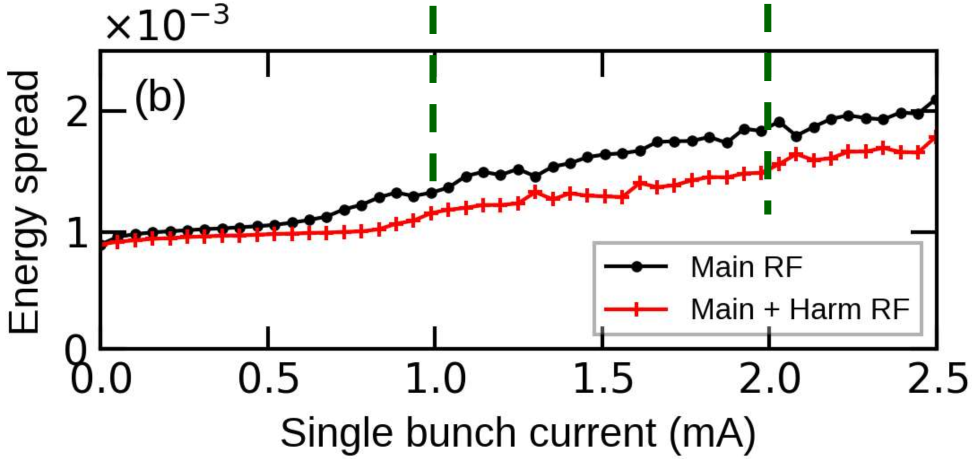
	β_x (m)	β_y (m)	σ_x (μm)	σ_x' (μrad)	σ_y (μm)	σ_y' (μrad)	σ_s (ps)	ε_s (10^{-3})
Standard straights	2.2	2.2	8.6	3.9	3.8	1.7	68	1.20
Long straights	4.0	4.0	11.6	2.9	5.2	1.3	68	1.20
Long straight north	5.0	5.0	12.9	2.6	5.8	1.2	68	1.20

operating modes under consideration

brightness mode full coupling: 1900 bunches 4 ns spacing 200 mA (1 nC per bunch)
emittance 20 pm; 100% coupling (12pm/12pm); energy spread 0.1 %

timing mode: 40 bunches 192 ns spacing 80 mA (15.6 nC per bunch)
emittance (charge dependent → 38pm/8pm); energy spread 0.15 %



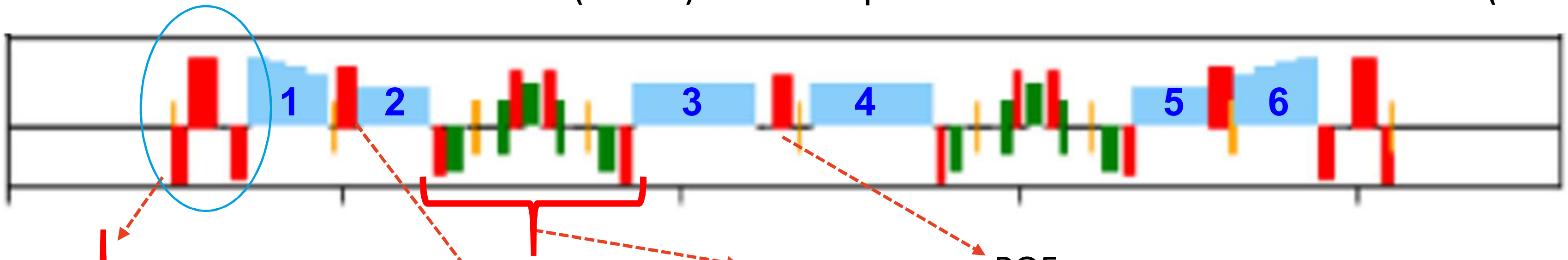


Emittance increase due to IBS limited by extensive use of Damping Wigglers

Layout of the PETRA IV cell: main parameters

PETRA IV. NEW DIMENSIONS

The lattice is based on a novel cell structure (**H6BA**) that is replicated identical across all octants (72 cells)



PQA:
L = 229 mm
r = 12.5 mm
115 T/m
860 W
0.55 l/m
PV poles

PQB:
L = 404 mm
r = 11 mm
112 T/m
1100 W
0.79 l/m
PV poles

PQC:
L = 220 mm
r = 12.5 mm
89 T/m
900 W
0.56 l/m

PQD:
L = 338 mm
r = 12.5 mm
97 T/m
1200 W
0.86 l/m
PV poles

PQE:
L = 167 mm
r = 12.5 mm
84 T/m
700 W
0.37 l/m
PV poles

PQF:
L = 309 mm
r = 12.5 mm
69 T/m
900 W
0.49 l/m

DLQ 1-2-3:
L = 0.30-0.27 mm per module
0.3-0.2 T
6-11 T/m
permanent magnets

PSA:
L = 314 mm
r = 12.5 mm
2500 T/m^2
115 W
0.55 l/m

PO:
L = 153 mm
r = 12.5 mm
120000 T/m^3
30 W
air cooled

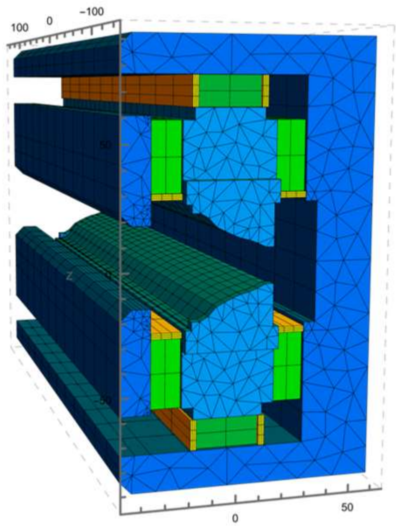
Standalone correctors:
L = 150 mm
r = 12.5 mm
650 urad
115 W
air cooled

Challenging magnets are prototyped and new concepts are developed based on the extensive use of permanent magnets

Magnet machining precision < 20 μm required to minimise magnetic errors

prototype PQA 115 T/m

Permanent magnet dipoles DLQs



The **arcs** contains (cell*72):

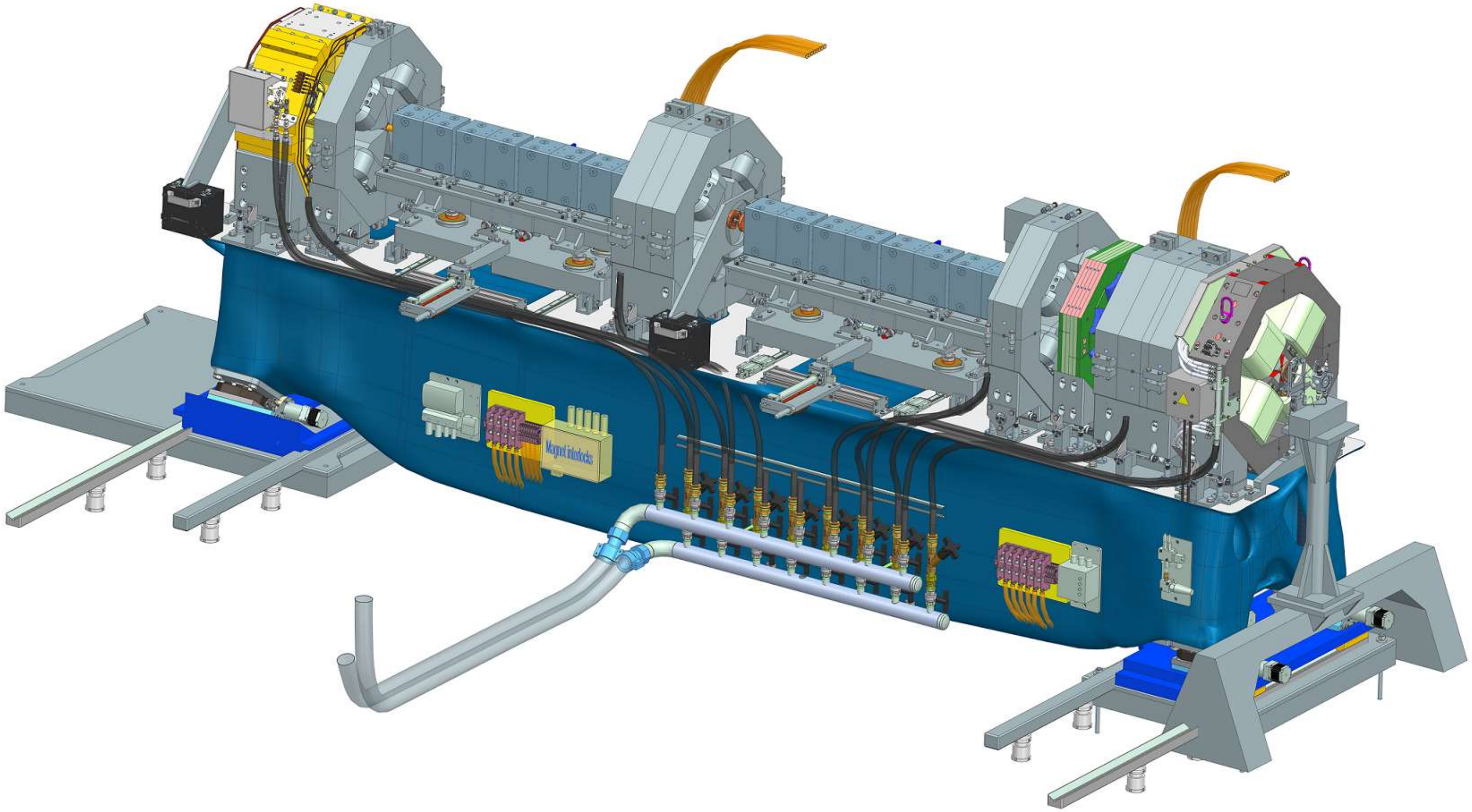
432	DLQs
1224	quadrupoles
432	sextupoles
288	octupoles
792	correctors

Including the straight sections,
PETRA IV will have ~3000 magnets

The **power consumption** of the resistive magnets in PETRA IV is about **2.3 MW**. The design has been optimized to reduce the power consumption. The PM dipoles will save **~1.6 MW**

PETRA IV girders prototype casted

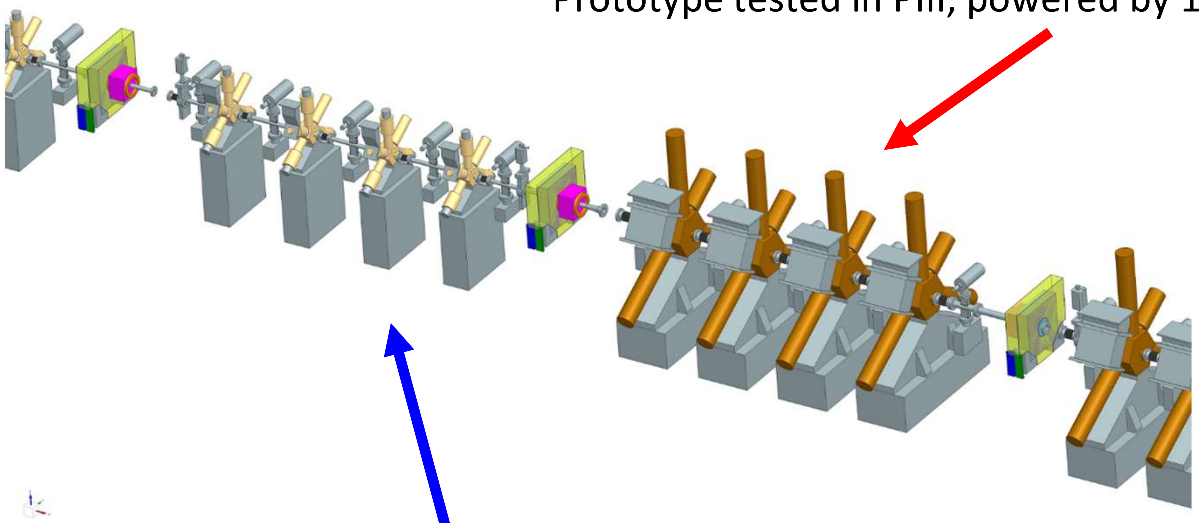
Topological optimised prototype girder has been casted
Girder mock-up assembly to start when girder pedestals and movers are on site

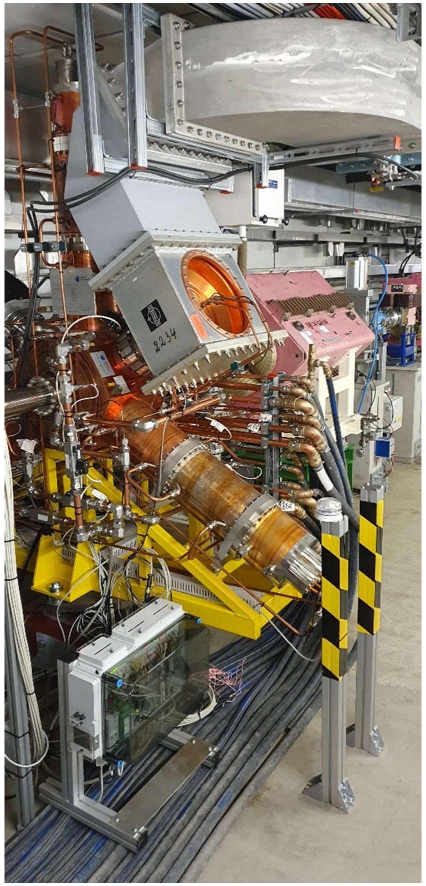


The RF system is designed. Prototypes are on-site and tested

The RF system provides the RF power necessary to keep the beam at the right energy in the machine. It will be installed in the straight section (North) and contains

24 RF cavities: 500 MHz cavities
Prototype tested in PIII, powered by 120 kW SS amplifiers

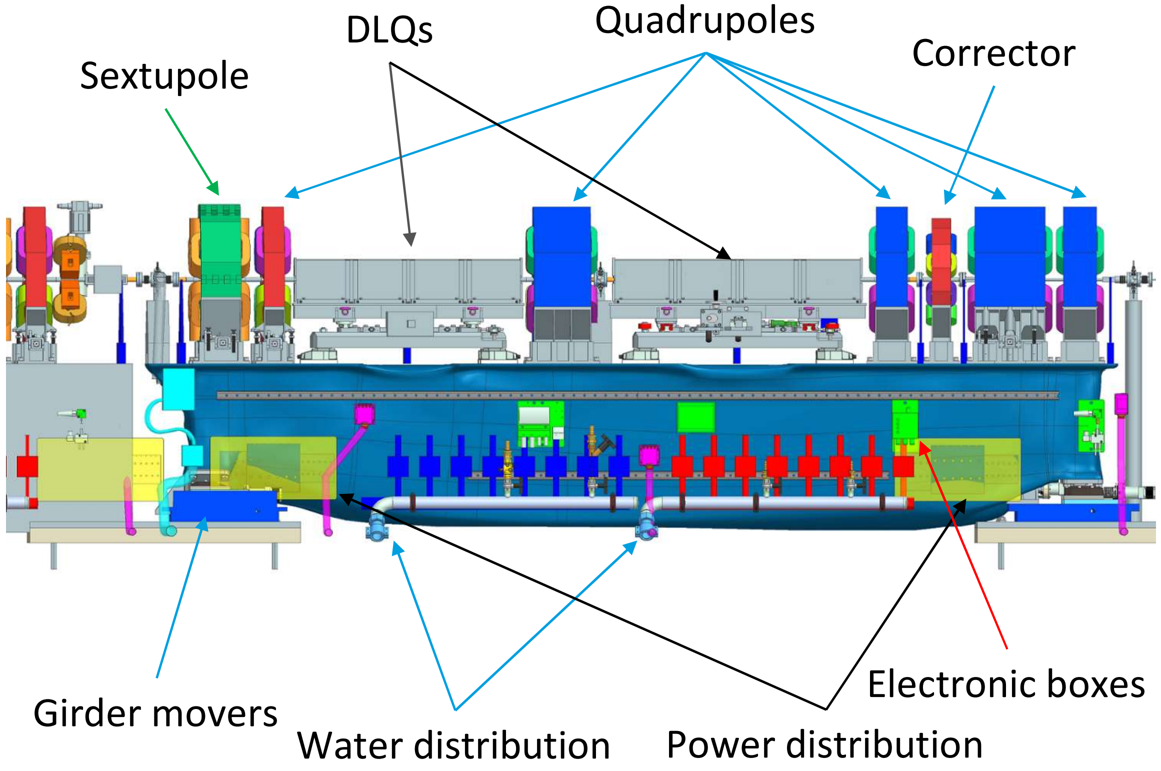


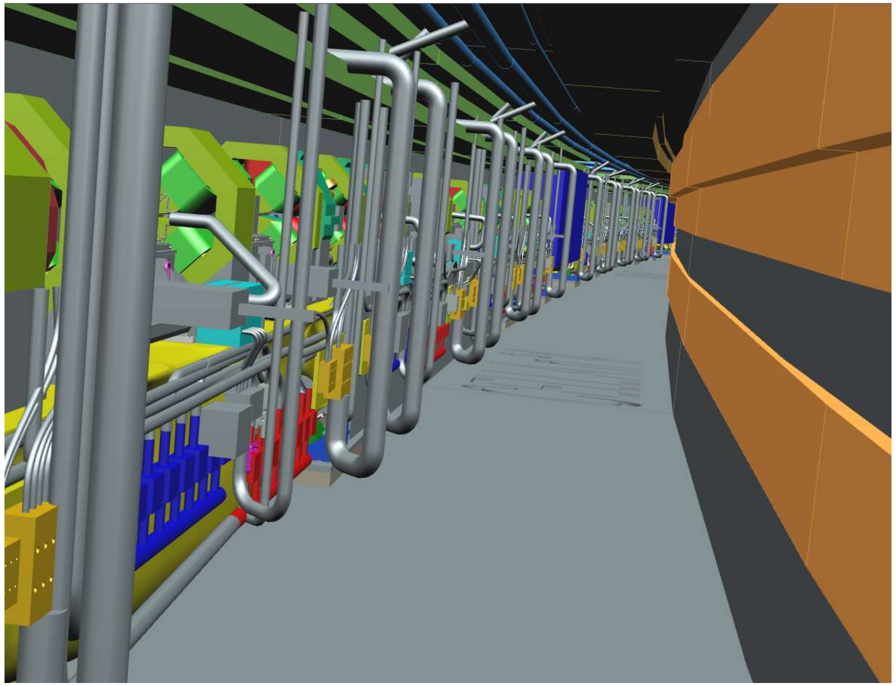


24 harmonic RF cavities: 1.5 GHz third harmonic cavities
Collaboration ALBA – HZB _DESY; tested at BESSY II

Engineering integration well advanced

Magnets, vacuum equipment, diagnostics will be assembled, aligned and tested on girder support structures.
PETRA IV will have 288 girders. Girder assembly will be done in the girder assembly building (GAB)





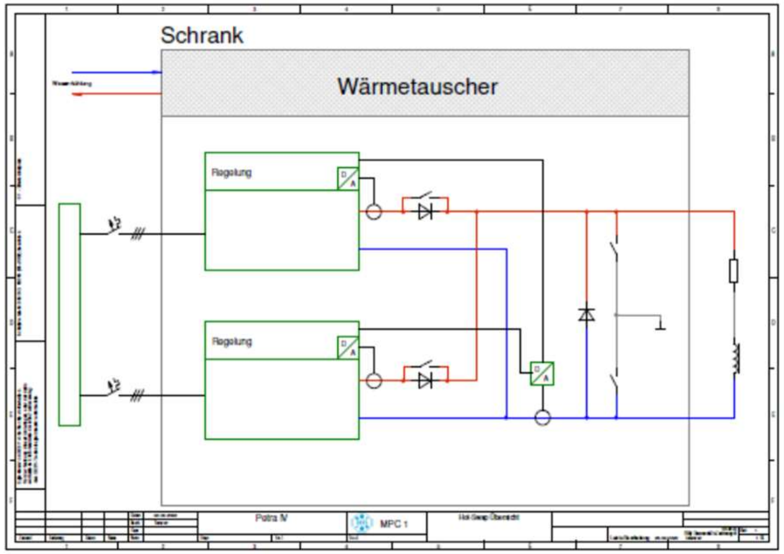
The precision of positioning and alignment of magnets on girders will be **<30 μm**
Girder-to-girder alignment precision needs to be **<100 μm**

Status of design: hot swap system

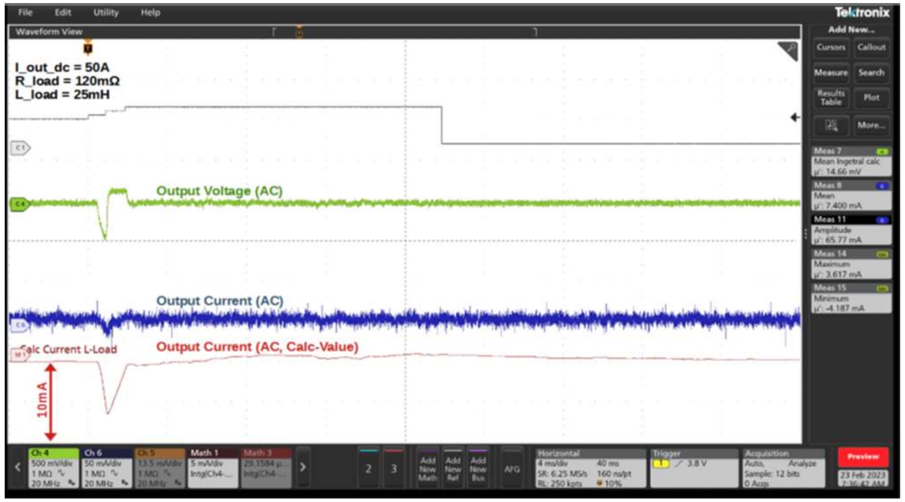
PS reliability at PIII is already very high: unlikely to improve reliability of a single unit

PIV will have 4400 PS more than PIII 859 – MTBF reduced accordingly

Hot swap is the only viable solution to further improve the reliability



Hot-swap tests at PETRA III were successful

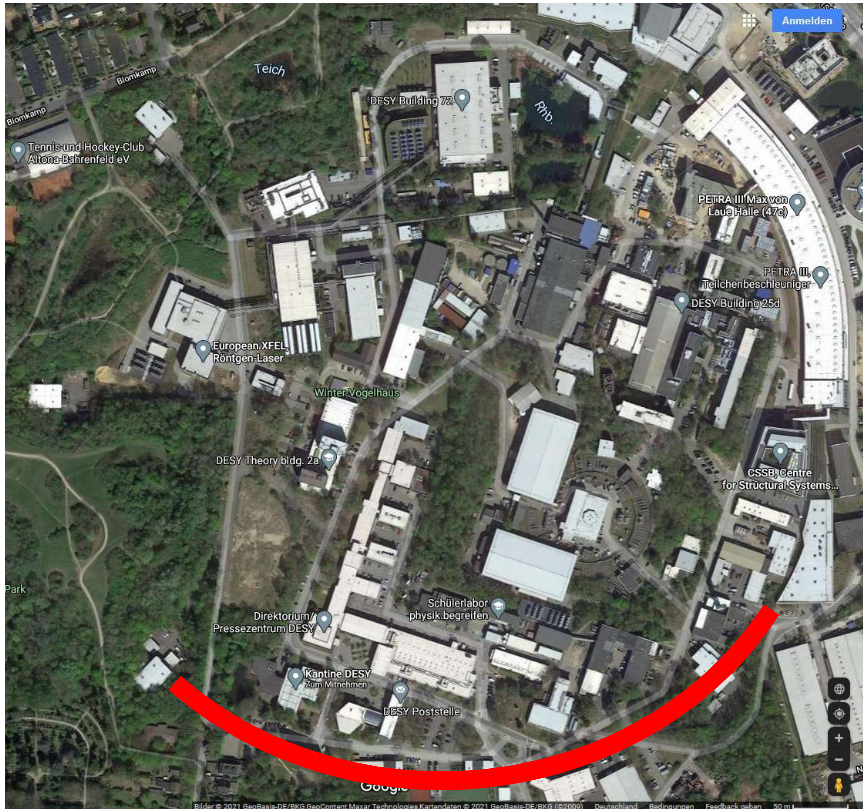


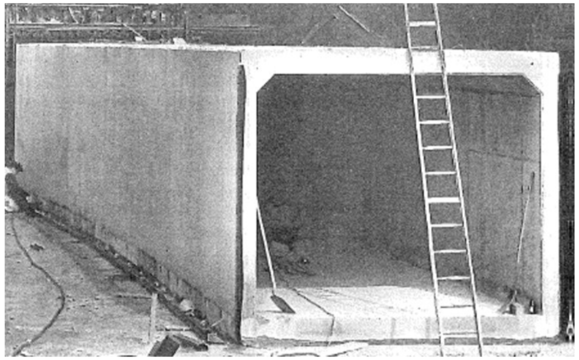
Current deviation 6e-4 over 2.5 ms during the hot-swap

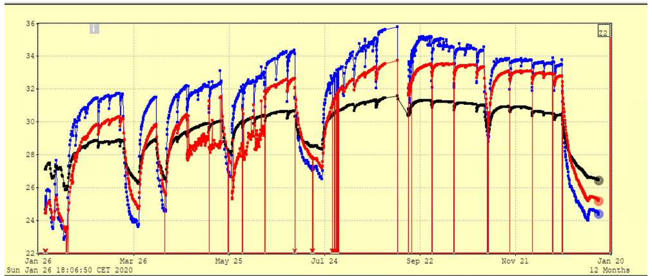
Collaboration with ESRF: under analysis: reduction of the hot-swap topology from 1:1 to 1:n for different PS type, their size, the rack capacity required, the cooling demands:

Accelerator stability is crucial for the success of PETRA IV

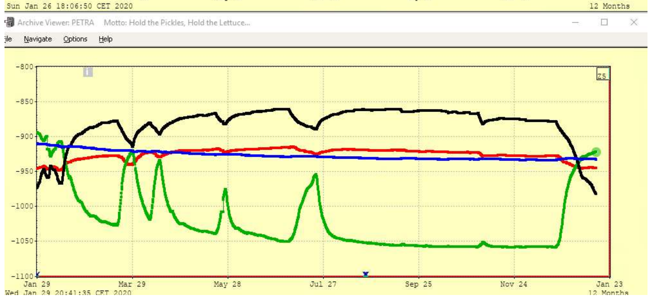
PETRA IV will reuse a large part of the original PETRA tunnel







Temperature up to $\Delta T \sim 10\ ^{\circ}C$



Movement up to 200μm

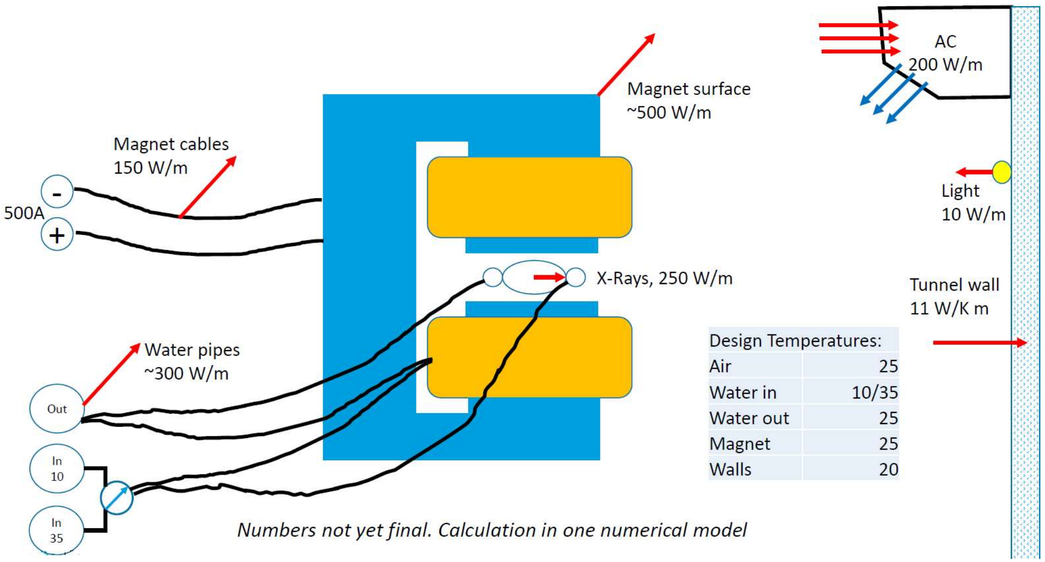
<u>The infrastructure upgrade (water cooling and ventilation) will guarantee the necessary temperature stability ±0.5 ℃ across the whole tunnel</u>

The infrastructure upgrade will guarantee temperature stability across the whole tunnel

Temperature stability to guarantee the stable operation of the accelerator is 0.5 °C locally (and 1.5 °C across the whole ring)

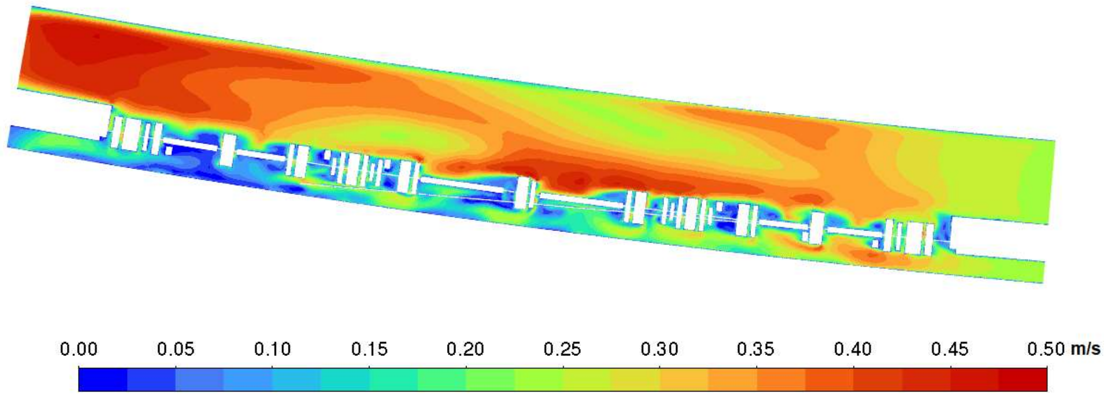
Water cooling of magnets, and vacuum system required (4 bars)
Air Handling Units necessary to guarantee local temperature stability

Complex thermal and fluidodynamic calculations are done in collaboration with Fraunhofer Institute Magdeburg to guarantee the required thermal stability



Design Temperatures:	
Air	25
Water in	10/35
Water out	25
Magnet	25
Walls	20

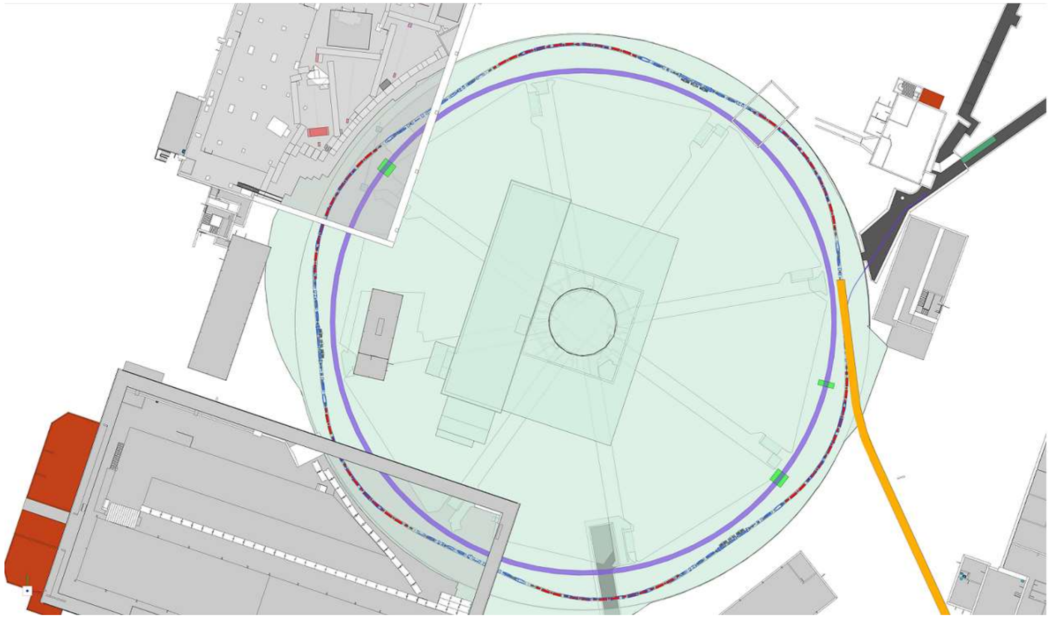
Numbers not yet final. Calculation in one numerical model



Status of DESY IV

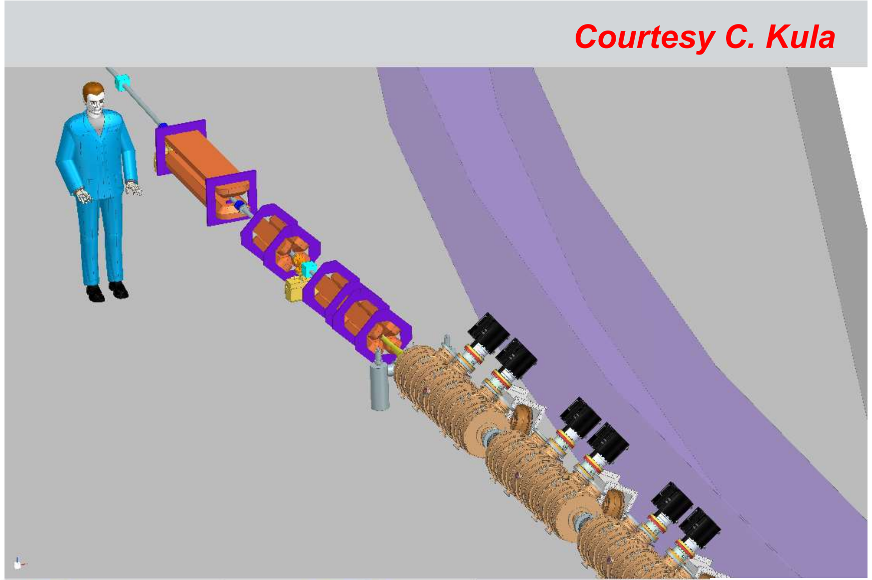
The PETRA IV project proposal includes the construction of a new booster DESY IV

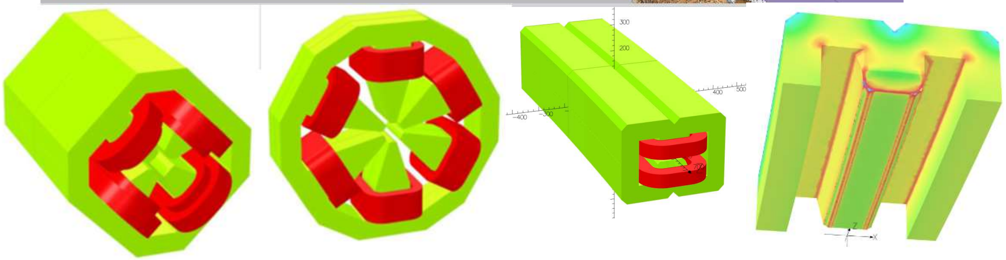
The lattice was frozen last year with a design delivering 20 nm – 1 nC single bunch operation reusing the LINAC-II and PIA ring



The DESY IV booster (316.8m) will have ***252 magnets*** and ***9 RF cavities***

System design and CAD integration progressed

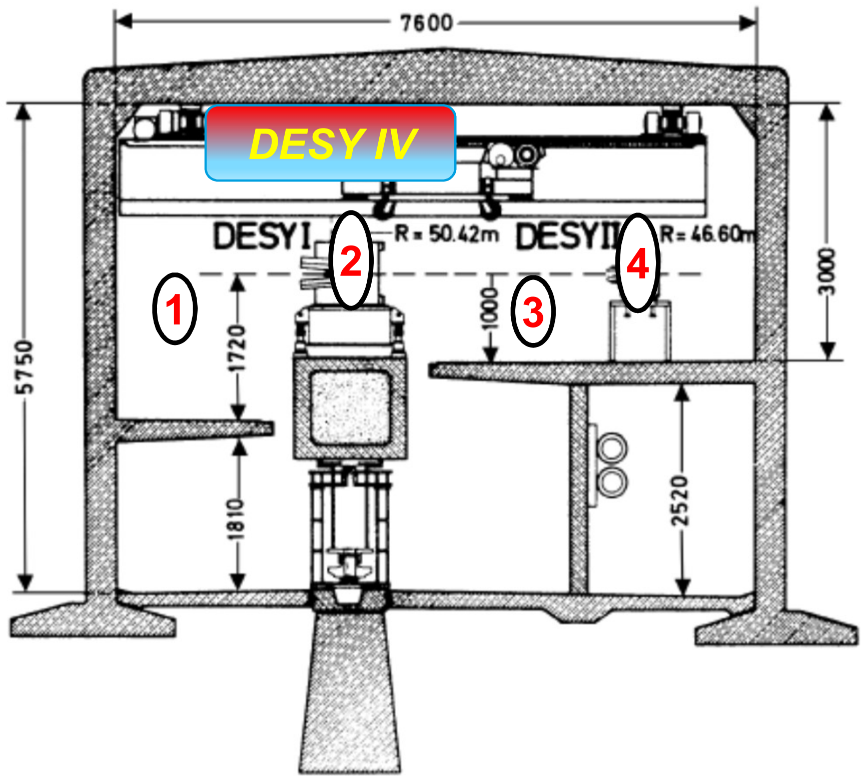




DESY IV: installation issues

The definition of detailed installation plans highlighted several issues:

Inherited building layout poses several constraints: installation on the ceiling turns out to be more costly than planned and with a complex logistics – not impossible, but triggered a review…



Different options were analysed in terms of lattice layout, stability and installation procedure:

Installation issues:

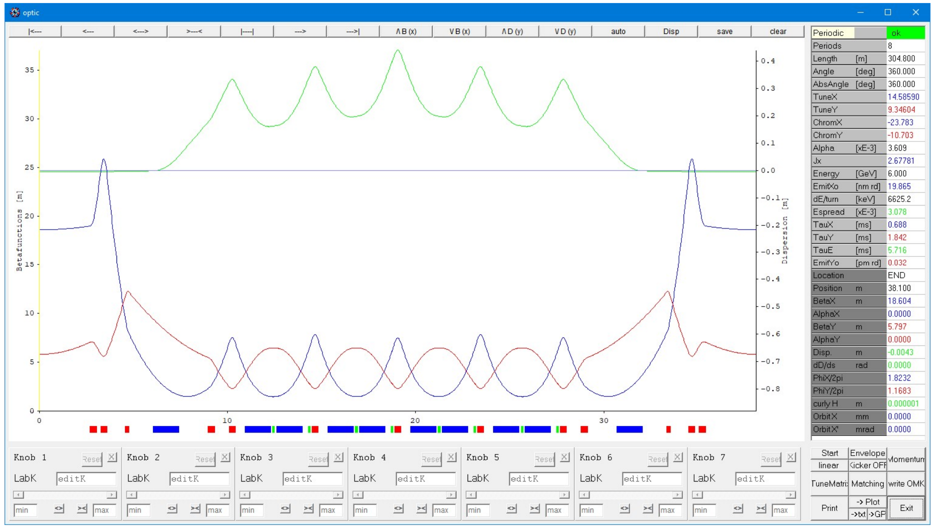
- Close to the maximum load:
  1.5 tons per magnet + 1.5 tons support
- Difficulties in drilling the holes on the ceiling due to the reinforced steel rod pattern on the ceiling (no wet drilling)
- Logistic concept requires a transport and lifting system and the outer floor load must be reinforced

Option 1: not favoured as the outer wall has no support pillars underneath the floor
Option 2: Ringtrager discarded on the basis of stability issues
Option 4: not favoured as the removal of DESY II does not allow start of installation before the PIII shutdown

DESY IV lattice revisited

PETRA IV. NEW DIMENSIONS

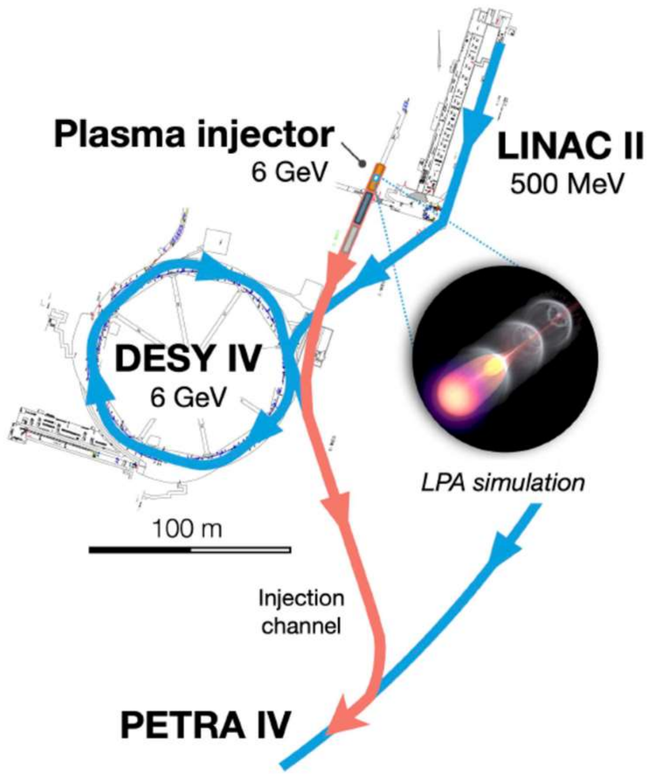
The Beam Physics group provided lattices for all options with equivalent performance to the baseline DESY IV: Moving from hexagonal to octogonal symmetry to follow the floor layout (and to provide better compatibility with the test beamlines)



Parameter	3h3l-v8 ceiling	Option 3 Intermediate
Circumference C	316.8 m	304.8 m
Nat. emittance $\varepsilon_{x,0}$	19.0 nm	19.0 nm
Tune Q_x/Q_y	17.37 / 12.15	15.18 / 8.27
Nat. chromaticity ξ_x/ξ_y	-41.7 / -13.8	-24.4 / -10.9
MCF α_c	$3.2\cdot10^{-3}$	$3.2\cdot10^{-3}$
Hor. damp. par. nr. J_x	2.56	2.29
Rel. energy spread σ_E	$2.6\cdot10^{-3}$	$2.1\cdot10^{-3}$
Energy loss/turn ΔE	6.5 MeV	6.6 MeV

DESY IV 8-fold symmetry is the new baseline lattice:
Engineering integration ongoing

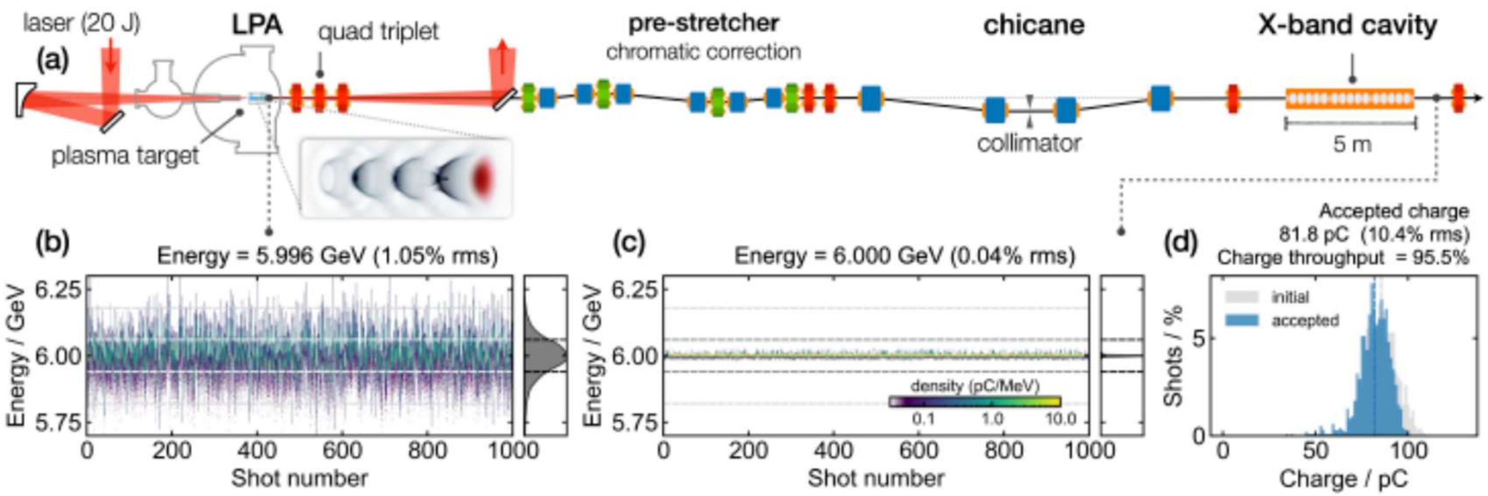
Alternative options for the pre-accelerator: LPA injector



Building on the strong R&D for the development of LPA at DESY, We propose to build a 6 GeV LPA injector for PETRA IV.

The next 3 years will be focused to the demonstration of high quality beam suitable for high efficiency injection in PIV AND high reliability of the injector

Challenges addressed with the RF dechirper experiment at LUX DESY and 450 MeV injection in DESY II by mid 2026

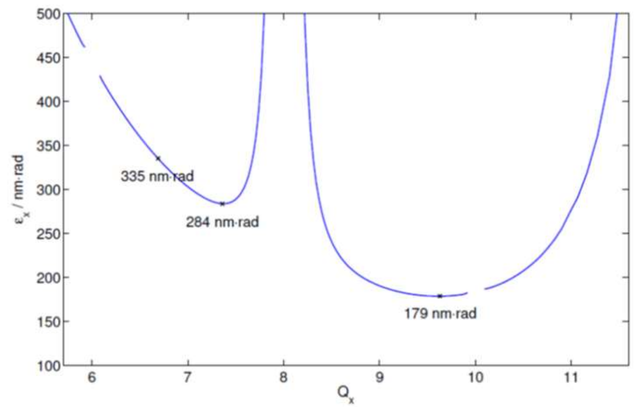


Alternative options for the pre-accelerator: reuse of DESY II

PETRA IV. NEW DIMENSIONS

Analysis of reusing DESY II pointed out that the large emittance 350 nm is unsuitable for injection in PIV. However, the idea of limited modifications to DESY II, could be appealing as a measure to save on the large investment for the DESY IV booster (76 M€ including refurbishment of the DESY tunnel infrastructure).

The emittance of DESY II can be reduced with new power supplies for the quadrupoles – J. Keil IPAC17 and operating off-energy down to 120 nm.



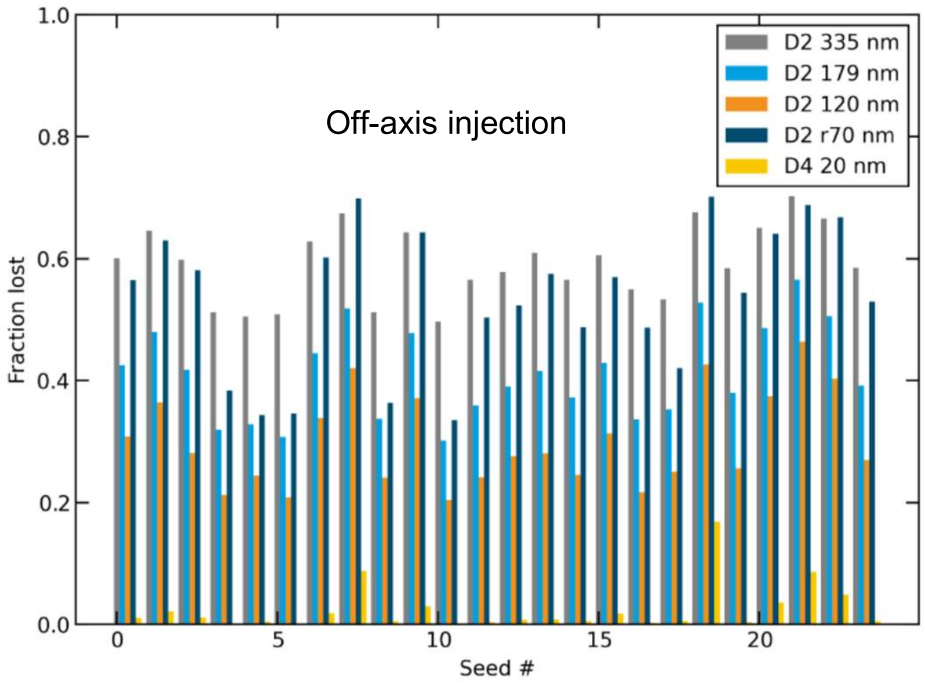
However a (strong) collimation in the transfer lines can be used to reduce the emittance of DESY IV to the level acceptable for injection in PETRA IV and reduce radiation issue at the injection point.

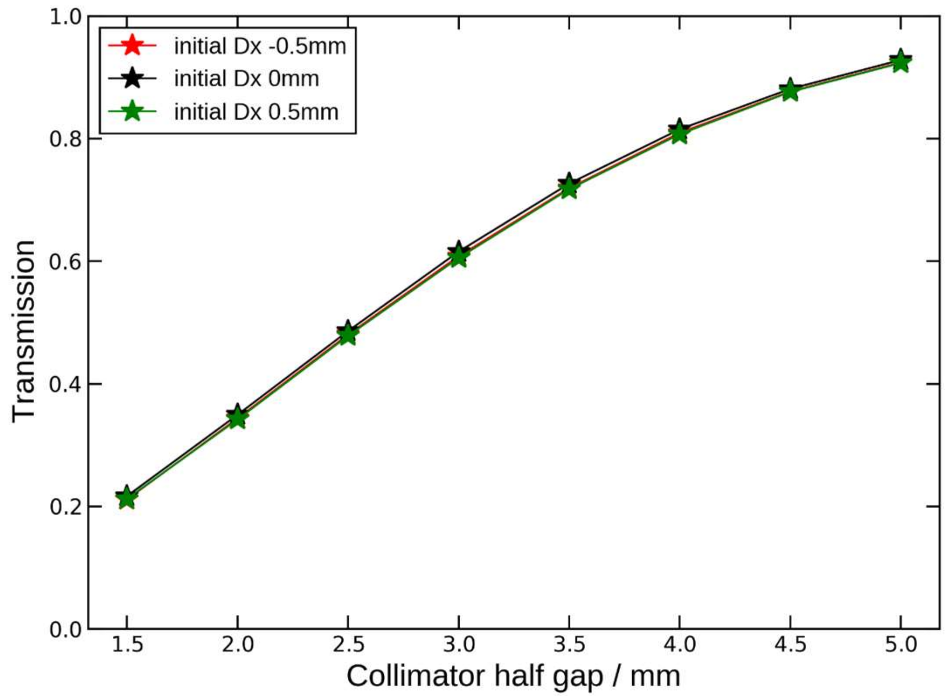
Currently a max of 3 nC can be accelerated in DESY II: Level of losses that can be tolerated under analysis (WIP)

This poses the question whether DESY II operation can be extended for few years, with limited refurbishment, until the LPA delivers a beam suitable as full injector for PETRA IV

Using existing DESY II as booster for PETRA IV reevaluated

- Simulation of injection of DESY II emittance-optimized beams into PETRA IV. Optics errors in main ring included, no transfer line and injection errors included. Assume 3 nC max bunch charge.
- Roughly 60% of the beam is lost during injection with present DESY II parameters.
- Strong collimation in the transfer line is necessary - WIP





Courtesy S. Antipov, C. Li

DESY.

Conclusions and future work

- PETRA IV is the highest priority project at DESY

- TDR ready
- Storage ring lattice well defined. Many elements of the machine are close to their final design.
- Prototypes are on the way
- DESY programme under revision – new lattice done

- Plans for a Laser Plasma injector strongly supported

- Timescale still unclear depending on funding agency decision.
- Present planes hinge on project approval 2025 and PIII shutdown in 2028-2029

Thanks to many colleagues that provided material for this summary

Thank you for your attention!