Lattice design for Petra IV
towards a diffraction-limited storage ring

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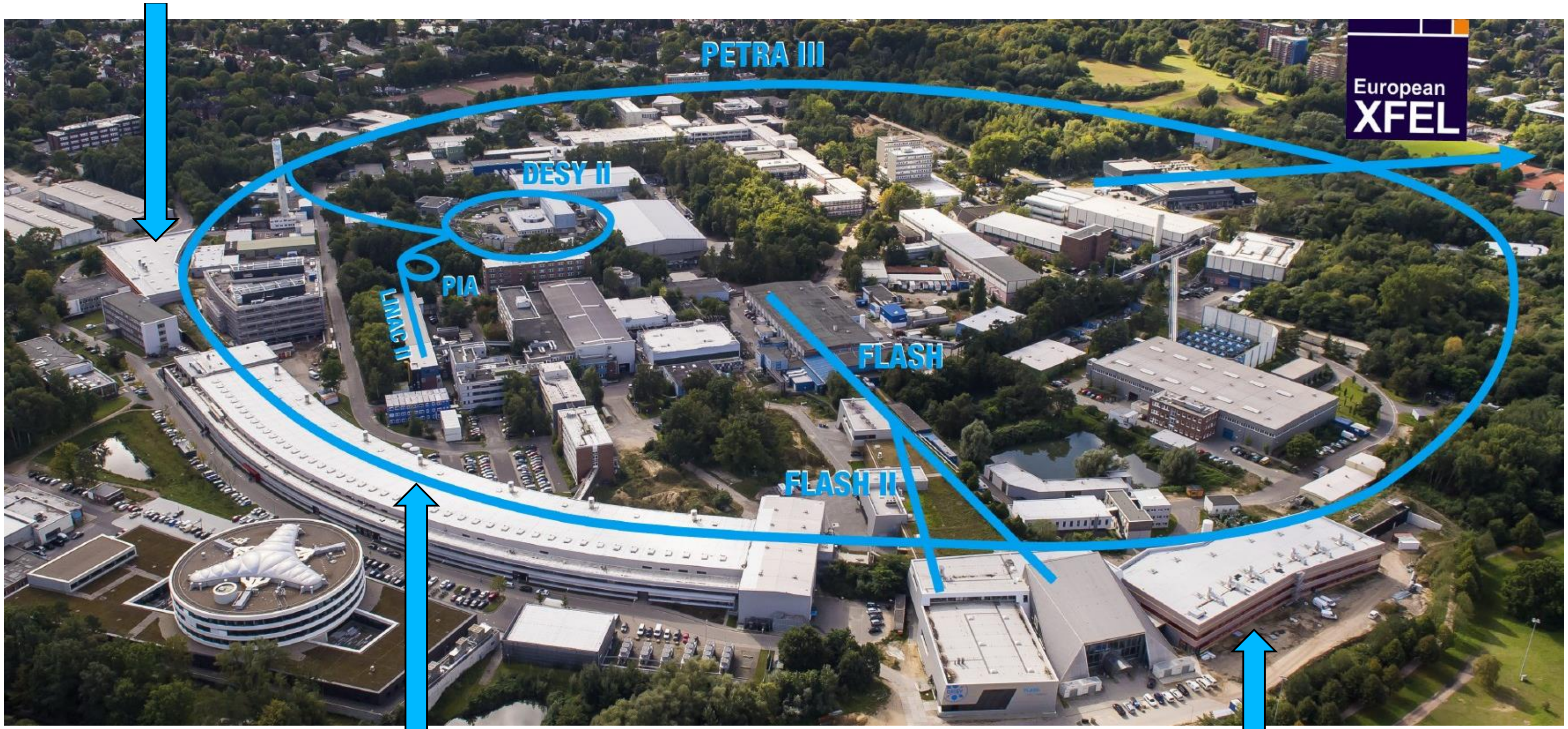
Content

- History and present status of PETRA, upgrade motivation
- PETRA IV project overview
- Lattice design status
- Technical challenges
- Outlook

PETRA III Overview

Extension Hall East
Ada Yonath 3 beam lines **(~ 3 free slots, status 2017)**

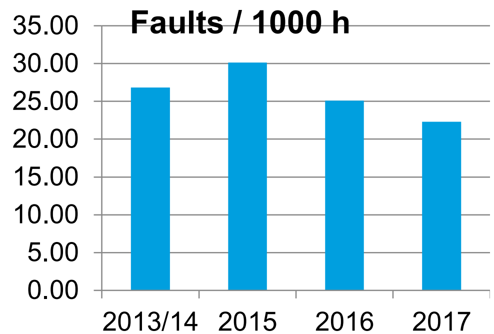


Max von Laue Hall
14 beam lines

Extension Hall North
Paul P. Ewald
2 beam lines
(3 free slots)

PETRA III

- HEP (Positron-Electron Tandem Ring Accelerator) 1978-1986, 1990-2007 (as HERA injector)
- SR source TDR 2004 (DESY 2004-035), Commissioned 2009 (K. Balewski, proc. IPAC'10)
- Staged extension project from 2014 (W. Drube et al., 2016 https://doi.org/10.1063/1.4952814)



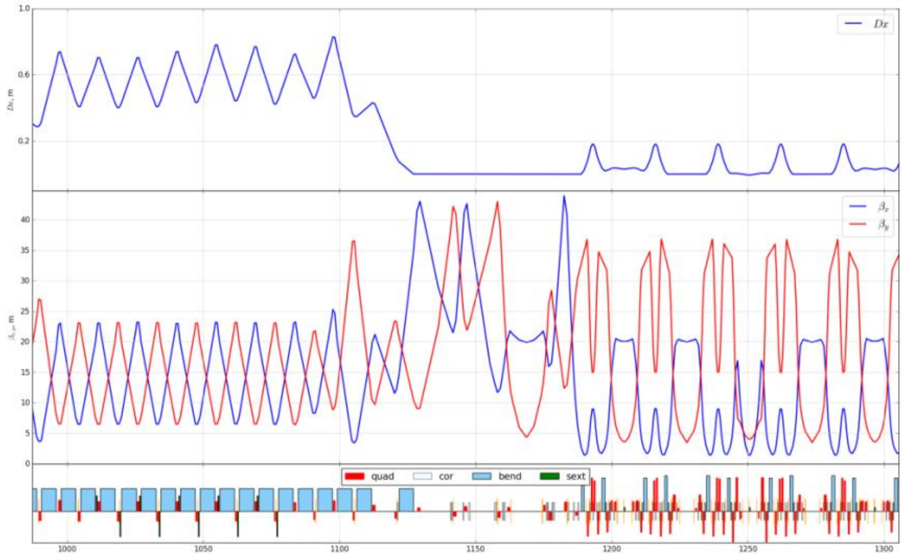
2017
Availability 98 %
MTBF 42.5 h
(without warm up time)

TABLE 1 PETRA III parameters incl. extension

Parameter			
Energy	6		GeV
Circumference	2304		m
Emittance (hor. / vert.)	1.2 / 0.012		nm rad
Total current	100		mA
Number of bunches	960	40	
Bunch population	0.5	12	10^{10} e^-
Bunch separation	8	192	ns

First upgrade considerations

- The extension project still ongoing, IDs/beamlines being added
- Emittance reduction potential of the present lattice with a different phase advance ~500 pm (V. Balandin et al., IPAC’15)
- With the new generation of machines (MAX-IV, ESRF-EBS, APS-U, Spring8-II,Sirius, Elettra and others) a much more significant reduction will be required by high-end users (e.g. coherence applications)
- To seamlessly continue the SR research programme, DESY will need to put a new machine in operation by late 2020s



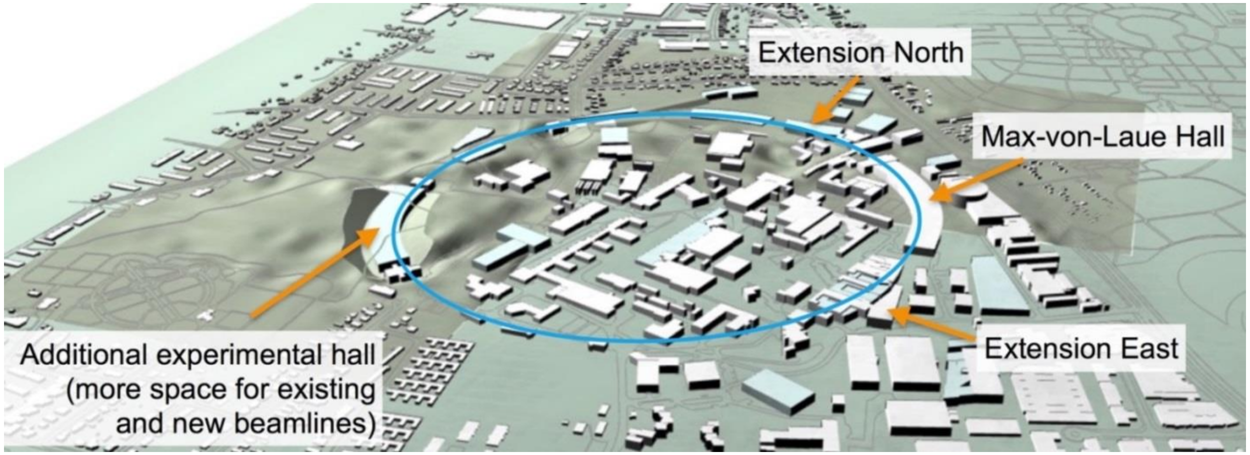
PETRA III optics (partial)

PETRA IV : “ultimate microscope”

Parameters and parameter range, status February 2016:

PETRA IV Parameter		
Energy	5 GeV	(4.5 – 6 GeV)
Current	100 mA	(100 – 200 mA)
Number of bunches	~ 1000	
Emittance horz.	20 pm rad	(10 – 30 pm rad)
vert.	20 pm rad	(10 – 30 pm rad)
Bunch length	~ 100 ps	

Goals:
2024 Start construction
2026 Start up PETRA IV

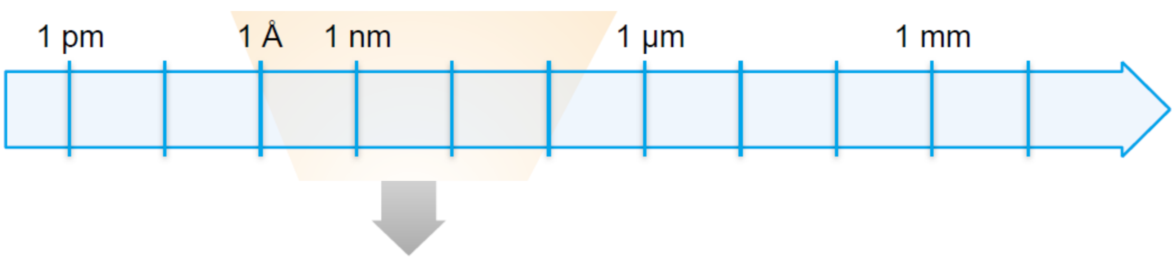


PETRA IV – Science case

PETRA IV - Decoding the Complexity of Nature
The ultimate 3D process microscope

http://photon-science.desy.de/facilities/petra_iv_project/index_eng.html

Closing the Gaps in the Complexity Window



diffraction-limited source: fusion of real and reciprocal space

PETRA IV

Joint Accelerator+FS workshop and 9 PETRA IV science workshops held so far

Photon emittance:

$$\epsilon_\lambda = \frac{\lambda}{4\,\pi} = \frac{1}{2}\,\hbar\,c\,\frac{1}{E_\lambda}$$

= 8 pm

for photons
0.1 nm or 12.3 keV

Diffraction limited source ←→ **beam emittance ~ photon emittance**

Brilliance

Brillance: > 10^{22} Photons / (sec mrad² mm² 0.1 % BW)

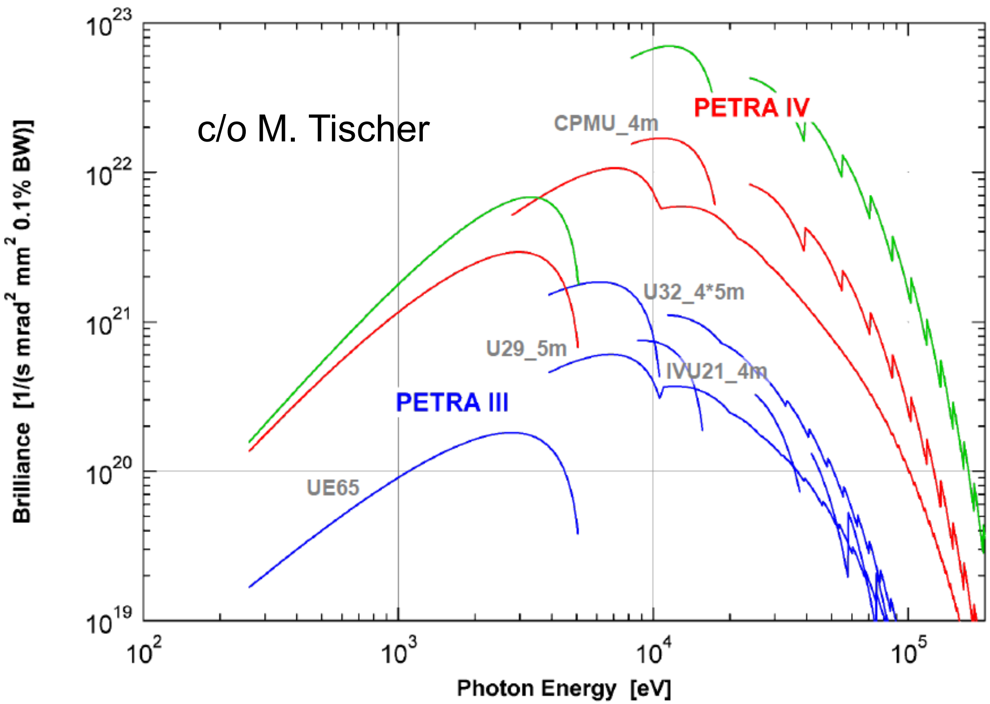
angle integrated photon spectral flux (undulator, beam intensity)

$$\mathcal{B}_n = \frac{\mathcal{F}_n}{4\pi^2 \Sigma_x \Sigma'_x \Sigma_y \Sigma'_y},$$

photon beam convoluted with the electron beam

$$\Sigma_{x,y} = \sqrt{\sigma^2_{x,y} + \sigma^2_{\lambda}},$$

$$\Sigma'_{x,y} = \sqrt{\sigma'^2_{x,y} + \sigma'^2_{\lambda}}.$$



PETRA III
ε_x = 1.2 nm, κ =0.25 %
β_x = 10 m, β_y = 2.5 m

PETRA IV
ε_x = 15 pm, κ =100 %
β_x = 5 m, β_y = 2.5 m

PETRA IV
ε_x = 10 pm, κ =50 %
β_x = 1 m, β_y = 1 m

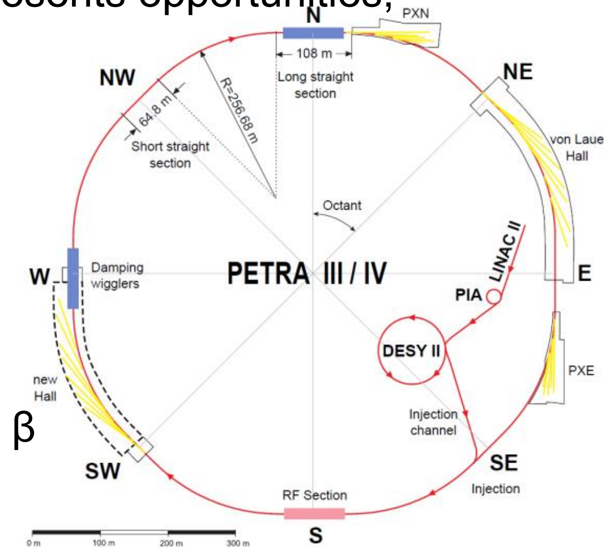
Parameter scans and benchmarks with SPECTRA/SRW being performed

Lattice design objectives

- Low (0-current) emittance lattice (~10-30 pm range)
- DA to assure some space for beam steering and possibly top-up (off-axis injection). Try to remove pressure from injector parameters
- Sufficient beam lifetime (keep Touschek scattering under control) MA of >2%
- Good beam parameters/ stability for high bunch charges (> 1mA/bunch)
- Reusing accelerator and experimental infrastructure when possible
- Cost efficiency (RF, magnets, alignment, etc. based on established technology)
- Issues not specific to low-emittance, but not to be forgotten: diagnostics, controls, (electron) optics measurement and correction

Lattice design specifics for Petra IV

- Several MBA lattice types can deliver natural (bare) emittances in the 10 pm range at 6 GeV with PETRA geometry
- At the same time, dynamic aperture for accumulation and even smooth operation (e.g. allowing enough space for optics and orbit correction, beam-based alignment etc.) is hard to achieve
- The PETRA geometry (long straights, low degree of symmetry) presents opportunities, e.g.
  - Non-local chromaticity correction schemes
  - Very long insertion devices
  - Damping wigglers
  - Optimized cell design for arcs with no IDs
  - ID straights at arc end with reduced restrictions on length and β
- …as well as difficulties
  - Large DA is generally harder to achieve in asymmetric rings
  - More effort for optics design in general compared to more conventional SR sources

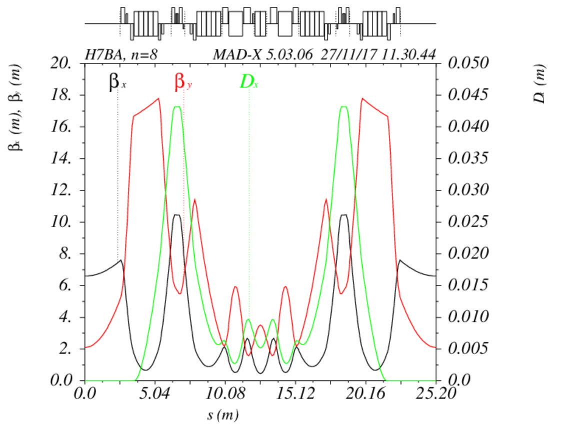


Optics options studied

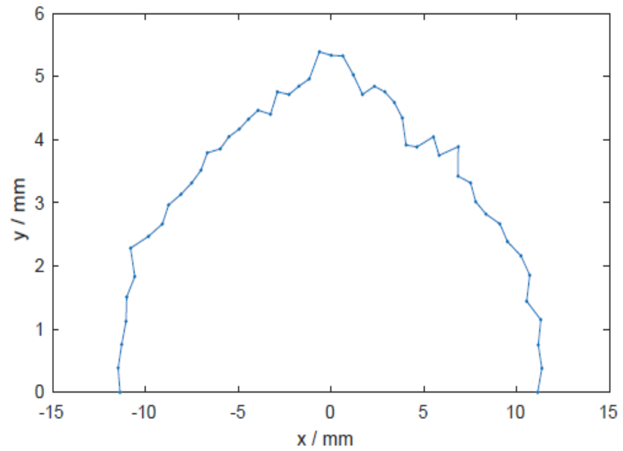
- 6 and 7 bend HMBA (scaled ESRF EBS)
- Non-interleaved (-I) options with 6 bend
  - Phase space exchange
  - Double –I
- 7bend HMBA used for reference
- Double –I 6BA needs further development but is promising

HMBA optics (ESRF-like)

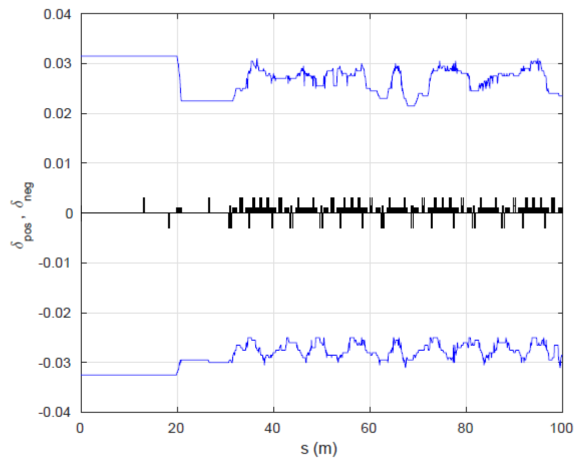
- Initial scaling of ESRF-EBS optics to 23m cell resulted limited DA and too strong magnets
- Approach taken further resulted in acceptable performance:
  - Longer cell (25 m) to relax magnet strength, 8 cells per arc
  - All arcs 4th order achromats (cell phase matching)
  - Scans of octupoles and chromatic sextupoles
  - MOGA



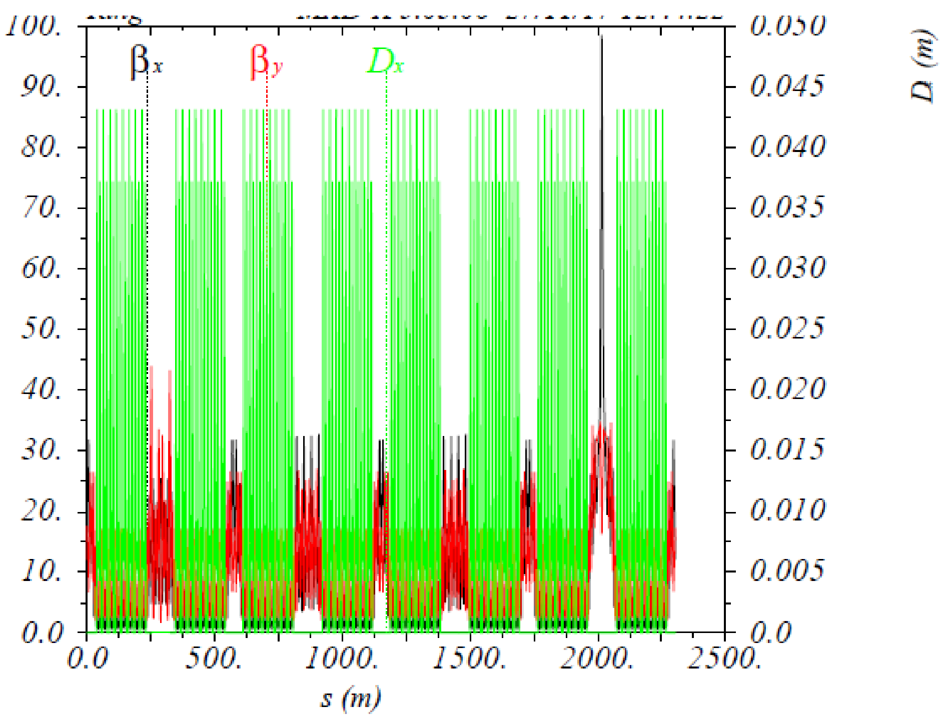
Dynamic aperture

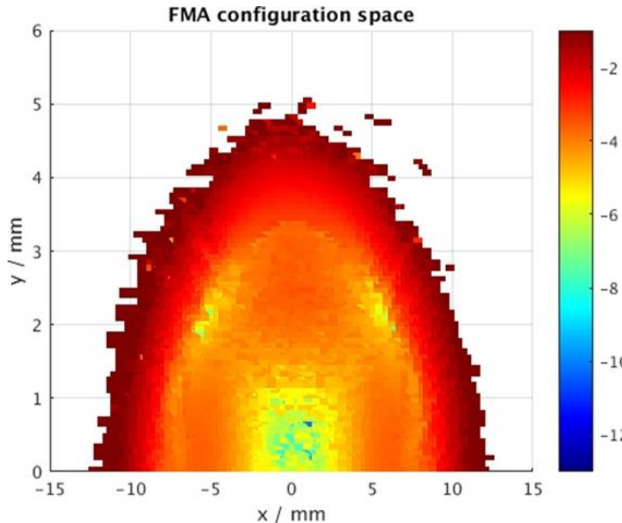


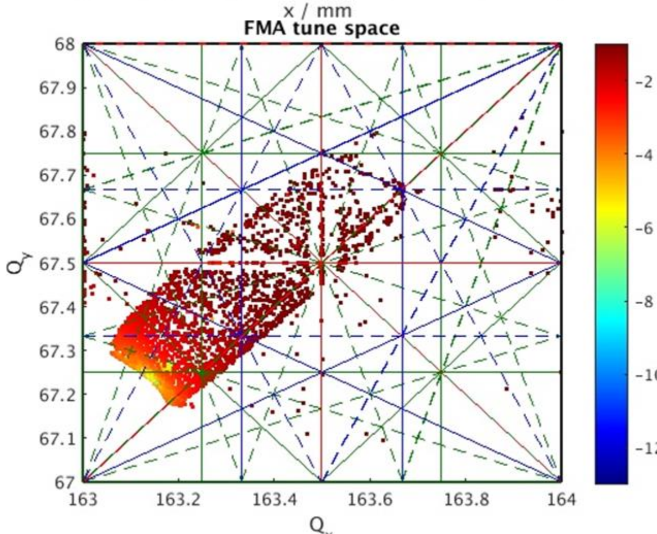
Momentum acceptance



HMBA optics

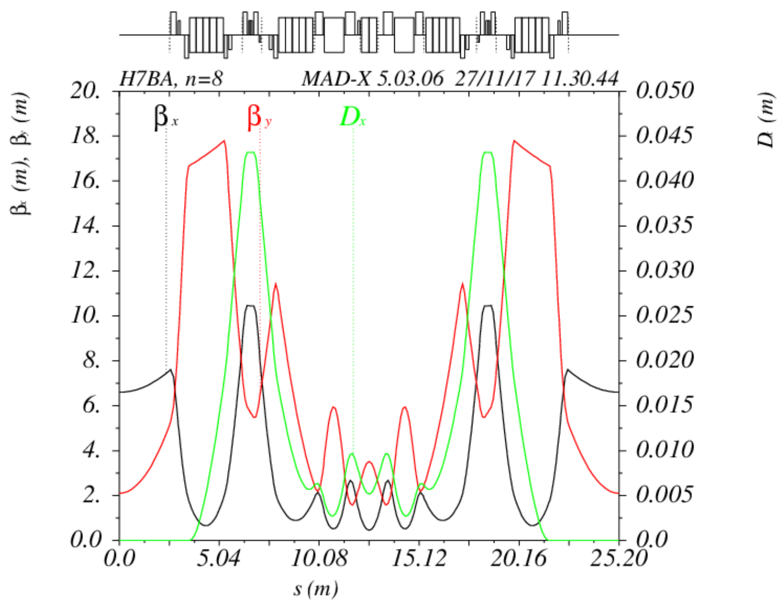

βx
βy
Dx
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.0
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.0
0.0
500.
1000.
1500.
2000.
2500.
s (m)
D (m)


FMA configuration space
y / mm
x / mm
6
5
4
3
2
1
0
−15
−10
−5
0
5
10
15
-2
-4
-6
-8
-10
-12


FMA tune space
Qy
Qx
68
67.9
67.8
67.7
67.6
67.5
67.4
67.3
67.2
67.1
67
163
163.2
163.4
163.6
163.8
164
-2
-4
-6
-8
-10
-12

Reference lattice

Parameter	PETRA III (DW)	H7BA 25.2 m (DW)
Total current	100 mA	100 mA
Nat. emittance ε_0 (with DW)	5100 pm (1280 pm)	15 pm (9.3 pm)
Energy spread σ_p (with DW)	$0.82 \cdot 10^{-3}$ ($1.23 \cdot 10^{-3}$)	$0.73 \cdot 10^{-3}$ ($1.44 \cdot 10^{-3}$)
Energy loss/turn U_0 (with DW)	1.3 MeV (5.1 MeV)	1.37 MeV (4.6 MeV)
Momentum compaction factor α_c	$1.13 \cdot 10^{-3}$	$1.46 \cdot 10^{-5}$
Max. gradient g	17 T/m	100 T/m
Dispersion D_x at SF	750 cm	4.2 cm



A_x = 1.35 mm·mrad Dynamic acceptance

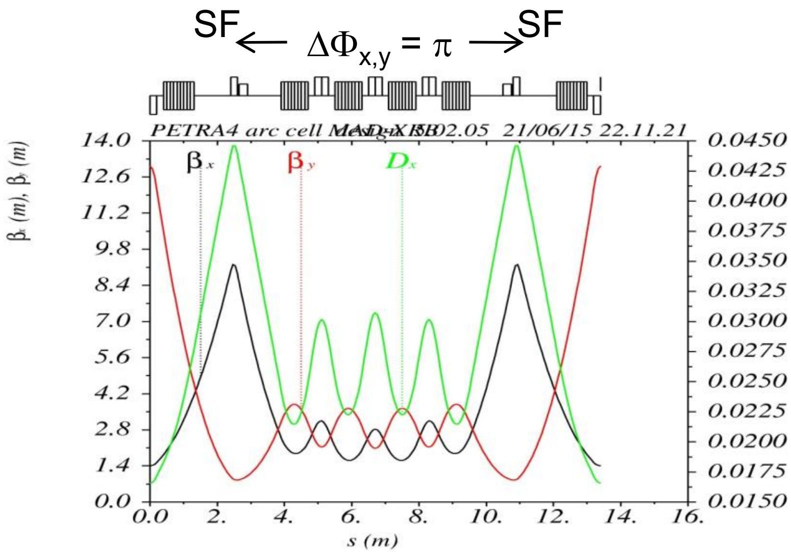
A_y = 1.24 mm·mrad (6 D tracking, **no errors**)

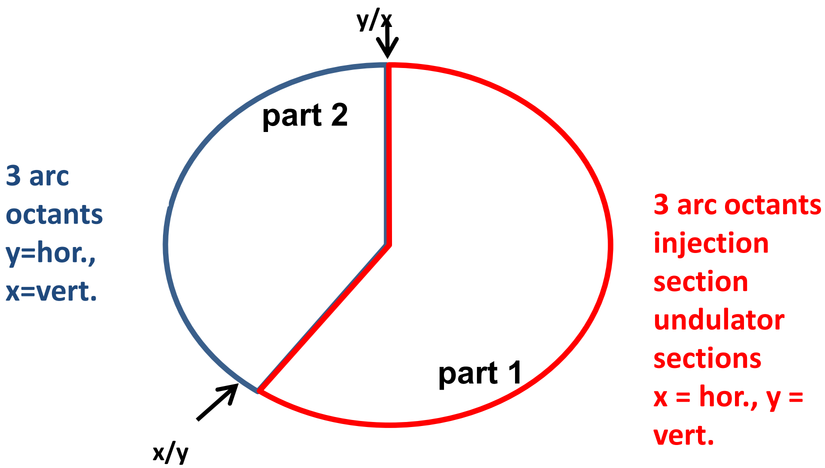
"Reference Lattice"

Hybrid Seven Bend Achromat scaled and adopted from ESRF-EBS
8 cells / arc (cell length: 25.2 m / new version ~ 26 m),
injection in one long straight section,
damping wigglers in another straight section

Phase space exchange optics (TMBA)

- Different lattice type investigated in parallel
- Concept to significantly improve DA (proposed R. Brinkmann Ideenmarkt 2015)
- Two phase space exchanges in the ring (similarity to Möbius scheme, but optics is always in one mode locally)
- Only sum chromaticity is corrected, allows to have a –I sextupole arrangement



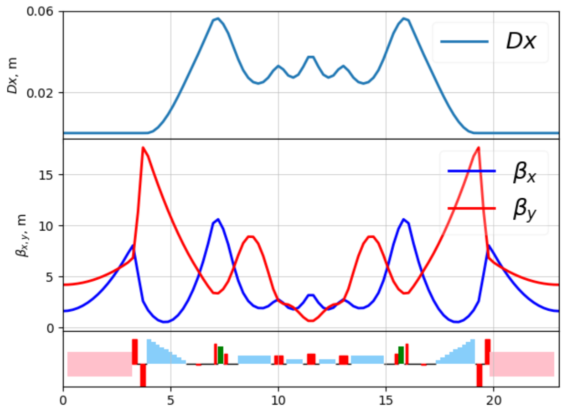


Phase space exchange (twist)

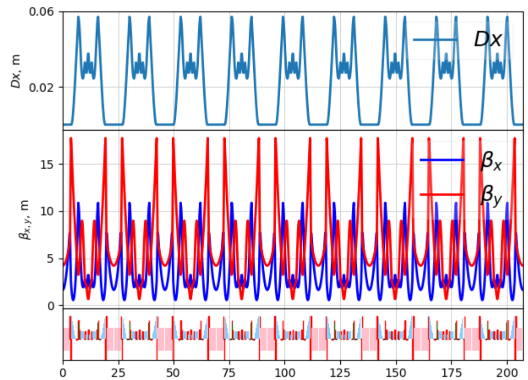
TMBA cells

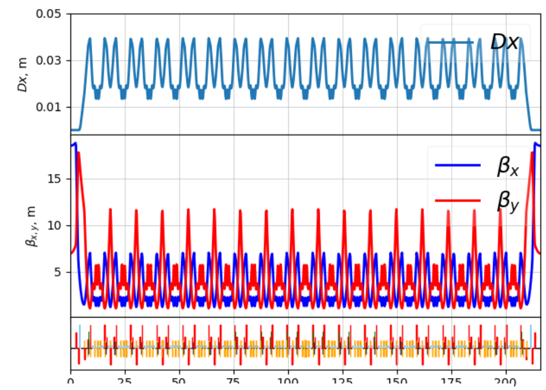
- Cells for arcs with and w/o IDs, 1 sextupole family, with π/π phase advance (-I transform)
- Distributed chromaticity correction
- DA > 2 mm mrad (limitted by path lengthening + RF).

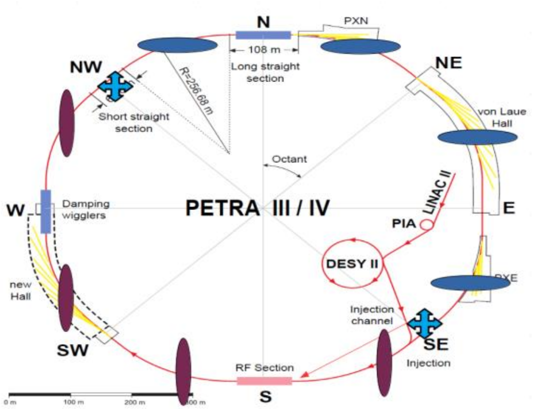
Cell layout, emittance range ~30 pm



Cell with no ID space based on same principle, emittance range 25-30pm, Long achromat

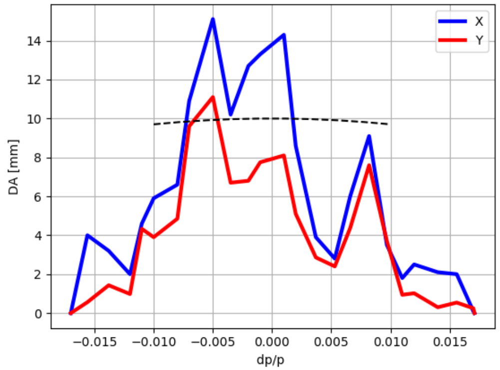






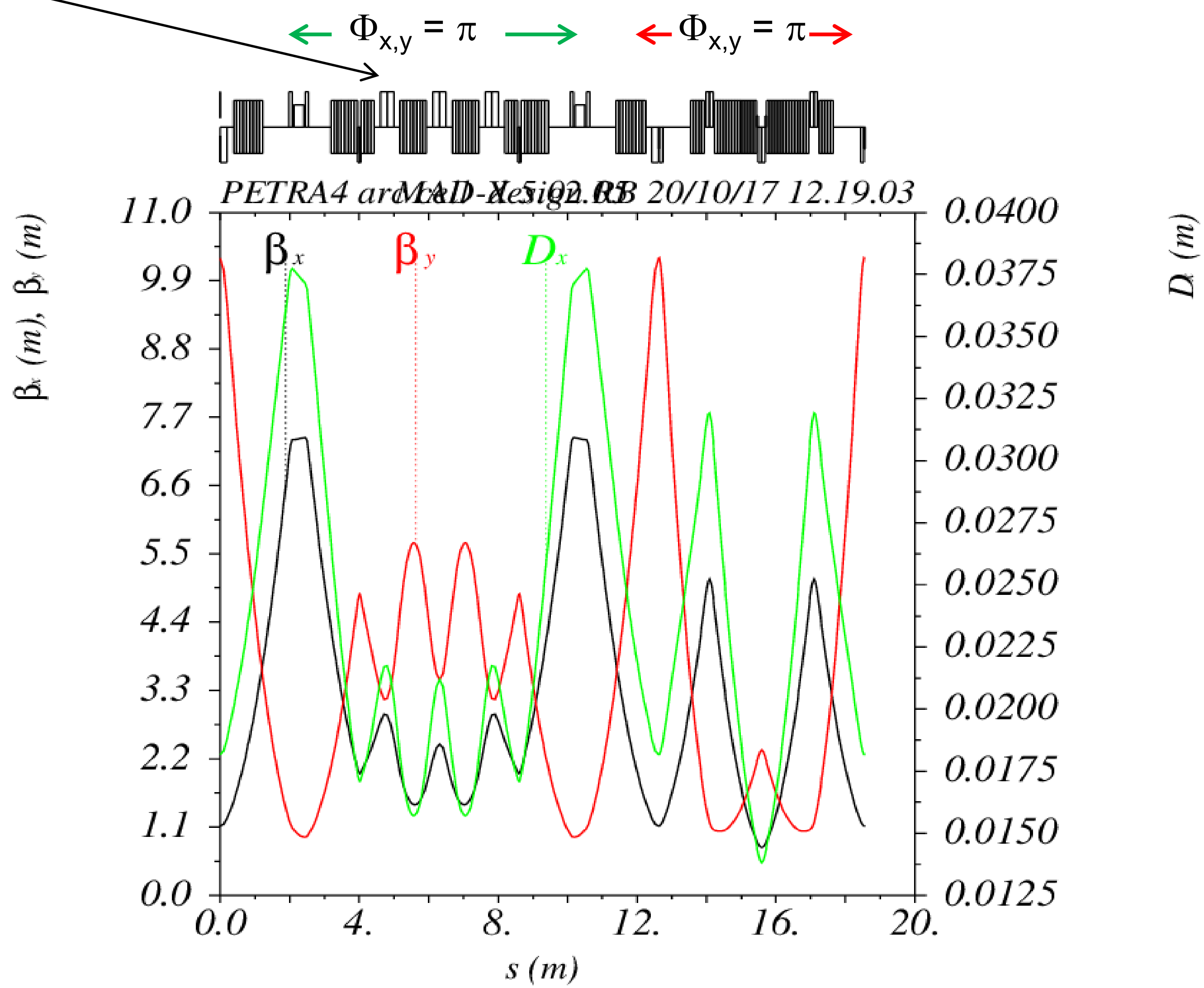
28/28 pm lattice
12/12pm with IDs

DA good
MA problematic but ok
(still ways to improve)
Round beams a limitation



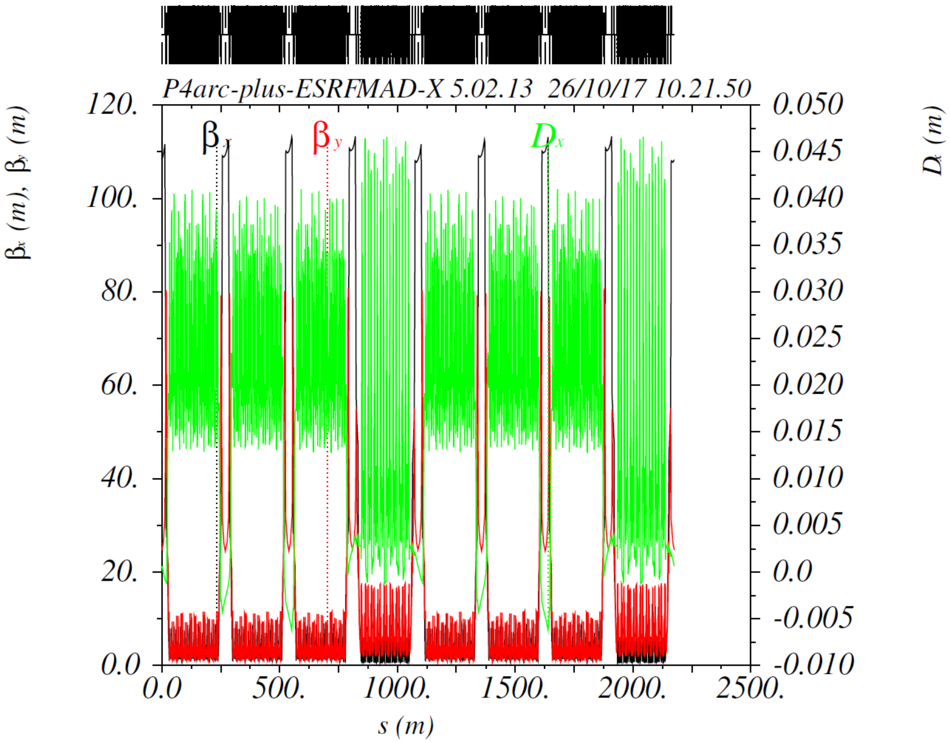
Double –I optics: arc w/o ID takes chromaticity correction

With inverse bends (total 1 mrad)

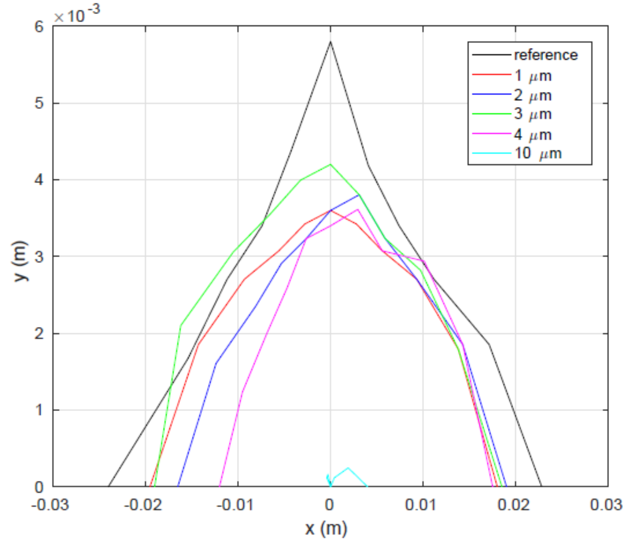


Double –I optics

- Ring with IDs (6BA cell with –I sextupoles) 30 pm bare emittance
- Ring emittance with IDs ~19pm, energy spread 0.10%, partitions J_x/E = 1.8/1.2



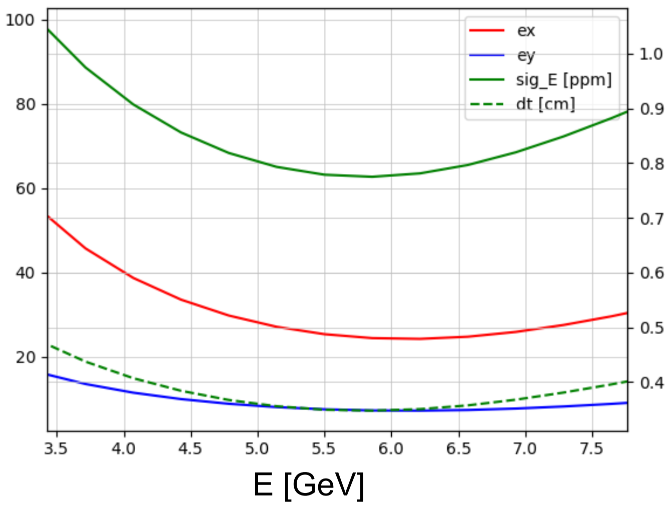
DA including misalignment tolerance (uncorrected)



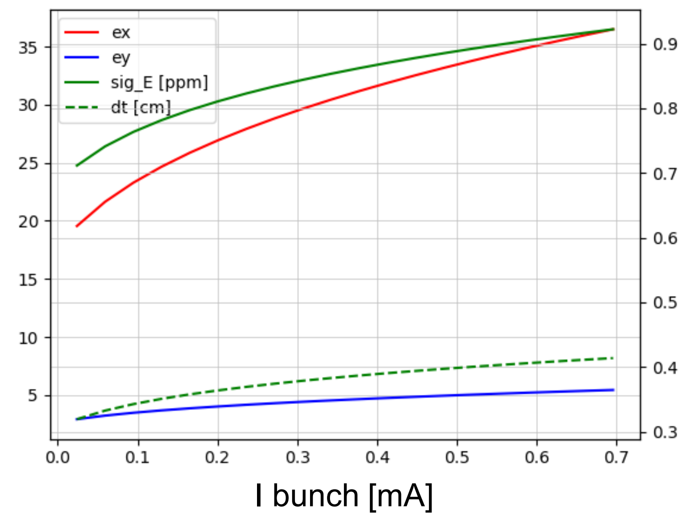
Target parameters – IBS limitation

- IBS limits the beam emittance for most operation scenarios and lattice types
- Lattices below 15 pm bare emittance are not considered presently, due to IBS limitation

Beam parameters as a function of beam energy for one of the H7BA scenarios (0.1mA)



Beam parameters as a function of beam current for one of the H7BA scenarios

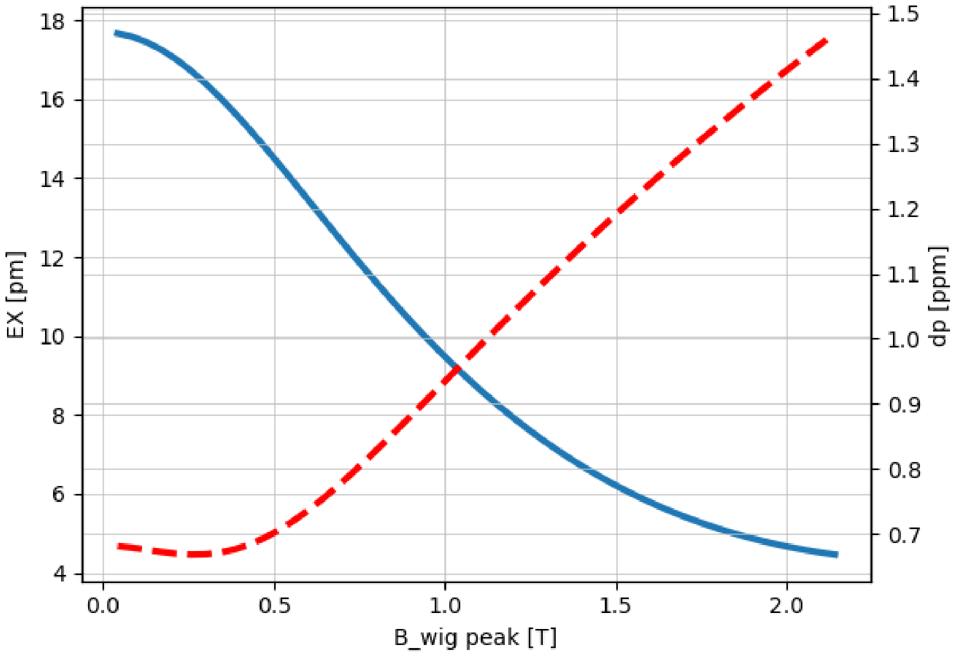


DESY

Target parameters – influence of undulators

- Undulators have significant impact on emittance
- Typical ID configuration gives 0.1% energy spread and 10 pm emittance (no canting, no IBS, no DW)

Scenario: all user IDs in operation (24 mm)



Target parameters -- canting

Effect of canting on emittance mostly due to non-zero dispersion at IDs, I_5 scaling as

$$\frac{LK^3\beta\theta^2}{{l_w}^3\ \gamma^3}$$

A simpler estimate of emittance neglecting contribution of the rest of the ring

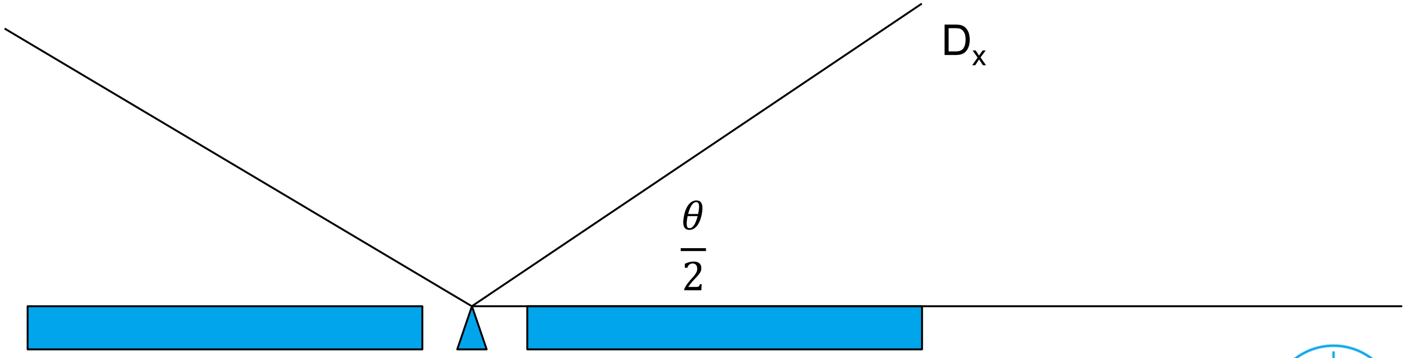
$$\varepsilon_{INS} = 2\,H\left(\frac{dp}{p}\right)^2$$

For 2 undulators with a canting magnet between, *H* is invariant and equal to $\mathrm{D}'^2\beta = \left(\frac{\theta}{2}\right)^2\beta$

ε_{INS} = ε_{RING} roughly sets the limit on the canting angle

$$\theta_{MAX}[mrad] \approx \sqrt{\frac{2\varepsilon_{RING}[pm]}{\beta[m]\ \frac{dp}{p}[ppm]}}$$

e.g. for an energy spread of 10^{-3} ,16 pm lattice and 2 m beta $\theta_{MAX}\ \approx 4\,mrad$

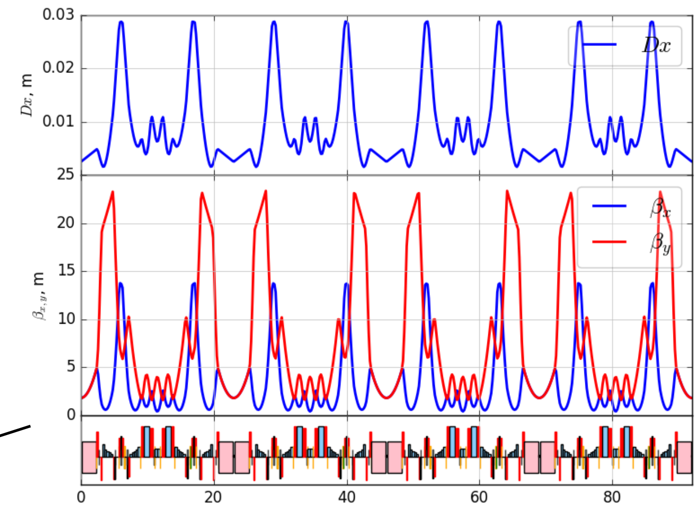


Estimates for P4 lattice

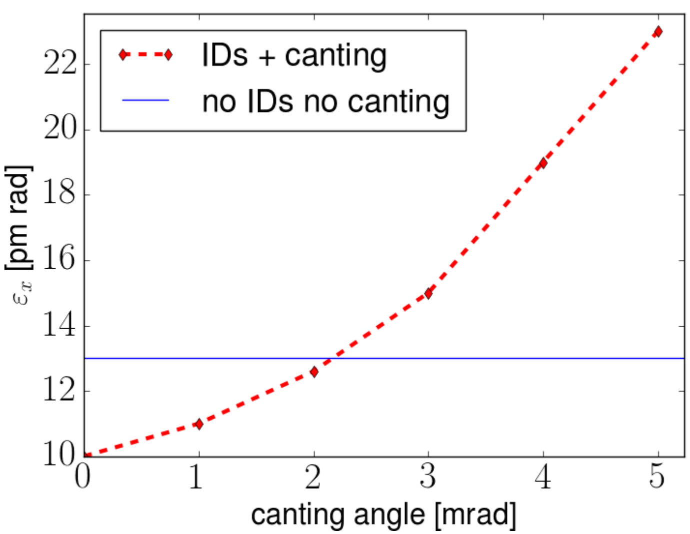
However putting a canting into various MBA versions of P4 results in bigger growths due to

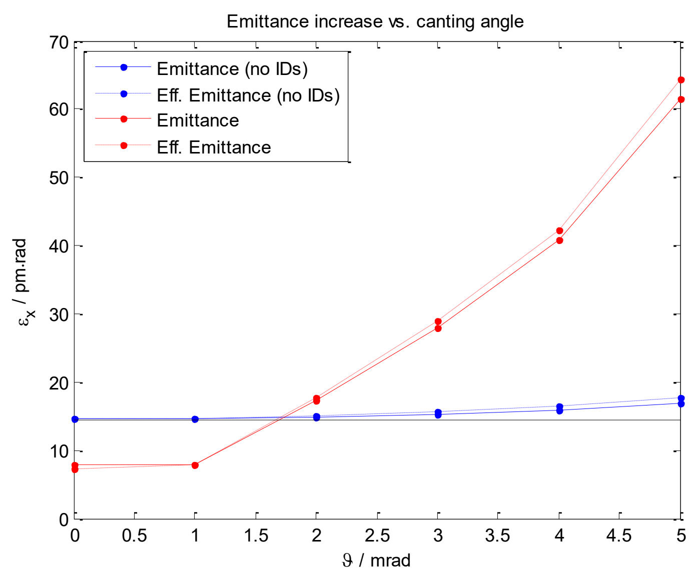
- Dispersion not perfectly matched to 0
- Beta at ID large

For the current reference lattice estimate on max canting angle is around 2 mrad



‘Low beta’ (~2m) cell 23 m cell
18 cells with ID 54 w/o





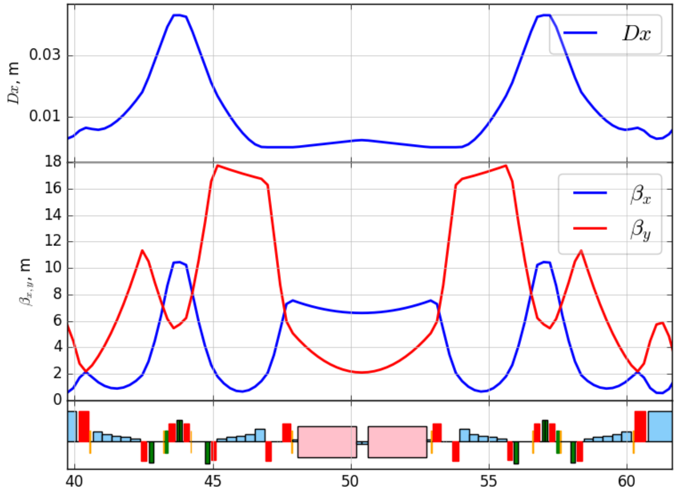
Reference
25 m cell
(6m beta)

3-magnet cell, 25m

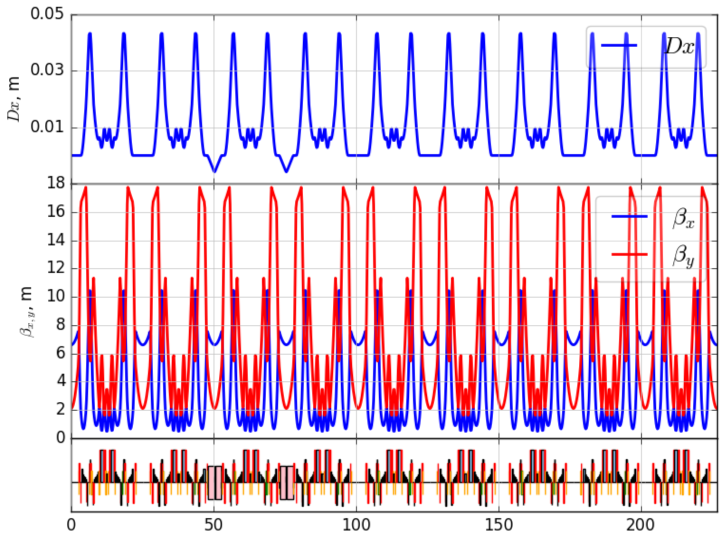
3-magnet canting is a way to make the canted insertion transparent for the rest of the optics

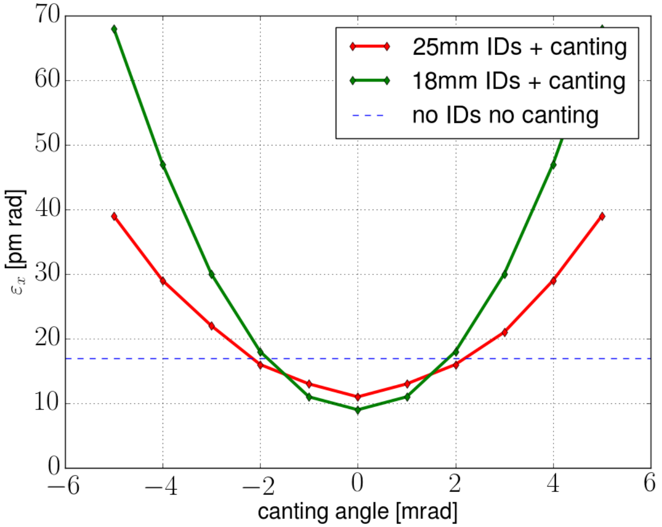
For the reference lattice it however is also not optimal for emittance and results again in about 2 mrad max canting angle (when all canted)

With partial canting and beta optimization 4 mrad possil



Mock-up 1: K=2, 25mm period, 2 canted IDs, 7 cell w/o IDs, 'few-ID case'

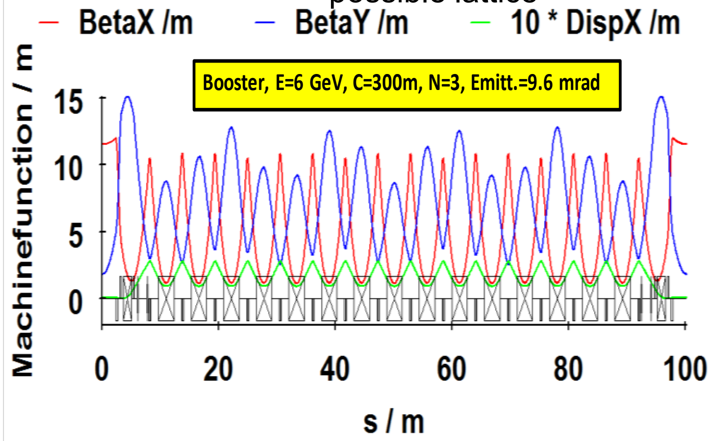




Injector

- Initial approach: use the existing PIII injector (DESY II, PIA, LINAC II)
- Turns out that a refurbishment of the 40 years old systems nearly all components (magnet coils, cables, vacuum system, etc.) must be exchanged
- The effort would be nearly as high as for a newly designed injector
- Another approach: new DESY IV inside the existing (then refurbished) DESY tunnel + new commercial LINAC IV (optional LINAC II / PIA as backup for commissioning)
  - consequent consideration of only the actual boundary conditions for PETRA IV, not of the old ones (10GeV capability, 7 in/extractions, two synchrotrons in one tunnel, reuse of old DESY I components etc.)
- DESY IV: usual „state of the art“ low emittance 6GeV booster (similar to the SLS booster concept and successors like ALBA)
- Combined function synchrotron, ramped at 3Hz, horizontal emittance in the order of 10nmrad, roughly 320m circumference, injection energy roughly 300MeV(?)
- plan B: booster ring in the PETRA IV tunnel

possible lattice



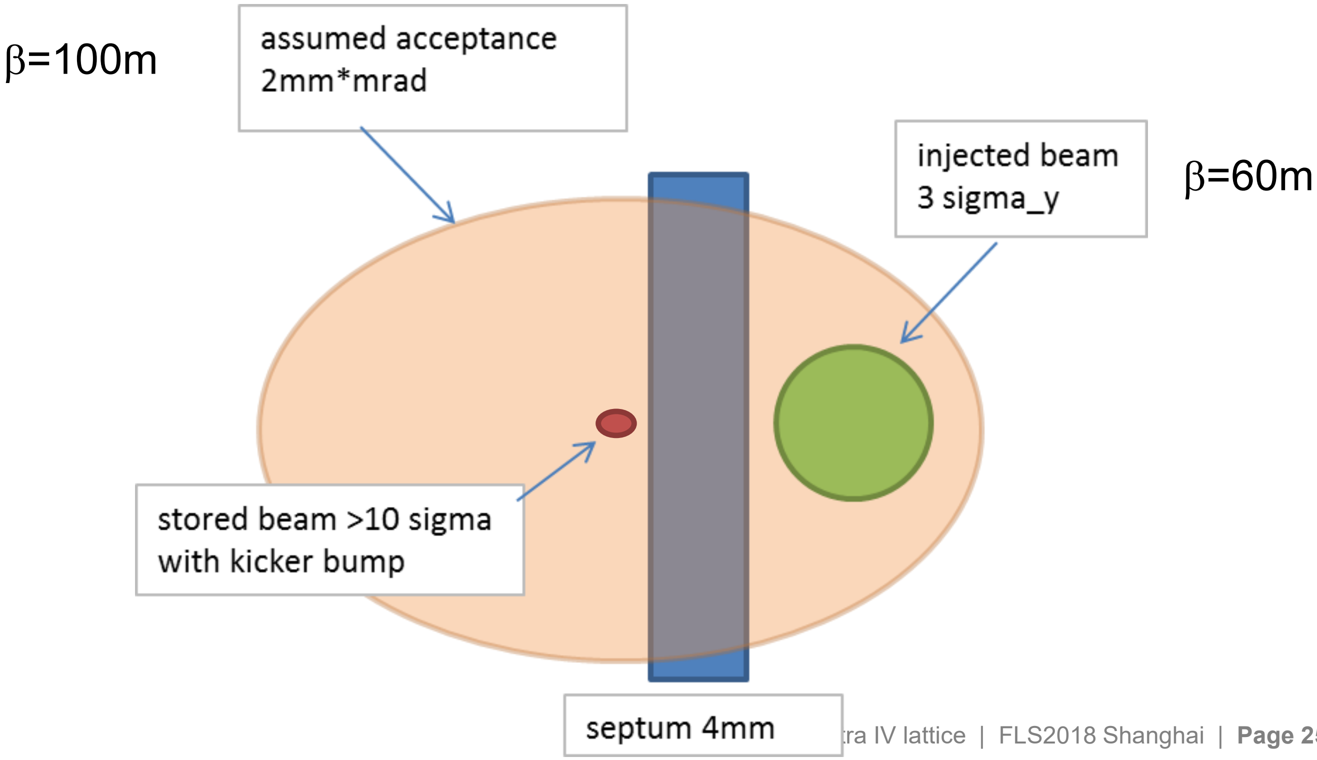
ALBA booster

SLS booster

Possibility of accumulation in the (y-) plane of smaller emittance from injector

(Similar concept pursued at HZB/BESSY2, P. Kuske, Proc. IPAC 2016)

- To further improve the injection efficiency, either inject vertically into PETRA ring or perform a 90 deg x-y phase space exchange in the transfer line
- Dynamic acceptance of 2 mm*mrad would be sufficient for accumulation
- On-axis injection in the other plane with ~200nm emittance no problem



High charge and advanced option issues

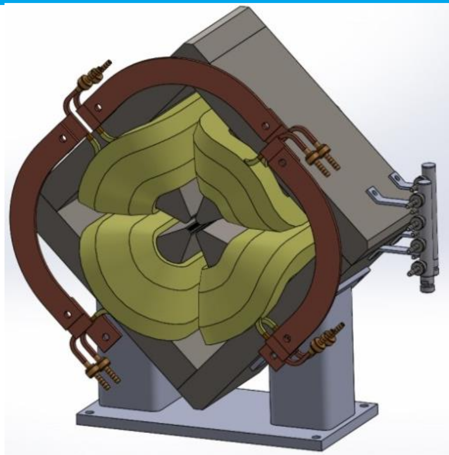
- Several advanced options depend on the possibility to accumulate high bunch charge
  - Hybrid and high charge fill patters
  - PETRA has space for long IDs: partial SASE or XFELO options under consideration
- From the injection perspective (sufficient DA) accumulation is likely possible
- Due to multi-bunch instabilities full current (100 mA) at Petra III only possible with feedbacks. Feedback performance and impedances being evaluated for PETRA IV to understand charge limitation. Preliminary estimates ~1 mA/bunch max current after preliminary impedance budget modeling (GdfidL), 500MHz + 3rd harmonic

$$I_{th} = \frac{4\sqrt{\pi}(E/e)\sigma_E \alpha_c \nu_\beta}{R Z_{t,\mathrm{eff}}} F$$

- Beam breakup simulations ongoing
- More aggressive optics design can require small apertures for lattice magnets and IDs, leading to larger impedance, which is bad for high charge operation
- Tradeoff between parameters under investigation

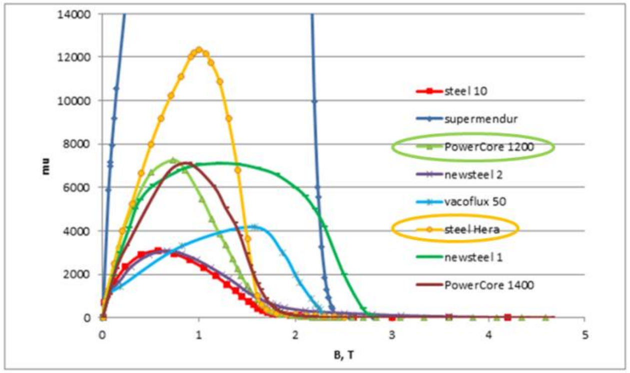
Technical concepts: Magnets, Girders

- Collaboration with Efremov Institute
  compact magnet design
  of high gradient magnets
- Contacts to industry (Thyssen Krupp)
  concerning magnet materials
- Building of prototypes QHG20
  with different materials (summer 2018)



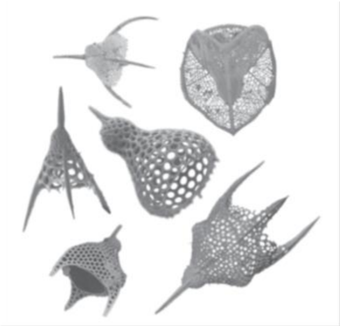
QHG20

HERA
steel



Parameters	Units	QHG20
Air gap	mm	**20**
Field gradient, G	T/m	**149,7**
Field quality at R= 0.6a		$3{,}7x10^{-4}$
Core length	mm	200
Number of turns per coil		56
Number of coils		4
Nominal current	A	200
Conductor	mm	6x6-d3.5
Total weight	kg	250

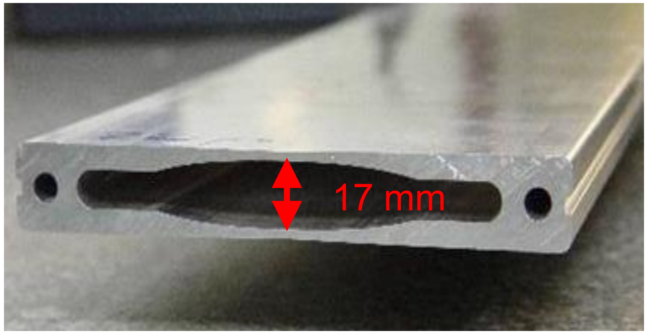
- Design study for Sextupole magnets
- presently factor 2.5 stronger as ESRF-EBS
- Collaboration with Alfred Wegener Institute: Bionic Lightweight Design of Girders



The AWI explores the principles that turn the exoskeletons (shells) of unicellular planktonic organisms into extremely light and stable constructions. (https://www.awi.de/en/science/special-groups/bionics.html)

Vacuum System

Experience at PETRA III:
80 m of damping wigglers
with NEG coated low gap chambers



Simulations have started based on MAX IV and ESRF-EBS vacuum systems

MAX IV chamber profile + NEG $(56\frac{l}{s\,m}$ at tube ∅ 15mm)

$<2 \cdot 10^{-12}\,\frac{\text{mbar}}{\text{mA}}$ for activated NEG (20 Ah)

$<5 \cdot 10^{-12}\,\frac{\text{mbar}}{\text{mA}}$ for activated NEG (1 Ah)

$\sim 1 \cdot 10^{-6}\,\frac{\text{mbar}}{\text{mA}}$ for unactivated NEG (1 Ah)

Multi-Step Simulation

- Ray-Tracing & 1-D transfer-Matrix pressure calculation (Mathematica, CALCVAC/VACLINE)
- Monte-Carlo simulations with SynRad and Molflow+ using 3-D geometries

Activities for PETRA IV:

- simulation of synchrotron radiation in small gap chambers including the reflectivity of the NEG material
- calculation of gas desorption
- pressure profiles

Plans for an experiment in 2018

- Install NEG-coated chambers in standard arc-section in PETRA III. Sputter coat standard dipole chambers
- *To study:*
- Self-activation by hitting chamber walls with photons possible?
- How fast this will provide sufficient pressure level ?
- Conditioning of vented section?

RF System

Two variants are considered
500 MHz or 100 MHz (option 125 MHz) System

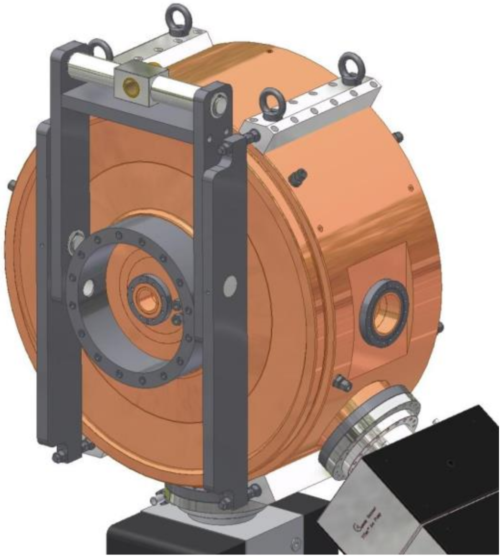
Cavities:

500 MHz single cells

100 MHz single cells, based on MAX IV design

Collaboration with Technische Universität Darmstadt, TEMF
Herbert De Gersem,
Wolfgang Ackermann

Cavity parameters,
HOM calculations,
etc.



Outlook

- Design study ongoing. Reference lattice based on H7BA in place
- A simpler and more robust 6BA solution exploiting the no-undulator arcs exists, but has to be worked out in more detail
- Lattice type decision and CDR moved to 2019. Whitepaper based on reference lattice 2018
- Projected baseline parameters: 100 or 200 mA current, 15pm/5pm emittances, ~0.1% energy spread, pulse duration 30-100 ps (FWHM)
- Possibility of timing/hybrid modes (40 or 80 bunches) is open, need to further investigate bunch dynamics with high charge and 3rd harmonic cavity (instability thresholds, feedback performance)
- Tolerance studies and commissioning simulations ongoing
- R&D on technical subsystems launched, personnel hired, CDR preparation in full swing

Thank you for attention