Lattice studies for PETRA-IV

I. Agapov for the Petra IV study group
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HELMHOLTZ GEMEINSCHAFT

DESY

Content

- Introduction / Machine performance goals for Petra upgrade
- Lattice studies
  - Scaled ESRF-type lattice
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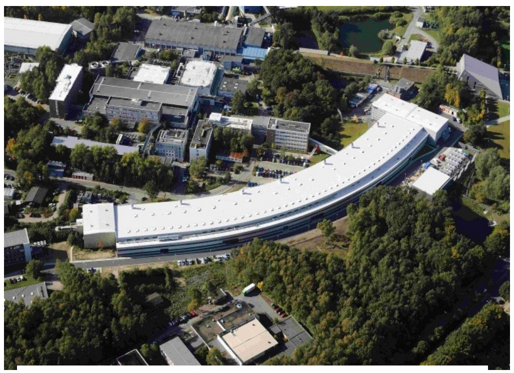
- Outlook

Petra III

> In operation from 2009; 1 nm emittance

> Extensions commissioned 2015. P64+P65 running, new beamlines in preparation (1.2 nm emittance)



High β_x

Low β_x

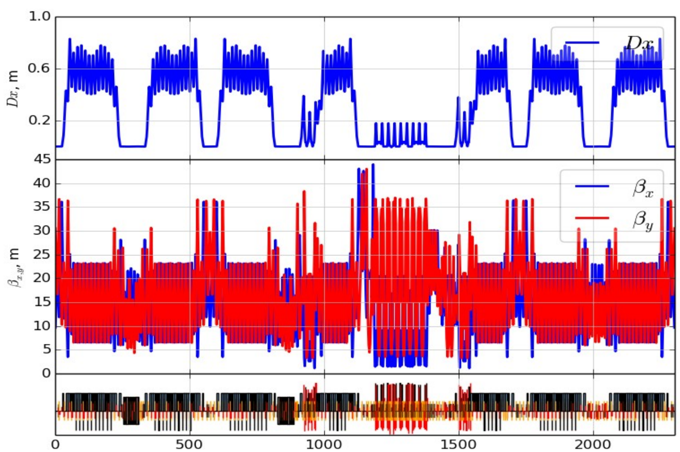
High beta: β_x = 20 m β_y = 4 m

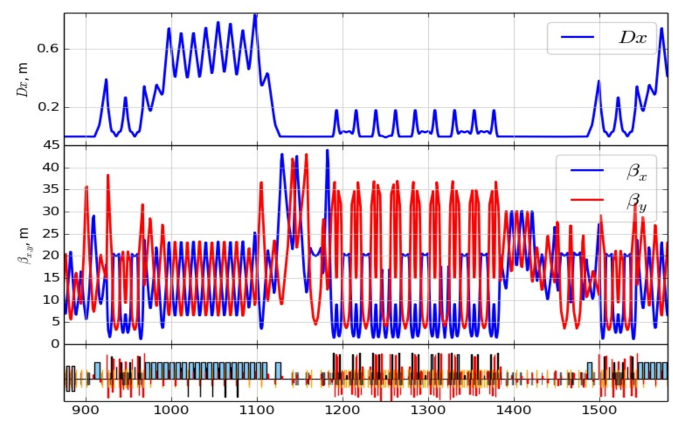
Low beta : β_x = 1.4 m β_y = 4 m

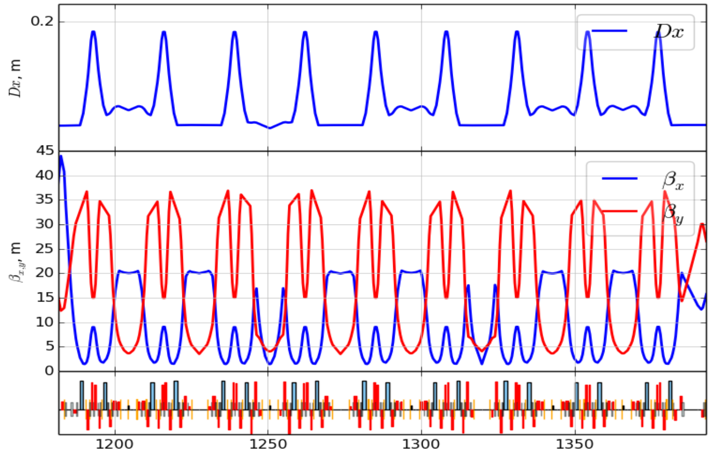
Number	ID Type	Energy range (keV)	Cell
P01	10 m U32 (2 x 5 m)	5 – 40	
P02	2 m U23	20 – 100	1
P03	2 m U29	8 – 25	1
P04	4 m U65 (APPLE)	0.2 – 3.0	2
P05	2 m U29	8 – 50	3
P06	2 m U32	2.4 – 50	3
P07 (option low beta)	4 m U19 (IV) (pres. 2m)	50 – 300	4
P08	2 m U29	5.4 – 30	5
P09	2 m U32	2.4 – 50	5
P10	5 m U29	4 – 25	6
P11	2 m U32	8 – 35	7
P12	2 m U29	4 - 20	7
P13	2 m U29	5 – 35	8
P14	2 m U29	5 - 35	8

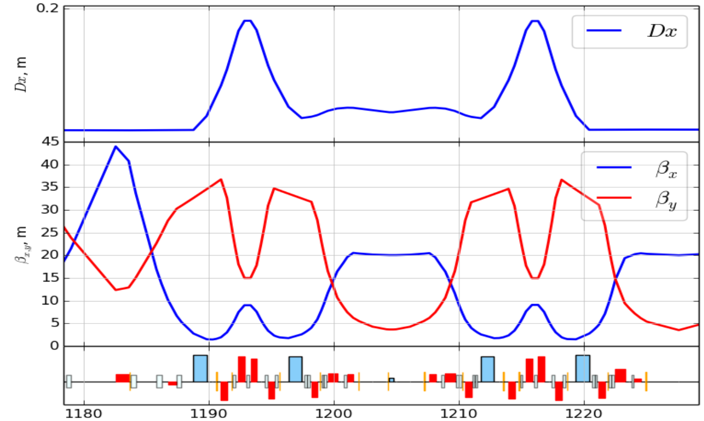
Petra III Optics

- FODO in arcs + 8x DBA cells von Laue + 4x DBA extensions. 1.2 nm emittance
- With present optics, about 2x reduction in emittance could be possible (different FODO phase advance) at the usual cost of DA (incompatible with present injection)



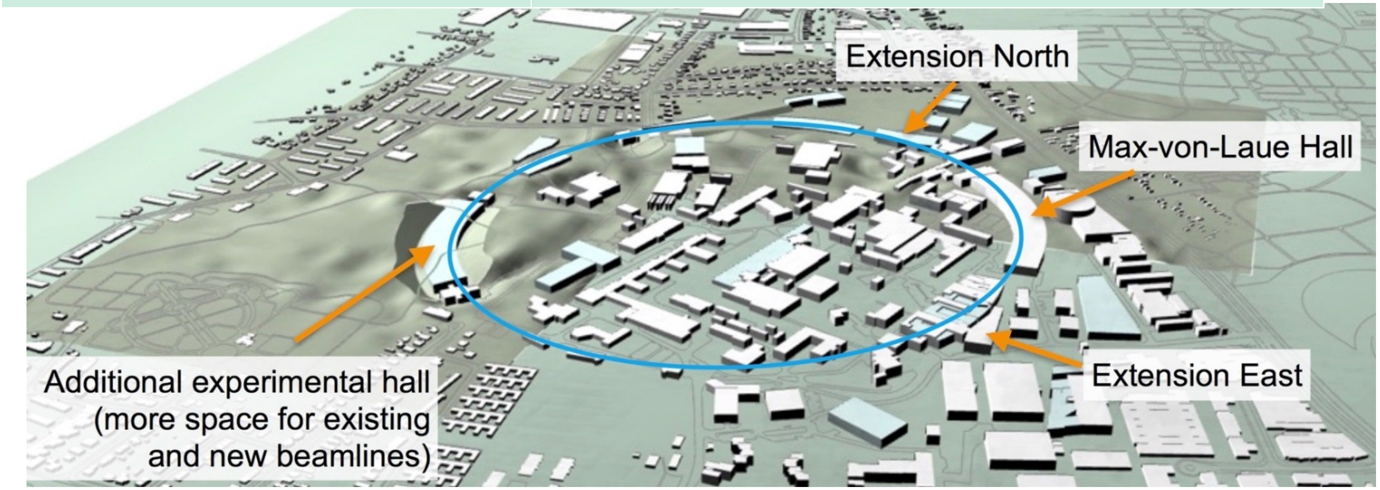






Petra upgrade – Petra IV – starting design studies

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	
Num. unndulators/BL	~ 30	



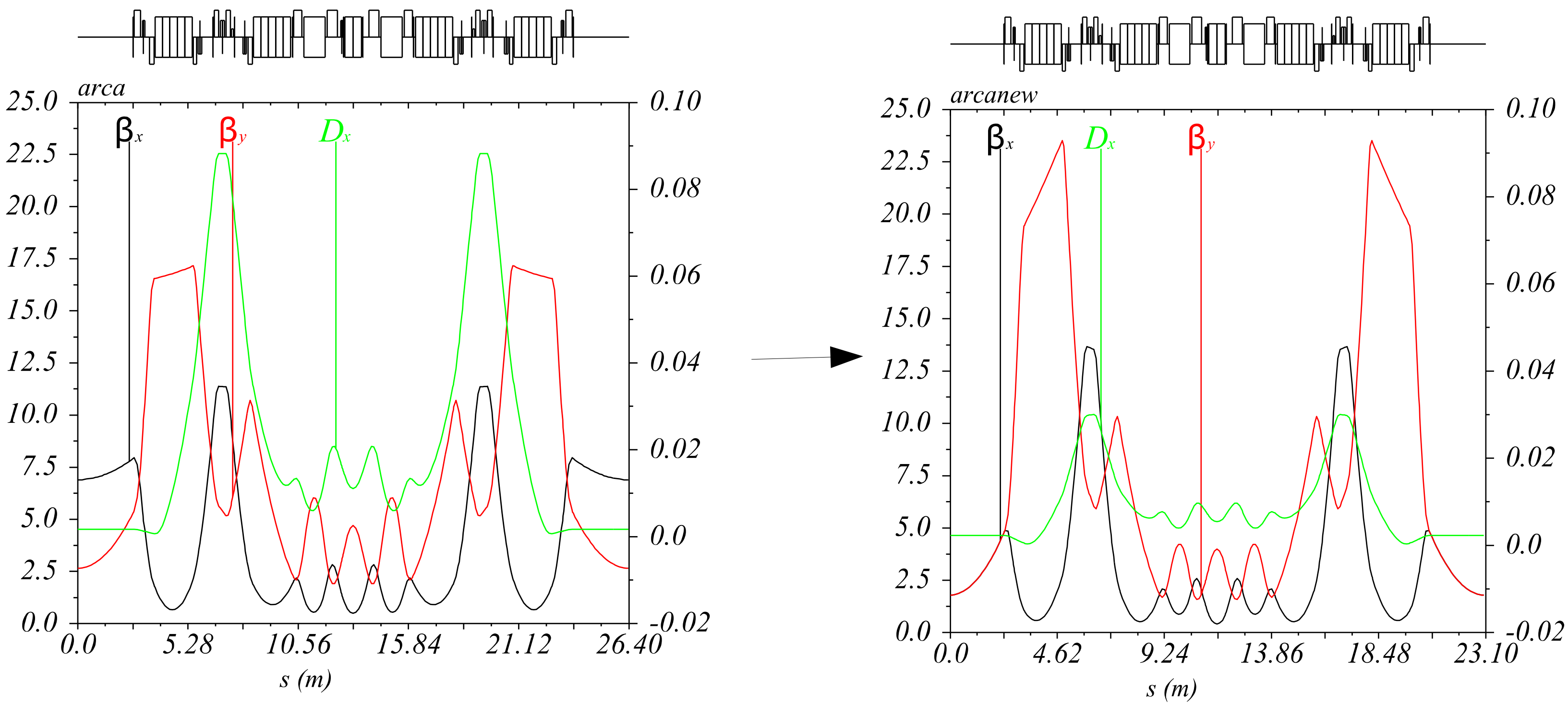
6 vs 5 GeV
1.44x larger ε
2x less IBS

Lattice issues

- MBA lattices are used in new generation machines (ESRF, MAX IV, APS,...).
- The 1 nm (current Petra III) emittance will no longer hold the record
- To keep up with these developments DESY would need an upgrade to below 50 pm (10-20 pm)
- MBA (7BA) lattice is state of the art for synchrotrons. It is excellent for L~1000m machines (~100 pm) and gives < 10 pm emittances when scaled to Petra size ~2000m (Petra, Pep-X)
- However the dynamic aperture becomes worse (smaller dispersion, stronger sextupoles), leading to several problems, most notably need for new injector
- We could use unique features of Petra (small number of insertions-to-circumference ratio) to exploit other schemes

ESRF-type cell, scaled to Petra III dimensions

- Length 26.374 → 23.013 m. Bending angle 11.25° → 5°
- Smaller dispersion, leads to worse DA

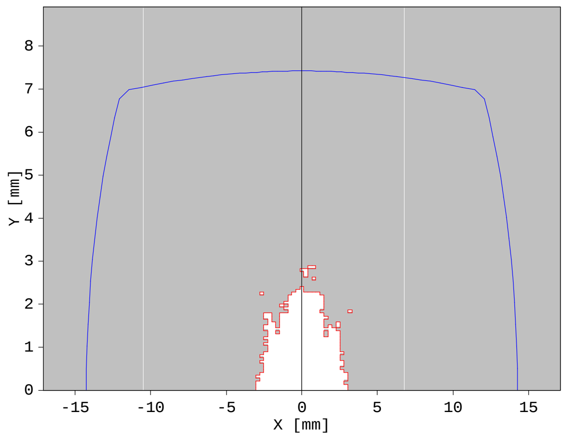


Scaled ESRF-type cell

- Direct scaling of the ESRF-type cell leads to a lattice with 7-10 pm @ 5GeV emittance but small DA due to the need of much stronger sextupoles
- Momentum acceptance good (4% - 6%)
- More optimization needed to get better performance estimate

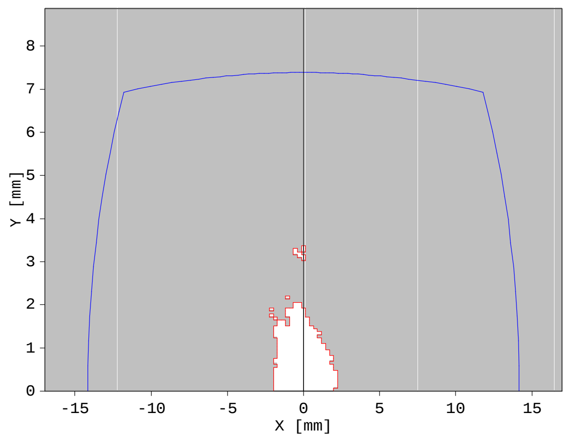
Cell DA

ε_x = 8 pm·rad, D_x = 1.2 mm @ ID
A_x = (3 mm)² / 6.9 m = 1.3 mm·mrad
A_y = (2.5 mm)² / 2.24 m = 2.8 mm·mrad



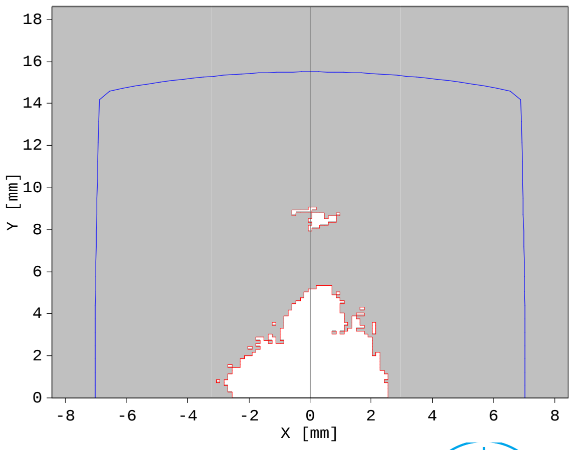
Cell DA

ε_x = 9 pm·rad, D_x = 0 mm @ ID
A_x = (2 mm)² / 9.1 m = 0.44 mm·mrad
A_y = (2 mm)² / 2.25 m = 1.8 mm·mrad



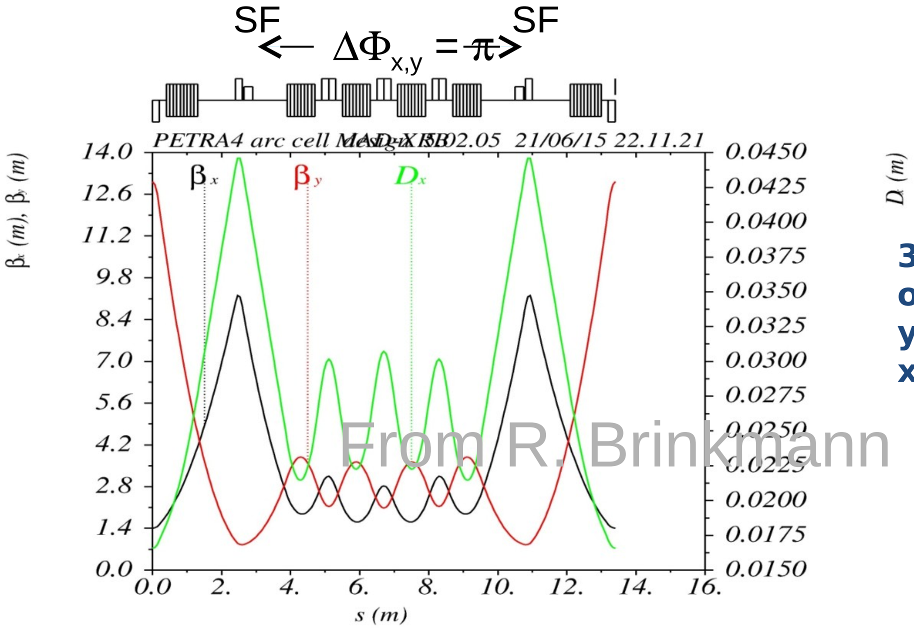
Ring DA (+ straights)

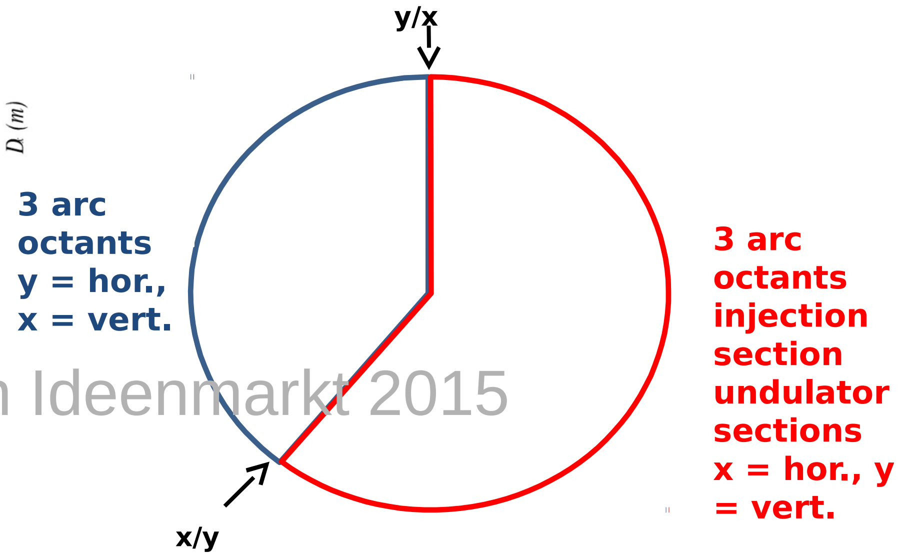
ε_x = 9 pm·rad, D_x = 0 mm @ ID
A_x = (2.5 mm)² / 21.4 m = 0.29 mm·mrad
A_y = (5 mm)² / 20.9 m = 1.2 mm·mrad



Phase space exchange solution

- Similar to Moebius scheme, with two phase space exchanges in the rings
- Correcting $\xi_x+\xi_y$ with few (e.g. one) sextupole families
- Allows non-interleaved sextupole scheme with π/π phase advance: large DA
- Single cell performance appeared promising. Started evaluating possibility of full lattice





From R. Brinkmann Ideenmarkt 2015

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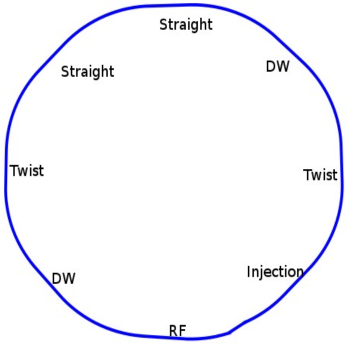
Optics v0

- Simple 'ring' to evaluate the concept
- 62 cells in north and 66 in south to simulate some asymmetry in chromaticity
- All straights same length
- Two sextupole families (for south and north)
- Straight sections used for tune matching
- Twist realized with 9 skew quadrupoles
- Geometry not directly realizable for Petra but reflects beam dynamics properties
- 17pm round beam emittance

Lattice:

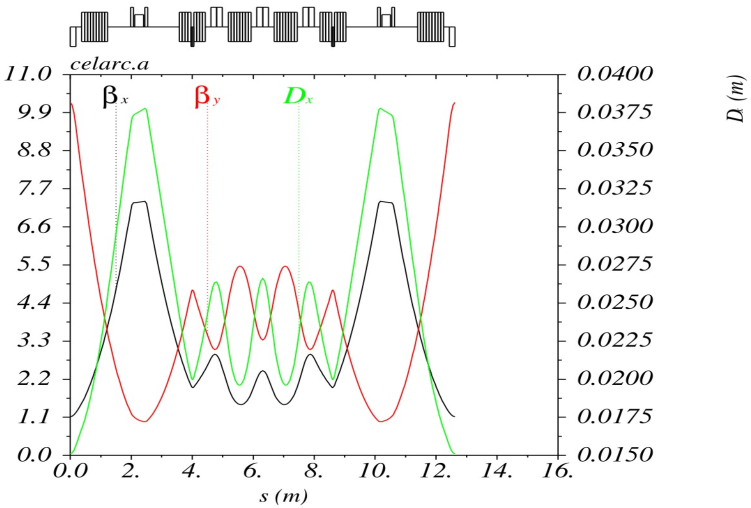
https://stash.desy.de/projects/MPET/repos/p4/browse/P4-T/p4_t.mad revision 7 Apr 2016

Schematic

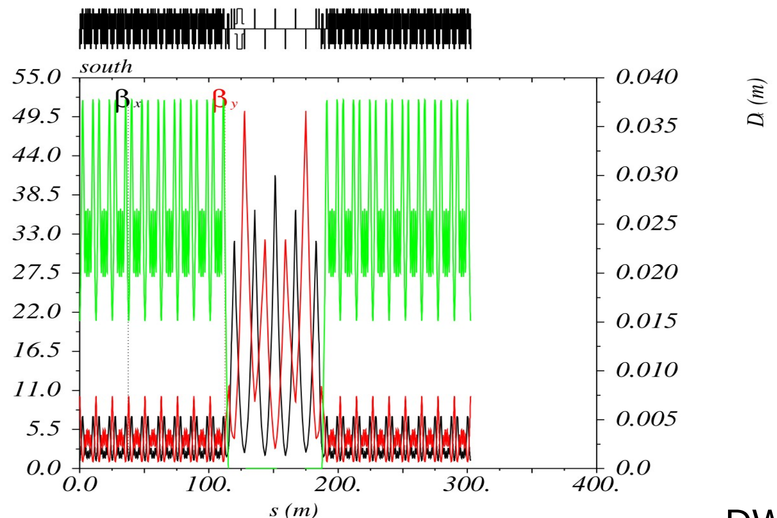


Lattice

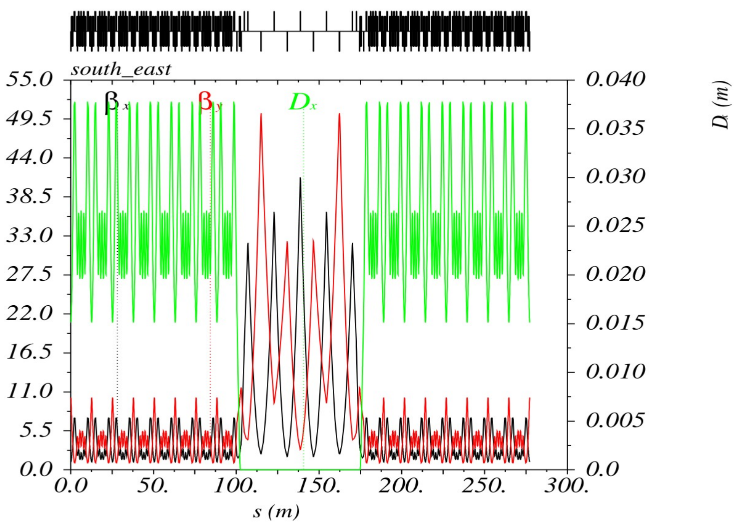
Arc cells, 2 sextupole families in north and south



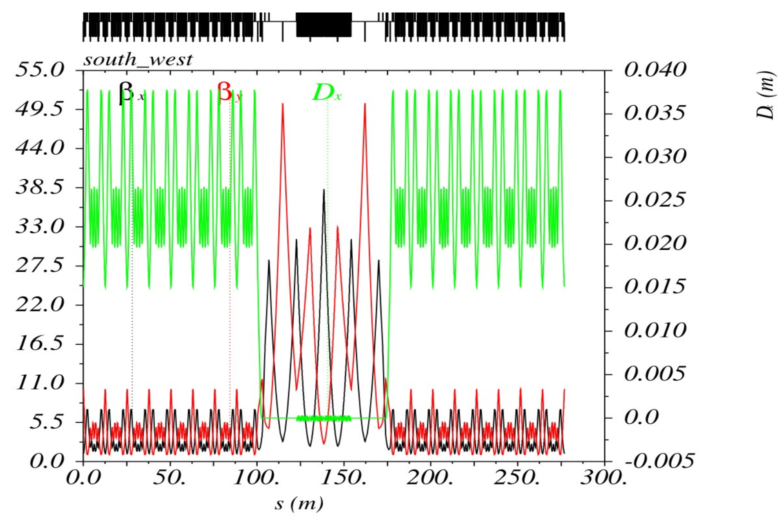
RF section with 1x7m RF module 100/500 MHz



Straight section and two half arcs (injection)



DWs



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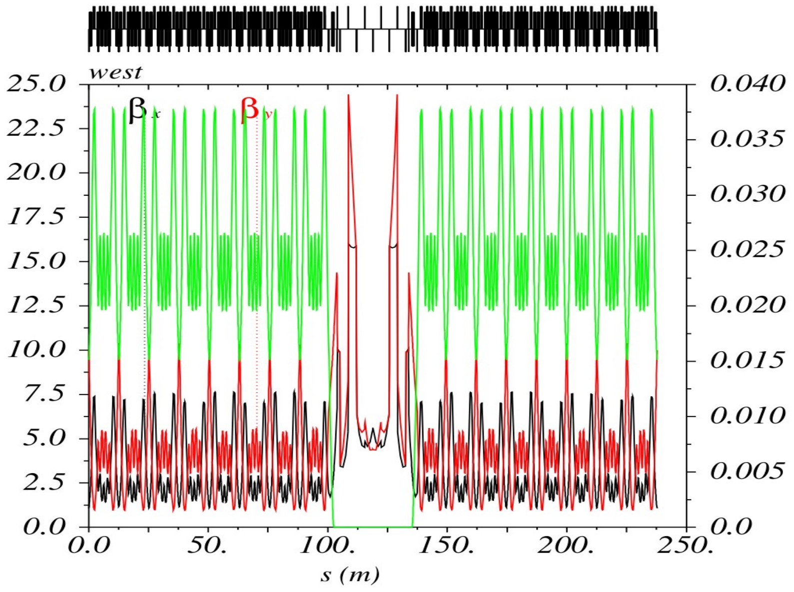
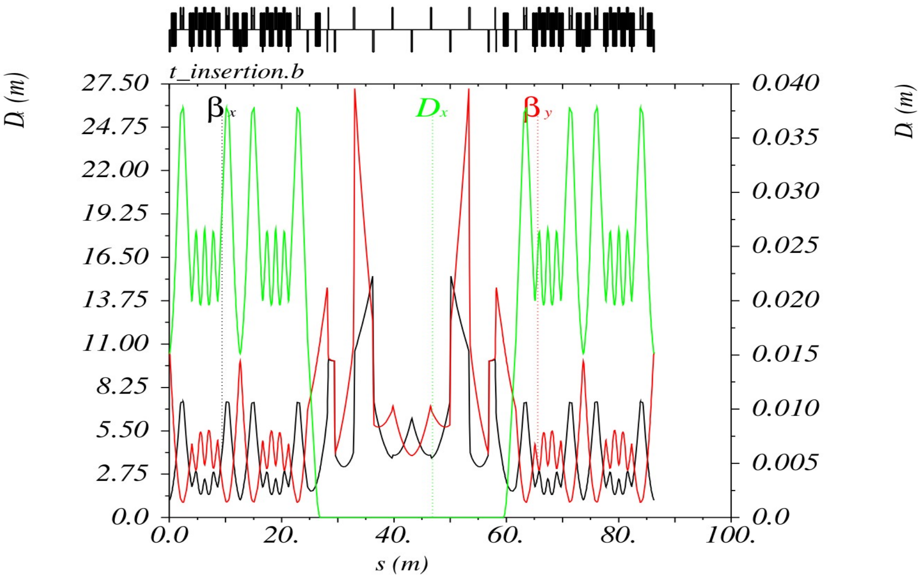
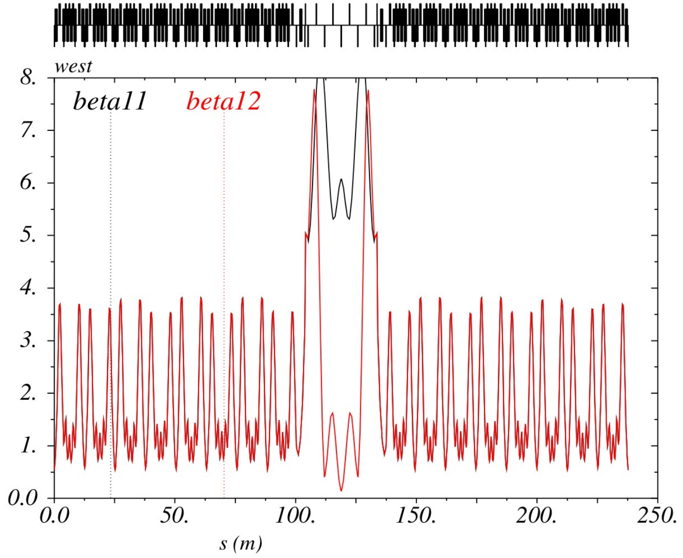
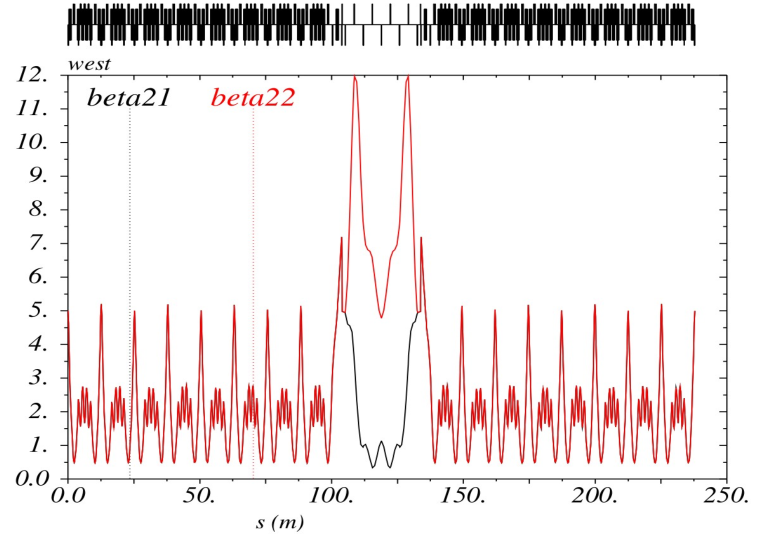
Phase space exchange section (twist)



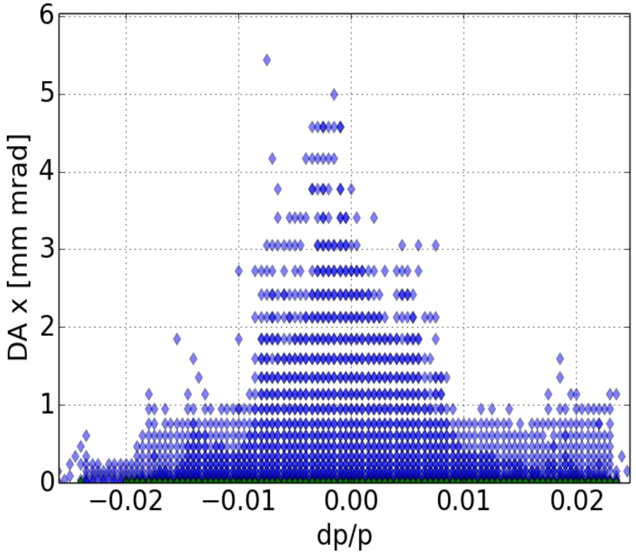




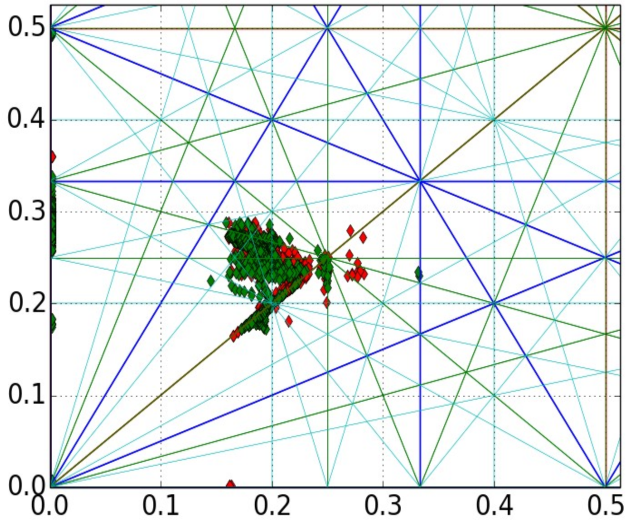


Dynamic Aperture

- Since 1 unit of sextupole strength (20cm length) contributes 10 units to ring chromaticity. Sextupole strength should be defined to a precision better that 0.1 to set small positive chromaticity
- Sextupole strength sf1/sf2 ms = 60/63
- Tracking with 100MHz RF

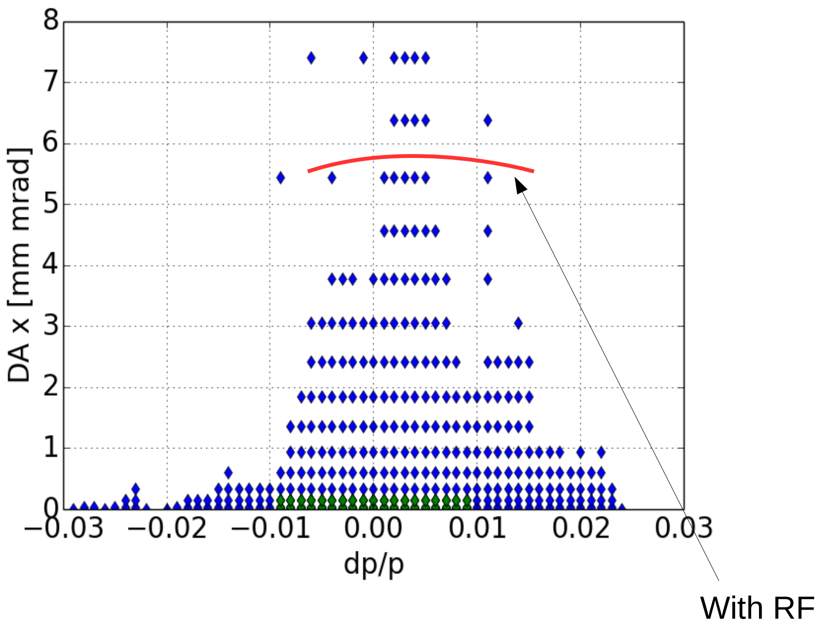


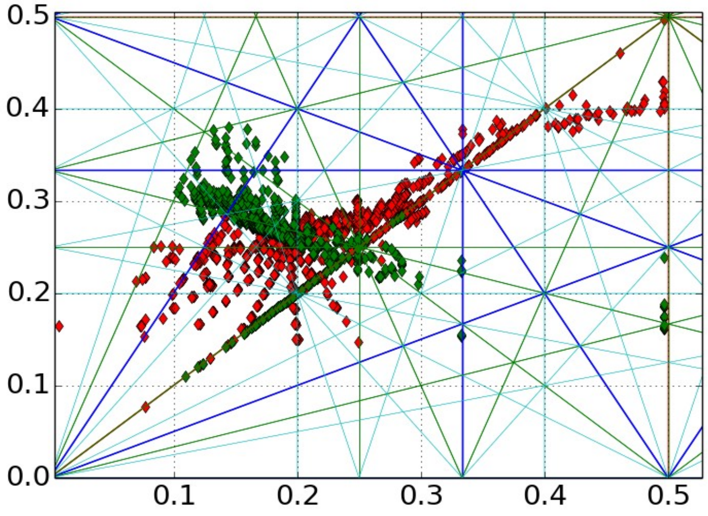
±2.4% energy acceptance

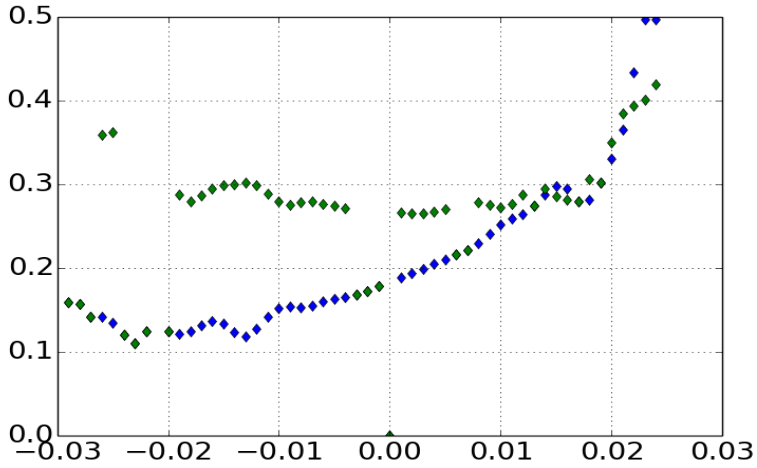


Tune footprint of stable particles (tracking data FFT, madx).
Mesh:
-3mm < x0 < 3mm (at 1m beta); y0=0
Red with positive energy offset, green with negative

Effect of overcompensated chromaticity



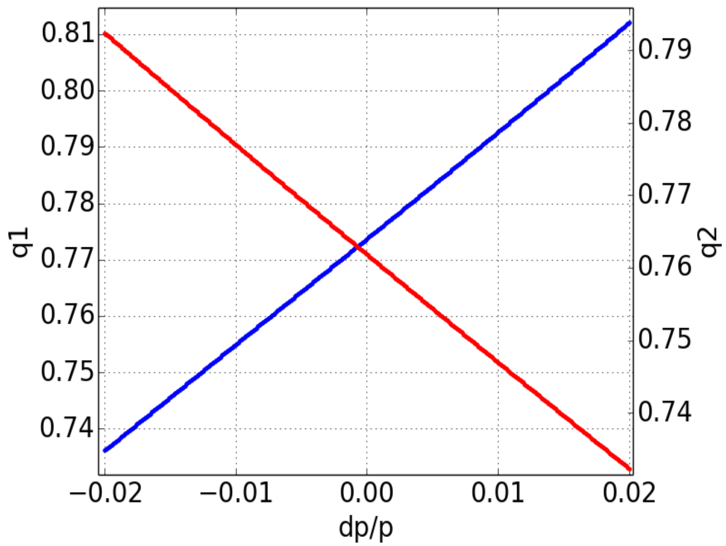


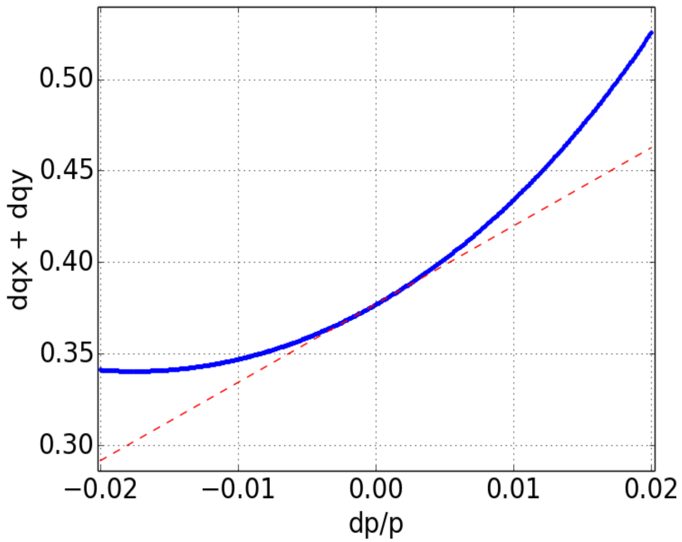


- With larger chromaticity (e.g. +5/+0) momentum acceptance is somewhat reduced, but tolerance to non-zero chromaticity seems ok
- The effect of RF is to reduce the DA for very large offsets, but little effect on energy acceptance

Nonlinear chromaticity

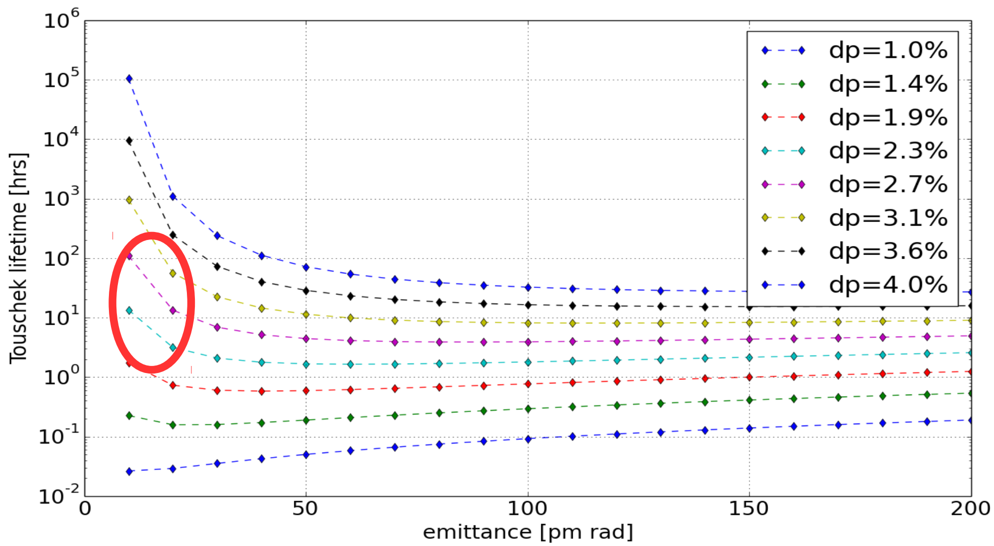
- One cell has 2nd order sum chromaticity +4 and 3rd order +150. The higher order terms for 128 cells take off around 2% energy offset 2%-energy tune spread would be 0.16 (roughly 64x cell sum) – roughly in agreement, slight overestimate
- There is still space to improve higher-order lattice chromaticities with straights phase advances





Dynamic aperture requirement

- Transverse DA mostly determined by injection requirements – need more than *3-4 mm mrad to have e.g. 20mm aperture for ε = 4 mm mrad and β=100 m*
- Energy acceptance requirements mostly determined by Touschek lifetime
- Touschek lifetime for 1 cm bunch length, 10^{-3} e-spread and 1.6 nC charge (10^{10} electrons/bunch: e.g. with 100MHz RF, 760 bunches 160mA) 6 GeV round beam one cell (Piwinski DESY 98-179)
- In the 10-20 pm range momentum acceptance of more than 2% desirable for a few hrs lifetime
- 2.5% energy acceptance for bare lattice (no IDs, w/o misalignment) should be acceptable



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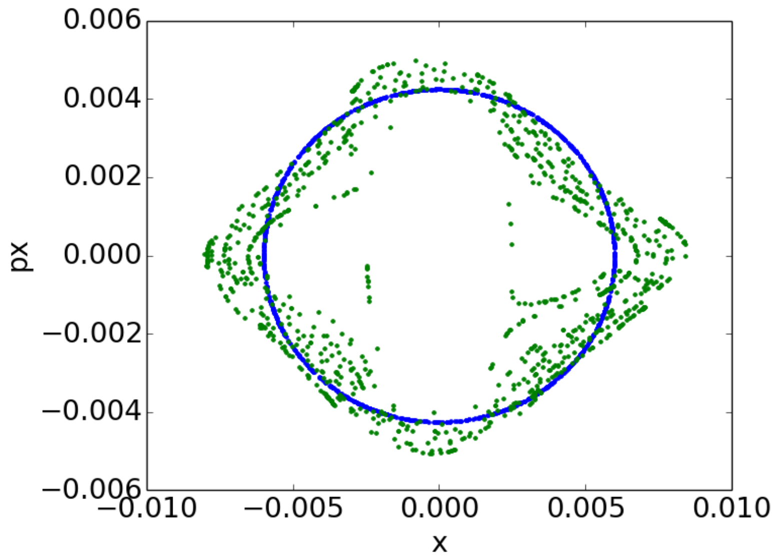
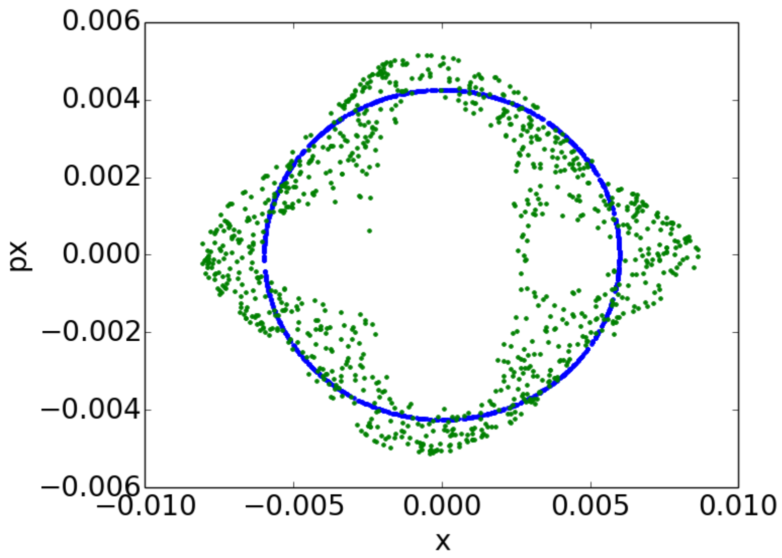
DA details

- For all cases stable region in phase space is not elliptic.
- some care should be taken when translating DA figures into the amplitudes of sustainable excitations, depending on the direction in phase space
- In picture : 1 cell on-momentum



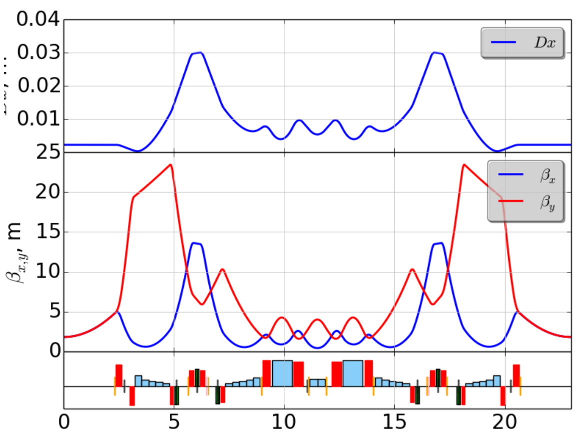
green: after 100 cell-turns
blue: initial

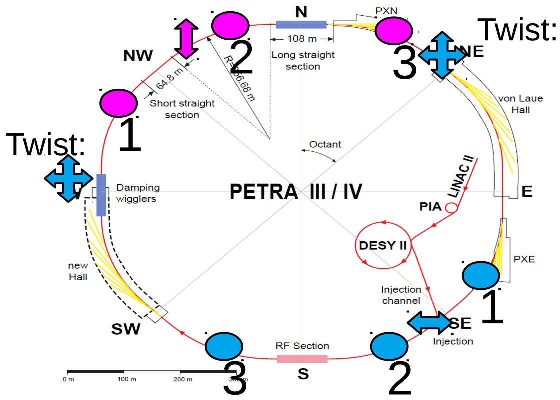


10000 cell-turns

Optics v1 (with undulator insertions)

- With rescaled ESRF cell (9 pm emittance, 5 GeV), rematched to 0 dispersion, for the undulator insertions
- 2 experimental halls (von Laue + 1 new). Current extensions not yet included.
- Emittance 19/18 pm (5 GeV, no DW). Almost round beam due to small contribution of the undulator cells.
- Issues:
  - Undulator influence on emittance not accounted for – would further reduce the emittance and squeeze the beam: could be compensated by e.g. having longer vertical Dws
  - North hall problem: a) vertical IDs b) vertical DWs + 2 arcs per vertical mode (can lead to large increase of sextupole strength)





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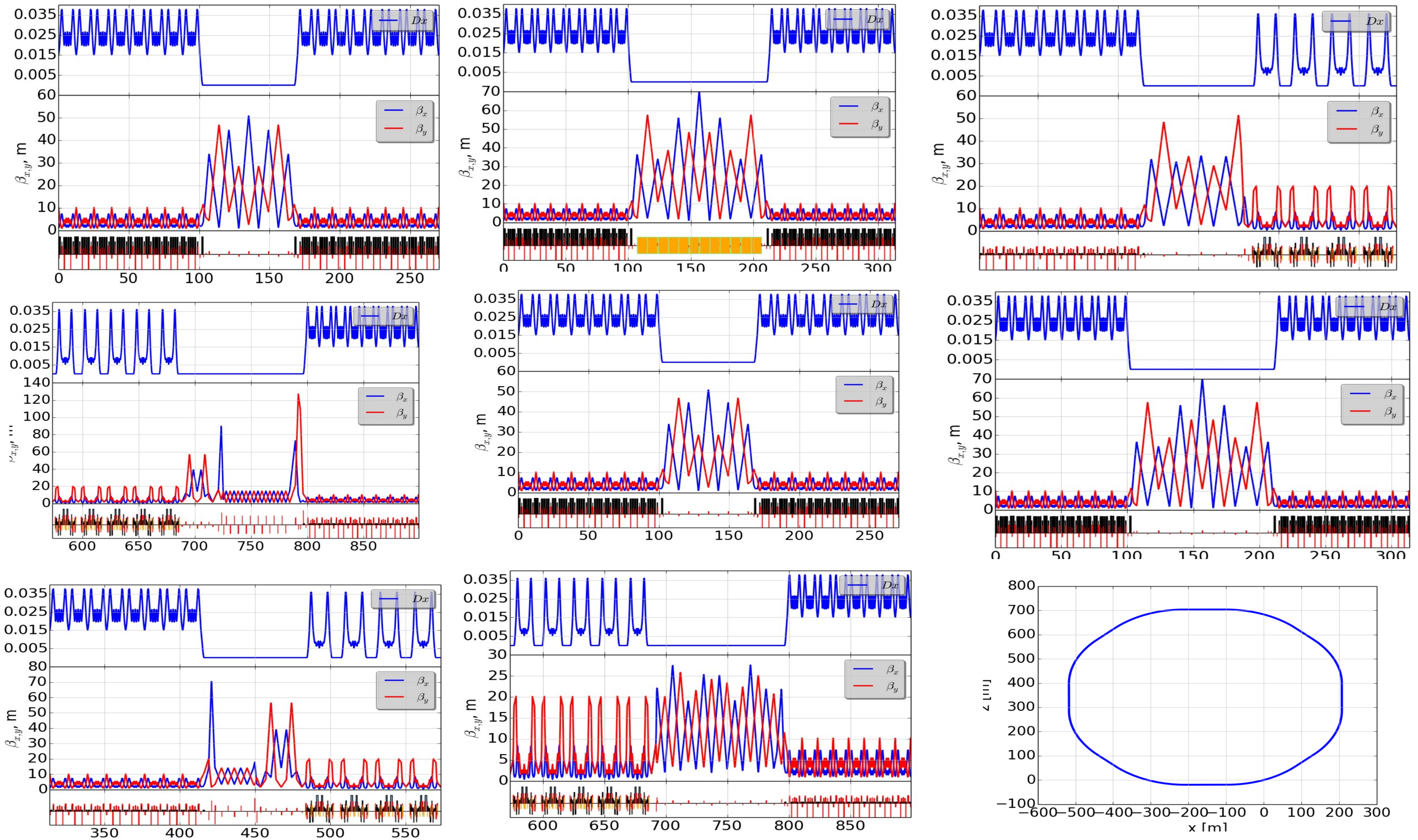
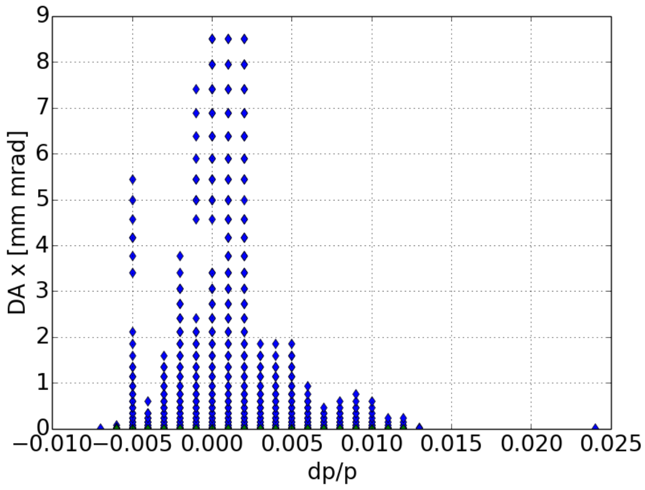
Optics v1 (with undulator insertions)

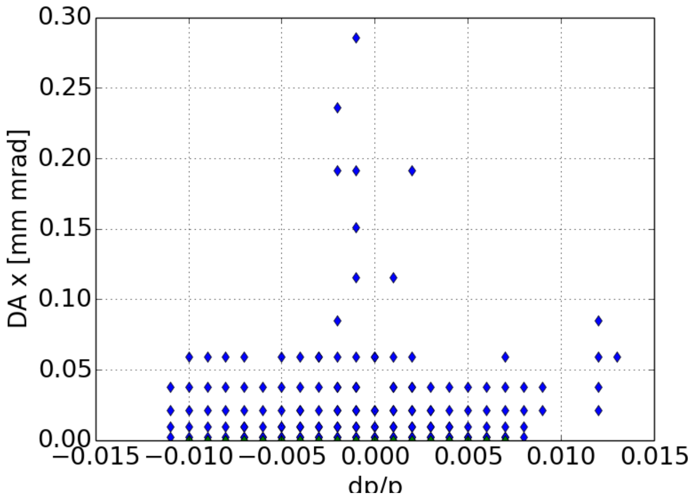


Optics v1 (with undulator insertions)

- Option 1: sextupoles in undulator cell off, compensation in the arcs. Stronger sextupoles needed (m2=100), DA worse than for the v0 lattice
- Option 2: sextupoles in undulator cell on. Global DA limited by the cell DA (0.4 mm mrad) in hor. Direction and by the arc DA in momentum
- With 75% of the ring taken by arcs, an undulator cell emittance much smaller than the arc emittance does not pay off (kind of Amdahl's law)
- Mixing cell types in such way not optimal



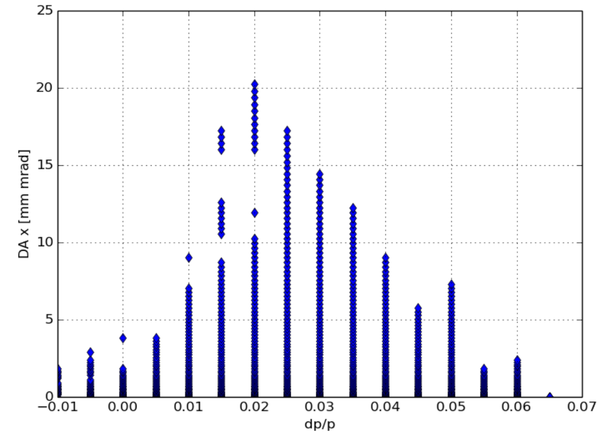
Undulator Sextupoles off

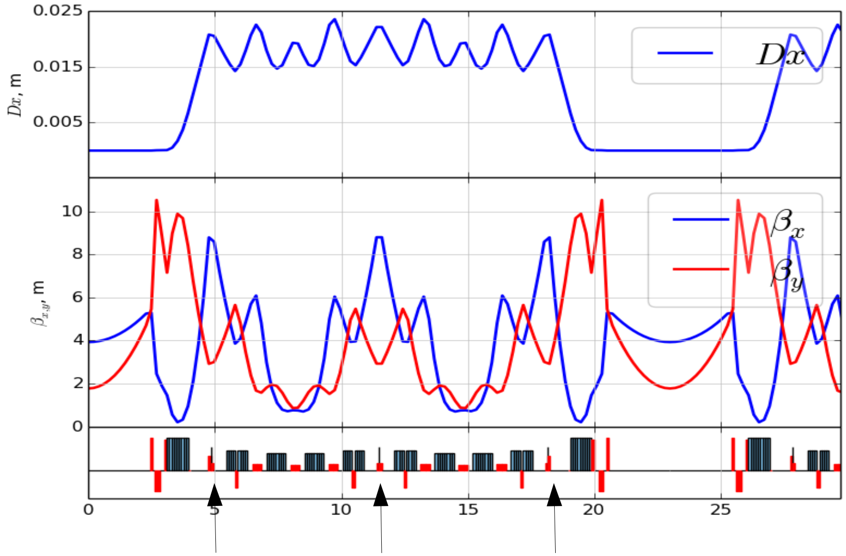


Undulator Sextupoles on

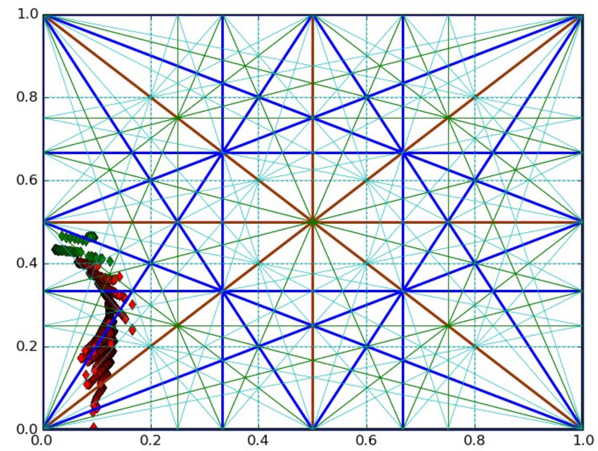
Non-interleaved undulator cell

- An undulator cell with non-interleaved sextupole scheme
- Triplet at cell end still 'dummy' (won't fit mechanically) – doublet is more restricting wrt. insertion length and possible beta functions – still work in progress
- Good cell DA (but asymmetric)
- 17pm (5GeV) – lower than the arc cell used above



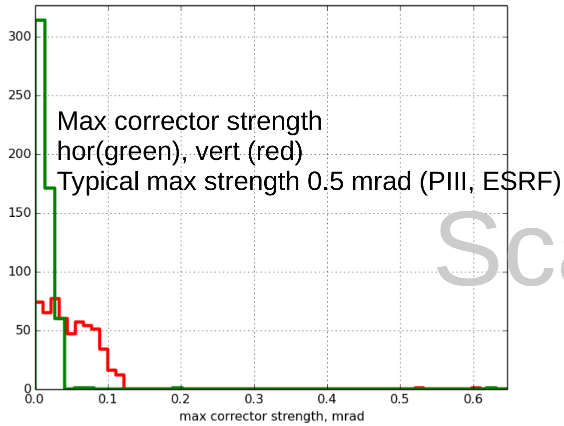


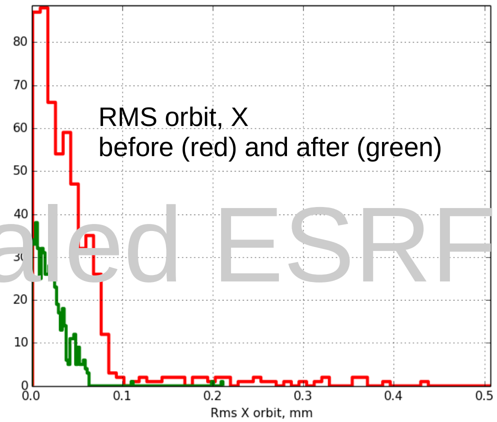
3 sextupoles per cell with 180° phase advance in both planes

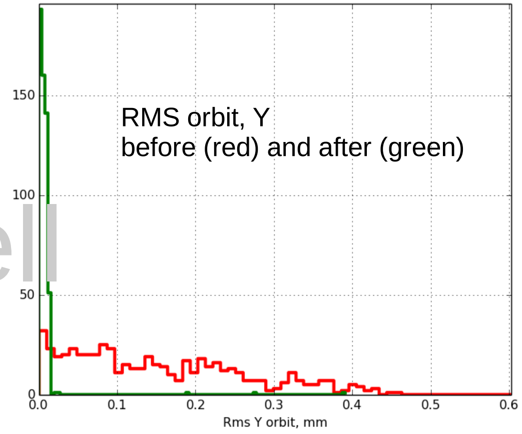


Tolerances

- Alignment error and field quality specs in progress
- Alignment is expected to be an issue in any type of low-emittance lattice (whenever DA is a problem)
- Petra III (TDR) – 250 μm old octants, 100 μm new octant alignment (Table 3.2.15)
- ESRF – 50 μm alignment (at more sensitive places)
- Scaled to Petra III radius, the ESRF cell becomes even more sensitive
- Procedure needed to evaluate alignment/field quality requirements: alignment + BPM resolution spec → orbit and optics correction → performance parameters (DA, etc.)
- (Quick) alignment and orbit correction simulation for scaled ESRF cell (64xcell, no straights) All quadrupoles and sextupoles misaligned, Gaussian statistics with Δx=Δy=25 μm rms, 2σ cut 45% cases – no closed orbit (1000 runs)







Scaled ESRF cell

Tolerances

- Some operating procedures (optics correction etc) should be part of the tolerance investigation procedure
- Orbit/optics correction etc. for coupled lattice still an open issue.
  - collaboration with CERN madx team contemplated
  - Interface design and extension of present operation tools (e.g. present optics toolbox) could be considered
- However the single cell (i.e. a 128x'twisted cell' machine) already shows better tolerances compared to scaled ESRF. Similar probability of non-existence of close orbits (to ESRF Δx=Δy=85 μm rms) is for a Δx=Δy=85 μm rms, 2σ cut misalignment
- Δx=Δy=70 μm rms, 2σ has close to 100% (within limited statistics) closed orbit existence
- This is consistent with following rough orbit perturbation and DA scaling. If *i* is the observation and *s* the kick (misalignment) location then

$$\Delta y_i \propto \sqrt{\beta_s \beta_i}\theta_s \qquad \Delta y_i \propto \sqrt{\beta_i DA} \qquad \theta_s \propto \sqrt{DA/\beta_s}$$

- Twisted lattice (v1, not optimized for DA in any sense) with ESRF-type undulator cell/sextupoles off has close to 100% probability of closed orbit existence for Δx=Δy=30 μm rms, 2σ

Conclusion/outlook

- Petra upgrade is necessary to strengthen DESY's leadership in synchrotron radiation
- Conventional MBA (ESRF-type) and phase space exchange (twisted) lattices are considered for the upgrade
- Non-interleaved undulator cell design is in progress for the twisted lattice
- Alignment error and field quality specs are in progress (both lattices)
- More options (damping wigglers, longitudinal gradient dipole, antibends etc., advanced optimization software) to be exploited to try to push the emittance down to 10/10pm (5 GeV), which is lucrative from the physics perspective (1Å diffraction limit) for the phase space exchange lattice
- 7BA ESRF-type lattice could further be optimized for better DA at the cost of emittance
- While more optimization is needed to evaluate expected lattice performance, it is our present understanding that the twisted lattice has better stability properties at the cost of a larger emittance and worse layout flexibility, compared to conventional (7BA, ESRF-type) lattice