Recent Studies of Injection System at PETRA III transport line and PETRA IV upgrade

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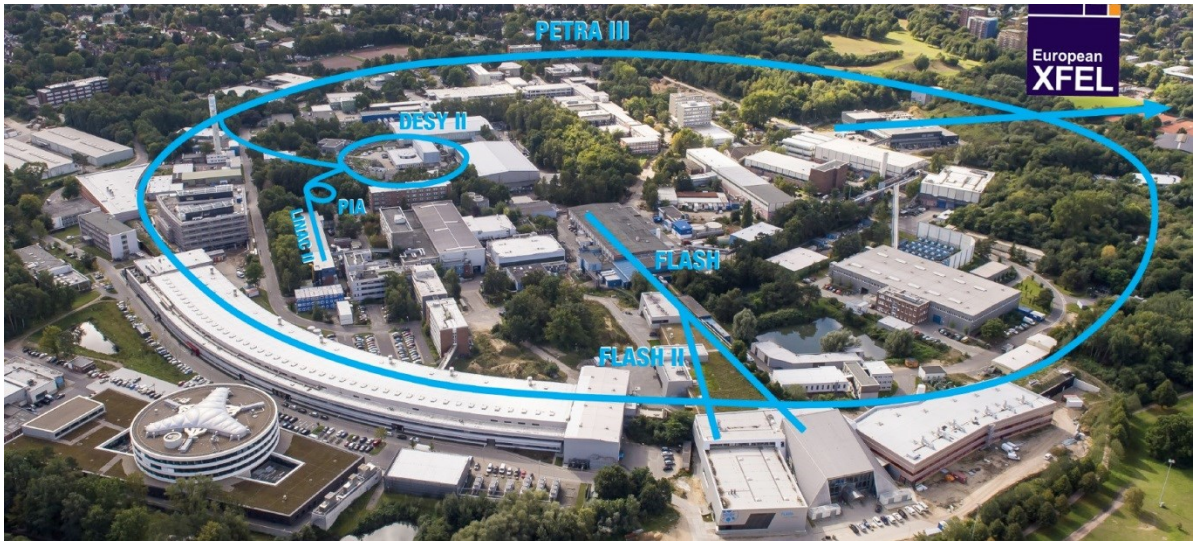
Topical Workshop on Injection and Injection Systems
28-30.08.2017, Berlin (Germany)

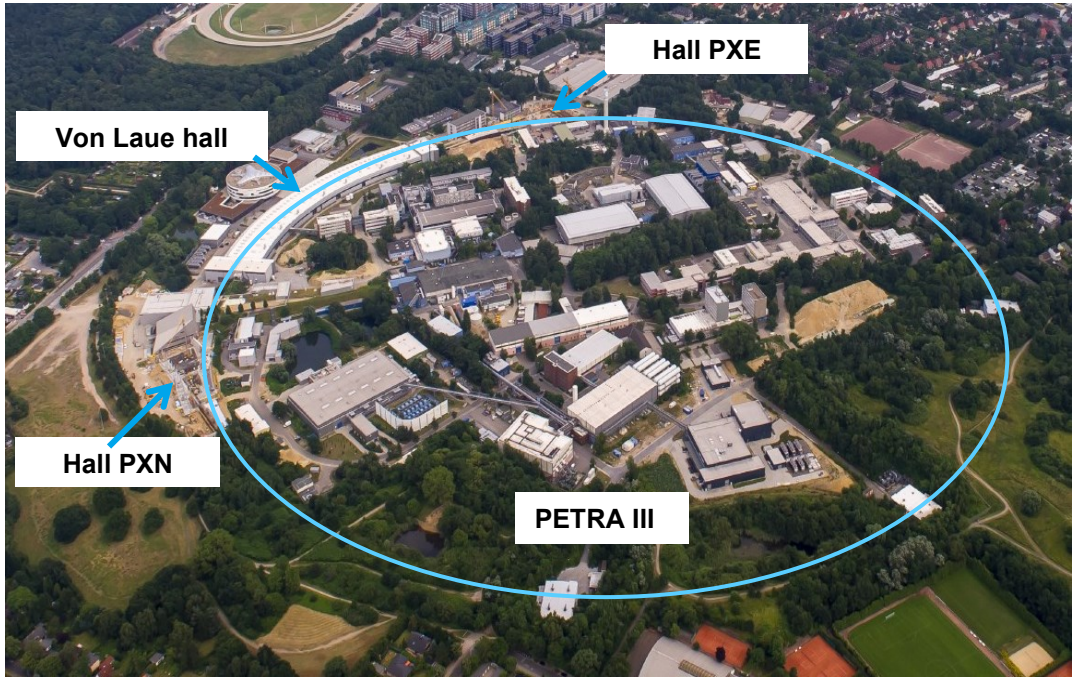


Outline

- Overview of PETRA III
  - Storage ring
  - Injection system
- Upgrade strategy of PETRA IV
- Recent studies
  - Measurement of emittance and optical functions on E-Weg
  - Reduce the emittance of DESY II
    - Increase the focusing and reduce the energy
    - Design a new PETRA IV-booster
- Conclusions

Overview of PETRA III

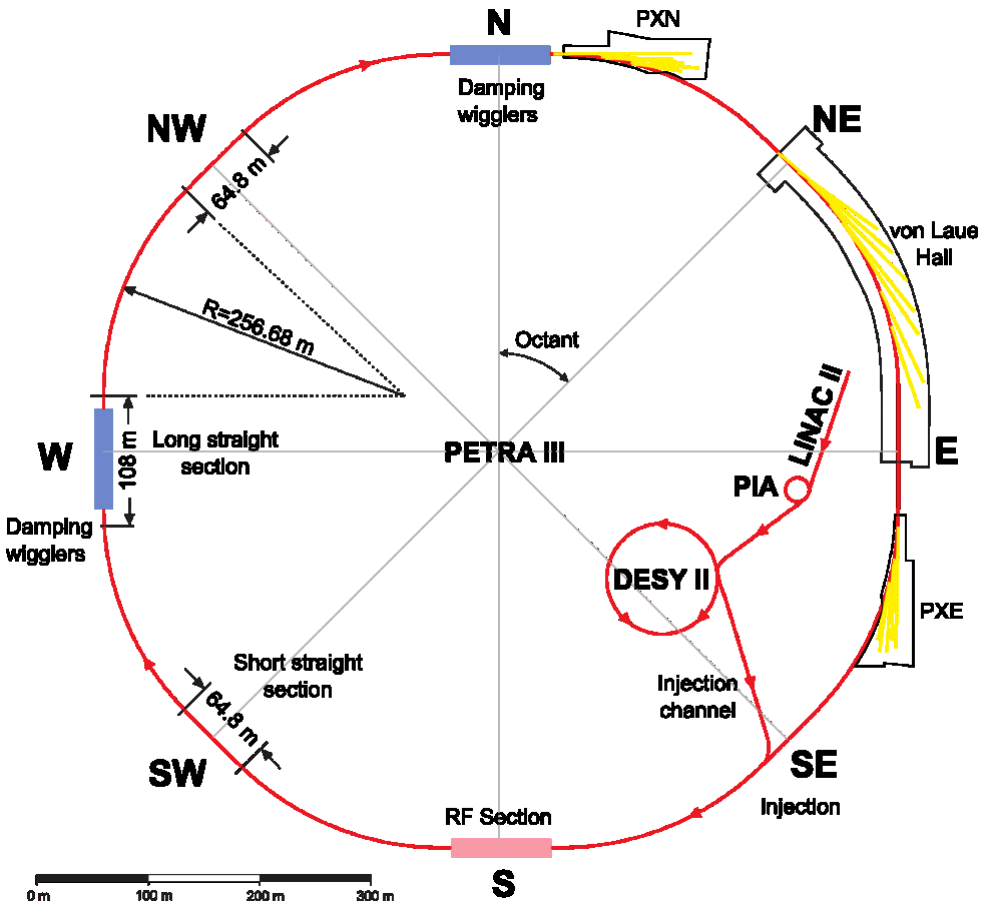
Parameter	Value
Energy	6 GeV
Current	100 mA, Top-Up
Hor. Emittance	1.2 nm·rad
Ver. Emittance	12 pm·rad
Bunches	40, 960
Circumference	2304 m
Harmonic number	3840
RF Voltage	20 MV
Energy loss/Turn	6.1 MeV



- PETRA I: $e^{\pm}$ collider (1978-1986), PETRA II: pre-accelerator for HERA (1990-2007)
- PETRA III: commissioned 2009; in operation for users since middle of 2010
- Max von Laue hall: 14 beam lines, PXE, PXN (2014): 7+5 beamlines -> **26 beam lines in total**

Layout of PETRA III

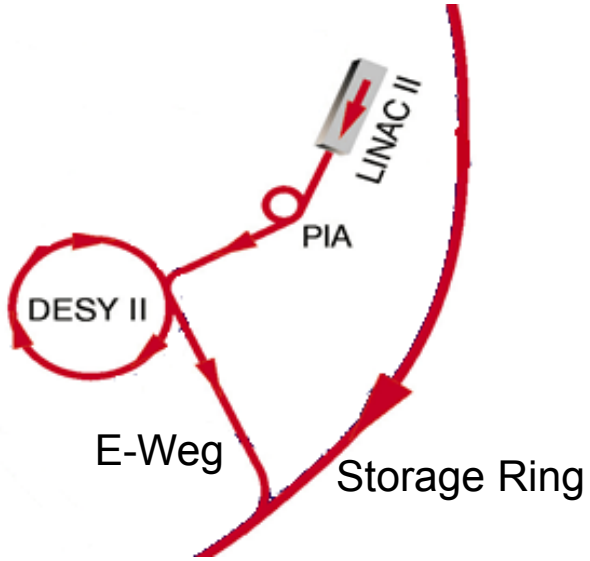
- Octagonal shape, circumference 2304 m, emittance 1.2 nm·rad
- **Eight Arcs** (45°), 201.6 m long
  - 5 pure FODO-arcs
  - 2 modified FODO arcs with 2 DBA-like cells at the beginning (PXN, PXE)
  - One arc build from 9 DBA cells L_{cell} = 23 m, 5 m ID straight sections
- **Eight straight sections**
  - 4 long straights N,S,E,W (108 m) 20 damping wigglers in N and W; RF cavities in S (20 MV)
  - 4 short straights NW,NE,SE,SW (64.8 m)
- **Beamlines**
  - Max von-Laue Hall:14; PXN:5; PXE: 7



Layout of PETRA III Injection System

➢ Linac II

S-Band Linac
e- → e+ converter (presently not used)
two guns (bombarder type + triode)



➢ PIA

accumulator ring (originally designed for e+ operation)

➢ DESY II

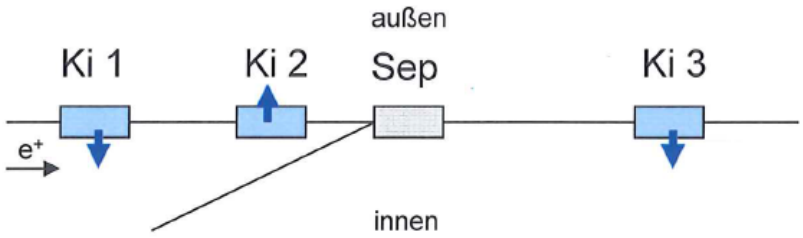
450 MeV → 6 GeV (max. 7 GeV)
Emittance (6 GeV, PETRA III) x/y **~ 350/15 nm.rad**
Intensity (# particles): max. 2 x 10^{10}, typical 1 x 10^{10}

➢ E-Weg: transport line DESY II -> PETRA III

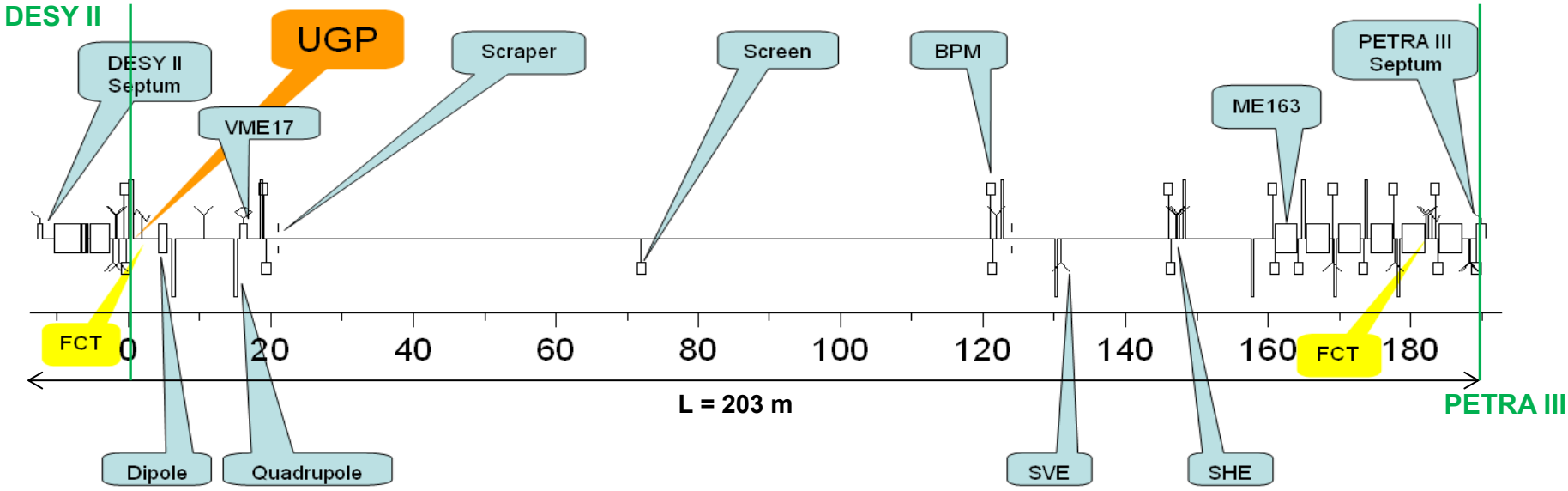
L = 203 m

➢ Storage Ring

3 kickers (deflection= 2.88 mrad, L= 590 mm) +
1 septum (4 mm)
39 mm Kicker Bump



E-Weg transport line



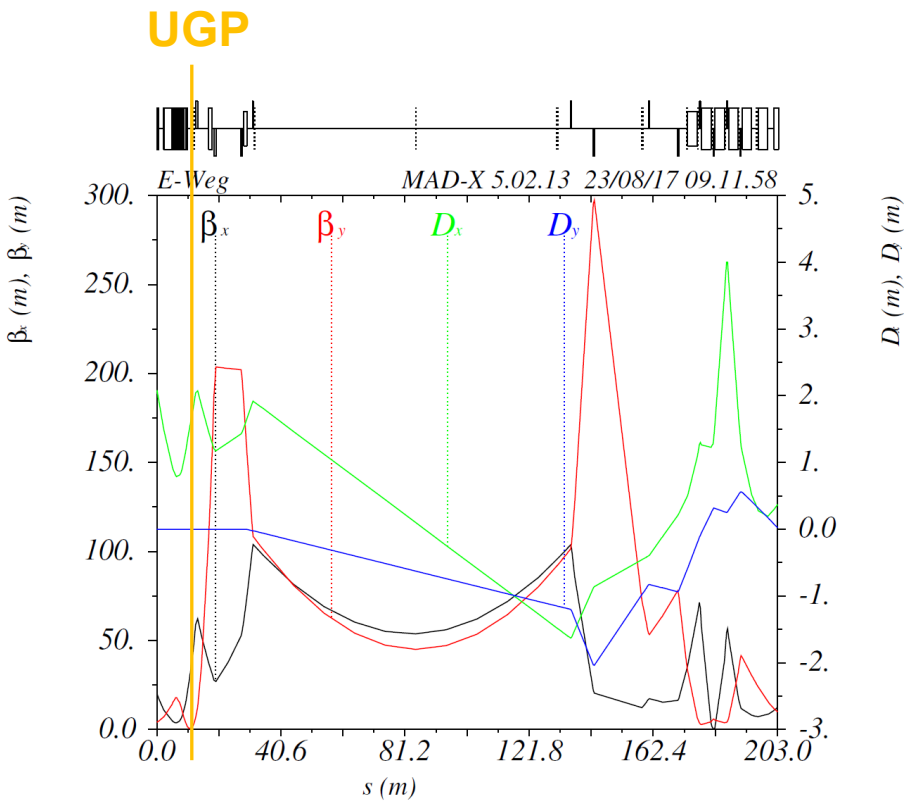
# Elements	Elements
12	Quadrupoles
7	H. dipoles
1	V. dipole
5	H. correctors
7	V. correctors
10	Screen Monitors
8	BPMs

To correct a difference in the vertical plane of 1.28 m between DESY II and PETRA III

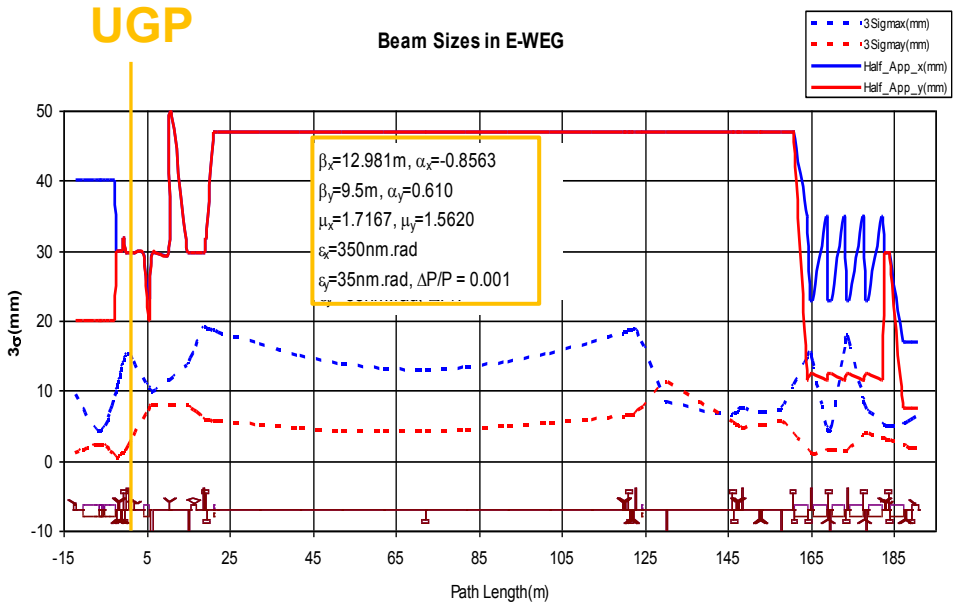
To estimate beam spot profiles (emittance and dispersion measurements)

E-Weg transport line

- Optical functions: matched at UGP point to take into account the effect of previous magnets of DESY lattice



- 3σ beam sizes in comparison to available physical aperture along E-Weg taking into account the beam emittances ε_x = 350 nm.rad, ε_y = 35 nm.rad



PETRA IV upgrade: Parameters and time scale

PETRA IV Parameter		
Energy	6 GeV	(4.5 – **6 GeV**)
Current	100 mA	(100 – 200 mA)
Number of bunches	~ 1000	
Emittance horizontal	10 pm.rad	(**10** – 30 pm.rad)
vertical	10 pm.rad	(**10** – 30 pm.rad)
Bunch length	~ 100 ps	
Number of beam lines	~ 30	

Investigate most challenging design parameters (6 GeV, 10 pm.rad) and determine the limits

- **Improve dynamic aperture (2 mm.mrad) and momentum acceptance (2%) (MOGA, AT)**
- **Error studies**

> Started to investigate two different lattice types

1. Based on the ESRF-HMBA cell (H6BA, H7BA with different cell lengths)
2. Based on 4D-phase space exchange and MBAs with non-interleaved sextupoles

PETRA IV	Jan.	Feb.	März	April	Mai	Juni	Juli	Aug.	Sep.	Okt.	Nov.	Dez.
2016		Study group						Studies				
2017												Lattice Design
2018				CDR								
2019												TDR

PETRA IV upgrade: Injection System

- Design goal:
  - to preserve as much as possible the current injector system.

    (at least an on-axis injection should be possible with the existing injector)
  - an injection with accumulation in PETRA IV is highly desirable.
- Recent studies and activities:
  1. Measure the optical functions (dispersion and betas) and emittance of E-Weg (G.K. Sahoo, et al., Proc IPAC 2017).
  2. We need to reduce the emittance of DESY II to inject in a storage ring of 10 pm.rad:
     - Increase the focusing and reduce the energy from 6 GeV to 5 GeV (J. Keil, et al., Proc IPAC 2017).
     - **Design a new booster** of **~10 nm.rad** (I. Agapov, et al., Proc IPAC 2017).

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Dispersion function measurement in E-Weg

> Measurement of dispersion from the centroid shift of the screen beam spot by extracting beam from DESY II at different energies (neglecting the change in quadrupole strength)

$$\Delta x = D_x \cdot \frac{\Delta p}{p}$$

$\Delta p/p$=0.6% E=6.0493 GeV ($\pm$ 0.0018 GeV)				
	Theoretical		**Measured**	
Name	D_x **(m)**	D_y **(m)**	D_x **(m)**	D_y **(m)**
M000	1.8802	0.0000	-0.5216	0.0308
M020	1.9107	-0.0266	0.3603	0.0356
M119	-1.4793	-1.1492	0.007	0.2602
M144	-0.4561	-0.9784	-0.8741	-0.6193
M161	0.4727	-0.6235	-1.1326	-0.5737
M169	1.2715	0.2927	0.0000	0.0000
M178	1.6634	0.5213	1.0812	0.1890
M185	0.3439	0.3439	0.8062	-0.0808

> Conclusion: the initial conditions of DESY II were not correct due to misalignment of magnets and resolution of BPMs that impacts the beam quality.

Emittance and optics measurements in E-Weg

> Based in matrix formalism: the elements of the beam matrix at point 1 can be known measuring the Twiss parameters propagated by the transfer matrix between point 1 and point 2:

beam matrix: $$\Sigma = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

Transport matrix from point 1 to point 2: $$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

Beam matrix at point 2: $$\Sigma_2 = M \Sigma_2 M^T$$

Beam size at point 2: $$\Sigma_{2,11} = {M_{11}}^2 \Sigma_{1,11} + 2 M_{11} M_{12} \Sigma_{1,12} + {M_{12}}^2 \Sigma_{1,22}$$

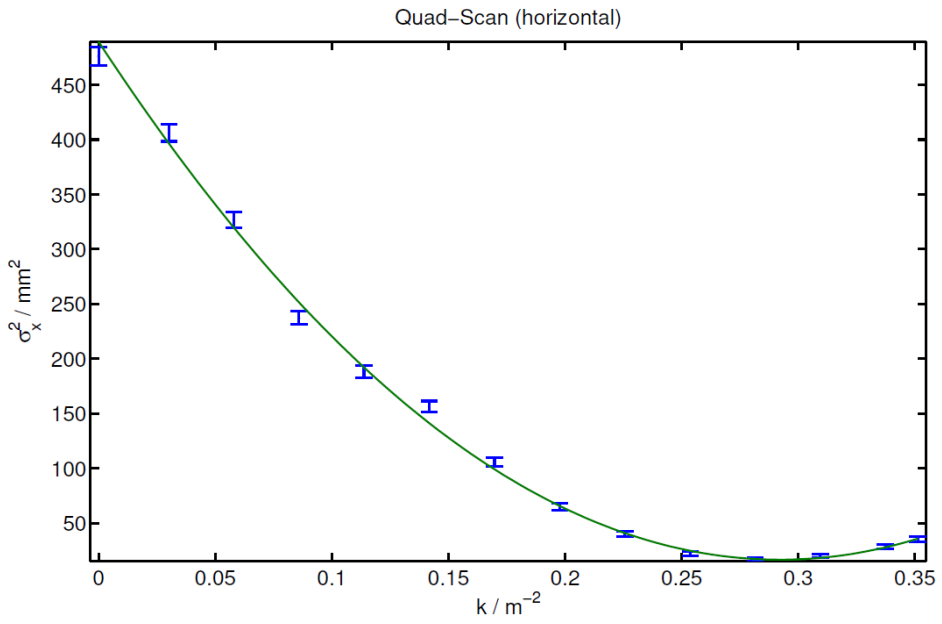
- Quadrupole Scan Method: fitting the beam size vs. the quadrupole strength just after the quadrupole

$$M = M_{quad}(k) \cdot M_{drift}$$

- Multiple Screen Method: using different screens to measure the beam size in the same drift space

$$M = M_{drift,1} \cdot M_{drift,2} \cdot M_{drift,3}$$

Quadrupole Scan Method



> Example of fitting of the beam size vs. the quadrupole strength for 6 GeV

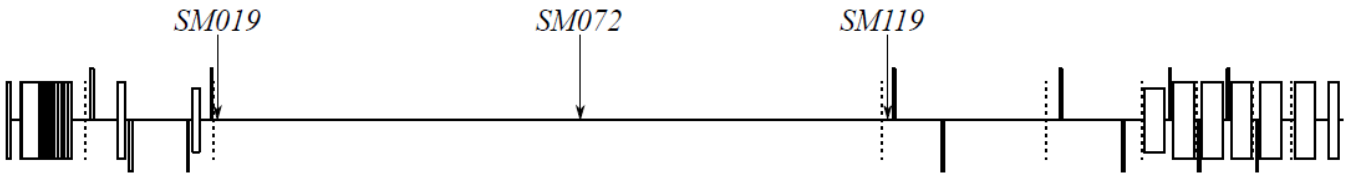
> Conclusion: the measured emittances agree with calculations.

> Disagreement in betas and alphas caused by an incorrect model of the stray field of the DESY II dipole magnet which the beam has to cross when extracted

	Theory		Measurement	
	5 (GeV)	**6 (GeV)**	**5 (GeV)**	**6 (GeV)**
ε_x **(nm.rad)**	241	331	253 ± 6	335 ±12
ε_y **(nm.rad)**	24	33	10 ± 0.5	15 ±0.5
β_x **(m)**	111	111	53 ± 2	56 ±2
β_y **(m)**	120	120	56 ± 4	56 ±3
α_x	-8.9	-8.9	-3.8 ± 0.1	-4.2 ±0.2
α_y	11.9	11.9	6.2 ± 0.4	5.9 ± 0.3

Multiple Screen Method

> Measurements done at screen monitors at 19 m, 72 m and 119 m from the beginning of E-Weg



Monitor	σ_x (mm)	ε_x (nm.rad)	β_x (m)	α_x
SM019	5.253482	357	77.3 (103)	0.83 (0.96)
SM072	4.337361	*	53 (54)	-0.39 (-0.02)
SM119	6.94860	*	135 (96)	-1.40 (-0.89)
Monitor	σ_y (mm)	ε_y (nm.rad)	β_y (m)	α_y
SM019	0.98797	12.5	78 (107)	1.05 (1.18)
SM072	0.74694	11.9	45 (45)	-0.45 (0.01)
SM119	1.344465	*	144 (92)	-1.70 (-1.03)

(*) not enough BPMs resolution

> Conclusion: disagreement caused by an incorrect model of the stray field of the DESYII dipole magnet which the beam has to cross when extracted

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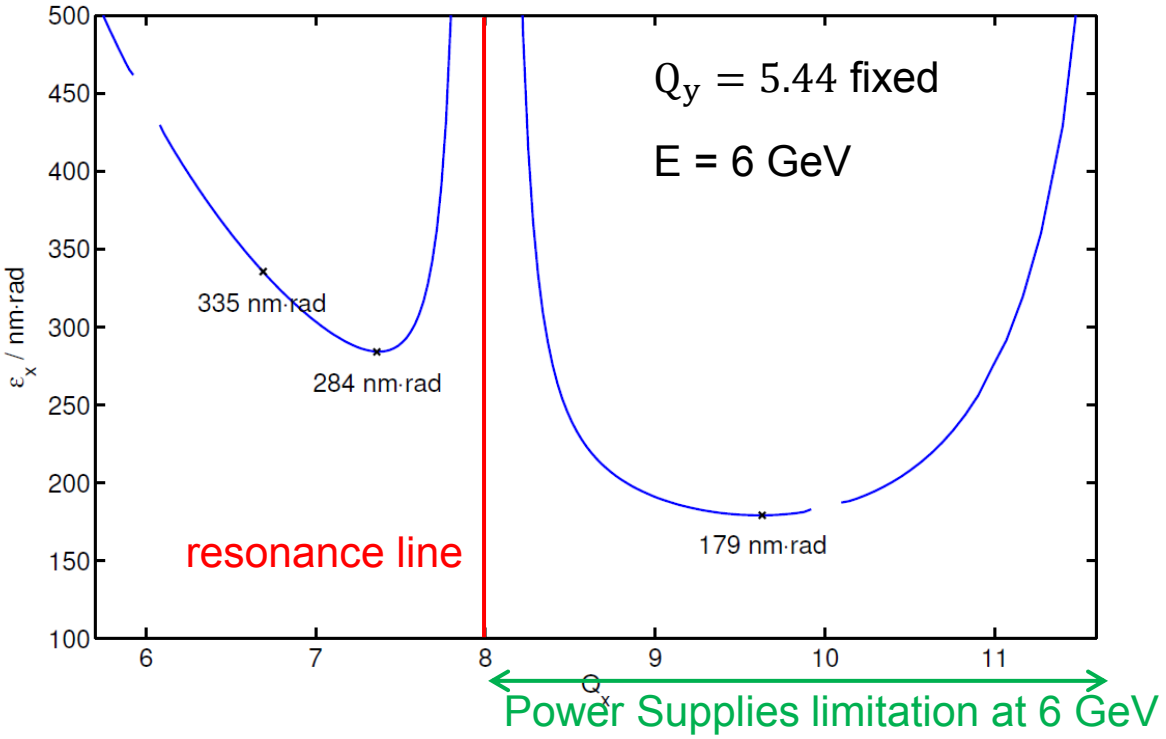
Emittance reduction in E-Weg

- DESY II consists of 8 supercells with L= 36.6m -> total L= 293 m.
- Each supercell is made of 3 FODO cells.
- Decreasing the energy from 6 GeV to 5 GeV, the emittance decreases from 330 nm.rad to 241 nm.rad (<10%).
- Increase focusing also helps to reduce the emittance.



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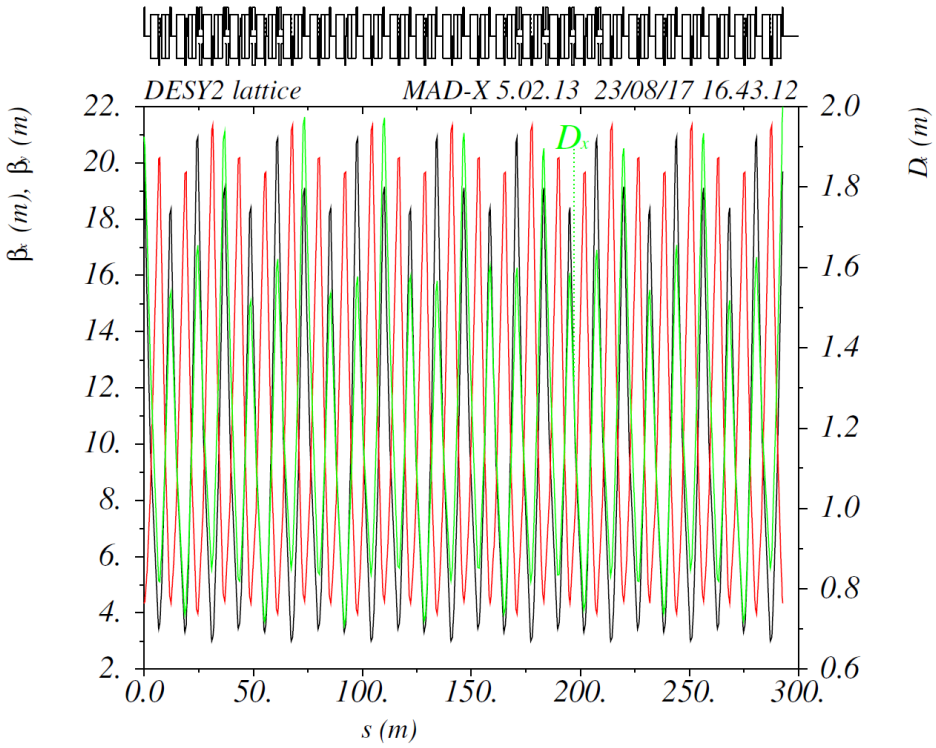
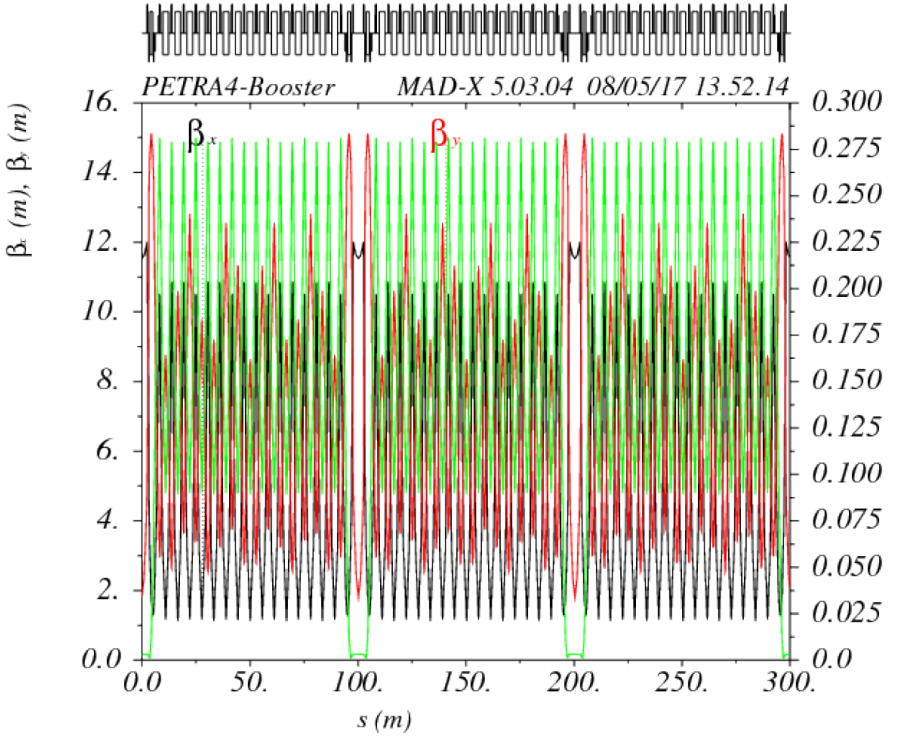
New PETRA IV- Booster lattice

> New PETRA IV-Booster lattice scaling the **ALBA booster**



8 supercells (3 FODO cells with L= 36.6m per supercell)

ε_x = 330 nm.rad



3-fold symmetry with 3 arcs and 3 straight sections

ε_x = 7 nm.rad

Conclusions

> The study of a new pre-accelerator of PETRA IV has already started thinking to reuse most parts of the current booster.

> The measurements of the emittance agree with theoretical expectations. However, the measured optical functions at the transport line show a disagreement with the theoretical values due to a no precise model of the effect of magnets.

> We must reduce the emittance of the PETRA IV pre-accelerator.

> A different working point of DESY II can provide a smaller emittance (from 335 nm.rad to 284 nm.rad). Further improvements would require new power supplies.

> A new booster lattice is also considered. First studies are based on a scaled version of the ALBA booster (7 nm.rad).

> The final choice of new injector will depend on the new storage ring configuration.

Thank you for your attention !!

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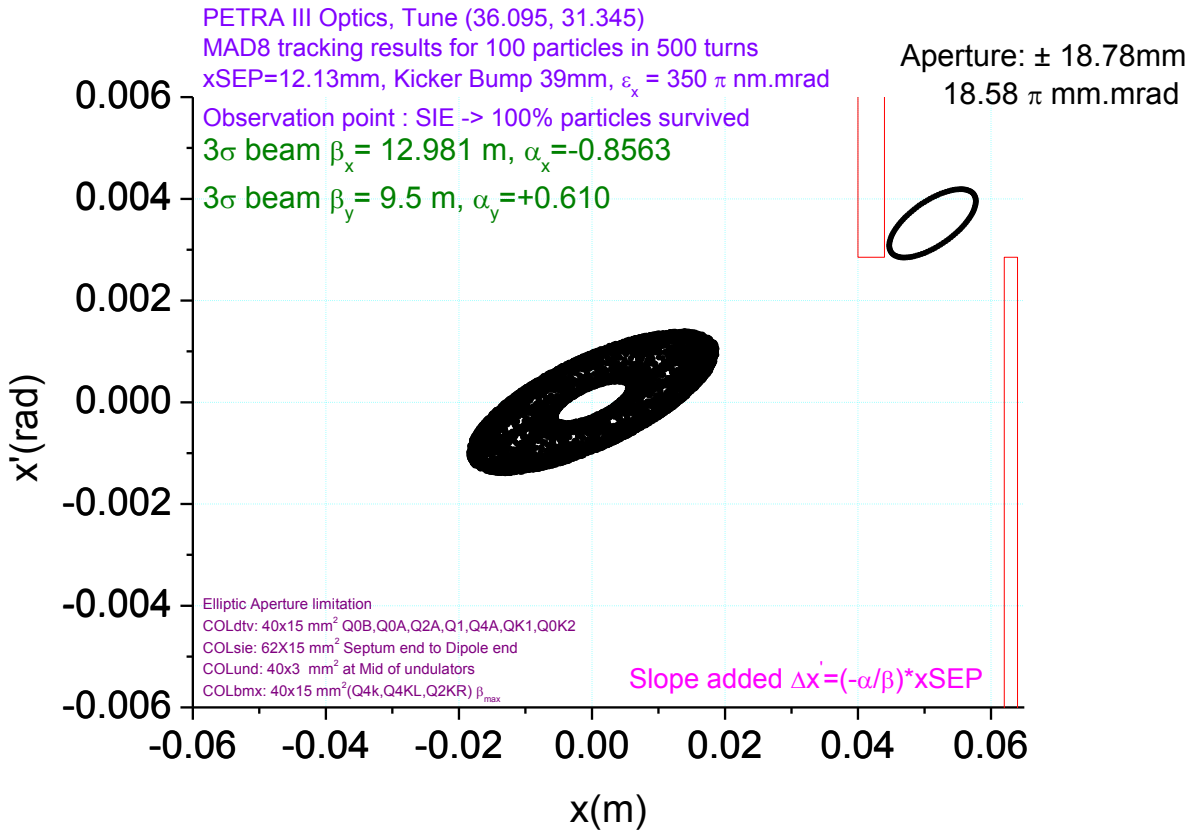
Backup Slides

Injector with 39 mm Kicker Bump

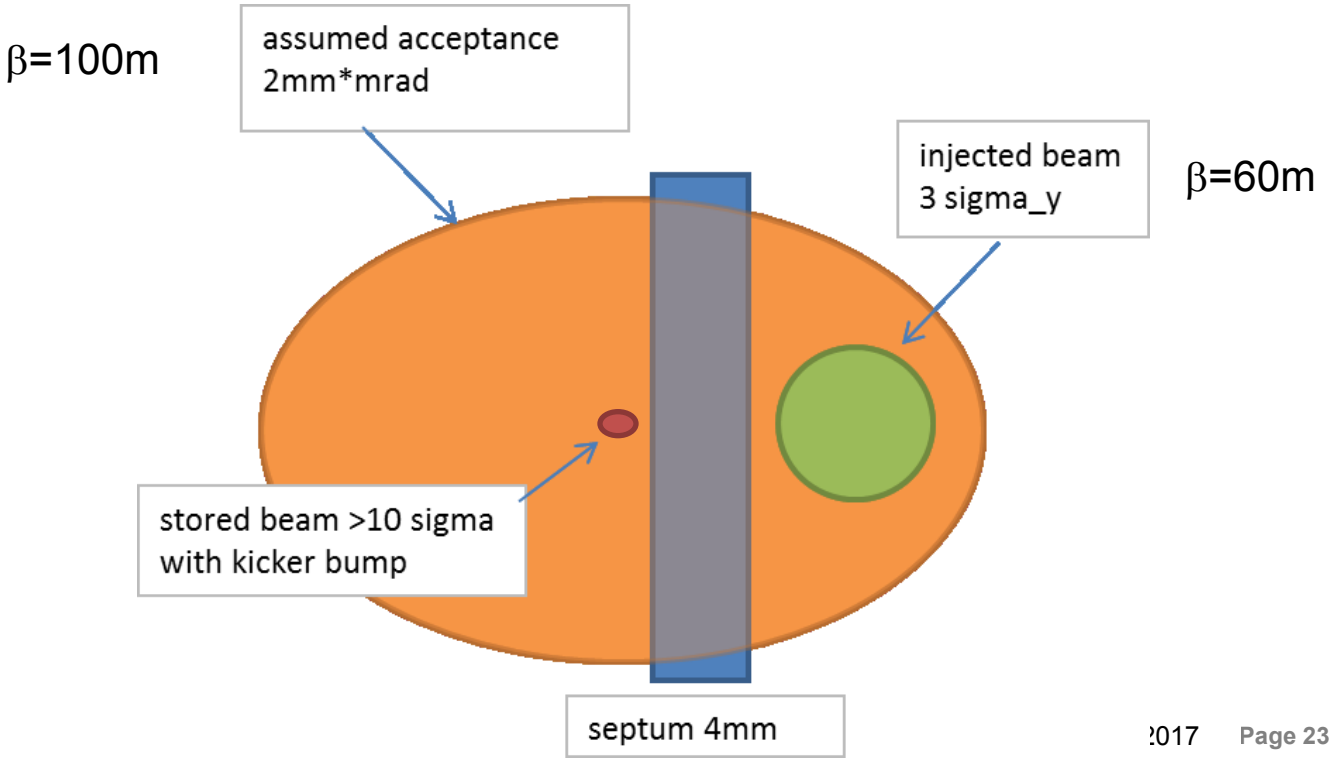
- An aperture of ± 18 mm is enough to inject 3σ beam



Recent idea: accumulation in the (y-) plane of smaller emittance from injector

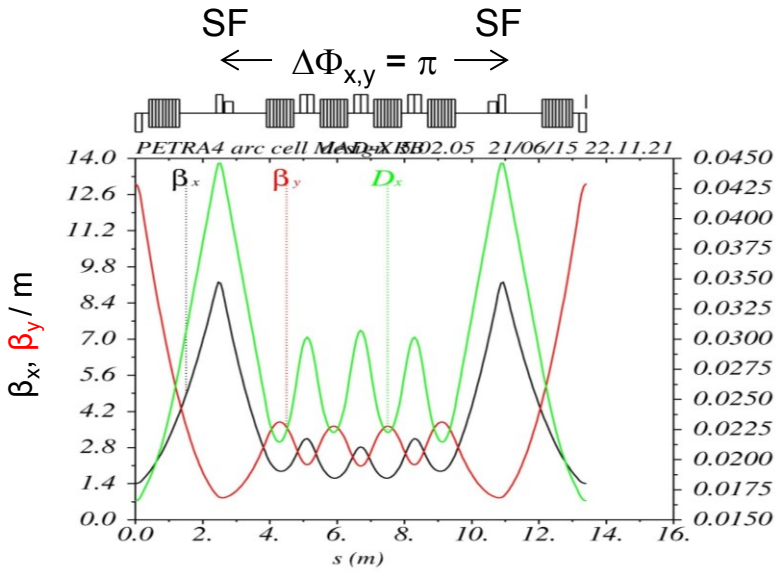
(Similar concept pursued at HZB/BESSY2, P. Kuske, Proc. IPAC 2016)

- Either inject vertically into PETRA III ring or perform a 90° x-y phase space twist in the transfer line
- Dynamic acceptance of 2 mm*mrad would be safely sufficient for accumulation
- On-axis injection in the other plane with ~200nm emittance no problem



Phase Space Exchange Lattice (TMBA Lattice)

- Lattice with **significantly more dynamic aperture**
  - Arc cells with non-interleaved sextupoles pairs and π/π phase advance
  - Enough DA to allow off-axis injection
- Provides **equal emittances** by using two *Twists*
  - *Twists:* Two *x-y* phase space exchange insertions in straight sections ("Double Möbius") – full coupled only within the twists
  - Horizontal natural emittance ε_0 is equally distributed in both planes → round beam
- The sum chromaticity of two half-arcs is corrected
- In addition cells for arcs without IDs are necessary



Non-interleaved arc cell