PETRA IV.
NEW DIMENSIONS

Design of slow extraction from low emittance electron booster rings

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Slow extraction workshop
Wiener Neustadt, Austria, 13.02.2024

HELMHOLTZ

DESY.

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- Introduction
  - Overview of DESY
  - Test beam facility
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- Slow extraction at DESY 4
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  - Slow extraction setting
  - Example: Extraction at 6 GeV
- Summary

Introduction

PETRA IV. NEW DIMENSIONS

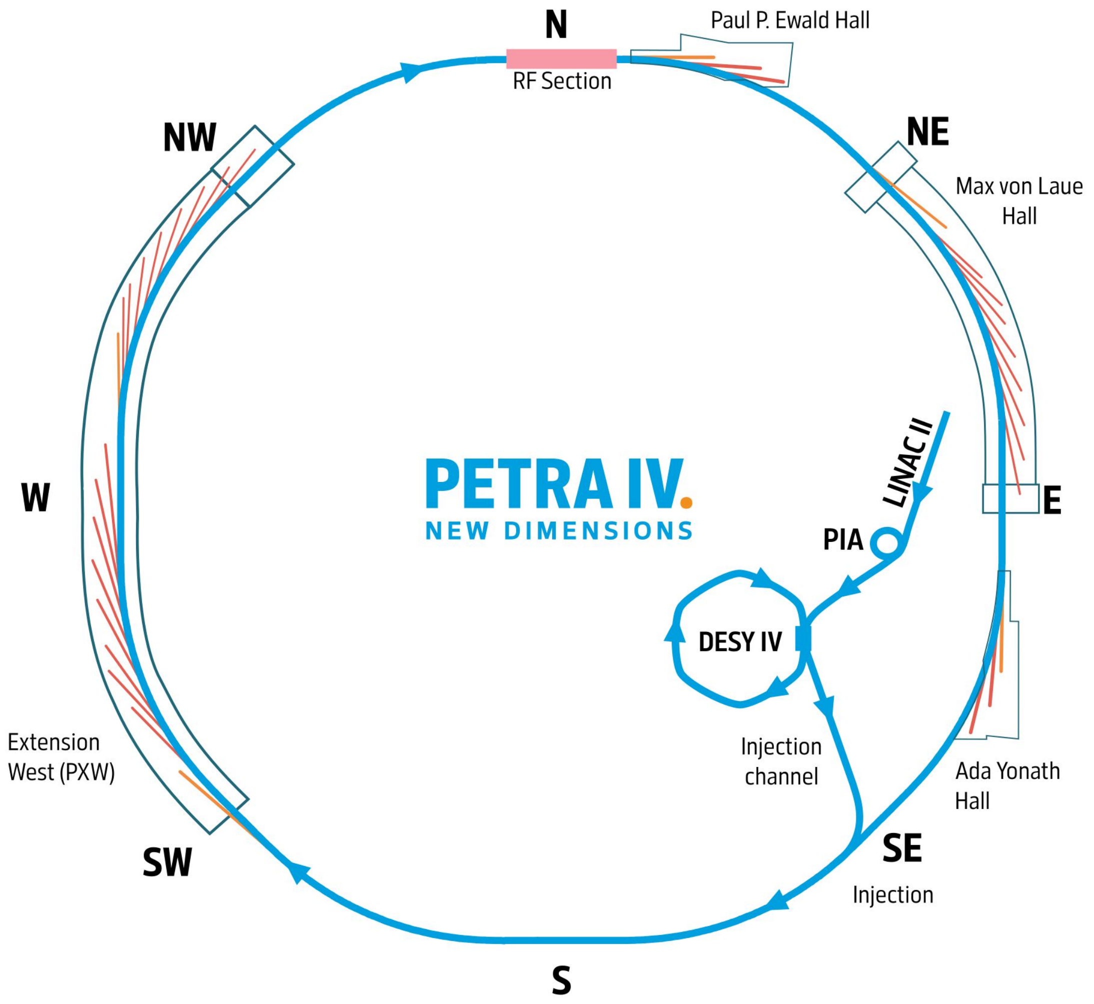
Facility overview

- Research centre of the Helmholtz Association
- Publicly funded national research centre
- Established in Hamburg on 18 December 1959

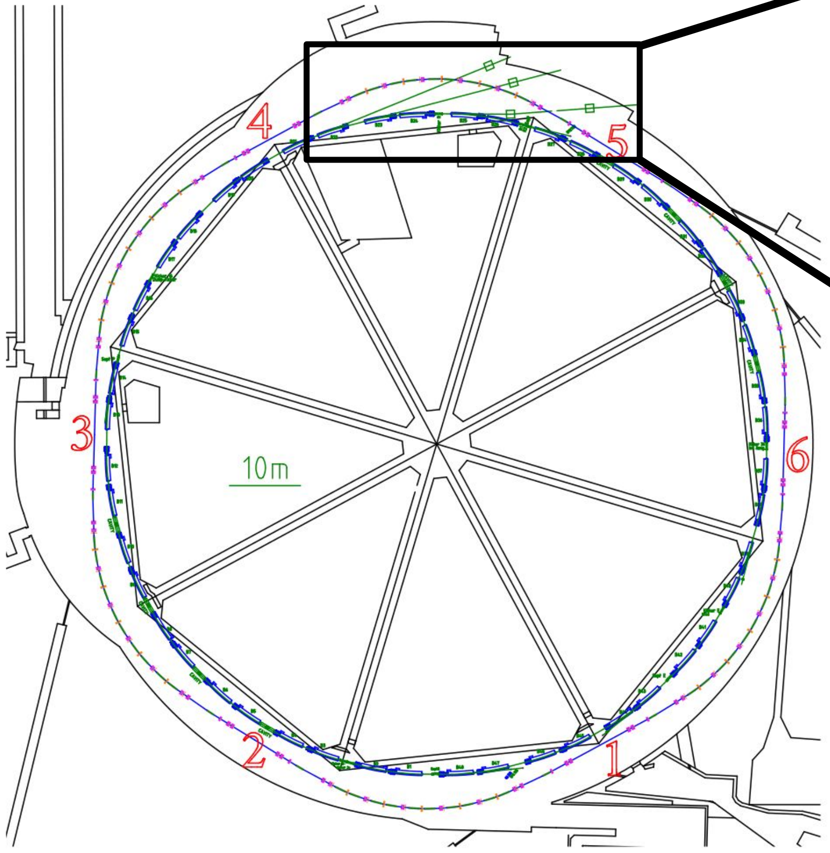
It houses three major accelerators:

FLASH, European XFEL and PETRA III.

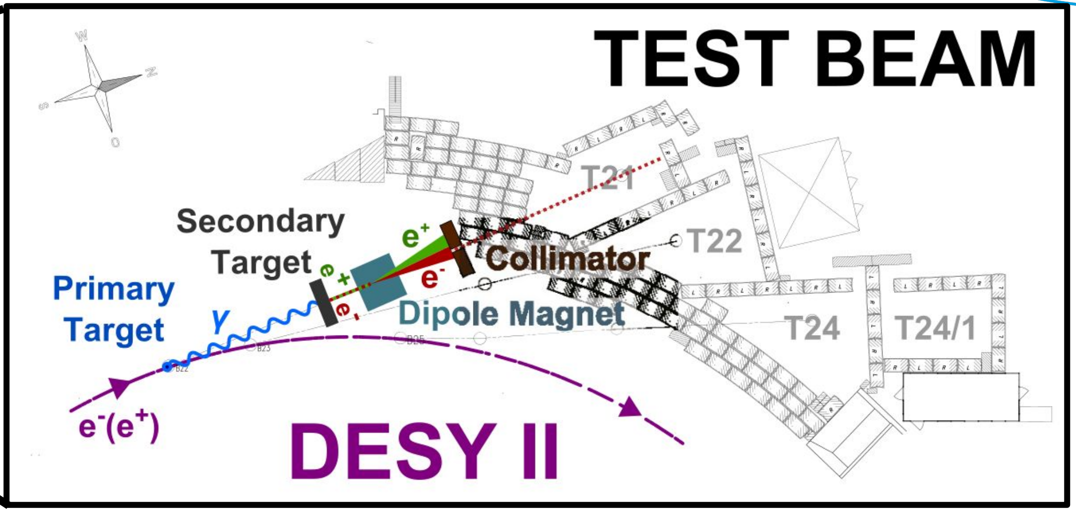
The largest synchrotron light source PETRA III will be soon upgraded to PETRA IV.



DESY II Test Beam



H-C. Chao, et. al. Design considerations of a high intensity booster for PETRA IV. IPAC21.



J. Dreyling-Eschweiler, et. al. The DESY II test beam facility, NIM-A, Vol. 922, 2019, https://doi.org/10.1016/j.nima.2018.11.133.

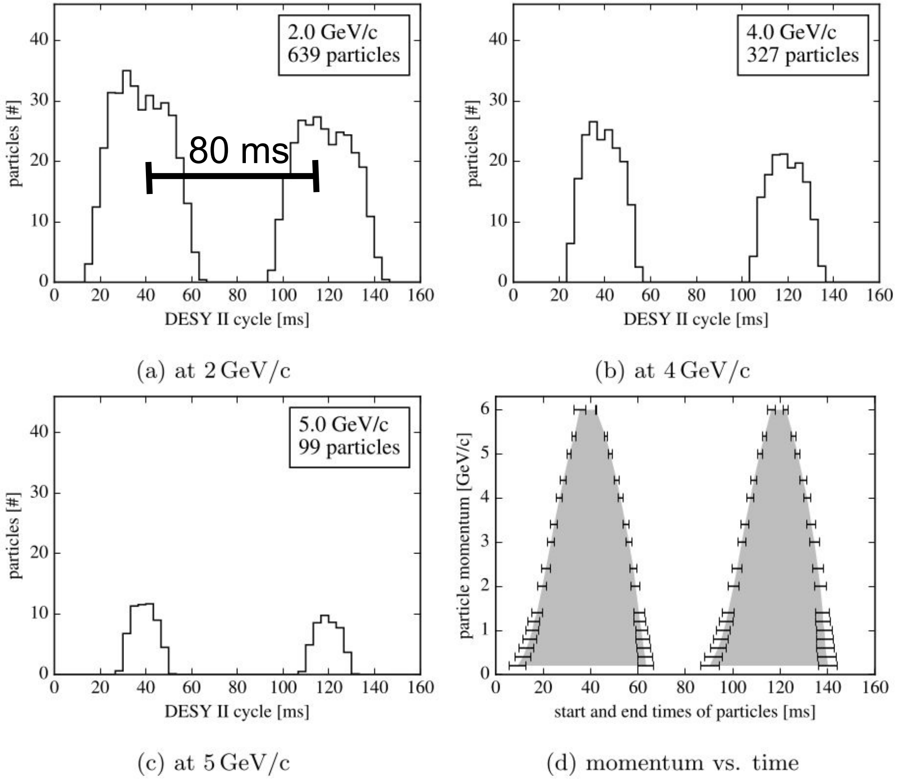
Test beam

- One of the few facilities where multi-GeV electron beams are offered
- Three independent beamlines
- Positron and electron beams with E = [1,6] GeV
- 1266 users from 2013-2017
- Runs parasitically to the DESY II operation with a fixed target in the ring (carbon-fiber wire 7 μm width)
- R&D of detector technology (mainly ATLAS & CMS)

DESY II Test Beam

Particle rate with the current setup

- ~10kHz every 12.5 Hz (DESY II cycle)



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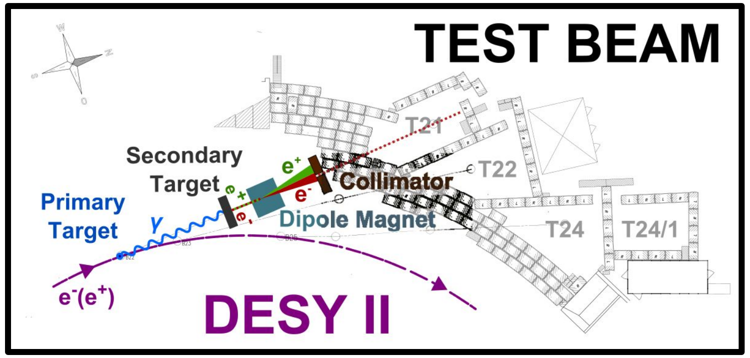


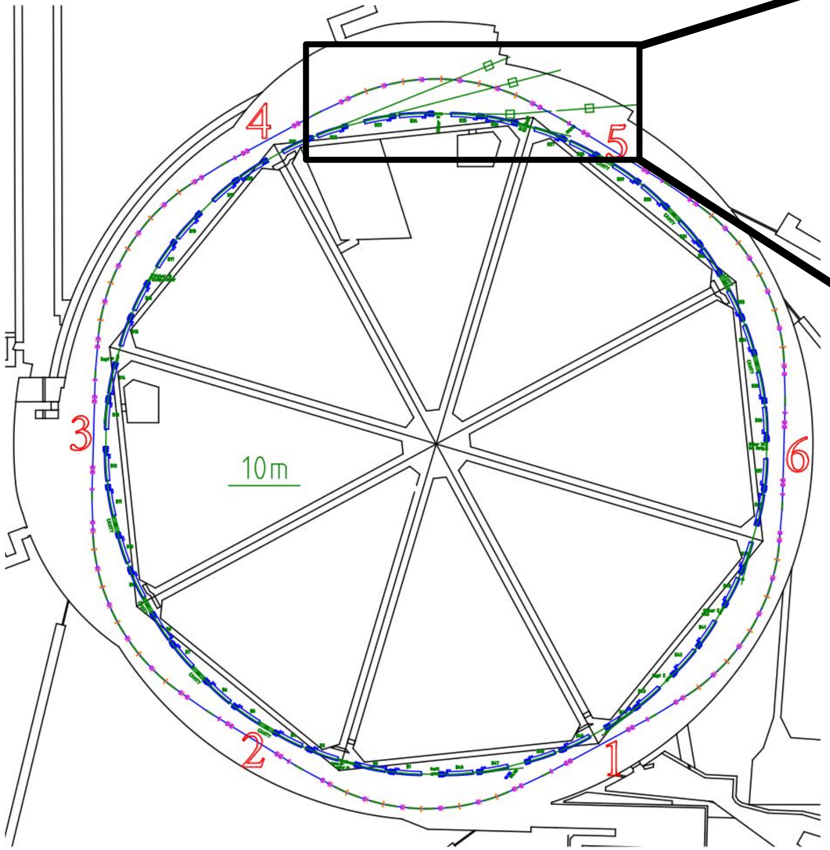
Test beam users' requirements ('wish list')

- Highest energy available is preferred
- Quasi-continuous beam
- Minimum preferred extracted particle rate : 10kHz
- Flexibility to choose the particle rate

Detector R&D

- Time resolution from 20ps to 1μs
- Currently more interested in the nanosecond regime

DESY II Test Beam



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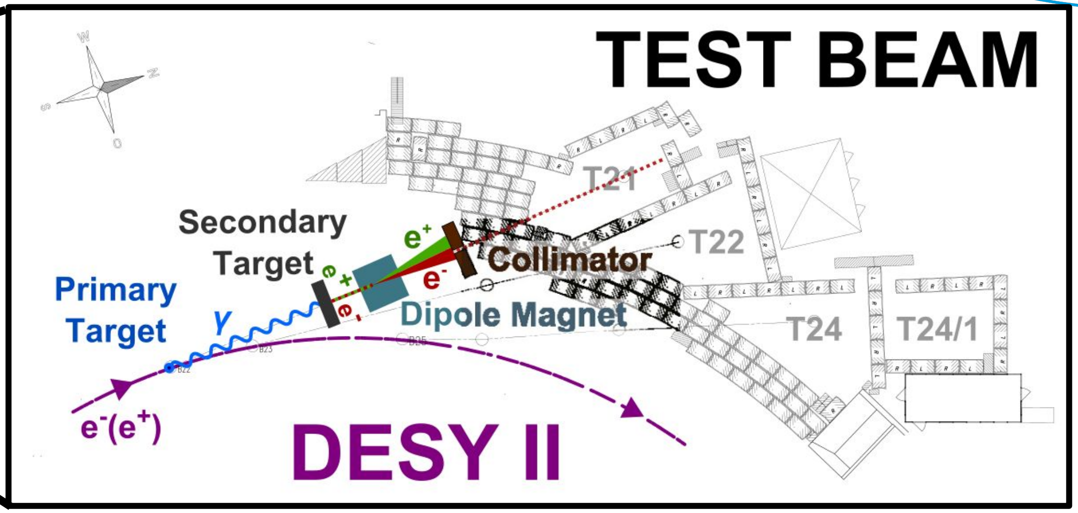

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With the upgrade from DESY II to DESY IV it might be a good idea to also upgrade to a more sophisticated extraction technique

Upgrade to DESY IV

PETRA IV. NEW DIMENSIONS

Low emittance lattices

- Strive to minimize the equilibrium emittance by reducing the radiation integrals

$$\varepsilon_x = \text{Constant}\,\frac{I_5}{I_2}$$

$$I_2 = \int \frac{1}{\rho^2}\,ds \qquad I_5 = \int \frac{\mathcal{H}}{|\rho|^3}\,ds$$

Bending radius

$$\mathcal{H} = \frac{1}{\beta_x}\left[D^2 + \left(\beta_x D' - \frac{1}{2}\beta_x' D\right)^2\right]$$

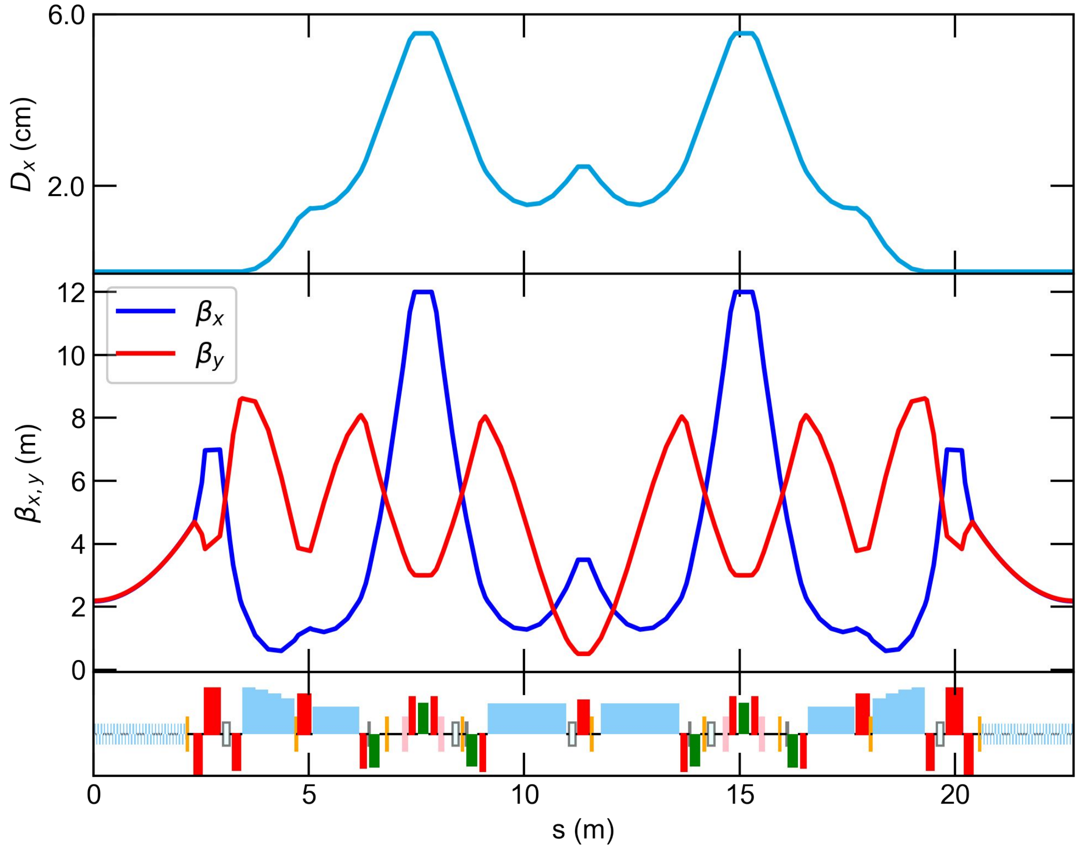
- The curly-H function can be optimized to decrease the contribution from I_5 by modifying the optics

- As a consequence low emittance lattices require strong quadrupoles, which create **high chromaticities**
- Simultaneously the have **low dispersion**, which then **increases the sextupole strengths** to correct for the high chromaticities

Upgrade to DESY IV

Low emittance lattices

- Example: PETRA IV H6BA cell



$$\mathcal{H} = \frac{1}{\beta_x}\left[D^2 + (\beta_x D' - \frac{1}{2}\beta_x' D)^2\right]$$

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Transversal dynamics

PETRA IV. NEW DIMENSIONS

Effective Hamiltonian

Kobayashi part

Amplitude detuning term

$$H = \underbrace{6\pi\delta J_x + \frac{S}{\sqrt{2}} J_x^{3/2} \sin 3\phi_x}_{\text{Kobayashi part}} + 3\pi \underbrace{\alpha_{xx}}_{\text{Amplitude detuning term}} J_x^2$$

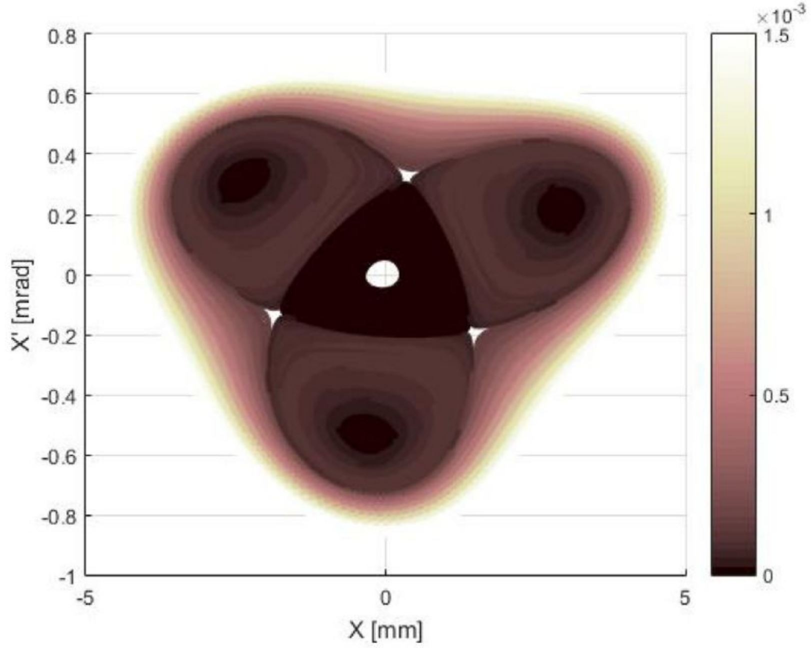
$$X = \sqrt{2J_x} \sin \phi_x$$

$$X = x/\sqrt{\beta_x}, \quad P = p_x\sqrt{\beta_x} + \alpha_x X$$

Oldest reference with this Hamiltonian I could find:

- K.R. Symon. Beam extraction at a third integral resonance. 1968.

- It has been studied for the generation of transverse resonance island buckets (TRIBs)



Picture taken from: D. Olsson & A. Andersson.
Studies on Transverse Resonance Island Buckets in third and fourth generation synchrotron light sources.
DOI: https://doi.org/10.1016/j.nima.2021.165802

Transversal dynamics

Effective Hamiltonian

Amplitude detuning term

Kobayashi part

$$H = \boxed{6\pi\delta J_x + \frac{S}{\sqrt{2}} J_x^{3/2} \sin 3\phi_x} + 3\pi \boxed{\alpha_{xx}} J_x^2$$

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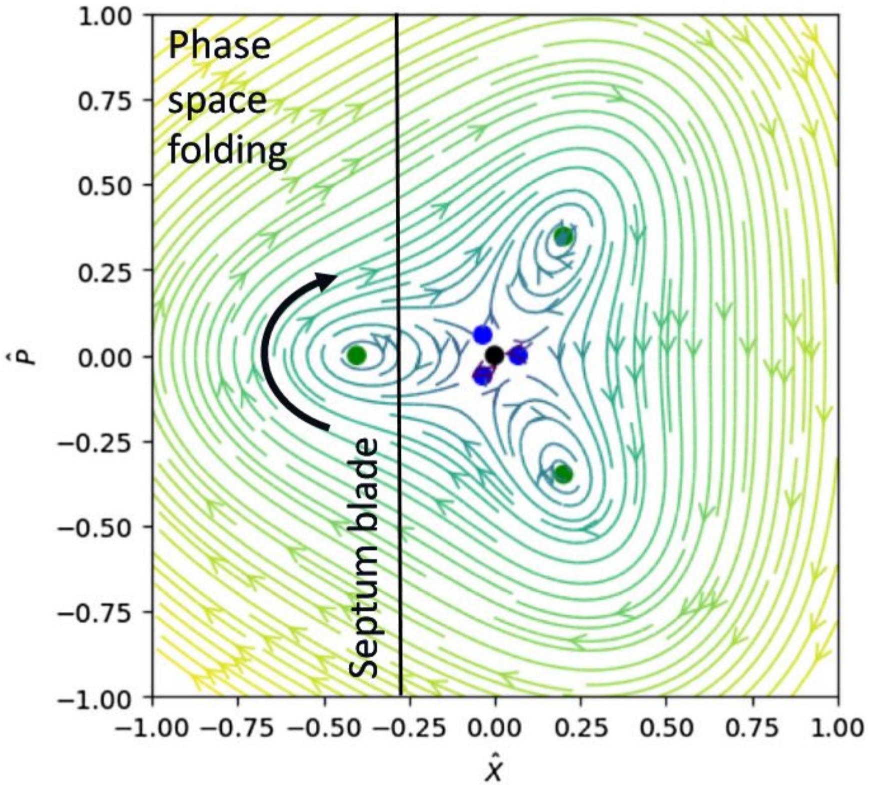
- K.R. Symon. Beam extraction at a third integral resonance. 1968.

- It has been studied for the generation of transverse resonance island buckets (TRIBs)
- It has been used for the bending of the separatrix arm at CERN SPS



Picture taken from: M. Fraser, et al.
Demonstration of slow extraction loss reduction with the application of octupoles at the CERN Super Proton Synchrotron. DOI: 10.1103/PhysRevAccelBeams.22.123501

Transversal dynamics

PETRA IV. NEW DIMENSIONS

Effective Hamiltonian

Kobayashi part

Amplitude detuning term

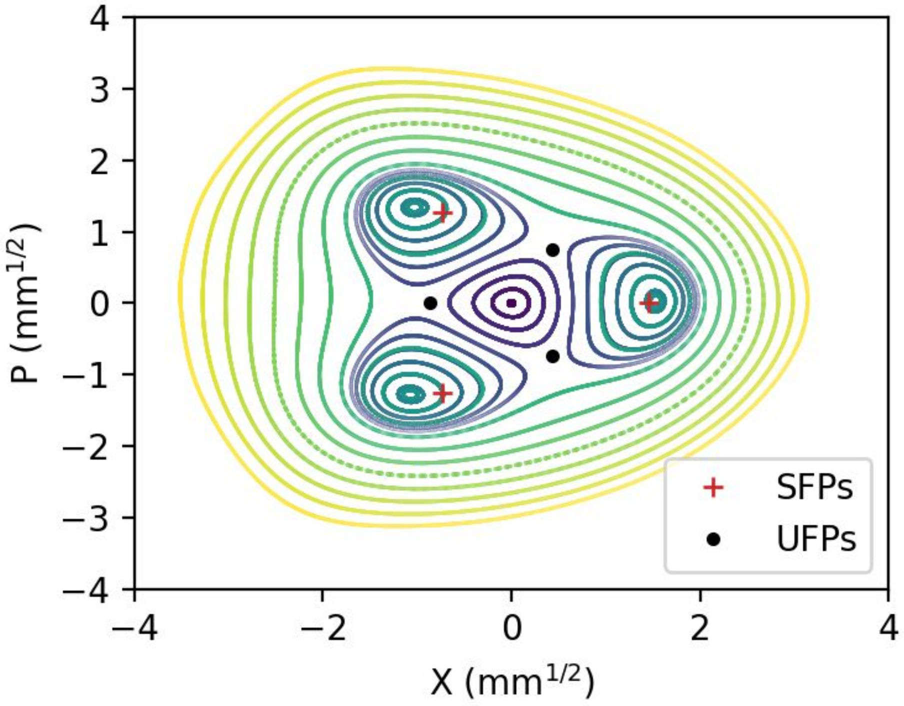
$$H = 6\pi\delta J_x + \frac{S}{\sqrt{2}} J_x^{3/2} \sin 3\phi_x + 3\pi\alpha_{xx} J_x^2$$

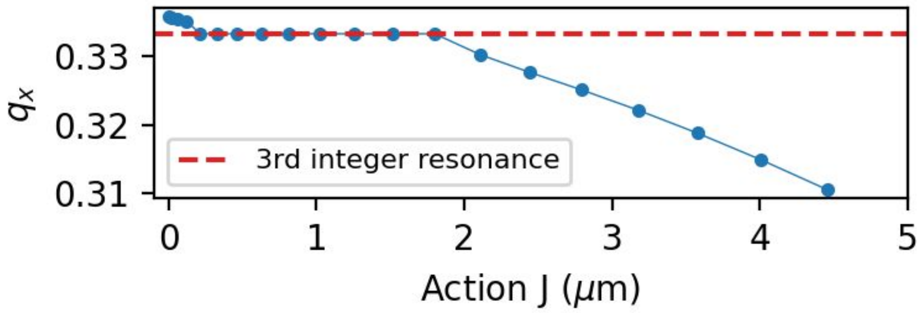
$$X = \sqrt{2J_x}\sin\phi_x$$

$$X = x/\sqrt{\beta_x}, \quad P = p_x\sqrt{\beta_x} + \alpha_x X$$

- The stable and unstable fixed points can be calculated with reasonable precision

$$J_{x,\pm}^{1/2} = \frac{1}{8\sqrt{2}\pi}\frac{S}{\alpha_{xx}}\left(1 \pm \sqrt{1 - 128\pi^2\frac{\delta\alpha_{xx}}{S^2}}\right)$$





Transversal dynamics

Effective Hamiltonian

Kobayashi part

Amplitude detuning term

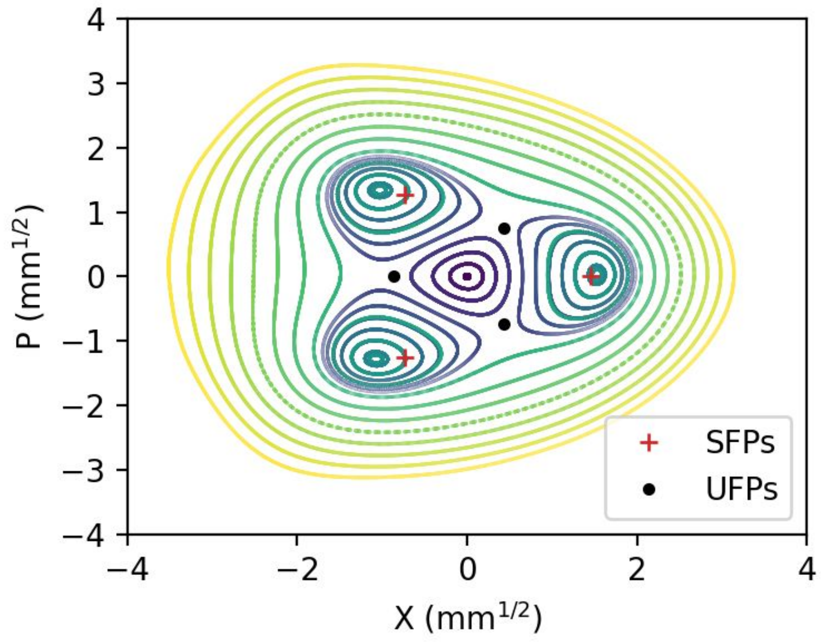
$$H = 6\pi\delta J_x + \frac{S}{\sqrt{2}} J_x^{3/2} \sin 3\phi_x + 3\pi\alpha_{xx} J_x^2$$

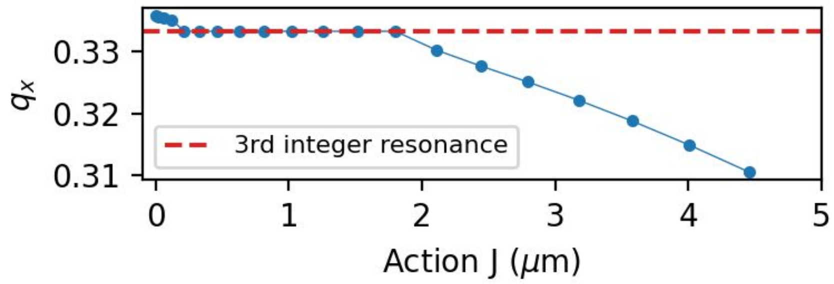
- An amplitude detuning term can be generated by the sextupoles to second order

$$\alpha_{xx} \propto \sum_i^N \sum_j^{j<i} (k'L)_i (k'L)_j ,$$

- These formulas are lengthy and not very precise
- The best way was to perform tracking to determine the amplitude detuning term

$$J_{x,\pm}^{1/2} = \frac{1}{8\sqrt{2}\pi} \frac{S}{\alpha_{xx}} \left(1 \pm \sqrt{1 - 128\pi^2 \frac{\delta\alpha_{xx}}{S^2}}\right)$$





Transversal dynamics

PETRA IV. NEW DIMENSIONS

Effective Hamiltonian

Kobayashi part — **Amplitude detuning term**

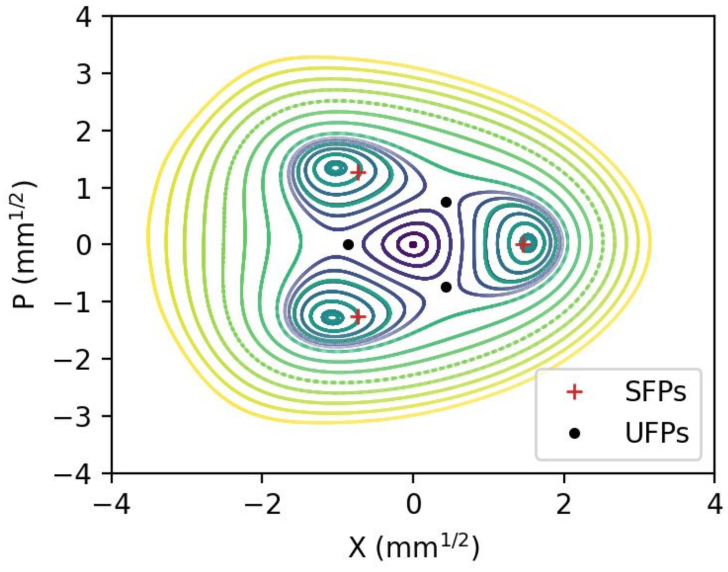
$$H = 6\pi\delta J_x + \frac{S}{\sqrt{2}} J_x^{3/2} \sin 3\phi_x + 3\pi\alpha_{xx} J_x^2$$

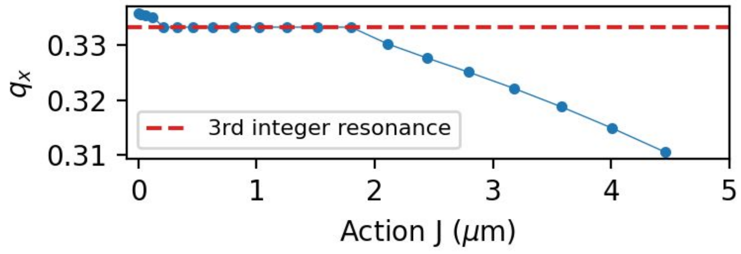
- An amplitude detuning term can be generated by the sextupoles to second order

$$\alpha_{xx} \propto \sum_i^N \sum_j^{j<i} (k'L)_i (k'L)_j ,$$

- For low emittance lattices, where sextupoles are strong, the value of the amplitude detuning term is considerable

$$J_{x,\pm}^{1/2} = \frac{1}{8\sqrt{2}\pi}\frac{S}{\alpha_{xx}}\left(1 \pm \sqrt{1 - 128\pi^2 \frac{\delta\alpha_{xx}}{S^2}}\right)$$





Transversal dynamics

Effective Hamiltonian

Kobayashi part

Amplitude detuning term

$$H = 6\pi\delta J_x + \frac{S}{\sqrt{2}} J_x^{3/2} \sin 3\phi_x + 3\pi\alpha_{xx} J_x^2$$

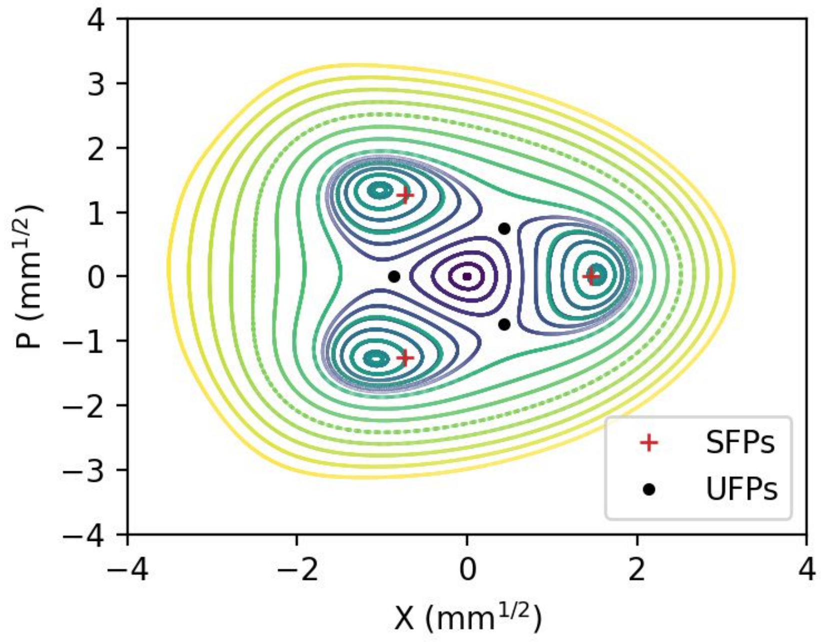
- An amplitude detuning term can be generated by the sextupoles to second order

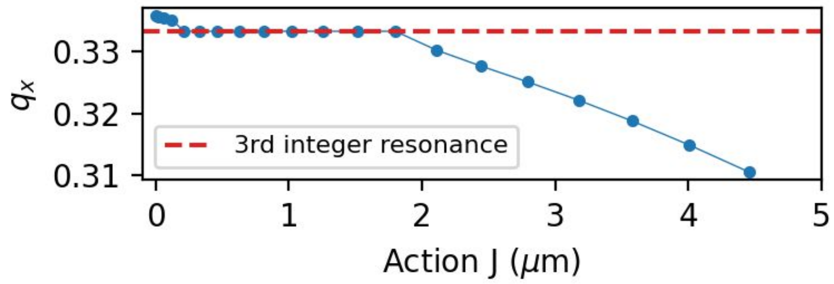
$$\alpha_{xx} \propto \sum_i^N \sum_j^{j<i} (k'L)_i (k'L)_j ,$$

- These term can also be generated, controlled and corrected with an octupole

$$\alpha_{xx,c} = \frac{K_3 L}{32\pi}\beta_x^2 , \quad K_3 = \frac{1}{B\rho}\frac{\partial^3 B_y}{\partial x^3}$$

$$J_{x,\pm}^{1/2} = \frac{1}{8\sqrt{2}\pi}\frac{S}{\alpha_{xx}}\left(1 \pm \sqrt{1 - 128\pi^2\frac{\delta\alpha_{xx}}{S^2}}\right)$$





Transversal dynamics

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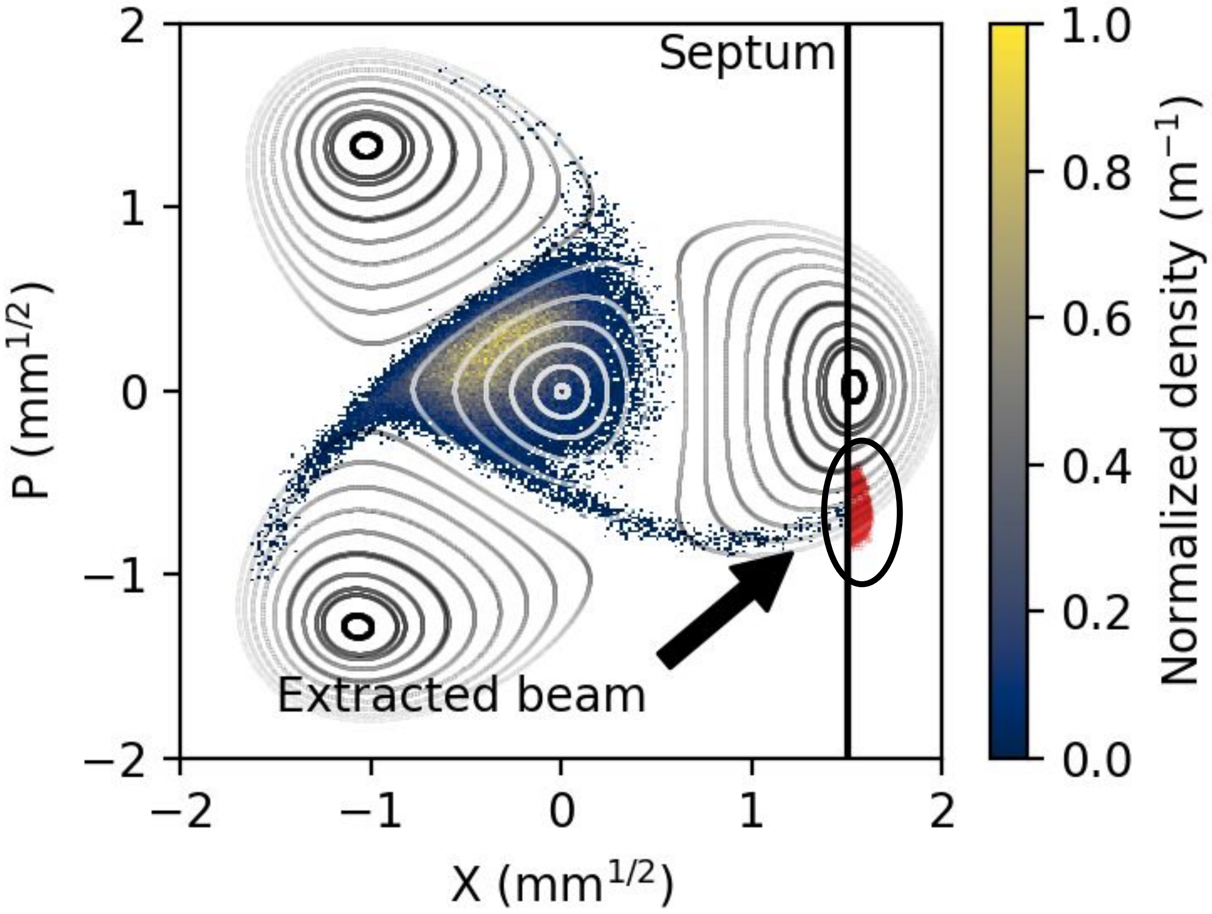
$$H = 6\pi\delta J_x + \frac{S}{\sqrt{2}} J_x^{3/2} \sin 3\phi_x + 3\pi\alpha_{xx} J_x^2$$

- For the design of the extraction optics one has to make use of three parameters

$$(S, \alpha_{xx}, \delta)$$

- The chromaticity has to be kept fully corrected, therefore the RFKO is a good option for the slow extraction at low emittance lattices



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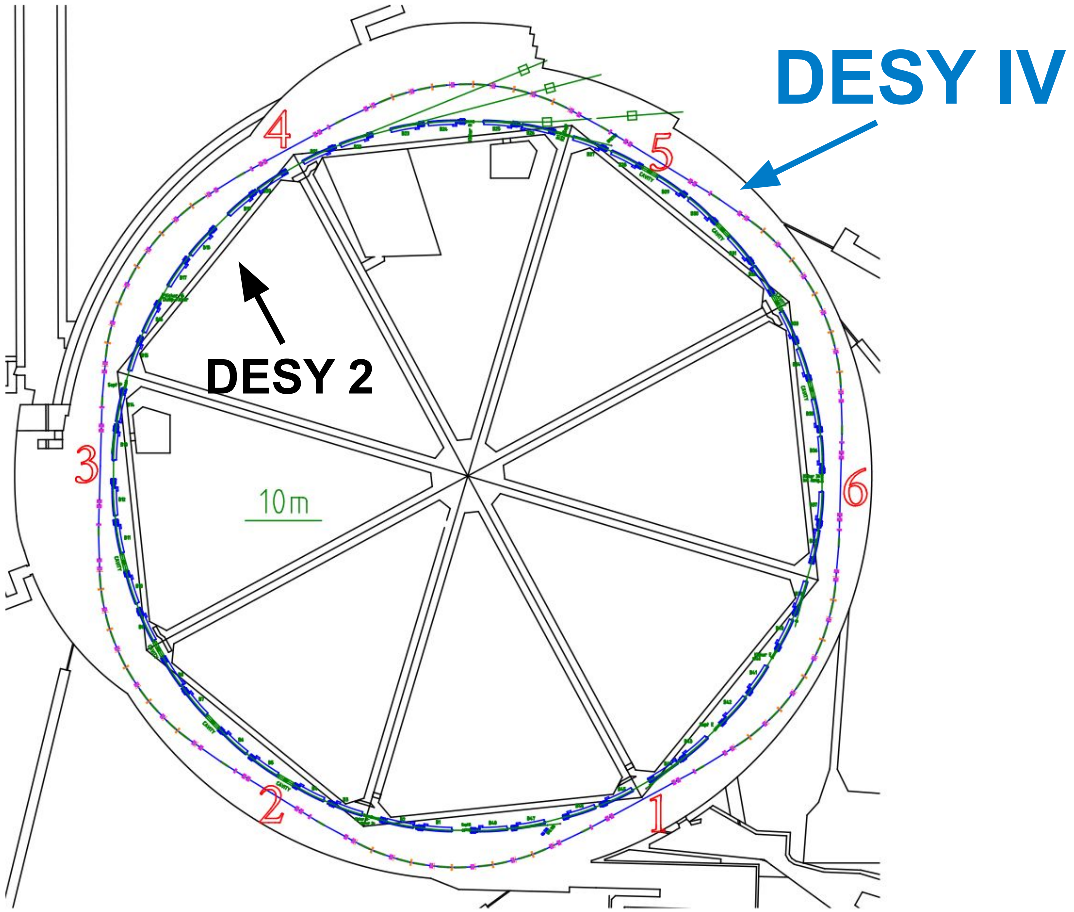
  - Transverse resonance islands buckets
- **Slow extraction at DESY 4**
  - **DESY 4 layout**
  - **Slow extraction setting**
  - **Example: Extraction at 6 GeV**
- Summary

DESY IV layout



Picture taken from H-C. Chao, et. al.
Design considerations of a high intensity booster for PETRA IV. IPAC21.

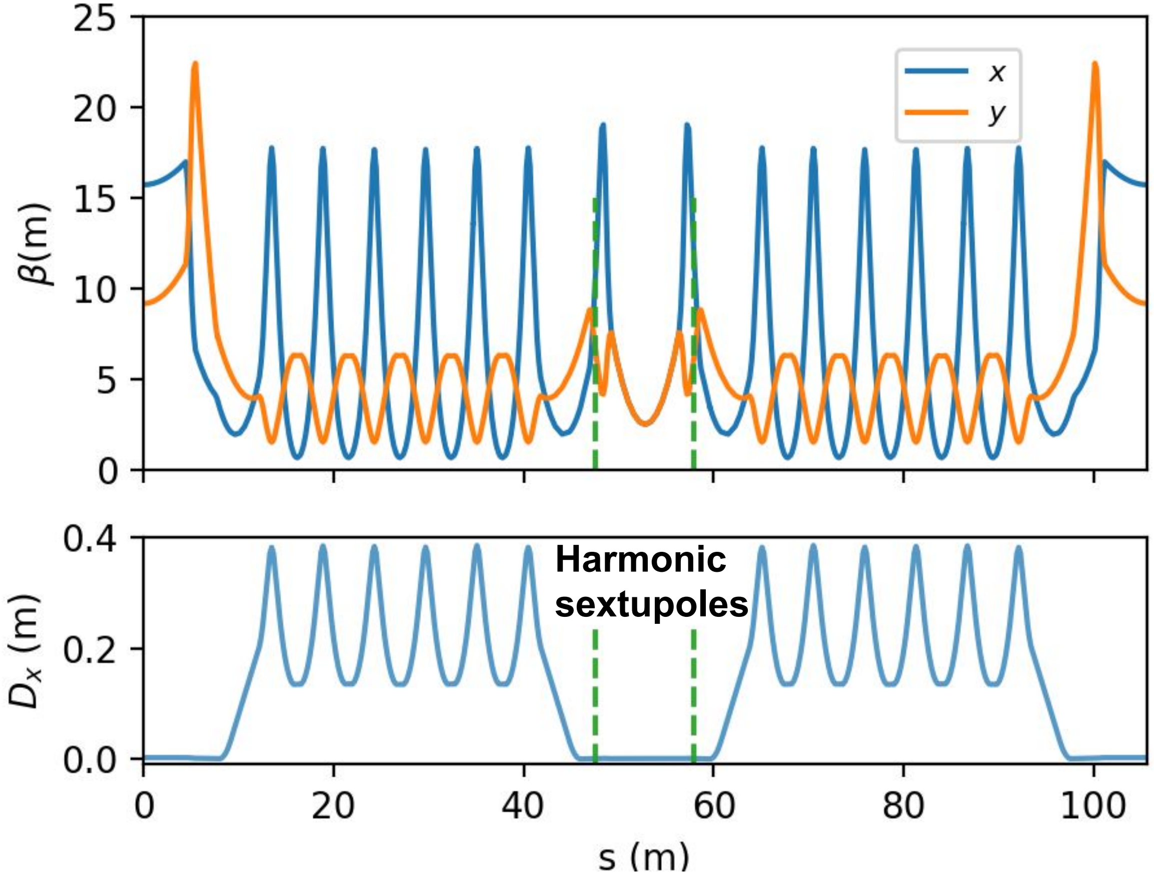
TABLE I. Parameters of the proposed DESY IV booster ring lattices and equilibrium parameters at 6 GeV.

Parameter	Symbol	3h3l	8-fold
Circumference	C	316.8 m	304.8 m
Tunes	Q_x/Q_y	17.37/12.15	15.13/9.29
Nat. chromaticity	ξ_x/ξ_y	-41.8/-13.8	-21.7/-10.4
Mom. compaction	α_c	3.17×10^{-3}	3.66×10^{-3}
Partition number	j_x	2.56	2.72
Natural emittance	ϵ_0	19.1 nm rad	19.4 nm rad
Momentum spread	$\Delta p/p$	2.64×10^{-3}	3.33×10^{-3}

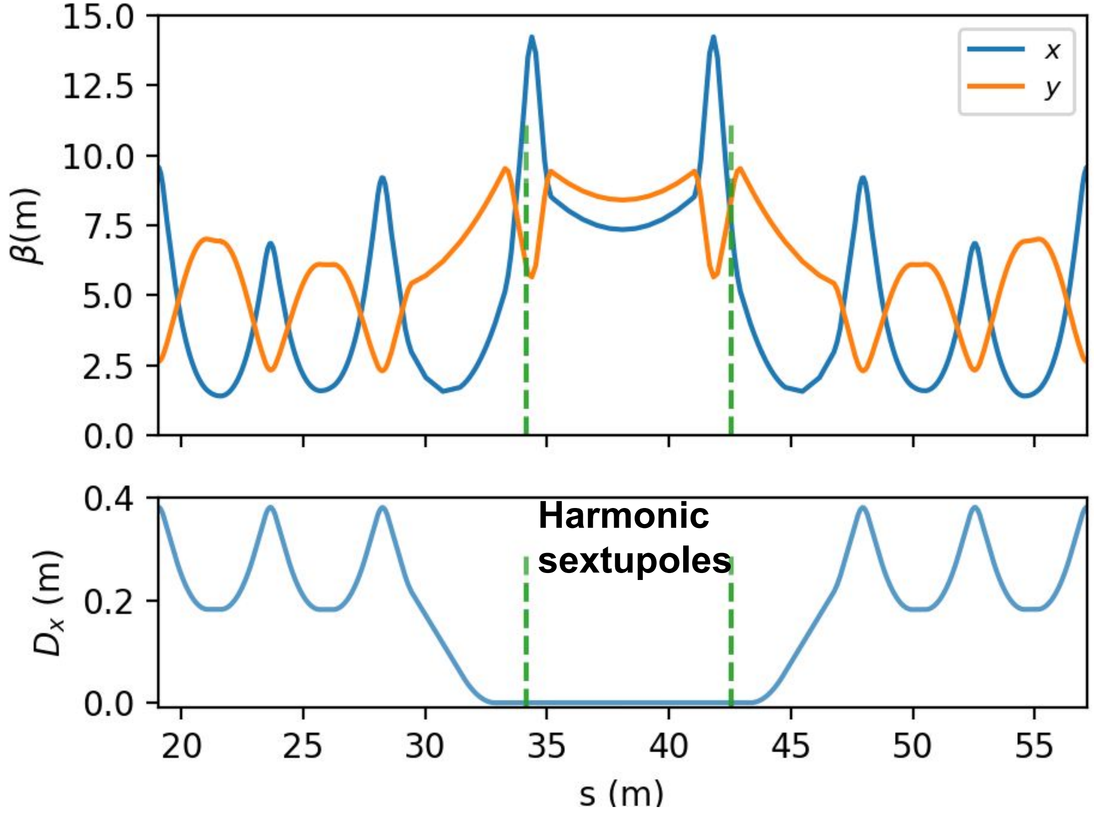
- Two lattices are been considered
- DESY IV will be the successor of DESY II
- Single bunch charge 1 nC
- Emittance (geo.) **20 nm rad**

Setting up the slow extraction

First option: 3h3l lattice

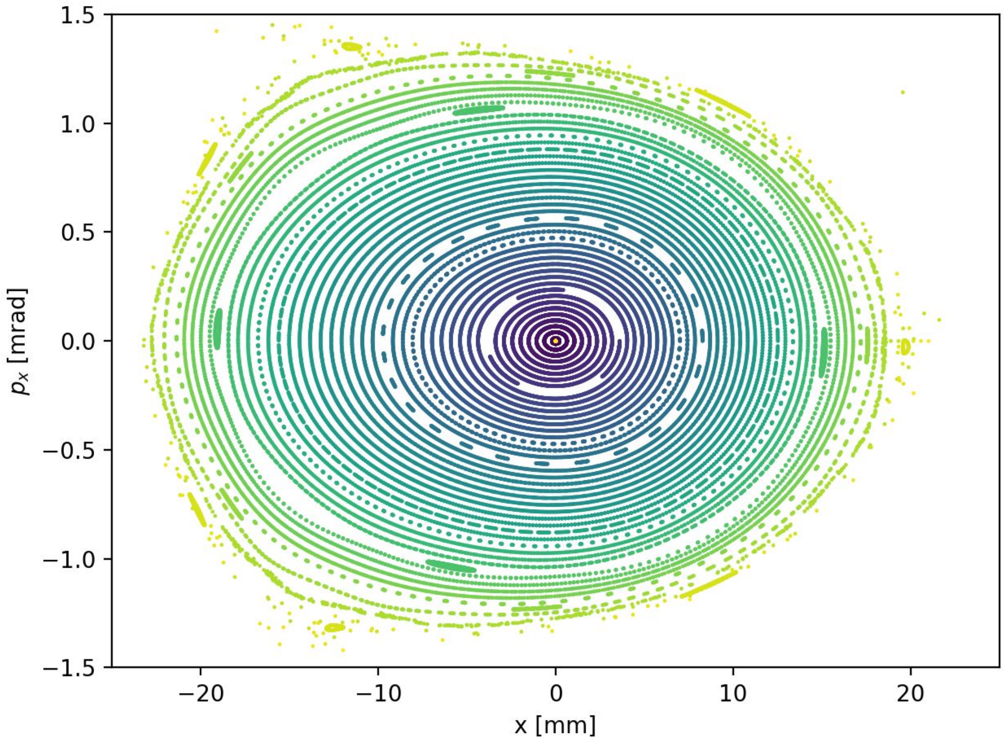


Second option: 8-fold symmetric

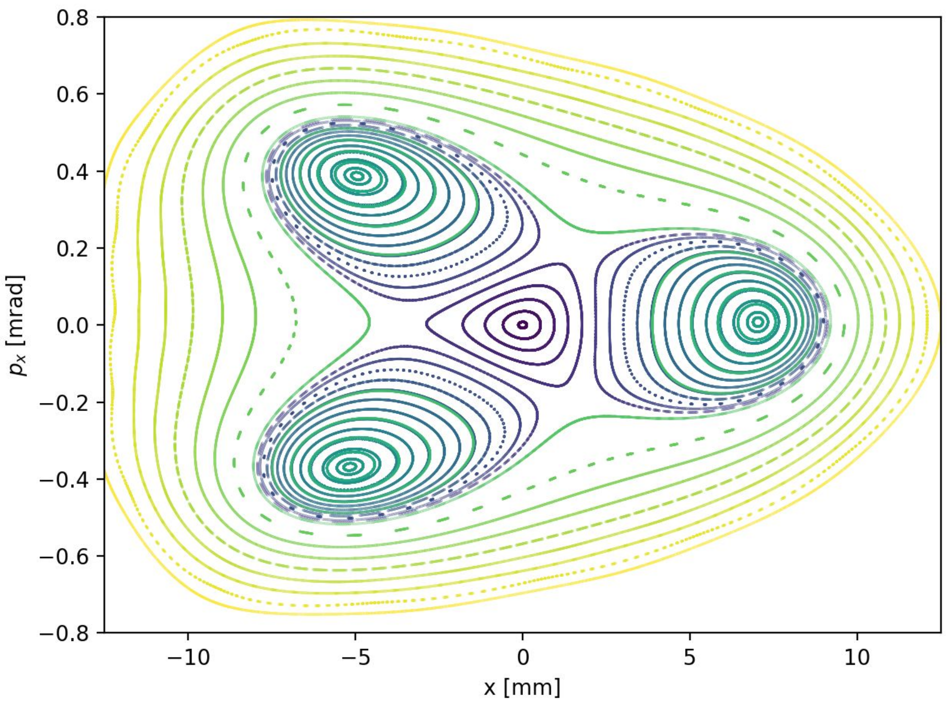


Slow extraction optics

DESY IV phase-space portrait with nominal optics (4D)



DESY IV phase-space portrait with slow extraction optics



- Tune near the resonance
- Chromatic correction sextupoles are ON
- TRIBs are in place

- The 3 RMS beam size is 1.5 mm
- The optics design is reduced to find a set of parameters (S, α_{xx}, δ)

Example: Extraction at 6 GeV

PETRA IV. NEW DIMENSIONS

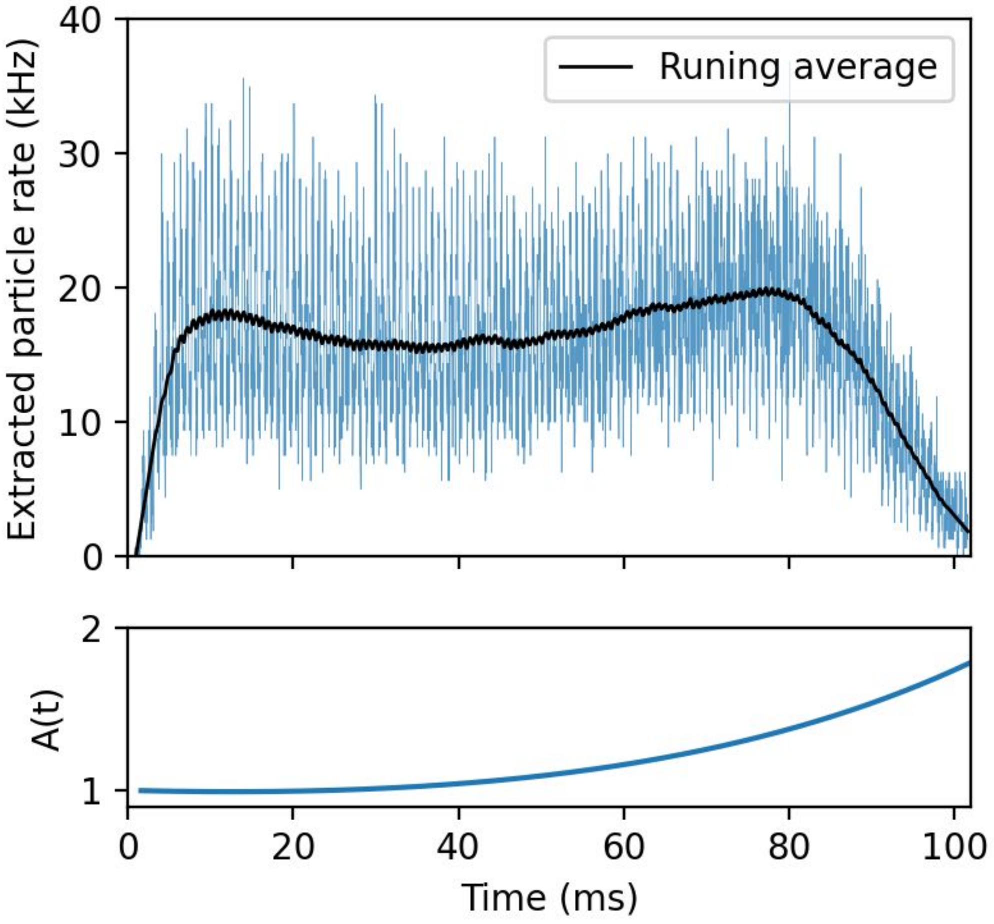


TABLE II. Simulated extraction efficiency with an RF-KO slow extraction.

Septum blade thickness (μm)	3h3l (%)	8-fold (%)
100	65	74
50	81	86
30	90	92

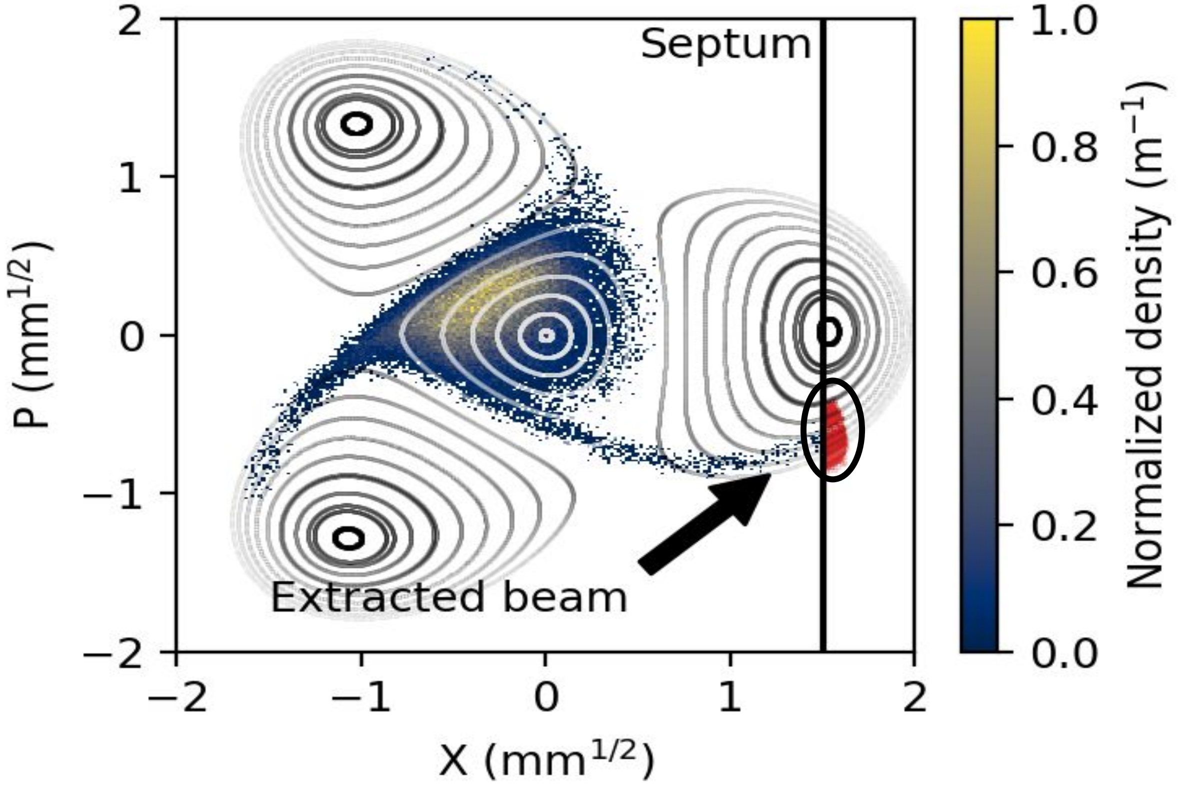
- Excitation: two sine waves and amplitude modulation
- Extraction efficiency at the 80% level
- Beam loss not in ESS at the 0.1% level
- Still some room for improvement but promising results
- The feedback loop has still to be implemented
- More than enough for the test beam users

Summary

- Low emittance lattices require strong sextupoles to correct chromaticity -> They produce an amplitude dependent term
- The dynamics can be well described with an extended version of the Kobayashi Hamiltonian
- The RFKO is a good option for slow extraction at DESY IV
- The design of optics includes three parameters

$$(S, \alpha_{xx}, \delta)$$

- Although the motion is bounded and synchrotron radiation brings the particles back to the stable fixed points a decent extraction efficiency could be achieved



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