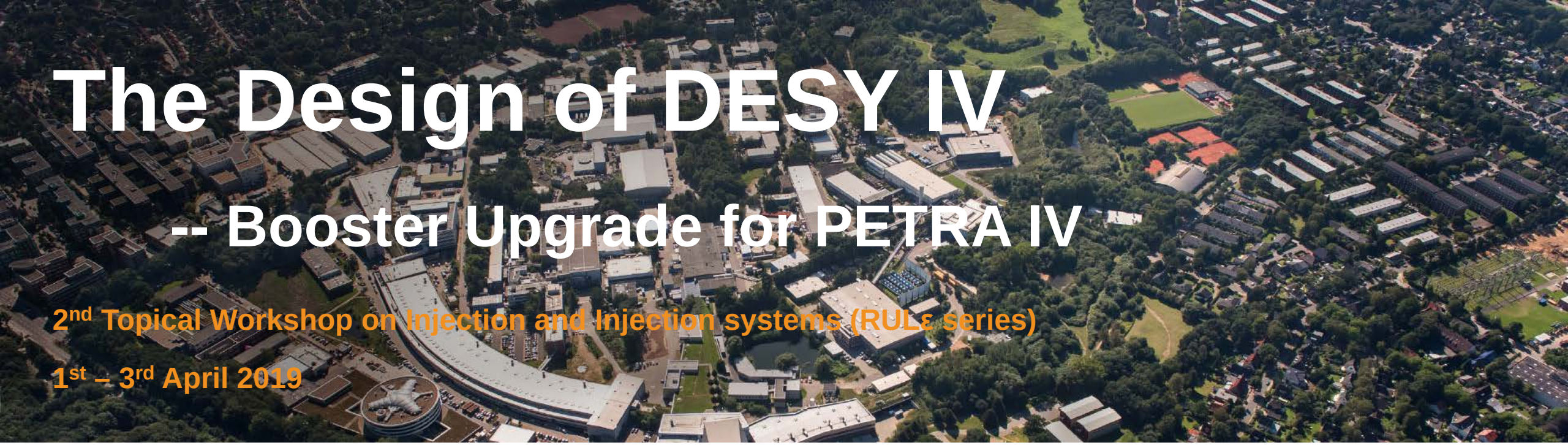


The Design of DESY IV

-- Booster Upgrade for PETRA IV

2nd Topical Workshop on Injection and Injection systems (RULε series)

1st – 3rd April 2019

Hung-Chun Chao
1st April 2019
Villigen PSI, Switzerland

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

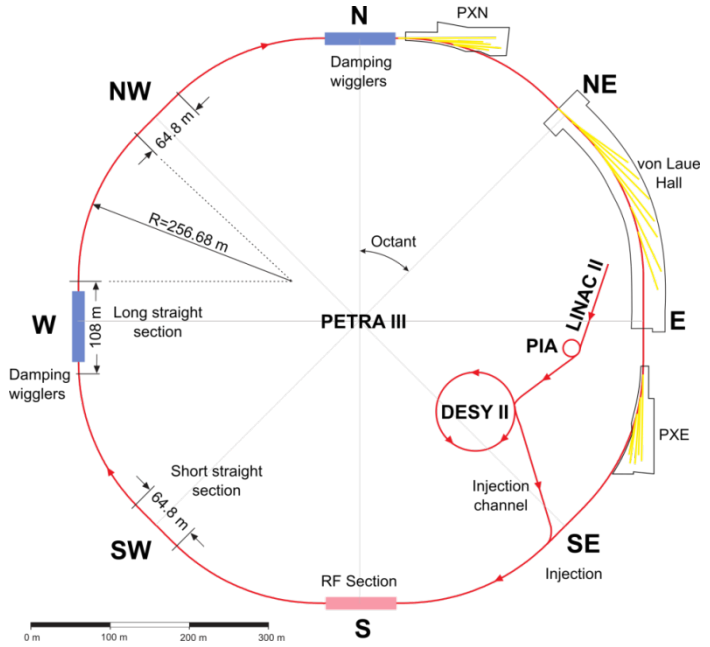
DESY.

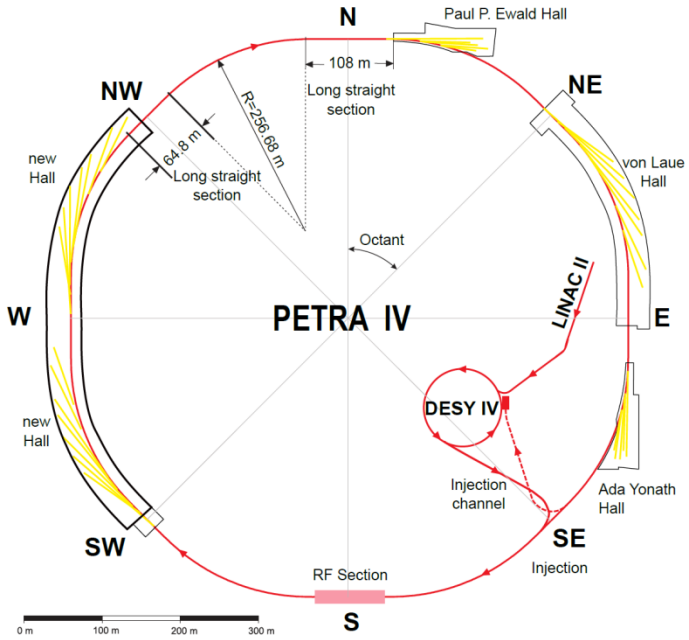
0. Outline

1. Introduction
2. Lattice
3. Layout
4. Orbit Correction
5. Magnets
6. Ramping Dynamics
7. Injections and Extraction
8. Beam Recycle [optional]
9. Summary

1. Introduction

- PETRA IV
  - Inherent PETRA tunnel (2304m w/ 8 arcs and 4+4 “long” straights)
  - 8 * Hybrid 7BA in each arc, emittance = 17 pm-rad (6 GeV), on-axis swap out injection
  - 200 mA 80 bunch trains for brightness mode, 80 mA 80 bunches for timing mode (4.8E10)
- Current injector complex
  - Thermionic DC gun -> Linac II (450 MeV) -> PIA -> DESY II (6GeV)
- Injector considerations
  - Intensity N > 5.4E10, emittance ε < 30nm-rad (DESY II: ε = 350 nm-rad)
  - Obey geometric constraints, Test beam facility, project timeline schedule, timing scheme
  - Beam uniformity, injection efficiency, cost, recycle beam(optional), etc
- Options for injector upgrade
  - ~~Full energy full intensity Linac (6 GeV)~~
  - ~~Linac II -> PIA -> DESY II booster -> Accumulator in PETRA tunnel (expensive)~~
  - Linac II -> DESY II accumulator -> DESY IV booster (low efficiency)
  - Linac II -> PIA -> DESY II booster -> DESY IV accumulator (complicate)
  - Linac II -> PIA -> DESY IV + beam stacking (cheapest)
  - Linac II -> PIA -> DESY IV + beam stacking (cheapest)
  - Linac II (700 MeV) -> PIA II -> DESY IV
  - ✓ Linac II (700 MeV) -> DESY IV (upgrade photocathode RF gun)
  - Laser plasma wakefield accelerator (under discussion)



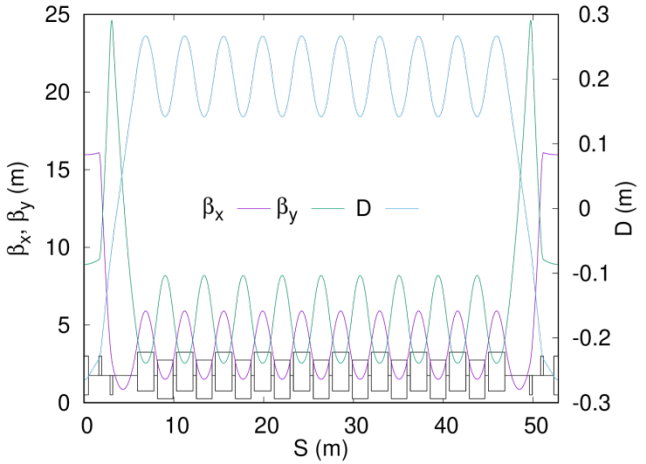


2. Lattice

Linear and non-linear properties

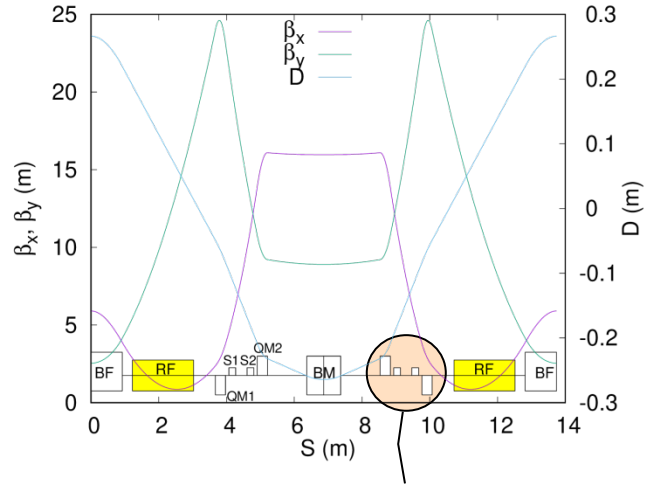
Parameters	Values	
Periodicity	6	
Circumference	316.8 m	
Harmonic Number	528*	
Straight Length	2.745 / 0.935 / 1.165 m	
Working Tune	18.25 / 10.37	
Natural Chromaticity	-22.2 / -19.4	
Damping Partition	-0.36	
Momentum Compaction	3.3 E-3	
Beam Energy	6 GeV	700 MeV
Energy Loss per Turn	4.04 MeV	0.748 KeV
Equilibrium Emittance	19.3 nm-rad	0.261 nm-rad
Equilibrium Energy Spread	1.12 E-3	1.23 E-4
Horizontal Damping Time	2.29 ms	1.44 s
Vertical Damping Time	3.14 ms	1.98 s
Longitudinal Damping Time	1.92 ms	1.12 s

* Use 500 MHz RF, h_{P4}/h_{D4}=80/11

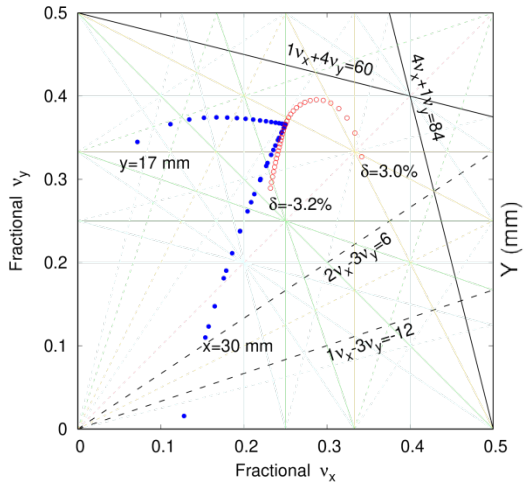


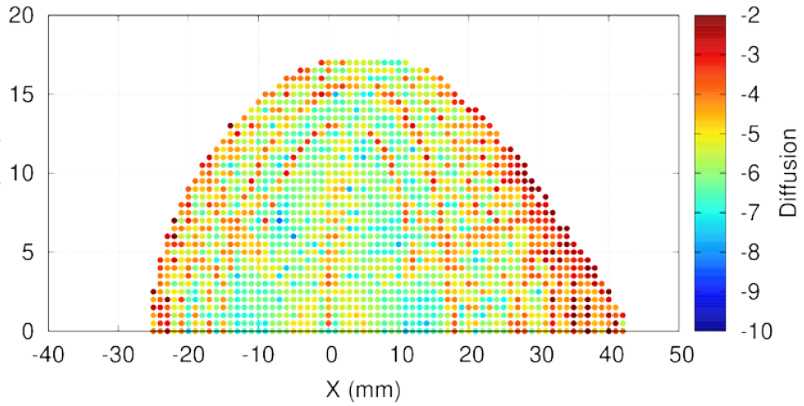
37 cm gap

Insertion Section



Dynamic tuning



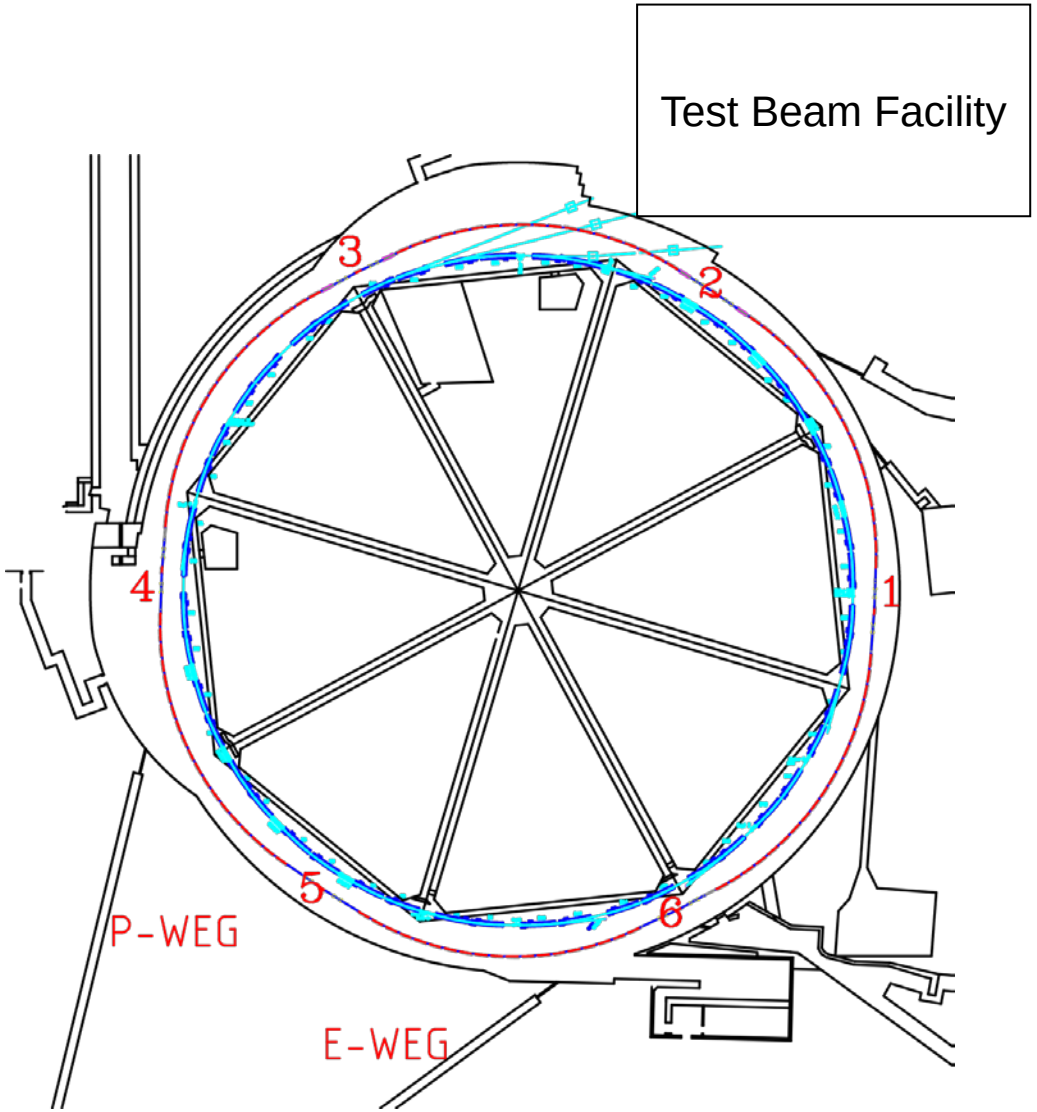


DA without errors (4D tracking)

3. Layout

Six insertion sections

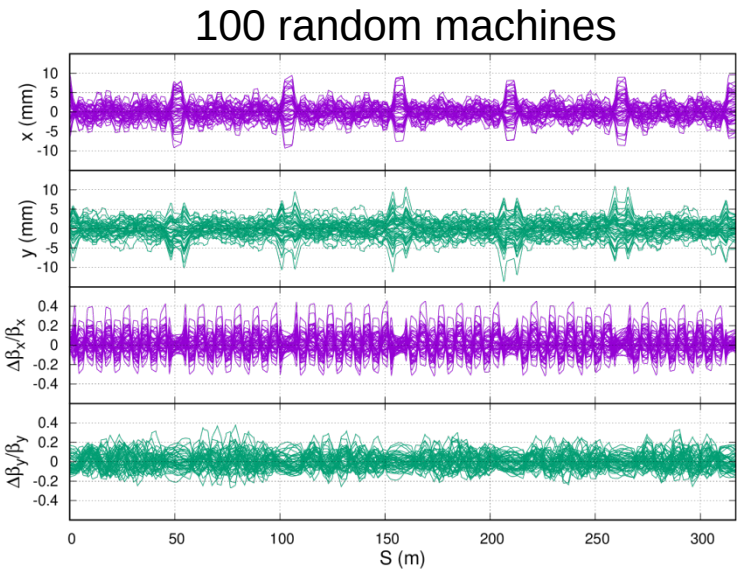
- The abandoned DESY III will be removed.
- DESY IV shares the tunnel with DESY II.
- It goes counter-clockwise. (opposite to DESY II)
- 6-fold symmetries: 3 insertion sections are for cavities and 3 for injections/extraction
- Insertion #1 has two fast bumpers and one septum installed for the low energy off-axis injection.
- Insertion #2, 3, 5 house 5 RF modules (one spare) and 1 harmonic cavity (optional).
- Insertion #4 has two bumpers, one fast kicker, and one or more septums for the extraction.
- Insertion #6 has some elements for the injection of the recycled beam.
- Insertion #4 and 6 are geometrically symmetric w.r.t transport lines.
- Test beam facility beamlines are extracted (from BD) around 3 o'clock position.



4. Orbit Correction Schemes

Different configurations

- Error sources
  - Alignment errors:
    - –Δx = 0.1 mm, Δy = 0.1 mm
    - –Δφ (rolling angle) = 0.2 mrad
  - Field errors:
    - – Dipole: 0.02%, Quadrupole: 0.2%
- Beam stay clear (BSC=3σ beam size + max COD) without orbit correction is estimated
  < 15 mm at insertion sections and
  < 12 mm at FODO-arcs
- Correctors ramp with energy
- Configuration C5 is efficient. (max str < 0.6 mrad)



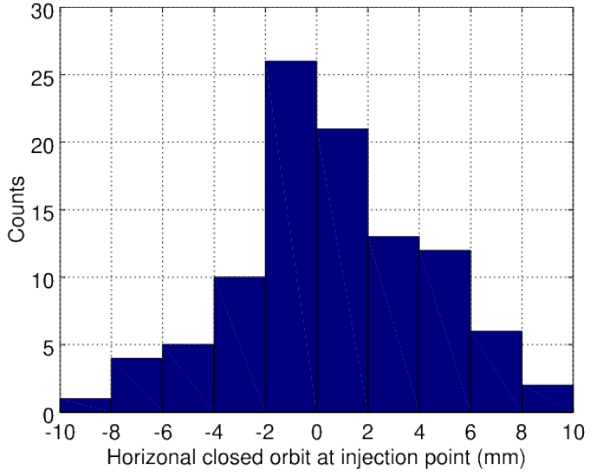
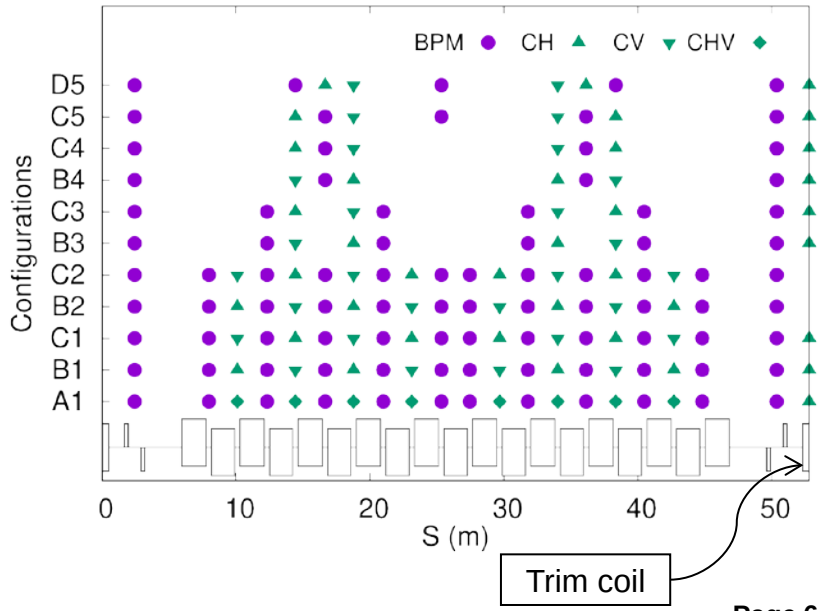


Table 4: Different correction schemes comparison.

Case	Number of elements			Strengths (mrad)				Before correction (mm)				After correction (mm)			
	BPM	CH	CV	Horizontal		Vertical		Horizontal		Vertical		Horizontal		Vertical	
				std	max	std	max	std	max	std	max	std	max	std	max
D5	30	18	12	0.12	0.96	0.15	0.52	1.34	4.84	1.60	8.20	0.09	0.88	0.41	1.83
C5	30	18	12	0.09	0.59	0.17	0.59	1.38	4.84	1.61	8.20	0.07	0.47	0.28	1.88
C4	24	18	12	0.09	0.60	0.23	1.08	1.45	4.84	1.71	8.20	0.05	0.23	0.22	2.15
B4	24	18	12	0.14	0.99	0.15	0.68	1.45	4.84	1.71	8.20	0.07	0.27	0.43	1.80
C3	36	18	12	0.08	0.51	0.18	0.86	1.26	4.84	1.54	8.20	0.13	0.91	0.40	2.58
B3	36	18	12	0.11	0.70	0.15	0.67	1.26	4.84	1.54	8.20	0.11	0.88	0.46	2.29
C2	72	24	24	0.10	0.57	0.10	0.51	1.16	4.84	1.37	8.20	0.21	1.31	0.28	1.51
B2	72	24	24	0.10	0.51	0.10	0.57	1.16	4.84	1.37	8.20	0.17	1.03	0.31	1.46
C1	72	30	24	0.07	0.51	0.10	0.51	1.16	4.84	1.37	8.20	0.10	0.79	0.28	1.51
B1	72	30	24	0.08	0.58	0.10	0.57	1.16	4.84	1.37	8.20	0.10	0.73	0.31	1.46
A1	72	54	48	0.06	0.43	0.13	0.61	1.16	4.84	1.37	8.20	0.05	0.53	0.18	1.28

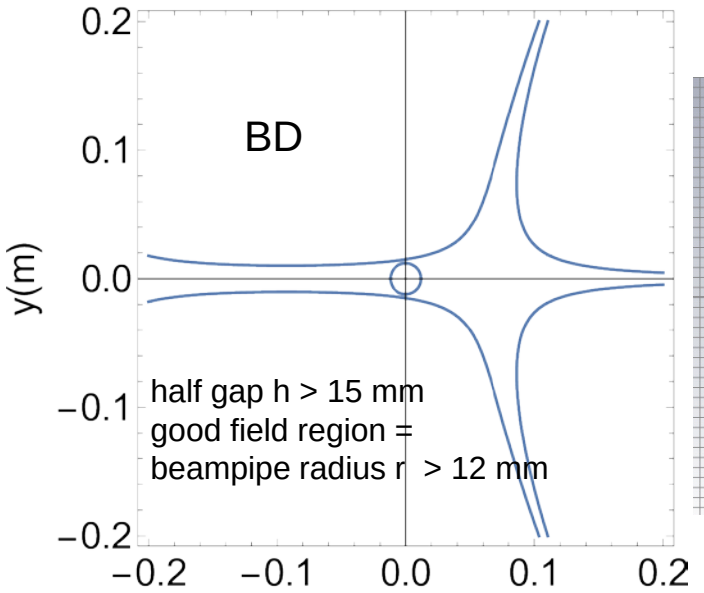


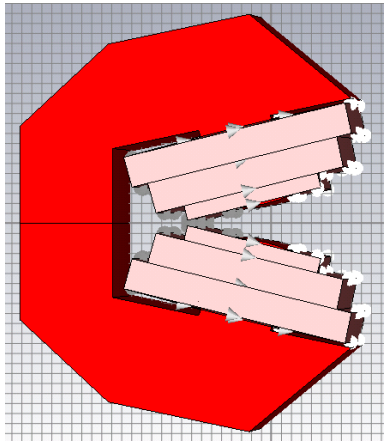
5. Magnets

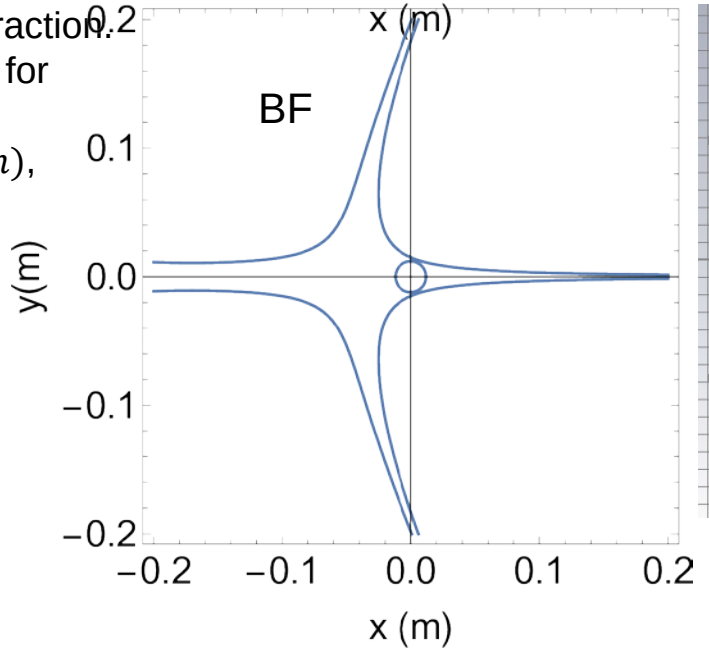
Combined function magnets

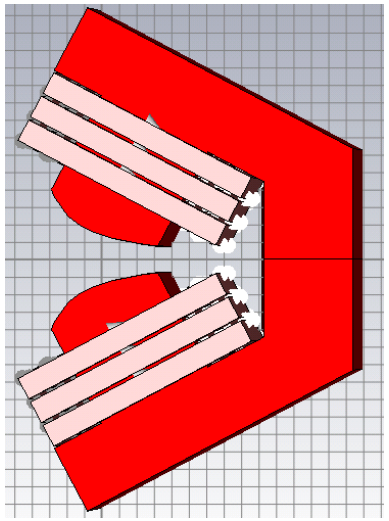
Magnet	BD	BF	BM	QM1	QM2	S1	S2
L (m)	1.75	1.85	1.00	0.3	0.3	0.2	0.2
B_0 (T)*	0.86	0.35	0.90				
K_0 (m^{-1})	0.043	0.0175	0.045				
K_1 (m^{-2})	-0.44	0.49		-1.84	1.66		
K_2 (m^{-3})	-4.78	2.89				3**	3**
# Elements	54	60	6	12	12	12	12

* Estimated at 6 GeV
** Maximal sextupole strengths normalized at 6 GeV







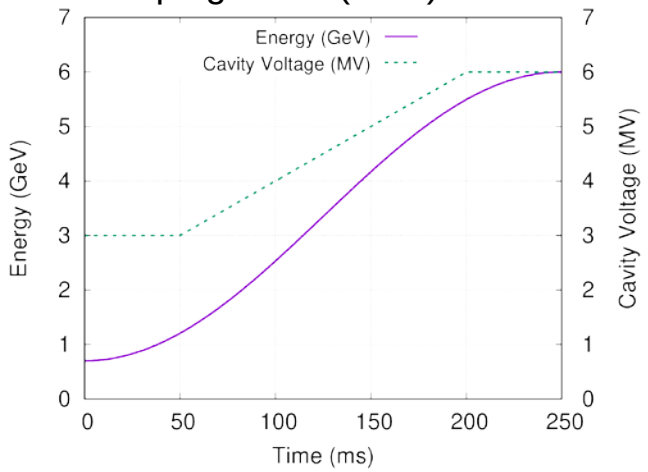


- BM is a C-type pure function dipole for the consideration of beam injection/extraction.
- Programmable independent power supplies for quad trim coils and sextupoles for dynamic tunning
- The ideal pole faces follows the equi-potential lines equation $\Phi(x,y) = \Phi(0,\pm h)$,
- where the 2D scalar potential is $\Phi(x,y) = K_0 y + K_1 xy + \frac{K_2}{6}(3x^2y - y^3)$.
- Defining $p \equiv \frac{2K_0}{K_2} + \frac{2K_1}{K_2}x + x^2$ and $q \equiv \frac{h^3}{2} - \frac{3K_0}{K_2}h$, around $x = 0$,
  - $y = \pm 2\sqrt{p}\cos(\frac{1}{3}\cos^{-1}(p^{-3/2}q) - \frac{2\pi}{3})$ for BF
  - $y = \pm 2\sqrt{|p|}\sinh(\frac{1}{3}\sinh^{-1}(|p|^{-3/2}q))$ for BD
- The actual pole faces need to be tweaked.
- Use H-type magnets instead of C-type

6. Ramping Dynamics

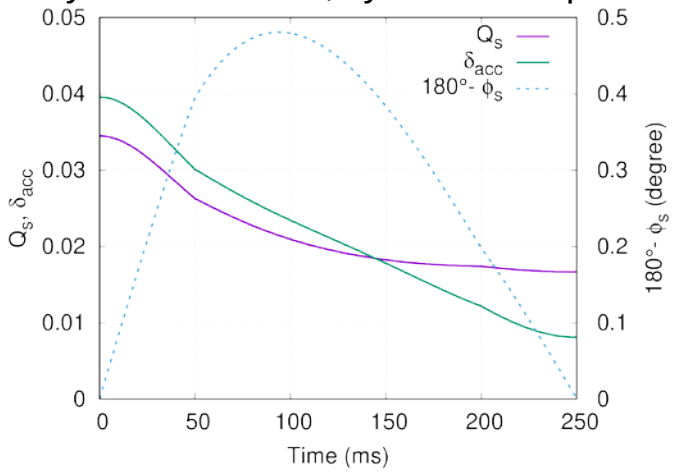
Repetition rate = 2~5 Hz

- Ramping curve (2 Hz)

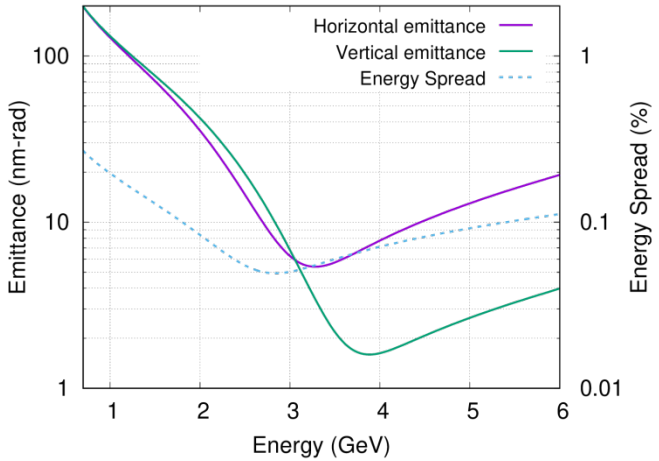


- Repetition rate is 2~5 Hz (default: 2 Hz)
- 500 MHz 5-cell PETRA cavity is used.
- Energy ramps from 0.7 MeV to 6 GeV sinusoidally.
- Initial RF voltage has to be large enough to accommodate 3 successive bunches from LINAC (Vi>1.8 MV)
- Final RF voltage has to provides sufficient longitudinal quantum lifetime (Vf >5.5 MV).

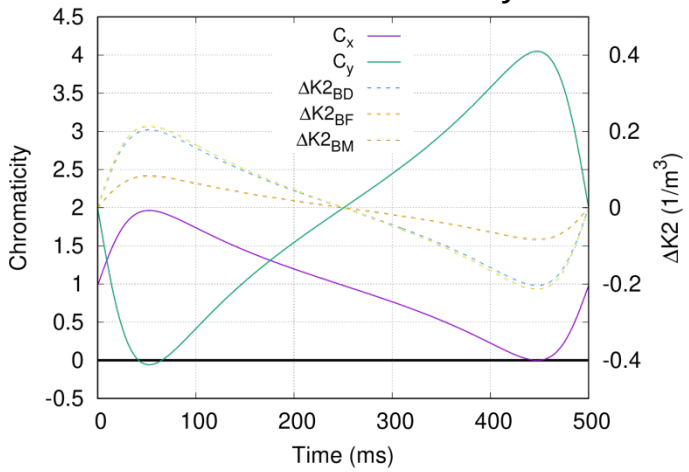
- Change of energy acceptance, synchrotron tune, synchronous phase



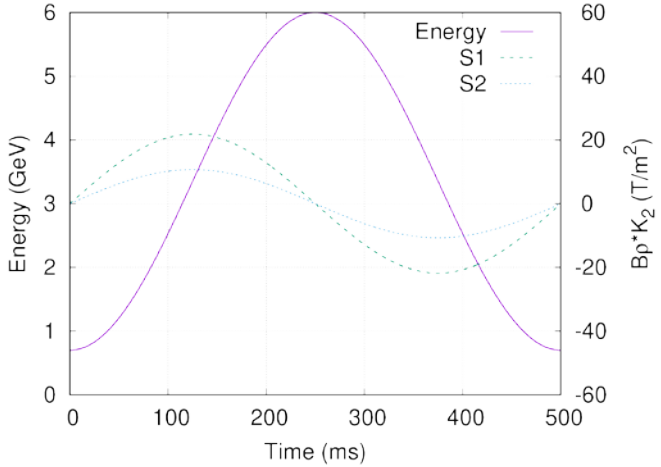
- Damping of the emittance and energy spread



- Eddy currents induced sextupole fields and the chromaticity shifts



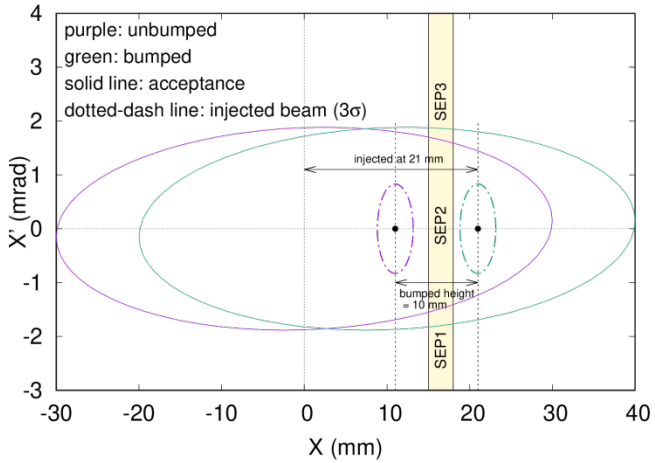
- Required additional sextupole strengths to compensate chromaticity shifts



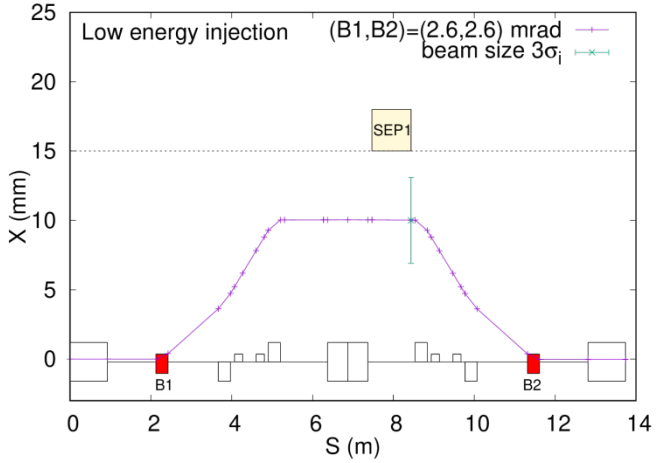
7. Injections and Extraction

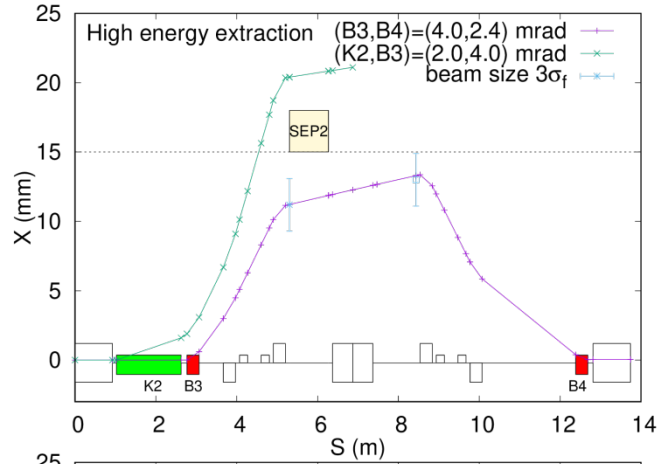
Based on π-bump

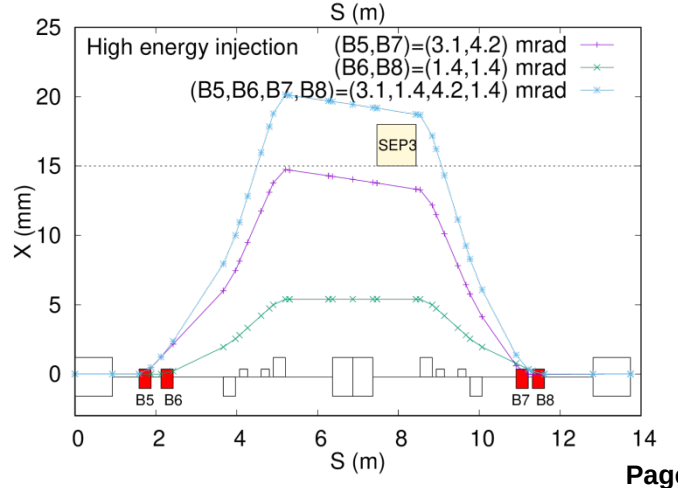
- Orbit bumps can also be used to control intensity.
- Needs intensity feedback system and sophisticated timing system for smart control of intensity
- The big dynamic aperture and orbit bumps enable the off-axis injection
- Use a four-kicker bump at high energy re-injection.
  - The bump is decomposed into 2 orthogonal interleaved π-bumps which can be independently controlled.
  - One is slow and stronger bump and the other is fast and weaker bump.
- Purposes of back-injection:
  (1) ramp-down->dump (2) recycle (replenish)



Assume the injected beam with 700 MeV and $\varepsilon_x = \varepsilon_y = 200$ nm-rad, $\sigma_\delta = 0.27\%$.







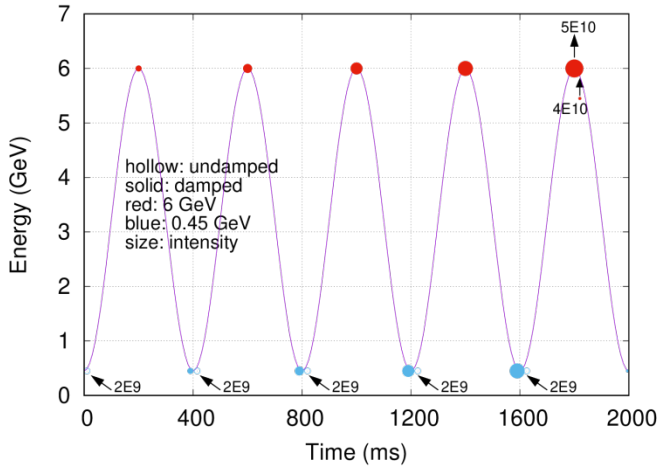
Magnet	B1/B2	K2	B3	B4	B5	B7	B6/B8
Length (m)	0.3	1.6*	0.3	0.3	0.3	0.3	0.3
Energy (GeV)	0.7	6	6	6	6	6	6
Deflection Angle (mrad)	2.6	2.0	4.0	2.4	3.1	4.2	1.4
Peak Field (mT)	20	25	267	160	207	280	93
Pulse Speed (μs) (rise / width / fall)	-/0.08/3.9	0.9/0.08/-	~ms	~ms	~ms	~ms	-/0.08/3.9

* Can be divided into more pieces

8. Beam Recycle (Optional)

Different ways to prepare high intensity beam

- Other than a new RF photocathode gun, possible alternative options for high intensity beam preparation are proposed. Two of them recycle the swapped-out beam into the booster.



1. [***Recycle beam first + top up at low energy***]

   - Reverse the high energy extraction as high energy injection
   - The recycled bunch can be replenished by fresh bunch at low energy by the method of transversely beam stacking with varying energy.
     (1) Take the swapped-out beam as the first beam
     (2) Ramp the beam energy down and fetch a fresh bunch in low energy injection section.
     (3) Raise the energy until the two bunches are fully damped and merged.
   - This method also provides a way to accumulate the beam in the booster.
     In such case step (1) is skipped and step (2) and (3) are repeated multiple times until the desired intensity is reached.
   - Concerns about particle loss during ramping. Instability is more significant at low energy.

2. [***HEPS option, pour recycled beam after***]

   - Firstly inject fresh bunches from LINAC and accelerate to 6 GeV, then pour the swapped-out beam to be merged with the existing beam.
   - Use a four-kicker bump for injection. This hardware configuration also works for the first option.
   - Need more precise orbit control

3. [***Phase space painting***][***No recycle***]

   - Accelerate two bunches painted at low energy [NSLS2, PRSTAB 14, 020101]

9. Summary

- Choose the feasible, simplest option for injector complex upgrade
  - New booster DESY IV with upgraded RF gun/LINAC II and without accumulator PIA
- DESY IV features
  - Tight ring fit into DESY tunnel
  - Small emittance by combined function magnets
  - A section dedicated for recycled beam injection
  - Independent programmable power supplies for trim coils in quads and sextupoles for dynamic tuning during ramping
  - π-bumps for injections and extraction
  - Simplified orbit corrector scheme
  - Ramping dynamics and beam recycle options for high intensity beam preparation are discussed.
  - DESY IV is the complement of PETRA IV.
- To-be-complete
  - Magnet design is underway. (pulsed/ramping)
  - Errors tolerance study
  - Impedance and instability study (Impedance budget for TMCI: $Z_{t,eff} < 0.6$ MΩ/m [Y.-C.Chae])
  - Intensity control and timing systems development
- **Thanks everyone!**