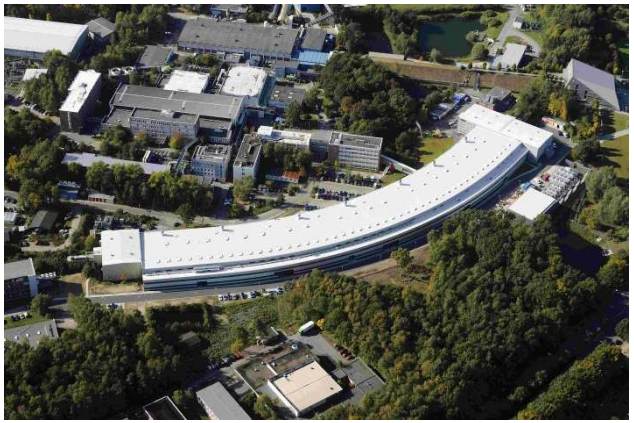
PETRA IV.

- **Conceptual Ideas, Physics Case**
- **Design Strategy, Status of the Lattice Design**
- **Technical Implications**



Rainer Wanzenberg
DESY - MPE -

7th Low Emittance Rings Workshop
Jan 15-17, 2018
CERN, Geneva

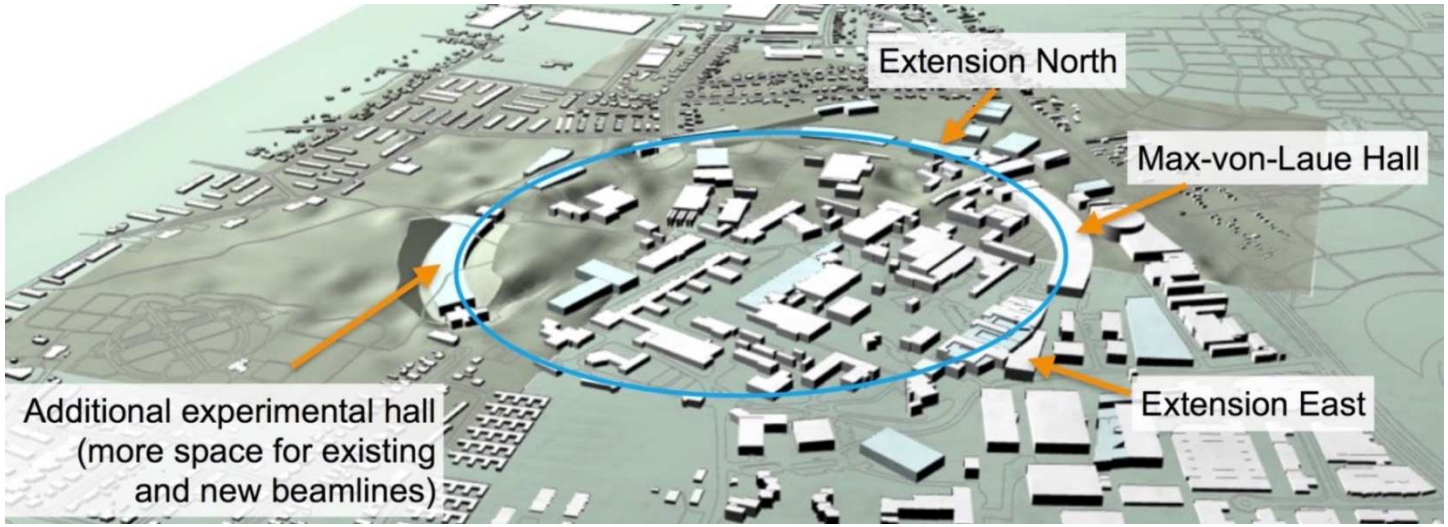
HELMHOLTZ ASSOCIATION

PETRA IV – conceptual ideas

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

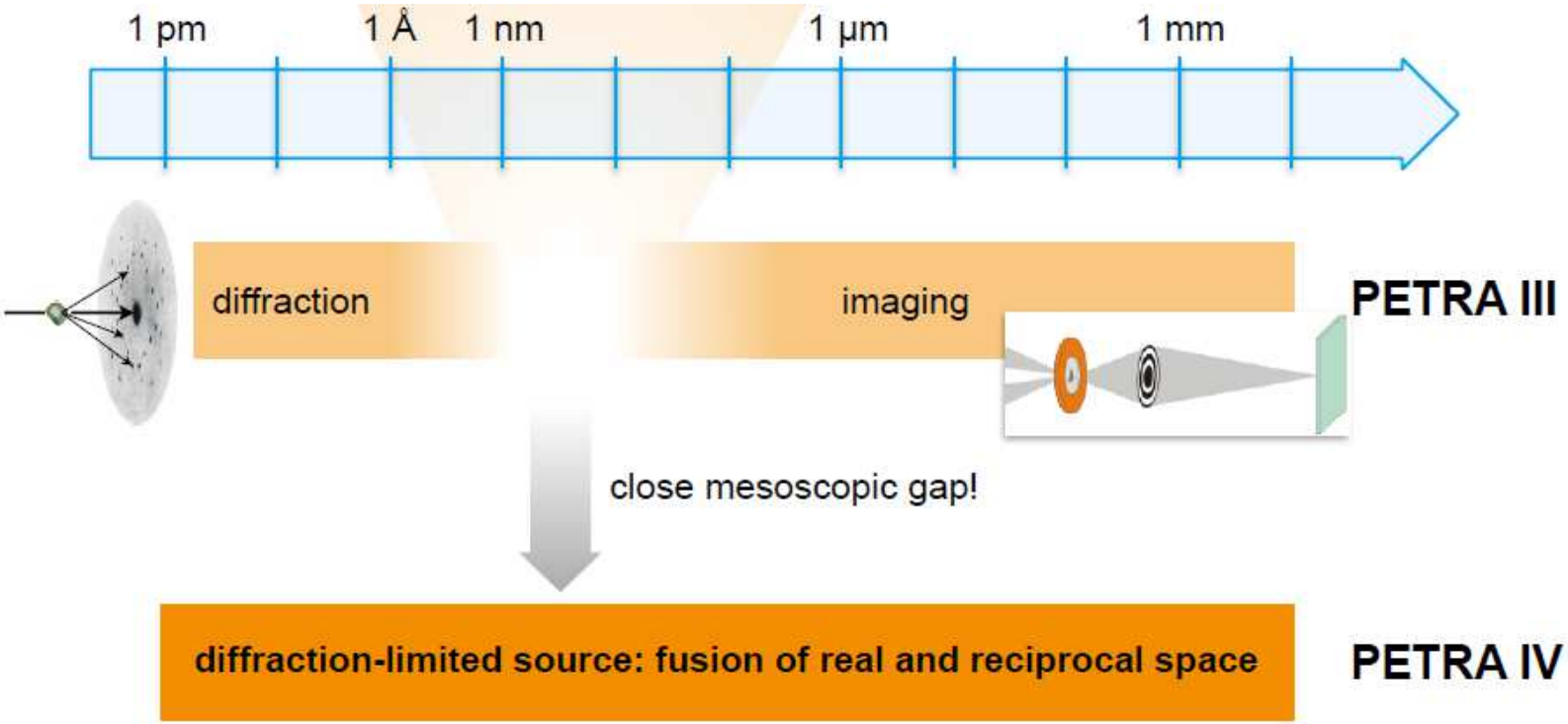


Understanding the Complexity of Nature

Bright, Tailored X-Rays
3D imaging on all length scales
spatially resolved properties:
chemical , mechanical, electronic, magnetic

structure and dynamics of biological molecules
dynamics in disordered systems
tracking of physical/chemical processes (nano seconds to days)

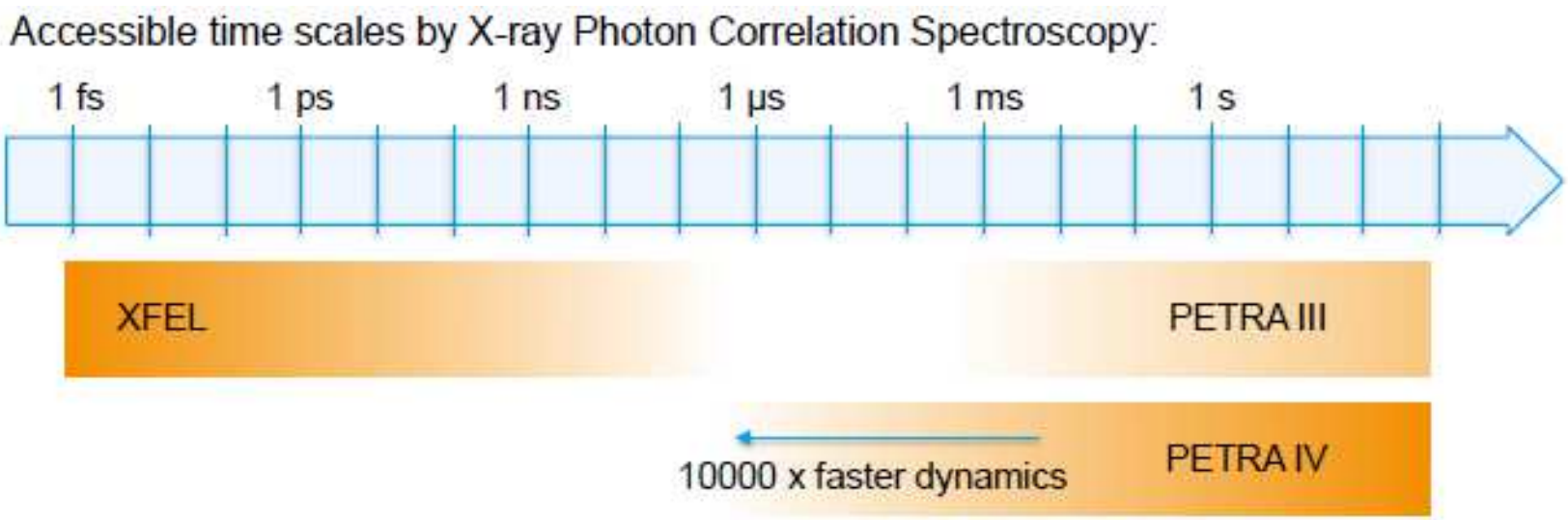
Closing the Gaps in the Complexity Window



PETRA IV – science case (cont.)

Understanding the Complexity of Nature

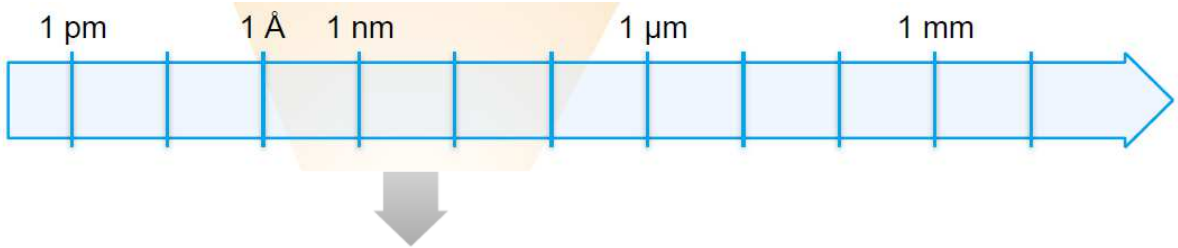
Closing Gaps in the Time Domain of Complexity



XFEL and PETRA IV are complementary

Closing the Gaps in the Complexity Window

Bohr radius of the hydrogen atom 0.053 nm



diffraction-limited source: fusion of real and reciprocal space

PETRA IV

$$\Delta x \cdot \Delta\theta \geq \frac{\lambda}{4\pi}$$

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

8 pm ~ vert. emittance of PETRA III

PETRA IV: horz. emittance in the range of the vert. emittance of PETRA III

$$\epsilon_\lambda = \sigma_\lambda \sigma'_\lambda, \qquad \sigma_\lambda = \frac{1}{2\pi}\sqrt{\frac{\lambda L_u}{2}}, \qquad \sigma'_\lambda = \sqrt{\frac{\lambda}{2 L_u}}$$

Brilliance

Brillance: > 10^{22} Photons / (sec mrad^2 mm^2 0.1 % BW)

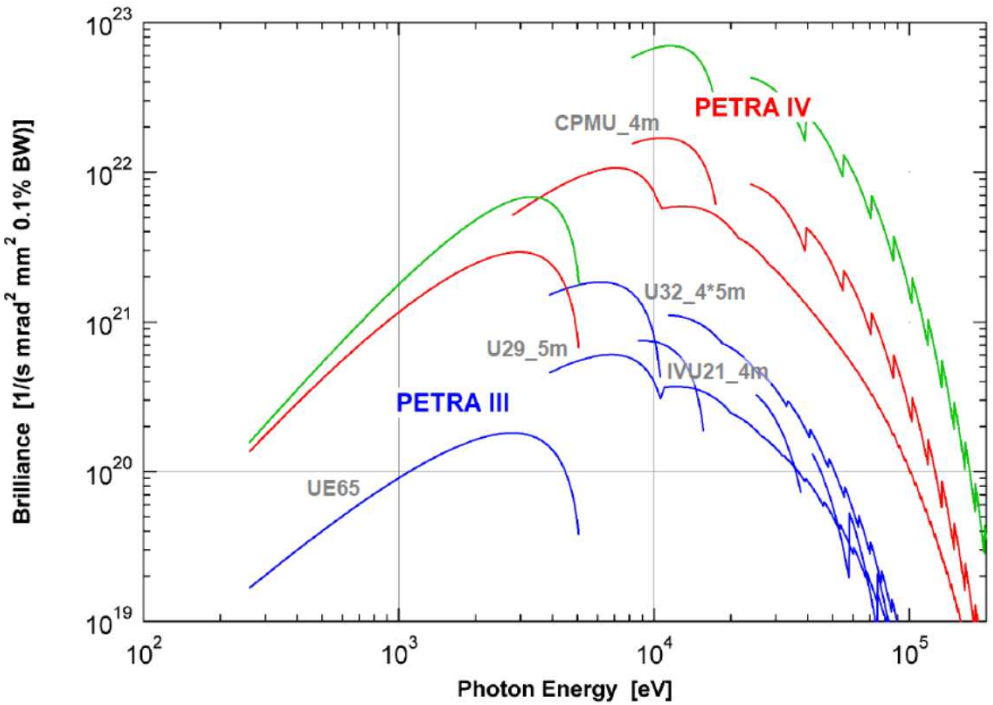
angle integrated photon spectral flux (undulator, beam intensity)

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

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

(Courtesy Markus Tischer)

Design Strategy

Lattice Design

Design goal: get an large dynamic acceptance
(ideal case: off-axis injection is possible)

- design based on a hybrid seven bend achromat (scaled from ESRF-EBS cell)
- option for the arc cells without undulators
  - cell with phase advance of π between sextupoles, double -I cell
    (first approch with: double twist in 4D-phase to enable chromatic correction in both planes)

Injectors

Design goal: reuse most parts of injector chain

- studies to improve emittance, including a new lattice for the synchrotron
- investigation of the technical requirements to maintain operation until 2045
- studies toward a new injector : additional booster ring, or linac

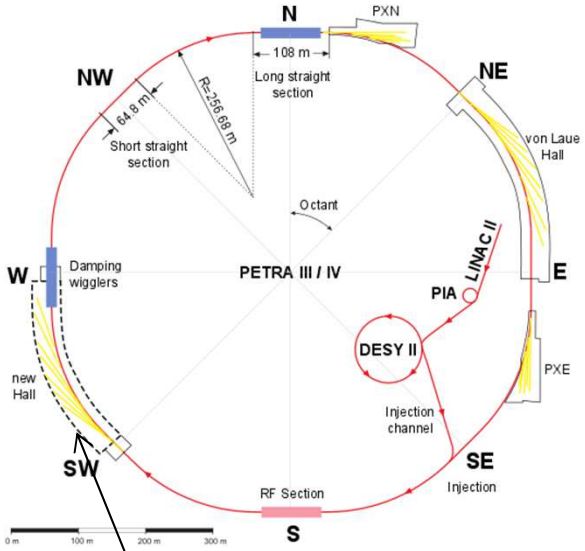
Technical design

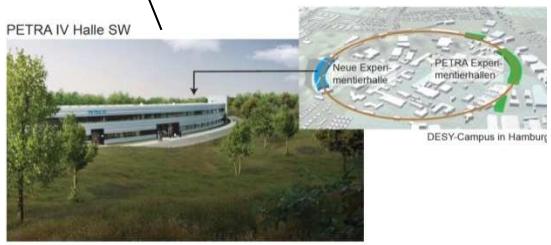
Investigation of the technical limits and possibilities at an early stage before a lattice design is finalized

- magnet design: design studies of quads, sextupoles, combined function magnets and dipoles with longitudinal gradient
- girder design: investigation of concepts with new materials, studies of alignment and installation concepts
- vacuum design: modeling of the system with small chambers
- fast kickers: on axis injection

PETRA IV – Lattice design status

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)	$0.82\cdot10^{-3}$ ($1.23\cdot10^{-3}$)	$0.73\cdot10^{-3}$ ($1.44\cdot10^{-3}$)
Energy loss/turn U_0 (with DW)	1.3 MeV (5.1 MeV)	1.37 MeV (4.6 MeV)
Momentum compaction factor α_c	$1.13\cdot10^{-3}$	$1.46\cdot10^{-5}$
Max. gradient g	17 T/m	100 T/m
Dispersion D_x at SF	750 cm	4.2 cm

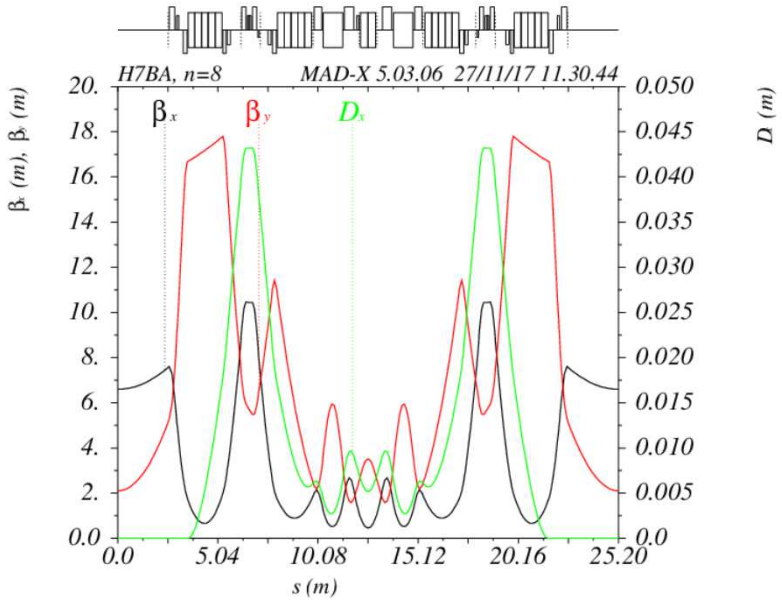


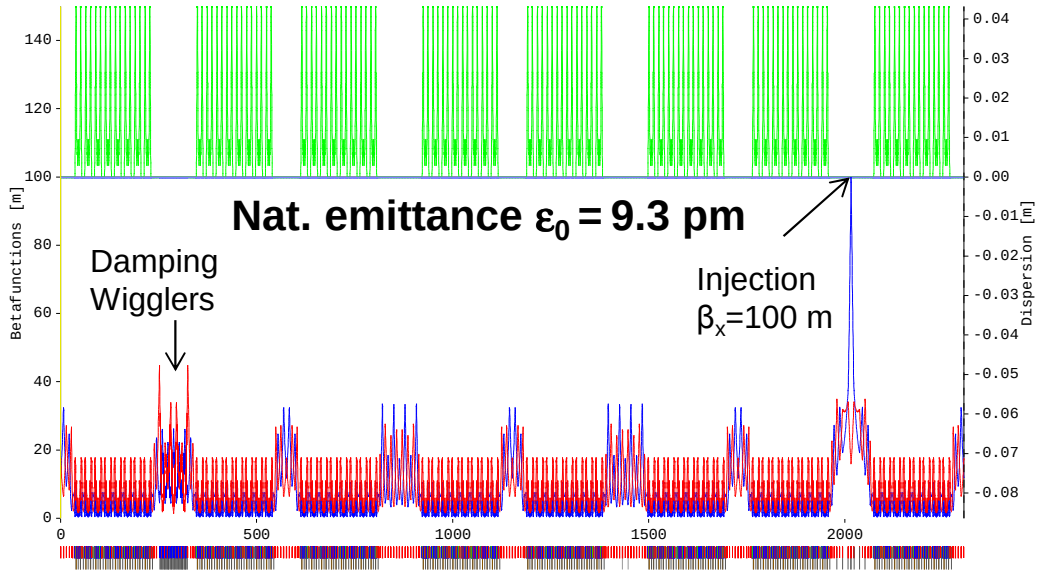


"Reference Lattice"

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

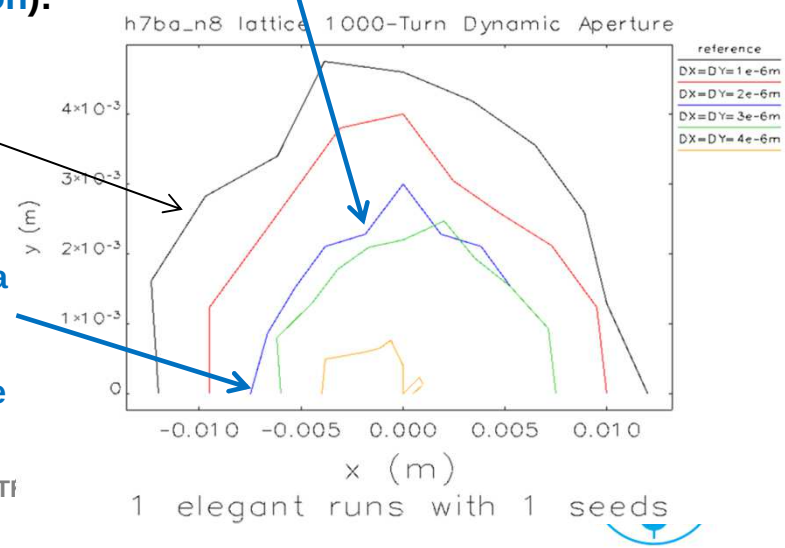
PETRA IV – Reference lattice, H7BA





- RF: 500 MHz, 6 MV, bucket height=3.3%
- A_x = 1.35 mm·mrad Dynamic acceptance
- A_y = 1.24 mm·mrad (6 D tracking, no errors)

sensitivity to errors (2 µm rms, all magnets, no correction):

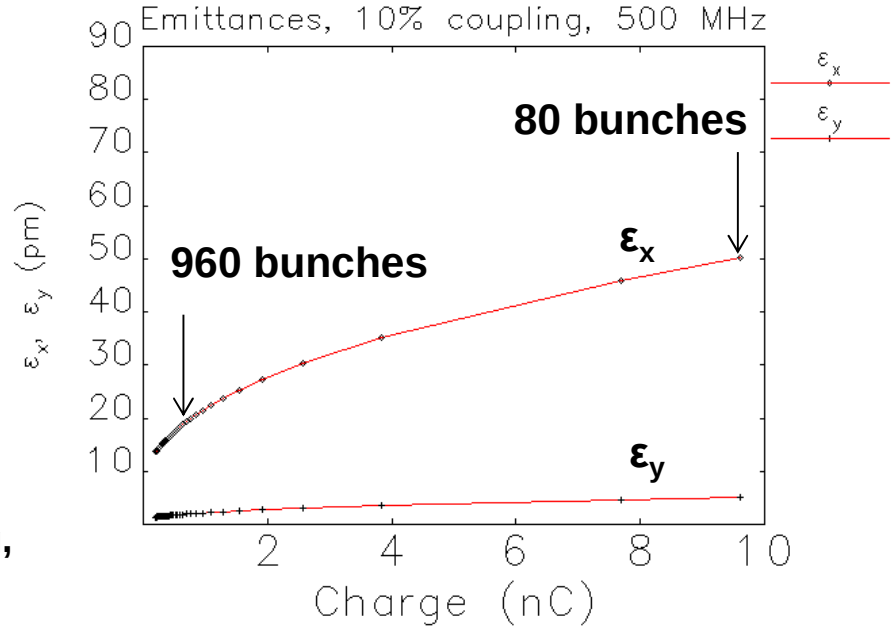


The DA is reduced by a factor 2 with respect to the ideal one

- an on axis injection seems to be required for a safe injection (with errors)

Intra beam scattering

Parameter	Continuous mode	Timing mode
Total current	100 mA	100 mA
Bunches	960	80
Bunch charge	0.77 nC	9.6 nC
Emittance (horz.) (vert.)	20 pm 2 pm	50 pm 5 pm
Energy spread	$1.5 \cdot 10^{-3}$	$1.7 \cdot 10^{-3}$
Touschek Lifetime	3.9 h	0.4 h



Intra beam scattering: Multiple Coulomb scattering, theory by A. Piwinski (1974)

$$\frac{1}{\tau_x} = \left\langle A \left[f(1/a, b/a, q/a) + \frac{{D_x}^2 {\sigma_h}^2}{{\sigma_{x\beta}}^2 f(a,b,q)} \right] \right\rangle \qquad A \sim \frac{N_0}{\gamma^4 \, \epsilon_x \, \epsilon_y \, \sigma_s \, \sigma_p}$$

Beam intensity

- **Using 1920 bunches** (not equally spaced) **would imply**
  - **200 mA operation with the same parameters or**
  - **100 mA operation with an emittance of 16 pm**
- First estimates indicate that the total current in the timing mode will be only 80 mA due to collective effects

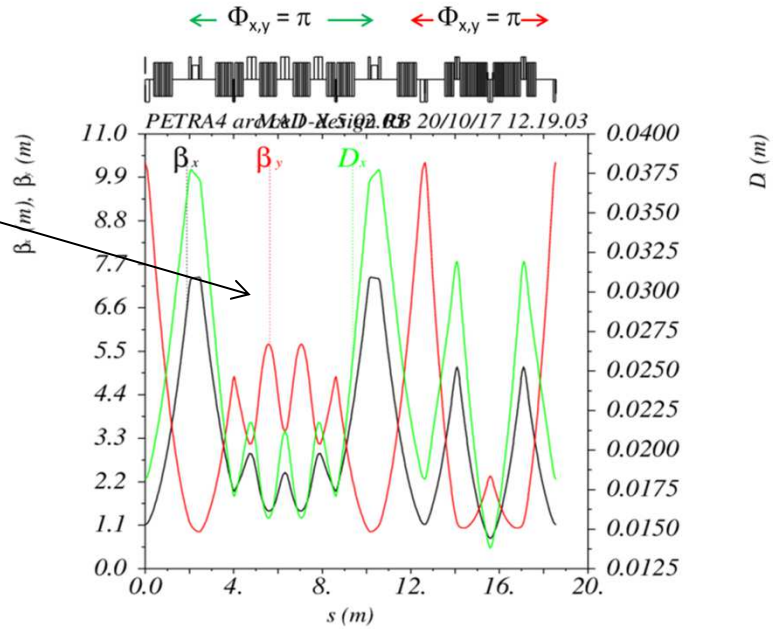
PETRA IV – Lattice design, beyond the H7BA

1. **-I Schemes**

- **Twist-lattice**
- **non interleaved double –I cells**

potential for larger transverse acceptance

seems to be limited for rings
with ε_x **~ 30 pm (nat. emittance)**
(non local chromatic correction)



2. **FODO type lattice in octants with no undulators**

first investigations did not lead to a satisfactory solution

Two cell types: Non interleaved double –I cell (on IDs), H7BA (cells with IDs)

Reduced sextupole strength in the H7BA

⇒ **larger DA ~ 4 mm mrad (factor 2.8 better)**
less sensitive to errors
off axis injection seems to be possible

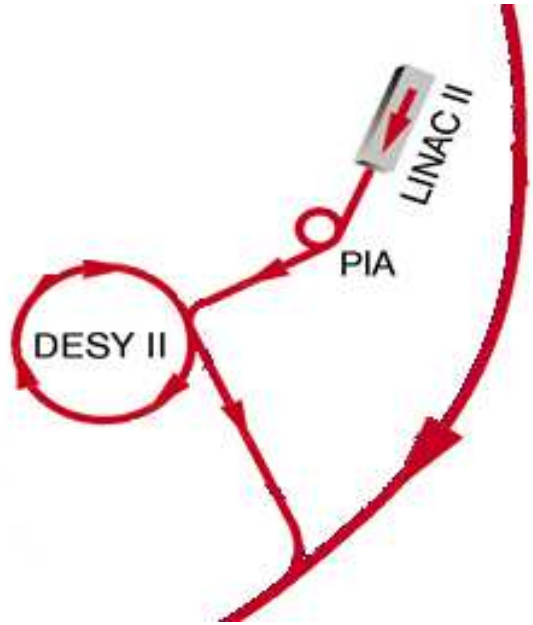
PETRA III/IV Injectors

Design goal: reuse/up-grade the injector chain

Linac
S-Band Linac (450 MeV)

PIA (accumulator ring)
10 ns Linac pulse → 500 MHz bucket

DESY II
450 MeV → 7 GeV,
Emittance (6 GeV) x/y ~ 350/15 nm
Intensity: max. 2 x 10^{10}, typical 1 x 10^{10}



Studies have started on the possibilities to improve the booster emittance

→ **With beam optics optimization + damping partition shift of present optics one may get ~200nm @6GeV**

→ **Rebuilding ring with smaller emittance lattice: DESY IV**

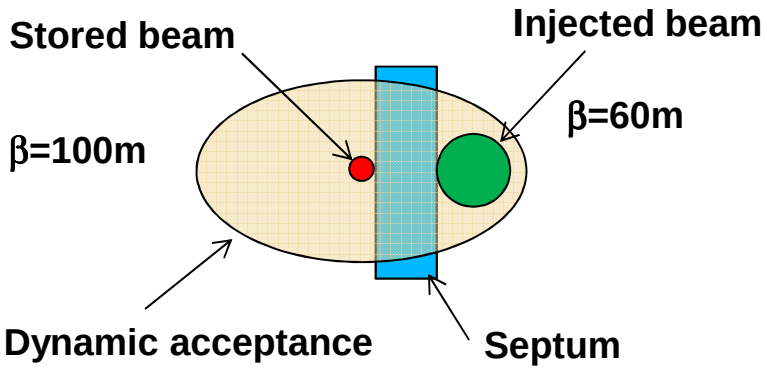
scaling the ALBA booster → 10 nm @6GeV

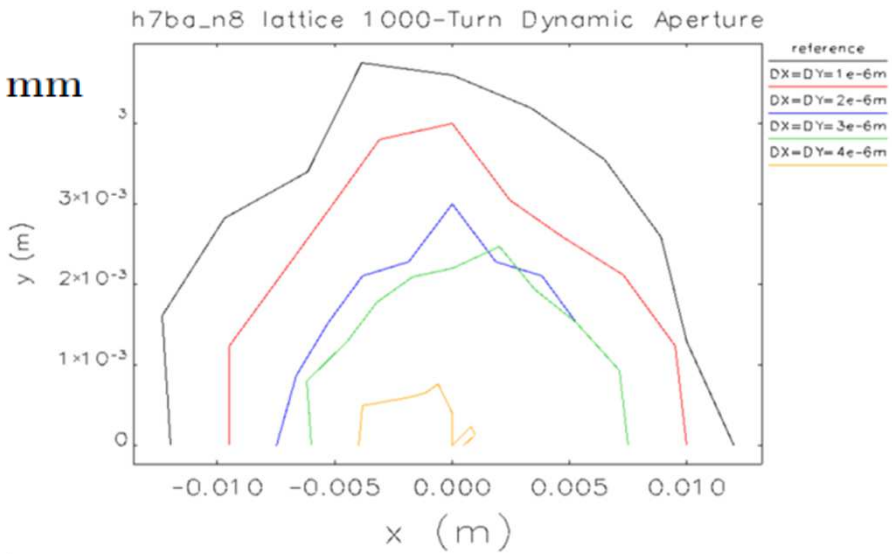
Injector options

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 ring or perform a 90 deg x-y phase space twist in the transfer line
- On-axis injection with ~200 nm emittance no problem

$$10\sqrt{15\,\mathrm{pm}\,100\,\mathrm{m}} + 3\,\mathrm{mm} + 3\sqrt{15\,\mathrm{nm}\,60\,\mathrm{m}} = 6.2\,\mathrm{mm}$$





$$0.38\,\mathrm{mm\,mrad} = \frac{(6.2\,\mathrm{mm})^2}{100\,\mathrm{m}}$$

A_x = 1.3 mm·mrad →
A_x = 0.65 mm·mrad (2 µm errors)

Accelerator – Beam Line Interface

Joint meeting: photon science and accelerator physics

PETRA IV Workshop in Jesteburg, July 12-13, 2017

Sessions:

- **Science Case and Lattice Design Status**
- **Brilliance and Flux**
- **Design and Technical Implications (Accelerator)**
- **Design and Technical Implications (Photon Beamlines)**

Joint meeting: photon science and accelerator physics

The workshop at Jesteburg has addressed several issues which can only be solved in a close collaboration between beamlines and accelerator physicist. Progress was made concerning:

- **Matching electron beam and photon beam**
- **Effect of canting of beam lines**
- **Beam divergence and energy spread**
- **Beam line requests / requirements**

- **A horizontal beta function of about 5 m is acceptable but not optimal,**
  → make use of the long straight section to implement low beta sections (beta ~ 2 m) for IDs

- **Small canting angles my require new monochromator and mirror developments**

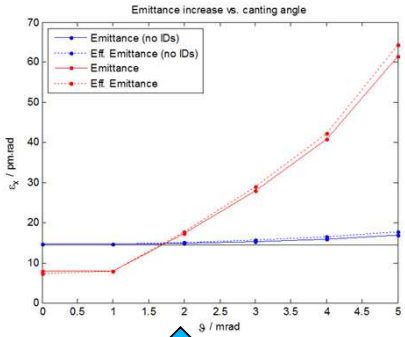
- **The brilliance and the beam divergence is strongly affected by the energy spread**

- **Further challenges for the lattice design and the stability of the beam:** individual beta functions at different IDs, stability 2 % of the beam size

Canting of the beam lines

First study, assuming:

- **maintaining the symmetry of the H7BA lattice cell**
- **canting of all cells with IDs (2 x 2 x 7 = 28)**



- Parameters of the undulators:

  B_{ID} = 1T, λ_{ID} =18 mm, N_{ID}=111 periods,

  L = 2 m
- Canting without IDs has almost no influence on the emittance
- **Without canting, without IDs: 15 pm·rad**
- **Emittance reduced by 50% when adding IDs (7.5 pm·rad)**

(nat. emittance no DW, no IBS)

- **2 mrad canting angle is acceptable,** (15 pm instead of 7.5 pm)
- **canting can be implemented as a 3 bump**

→ specially designed cells allow larger canting angles ~ 4 mrad

two octants: 2 x (7+1) = 16 beam lines

two extensions: 2 x (2x2 + 1) = 10 beam lines

Undulator beam lines (total) 26 beam lines

presently considered configuration of undulator beam lines

+ side beam lines
+ dipole beam lines

2 = canting 1 = straight section (low beta)

Technical Implications

Design Strategy

Investigation of the technical limits and possibilities at an early stage before a lattice design is finalized

Magnets, Girder

- **Collaboration with Efremov Institutemagnet design of high gradient magnets**
- **Contacts to industry (Thyssen Krupp) concerning magnet materials**
- **Collaboration with Alfred Wegener Institutemaster thesis on bionic girders,**
  Ph. D. student has started in Dec. 2017

Vacuum System

- **Simulation of synchrotron radiation in small gap chambers using: MAX IV chamber profile + NEG**
- **Plans for an experiment at PETRA III**

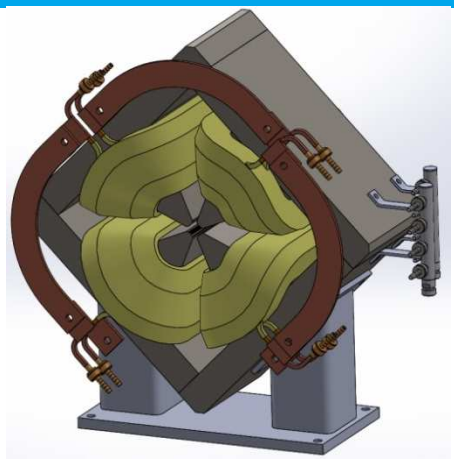
RF System

500 MHz or 100 MHz (option 125 MHz) **System**

- **Collaboration with Technische Universität Darmstadt, TEMF**

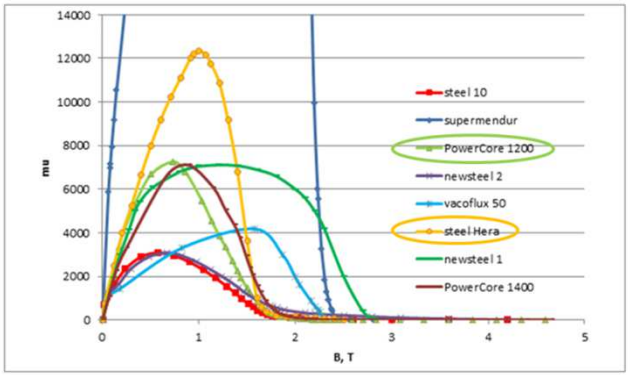
Technical concepts: Magnets, Girders

- **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



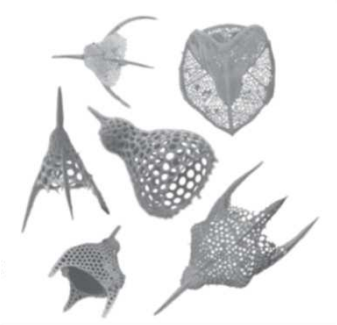
Parameters	Units	**QHG20**
Air gap	mm	**20**
Field gradient, G	T/m	**149,7**
Field quality at R= 0.6a		$3{,}7 \times 10^{-4}$
Core length	mm	200
Number of turns per coil		56
Number of coils		4
Nominal current	A	200
Conductor	mm	6x6-d3.5
Total weight	kg	250

- **Design study for Sextupole magnets**

  presently factor 2.5 stronger as ESRF-EBS
- **Collaboration with Alfred Wegener Institute:**

  Bionic Lightweight Design of Girders

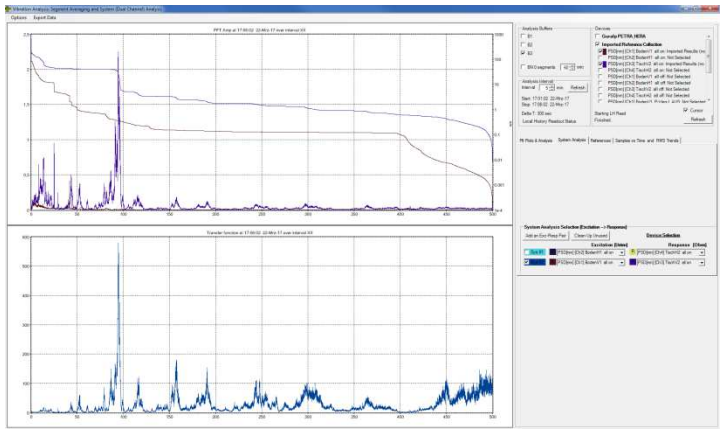
The AWI explores the principles that turn the exoskeletons (shells) of unicellular planktonic organisms into extremely light and stable constructions. (https://www.awi.de/en/science/special-groups/bionics.html)



Vibrations measurements

Test set-up established

1t test mass with adjustable feet and shaker attached, Alu test plate. Seismometer, Geophones (two types bigger yellow, smaller red/yellow),

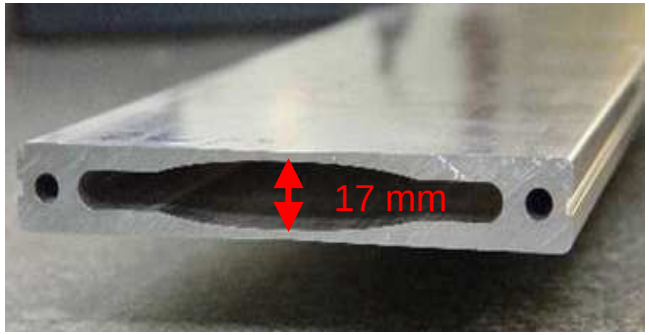


- **Magnet Support/Girder**
  - **➔ Resonances > 55Hz**
  - **Bionic, Light & Stiff**
    Collaboration with AWI, Bremen
- **Measurement Equipment**
  - **Common Software**
  - **Common Database**
  - **Ad-Hoc Analysis**
  - **Different Sensors**
    (Seismometer, Geophones, Piezo Sensors)

Will be ready 2018

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)

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

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

$\sim 1 \cdot 10^{-6}\ \frac{\mathrm{mbar}}{\mathrm{mA}}$ 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**

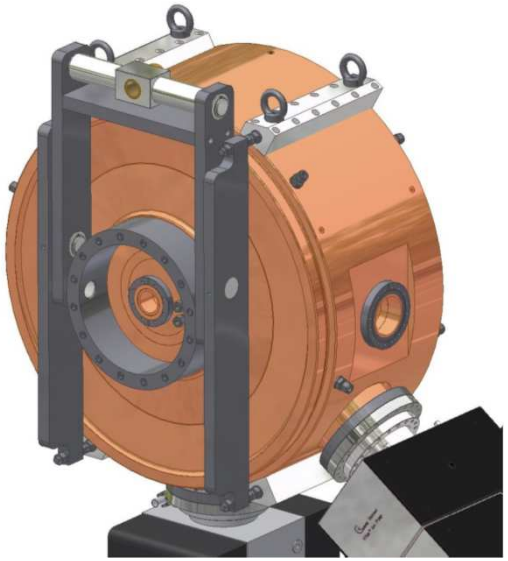
Cavities:

500 MHz single cells

100 MHz single cells, based on MAX IV design

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

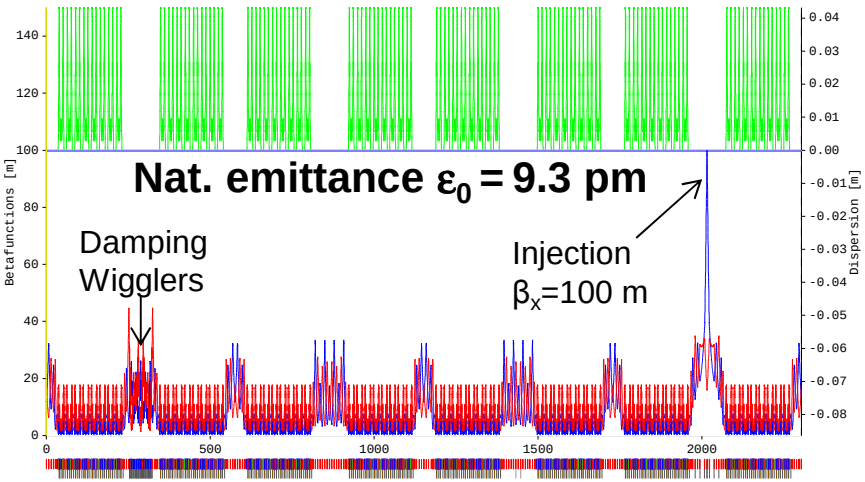
Cavity parameters, HOM calculations, etc.

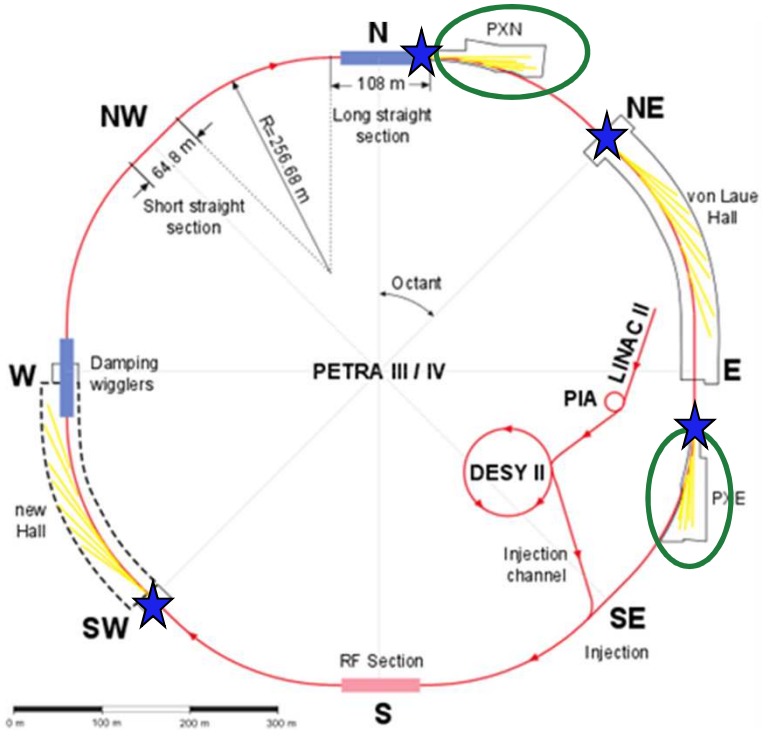


Next steps

Lattice design:

- **optimize the cell length with respect the tunnel geometry**
- **design of cells with canted IDs**
- **special low beta section in the straight sections**
- **investigation of lattice options (double –I cells)**





Goal:

Summer 2018:
Publication on the Design Status

First prototype of a high gradient qudrupole

Collaborations

- **ESRF**
  supporting the lattice design, sharing lattice files
  visit to ESRF (June) , visitor (Simone Liuzzo) from ESRF at DESY (Aug.)

- **Mikael Eriksson**
  joined the PETRA IV project preparation as a generalist from June 2016

- **SLAC – DESY collaboration**
  visit to SLAC in Oct 2016 (host Bob Hettel)
  discussing on lattice theory, impedance and collective effects
  Yunhai Cai visited DESY in April 2017, **LEGO, lie algebra methods**

- **Efremov institute - DESY collaboration: magnet design**

- **Alfred Wegener institute - DESY collaboration: girder design**

- **Technical University of Darmstadt: RF calculation, 100 MHz cavity**

Thank you for your attention !