# PETRA IV Beam Diagnostics

1st FCCee Beam Instrumentation Workshop
21.-22. November 2022, CERN

Gero Kube
Geneva, 22.11.2022

## Outline

- introduction / PETRA IV
- diagnostics overview
- BPM system
- bunch current measurements
- emittance diagnostics

# Deutsches Elektronen Synchrotron (DESY)

## Areal View (at present)

# PETRA @ DESY

## History

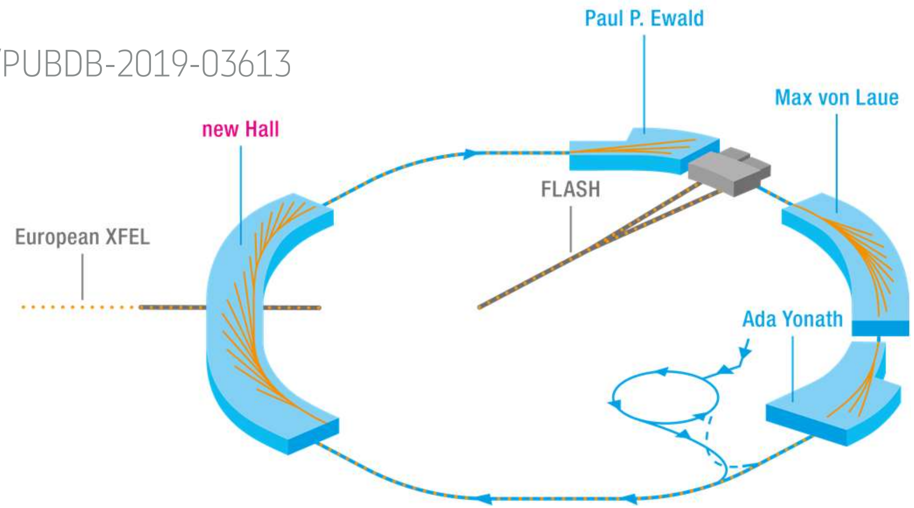
- 1978 – 1986: e+e- collider PETRA (up to 23.3 GeV / beam)
- 1988 – 2007: pre-accelerator PETRA II for HERA (p @ 40 GeV, e @12 GeV)
- since 2007: dedicated 3rd generation light source PETRA III, commissioned in 2009 TDR: DESY 2004-035

  → 14 beamlines (15 experimental stations) operating in parallel
- from 2014: staged extension project W. Drube *et al.*, 2016 https://doi.org/10.1063/1.4952814

  → up to 12 additional beamlines (presently not all of them in operation)
- at present: work on PETRA IV project CDR: DOI: 10.3204/PUBDB-2019-03613

  ring-based diffraction limited light source

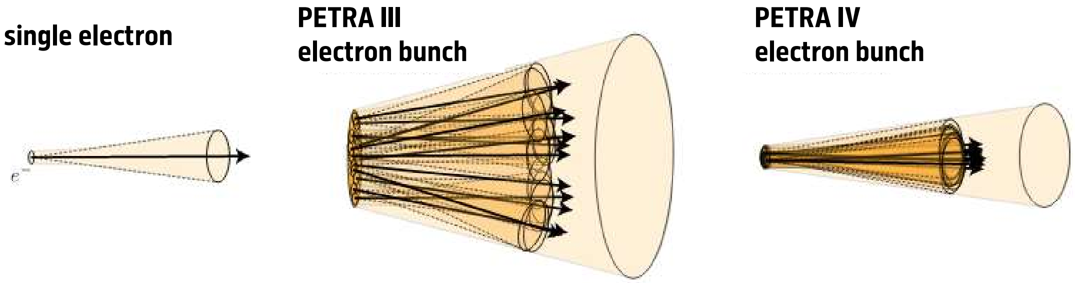
  Ch. Schroer *et al.*, J. Synchrotron Rad. 25 (2018) 1277

# Diffraction Limited Storage Ring

## Principle Ideas

**Diffraction Limit**




- natural emittance scaling

$$\varepsilon_x \propto \gamma^2 \theta^3 \Gamma$$

$\gamma = E/_{m_0 c^2}$ Lorentz factor

$\theta$: bend. magnet angular deflection

$\Gamma$: magn. lattice design of storage ring

- emittance reduction
  - reduction of beam energy
    → E defines radiation spectrum: $\hbar\omega_c \approx 0.665 E^2 B$
  - reduction of deflection angle $\theta$ per bend
    → from double bend achromat (2)
    to multi-bend achromat (5,6,7,9,...)
    → MAX-IV, ESRF-EBS, SIRIUS
    → APS-U, DLS, PETRA IV, ...

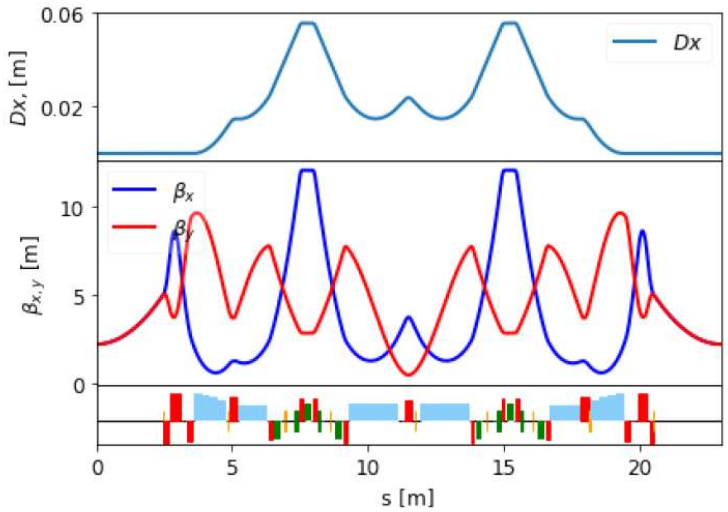
# PETRA IV

## Layout and Parameters

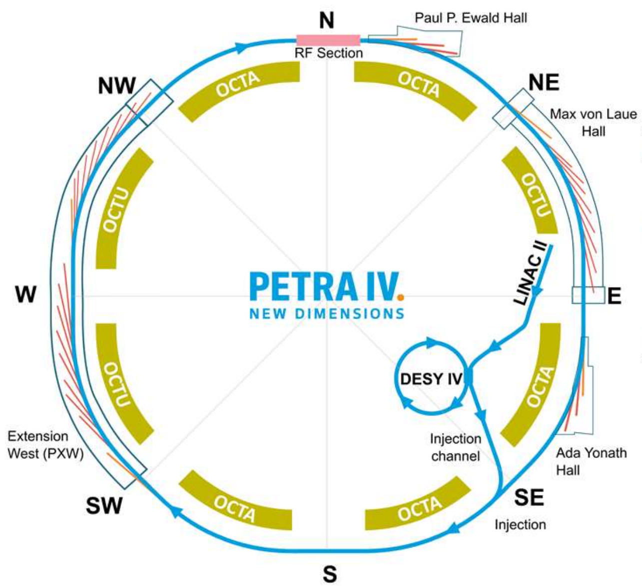
I. Agapov *et al.*, submitted to Phys. Rev. Accel. Beams

- Hybrid 6-Bend Achromat (H6BA) lattice
  - natural emittance: ε ≈ 43 pm.rad

    → use of damping wigglers: ε = 20 pm.rad




- general machine layout




| Parameter | Value |
|---|---|
| Tunes $\nu_x$,$\nu_y$ | 164.18, 68.27 |
| Natural chromaticity $\xi_x$,$\xi_y$ | -230, -196 |
| Corrected chromaticity $\xi_x$,$\xi_y$ | 6, 6 |
| Momentum compaction factor $\alpha_C$ | 3.3 $10^{-5}$ |
| Standard ID space | 4.9 m |
| $\beta_{x,y}$ at ID, standard cell | 2.2 m, 2.2 m |
| $\beta_{x,y}$ at ID, flagship IDs | 4 m, 4 m |
| Nat. hor. emittance $\varepsilon_x$ with IDs, zero current | 20 pm rad |
| Rel. energy spread $\delta_E$ with IDs, zero current | 0.91 $10^{-3}$ |

$f_0$ = 500 MHz

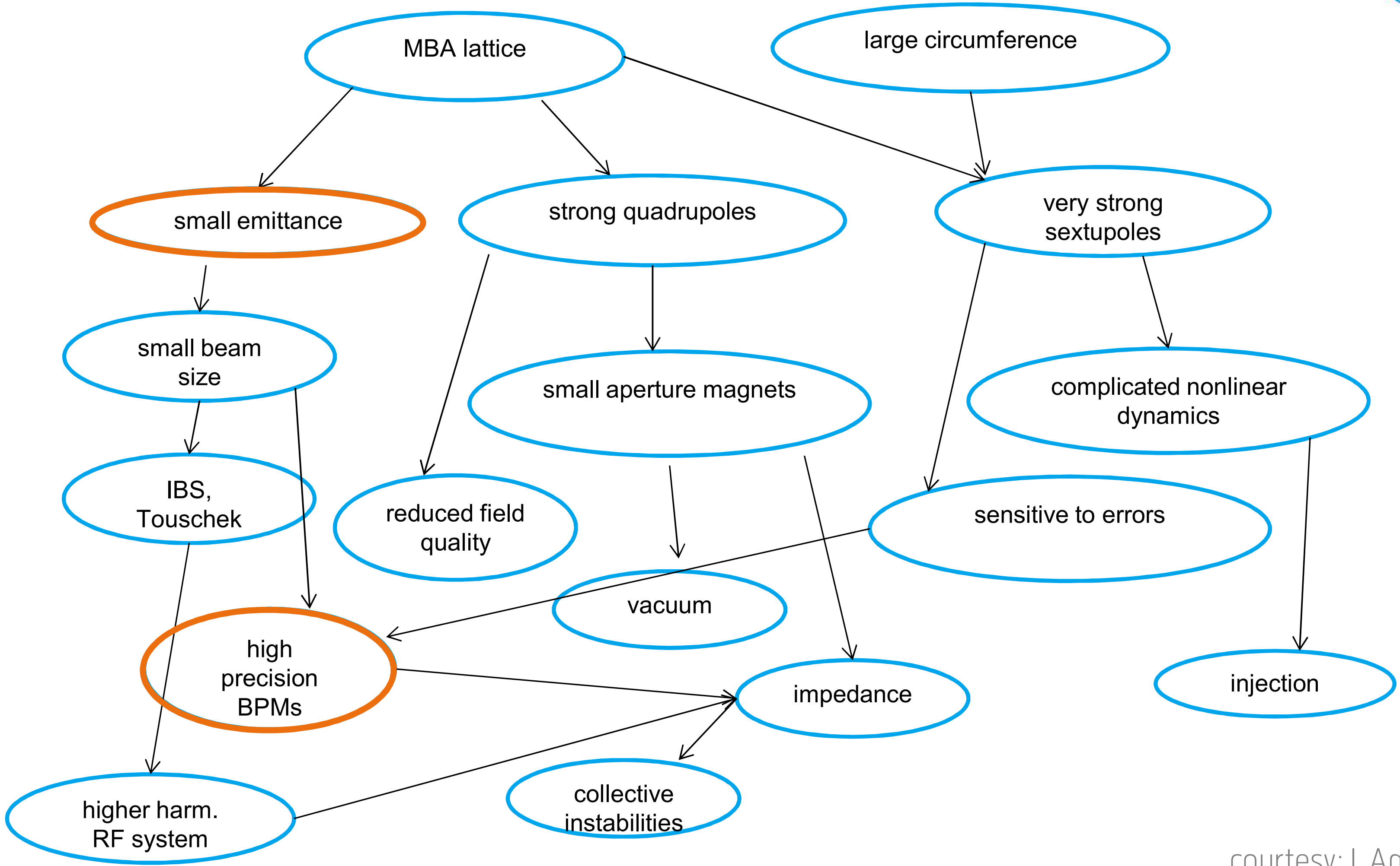
$f_1$ = 1.5 GHz

- operational modes (baseline design)
  - brightness mode: 1920 bu. (Δt = 4ns) in 200 mA
  - timing mode: 80 bu. (Δt = 96ns) in 80 mA

- extensions (under discussion)
  - 3840 bu. (Δt = 2ns) operation (each bucket filled)
  - 40 bu. (Δt = 192ns) in 80 mA → ≈ $10^{11}$ particles / bunch

# DLS Design

## Implications




courtesy: I. Agapov (DESY)

# Engineering Challenges

## DLS Design

R.T. Neuenschwander *et al.*, Proc. IPAC'15, Richmond (VA), USA, TUXC2, p. 1308

- basic idea → dispersion function plays important role in determining equilibrium emittance
  - has to be kept focused to small values in dipoles
    - → strong focusing quadrupoles between dipoles
    - → strong sextupoles to compensate for chromatic aberrations

- strong sextupoles → introduce nonlinear effects (beam dynamics)
  - reduction of dynamic aperture and clearance for injection
    - → novel injection schemes (?)

- strong magnetic fields
  - bore radius has to shrink
    - → reduce vacuum chamber aperture

- vacuum sytem
  - small beam pipe aperture
    - → reduced conductance of vacuum system
    - → internal NEG coating

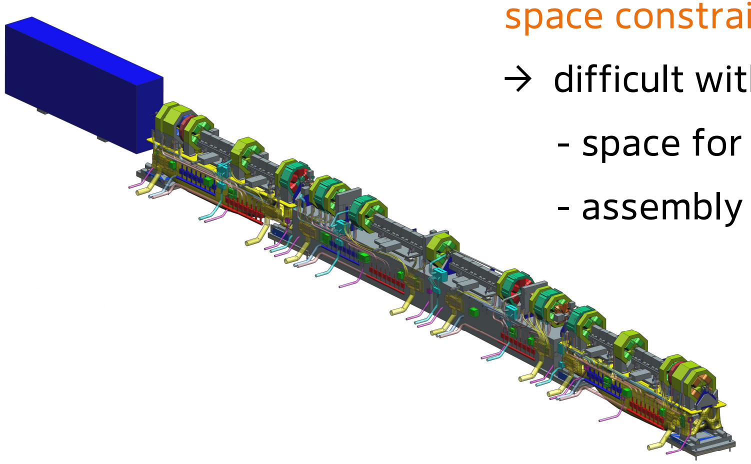
- resistive wall impedance becomes issue
  - may require new materials
    - → higher electrical conductivity

# Engineering Challenges (2)

## DLS Design

R.T. Neuenschwander et al., Proc. IPAC'15, Richmond (VA), USA, TUXC2, p. 1308

- strong magnetic field gradients
  - large orbit amplification factors
    → orbit amplitude extremely sensitive to magnet alignment errors
- large orbit amplification factors & small beam sizes
  - stringent tolerance requirements for magnet alignment + vibration amplitudes
    → tight tolerances for floor / girder vibrations
    → massive beamline girders
- high requirements for orbit stability
  - pushing technology of
    → beam diagnostics
    → fast feedback systems



space constraints

→ difficult with

- space for monitos
- assembly space

# Instrumentation for PETRA IV

## Systems provided by Beam Diagnostics Group

**Information about Machine Parameters**

- Beam Position Monitor (BPM) system
  - beam orbit, input to FOFB system
- beam current measurements
  - DC current, bunch current
- profile / emittance diagnostics
  - $\varepsilon_{x,y}$ , $\Delta p/p$, $\sigma_t$
- screen monitors
  - transfer lines, injection and extraction
- parasitic bunch measurement
  - bunch purity (→ time resolved measurements)
- High Frequency Movement Monitor (HF-Momo)
  - monitor movement of BPM blocks

**Safety Aspects**

- Beam Loss Monitor (BLM) system
- temperature measurement system
- Machine Protection System (MPS)
- online dosimetry

**System provided by other Groups**

- Fast Orbit Feedback (FOFB) system
- Multi Bunch Feedback (MBFB) system
  - 1.5 GHz stripline monitor design
- X-ray BPMs

# Beam Position Monitor (BPM) System for PETRA IV

## Requirements

**Performance** (Electronics)

| | | |
|---|---|---|
| • resolution on single bunch / turn | (0.5 mA / bunch) | < 10 µm |
| • resolution on closed orbit | (200 mA in 1600 bunches @ 1 kHz BW) | < 100 nm (rms) |
| • beam current dependence | (60 dB range, centered beam) | ± 2 µm |
| • long term stability | (measured over 6 days, temperature span ±1°C within a stabilized rack) | < 1 µm |

**First Turn Steering Tolerances** (Mechanics & Electronics) < 500 µm

- manufacturing (pickup, feedthroughs, …)
- alignment
- electrical offset

➡ margin of 150 µm for each

# BPM System for PETRA IV

## Mechanics

### Actual Status

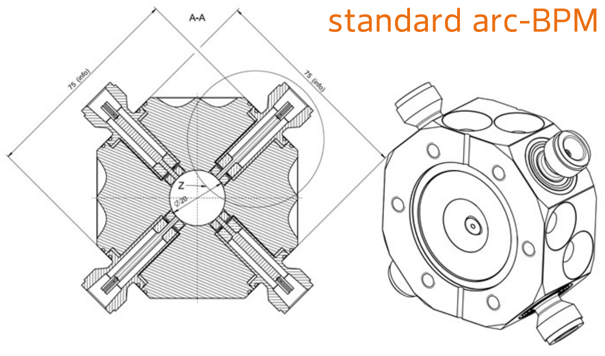
- worked out matched feedthrough design
  - glass ceramics with $\varepsilon_r = 4.1$
- design of standard cell BPM / ID-BPM
  - round Ø 20mm / elliptical 22mm x 13mm
- order for batch of feedthroughs was sent out
  - critical: NEG activation temperature and temperature resistance of glass ceramics

    → has to be tested in LAB
  - alternative design (MAX-IV) under investigation
- tolerance study performed: **S = 124 µm**

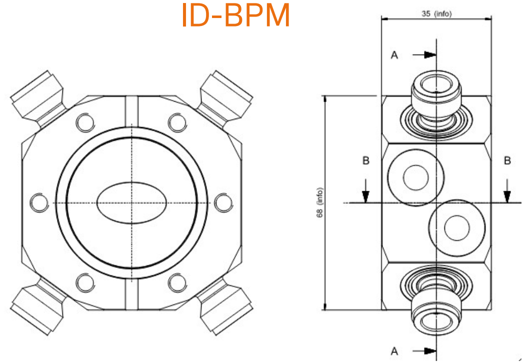
  well below requested limit of 150 µm

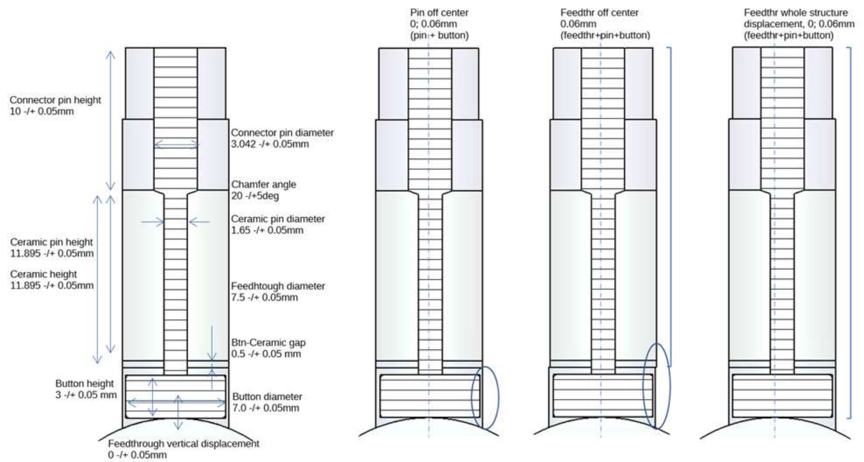
S. Strokov *et al.*, Proc. IBIC 2022, Krakow (Poland) TUP13.

standard arc-BPM




ID-BPM



# BPM System for PETRA IV

## BPM Electronics: Boundary Conditions

**Number of BPMs:** about 800

- 9 BPMs per cell / 72 cells → 648 BPMs in arcs
- additional BPMs in short/long straight sections

787 BPMs (incl. spares: ~800)

➡ cost / space are important factors

≤ 10 k€ (per channel)

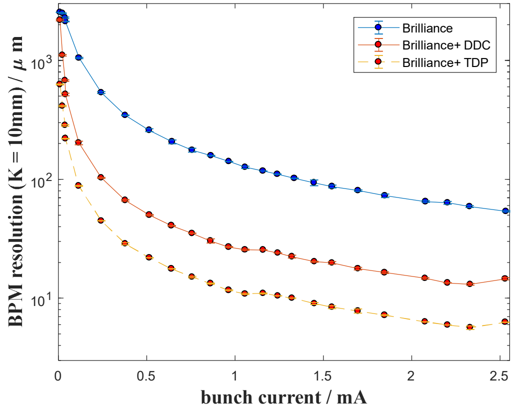
**In-house Development:** no time and manpower ➡ commercial solution

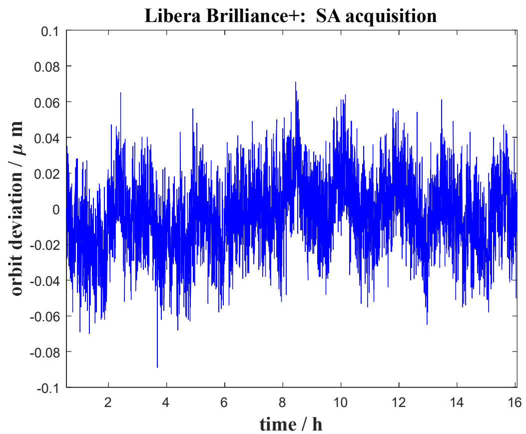
**Libera Brilliance:** will not fulfil requirements

G. Kube *et al.*, Proc. IBIC 2019, Malmö (Sweden) WEPP005.

**Libera Brilliance+:** would fulfil requirements

- in use at MAX-IV
- planned for APS-U



# BPM System for PETRA IV

## BPM Electronics: DESY Strategy

**Drawback Libera Brilliance+**

- long term stabilization starts at RF front-end ➡ influence of cable paths !
- about 10 years old technical platform ➡ obsolence of components

**DESY Lab Strategy:** MTCA.4 as technical platform

**Development Project with Industrial Partner**

INSTRUMENTATION TECHNOLOGIES

- prototype development of MTCA.4 based BPM system
- long term stabilization scheme including cable paths
- functional prototype at end of TDR phase → fully equipped crate ready for tests at PETRA III

**Long Term Strategy**

- industrial partner brings in ability to perform mass production & QA for PETRA IV

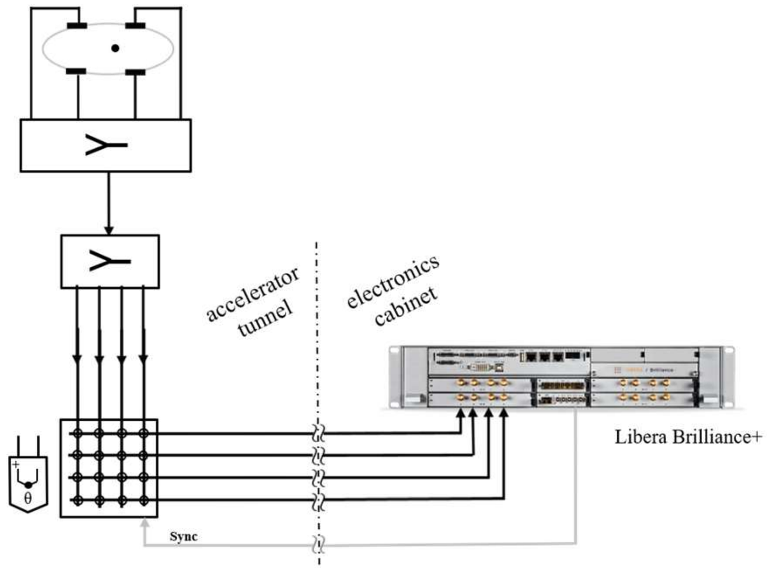
# BPM System for PETRA IV

## Long-Term Drift Compensation

**long term stabilization scheme including cable paths** F. Schmidt-Föhre *et al.*, Proc. IBIC 2021, Pohang (Korea) MOPP36.

- pilot tone compensation
- external crossbar switching

**performance studies at PETRA III**



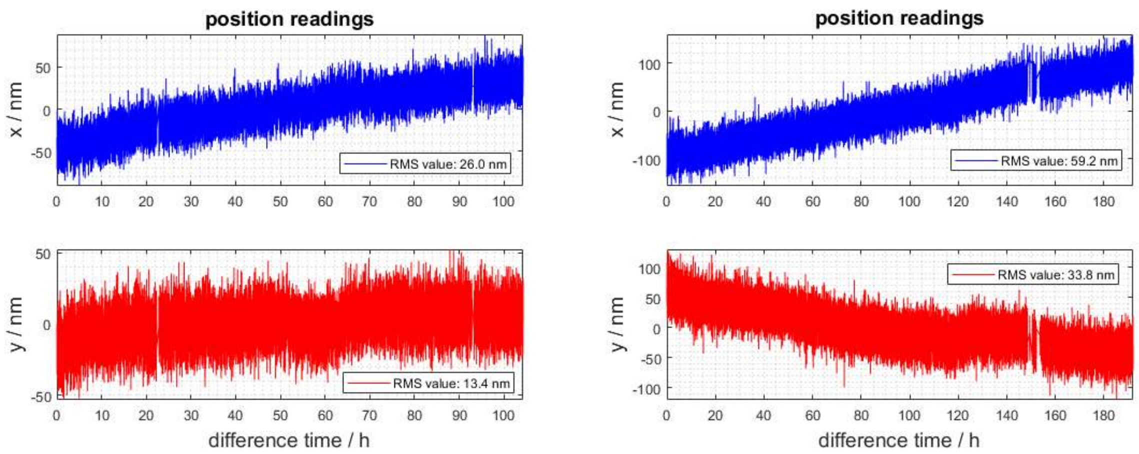

**long-term drift study** G. Kube *et al.*, Proc. IBIC 2022, Krakow (Poland) WEP08.

**continuous mode**

- 480 bunches @ 120 mA

**timing mode**

- 40 bunches @ 100 mA

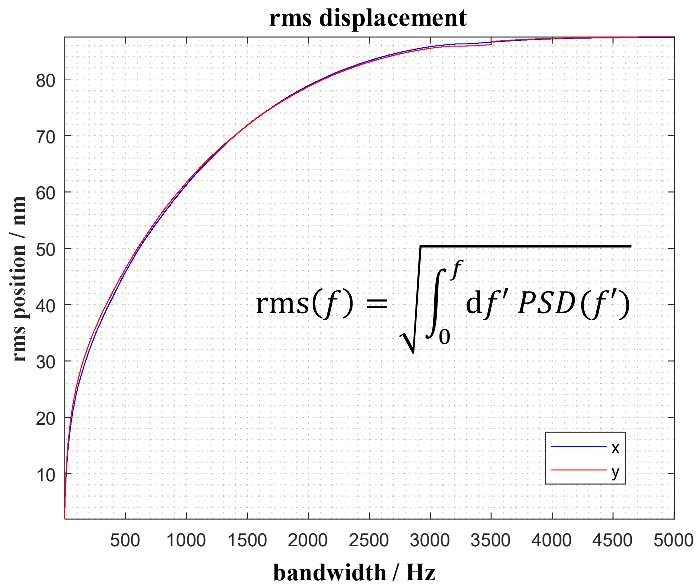



➡ well within specifications **< 1 µm**

# BPM Tests at PETRA III

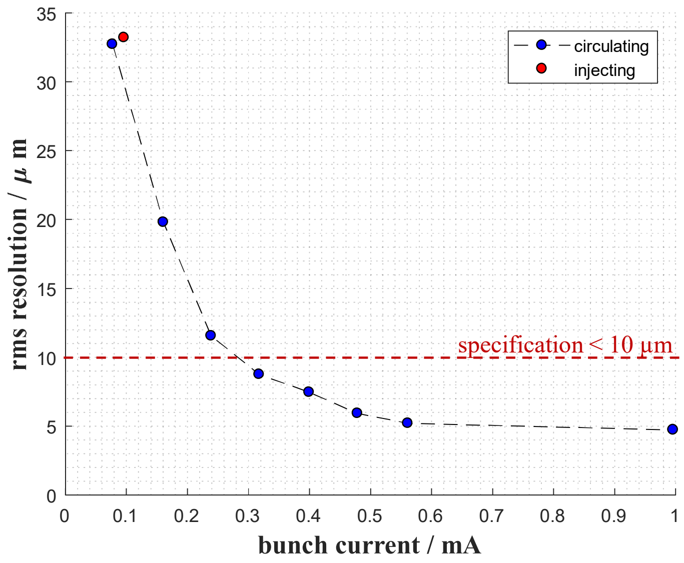
## Additional Measurements

### Closed Orbit Resolution



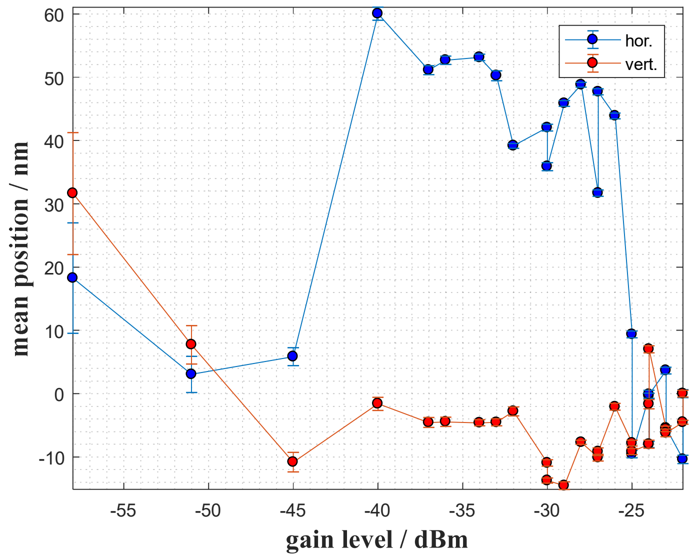

< 100 nm (rms)
@ 1 kHz BW

### Single Bunch (Single Turn) Resolution




< 10 µm
0.5 mA bunch current

### Beam Current Dependency (SA)




± 2 µm
60 dB range, centered beam

➡ well within specifications

# BPM System for PETRA IV

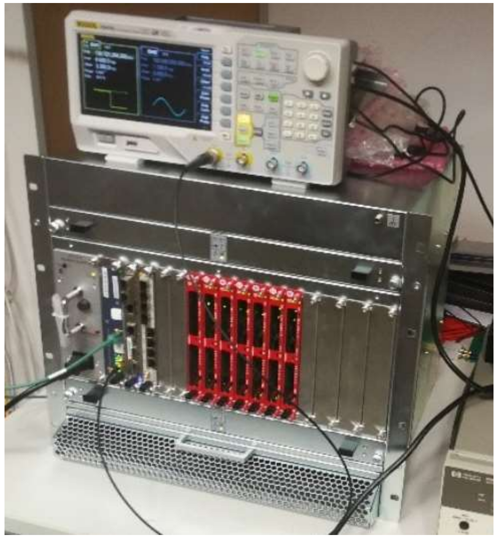
## System Parts - Readout Electronics

**Actual Status**

- RTM evaluation ongoing
- switching module production (Libera XBS FE) ongoing
- FPGA/SW implementation ongoing
- two fully populated MTCA crate in operation at I-Tech
  - 2x 6 AMC boards → each for 12 BPMs
- basic checks with equipped crates done
  - PLL locking, timestamps, signal acquisition (ADC, TbT, FA, SA)
- one MTCA crate already delivered to DESY
  - installation performed last week in PETRA III environment

➡ plan: start with prototype tests at PETRA III next week





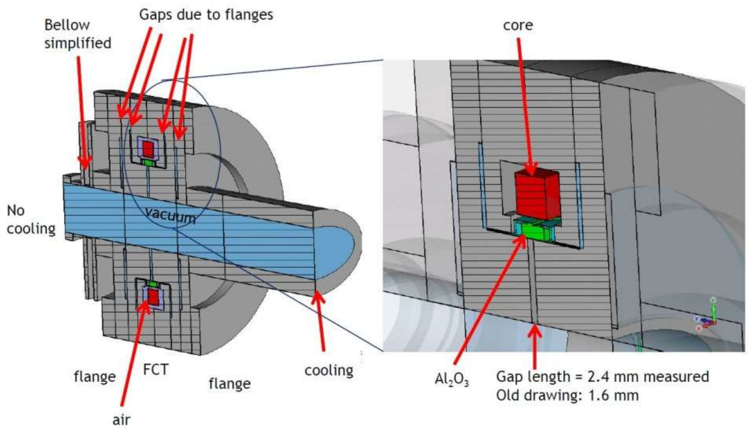
# Beam Current Monitors

## Plans and Operational Experience

### PETRA IV Beam Current Monitors

- DC current measurement: water cooled ceramic gap + commercial in-air NPCT (Bergoz)
- bunch current measurement: modified in-flange FCT design
  - FCT requirements (beyond CDR specifications)
    - → 2 ns bunch resolution: high bandwidth → **large** ceramic gap
    - → 40 bunch operation: critical transient heating → **small** ceramic gap

➡ common design with company *Bergoz*



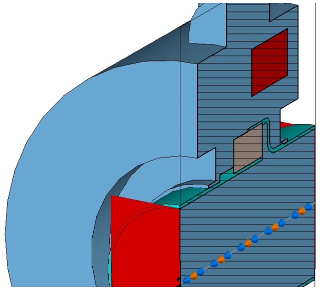

### Operational Experience from PETRA III

- 2 damaged in-flange FCTs (timing mode operation: ~$10^{11}$ particles / bunch) → interpretation: transient effects
- power deposition in thermally isolated core ($P_{loss}$ = 48 W) → temperatures between 100°C and 200°C possible
- monitor improvements: replacement of magnet core, better air cooling, temperature sensors…

➡ new monitors operate since years in PETRA III without problems

# Beam Current Monitors

## Modifications and Tests

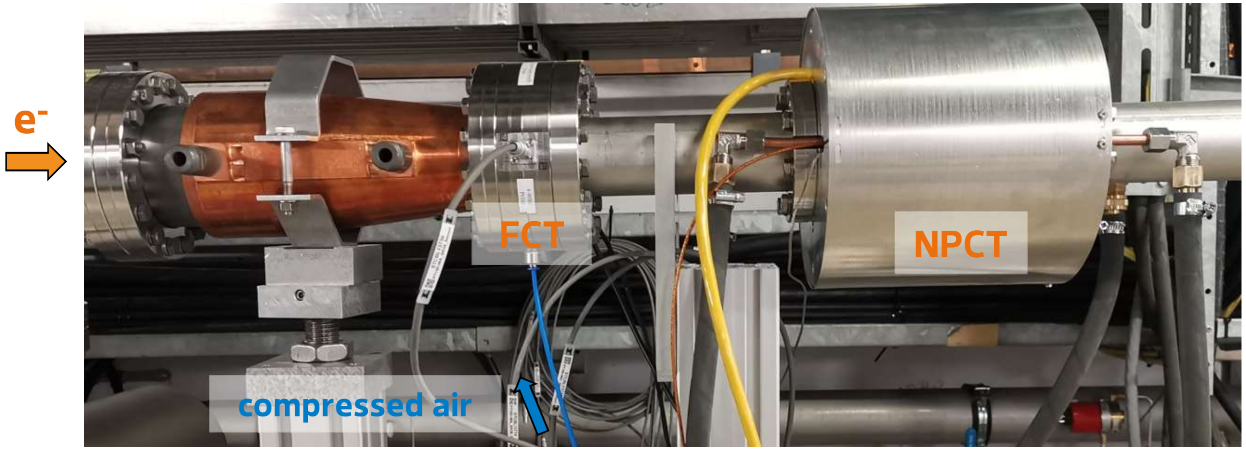


**Remedies**

- outcoupling geometry → reduction of induced power by ~ factor 2
- FCTs with larger beam pipe cross section → Ø 40mm instead of 20mm

  benchmarking of simulations ⇨ 1 FCT ordered (Ø 60mm) for tests @ PETRA III

**Diagnostic Section in PETRA III**




- FCT tests
  - bandwidth
  - transient heating impact

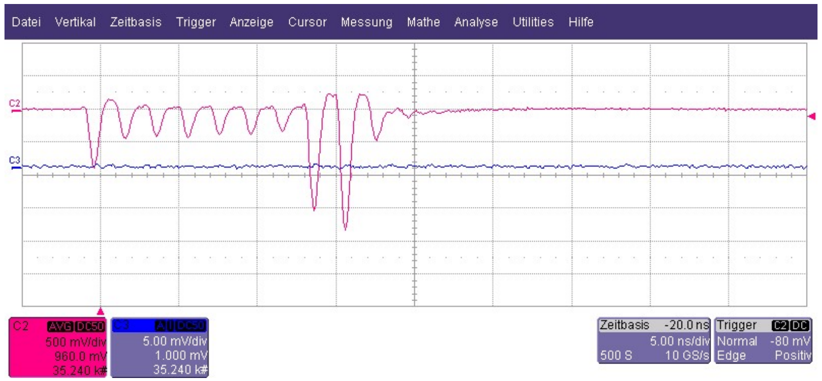
    → temperature sensor at core
- NPCT tests
  - recently started

# Beam Current Monitors

## FCT Tests

### Bandwidth

- test at PETRA III: 10 bunches, 2ns bunch spacing




➡ meets specifications

### Transient Heating Impact

- environmental influence constant
  - constant air flow with 1.25 bar for core cooling
- measurement for different bunch patterns
  - 40 bunches / 100 mA: 139°C
  - 80 bunches / 100 mA: 91°C
  - 480 bunches / 120 mA: 51°C

➡ small vacuum leakage
(after < 1 month of operation)

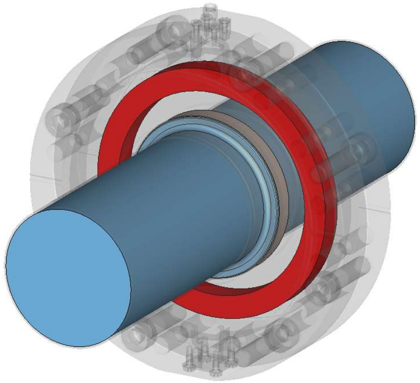
# Beam Current Monitors

## FCT- Wakefield and Thermal Simulations

### Design FCT-CF6'-60.4_e3-40-UHV-LWL, 60 mm Beam Pipe

- Induced power

$\mathbf{P = I^2 \times t \times k_{loss}/Nb,}$
with
$I$: total beam current
$t$: revolution time
$k_{loss}$: wake-loss factor
$N_b$: number of bunches

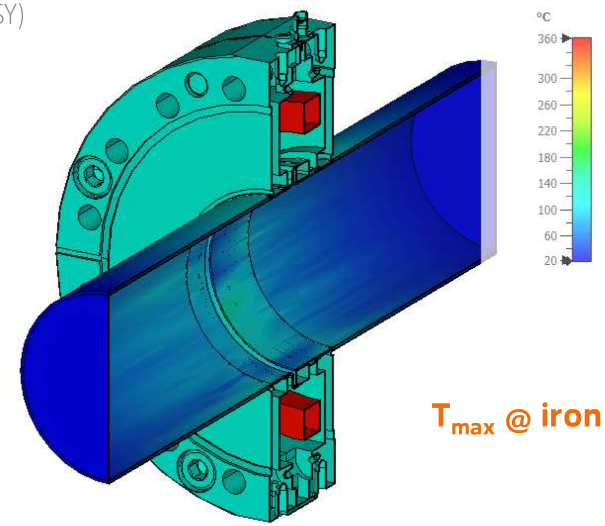


| | Timing mode | Second mode |
|---|---|---|
| Total beam current, mA | 100 | 100 |
| Number of bunches | 40 | 80 |
| Bunch length | 44 ps (13.2 mm) | |
| Wake-loss factor | $2.2\times10^{-2}$ V/pC | |
| Rev time, µsec | 7.68 µsec | |
| **Induced heating power, W** | **42 W** | **21 W** |

### Thermal load simulation with induced heating power of 42 W (no cooling)

- ambient temperature: 20°C
- fixed temperature: 20°C at edges of beam pipe
- stainless steel: thermal conductivity 15 W/m/K
- iron core: thermal conductivity 79.5 W/m/K

courtesy: S. Strokov (DESY)



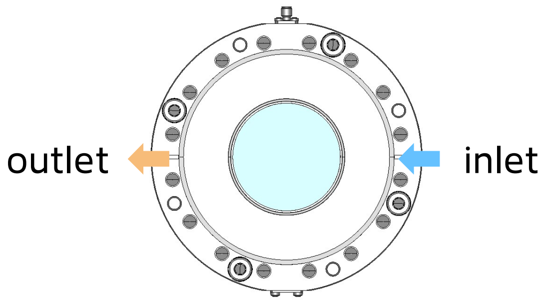

$T_{max}$ @ iron core: 360° C

# Beam Current Monitors

## Thermal Simulations: Fan applied to Cavity with Iron Core

**Flow Rate 0.3 m³/h of Air with 20°C Temperature - no Heat Losses by Radiation**

- Fan is installed on the right Side of FCT, Outlet on the left
  Diameter of Inlet Window: 3 mm

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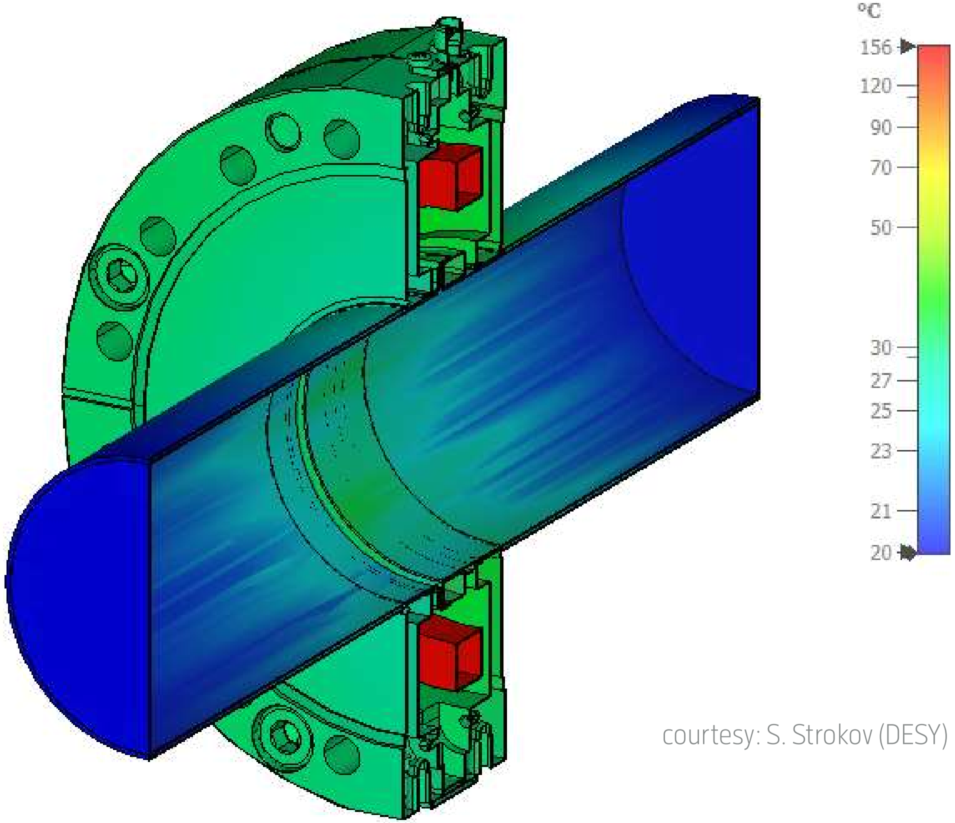
$T_{max}$ @ iron core: 156° C
$T_{meas}$ = 139°C

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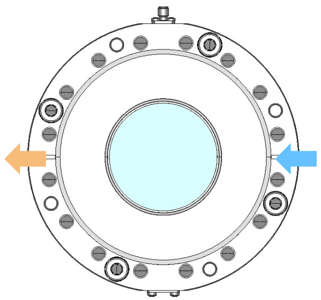


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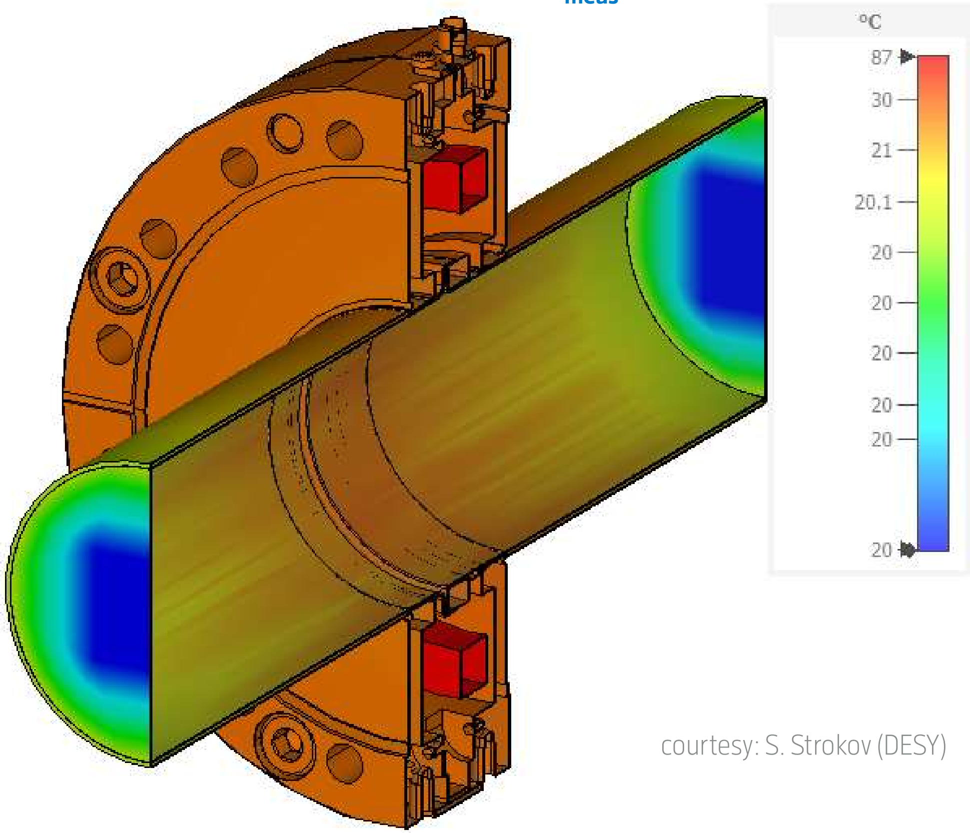
| Rev time, µsec | 7.68 µsec | |
| **Induced heating power, W** | **42 W** | **21 W** |

$T_{max}$ @ iron core: 87° C
$T_{meas}$ = 91°C




courtesy: S. Strokov (DESY)

# Beam Current Monitors

## FCT for PETRA IV

PETRA IV. NEW DIMENSIONS

**Staus**

- FCT core temperature too high for timing mode operation at PETRA III
  - 40 bunches at 100 mA, beam pipe diameter Ø 60 mm
  - magnet core specification $T_{max} \lesssim 150°C$
- monitor was removed → in contact with Bergoz: repair / improvements ⇨ discussion to increase air flow (Bergoz: up to 3 bar could be possible)

**Outlook PETRA IV**

- FCT operation considerations for (new) 40 bunch mode
  - 40 bunches at 80 mA, beam pipe diameter Ø 40 mm
    → monitor most probably will be destroyed in this operation mode
- remedies
  - forget about 40 bunch operation
  - place monitor at location with larger cross section
  - alternative monitor concepts → optical measurement, stripline monitor

⇨ presently under discussion

# Emittance Diagnostics

## General Considerations

### Performance Requirements

- horizontal / vertical emittances — 18 pm.rad / 2 pm.rad
  - brightness mode, $I_{bunch}$ = 0.1 mA
- horizontal / vertical resolution — 1.0 pm.rad / 0.5 pm.rad
- emittance measurement
  - measurement of beam size
  - expected beam sizes $\sigma_x$ = 7.7 µm, $\sigma_y$ = 2.1 µm

with $\frac{\Delta\sigma}{\sigma_0} = \frac{\Delta\varepsilon}{2\varepsilon_0}$ → $\Delta\sigma$ = 0.2 µm

→ goal: $\Delta\sigma$ = 0.1 µm

### Emittance & relative Momentum Spread

- 2 parameters to be measured:

$$\sigma = \sqrt{\varepsilon \cdot \beta + \left(D \cdot \frac{\Delta p}{p}\right)^2}$$

→ 2 independent measurements:

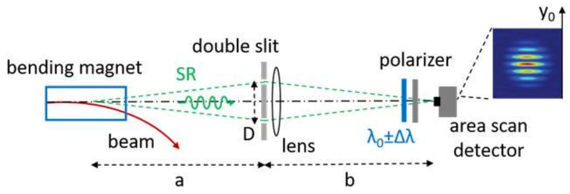
$$\varepsilon = \frac{\sigma_2^2 - \left(\frac{D_2}{D_1}\right)^2 \sigma_1^2}{\beta_2 - \left(\frac{D_2}{D_1}\right)^2 \beta_1} \qquad \frac{\Delta p}{p} = \left[\frac{\sigma_2^2 - \left(\frac{\beta_2}{\beta_1}\right)\sigma_1^2}{D_2^2 - \left(\frac{\beta_2}{\beta_1}\right) D_1^2}\right]^{1/2}$$

# Emittance Diagnostics

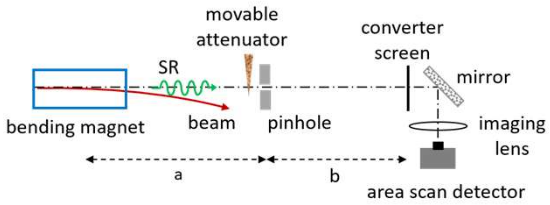
## Measurement Concept

**Conceptual Idea:** high sensitivity on few micron beam sizes

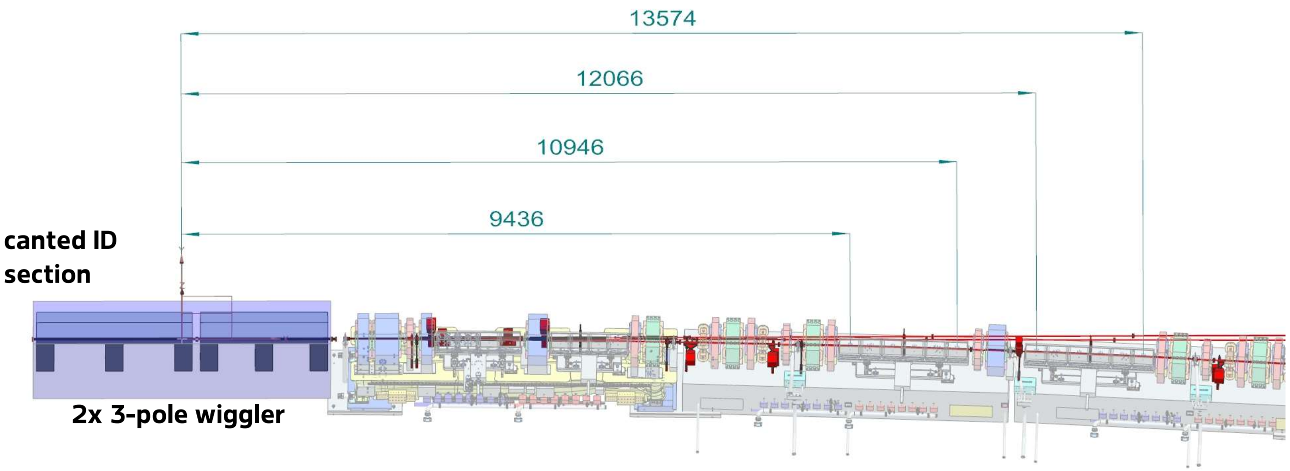
- SR interferometer (diffractometer) → visible light




- SR based beam imaging → X-rays




**SR Extraction**




- rms opening angle (visible SR light)

$$\Psi_y = 0.4488 \left(\frac{\lambda}{\rho}\right)^{1/3} \sim 1 \text{ mrad}$$

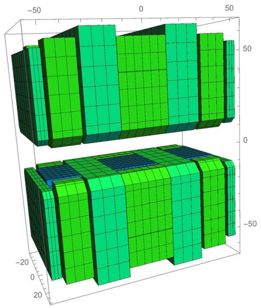
→ unperturbed visible light extraction not possible

⇨ X-ray based

# Emittance Diagnostics

## X-Ray based Beam Size Measurements

PETRA IV. NEW DIMENSIONS



ESRF type

courtesy: J. Chavane (ESRF)

magnetic gap 22mm
peak field: 0.86 T
PM material: $Sm_2Co_{17}$
magnetic length: 108mm

### 2 Diagnostic Beamlines

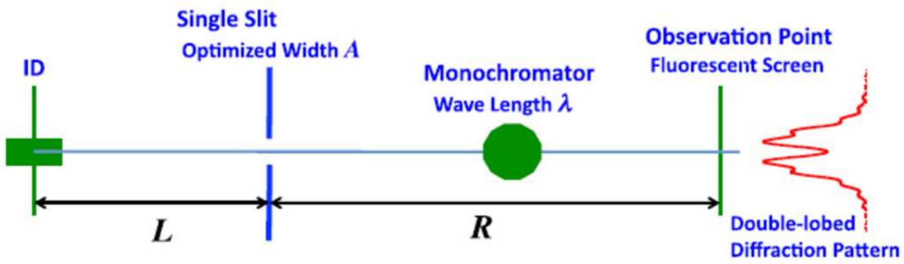
- canted ID section (±2.5 mrad) with 2x 3-pole wiggler
- each beamline equipped with
  - pinhole imaging (XPC): σ = 10 µm … 500 µm
  - Fresnel diffractometry (XFD): σ = 0.9 µm … 18 µm
  - (station for bunch purity diagnostics)

**principle beamline setup:**

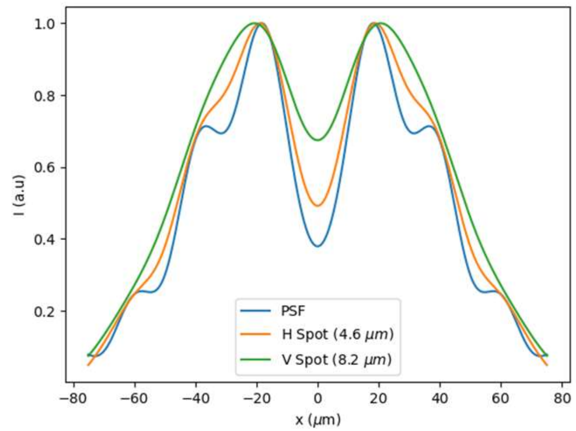
courtesy: M. Marongiu (DESY)


### Fresnel Diffractometry (PSF dominated Imaging)

- principle: pinhole operated in Fresnel regime




M. Masaki *et al.*, Phys. Rev. ST Accel. Beams 18 (2015) 042802




beam size information from smearing out of central minimum

# Summary

- overview of PETRA IV project
- brief introduction to diagnostic systems
  - BPM system → concept of external crossbar switching works well
  - bunch current measurements → transient heating is critical for FCTs in modern light sources
  - emittance diagnostics → X-Ray based beam size measurements for large circumference machines
- thank you for your attention

**Contact**

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