Collective effects – expertise and plans at DESY

Kickoff meeting

The Future Circular Collider

Innovation Study

Rainer Wanzenberg

FCC November Week 2020, November 9-13, 2020

Outline

Introduction

- Large facilities at DESY
- Collective effects: basic concepts

Expertise at DESY

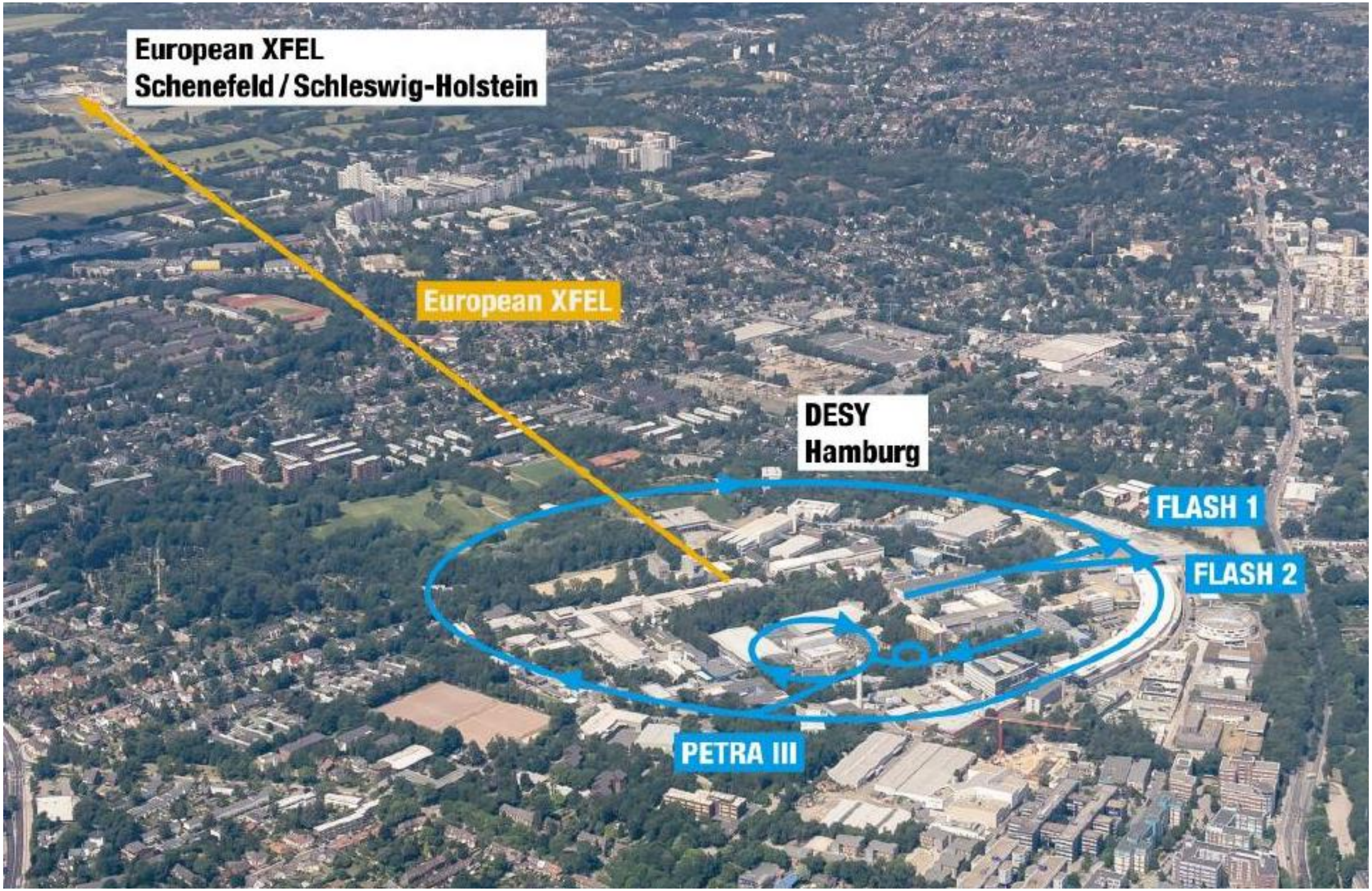
- Operation of particle accelerators
- Calculation of Wake fields and Impedances
- Teaching at CERN schools

Plans at DESY

- Upgrade of PETRA III
- Contribution to FCC

Large facilities: PETRA III, FLASH, Eu-XFEL

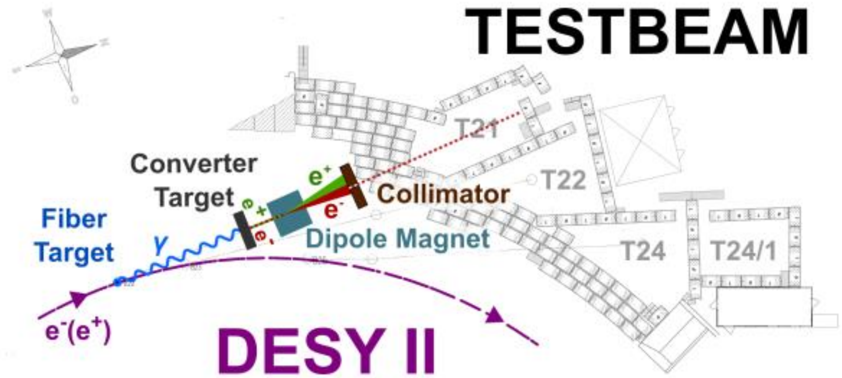
DESY is operating three major photon science facilities



High energy physics

DESY experts participate in the LHC experiments

Test beams at the booster synchrotron DESY II

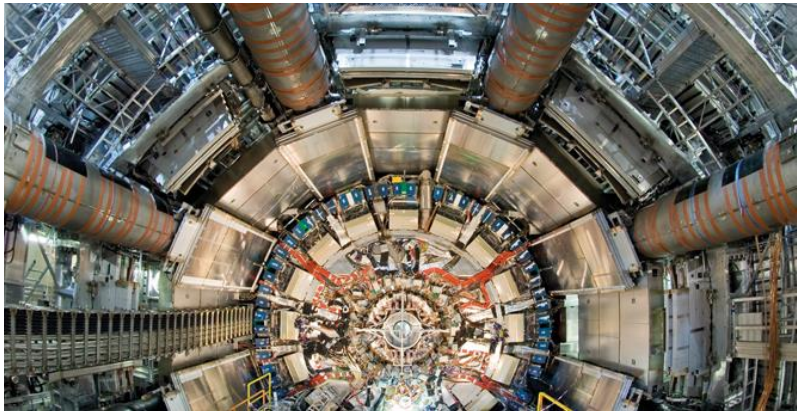


”The DESY II test beam facility”
https://doi.org/10.1016/j.nima.2018.11.133
NIMA, Volume 922, 1 April 2019, Pages 265-28

Detector Assembly Facility at DESY in Hall I

DESY contributes to LHC experiments ATLAS, CMS, ALICE und LHCb

DESY itself has more than 100 experts working at ATLAS and CMS.



DESY also provides large computing and storage systems for the data processing of ATLAS, CMS and LHCb. This so-called Tier-2 centre is one of the largest among the more than 170 centres of the worldwide LHC computer network

Collective effects are of high importance

An issue of the ICFA beam dynamics newsletter was devoted to the topic

International Committee for Future Accelerators

Sponsored by the Particles and Fields Commission of IUPAP

Beam Dynamics Newsletter

No. 69

Issue Editor:
E. Métral

Editor in Chief:
Y. H. Chin

December 2016

Collective effects can **limit performance** of particle accelerators or colliders, e.g.

- beam intensity
- beam brightness

due to **beam instabilities**

linac-based free electron lasers **rely on collective effect**

- SASE FEL
  (Self-Amplified Spontaneous Emission)

Collective effects refers to **interaction of beam particles with each** other through a variety of **processes**

- Space charge forces
- **Electro-magnetic Wake Fields**
- Particle-particle scattering inside the beam
- gas ionization, ion clouds
- secondary electrons / electron cloud effects

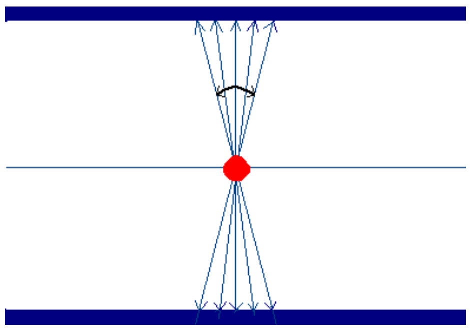
The concept of Wakefields and Impedance

Wake Field = the track left by a moving body (as a ship) in a fluid (as water); broadly : a track or path left

Impedance = Fourier Transform (Wake Field)

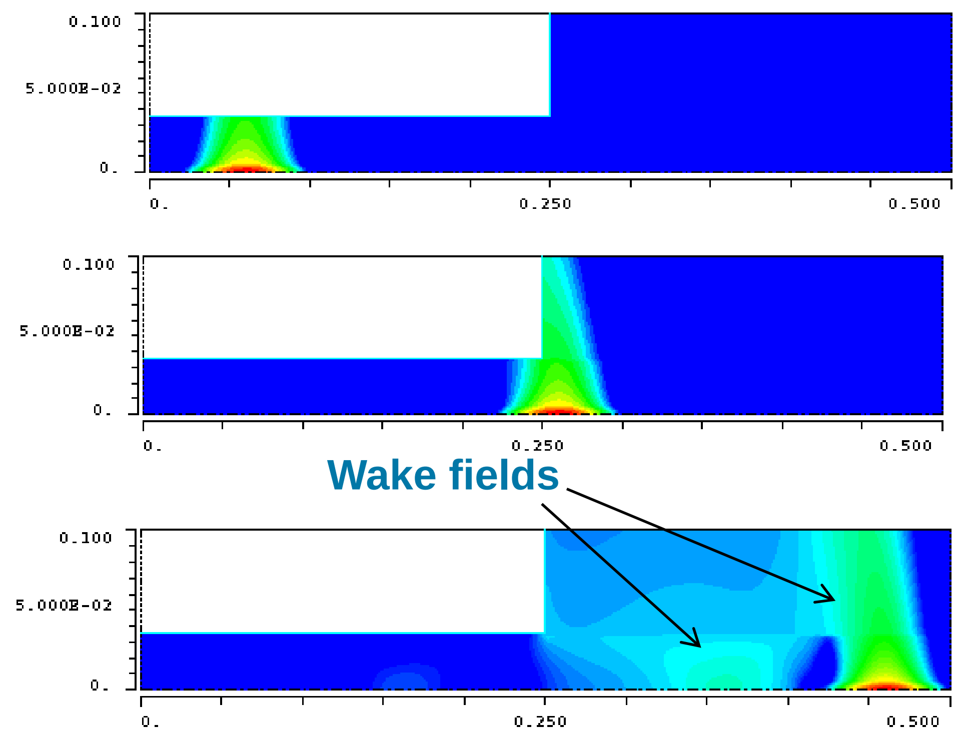
This concept can be translated to electro magnetic fields

Point charge in a beam pipe



Opening angle: 0.511 MeV / E
E = energy of the particle

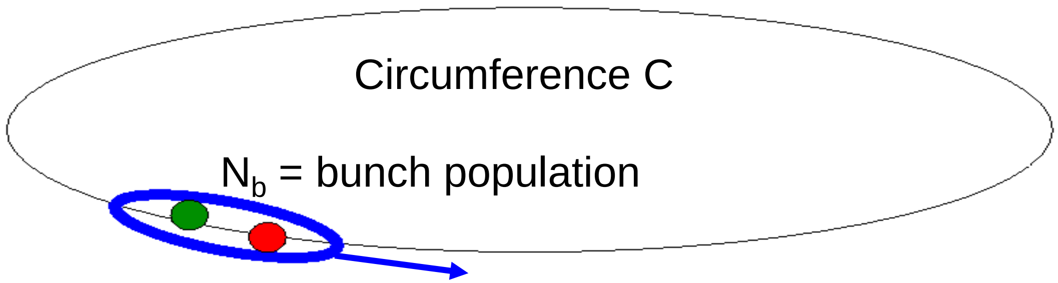
Gaussian Bunch, Step out transition



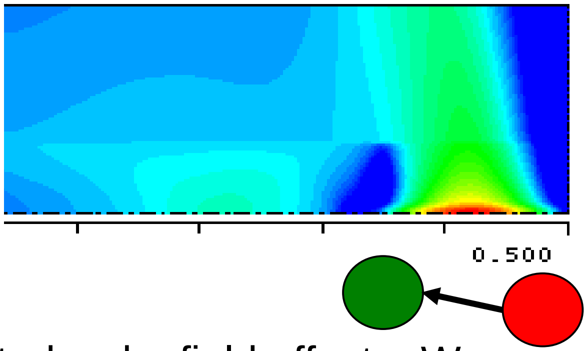
Beam instabilities driven by wake fields

The head tail instability in a storage ring

Storage ring



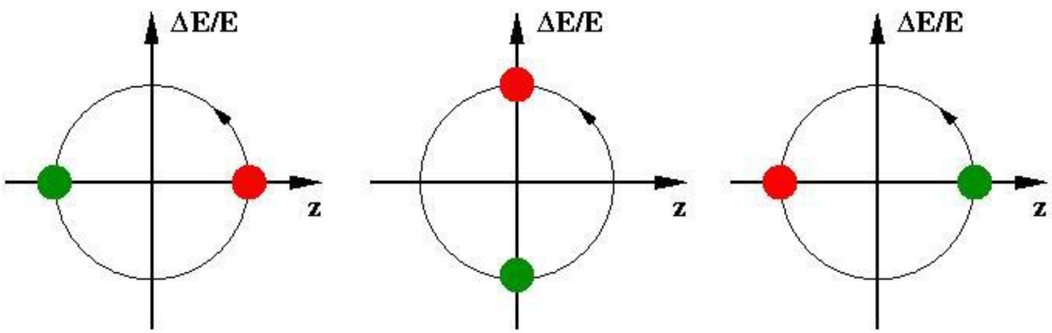
Wakefield: Tail ← Head



Integrated wake field effect: W_0

Synchrotron oscillations:

Positions of
Head and Tail are exchanged
after one synchrotron oscillation period



Equation of motion can be solved
Separately for $T_s/2$ of a synchrotron
period.

➔ Criteria for stability

$$\Upsilon = \frac{\pi N_b e^2 W_0}{4 m_0 \gamma C \omega_\beta \omega_s} \leq 2$$

G. Rumolo: *Beam Instabilities* CAS - Trondheim, Norway, 18-29 Aug 2013

Expertise at DESY

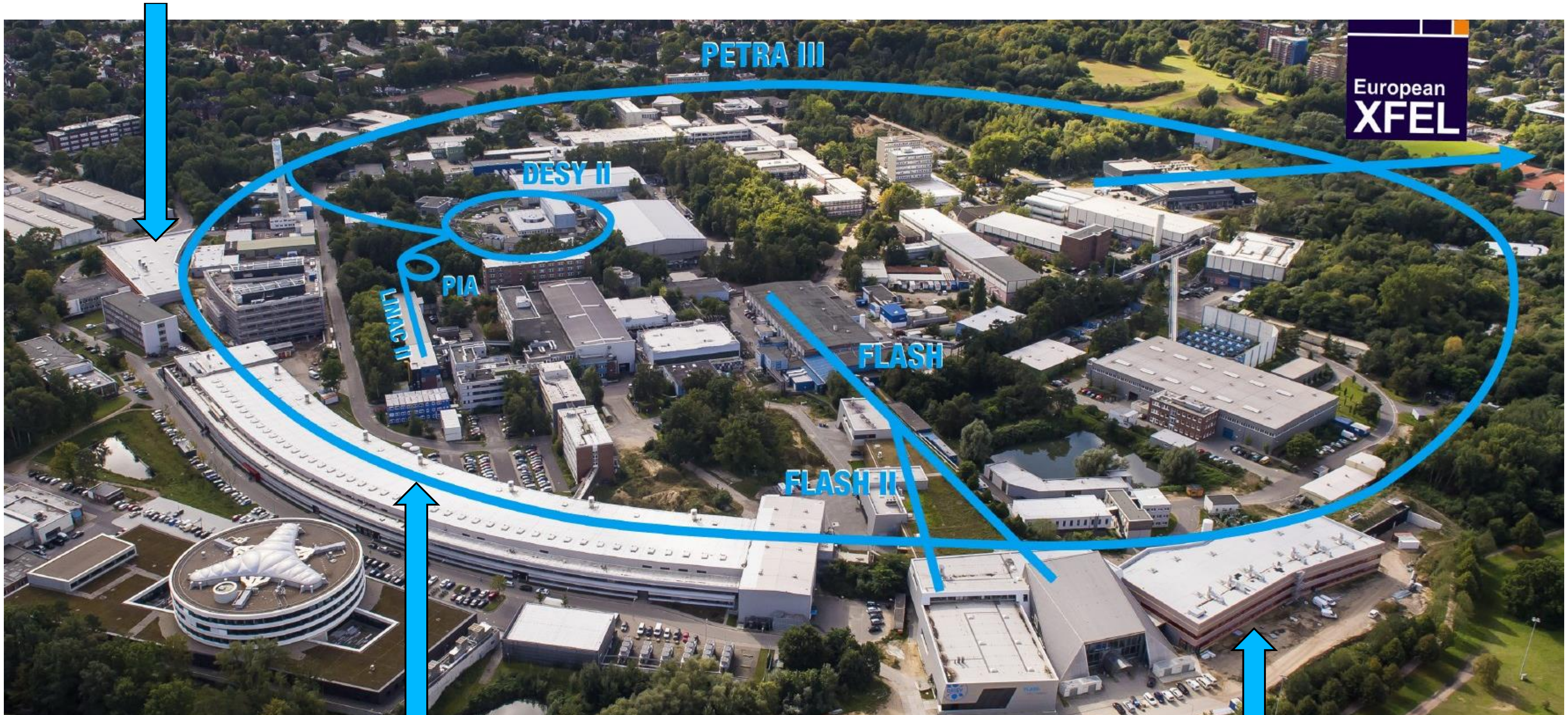
There is a wide range of expertise at DESY

- **Operation of particle accelerators**
  - **Studies related to collective effects**
  - **Mitigation strategies**
- **Calculation of Wake fields and Impedances**
  - **Impedance model for PETRA III**
  - **Calculation of HOM in cavities**
  - **Contribution to the HL-LHC**
- **Teaching at CERN schools**

PETRA III is one of the core facilities at DESY

Parameter	PETRA III
Energy / GeV	6
Circumference /m	2304
Emittance (horz. / vert.) /nm	1.3 / 0.013
Total current / mA	100

Ada Yonath Hall
Extension Hall East



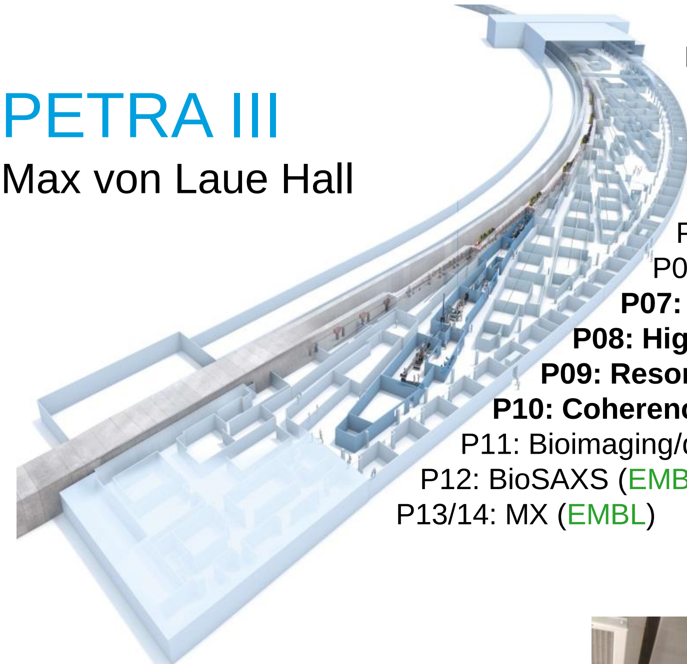
Max von Laue Hall

Paul P. Ewald Hall
Extension Hall North

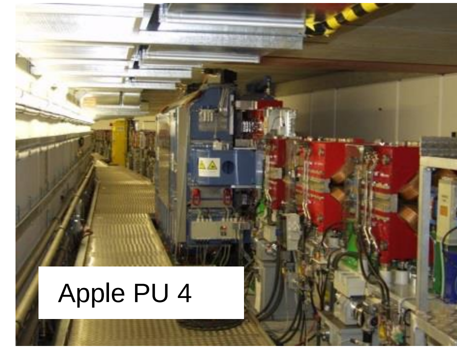
Beamlines at PETRA III

PETRA III

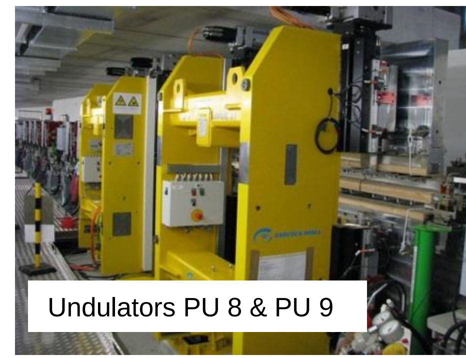
Max von Laue Hall



P01: Dynamics beamline, IXS, NRS
P02.1: Powder diffraction & total scattering
P02.2: Extreme conditions
P03: Micro-, nano-SAXS, WAXS
P04: Variable polarisation XUV
P05: Micro-, nano-tomography (HZG)
P06: Hard X-ray micro-, nanoprobe
P07: High-energy materials sci. (HZG, DESY)
P08: High-resolution diffraction
P09: Resonant scattering/diffraction
P10: Coherence applications
P11: Bioimaging/diffraction
P12: BioSAXS (EMBL)
P13/14: MX (EMBL)



Apple PU 4

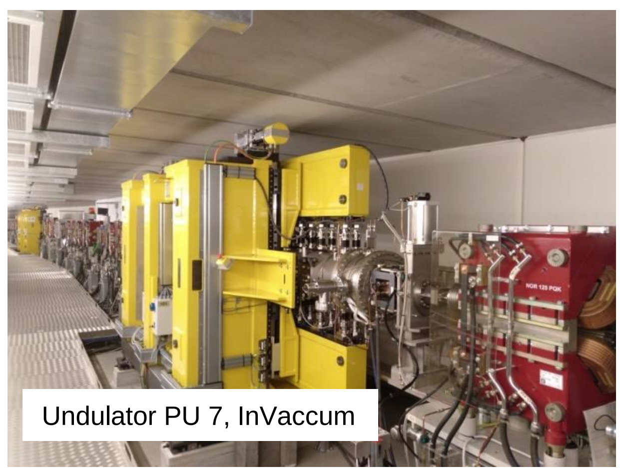


Undulators PU 8 & PU 9

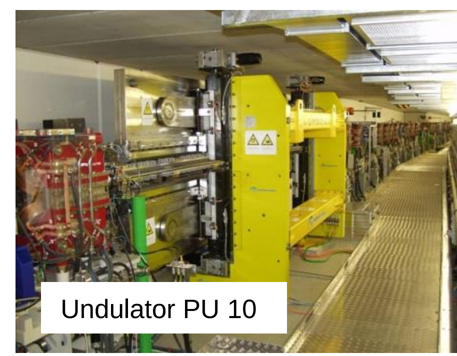
Beam size:
~ 150 μm x 6 μm
(high beta)

Orbit stability requirement:

submicron
~ 0.6 mm
(vert.)



Undulator PU 7, InVaccum

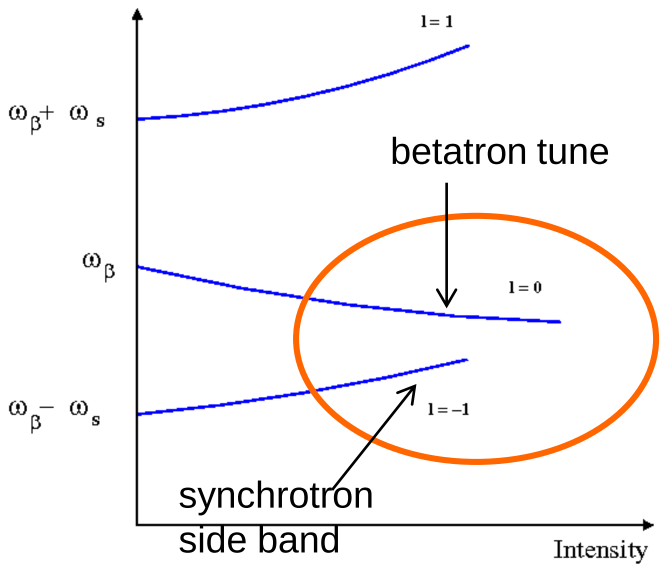


Undulator PU 10

Studies related to collective effects

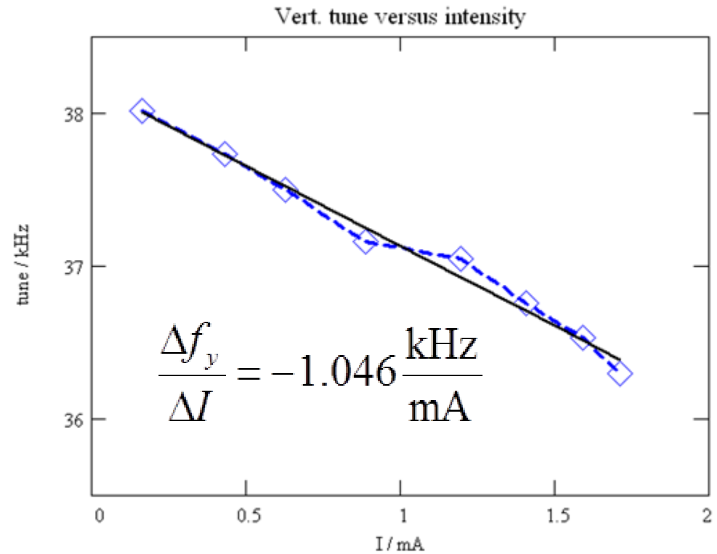
Measurement of the tune shift with amplitude

TMCI = Transverse Mode Coupling Instability



Modes of the charge distribution (Vlasov equation with wakefields)

Measurement (2009) PETRA III



$Q_z = 30.31, \quad f_x = 39.5$ kHz

$Q_s = 0.049, \quad f_s = 6.1$ kHz

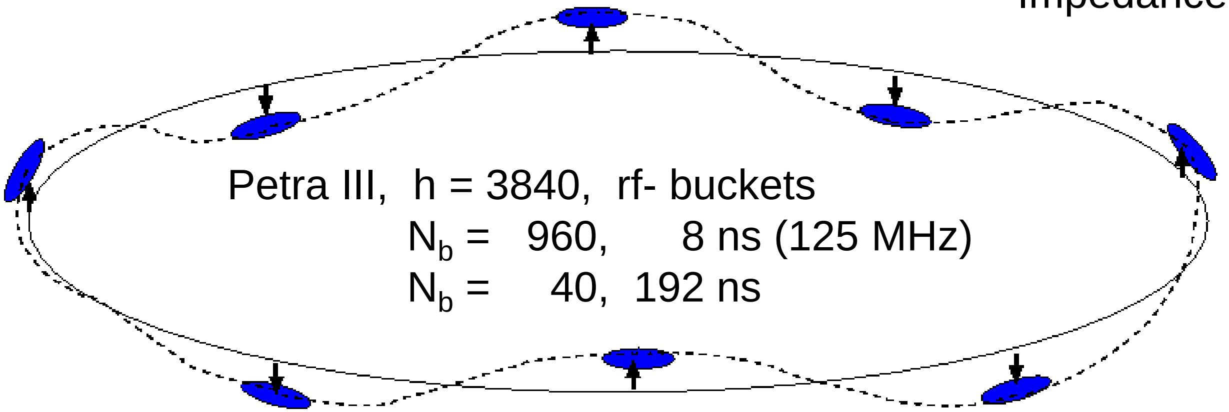
f_0 =130 kHz

40 bunche mode, I_{bunch} = 2.5 mA

Tune change: ~ 0.02

Multi bunch instabilities

Measurement of threshold currents

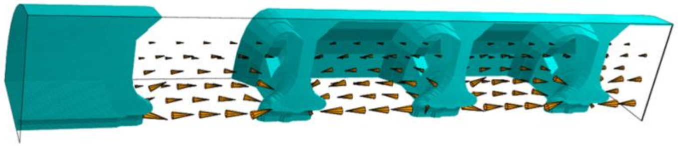


Impedance: HOMs in PETRA Cavities

	longitudinal	horizontal	vertical
I_{thres} (mA)	**7**	**6**	**6**
1/τ (Hz)	**35**	**50**	**60**
Z_{eff}	**3.6 MΩ**	**45 MΩ/m**	**54 MΩ/m**

$$\frac{1}{\tau_\perp} = \omega_0 \frac{I_{\mathrm{tot}} \langle \beta_x \rangle}{4\pi E / e} Z_{\mathrm{eff}\,\perp}$$

$$\frac{1}{\tau_{||}} = \Omega_s \frac{I_{\mathrm{B}}}{2\, V_{\mathrm{rf}}} Z_{\mathrm{eff}\,||}$$



f = 500 MHz, R/Q = 830 Ohm

f = 728 MHz, R/Q = 89 Ohm

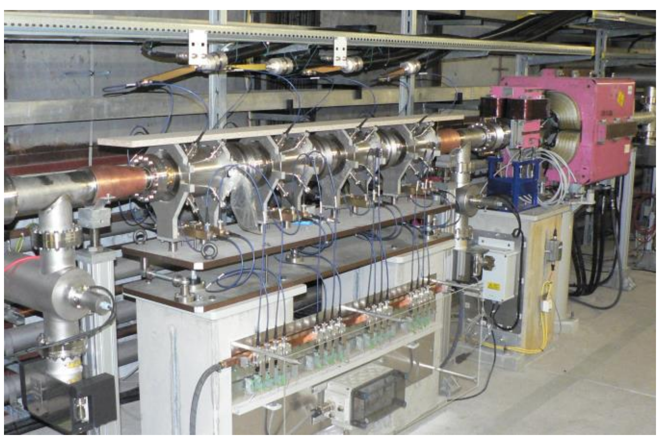
Mitigation strategies

Feedback systems and improved vacuum chamber designs

PETRA III Feedback Systems:
required damping $1/\tau$:
Longt. 800 Hz or 1/1.25 ms
Horz./Vert. 1400 Hz or 1/ 0.7 ms
Bandwidth 62.5 MHz

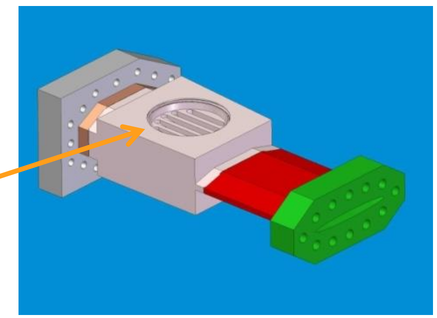
J. Klute, K. Balewski et al., DIPAC'11, TUPD81

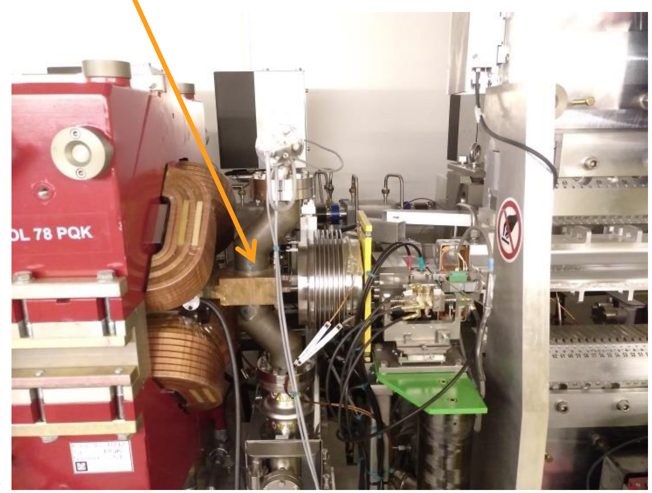
Longitudinal feedback cavities



Tapered transitions in front of the undulators, optimization of the vacuum chamber

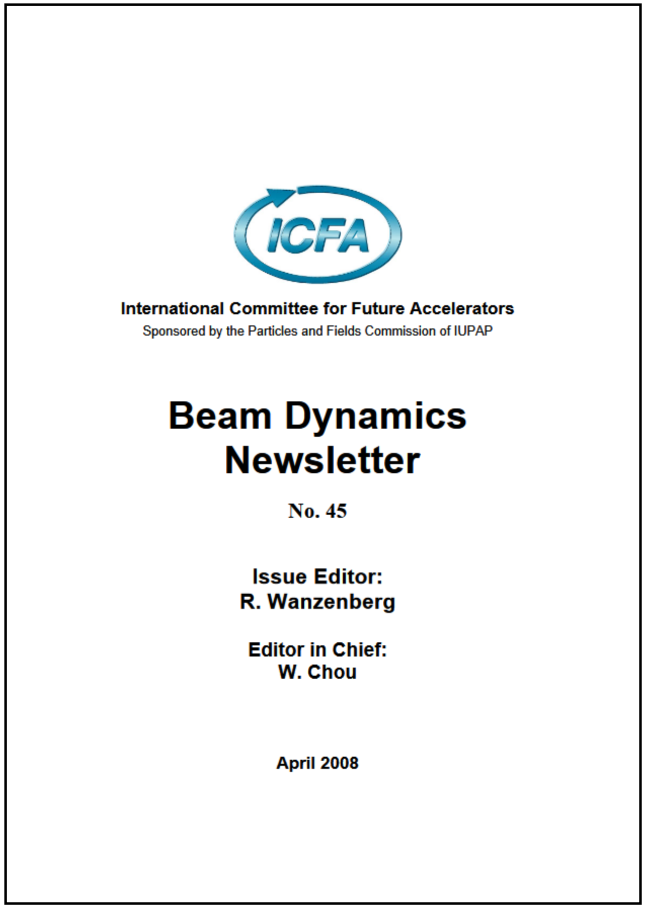
Pump ports





Calculation of Wake Fields and Impedances

Impedance model for PETRA III is published in ICFA Beam Dyn.Newslett.45:114-125, 2008



International Committee for Future Accelerators
Sponsored by the Particles and Fields Commission of IUPAP

Beam Dynamics Newsletter

No. 45

Issue Editor:
R. Wanzenberg

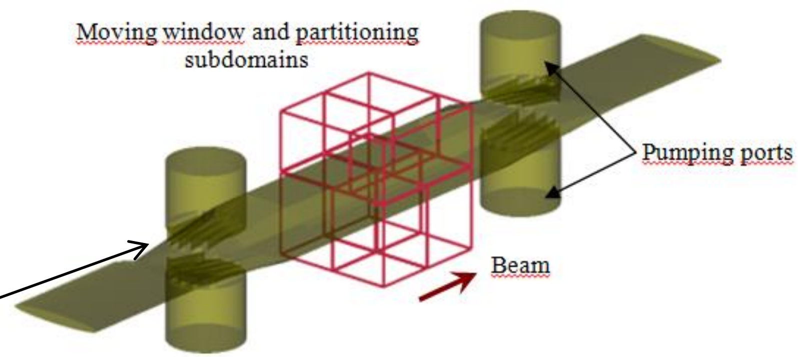
Editor in Chief:
W. Chou

April 2008

The impedance model in terms of loss and kick parameters has been summarized in:

K. Balewski, R.W., O. Zagorodnova
The Impedance Model of PETRA III

E. Gjonaj, T. Lau, T. Weiland, University of Darmstadt, Germany
Computation of Short Range Wake Fields with PBCI

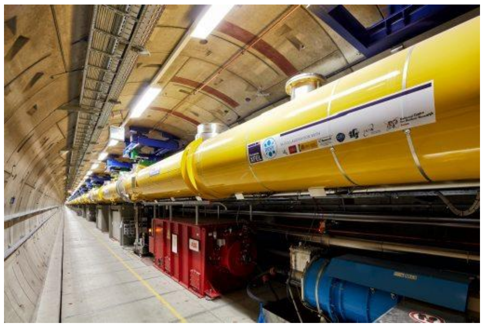


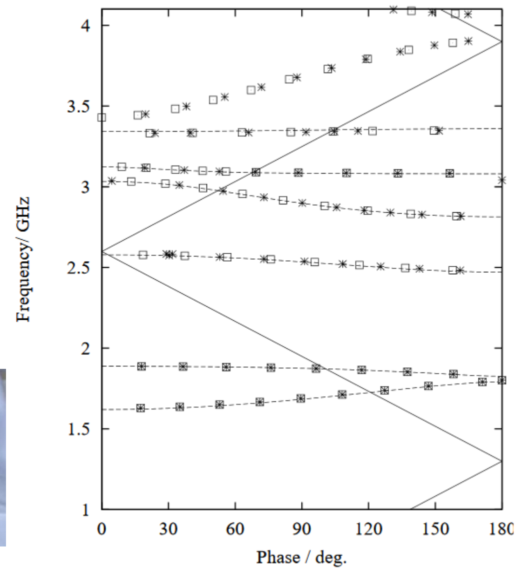
Tapered transition at the undulators

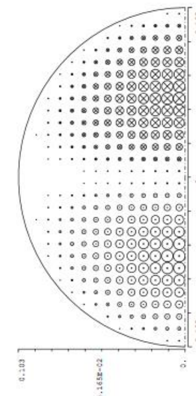
Geometry of the tapered transition together with a schematic view of the moving computational window.

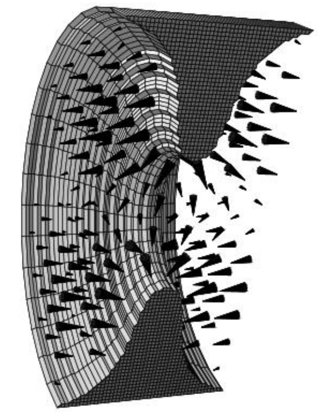
Calculations of HOM in cavities

European XFEL: superconducting 9 cell cavity









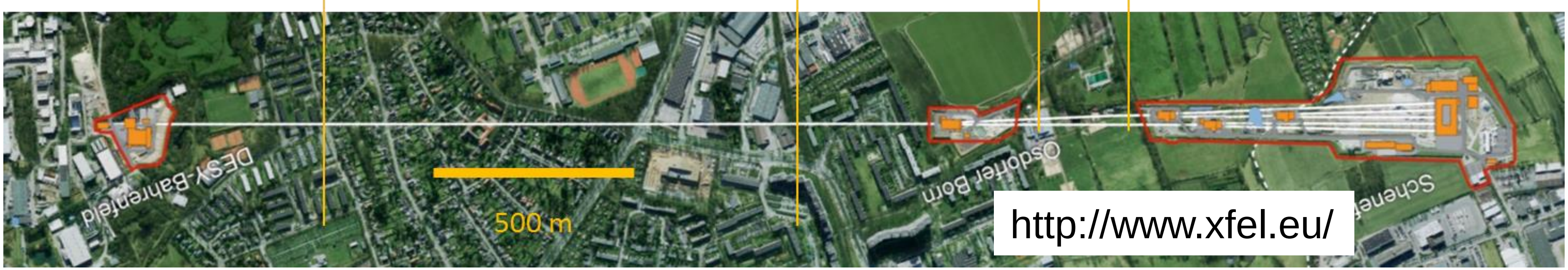
Monopole, Dipole and Quadrupole Passbands of the TESLA 9-cell Cavity, **TESLA 2001-33, Sep. 2001**

main linac, L_{tot} = 1179 m

L_{act} = 640 × 1.038 m = 664 m

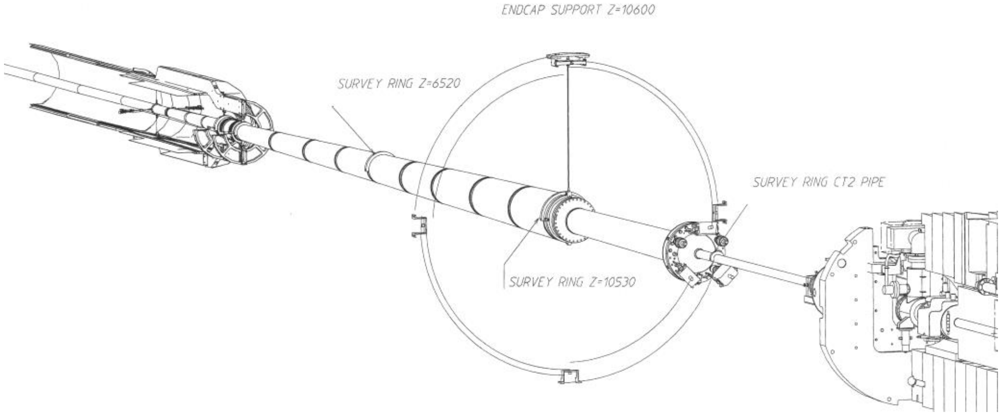
SASE1 L_{tot} = 225 m

L_{act} = 35 × 4.96 m = 174 m



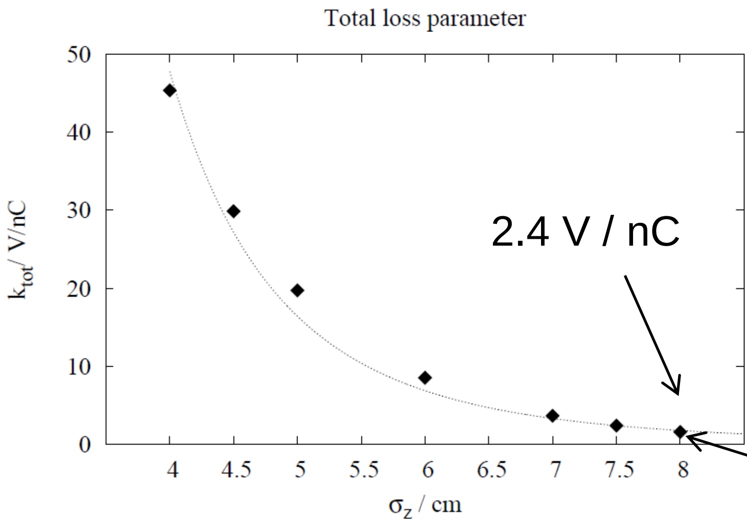
Contribution to the HL-LHC

CMS experimental chamber, loss parameter and transient heating



$$k_{||\mathrm{tot}}^{(0)} = \frac{1}{\pi} \int_0^\infty d\omega \; h(\omega) \, \Re(Z_{||})(\omega)$$

$$h(\omega) = \exp\left(-\left(\frac{\sigma_z}{c}\omega\right)^2\right)$$



2.4 V / nC

rms bunch length →

Transient heating

$$P = N_b \, f_R \, {q_b}^2 \, k_{||\mathrm{tot}}^{(0)}$$

revolution frequency

Number of bunches

single bunch charge

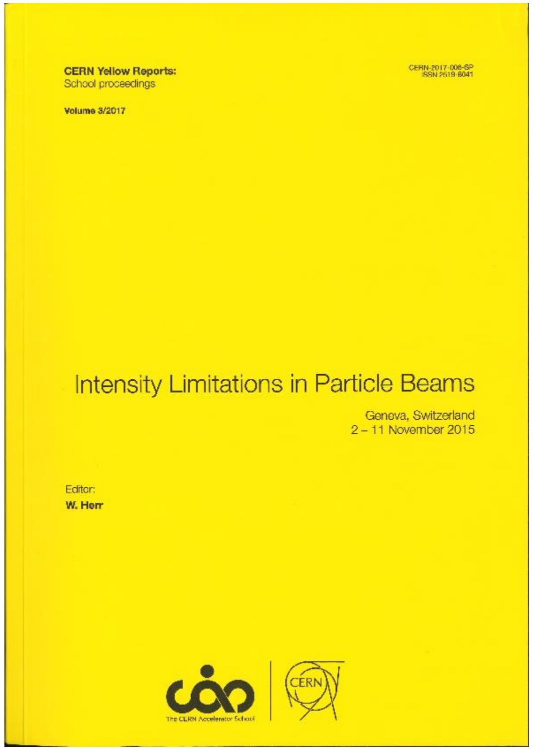
HL-LHC parameters: P ~ 100 W
(2800 bunches, 35 nC)

CERN-ATS-Note-2013-018 TECH

Teaching at CERN schools

DESY has contributed to the CAS in 2015 (Intensity Limitations) and 2017 (Vacuum)

http://cds.cern.ch/record/2276820/files/ http://cds.cern.ch/record/2721872/files/



Martin Dohlus and R.W.
An Intoduction to Wake Fields and Impedances

R.W.
Impedances and Instabilities
https://arxiv.org/abs/2006.06540

Plans at DESY

Focus on plans related to FCC Innovation Study

- **Upgrade of PETRA III**
  - **PETRA IV**
  - **Studies at PETRA III**

- **Contribution to FCC Innovation Study**
  - **Expertise at DESY**
  - **Calculation of Wake fields and Impedances**

PETRA IV is the planned upgrade of PETRA III

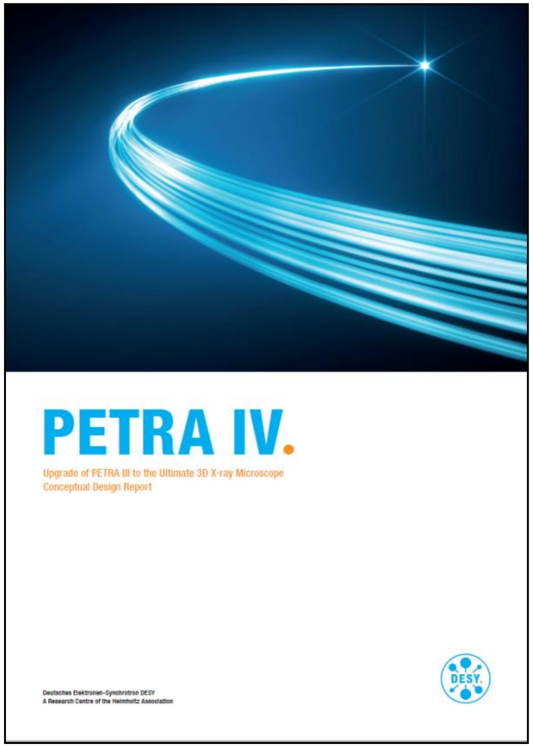
The high brightness synchrotron light facility will directly contribute to almost all of the 17 Sustainable Development Goals of the UN

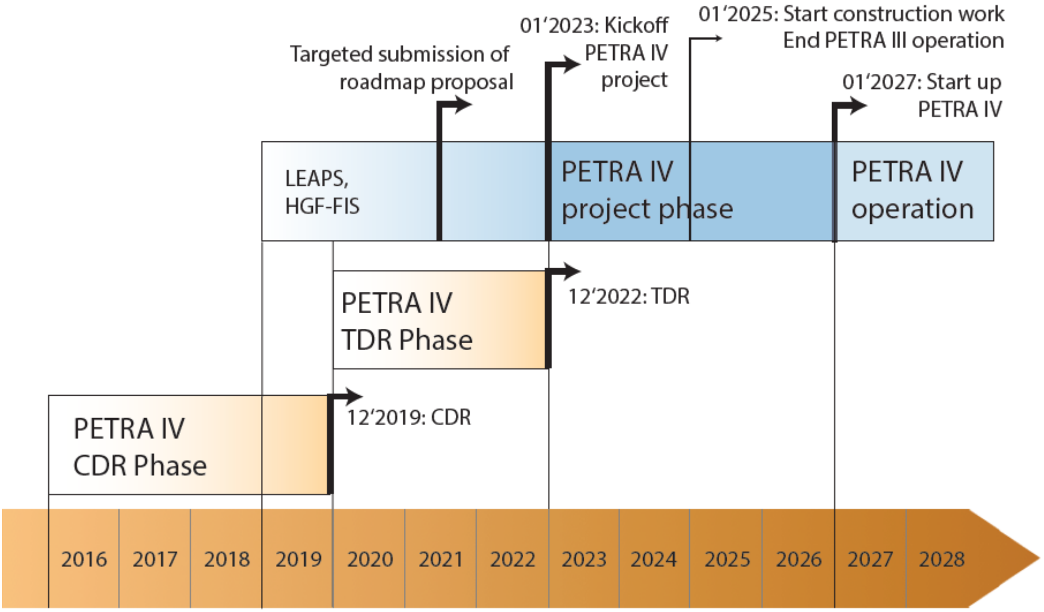
PETRA IV

Upgrade of PETRA III to the Ultimate 3D X-ray Microscope

CDR has been completed
available from:
http://doi.org/10.3204/PUBDB-2019-03613

TDR
Project leader: Riccardo Bartolini





Studies at PETRA III towards the PETRA IV TDR

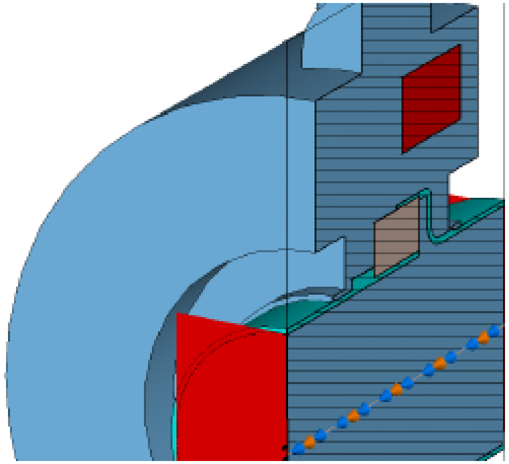
There is an opportunity to enable synergies also for the FCC

Opportunities for studies at PETRA III

- Beam stability concepts
- Accelerator physics / beam dynamics
  - **Test of commissioning strategies**
  - **Test of impedance models**
- Technical subsystems
  - Accelerator Controls
  - Vacuum system
  - RF system
  - Diagnostics

Example:
Beam Current Monitor
Current monitor optimized for wake losses

Test new design proposals at PETRA III

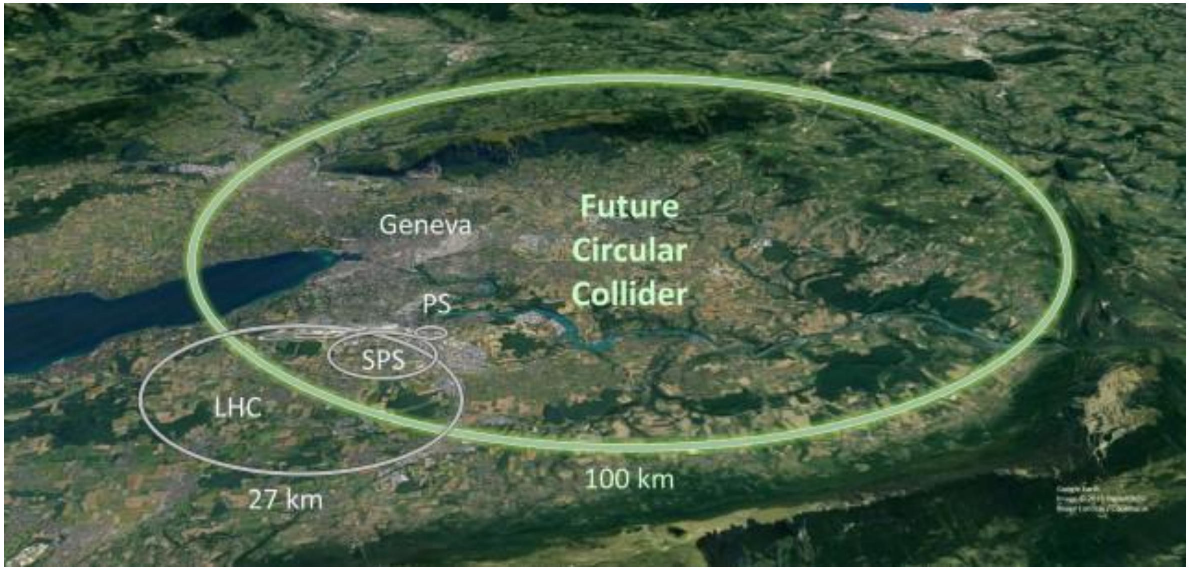


Contribution to FCC Innovation Study

New research infrastructure to unlock mysteries of the universe

HORIZON 2020

Future Circular Collider Innovation Study



Collective effects are part of the WP2: Collider Design
Task: *Analyse and design the mitigation for impedance and single-beam collective effects*
with participants from CERN, University of Rome 'La Sapienza', INFN, DESY, …

Expertise at DESY

The contribution to the FCC IS will follow the previous collaboration on HL-LHC

The funding from the Horizon 2020 program will allow to hire a postdoc, contributing to the impedance calculations for the FCC

the planning will be done in close collaboration with the WP leader

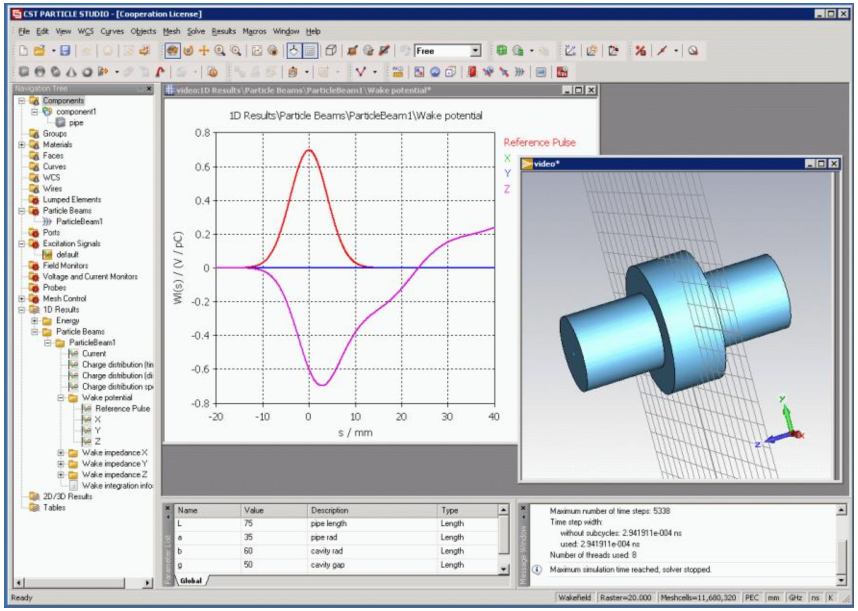
Previous collaboration for the HL-LHC was very successful:

Calculation of Wakefields and Higher Order Modes for the Vacuum Chamber of the CMS, ATLAS, ALICE and LHCb Experiments for the HL-LHC
10.18429/JACoW-IPAC2017-WEPIK066
Calculation of Wakefields for the New Design of the LHCb Vertex Locator
CERN-ACC-NOTE-2017-0034
Calculation of Wakefields and Higher Order Modes for the New Design of the Vacuum Chamber of the ALICE Experiment for the HL-LHC
CERN-ACC-NOTE-2017-0033
Calculation of Wakefields and Higher Order Modes for the Vacuum Chamber of the ATLAS Experiment for the HL-LHC
CERN-ACC-NOTE-2013-0046
Calculation of Wakefields and Higher Order Modes for the New Design of the Vacuum Chamber of the CMS Experiment for the HL-LHC
CERN-ATS-Note-2013-018-TECH

Calculation of Wake fields and Impedances

The necessary tools are available at DESY

Example:
Numerical calculation with the CST Studio suite (commercial 3D code)



Example:
Analytical calculation of resistive all impedances based on the experience at PETRA III

$$Z_{\parallel}^{(0)}(\omega) = \left(1 - \frac{\omega}{|\omega|}\, i\right)\, L\, \frac{1}{2\pi\, b}\, \sqrt{\frac{|\omega|\ \mu}{2\,\sigma}}$$

$$Z_{\perp}^{(1)}(\omega) = \frac{c}{\omega}\, \frac{2}{b^2}\, Z_{\parallel}^{(0)}(\omega)$$

Conclusion: Less is More

less impedance → more beam current
more luminosity

⇩

Optimization of
vacuum chamber design

small loss and kick parameters

$$k_{tot} = \int ds\, \lambda(s)\, \mathcal{W}(s)$$

$$\Delta Q_\beta = \frac{I_B\, T_0}{4\pi\, E/e} \langle \beta \rangle k_\perp < Q_s \frac{1}{2}$$

reduced power losses

$$P = N_b\, f_R\, {q_b}^2\, k^{(0)}_{||\mathrm{tot}}$$

Thank you

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

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