PETRA IV

Overview
Collective Effects

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DESY-TEMF Collaboration Meeting
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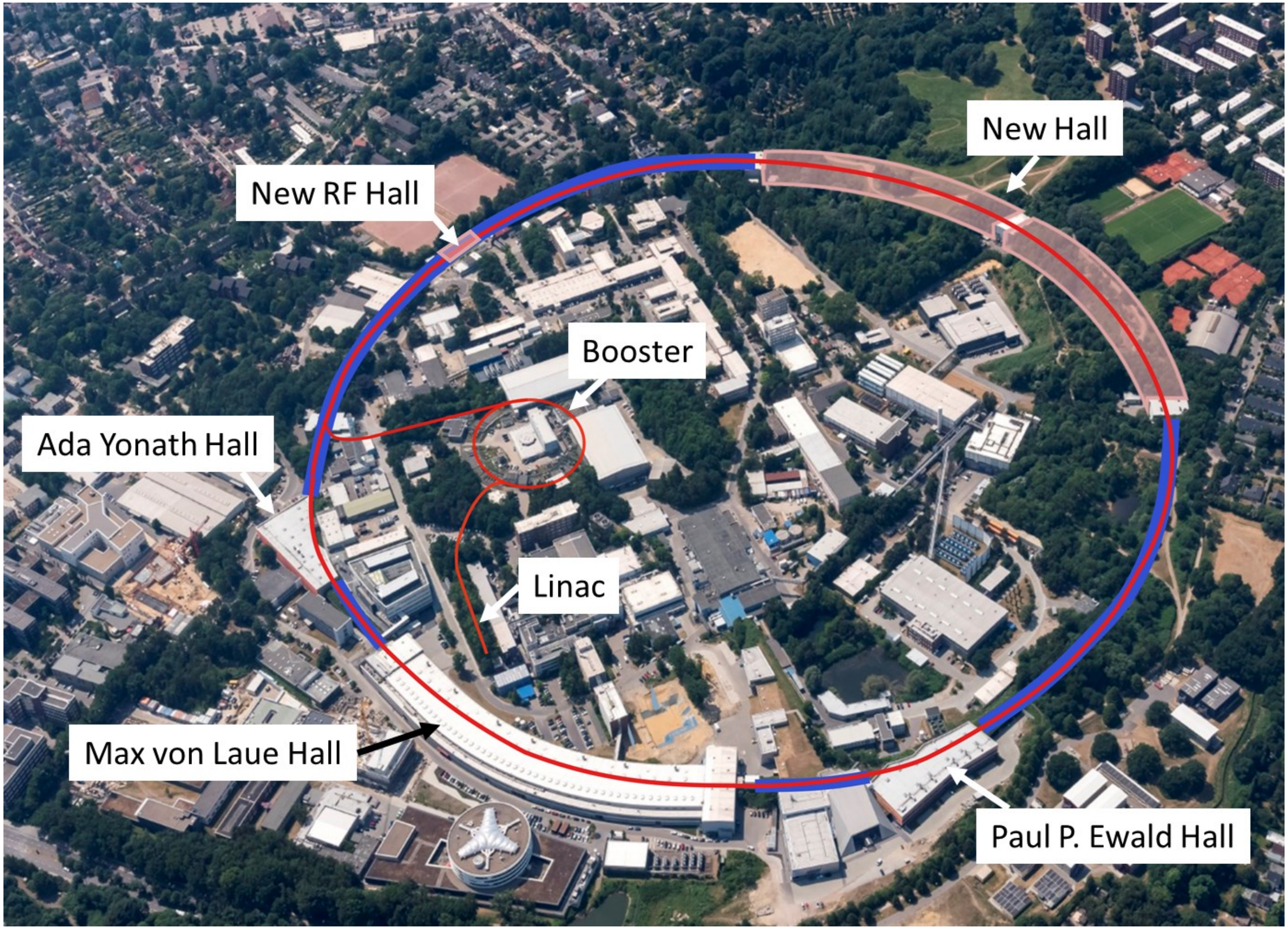
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Scope of Project (Excerpt from CDR)

The project includes

- Upgrade of the storage ring PETRA III into a storage ring with ultra-low emittance,
- Upgrade and refurbishment of the pre-accelerators,
- Relocation, refurbishment/upgrade and in part new construction of photon beamlines,
- Construction of a new experimental building in the west of the PETRA ring.

PETRA III and IV



PETRA IV – MBA Based Storage Ring

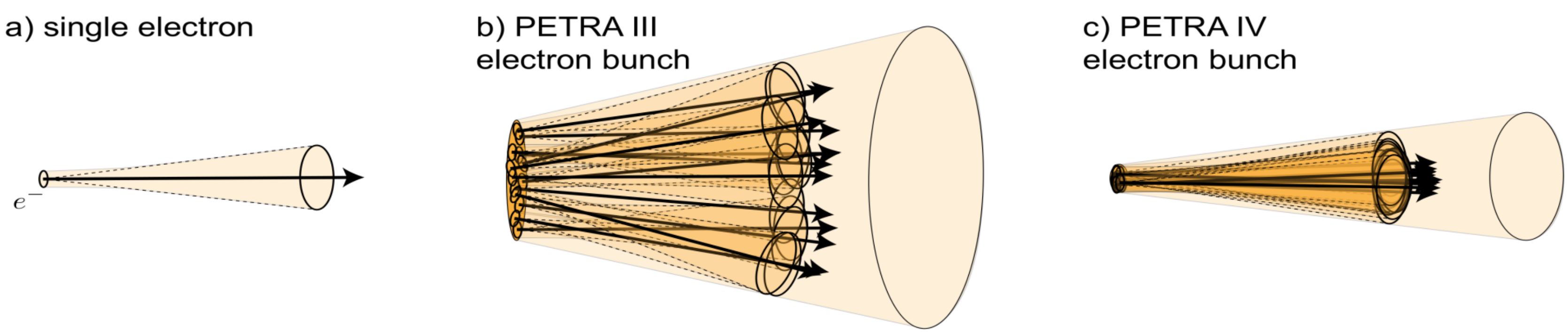
PETRA IV – Diffraction Limited Source

$$\mathcal{B} = \frac{F}{4\pi^2 \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

F - spectral flux

$$\Sigma_{x,y}^2 = \sigma_{x,y}^2 + \sigma_R^2$$

$$\Sigma_{x',y'}^2 = \sigma_{x',y'}^2 + \sigma_{R'}^2$$



$$\varepsilon_R = 10 \text{ pm}$$

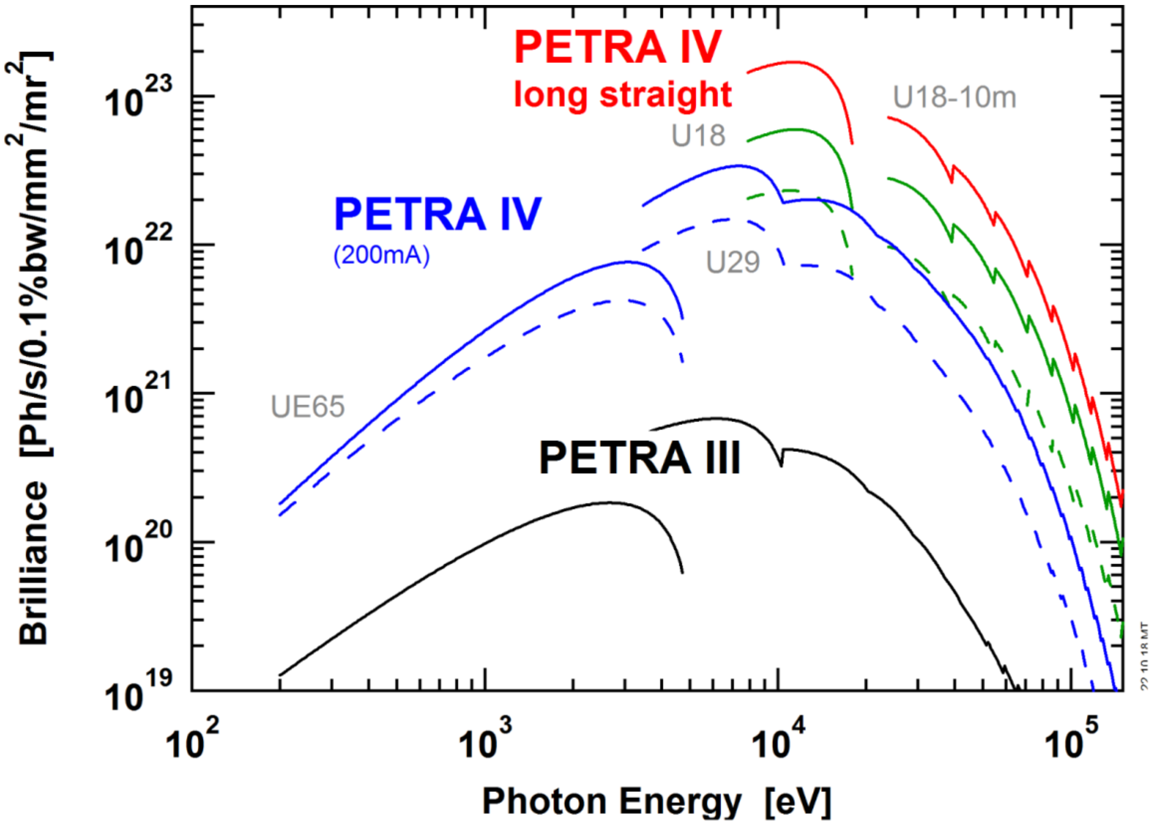
$$\lambda = 0.125 \text{ nm}$$

$$\varepsilon_R = \frac{\lambda}{4\pi}$$

$$\varepsilon_x = 1200 \text{ pm}$$

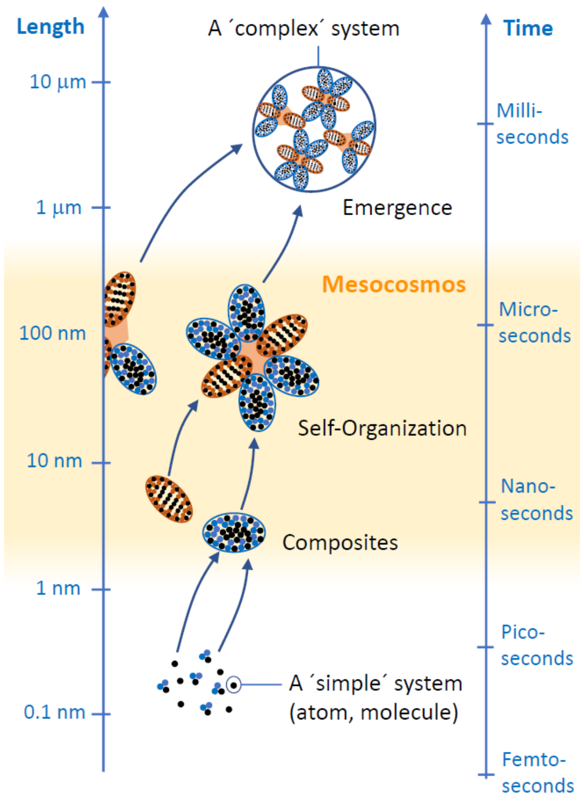
$$\varepsilon_x = 10 \sim 30 \text{ pm}$$

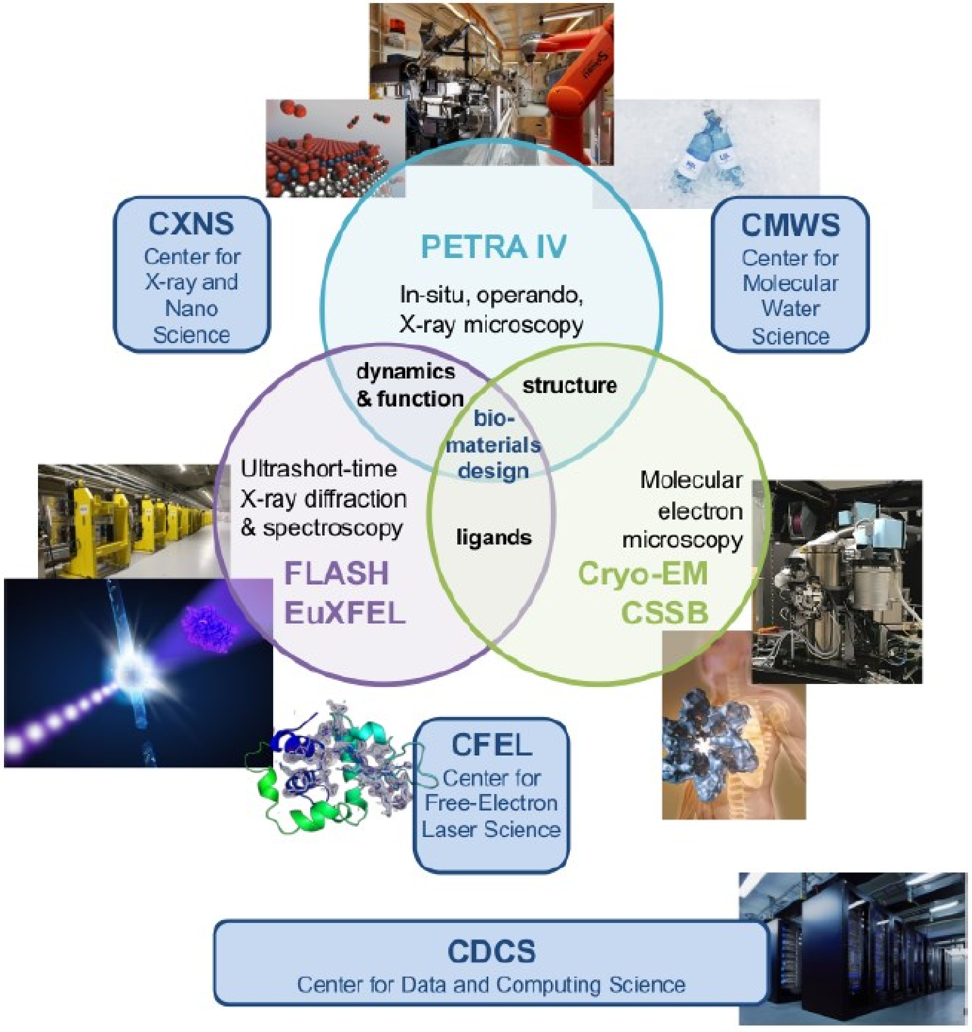
PETRA IV – High Brilliance Light Source



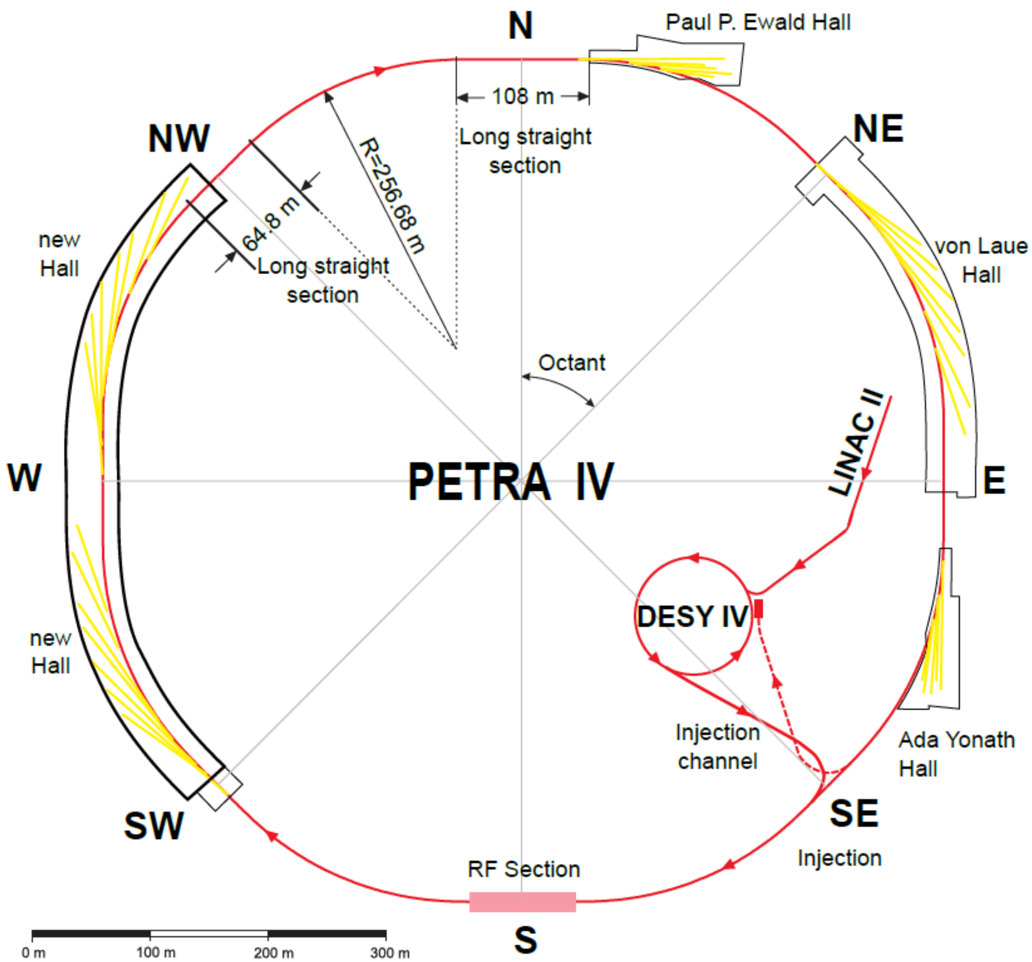
Science Case

PETRA IV contributes to the analytic techniques that are available at DESY and the Science City Bahrenfeld





PETRA IV Conceptual Design



Storage Ring:
Baseline: H7BA style lattice (64 cells) (ESRF-EBS style lattice)
on axis injection,
Option (considered during TDR)
maintain several beamlines
(23 m long cell with strong magnets)

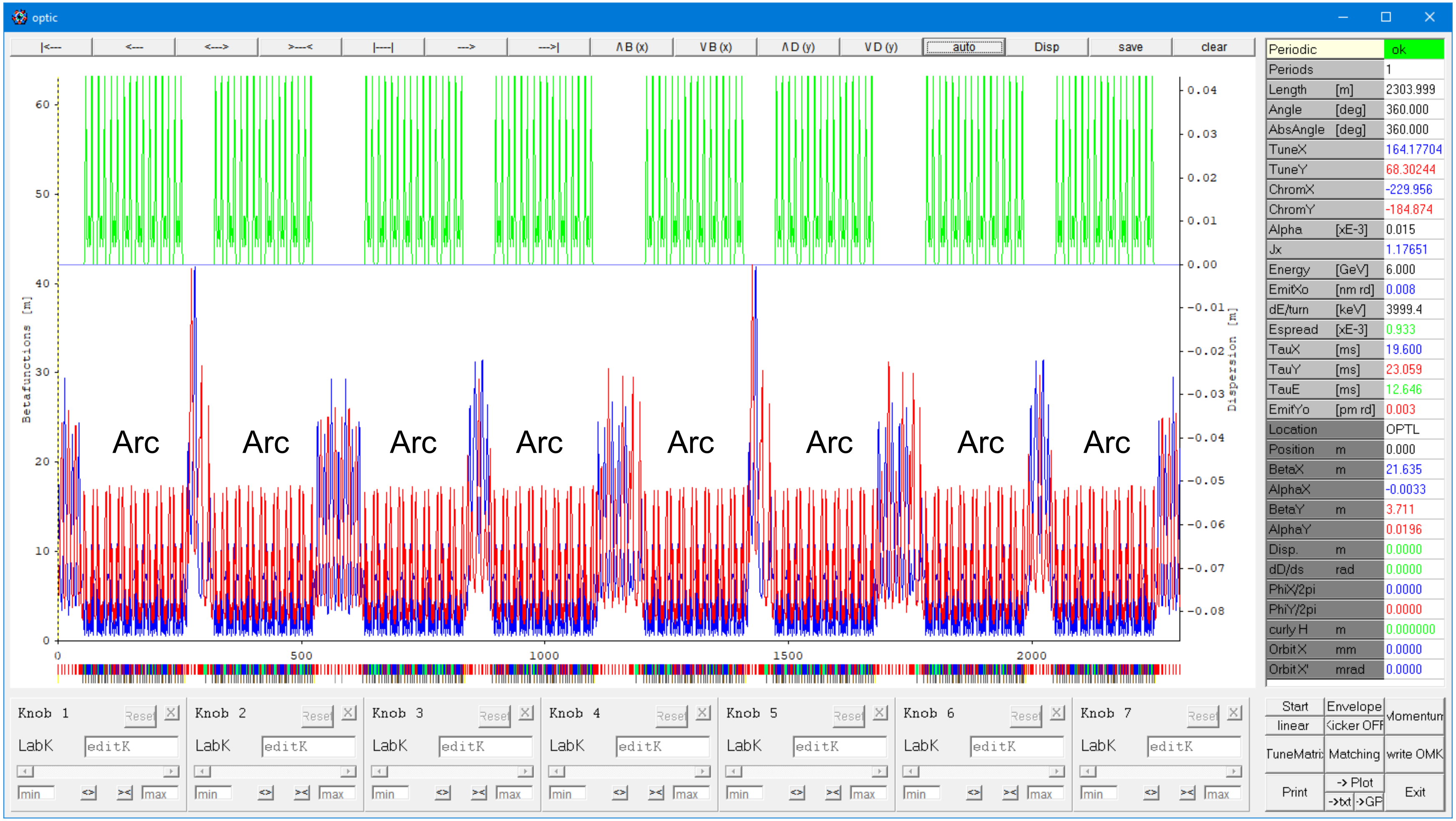
Injector:
new booster synchrotron, DESY IV
low emittance ~ 20 nm rad
refurbished Linac II
with full intensity gun
Option
consider the possibility to include in the future an injector based on laser plasma wakefield acceleration

Technical sub-sytems:
Magnets, bore radius 13 mm
Option: 9 … 10 mm
Vacuum system, 10 mm inner radius
Option: 7 mm

PETRA IV Storage Ring

PETRA IV – baseline lattice design

- Hybrid 7BA cell
- 64 cells in 8 arcs
- 26 x 5-m long IDs
- No reverse bend
- Injection with moderate beta (~21m)
- 4 x 10-m long "super-IDs" with 4m beta



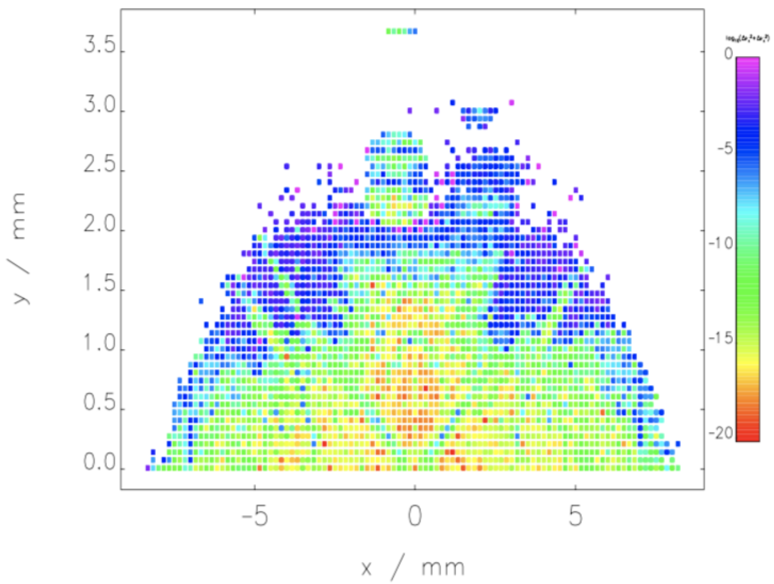
Baseline lattice parameter summary

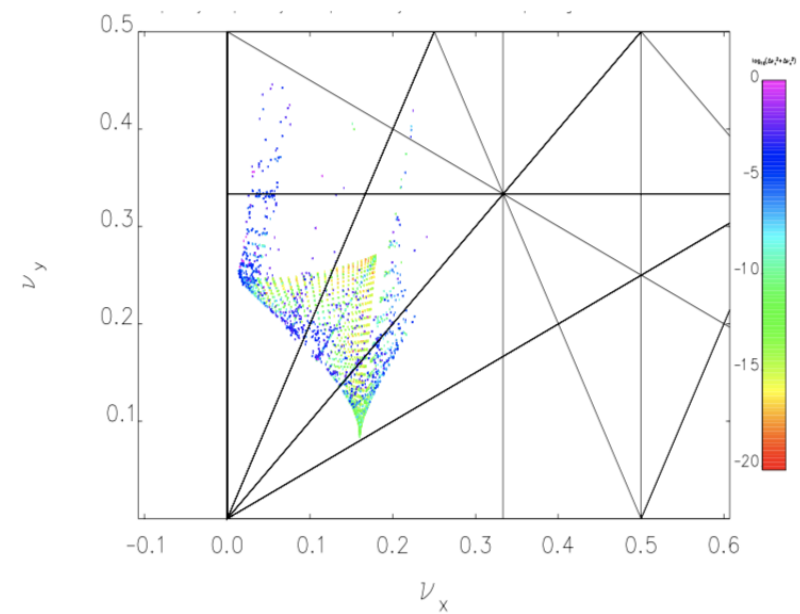
Parameter	Value (IDs open)	Value (all IDs closed)[1]
Energy E	6 GeV	6 GeV
Circumference C	2304 m	2304 m
☆ Natural emittance ϵ_0	17.4 pm rad	7.6 pm rad
Tunes Q_x, Q_y	164.18, 68.27	164.18, 68.27
☆ Momentum compaction factor α_p	1.485×10^{-5}	1.485×10^{-5}
Natural chromaticities ξ_{x0}, ξ_{y0}	-229.9, -185.1	-229.9, -185.1
Chromaticities ξ_x, ξ_y	$+5$, $+5$	$+5$, $+5$
Damping partition number J_x	1.536	1.175
Damping times τ_x, τ_y, τ_s	45.6 ms, 70.0 ms, 47.8 ms	19.5 ms, 22.9 ms, 12.6 ms
Energy spread σ_p	0.678×10^{-3}	0.903×10^{-3}
☆ Bunch length σ_s	1.24 mm	1.52 mm
Bunch length σ_t	4.14 ps	5.07 ps
Energy loss per turn U_0	1.317 MeV	4.024 MeV
RF voltage V_{RF}	6 MV	8 MV
☆ Bucket half height $\Delta p/p$	8.7 %	7.1 %
☆ Synchrotron frequency f_s	387 Hz	421 Hz
Hor. beta function β_x at ID	6.86 m	6.86 m
Ver. beta function β_y at ID	2.36 m	2.36 m
Hor. dispersion function D_x at ID	0 m	0 m
Space L for ID	5 m	5 m

[1] For the insertion devices a 5 m long U32 undulator with a peak field of 0.91 T was assumed.

CDR baseline DA sufficient, more optimization work foreseen

- Acceptance from 6D tracking without errors > 1*mm mrad* in x and y
- Nonlinear dynamics optimization based on the achromat concept with additional resonance compensation in the long straights and scans of sextuple and octuple strength, tunes and cell phase advances
- More systematic optimization (e.g. MOGA) studies foreseen





4D tracking, tracking location with β_x=21.7m, β_y=3.7m

PETRA IV Intensity Limit

Requirement

- Store 200 mA in 1600 bunches for brightness mode
- Store 80 mA in 80 bunches for timing mode

200 mA for brightenss mode (0.125 mA per bunch)

- Ion instability is not critical because its risk in PETRA IV will be smaller than PETRA III.
- Will use HOM-damped EU cavities to suppress the coupled bunch instability whose impedances are below stability threshold.
- Transvers instbaility caused by resistive wall impedance is slower than the feedback system (impedance growth 4500 s^{-1} vs. feedback damping 10,000 s^{-1}).
- It seems possible.

80 mA for timing mode (1 mA per bunch)

- Peak current is as high as 800 A (σ_t = 4 ps) ➔ we will use Landau cavity to reduce the peak current.
- Transverse impedance will be greater than 1 MΩ/m ➔ we will operate the ring at high chromaticity to reduce the effective impeance $Z_t(\omega-\omega_\xi)$.
- Need to investigate with the impedance model.

Wakefield and Impedance

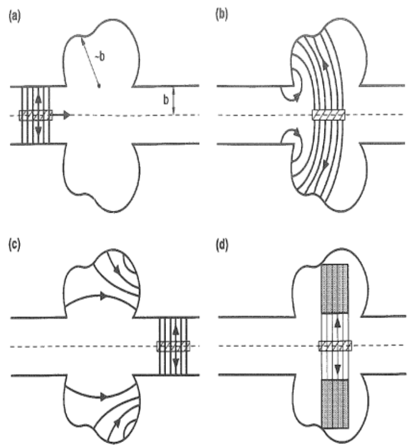
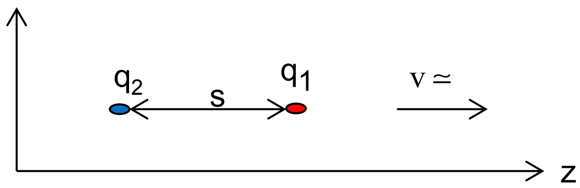


Figure 2.16. (a), (b), and (c), Field patterns as a beam bunch is traversing a cavity structure. (d) The energy loss of the beam can be estimated by calculating the field energy contained in the shaded region. The bunch length and the size of the cavity are both taken to be comparable to the pipe radius *b*.



Wakepotential

$$W_z(s) = -\frac{1}{q_1}\int_{-\infty}^{\infty} E_z(z,s)dz$$

$$V(s) = \int_{-\infty}^{s} \lambda(s')W_z(s-s')ds'$$

Impedance

$$Z(\omega) = \int_{-\infty}^{\infty} W_z(s)\exp\left(-\frac{j\omega s}{c}\right)\frac{ds}{c}$$

$$Z(\omega) = \frac{V(\omega)}{\lambda(\omega)}$$

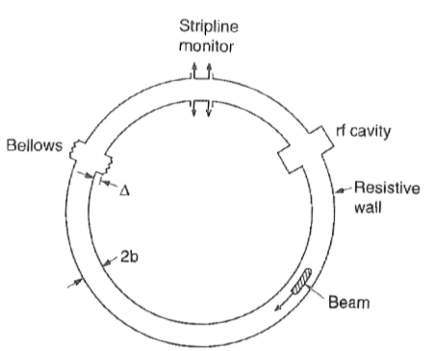


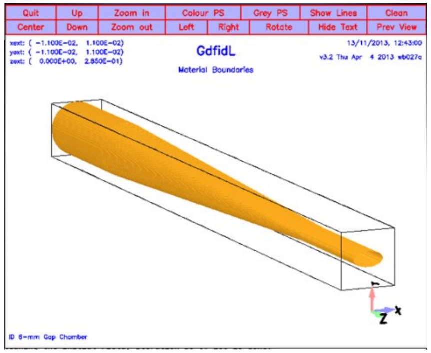
Figure 2.19. An accelerator with objects that contribute to impedances.

$$\beta * Z(Ring) = \sum_{j}^{Elemetns} \beta_j \times Z_j,$$

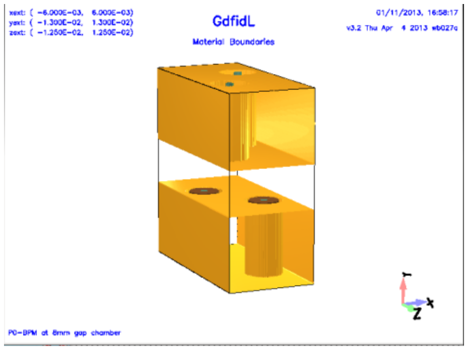
where β_j is the lattice function at the impedance element Z_j.

Impedance Elements – Geometric Model (GdfidL*)

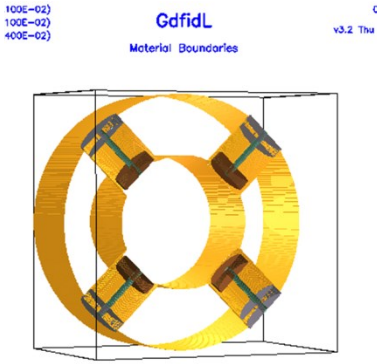
ID Chamber (6-mm)



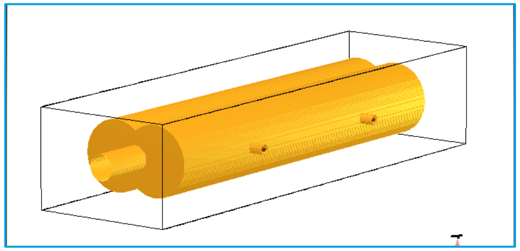
ID BPM



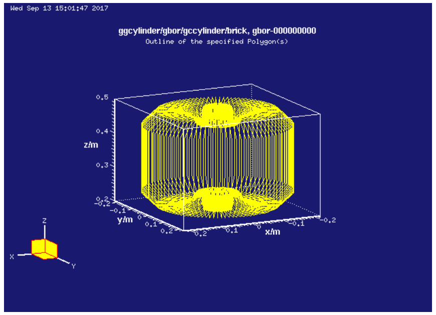
P0-BPM



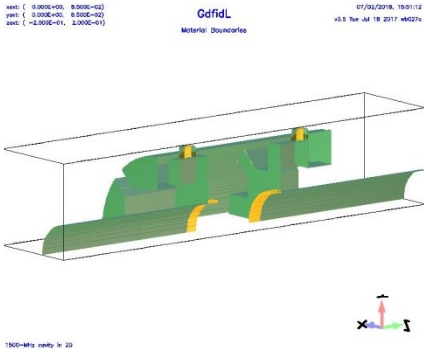
Stripline Kicker



500 Mhz RF Cavity

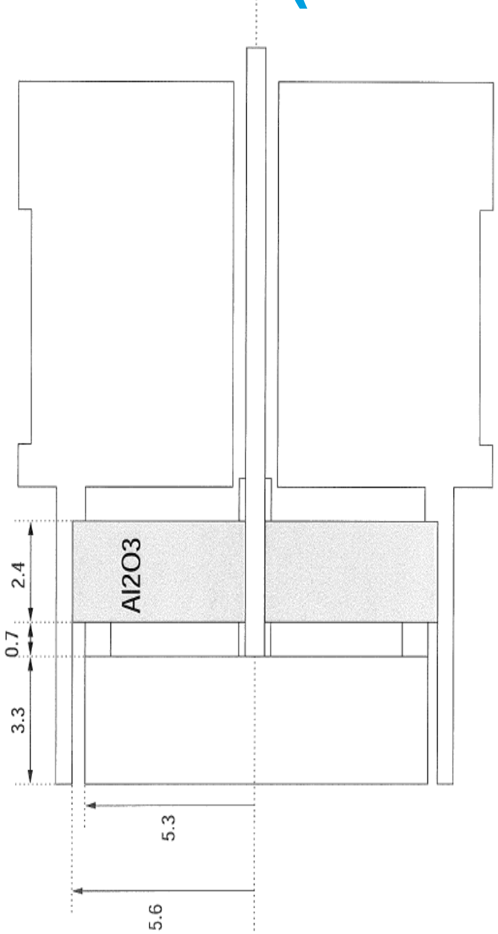


Long Feedback Cavity

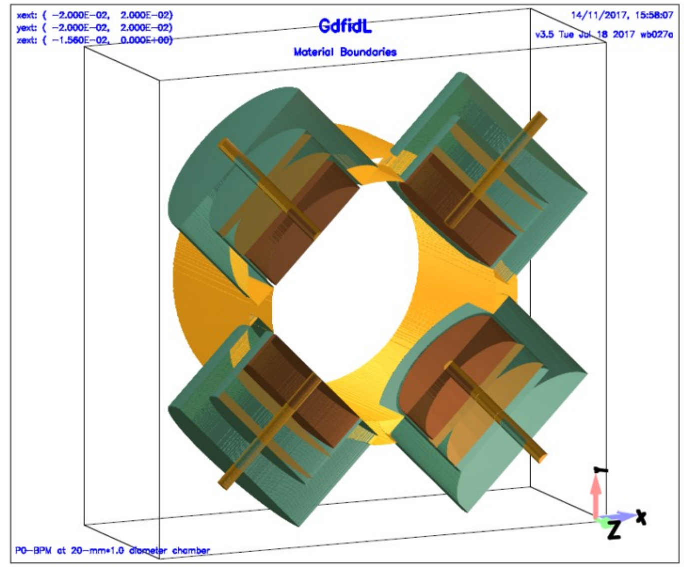


* Dr. W. Bruns allowed us to use GdfidL at his company‘s cluster free of charge.

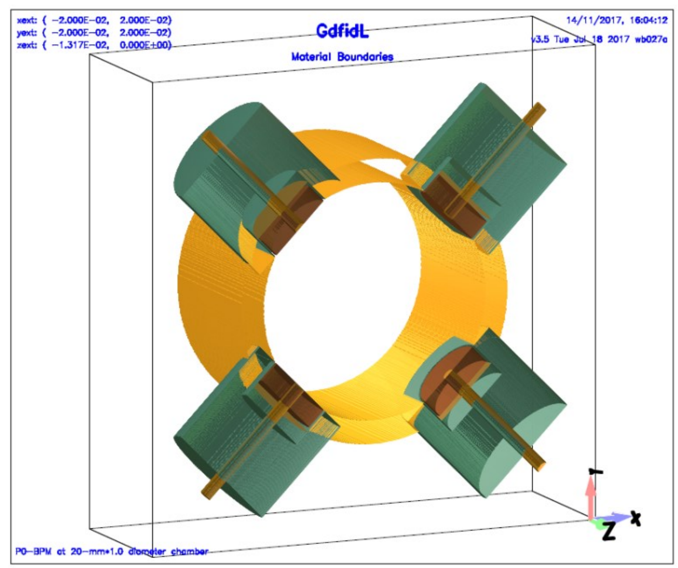
P0-BPM (PETRA IV)



x 1.0 =>



x 0.566 =>



- Al_2O_3 is a ceramic used as the vacuum-separator.
- Assigned it as a no-lossy insulator with dielectric constant of 9.1 (GdifidL).

Undulator Chamber: Taper and Scaling

Circular Taper

K. Yokoya (CERN SL/90-88, 1990)

$$Z_t(k) = j\frac{Z_0}{2\pi}\int_{-\infty}^{\infty}\left[\frac{a'}{a(z)}\right]^2 dz$$

Rectangular Taper

G. Stupakov (SLAC-PUB-7167, 1996)

$$Z_y(k) = j\frac{Z_0 w}{4}\int_{-\infty}^{\infty}\frac{h'(z)^2}{h(z)^3}dz$$

Attempt to correct to the next order

B. Podobedov, S. Krinsky(PRST AB 9, 054401, 2006)

$$Z_t(k) = j\frac{Z_0}{2\pi a_{av}}\frac{\varepsilon\tan\theta}{1-\varepsilon^2}\left(1-\frac{0.18}{\varepsilon}\tan\theta\right),\ \text{where}\ \varepsilon = \frac{a_2-a_1}{a_2+a_1}$$

Scaling in longitudinal dimension

G. Stupakov , K. Bane, I. Zagorodnov (PRST AB 14, 014402, 2011)

$$U(x,y,z;\lambda) = V\left(x,y,\frac{z}{\lambda}\right) \quad Z_t(k;\lambda) = \frac{1}{\lambda}R_t\left(\frac{k}{\lambda}\right),\quad W_t(s;\lambda) = u_t(s\lambda)$$

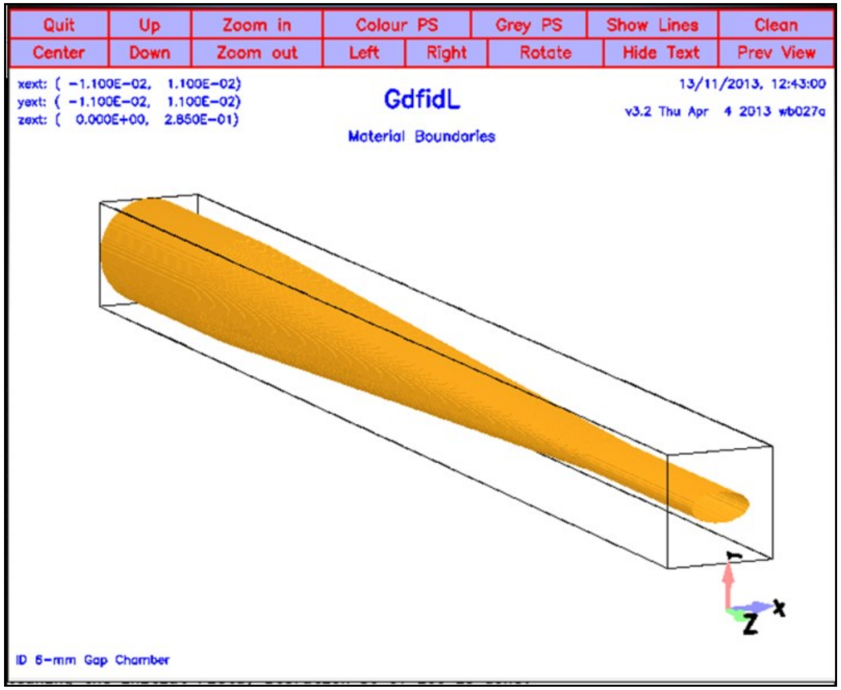
Undulator 6-mm Gap Chamber

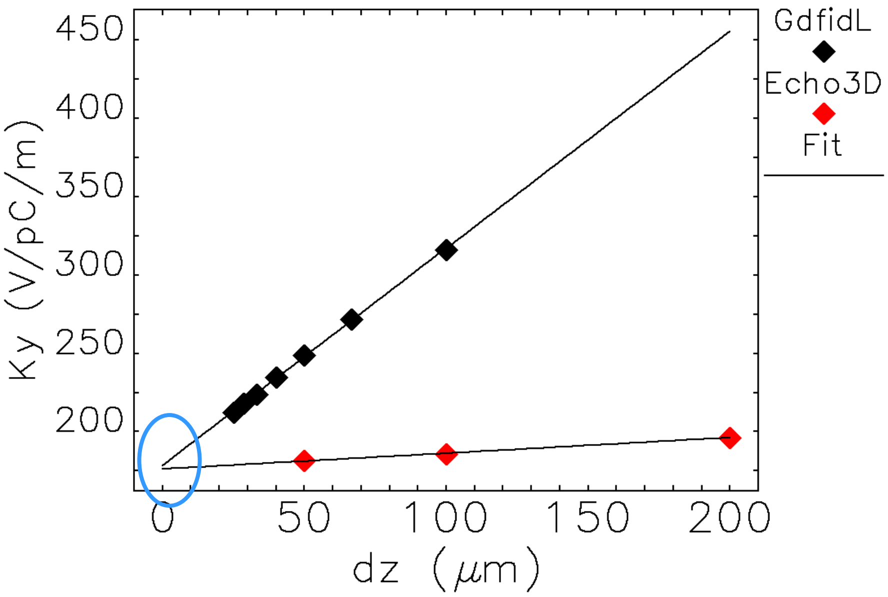
Transition is from Circular to Elliptic Chamber:

- Analytic formula does not exist

Transition length is fixed but aperture varies:

- Longitudinal scaling law may require a careful interpretation.

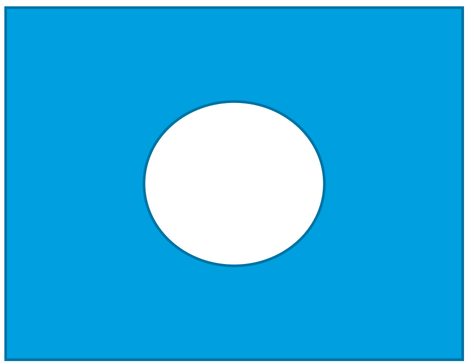


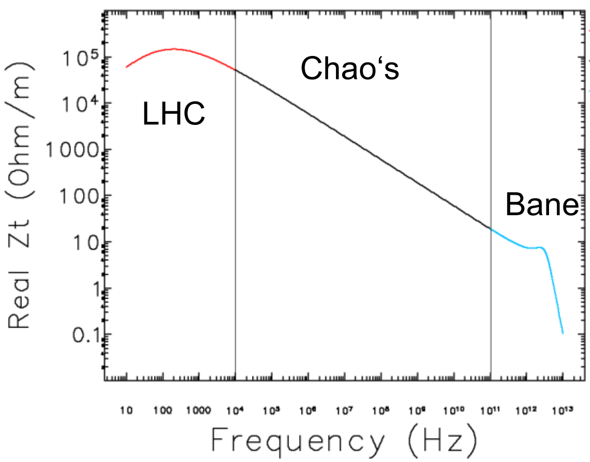


Resistive Wall Impedance

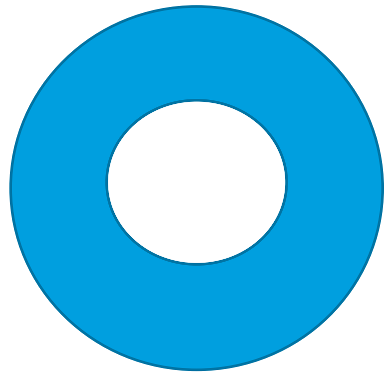
ImpedanceWake2D (IW2D)

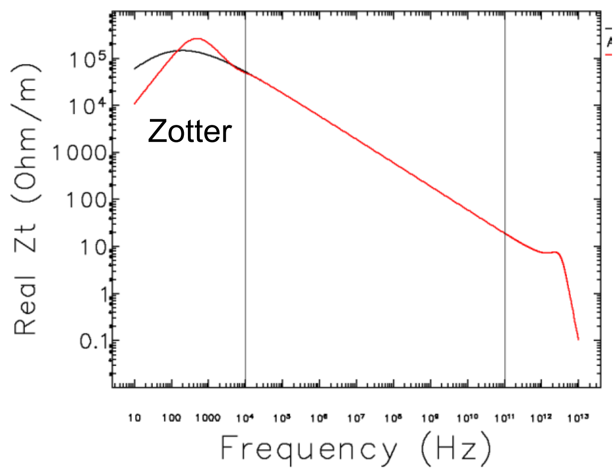
One Layer



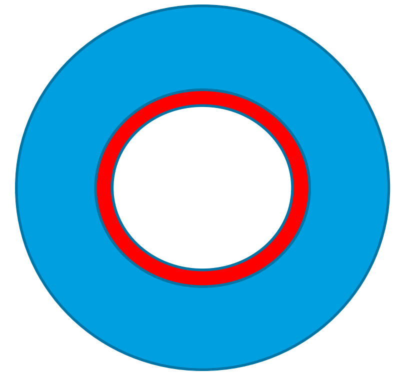


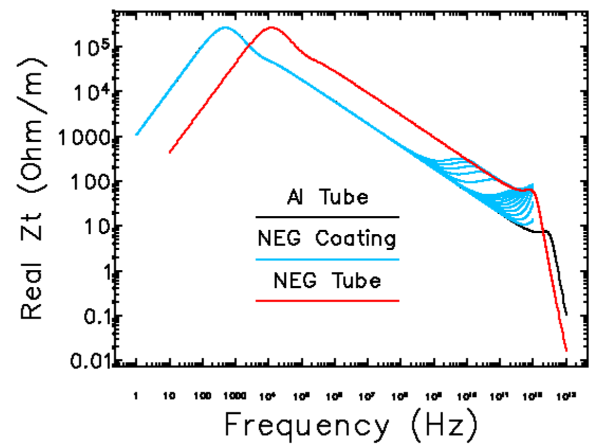
Two Layers





Three Layers





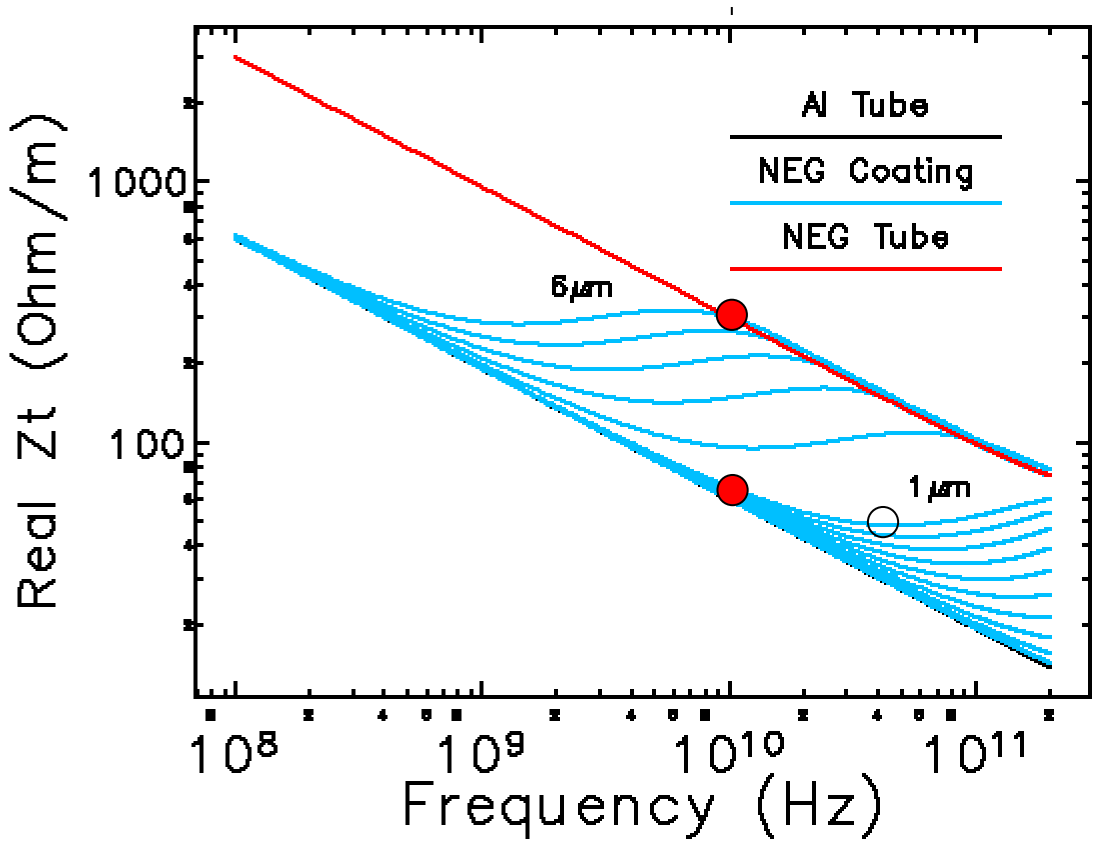
NEG Coated Aluminum Chamber

- NEG (Non Evaporative Getter) compound (Zr, Ti, V) with resistivity: (41.0, 55.6, 26.1) × 10^{-8} Ωm ➔ ρ_{NEG} = 40 × 10^{-8} Ωm (theoretical value)

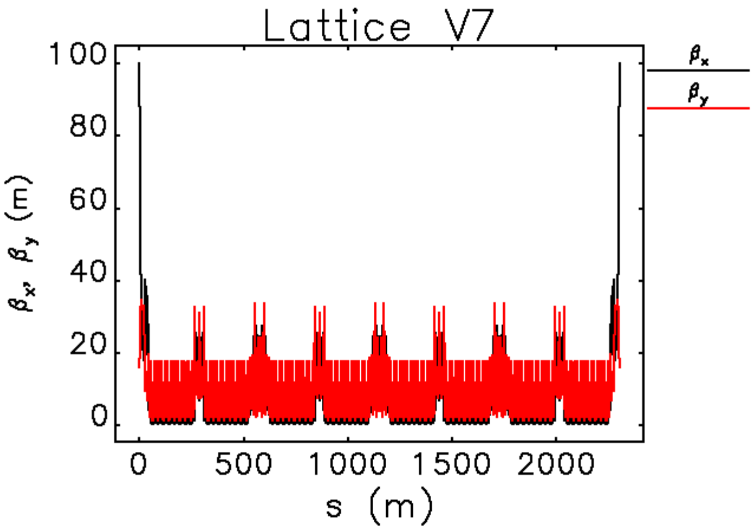
Recent measurement on ρ_{NE}

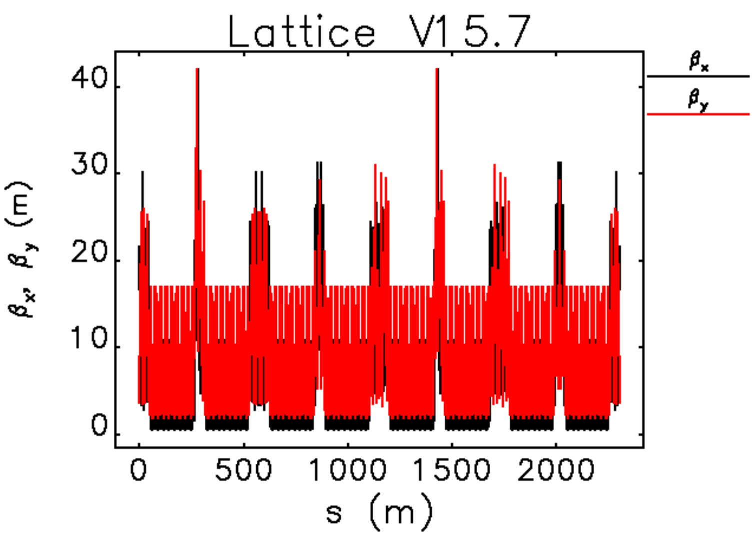
- ρ_{NEG} = 100 × 10^{-8} Ωm at 10-GHz with 6 μm coating thickness (DIAMOND)
- ρ_{NEG} = ρ_{Al} at 10 GHz with 1 μm coating thickness (APS)

We had used the conservative value on ρ_{NEG} = 100 × 10^{-8} Ωm with 1 μm coating thickness



Lattice Considered

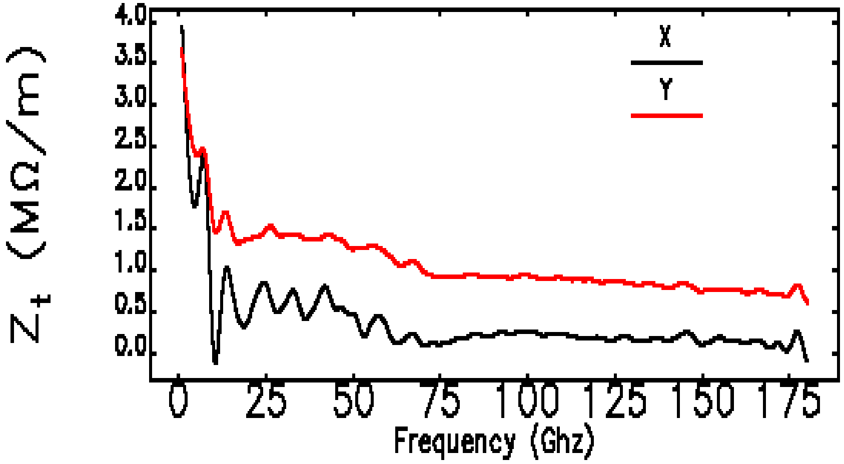


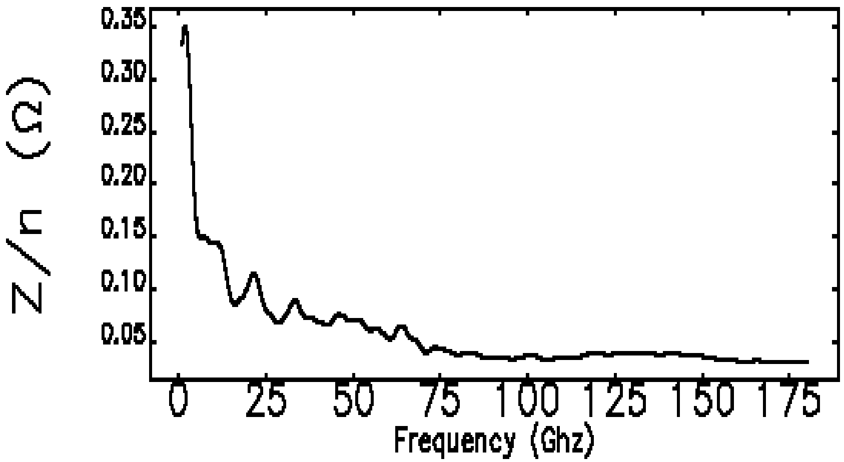


	Version 7	Version 15.7
Injection	High Beta	Low Beta
Energy	6	6
Tune	163.14/ 67.27	164.18/ 68.27
Nat. emittance [pm rad]	18.7	17.4
Energy spread [10^{-3}]	0.67	0.68
Energy loss/turn [MeV]	1.33	1.32
Momentum compaction [10^{-3}]	0.0160	0.0148
V_{rf} [MV]	6.0	6.0

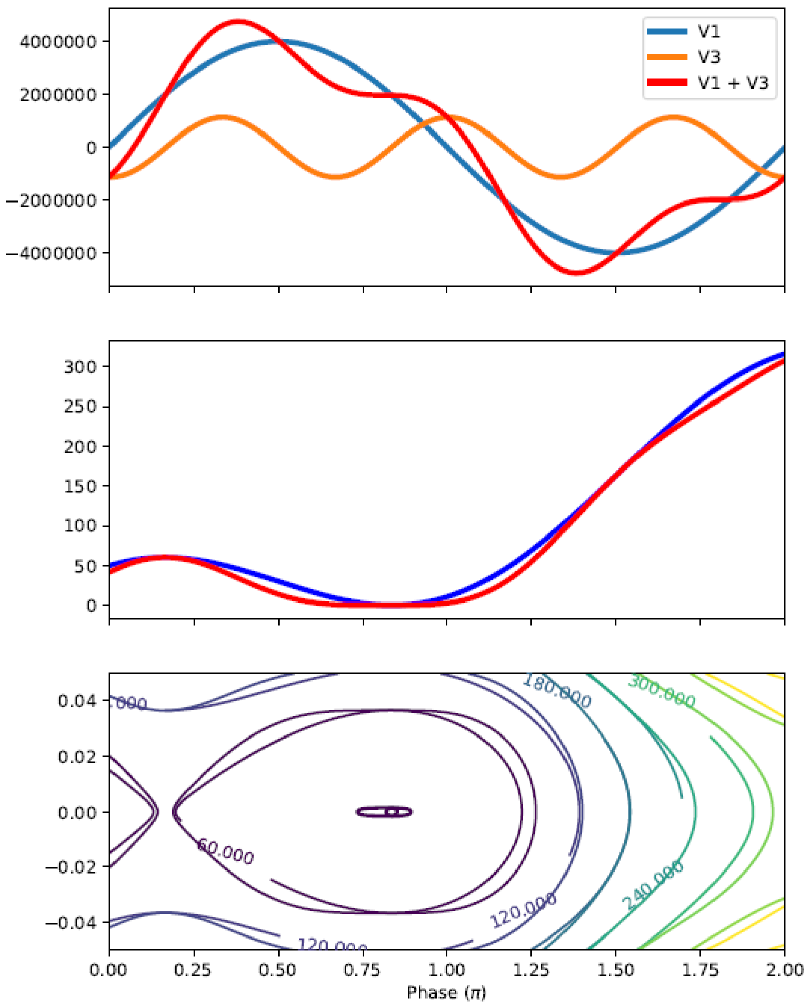
PETRA IV Impedance (Longitudinal, Transverse)

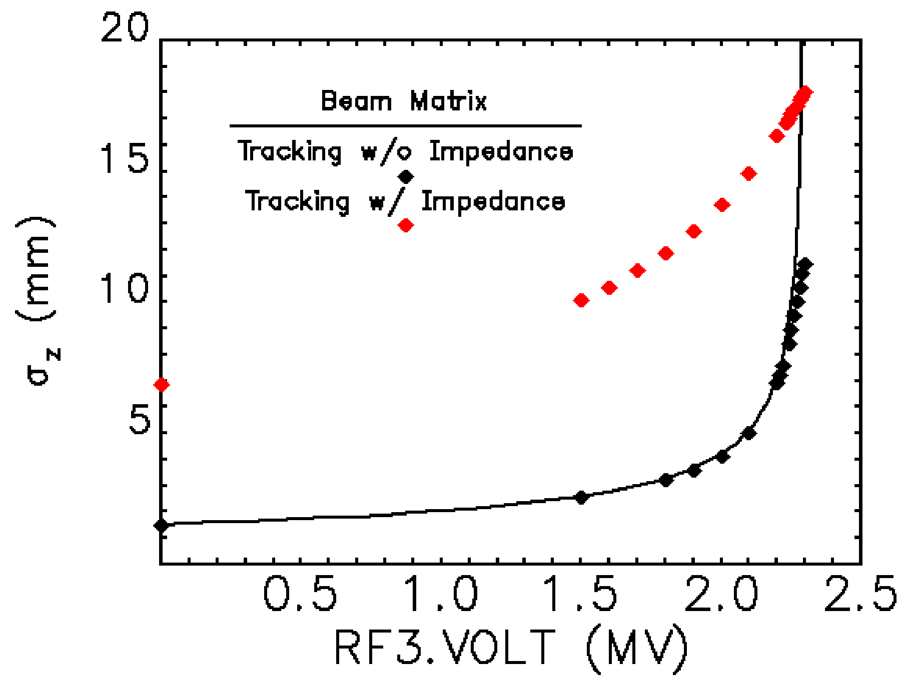
Element	Number	b_x	b_y	Remarks
Ring Common				
BPM	1190	6.0	8.8	
Bellow	375	2.2	5.37	
Flange	375	2.23	5.37	
Absorber	3.75	2.23	5.37	
Arc with Insertion Devices				
ID6mm	25	7.8	5.0	5-m ID
P06mmR	50	7.8	5.0	ID BPM
ID6mm	4	10.3	10.3	10-m ID
P06mmR	4	7.8	5.0	ID BPM
Bellow	125	2.2	5.37	
Flange	125	2.23	5.37	
Absorber	125	2.23	5.37	
Long Straight Section (LSS)				
RF1	24	7.9	7.8	Fundamental RF
RF3	24	7.9	7.8	Harmonic RF
LFB	8	7.9	7.8	Longitudinal Feedback
FCT	4	7.9	7.8	Fast Current Monitor
Short Straight Section (SSS)				
TFBV	2	11.0	8.4	Transverse Feedback
TFBH	2	11.0	8.4	Transverse Feedback
HSCR	1	7.4	9.3	Scraper
VSCR	1	7.4	9.3	Scraper
VCOL	4	7.4	9.3	Collimator
Injection Straight				
InjKicker	4	11.0	8.4	Kicker
ExtKicker	4	11.0	8.4	Kicker





Landau Cavity (harmonic number = 3)





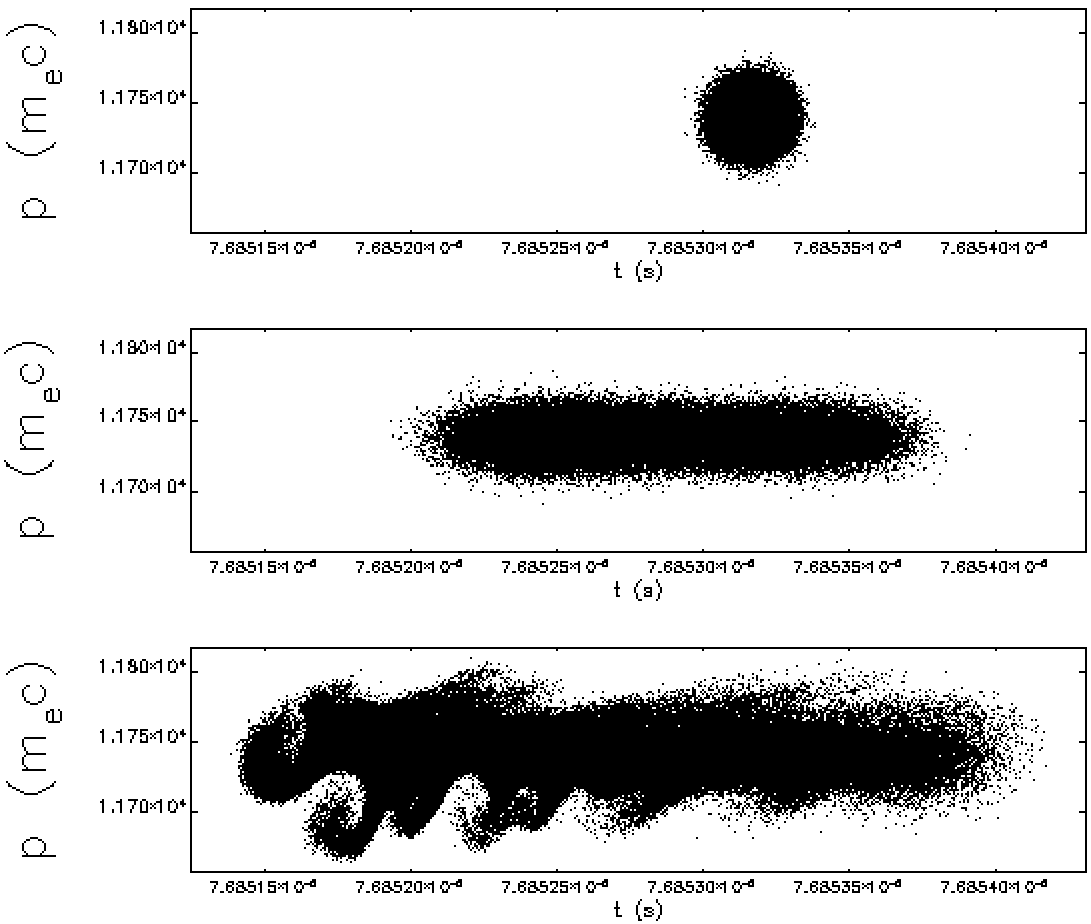
Beam Moments Computation by *elegant*

1. K. Ohmi, K. Hirata, K. Oide, From the beam-envelope matrix to synchrotron-radiation integrals, Phys. Rev. E **49**, 751, January 1994

2. M. Borland, Implementation and Performance of Beam Moments Computations in elegant, OAG-TN-2008-002, Advanced Photon Source.

Impedance Effect on Phase Space (t-p)

Current = 1 mA



Zz = 0.0 Ohm
V1= 8.0 MV
V3 = 0.0 MV

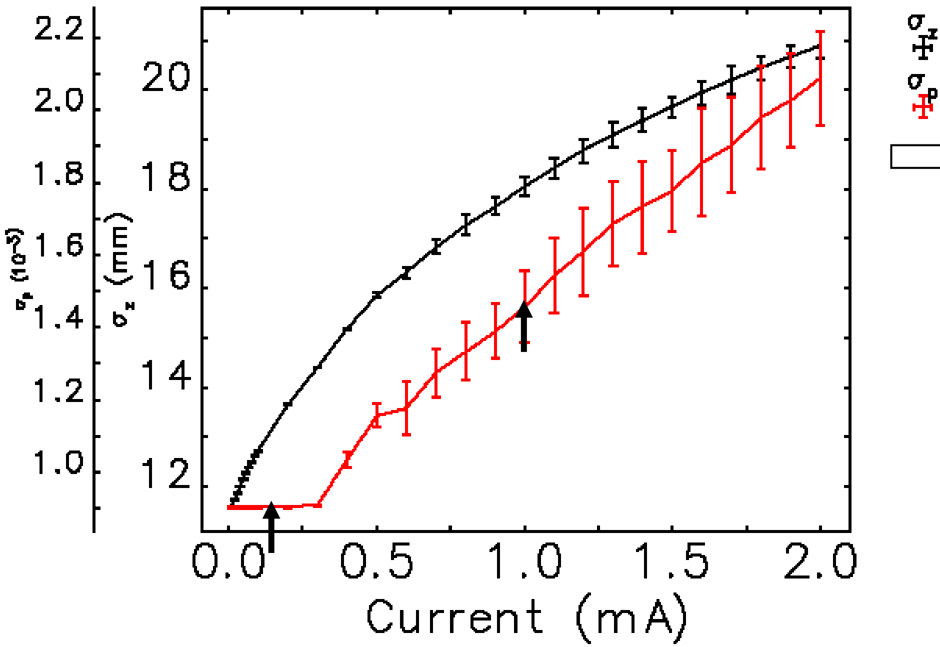
Zz = 0.0 Ohm
V1 = 8.0 MV
V3 = 2.3 MV

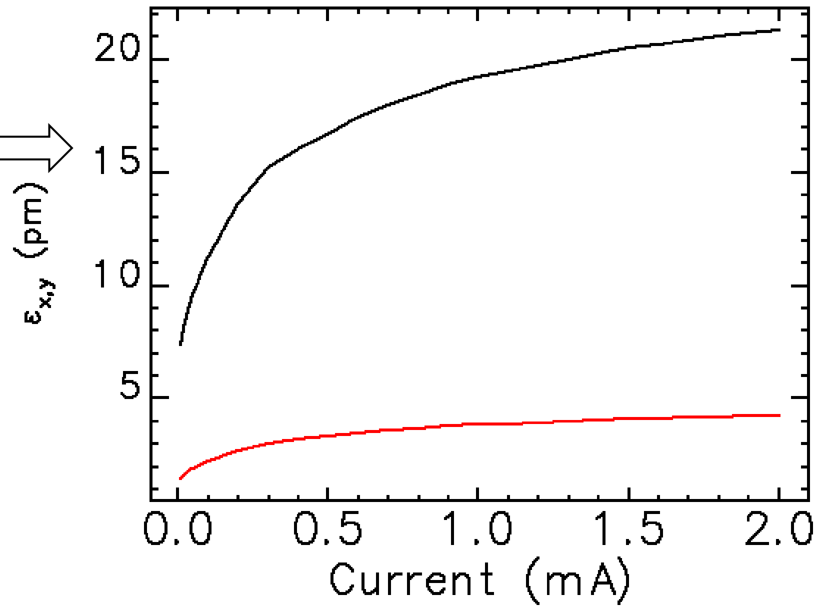
Zz Included
V1 = 8.0 MV
V3 = 2.3 MV

Zz: Impedance, V1: RF voltage, V3: Harmonic voltage

Longitudinal Impedance and IBS Effect

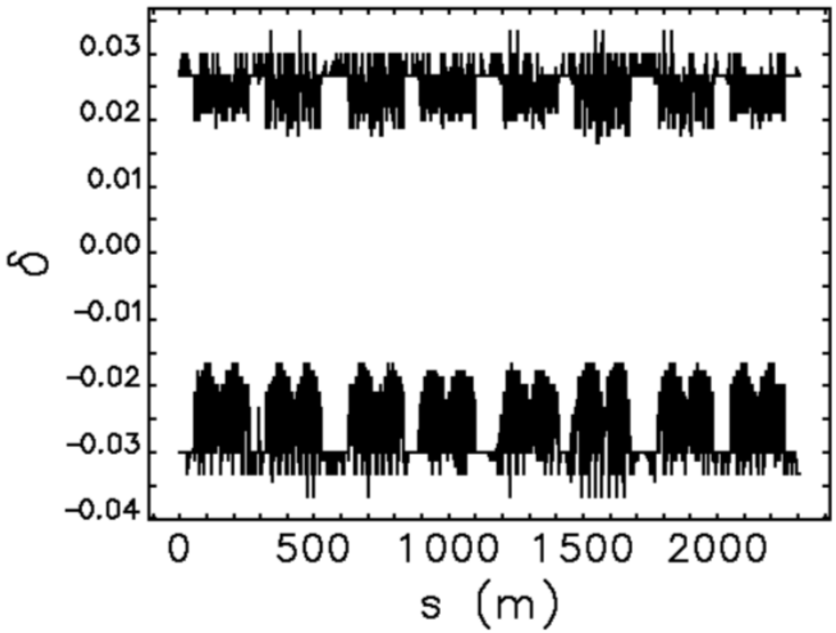
- Because of the small momentum compaction factor α = 1.45 x 10^{-5}, the microwave instability starts very early I_{th}=0.3 mA. Howver, this is still below the brightness mode current (0.125 mA/bunch) and, for the timinng mode experiment (1.0 mA/bunch), the energy spread is not as critical as for the brightness mode.
- Intra-beam scattering is due to multiple Coulomb scattering, which changes the beam dimensions.

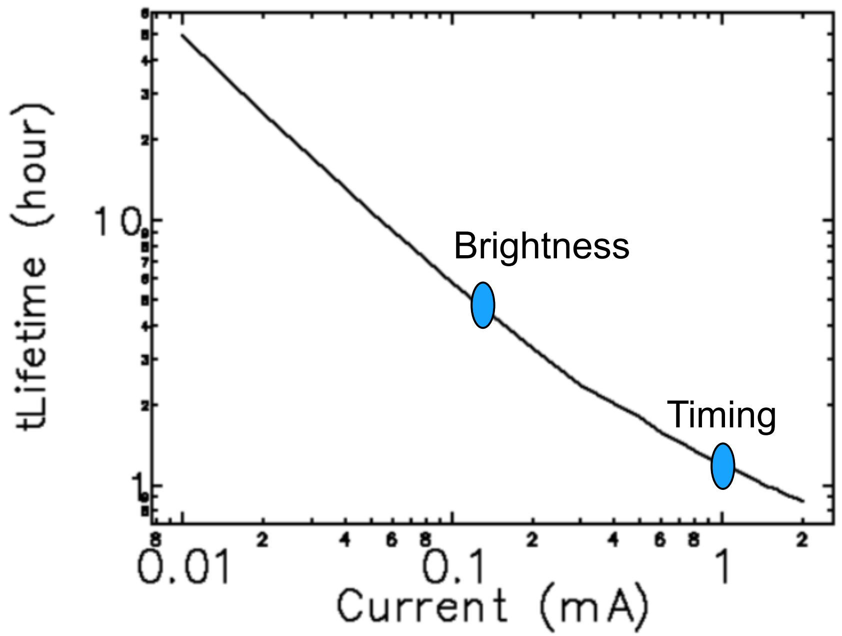




Beam Lifetime

- The radiation safety sets the requirement of 0.5 hour lifetime for 100-mA stored beam.
- In PETRA IV storage ring the beam lifetime is dominated by Touschek-effect.
- Even if we provide >7% rf acceptance, the local momentum acceptance (LMA) determines the upper limit due to strong nonlinearity.
- We have a sufficient LMA for the timing mode (1.2 hour for 1 mA per bunch).





20% coupling

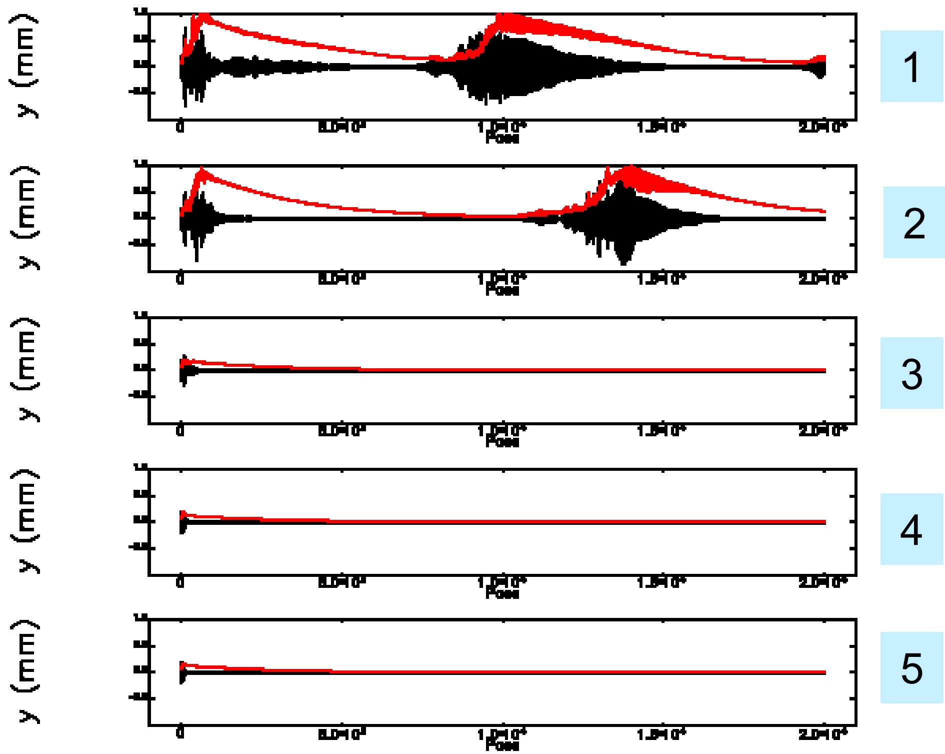
Bunch Parameters of PETRA IV (CDR Version)

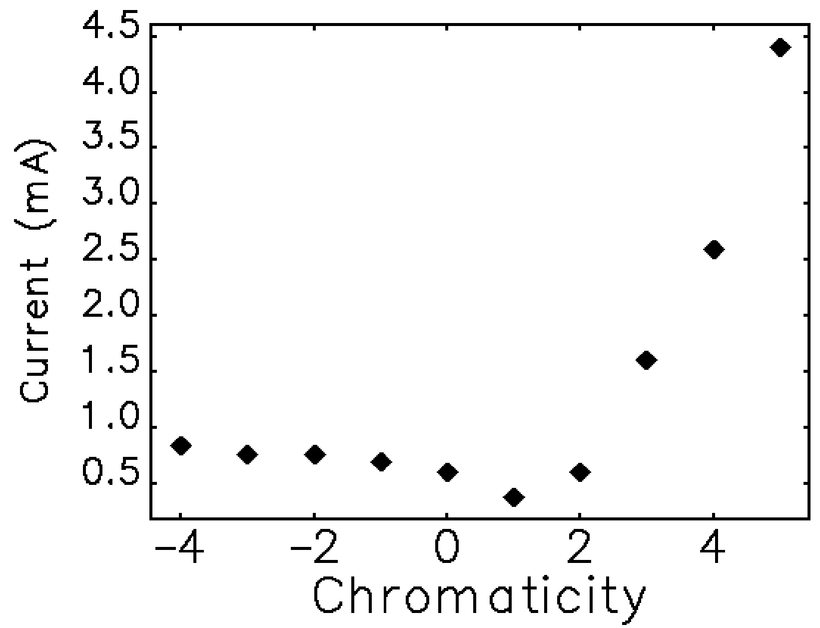
	Reference	Brightness Mode	Timing Mode
Current (mA)	0.01	0.125	1.0
ε_x (pm)	7.37	11.60	19.21
ε_y (pm)	1.46	2.32	3.84
σ_z (mm)	11.7	13.7	19.3
σ_t (ps)	39.1	45.7	64.3
σ_p (10^{-3})	0.914	0.963	1.562
Lifetime (hrs)	49.4	4.7	1.2

- Final beam parameters including the effects of IBS, higher-harmonic RF system, and impedance.

Single Bunch Current Limit

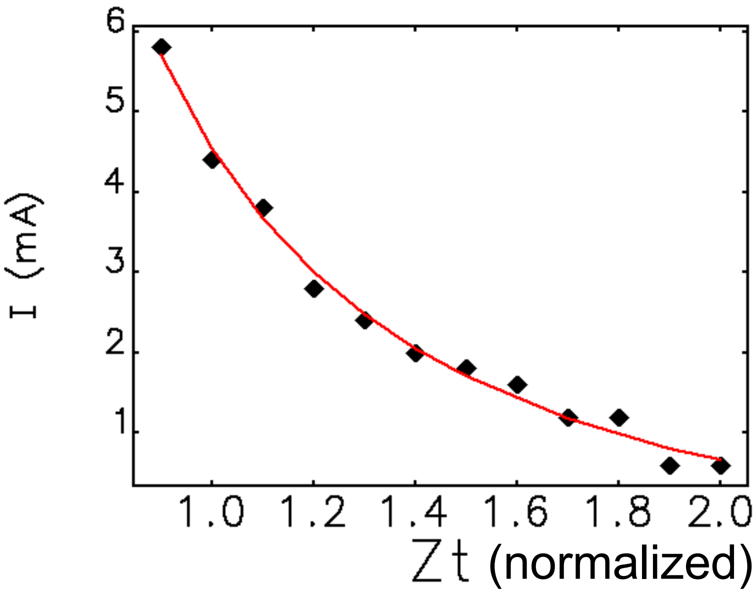
- In PETRA IV the full intensity of charge per bunch is injected on-axis.
- It is well knwon that increasing the head-tail phase $\chi=4\omega_\xi\sigma_\tau$ will reduce the growth rate as ~1/(1+m), where m is the azimuthal mode close to $\chi/2\pi$. It also reduce the effective imepdance.
- We can store up to 4 mA per bunch based on the impedance model. However, the radiation safety sets the limit to be 2 mA (storage ring limit).





Impedance Model Error Tolerance (40%)

- The required single bunch current for the timing mode is at least 1 mA per bunch.
- With bunch-lengthening and high chromaticity we found the timing mode is possible.
- We set the intensity to deliver in the ideal condition is 2 mA per bunch. This sets the impedance budget to be 40% higher than the current model. This allows us to:
  - ❖ reduce the aperture of round chamber down to 17 mm from 20 mm,
  - ❖ increase the undulator chambers impedance by 30%, and
  - ❖ add the geometric impedance of unknown components to the model up to 40% increase in the magnitude.



	Impedance (MΩ/m)	Normalized (%)	Risk Analysis	Increase (%)	Budget (MΩ/m)
RW (Ring)	0.286	20.6	Smaller aperture	63	0.47
RW (ID)	0.701	50.3	Smaller gap NEG surface impedance	30	0.91
Geometric	0.404	29.1	Unknown elements	40	0.56
Total	1.390	100		40	1.94

Collective Effects in Progress

We can deliver the beam with the required property; however, we still need to investigate:

Beam Dynamics

- Steady state beam profiles with transient beam loading effect of an arbitrary fill pattern in collabortion with MAX IV.
- Booster ramping simulation to establish the impedance budget.
- Injection simulation of stroage ring with nonlinear magnet effects to determine the injection efficiency.
- Coupled bunch instability analysis in the combined rf systems including Landau cavities and the active feedback system.
- Quantitative evaluation of ion trap and instabilities of an arbitrary fill pattern in the storage ring in collaboration with Argonne.

Impedance Model

- Develop the surface impedance model of rough surface
  - NEG coated chamber,
  - Microwave range (10~100 GHz) bridging the gap between the low (K.Bane) and high (A.Novokhatski) frequency model of 1 μm protrusion.
- Develop the short bunch wake potentials of PETRA IV (TDR)
  - σ_t = 1 ps (σ_z = 0.3 mm).

PETRA IV Project Office

Project structure established

- DIR
- PETRA IV Steering Board
- Technical Coordination — PETRA IV Management Board — Project office

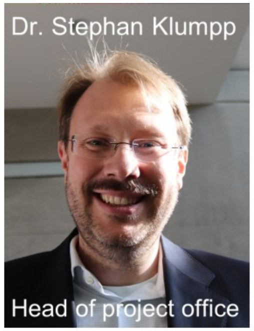
WP 1: PETRA IV Strategy & Management
- WP 1.01: Science Case
- WP 1.02: Industrial Case
- WP 1.03: Purchasing
- WP 1.04: Sustainability

WP 2: Accelerators Storage Ring and Preaccelerators
- WP 2.01: Accelerator physics
- WP 2.02: Radiation Safety
- WP 2.03: Interlock Systems
- WP 2.04: Magnets
- WP 2.05: Girders
- WP 2.06: Alignment
- WP 2.07: Vacuum systems
- WP 2.08: Diagnostics
- WP 2.09: RF Systems
- WP 2.10: Magnet Power Supplies
- WP 2.11: Magnet Water Cooling
- WP 2.12: Accelerator Utilities
- WP 2.13: Feedbacks and Timing Systems
- WP 2.14: Injection & Extraction Systems
- WP 2.15: Controls
- WP 2.16: Linac II and PIA II Accumulator Ring
- WP 2.17: DESY IV Booster Synchrotron and Transport Lines

WP 3: Experiments
- WP 3.01: Experiments
  - WP 3.01.01: Beamline P01
  - ⋮
  - WP 3.01.27: Beamline P65
- WP 3.02: Optics
- WP 3.03: Ultraprecision mechanics
- WP 3.04: Detectors
- WP 3.05: Sources
- WP 3.06: Data Management & Analysis
- …

WP 4: Buildings and Infrastructure
- WP 4.01: Buildings
- WP 4.02: General Safety
- WP 4.03: Networks and Communication Systems
- WP 4.04: General Mains and Utilities
- WP 4.05: Storage & Logistics

Project office established



Project office
- Costs, Schedule, Change Management
- Controlling, Documentation
- Recruitment
- Legal Support
- Stakeholder Relations

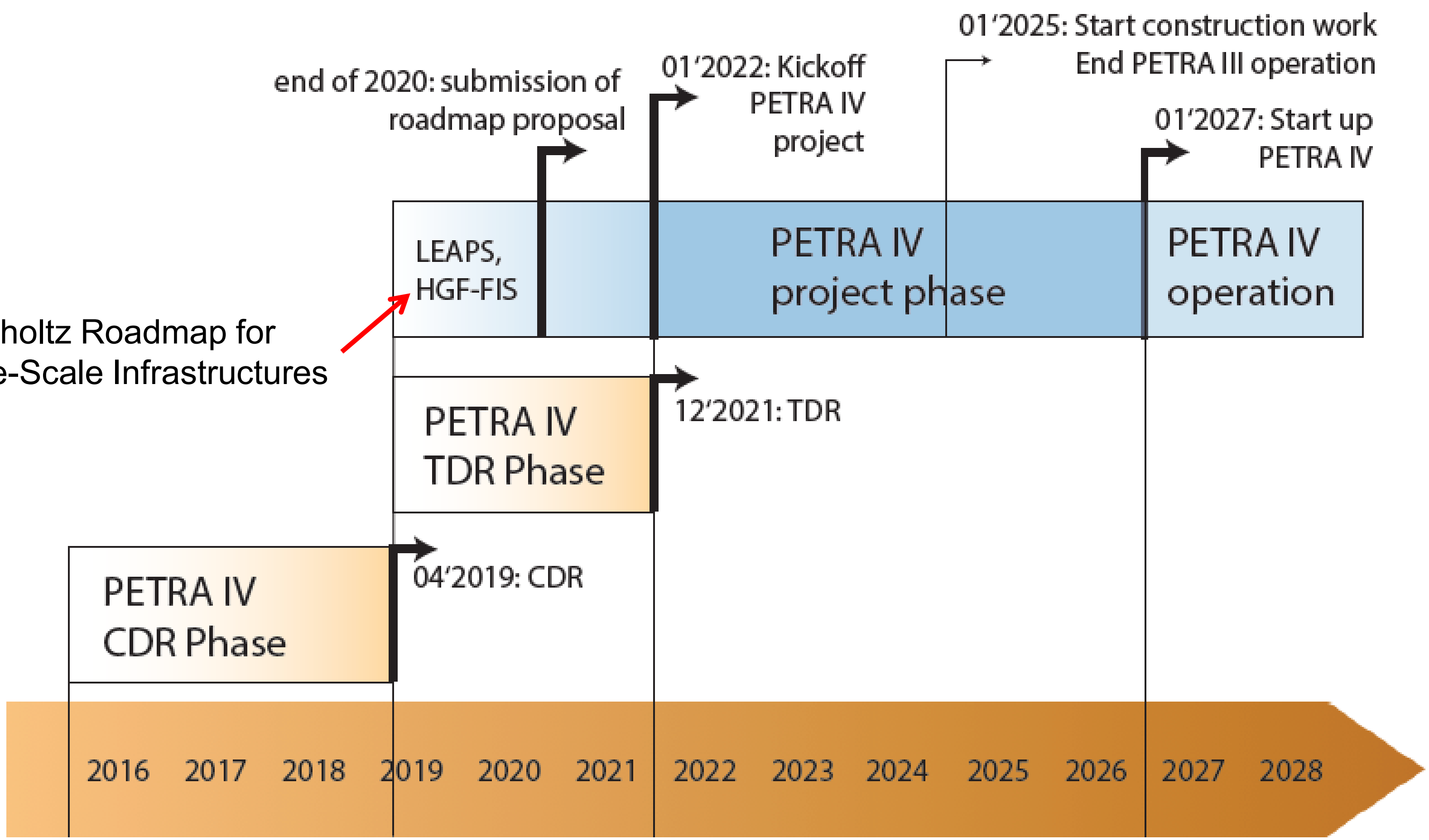
PETRA IV – Timeline (Old Reference)

Presently: CDR preparation phase

FIS-process pre-proposal submitted

Helmholtz association:
FIS = **F**orschungs**I**nfra**S**truktur
Large-scale research infrastructure

Helmholtz Roadmap for Large-Scale Infrastructures



XFEL, FLASH and PETRA IV will be major research facilities of the Science City Bahrenfeld

2019/01/22
The Hamburg Senate, the Altona district, DESY and the University of Hamburg presented the plans for a science district in western Hamburg at a press conference.

We hope a bright source and a bright future in Hamburg.

Thank you very much for your time and attention!