Coupled Bunch Effects in the Synchrotron Light Source BESSY VSR

Martin Ruprecht[1]

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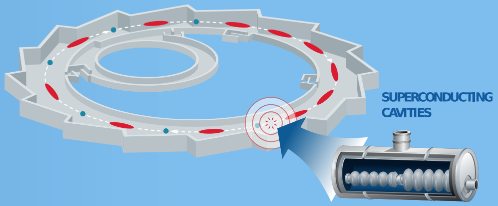
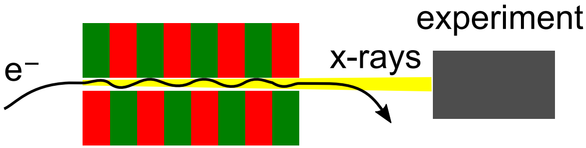


2nd Annual MT Meeting (Helmholtz Programme "Matter and Technologies")
8-10 March 2016 KIT Campus South, Karlsruhe, Germany

Outline

Synchrotron radiation essential tool:

- energy, environment and climate
- life science
- information technology
- material science



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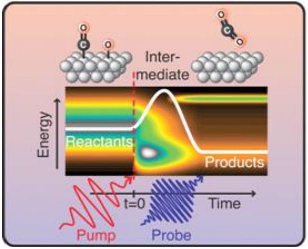
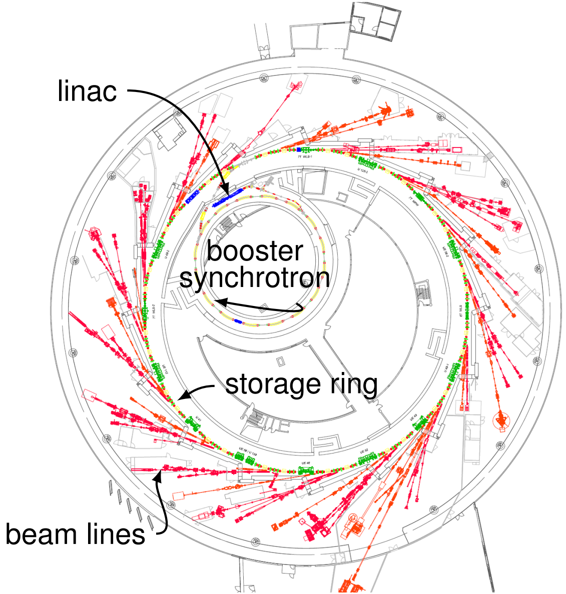


Source: BESSY VSR scientific case

BESSY VSR

- Figures of merit:
  spectrum, intensity, source size, divergence, temporal and spacial coherence, pulse structure (length)

Introduction: From BESSY II to BESSY VSR



Circumference	240 m
Energy E	1.7 GeV
Horizontal emittance ϵ_x	5 nm rad
Total beam current I_{DC}	300 mA
Harmonic number	400
Mom. comp. factor α	7.3×10^{-4}
Synchrotron frequency f_{s}	8.0 kHz
RF voltage at 500 MHz	1.5 MV
Effective bunch length (rms)	15 ps

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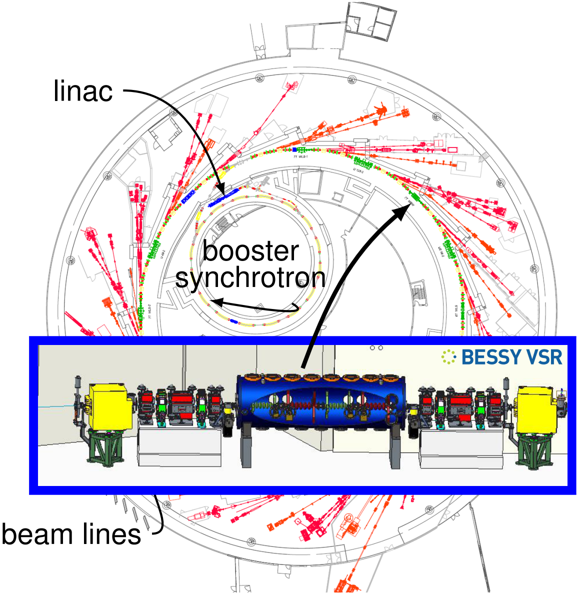

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RF voltage at 1.5 GHz	20 MV
RF voltage at 1.75 GHz	17 MV
Effective bunch length (rms)	1.7 ps

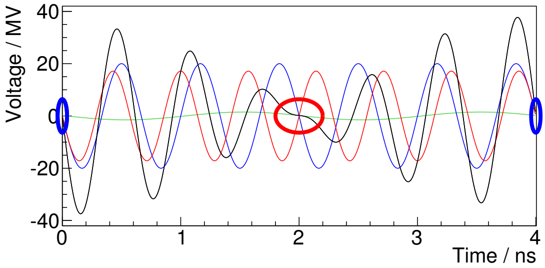
Introduction: From BESSY II to BESSY VSR

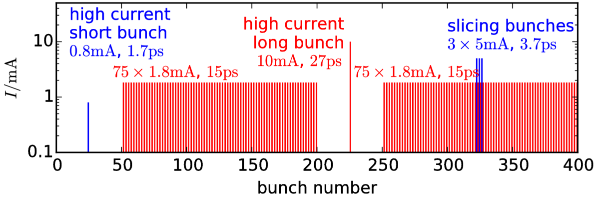
- Bunch length:

$$\boxed{\sigma_0 \propto \sqrt{\left|\frac{\alpha}{V'}\right|}}, \quad I_{\mathrm{CSR}} \propto \alpha$$

f	V	$V' = \frac{\mathrm{d}V}{\mathrm{d}t}/2\pi$
500 MHz	1.5 MV	0.75 MV GHz
1.5 GHz	20 MV	30 MV GHz
1.75 GHz	17.1 MV	30 MV GHz

- short, stable, high intensity bunches
- 300 mA basic operation maintained
- impedance heating / Touschek losses mitigated





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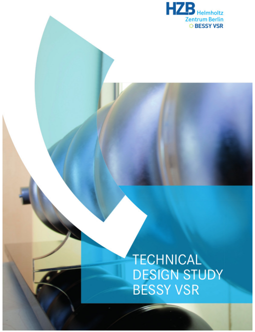
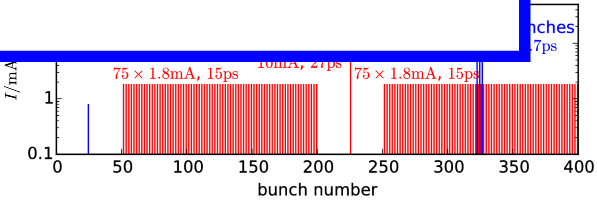


BESSY VSR Technical Design Study
June 2015

`http://dx.doi.org/10.5442/R0001`



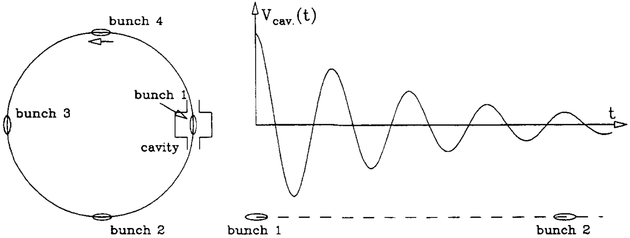
2 × 1.5 GHz, 2 × 1.75 GHz cavities:

- 5 cells, SC, high field
- $R_{s,0}/Q = 250\,\Omega$
- $Q_L = 5 \times 10^7$

1.5 GHz model *[A. Vélez (HZB), 2015]*

Focus of this talk: **beam - cavity interaction**

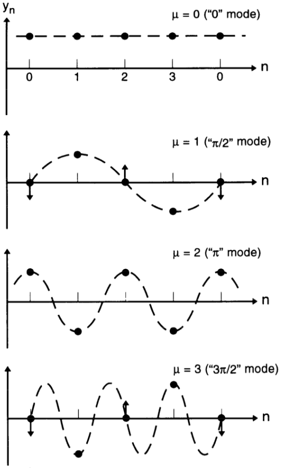
- through wake fields / impedance



- Coupled bunch effects, $\propto I_{\text{total}}$

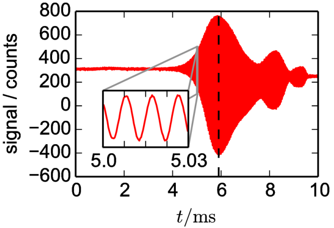
Coupled bunch instability (CBI) and stable induced field (beam loading)

Coupled Bunch Modes



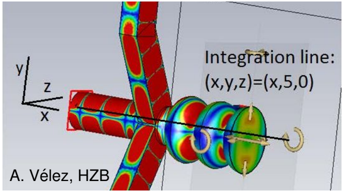
A. Chao: Phys. of Coll. Beam Inst.

→ Bunch oscillation: exponential growth



grow / damp measurement at the MLS

- beam blow up
- beam loss

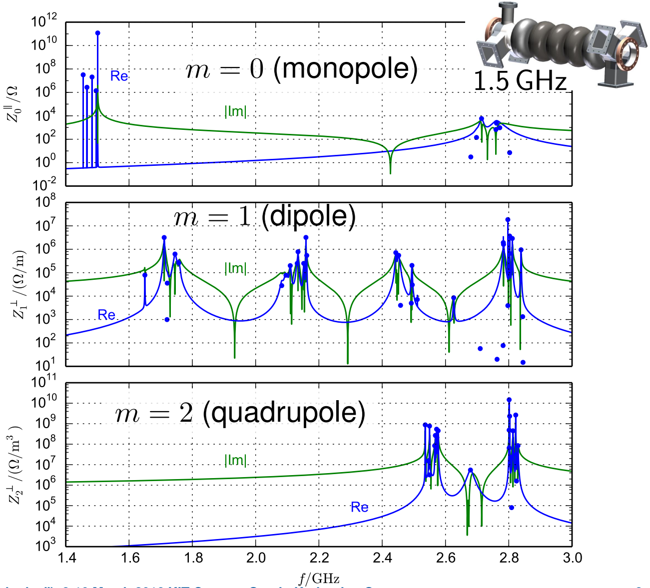


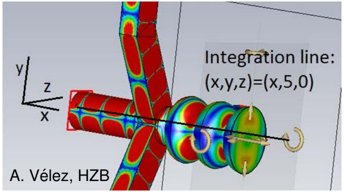
Shunt impedance:

$$\frac{R_{s,m}}{Q} \propto \frac{|V_{\mathrm{acc}}^{\|}(r)|^2}{r^{2m}}$$

Impedance:

$$Z_m^{\|}(\omega) = \frac{R_{s,m}}{1 + iQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)}$$





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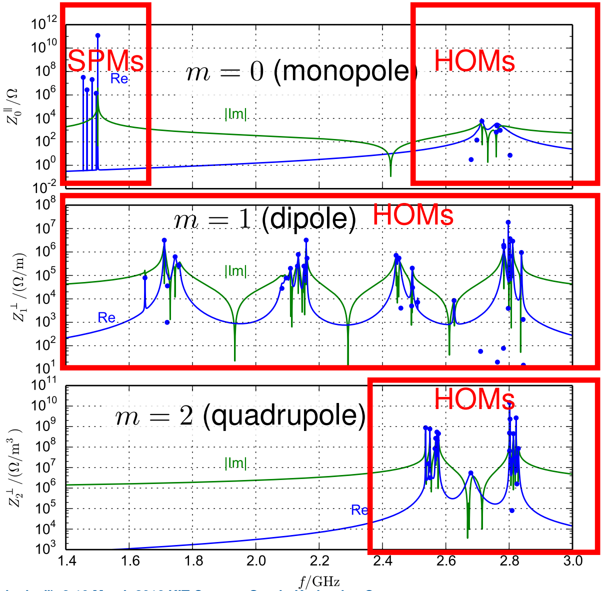


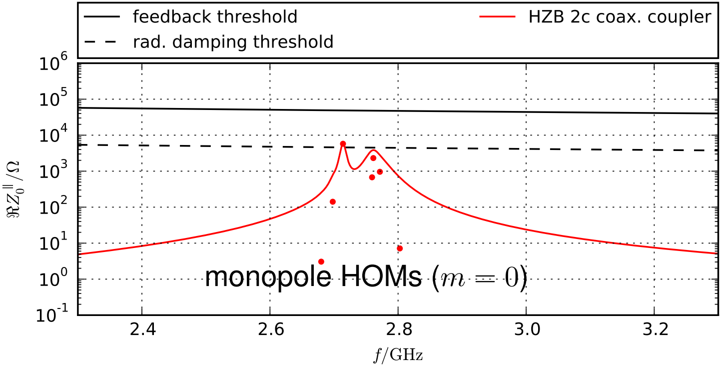
Longitudinal dipole instability ($m = 0$):

Damping rates:

- BBFB (BESSY II *) $\tau_{\mathrm{fb}}^{-1} = 1333\,\mathrm{s}^{-1}$
- Rad.: $\tau_{\parallel}^{-1} = 125\,\mathrm{s}^{-1}$

Instability threshold:

$$\boxed{Z_{\mathrm{th}}^{\parallel}(\omega, \tau_{\mathrm{d}}^{-1}) = \frac{\tau_{\mathrm{d}}^{-1}}{\omega} \frac{4\pi\omega_{\mathrm{s}} E/e}{\omega_{\mathrm{rev}} I_{\mathrm{DC}} \alpha}}$$



HZB 2c coax. coupler

** measured: A. Schälicke et al., IPAC2014, TUPRI072*

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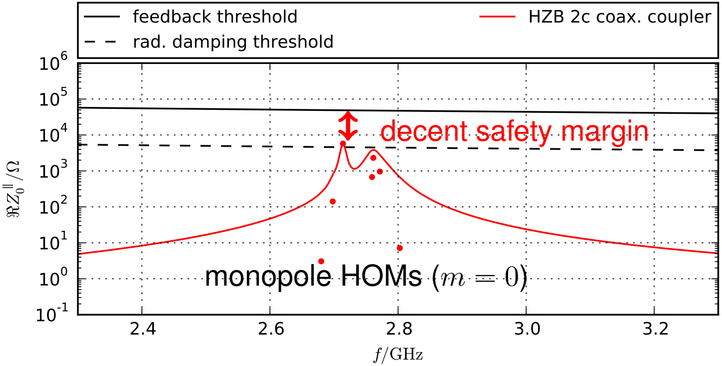

HZB 2c coax. coupler

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Longitudinal dipole instability ($m = 0$):

Damping rates:

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Instability threshold:

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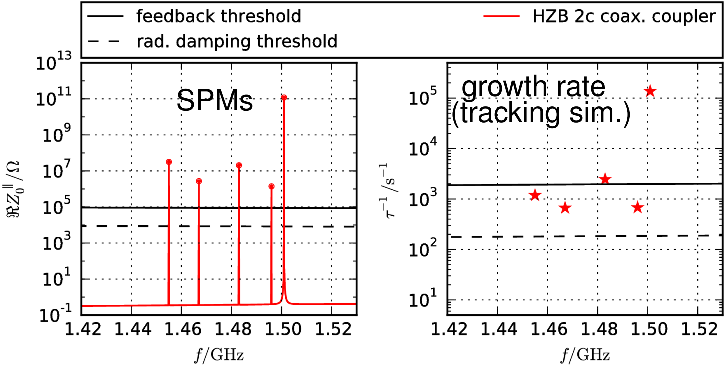


HZB 2c coax. coupler

Coupled Bunch Instabilities: Impedance Thresholds

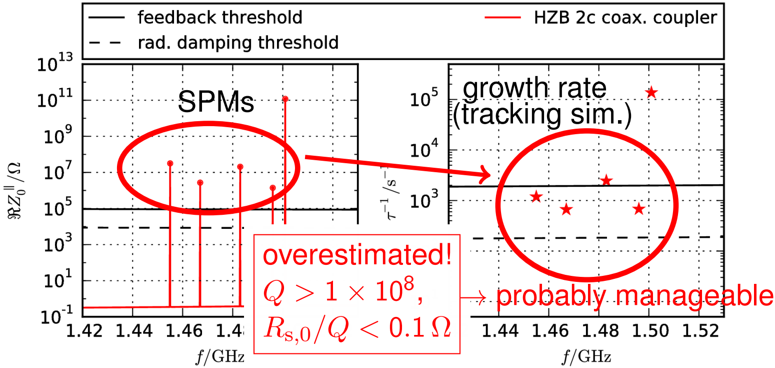
Longitudinal dipole instability ($m = 0$):

Damping rates:

- BBFB (BESSY II meas.)
  $\tau_{\mathrm{fb}}^{-1} = 1333\,\mathrm{s}^{-1}$
- Rad.: $\tau_{\parallel}^{-1} = 125\,\mathrm{s}^{-1}$

Instability threshold:

$$\boxed{Z_{\mathrm{th}}^{\parallel}(\omega, \tau_{\mathrm{d}}^{-1}) = \frac{\tau_{\mathrm{d}}^{-1}}{\omega} \frac{4\pi\omega_{\mathrm{s}} E/e}{\omega_{\mathrm{rev}} I_{\mathrm{DC}} \alpha}}$$



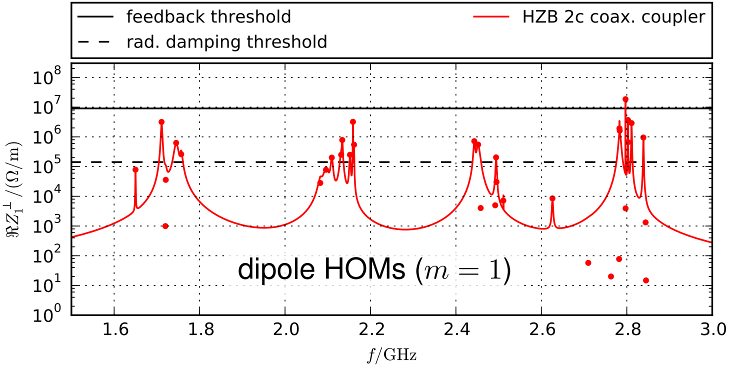
Transverse dipole instability ($m = 1$):

Instability threshold:

$$\boxed{Z_{\mathrm{th}}^{\perp}(\tau_{\mathrm{d}}^{-1}) = \frac{\tau_{\mathrm{d}}^{-1}}{\beta} \frac{4\pi E/e}{\omega_{\mathrm{rev}} I_{\mathrm{DC}}}}$$

Damping rates:

- BBFB $\tau_{\mathrm{fb}}^{-1} = 4000\,\mathrm{s}^{-1}$
- Rad.: $\tau_{\parallel}^{-1} = 62\,\mathrm{s}^{-1}$



$\rightarrow$ close to threshold but probably manageable

Transverse quadrupole instability ($m = 2$):

$$\tau^{-1}(M_2) \overset{*}{\approx} \frac{M_2}{2} \frac{\omega_{\mathrm{rev}} I_{\mathrm{DC}}}{4\pi E/e} \beta \Re Z_2^{\perp}(\omega_{\mathrm{beam}} + 2\omega_\beta) \qquad (1)$$

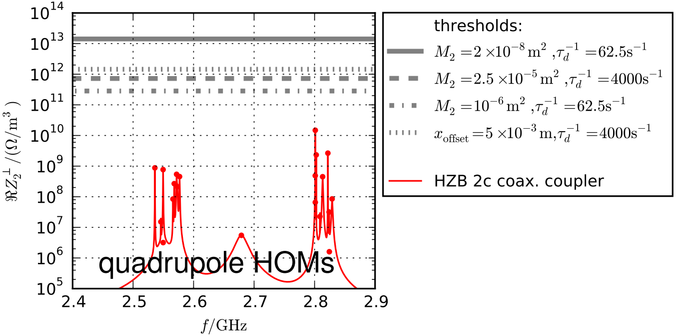
Quadrupole moment: $M_2 = \langle \bar{x}^2 - \bar{y}^2 \rangle$

* obtained from tracking

Instability threshold:

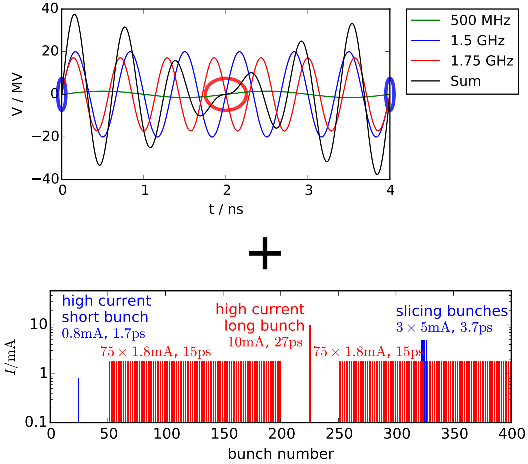
$$\boxed{Z^{\perp}_{2,\mathrm{th}}(\tau_{\mathrm{d}}^{-1}, M_2) \approx \frac{2}{M_2} \frac{\tau_{\mathrm{d}}^{-1}}{\beta} \frac{4\pi E/e}{\omega_{\mathrm{rev}} I_{\mathrm{DC}}}}$$

- Damping rate: τ_{fb}^{-1} or $\tau_{\perp}^{-1}$
- 4 realistic (but extreme) scenarios



$\rightarrow$ low risk

BESSY VSR: Influence on 3 cavity setup?

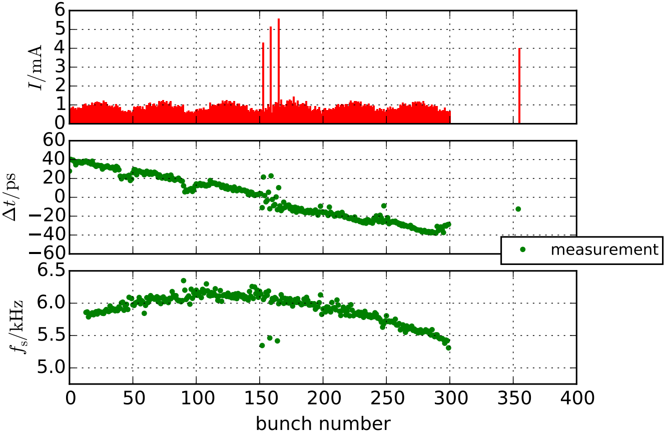


Transient Beam Loading: Situation at BESSY II

BESSY II with 3rd harm. Landau cavities

Effects:

- Phase transient (mostly harmless)
- Variation of bunch length (undesired reduction)



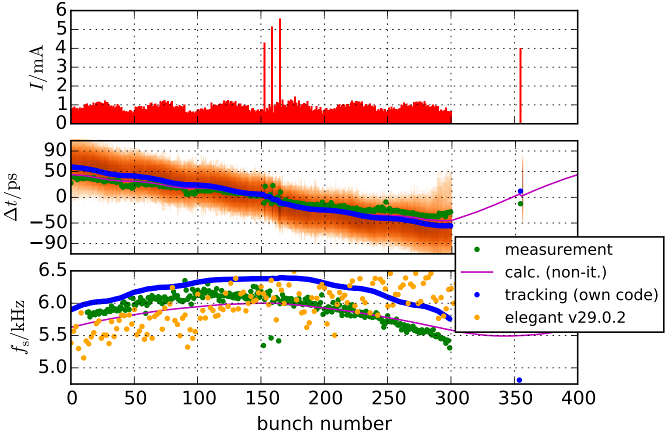
BESSY II with 3rd harm. Landau cavities

Effects:

- Phase transient (mostly harmless)
- Variation of bunch length (undesired reduction)

Calculation:

- Directly from fill pattern:
  $V_m = M\mathcal{F}^{-1}[2\mathcal{F}[i_k]_p \cdot Z_0^{\|}(\omega_p)]_m$
- Tracking / iterative methods:
  $\rightarrow$ closes the loop

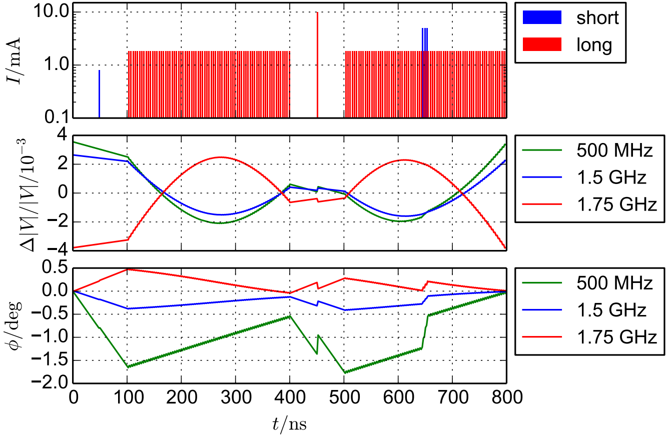


Transient Beam Loading: BESSY VSR Tracking Simulations

Tracking simulation:

	500 MHz	1.5 GHz	1.75 GHz
V_{set}	1.5 MV	20 MV	17.5 MV
ϕ_{set}	0	0	180
$R_{\mathrm{s},0}/Q$	460 Ω	500 Ω	500 Ω
Q	26 700	5×10^7	5×10^7
Δf_{r}	−45 kHz	−11.3 kHz	15.3 kHz

- Baseline fill pattern
- All cavities active



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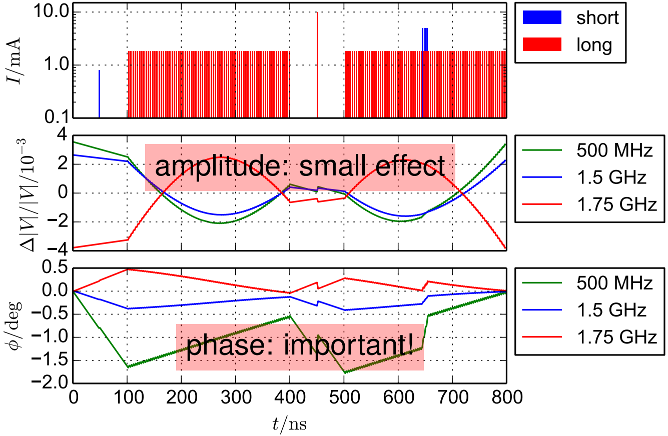
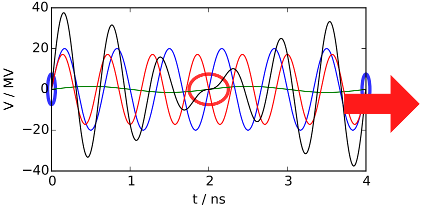
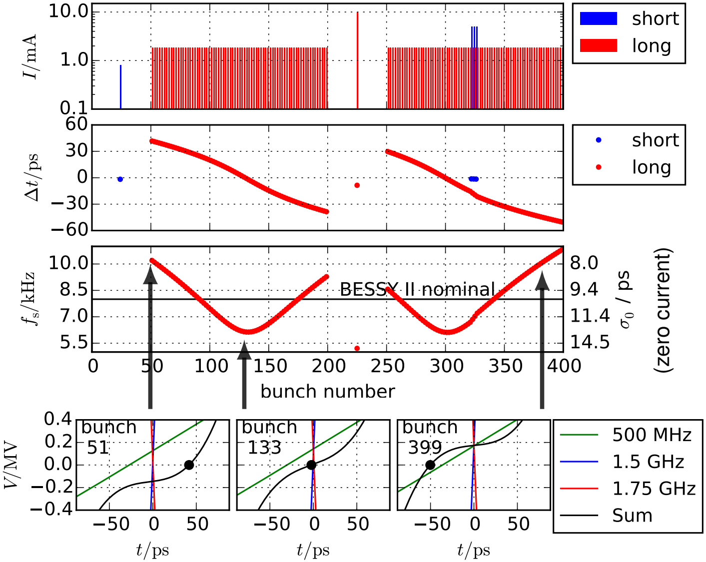
- Baseline fill pattern
- All cavities active
- ΔV small: all cavities near zero crossing
- ϕ small but important!



Transient Beam Loading: BESSY VSR Tracking Simulations

- short bunches robust / long bunches sensitive
- phase transient similar to BESSY II
- large variation in synch. frequency / bunch length
  - increased Touschek losses!





Transient Beam Loading: BESSY VSR Tracking Simulations

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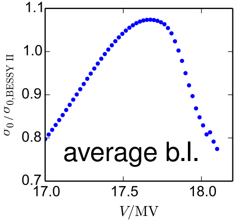
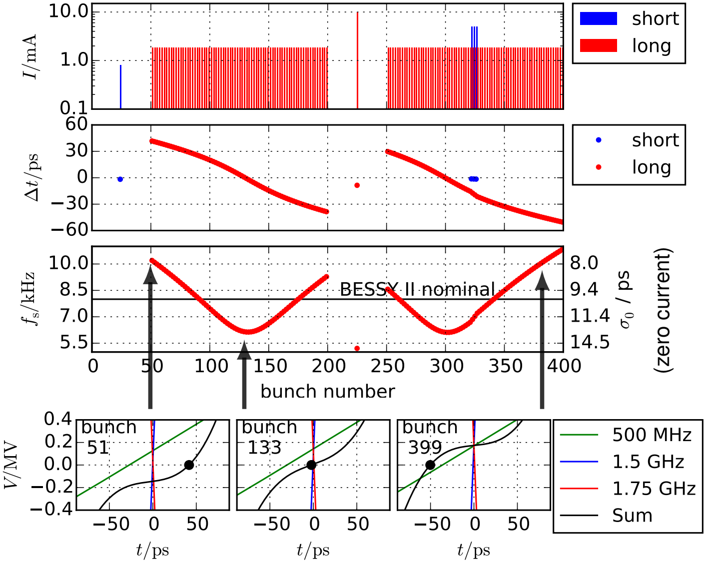
  - increased Touschek losses!
  - Elongation limited

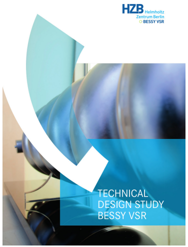




Summary / Outlook

- Coupled Bunch Instability:
  - comparison cavity designs
  - HZB cavity model promising
- Transient Beam Loading
  - strong effect on long bunch
- Open questions:
  - Impedance of 4-cavity structure, 1.75 GHz cavity
  - Alternative fill pattern (reduce transient b.I.), Touschek lifetime optimization

BESSY VSR TDS



10.5442/R0001

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2015 M. Ruprecht et al. “Influence of Transient Beam Loading on the Longitudinal Beam Dynamics at BESSY VSR”. IPAC2015, Richmond, USA.

2014 M. Ruprecht et al. “Analysis of Coupled Bunch Instabilities in BESSY-VSR”. IPAC2014, Dresden, Germany.

HZB Helmholtz Zentrum Berlin

BESSY VSR

Acknowledgment:

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