Peter Kuske,
on behalf of the BESSY VSR team

FILLING PATTERN, TIMING MODES, AND BUNCH SEPARATION SCHEMES FOR THE BESSY VSR PROJECT

HZB Helmholtz Zentrum Berlin

INTRODUCTION – BESSY VSR

TIMING MODES

FILLING PATTERN

BUNCH SEPARATION SCHEMES

SUMMARY

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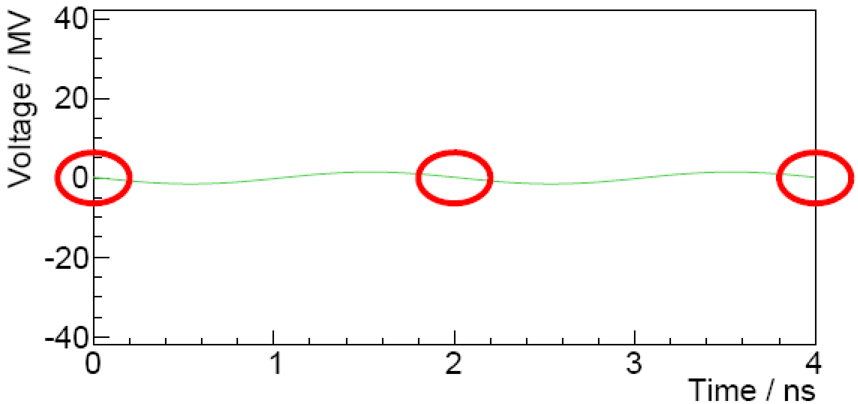
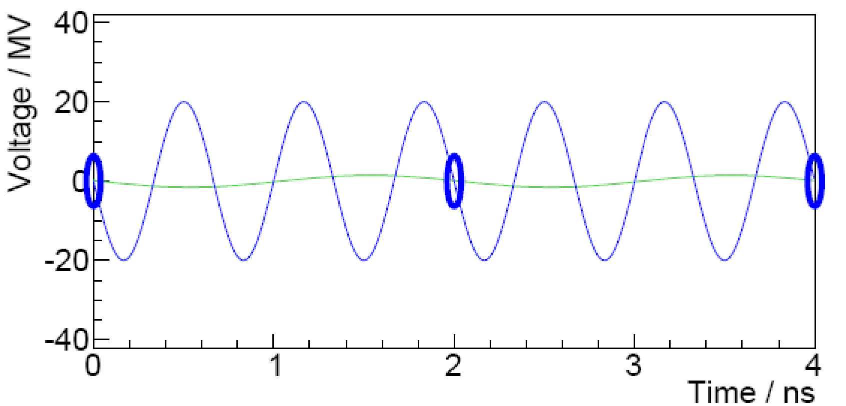
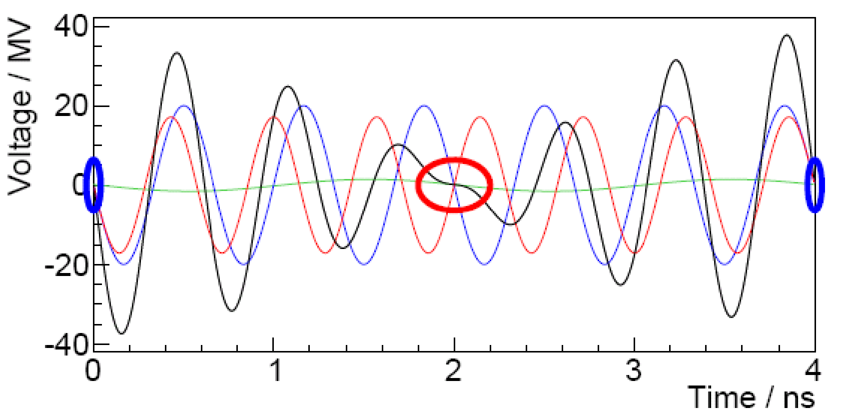






Bunch length:

$$\sigma_z \approx \sqrt{\frac{\alpha}{dV/dt}} \cdot \sigma_E$$

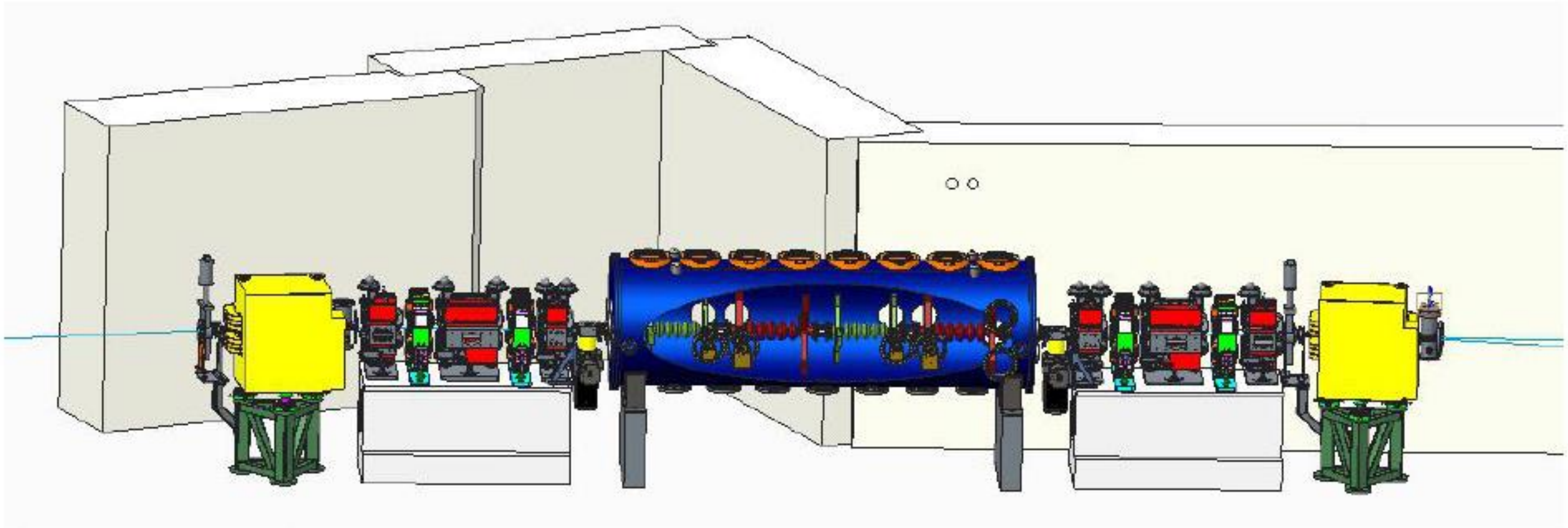
Momentum compaction factor:

$$\alpha = \frac{\delta L / L}{\delta p / p}$$

Expected parameter:

	Bunch length σ_z/ps	Threshold current $I_{\mathrm{th}}/\mathrm{mA}$
Standard optics		
long bunch	15	1.8
short bunch	1.7	0.8
Low α optics		
long bunch	3	0.045
short bunch	0.3	0.04

BESSY VSR TDS, to be published



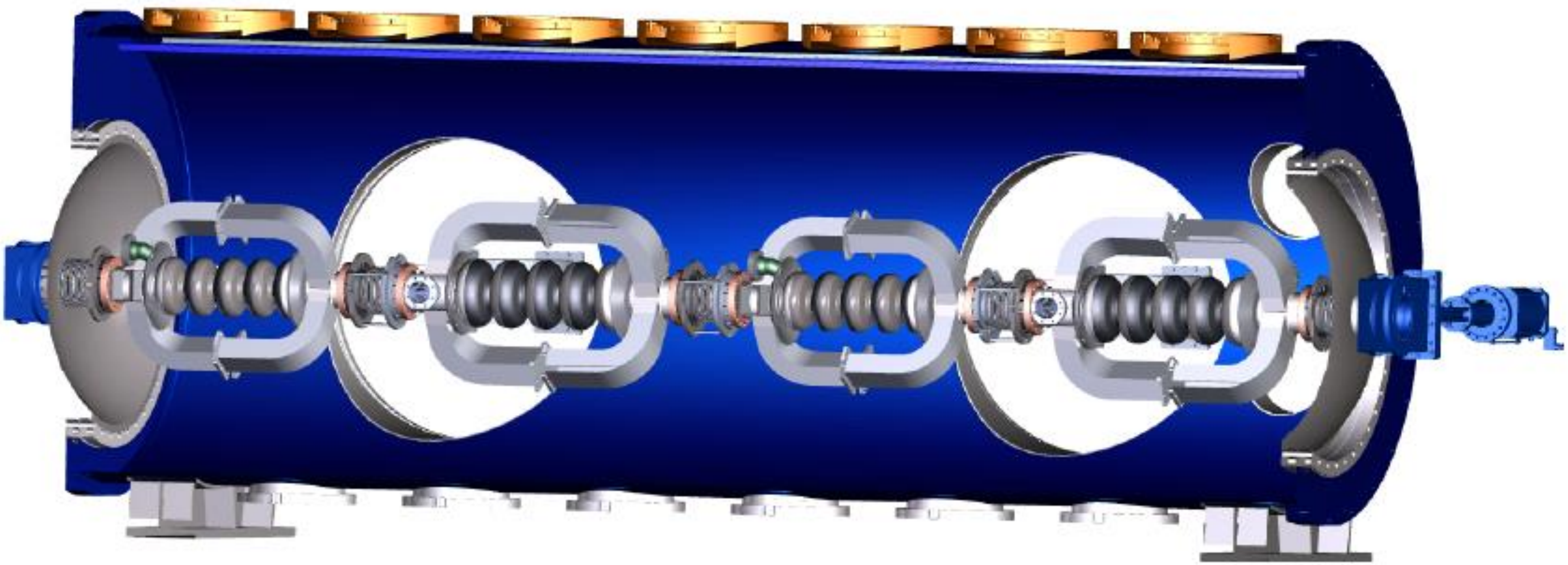
Schematic view of the BESSY VSR cavities straight

Cavity systems for BESSY VSR

Cavity	Frequency f/GHz	Integrated voltage V/MV	Number of cavities
NC	0.5	1.5	4
SC$_1$	1.5	20	2 × 5 cells
SC$_2$	1.75	17.14	2 × 5 cells

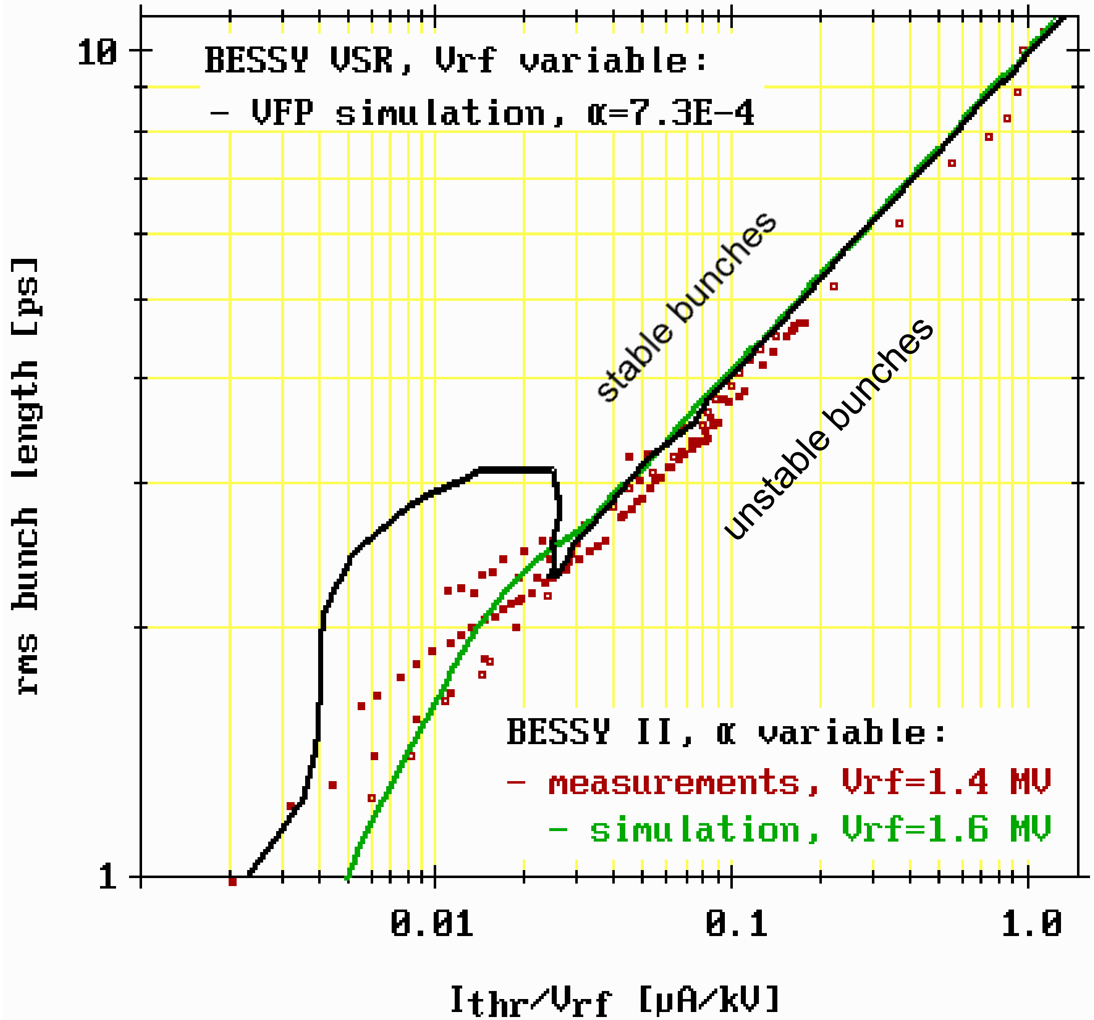
BESSY VSR TDS, to be published

BESSY VSR cryomodule design concept



- •HOM damping by design and dampers – additional suppression of CBI by active feedback systems
- •Robinson instability controlled by LLRF feedback – studies ongoing
- •Active RF-system – ~10 kW RF-power with Cornell-type 60 kW coupler
- •Parking – pair wise compensation of fundamental accelerating modes by tuning

BESSY VSR TDS, to be published



CSR-interaction, parallel plate model

found good agreement with experimental observations at MLS, ANKA, CLS, …

Instability threshold scaling with bunch current/voltage on horizontal axis and zero current bunch length on vertical axis

BESSY VSR TDS, to be published

Limits of short bunches at BESSY VSR

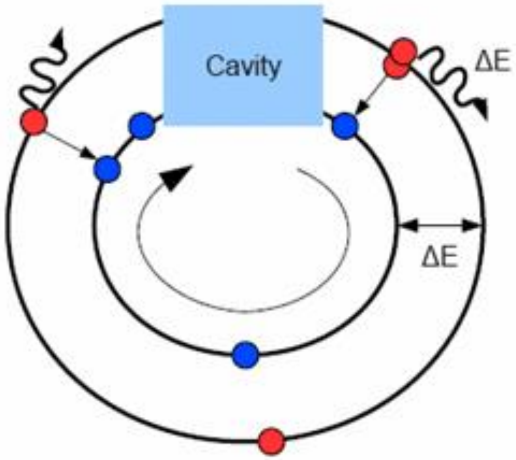
BESSY VSR

Single particle effects - recent studies

borrowed from: P. Goslawski, et al.,
talk at the DPG 2014, Dresden

Longitudinal rad. excitation

Y. Shoji et al., Phys. Rev. E 54, 4556 (1996).

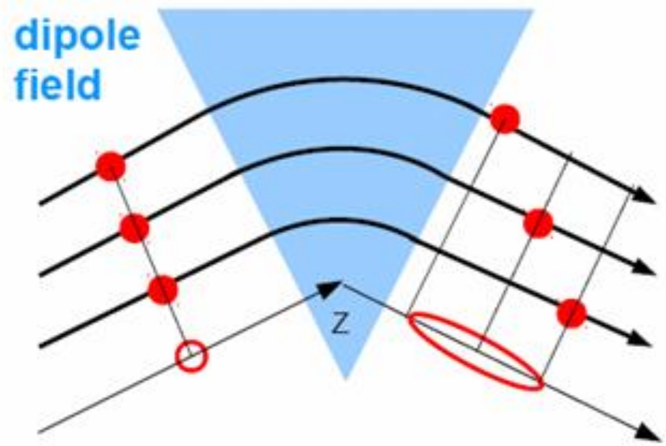


- Path length variations according to where photo-emission takes place
- α non-constant over the ring
- BESSY VSR: $\sigma_{\text{lim}} = 70\,\text{fs}$

P. Goslawski et al., IPAC2014

Horizontal longitudinal coupling

Y. Shoji, Phys. Rev. ST-AB 7, 090703 (2004).



- Limit depends on observation point and applied machine optics
- Limit: $\sigma_{\text{lim}} = 100\,\text{fs} - 200\,\text{fs}$
- BESSY VSR: $\sigma_{\text{tot}} = 270\,\text{fs} - 320\,\text{fs}$

BESSY VSR TDS, to be published

Limits of short bunches at BESSY-VSR

Horizontal longitudinal coupling

borrowed from: P. Goslawski, et al.,
talk at the DPG 2014, Dresden

- Transfermatrix $\overline{M}$ describes particle motion: $\vec{X}_f = \overline{M}\,\vec{X}_i$

$$\vec{X}_f = \begin{pmatrix} x_f \\ x'_f \\ z_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & 0 & m_{16} \\ m_{21} & m_{22} & 0 & m_{26} \\ m_{51} & m_{52} & 1 & m_{56} \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_i \\ x'_i \\ z_i \\ \delta_i \end{pmatrix}$$

- Coupling of horizontal into longitudinal via

$$\boxed{\Delta z = m_{51} x_i + m_{52} x'_i} \quad \stackrel{!}{=} \quad \sqrt{\epsilon H}$$

$$\Delta z = (m_{21} m_{16} - m_{11} m_{26}) x_i + (m_{16} m_{22} - m_{12} m_{26}) x'_i$$

- $m_{11}, m_{12}, m_{21}, m_{22}$ expressed by Twiss functions β, α, γ
- m_{16}, m_{26} replaced using transformation of dispersion vector

$m_{16} = D_f - (m_{11} D_i + m_{12} D'_i)$ and $m_{26} = D'_f - (m_{21} D_i + m_{22} D'_i)$

- And dispersion replaced by the chromatic H function and phase φ_H

$H = H(s) = \gamma D^2 + 2\alpha D D' + \beta D'^2$

$D = \sqrt{H\beta}\cos\varphi_H$ and $D' = -\sqrt{H/\beta}(\alpha\cos\varphi_H + \sin\varphi_H)$

Variance of the momentum compaction I_α, the associated radiation excitation bunch length limit σ_{re} and zero current bunch length σ_0, for standard and low α optics in BESSY VSR

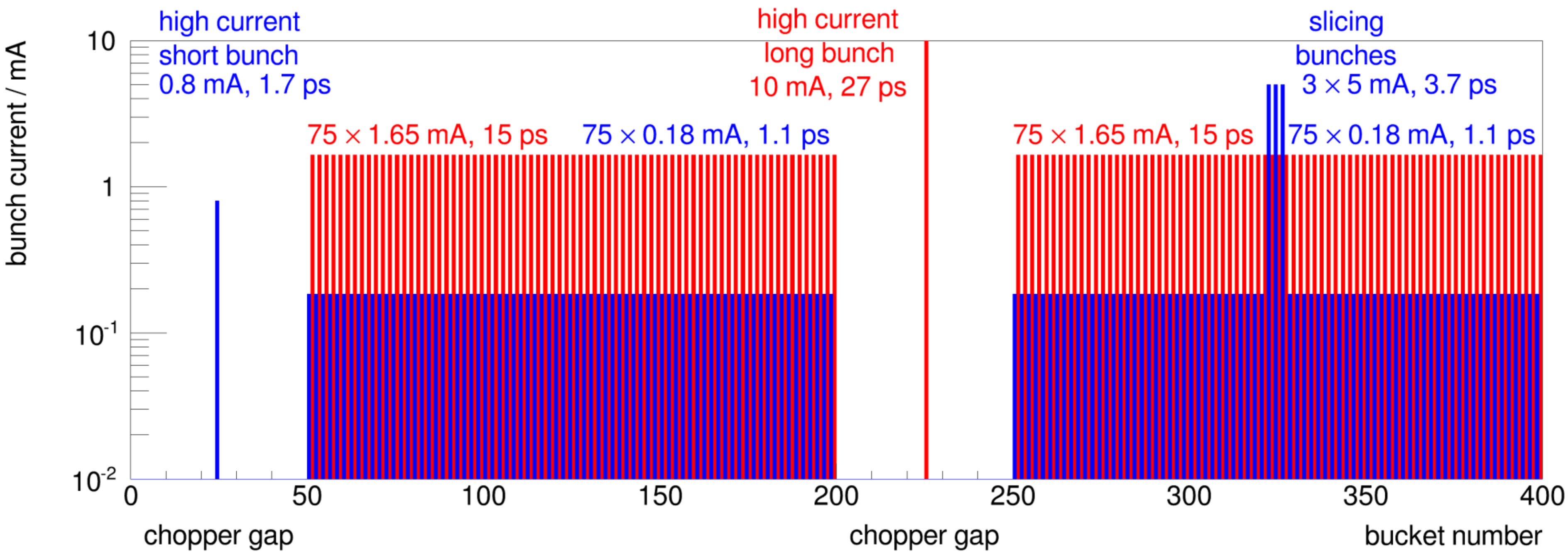
	Standard	**Low α**
Variance of mom. comp. I_α	$4.5 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$
Radiation excitation limit σ_{re}	0.12 ps	0.07 ps
Zero current bunch length σ_0	1.1 ps	0.25 ps

Limit from horizontal coupling and the effective bunch length.

	Limit σ_H	**Effective bunch length σ_{eff}**
Cavity straight	0 fs	250 fs
Dipoles	100 fs	270 fs
ID straight	195 fs	320 fs

BESSY VSR TDS, to be published

BESSY-VSR – project parameters



- 300 mA average current
- camshaft single bunches (short and long) in gaps
- ion clearing provided through gaps

in low alpha mode
350 fs @ 0.04 mA / bunch

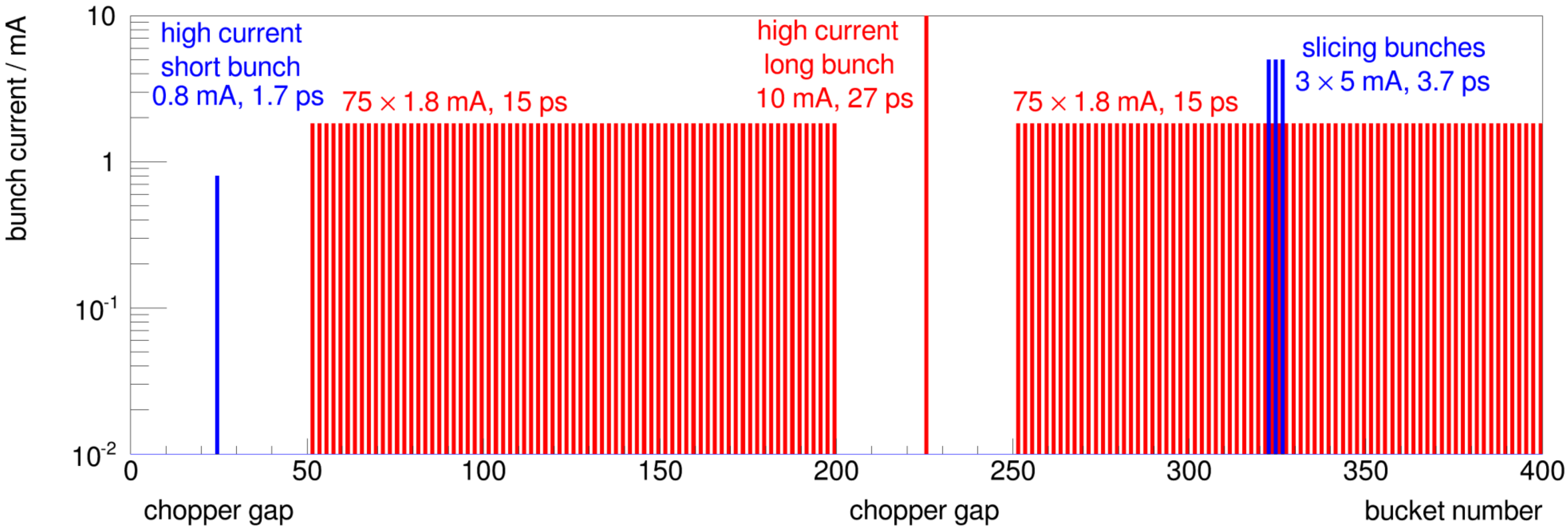
multi functional hybrid mode

ps short single bunch, high current single bunch, slicing bunches, high average brilliance, and high THz-power

preserving BESSY II emittance and TopUp capabilities
→ 5 nm rad, lifetime > 5h, average inj. eff. > 90%

from A. Jankowiak's talk at the 11th HZB-SAC meeting, 17.11.2014

BESSY-VSR – project parameters



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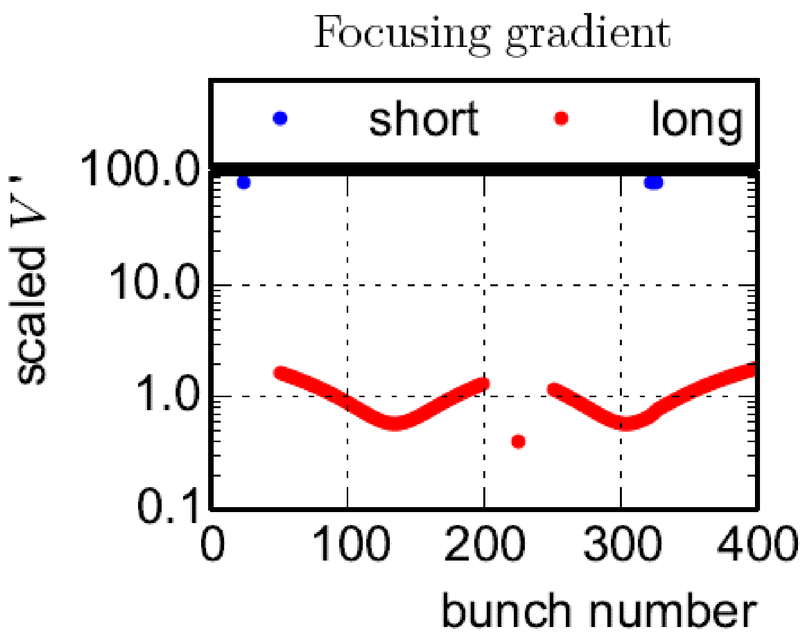
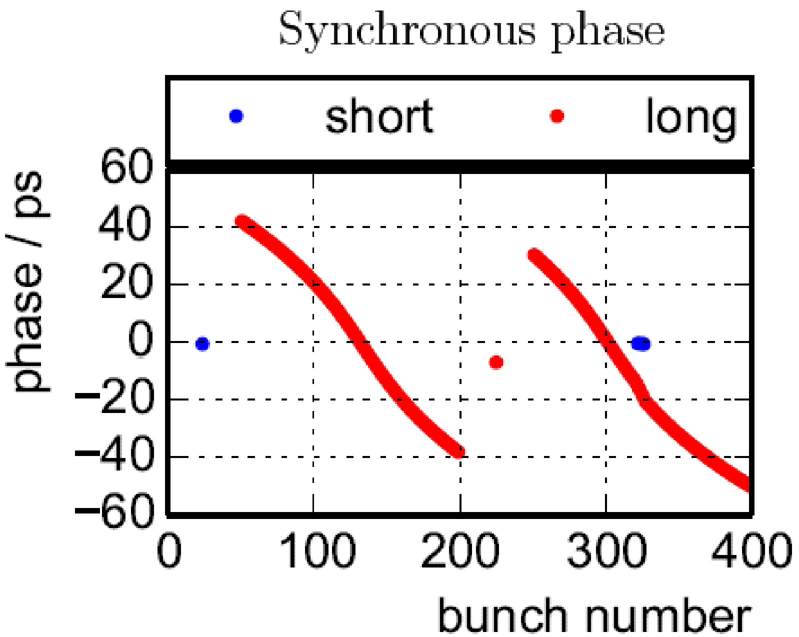
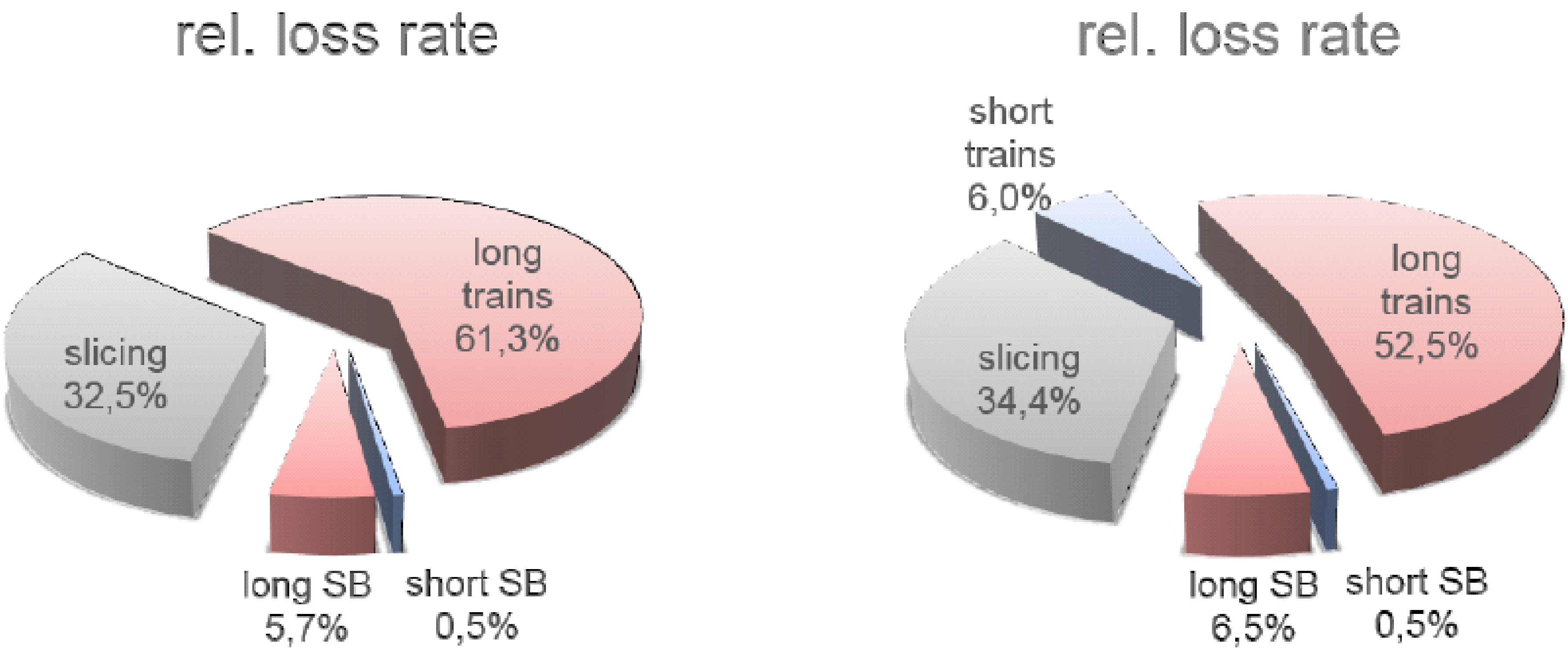
Calculations with the basic BESSY VSR fill pattern
scaled to the nominal values of BESSY II of $V' = 2\pi \cdot 0.5\,\mathrm{GHz} \cdot 1.5\,\mathrm{MV}$





Focusing gradient varies along bunch trains:
- phase transients → synchrotron tune spread
- bunches not as long as desired
- both fill patterns lead to a sufficient life time

BESSY VSR TDS, to be published



Relative contributions to the Touschek loss rate from different parts of the fill pattern

Compared to the standard operation mode resistive wall and CSR-impedance lead to increased power losses of up to 15 kW – could heat chamber and increase pressure resulting in larger contribution of residual gas scattering to life time.

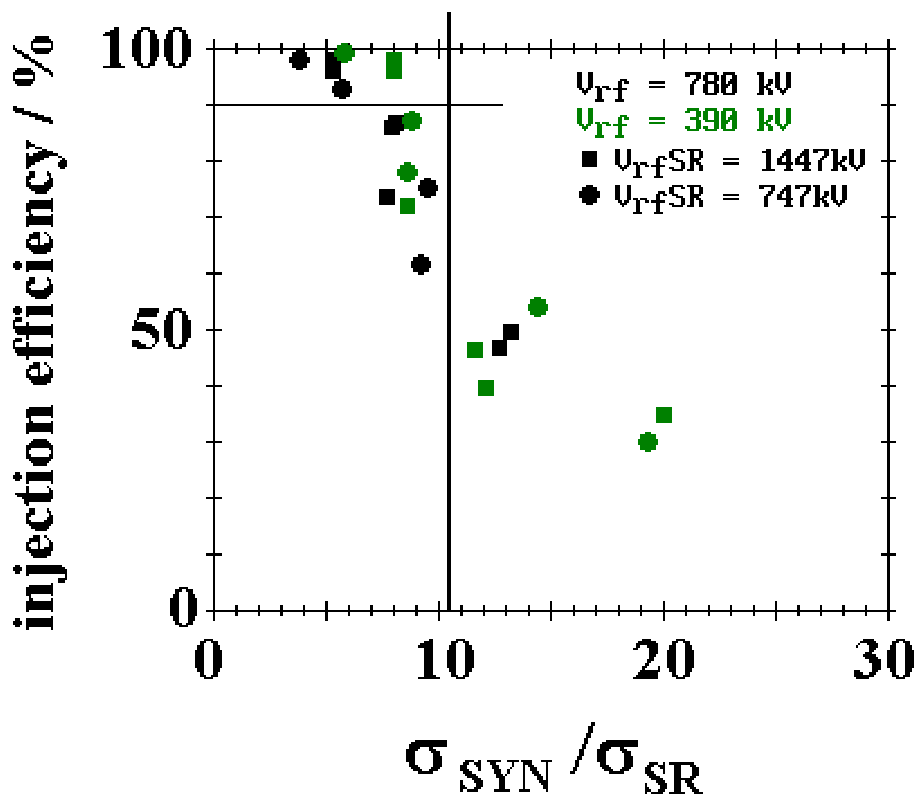
BESSY VSR TDS, to be published

Mismatch of longitudinal phase space in synchrotron, SYN, and storage ring, SR:

bunch length: $\sigma_{SYN} >> \sigma_{SR}$

energy spread: $\sigma_{SYN}^{\delta} \cong \sigma_{SR}^{\delta} \approx 7 \cdot 10^{-4}$

High efficiency requires: $$\frac{\sigma_{SYN}}{\sigma_{SR}} \leq \frac{\varepsilon_{RF}}{3 \cdot \sigma_{SR}^{\delta}} \sim \frac{2.0\%...2.5\%}{3 \cdot 0.7 \cdot 10^{-3}} \sim 10.5$$



Experimental finding: $\frac{\sigma_{SYN}}{\sigma_{SR}} \leq 8$

ε_{RF} depends on transverse momentum of particles

Reduce bunch length in SYN with high power S-Band cavity structure and improvement of transverse acceptance in SR and reduction of transverse momentum of injected beam

BESSY VSR TDS, to be published

Pulse Picking – quasi resonant excitation

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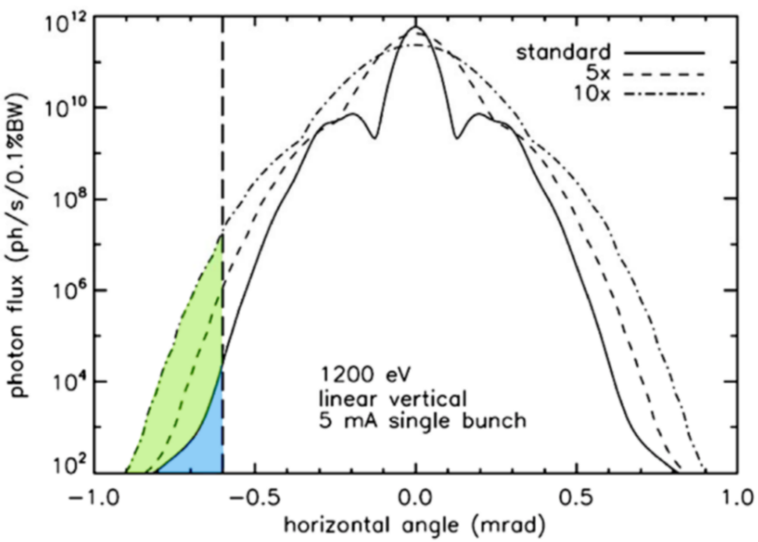
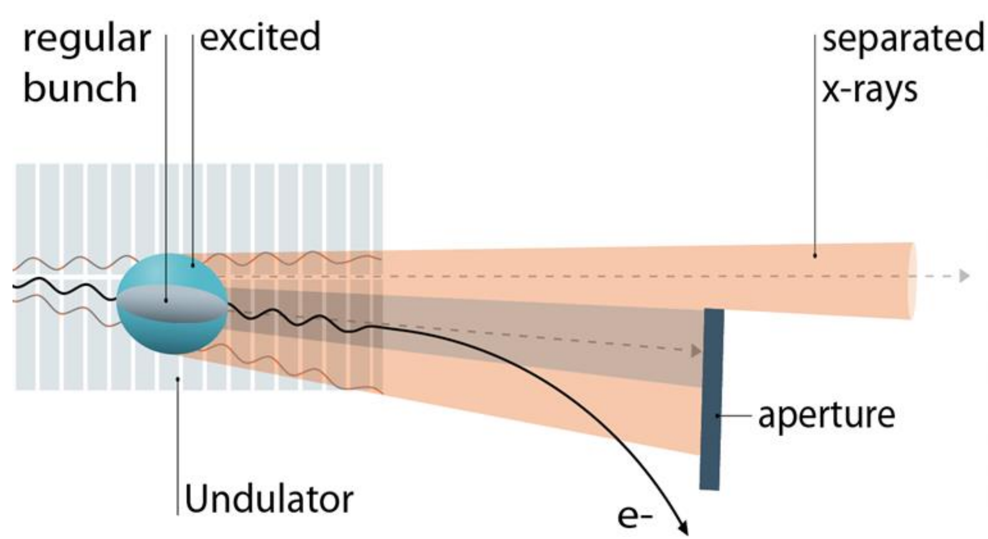
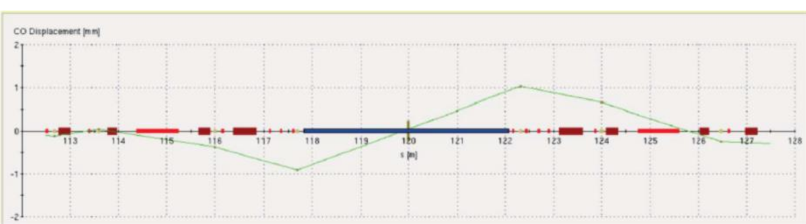
Motivation and idea:

Time resolved measurements like in single bunch mode
Like bunch separation in fs-slicing
increased emittance of one bunch – in combination with ARTOF







Established on a couple of beam lines
Digital bunch-by-bunch feedback very helpful

Bunch separation with a chopper wheel delivers full intensity.

nature COMMUNICATIONS

Single bunch X-ray pulses on demand from a multi-bunch SR source
K. Holldack et al.
Nature Communications 5, 4010, doi: 10.1038/ncomms5010, 30.05.2014

How to increase the emittance of just one bunch?
Horizontal beam size 5 times larger than usual and center-of-mass motion as small as possible.

Recipe:

- Gated excitation of the bunch – window a couple of ns long – like we did in the old days for improving bunch purity
- Modulate the excitation frequency with a bandwidth of 2 times the mains frequency – true tune of the bunch will be modulated with the mains frequency
- Bunch-by-bunch feedback should not counteract this excitation of the dedicated bunch – we use the flexible Dimtel system and switch off feedback for this bunch
- Excitation could be done through feedback – we use extra path and signal-generator (gives more flexibility)
- For efficient TopUp-injections the excitation has to be switched off (through the 50ms-long blank pulse)

How to make the beam blow-up (incoherent effect) large while keeping the (coherent) oscillation of the bunch small?

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Landau-damping

In storage rings the tune of particle i at time t is given to second order by:

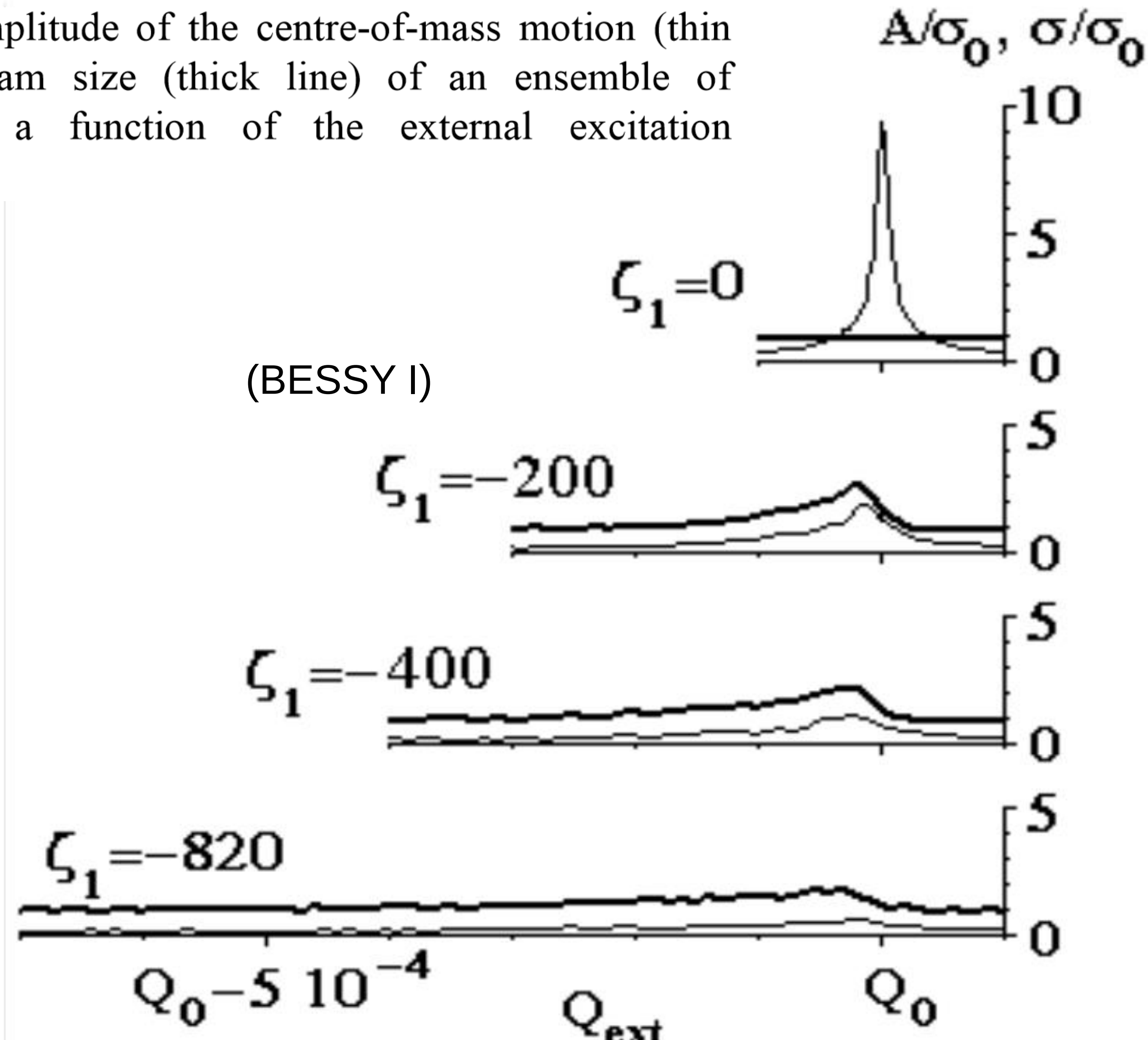
$$Q_i(t) = Q_0 + \xi_0 \cdot \delta p_i(t) + \xi_1 \cdot \delta p_i^{\,2}(t) + \frac{\partial Q}{\partial E_y} \cdot E_{y_i}(t) + \frac{\partial Q}{\partial E_x} \cdot E_{x_i}(t) + \ldots$$

with chromatic contributions, $\xi_{0,1}$, proportional to the individual relative momentum deviation, δp_i, and amplitude dependent terms proportional to the emittance of the particle, $E_{x,y}$. At BESSY the ξ_1-term has been extracted from measurements of the chromaticity: $\xi_1=-820$. The contribution to the tune spread with the natural energy spread of $5\cdot 10^{-4}$ is much larger than the spread caused by the amplitude dependent effects since the emittances are rather small[3].

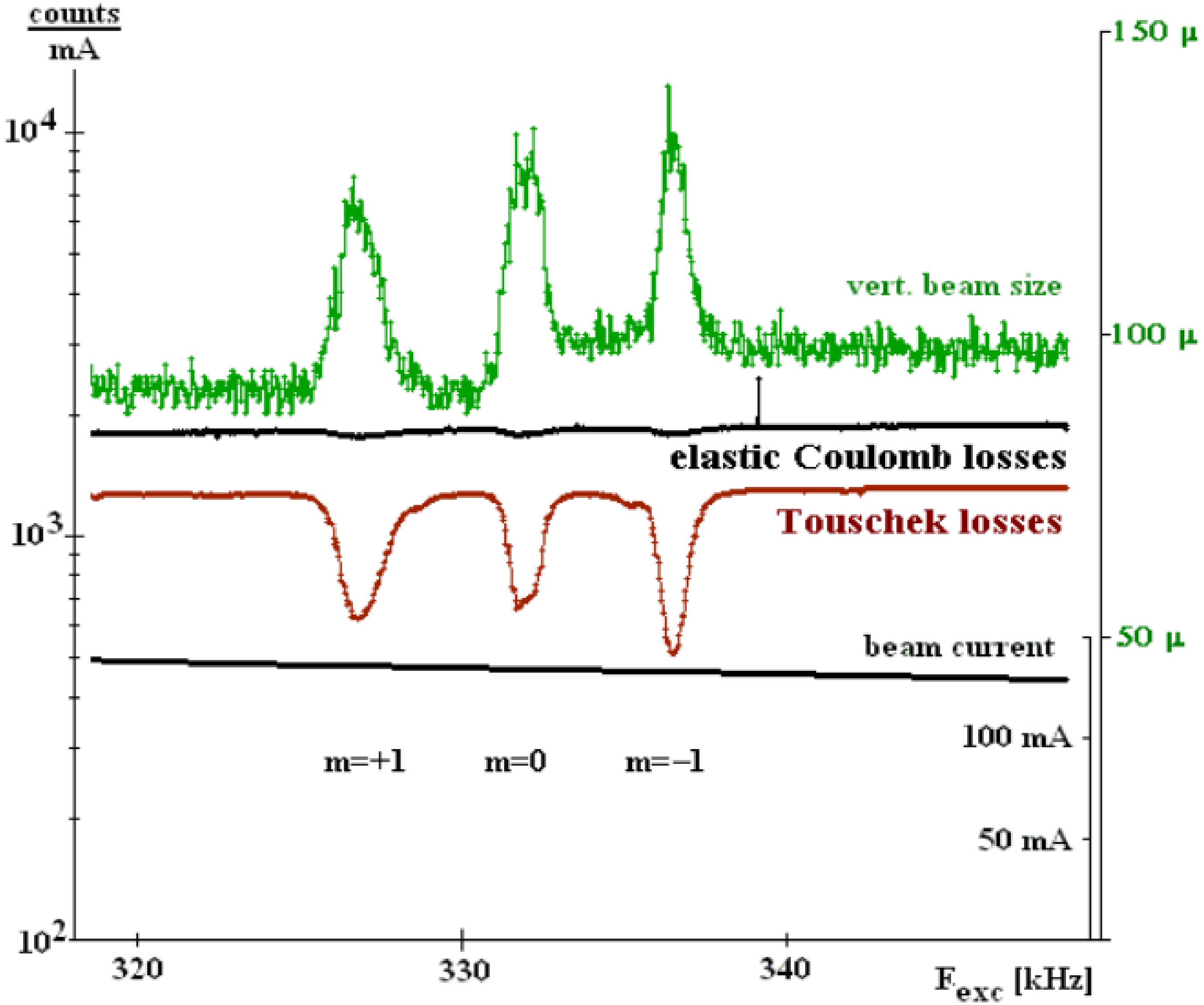
(BESSY I)

P. Kuske, EPAC 1998, THP14G

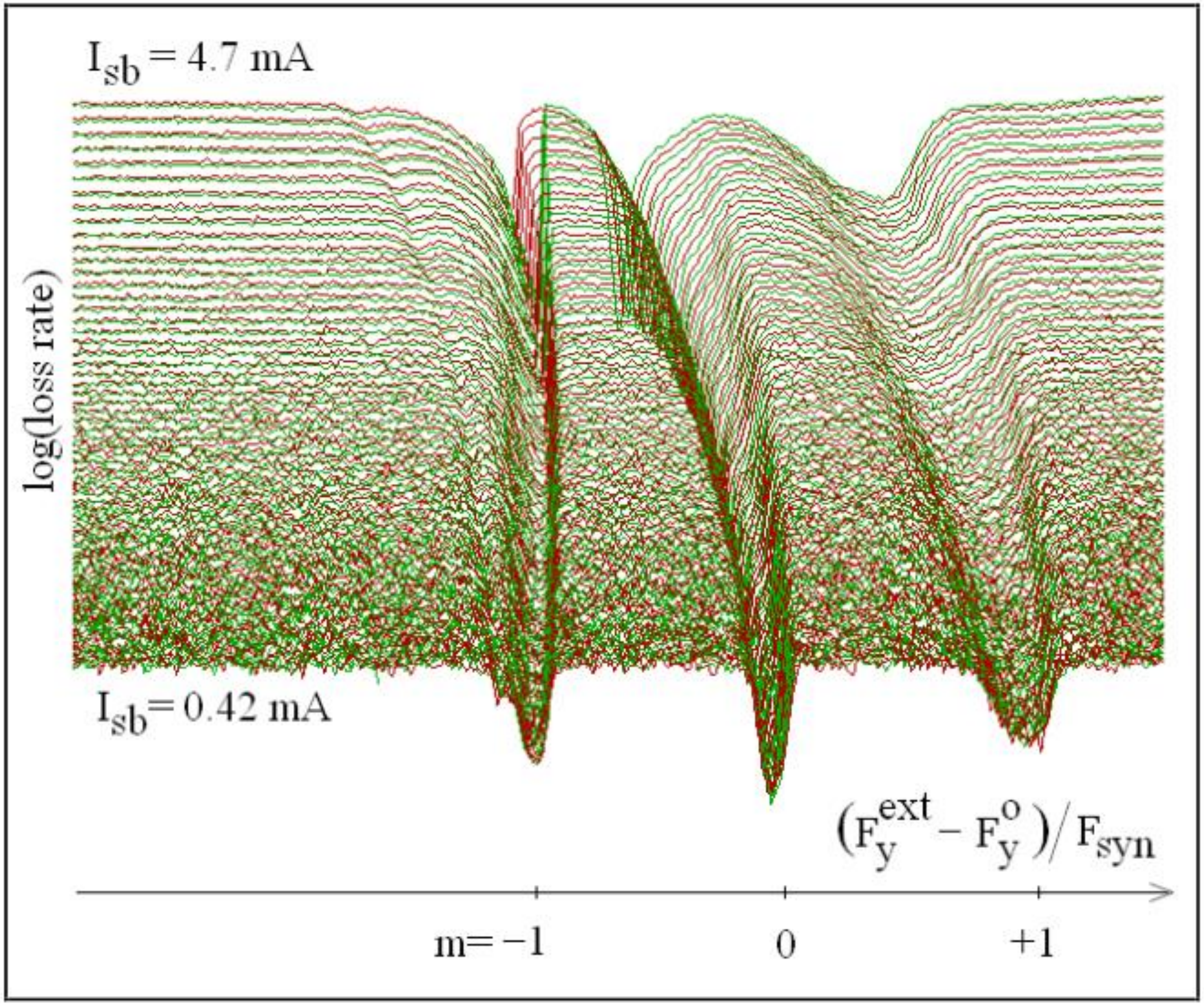
Figure 4: Amplitude of the centre-of-mass motion (thin line) and beam size (thick line) of an ensemble of particles as a function of the external excitation frequency.



P. Kuske, EPAC 1998, THP14G



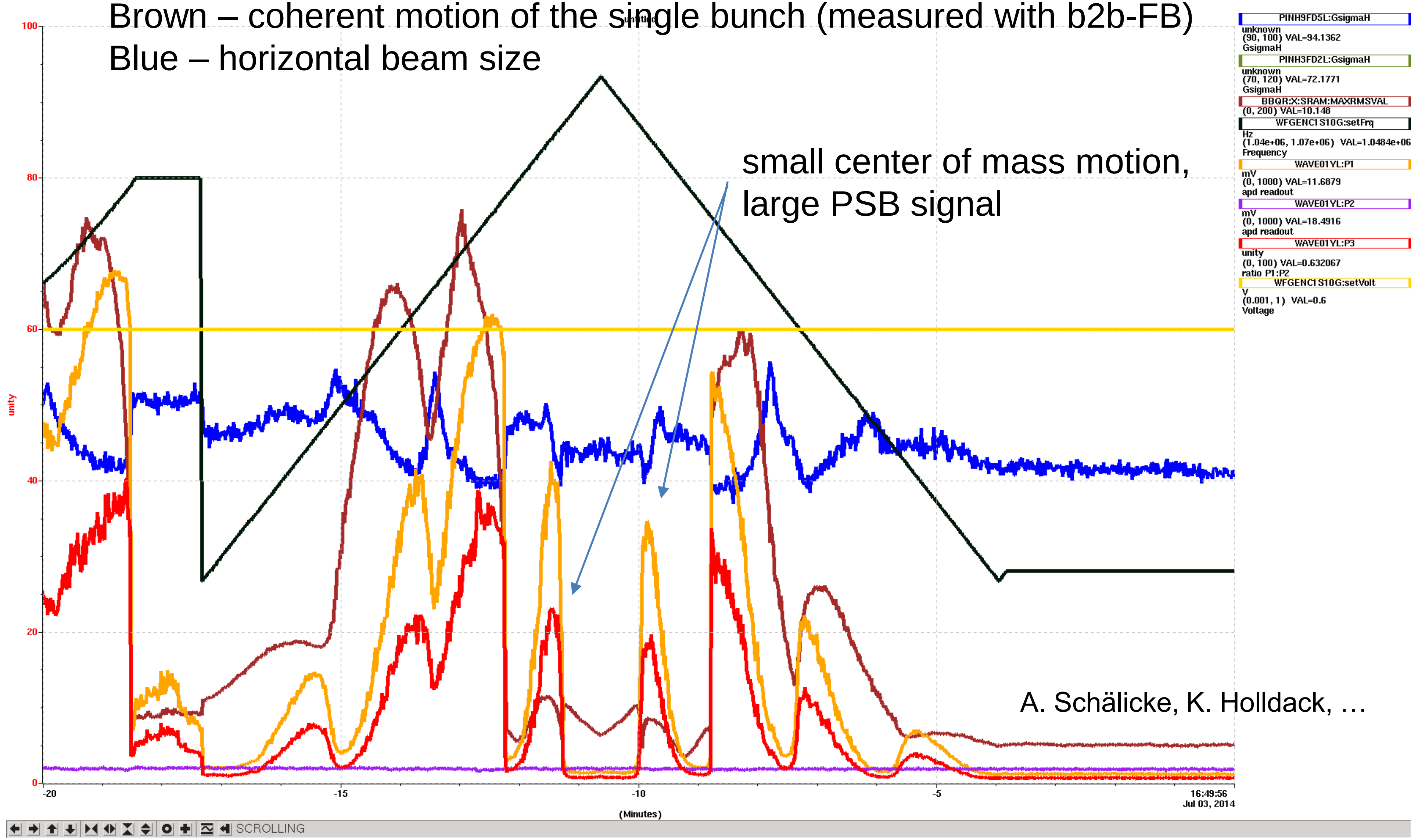
Special excitation technique and zero chromaticity, see P. Kuske, DIPAC 2001, IT07



Special excitation technique and zero chromaticity, see P. Kuske, DIPAC 2001, IT07

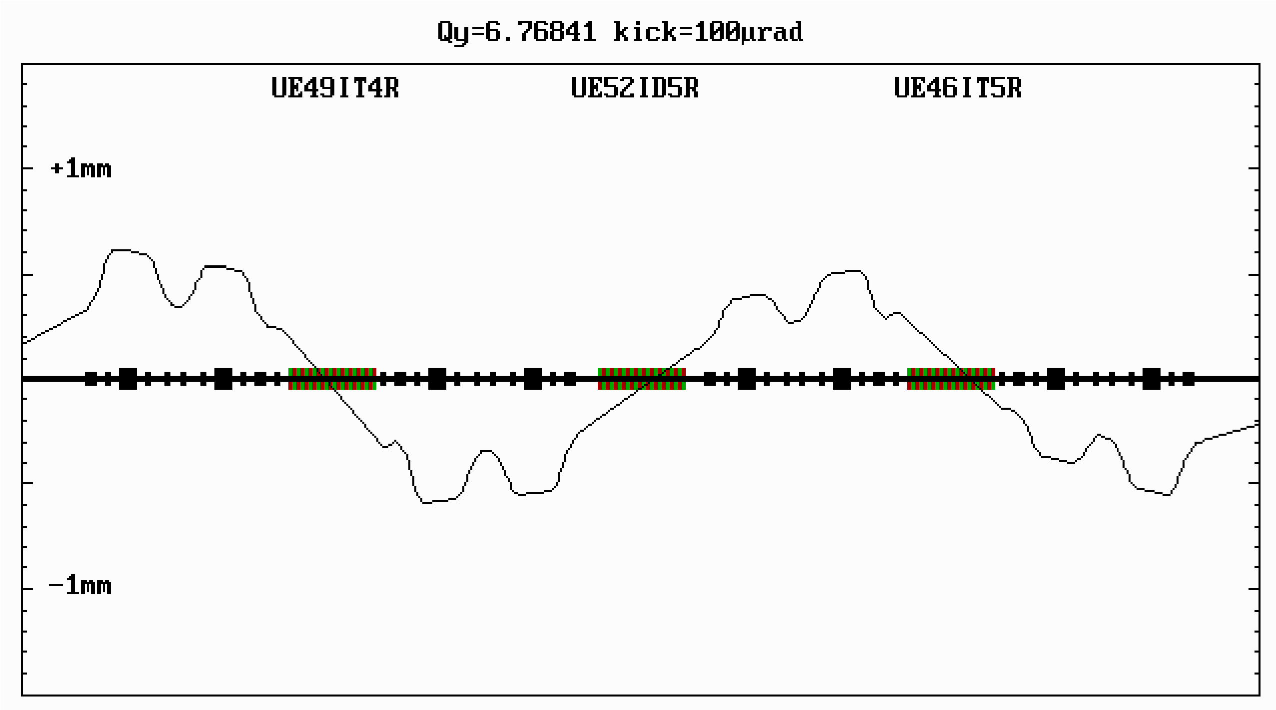
HORIZONTAL RESONANT BEAM EXCITATION – REALITY

Black – excitation frequency
Orange and red – beam line signal from single bunch (APD behind slit)
Brown – coherent motion of the single bunch (measured with b2b-FB)
Blue – horizontal beam size



Orbit distortion at i from kick Θ at position k:

$$\Delta_i = \frac{\Theta\sqrt{\beta_i \beta_k}}{2\sin(\pi Q)}\cos(|\mu_i - \mu_k| - \pi Q)$$



C. Sun, et al., PRL **109**, 264801 (2012)

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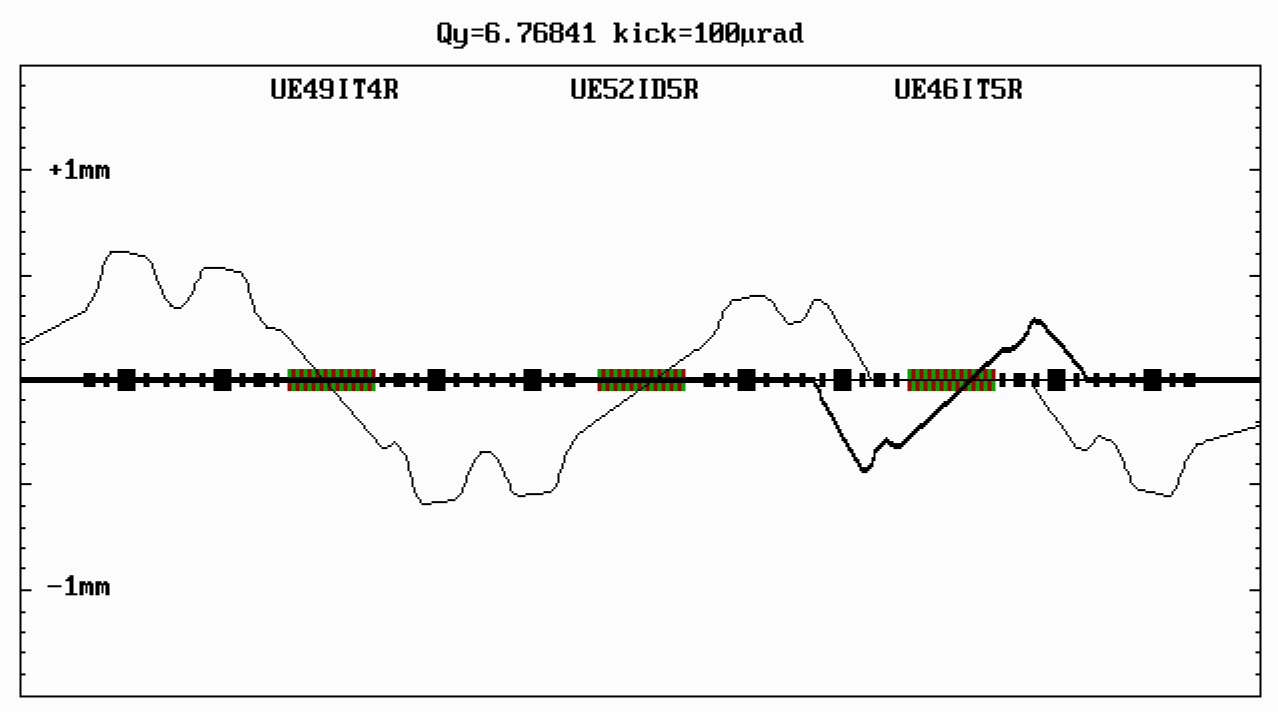

With a 4-kicker bump the displaced bunch can be brought back on axis and the intense light of the many bunches can be blocked by an aperture

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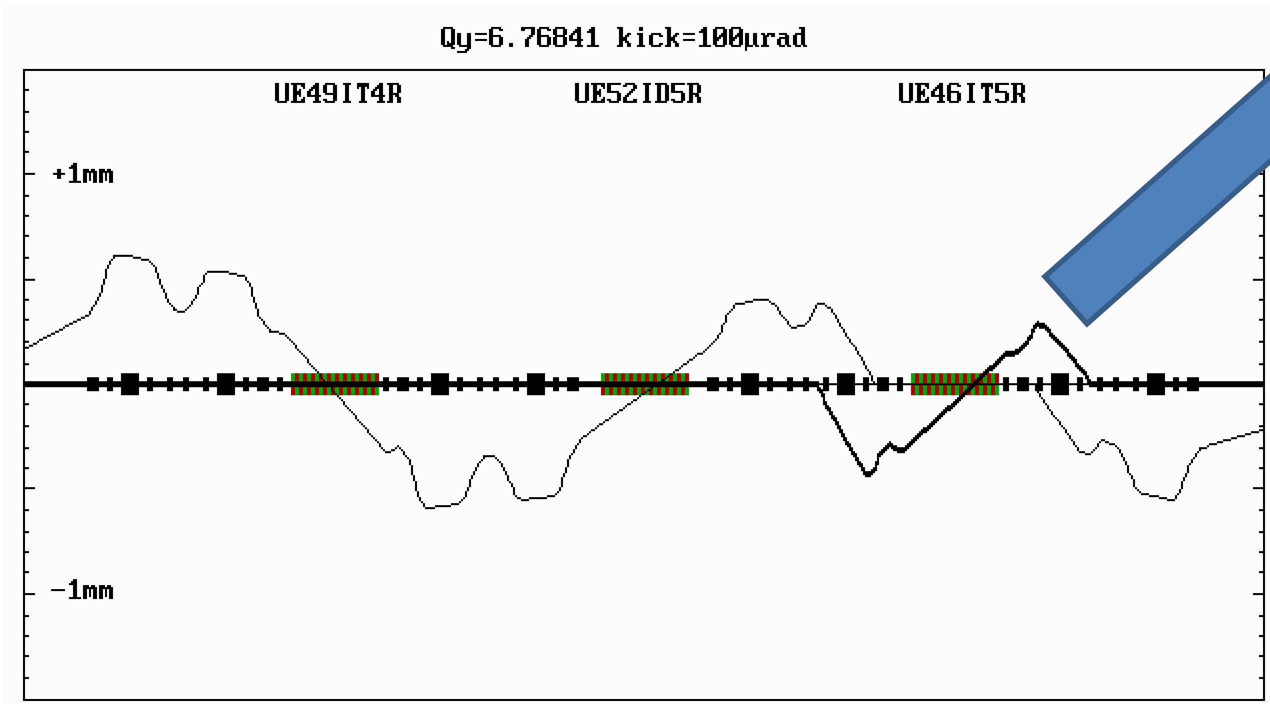

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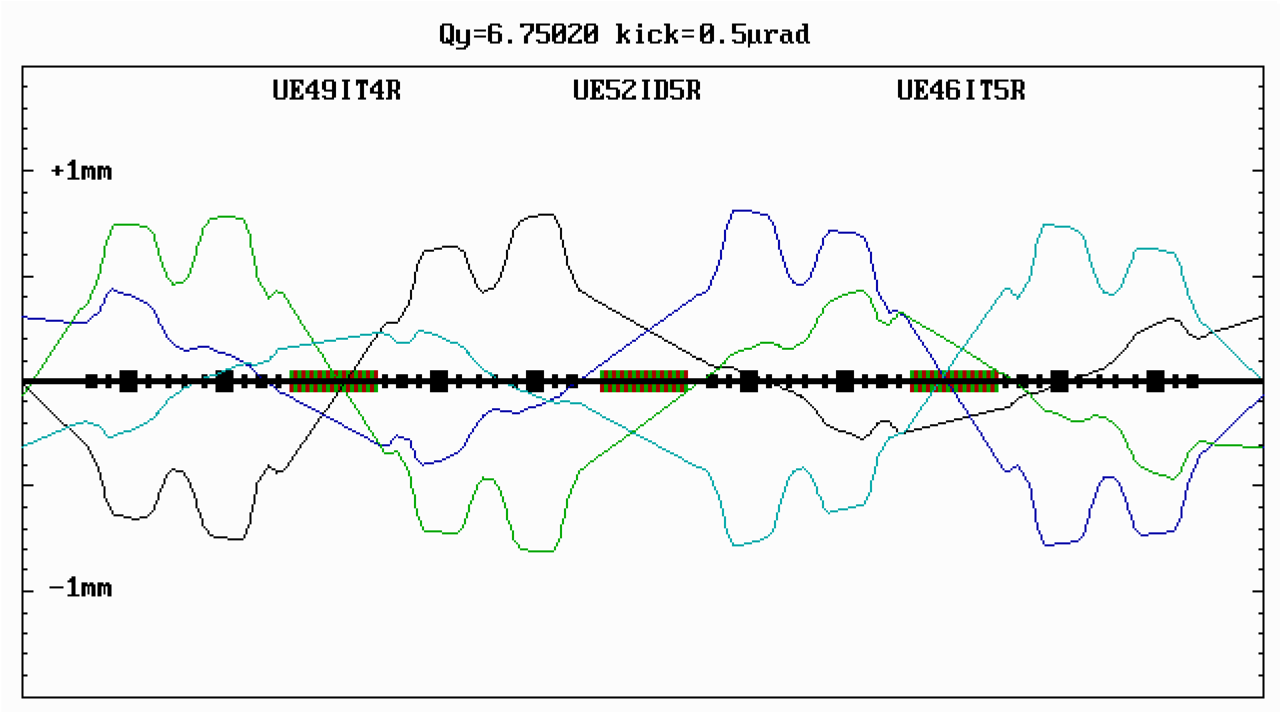

If sin(πQ) close to zero only very small kicks are required

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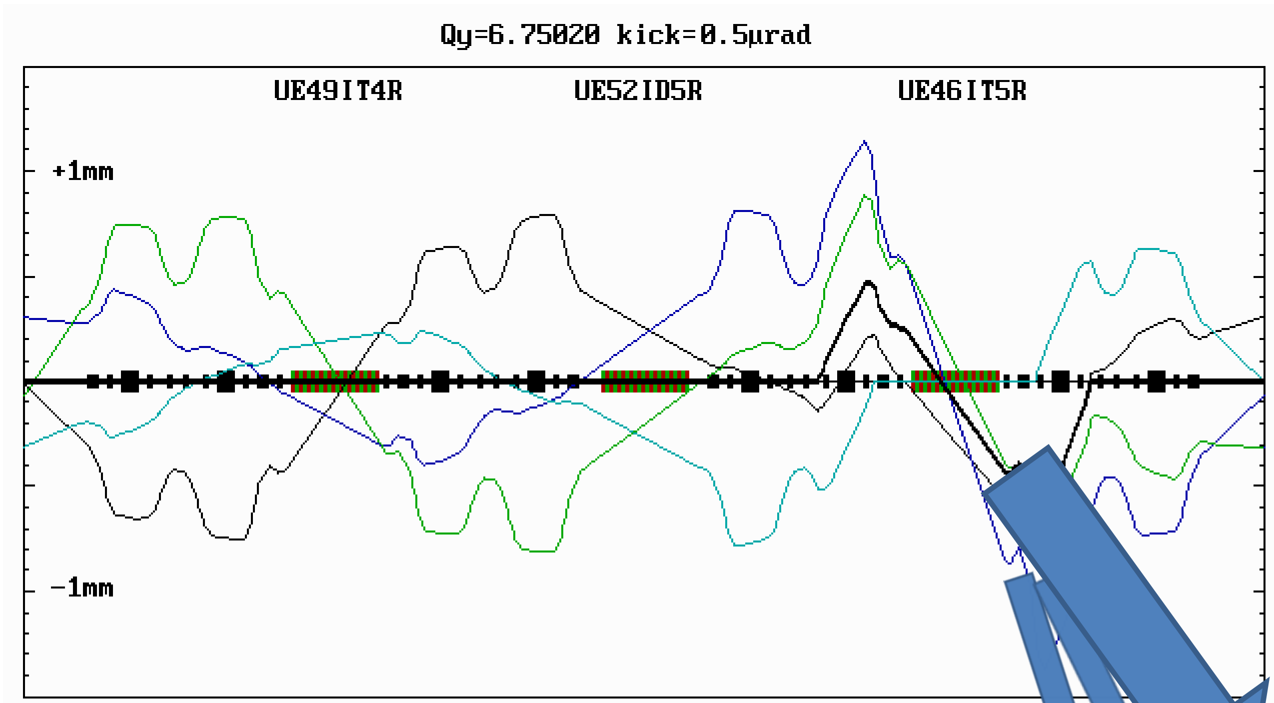


If sin(πQ) close to zero only very small kicks are required

the repetition rate would be reduced

During the passage along the kicker electrodes the beam gains transverse momentum:

$$\Delta p_{\perp} = 2F_{\perp} \cdot \Delta t = \frac{4eV_g}{d} \cdot \frac{l}{c} \qquad (4)$$

Taking into consideration that:

$$\frac{\Delta p_{\perp}}{p} = \tan\Theta \cong \Theta \quad \text{and} \quad E = p \cdot c$$

the required amplitude of the kicker pulse on each plate equals:

$$V_g = \frac{E \cdot d \cdot \Theta}{4 \cdot l \cdot g} \qquad (5)$$

where: E -beam energy (in eV)

d -distance between kicker plates

Θ -deflecting angle

l -kicker length

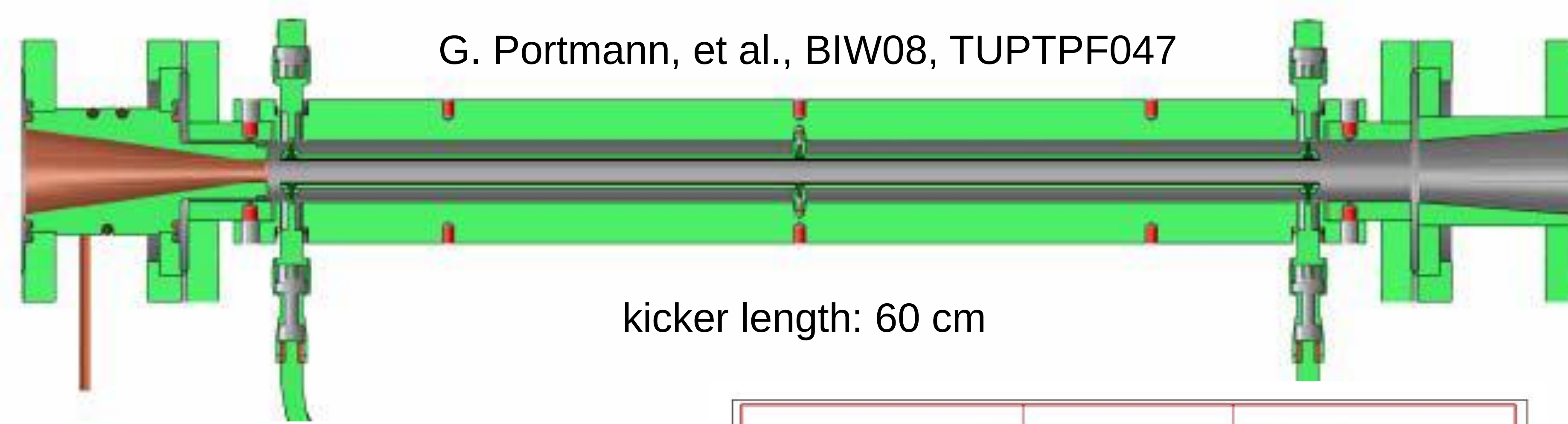
g -geometry factor for long flat electrodes [2]

g=tanh(πw/2d)

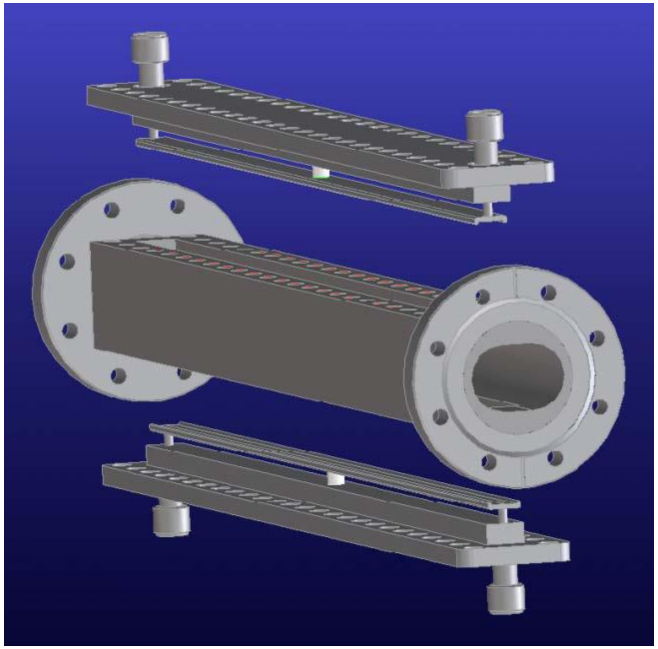
w -stripline width

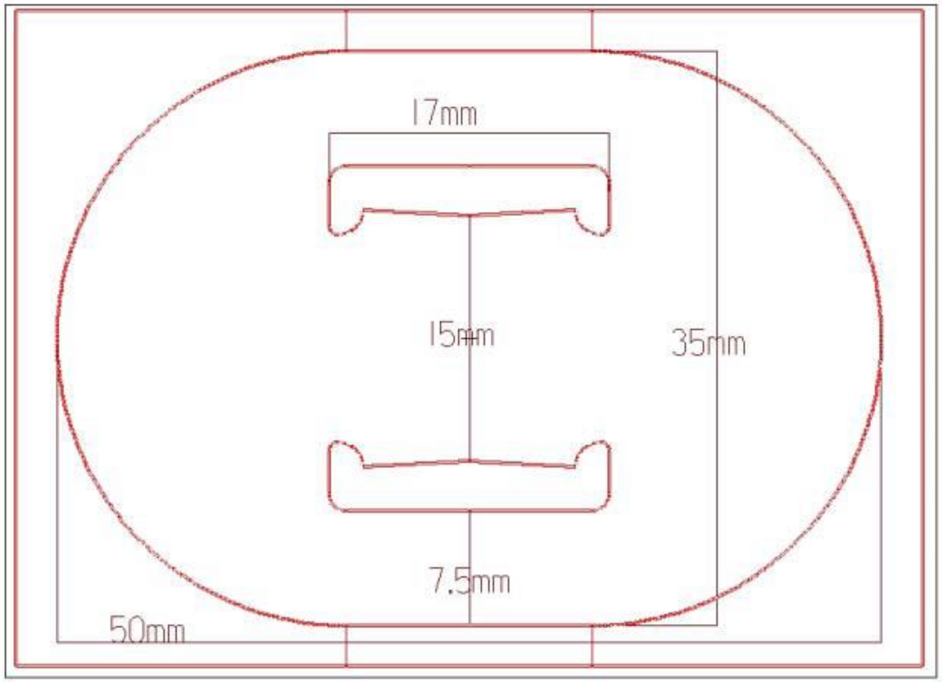
S. Kwiatkowski, et al., THPLS114, EPAC 2006

G. Portmann, et al., BIW08, TUPTPF047

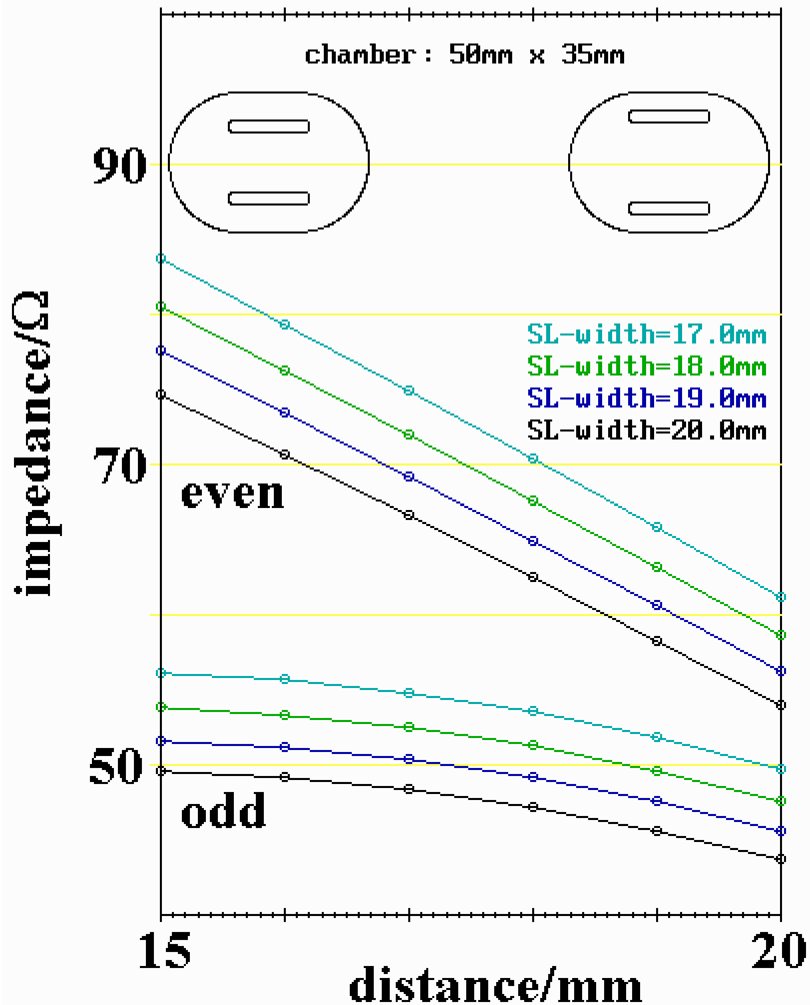


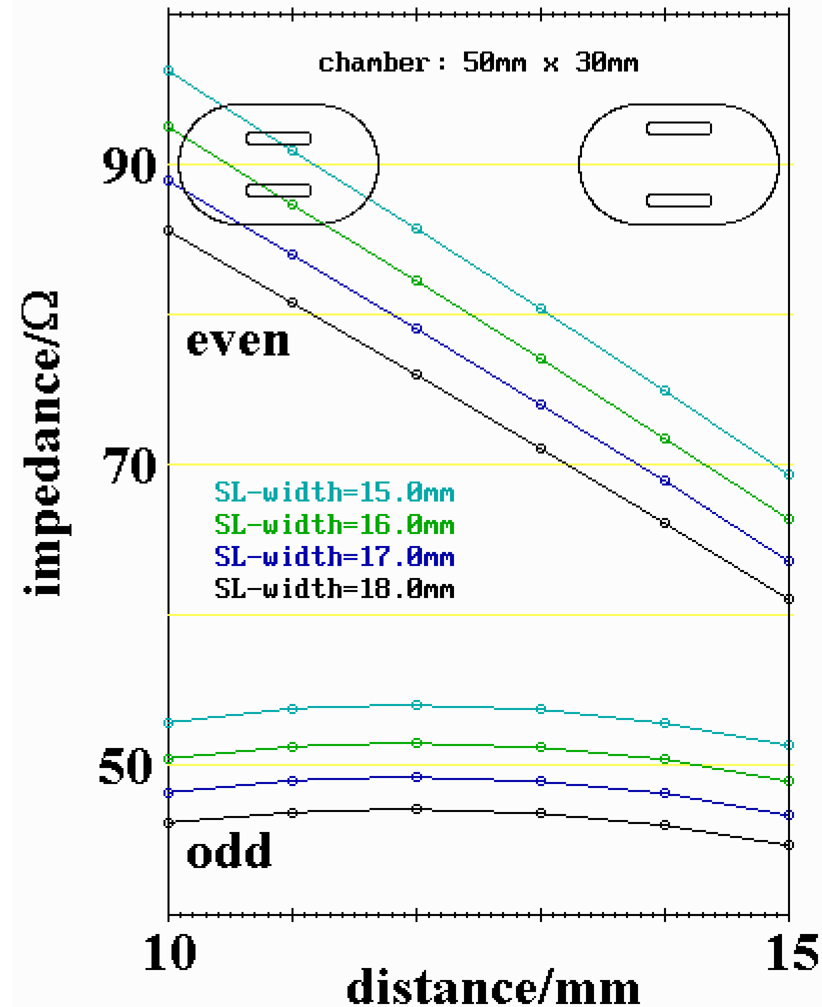
kicker length: 60 cm





S. Kwiatkowski, et al., THPLS114, EPAC 2006

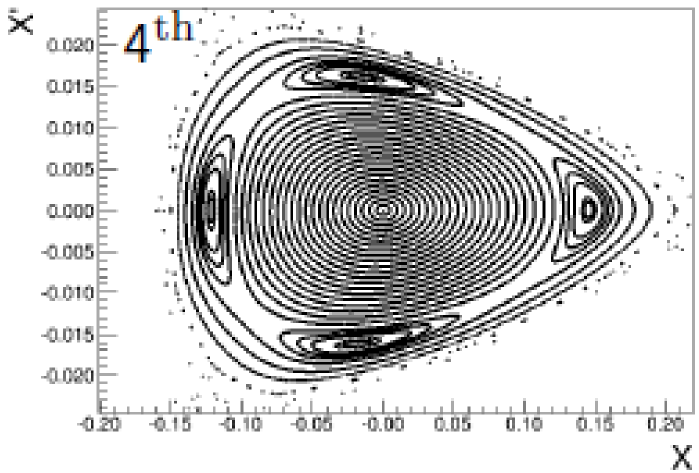




Issues: even mode impedance > 50 Ω and increased power loss from image currents (for 500 mA, and σ=20ps S. Kwiatkowski, et al. quoted 1.5W per electrode) - feasible to reduce distance down to 10 mm and gain 50%

Resonance island buckets at MLS

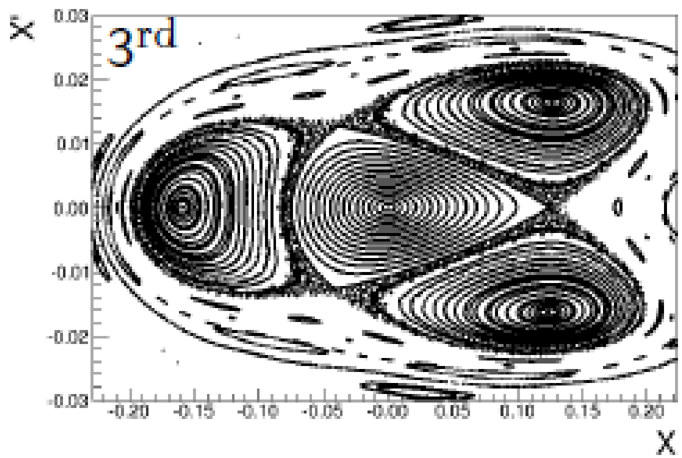
Examples of islands - (x', x) phase space simulations

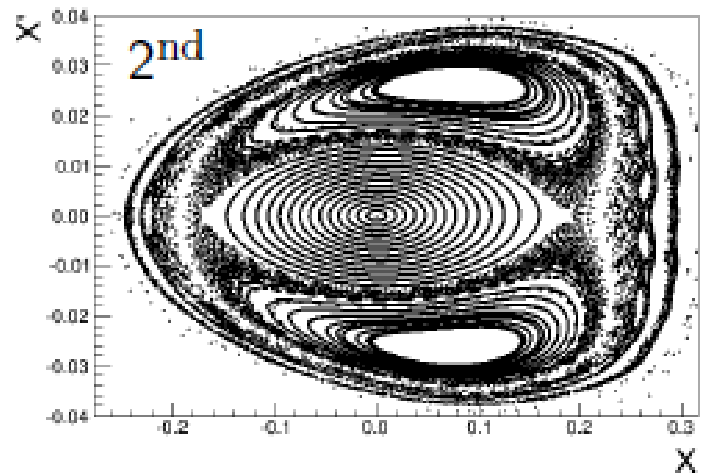


Near resonance

- Additional stable buckets
- Number of buckets = order of resonance

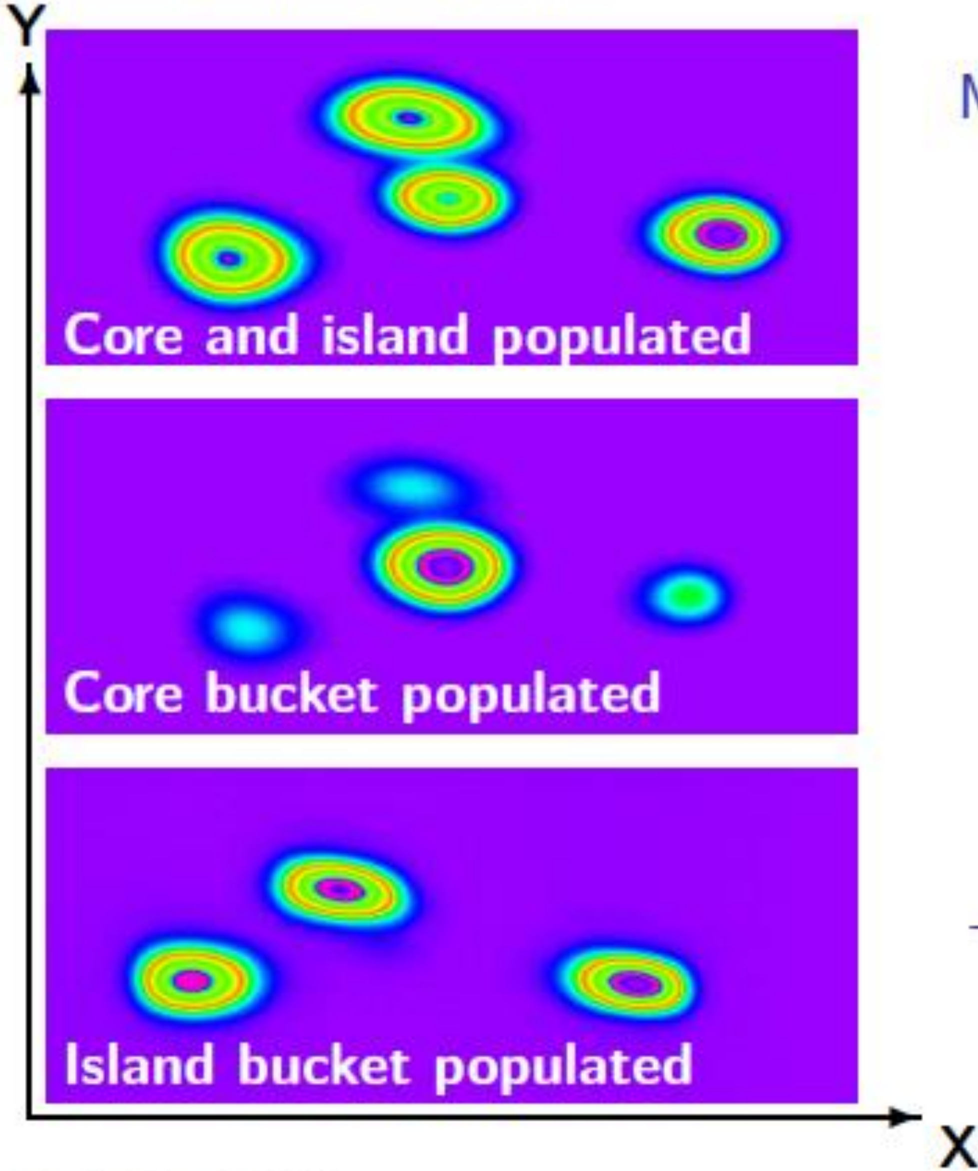
$\rightarrow$ Resonance island buckets





Experiments with resonance island buckets at MLS

3rd order buckets best studied

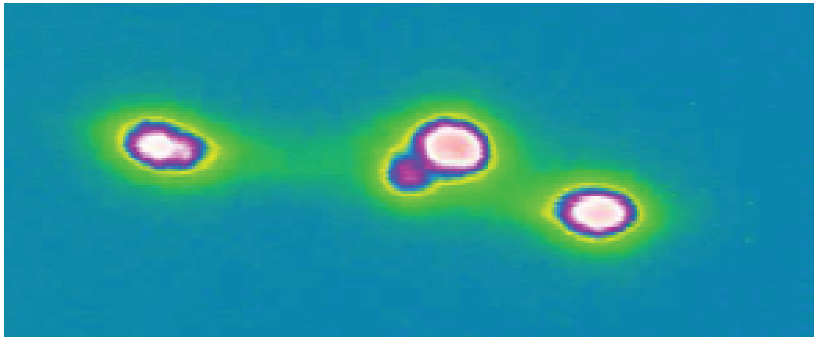


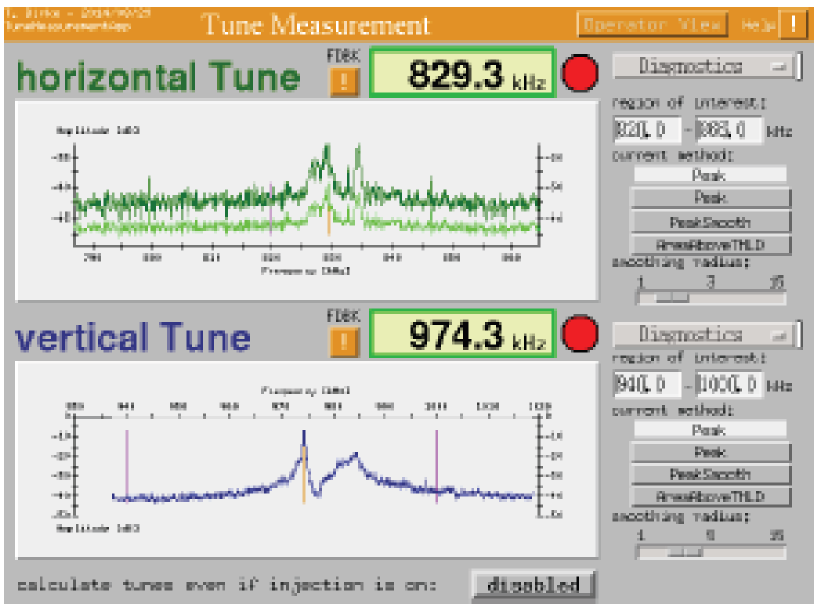
Manipulating the buckets

- Position of island shifts by quads, sextupoles, octupoles
- Rotated by skews, i.e., x-y coupling
- Tunes of core and island bucket different and separated by resonance
- Current manipulation by transverse excitation

→ Single bunch in resonance island using Bunch-to-Bunch Feedback

Experiments with resonance island buckets at BESSY II





First measurements

- Tests with 50 mA
- 3rd order resonance at $f = 833\,\mathrm{kHz}$
- Core tune $f_{qx} = 835\,\mathrm{kHz}$
- Island tune $f_{qx} = 825\,\mathrm{kHz}$

$\rightarrow$ Experiences of MLS experiments helped a lot

$\rightarrow$ Identifying the effective knobs

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Photon beam properties at BESSY VSR compared to different modes of BESSY II. Brilliance values refer to the UE49 undulator in planar mode at the BESSY II design emittance of 6 nm rad and 2% coupling.

Facility	**Peak brilliance**	**Average brilliance**	**Number of bunches**	**Pulse duration**
	ph/s/mrad^2/mm^2/0.1 %BW	(multi bunch curr.)		ps (rms)
BESSY II				
standard	6.1e21	4e19 (300 mA)	350	15
low α	1.9e20	2.5e17 (15 mA)	350	3
BESSY VSR				
total	varying	4e19 (300 mA)	varying	varying
std. long pulses	1.2e22	3.3e19 (248 mA)	150	15
std. short pulses	1.7e22	3.6e18 (27 mA)	150	1.1
long camshaft	3.95e22	1.3e18 (10 mA)	1	27
short camshaft	5.1e22	1e17 (0.8 mA)	1	1.7
low α	2.2e21	1.2e17 (7.5 mA)	150	0.3

BESSY VSR TDS, to be published

Working on the Technical Design Study (TDS) for BESSY VSR has not shown any show stopper.

Major progress in the design of low HOM or HOM damped sc cavity strings - Coupled bunch instabilities can be damped with up to date bunch-by-bunch FB

Robinson instability controlled with LLRF regulation – more simulations needed

Efficient TopUp injections demand shorter bunches from the synchrotron – work is on-going – higher RF-accelerating gradients + low alpha mode in the synchrotron?

No chance to inject efficiently into the ultra short bunches (σ~0.3ps) without dedicated LINAC – low current in this mode allows for decay mode

Lack of model for chamber impedance at very high frequency – inductive impedance would stabilize bunches with higher charge

Our vision of the next generation light source is a combination of a sc cw LINAC (as FEL-driver for ultra short and intense light pulses) and a diffraction limited SR with alternating very high and very low gradients like in BESSY VSR in order to produce short light pulses at high rep rate.

Important to apply for funding now and get BESSY VSR going – hope for short pulses in early 2020.