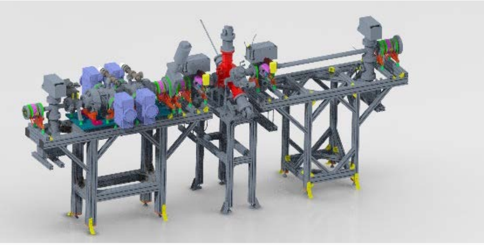
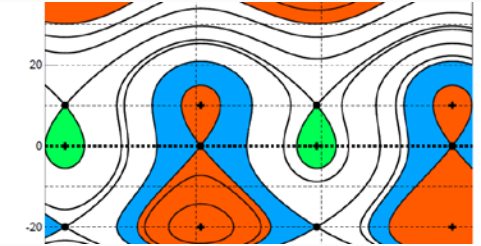
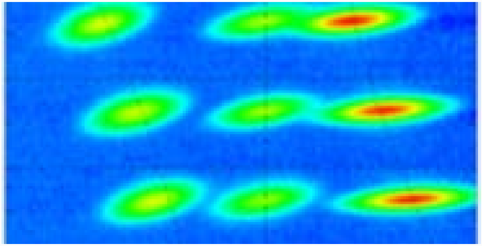
Shaping the longitudinal phase space at BESSY II and MLS

Markus Ries on behalf of the BESSY II / MLS machine group







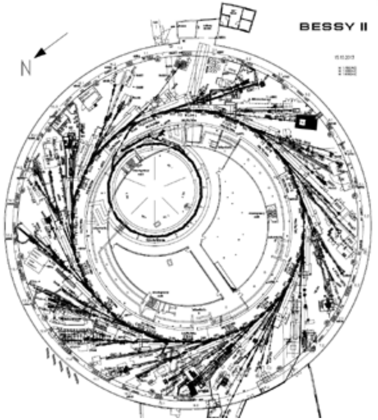
Shaping the longitudinal phase space at BESSY II and MLS

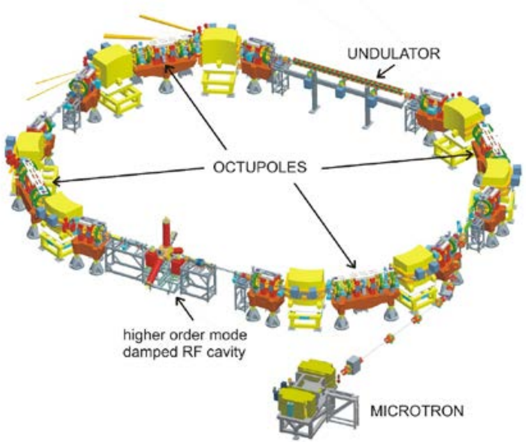
Michael Abo-Bakr, Terry Atkinson, Jörg Feikes, Paul Goslawski, Arne Hoehl, Karsten Holldack, Ji-Gwang Hwang, Andreas Jankowiak, Roman Klein, Jens Knobloch, Marten Koopmans, Peter Kuske, Ji Li, Tom Mertens, Roland Müller, Markus Ries, Andreas Schälicke, Gregor Schiwietz, Adolfo Velez, Godehard Wüstefeld

… and many more colleagues from the BESSY II / MLS machine group and PTB

Disclaimer: I am sorry…

A compilation of sketches of projects and ideas that we have done, we wanted to do, we want to do and we will do which is thoroughly incomplete.
Please feel free to ask questions in every direction.

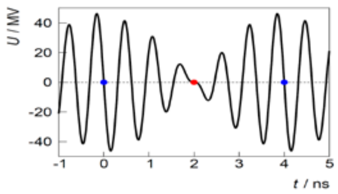


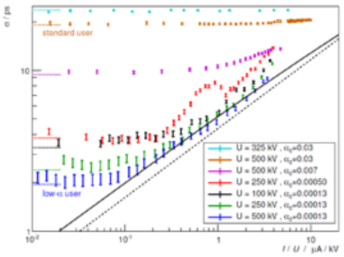


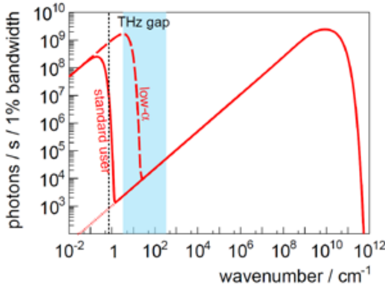
Parameters	BESSY II	MLS
Energy	1.7 GeV	0.63 GeV
Circumference	240 m	48 m
Horizontal emittance	7 nm rad	100 nm rad
Beam current	300 mA	200 mA
RF frequency	500 MHz	500 MHz
max. RF voltage	2.0 MV	0.5 MV
Bunch length (zero current) low-α	10 ps 2 ps	19 ps 1.3 ps
Mom. Comp. factor low-α	7.5×10^{-4} 3.5×10^{-5}	3.0×10^{-2} 1.3×10^{-4}

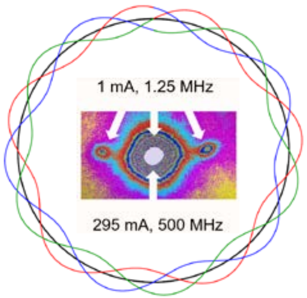
Why / how shape the longitudinal phase space?

- short bunch lengths / pulse lengths
- microbunching
- low alpha
- negative alpha
- coherent synchrotron radiation
- momentum acceptance
- damping
- instabilities
- timing users
- beam separation
- Slicing
- in-vacuum IDs









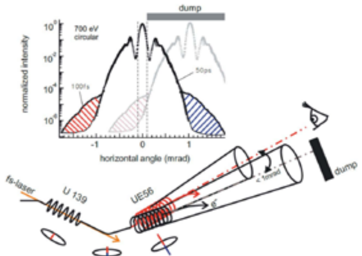
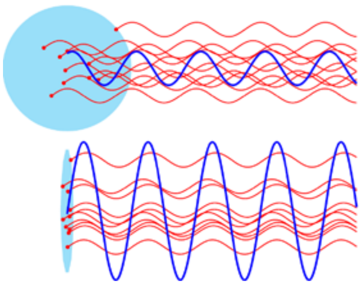
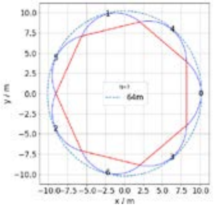
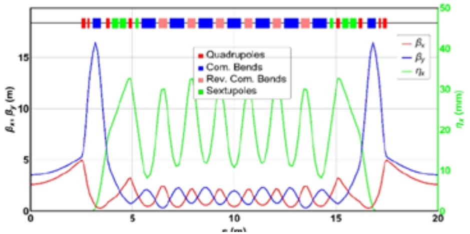


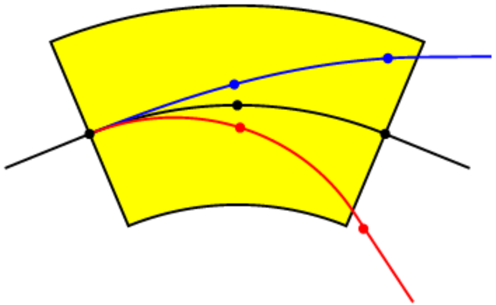
Figure 1
Principle of femtoslicing at BESSY II. After being laser-energy



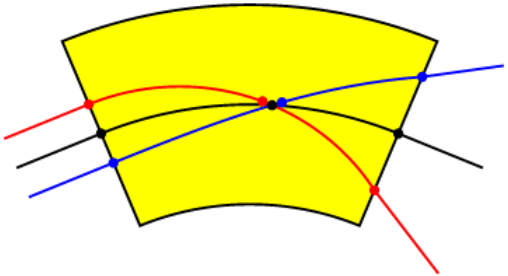




$$\frac{\Delta L}{L_0} = \alpha \frac{\Delta p}{p_0}$$



(a) DBA lattice path length



(b) isochronous lattice path length

HZB Helmholtz Zentrum Berlin

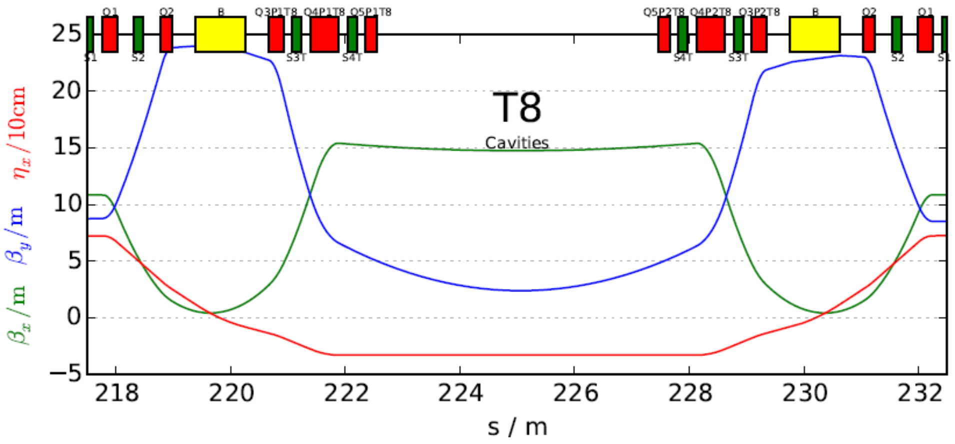
- user operation > 10a
- 2 weeks / a
- 100 mA (bursting), up to 250 mA
- 2 MV + 0.7 MV eff RF voltage
- no TopUp
- α ~ 3.5e-5 (edge is around 1e-5)

VOLUME 88, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 2002

Steady-State Far-Infrared Coherent Synchrotron Radiation detected at BESSY II

M. Abo-Bakr, J. Feikes, K. Holldack, and G. Wüstefeld
BESSY mbH, Albert-Einstein-Straße 15, 12489 Berlin, Germany

H.-W. Hübers
DLR, Rutherford Strasse 2, 12489 Berlin, Germany
(Received 29 October 2001; revised manuscript received 8 April 2002; published 4 June 2002)



Beamtime	2021/1																	
Month	May																	
Week	17		18							19								
operation-mode	MC		low-a							MB								
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	1
Shift 1 (07:00 - 15:00)																		
Shift 2 (15:00 - 23:00)																		
Shift 3 (23:00 - 7:00)																		

low alpha operation at MLS

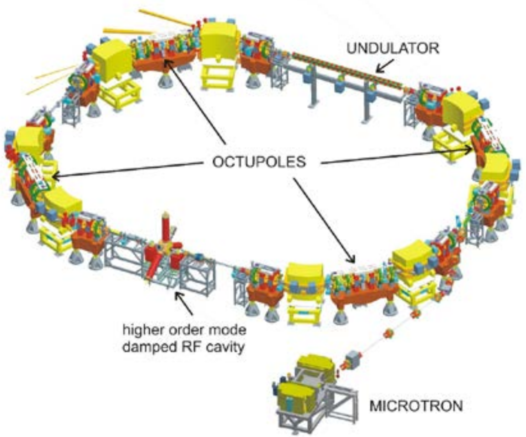
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 030705 (2011)

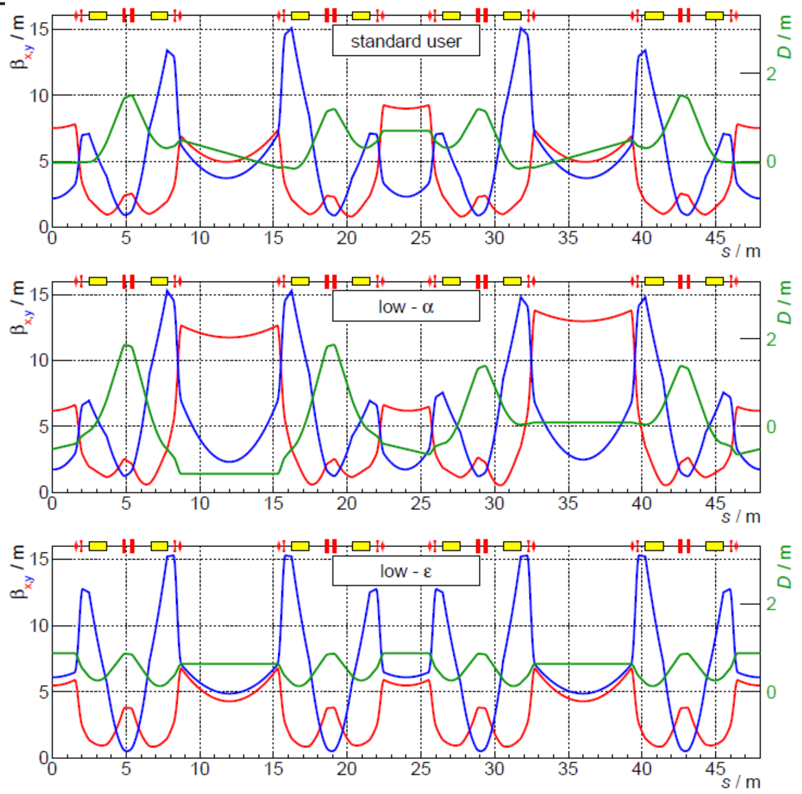
Metrology Light Source: The first electron storage ring optimized for generating coherent THz radiation

J. Feikes, M. von Hartrott, M. Ries, P. Schmid, and G. Wüstefeld*
Helmholtz-Zentrum Berlin (HZB), Albert-Einstein-Straße 15, 12489 Berlin, Germany

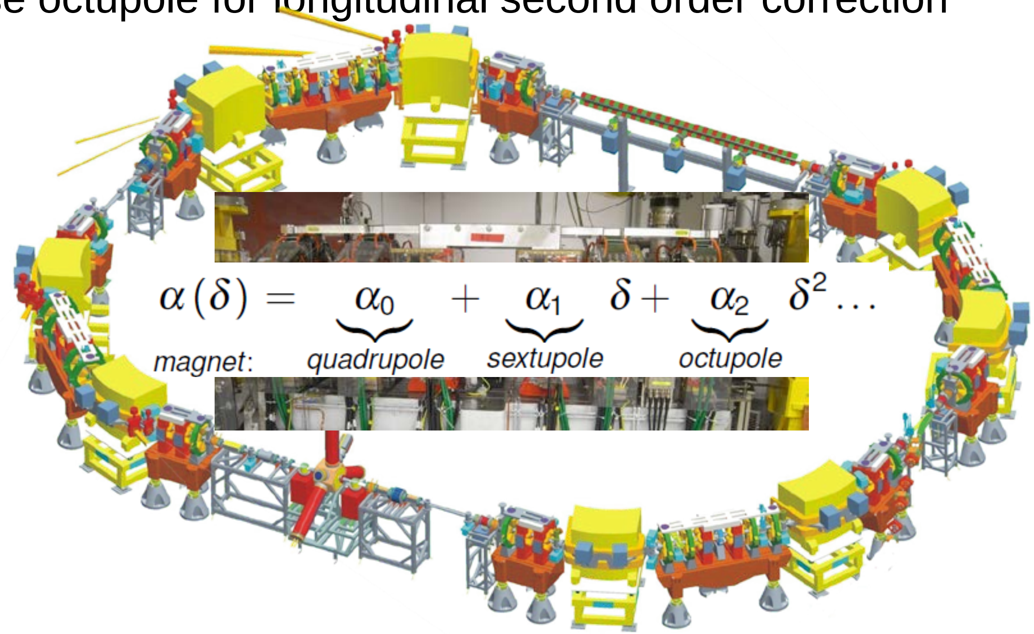
A. Hoehl, R. Klein, R. Müller, and G. Ulm
Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2-12, 10587 Berlin, Germany

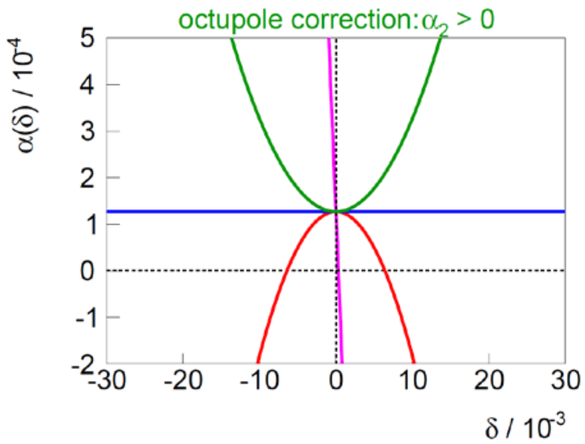
(Received 16 July 2009; published 22 March 2011)

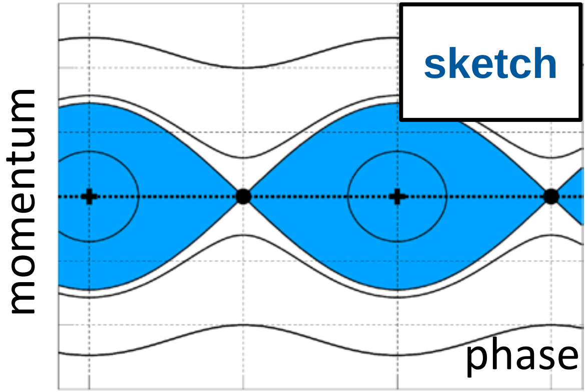




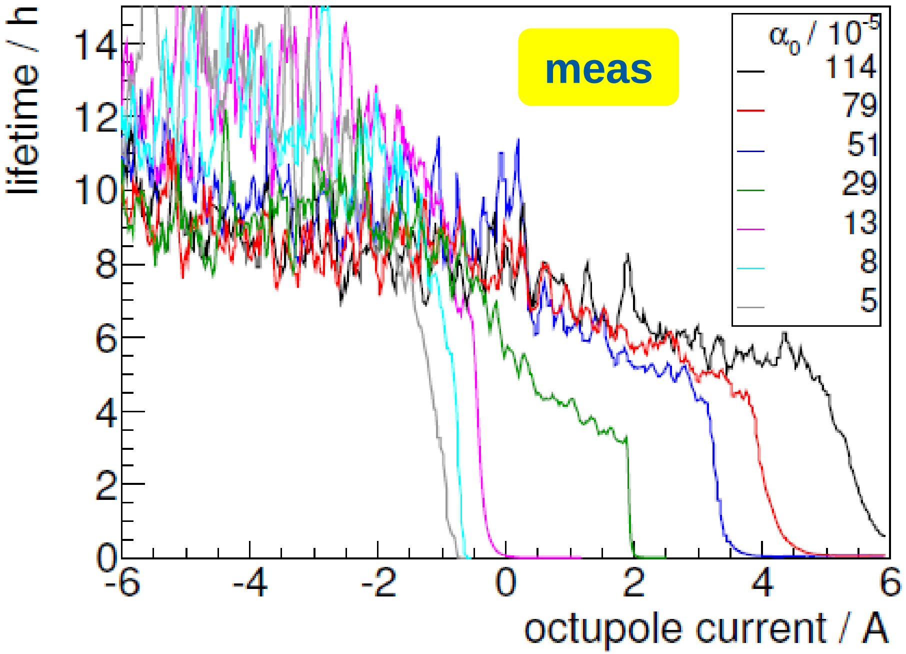
- additional families of sextupoles & octupoles
- carefully set up 3D chromaticities on optic ramp (while shortening the beam)
- use octupole for longitudinal second order correction



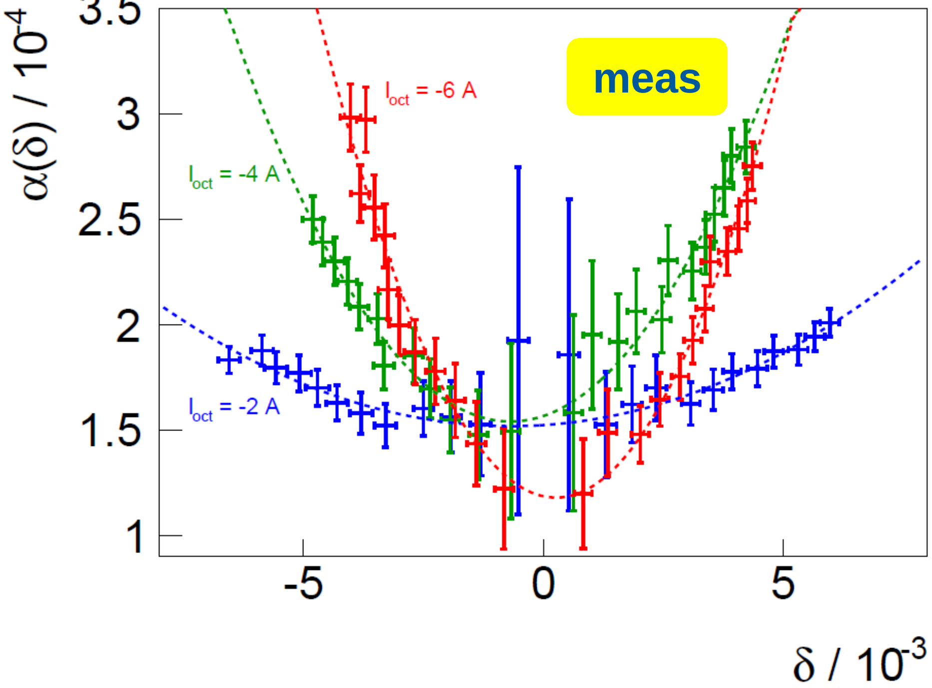




octupole relevance

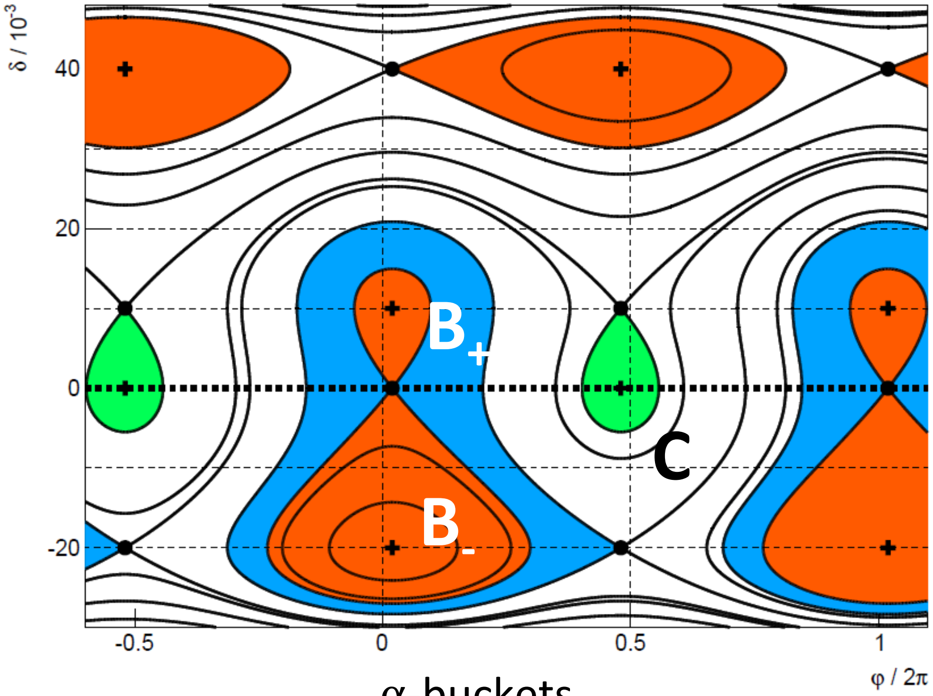


direct measurement of $\alpha(\delta)$ using Compton backscattering

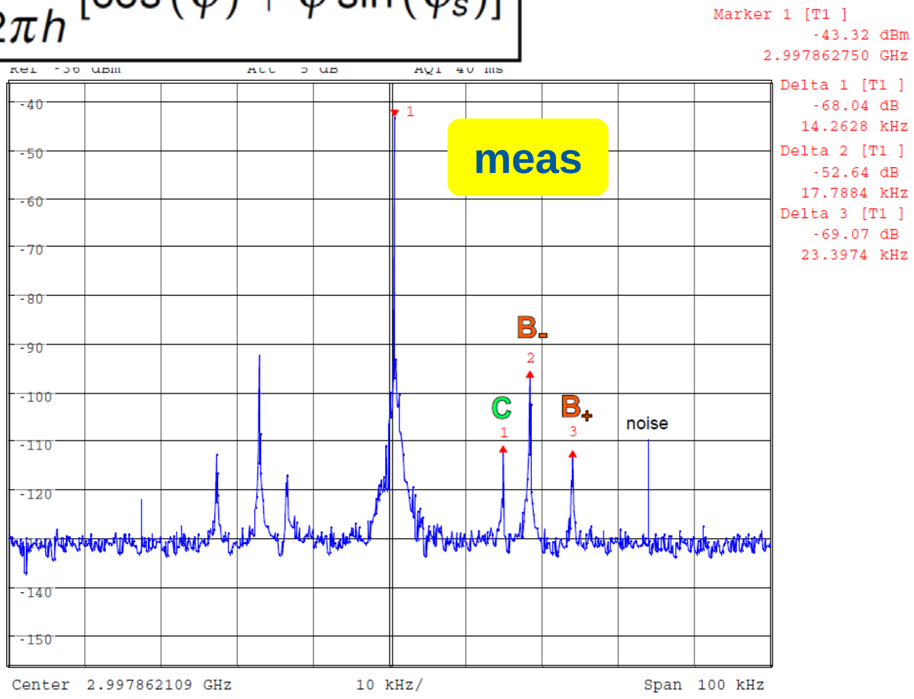


Controlling higher order momentum compaction at MLS

$$\mathscr{H}(\varphi,\delta) = -\beta_0^2 E_0 \int \alpha\delta \, \mathrm{d}\delta - \frac{eU}{2\pi h}\left[\cos(\varphi) + \varphi \sin(\varphi_s)\right]$$



α-buckets



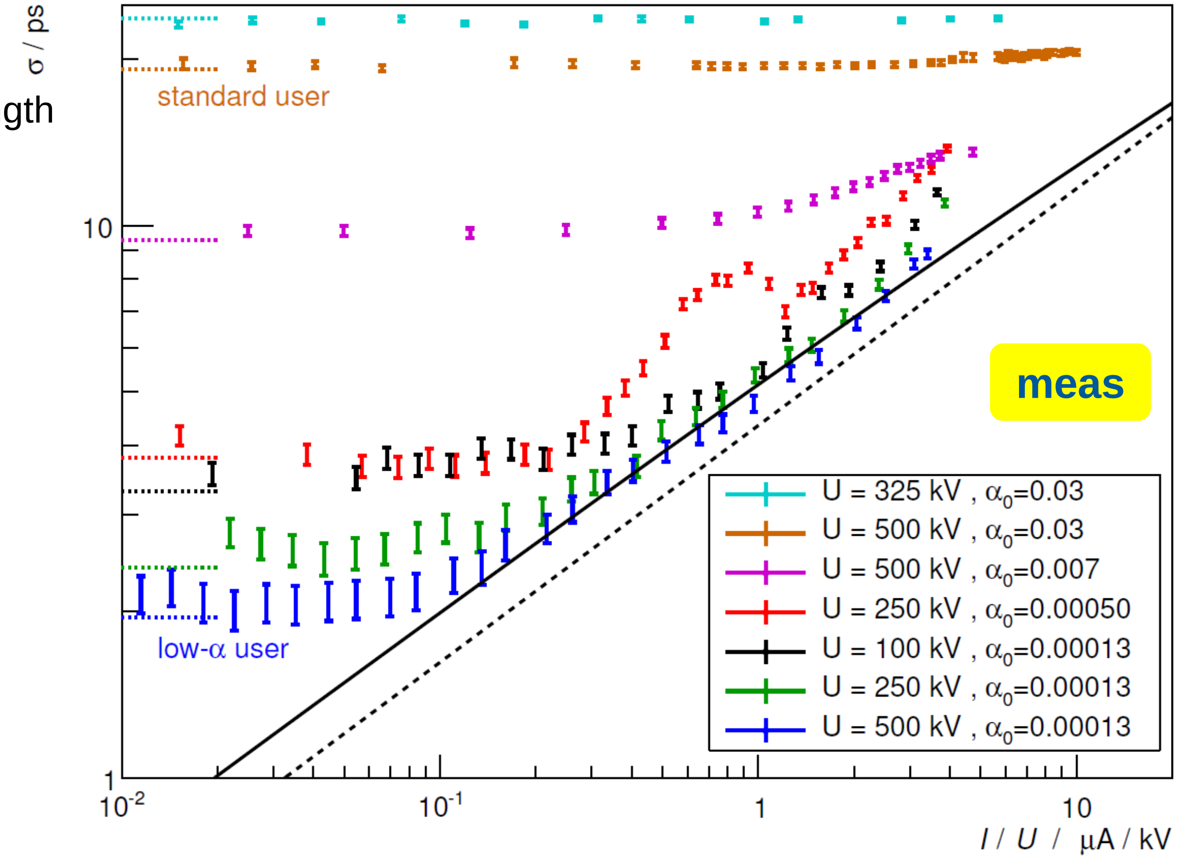
Bunch lengthening

- measurement of zero current bunch length agree well with simulations
- model of bursting is not too bad either

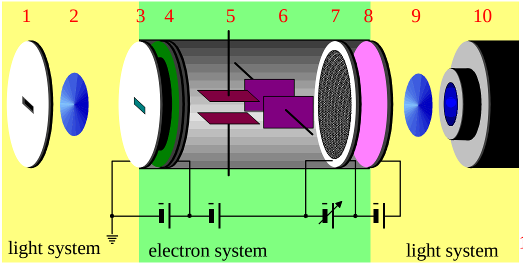
- better streak camera now

- small jitter
(for low-α purpose)

- strong excitation at 33 kHz
  - amplitude & phase
  - order of (0.5…1) ps (rms)



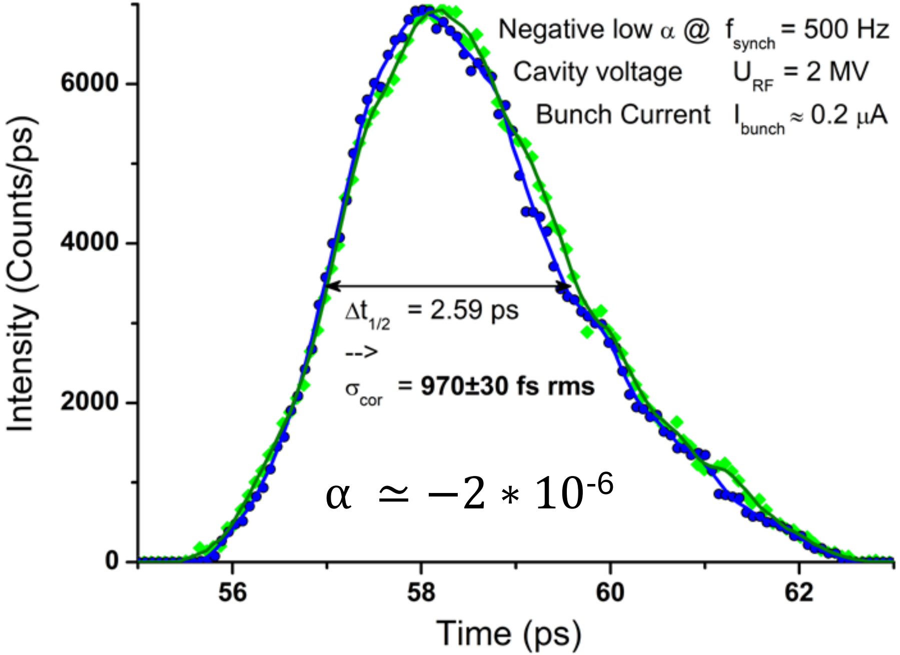
Streak Camera Principle



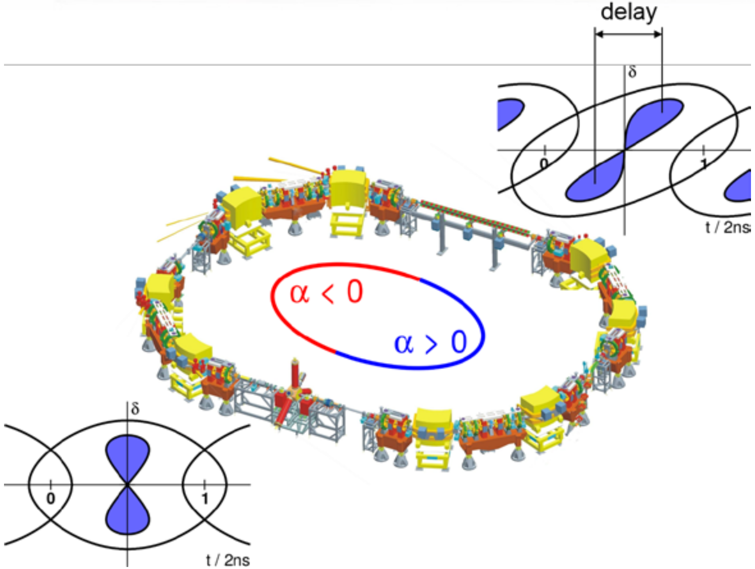
1 – entrance slit
2 – input optics
3 – photo cathode
4 – acceleration plus focussing electrode
5 – vertical sweep
6 – horizontal sweep
7 – Multi-Channel Plate
8 – phosphor screen
9 – output optics
10 – CCD camera

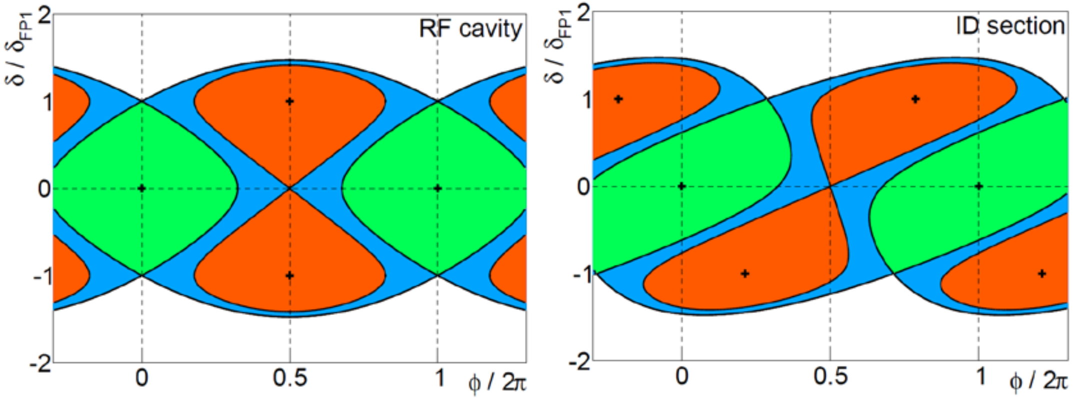
Fast Streak Camera (HAMAMATSU) with

- t vs x mode
- improved toroidal mirror
- improved 125 MHz generation (OPTRONIS)

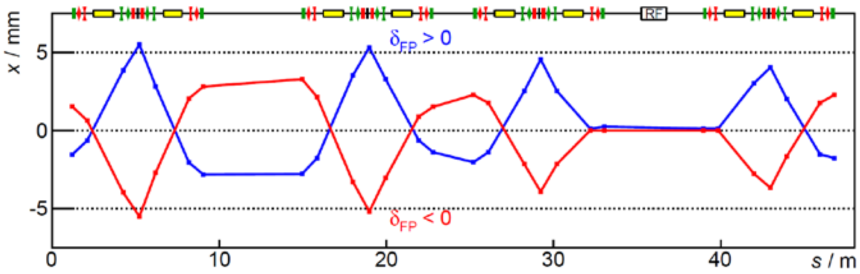


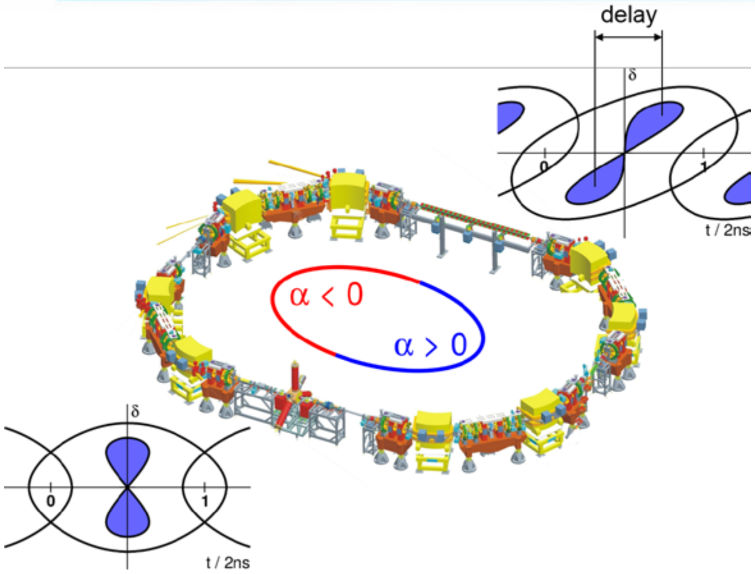
delayed alpha buckets… second encounter with partial mom. comp.

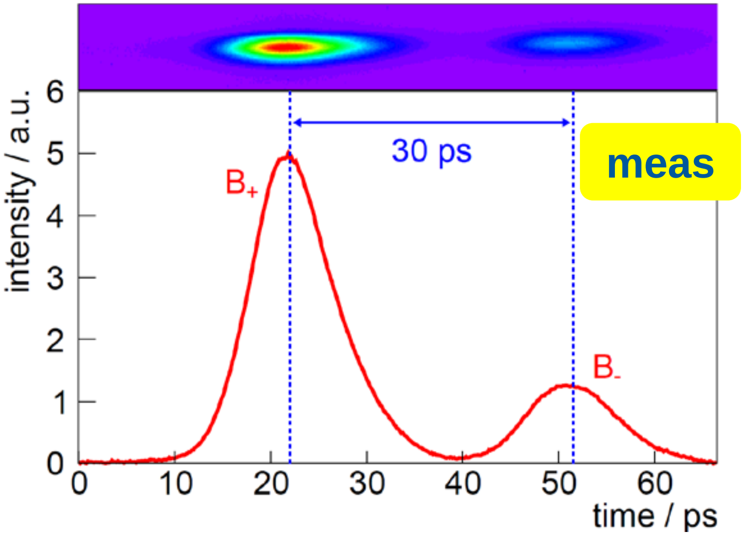


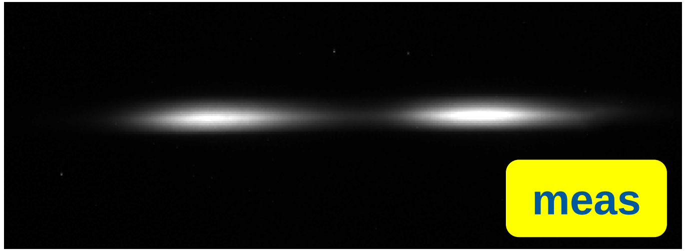


- based on alpha buckets / nonlinear longitudinal beam dynamics
- idea: make both buckets race each other
- alpha buckets need to be in the RF cavity at the same time(diff. ene
- breaking longitudinal symmetry of the ring
- low-α lattice (on average!)
- large partial momentum compaction of different signs in both halves









- delay is tunable
- accessible bunch length range corresponds to low-alpha range (factor $\sqrt{2}$ due to α-buckets)
- only THz usage so far

FEMTO SLICING

FemtoSpeX: a versatile optical pump–soft X-ray probe facility with 100 fs X-ray pulses of variable polarization

K. Holldack et al., J. Synchrotron Rad. (2014). 21, 1090–1104

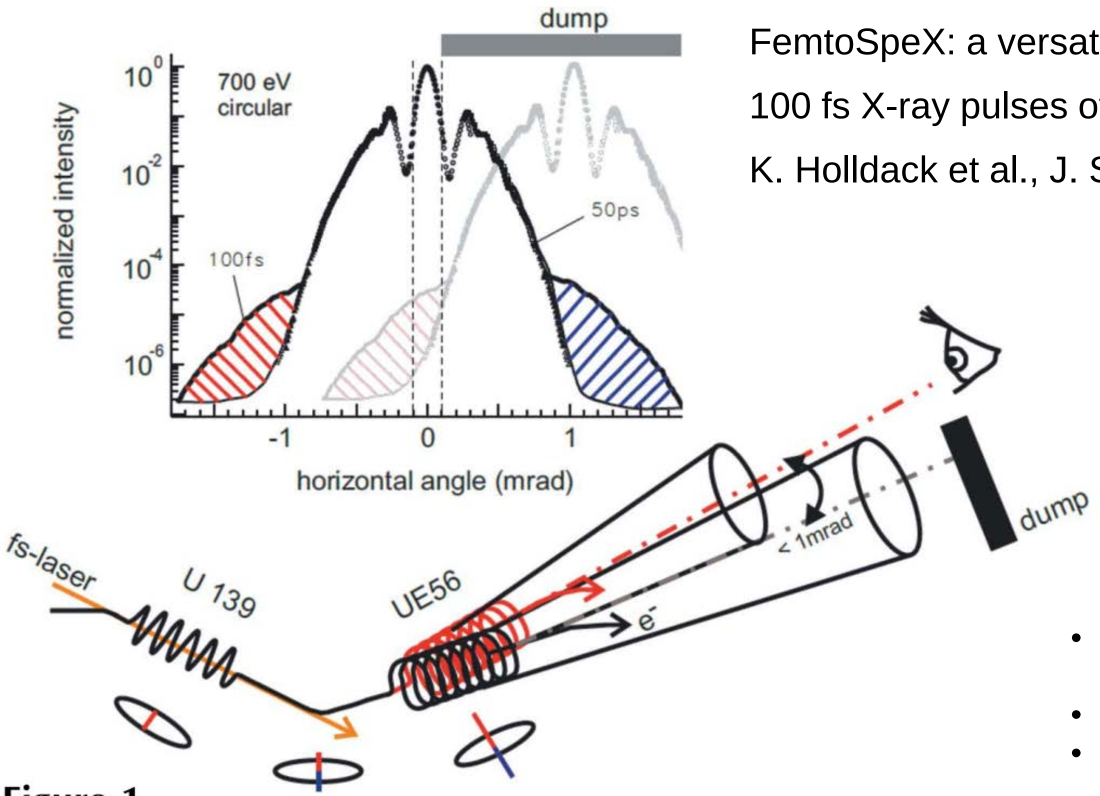
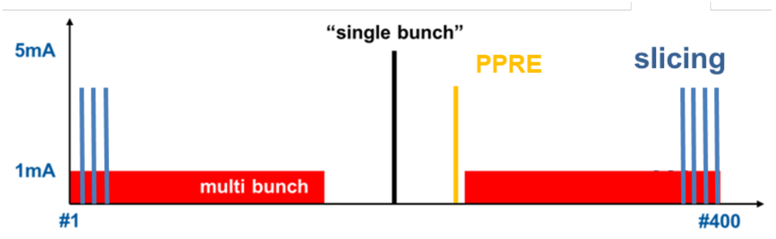


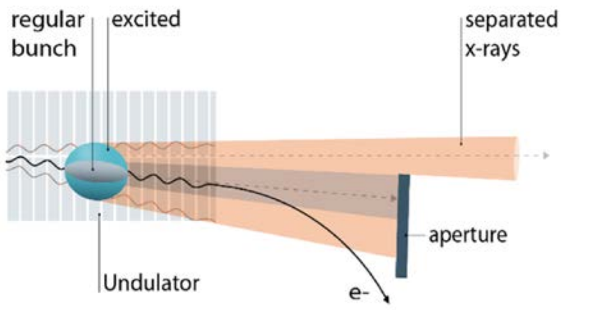
Figure 1

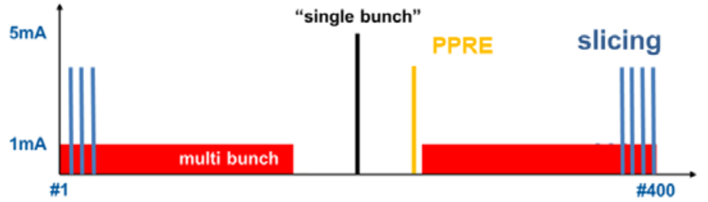
Principle of femtoslicing at BESSY II. After being laser-energy



- Laser @ 6 kHz jumping over 7 bunches with 3 mA stored beam current each
- Laser pulse length ~ 100 fs FWHM
- ~1 % energy modulation

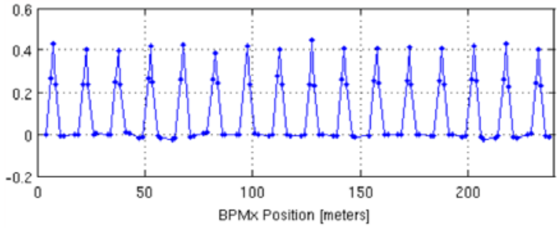
PPRE in normal user operation and in low alpha

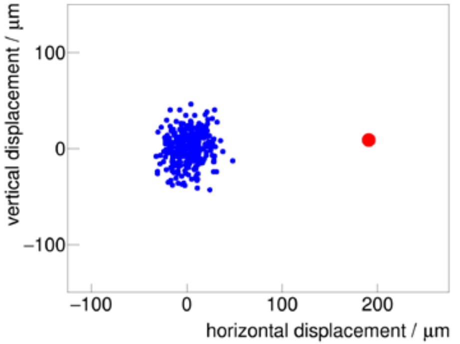




- normal operation: couple hor and long plane and blur the hor emittance of a single bunch
- fundamentally different principle than in high alpha
  - transverse coherent motion leads to path lengthening
  - matching to revolution frequency leads to energy shift
  - Dispersive orbit lead to beam separation

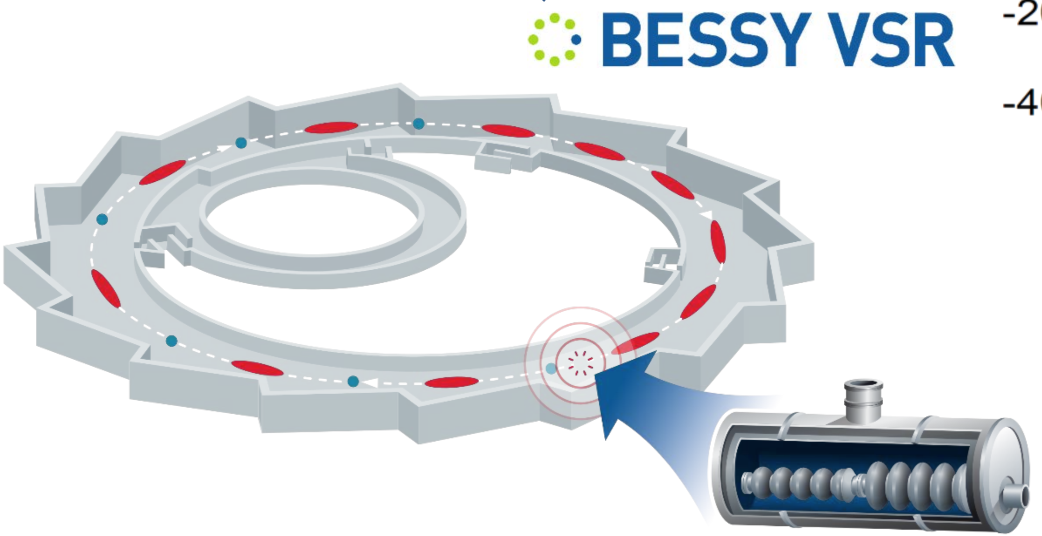
$$\frac{\Delta L}{L_0} = \alpha \frac{\Delta p}{p_0}$$

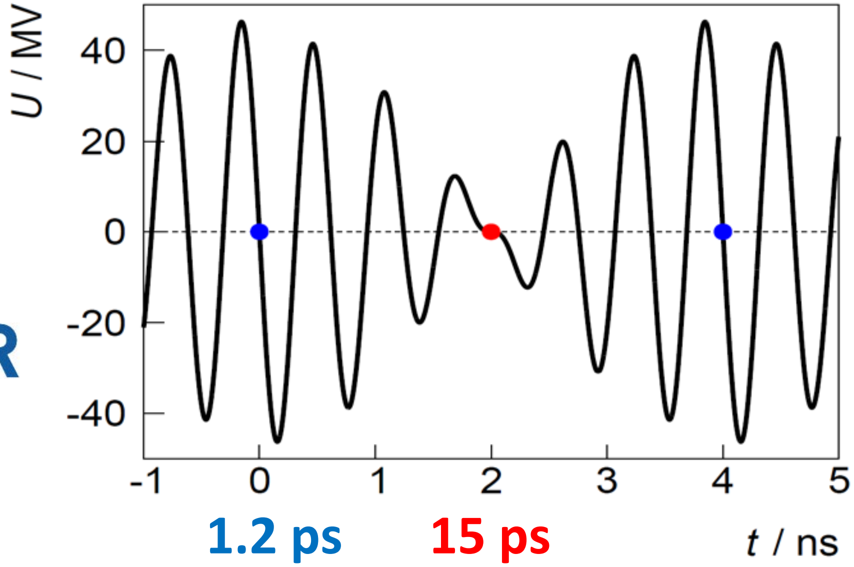




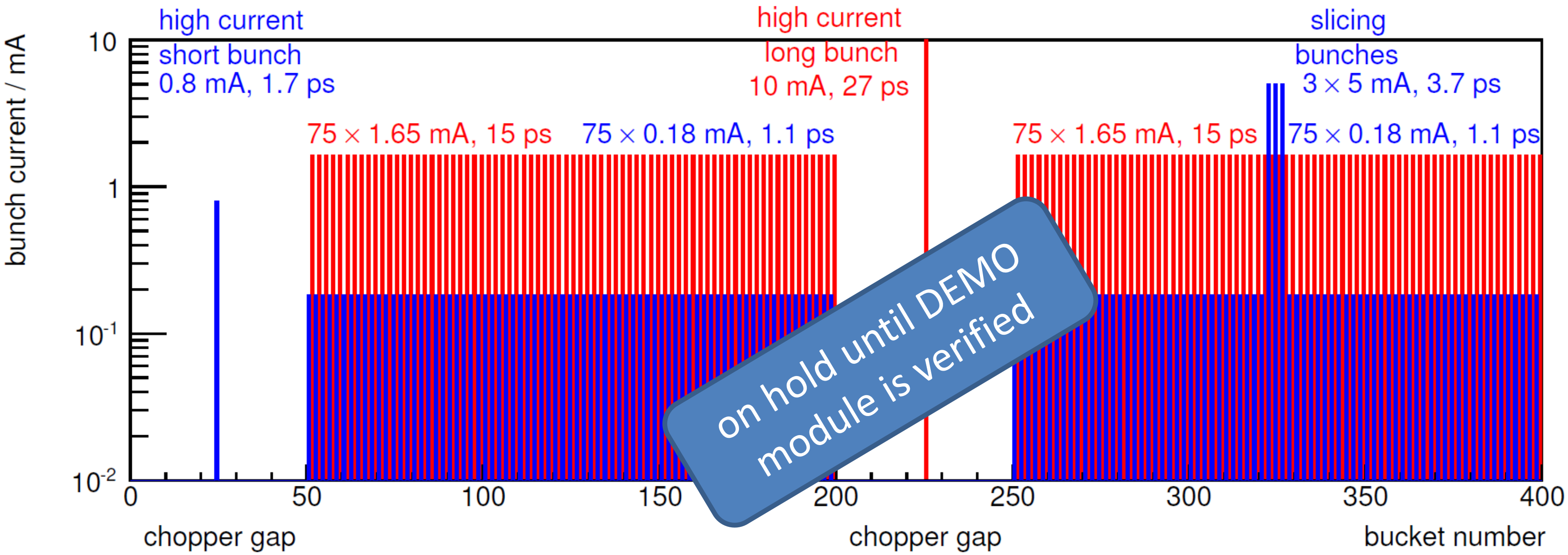
$$\text{bunchlength} \sim \sqrt{\frac{\alpha}{U'}}$$

low-α

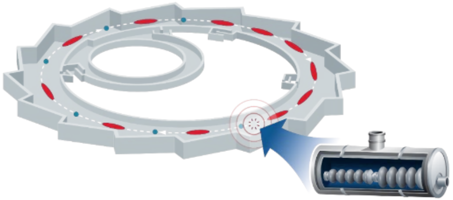




NC module: 500 MHz, 1.5 MV
SC modules: 1.5/1.75 GHz, 20/17 MV



- charge variation ~ x 50
- charge density variation ~ x 10
- uncharted territory included



NC ACTIVE HOM-DAMPED HARMONIC CAVITIES

HZB Helmholtz Zentrum Berlin

ALBA

HZB Helmholtz Zentrum Berlin

DESY.

EUROPEAN UNION
European Regional Development Fund

SUPRALAB@HZB

BESSY II

LEAPS

PTB
Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

MLS II
MLS
BESSY II
BESSY III

HZB Helmholtz Zentrum Berlin

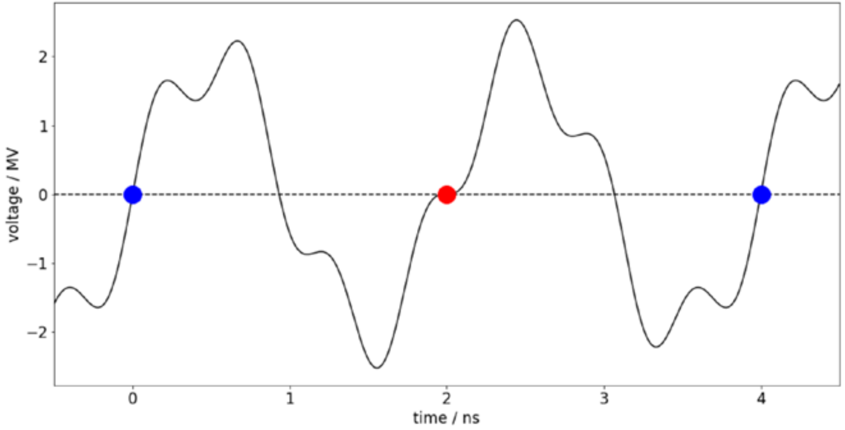
harmonic cavities as technological basis for bunch length control required in 4^{th} generation storage rings

→ increasing the pulse length by factors to the scale of 100 ps

→ Active cavities may mitigate the impact of complex filling patterns

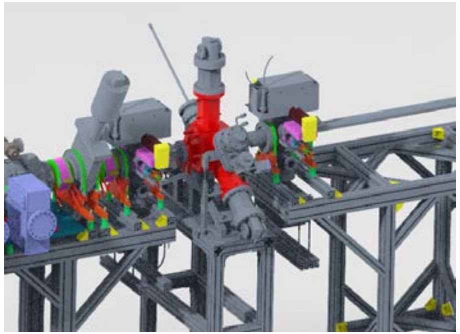
NC ACTIVE HOM-DAMPED HARMONIC CAVITIES

- rescale existing harmonic NC cavities to 1.75 GHz
- generate beating between fundamental 500 MHz and 3.5th harmonic
- preserve the option for ps-scale pulse lengths while providing the required bunch lengthening option for 4th generation storage rings



→ prototype could be tested and applied at BESSY II

→ Upon implementation would deliver something like 7 ps & 35 ps simultaneously



OUTLOOK

- low-alpha operation challenges gained interest in recent years fueled in particular by design of DLSR
- resolve seemingly conflicting measurement results

- short x-ray pulses ~ ps seem to be interesting -> there is a timing community

- BESSY III CDR → how low is alpha allowed to be for reasonable
- How to design MLS2 in the light of low-alpha / low-emittance / SSMB?

- Synchrotron oscillation in optical bucket ;)

ACKNOWLEDGEMENT

Backup

24

nonlinear momentum compaction factor

- $\alpha \rightarrow$ change of orbit length with respect to the momentum deviation $\delta = \frac{\Delta p}{p_0}$, $\frac{\Delta L}{L_0} = \alpha\delta$
- α is one of the parameters that determine the bunch length

$$\sigma \propto \sqrt{\frac{E\alpha{\delta_0}^2}{U}}$$

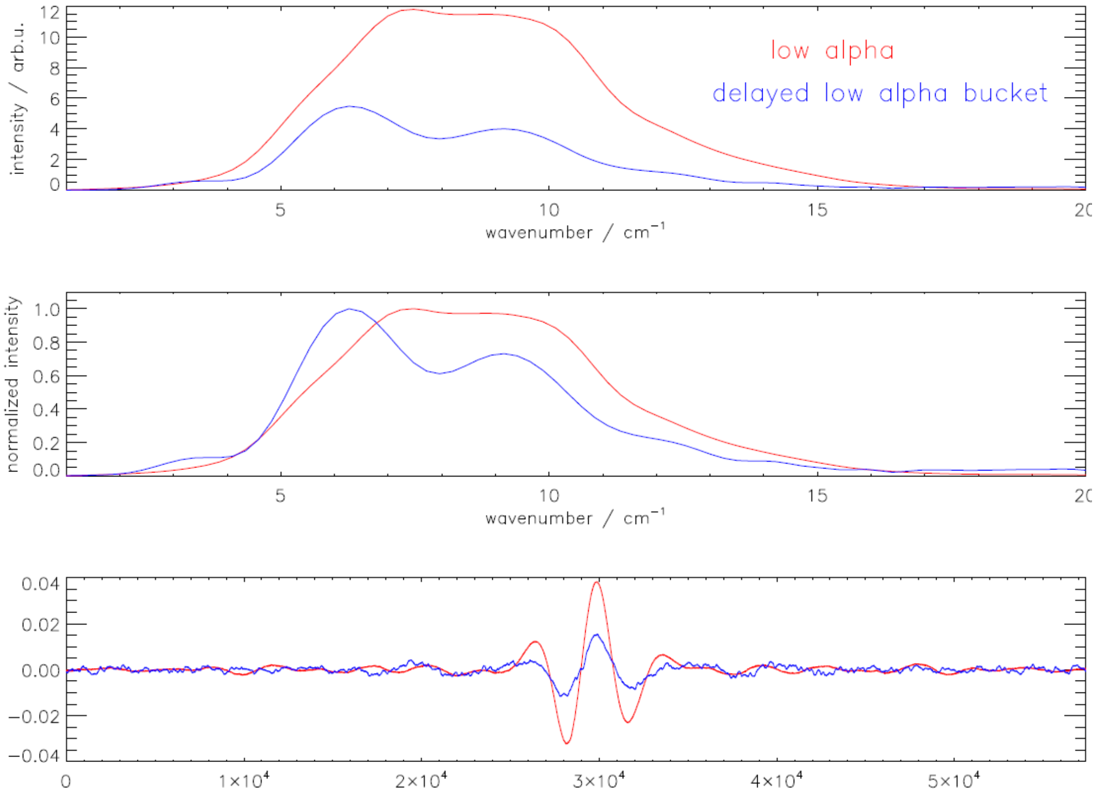
- α itself can be momentum dependent

$$\alpha(\delta) = \underbrace{\alpha_0}_{\text{quadrupole}} + \underbrace{\alpha_1}_{\text{sextupole}}\delta + \underbrace{\alpha_2}_{\text{octupole}}\delta^2 \ldots$$

magnet: quadrupole, sextupole, octupole

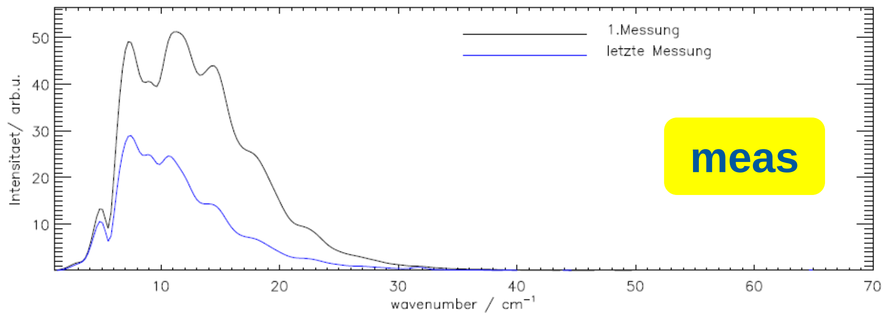
- higher orders are important for quasi-isochronous optics

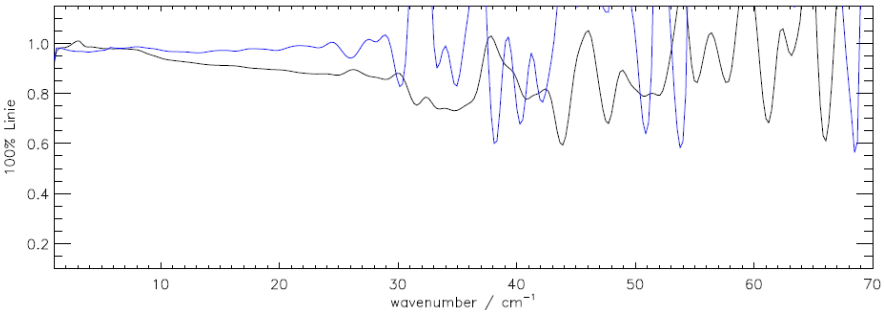
DELAYED ALPHA BUCKETS – THZ SPECTRA



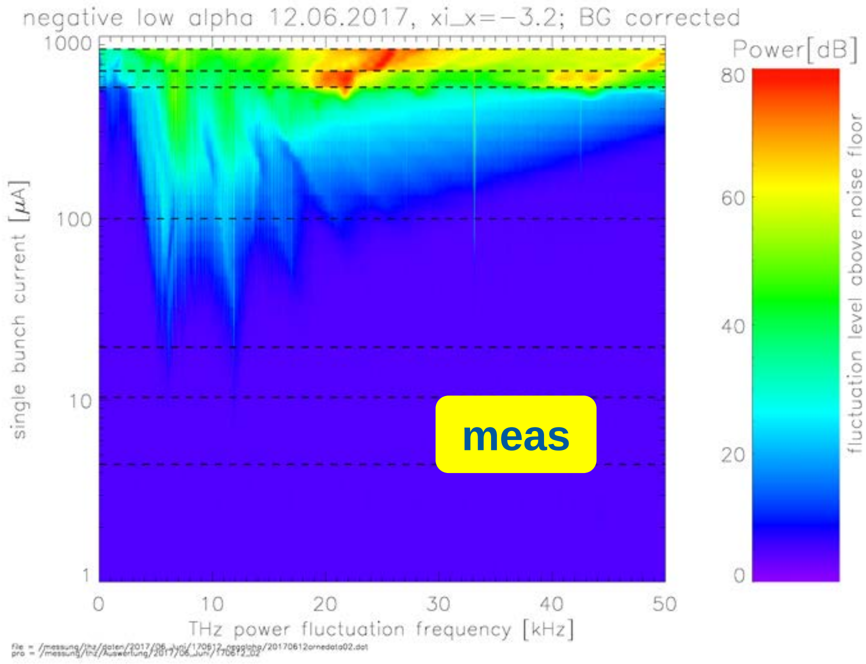
Bursting

THz spectra

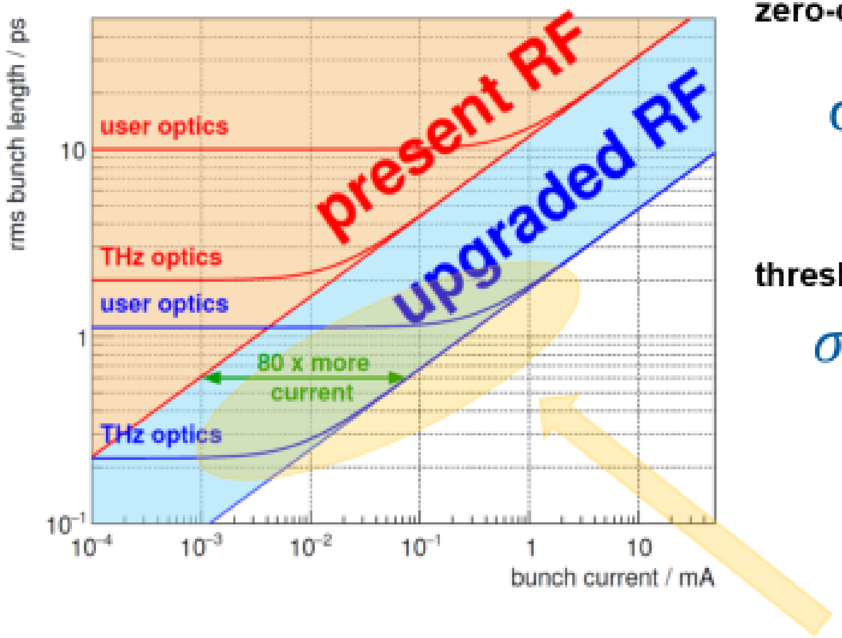




temporal fluctuations



CSR DRIVEN INSTABILITY THRESHOLD



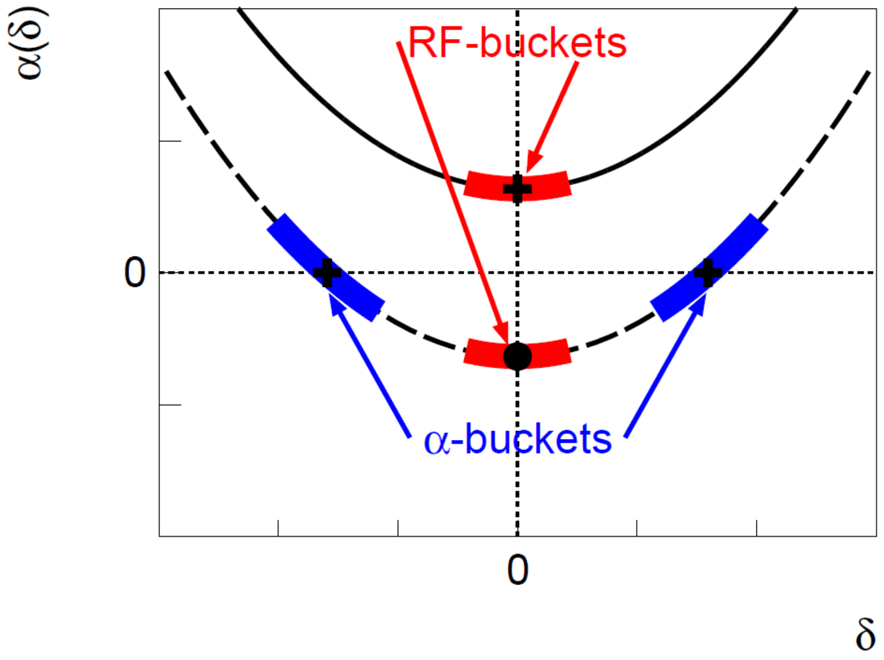
zero-current bunch length

$$\sigma_0 \sim \sqrt{\frac{\alpha}{U}}$$

threshold current scaling:

$$\sigma = \text{const.}$$
$$\rightarrow I_{th} \sim \alpha$$

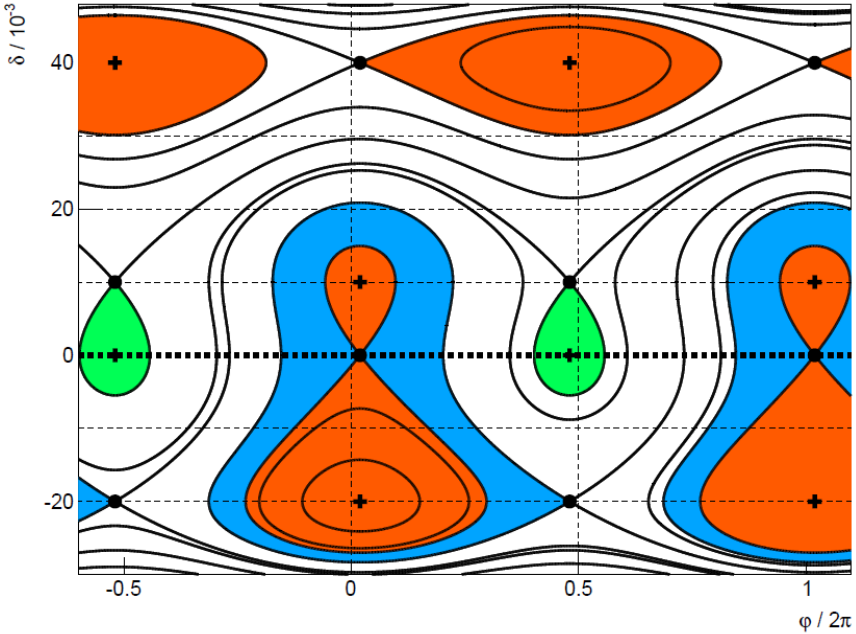
uncharted territory included !

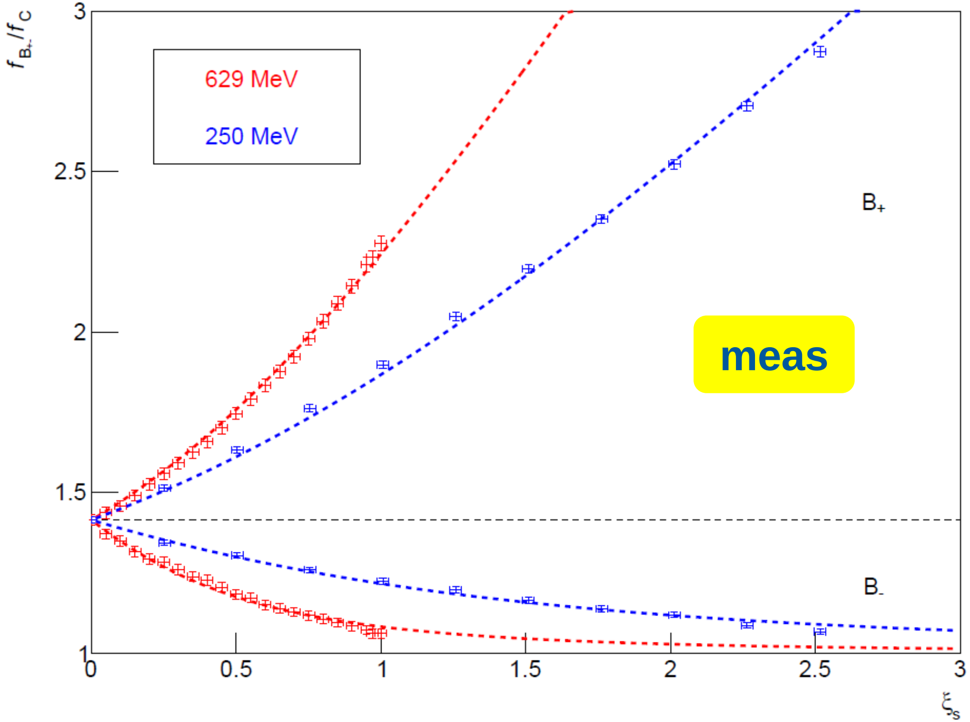


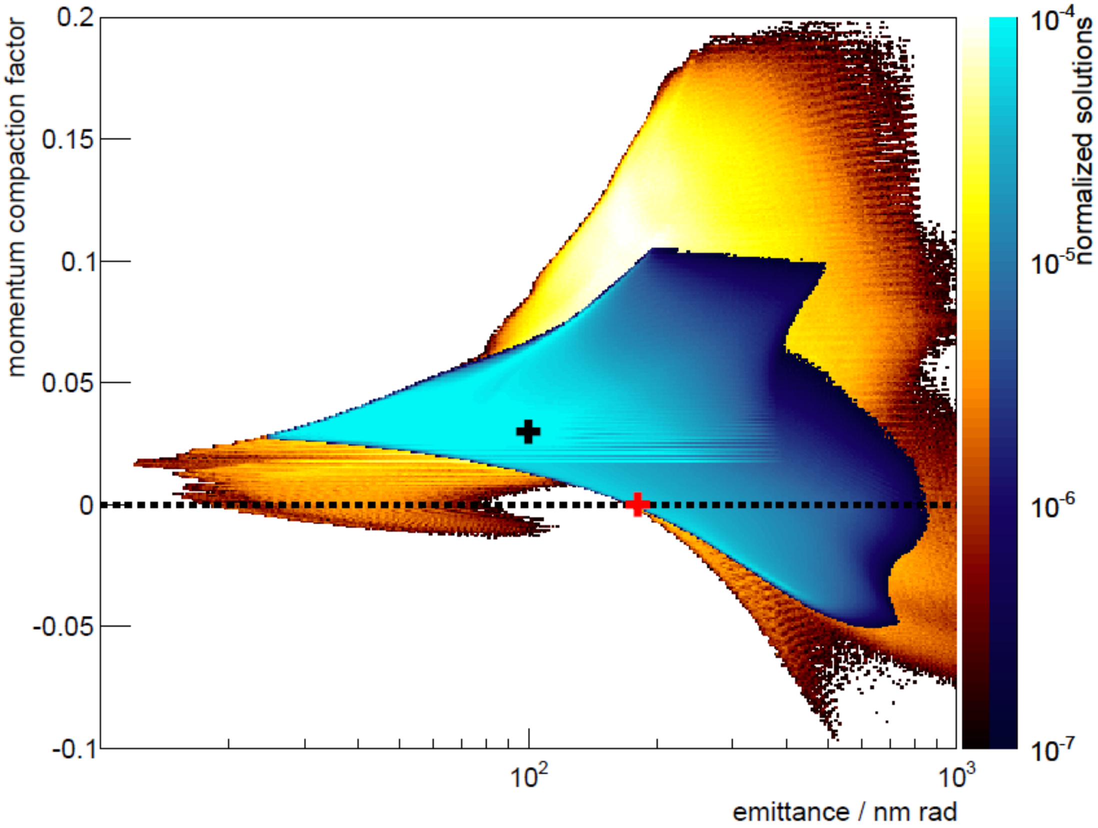
$$\alpha(\delta) = \alpha_0 + \alpha_1 \delta + \alpha_2 \delta^2 \ldots$$

$$\frac{\Delta\varphi}{\text{turn}} \approx 2\pi h \alpha \delta$$

Asymmetric α-Buckets: Tunes







momentum compaction factor
0.2
0.15
0.1
0.05
0
-0.05
-0.1
10^2
10^3
emittance / nm rad
normalized solutions
10^{-4}
10^{-5}
10^{-6}
10^{-7}

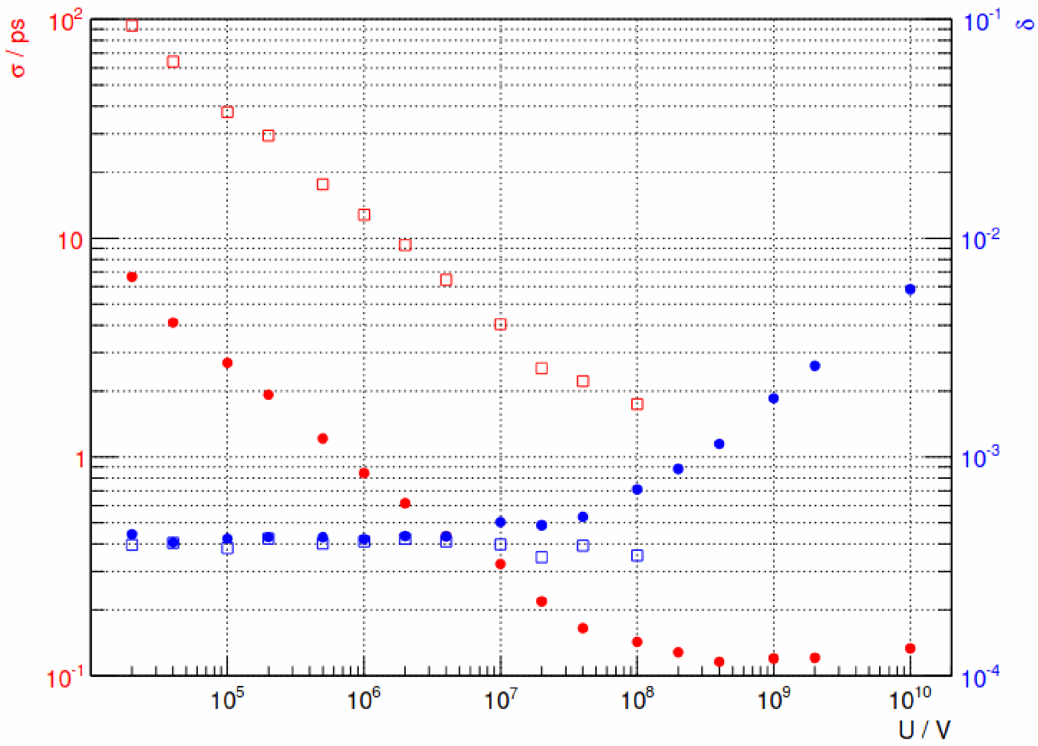
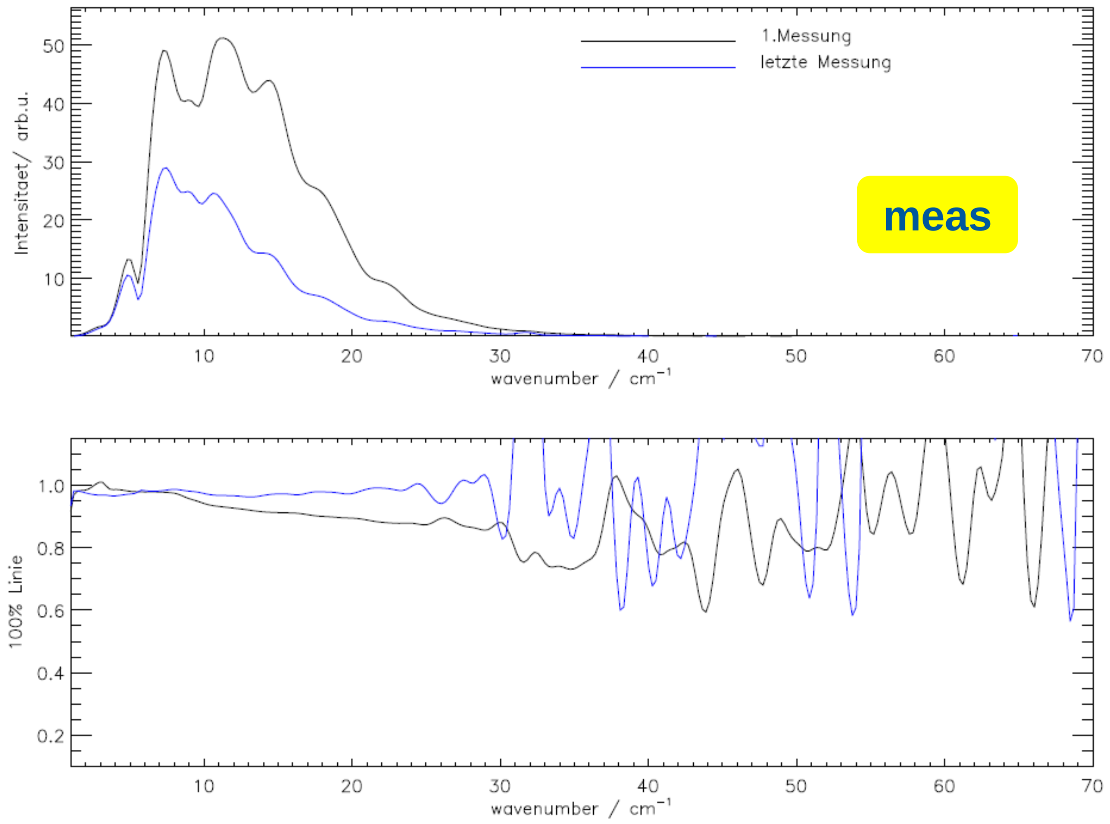


Figure 3.17: Tracked bunch length (red) and energy spread (blue) as a function of RF cavity voltage at the MLS. Tracking was done for the standard user mode (hollow squares, $\alpha_0 = 0.03$) and for low alpha user operation $\alpha_0 = 1.3 \times 10^{-4}$ (dots).



1.Messung
letzte Messung
meas
Intensitaet/ arb.u.
50
40
30
20
10
10
20
30
40
50
60
70
wavenumber / cm⁻¹
1.0
0.8
0.6
0.4
0.2
100% Linie
10
20
30
40
50
60
70
wavenumber / cm⁻¹

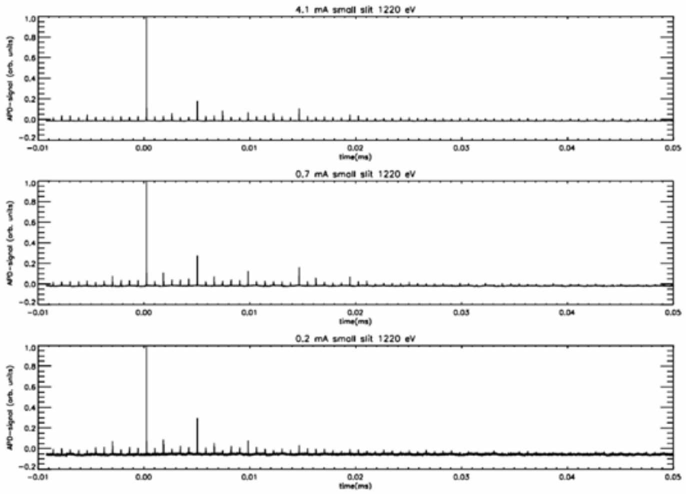


Fig. 4: Evolution of the halo signal normalized to the fs-signal at 1221 eV during the first few turns after the initial energy modulation for different bunch currents (0.2-4.1 mA) in the slicing bunches.

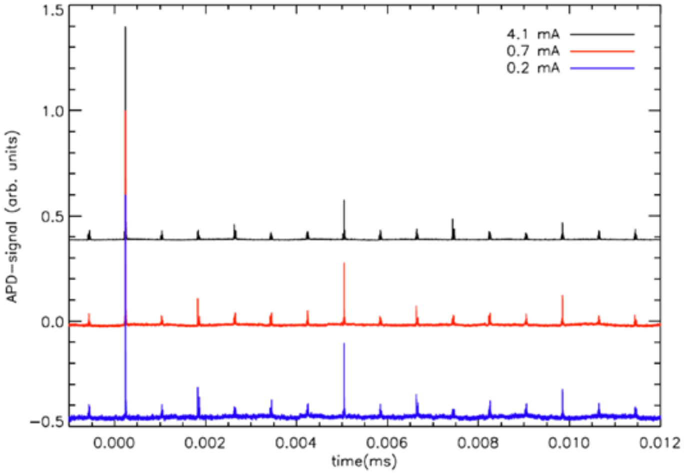
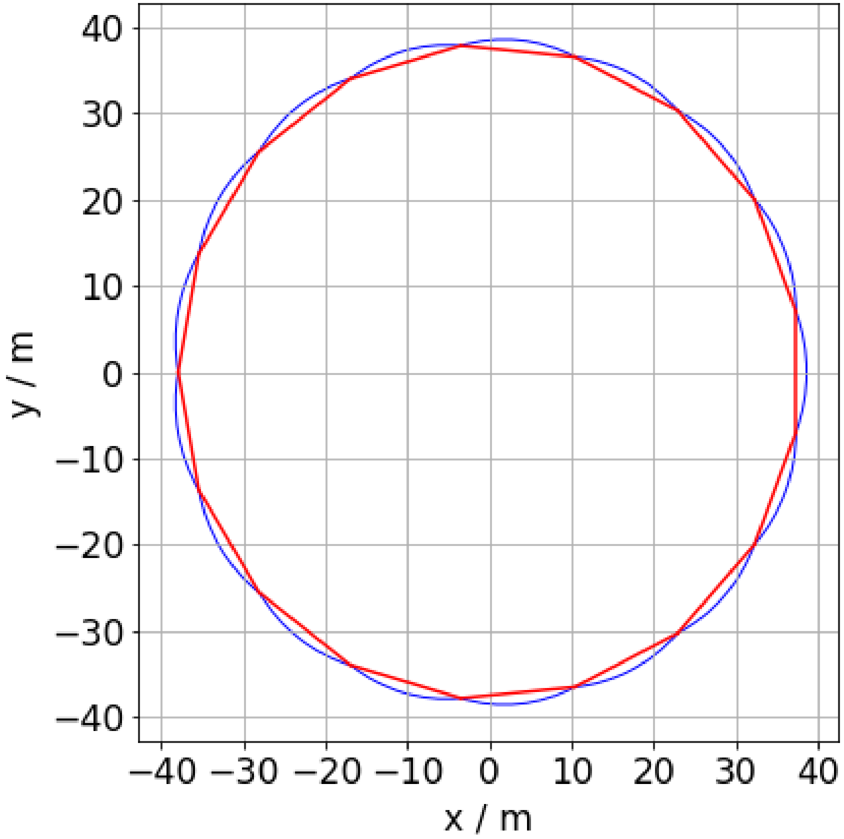


Fig. 5: Evolution of the halo signal at 1221 eV during the very first few turns after the initial energy modulation for different bunch currents (0.2-4.1 mA) in the slicing bunches. At higher bunch charge (4.1 mA) there is a slightly better short term damping of the Betatron-oscillation than at low bunch charge (0.2 mA).



N = 17

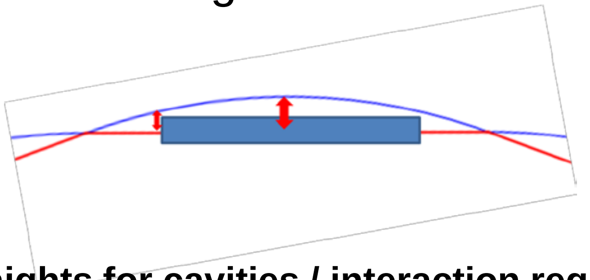
Circ = 240m (473m)

Nstraights = 17

Lstraight ~ 14m (10m usable?)

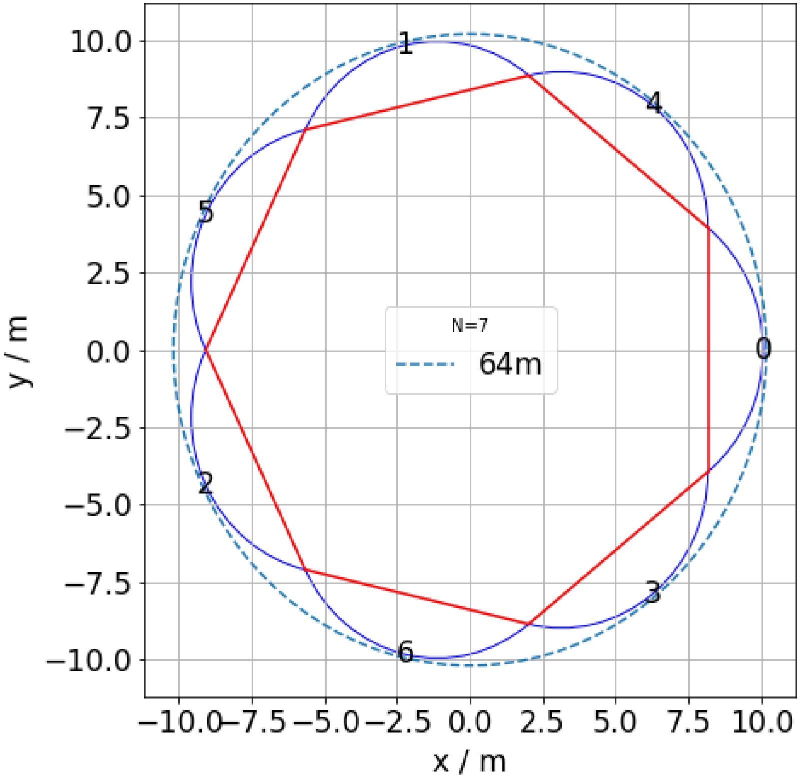
Larc ~ 14m

max. arc-straight distance = 1.3 m



- **More straights for cavities / interaction regions**

36



N = 7

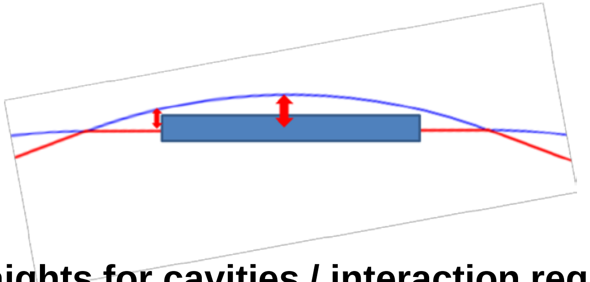
Circ = 64m (126m)

Nstraights = 7

Lstraight ~ 8m (5m usable?)

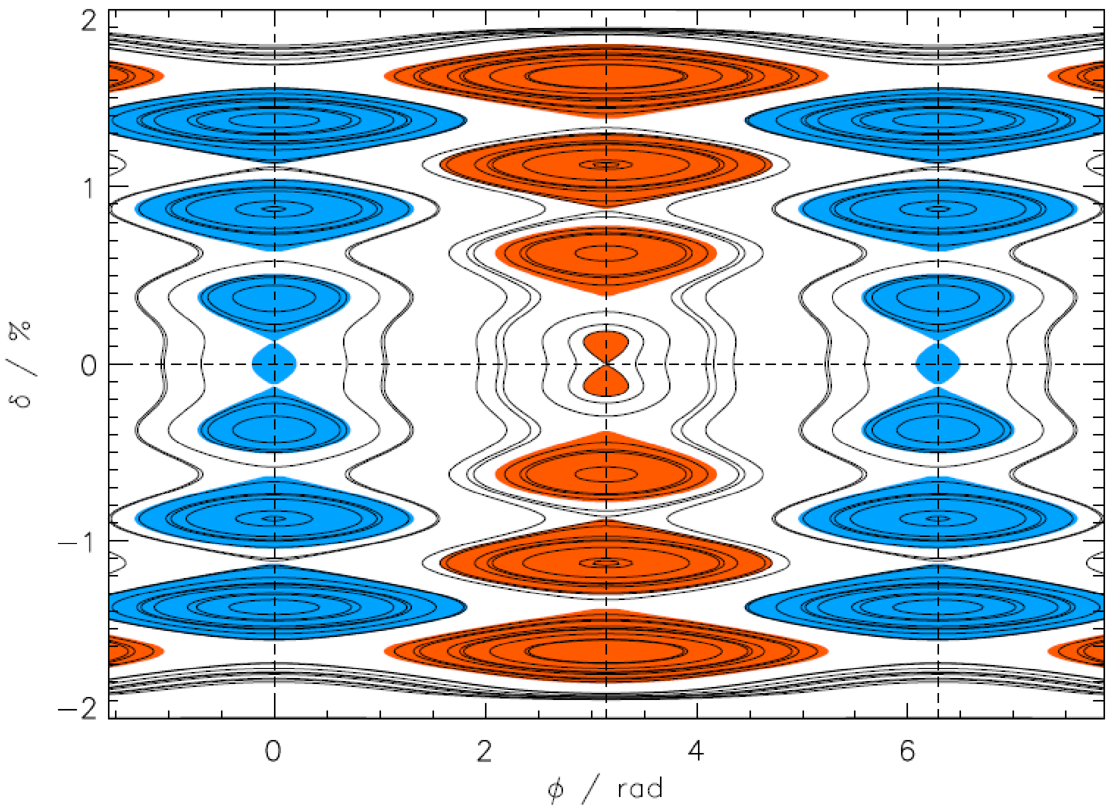
Larc ~ 9m

max. arc-straight distance = 1.9 m



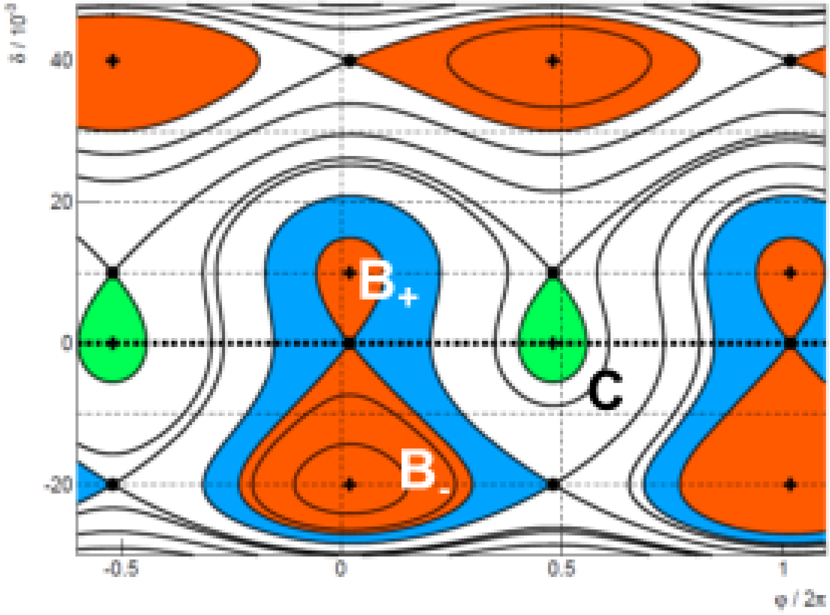
More straights for cavities / interaction regions

PERIODIC MOMENTUM COMPACTION FUNCTION

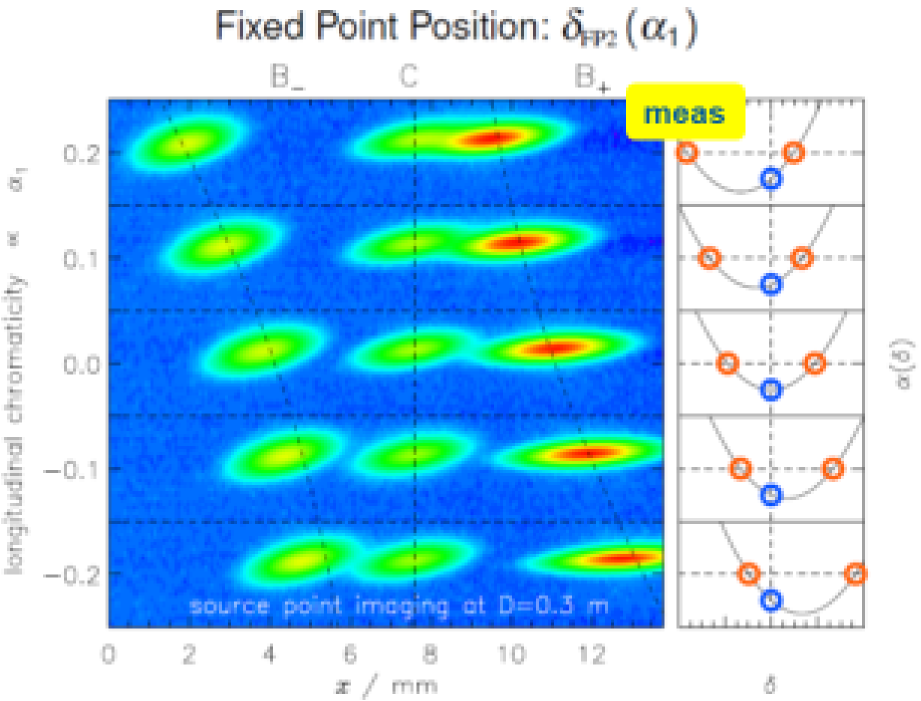


DYNAMICS DOMINATED BY NONLINEAR MOMENTUM COMPACTION

$$\mathscr{H}(\varphi, \delta) = -\beta_0^2 E_0 \int \alpha\delta \, \mathrm{d}\delta - \frac{eU}{2\pi h}\left[\cos(\varphi) + \varphi \sin(\varphi_s)\right]$$

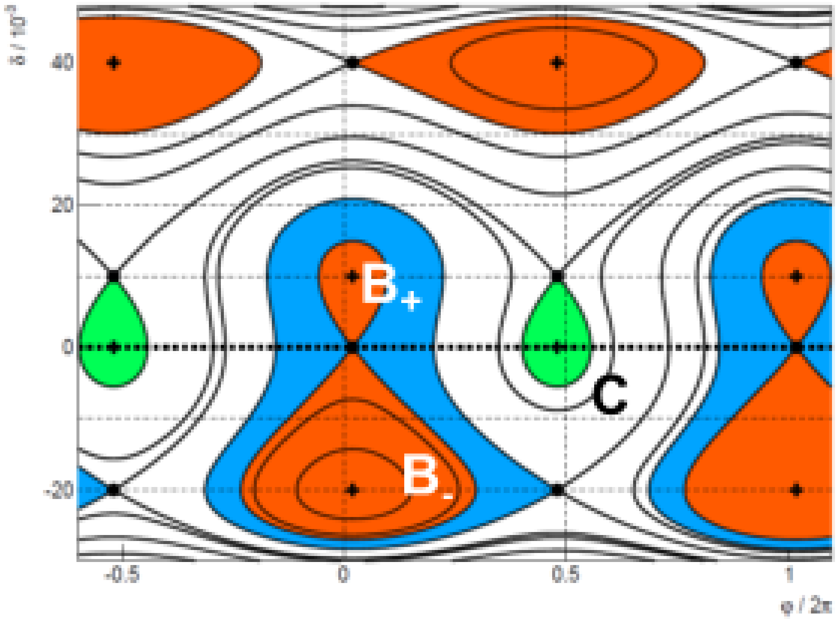


α-buckets

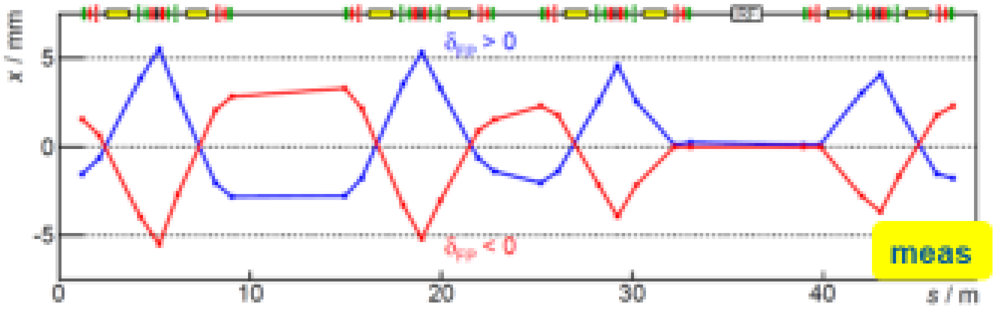


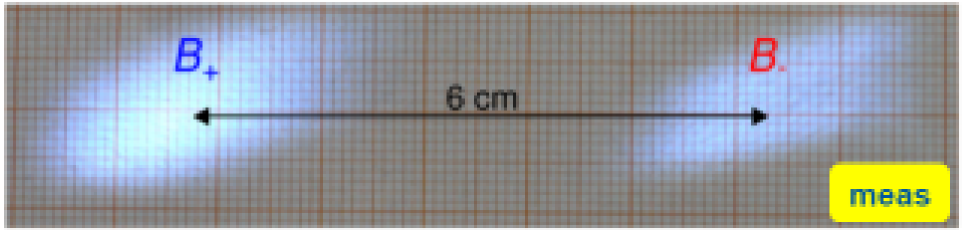
DYNAMICS DOMINATED BY NONLINEAR MOMENTUM COMPACTION

$$\mathscr{H}\left(\varphi,\delta\right) = -\beta_0^2 E_0 \int \alpha\delta \, \mathrm{d}\delta - \frac{eU}{2\pi h}\left[\cos\left(\varphi\right) + \varphi \sin\left(\varphi_s\right)\right]$$



α-buckets





short and long term stability comparable
to regular RF-bucket operation