Simultaneous Long and Short Bunch Operation in an Electron Storage Ring – a Hybrid Mode based on Nonlinear Momentum Compaction

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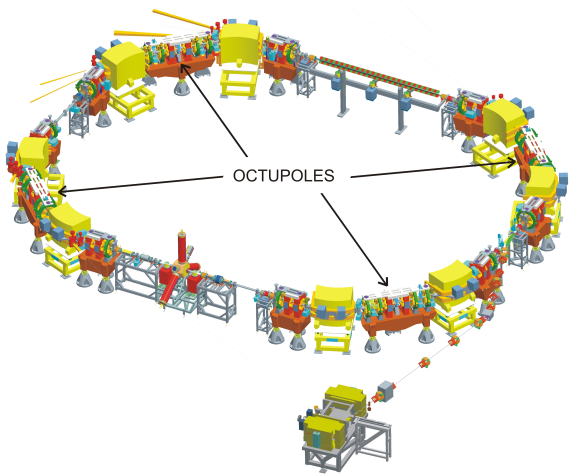
α-buckets in action

$E = 630$ MeV $\qquad I = 160$ mA $\qquad \tau \approx 6h$

real time source point imaging (synchrotron radiation)

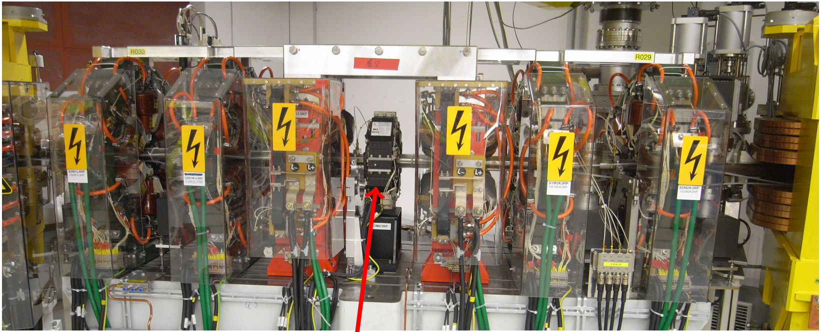
Metrology Light Source (MLS)

MLS owned by the Physikalisch-Technische Bundesanstalt (PTB), Germany



- $2\pi R = 48$ m
- $E_e = 105 \ldots 630$ MeV
- $\delta_0 = 0.7 \cdot 10^{-4} \ldots 4.2 \cdot 10^{-4}$
- $\tau_{\rm damp} = 5$ s $\ldots 5$ ms
- $|\alpha| = 1 \cdot 10^{-5} \ldots 7 \cdot 10^{-2}$
- $f_{\rm RF} = 500$ MHz
- $V_{\rm RF} = 500$ kV

octupole setup



octupole

nonlinear momentum compaction factor α

- $\alpha \rightarrow$ change of orbit length with respect to the momentum deviation $\delta = \dfrac{\Delta p}{p_0}$

$$\frac{\Delta L}{L_0} = \alpha \frac{\Delta p}{p_0} + \ldots \approx \alpha\delta$$

- α itself can be momentum dependent

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

- higher orders are important for quasi-isochronous optics

simplified longitudinal Hamiltonian

$$\mathscr{H}(\phi,\delta) = 2\pi q f_{\mathrm{rev}} \left(\frac{\alpha_0}{2} + \frac{\alpha_1}{3}\,\delta + \frac{\alpha_2}{4}\,\delta^2 \ldots \right) \delta^2 + \frac{eU_0 f_{\mathrm{rev}}}{\beta^2 E_0} \cos(\phi)$$

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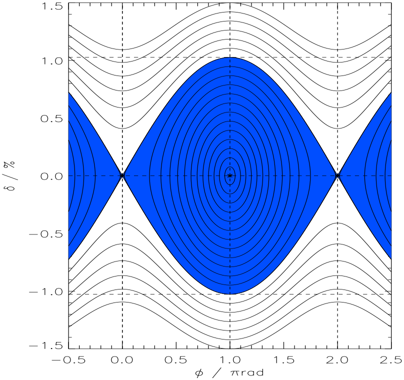

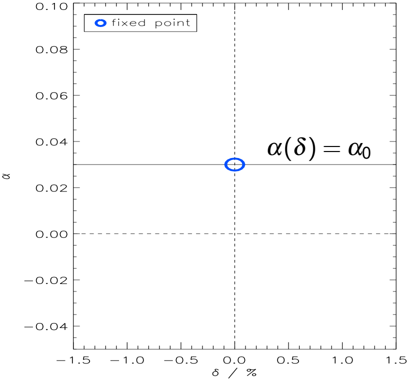

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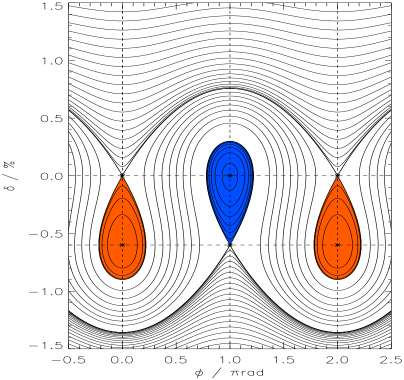

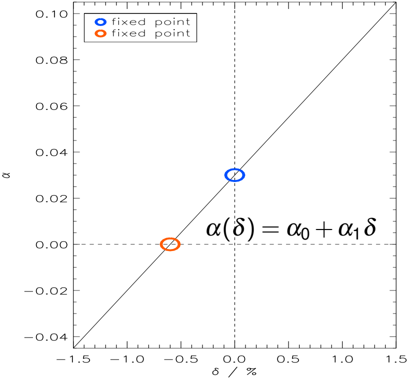

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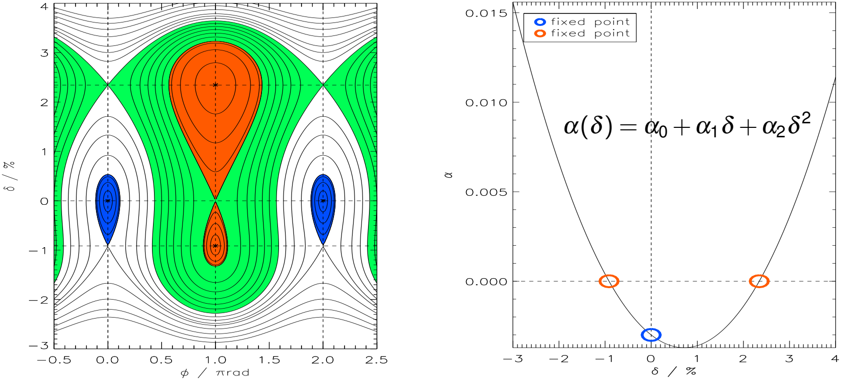
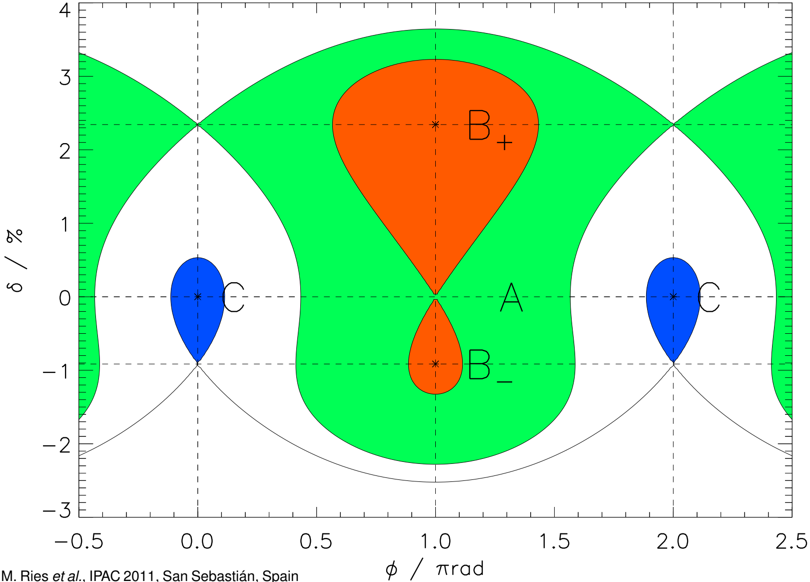
$$\mathscr{H}(\phi,\delta) = 2\pi q f_{\mathrm{rev}}\left(\frac{\alpha_0}{2} + \frac{\alpha_1}{3}\delta + \frac{\alpha_2}{4}\delta^2\dots\right)\delta^2 + \frac{eU_0 f_{\mathrm{rev}}}{\beta^2 E_0}\cos(\phi)$$

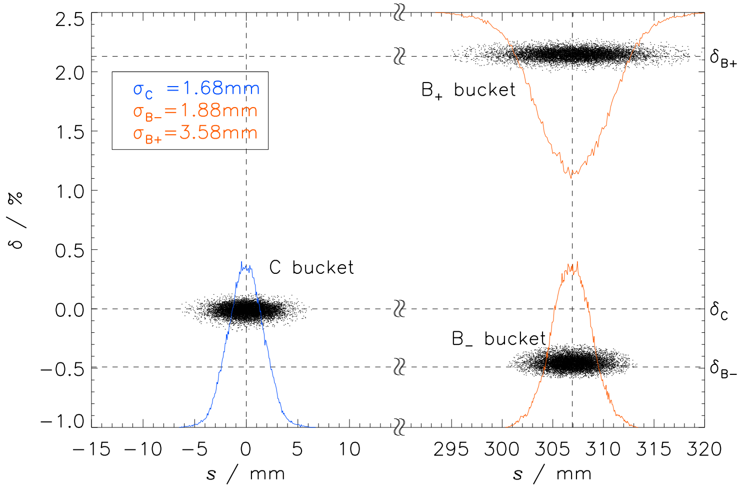


α_2-dominated bucket: quantities



MAD-X tracking results

$E = 630\ \mathrm{MeV} \qquad U = 250\ \mathrm{kV}$



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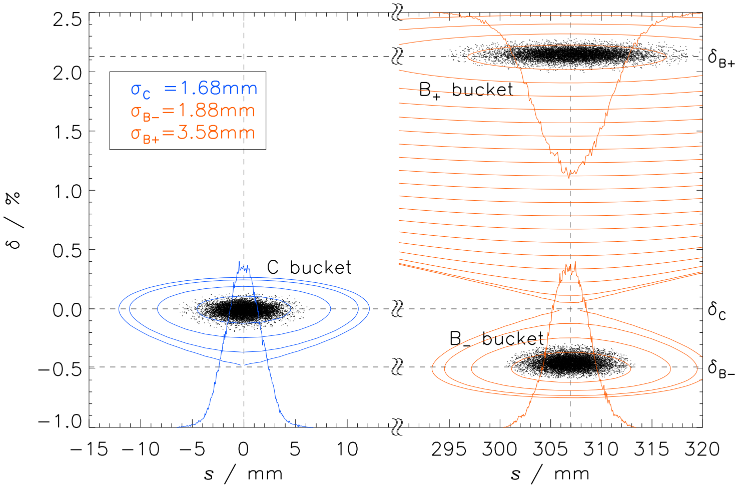
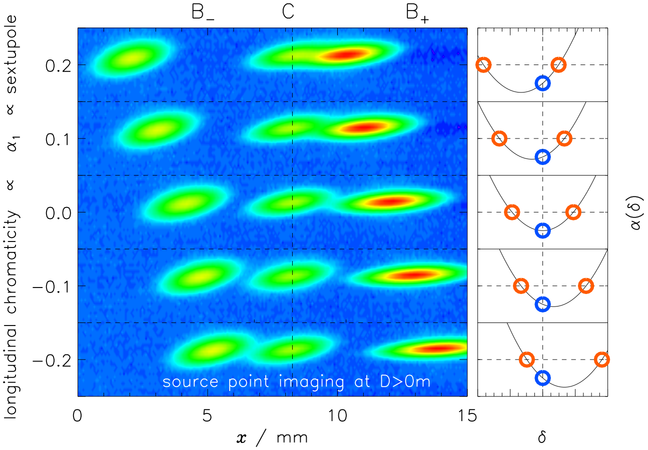


measurement: fixed point variation

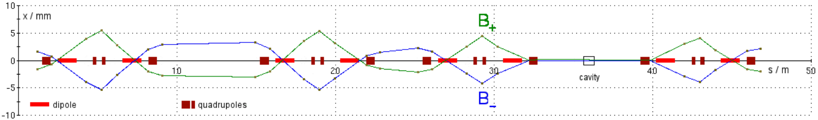
$$\delta_C = 0 \qquad \delta_{B_\pm} = -\frac{\alpha_1}{2\alpha_2} \pm \frac{1}{2\alpha_2}\sqrt{\alpha_1{}^2 - 4\alpha_0\alpha_2}$$



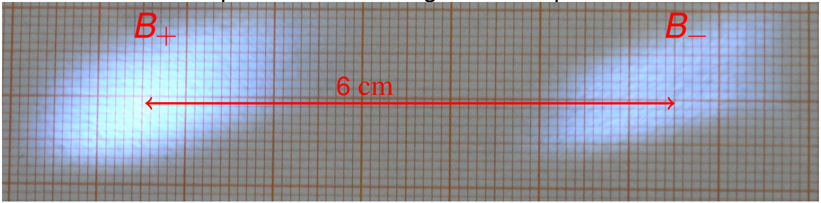
measurement: dispersive orbit separation

$$\delta_C = 0 \qquad \delta_{B_\pm} = \pm\frac{1}{2\alpha_2}\sqrt{-4\alpha_0\alpha_2}$$

BPM based orbit measurement $(\alpha_1 = 0)$



photon beam image at beamport



longitudinal tune spectra

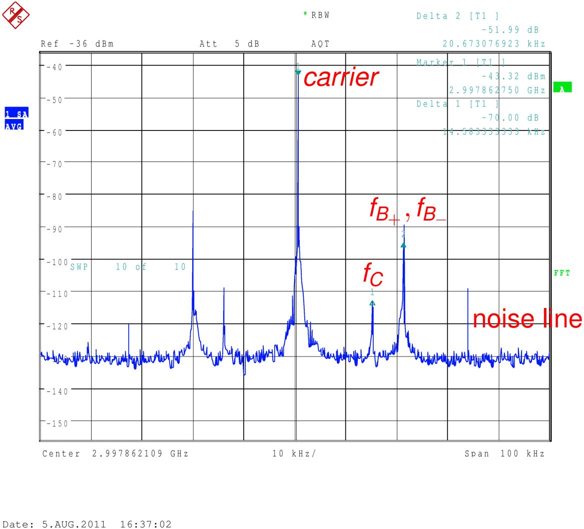
- expand the Hamiltonian around the fixed points: $\delta = \delta_{\rm FP} + \tilde{\delta}$
- neglect higher orders $\mathscr{O}(\tilde{\delta}^3)$
- $\hookrightarrow \sigma = \frac{\alpha_{\rm eff}}{\omega_s}\delta_0$

$$\omega_C{}^2 = -\frac{q\omega_{\rm rev}^2 eU_0 \cos(\phi_C)}{2\pi\beta^2 E_0} \cdot \underbrace{\alpha_0}_{\alpha_{\rm eff}}$$

$$\omega_{B_\pm}{}^2 = \frac{q\omega_{\rm rev}^2 eU_0 \cos(\phi_B)}{2\pi\beta^2 E_0} \cdot \underbrace{\left(2\alpha_0 - \frac{\alpha_1{}^2}{2\alpha_2} \pm \frac{\alpha_1}{2\alpha_2}\sqrt{\alpha_1{}^2 - 4\alpha_0\alpha_2}\right)}_{\alpha_{\rm eff}}$$

$$\omega_{B_\pm}{}^2\Big|_{\alpha_1=0} = \frac{q\omega_{\rm rev}^2 eU_0 \cos(\phi_B)}{2\pi\beta^2 E_0} \cdot \underbrace{2\alpha_0}_{\alpha_{\rm eff}}$$

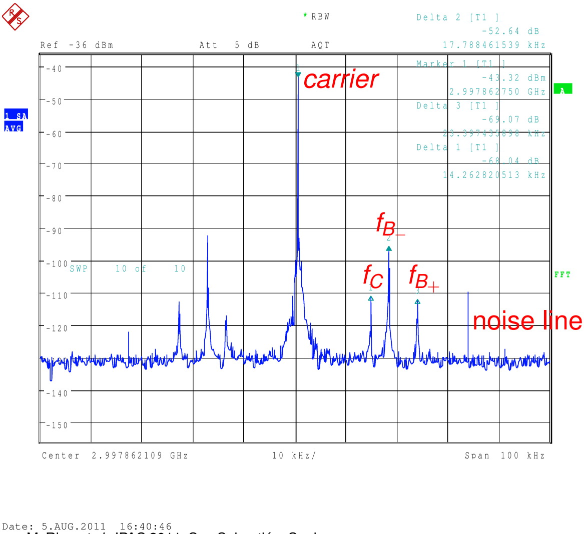
$\alpha_1 = 0$



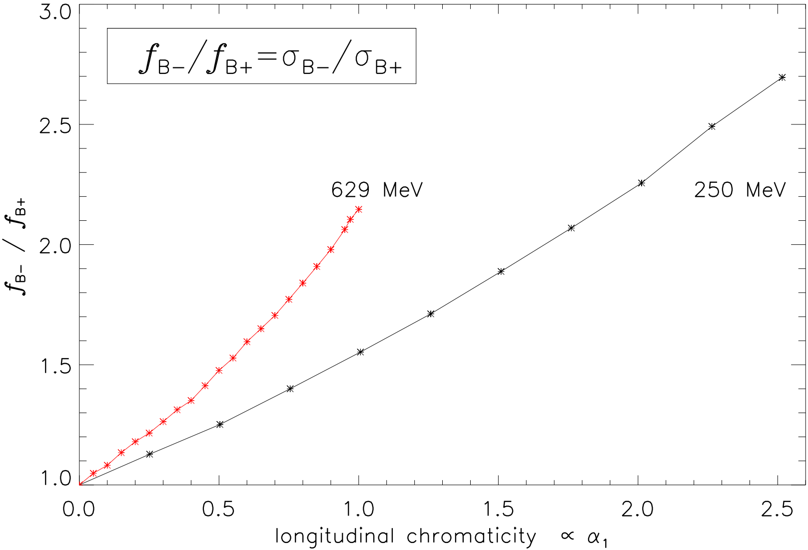
$$\frac{f_{B_\pm}}{f_C} = \sqrt{2}$$

measurement: longitudinal tune spectra

$\alpha_1 < 0$



measurement: longitudinal tune ratio



Summary

- experimental verification of α-bucket operation
- 175 mA at $\tau \approx 7$ h achieved
- good agreement between theoretical understanding and experiment
- a tune i.e. bunch length factor of 2.7 was generated at the MLS, limited by machine momentum acceptance
- α-buckets could provide framework for bunch tailoring by other means

thank you

MLS building

for further reading

[1] D. Robin et al., EPAC'08, Genoa, Italy, p. 2100-2102 (2008).

[2] J. Feikes et al., Phys. Rev. ST Accel. Beams 14, 030705 (2011).

[3] J. B. Murphy and S. L. Kramer, Phys. Rev. Lett, Vol. 48 Num. 24 (2000).

[4] A. Loulergue, Presentation, ESLS XV, (2007).

[5] G. Wüstefeld, "Coherent Synchrotron Radiation and Short Bunches in Electron Storage Rings", slides EPAC'08, Genoa, Italy (2008).

[6] I.P.S. Martin et al., Phys. Rev. ST Accel. Beams 14, 040705 (2011).

[7] B. Beckhoff et al., Phys. Status Solidi B 246, p. 1415–1434 (2009).

[8] D. Robin et al., Nucl. Instr. and Meth. A 622, p.518-535 (2010).

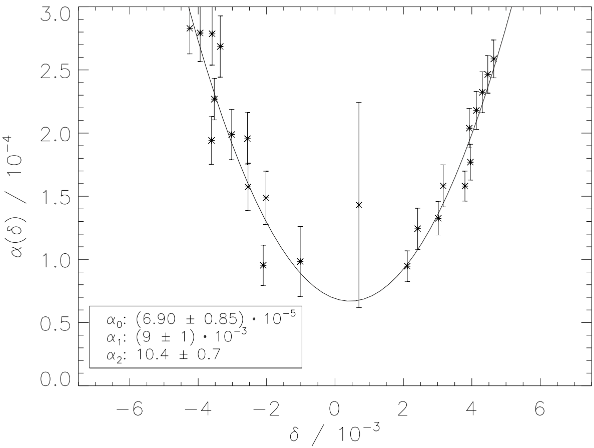
[9] K.Y. Ng, Nucl. Instr. and Meth. A 404, p.199-216 (1998).

[10] MAD-X 5.00.00, CERN, Geneva, Switzerland.

[11] G. Wüstefeld et al., "Simultaneous Long and Short Electron Bunches in the BESSYII Storage Ring", Proceedings of IPAC 2011, San Sebastián, Spain (2011).

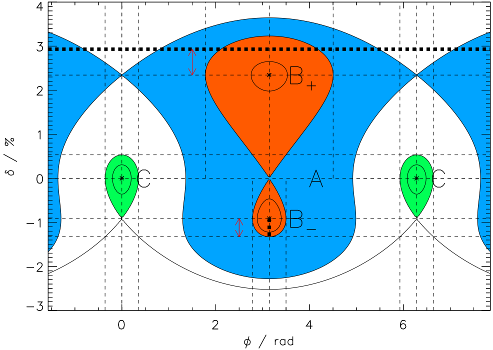
measured nonlinear momentum compaction at the MLS

Compton Backscattering based measurement of $\alpha(\delta)$ at the MLS (630 MeV)



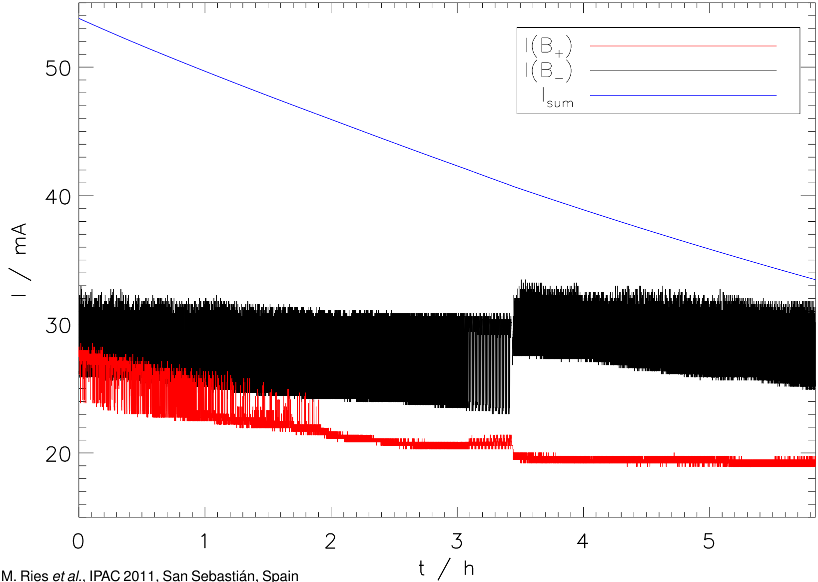
$$\alpha\delta = \frac{\Delta L}{L} = -\frac{\Delta f_{\rm rf}}{f_{\rm rf}}$$

limitations

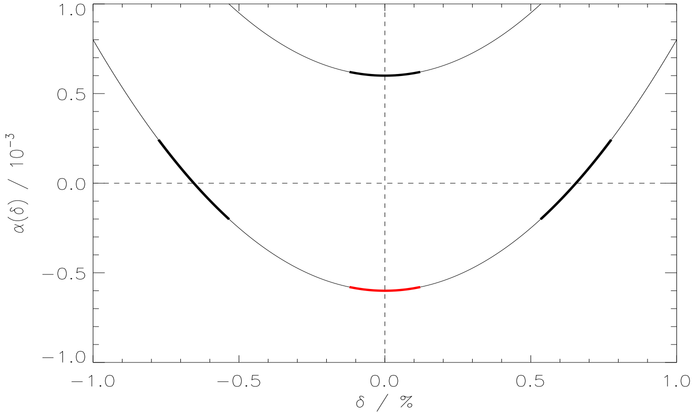


- momentum acceptance of the machine (long bunch)
- natural momentum spread to be stored (short bunch)
- $\alpha_0, \alpha_1, \alpha_2$ capabilities of the machine
- $\hookrightarrow \dfrac{\sigma_{B_\pm}}{\sigma_{B_\mp}} = \dfrac{f_{B_\pm}}{f_{B_\mp}}$

measurement: double beam top-up



$\alpha(\delta)$ and quasi-isochronous operation



$$\dot{\phi} = 2\pi q f_{\text{rev}} \left[\alpha_0 + \alpha_1\delta + \alpha_2\delta^2\right]\delta \qquad \dot{\delta} = \frac{eU_0}{\beta^2 E_0}\sin(\phi)$$

δ measurement

energy measurement based on Compton Backscattering