Spurious Dispersion Effects at FLASH

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HELMHOLTZ
GEMEINSCHAFT

DESY

FLASH

Overview

- Introduction
- Generation mechanisms of dispersion
- Measurement and correction
- Effects on transverse beam quality at FLASH
- Effects on FEL performance at FLASH
- Conclusion

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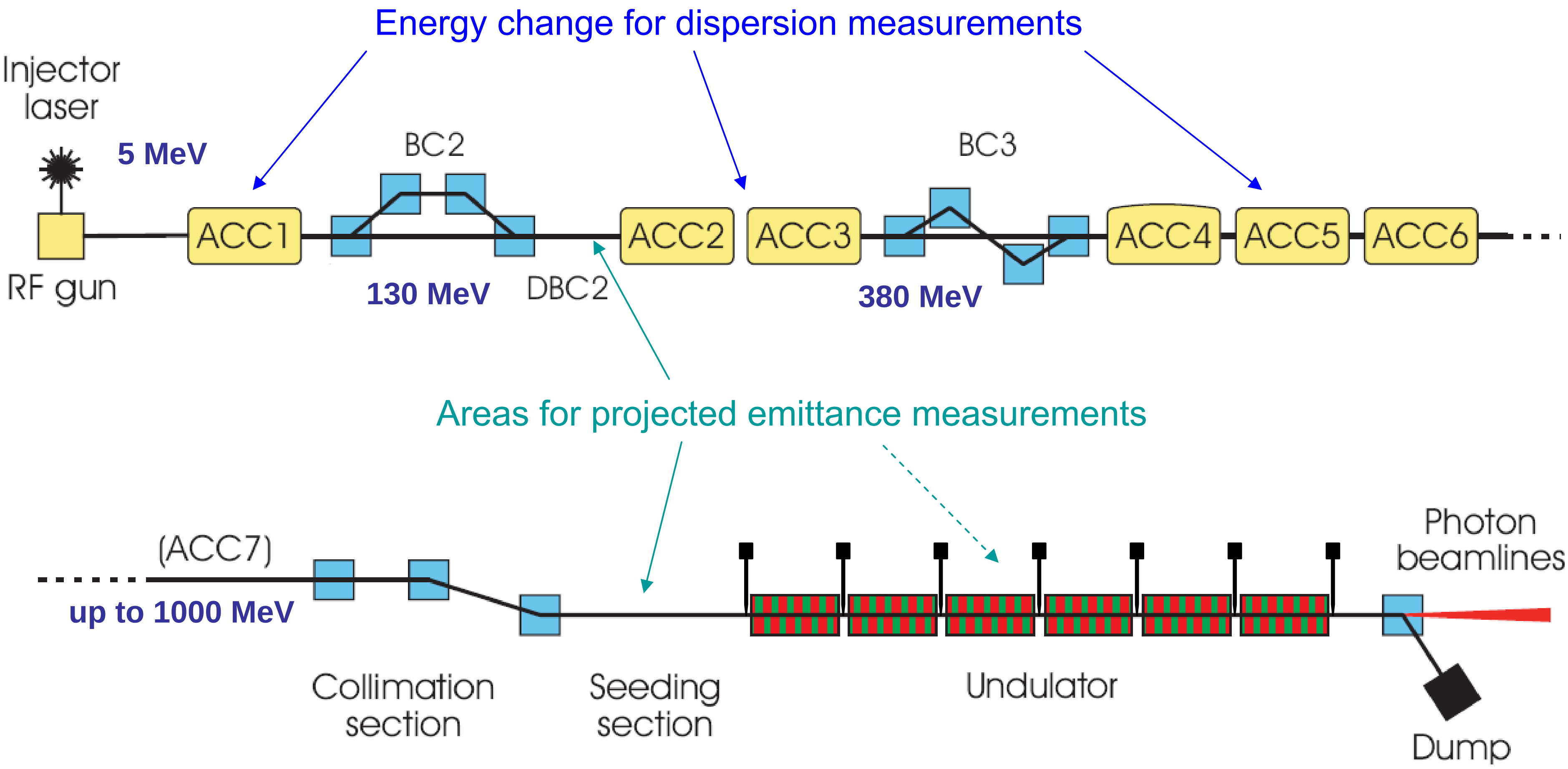
FLASH

Free-electron LASer in Hamburg

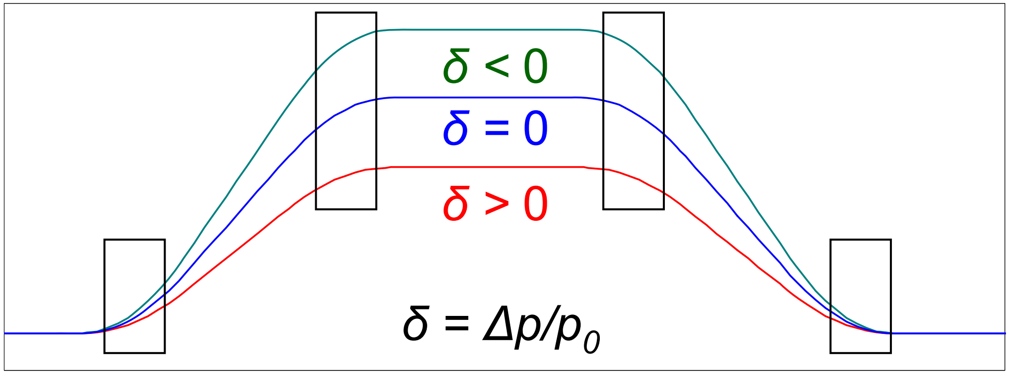

Energy change for dispersion measurements

Areas for projected emittance measurements

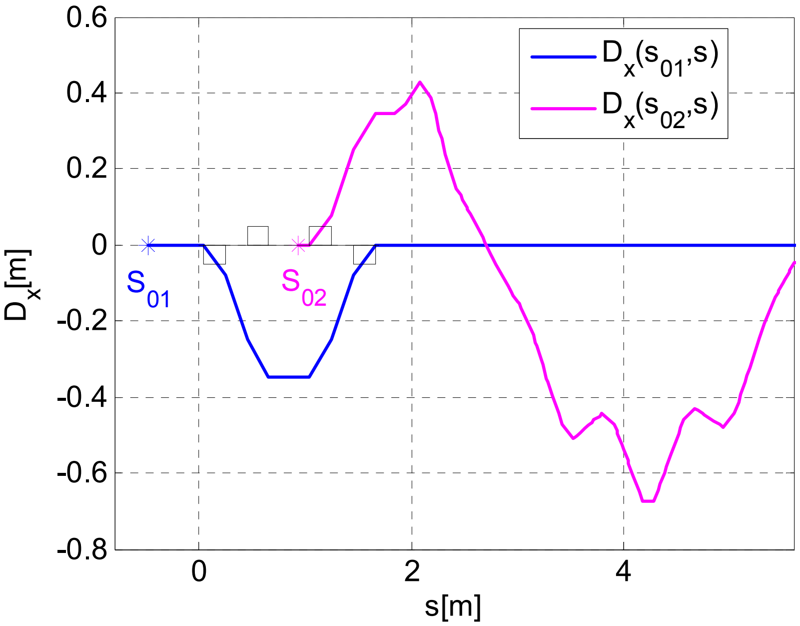
Dispersion in linacs

Dispersion is the momentum dependence of charged particle deflections in a magnetic field

$$\frac{1}{\rho} = \frac{eB}{p}$$



The dispersion functions $D_x(s_0,s)$ and $D_y(s_0,s)$ describe the change in transverse phase-space coordinates at s due to a momentum change at s_0.
They depend on the point where the momentum changes.



Effects to a single particle
Beam offsets and angles

$$\Delta x_D(s) = D_x(s_0,s)\cdot\delta(s_0) + D_{xx}(s_0,s)\cdot\delta^2(s_0) + \ldots$$

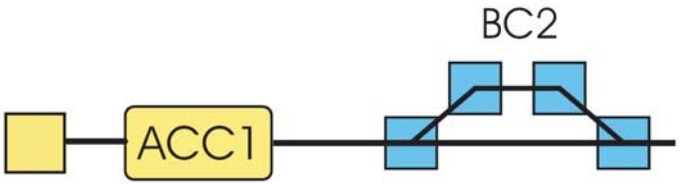
$$\Delta x'_D(s) = D'_x(s_0,s)\cdot\delta(s_0) + D'_{xx}(s_0,s)\cdot\delta^2(s_0) + \ldots$$

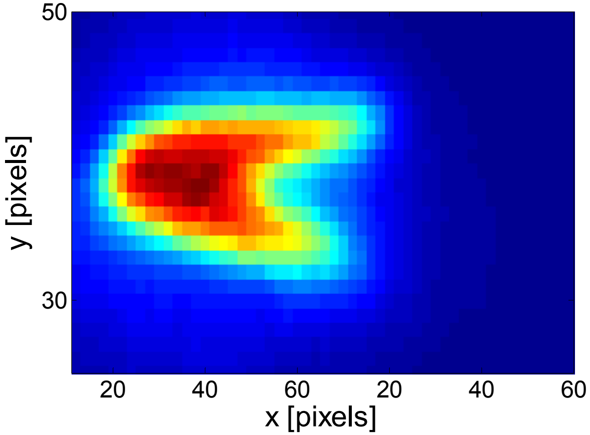
Effects on the electron beam distribution

Circular accelerators → moments of energy distribution = constant
Linacs → moments of energy distribution ≠ constant

The impact of dispersion depends on the position of the dispersion sources

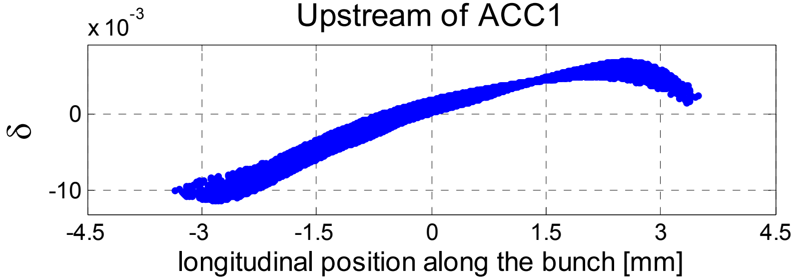
Example: c-shape effect at BC2 (FLASH)

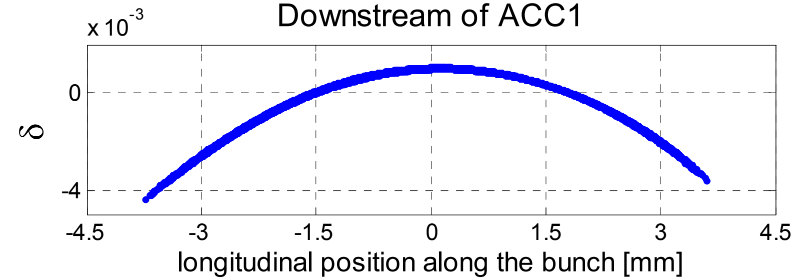




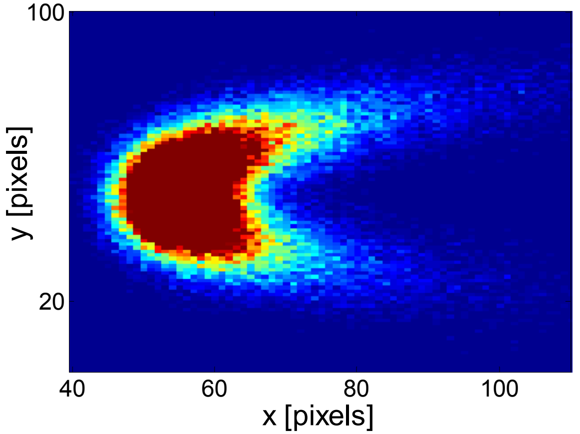
Measured beam image at BC2 (D_x = -35 cm)

Momentum distributions


Upstream of ACC1


Downstream of ACC1

Simulated beam image at BC2
(vertical dispersion source upstream of ACC1)

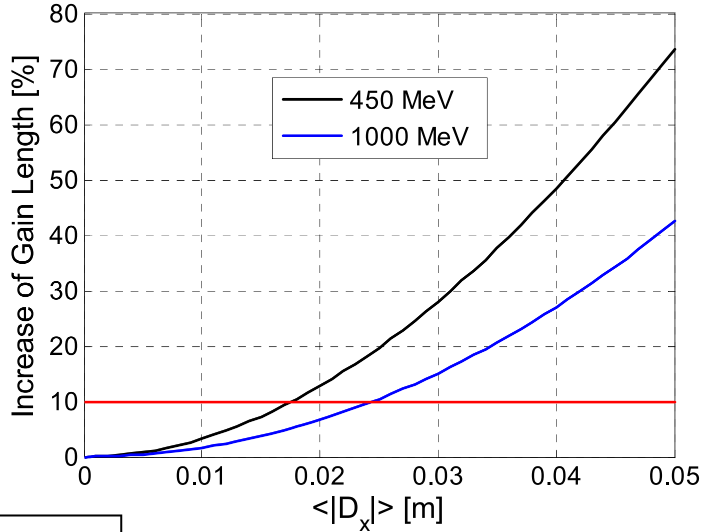


Effects on the FEL process

1) Dispersion causes FEL power jitter due to electron energy fluctuations

2) $D \rightarrow \sigma \uparrow \rightarrow$ gain length ↑, power↓

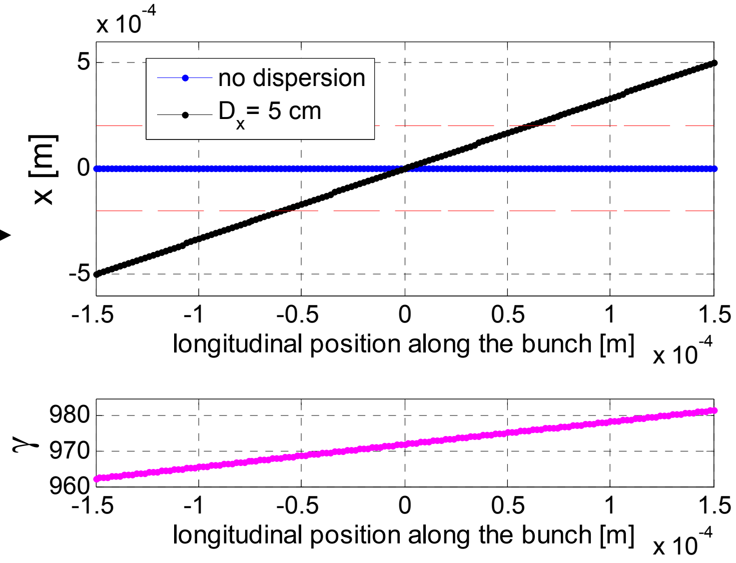
Increase of gain length for FLASH design parameters →



$D < 1.8$ cm → Increase of gain length < 10%

3) D → Intrabunch trajectory deviations → power ↓

Example of offset along the bunch with and without dispersion →



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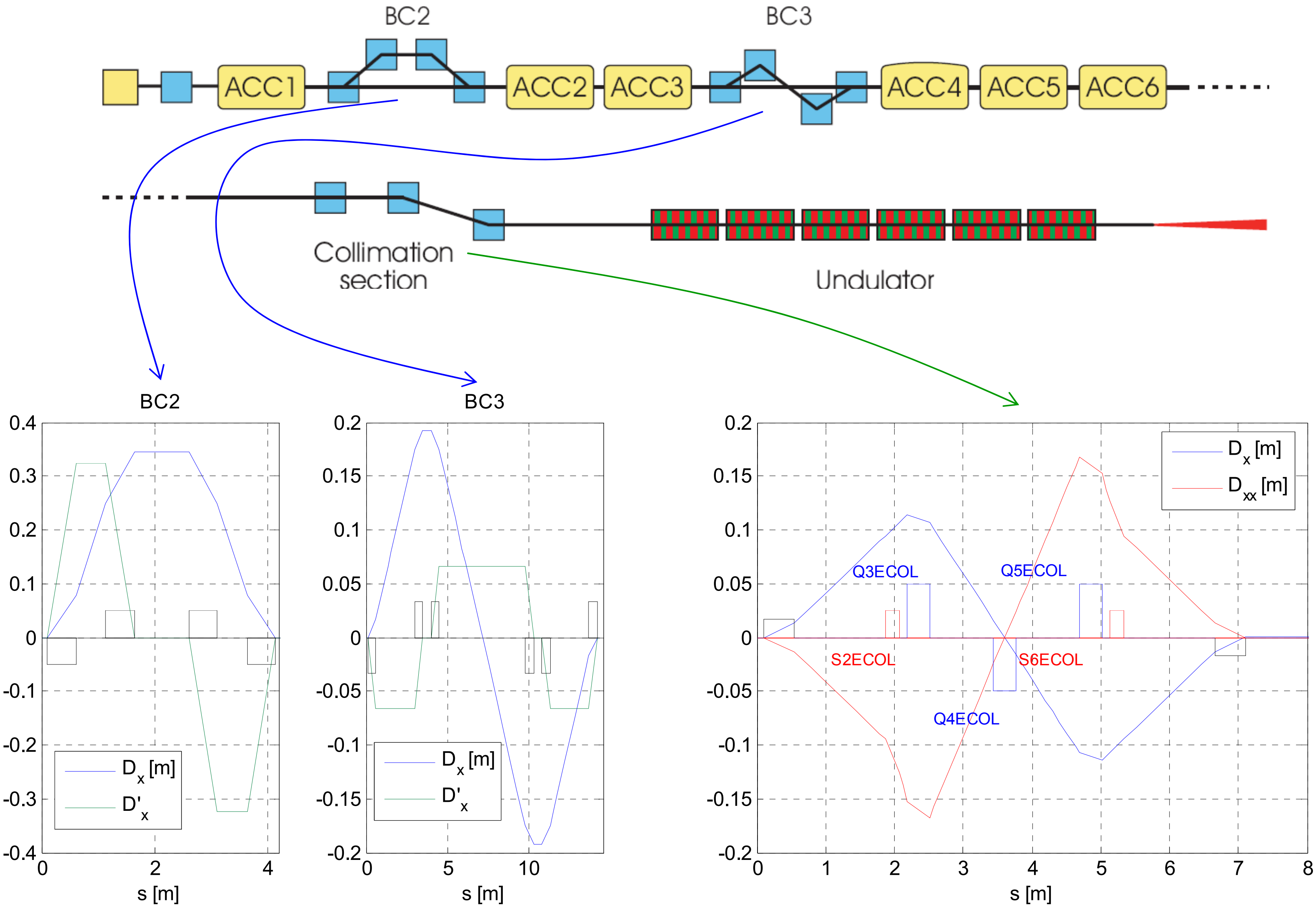
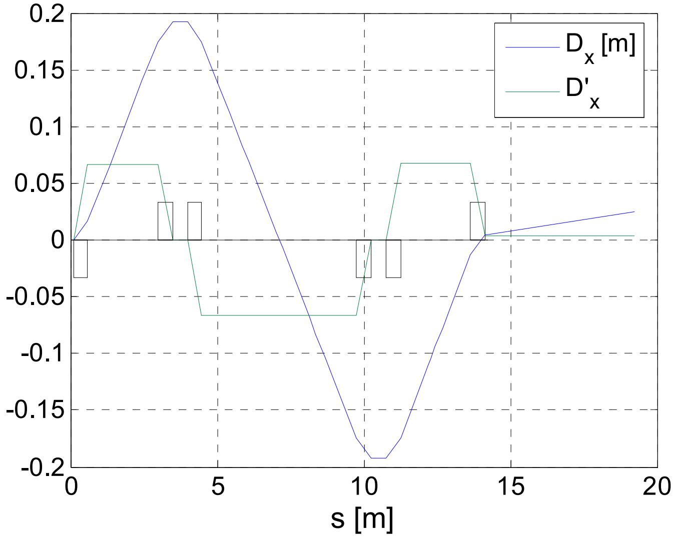
Dispersive sections in FELs

Bunch compressors and collimator sections

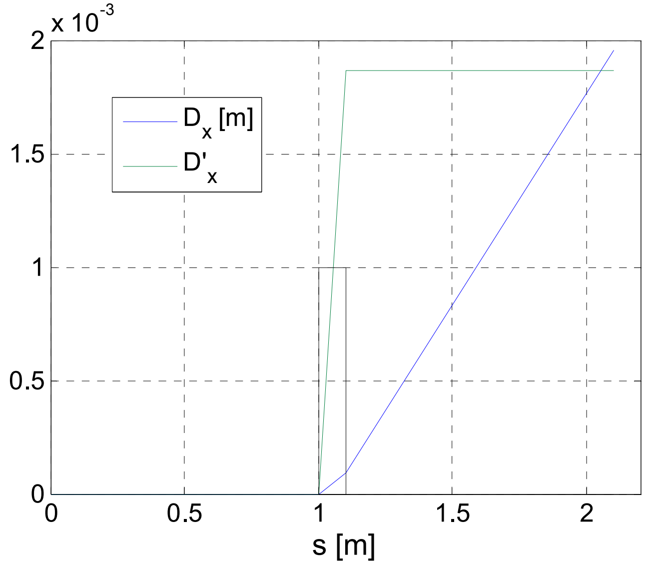


Spurious dispersion sources

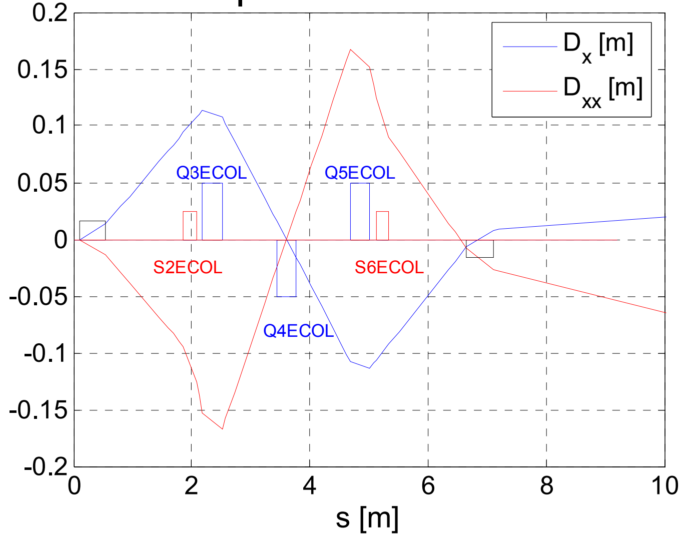
Dipole field errors



Trajectory errors and misalignments



Quadrupole and sextupole field errors at dispersive sections



Other sources:

- any additional dipole field (e.g. coupler kicks)
- any additional quadrupole (and sextupole) field in dispersive sections

Sensitivities for FLASH

Required amount of error to generate 10 mm of dispersion in the undulator (RMS)
No orbit correction is performed
(average results over 200 seeds)

Error type	Required ammount
Quadrupole misalignment	x: 17 μm y: 18 μm
Quadrupole field error	1.31 %
Quadrupole component in dipoles	$4.1 \cdot 10^{-3}$ m^{-2}
Vertical dipole misalignment	215 μm
Dipole field error	0.13 %
Cavity misalignment	x: 2.0 mm y: 1.8 mm

Quadrupole misalignments are the most important dispersion sources

Collimator is a critical area

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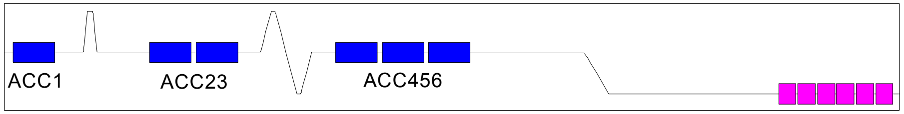
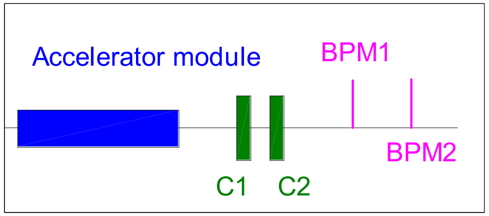
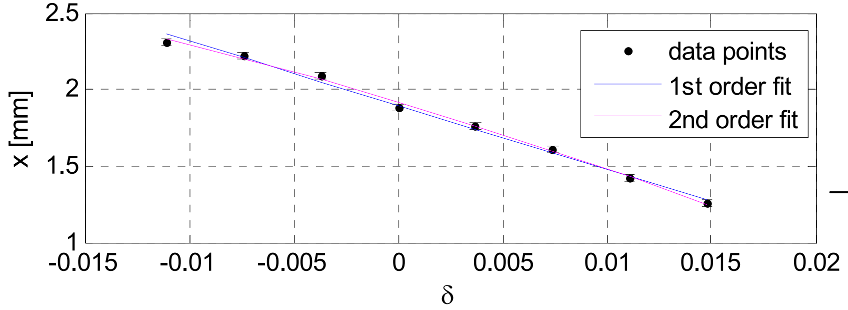
Dispersion measurement

It is based on measuring the orbit for different beam energies



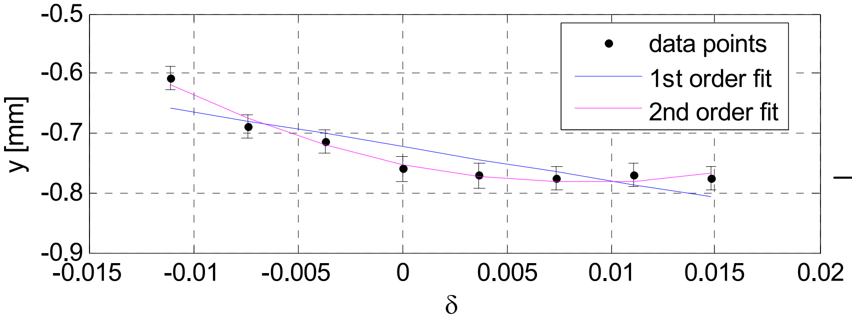
1. Change RF gradient of the module
2. Apply orbit correction to compensate RF steering effect
3. Read BPM positions downstream last correction BPM





$$x(s) = x_0 + D_x(s_0,s)\cdot\delta(s_0) + D_{xx}(s_0,s)\cdot\delta^2(s_0)$$

Dispersion



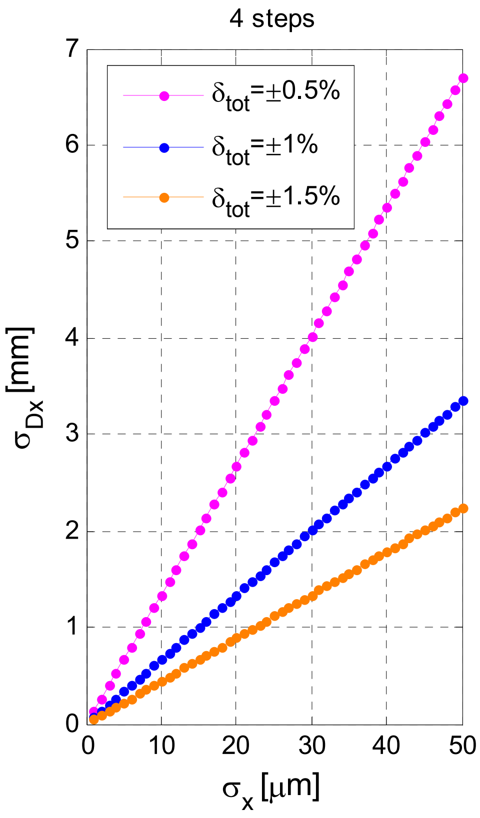
$$y(s) = y_0 + D_y(s_0,s)\cdot\delta(s_0) + D_{yy}(s_0,s)\cdot\delta^2(s_0)$$

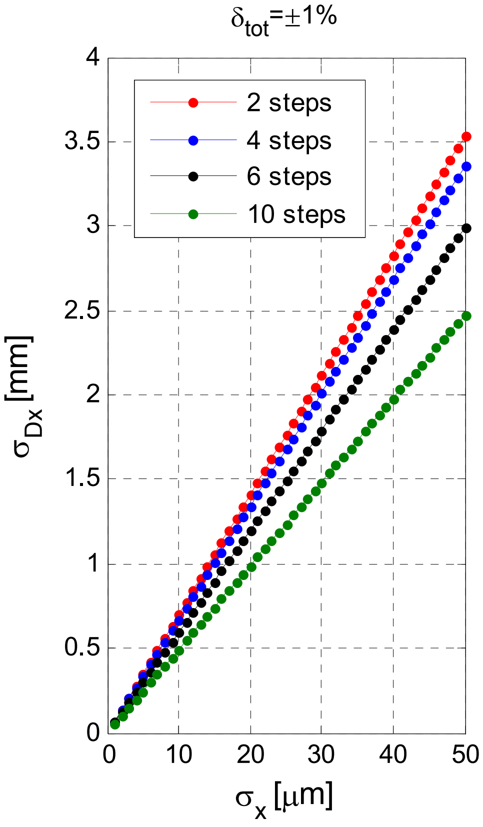
Dispersion measurement errors

- Statistical errors

$$\sigma_{D_x} = \sqrt{\frac{\sum_i \frac{1}{\sigma_{x_i}^2}}{\sum_i \frac{1}{\sigma_{x_i}^2}\cdot\sum_i\frac{\delta_i^2}{\sigma_{x_i}^2} - \left(\sum_i \frac{\delta_i}{\sigma_{x_i}^2}\right)^2}}$$

$$\left.\begin{array}{l}\sigma_x = 20:50\,\mu\text{m}\\ \delta_{\text{tot}}\approx\pm1\%\\ 3-4\text{ steps}\end{array}\right\}\rightarrow \sigma_{D_x}=1:3\,\text{mm}$$

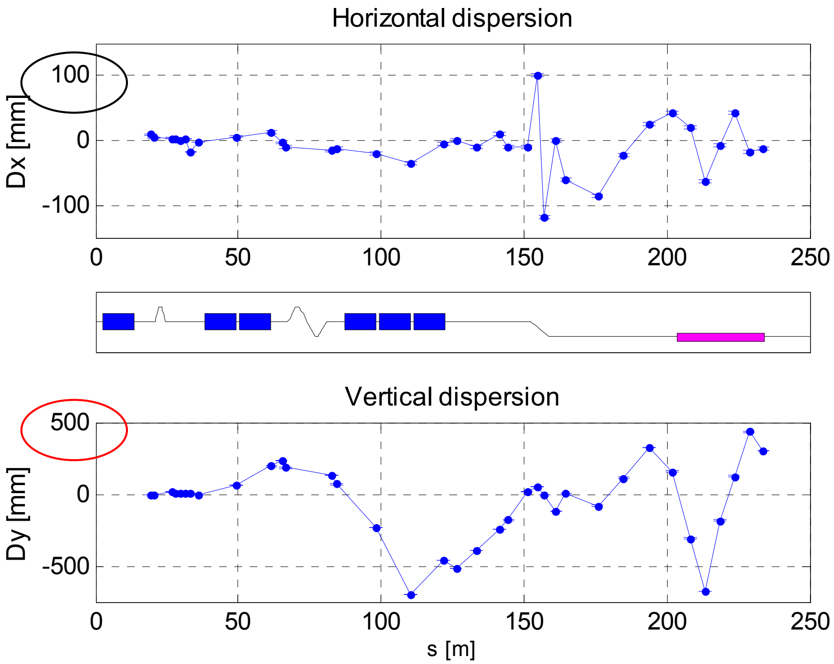




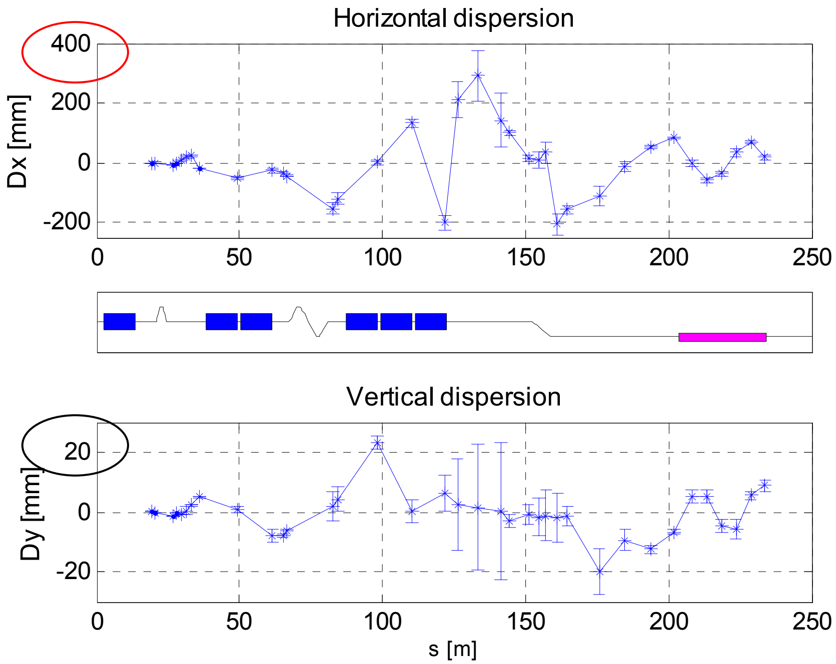
- Systematic errors:
  - RF steering: corrected
  - Calibration errors for *δ*: < 0.3%
  - BPM calibration errors: ~ 5%
  - BPM nonlinearities: negligible if *D* = ±10 cm (assuming no BPM off-set and δ_{tot} = ±1%)
  - Drifts (negligible because of the short measurement time)

Examples of measurements at FLASH

Day 1



Day 2 (SASE conditions)



Different errors change the spurious dispersion depending on the actual operating conditions of the accelerator, so dispersion must be measured and controlled frequently.

Dispersion correction algorithm

It corrects both orbit and dispersion, using dipole magnets and quadrupole movers.

The optimal settings are calculated using the orbit and dispersion response matrices.

- Orbit response term $O_{i,j} = \dfrac{\Delta x_i}{\Delta \theta_j}$
- Dispersion response term $\Delta_{i,j} = \dfrac{\Delta D_i}{\Delta \theta_j}$

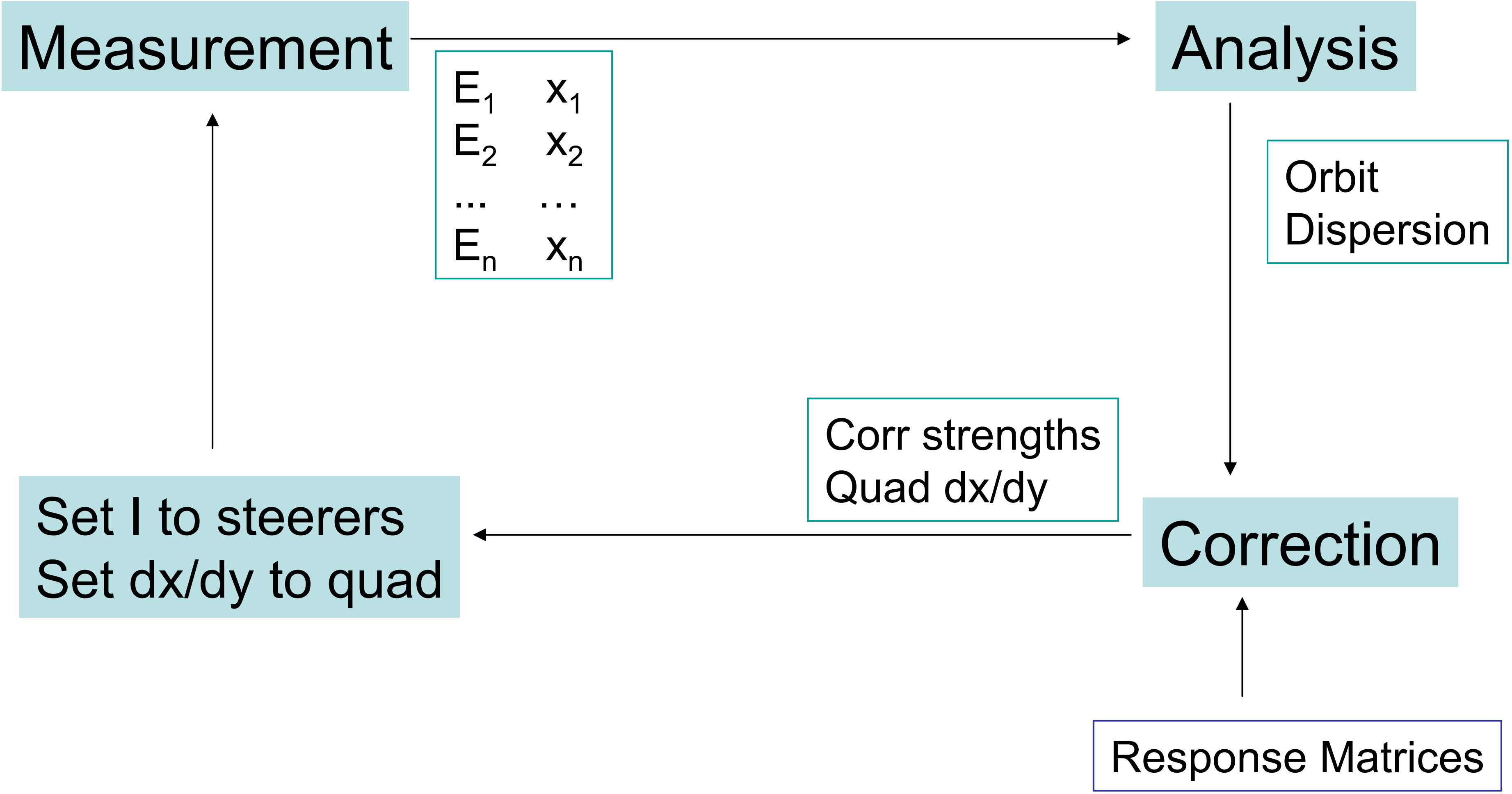
Δx_i / ΔD_i ----------> change of the orbit / dispersion at the BPM *i*
$\Delta\theta_j$ -----------> change of the kick angle of the steerer *j*

$$\begin{pmatrix} \hat{O} \\ \hat{\Delta} \end{pmatrix} \cdot \Delta\vec{\theta} = \begin{pmatrix} \vec{x}_{ind} \\ \vec{D}_{ind} \end{pmatrix}$$

$$\boxed{(1-w)\left\| \vec{x}_{meas} + \vec{x}_{ind} - \vec{x}_{gold} \right\|^2 + w\left\| \vec{D}_{meas} + \vec{D}_{ind} - \vec{D}_{gold} \right\|^2 = \min}$$

ind = induced, *meas* = measured, *gold* = golden (target)
w: weighting factor (*w* = 0 only orbit correction, *w* = 1 only dispersion correction)

Scheme for dispersion correction procedure



Measurement

E_1 x_1
E_2 x_2
… …
E_n x_n

Analysis

Orbit
Dispersion

Correction

Corr strengths
Quad dx/dy

Set I to steerers
Set dx/dy to quad

Response Matrices

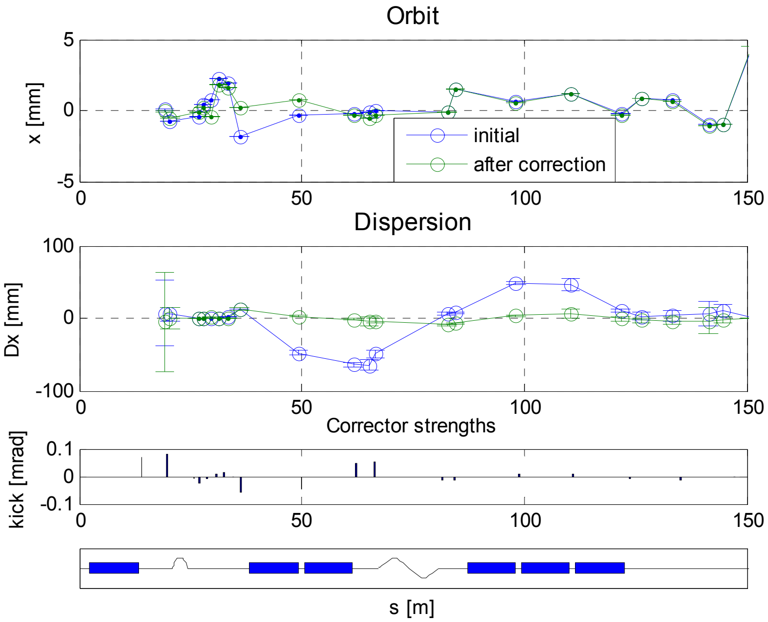
Dispersion tool at FLASH

The dispersion measured from all accelerator modules can be kept below 5 mm (RMS) in both planes.

Examples

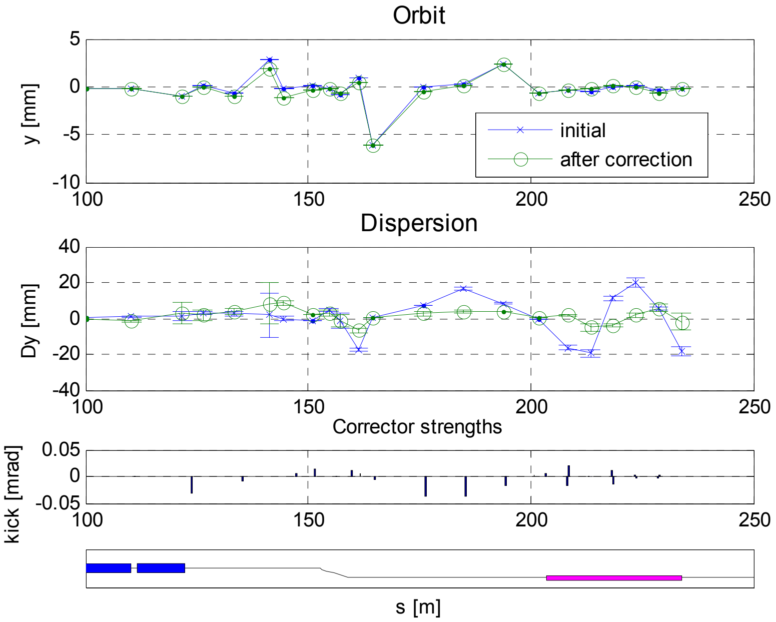
From **ACC1**

D_x corrected from 30 to 5 mm (RMS)



From **ACC456**

D_y corrected from 17 to 4 mm (RMS)



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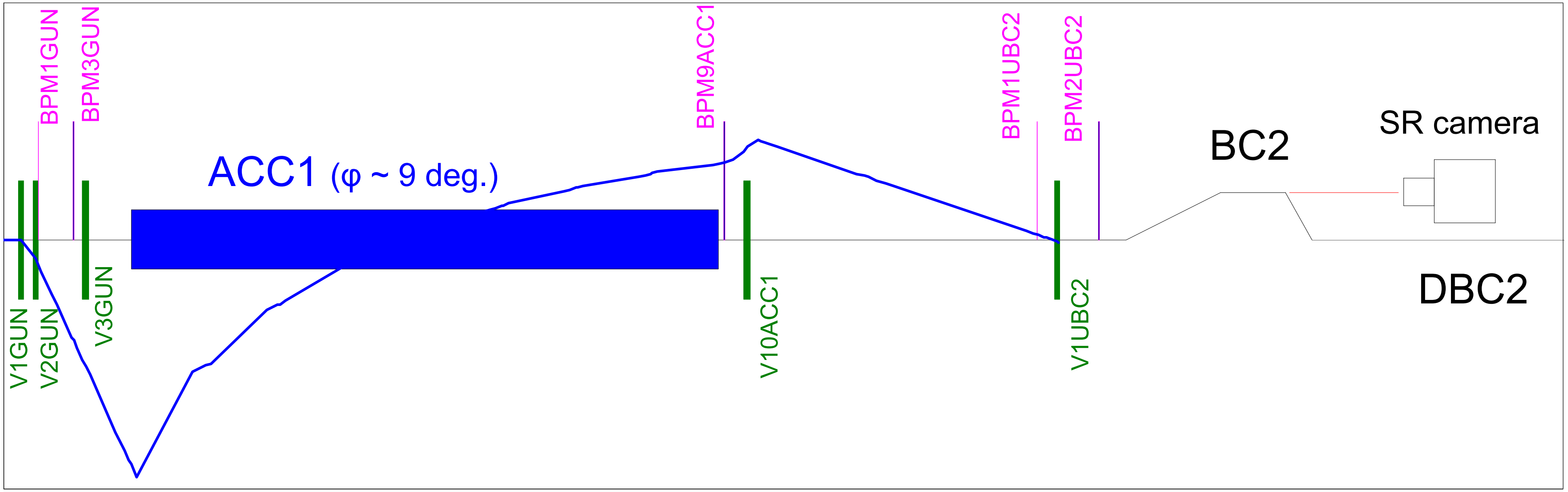
Beam tilt experiment

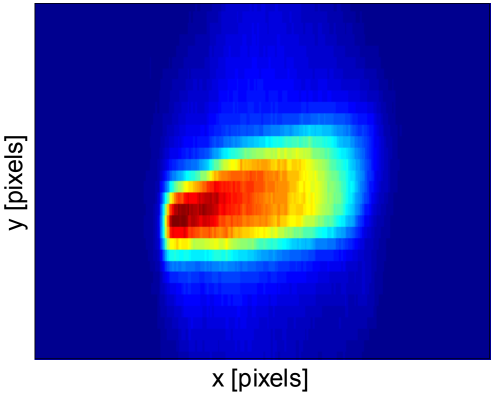
(with C. Gerth and K. Hacker)

Studies on how vertical dispersion tilts the beam at BC2 and causes an increase of the emittance. The dispersion is generated by applying vertical trajectory bumps through ACC1.



Bump	Relative bump amplitude at BMP9ACC1 [mm]
ref. (y = -2.8 mm)	0.0
1	-5.3
2	-3.1
3	-2.0
4	1.7
5	3.5
6	4.6

Image with SR camera

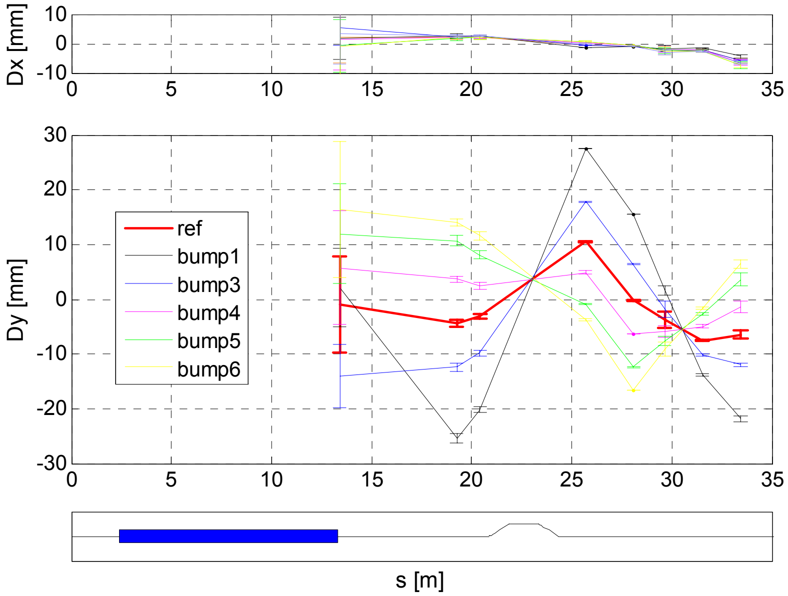


Beam tilt experiment. Measurements.

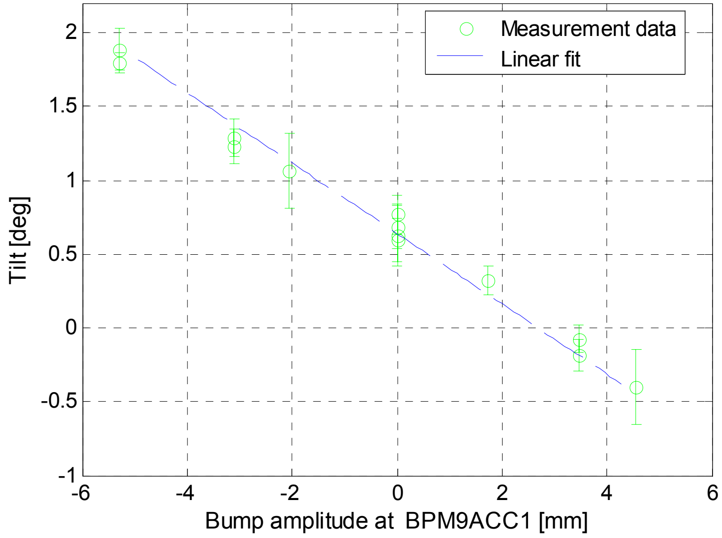
Measurements per each bump:

1. Dispersion from ACC1
2. Beam tilt at BC2
3. Projected emittance at DBC2

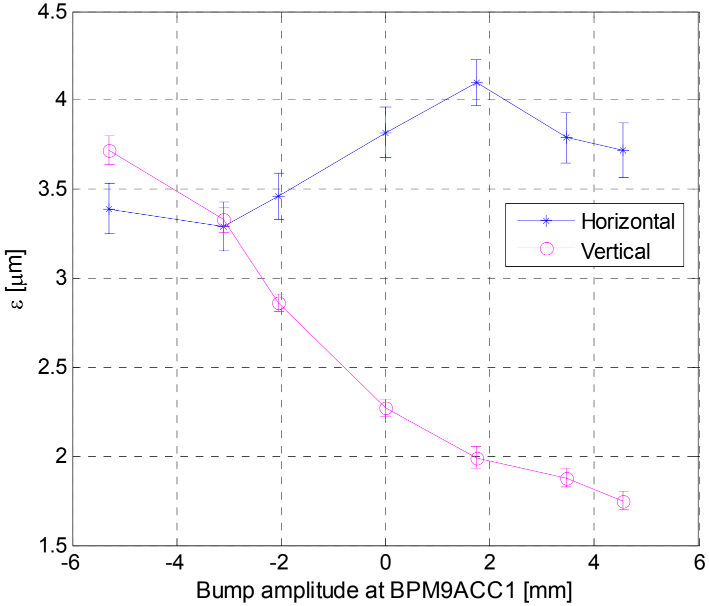
Dispersion



Beam tilt



Emittance

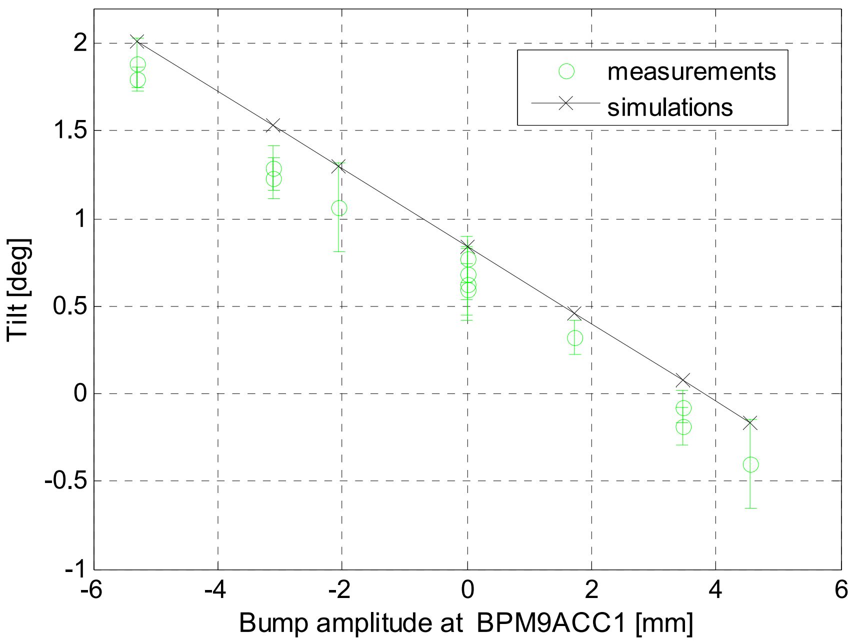


Beam tilt experiment. Simulations.

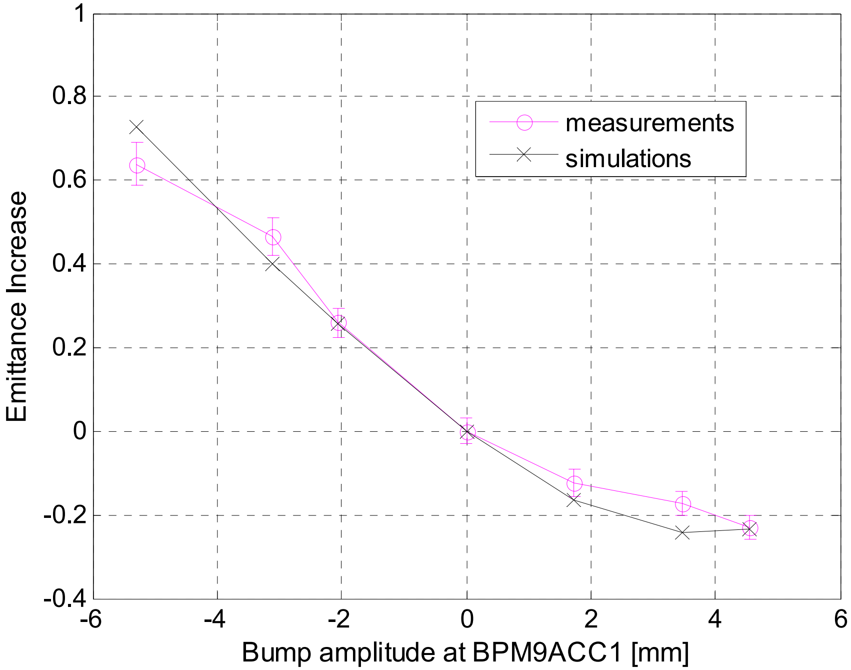
Simulations done with elegant

Initial vertical trajectory offset of 3.0 mm reproduces the measurements (orbit, dispersion, beam tilt and emittance)

Beam tilt



Emittance

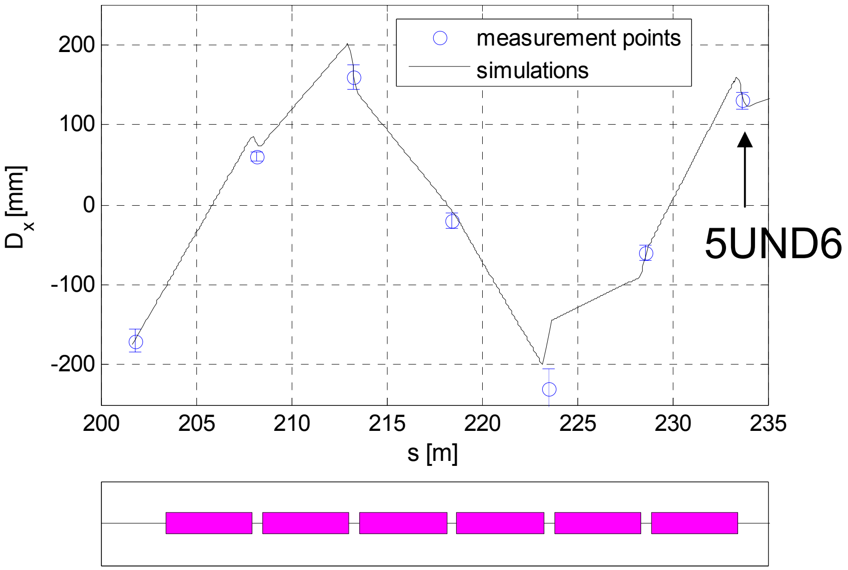


- The required steering to improve the beam quality was counteracting a vertical kick which is in accordance with a relative solenoid misalignment of ~ 300 μm.

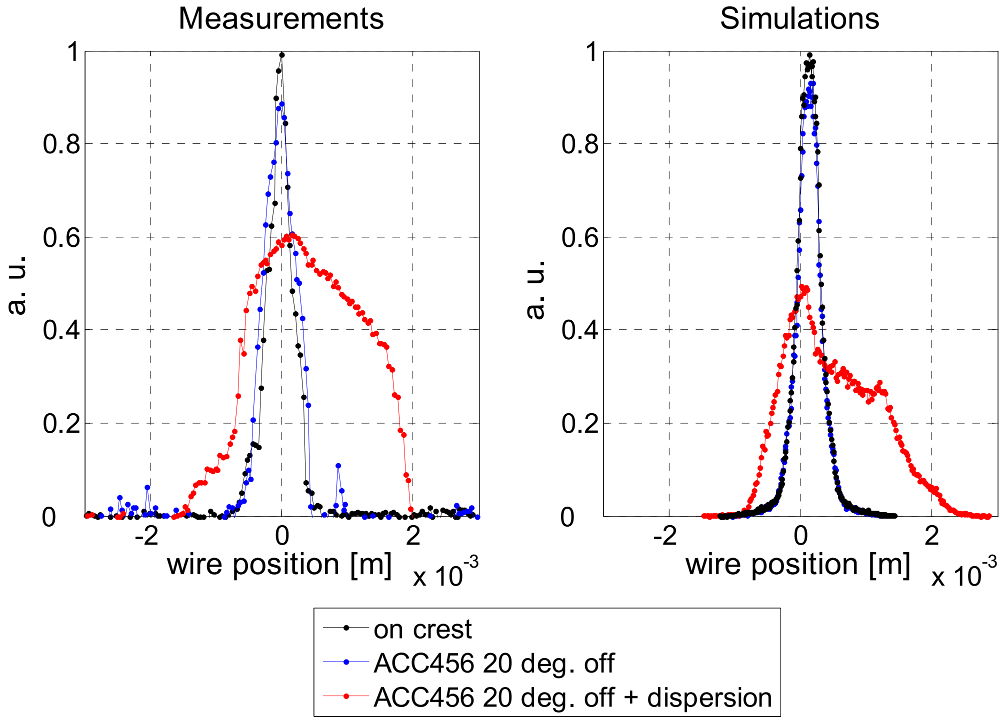
Dispersion generation in the undulator

Current of Q3/5ECOL was decreased by 10% → D_x = 140 mm (RMS)

Dispersion generation

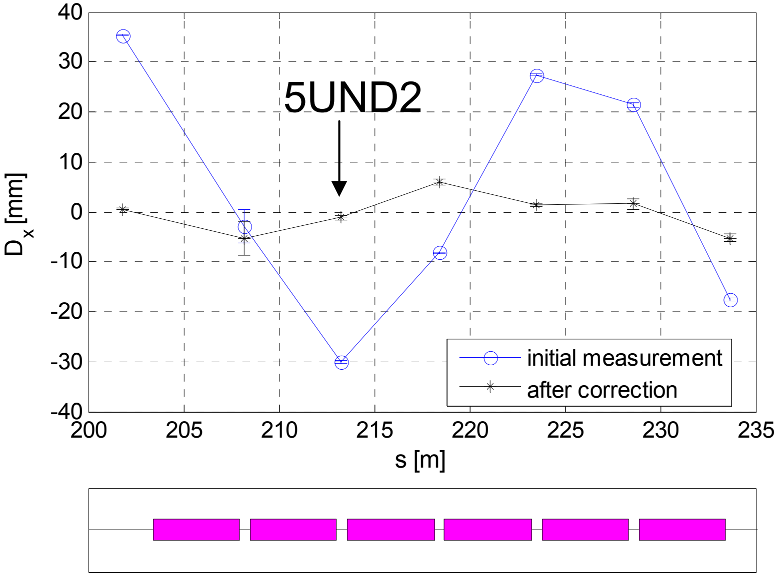


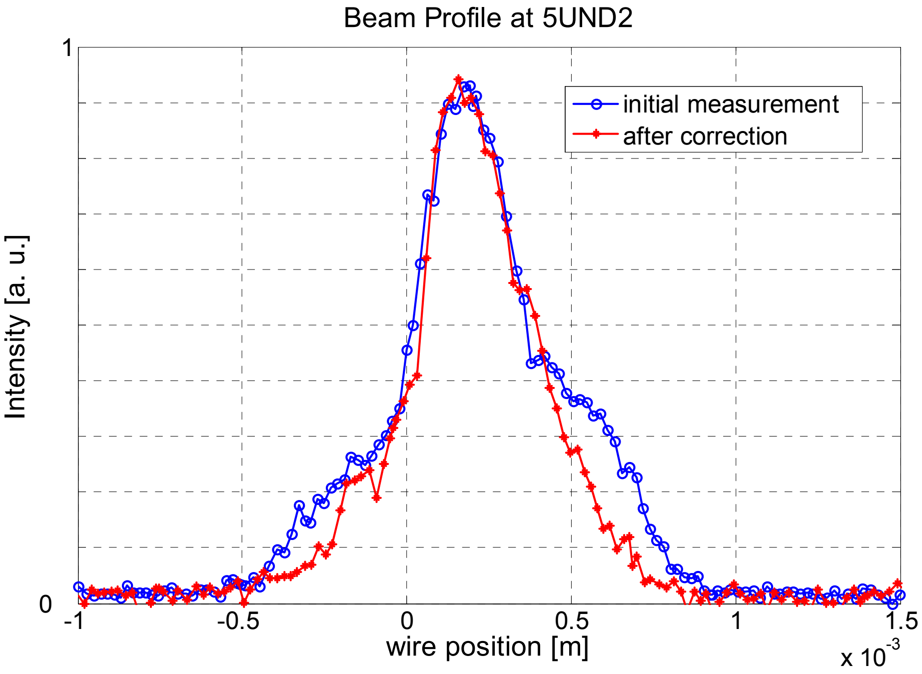
Profile at 5UND6 (50 µm W - wire)



Dispersion correction in the undulator

Correction of D_x in the undulator from 22 to 4 mm (RMS)
Beam emittance reduced by 20% (from 5.8 to 4.7 µm)
Beam shoulders vanished due to dispersion correction





Emittance transport

(with F. Loehl and K. Honkavaara)

Results of projected emittance at FLASH for 2 different days after **linac optimization** (i.e. orbit and dispersion correction)

Normalized values for 90% beam intensities

Design emittance is 2 µm

Day	17-02-2007		08-09-2007	
Section	ε_x [µm]	ε_y [µm]	ε_x [µm]	ε_y [µm]
DBC2	**2.4**	**2.5**	**2.2**	**2.1**
Seeding	**2.0**	**2.2**	**1.8**	**2.3**

Statistical measurement errors = 0.1 µm

Systematic errors > 0.1 µm

Dispersion correction (to less than 10 mm) is necessary for the conservation of the projected emittance

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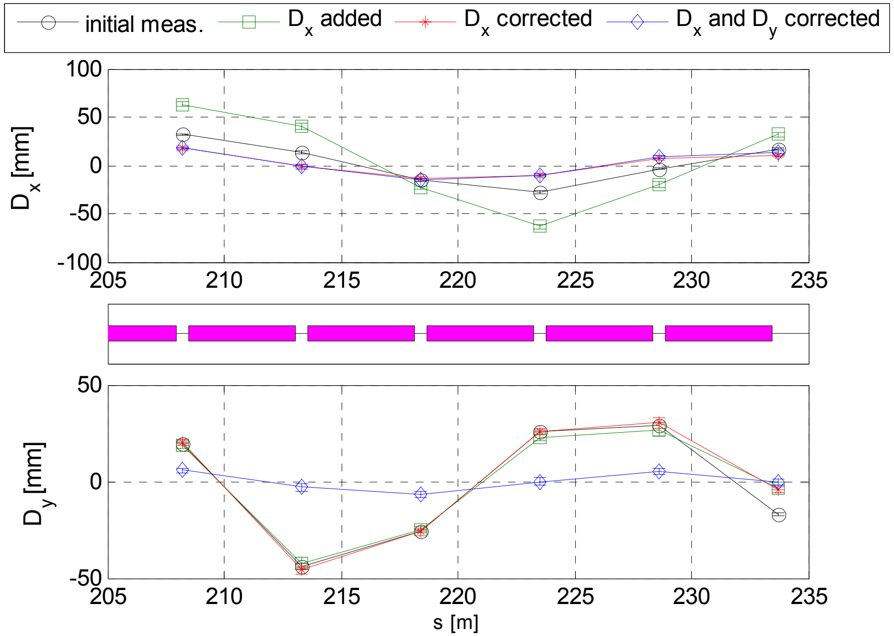
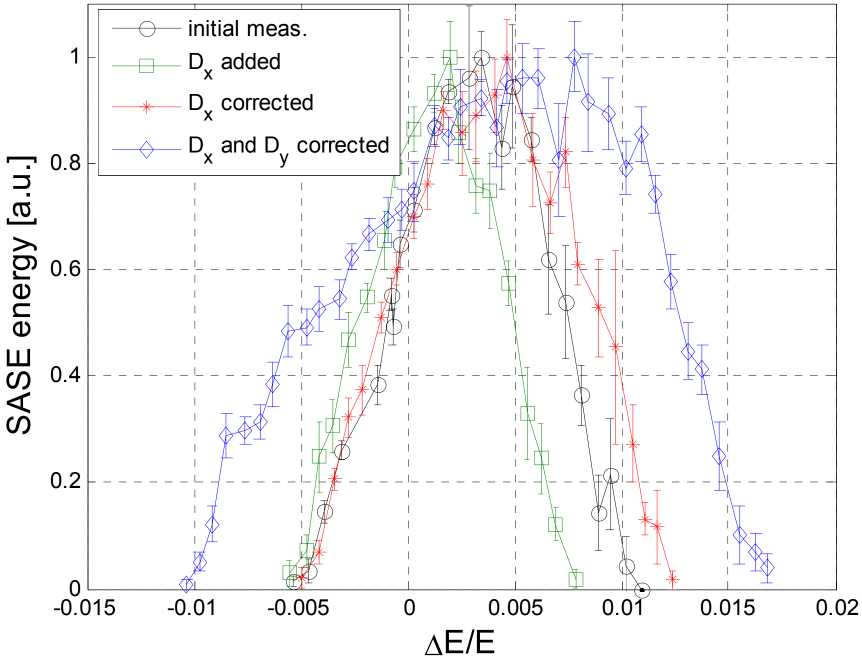
  - SASE sensitivity to electron beam energy offset
  - Dispersion impact on SASE spectrum
- Conclusion

SASE sensitivity to electron beam energy offset. Measurements.

Motivation: show that by correcting the dispersion inside the undulator, the SASE power jitter due to electron beam energy fluctuations decreases





Condition	D_x (RMS)	D_y (RMS)	FWHM in $\Delta E/E$
Initial measurement	22 mm	30 mm	0.82 %
D_x generated	48 mm	28 mm	0.74 %
D_x corrected	12 mm	31 mm	1.06 %
D_x and D_y corrected	11 mm	5 mm	1.72 %

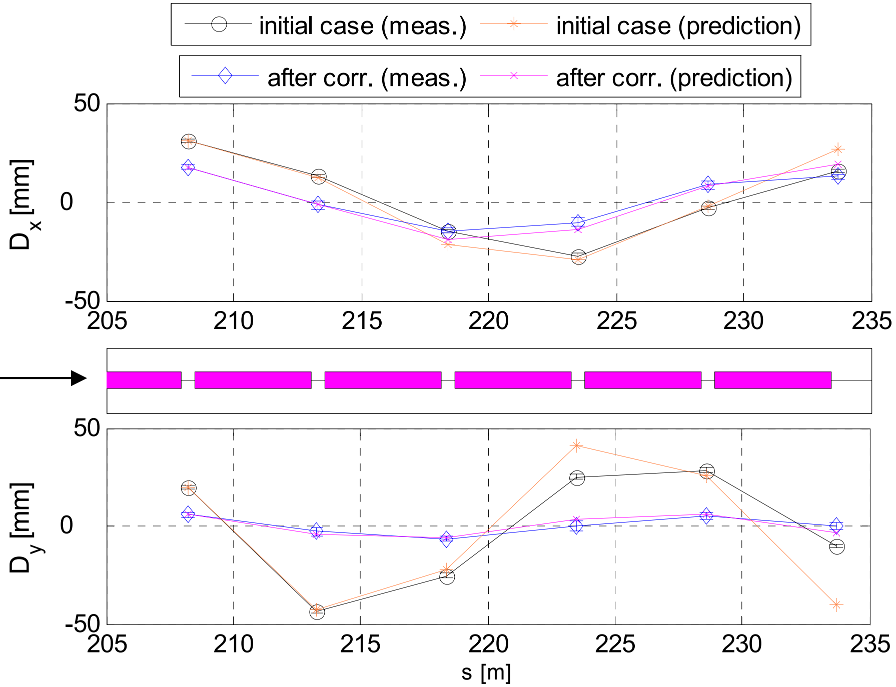
SASE sensitivity to electron beam energy offset. Simulations.

Simulations done with Genesis 1.3 (only initial and last cases)

Effects

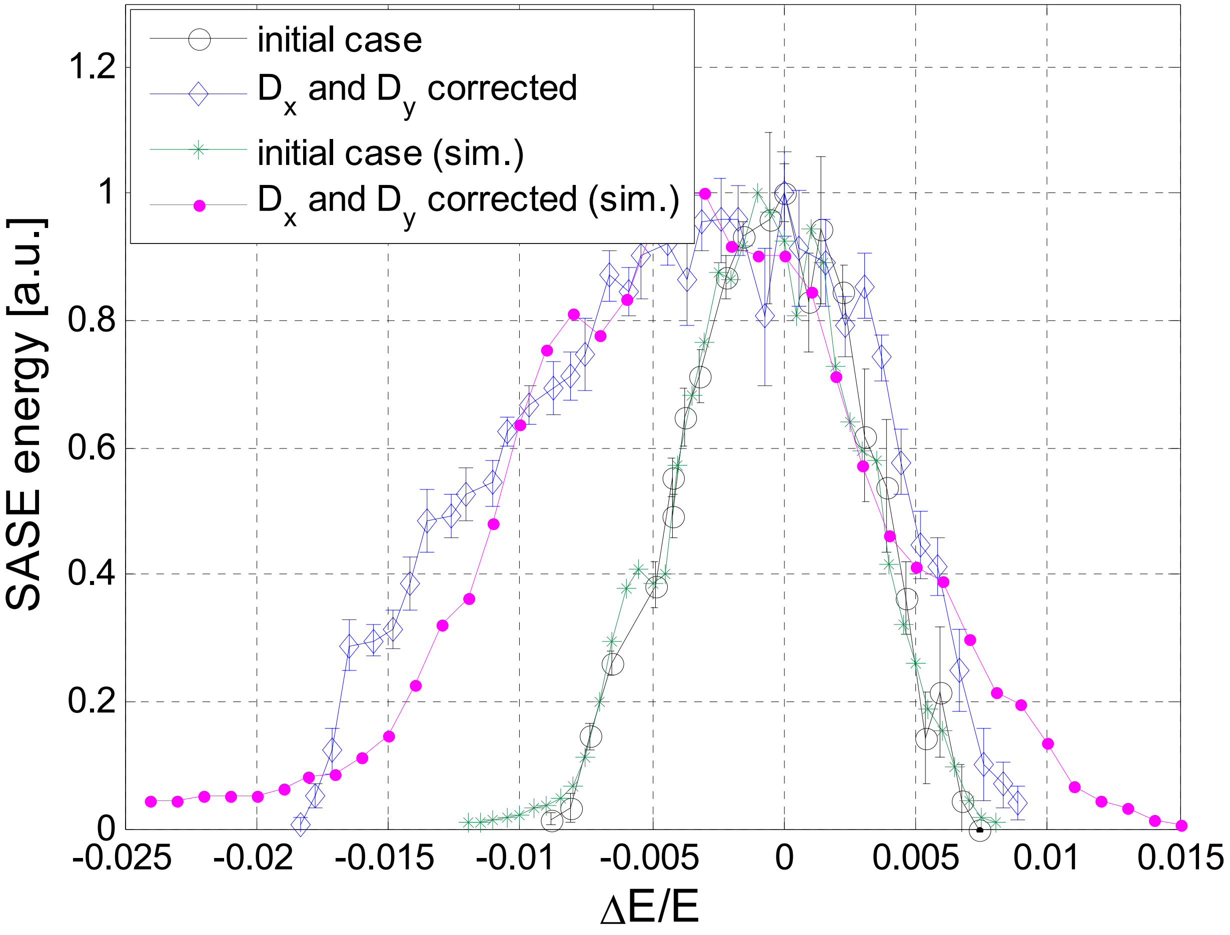
- trajectory changes:
  - $\Delta x,y = D_{x,y} \cdot \delta$
  - $\Delta x',y' = D'_{x,y} \cdot \delta$
- energy:
  - optics
  - undulator field
  - undulator focusing

Dispersion along the undulator: measurements and predictions according to the dispersion functions at the undulator entrance.

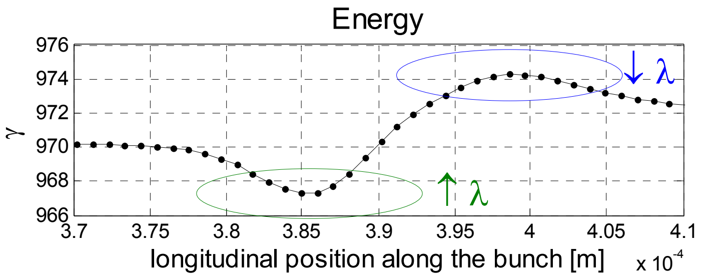


No dispersion is generated inside the undulator

SASE sensitivity to electron beam energy offset. Measurements and simulations.



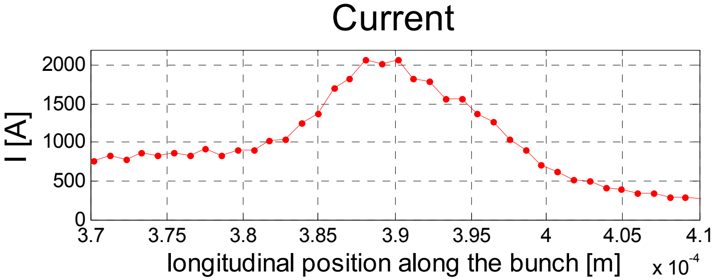
Dispersion impact on the SASE spectrum



Energy

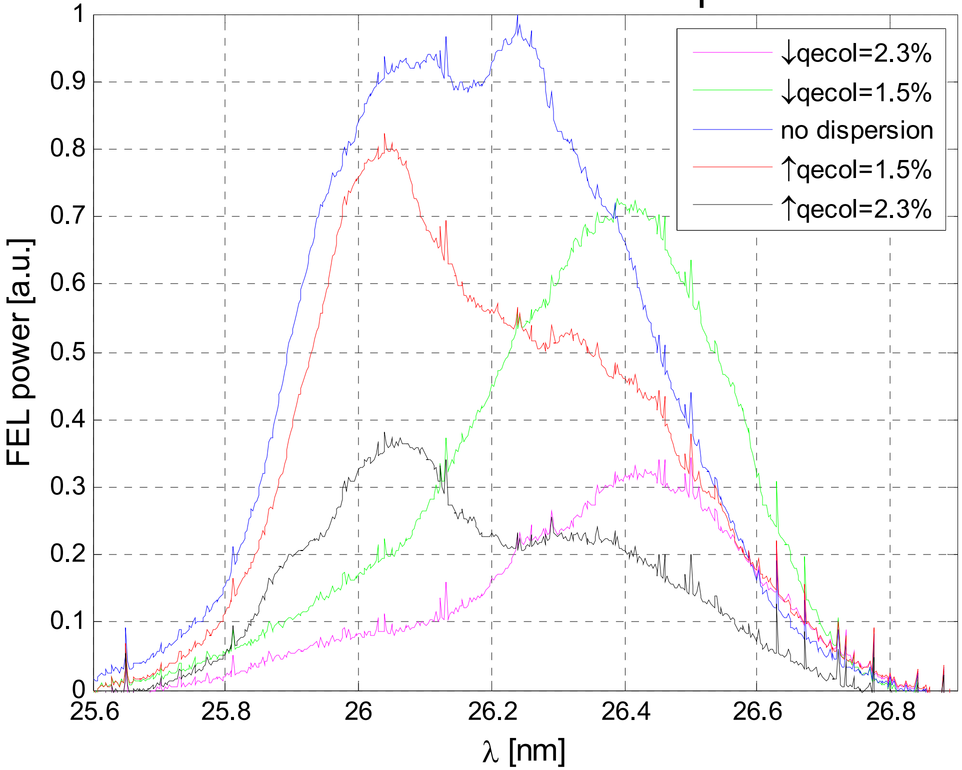
Dispersion deviates off-energy particle trajectories:

- FEL power ↓
- spectrum bandwidth ↓



Current

Measurements of SASE spectrum
for different horizontal dispersions



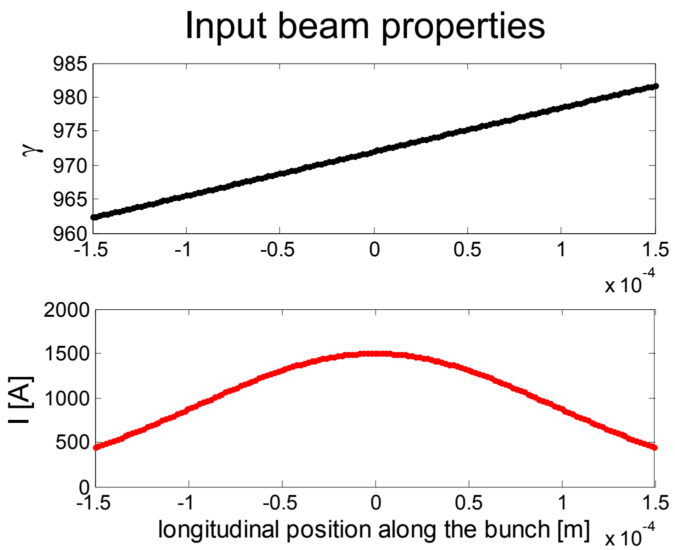
QECOL*1.01 → D_x = 10 mm (RMS)

$|D_x|$ > 0 → FEL power ↓
QECOL ↑ → λ_c ↓
QECOL ↓ → λ_c ↑

Dispersion impact on the SASE spectrum. Simulations with a Gaussian electron beam

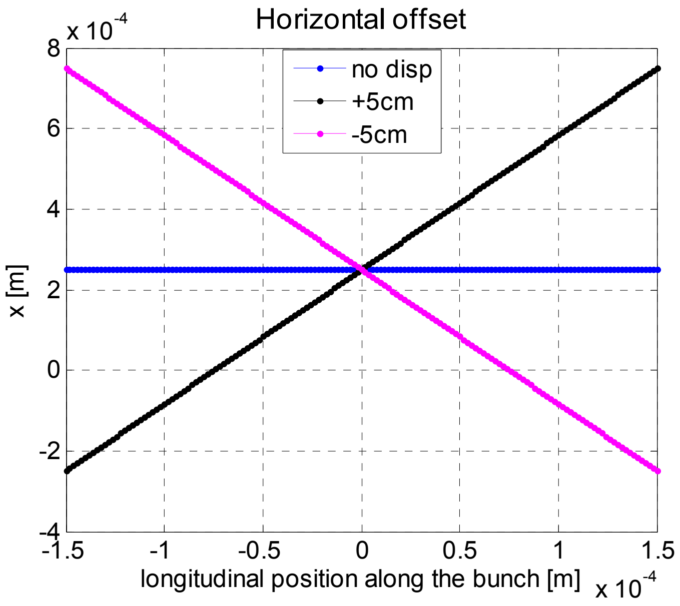
Study restricted to the impact of D_x and x

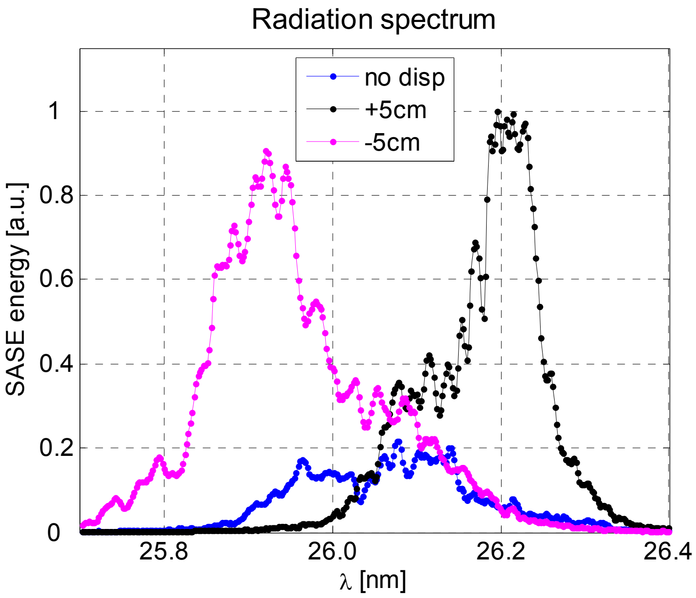
3 dispersion scenarios: $D_x = 0$
$D_x = +5$ cm
$D_x = -5$ cm



Initial offset distributions:

1. Zero offset along the bunch
2. Non-zero offset along the bunch
3. Quadratic x-energy correlation





Dispersion impact on the SASE spectrum. Realistic Simulations

Electron properties obtained from s2e simulations (M. Dohlus)

Considered cases:
- No dispersion
- Changes of QECOL of ±1.5%

Trajectory changes:

$x(i) = x_0(i) + D_x \cdot \delta(i)$

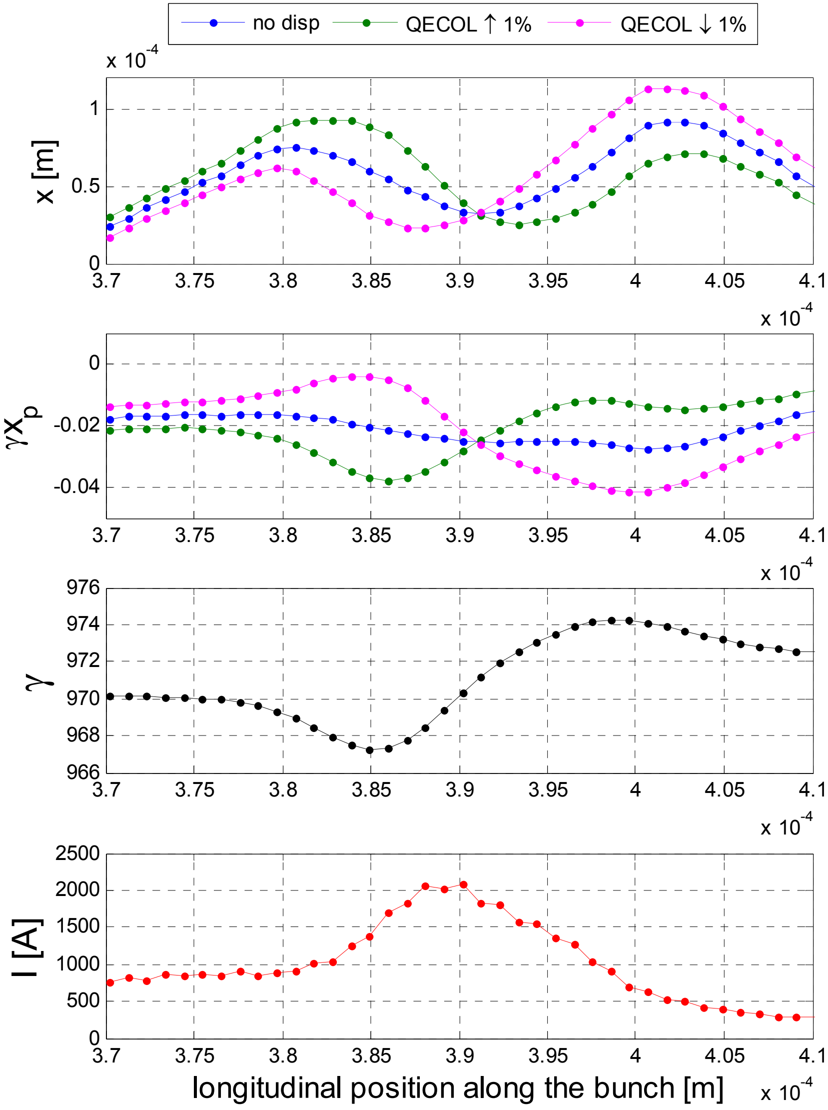
$x'(i) = x'_0(i) + D'_x \cdot \delta(i)$

There is a 2nd order correlation between x and energy (e.g. due to CSR effects). In addition:

$x_0 = 50\ \mu m$

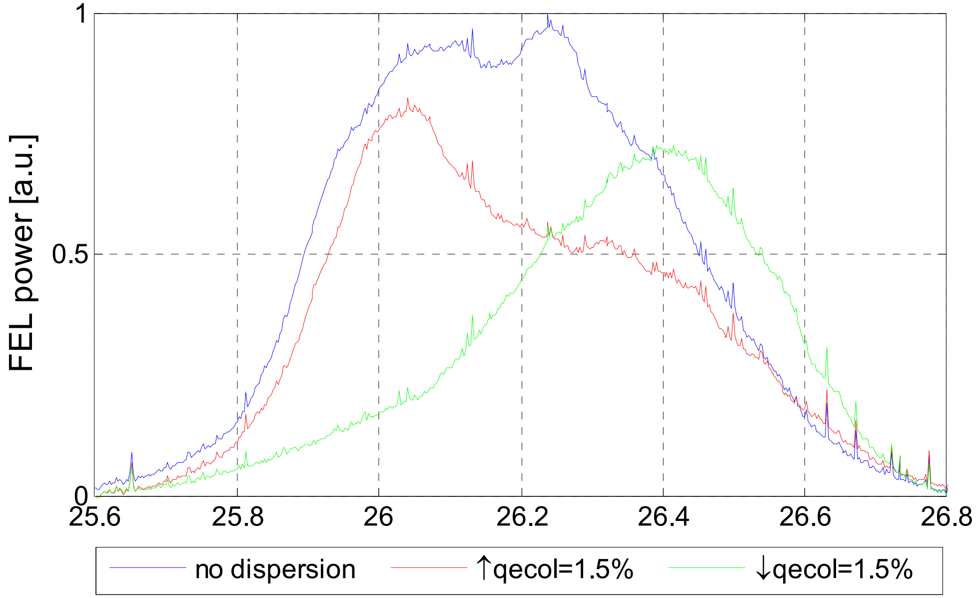
$x'_0 = -20\ \mu rad$

x and x' along the bunch

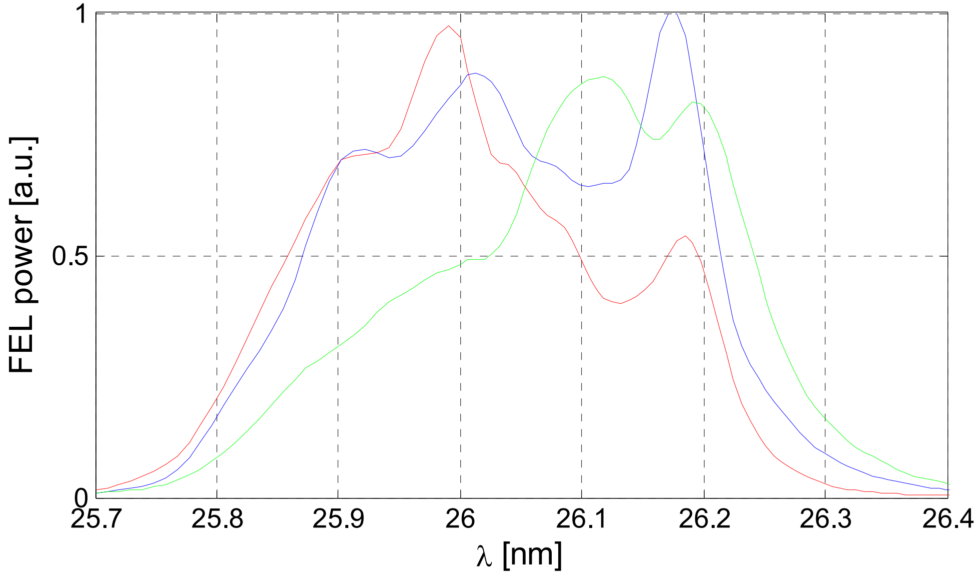


Dispersion impact on the SASE spectrum
Measurements versus simulations

Measurements



Simulations



Qualitative agreement

$|D_x| > 0 \rightarrow$ FEL power ↓

QECOL ↑ $\rightarrow \lambda_c$ ↓

QECOL ↓ $\rightarrow \lambda_c$ ↑

Difference: wavelength range is bigger in the measurements (due to a bigger energy chirp)

- Introduction
- Generation mechanisms of dispersion
- Measurement and correction
- Effects on transverse beam quality at FLASH
- Effects on FEL performance at FLASH
- Conclusion

Conclusion

- → A method to measure and correct dispersion has been presented. A tool based on this method able to correct the dispersion down to 5 mm has been implemented at FLASH.
- → Dispersion correction is a key issue for the optimization of the transverse beam quality at linac-based FEL facilities.
- → The SASE power jitter due to electron energy fluctuations was decreased by correcting dispersion.
- → The presence of dispersion reduces the FEL power and makes the radiation spectrum narrower.
- → It has been shown that dispersion can be used to shift the central wavelength of the SASE spectrum at FLASH.

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