Measurements and Analysis of Coherent Synchrotron Radiation Effects at FLASH

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Disputation
13.11.2007

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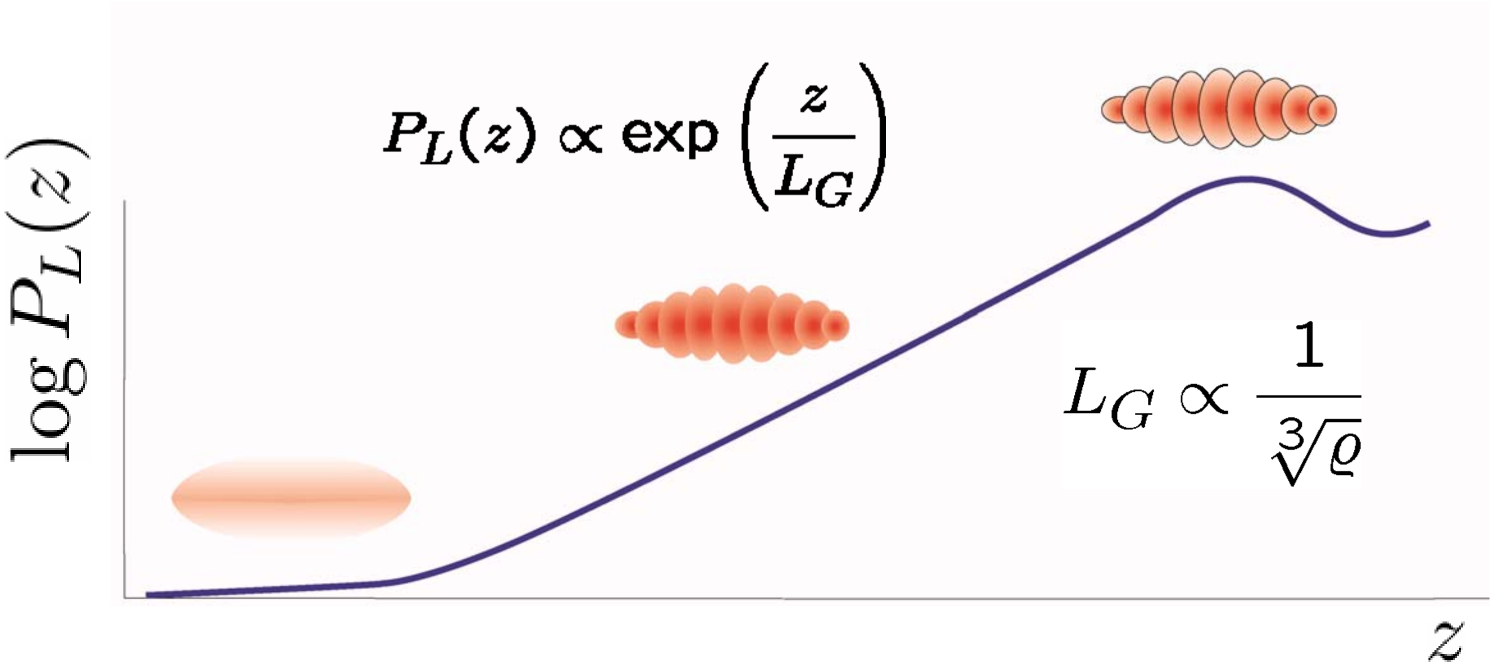
DESY

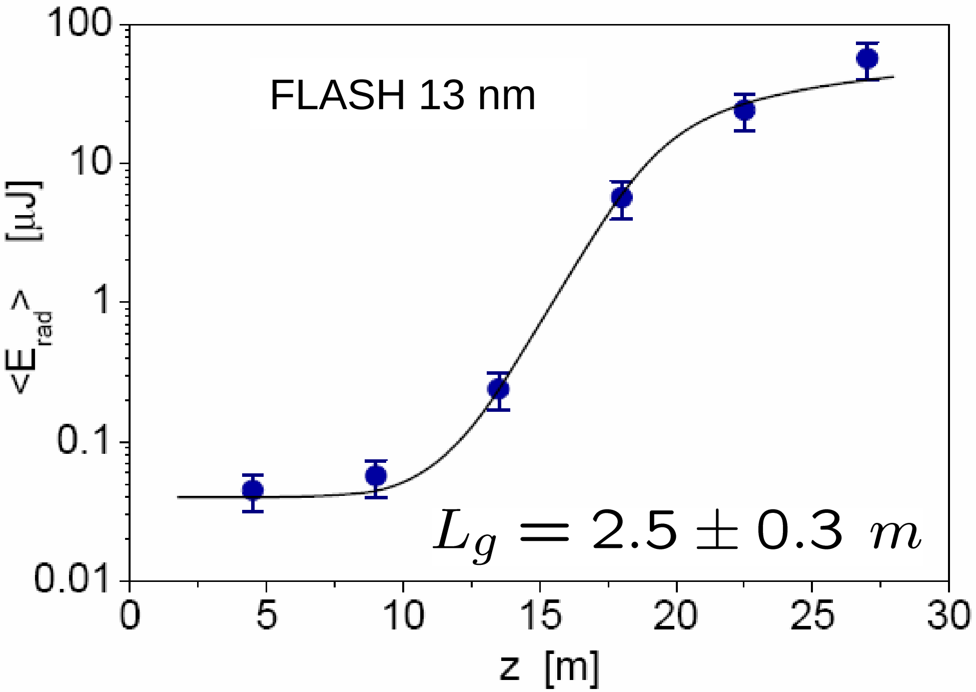
- Free Electron Lasers and Linear Colliders require electron bunches of high charge density in phase space
  - Electromagnetic fields generated by these electron bunches interact with the beam itself spoiling beam quality
  - Emission of coherent synchrotron radiation in the bunch compressors is one important effect in the beam dynamics of such accelerators

- In this thesis the influence of coherent synchrotron radiation (CSR) effects on the electron beam at FLASH were studied
  - Numerical analysis provided an understanding of the physical effects
  - Experiments on these effects were done with a transverse RF-deflecting structure
  - Coherent synchrotron radiation effects were observed and compared with simulations which provided a good benchmark for such tracking tools



Radiation output power of an SASE (“Self Amplified Spontaneous Emission”) free electron laser grows exponentially along the undulator.

Radiation gain length L_G depends on the charge density of the electron bunch. Transverse and longitudinal bunch dimensions determine the required length of the undulator to reach maximum output power.



SASE at FLASH:	Wavelength	47 – 6 nm
	Energy per pulse (peak/average)	70μJ / 40μJ (at 13.7 nm)
	Photon pulse duration	10 fs
	Power (peak/average)	10 GW / 20 mW

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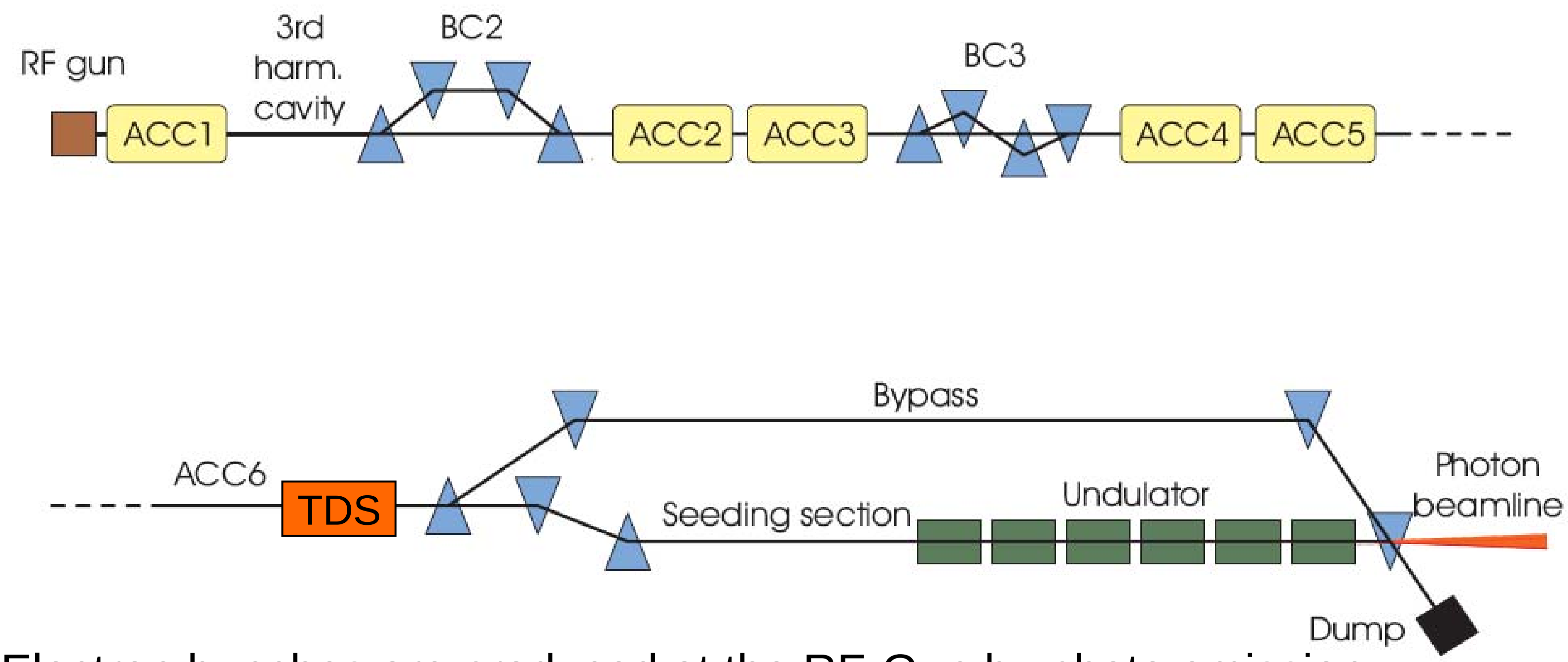
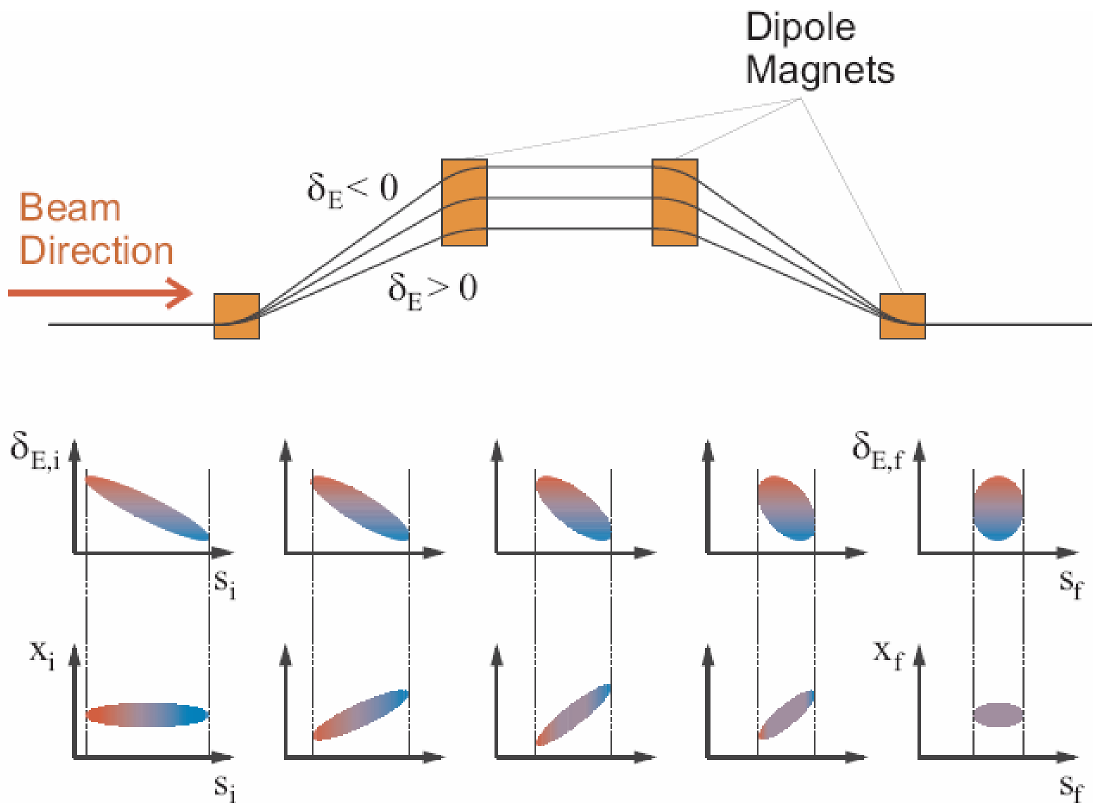


- Electron bunches are produced at the RF-Gun by photo emission
- Peak current of about 50 A with a bunch length of about 3 ps
- Acceleration in TESLA-type cavities in cryomodules of eight cavities each (~20MV/m)
- Longitudinal bunch compression in two chicanes (BC2 and BC3) to reach about 2 kA in the undulator
- A transverse deflecting RF-structure (TDS) was used for coherent synchrotron radiation experiments

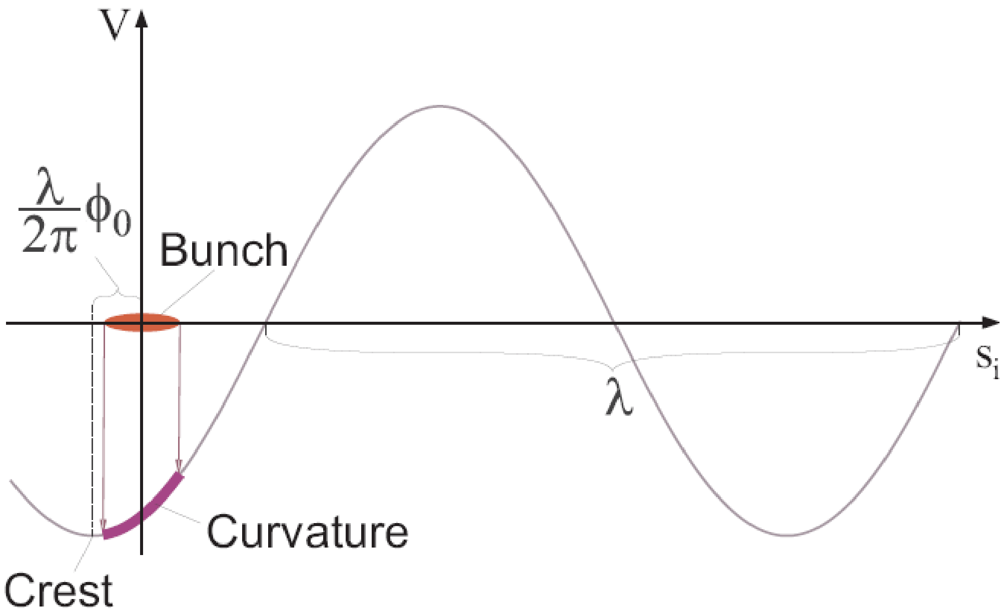
Head particles have a lower energy…

…than the tail particles.



The tail electrons move on a shorter path which allows them to overtake the leading electrons.

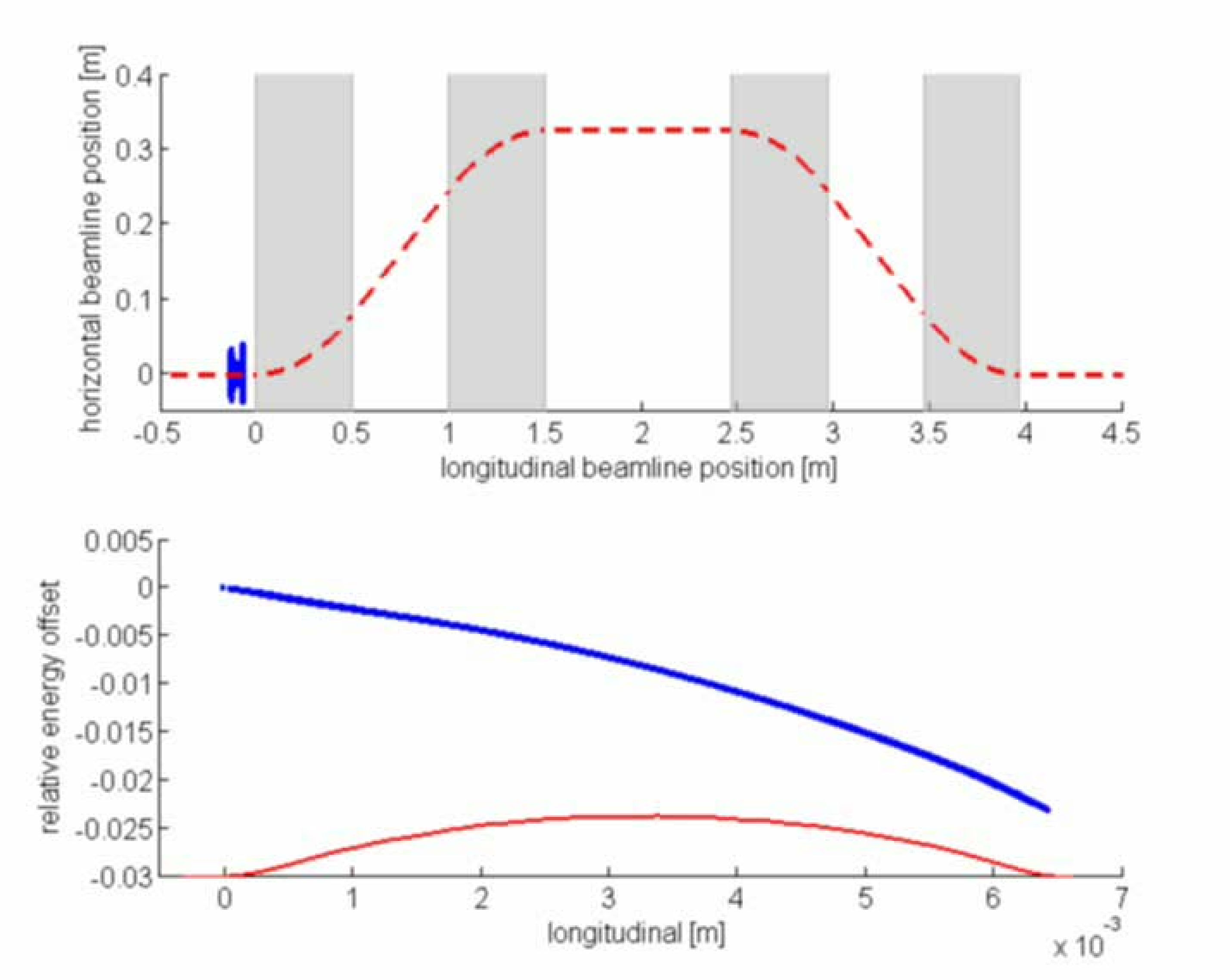
Accelerating field in a RF-cavity: $E(s) = eV \cos\left(\phi + \frac{2\pi}{\lambda}s\right)$



Correlated energy offset along the bunch:

$$\begin{aligned}\delta_{\mathrm{RF}}(s) &= \frac{\Delta E}{E} = \frac{E(s) - E(0)}{E} \\ &= -\frac{2\pi eV}{E\lambda}\sin\phi s - \frac{2\pi^2 eV}{E\lambda^2}\cos\phi s^2 \\ &\approx As + Bs^2\end{aligned}$$

Bunch Compression



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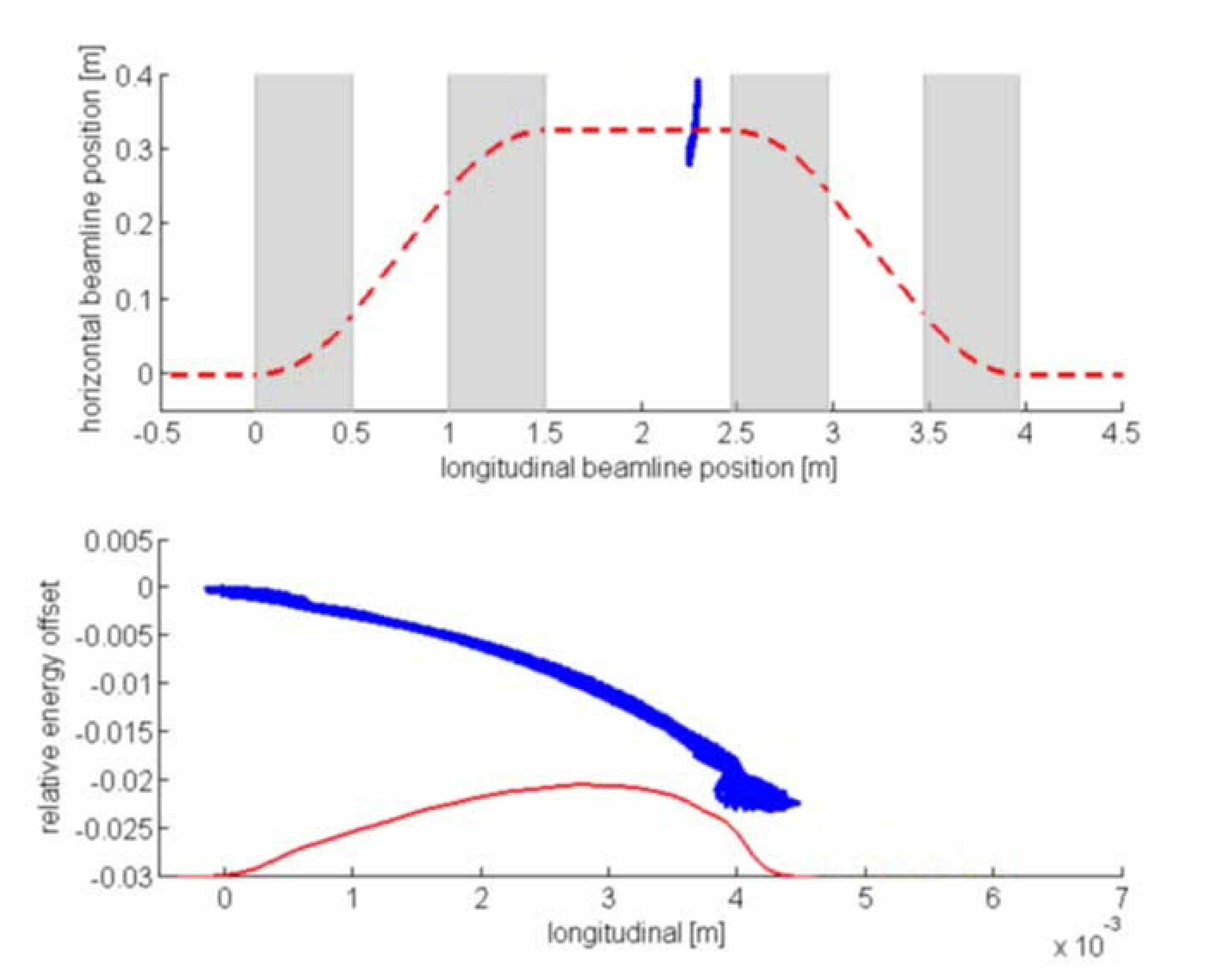
horizontal beamline position [m]
0.4
0.3
0.2
0.1
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
longitudinal beamline position [m]
relative energy offset
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
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1
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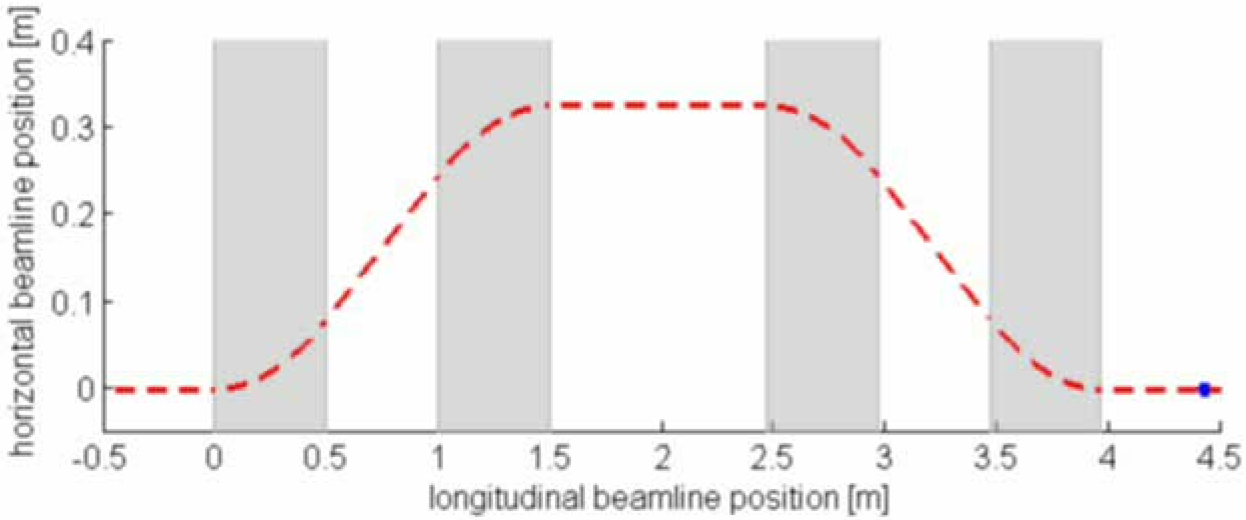
6
7
longitudinal [m]
x 10^-3


horizontal beamline position [m]
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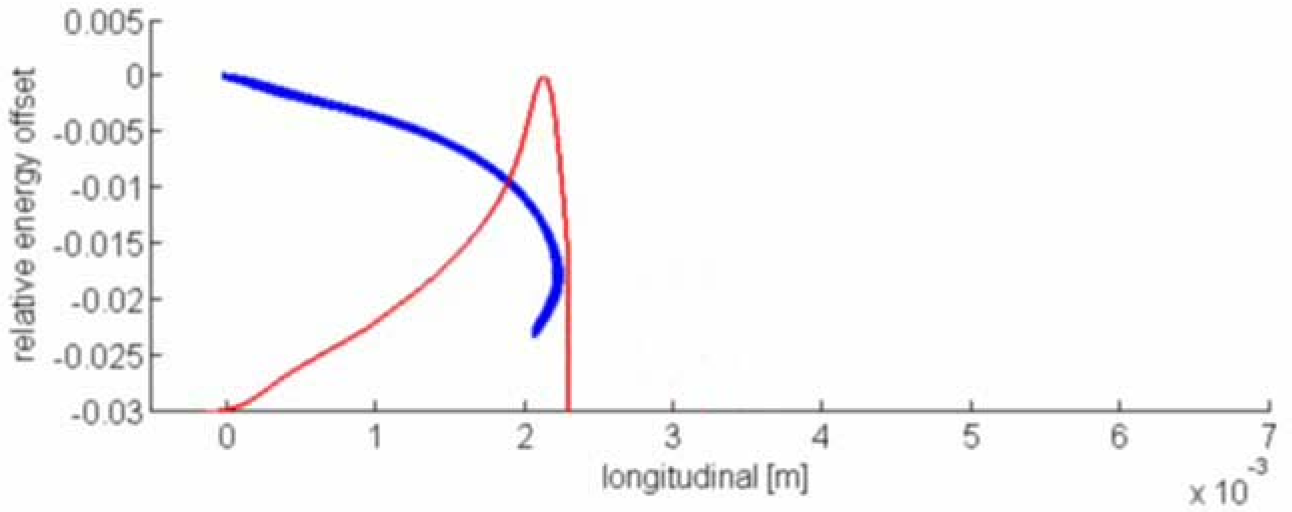
longitudinal beamline position [m]


relative energy offset
0.005
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-0.005
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-0.015
-0.02
-0.025
-0.03
0
1
2
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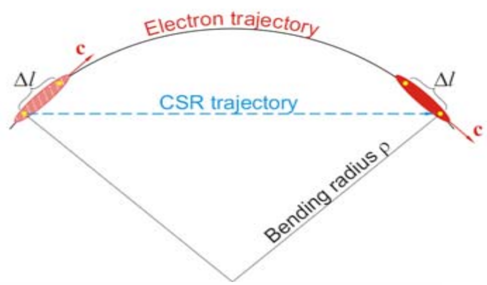
4
5
6
7
longitudinal [m]
x 10^-3

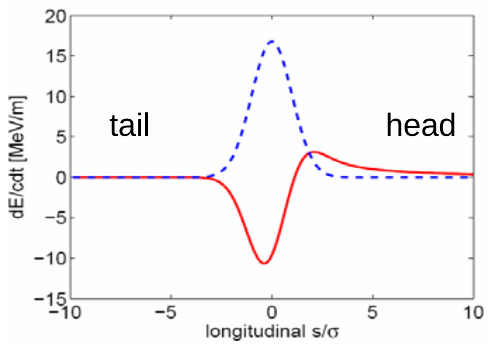
Self Interactions

High charge densities give rise to strong electro-magnetic fields generated by the electron bunches.

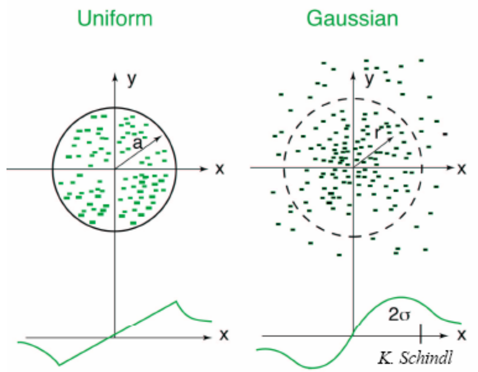
Electrons within the bunch experience these fields.

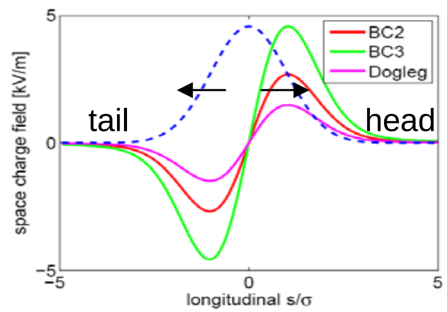
- Coherent Synchrotron Radiation



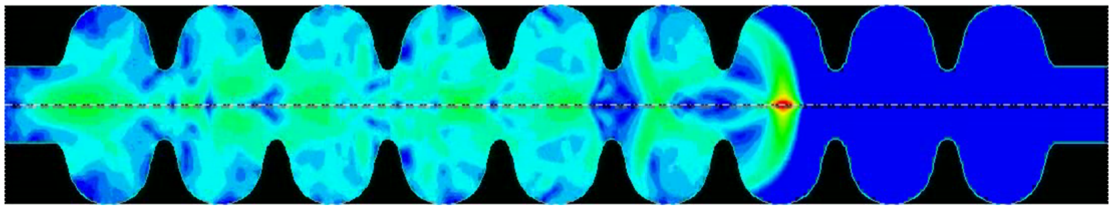


- Space Charge fields

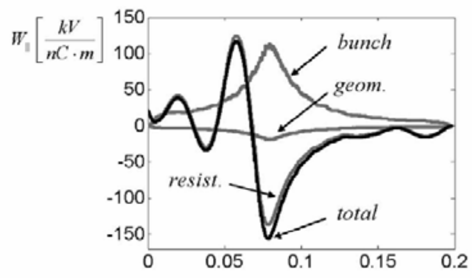




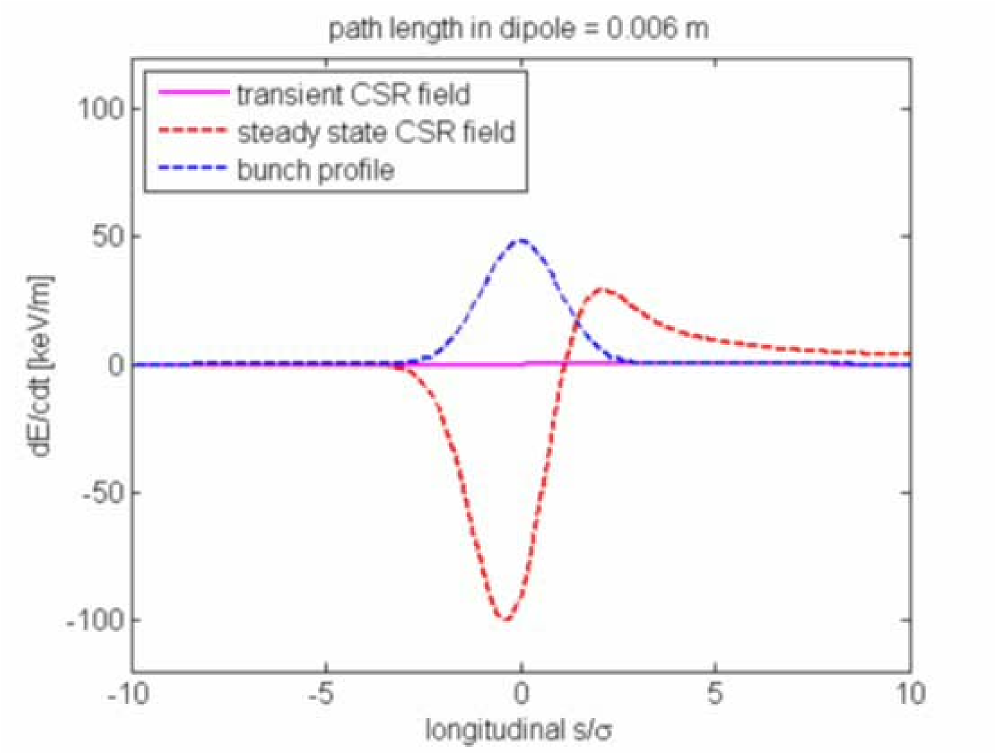
- Wake fields



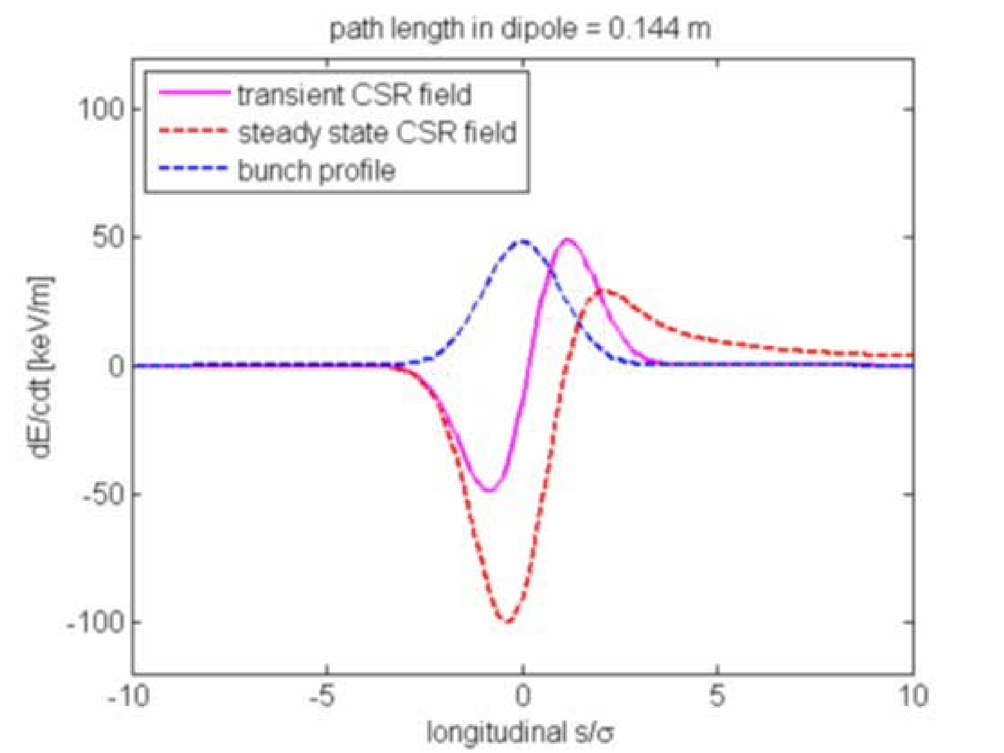
M. Dohlus



I.A. Zagorodnov



- Circular motion model not sufficient for entrance and exit of the bending magnets
- Transient CSR field converges toward the circular motion solution
- Analytic models are available base on 1D line charge density of the electron bunch



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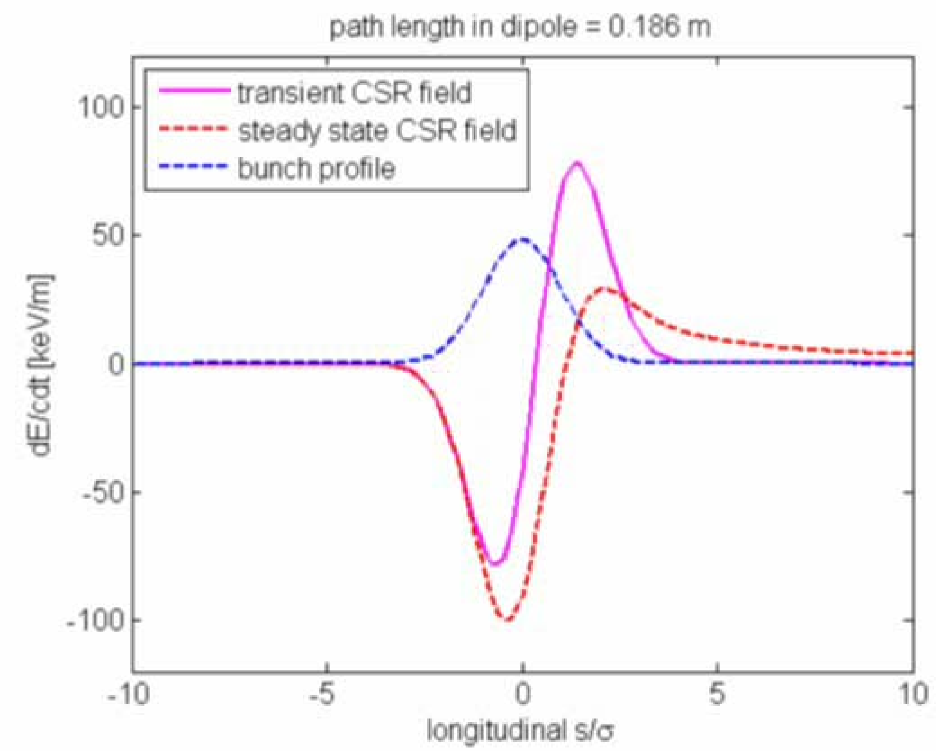
Coherent Synchrotron Radiation



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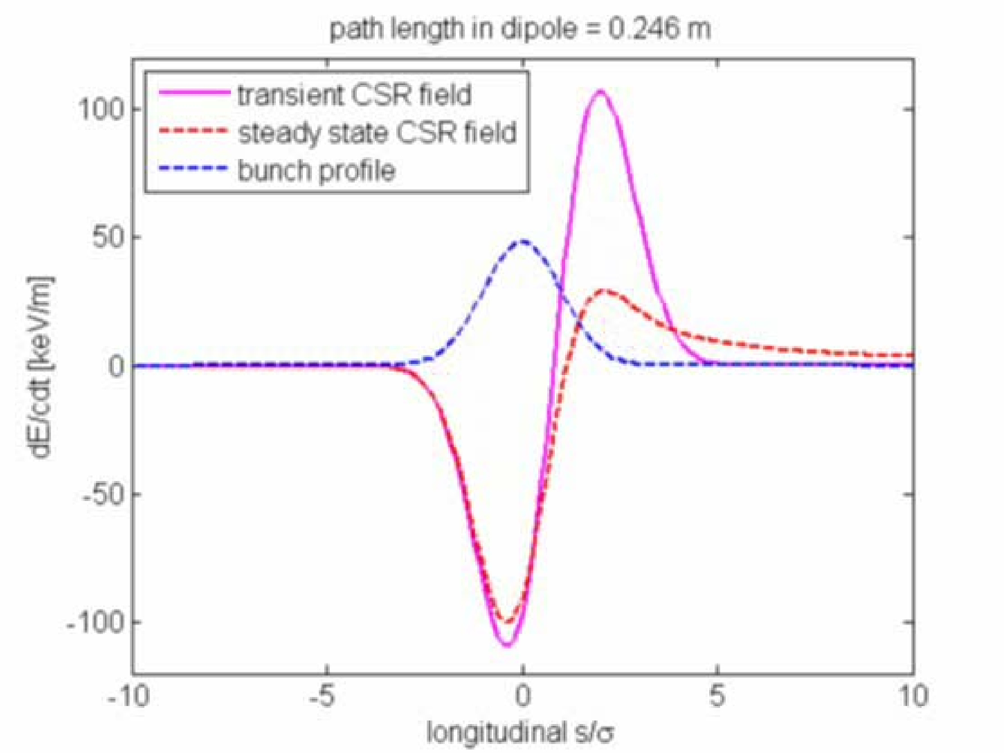

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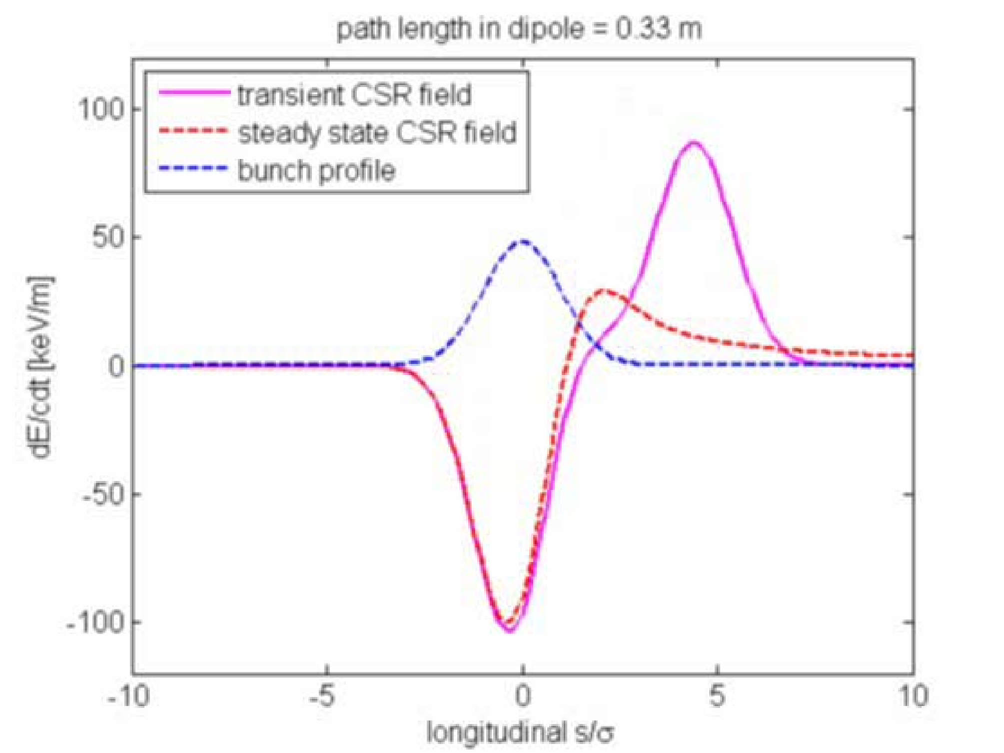

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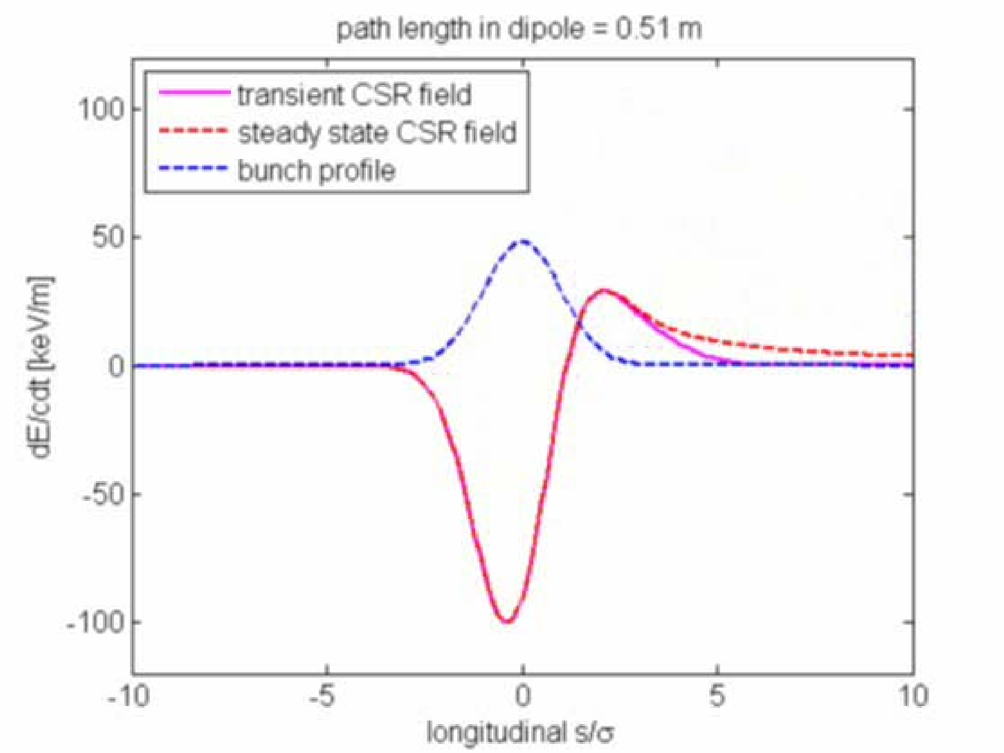

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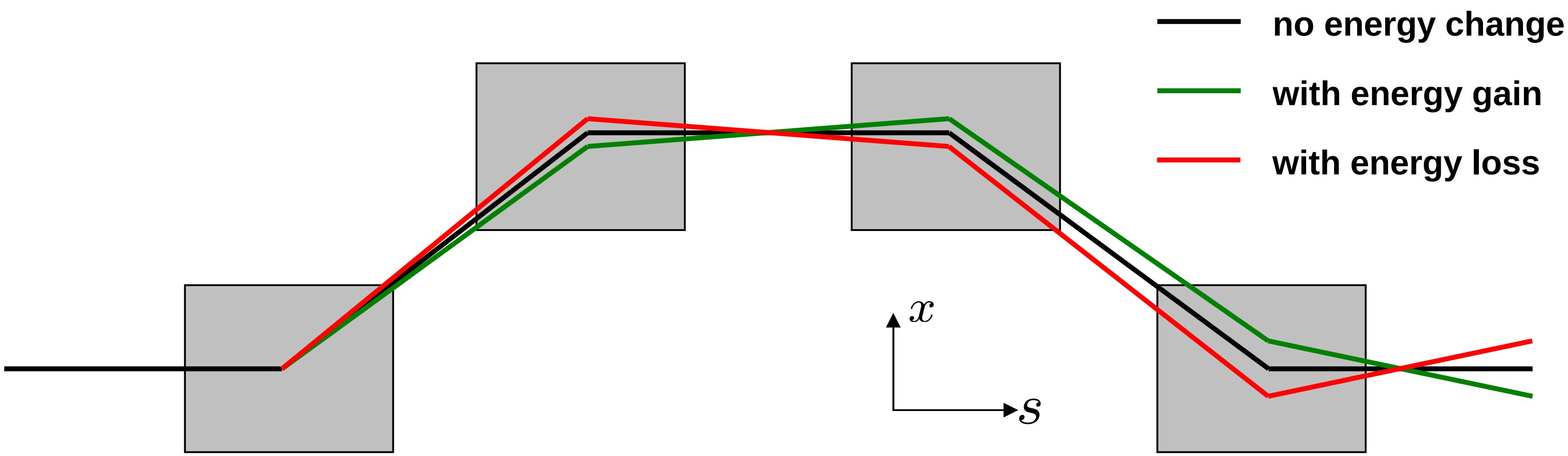
Effects of Coherent Synchrotron Radiation on Beam emittance



Every particle will have an individual angle x'(s) and offset x(s) behind the chicane.

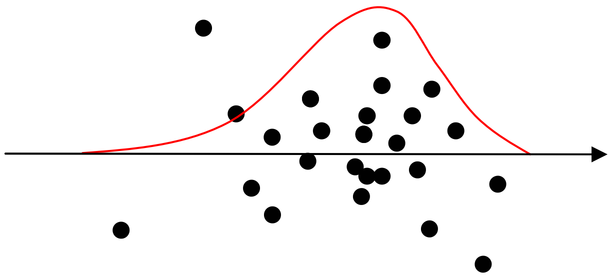
Emittance :

$$\varepsilon = \gamma\sqrt{< x^2 >< x'^2 > - < xx' >^2}$$

⇒The CSR interaction leads to emittance growth in an bunch compressor

- Self-fields are calculated from macro-particles

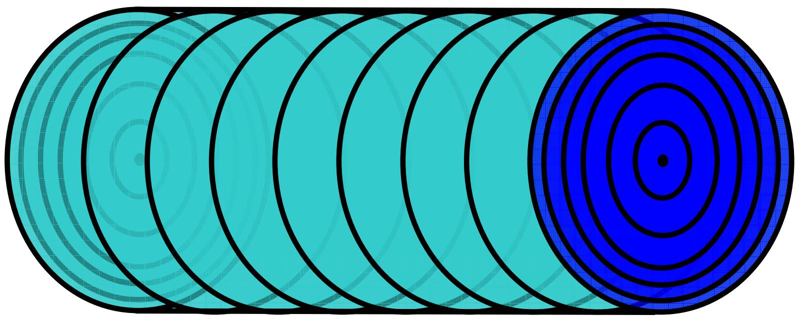
- Each time step each test particle experiences the force of the whole particle distribution

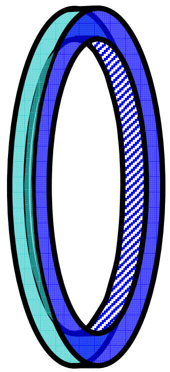


- From updated particle positions at each time step new fields are calculated

- Different methods and approximations for field calculations are used for different types of self-effects (Space Charge forces, CSR effects, Wake fields….)

e.g. ASTRA (A Space charge TRacking Algorithm):





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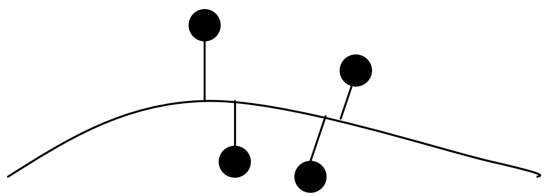
Different Methods for CSR Tracking Calculations

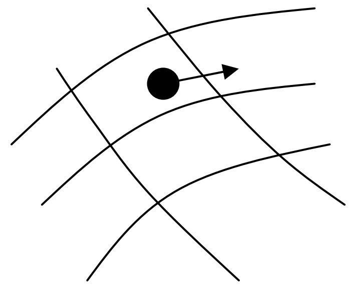
"Projected Method" (1D): (e.g. ELEGANT, CSRTrack, ASTRA)

- analytic calculation for 1D Charge profiles
- fast but neglects transverse effects
- N~100.000 particles



"Green's Function Method" (2D): (e.g. CSRTrack)

- calculation of longitudinal and transverse fields on a 2D mesh
- not as fast as 1D calculations but more accurate
- N~10.000 particles

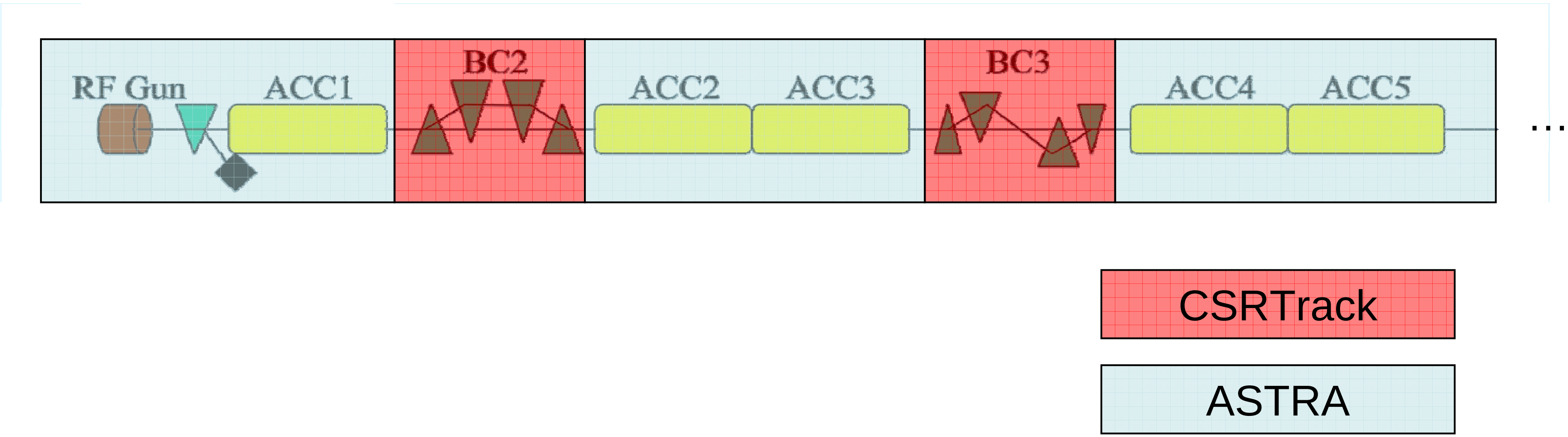


"Direct / Convolution Method" (3D): (e.g. TraFiC4 and CSRTrack)

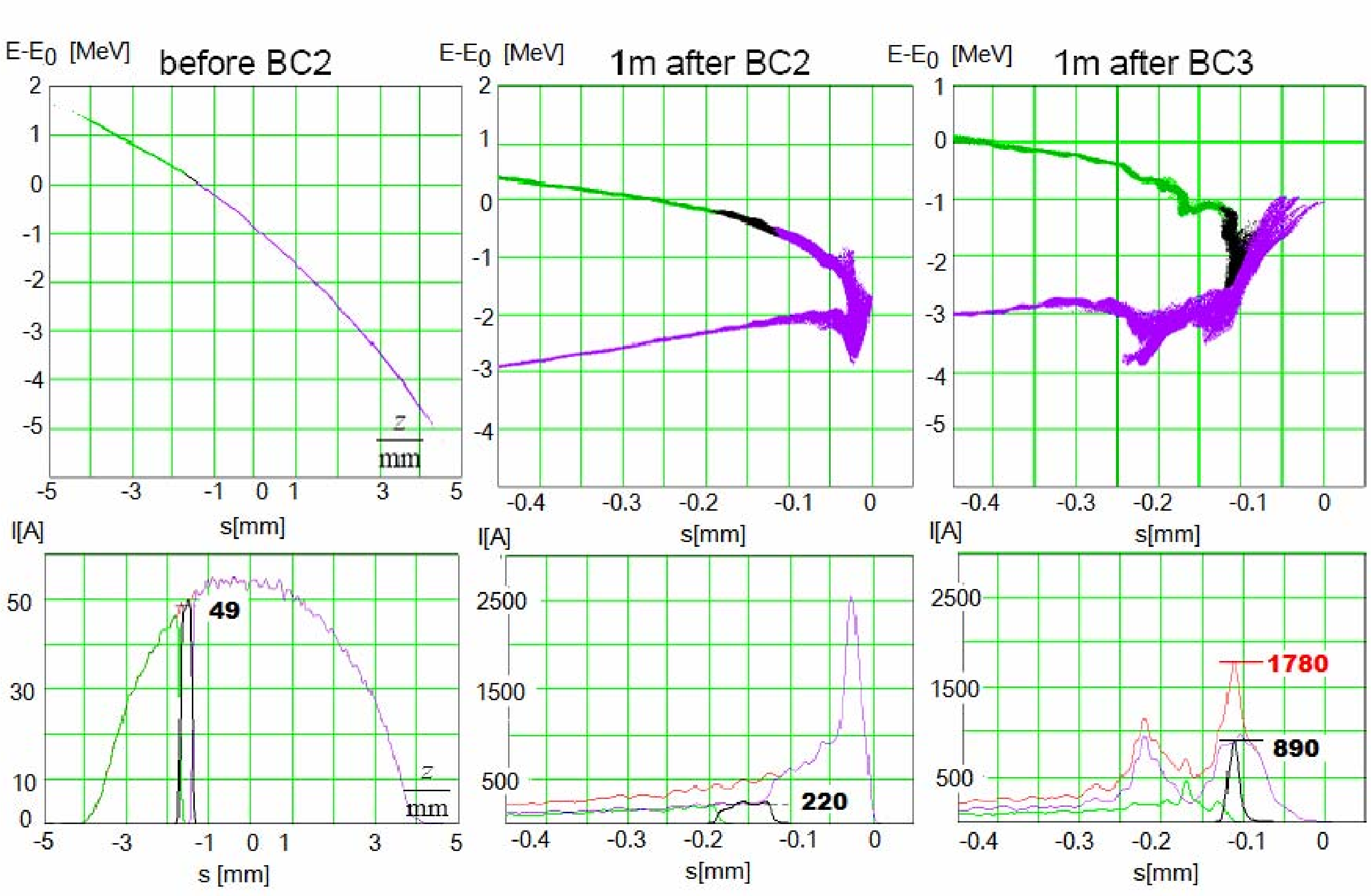
- numeric 3D integration of scalar and vector potentials
- slow but very accurate
- only N~1000 particles

- Particle distributions are tracked from the electron source toward the end

- Different tracking codes are used for different parts of the beamline were different self field effects are expected
  - ASTRA optimised for space charge forces and photo emission (K. Flöttmann)
  - CSRTrack is offers different methods for CSR calculations (M. Dohlus)



ACC1 14 deg off-crest



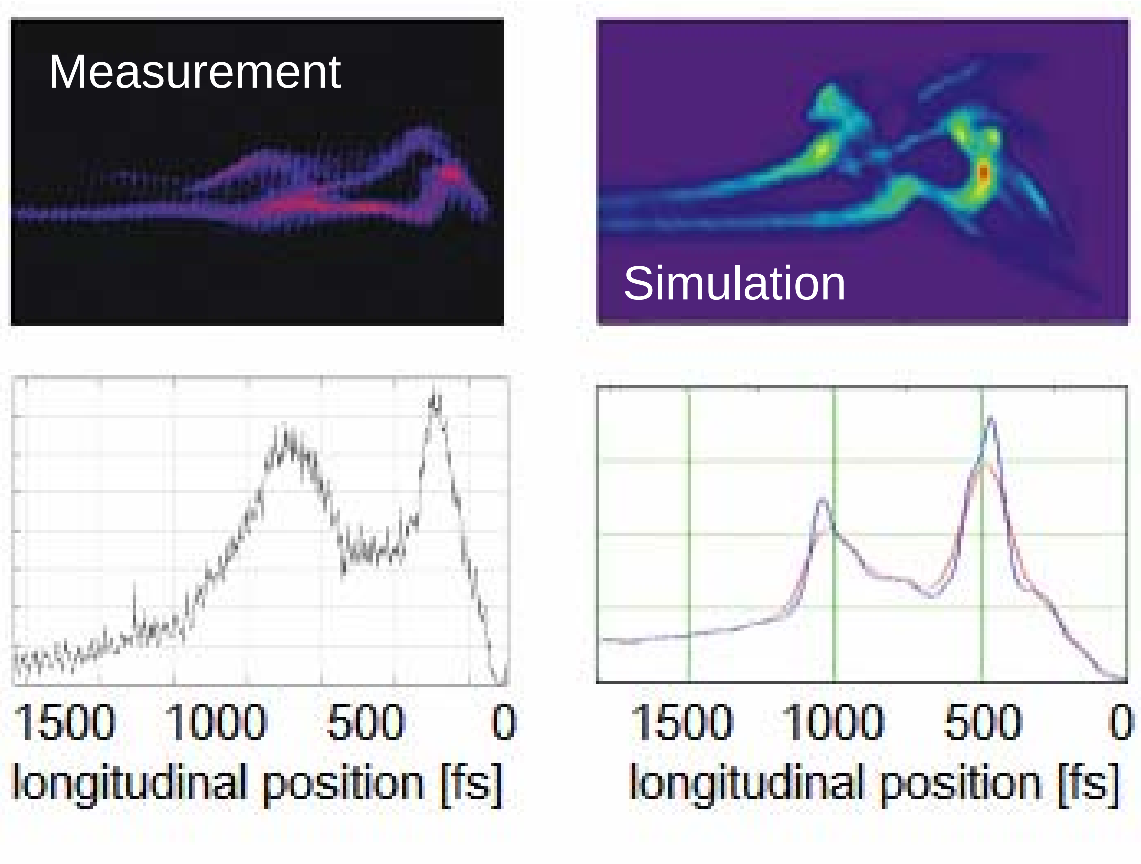
M. Dohlus

Comparison of FLASH Simulations with Measurements

Qualitative agreement between tracking calculations and measurements.

Space Charge and CSR effects are commingled, which leads to complicated beam profiles.

Dedicated studies on CSR effects requires an operation mode without these complicated behaviour.



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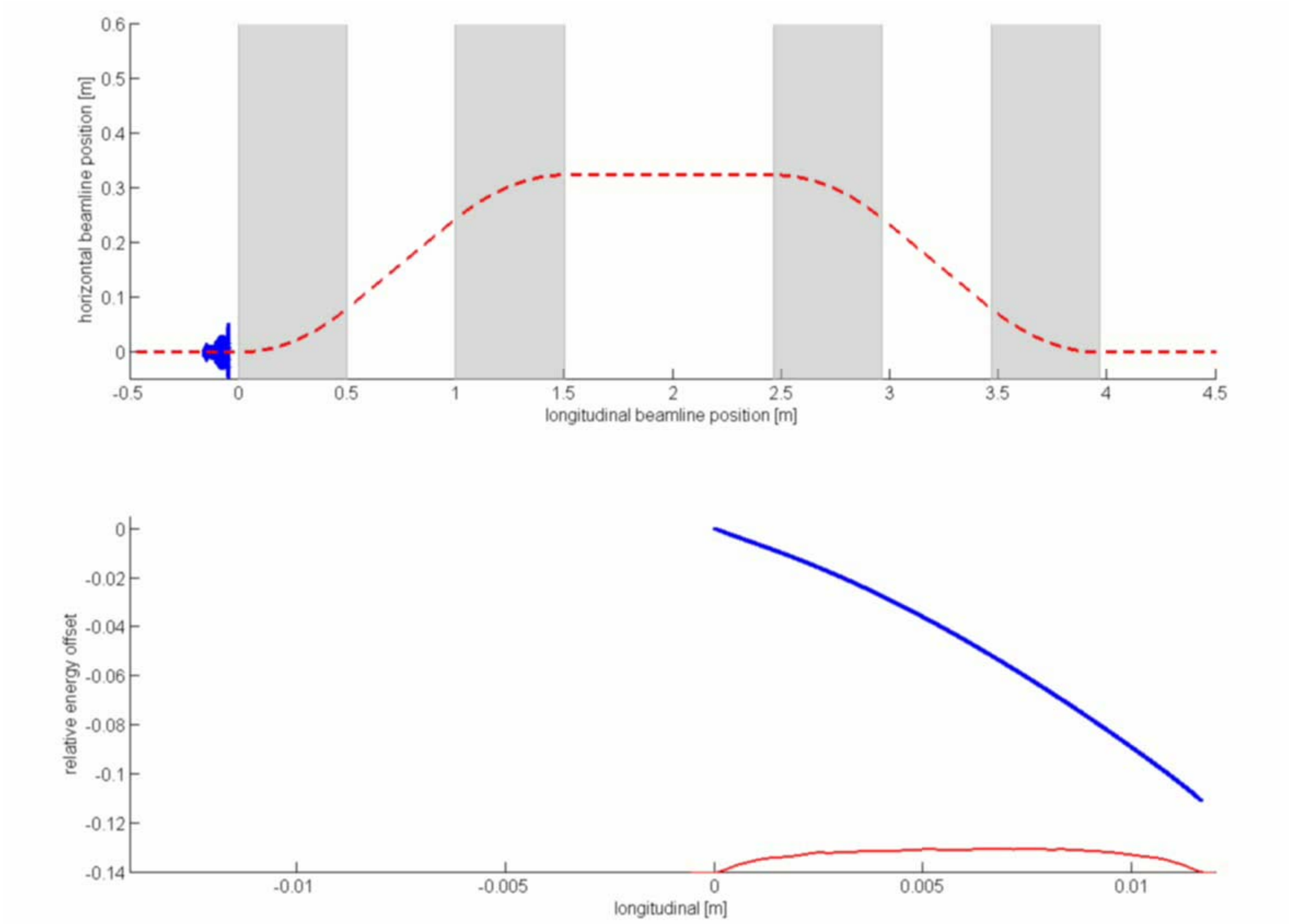
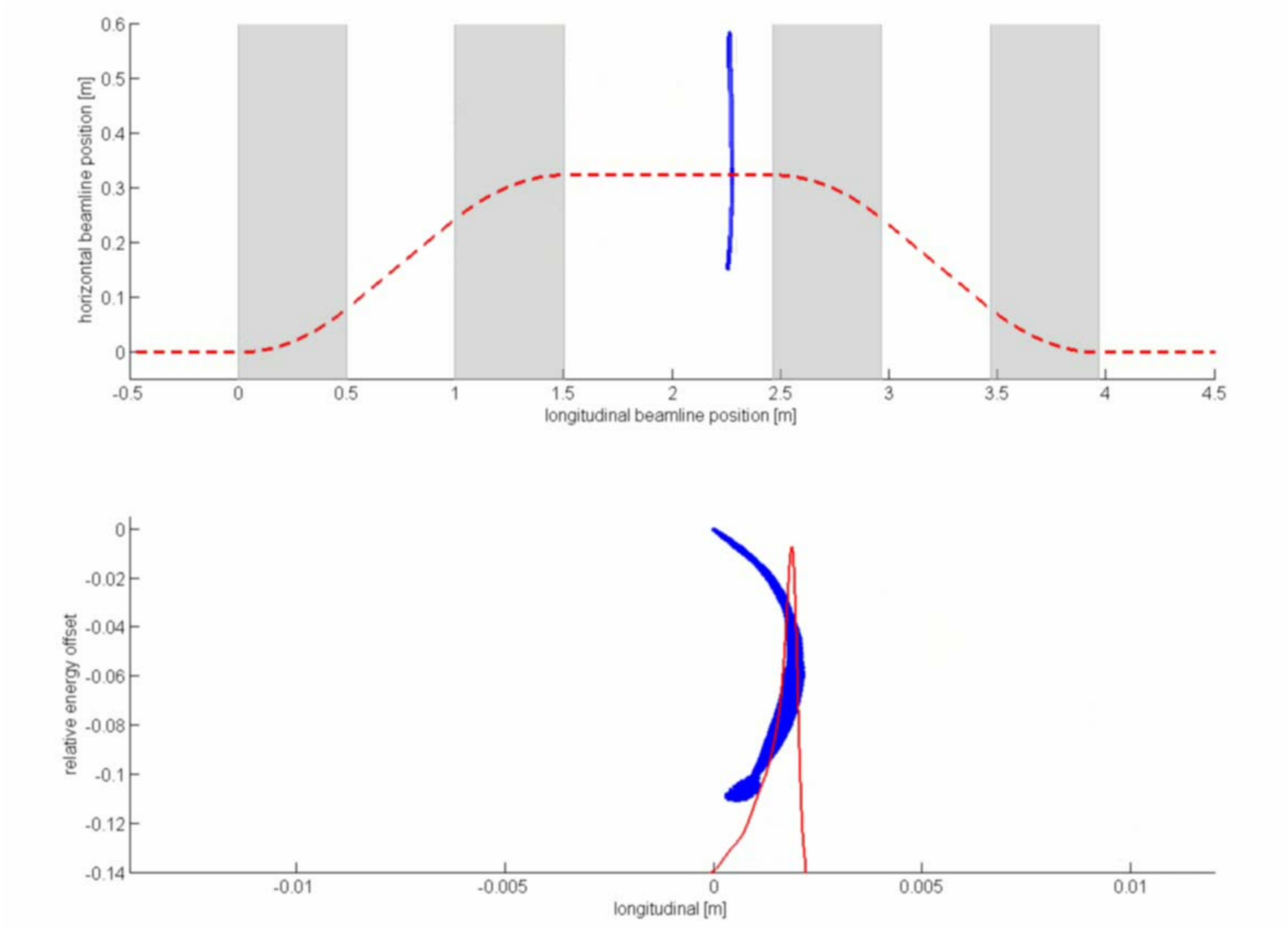
Dedicated Experiment on CSR interactions

Over-Compression leads to a high peak current inside the chicane and a low peak current downstream mitigating self field effects.



Dedicated Experiment on CSR interactions

Over-Compression leads to a high peak current inside the chicane and a low peak current downstream mitigating self field effects.



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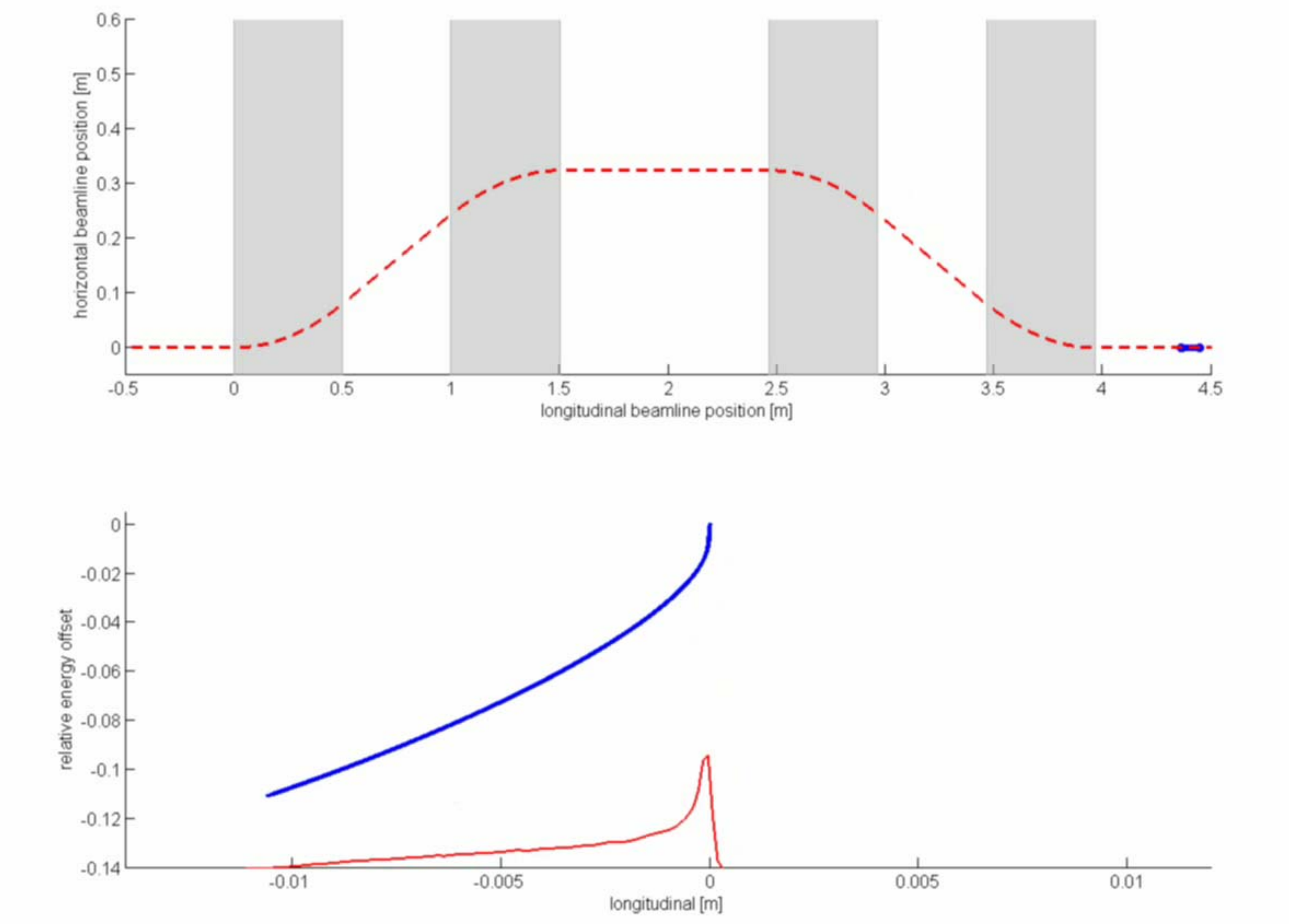

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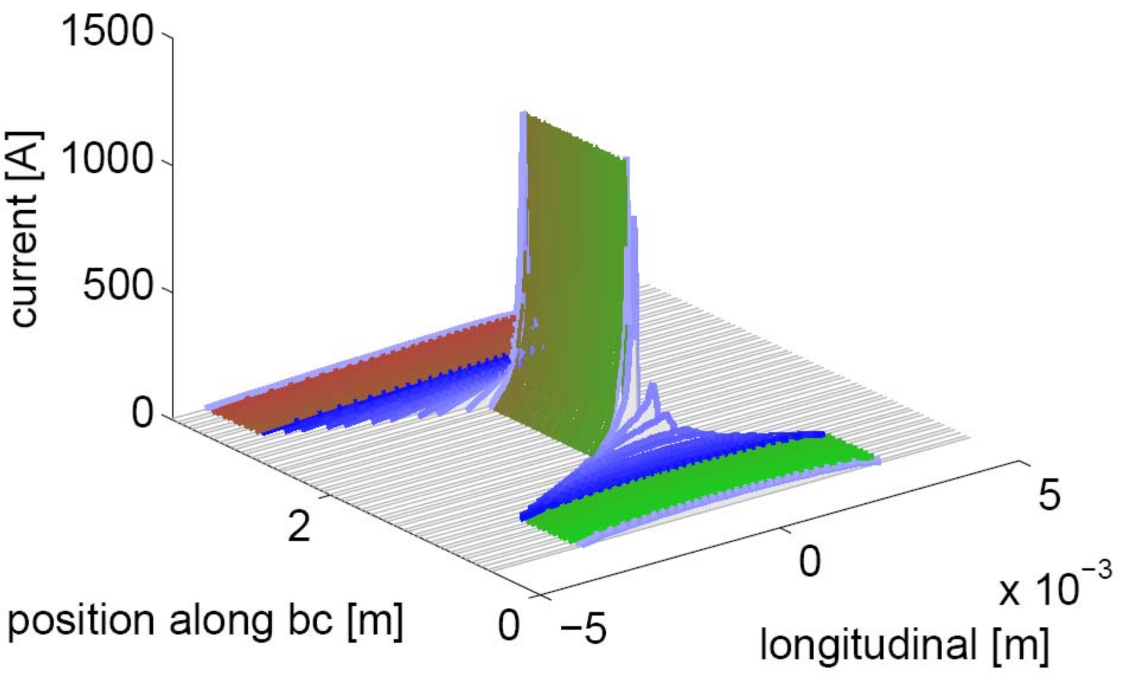
Peak Current in Over-Compression

- Over-compression in BC2 bunch length is only short within the chicane
- High beam current only within the inner dipoles of BC2.
- self field effects except CSR are substantially reduced



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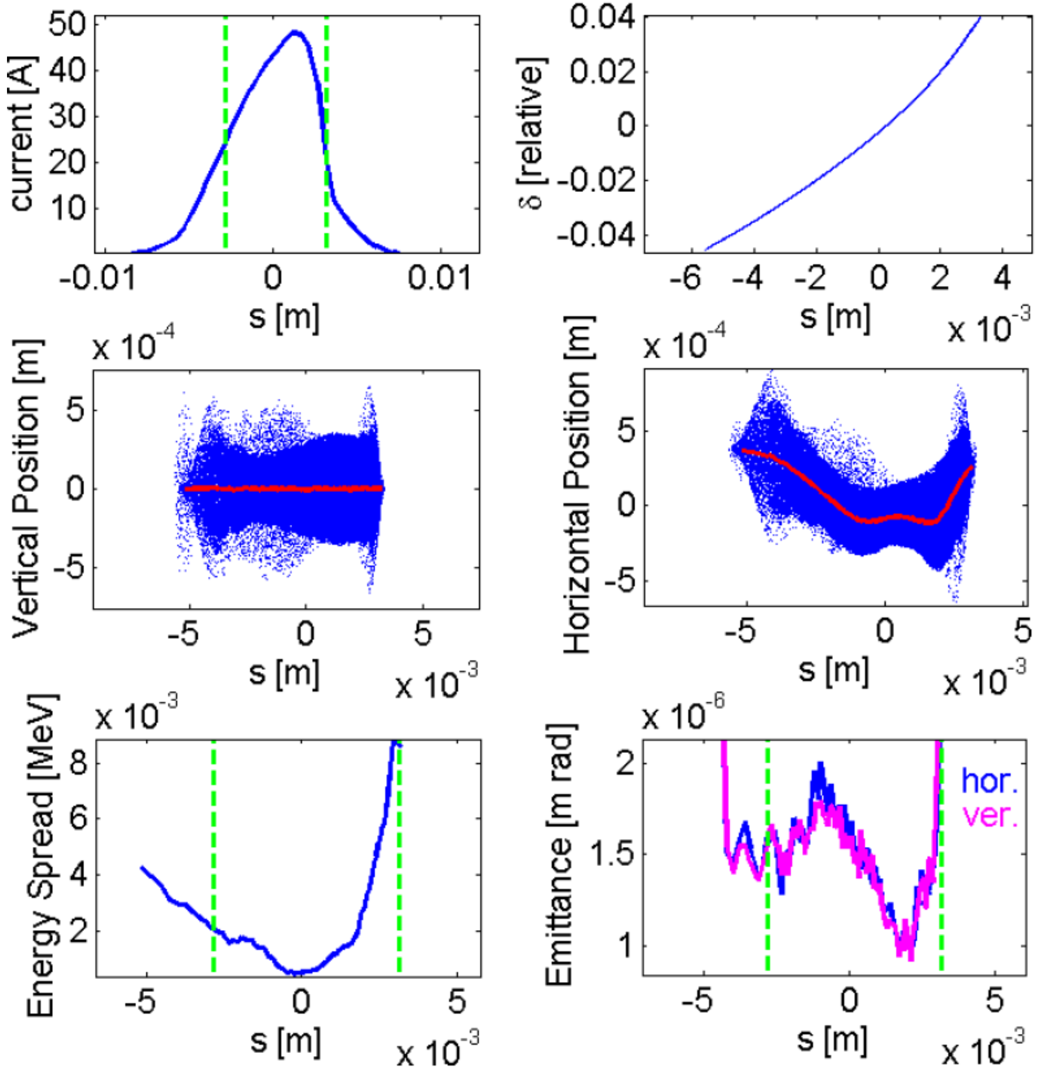
Beam Properties after Over-Compression

Downstream BC2:

- Peak current is below 50 A
- Longitudinal phase space is reversed
- Vertical profile is nomal
- Strong shift of horizontal slice centroid positions
- Low effect on the energy spread
- Small slice emittance increase at bunch centre

=> Horizontal centroid shift are a good measure for CSR effects



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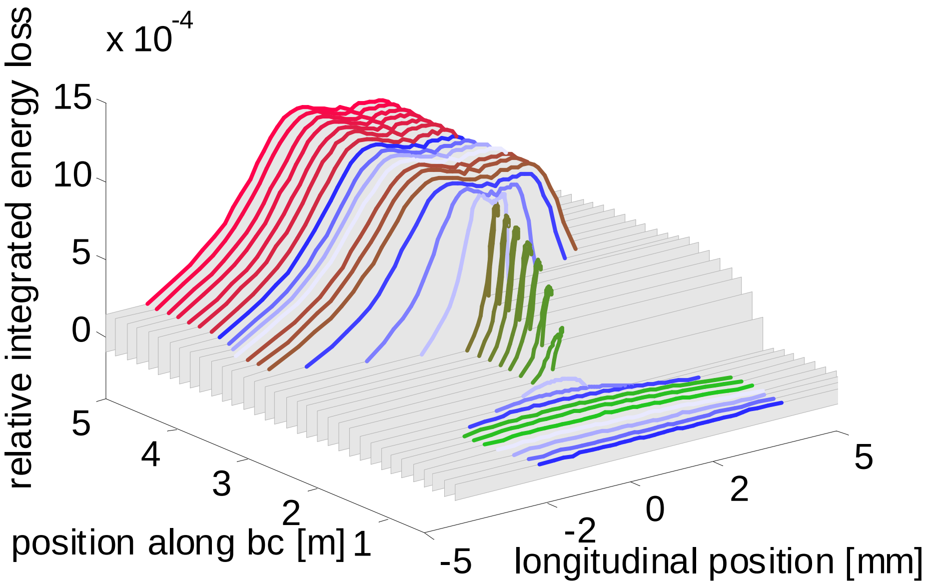
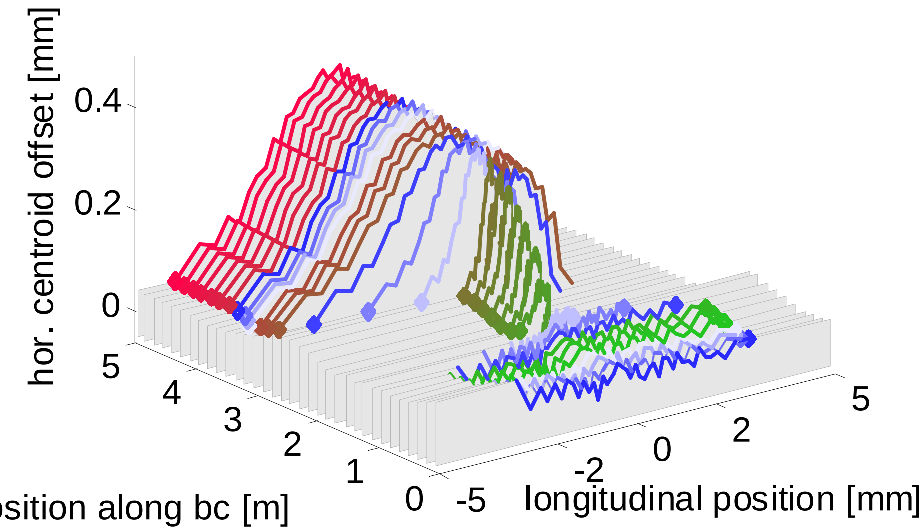
Evolution of CSR induced Centroid Shifts

- CSR energy loss between the 2nd and 3rd dipole of BC2.
- Particles with changed energy don't return to design orbit in the last dipoles.
  => Horizontal displacement of the beam centroids





Subtraction of the dispersion contributions to the horizontal position makes the centroid shift effect visible along the chicane.

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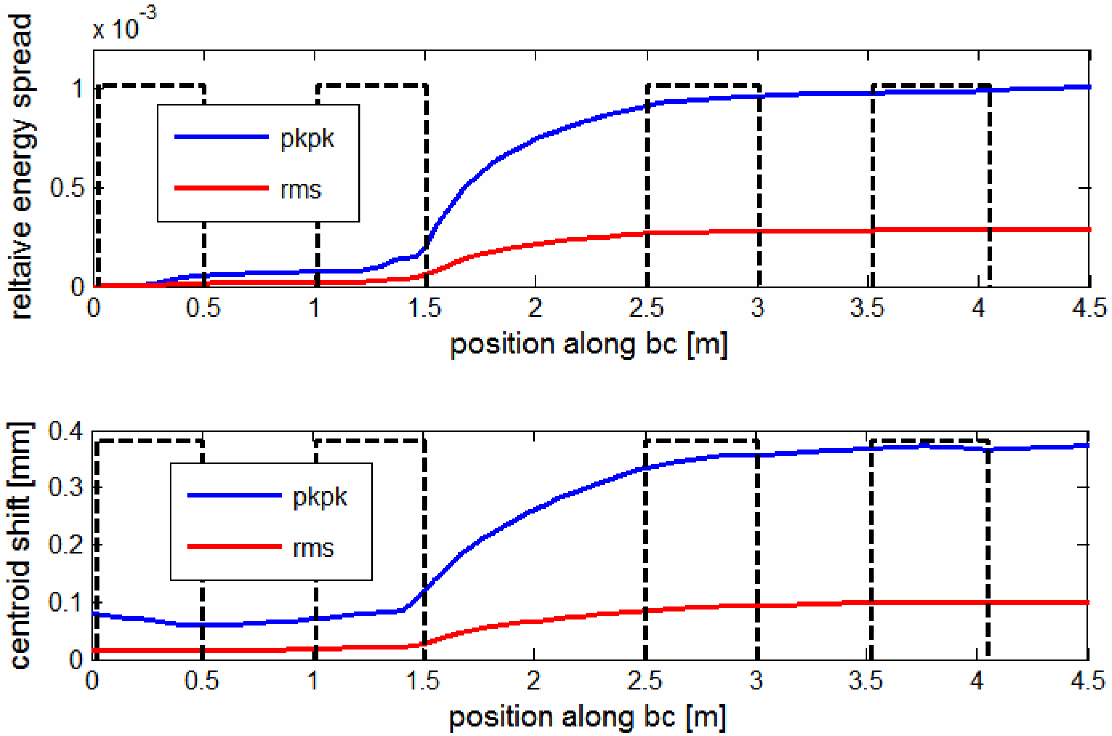
CSR induced centroid shifts



- emittance increase by CSR centroid shifts
- Main contribution between the inner dipoles by short bunch length
- Transient CSR fields at the exit of the second dipole magnet increase the energy spread in the drift between the second and third dipole.

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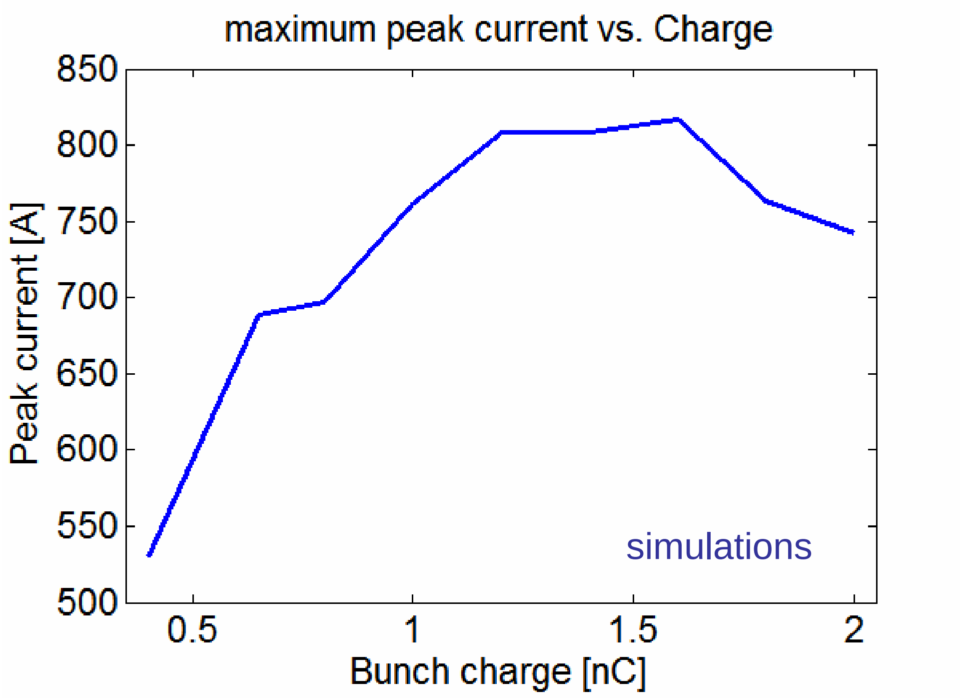
Charge Dependence of Centroid Shifts

- Parameter scan to test the quality of the numerical tools
- Peak current determines the strength of CSR effects
- Bunch compressor is set to over-compression

=> Peak current is varied with bunch charge

- Peak current increase is limited by space charge interactions in the injector



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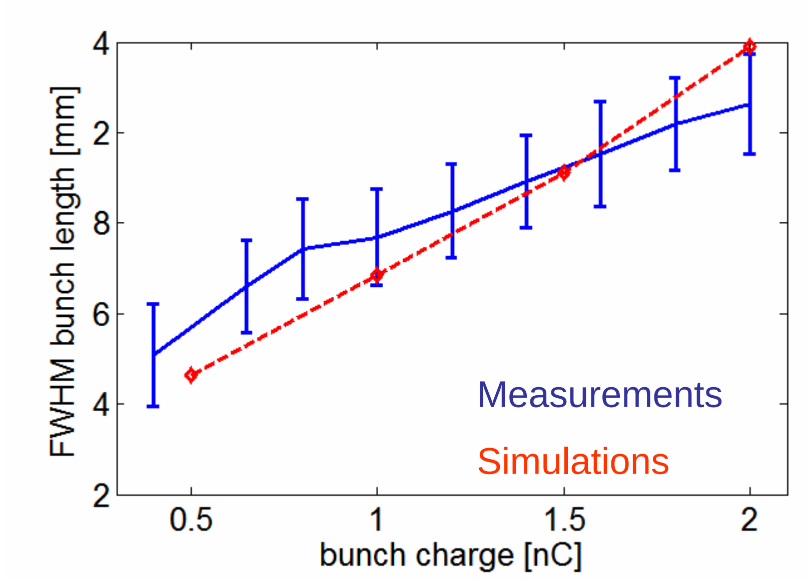
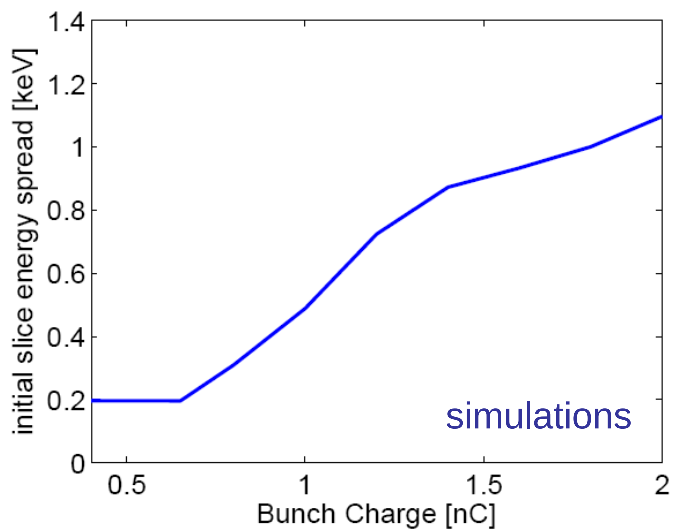
Peak Current Reduction with Charge

- Bunch length increases with bunch charge
  => Reduction of current increase

- Uncorrelated energy spread blows up with charge
  => Reduction of peak current





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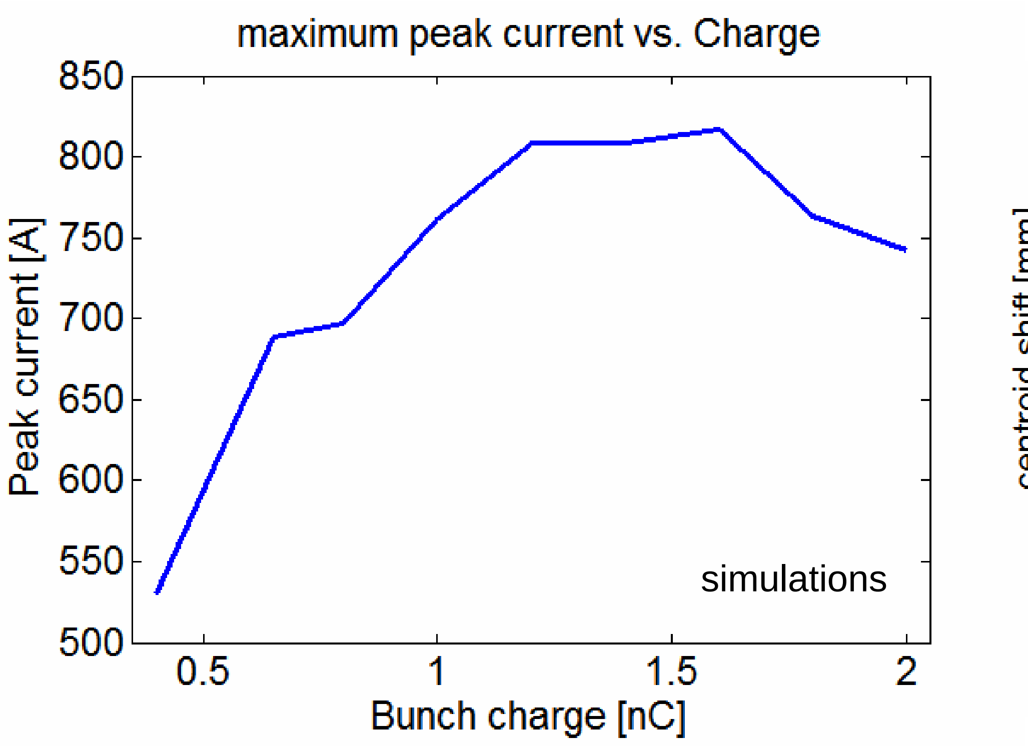
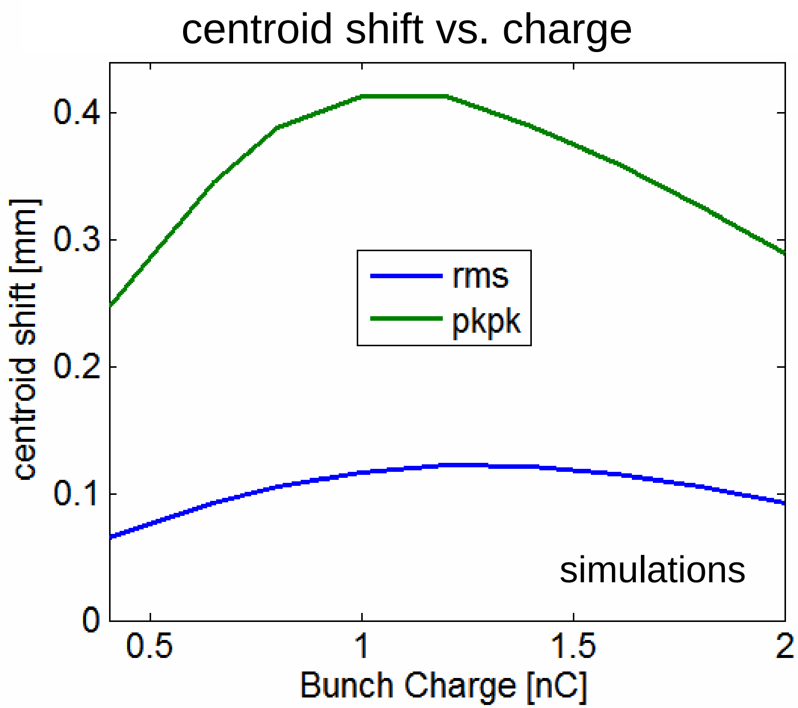
Peak Current and CSR Centroid Shift vs. Charge

Decrease of peak current towards high bunch charges is mapped to the behaviour of the CSR induced centroid shift.





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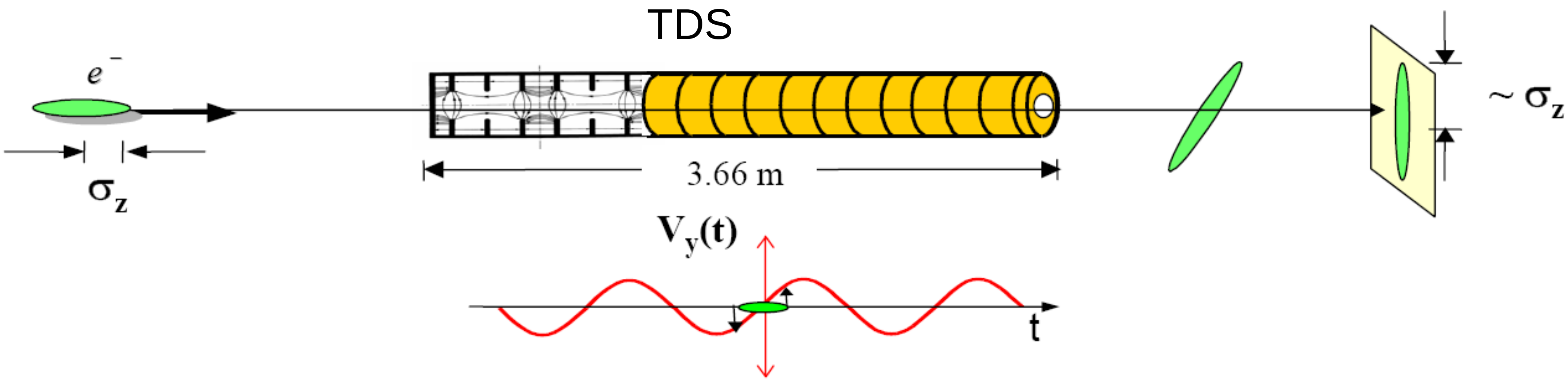
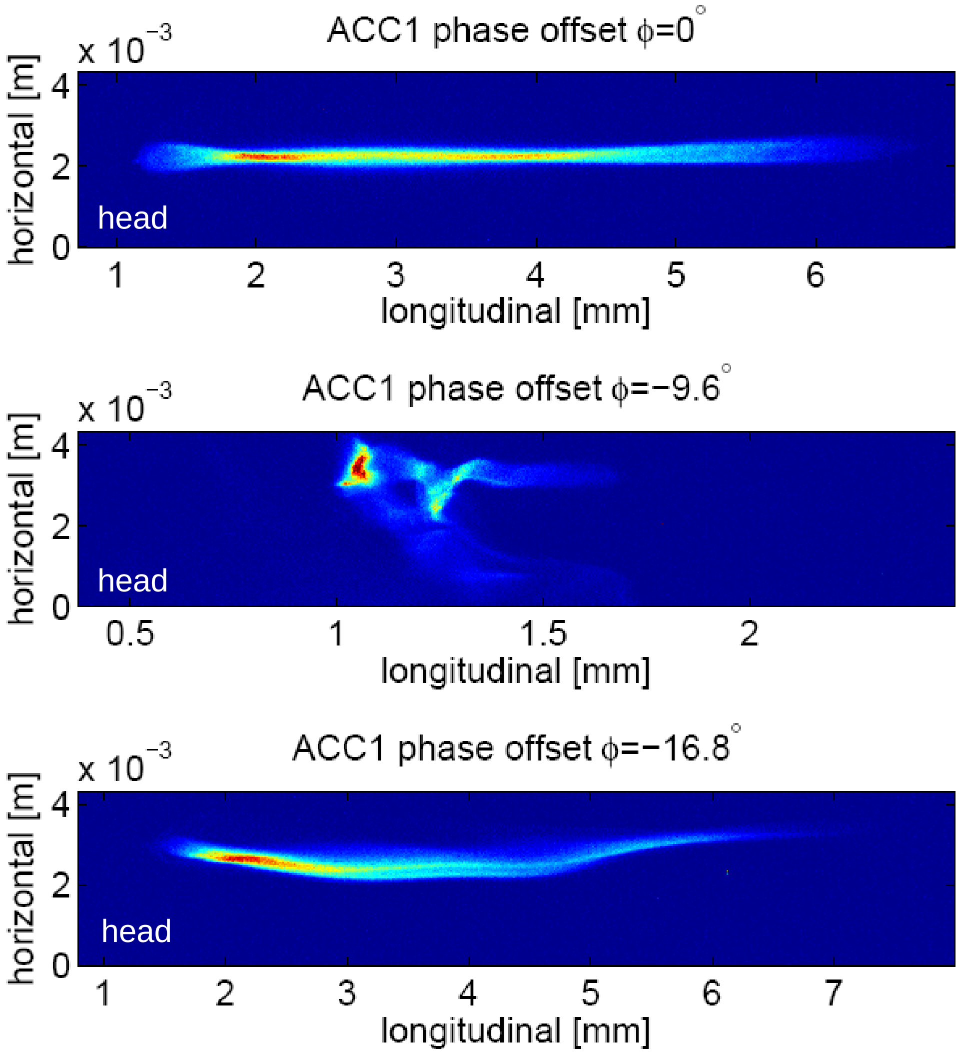
A vertical deflecting RF structure is used for beam diagnostics. The beam receives a time dependent kick, which translates to a correlation between time and vertical offset.



Length: 3.64 m ; Nominal operating frequency: 2856 MHz
Filling time: 0.645 μs ; Nominal deflecting voltage: 26 MV
Mode type: TM 11 (Hybrid Mode)



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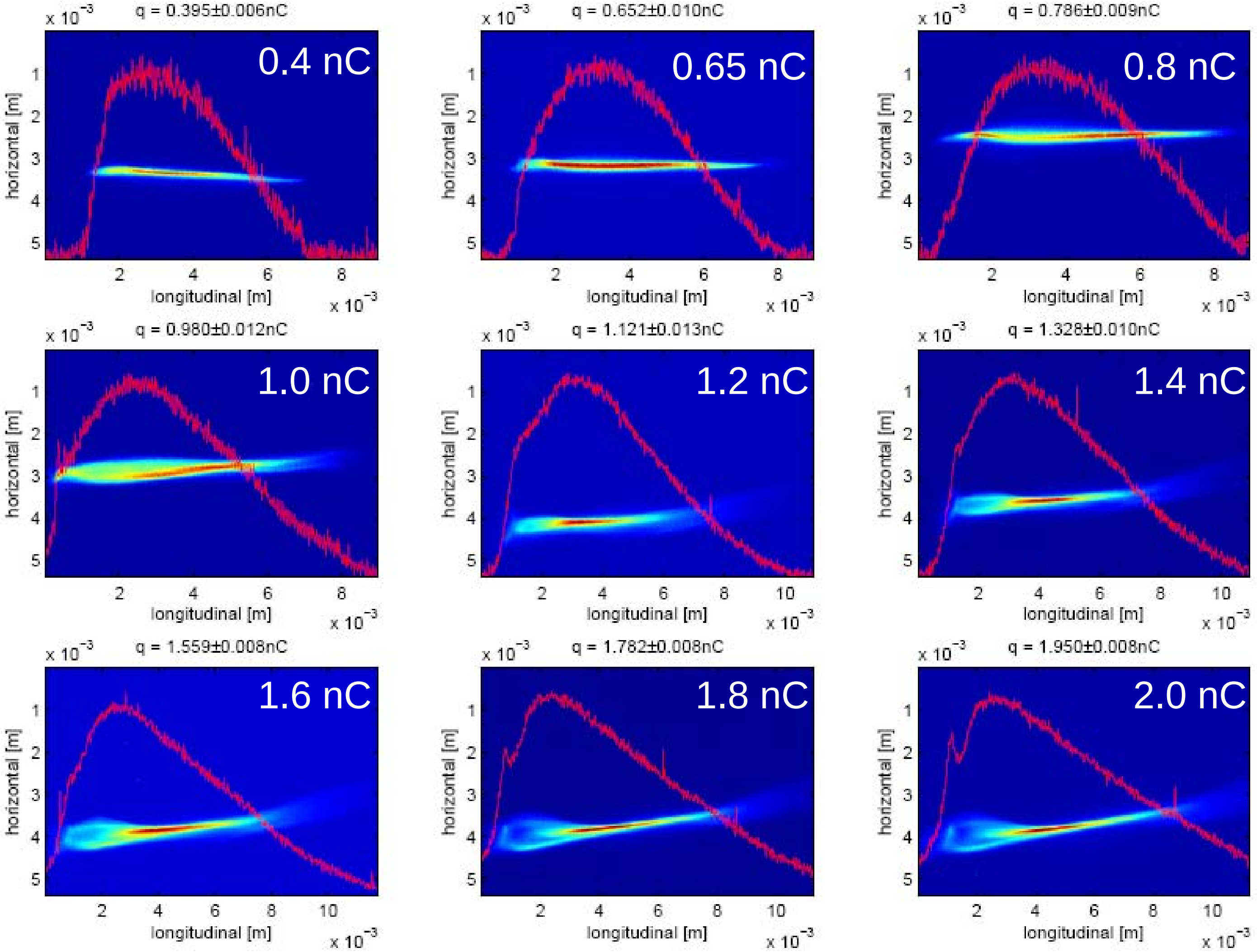
Measured Beam Images vs. Bunch Charge (0 deg)



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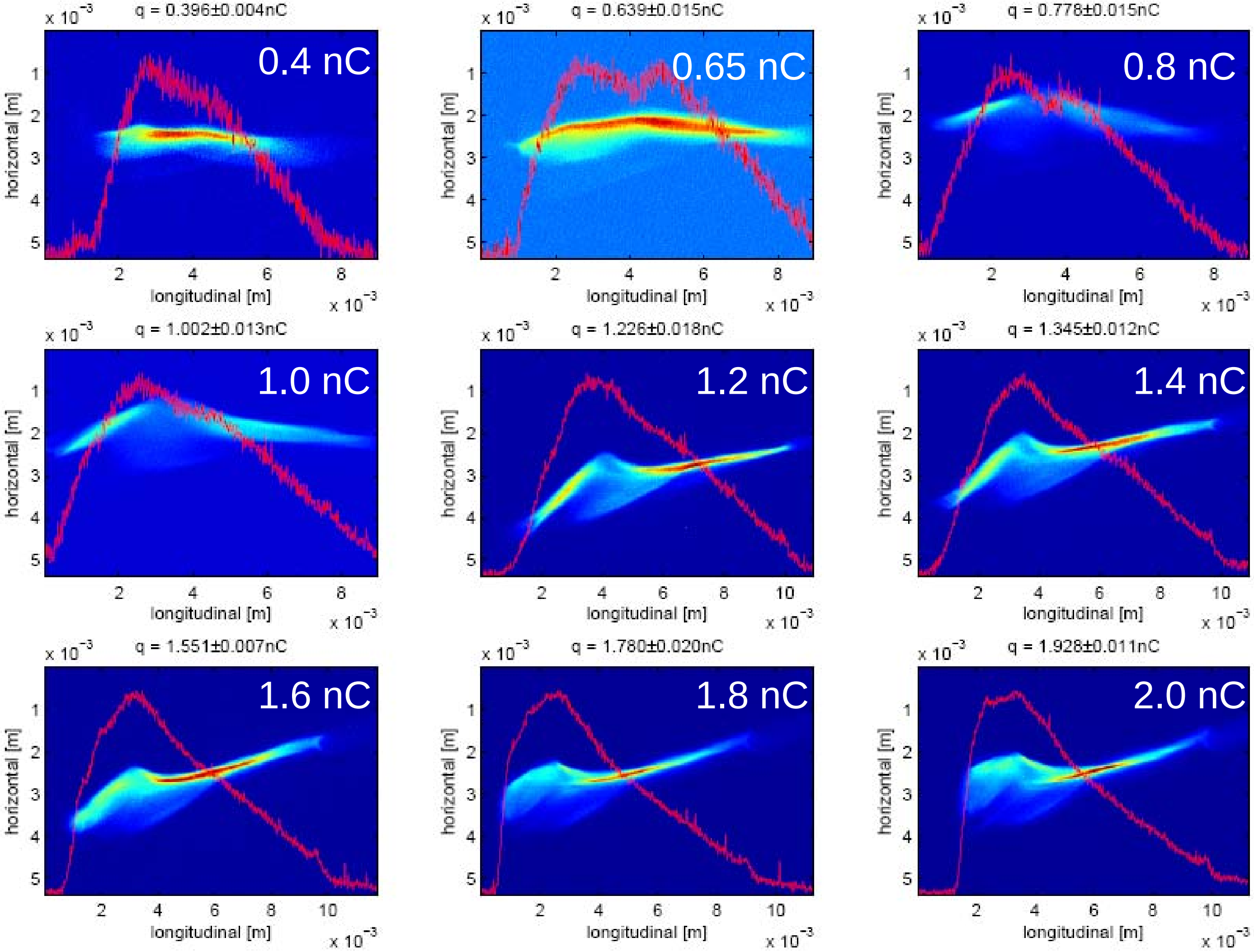
Measured Beam Images vs. Bunch Charge (-26 deg)



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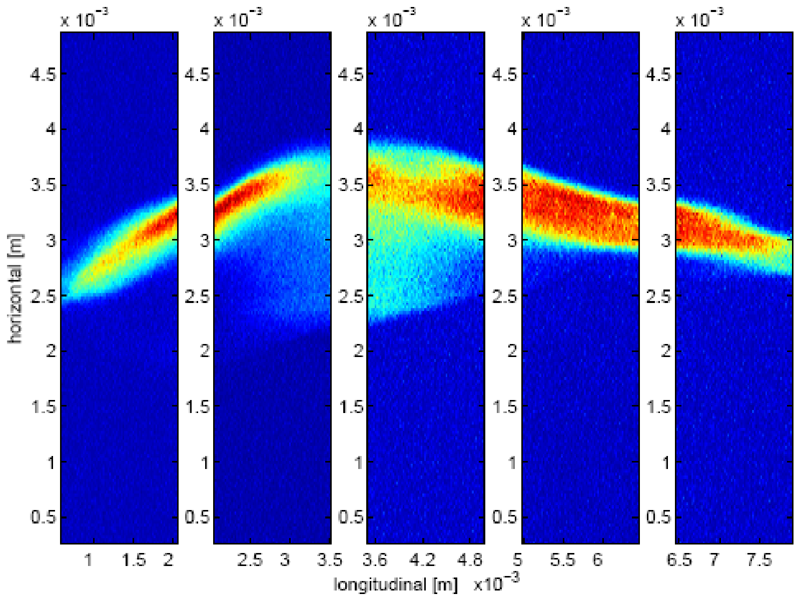
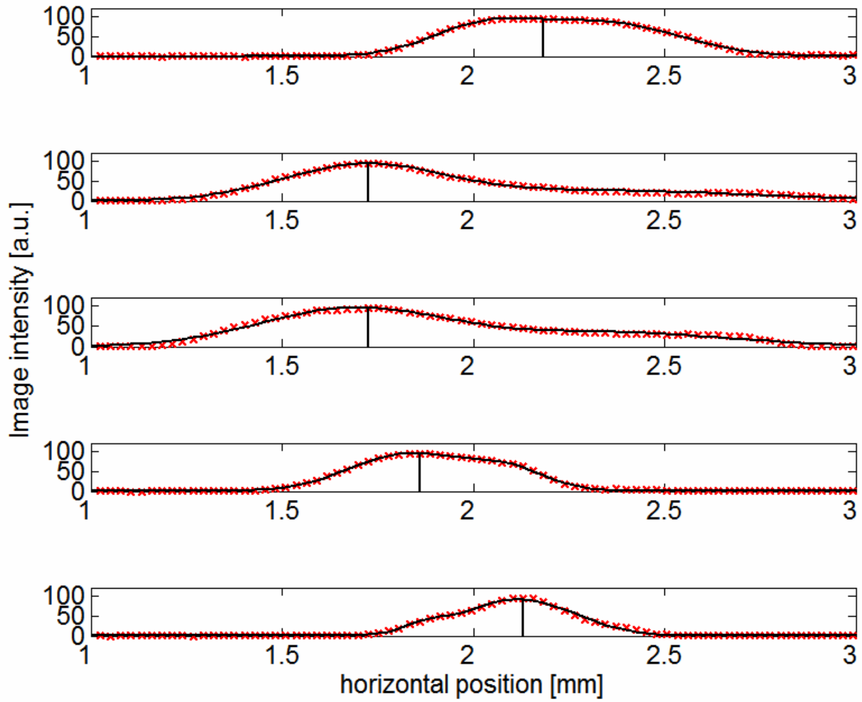
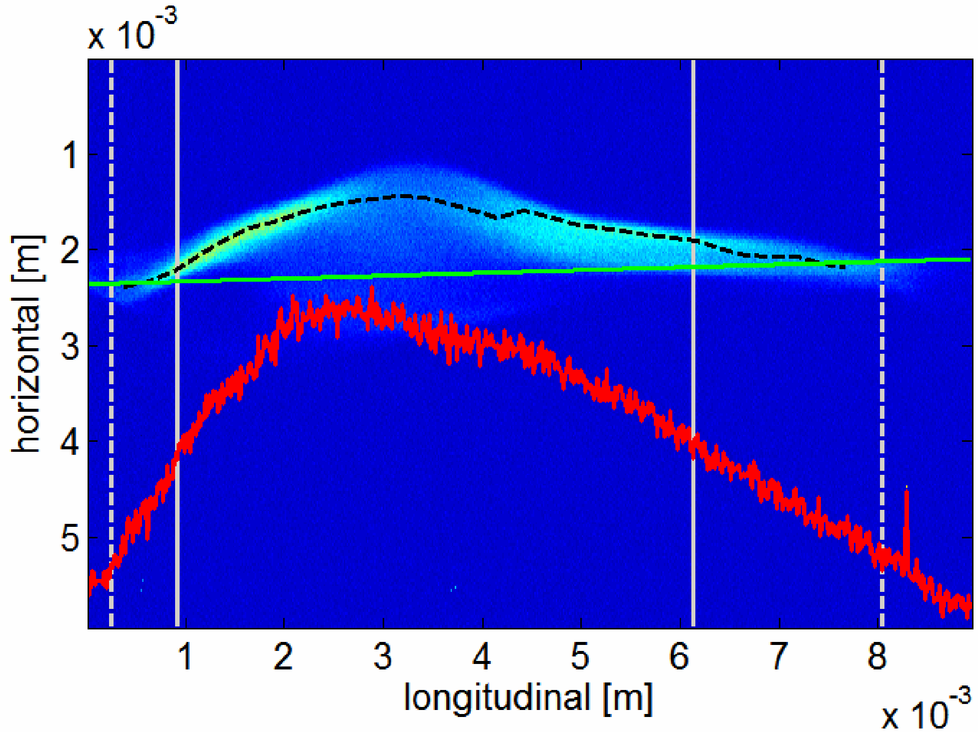
Centroid Curve Determination





- Background subtraction
- Beam image is cut into slices (typical 20 slices)
- Intensity profile is determined by projection on the horizontal axis
- Centroid position is determined using a Double Gaussian fit

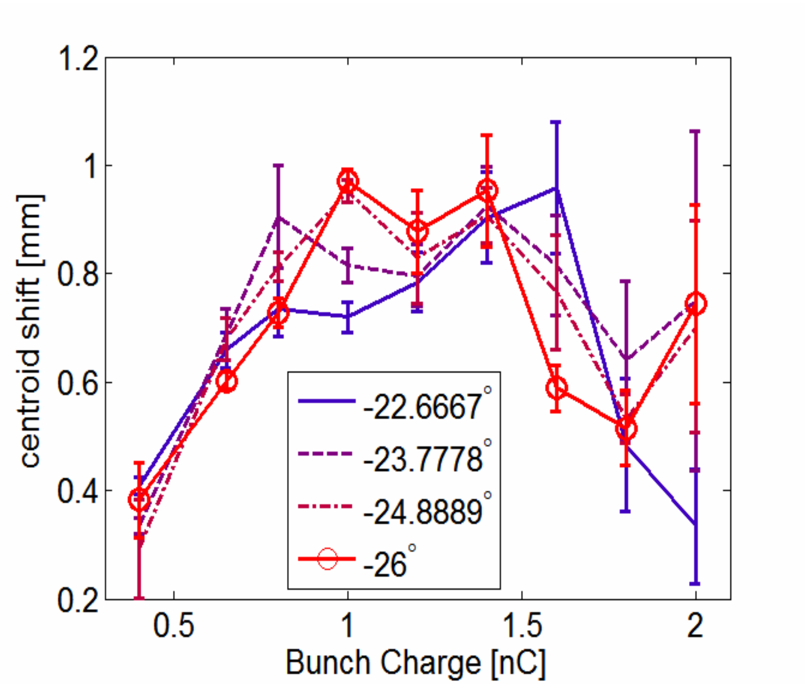


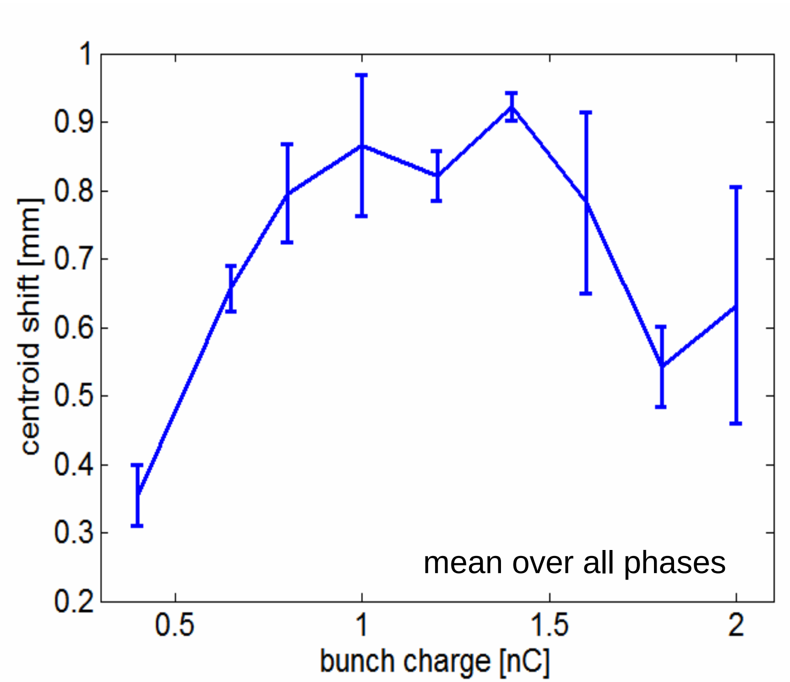
- Centroid curve is determined
- Overall linear slope is calculated (“beam tilt”)
- Slope is subtracted from the centroid curve
- Peak to peak width of the corrected centroid curve is used as a measure for the strength of CSR effects (“centroid shift”)

Measured Centroid Shifts vs. Bunch Charge

- Centroid shift is determined for different bunch charges and phase offsets in ACC1
- Increase of centroid shift between 0.4 nC and 1 nC / decrease after 1.4 nC

=> Qualitative agreement with predictions





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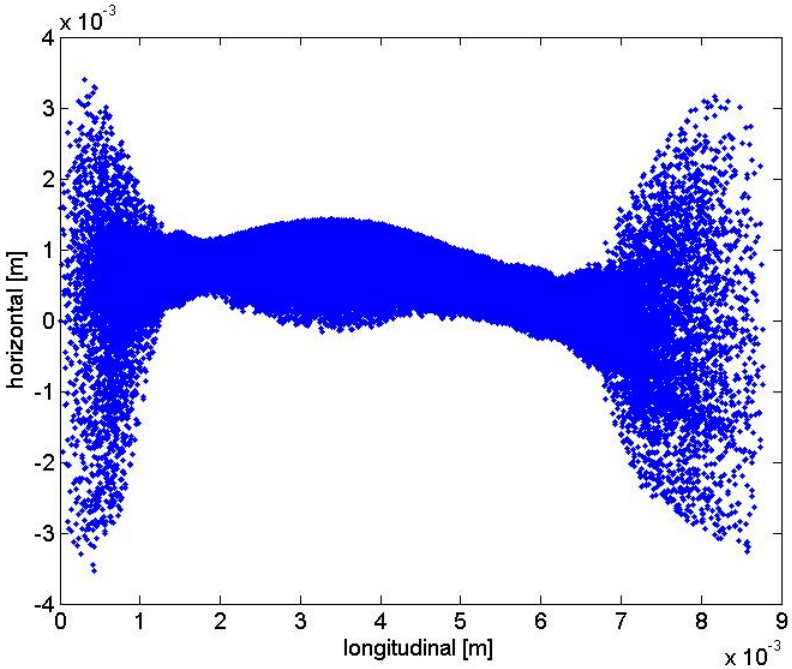
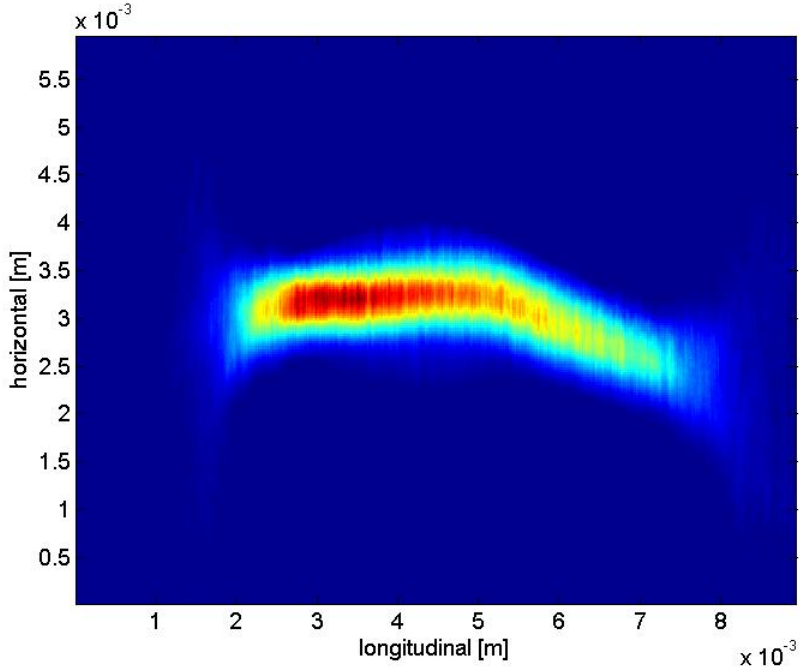
Simulation of Beam Images

- Phase space distributions are determined by tracking an ensemble (100k macro-particles) from the RF-Gun to the TDS with actual machine parameters
- Each macro-particle is represented by a 2D-Gaussian
- A charge threshold is subtracted to simulate a lower visibility limit on the screen
  => tails of the bunch are skipped
- Images are analysed with the same image analysis tools as the measurements





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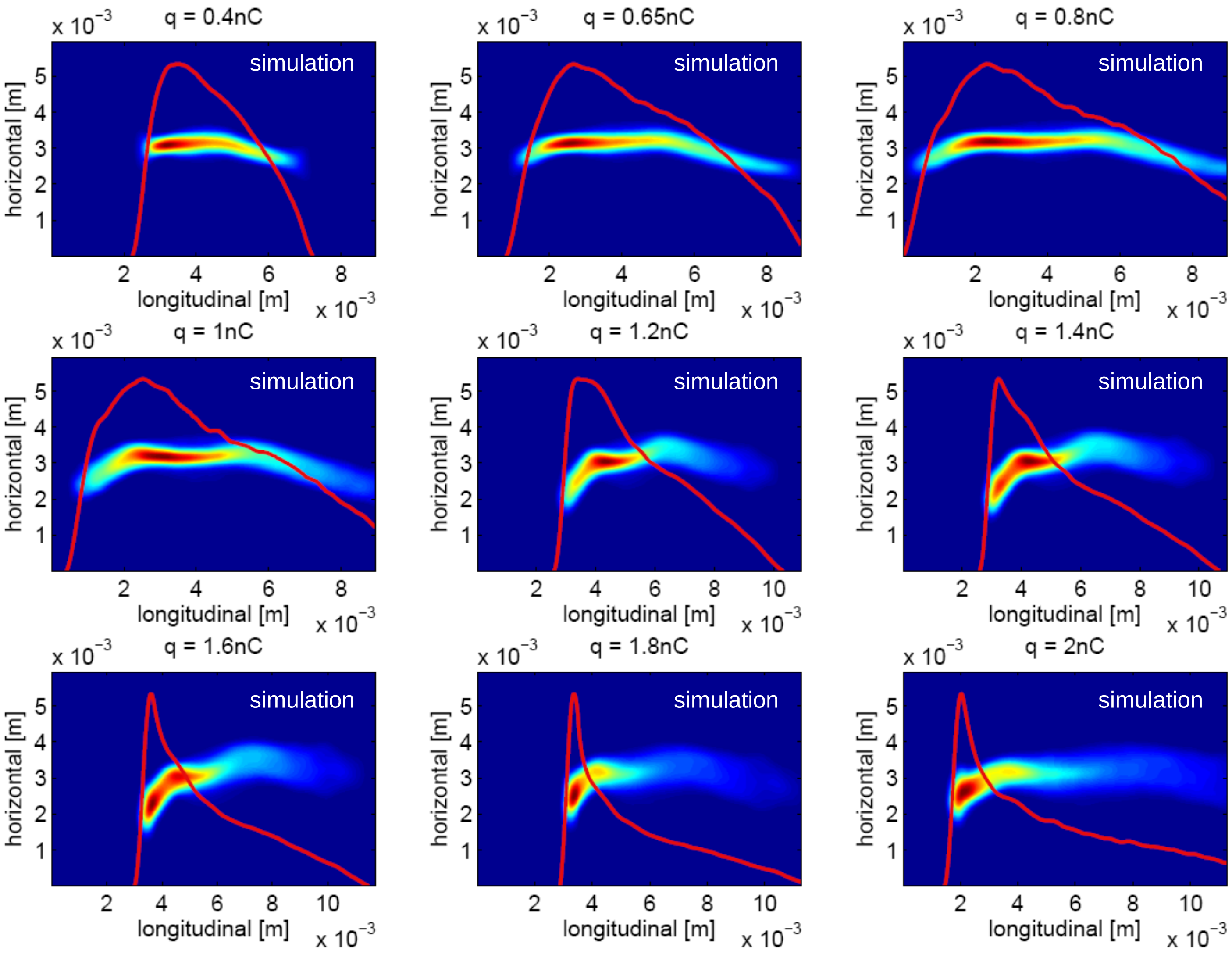
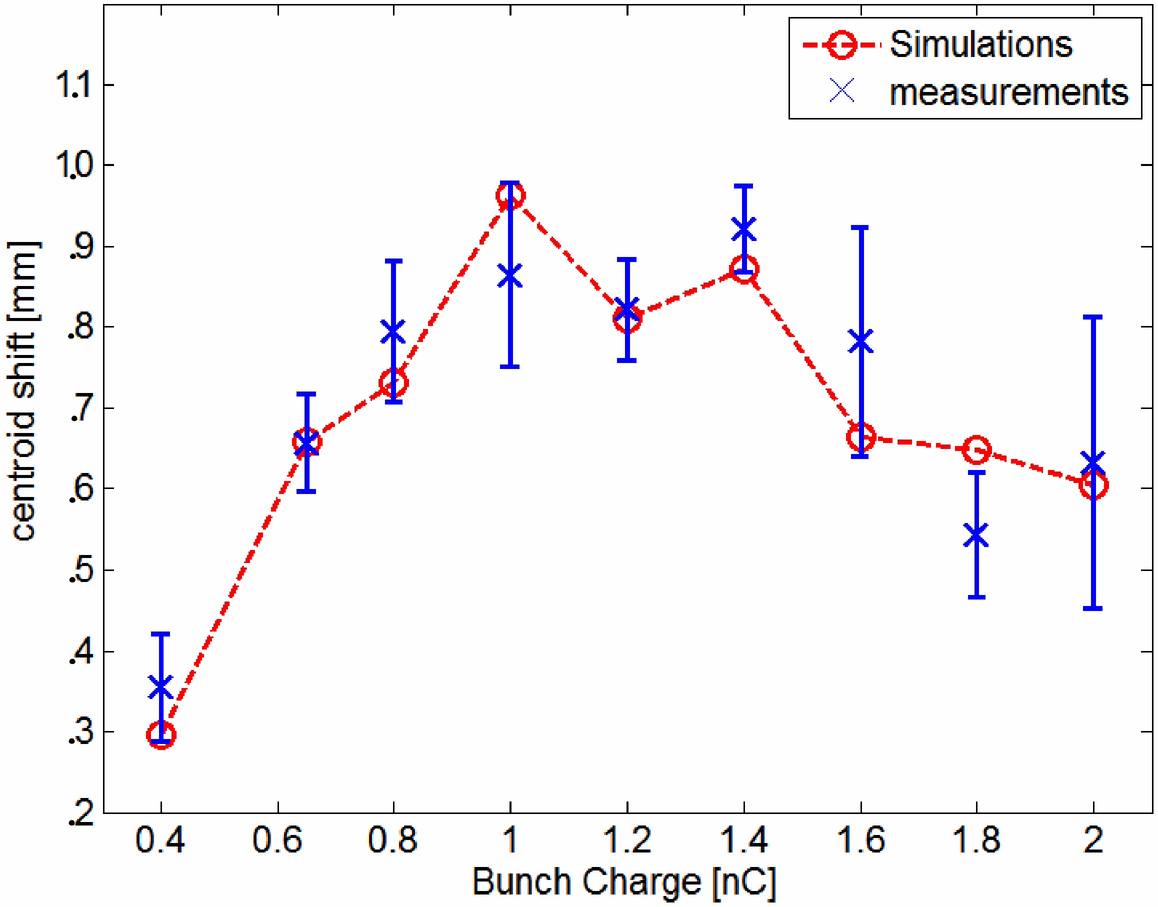
Simulated Beam Images



Comparison of Measurements and Simulations

Centroid shifts obtained by image analysis applied on the simulated beam images agree with the results from the measurements.



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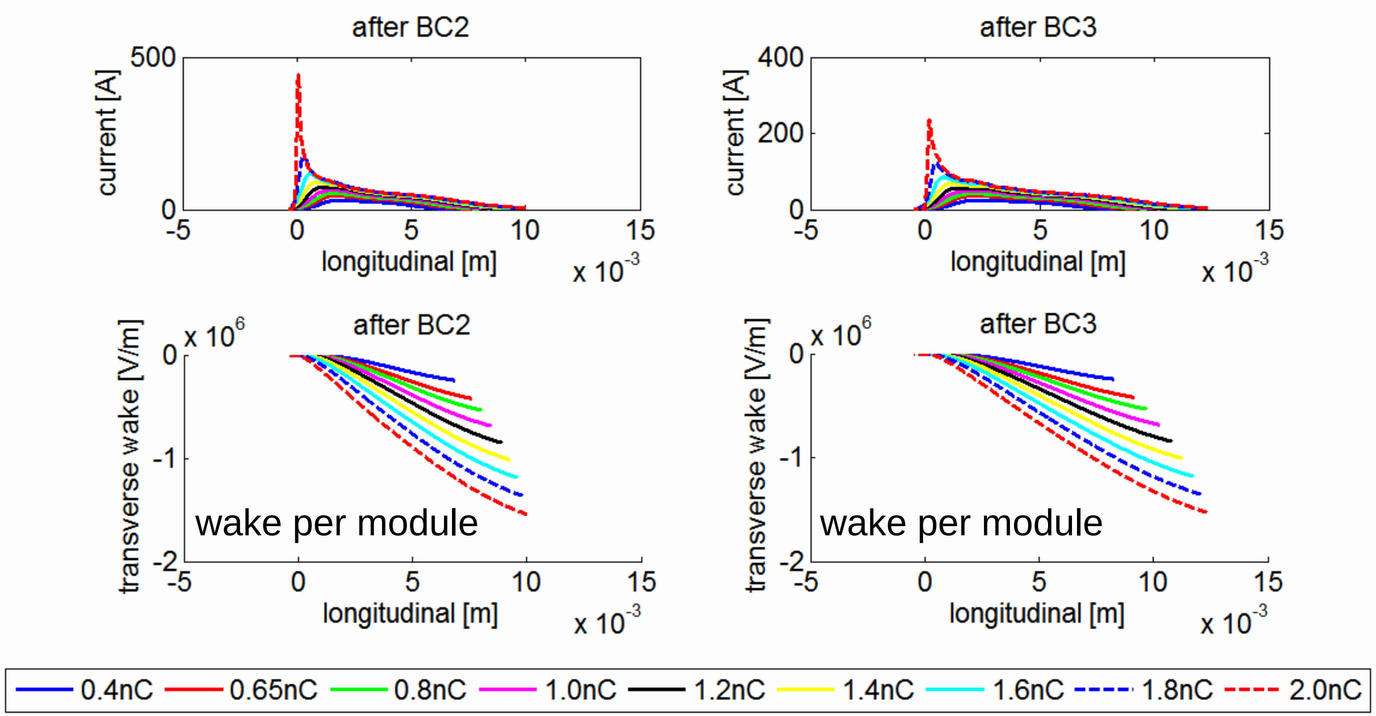
The measured beam tilts are observable even on-crest were the beam is not compressed. Therefore those beam tilts can not be explained by CSR interactions.

=> transverse wake fields in the acceleration cavities have the right properties



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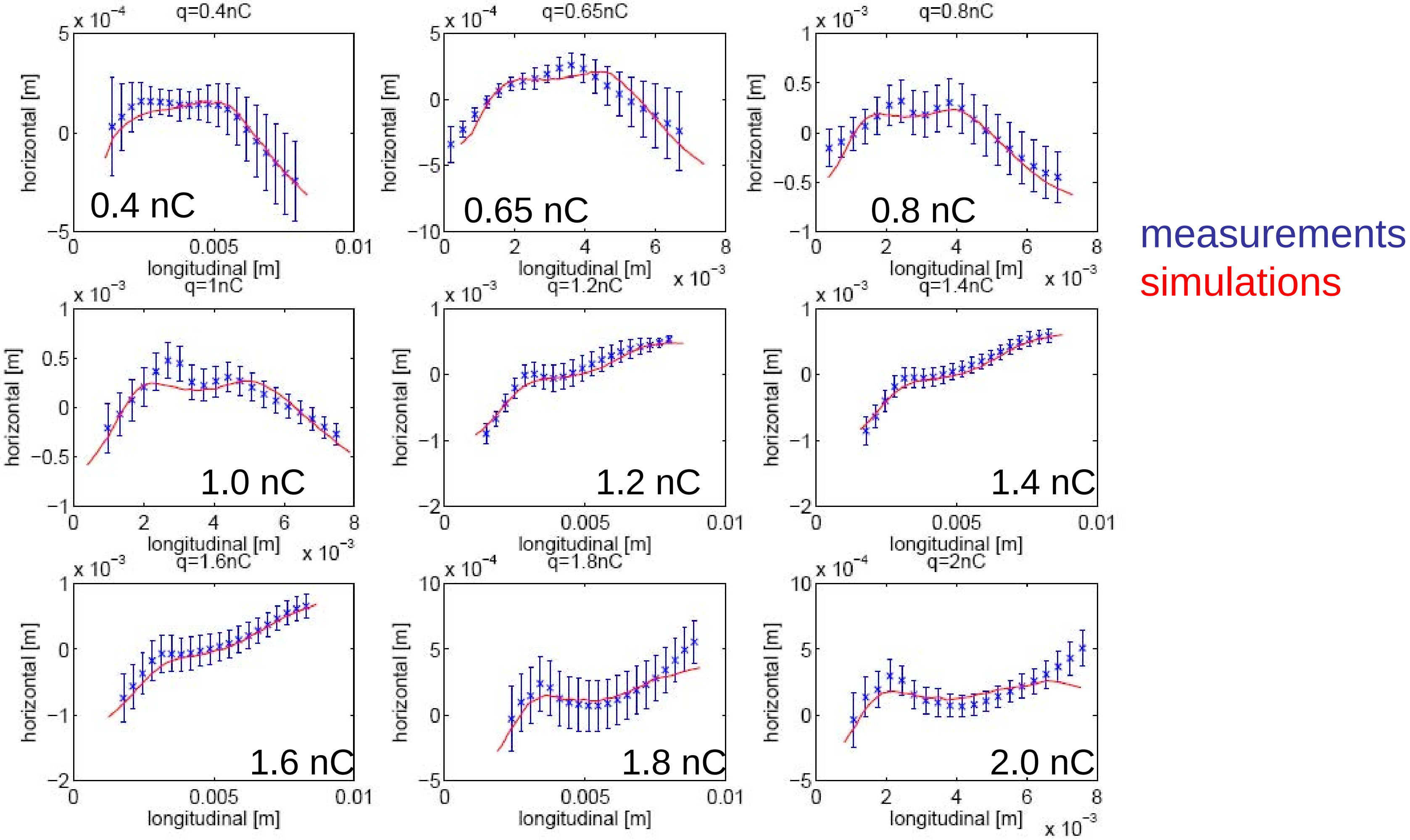
Comparison of Measured and Simulated Centroid Curves

Good agreement between measured and simulated centroid curves.



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Summary and Conclusions

- Self-interactions of the electron bunch are an important part of the beam dynamics at FLASH (SASE, CSR,….).
  - Numerical tools are used to analyse the beam dynamics, supplemented by beam diagnostics at FLASH.
  - Studies on coherent synchrotron radiation effects are complicated by self field effects downstream of the bunch compressor.

- In my thesis studies on CSR effects were done both numerically and experimentally.
  - An over-compression scheme was used to minimise other self field contributions
  - Prediction of CSR induced centroid shifts in over-compression operation by numerical analysis
  - First measurements on CSR effects using a transverse deflecting structure at FLASH were done successfully.
  - My work provided direct observations of CSR effects on electron beams of high charge density as well as a benchmark of numerical analysis tools.

Thank you for your attention….

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