

Origins and mitigation strategies of beam centroid offsets

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DESY and University of Hamburg



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Centroid offsets in plasma-wakefields and hosing instability

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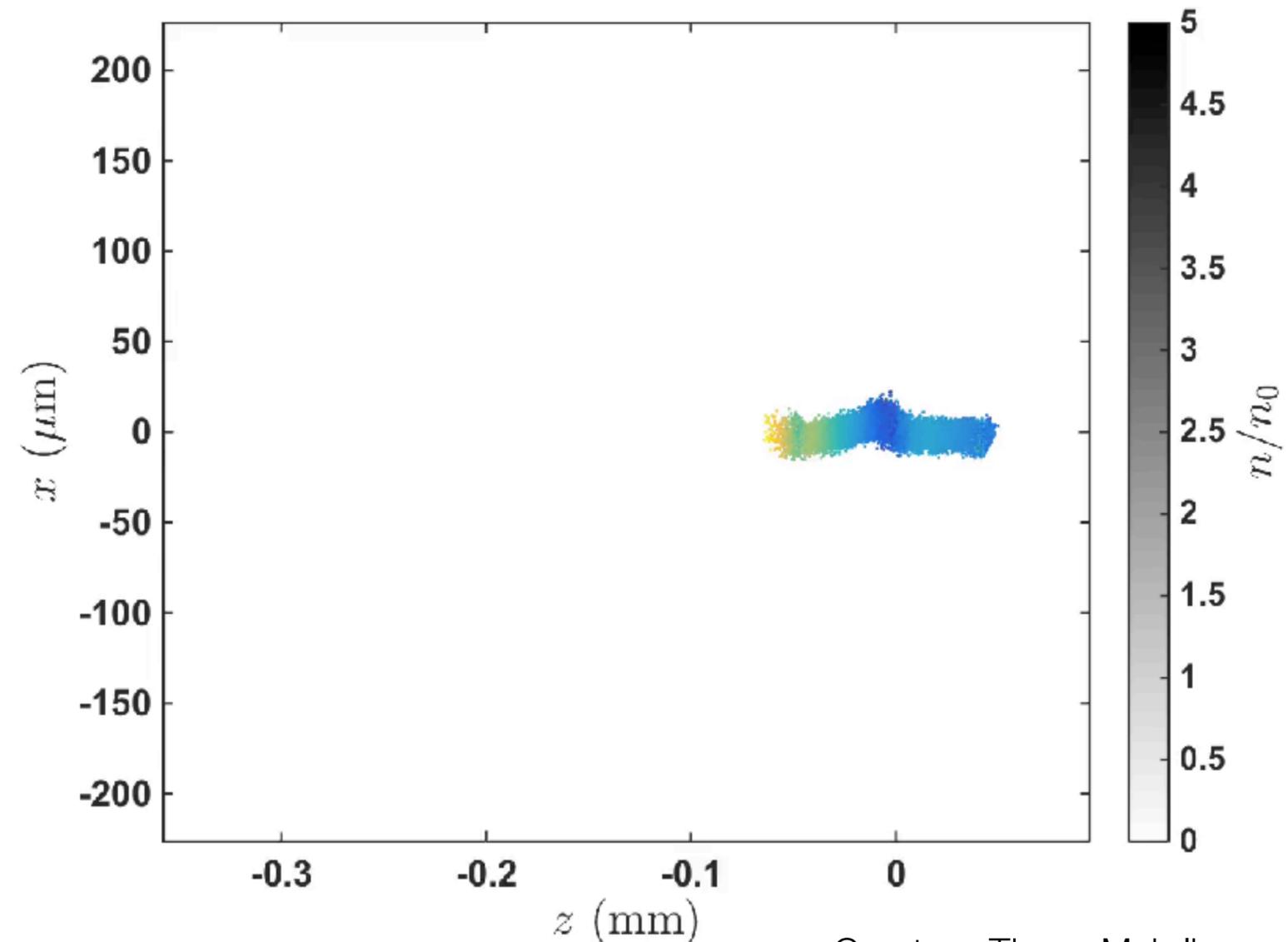
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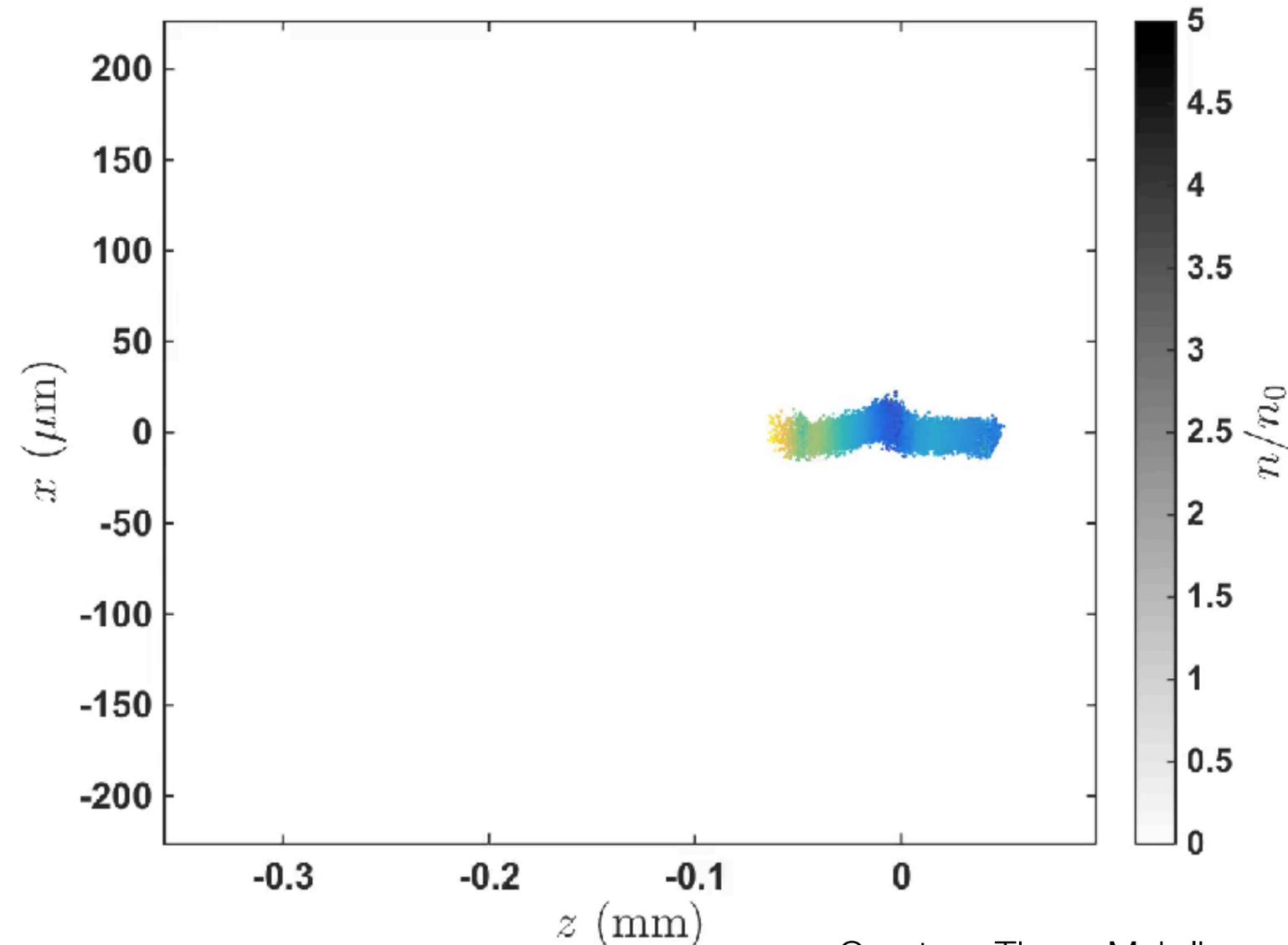
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Courtesy Timon Mehrling

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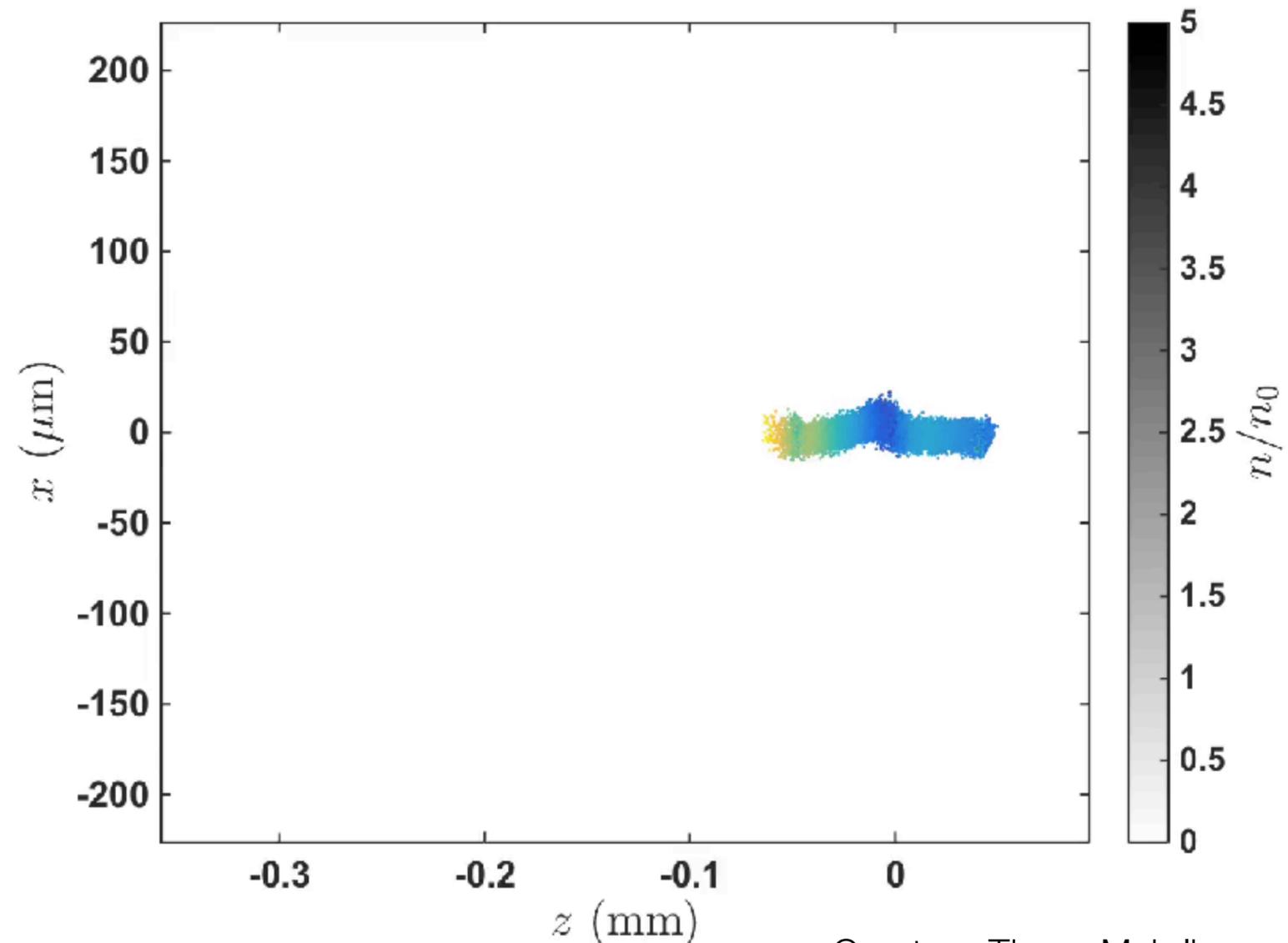
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- > Sources of centroid deviations
 - > Coherent synchrotron-radiation (CSR)
 - > RF-coupler kicks
 - > Geometric wakefields (see talk I. Zagorodnov)



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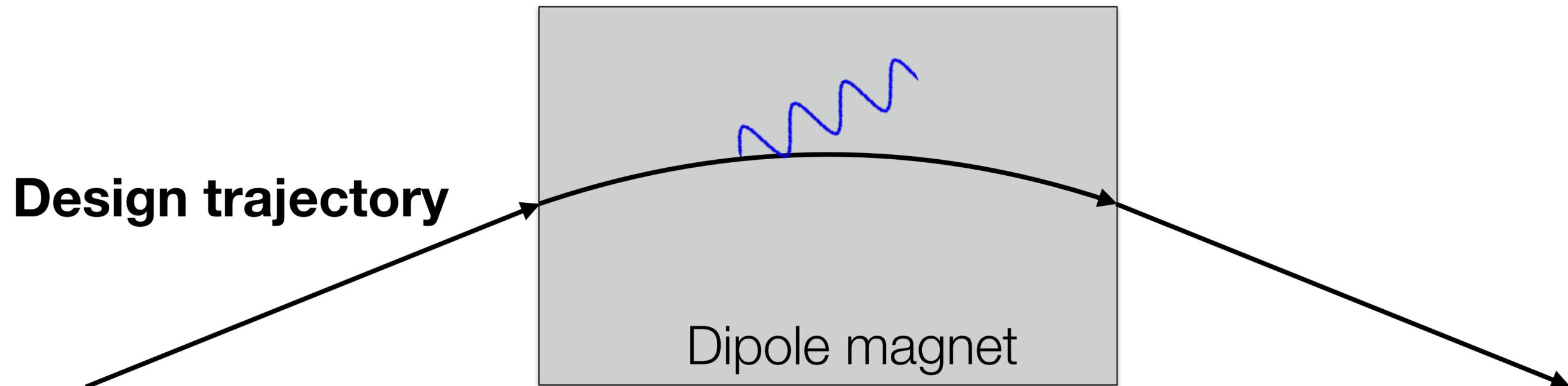


Coherent-synchrotron radiation effects

Coherent-synchrotron radiation and centroid offsets

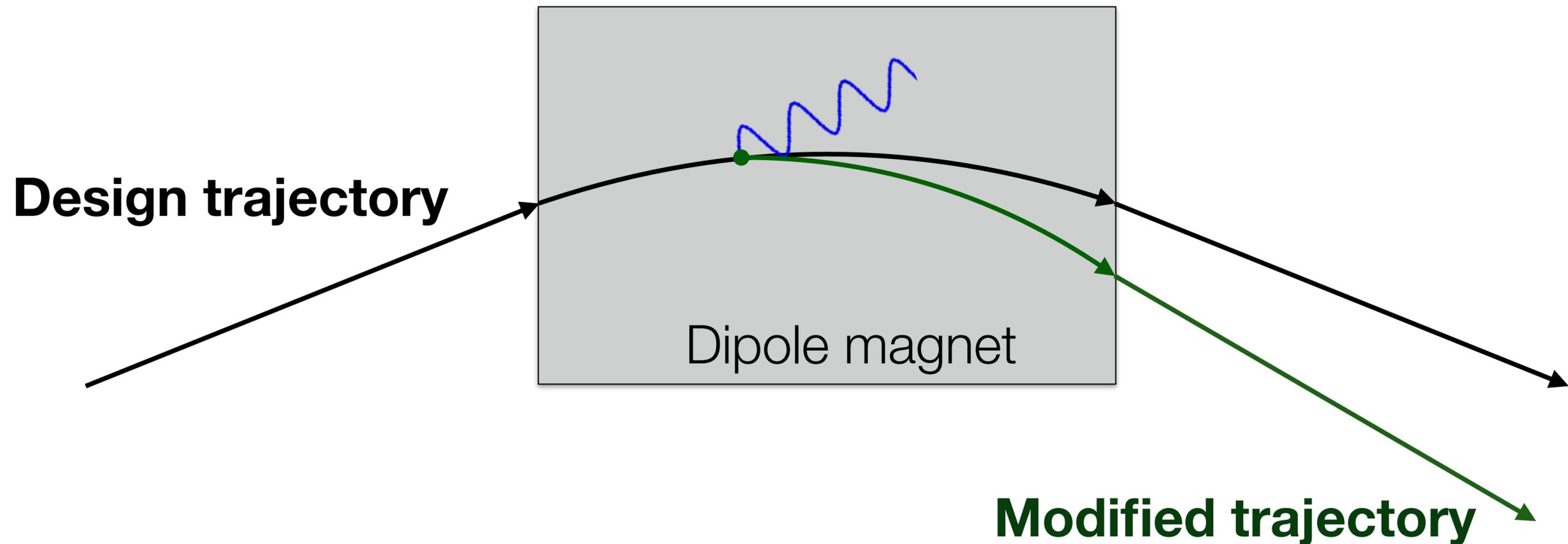
Coherent-synchrotron radiation and centroid offsets

- > When moving on a curved trajectory, electrons radiate and reabsorb photons, therefore they loose or gain energy



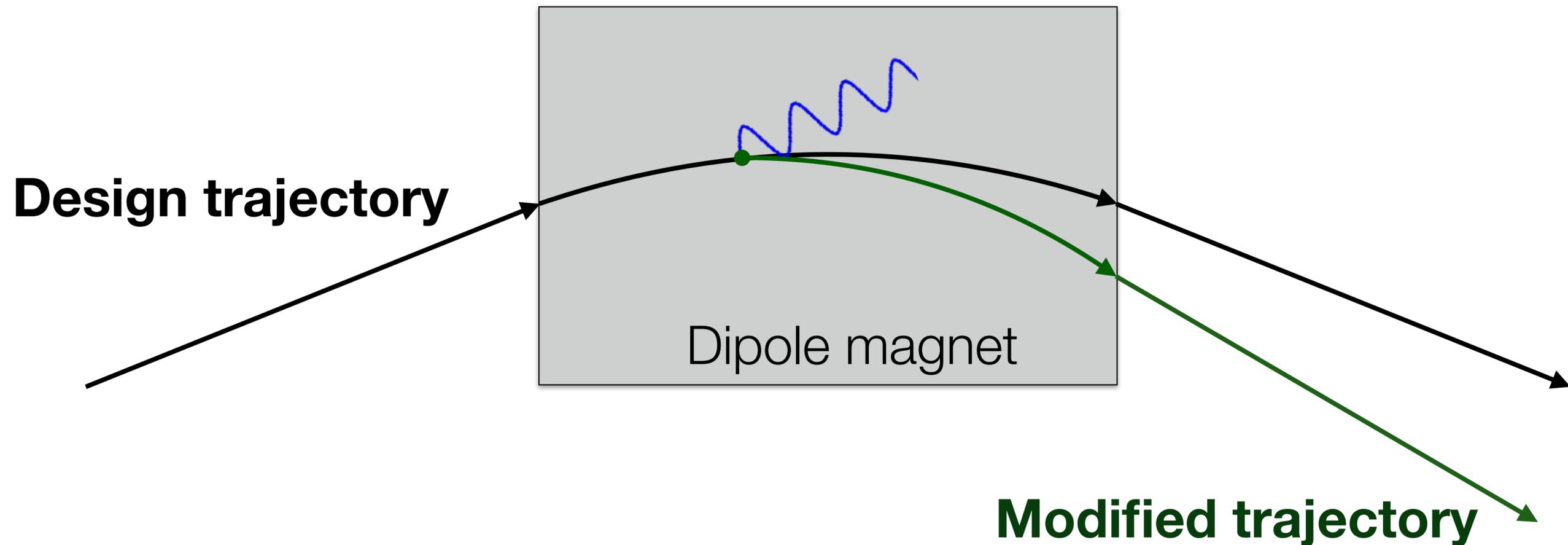
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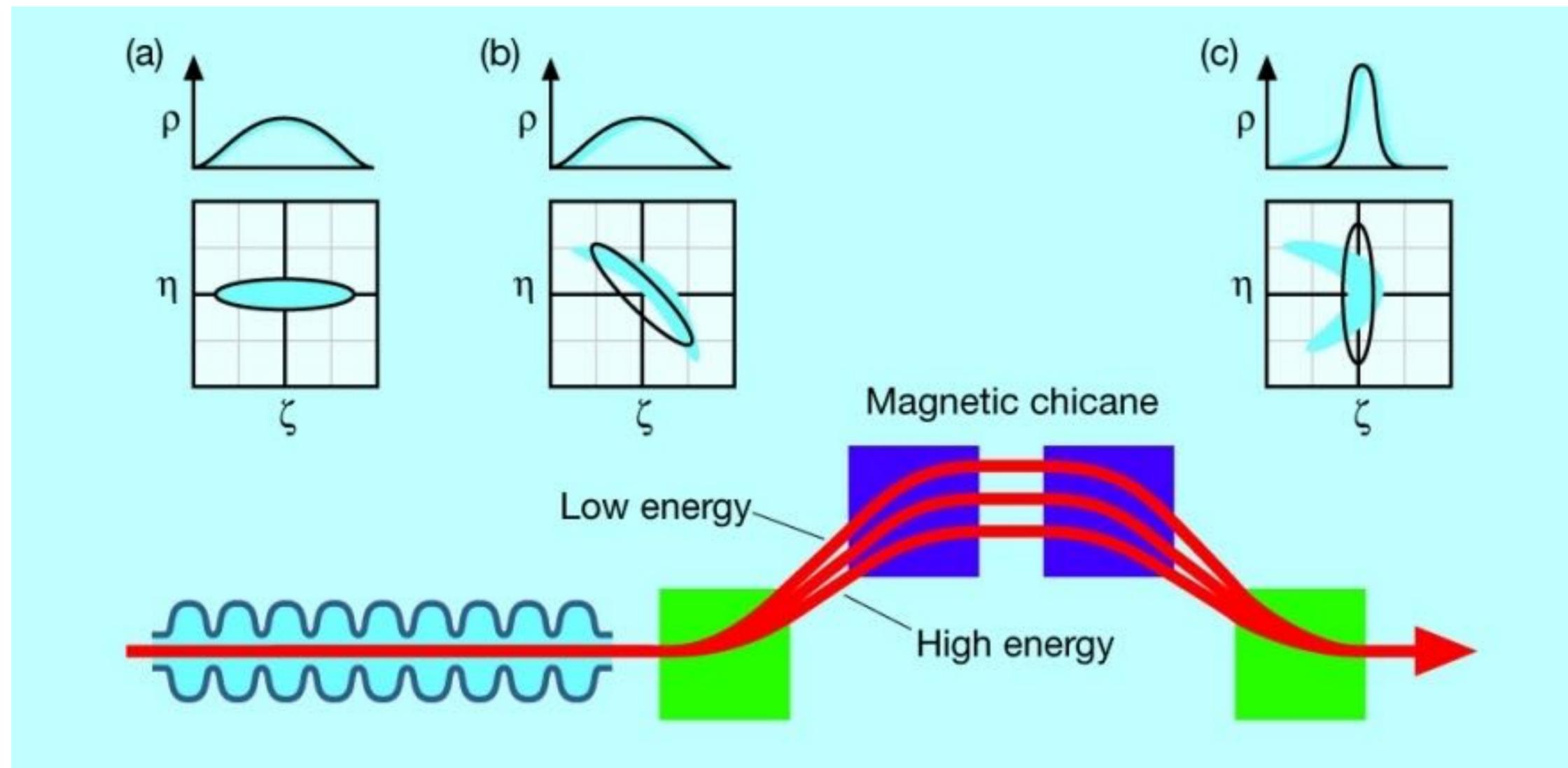
- > When moving on a curved trajectory, electrons radiate and reabsorb photons, therefore they lose or gain energy
- > Since this is a dispersive section, the trajectory is modified and leads to transverse offsets
- > Energy gain depends on the position within the bunch (CSR 'wake') -> slice offsets



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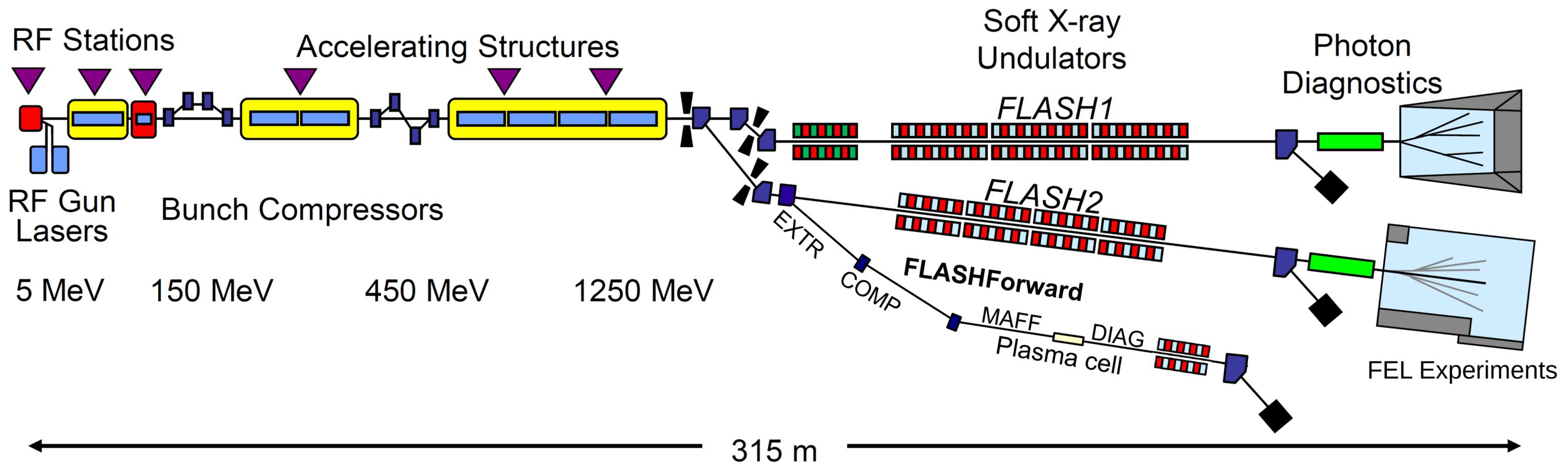
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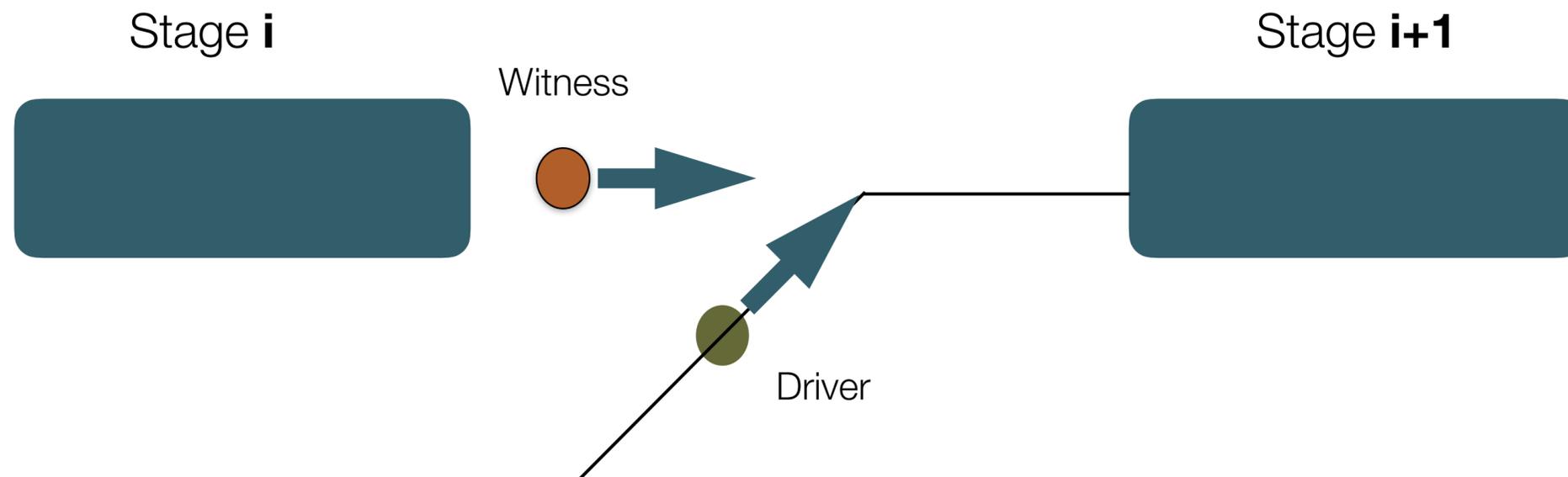
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Dipole magnets are abundant in conventional accelerators

- > Bunch compressors (short bunches are required for FELs or to drive PWFA)
- > Extraction and delivery lines
- > Multi-stage PWFA

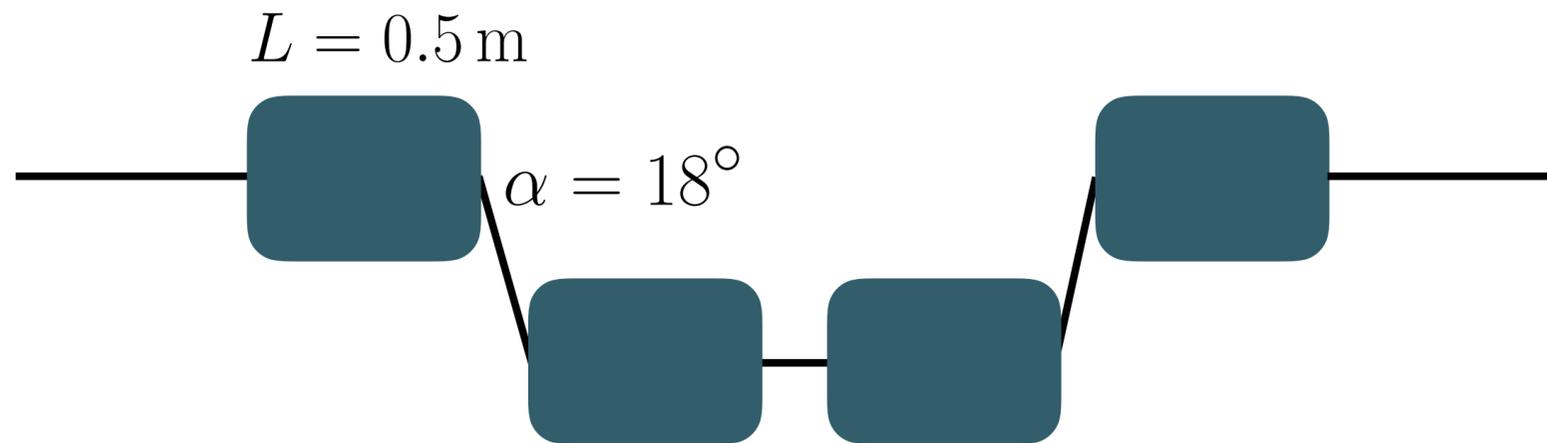


Both driver and witness must go through bends

CSR forces affect bunch dynamics drastically

- > Consider a 4-dipole chicane (parameters as BC2 at FLASH)

Beam parameters:
0.5 nC, 0.3kA, 150 MeV, 1 μm
no chirp (no compression)



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Simulations with elegant

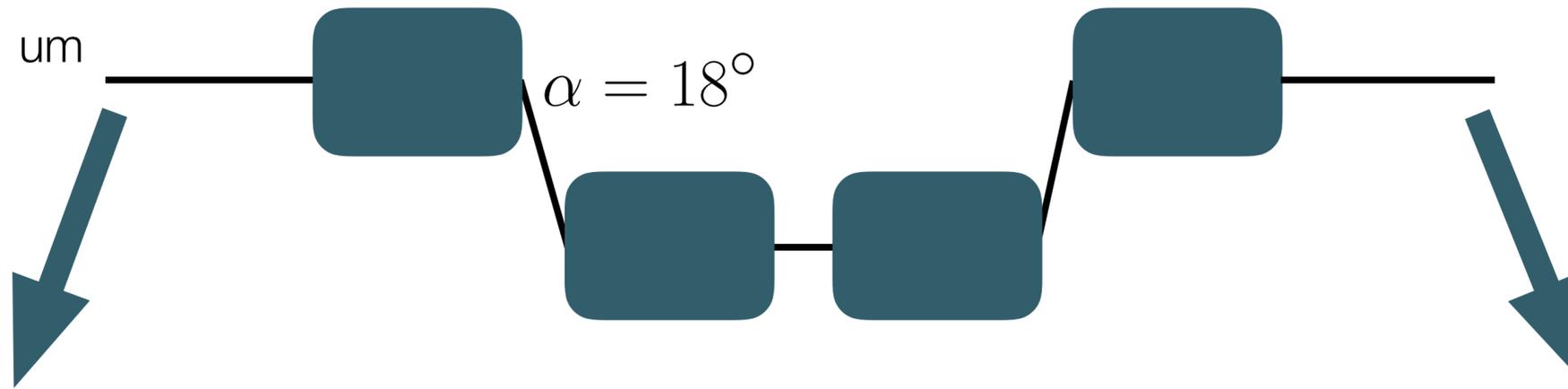
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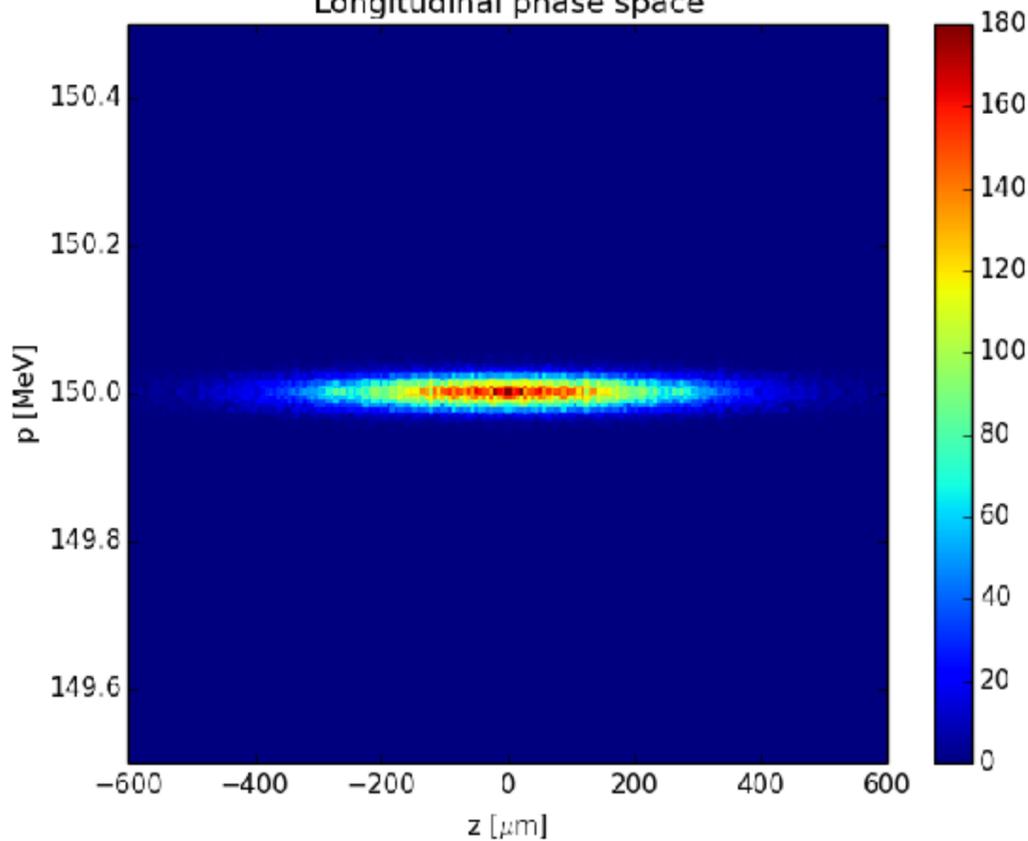
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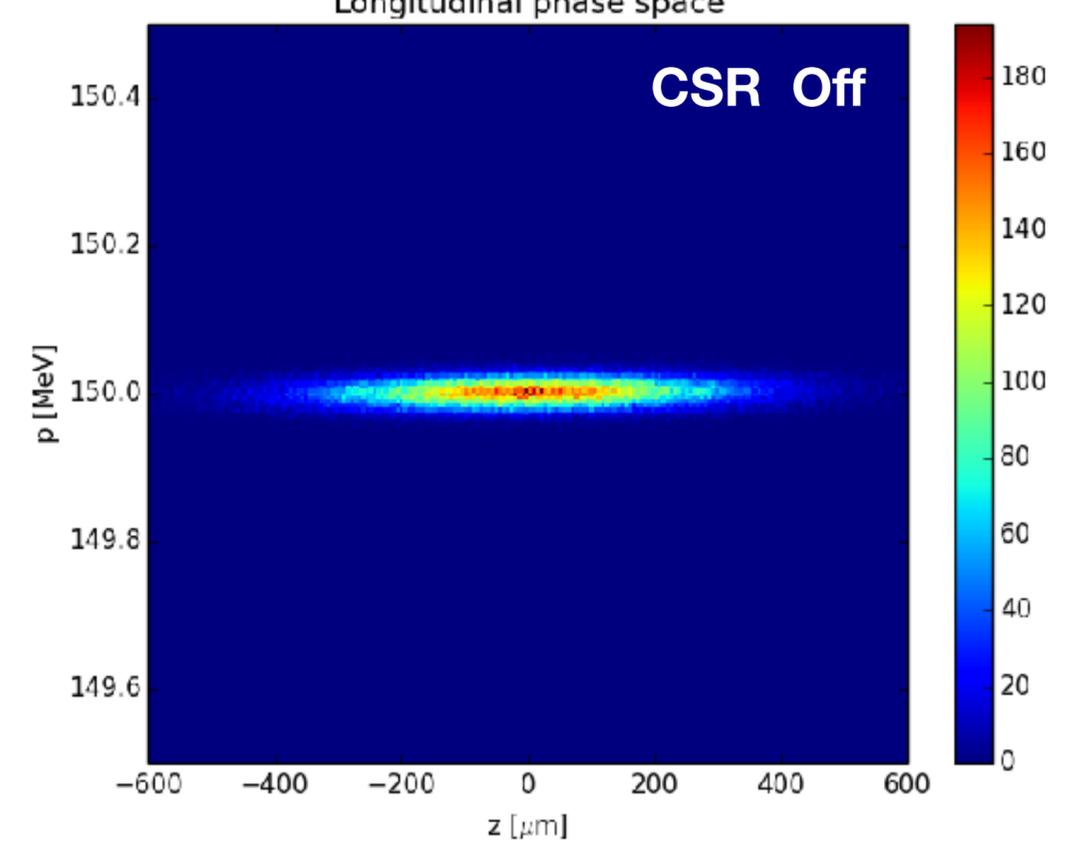
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Longitudinal phase space



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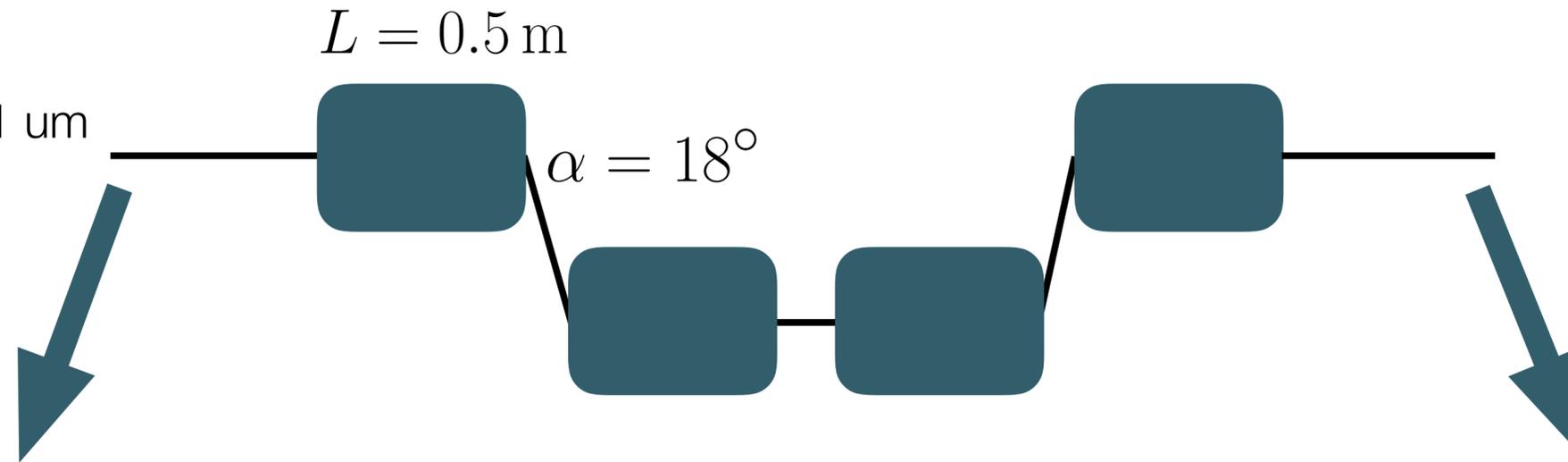


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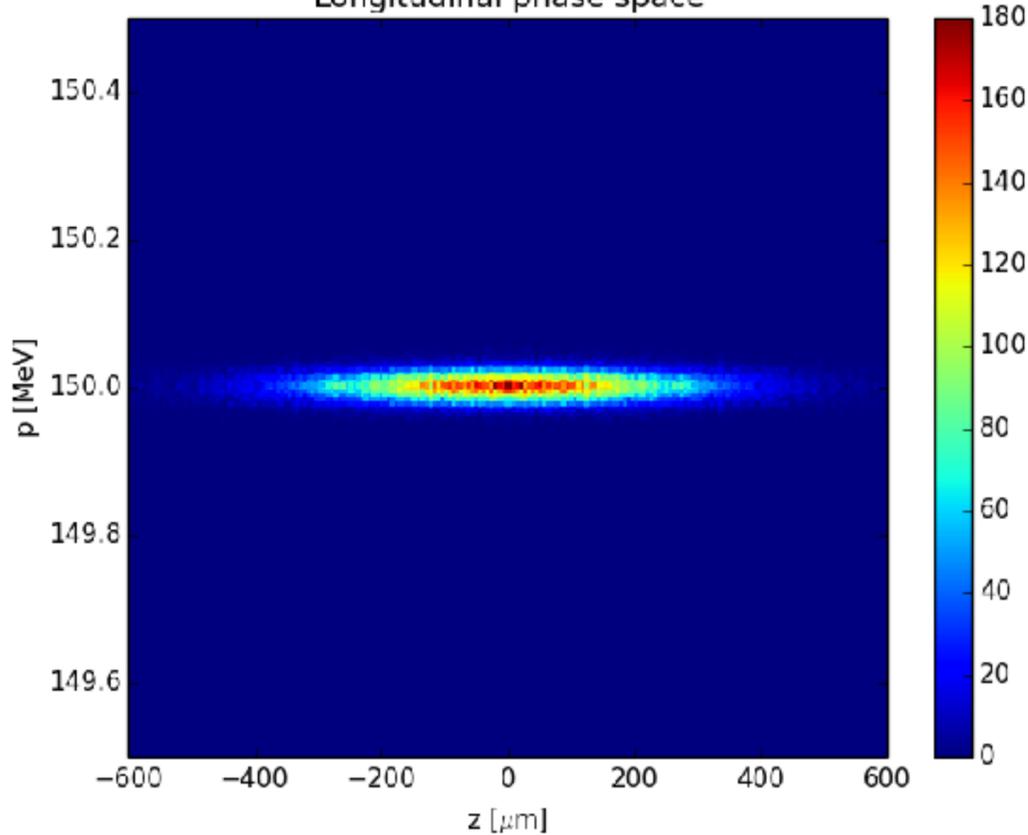
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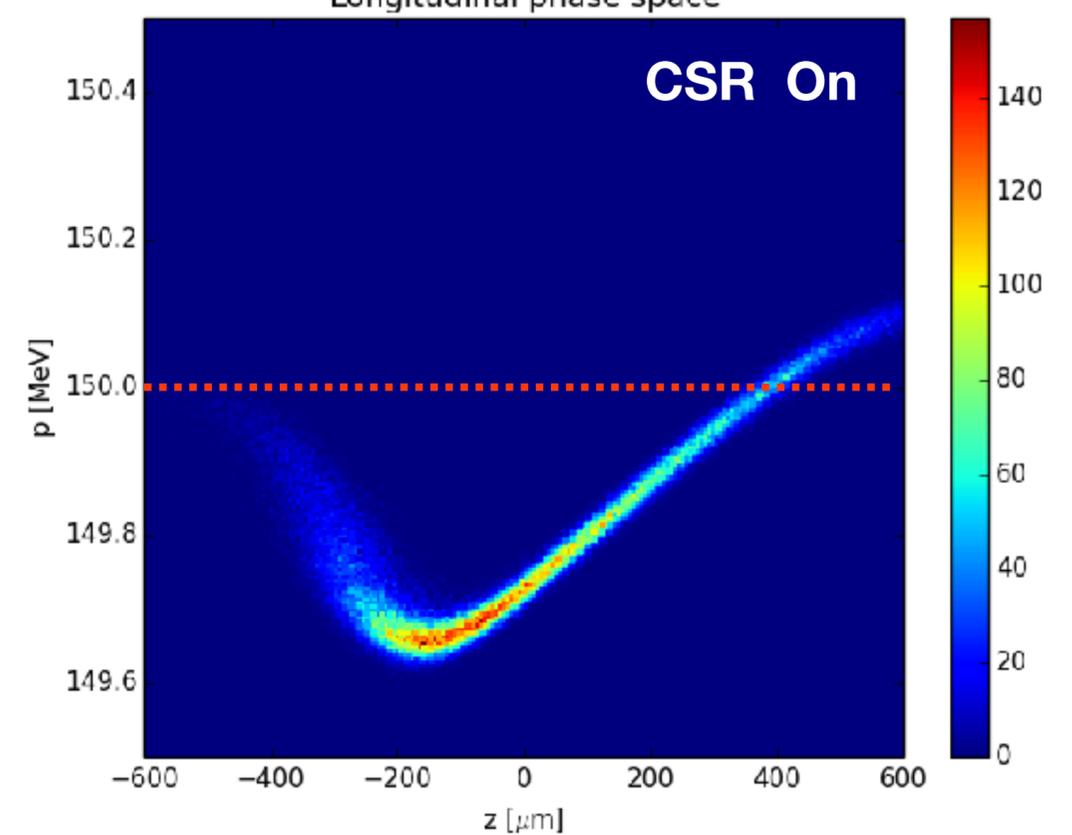


Longitudinal phase space



Head (tail) of the bunch gains (loses) energy

Longitudinal phase space



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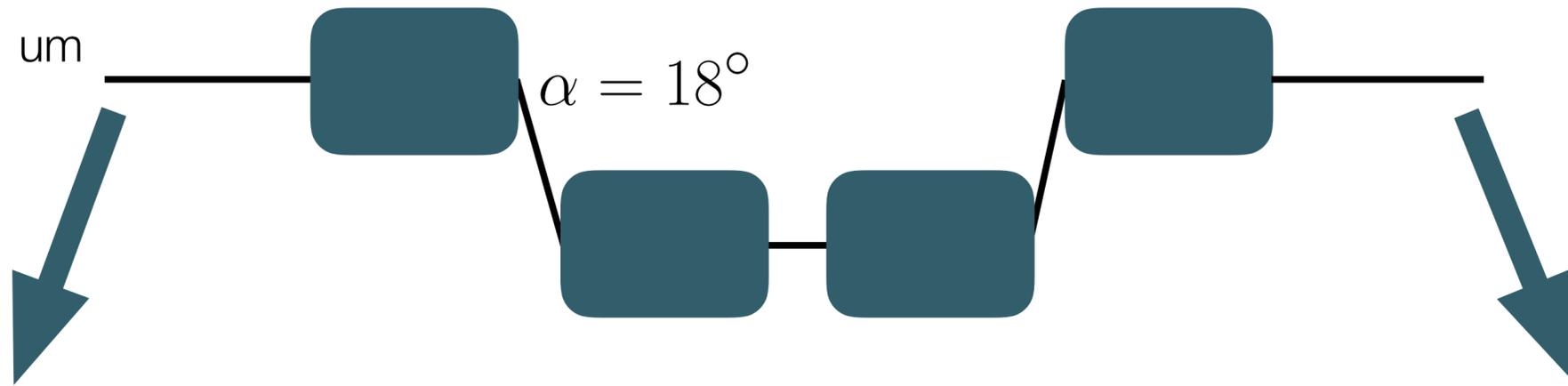
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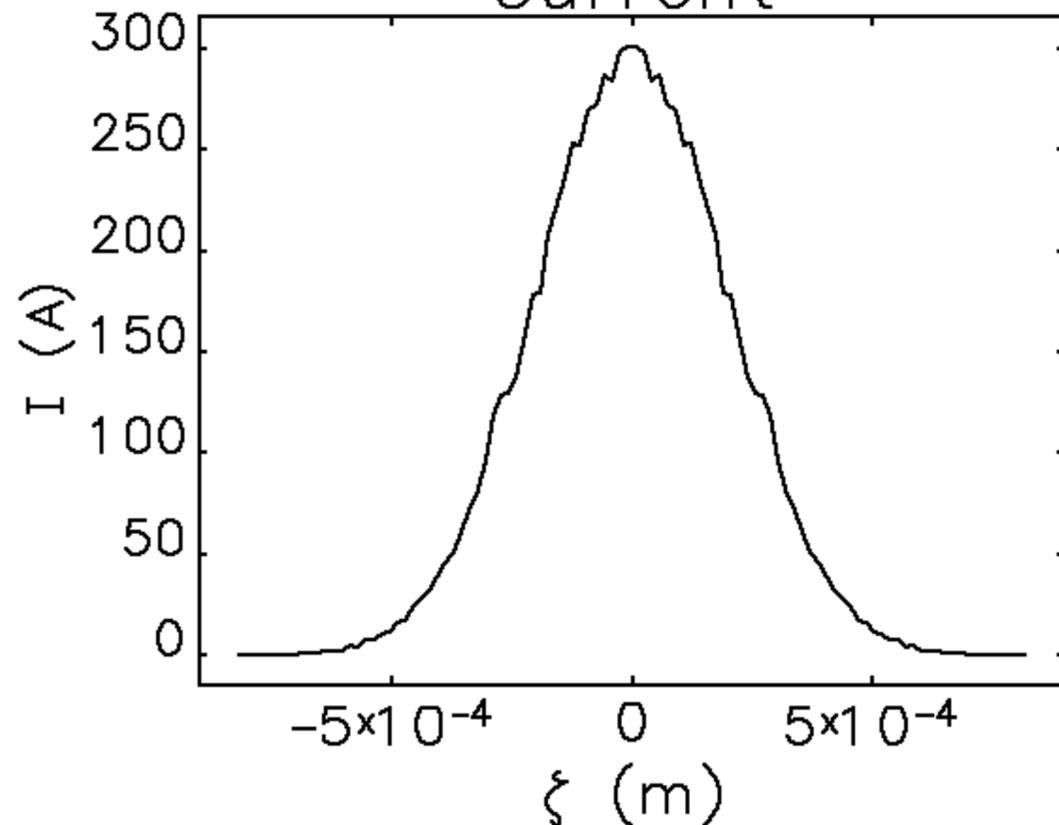
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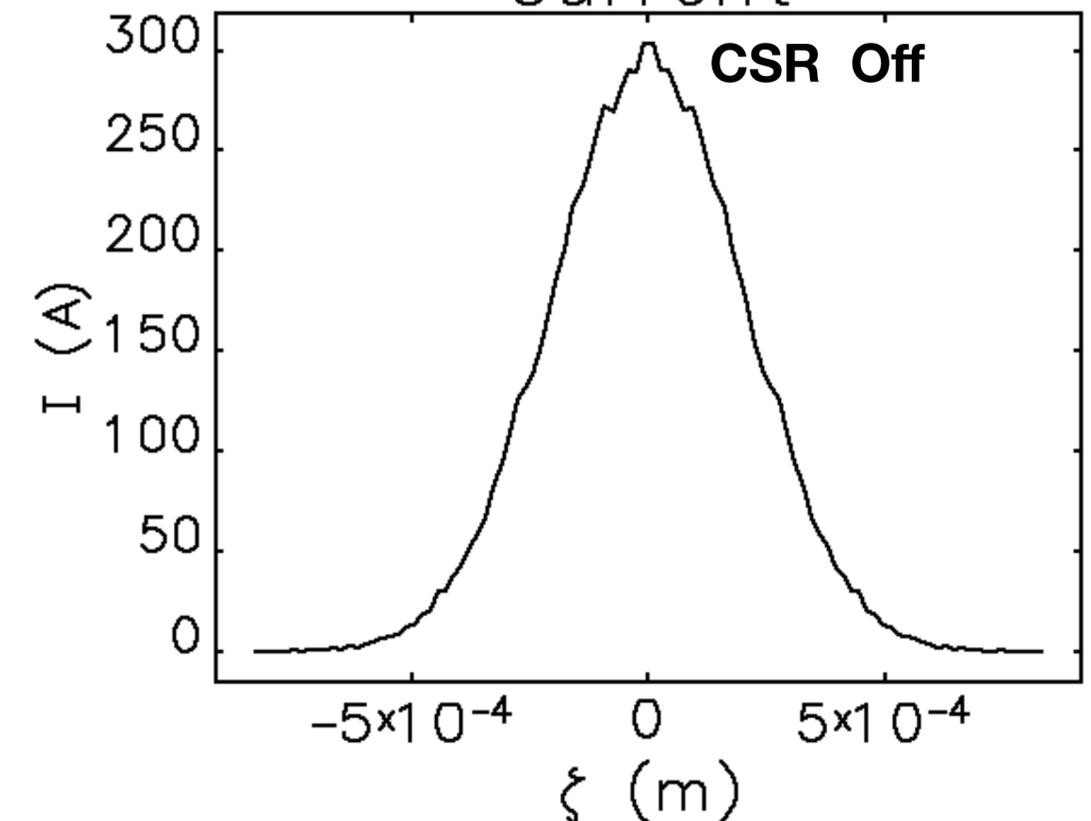
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Current



Current



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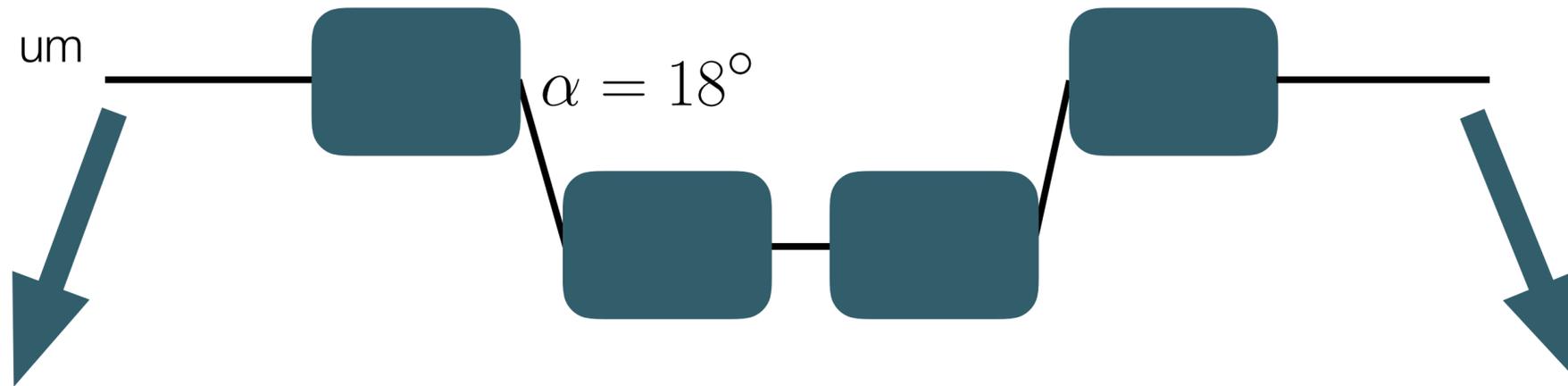
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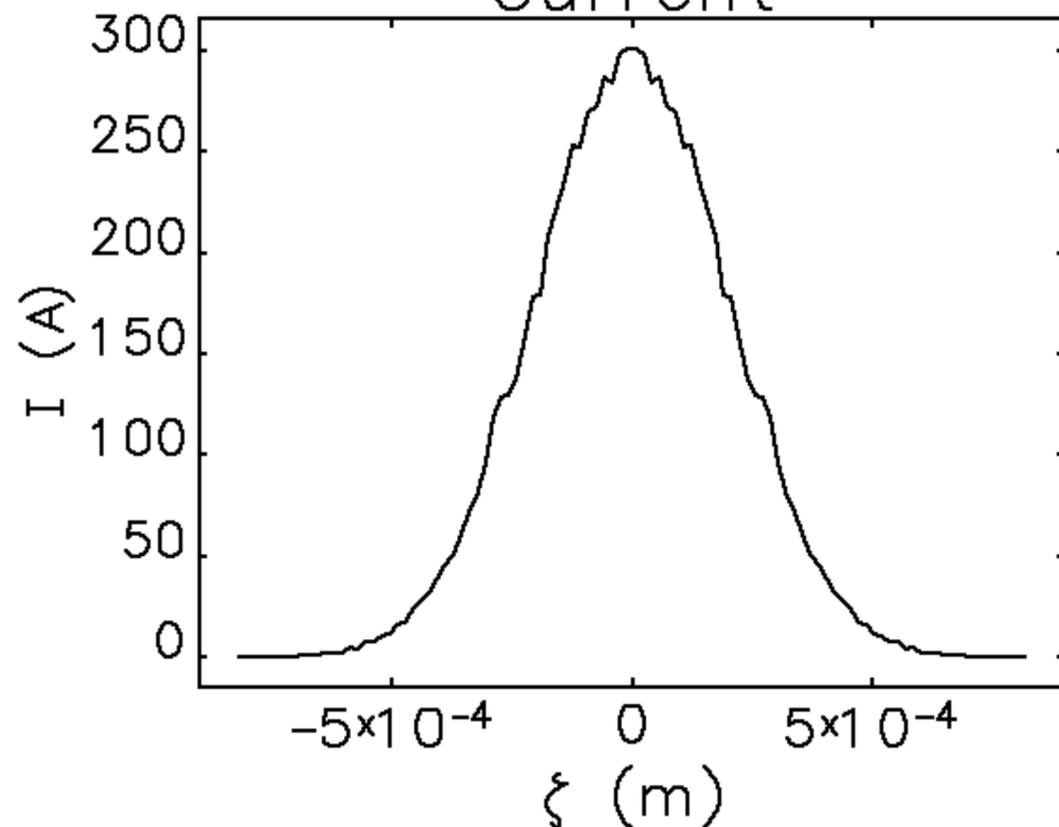
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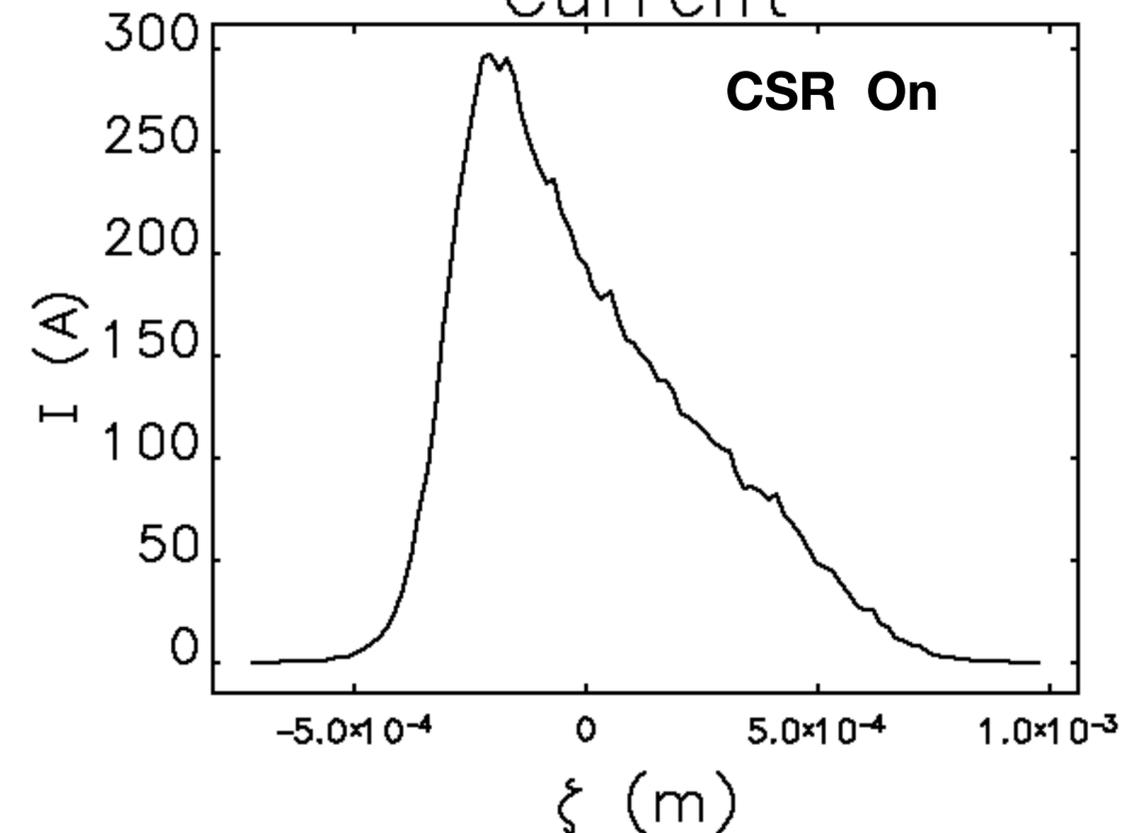
Current



Head (tail) of the bunch gains (loses) energy

Local compression/decompression due to locally varying chirp

Current



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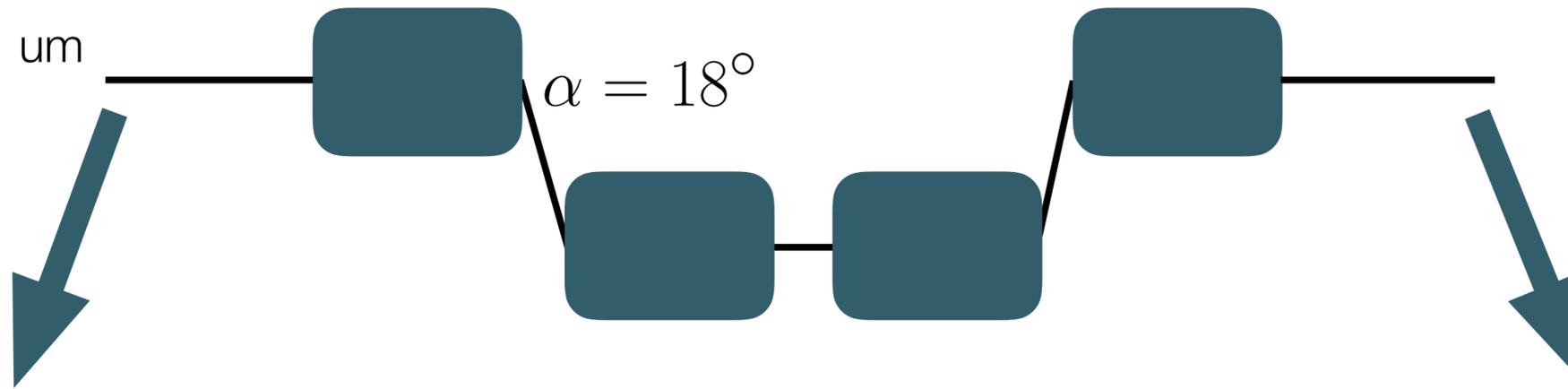
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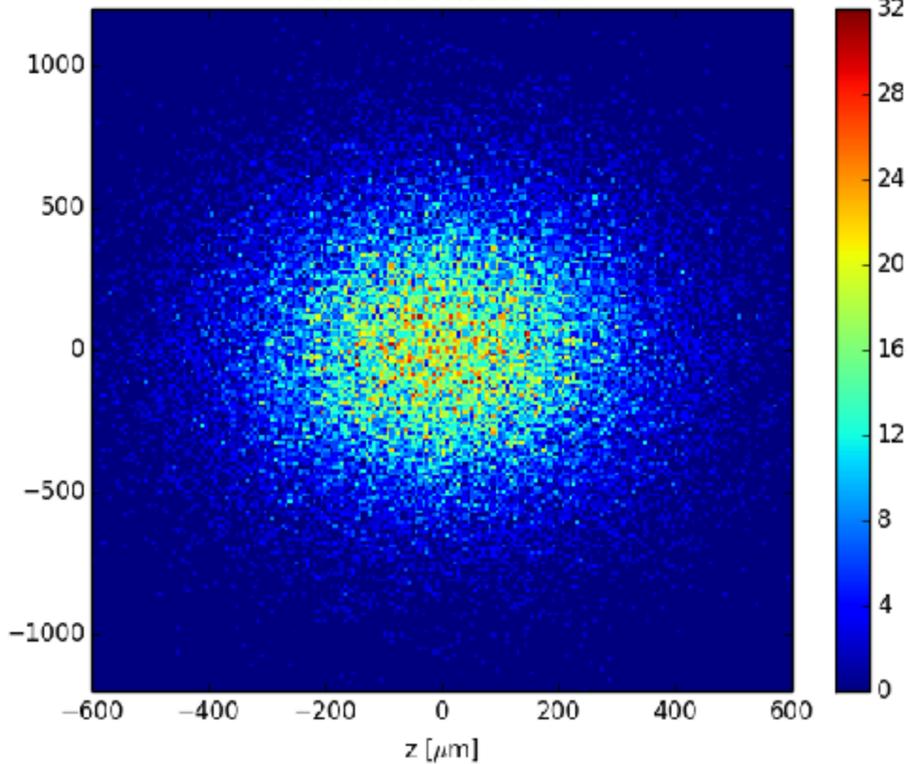
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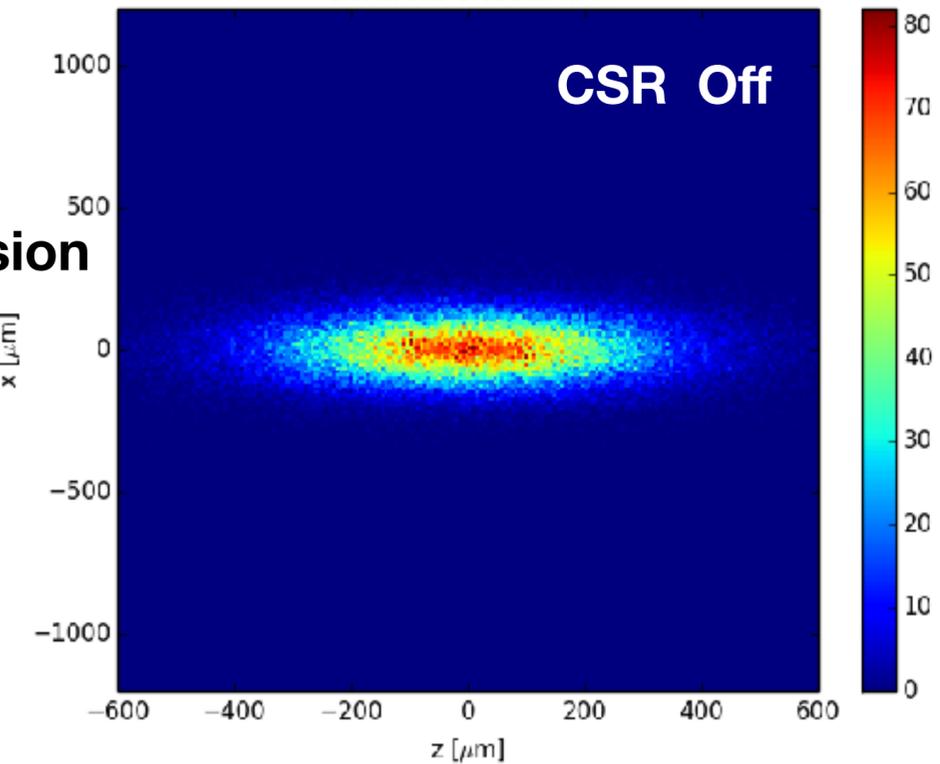
Centroid offsets in x



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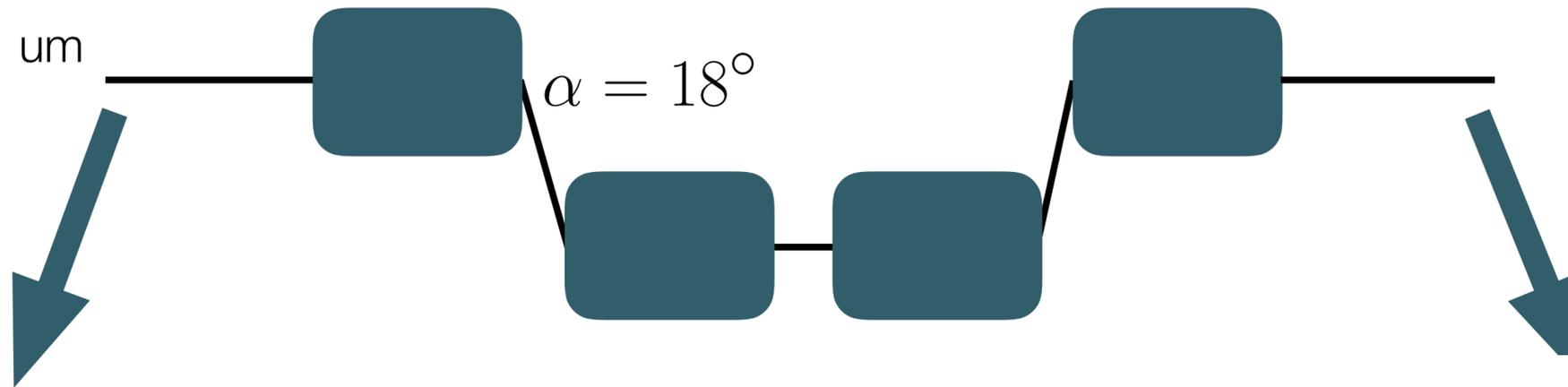
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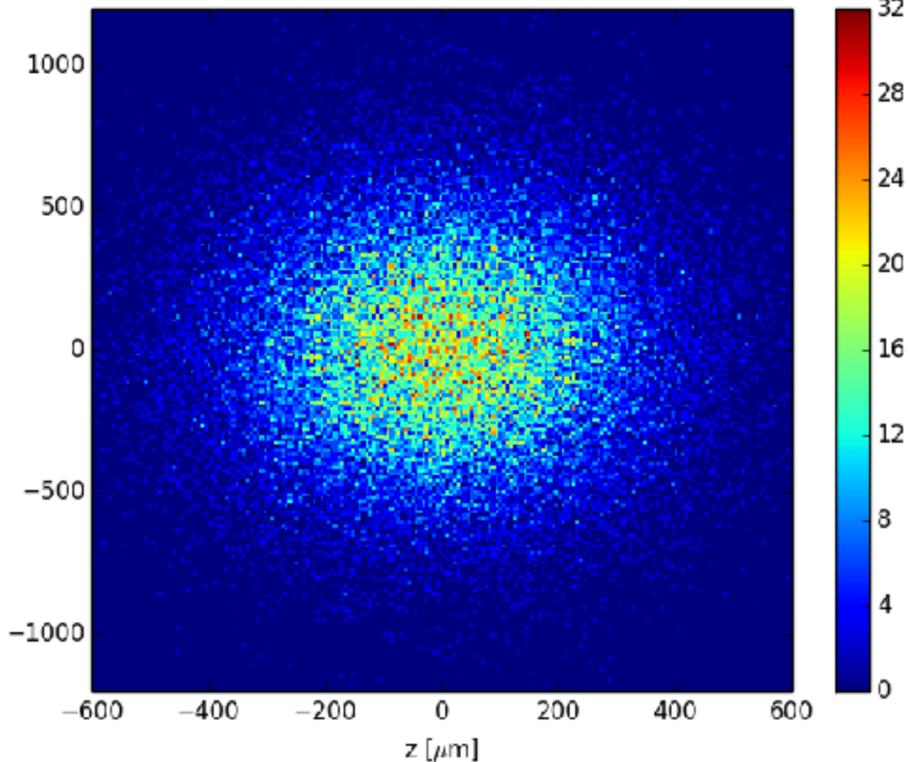
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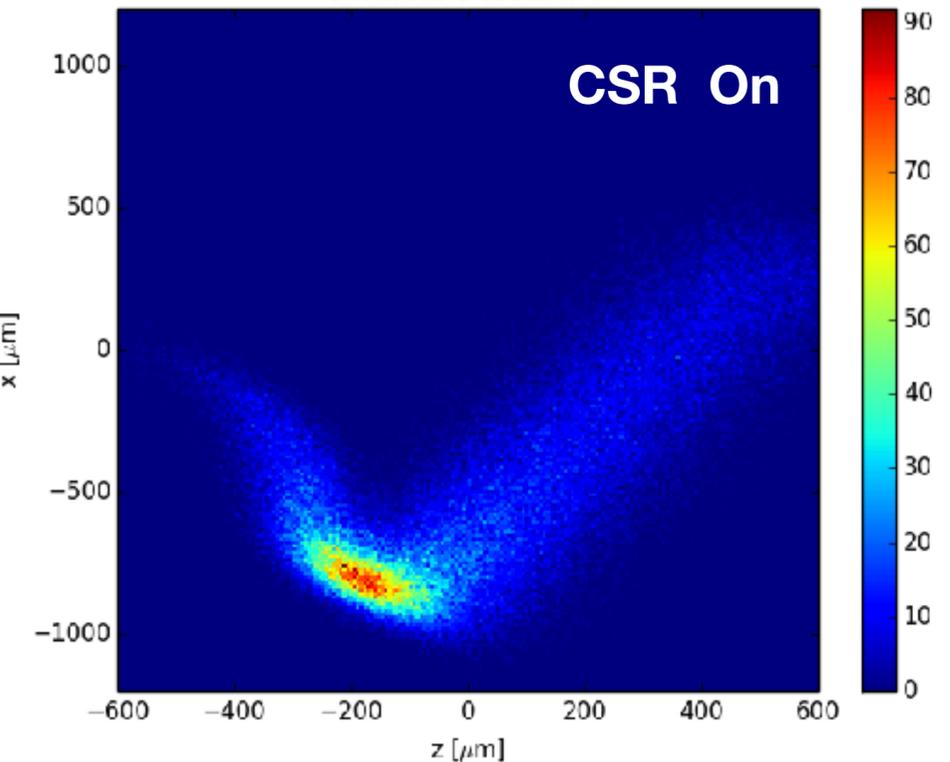
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Local compression/decompression due to locally varying chirp

Centroid offsets, horizontal emittance growth

$$\epsilon_x = 5.4 \mu\text{m} \quad \epsilon_y = 1.00 \mu\text{m}$$

Centroid offsets in x



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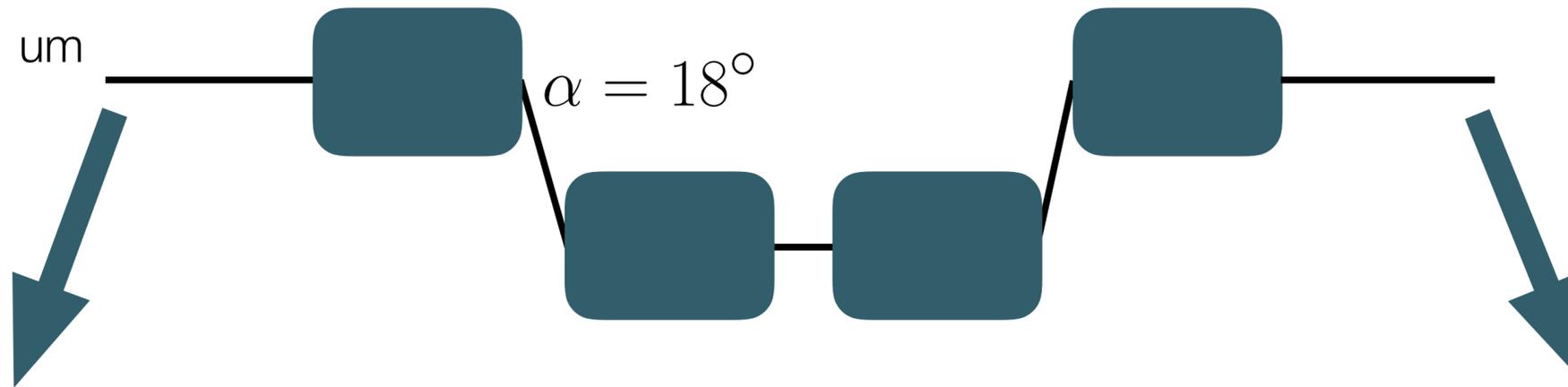
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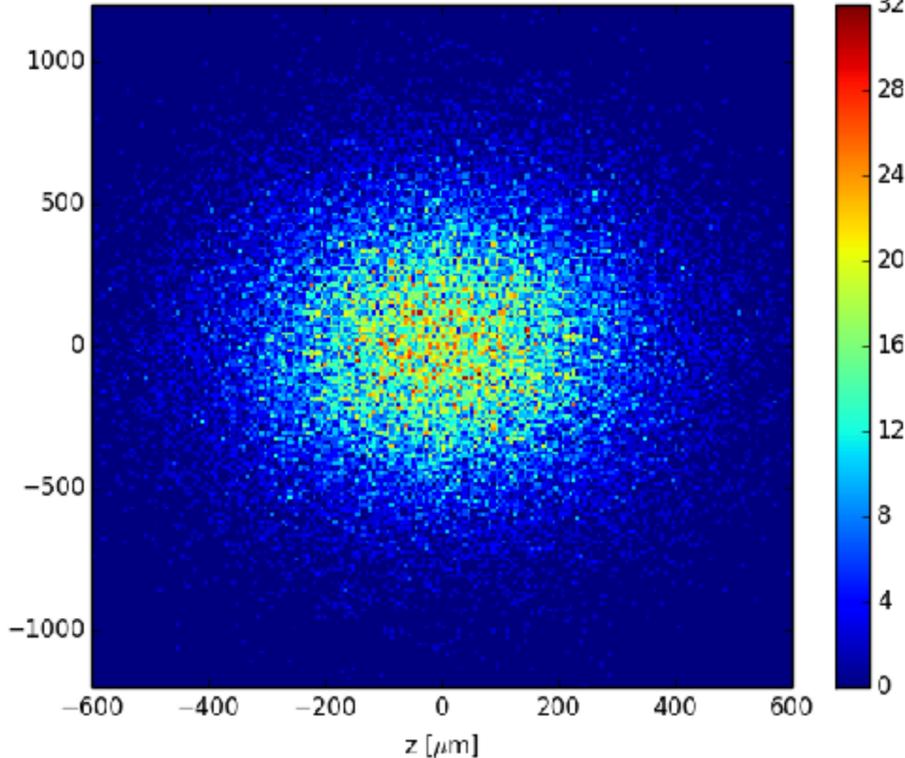
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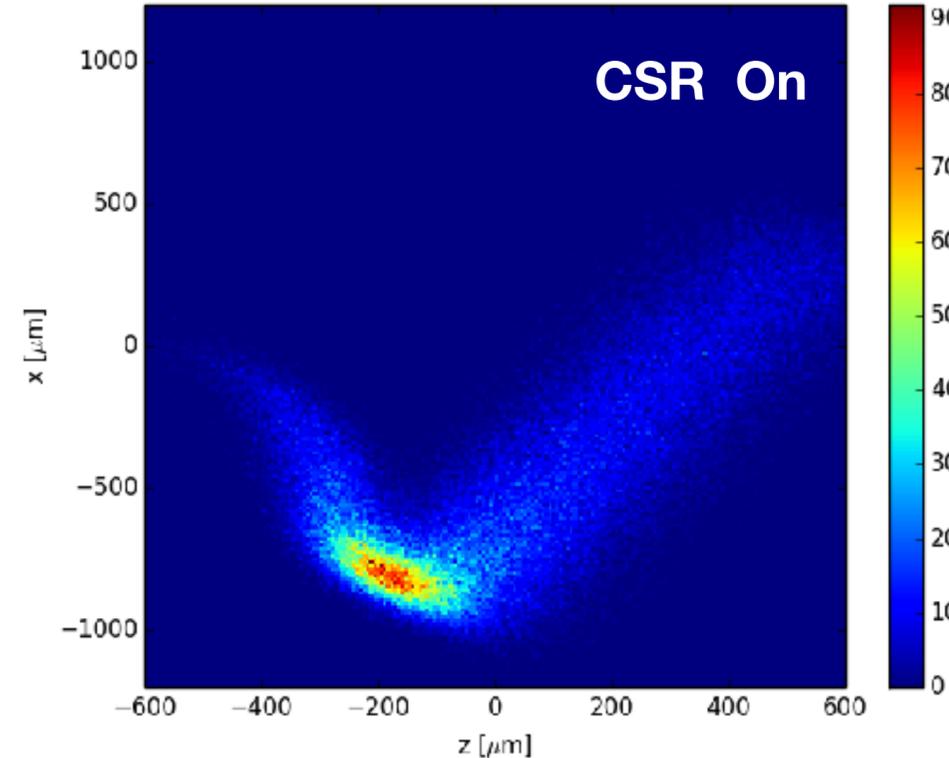


Offset clearly correlated with the energy loss

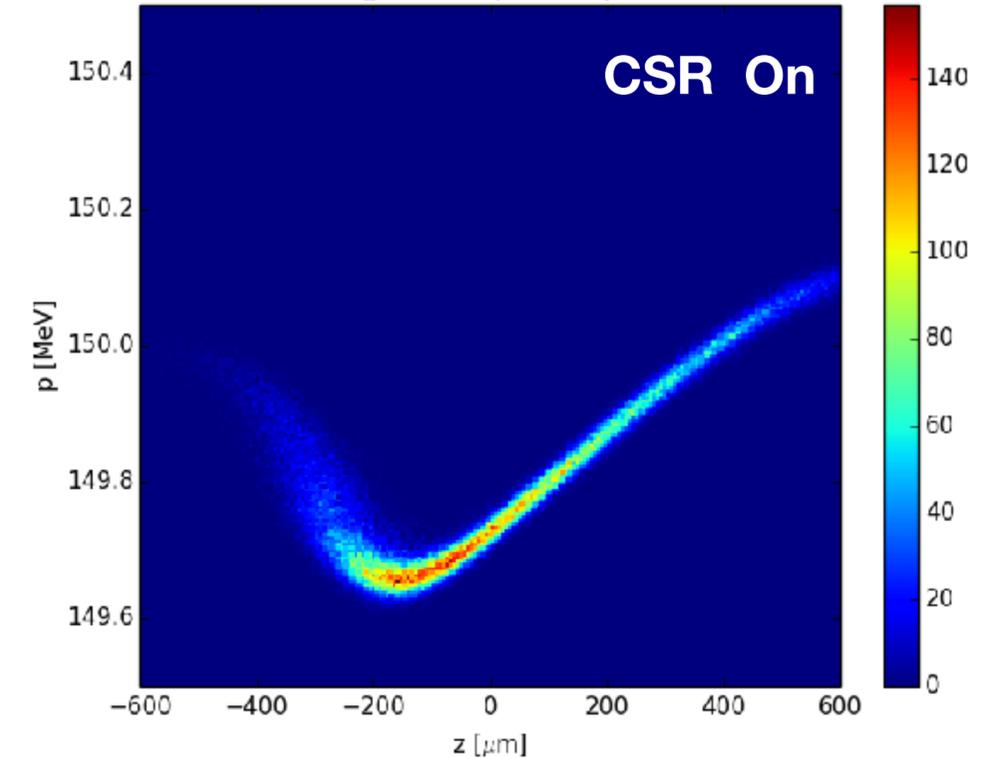
Centroid offsets in x



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Longitudinal phase space

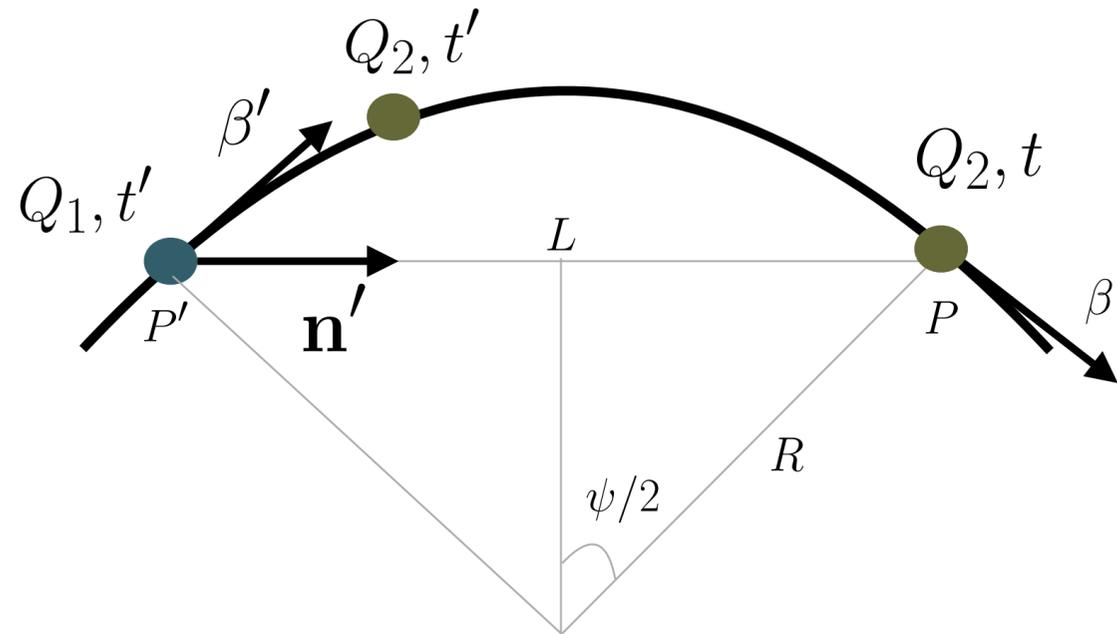


Understanding CSR effects is essential

Calculation of longitudinal CSR wakes

Saldin, Schneidmiller, Yurkov, NIM **A 398** (1997) 373

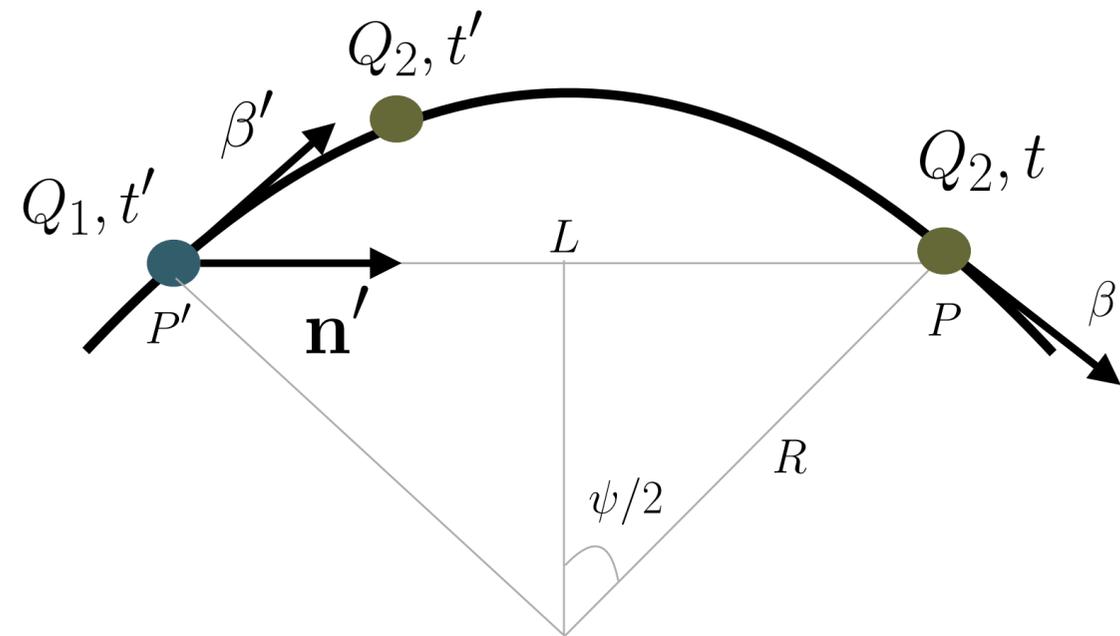
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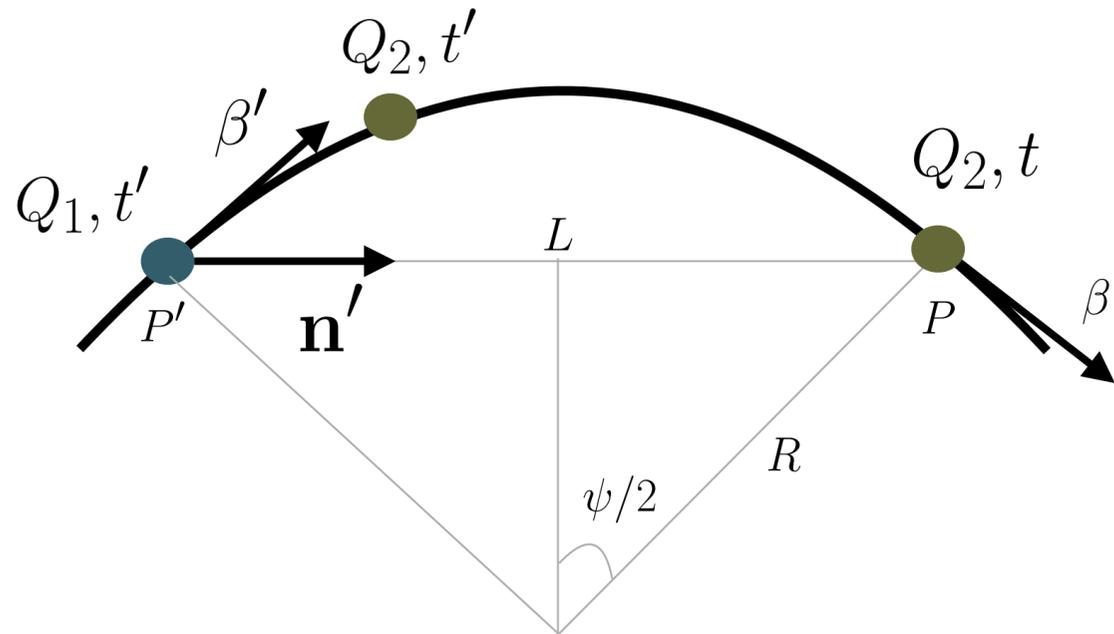
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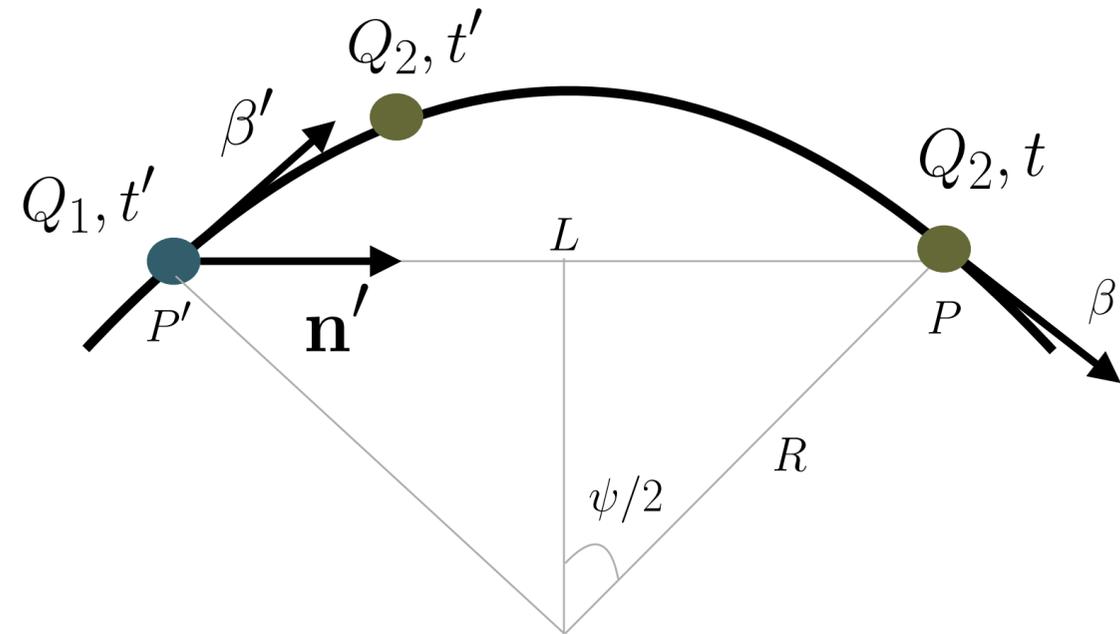
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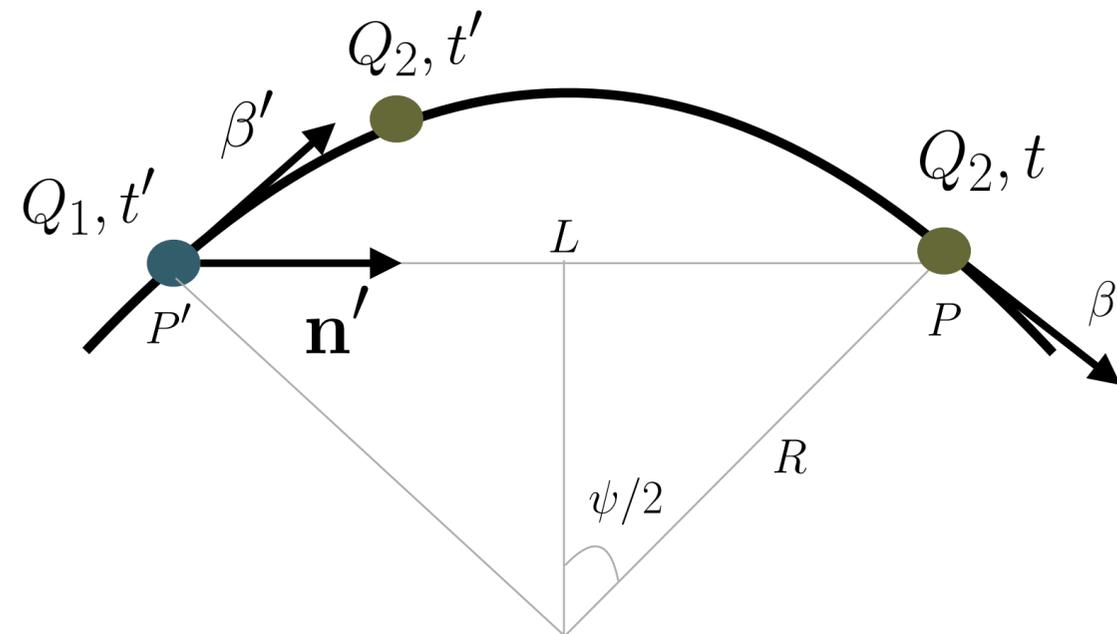
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CSR wake definition: ('regularisation')

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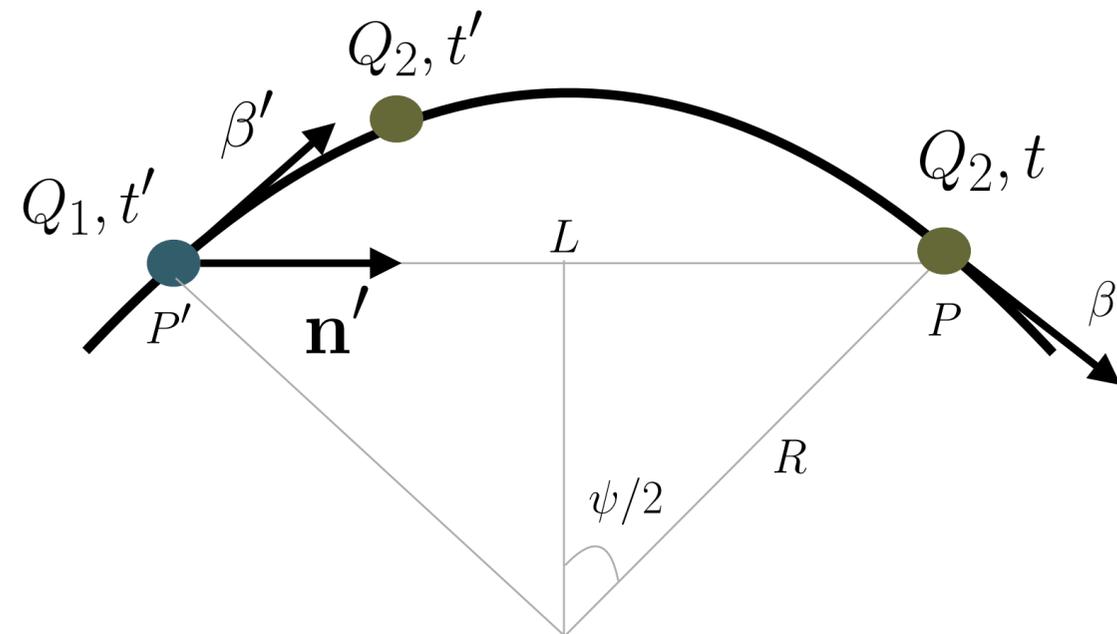
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Small distances $\psi\gamma \ll 1, s - s' \ll R/\gamma^3$

$$\left(\frac{d\mathcal{E}}{cdt}\right)_{\text{CSR}} = -\frac{4e^2\gamma^4}{3R^2} < 0$$

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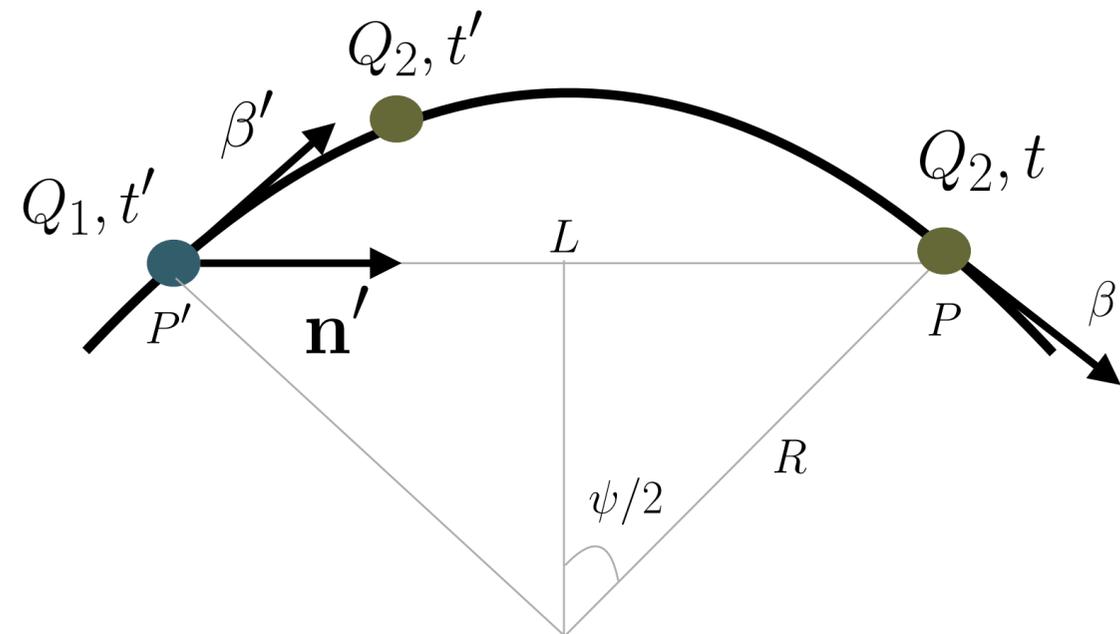
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Our compressor example:

$$R = \frac{L}{\theta} = \frac{0.5 \text{ m}}{0.3 \text{ rad}} = 1.6 \text{ m}$$

$$\gamma = 300$$

$$\frac{R}{\gamma^3} \approx 6 \cdot 10^{-8} \text{ m}$$

Calculation of longitudinal CSR wakes

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- > In order to calculate the energy gain at position s within the bunch (CSR wake) need to sum the effects due to all electrons behind

$$\frac{d\mathcal{E}}{cdt} = \int_{-\infty}^s ds' \lambda(s') G(s - s')$$

Example, gaussian. bunch (long bunch):

$$\left(\frac{d\mathcal{E}}{cdt}\right)_{CSR} \simeq -\frac{2Ne^2}{(2\pi)^{1/2} 3^{1/3} R^{2/3} \sigma^{4/3}} F\left(\frac{s}{\sigma}\right) \quad F(x) = \int_{-\infty}^x \frac{dx'}{(x-x')^{1/3}} \frac{d}{dx'} e^{-(x')^2/2}$$

- > In the long bunch limit (compared to R/γ^3) **independent of energy**
- > Depends on **bunch length, bending radius** and on **charge**

Projected emittance growth

M. Dohlus, T. Limberg, PAC 2005 proc.

- > Centroid slice offsets is the main mechanism of the emittance growth

$$\epsilon^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2$$

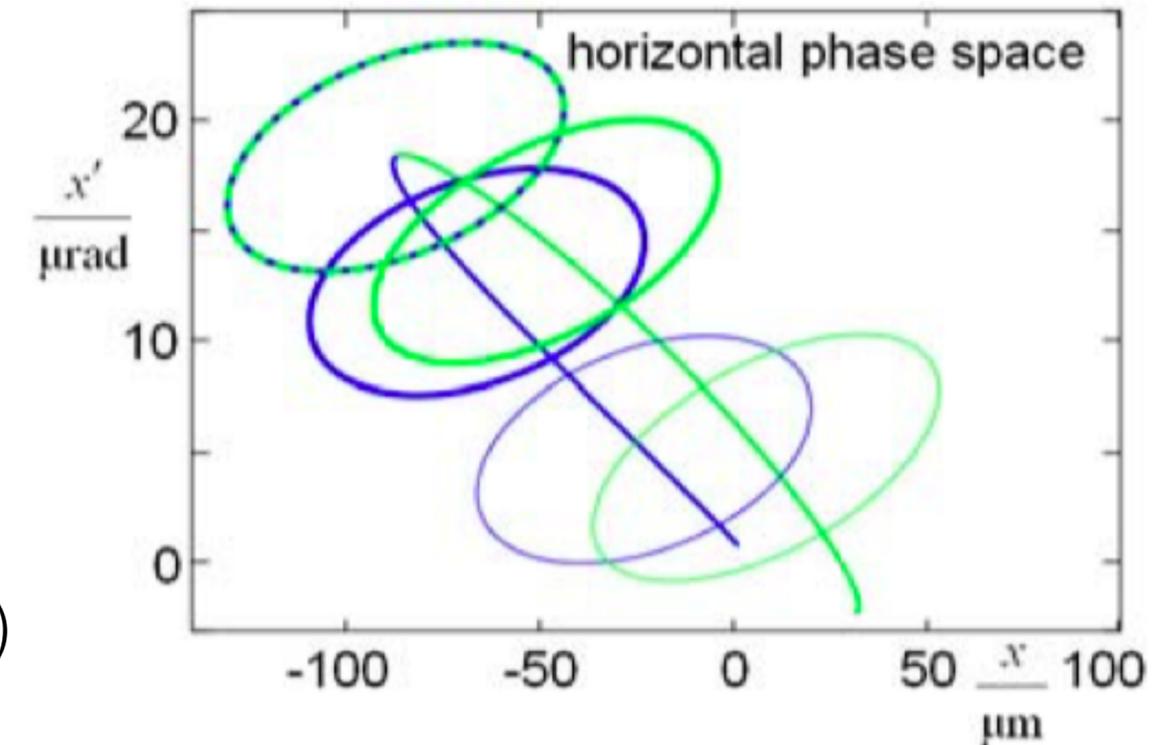
- > In the 'single-kick' approximation:

$$x \rightarrow x + \eta \delta \quad x' \rightarrow x' + \eta' \delta$$

$$\epsilon^2 \rightarrow \epsilon^2 + \epsilon H \sigma_\delta^2 \quad H = \beta \eta'^2 + 2\alpha \eta \eta' + \gamma \eta^2$$

- > If the dispersion is small (like at the end of the 4-dipole chicane)

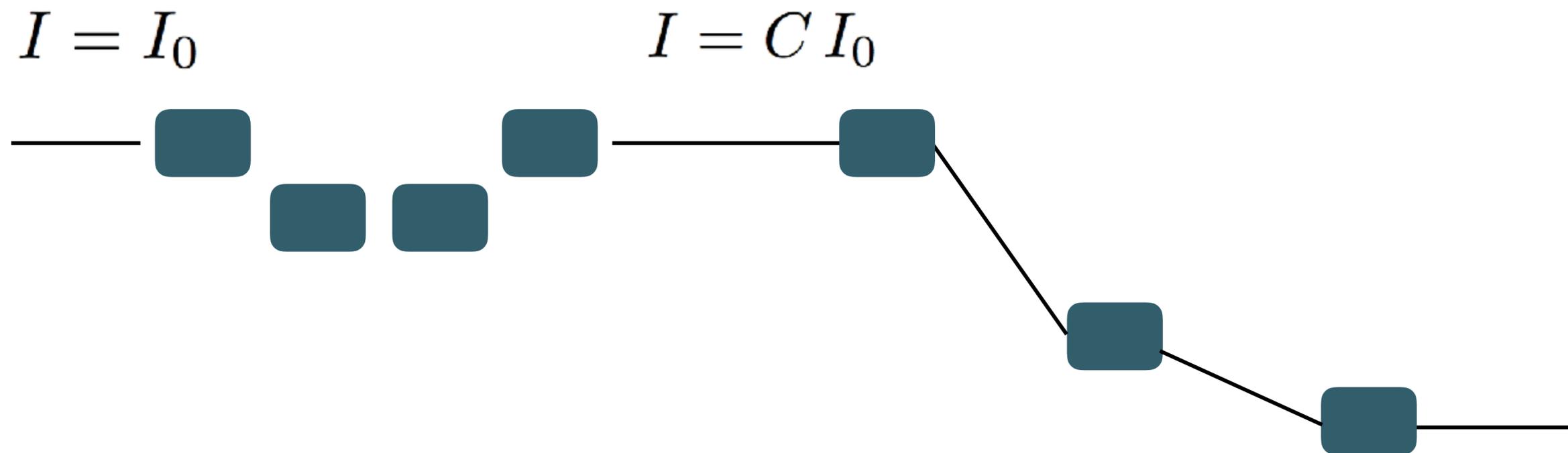
$$\epsilon^2 \rightarrow \epsilon^2 + \beta \epsilon \eta'^2 \sigma_\delta^2$$



CSR Mitigation strategies

1. Compression scheme

- > Magnitude of the CSR wake increases for shorter bunches, therefore it is beneficial to compress as late as possible



$$\left(\frac{d\mathcal{E}}{cdt}\right)_{CSR} \simeq -\frac{2Ne^2}{(2\pi)^{1/2}3^{1/3}R^{2/3}\sigma^{4/3}} F\left(\frac{s}{\sigma}\right)$$



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$$I = I_0$$

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$$I = C I_0$$

2. Energy

> In the limit of long bunches (compared to R/γ^3) CSR wake is independent of beam energy

> Relative energy change decreases with energy, so should the offsets and emittance growth

$$\epsilon \rightarrow \epsilon + \beta\eta'^2\sigma_\delta^2$$

2. Energy

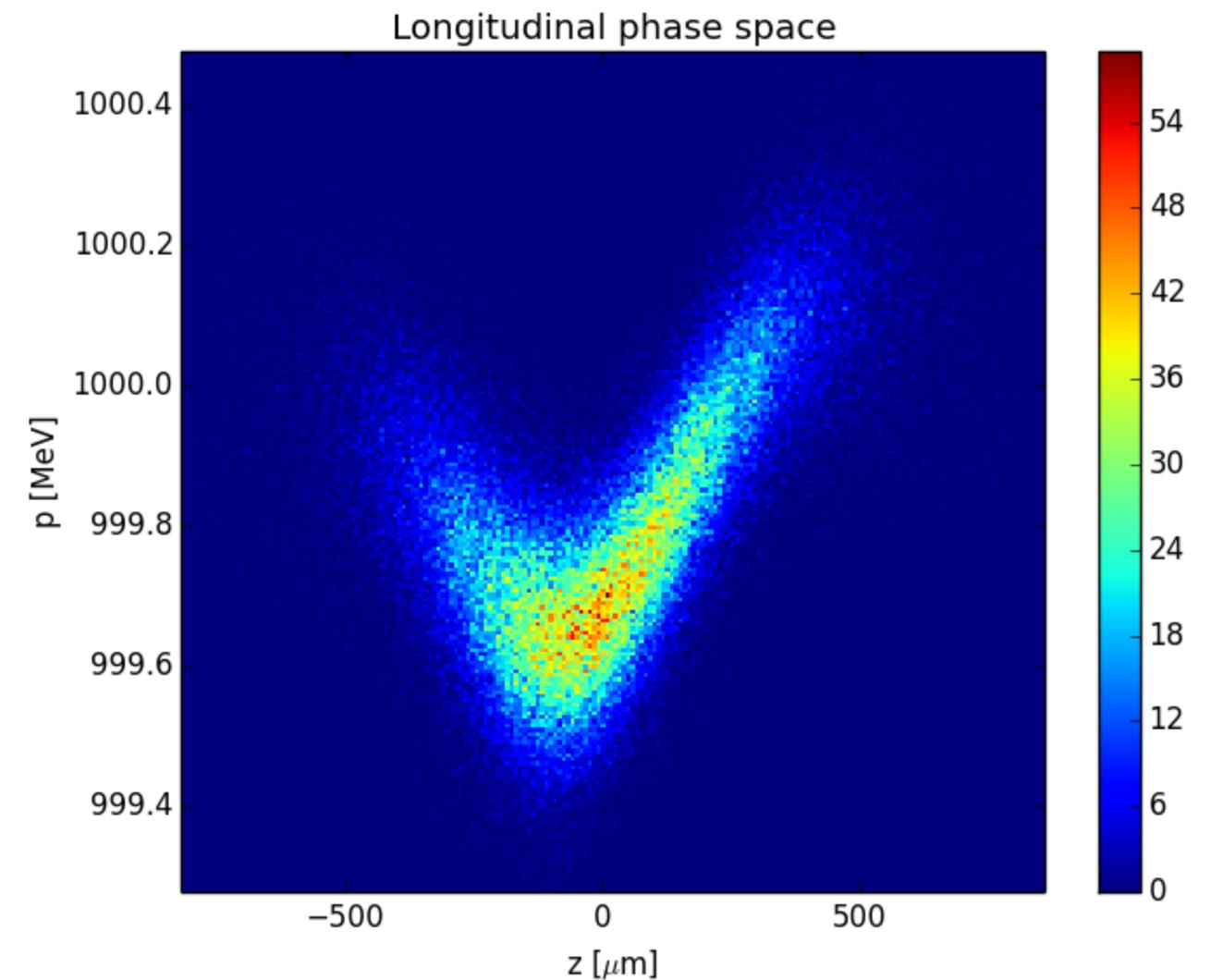
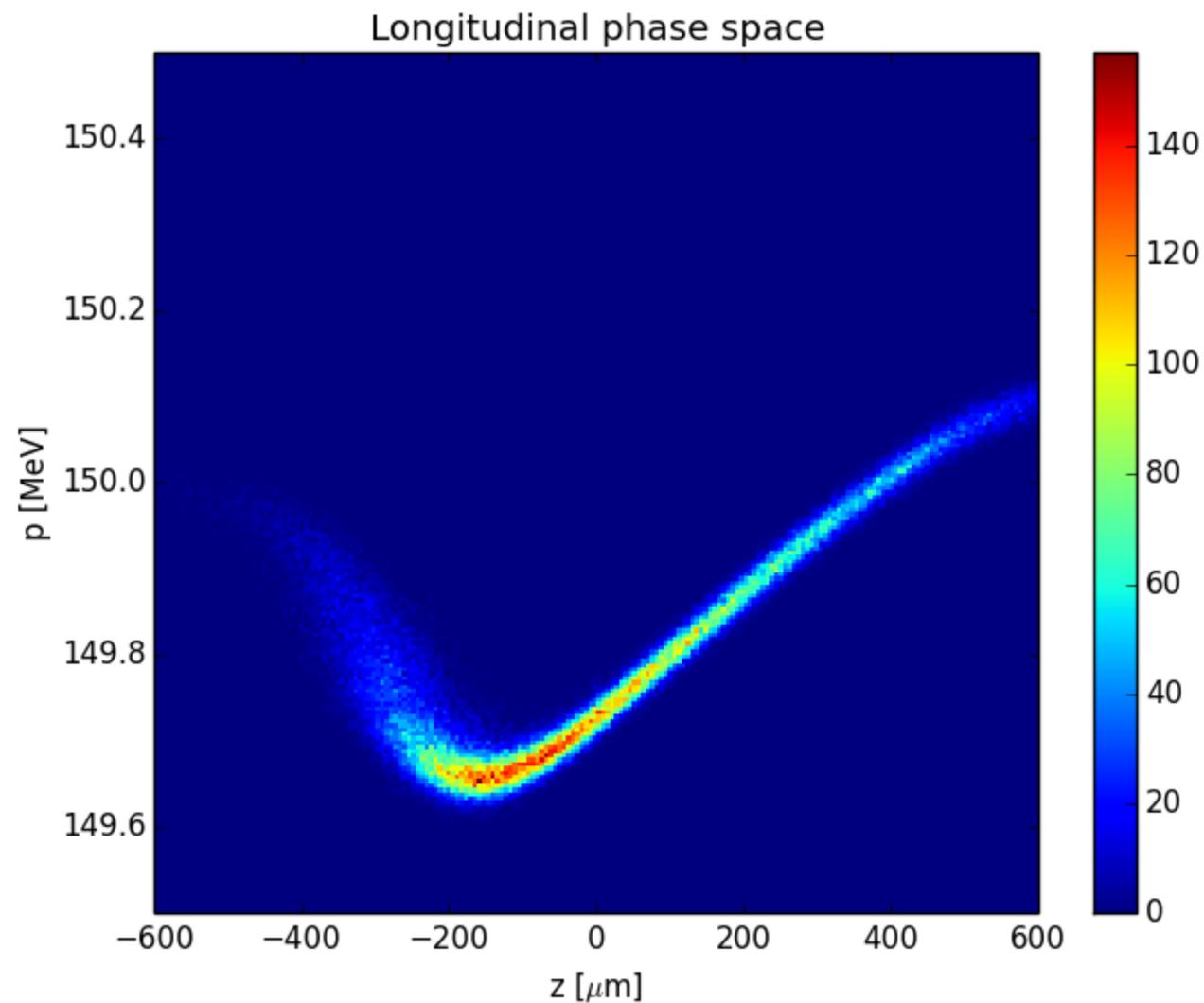
> In the limit of long bunches (compared to R/γ^3) CSR wake is independent of beam energy

> Relative energy change decreases with energy, so should the offsets and emittance growth

150 MeV

1000 MeV

$$\epsilon \rightarrow \epsilon + \beta\eta'^2\sigma_\delta^2$$

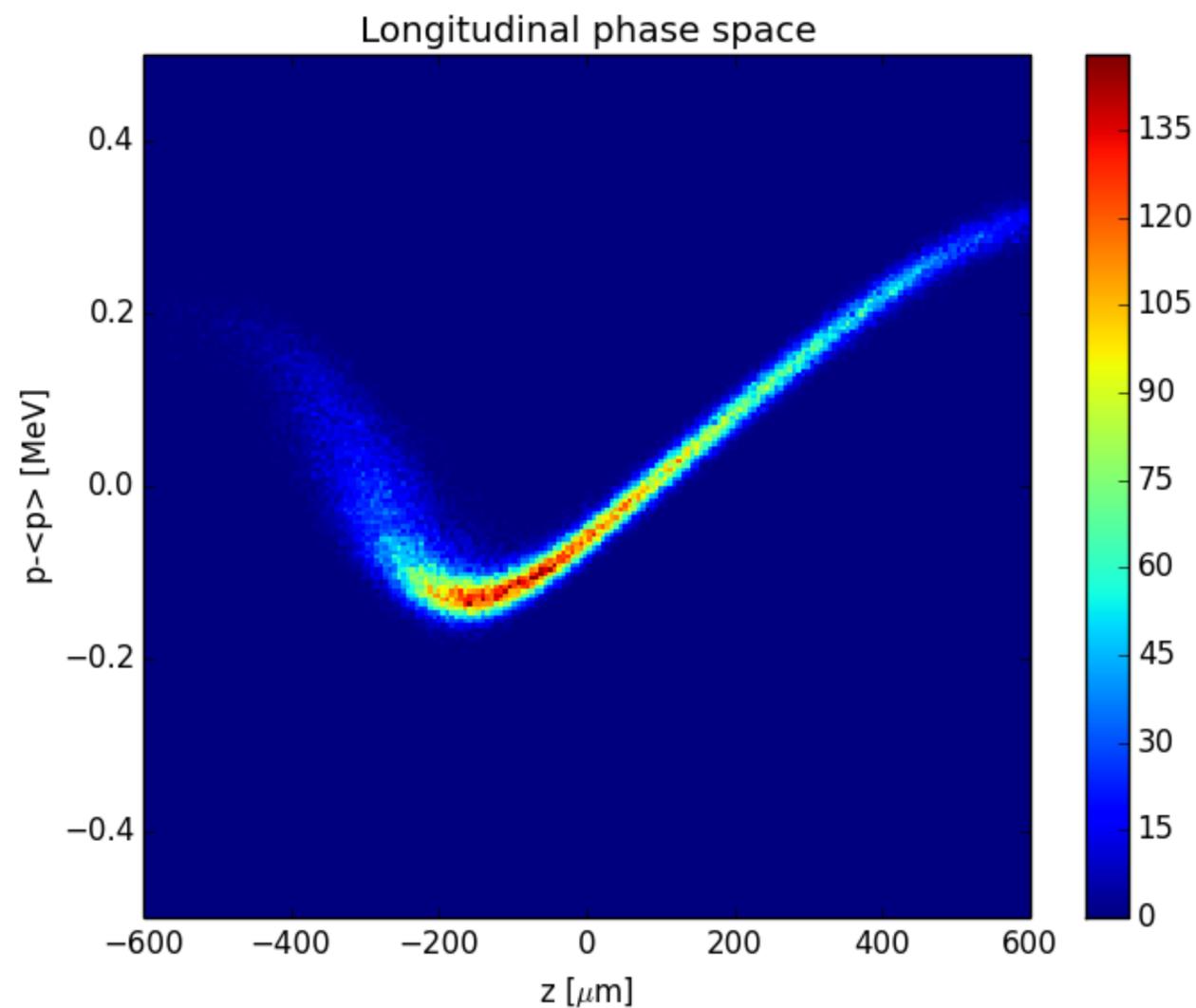


2. Energy

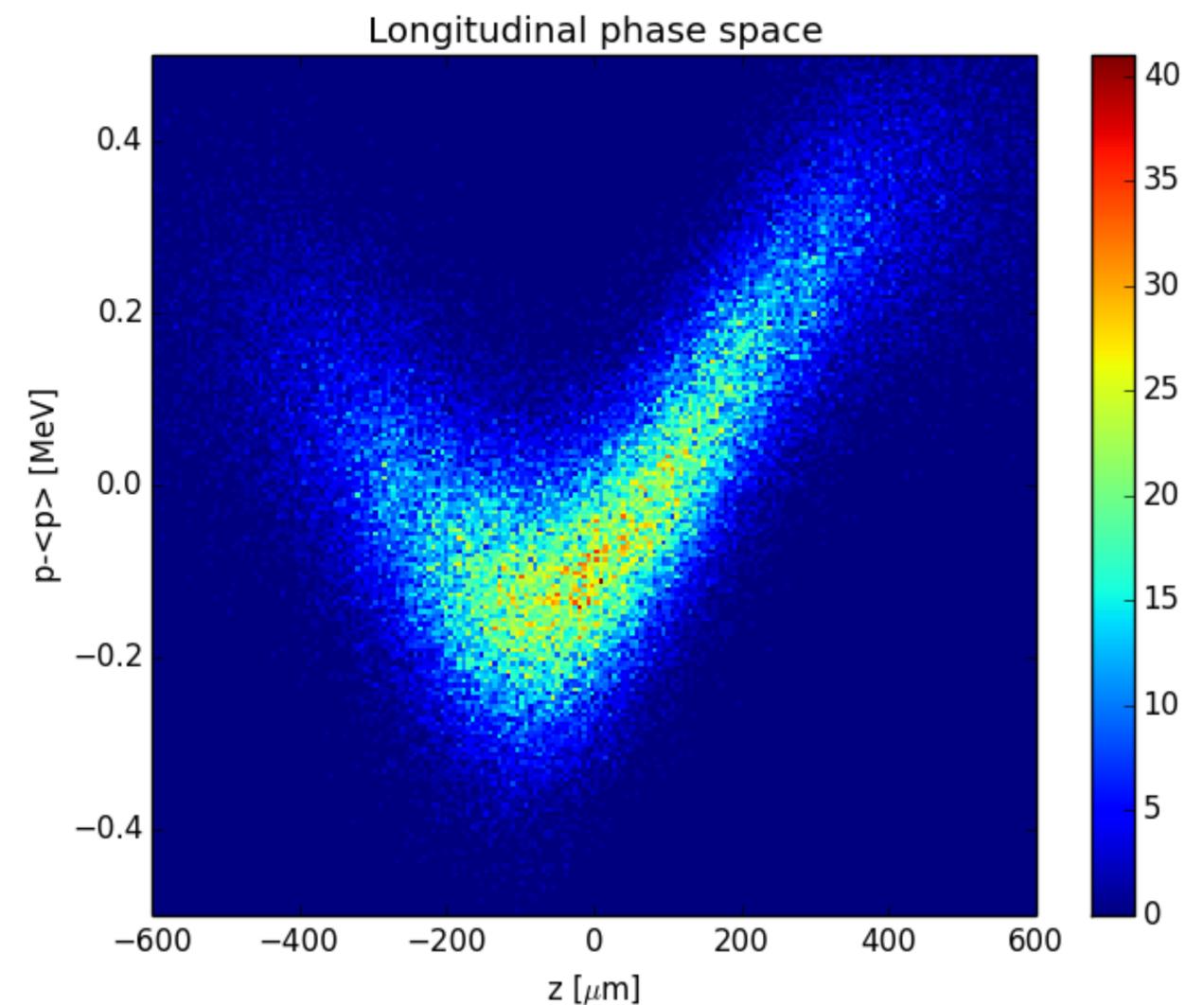
➤ In the limit of long bunches (compared to R/γ^3) CSR wake is independent of beam energy

➤ Relative energy change decreases with energy, so should the offsets and emittance growth

150 MeV



1000 MeV



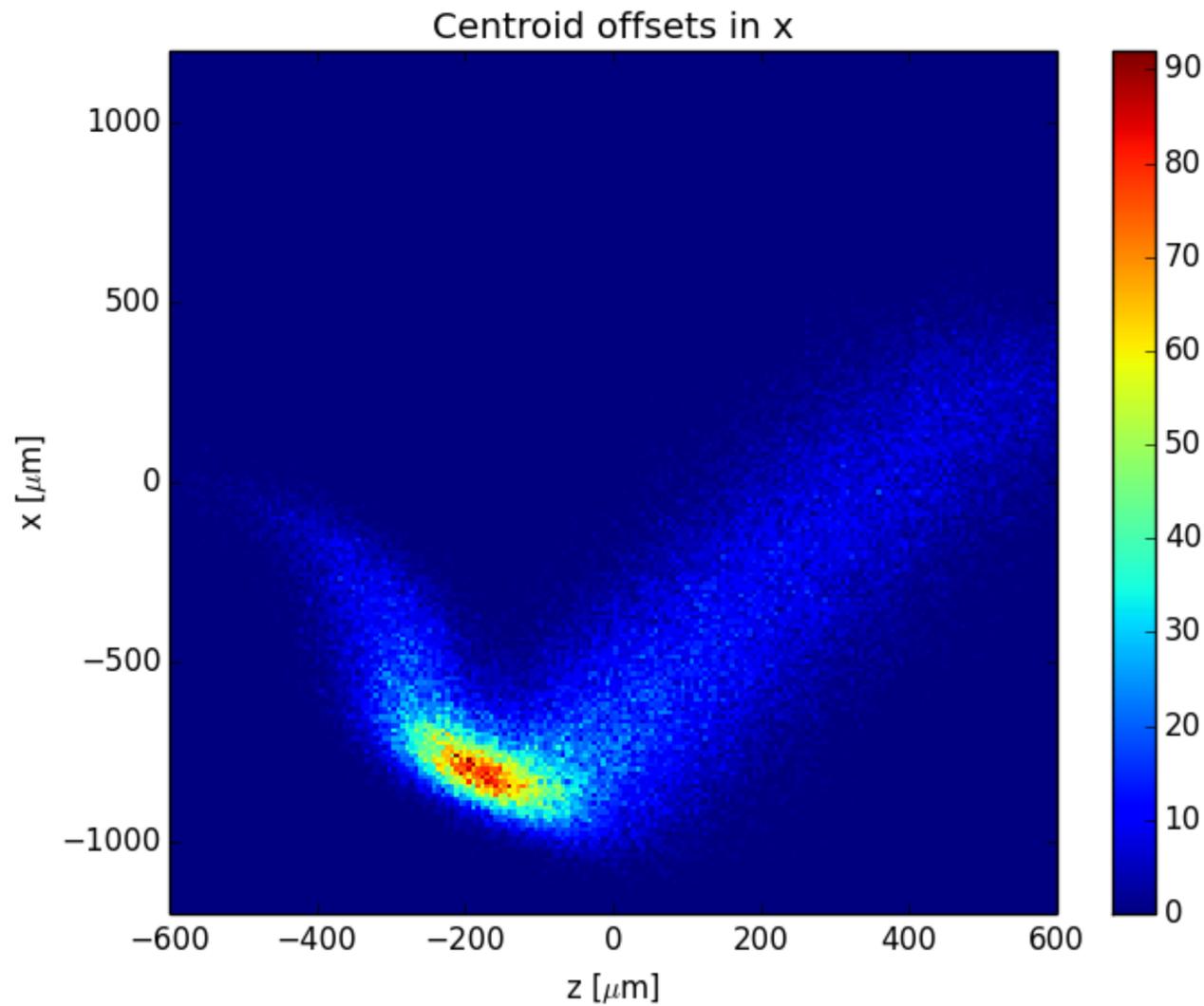
$$\epsilon \rightarrow \epsilon + \beta \eta'^2 \sigma_\delta^2$$

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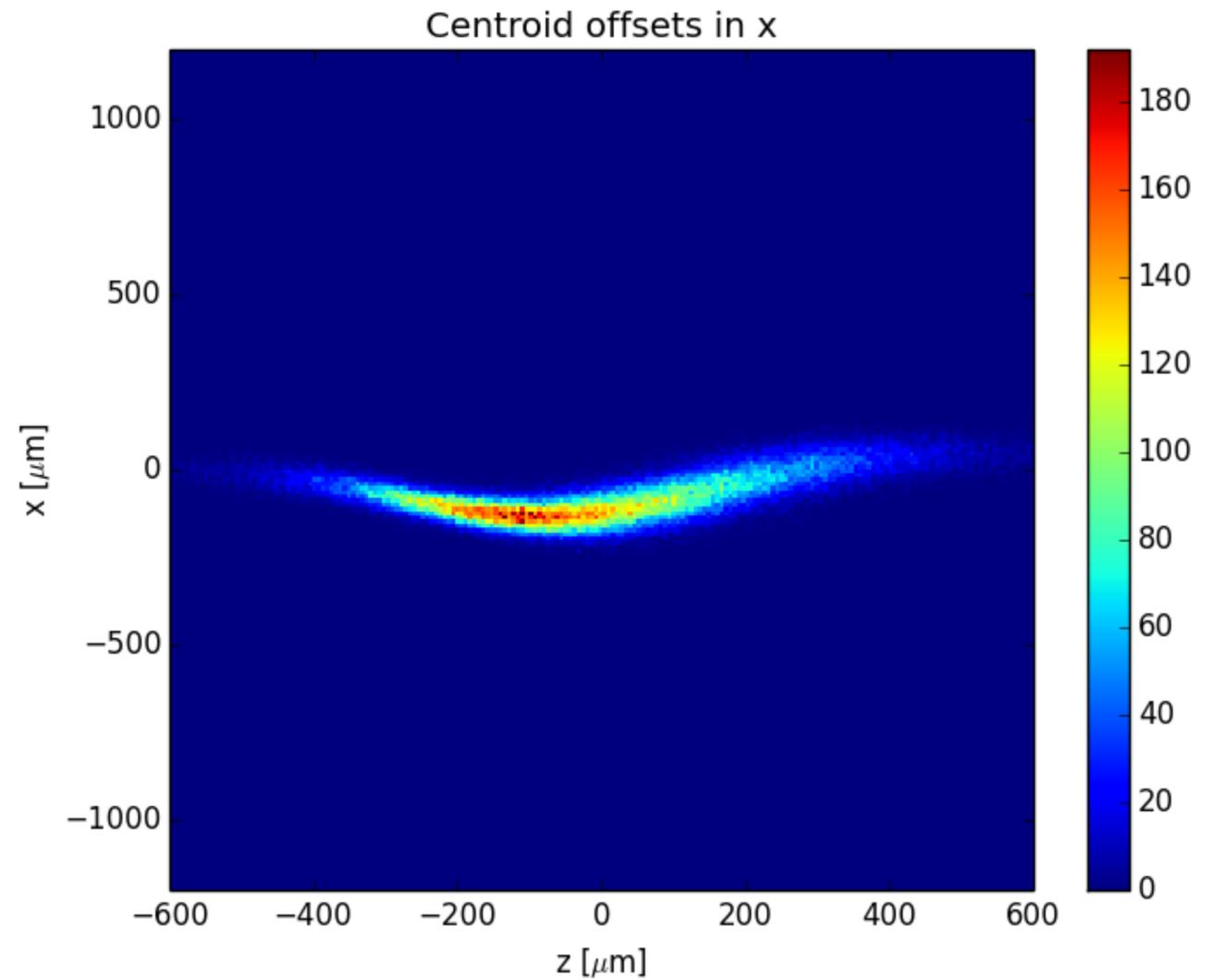
150 MeV



$$\epsilon_x = 5.40 \mu\text{m}$$

1000 MeV

$$\epsilon \rightarrow \epsilon + \beta\eta'^2\sigma_\delta^2$$

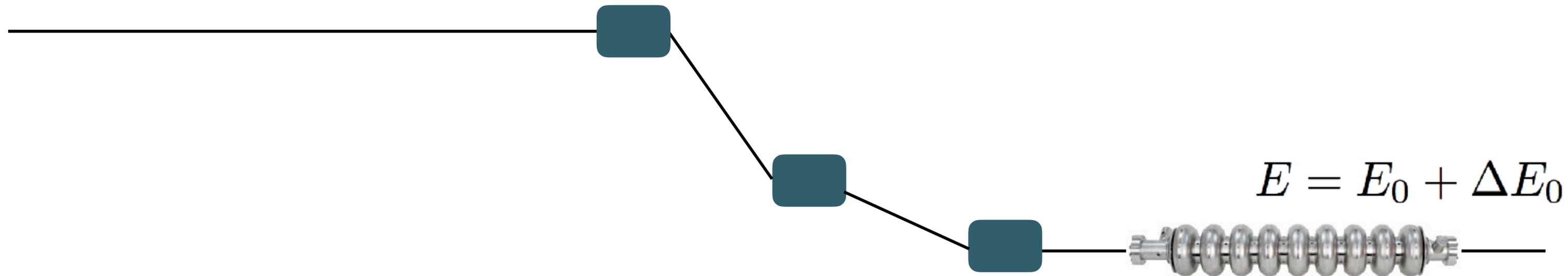


$$\epsilon_x = 2.28 \mu\text{m}$$

2. Energy

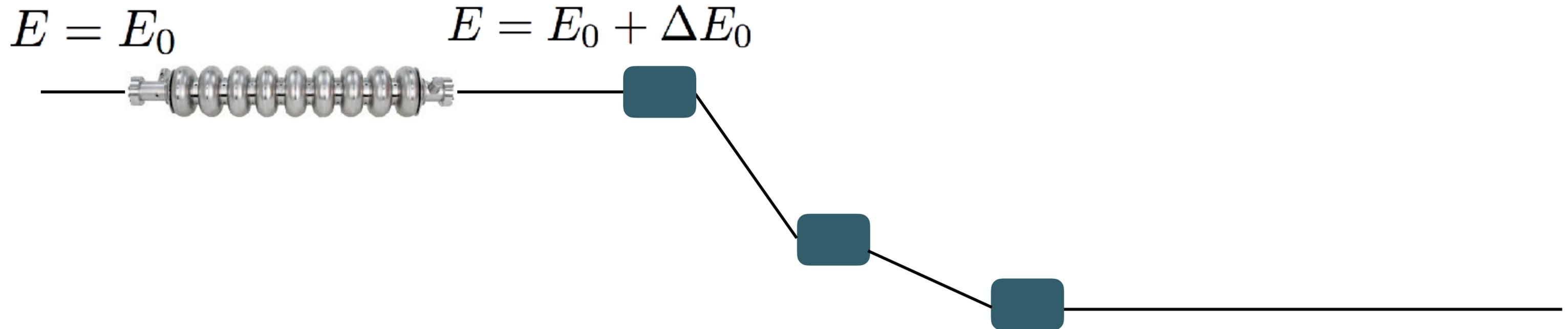
- > In the limit of long bunches (compared to R/γ^3) CSR wake is independent of beam energy
 - > Relative energy change decreases with energy, so should the offsets and emittance growth
 - > Therefore, it is beneficial to bend the beam at higher energies

$$E = E_0$$



2. Energy

- > In the limit of long bunches (compared to R/γ^3) CSR wake is independent of beam energy
 - > Relative energy change decreases with energy, so should the offsets and emittance growth
 - > Therefore, it is beneficial to bend the beam at higher energies



3. Twiss parameters in bends

> Emittance growth depends on optics, need small value of the H-function

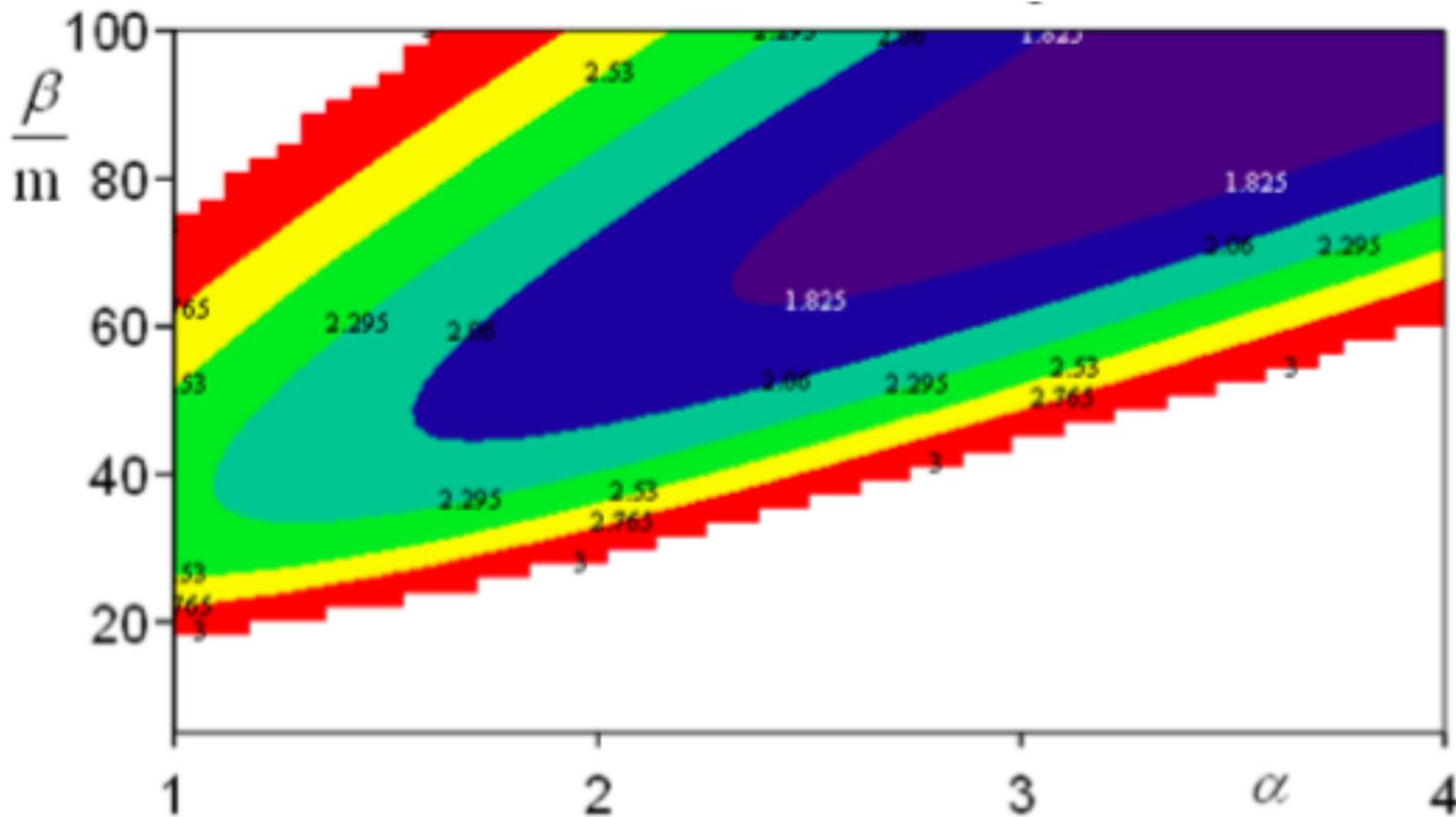
$$\epsilon^2 \rightarrow \epsilon^2 + \epsilon H \sigma_\delta^2$$

$$H = \beta \eta'^2 + 2\alpha \eta \eta' + \gamma \eta^2$$

> In a four-dipole chicane need a small beta-function in the last bend

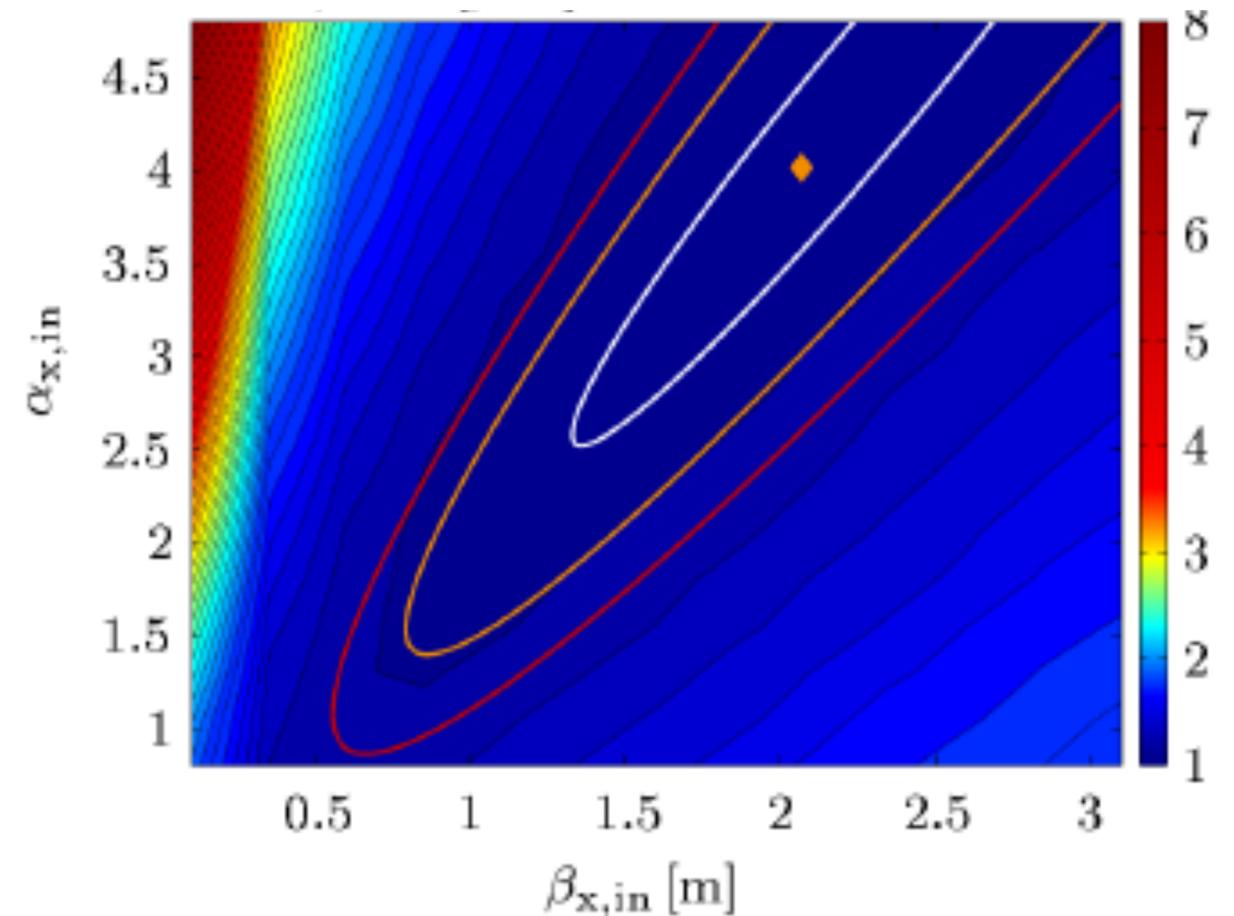
$$\epsilon^2 \rightarrow \epsilon^2 + \beta \epsilon \eta'^2 \sigma_\delta^2$$

M. Dohlus, T. Limberg, PAC 2005 proc.



4-dipole chicane ('Zeuthen-chicane')

M. Scholz, DESY-THESIS-2014-002

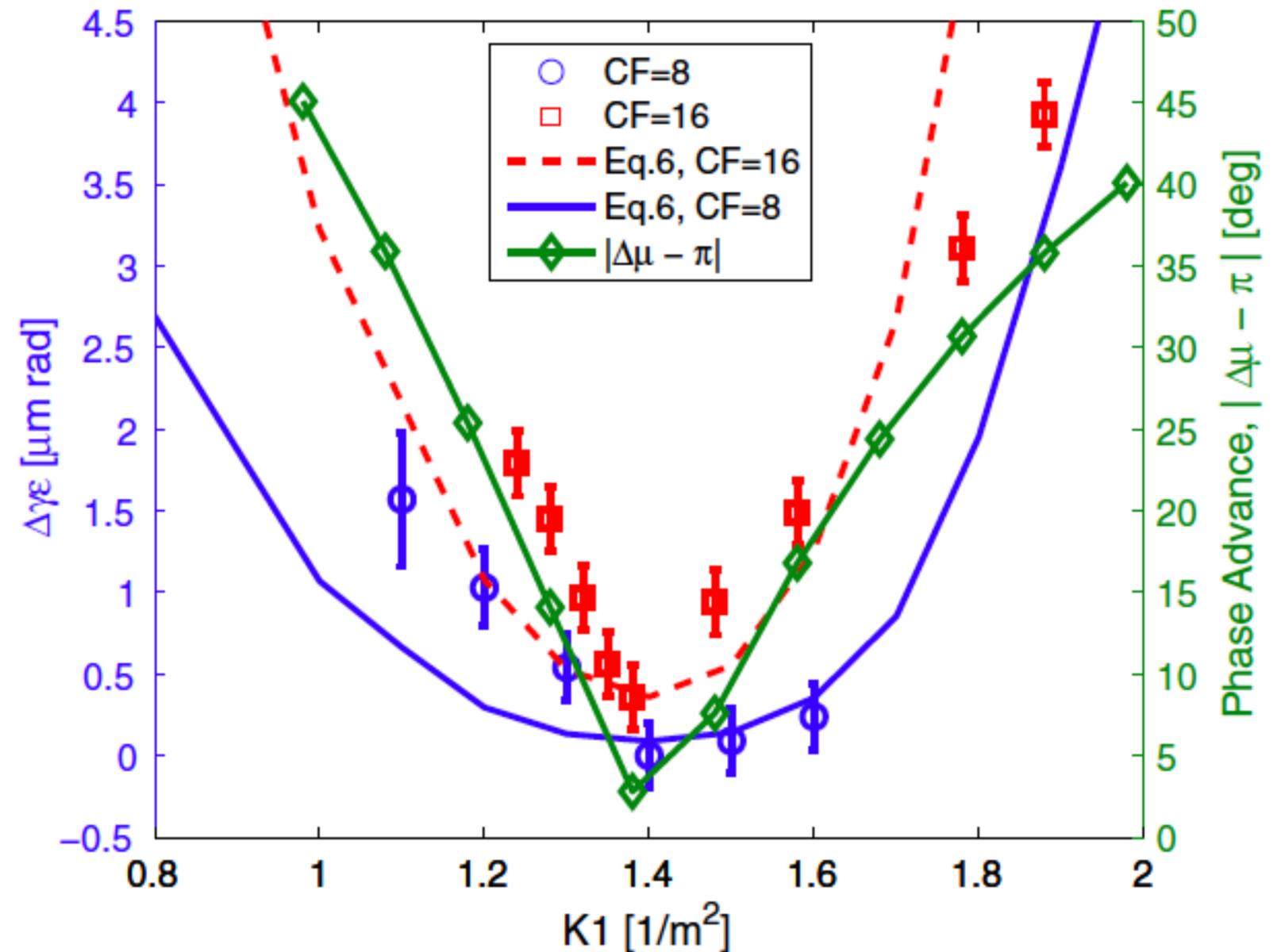
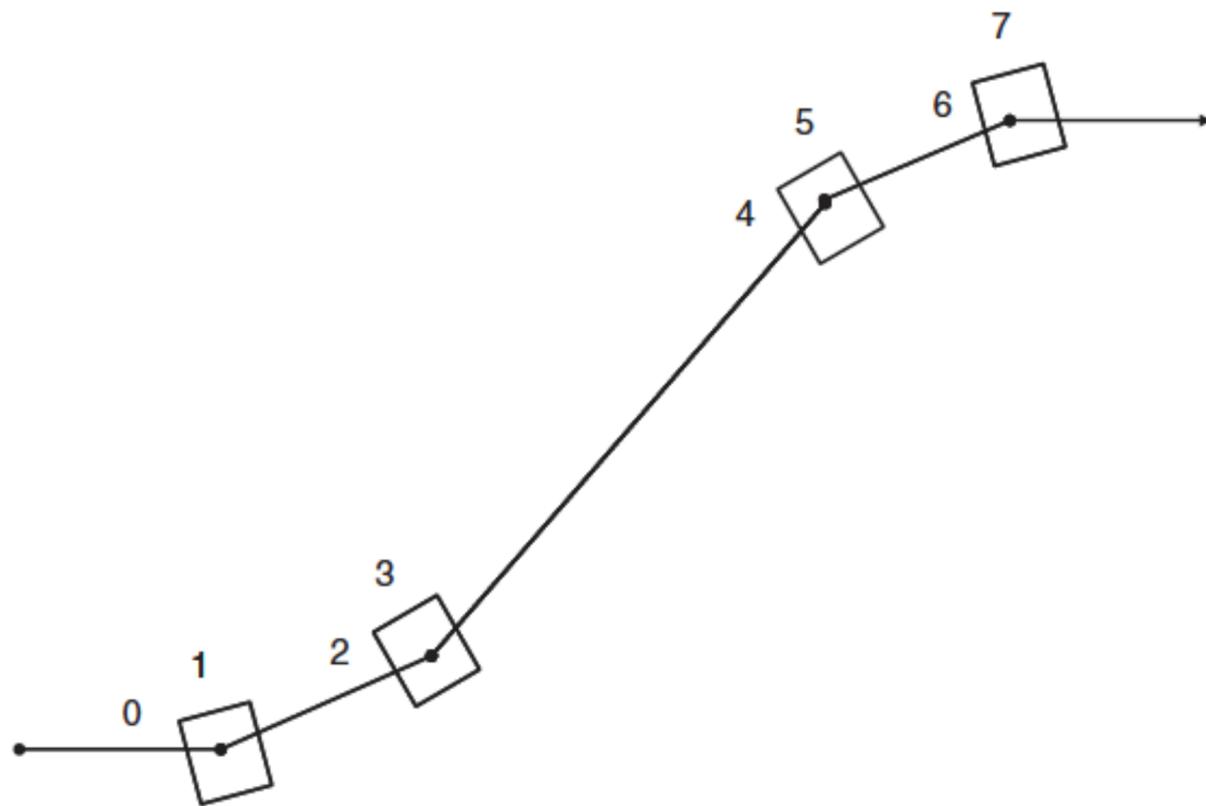


FLASH2-extraction

4. CSR cancellation in successive bends

S. Di Mitri et al, PRL **110** (2013) 014801

- > Kicks induced in one bend may be compensated in the other bend
- > For exact compensation need same magnitude of CSR, symmetric optics, and specific phase advance (π for symmetric optics)
- > Demonstrated at FERMI

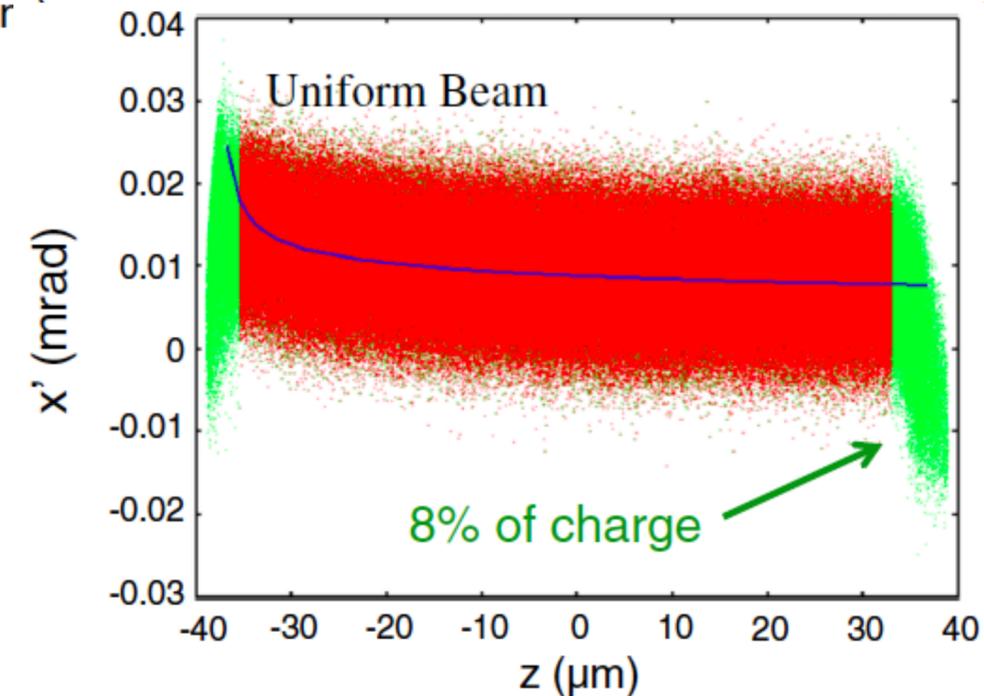
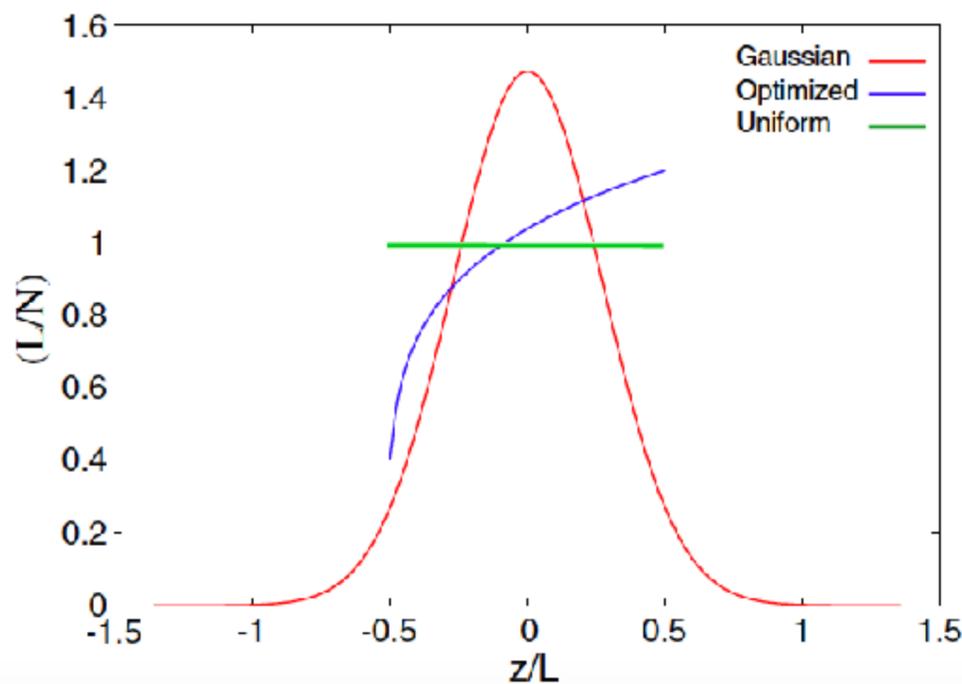
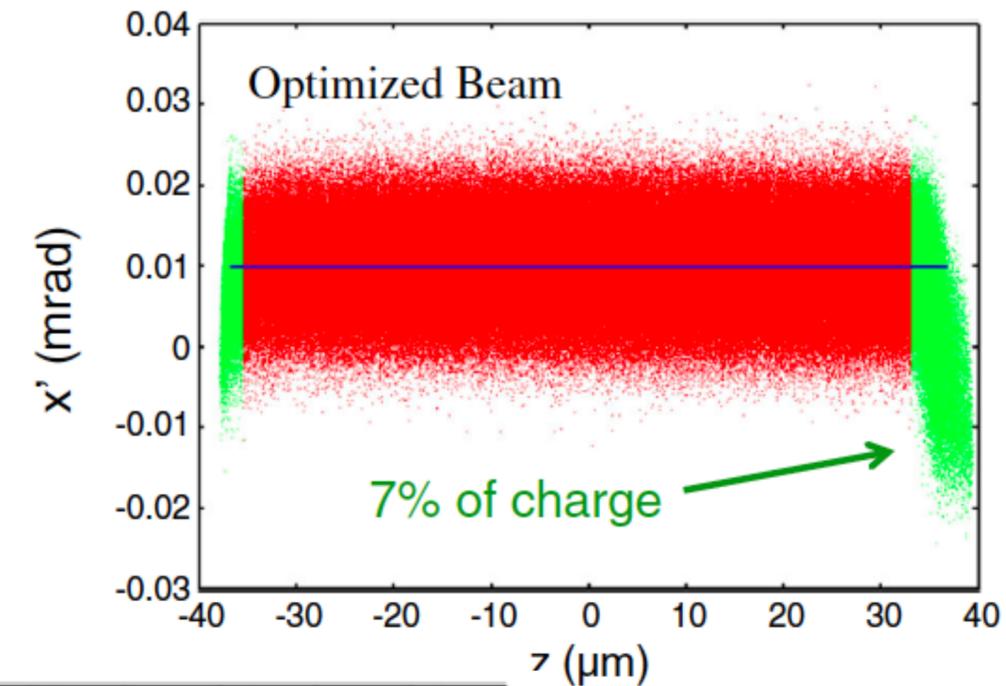
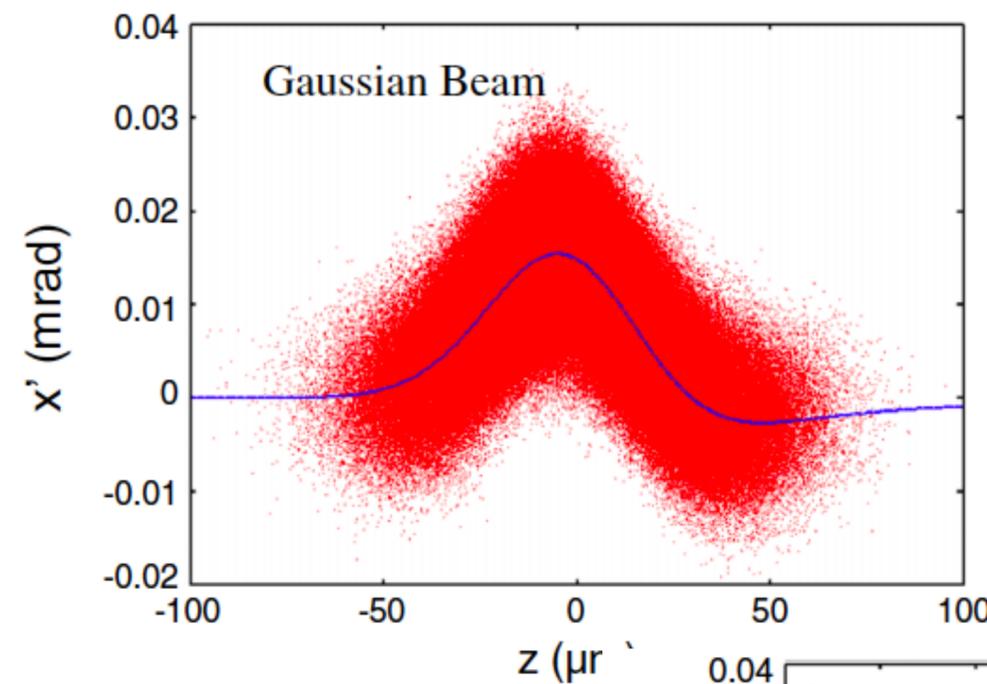
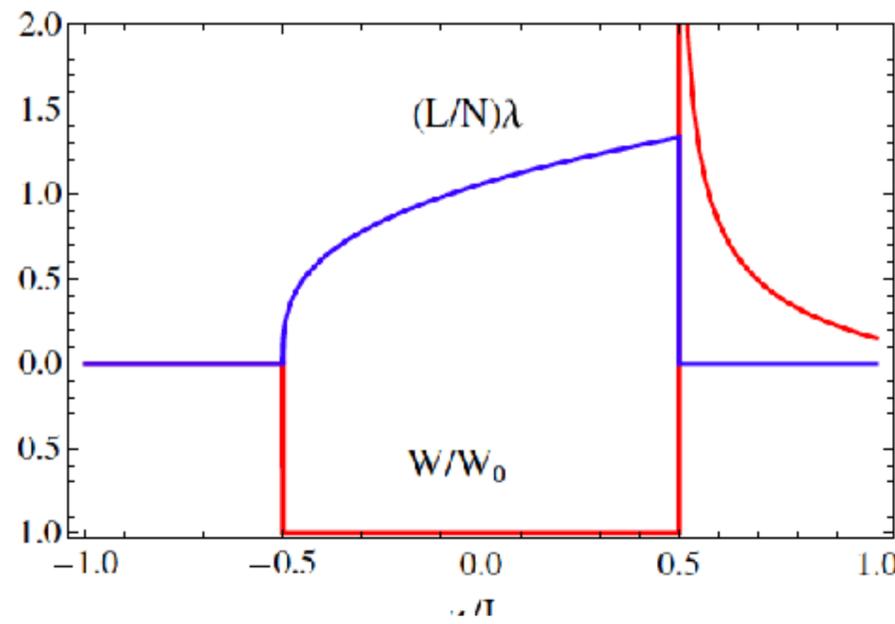


5. Longitudinal profile shaping

> CSR wake depends on the bunch shape

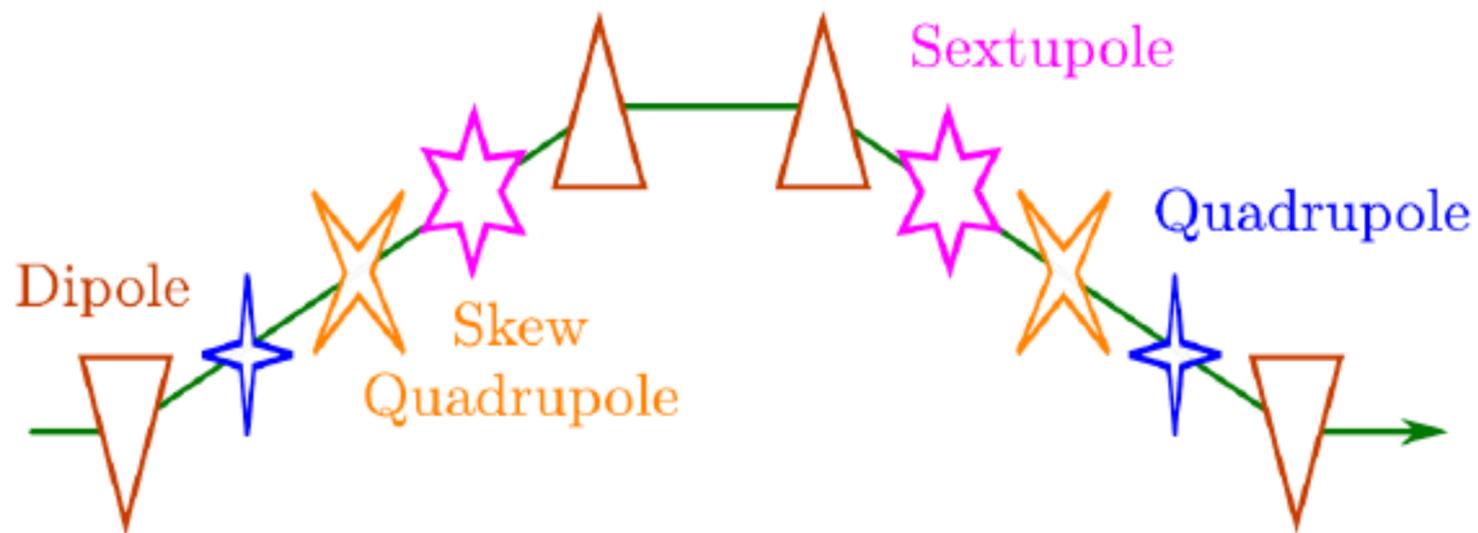
$$\frac{d\mathcal{E}}{cdt} = \int_{-\infty}^s ds' \lambda(s') G(s - s') \quad \epsilon^2 \rightarrow \epsilon^2 + \epsilon H \sigma_\delta^2$$

> It is possible to construct a bunch profile yielding constant CSR energy loss along the bunch!

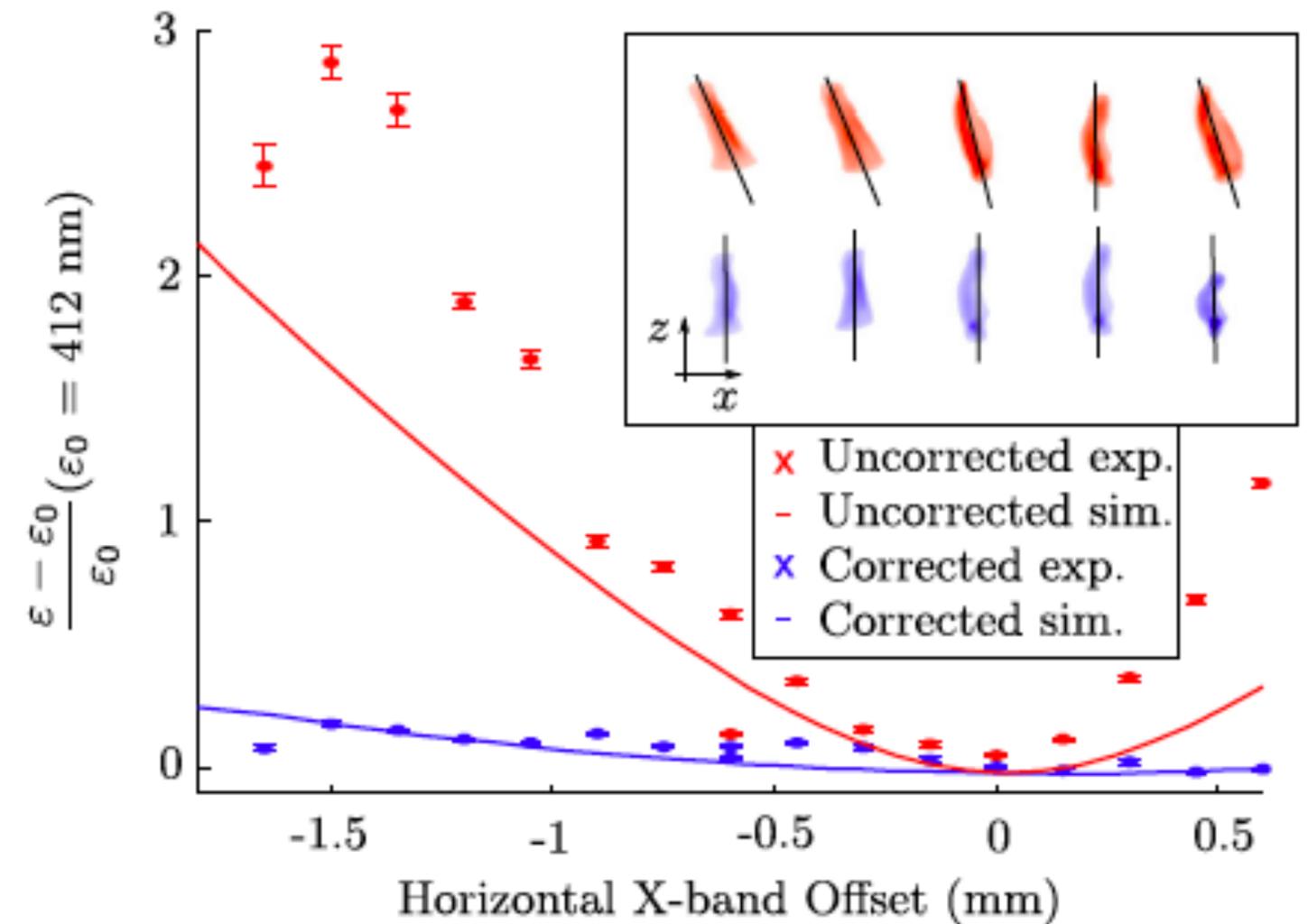


6. Special lattice design

- > Dispersion-based beam-tilt correction:
 - > Quadrupoles, skew quadrupoles and sextupoles in a dispersive section can be used to correct the beam tilts



- > Measurements at PSI



Summary

- > **Coherent-synchrotron radiation** is an important effect which might limit PWFA
- > Various ways to **mitigate** exist:
 - > Bend the beam at **high energy** and **low current**
 - > **Optimise optics** in and between the bends to reduce/cancel the offsets
 - > **Longitudinal shaping** of the bunch
 - > Special lattice designs
- > Discussion points:
 - > How do we compress the beam? If magnetic chicanes - at which energies, how many stages?
 - > Layout of driver injection line (stages)
 - > Identify next steps

CSR Codes

- > CSRTrack
- > elegant
- > LCLS measurements
- > FLASH measurements
- > XFEL measurements