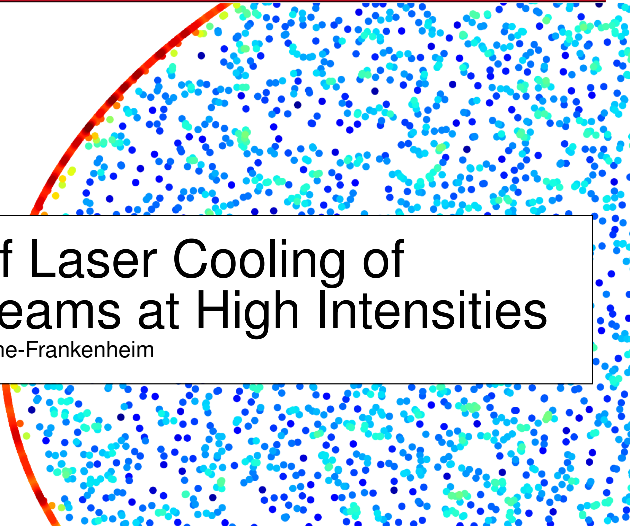
COOL15 - International Workshop on Beam Cooling and Related Topics

TECHNISCHE UNIVERSITÄT DARMSTADT



Simulation of Laser Cooling of Heavy Ion Beams at High Intensities

L. Eidam, D. Winters, O. Boine-Frankenheim

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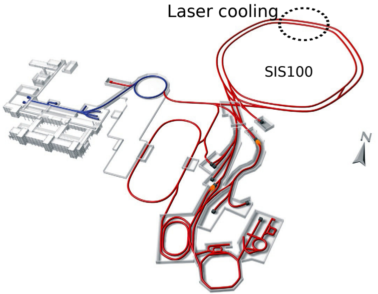
Motivation

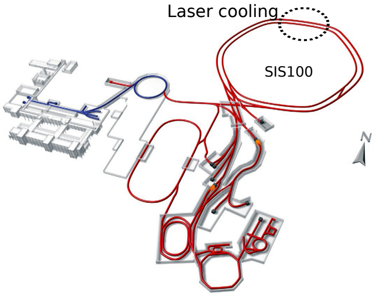
Laser Cooling at FAIR



- first time of laser cooling at high beam energies
- high beam intensities available

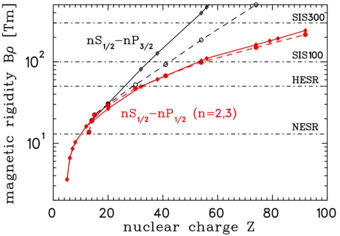
Motivation

Laser Cooling at FAIR



Doppler shift: $\lambda' = \frac{\lambda_L}{\gamma(1-\beta)}$

for Li-like ions:(λ_L = 257 nm)



[U. Schramm, 2004]

- first time of laser cooling at high beam energies
- high beam intensities available
- high magnetic rigidity allows cooling of heavy ions

Cooling at High Energies

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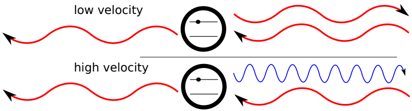
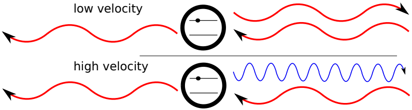


- $\langle \Delta p_{lab} \rangle = \frac{\hbar \omega_{lab}}{c_0} \cdot \gamma^2 (1 + \beta)$
- $\frac{\langle \Delta p_{lab} \rangle}{p}$ nearly constant

Cooling at High Energies



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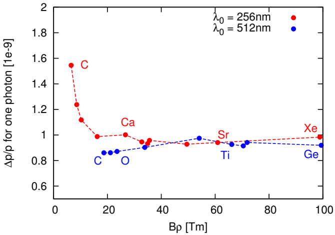
Li-like (2p1/2 - 2s1/2):



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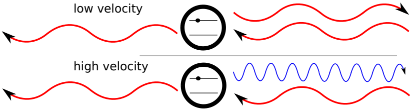

- $\langle \Delta p_{lab} \rangle = \frac{\hbar\omega_{lab}}{c_0} \cdot \gamma^2(1 + \beta)$
- $\frac{\langle \Delta p_{lab} \rangle}{p}$ nearly constant
- for low/high energies ions with similar cooling force exist
  $\Rightarrow$ pick the right ion & transition
- adiabatic damping
  $\Rightarrow$ no pre-cooling necessary

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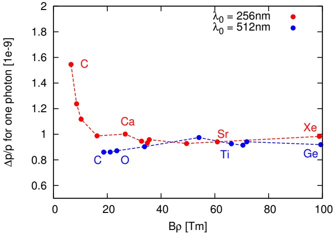

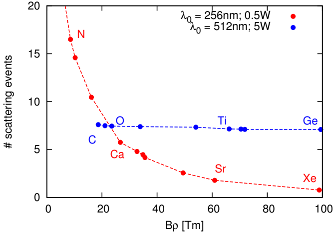

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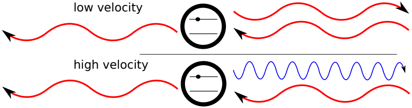

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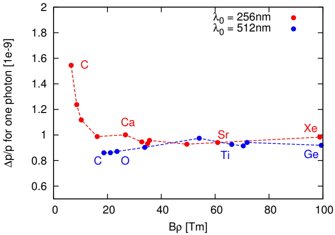
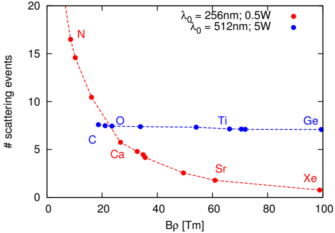
- speed of synchrotron motion:
  $Q_s = -\frac{L\eta}{2\pi} \frac{\hat{\delta}_0}{\hat{z}_0}$ with $\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$

Li-like (2p1/2 - 2s1/2):





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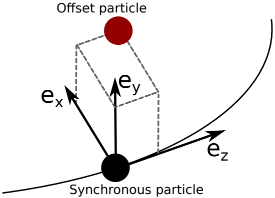
Simulation Tool

Solve Vlasov-Fokker-Planck Equation:

$$\frac{\partial f}{\partial t} - \eta\beta c\delta \frac{\partial f}{\partial z} + \frac{qV(z,t)}{p_0}\frac{\partial f}{\partial \delta} = \left(\frac{\partial f}{\partial \delta}\right)_c$$

- use macro particles (PIC-code)
- macro particles : $N_{macro} \approx 10^5 - 10^7$
- discretization of time (T_{rev})



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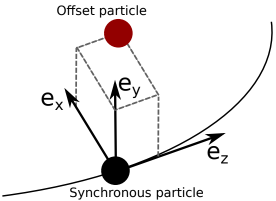

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  $\Rightarrow$ 1D longitudinal problem

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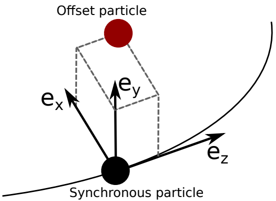

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No direct coulomb interactions
$\Rightarrow$ results not exact at very low temperatures
$\Rightarrow$ concentrate on cooling process

Simulation Tool
Modeling of Laser Force

simple two level system in electromagnetic mode $\Rightarrow$ optical Bloch equations

$$\dot{\rho} = \frac{i}{\hbar}[\rho, H] - \frac{1}{\tau}\rho \quad \text{with} \quad H = \begin{pmatrix} \hbar\omega_e & (\hbar\frac{\Omega}{2})e^{-i\omega t} \\ (\hbar\frac{\Omega}{2})e^{i\omega t} & \hbar\omega_g \end{pmatrix}; \rho = \begin{pmatrix} \rho_{ee} & \rho_{eg} \\ \rho_{ge} & \rho_{gg} \end{pmatrix}$$

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  $k(\delta) = \frac{1}{\tau} \cdot \rho_{ee}(\delta)$
- cooling Force:
  $F_{Laser}(\delta) = \Delta p_{lab} \cdot k(\delta)$

Simulation Tool
Modeling of Laser Force

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  U_j: uniform random number
- $\Delta p_{lab} = \frac{\hbar\omega_{lab}}{c_0} \cdot \gamma^2(1+\beta) \cdot 2U_{j2}$

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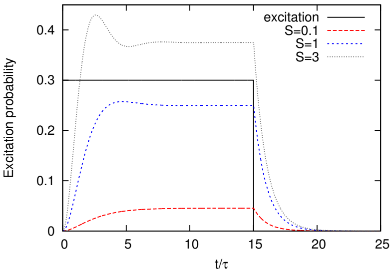

$$\rho_{ee}^{Sat} = \frac{1}{2}\frac{S}{1+S+(2\Delta v\cdot\tau)^2}$$

Simulation Tool
Modeling of Laser Force

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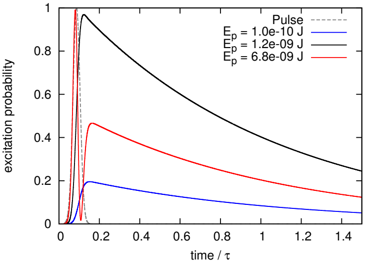
pulsed laser:



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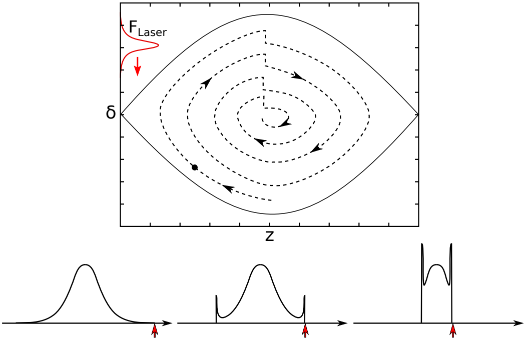
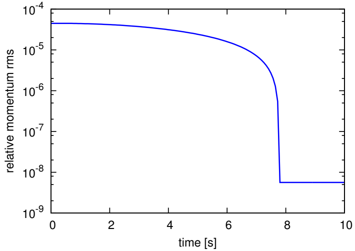
Cooling at Low Intensities

Cooling Process





Cooling at Low Intensities

Cooling Process

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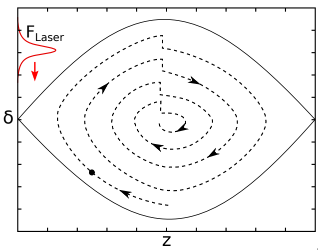
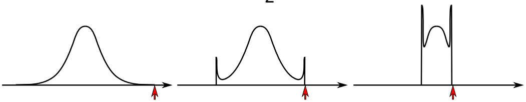
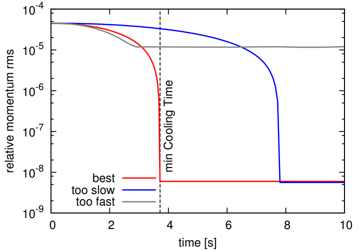
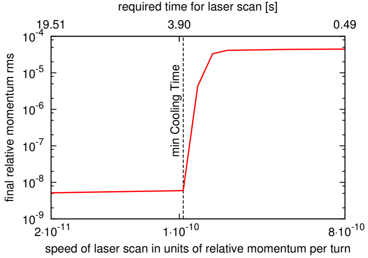


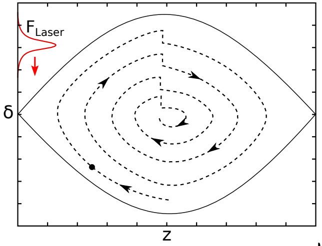


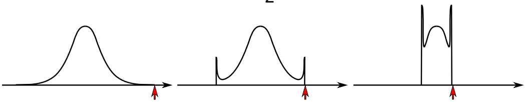


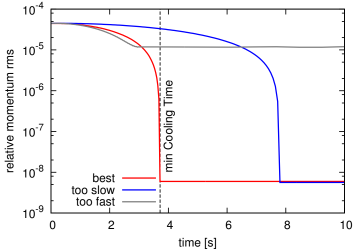


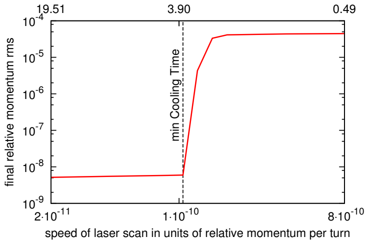
Cooling at Low Intensities

Cooling Process







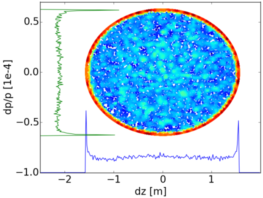


- influence of synchrotron frequency?
  Synchrotron tune:
  $$Q_s = \frac{-L\eta\cdot\hat{\delta}}{2\pi\hat{z}} \text{ with } \eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

Cooling at Low Intensities

Dependence of Synchrotron Tune

high Qs ($\approx 10^{-3}$)



- verified in storage rings
- symmetric reduction of momentum spread and bunch length

Cooling at Low Intensities

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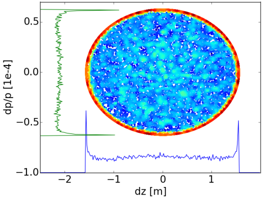

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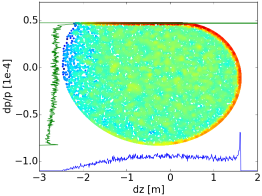
medium Qs ($\approx 10^{-4}$)



- particles are captured by laser force
- non-symmetric

Cooling at Low Intensities

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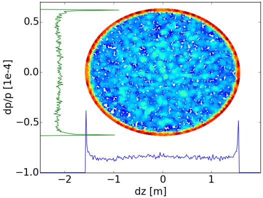

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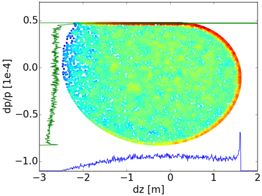

- particles are captured by laser force
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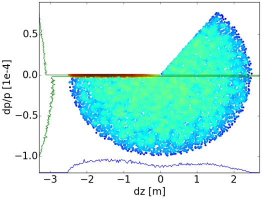
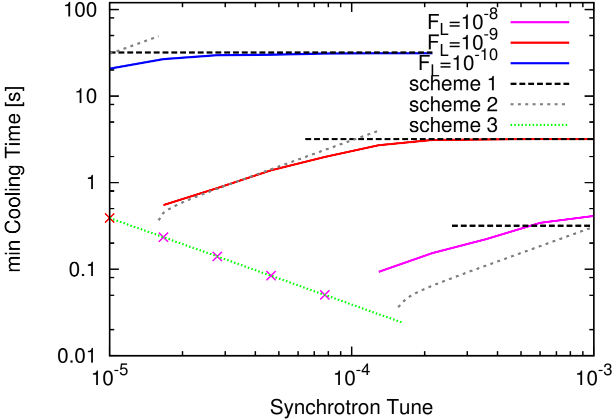
low Qs ($\approx 10^{-5}$)

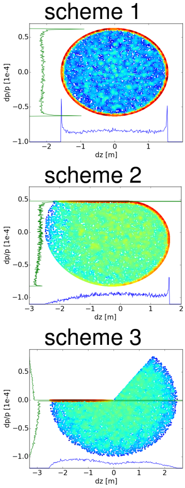


- laser position is fixed
- laser counteracts rf kick
- particles are rotated into laser force

Cooling at Low Intensities

Required Cooling Time





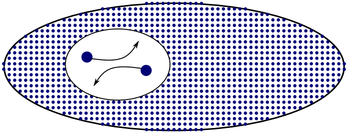
$\delta_{Laser} = 10^{-9}$ $\Delta_{FWHM} = 10^{-7}$ $\hat{\delta} = 10^{-4}$

$T_{excitation} = 10\tau$ $\hat{z} = 2.5\,m$

Contents

Intensity Effects

Intra Beam Scattering



- transverse oscillations heat longitudinal motion

Space Charge

Intensity Effects

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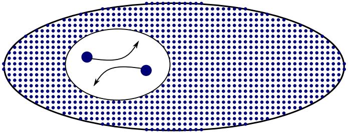
Intra Beam Scattering



- transverse oscillations heat longitudinal motion
- described by diffusion in FPE

$$\delta_{IBS} = Q_j \cdot \sqrt{2D_{zz}\frac{L_{acc}}{\beta c_0}}$$

Space Charge

Intensity Effects

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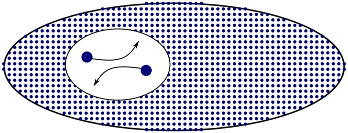
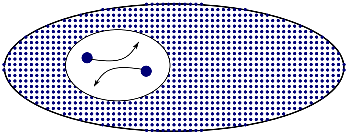


- transverse oscillations heat longitudinal motion
- described by diffusion in FPE
  $\delta_{IBS} = Q_j \cdot \sqrt{2D_{zz}\frac{L_{acc}}{\beta c_0}}$
- non-Gaussian distribution $\Rightarrow$ local diffusion model (BETACOOL)
  $D_{zz} = \frac{e^4 Z^4 \Lambda \sqrt{2}}{128\pi m_i^2 \epsilon_0^2 c_0^3 \gamma^3 \beta^3 \left\langle \beta^{1/2} \right\rangle \epsilon_\perp^{3/2}} \cdot n$

Space Charge

Intensity Effects

Intra Beam Scattering



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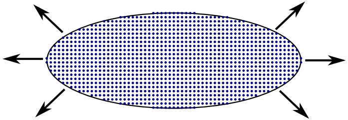
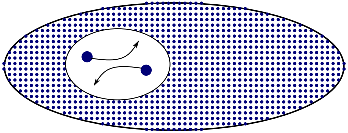


- describes interaction of particle with electric field of the bunch in perfectly conducting pipe

Intensity Effects

Intra Beam Scattering



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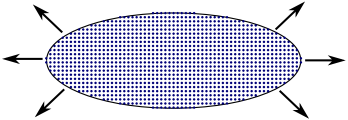

- describes interaction of particle with electric field of the bunch in perfectly conducting pipe
- space charge impedance:
  $Z_{sc} = -i \cdot f \frac{g L_{acc}}{2 \epsilon_0 \beta^2 c^2 \gamma^2}$ with
  $g = 1 + 2 \log(b/a)$
- potential:
  $U_{sc}(z) =$
  $Z_{ion} \cdot q \cdot IFFT\{Z_{sc}(\omega) \cdot FFT\{\lambda(t)\}\}$

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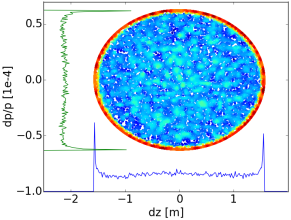
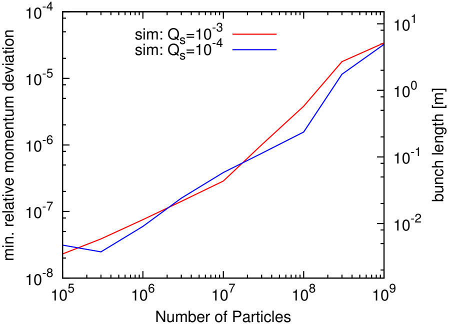
high synchrotron tune $Q_s \approx 10^{-3}$





Intensity Effects
Intra Beam Scattering (IBS)

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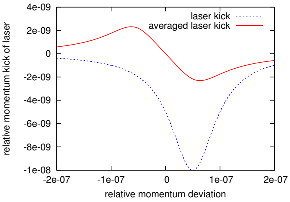
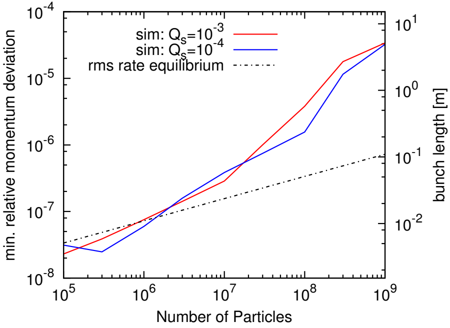
rms rate equilibrium:





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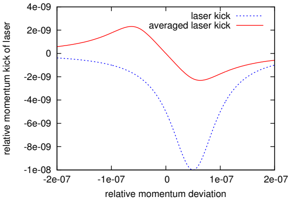

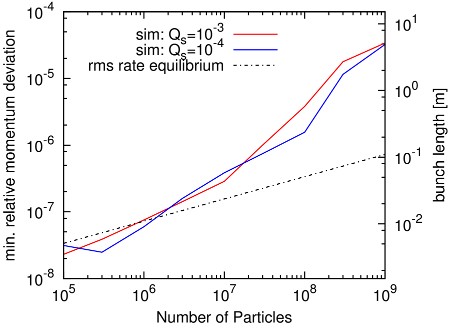

$$\tau_{IBS}^{-1} + \tau_{Laser}^{-1} = 0$$

$$\tau_{Laser}^{-1} = \frac{1}{T_{rev}} \cdot \left.\frac{\partial \langle \Delta\delta \rangle_{syn}}{\partial \delta_{pos}}\right|_0$$

$$\langle \Delta\delta \rangle_{syn} = \frac{1}{\pi} \int_0^{\pi} \cos(\phi) \cdot \Delta\delta(\delta_{pos} \cdot \cos(\phi)) d\phi$$

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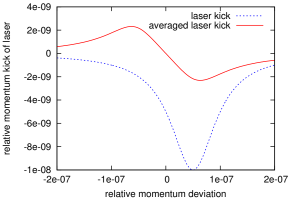

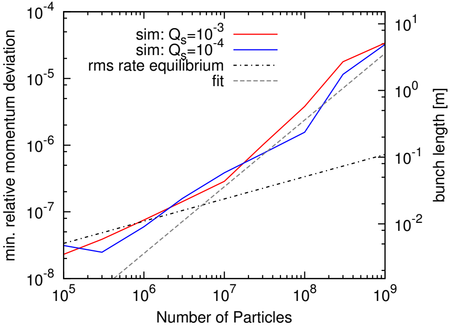

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fit: $\langle \delta_{IBS} \rangle = f(\delta_{laser}) = const.$

$$D_{\| \, max}^{IBS} \propto \frac{N}{L_{bunch}} \propto \frac{N}{\delta_{rms}}$$

Intensity Effects
Intra Beam Scattering (IBS)

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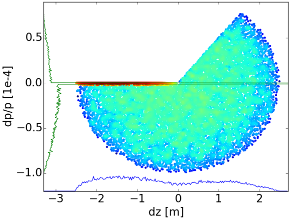
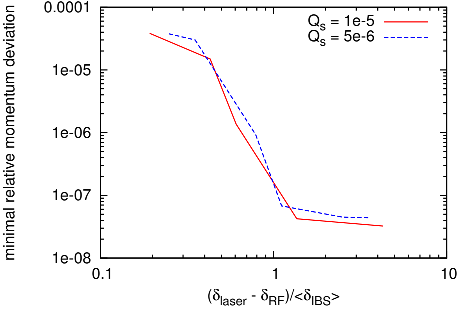
low synchrotron tune $Q_s \approx 10^{-5}$

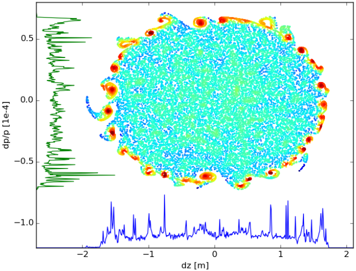




- limit: $\frac{\hat{\delta}_{laser} - \hat{\delta}_{rf}}{\langle \delta_{IBS} \rangle} > 1$ (changed N_p -> $\langle \delta_{IBS} \rangle$)
  $\Rightarrow$ Barrier of laser has to be higher than IBS kicks
- longitudinal density increases only by factor 2

Intensity Effects
Space Charge

high synchrotron tune $Q_s \approx 10^{-3}$



Intensity Effects
Space Charge

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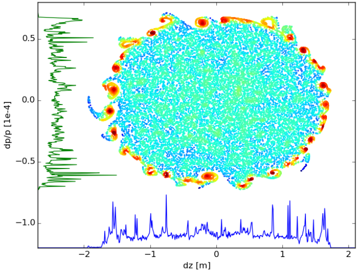
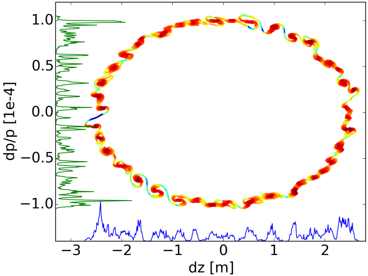


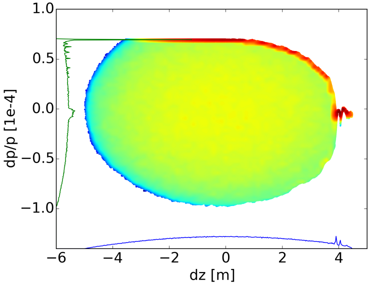


kind of two stream instability:

- perturbation in one stream produces bunching of second $\Rightarrow$ bunching increases amplitude of perturbation
- in progress $\Rightarrow$ comments are welcome

Intensity Effects
Space Charge

medium synchrotron tune $Q_s \approx 10^{-4}$



Intensity Effects
Space Charge

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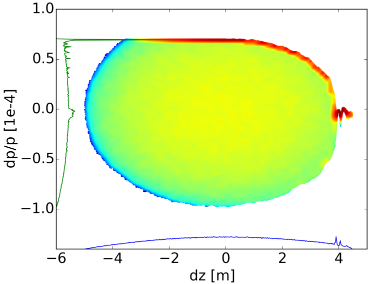
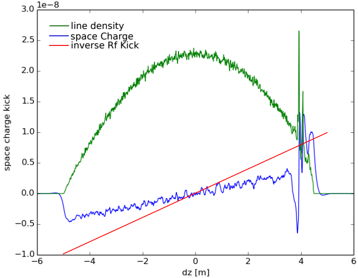
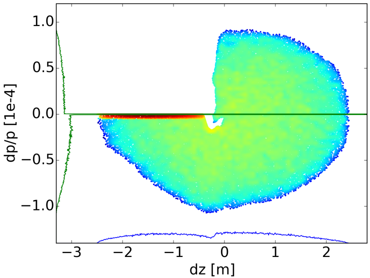


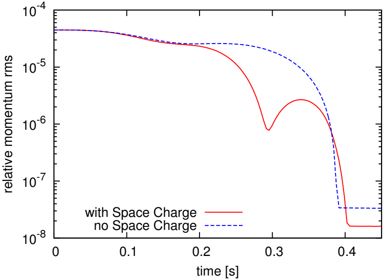


- space charge compensates Rf-kick
  $\Rightarrow$ synchrotron oscillation is stopped

Intensity Effects
Space Charge

low synchrotron tune $Q_s \approx 10^{-5}$





- space charge deforms bunch

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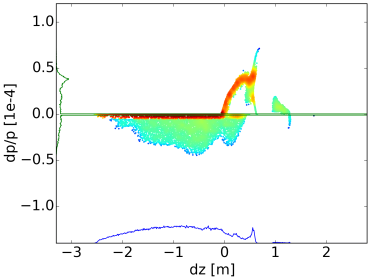

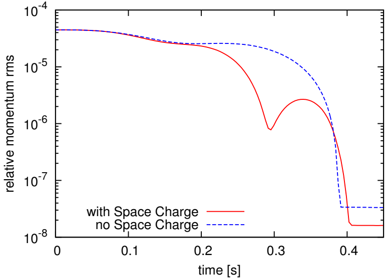

- space charge deforms bunch
- if deformation too strong $\Rightarrow$ space charge exceeds laser force (not stable)

Contents

Conclusion and Outlook

- laser force implemented successfully in tracking code
- laser cooling looks promising at high beam energies
- cooling time and efficiency depend strongly on the way of laser scan
- IBS limits the beam intensity
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Conclusion and Outlook

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- influence on transverse motion
- study pulsed laser system
- combine everything for realistic conditions

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Thank you for your attention!