Electron Cloud Effects in Heavy Ion and Proton Machines

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Outline

FAIR

- Introduction
- Electron cloud effects due to the residual gas ionization in coasting beam
- Simulation results for FAIR coasting beams
- Simulation results for FAIR bunched beams
- FAIR Conclusions and Outlook

Short Relativistic Proton Bunches

- Simulation of electron cloud wake fields and stopping powers for short LHC like bunches.
- Conclusions and Outlook

FAIR
Facility for Antiproton and Ion Research

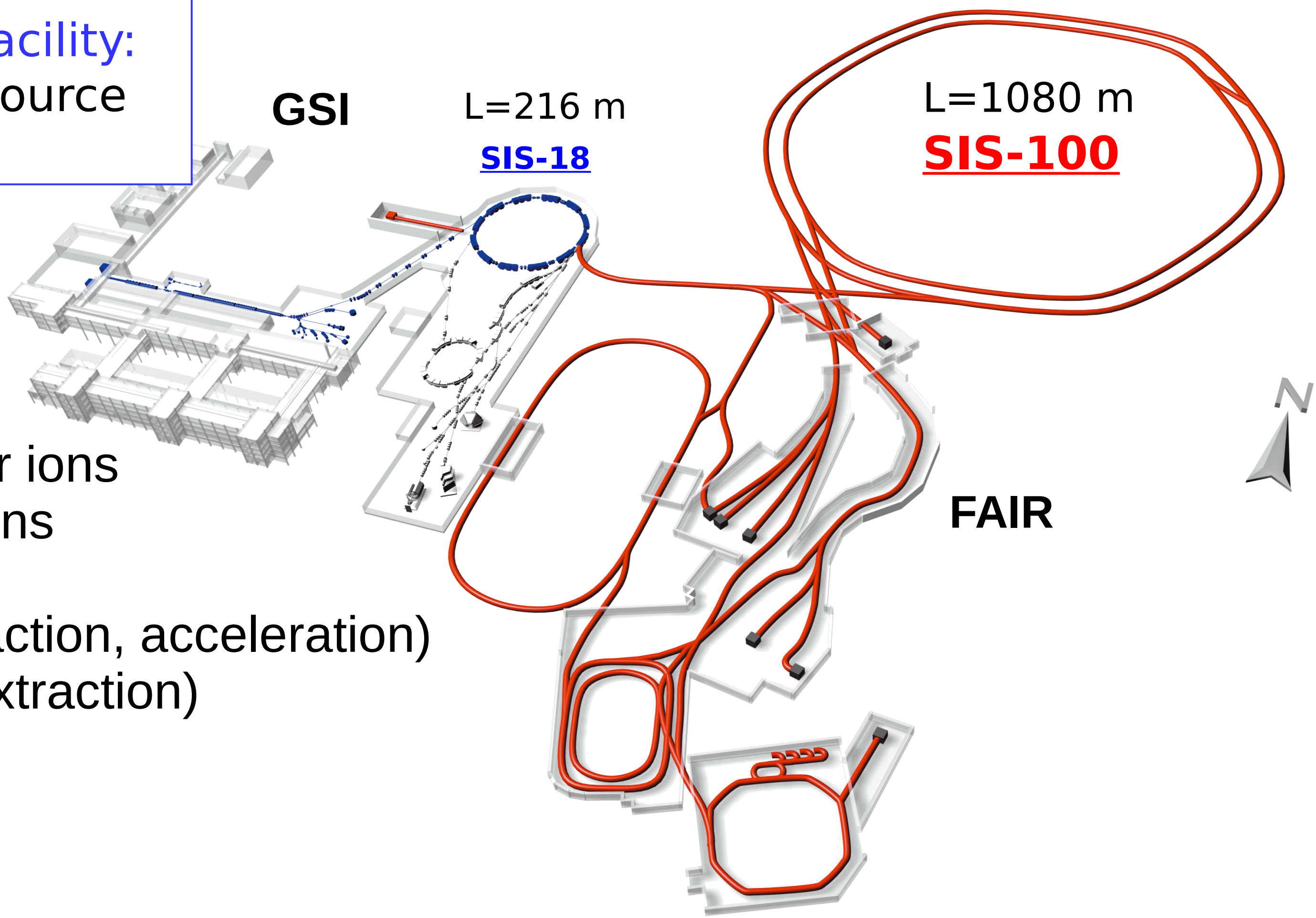
Existing facility
UNILAC/SIS-18 GSI facility:
provides ion-beam source and injector for FAIR

Particles:
- heavy ions
- protons

Energies:
- up to 2.7 GeV/u for ions
- 29 GeV/u for protons

Beams:
- bunched(fast extraction, acceleration)
- coasting(at slow extraction)

Intensities:
- $4 \cdot 10^{13}$ protons
- $5 \cdot 10^{11}$ U^{28+}



How Many Electrons Produces One Ion Per Second due to Ionization?

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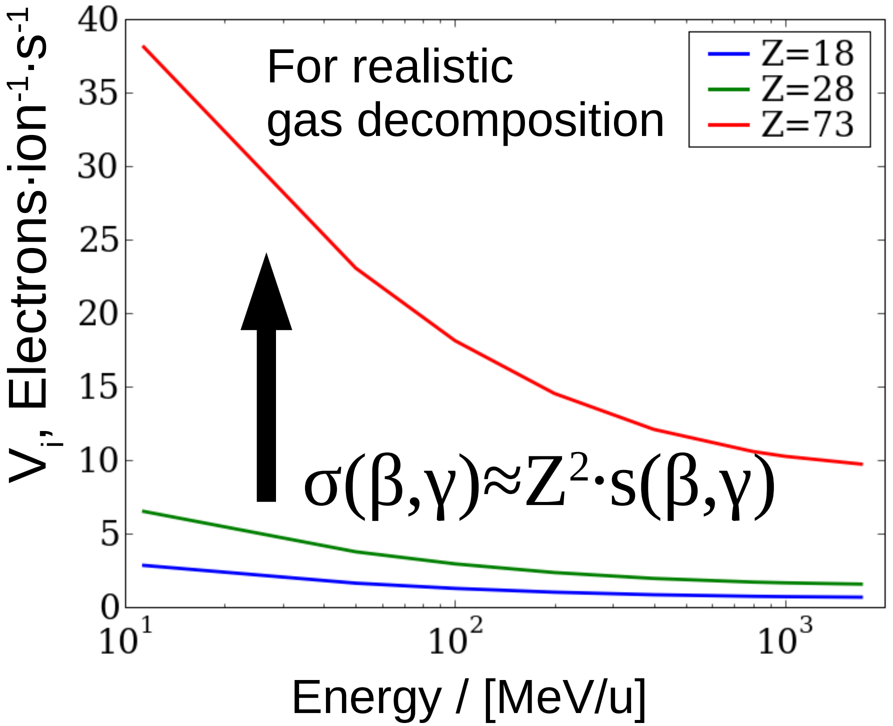
Pressure in SIS18 vacuum chamber is
$P=10^{-11}$ Torr=353000 cm^{-3}



$$V_i = \sigma \beta c \rho_g$$

The higher is the charge of ion the faster it can be neutralized by the residual gas ionization.

Neutralization time scale ~ 1 s
<u>Comparable or smaller than slow extraction time</u>

The same pressure is used in simulations for SIS100.

Cross sections are calculated using Kaganovich, NJP 2006

Electron Interaction with Coasting Beam

Electron-beam coupled motion for fixed neutralization is described by

$$\begin{cases} \left(\frac{\partial}{\partial t} + \omega_0 \frac{\partial}{\partial \theta}\right)^2 y_i + Q_b^2 \omega_0^2 y_i = -Q_i^2 \omega_0^2 \left(y_i - \bar{y}_e\right) \\ \frac{d^2 y_e}{dt^2} = -Q_e^2 \omega_0^2 \left(y_e - \bar{y}_i\right) \end{cases}$$

driving term

Q_e – *electron trapping tune*

Q_b – *betatron tune*

$Q_{i,sc}$ is neglected it play role at injection in SIS18 at 11.4 MeV/u

$Q_{e,sc}$ is also neglected at this moment

Electron Interaction with Coasting Beam

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driving term

Q_e – electron trapping tune

Q_b – betatron tune

Algebraic equation for eigenfrequencies. Im(Q) – gives the instability growth rate

$$\left(Q^2-Q_e^2\right)\left[\left(n-Q\right)^2-Q_b^2-Q_i^2\right]-Q_e^2 Q_i^2=0$$

If dp/p is present and chromaticity is corrected the threshold growth rate is given by

$$\gamma_{thresh}=\sqrt{\frac{2}{\pi}}\,\omega_0\,\eta\,n\,\frac{dp}{p}$$

$Q_{i,sc}$ is neglected it play role at injection in SIS18 at 11.4 MeV/u

$Q_{e,sc}$ is also neglected at this moment

*Intensity dependent beam instabilities, Ng

Coasting Beam Operation in FAIR. Simple Analysis of Parameters.

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If intensity is limited by the space charge limit at injection in SIS18

Total number of particles

$$N_i \propto \frac{m_i}{Z^2}$$

Electron trapping frequency

$$\omega_e = \sqrt{\frac{Z N e^2}{2\pi \epsilon_0 a^2 m_e}} \propto \sqrt{\frac{m_i}{Z}}$$

Threshold

$$\boxed{\gamma_{damp} \approx \sqrt{\frac{2}{\pi}} \omega_e \frac{dp}{p} \eta \propto \sqrt{\frac{m_i}{Z}}}$$

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Ionization rate

$$V_i = N_i \rho_{gas} Z^2 s(\beta, \gamma) \propto m_i$$

Electron trapping frequency

$$\omega_e = \sqrt{\frac{Z N e^2}{2\pi \epsilon_0 a^2 m_e}} \propto \sqrt{\frac{m_i}{Z}}$$

Number of electrons

$$n_e = V_i T \propto m_i$$

Threshold

$$\boxed{\gamma_{damp} \approx \sqrt{\frac{2}{\pi}} \omega_e \frac{dp}{p} \eta \propto \sqrt{\frac{m_i}{Z}}}$$

Driving term

$$\boxed{\omega_i = \sqrt{\frac{Z n_e e^2}{2\pi \epsilon_0 a^2 m_i \gamma}} \propto \sqrt{Z}}$$

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Ion	$\sqrt{\frac{A}{Z}}$ damp	$\sqrt{Z}$ drive
U^{73+}	1.80	8.5
U^{28+}	2.91	5.3
Ar^{18+}	1.49	4.2
p	1	1

For beams with equal energies with intensities defined by the space charge limit U^{73+} is less stable than U^{28+} and Ar^{18+}

<u>If the vacuum is good then threshold is not reached. Why?</u>

Estimation of the Coulomb Heating Effect

Electrons collide with beam ions and gain energy

Heating rate

$$\boxed{V_{heat} = \frac{dW_e}{dt} = E_0 \frac{4\pi c \rho_i r_e^2 Z_i^2}{\beta} L_{Coul}}$$

Lifetime

$$\boxed{t_{life} = \frac{U_{wall}}{V_{heat}}}$$

Neutralization degree

$$\boxed{\chi_e = \frac{V_i t_{life}}{N_i Z}}$$

Z cancels

N_i – ion intensity
V_i – ionization rate
U_{wall} – wall potential
E_0 – rest energy

**Zenkevich, AIP Proceedings 480, 1998*

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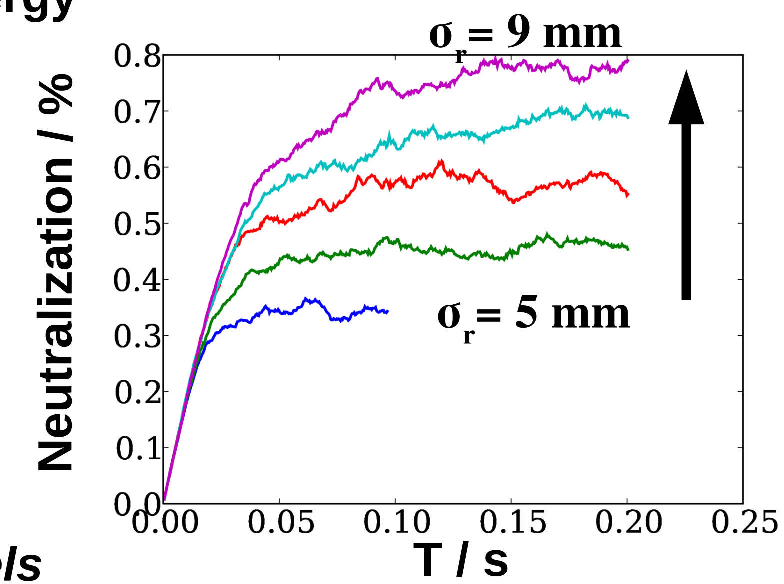


At 1 GeV/u assuming radius of the pipe 5 cm

Ion	$\mathbf{N_i}$	$\mathbf{V_{heat}}$	$\mathbf{U_{wall}}$	$\mathbf{t_{life}}$	$\boldsymbol{\chi_e}$
Ar^{18+}	$2\cdot10^{11}$	143 eV/s	26 eV	0.18 s	<1%
U^{28+}	$5\cdot10^{11}$	868 eV/s	104 eV	0.12 s	<1%
U^{73+}	$7\cdot10^{10}$	826 eV/s	38 eV	0.046 s	<1%

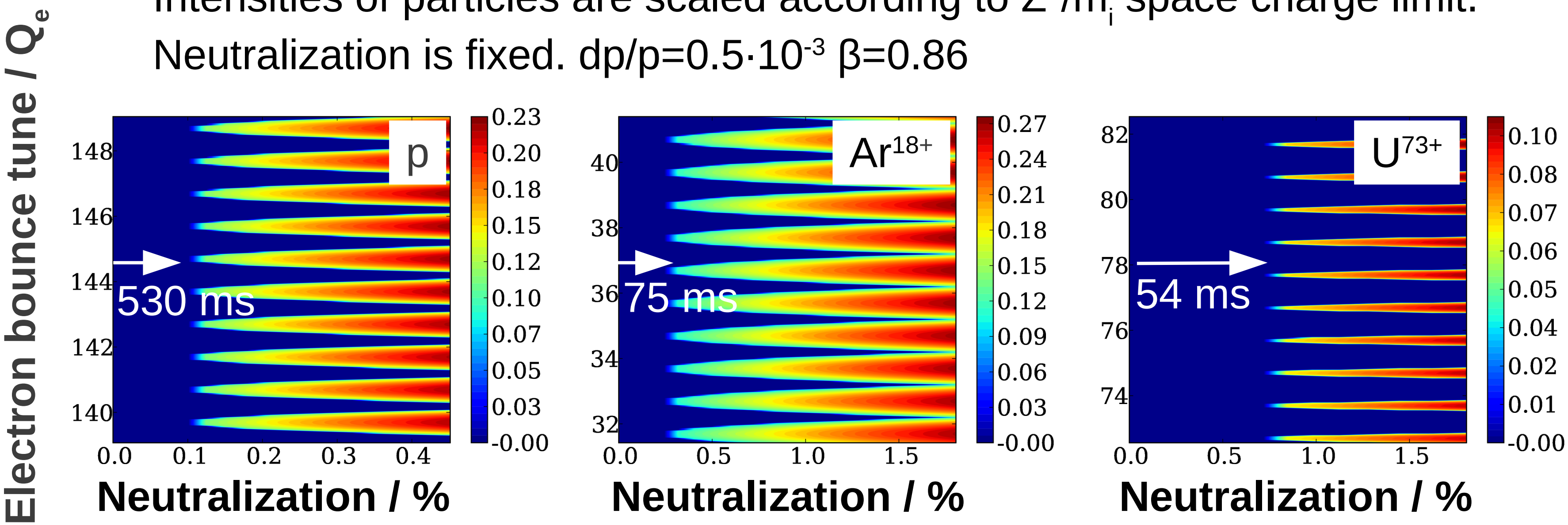
N_i – ion intensity
V_i – ionization rate
U_{wall} – wall potential
E_0 – rest energy

**Zenkevich, AIP Proceedings 480, 1998*

Thresholds in Linear Theory with Landau Damping due to dp/p

Intensities of particles are scaled according to Z^2/m_i space charge limit.

Neutralization is fixed. $dp/p=0.5\cdot10^{-3}$ $\beta=0.86$



U^{28+} has the biggest threshold. Protons has the smallest threshold.

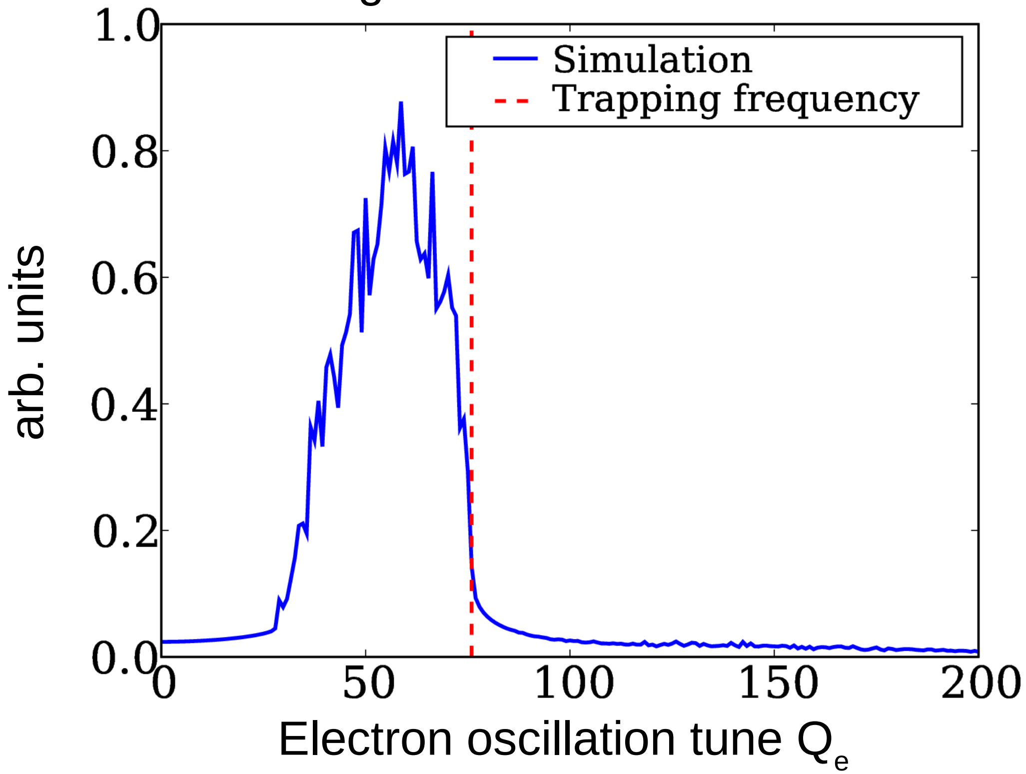
$$\omega_e^2=\frac{Z N e^2}{2\pi\epsilon_0 a^2 m_e}=Q_e^2\omega_0^2$$

$$\omega_i^2=\frac{Z n_e e^2}{2\pi\epsilon_0 a^2 m_e \gamma}=Q_i^2\omega_0^2=Q_e^2\omega_0^2\chi Z\frac{m_e}{m_i\gamma}$$

Taking into account speed of neutralization the threshold will be first reached by U^{73+}

Width of Electron Oscillation Spectrum

Spectrum of electrons produced by residual gas ionization.



Number of electrons produced outside σ_r is over 60%.

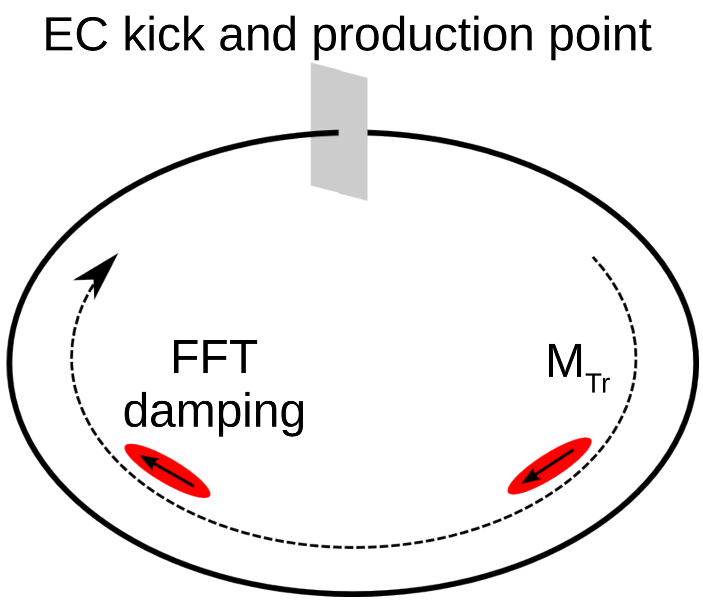
Spectrum width is about 20% of linear trapping tune.

Strongly shifted to lower frequencies.

This causes significant change in thresholds

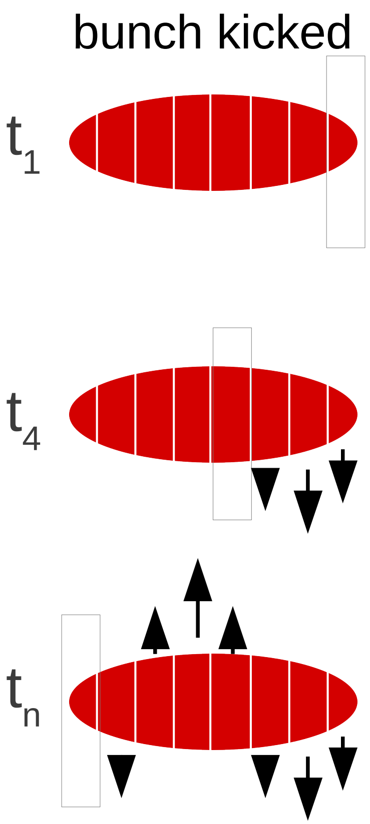
General Principle of Simulation in Rigid Slice Code

Model of the machine



This is the same principle as in HEADTAIL and ECLOUD codes.

Model of the beam-cloud interaction

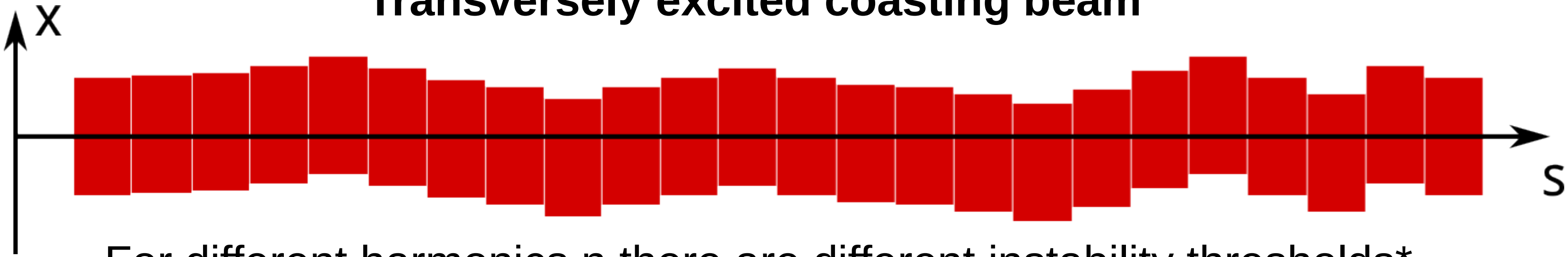


In our case one and the same code is used for the build-up studies and for the instabilities simulations.

Coasting Beam Rigid Slice Model with Landau Damping

Build-up simulations in bunches were performed using ECLOUD and our own code

Transversely excited coasting beam



For different harmonics n there are different instability thresholds*

$$\nu_n = \sqrt{\frac{2}{\pi}}\,\sigma_{\omega_0,n} \xrightarrow{\text{one turn amplitude decrease}} \alpha_n = e^{-\sqrt{\frac{2}{\pi}}\,\sigma_{\omega_0,n} T}$$

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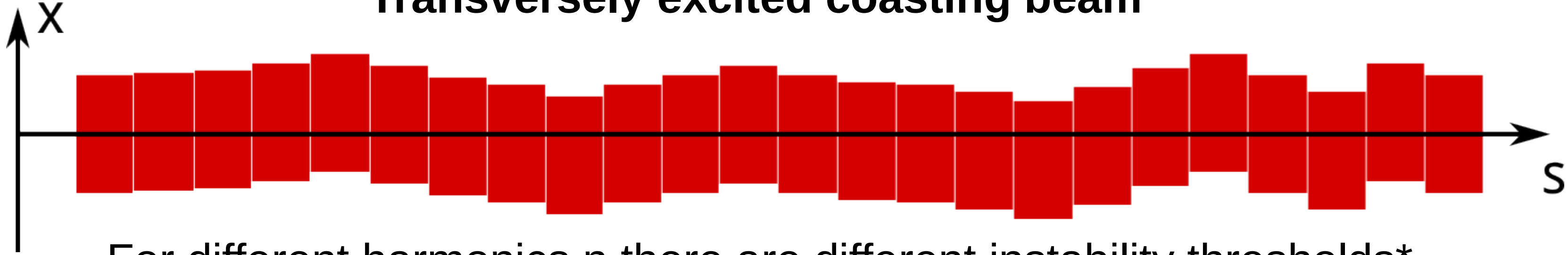

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$$(x_0, x_1, \ldots, x_N) \xrightarrow{\text{FFT}} (k_0, k_1, \ldots, k_N) \longrightarrow (\alpha_0 k_0, \alpha_1 k_1, \ldots, \alpha_N k_N)$$

**A. Hofmann,, Landau Damping, CERN school*

Coasting Beam Rigid Slice Model with Landau Damping

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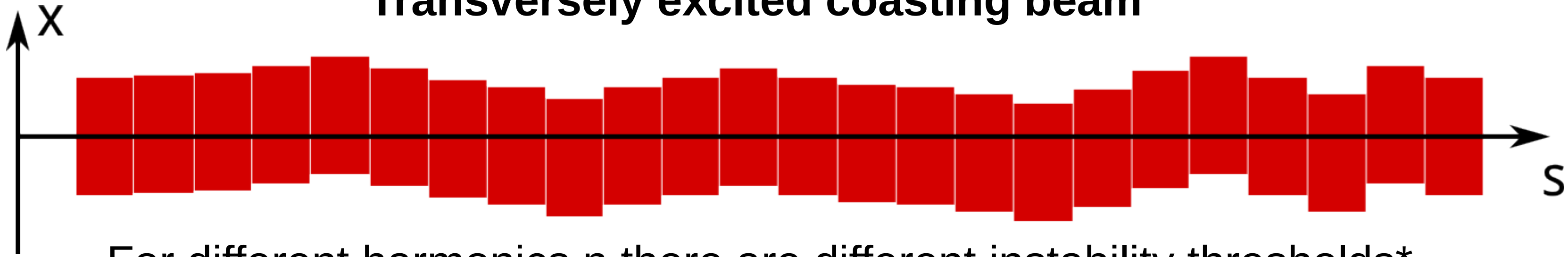

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Inverse FFT gives us a new damped set of beam coordinates which is used in the next iteration.

This way we <u>reproduce</u> the instability <u>threshold</u> in a rigid slice simulation.

The production of electrons happens every timestep. Interaction is HEADTAIL like.

**A. Hofmann,, Landau Damping, CERN school*

Comparing Rigid Model with Full Particle-in-Cell Model

Electron cloud effects have similarities with impedances.

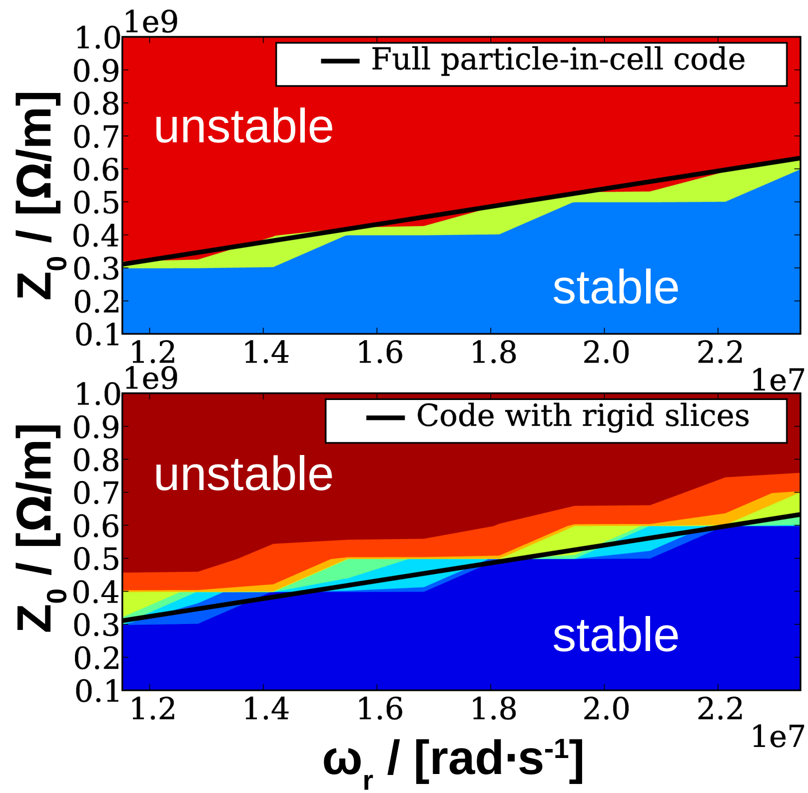
To check the correctness of our model we apply the broad band impedance to our rigid beam and compare with the full Particle-in-Cell model as well as with analytical theory.

Broad band impedance

$$Z_{Tr}(\omega)=\frac{\omega_r}{\omega}\frac{Z_0}{1+iQ\left(\frac{\omega_r}{\omega}-\frac{\omega}{\omega_r}\right)}$$

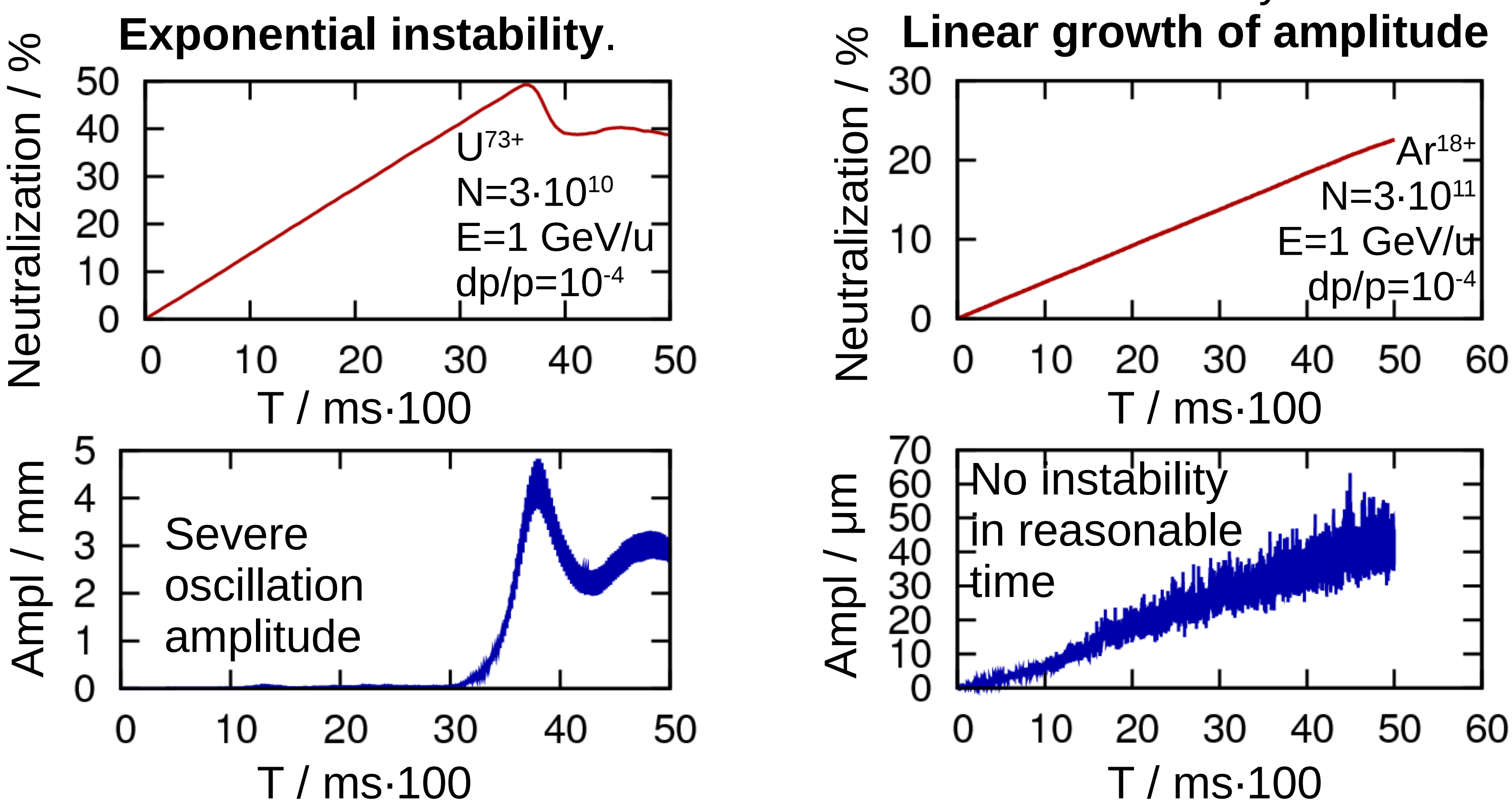
Stability Border

$$\sqrt{\frac{2}{\pi}}\omega_r\frac{dp}{p}\eta=\frac{Nq^2\beta}{8\pi^2 m_i\gamma R Q_x}Re\left(Z_{Tr}\right)$$



Build-up and Instability in SIS100 Without Coulomb Heating

To reduce the simulation time ionization rate was increased by **factor 100.**



Scan over parameters revealed that among U^{73+}, U^{28+},Ar^{18+} and protons only U^{73+} reaches the threshold in several seconds.

Threshold is significantly higher then density due to the heating.

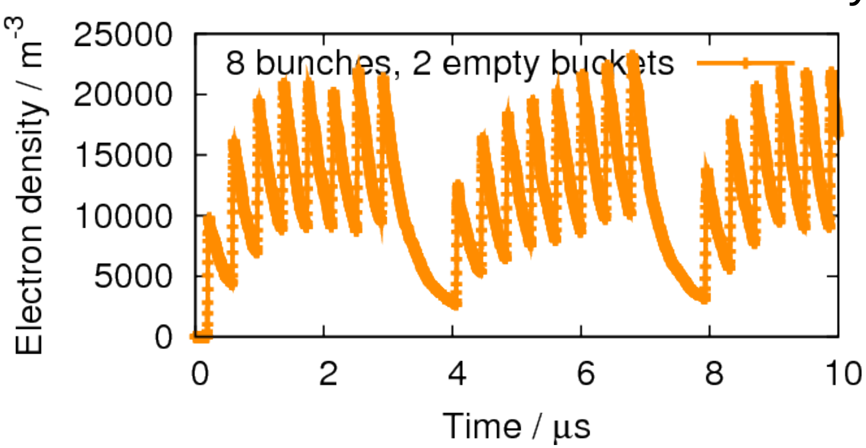
Electron Cloud Build-up During Bunched Beam Operation

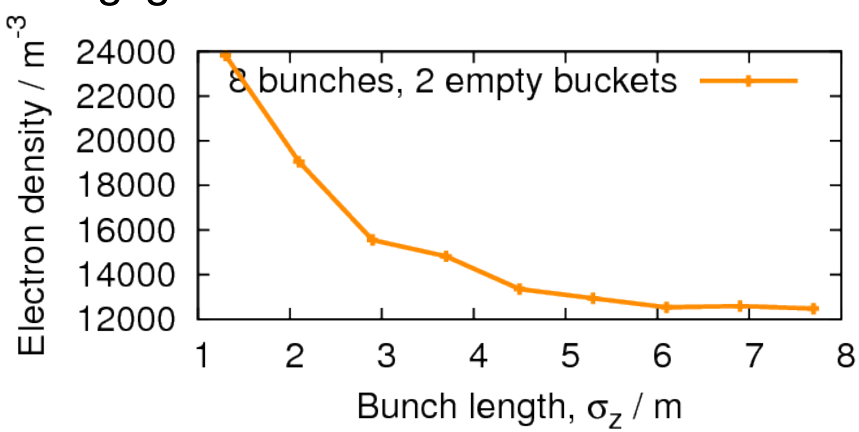
Scan over bunch parameters in SIS100 to reveal dangerous conditions

Circumference	1080 m
Design bunch length, σ_z	4 m
Ion type	U^{28+}
Intensity	$5\cdot10^{11}$
Energy	1 GeV/u

Possible danger:
SIS100 will not be covered by any coatings.
Advantage:
1. Beam pipe size is significantly smaller and potential U_{wall} should be also smaller
2. 2 empty buckets = 216 m of free space where electrons decay

Electron cloud density is negligible for SEY < 2.2





Conclusion and Outlook for FAIR

Coasting beams

- Realistic Landau damping in rigid slice coasting beam model
- Faster instability for highly charged heavy ions
- Proton beam has a low threshold.
- Time for electrons to accumulate in proton beam is very long
- Coulomb heating is very powerful electron loss mechanism under the designed FAIR conditions
- Most probably the Instability thresholds for heavy ions will not be reached in FAIR
- Pressure deteriorated to 10^{-9}-10^{-8} Torr (beam loss) can make the threshold reachable.

Bunched beams

- No multipacting happens in SIS18 and in SIS100 for the designed bunch length and intensities for SEY < 2.0-2.2

Outlook: To analyse the effect of other sources(losses on the wall)

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- Simulation models
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- Simulation results for FAIR coasting beams
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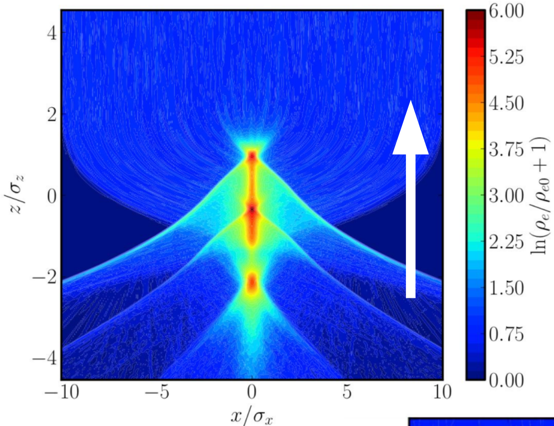
- Simulation of electron cloud wake fields and stopping powers for short LHC like bunches.
- LHC Conclusions and Outlook

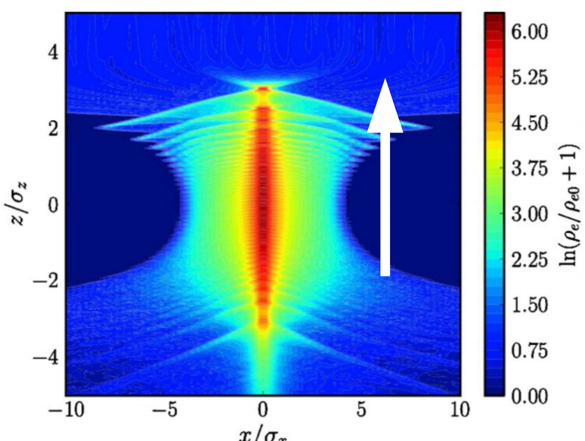
Energy Loss of Relativistic Short Proton Bunches in Electron Clouds

Density profile of electron cloud pinched in the field of the bunch



$N_i = 10^{11}$

$N_i = 10^{13}$



If there is already an electron cloud when the bunch passes it is attracted towards the center of the bunch.

The non-uniformity of the cloud results into the longitudinal electric field which <u>tries to stop the bunch</u>

This is seen in measurements of rf phase shift

Published in Phys. Rev. ST Accel. Beams 15, 054402 (2012)

Energy Loss and RF Phase Shift

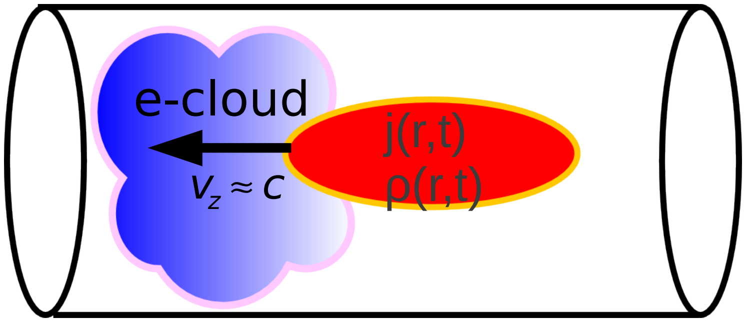
Bunch line density:

$$\lambda_z = \frac{N_i}{\sqrt{2\pi\sigma_z}} \exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

Stopping power:

$$\frac{dW}{ds} = -\int \rho_i(r) E_z(r)\, dr = -q \int \lambda(z) E_z(z)\, dz$$

$N_e = 10^{12}\text{-}10^{13}\,m^{-3}$

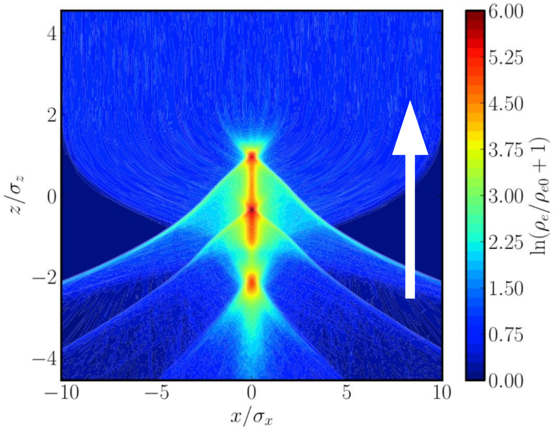


Energy loss per turn and particle:

$$\Delta W_z = \frac{L}{N_i} \frac{dW}{ds}$$

rf phase shift:

$$\boxed{\sin(\Delta\varphi_s) = \frac{\Delta W_p}{q V_{rf}}}$$



Obtaining Longitudinal Wake Fields in Code with 2D Poisson Solver

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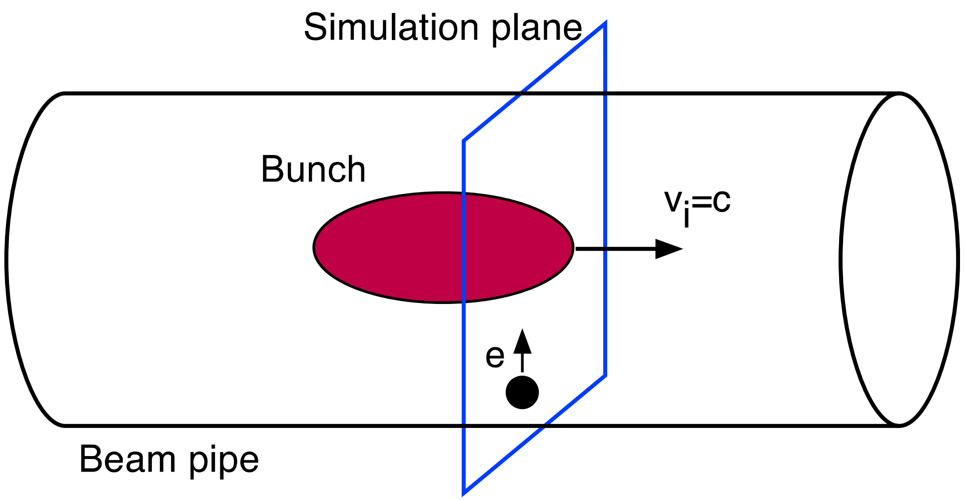
Transverse electric field of the bunch:

$$E_r^i(r,z) = \frac{q\lambda(z,t)}{2\pi\epsilon_0 r}\left[1-\exp\left(-\frac{r^2}{2\sigma_r^2}\right)\right]$$



Electron's equation of motion:

$$r'' + k^2(r,z)\,r = \frac{e\,E_r^i(r,z)}{m_e c^2}$$

where

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{m_e \epsilon_0}} \qquad k = \omega_{pe}/c$$

Electron cloud's space charge field:

$$\epsilon_0 \nabla \cdot E^e(r,z) = \rho_e(r,z)$$

The same model used for FAIR simulations

2D cloud distribution is saved each step

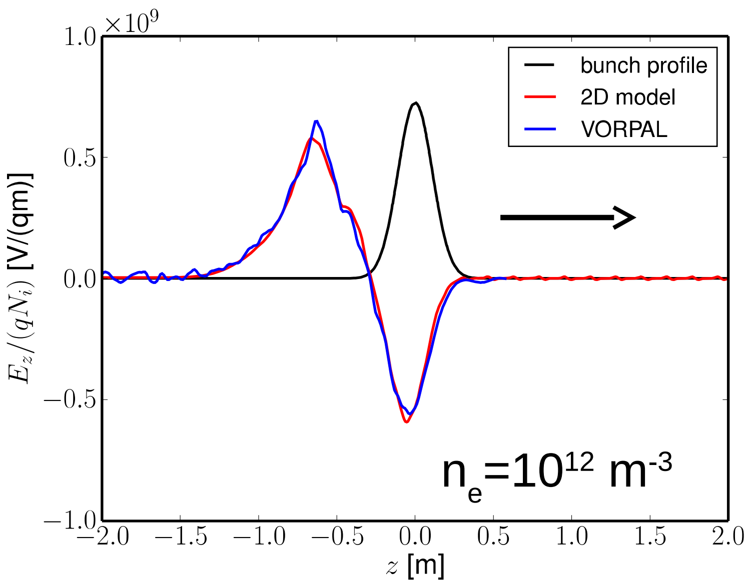
At the end of simulations one has a 3D density profile which is used to find E_z

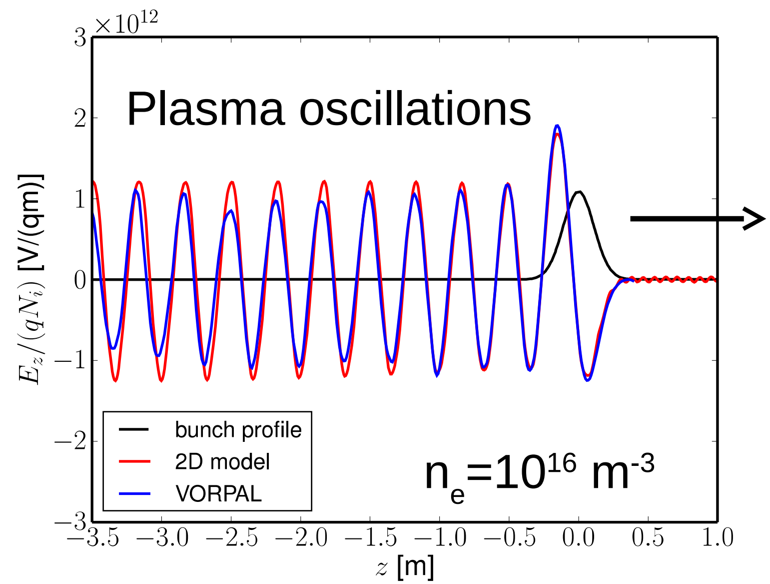
<u>Need to crosscheck with 3D code</u>

Comparison of Longitudinal Wakes in 2D code and VORPAL

VORPAL is a commercial program for 3D electro-magnetic Particle-in-Cell simulations.

Bunch rms length	0.11 m
Bunch intensity	10^{11}
Bunch radius	2 mm





VORPAL results agree very well with the simplified 2D ES simulations

Energy Loss of Short Bunches

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Transverse field of the Gaussian bunch

$$E_r^i(r,z)=\frac{q\lambda(z,t)}{2\pi\epsilon_0 r}\left[1-\exp\left(-\frac{r^2}{2\sigma_r^2}\right)\right]$$

If the bunch is short most of the electrons see a short transverse kick

$$\Delta_\perp p(b)=\frac{1}{c}\int_{-\infty}^{\infty}F_\perp(b,s)\,ds \qquad F_\perp=-e\,E_\perp^i(b,s)$$

The energy used to kick electrons comes to stopping power

$$\frac{dW_e}{ds}=\frac{n_e}{2m_e}\int_0^{R_p}2\pi\,\Delta p_\perp^2(b)\,b\,db$$

$$\boxed{S=\frac{dW_e}{ds}\approx\frac{4\pi}{\epsilon_0}Q_i^2 n_e r_e\ln\left(\frac{R_p}{a}\right)} \qquad \boxed{\frac{d\Delta\varphi_s}{ds}\approx\frac{4\pi Q_i n_e r_e}{\epsilon_0 V_{rf}}\ln\left(\frac{R_p}{a}\right)}$$

High electron densities shield the bunch field
and the stopping power goes down.

Energy Loss at High Electron Densities

Equation for electron offset

$$\delta'' + \frac{\omega_{pe}^2}{c^2}\delta = k^2(b,z)\,b$$

Oscillator amplitude at s=∞

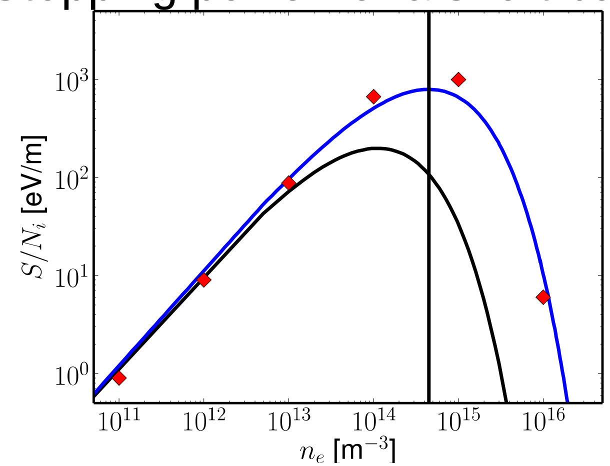
$$\hat{\delta}(b) = \frac{b}{k_e}\int_{-\infty}^{\infty} k(b,s)^2 \cos(k_e s)\,ds$$

Stopping power is proportional to energy transferred to oscillations

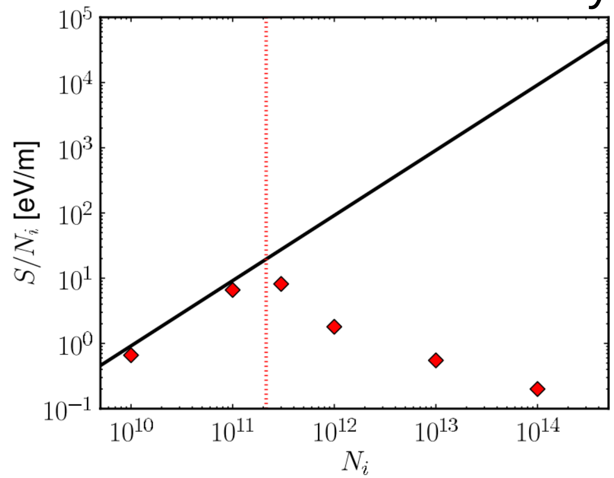
$$\frac{dW_e}{ds} = \frac{1}{2} m_e n_e \omega_{pe}^2 \int_0^{R_p} 2\pi \hat{\delta}^2 b\,db$$

$$\boxed{\frac{dW_e}{ds} \approx \frac{Q_i^2 k_e^2}{4\pi\epsilon}\ln\left(\frac{R_p}{a}\right)\exp\left(-k_e^2\sigma_z^2\right)}$$

Stopping power for a short bunch



As a function of intensity

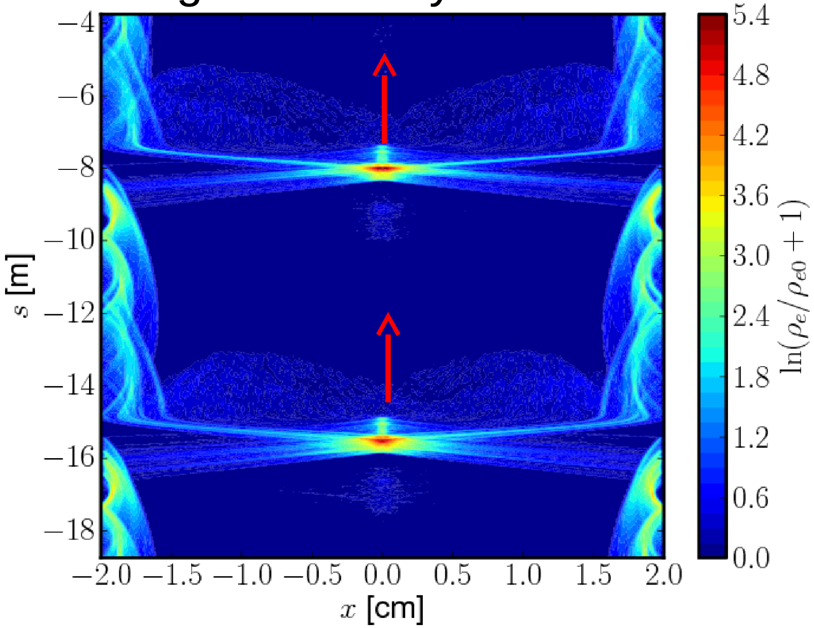


Longitudinal Wakes with Multi-Bunch Effects

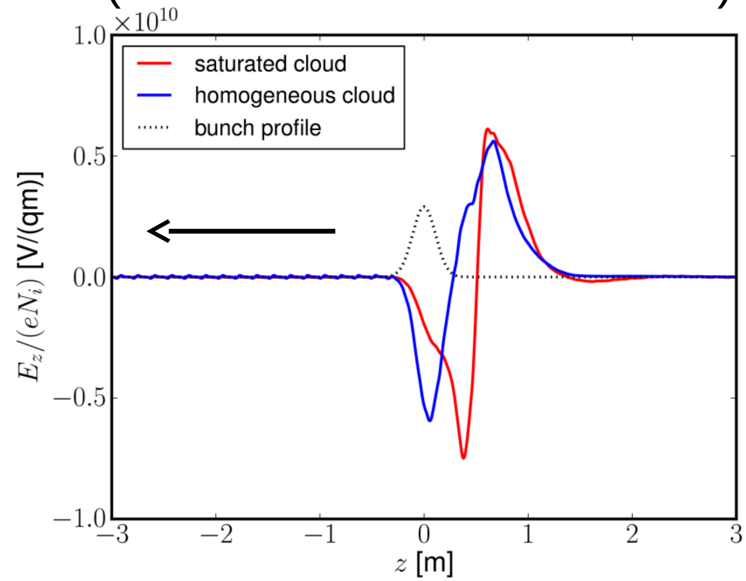
Saturated e-cloud density:

$$n_{es} \approx \frac{E_s}{\pi m_e c^2 R_p^2 r_e} \approx 10^{12} m^{-3}$$

Ring like density distribution



Longitudinal wake field
(bunch at the end of the train)



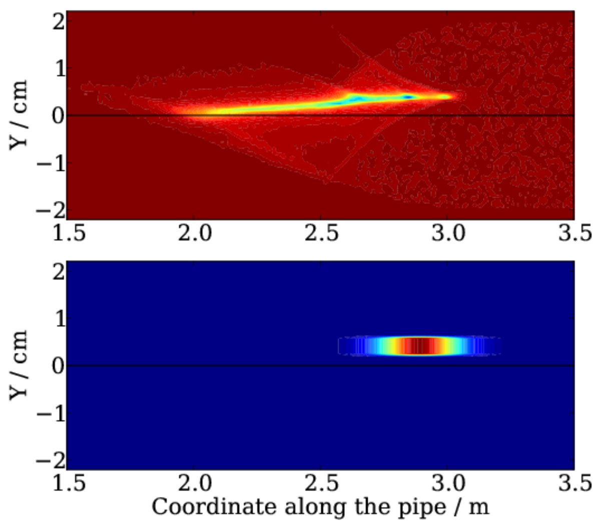
Realistic cloud acts weaker on the bunch → weaker stopping power

Transverse Wake Fields for the k=0 Head-Tail Mode (offset)

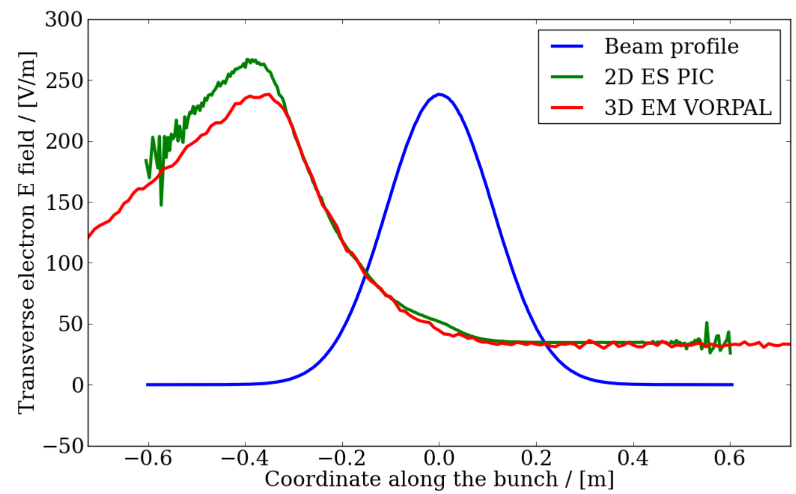
In comparison with longitudinal case transverse wakes are obtained using 2D solver directly in the code

Δr=0.004 mm

Pinching of the cloud around the bunch with and offset



Transverse wake fields obtained with 2D PIC and VORPAL



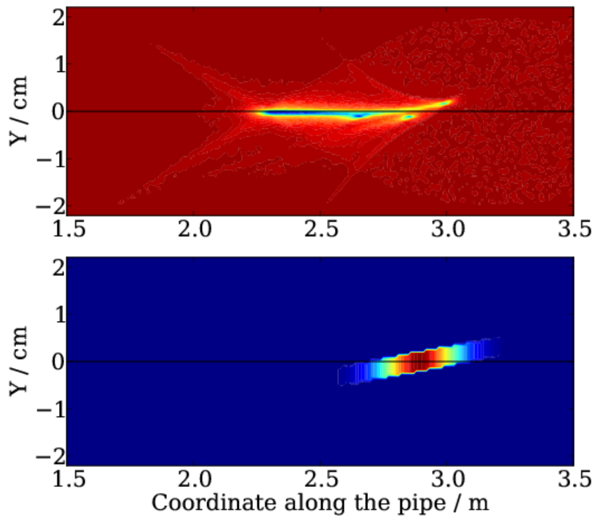
The only disagreement is seen at the end of the bunch.
However, the fraction of beam particles affected is very small.

Transverse Wake Fields for the k=1 Head-Tail mode (tilt)

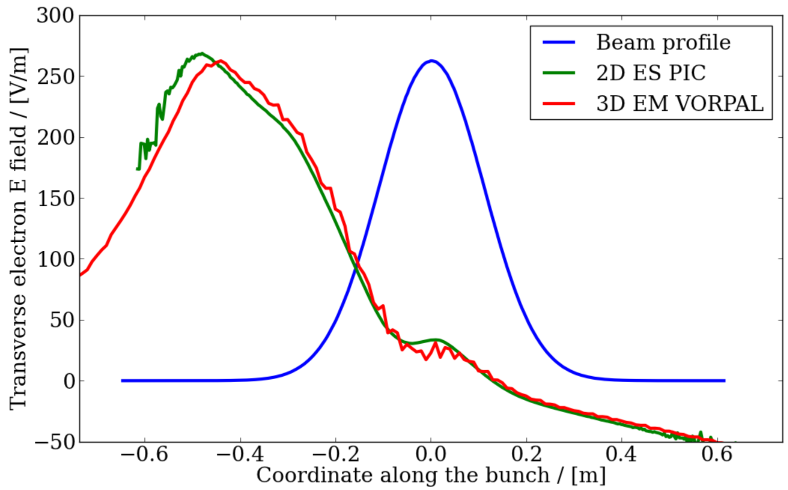
In this simulation bunch is traveling along the pipe with an angle between the pipe and the bunch axis

$\tan(\varphi)=0.01$

Pinching of the cloud around the tilted bunch



Transverse wake fields obtained with 2D PIC and VORPAL



The agreement is again very good.

Conclusions and Outlook

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- Analytical theory connecting rf phase shift and electron cloud density
- Realistic cloud shape reduces significantly the stopping power if the electron number is preserved
- Electron cloud wake field obtained in 2D electrostatic simulations and 3D electromagnetic VORPAL simulations agree very well
- 2D Poisson solver can be used for short relativistic bunches

Future work: - fast e-cloud solver on GPUs
- Parametrization of the wake fields (Impedances ?)

German government accepted proposal for 3 years on electron cloud studies in LHC and FAIR.

Thank you for your attention!

Thank you for your attention and questions.

Simplified Model of Emittance Growth of an Oscillating Beam

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What happens with the emittance when beam oscillates?

Initial emittance

$$\epsilon_{x,0} = N_i \frac{\sigma_{r,0}^2}{\beta_x}$$

Oscillations with coherent energy

$$\epsilon_{coh} = N_i \frac{\sigma_{coh}^2}{\beta_x}$$

If there is a damping due to dp/p and restoring energy source

$$\gamma_{damp} = \sqrt{\frac{2}{\pi}} \omega_0 \frac{dp}{p} n \eta$$

Emittance growth is linear

$$\boxed{\epsilon_x(t) = \epsilon_{x,0} + 2\gamma_{damp} \epsilon_{coh} t}$$

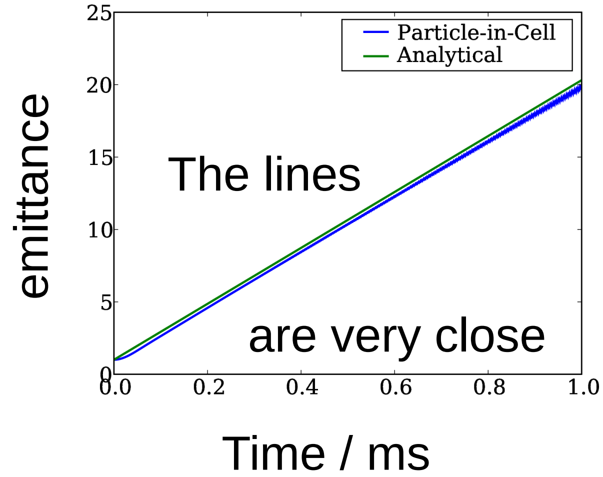
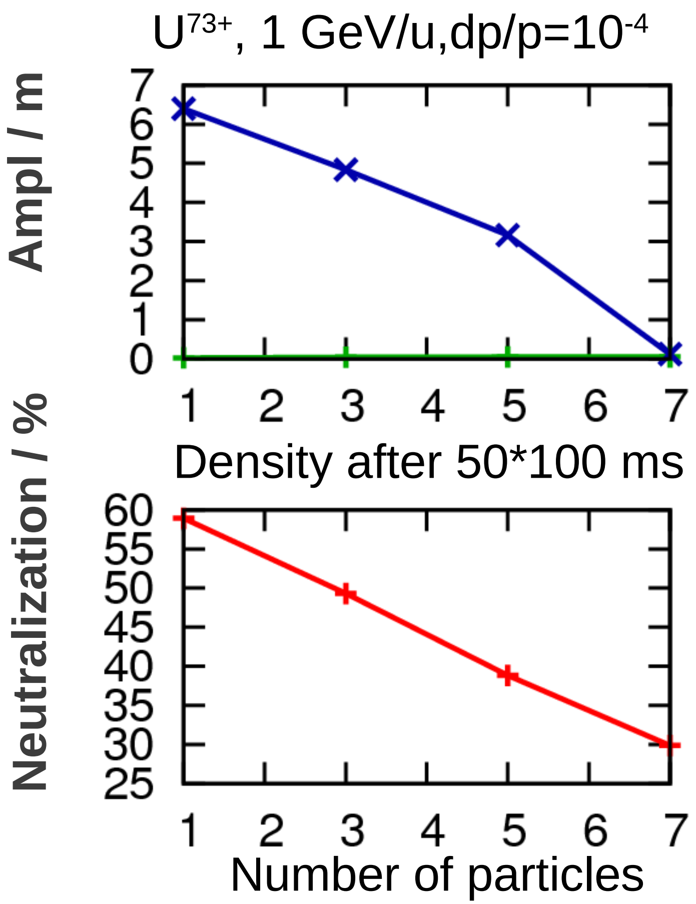
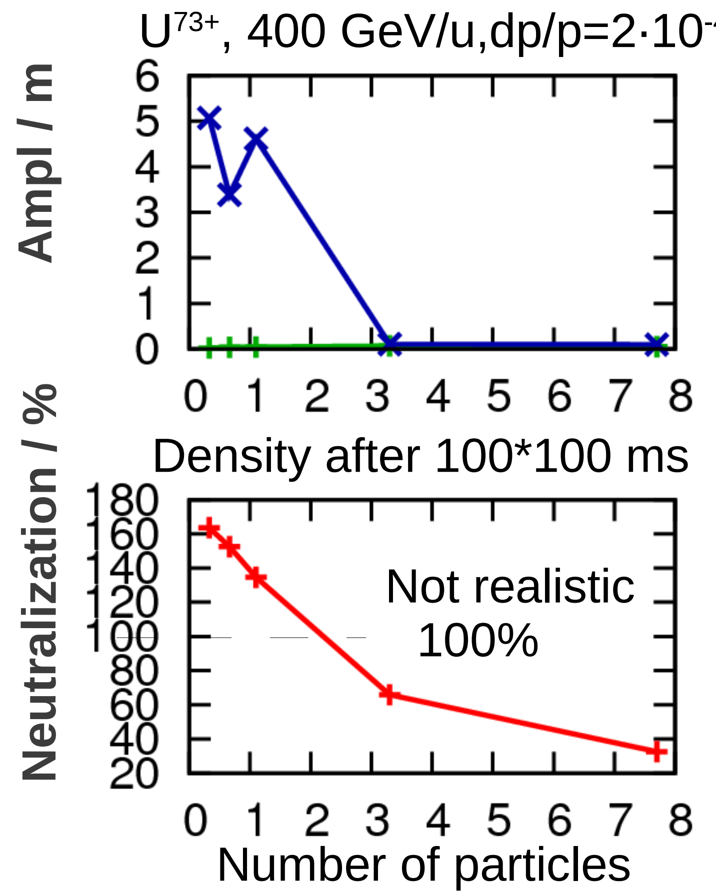


Table 1. How fast does emittance double if oscillation amplitude is 10^{-4} m, $\beta=0.86$

dp/p / harmonic	10^{-4}	$2\ 10^{-4}$	$5\ 10^{-4}$
n=20	15.4 s	7.7 s	3.1 s
n=30	10.3 s	5.1 s	2.1 s
n=100	3.2 s	1.5 s	0.6 s

Scan Over Intensities for U^{73+} with Lowest Momentum Spreads





Threshold electron densities given by the simulation are much bigger than the limiting densities due to the Coulomb heating.