Electron Cloud Studies for FAIR

Fedor Petrov, Oliver Boine-Frankenheim, Thomas Weiland

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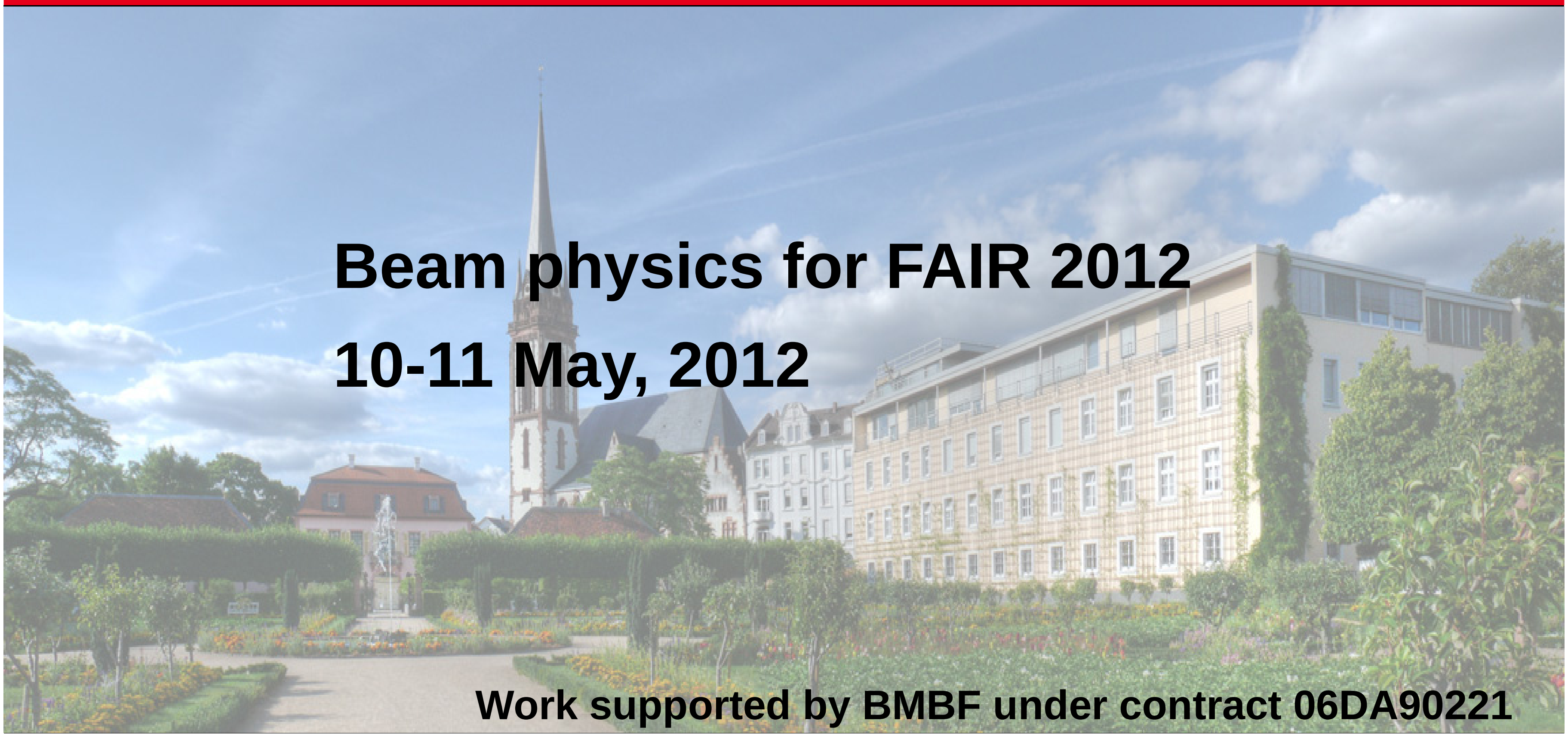

Beam physics for FAIR 2012

10-11 May, 2012

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Outline

- Motivation
- Electron cloud sources and effects
- Numerical model
- Results of e-cloud simulations in FAIR bunched beams
- Results of simulations in FAIR coasting beams

If I have time

- LHC: Wake-fields and stopping powers.

Motivation

FAIR

- FAIR is a new accelerator facility with increased intensities of heavy ion beams.
- Heavy-ion beam energy ranges from 11.4 MeV/u at injection in SIS18 up to 1.7 MeV/u at extraction in SIS100
- In this energy range the residual gas ionization by beam ions is very efficient.
- This electrons can accumulate in the coasting beam or serve as a seed electrons for multipacting in the bunched beam operation.

Electron Cloud is a known problem of LHC

- rf phase shift due to the electron cloud space charge was observed.

Operation Regimes. Bunched and Coasting Beams

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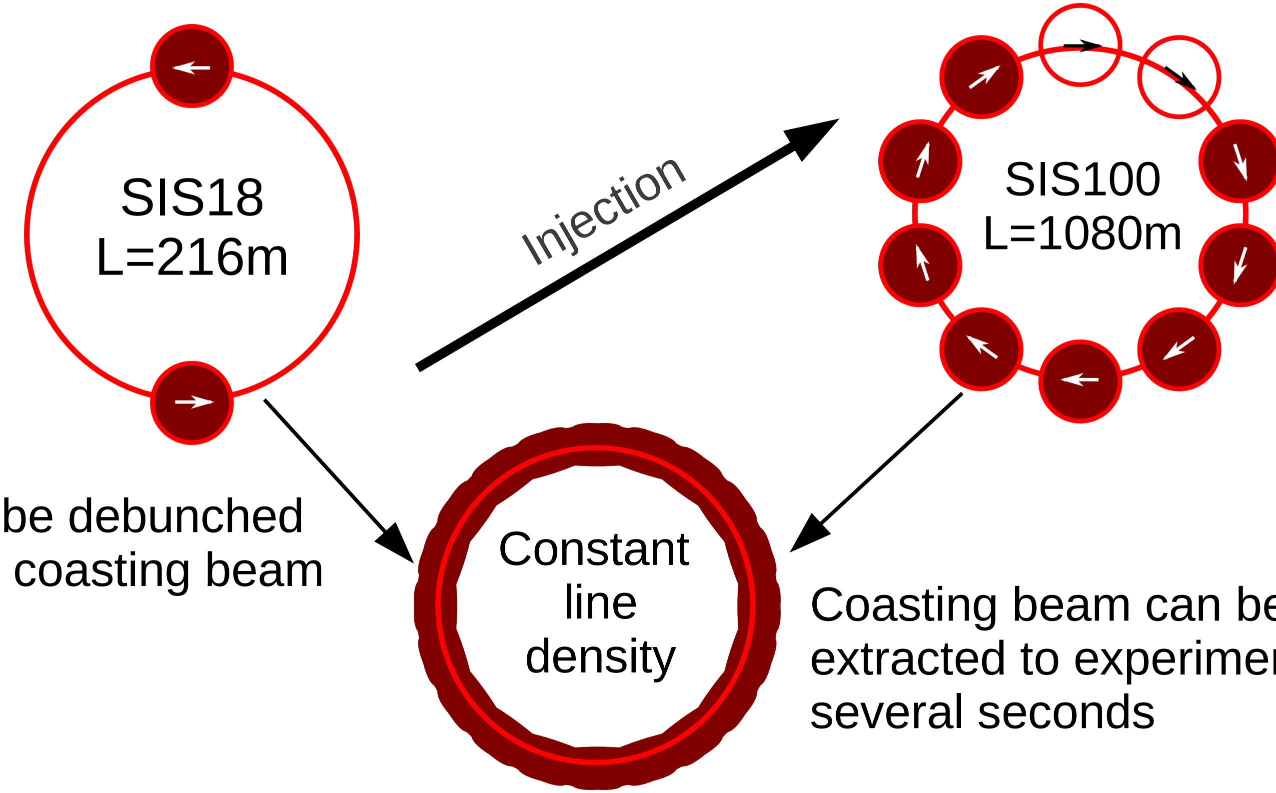
Bunched beam operation SIS18

SIS100 heavy ion operation
8 bunches 2 empty buckets



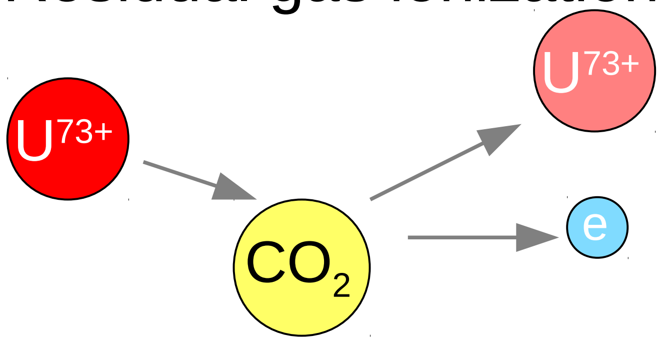
Can be debunched
to get coasting beam

Coasting beam can be continuously extracted to experimental area for several seconds

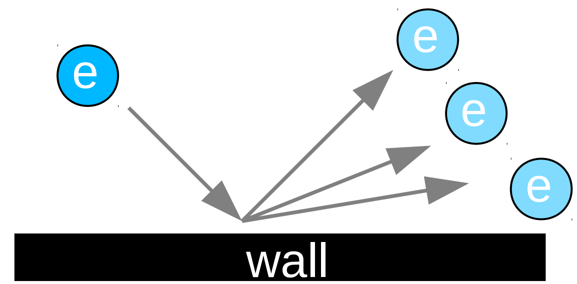
Electron cloud problems show-up differently depending on the regime

Possible Electron Cloud Origin

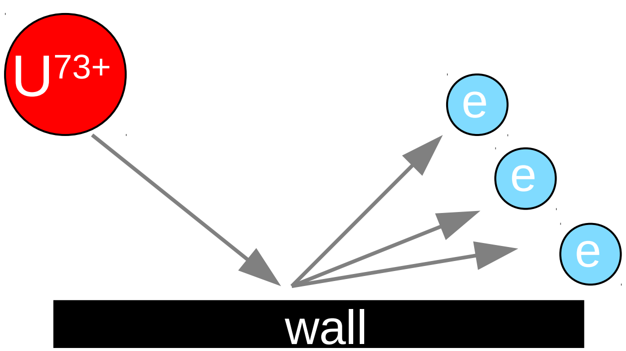
Residual gas ionization



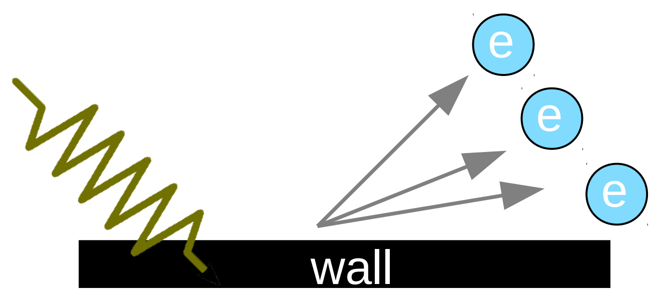
Electron secondary emission



Ion induced secondary emission



Photon induced secondary emission



Under FAIR conditions the most concern are the upper two.

Possible Electron Cloud Origin

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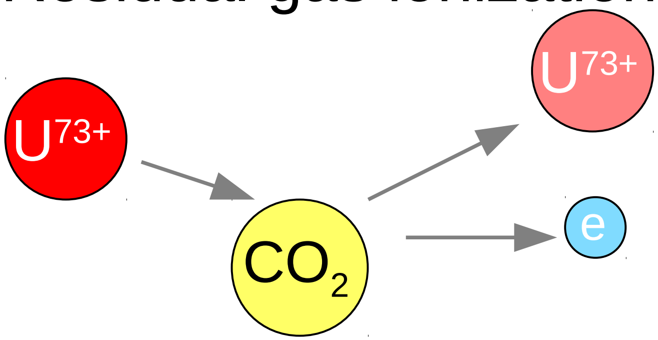
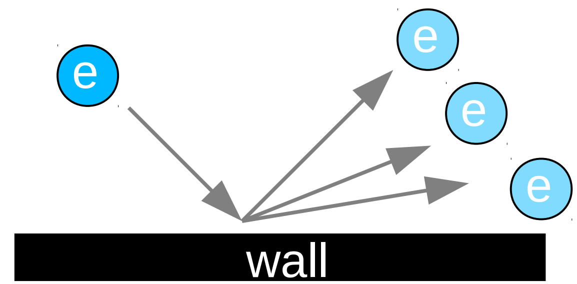
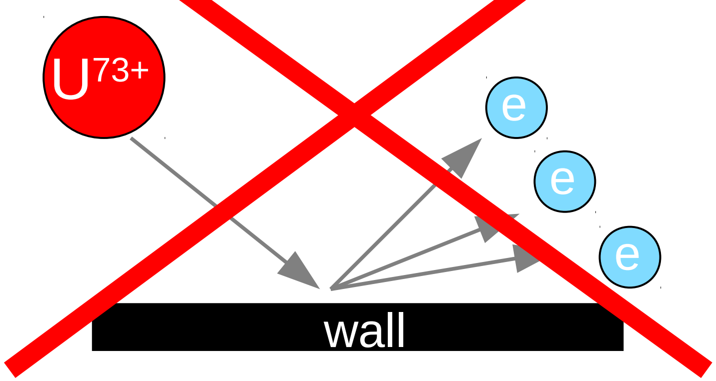
Residual gas ionization



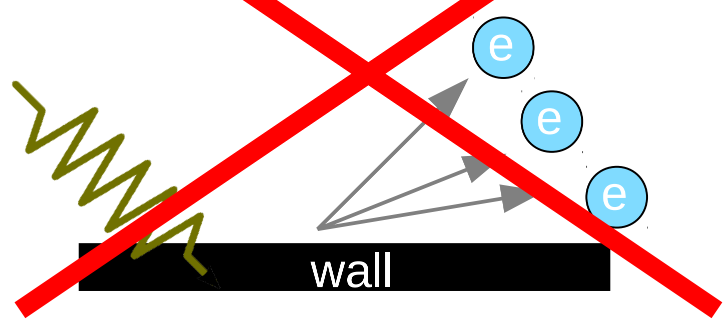
Electron secondary emission



~~Ion induced secondary emission~~



~~Photon induced secondary emission~~



Under FAIR conditions the most concern are the upper two.

Main Electron Sources Depending on the Beam Form

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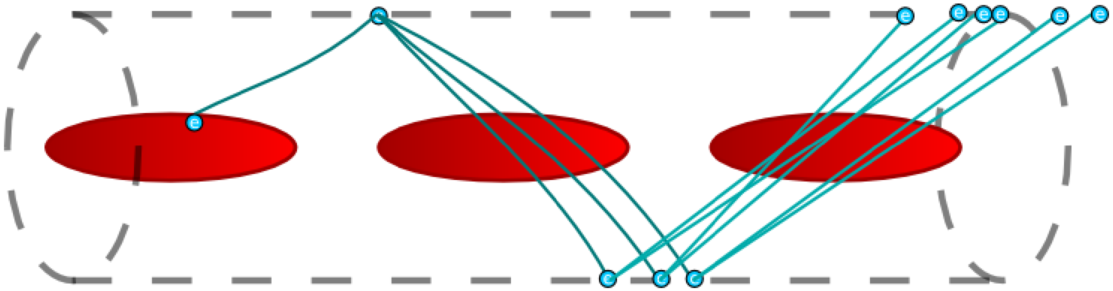
Bunched Beam



Seed electrons from the slow sources multiplied exponentially by multipacting
Electron density can grow rapidly until the neutralization ~ 100 µs

Main Electron Sources Depending on the Beam Form

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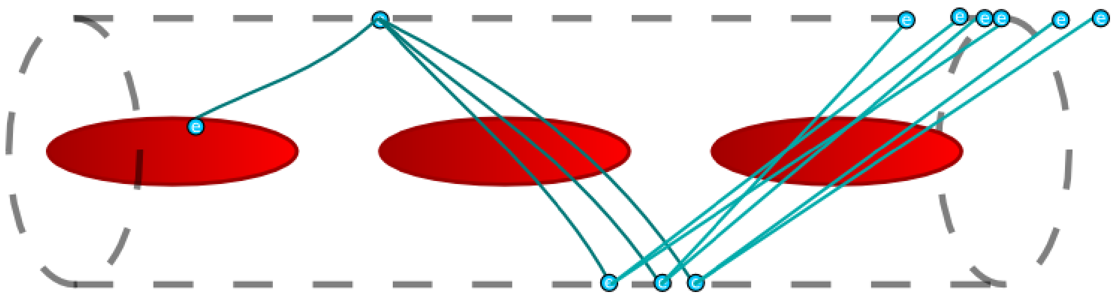

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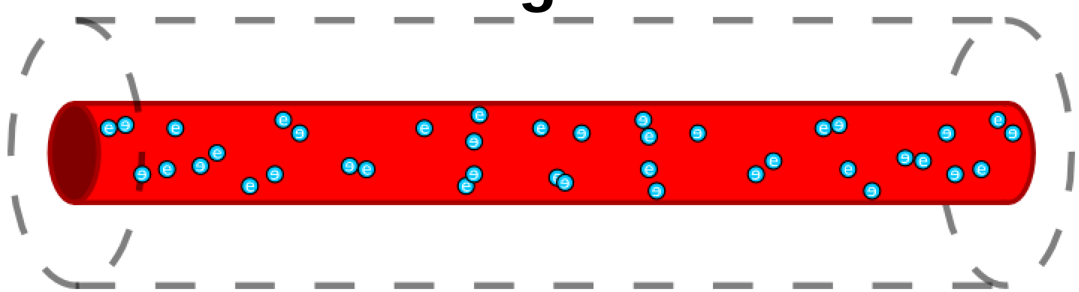
Coasting Beam

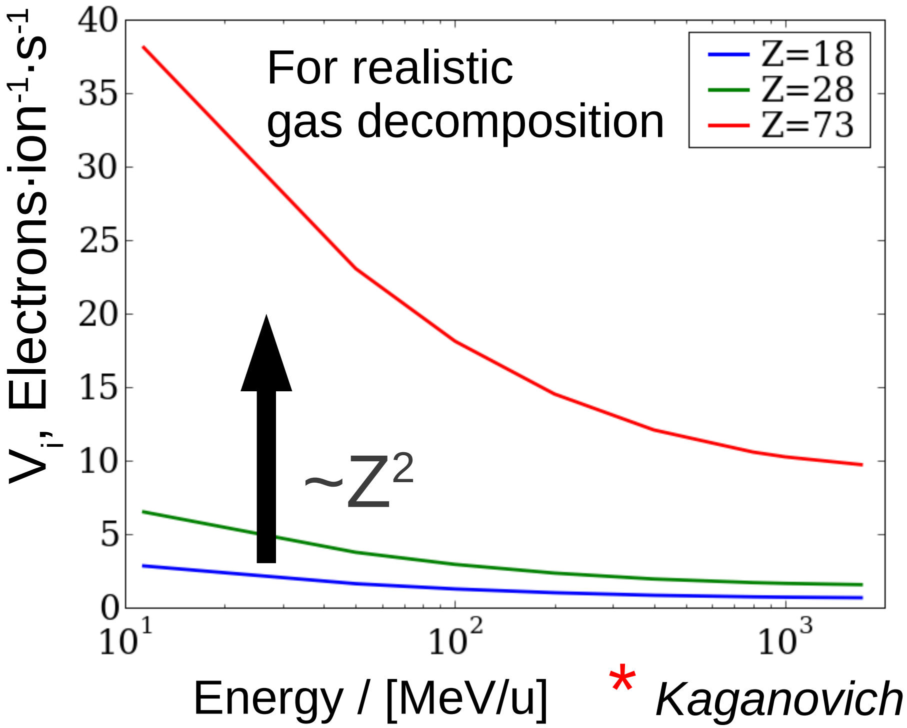


Electrons come from residual gas ionization, trapped in the beam potential.
It can take 0.1-1 s until we get into trouble i. e. two-stream instability or emittance growth.

How Many Electrons Produces One Ion Per Second?

Expected pressure in vacuum chamber is
P=10^{-11} Torr=353000 cm^{-3}

Gases in SIS18 chamber Ar, N_2, CO, CO_2,H_2



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

The higher is the charge of ion the faster it can be neutralized by the residual gas ionization.
Time scale ~ 1 s

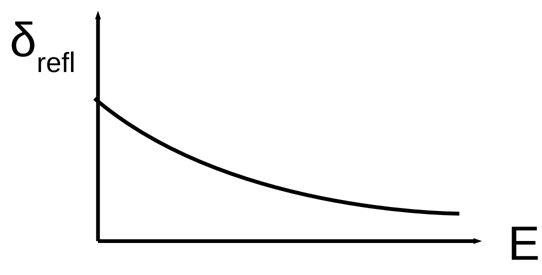
* *Kaganovich et al, New Journal of Physics 8 (2006) 278*

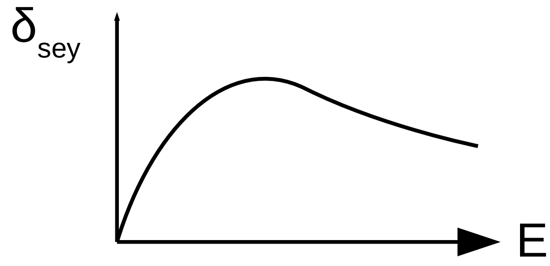
Wall Effects. Reflection. Secondary Emission

When electron hits the wall it can produce secondary electrons or be reflected. Both of these effects depend on energy of the incidence electron.

$$\delta_{refl}(E)=\delta_0\left(\frac{\sqrt{E}-\sqrt{E+E_0}}{\sqrt{E}+\sqrt{E+E_0}}\right)^2$$

E_0 – energy scale(how fast it decays for bigger energies)
δ_0 - reflection probability at zero incidence energy





Secondary emission yield(SEY)
E_{max} – energy at which SEY has maximum
$\delta_{sey,max}$ – value of secondary emission at maximum

$$\delta_{SEY}(E)=\delta_{max}\cdot\left(\frac{E}{E_{max}}\right)^{-0.35}\cdot\left(1-e^{-2.3\cdot\left(\frac{E}{E_{max}}\right)^{1.35}}\right)$$

Electron Interaction with Coasting Beam

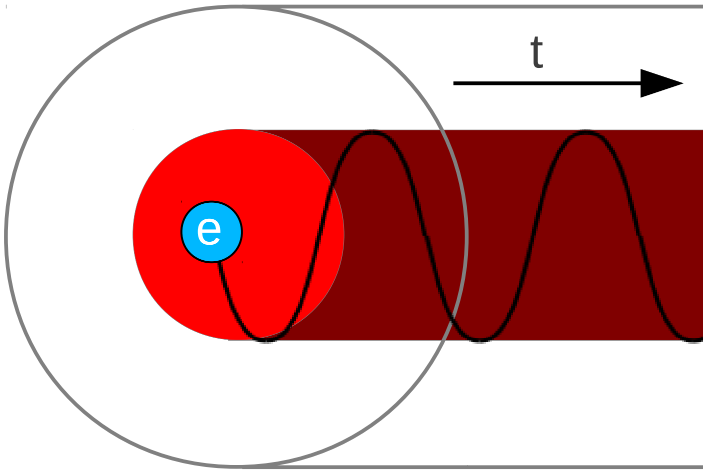
Initial electron velocity v_0=0

Immediately after production it starts to oscillate

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

Beam responds to these oscillations much slower

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



Electron-beam coupled motion is described by this system of equations

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

**Ng book, Chapter 19*

Beam-Electron System of Coupled Equations.

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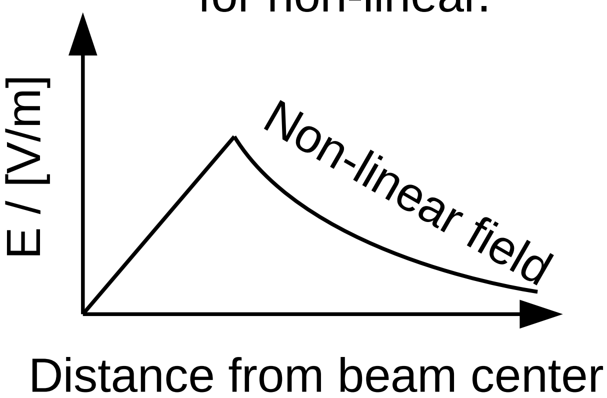
To find eigenfrequencies of the system one has to solve the 4-order algebraic equation. If it has complex solutions then the instability starts.

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

In reality* electrons gain large amplitudes much faster than ions ~m_i/m_e

↓

Strongly non-linear motion. Up to now it was studied only numerically. In one of the works* it was indicated that linear instability is necessary for non-linear.



For real beam Landau damping term should be included as

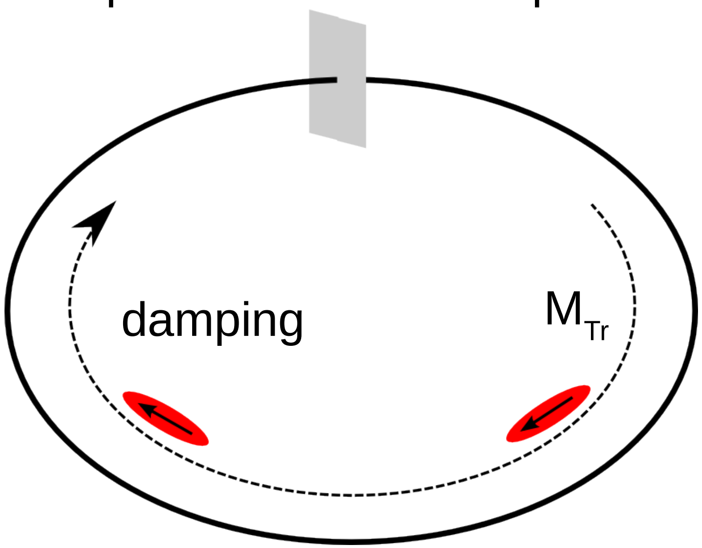
$$\gamma_d = \sqrt{\frac{2}{\pi}}\,\omega_0\,\eta\, n\,\frac{dp}{p}$$

*Startsev
**M. Channel

General Principle of Simulation in One Slide.

Model of the machine

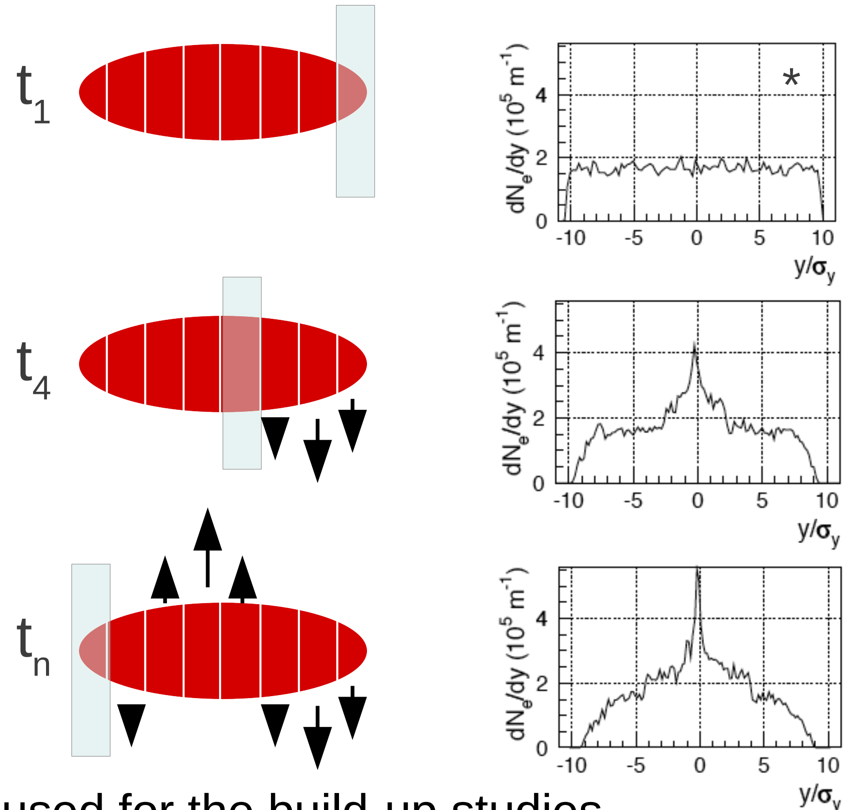
EC production and kick point



This is almost the same principle as in CERN HEADTAIL and ECLOUD Codes.

Model of the beam-cloud interaction

bunch kicked cloud kicked

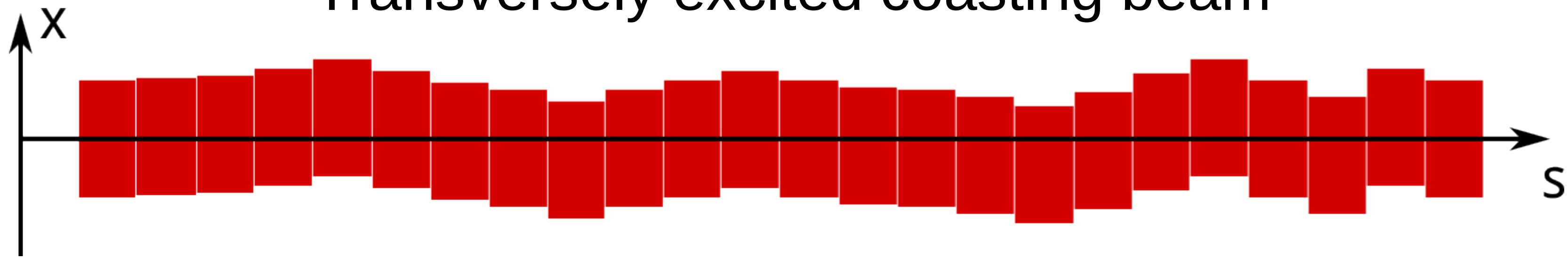


In our case one and the same code is used for the build-up studies and for the instabilities simulations.

*G. Rumolo

Landau Damping in Rigid Slice Model.

Transversely excited coasting beam



Damping rate of the signal on the n-th band*

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

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

Inverse FFT gives us a new damped set of beam coordinates which is used in the next iteration.
We need a broad band damping because EC acts on a very wide spectral range.

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

Comparing Rigid Model with Full Particle-in-Cell Model.

Electron cloud effects have similarities with impedances.

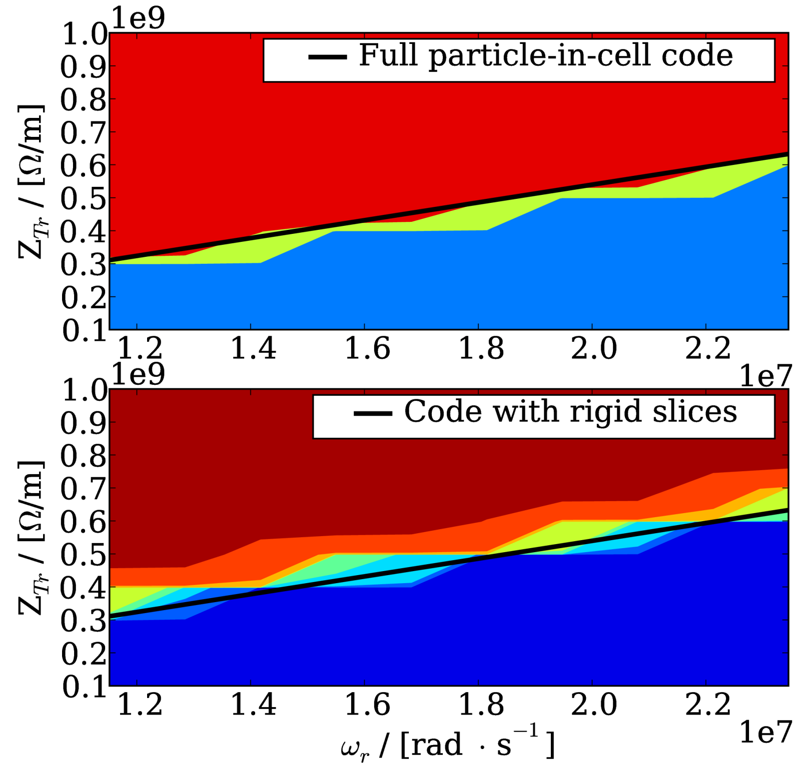
To check the correctness of our model we apply the broad band impedance to our rigid beam and compare with the full Particle-in-Cell model as well as with analytical theory.

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

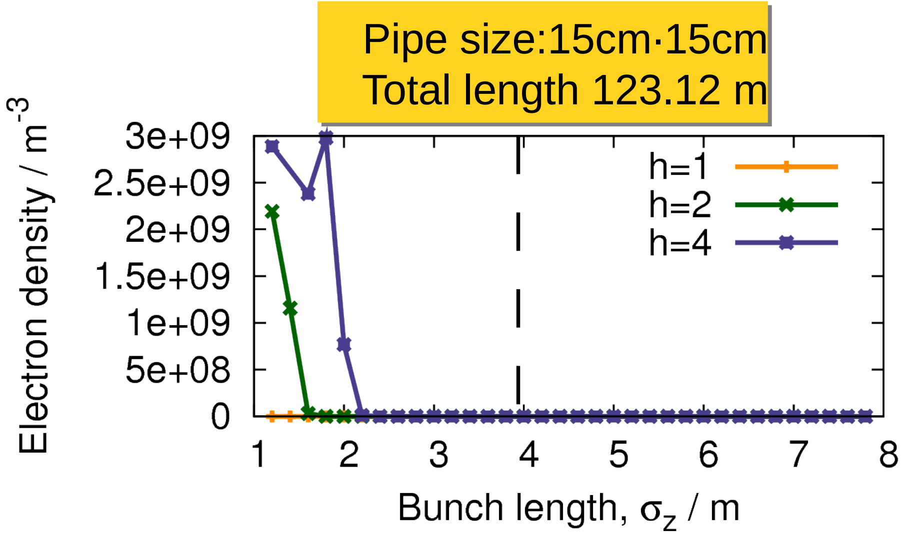
$$\sqrt{\frac{2}{\pi}}\omega_r\frac{dp}{p}\eta=\frac{Nq^2\beta}{8\pi^2 m_i\gamma R Q_x}Re(Z_{Tr})$$

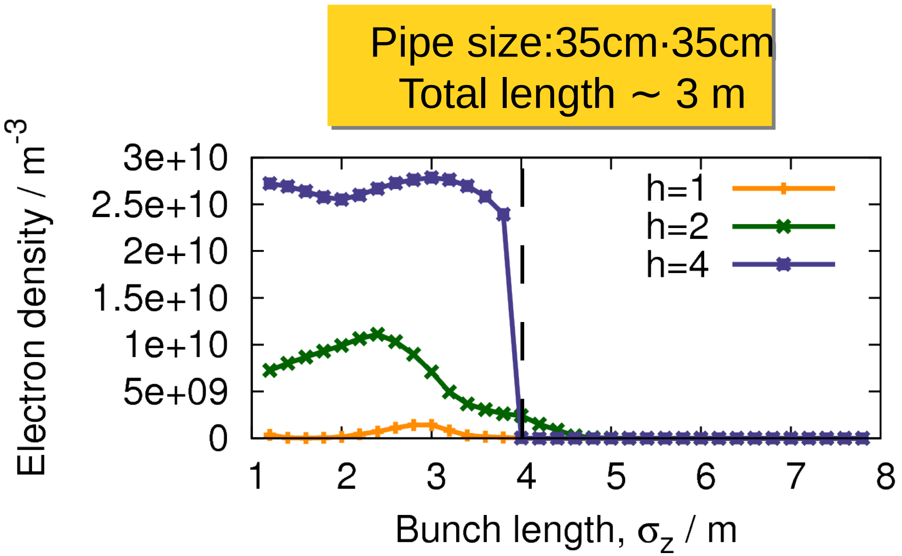


Electron Cloud Build-up During Bunched Beam Operation in SIS18.

Scan over bunch parameters in SIS18 to reveal dangerous conditions

Circumference	216 m
Design bunch length, σ_z	4 m
Ion type	U^{28+}
Intensity	10^{11}
Energy	1 GeV/u





In drift section build-up can happen for bunches far shorter than it is designed.

No build-up for the scan parameters in drift and dipole sections because of the NEG coating.

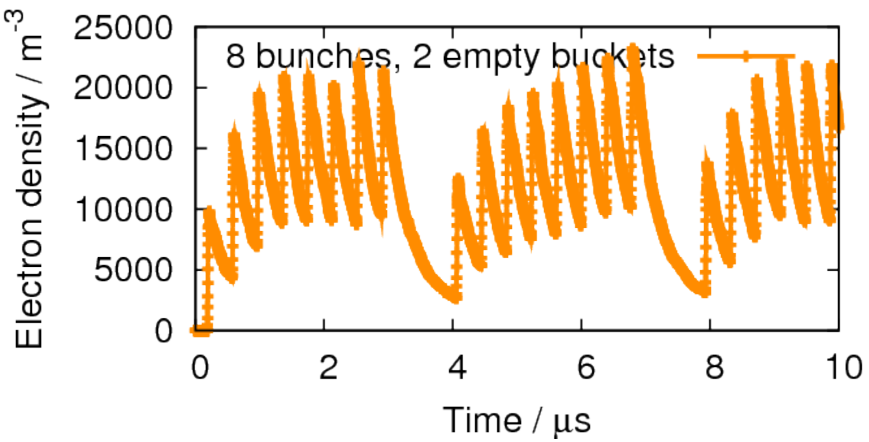
Electron Cloud Build-up During Bunched Beam Operation in SIS100

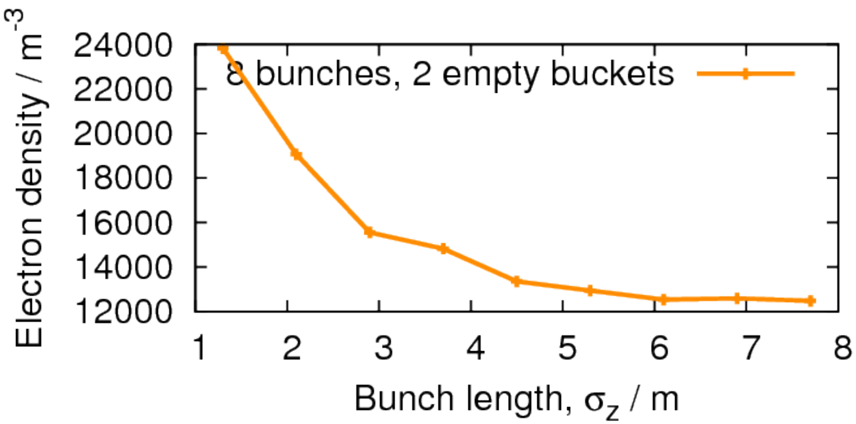
Scan over bunch parameters in SIS100 to reveal dangerous conditions

Circumference	1080 m
Design bunch length, σ_z	4 m
Ion type	U^{28+}
Intensity	$5 \cdot 10^{11}$
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.





Coasting Beam Operation in FAIR. Simple Analysis of Parameters.

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Dependence of the main simulation parameters on the type of ion and energy. Y,A,W,P – constants for given energy

Maximum intensity

$$N_i = Y \frac{m_i}{Z^2}$$

Total ionization rate

$$V_i = A(\beta, \gamma)\beta m_i$$

$$n_e = V_i T$$

Driving term at the fixed moment

$$\boxed{\omega_i^2 = X(\beta, \gamma) Z \beta^2}$$

Momentum spread

$$\frac{dp}{p} = \frac{P}{\sqrt{\beta\gamma}}$$

$$\omega_e^2 = \frac{S \cdot \beta \gamma m_i}{Z}$$

Damping term

$$\boxed{\psi = W \sqrt{\frac{m_i}{Z}} \eta}$$

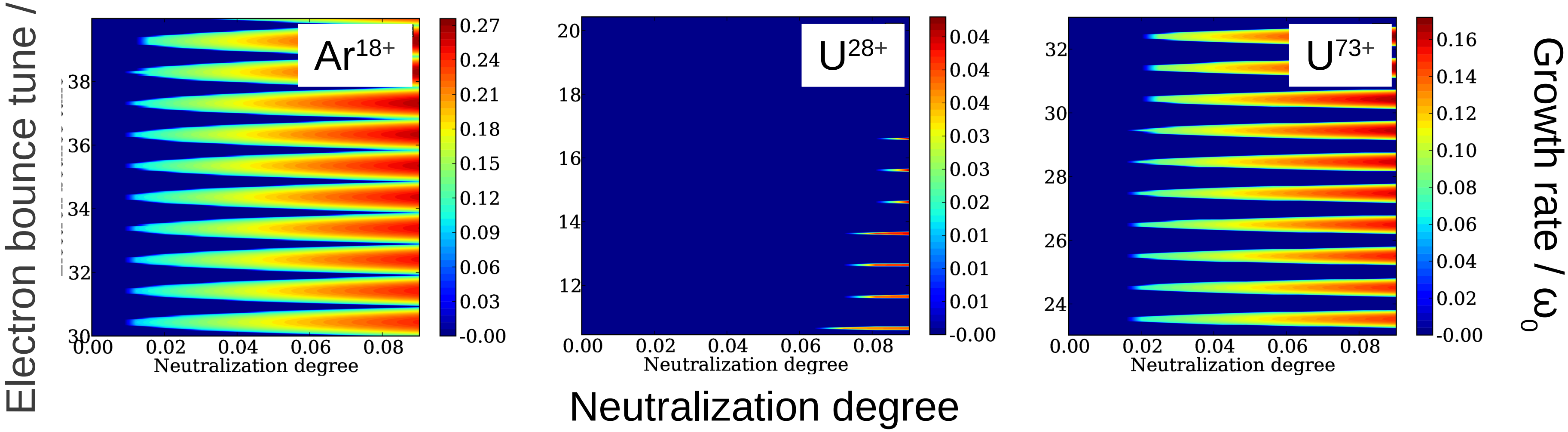
We see that with increasing Z driving term increases and damping term on trapping frequency decreases.

U^{73+} worse than U^{28+} and Ar^{18+}

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.

Cloud is fixed. $dp/p=2\cdot 10^{-3}$ $\beta=0.86$



U^{28+} has the biggest stable area. Ar^{18+} has the smallest stable area.

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

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

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

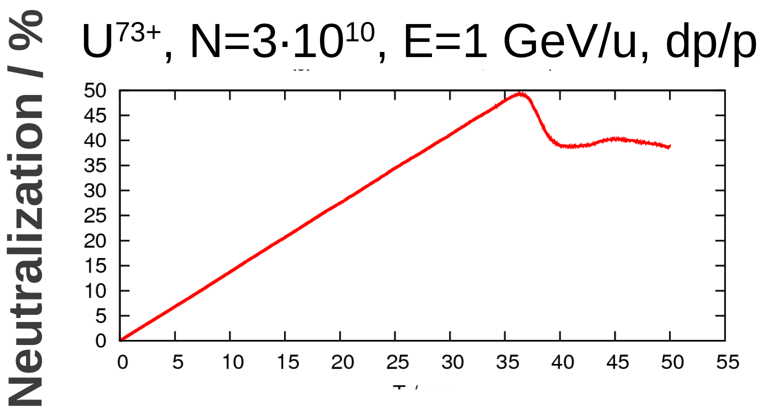
Build-up and Instability in SIS100

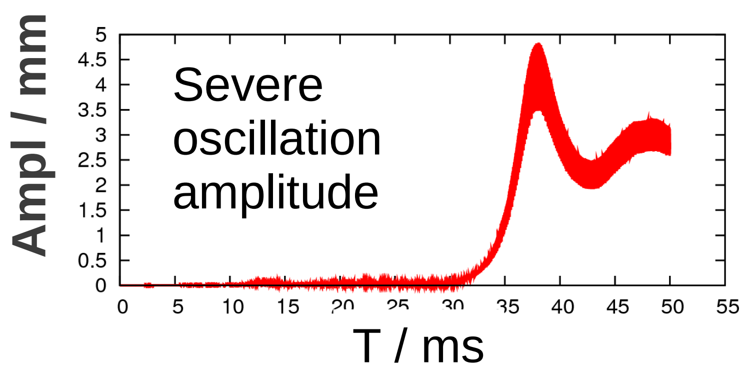
To reduce the simulation time ionization rate was increased by **factor 100.**
Ions are Ar^{18+} and U^{73+}, energies 400 MeV/u and 1 GeV/u

How it looks when there is a nonlinear instability.

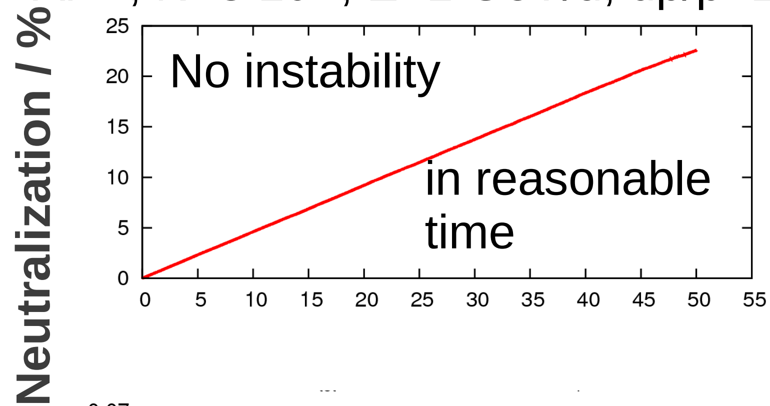
Linear growth of amplitude no exponential growth

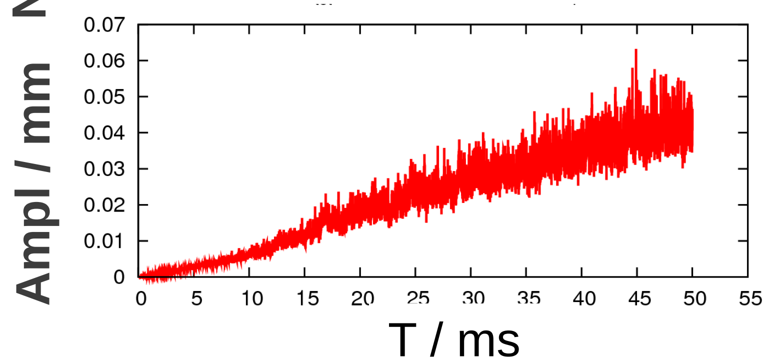
U^{73+}, N=$3\cdot10^{10}$, E=1 GeV/u, dp/p=10^{-4}





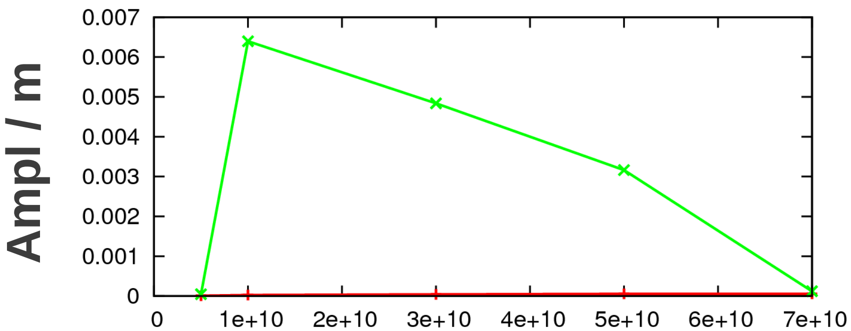
Ar^{18+}, N=$3\cdot10^{11}$, E=1 GeV/u, dp/p=10^{-4}



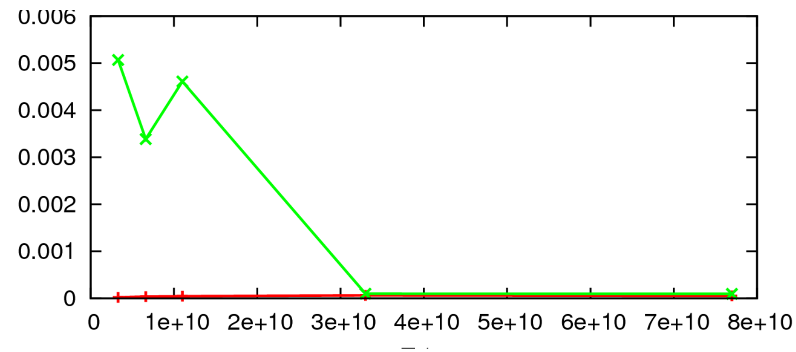


Scan Over Intensities for U^{73+} with Lowest Momentum Spreads

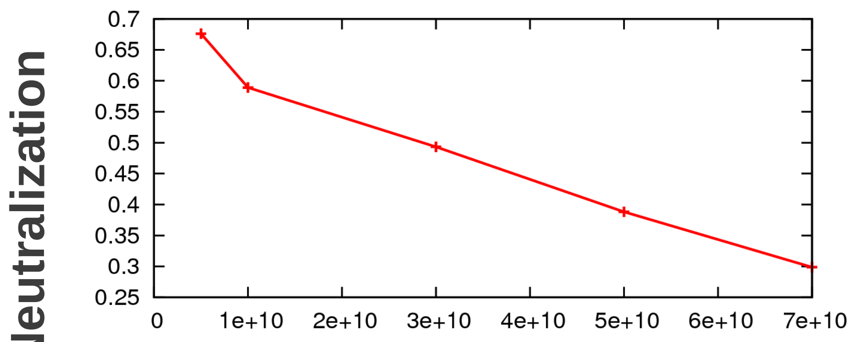
U^{73+}, 1 GeV/u, $dp/p=10^{-4}$



U^{73+}, 400 GeV/u, $dp/p=2\cdot10^{-4}$

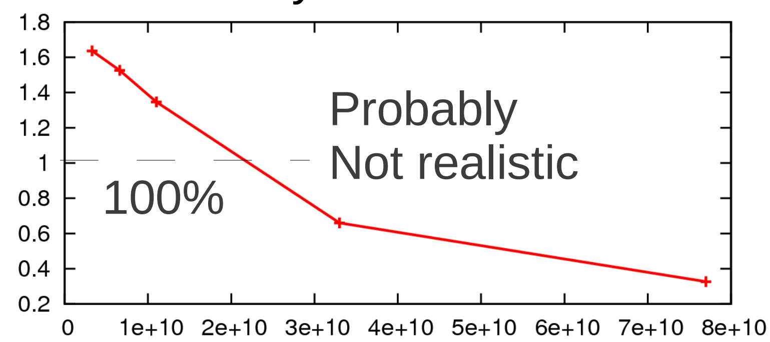


Density after 50*100 ms



Number of particles

Density after 100*100 ms

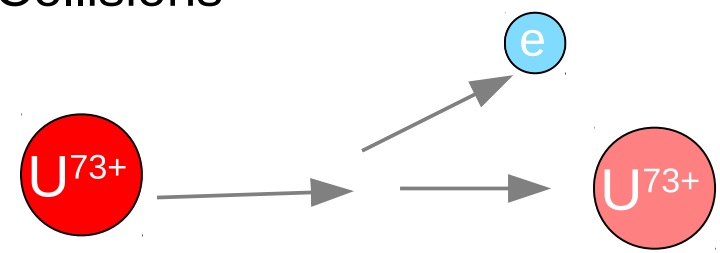


Number of particles

Increasing momentum spread to $dp/p=5\cdot10^{-4}$ removes the exponential instability. Amplitudes stay at level 10^{-1}-10^{-2} mm. Even for small dp/p Ar^{18+} - no instability.

Coulomb Heating

Electron Gets Energy from Collisions



Heating rate

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

Coasting beam parameters at 1 GeV/u assuming radius of the pipe 5 cm

Ion	Intensity	Heating rate	Potential	Estimated lifetime	Instability time
Ar^{18+}	$2 \cdot 10^{11}$	143 eV/s	26 eV	0.18 s	>10 s
U^{28+}	$5 \cdot 10^{11}$	868 eV/s	104 eV	0.12 s	>10 s
U^{73+}	$7 \cdot 10^{10}$	826 eV/s	38 eV	0.046 s	2-3 s

Times are much smaller than time needed for the instability.
This factor significantly reduces the danger.

*Zenkevich, Adiabatic Theory of Electron Oscillations

Simplified Model of Emittance Growth of an Oscillating Beam

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What happens with the emittance when beam oscillates?

We have beam with initial emittance $\epsilon_{x,0} = N_i \frac{\sigma_{r,0}^2}{\beta_x}$

We bring it to oscillations with coherent energy $\epsilon_{coh} = N_i \frac{\sigma_{coh}^2}{\beta_x}$

We have damping rate and the energy source restoring the amplitude - EC

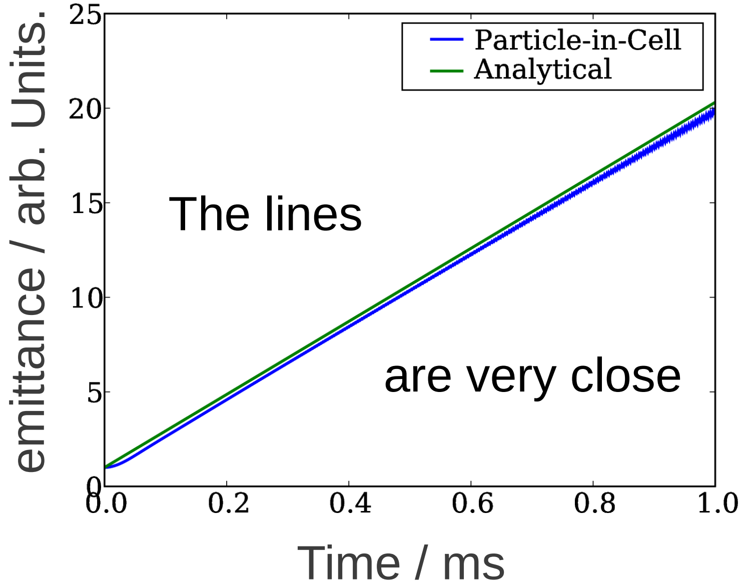
$$\gamma_{damp} = \sqrt{\frac{2}{\pi}}\omega_0 \frac{dp}{p} n \eta \xrightarrow{\text{Energy fraction}} 1 - e^{-2\gamma_{damp} dt} = 2\gamma_{damp} dt$$

Emittance growth is then a linear function of time

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

PIC Code and Analytical Model Comparison. Emittance Growth.

The beam was excited at n=30, dp/p=5 10^{-4}



Agreement is good

Table 1. How fast does emittance double if oscillation amplitude is 10^{-4} m, β=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=50	6.2 s	3.1 s	1.2 s

Growth times are long.
If the beam is coasting for ~10 s then the emittance can increase significantly.

Gap in The Beam Can Also Solve the Problem of Electron Accumulation

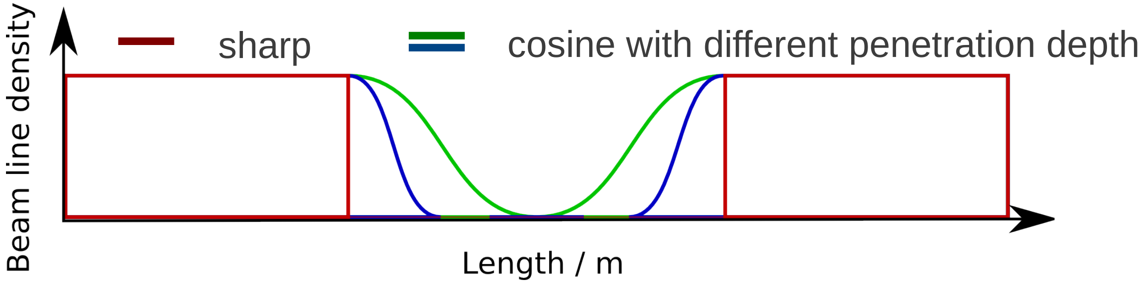
If the beam is stable the electron equation of motion is a Hill's equation

$$\ddot{x} = K(t, z_0) \cdot x = \left(\omega_+^2 - \omega_e^2(t, z_0)\right) \cdot x$$

Until the density of electrons is low $\omega_+ \approx 0$

This equation can be solved to find maximum amplitudes of electrons

If it is bigger than the beam size then electrons are lost



Some simple theory* was previously developed * to find out if the electrons are trapped in the gap.

Simulations indicate that in case of realistic Gaussian transverse profile for clean gap accumulation never happens in contrast to KV beam.

*Ng, Intensity Dependent Beam Instabilities

Conclusion for FAIR Project

Bunched beams

- Electron cloud effects were studied for conditions relevant to FAIR project
- No multipacting happens in SIS18 and in SIS100 for the designed bunch length and intensities

Coasting beams

- A new realistic way to treat Landau damping in rigid slice coasting beam model is introduced
- Electron clouds are a much bigger danger for highly charged ions.
- Simulations indicate the two-stream instability if slow extraction time is longer than 2 s
- However, Coulomb scattering of electrons on beam ions can significantly reduce the chance for instability especially for high Z

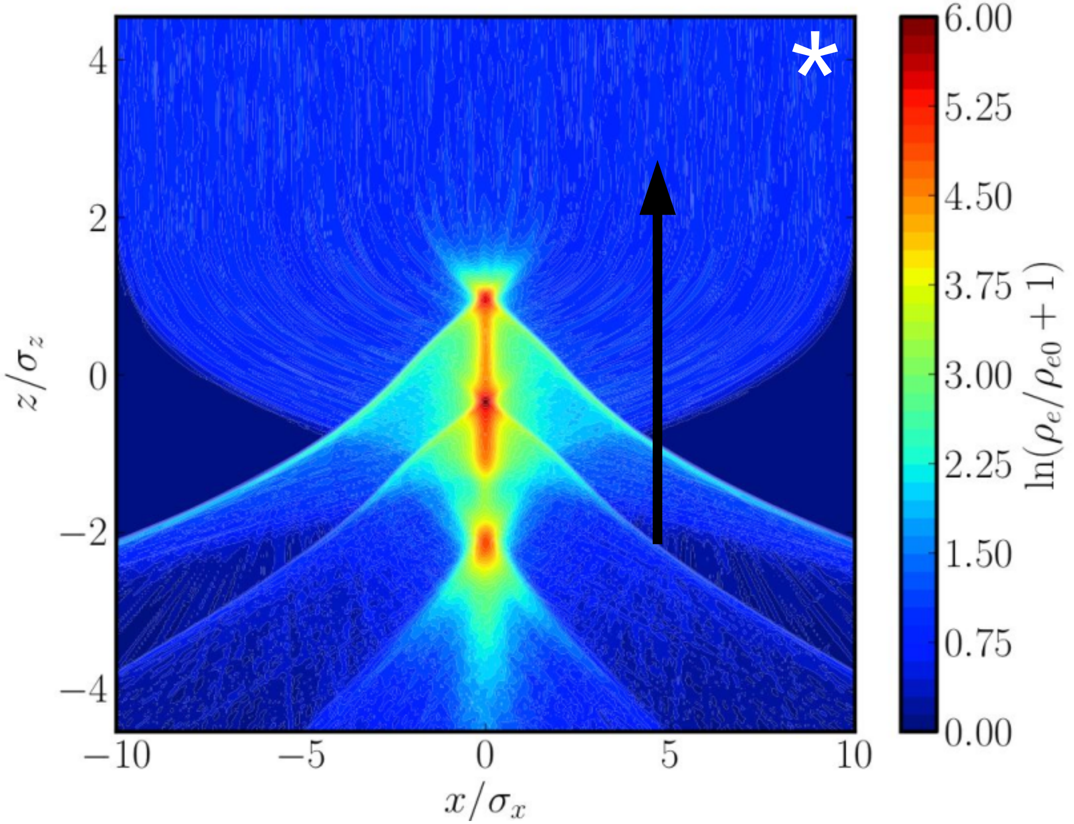
Outlook

- To clarify if one can scale the problem by increasing the ionization rate (long term diffusion, Coulomb heating).
- Make couple of simulations of instabilities including Langevin heating term
- Still necessary to make a finer scan over beam intensities and momentum spreads including Coulomb heating

LHC Wake Fields and Stopping Powers

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

O. Boine-Frankenheim,
F. Petrov, Th. Weiland
E. Gjonaj, F. Yaman, G. Rumolo

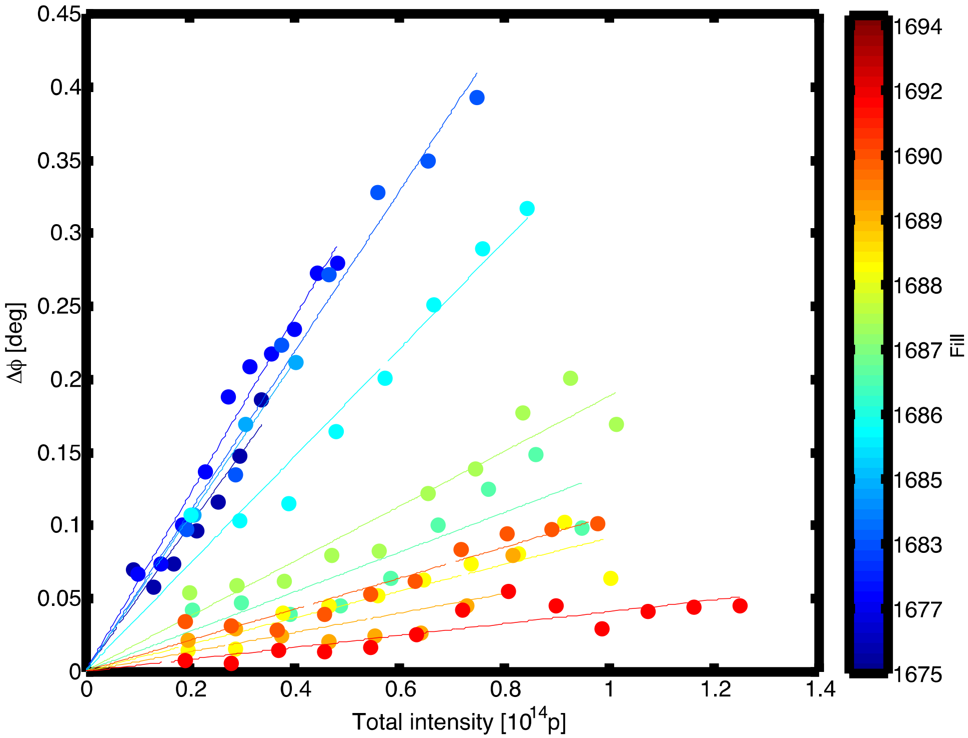


If there is already an electron cloud when the bunch passes it is attracted towards the center of the bunch.
The resulting non-uniformity of the cloud results into the longitudinal electric field which tries to stop the bunch

* O. Boine-Frankenheim

RF Phase Shift in LHC

J. Esteban-Müller, E. Shaposhnikova



- The slope of the phase shift with intensity has gradually decreased over the period of the scrubbing run (50 ns beams)
- The slope $\Delta\phi s/\Delta N$ has lost one order of magnitude thanks to scrubbing!

Energy Loss and RF Phase Shift

Energy loss per unit length (stopping power):

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

Bunch line density:

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

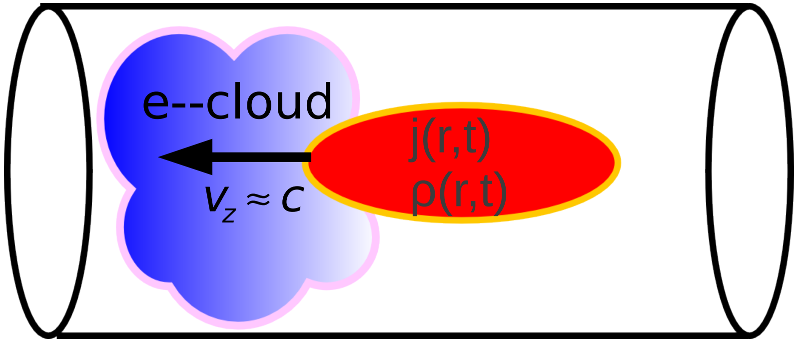
Energy loss per turn and particle:

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

rf phase shift:

$$\sin(\Delta\phi_s) = \frac{\Delta W_p}{qV_{rf}}$$

$n_e \approx 10^{12} - 10^{13}\ \mathrm{m}^{-3}$



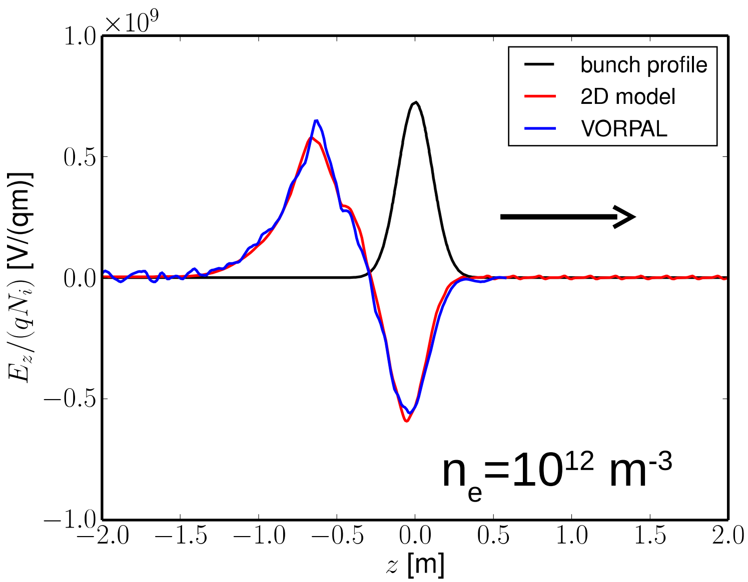
Electron's equation of motion:

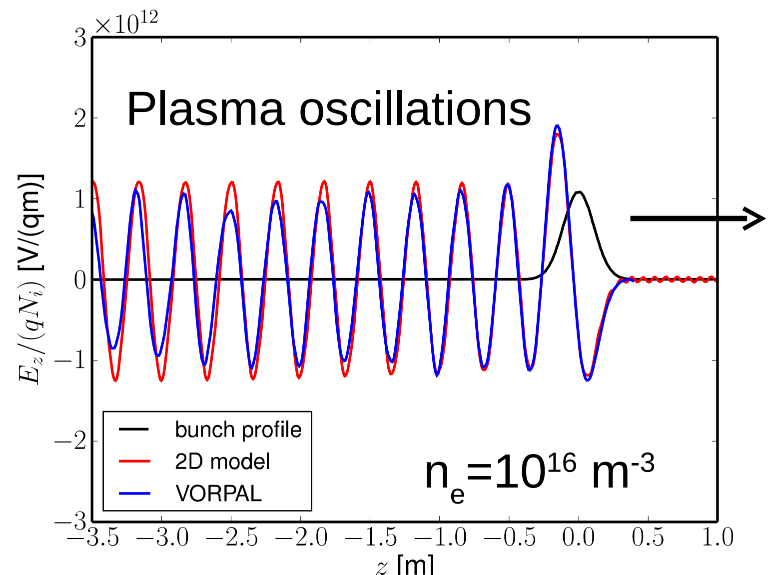
$$r'' + k^2(r,z) r = \frac{e\, E_{e,r}(r,z)}{m_e c^2}$$

Comparison of Longitudinal Wakes in 2D code and VORPAL

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

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





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

Energy Loss of Short Bunches

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

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

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

$$F_\perp=-e\,E_\perp^i(b,s)$$

The energy used to kick electrons comes to stopping power

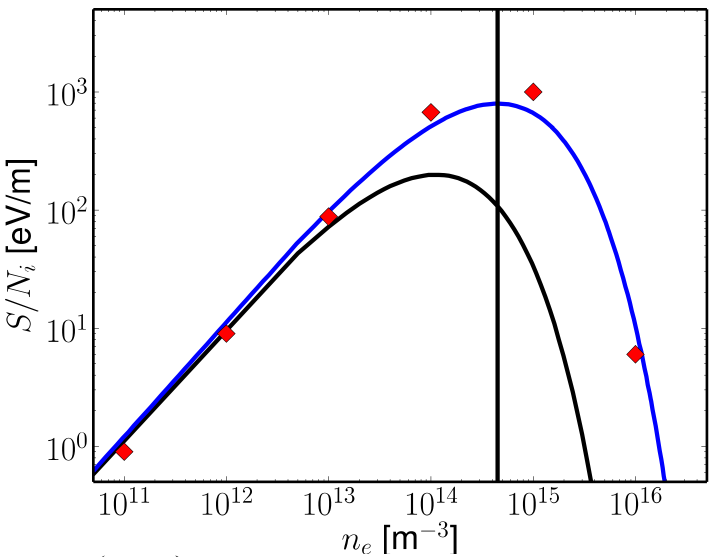
$$\frac{dW_e}{ds}=\frac{n_e}{2m_e}\int_0^{R_p}2\pi\,\Delta p_\perp^2(b)\,b\,db$$

Electron space charge:

$$\omega_{pe}=\sqrt{\frac{e^2 n_e}{m_e\epsilon_0}}\qquad \kappa_e=\omega_{pe}/c\qquad S\approx S_0\exp(-\kappa_e^2\sigma_z^2)$$

(Plasma frequency) (Debye length)

Stopping power for a short bunch



For KV-beam stopping power and phase shift

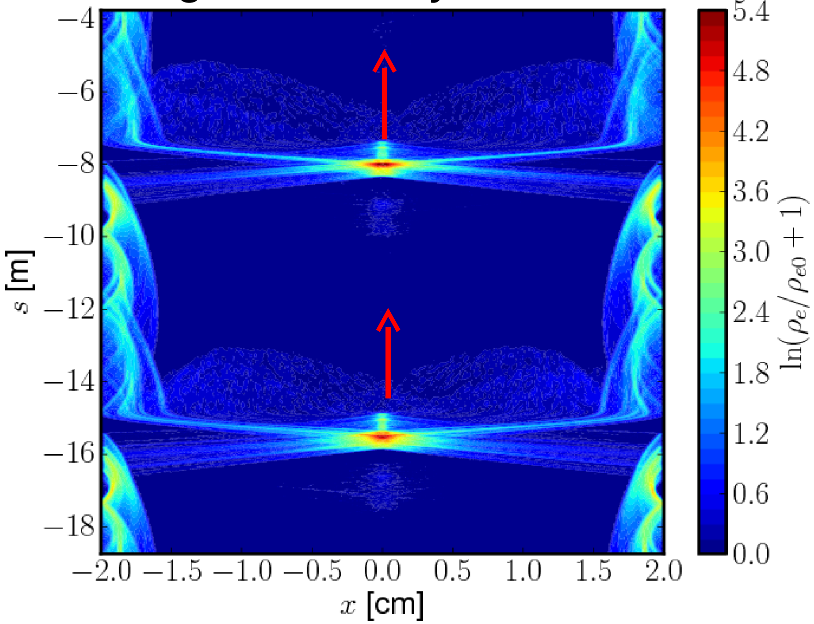
$$\frac{d\Delta\phi_s}{ds}\approx\frac{4\pi Q_i n_e r_e}{\epsilon_0 V_{rf}}\ln\left(\frac{R_p}{a}\right)\qquad S=\frac{dW_e}{ds}\approx\frac{4\pi}{\epsilon_0}Q_i^2 n_e r_e\ln\left(\frac{R_p}{a}\right)$$

Longitudinal Wakes with Multi-Bunch Effects

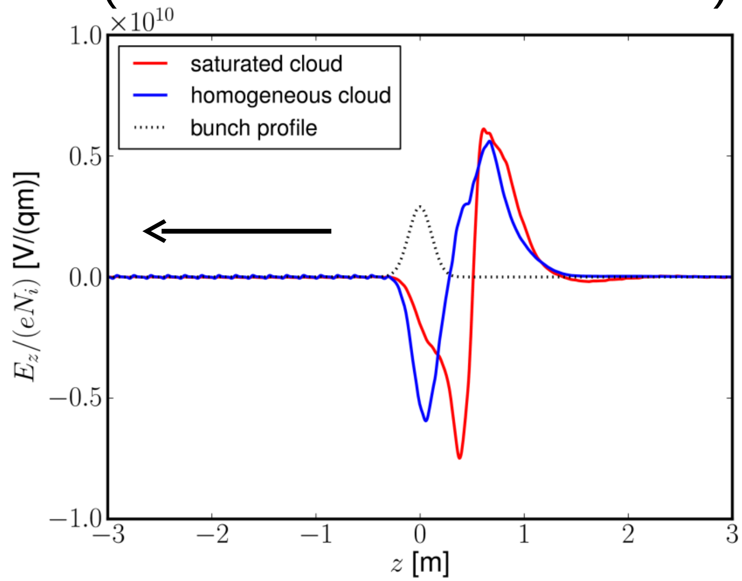
Saturated e-cloud density:

$$n_{es} \approx \frac{E_s}{m_e c^2 R^2 r_e} \approx 10^{13} m^{-3}$$

Ring like density distribution



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



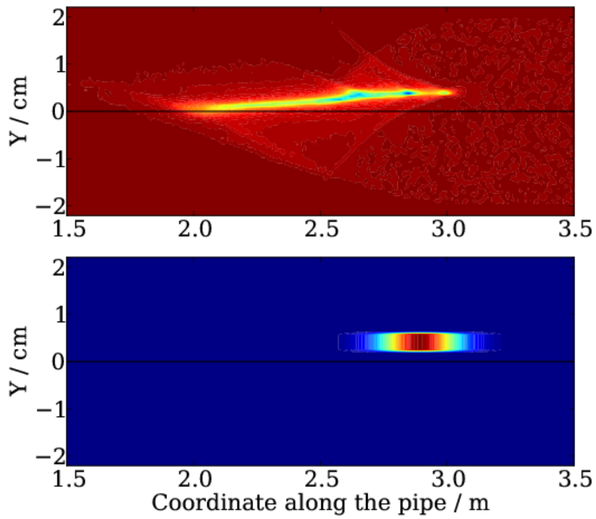
Realistic wake acts weaker on the bunch → weaker stopping power

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

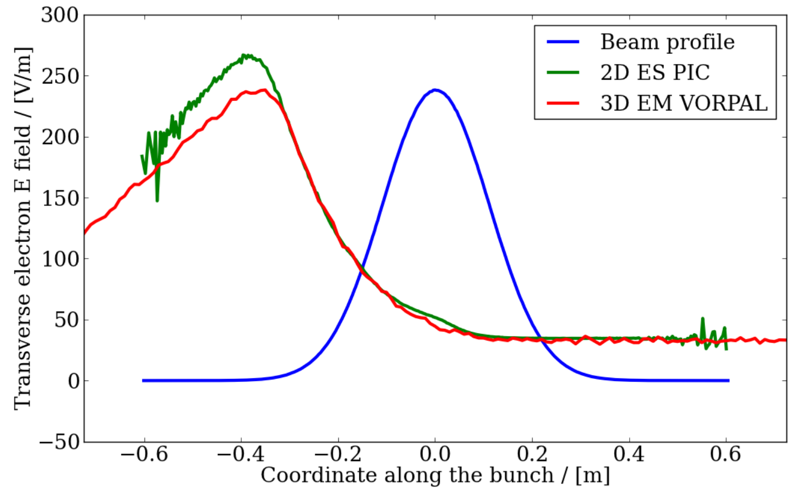
In comparison with longitudinal case transverse wakes are obtained using 2D solver directly in the code

Δr=0.004 mm

Pinching of the cloud around the bunch with and offset



Transverse wake fields obtained with 2D PIC and VORPAL



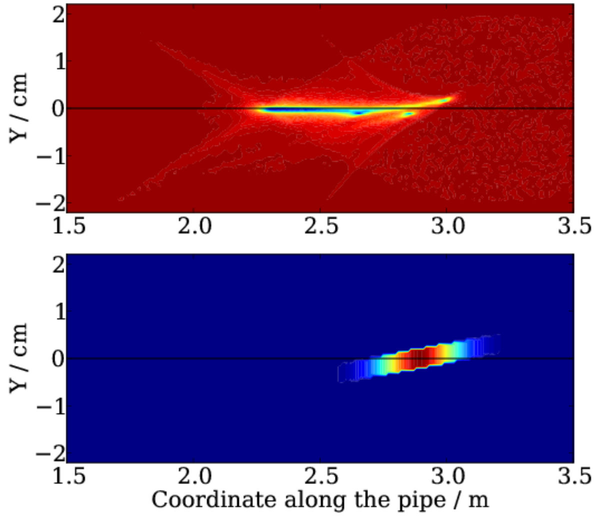
The only disagreement is seen at the end of the bunch.
However, the fraction of beam particles affected is very small.

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

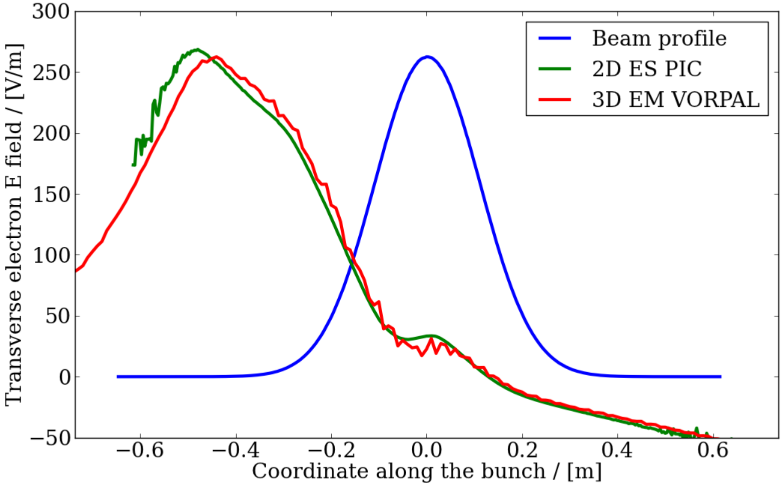
In this simulation bunch is traveling along the pipe with an angle between the pipe and the bunch axis

$$\tan(\varphi)=0.01$$

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

- Analytical theory to connect rf phase shift and electron cloud density was proposed.
- It was shown that talking into account realistic cloud shape reduces significantly the stopping power if the electron number is preserved.
- It was shown that electron cloud wake field obtained in 2D electrostatic simulations and 3D electromagnetic VORPAL simulations agree very well
- 2D Poisson solver can still be used for short relativistic bunches

Future work: - fast e-cloud solver on GPUs
- Parametrization of the wake fields

Thank you for your attention!

Thank you for your attention.
Questions?