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Nonlinear Features of the Longitudinal Instability

Workshop on Instabilities

Long Island, June 28 - July 1, 1999

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Outline

- Linear Regime (Observation / Simulation, Limits)
- Nonlinear Saturation and Overshoot
- Self-Stabilizing Tails

co-workers: O. Boine-Frankenheim, G. Rumolo

"History" of Longitudinal Instability

- **Longitudinal instability of coasting beams or long bunches** driven by resistive impedance is of major concern in high intensity machines

  Linear theory in 60's: *L.J. Laslett, V.K. Neil and A.M. Sessler, 1961*

  A.G. Ruggiero and V.C. Vaccaro, 1968 etc.

  Keil-Schnell circle criterion
- Numerous observations in many machines on appearance and saturation predominantly for negligible or weak space charge effects; theoretical + simulation models (overshoot etc.)
- Specific interest in connection with Heavy Ion Inertial Fusion drivers far outside Keil-Schnell circle (space charge impedance of kOhm)
  - Simulation claiming "self-stabilizing tails" (I.H., 1985)
  - Recently observation in space charge dominated regime:
    - time domain in linear e-resistive channel at Maryland (*J.G. Wang et al., PRL 1997*) generating separately localized slow and fast waves and observing linear growth
    - in frequency and time domain in ESR+SIS / GSI with initially single modes driven by passive RF cavity (*G. Rumolo et al., NIM 1998, EPAC98, O. Boine-Frankenheim et al., PRL 1999*) with observations and simulation in nonlinear regime

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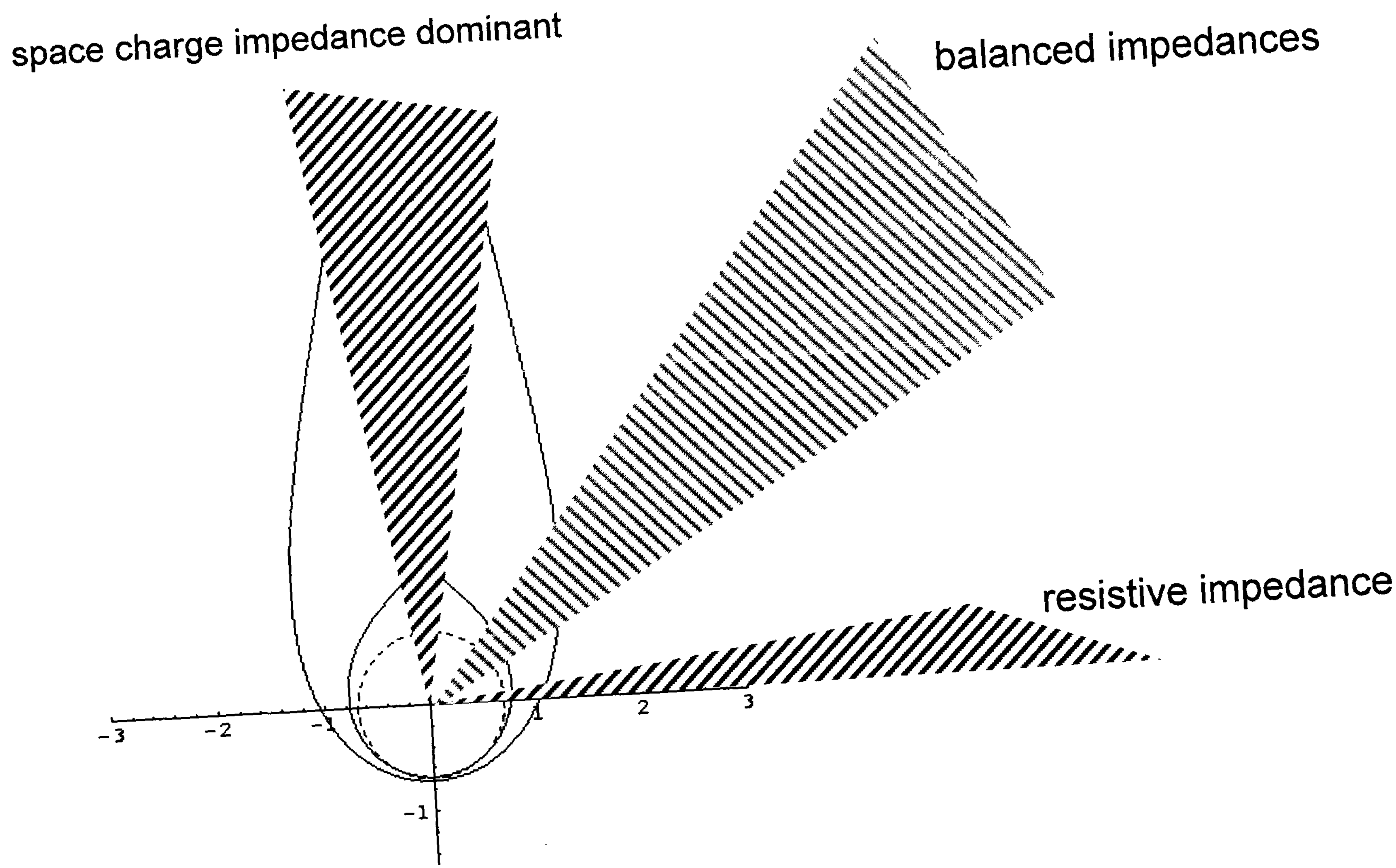
Questions of interest

- is the linear theory confirmed by experiments?
- is linear stability necessary?
- what is the influence of the impedance distribution (over n) on nonlinear behaviour?
  - narrow-band vs. broad-band
  - space charge impedance significant factor

Discussion of regimes in stability diagram (impedance plane)



Experimental Storage Ring for heavy ions at GSI

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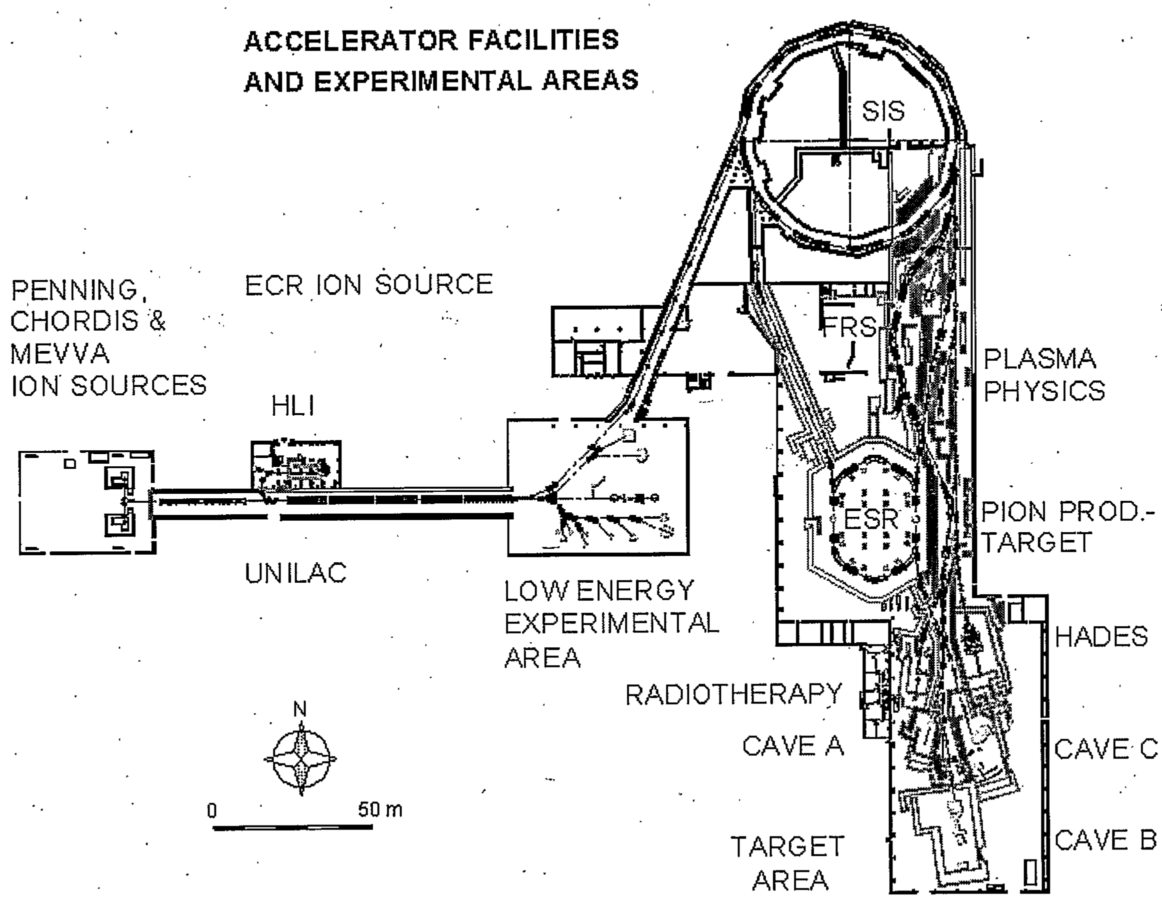

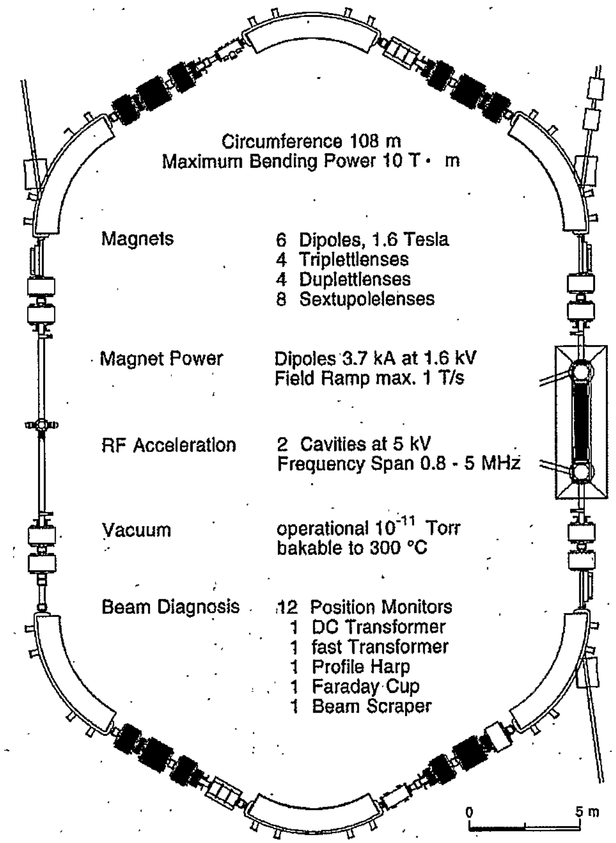

ESR experiments with e-cooled C^{6+} beam at 340 MeV/u

- key to new understanding of space charge regime

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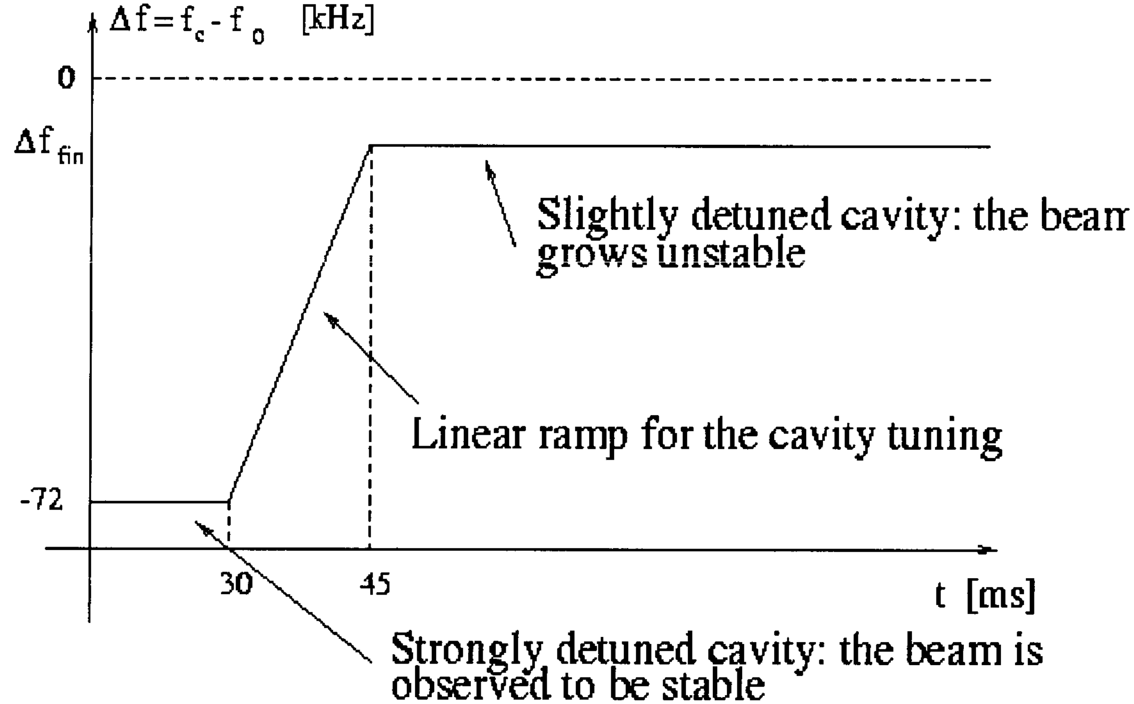
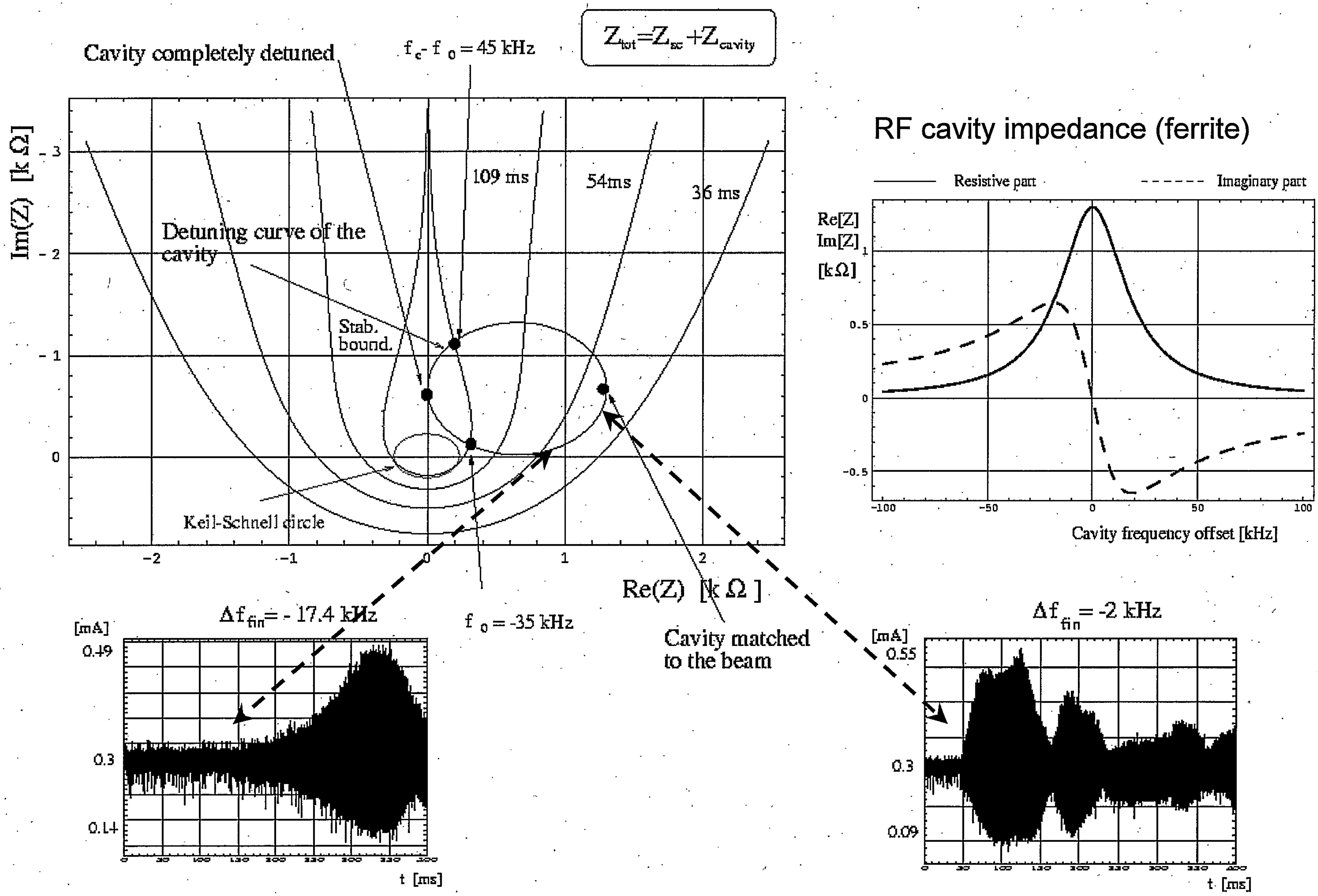
- prior to the onset of instability the beam adopts a very clean Gaussian momentum distribution due to e-cooling
- RF cavity (h=1) destabilizes beam (ecool on or off)
- current signal stored on LeCroy digital analyzer



RF cavity detuning effect on working point



Comparison of observation and simulation

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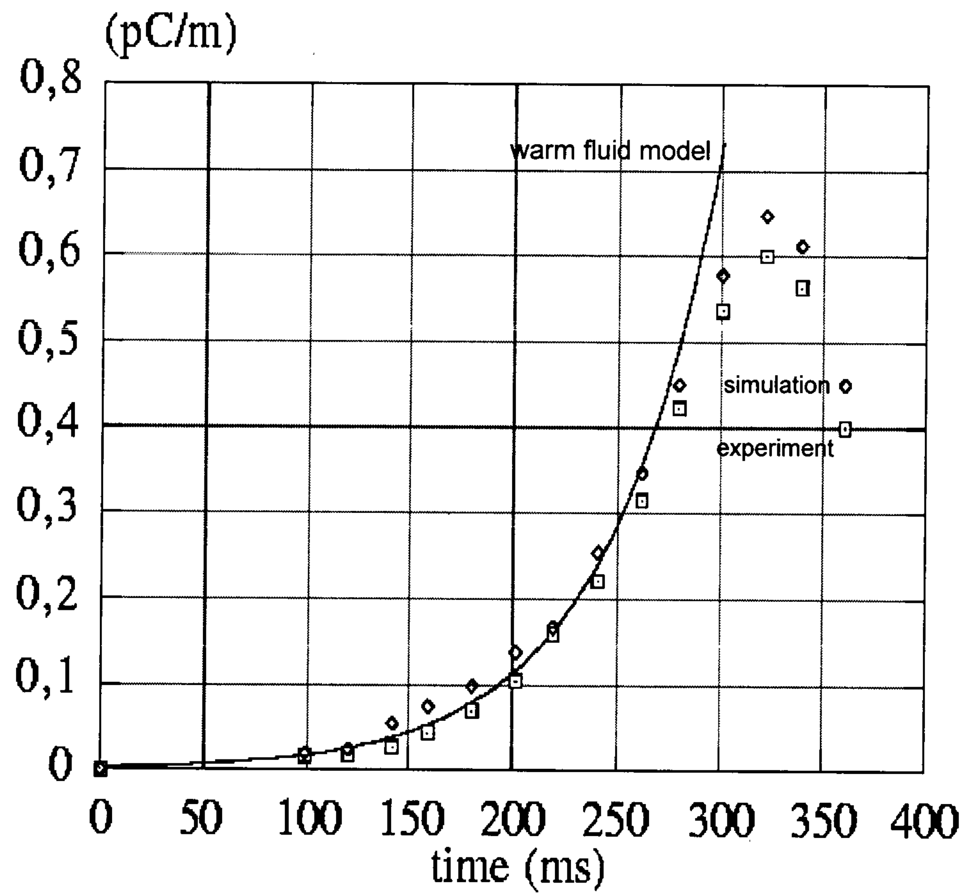
- in **linear** phase
  - experiment in ESR with electron cooled initially smooth beam (linear phase!) with residual voltage on RF cavity gap
  - growth rate reduced by inductive impedance ~ $ReZ/(ImZ)^{1/2}$ - in agreement with simulation and analytical theory except for effect of residual voltage
- in **nonlinear** phase new phenomena arise, and we have compared experiment with Vlasov code (generally in agreement with PIC code)

-17.4 kHz detuning: RF voltage is negligible



Comparison of initial growth times

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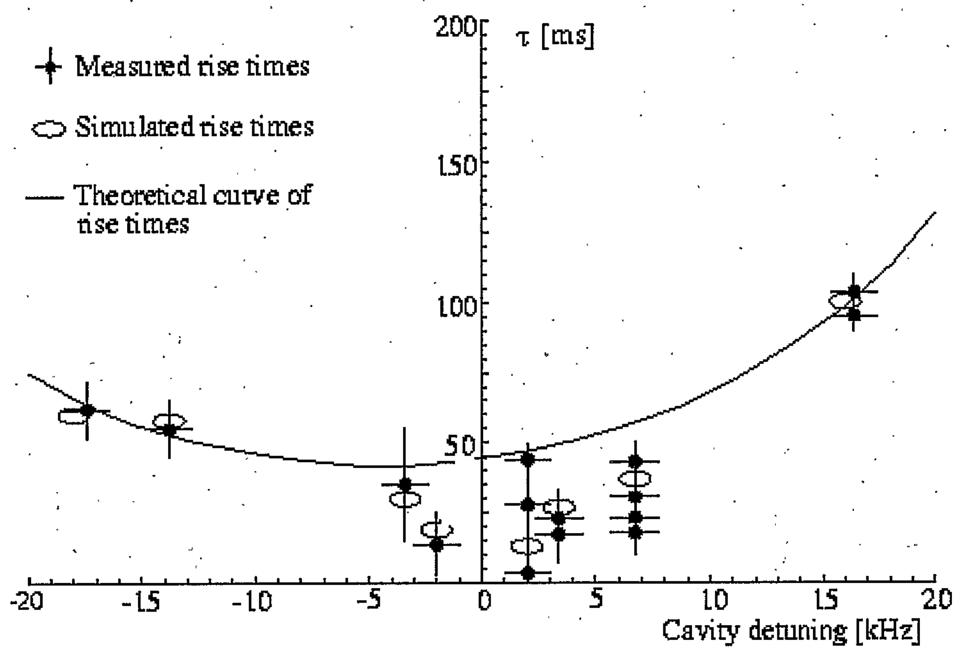
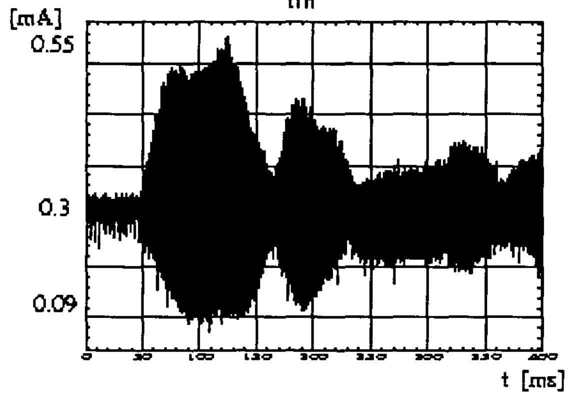
The RF voltage of 300 V strongly modulates the beam for small detuning

- growth is faster than predicted by linear theory (experiment and simulation)

- growth not exponential (linear?)

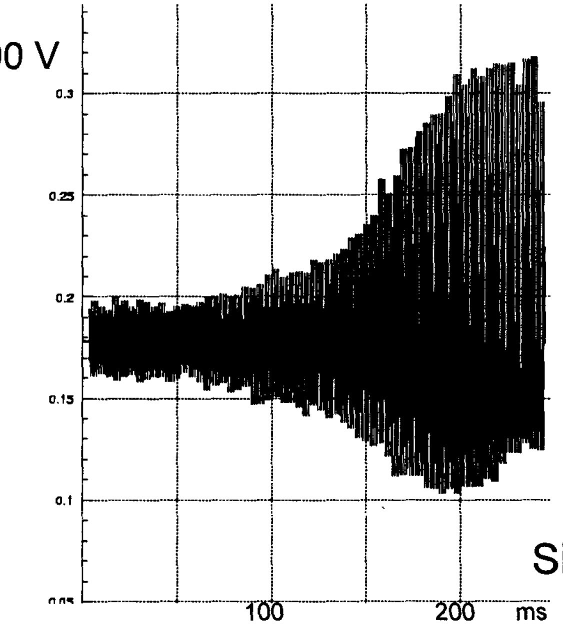


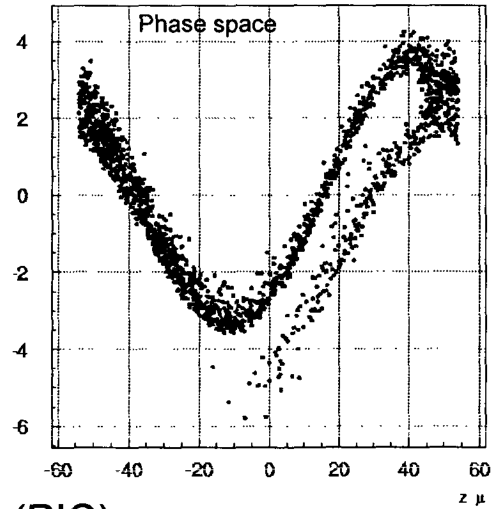
Influence of RF Modulation



Experiment

With 300 V

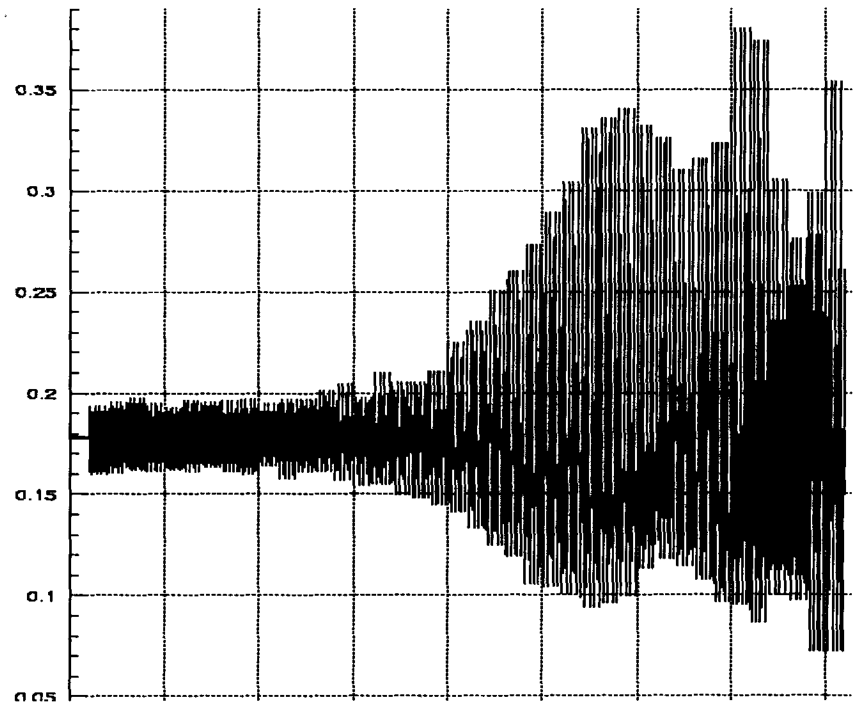




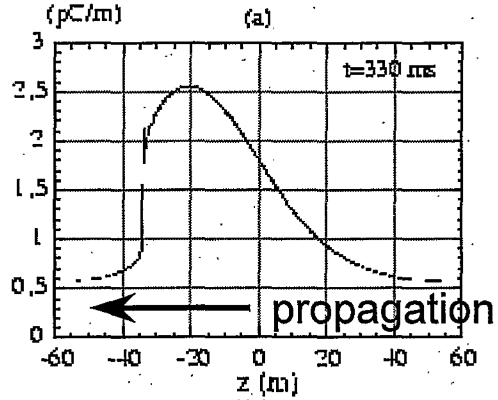
Simulation (PIC)

t=212.0ms

no RF

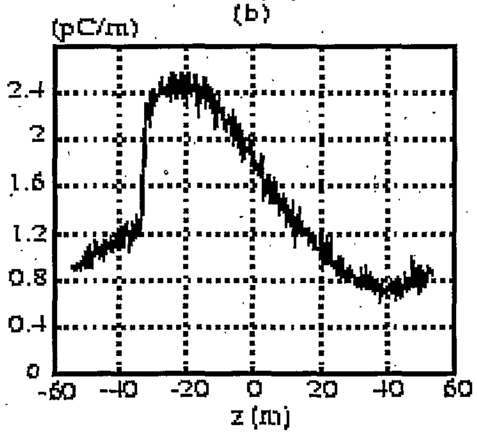


Wave steepening described well by PIC and cold/warm fluid model

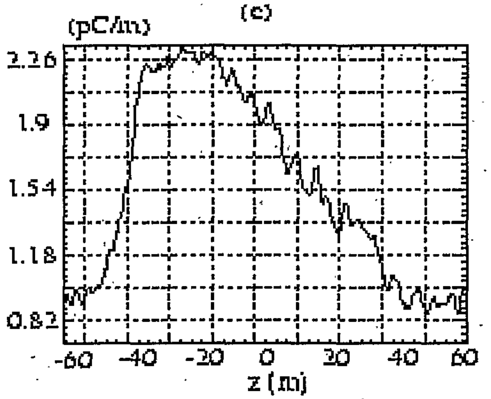


fluid model

- cannot explain maximum that self-bunching reaches saturation



ESR experiment



PIC simulation

Direct Vlasov solvers are advantageous for long-time studies

- experiment: no measurements on momentum distribution during evolution of instability - require simulation
- Vlasov Solver: partial differential equation for distribution function $f(z,p_z,t)$ integrated on a grid :
  - 1D for longitudinal dynamics
    uses 3D Poisson solver with transverse rms envelope equations
  - smooth distribution functions (on grid)
  - nearly no granularity
  - **resolve fine structures** in phase space
- have gained better insight into evolution than with PIC (in good agreement)

Mountain range diagrams have shown absence of real saturation (Landau damping) - memory effect

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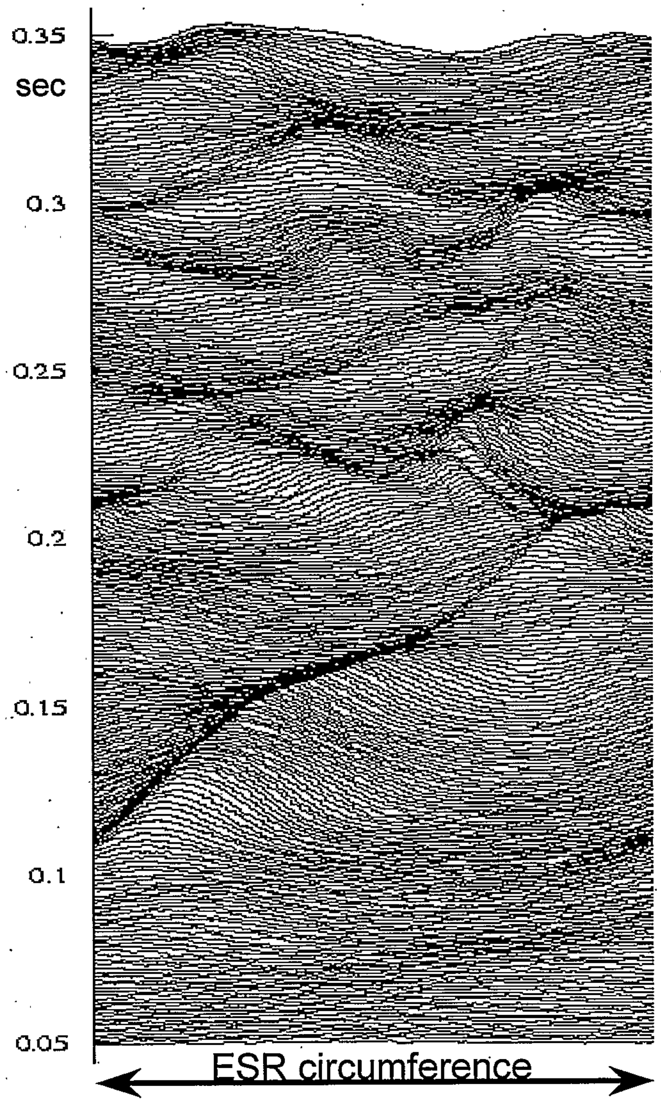
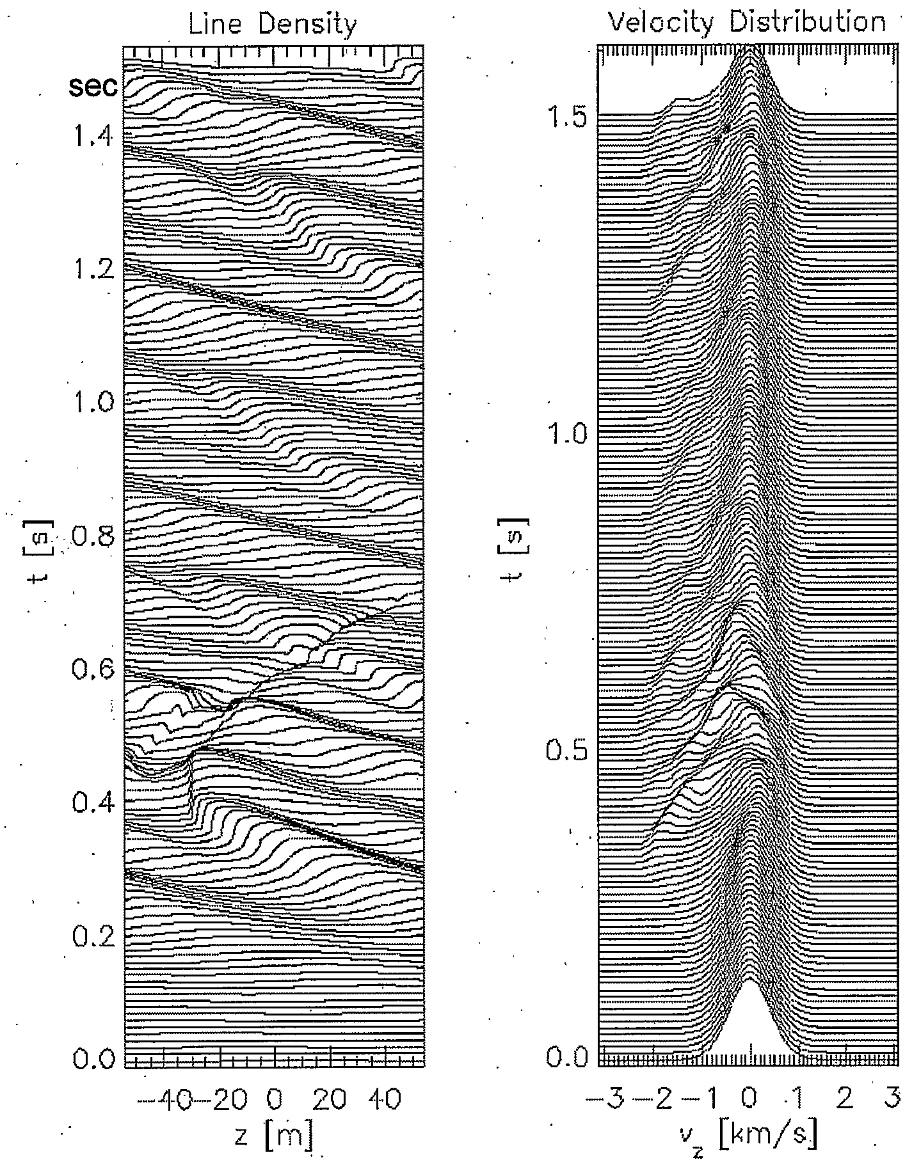
Experiment



Vlasov Simulation



Holes are continuously trapped in phase space

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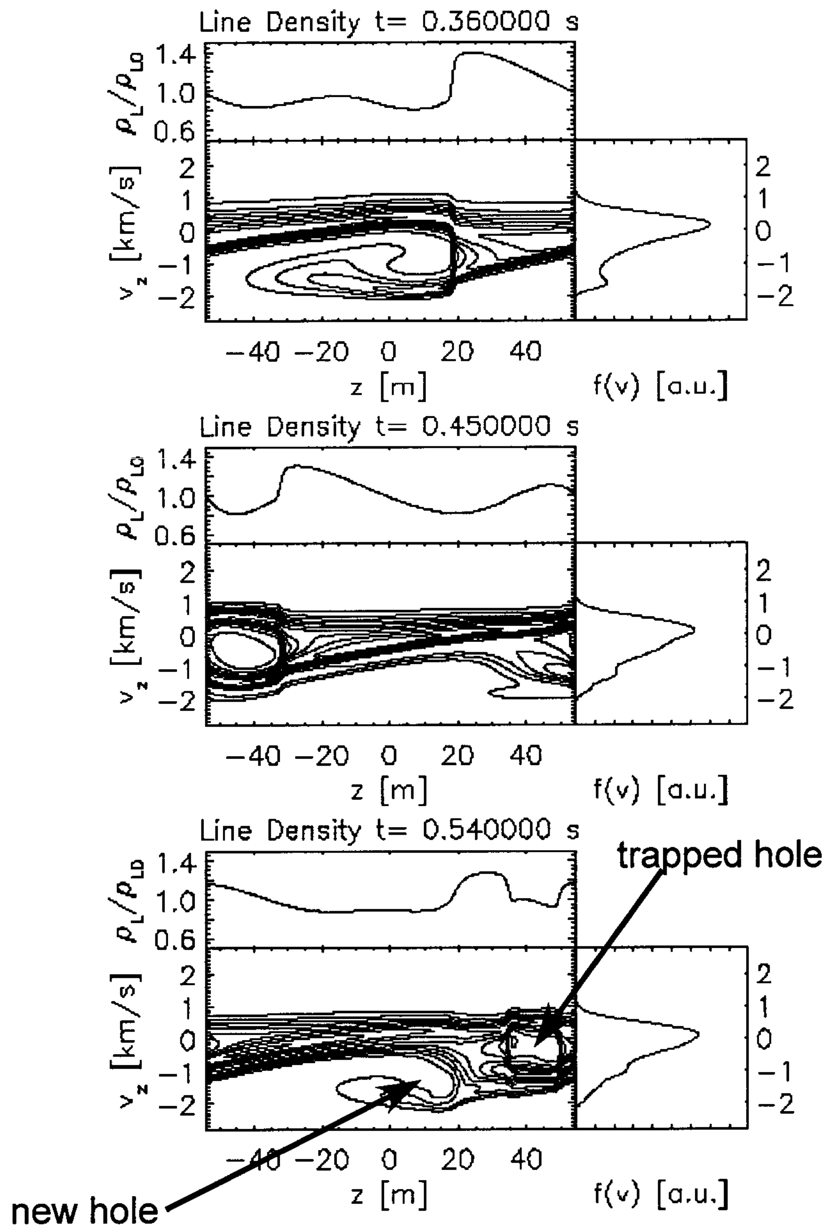
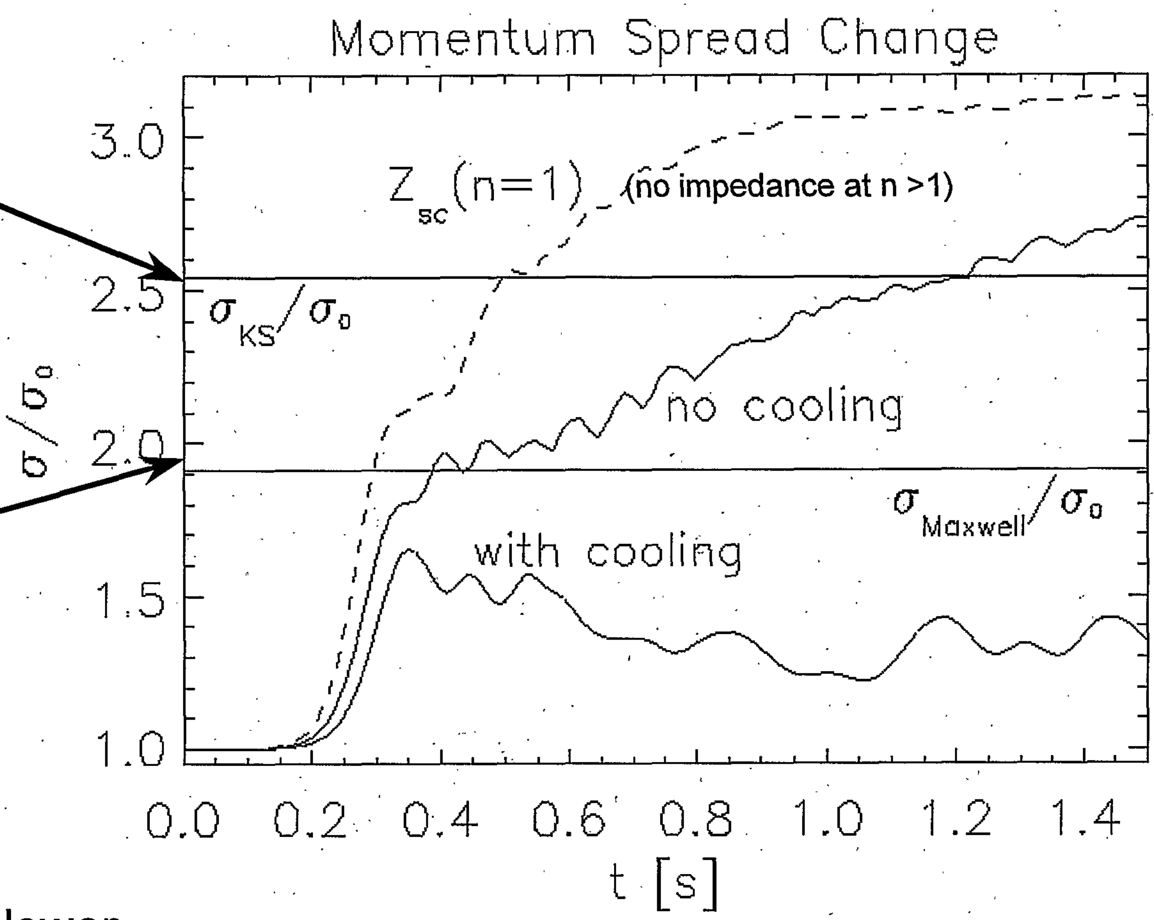
- wave is generated at lower momentum edge
- the fast instability leads to hole structures traveling in the direction of larger momentum (self-buckets)
- result is a momentum broadening and slight deceleration of beam (energy source=longitudinal motion)
- broad band impedance nature of space charge modifies results



Overshoot and long-time behaviour

circle criterion threshold

Gaussian distribution function threshold



Due to ReZ>ImZ Gaussian threshold (in $\Delta p/p$) only 20% lower

Purely resistive impedance: broadening effect

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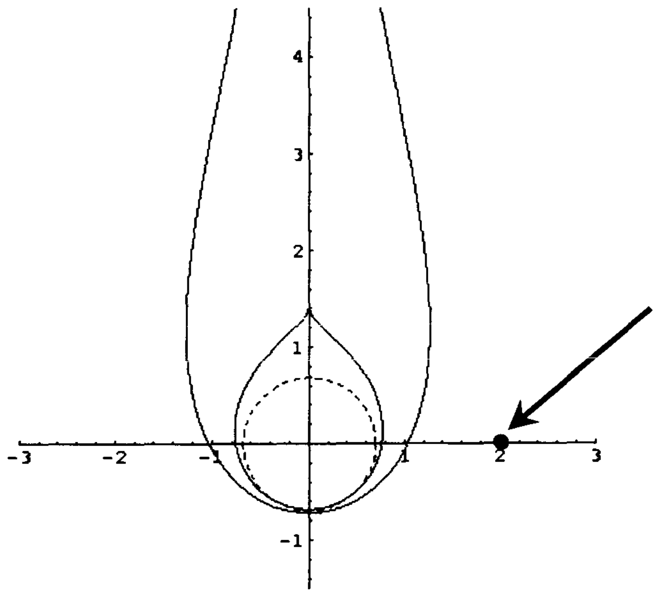

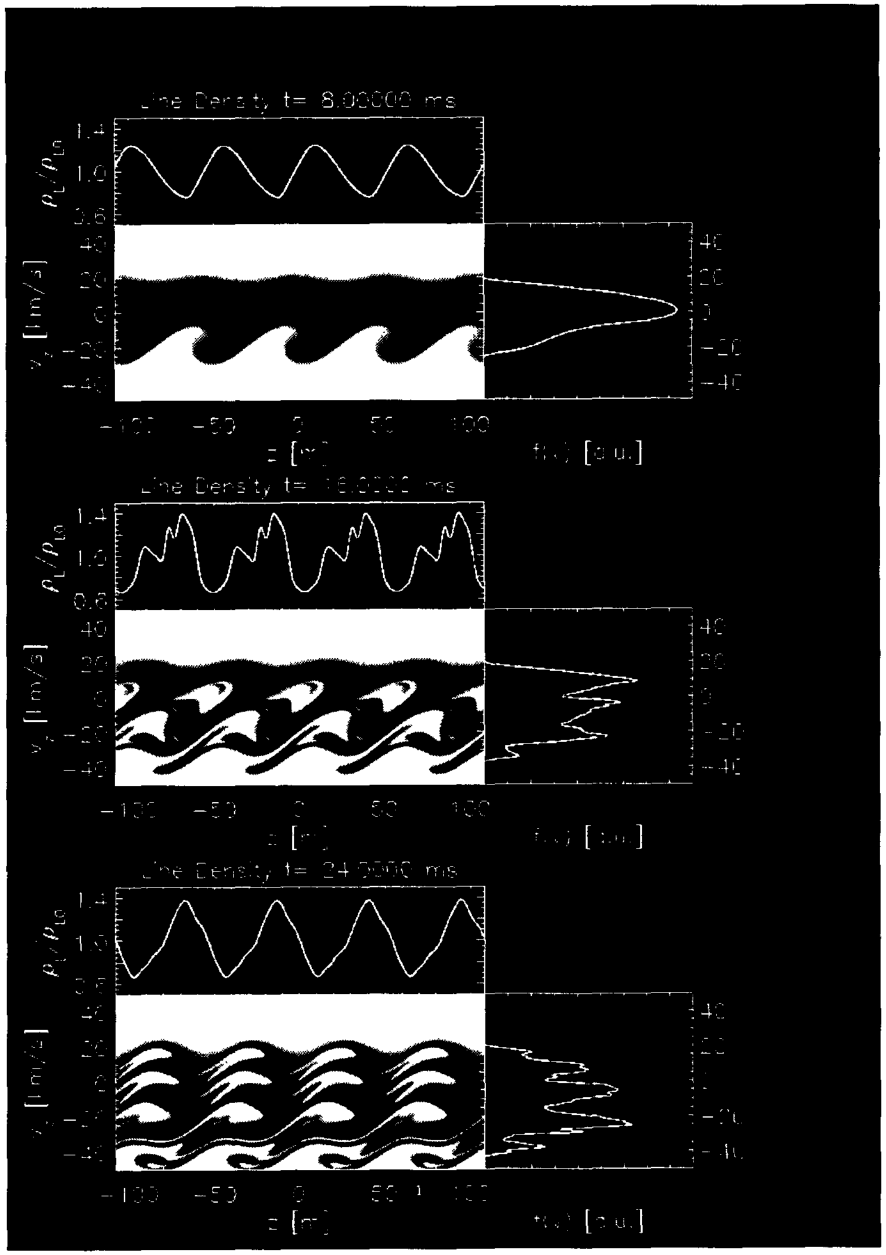

- typical behaviour at high energy
- layers of self-trapped buckets generated at lower edge of momentum space with strong progressive filamentation
- results in broadening (to lower momenta)

ImZ>>ReZ on one harmonic (n=12) only

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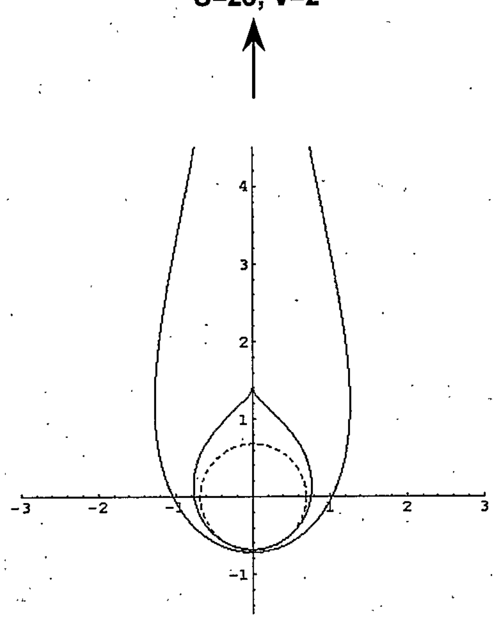

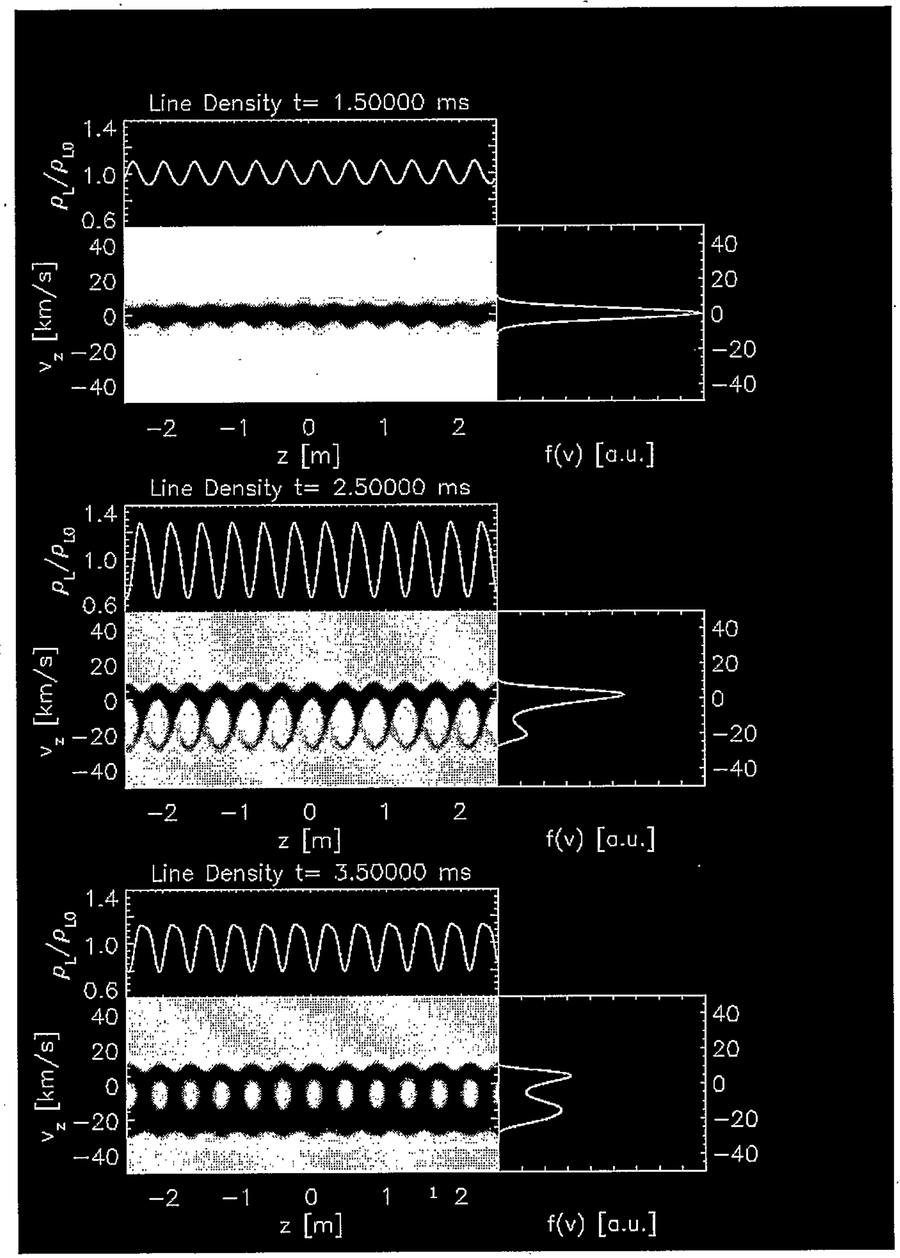

isolated impedance on imaginary axis degrades beam quality by single harmonic instability

Self-stabilization by tail with dominant space charge impedance

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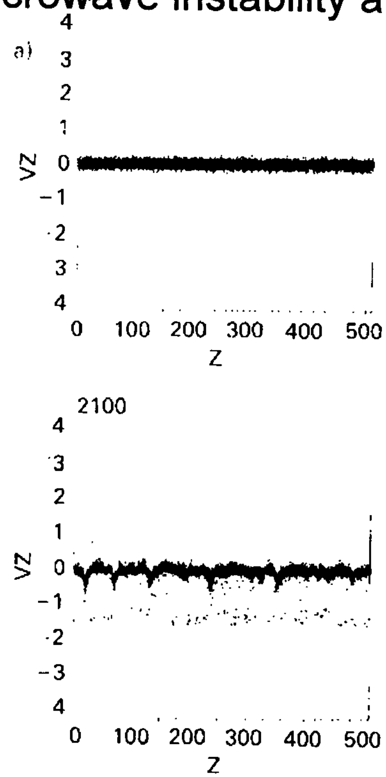
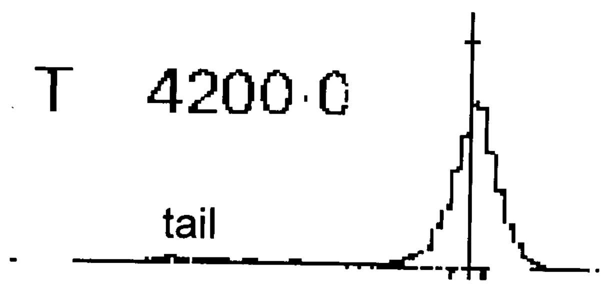
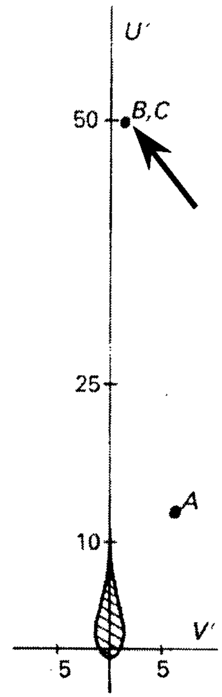
- assume ReZ<<ImZ and very dense, initially unstable beam:

  in 1985 we claimed self-stabilization occurs with tail to smaller momenta(I.H., "Suppression of Microwave Instabilities", Laser and Particle Beams, 1985)
- broad-band nature of space charge impedance is crucial to obtain this stabilization by coupling to higher order modes (cutoff, where Z/n drops to zero)
- also applies to microwave instability at high n







Vlasov simulation of self-stabilization

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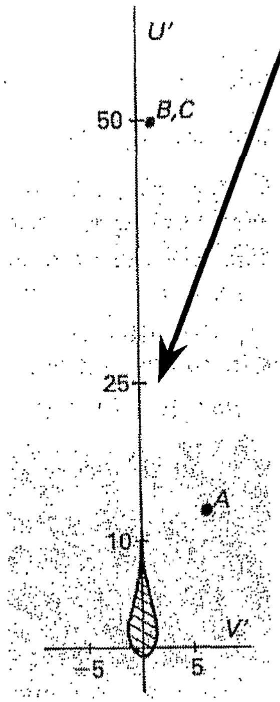
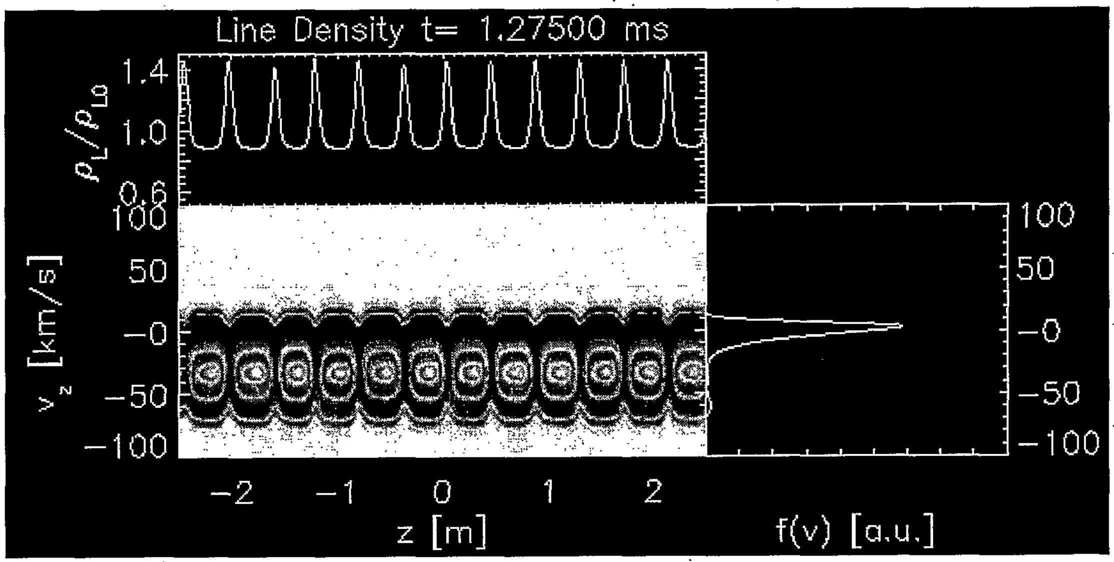
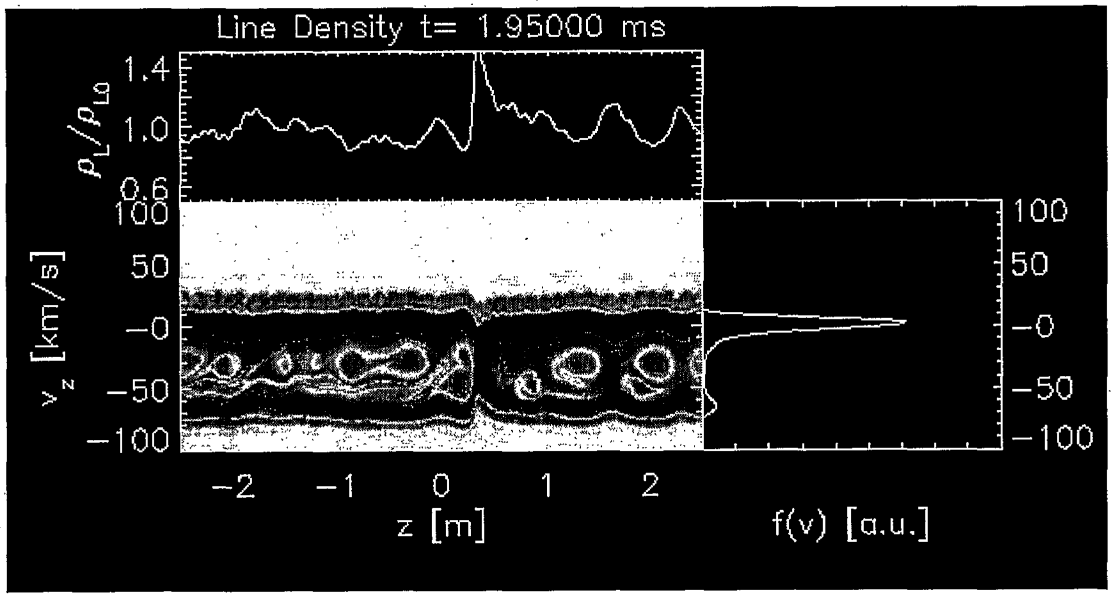
confirmed by recent Vlasov simulation







Influence of Impedance Distribution

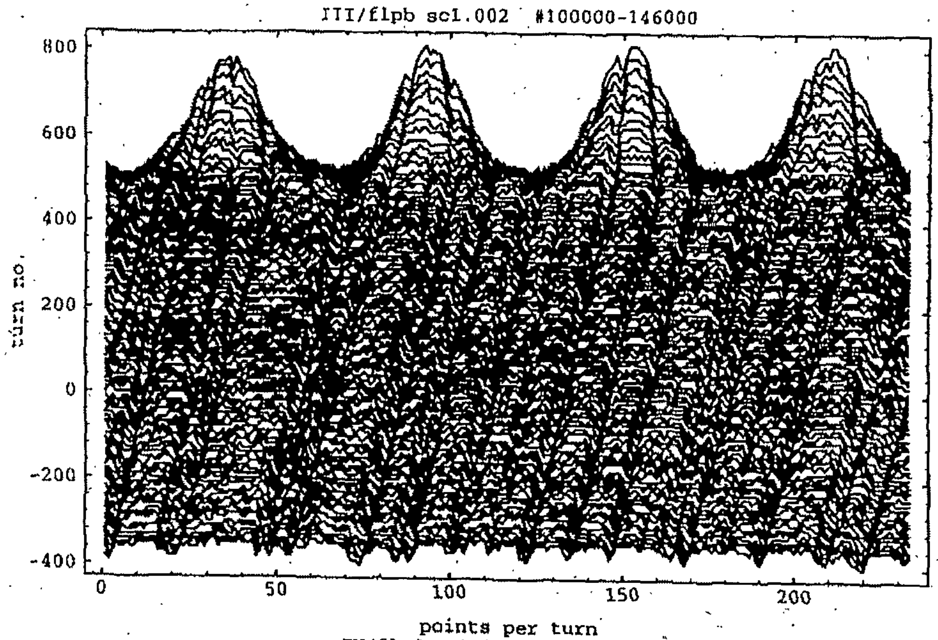
- for initial linear behaviour single harmonic relevant
- for nonlinear behaviour distribution of impedances essential (coupling between modes)
- stabilizing tails require broad-band nature and gentle drop of space charge impedance near cut-off frequency
- assume broadband machine impedance has similar effect

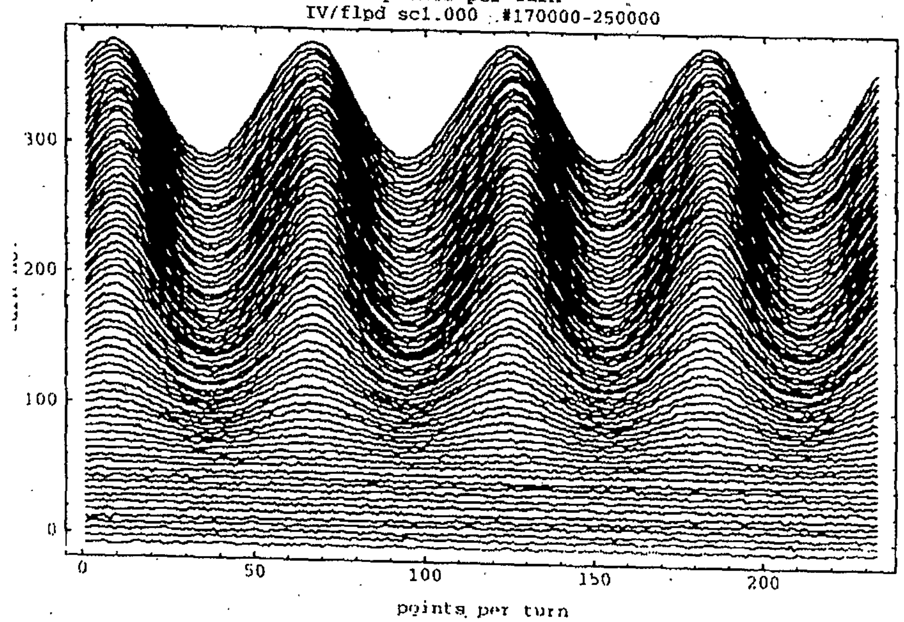
SIS measurement after injection

early after injection of
1.5 10^{10} ions of Ne^{10+} at 11 MeV/u

assume beam was near stability boundary of Gaussian

allowed 200 ms injection flat-top
-> smoothing by IBS or Landau damping





Near stability boundary

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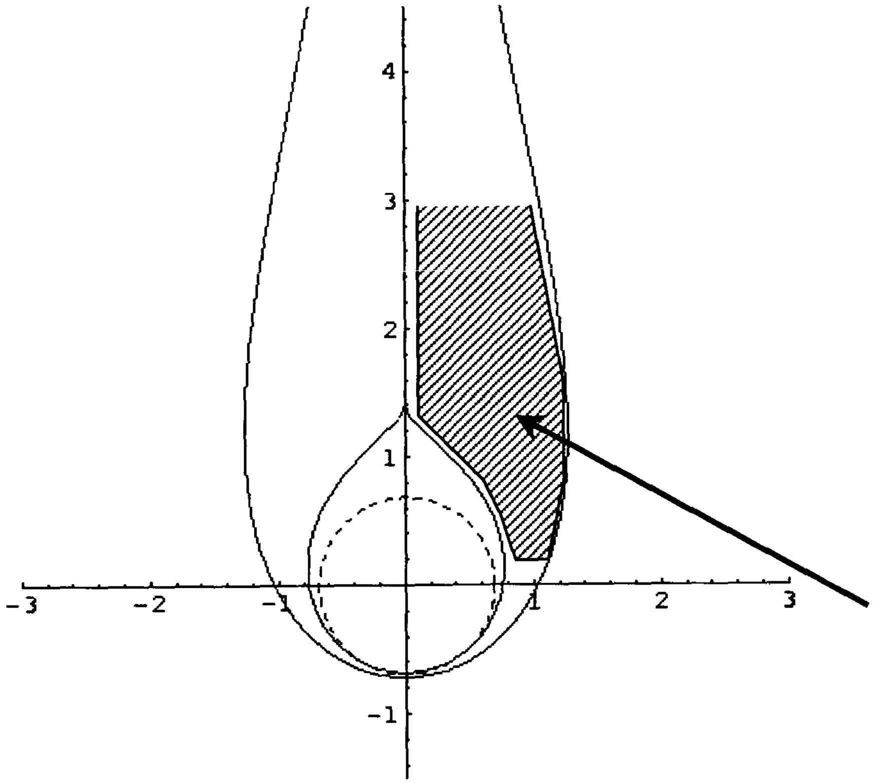

quadratic unstable,
but Gaussian stable

Simulation of marginally unstable distributions

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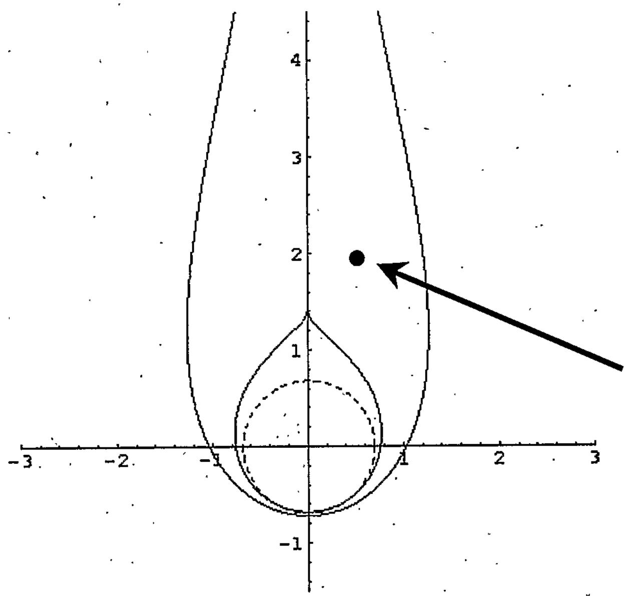
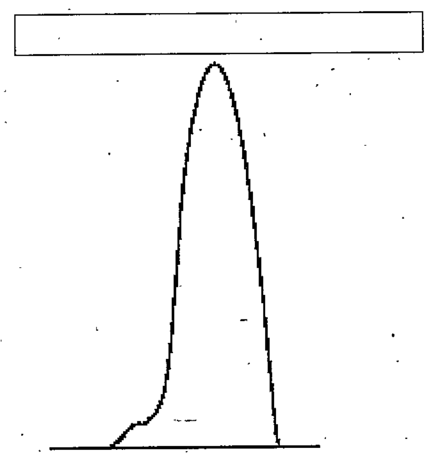
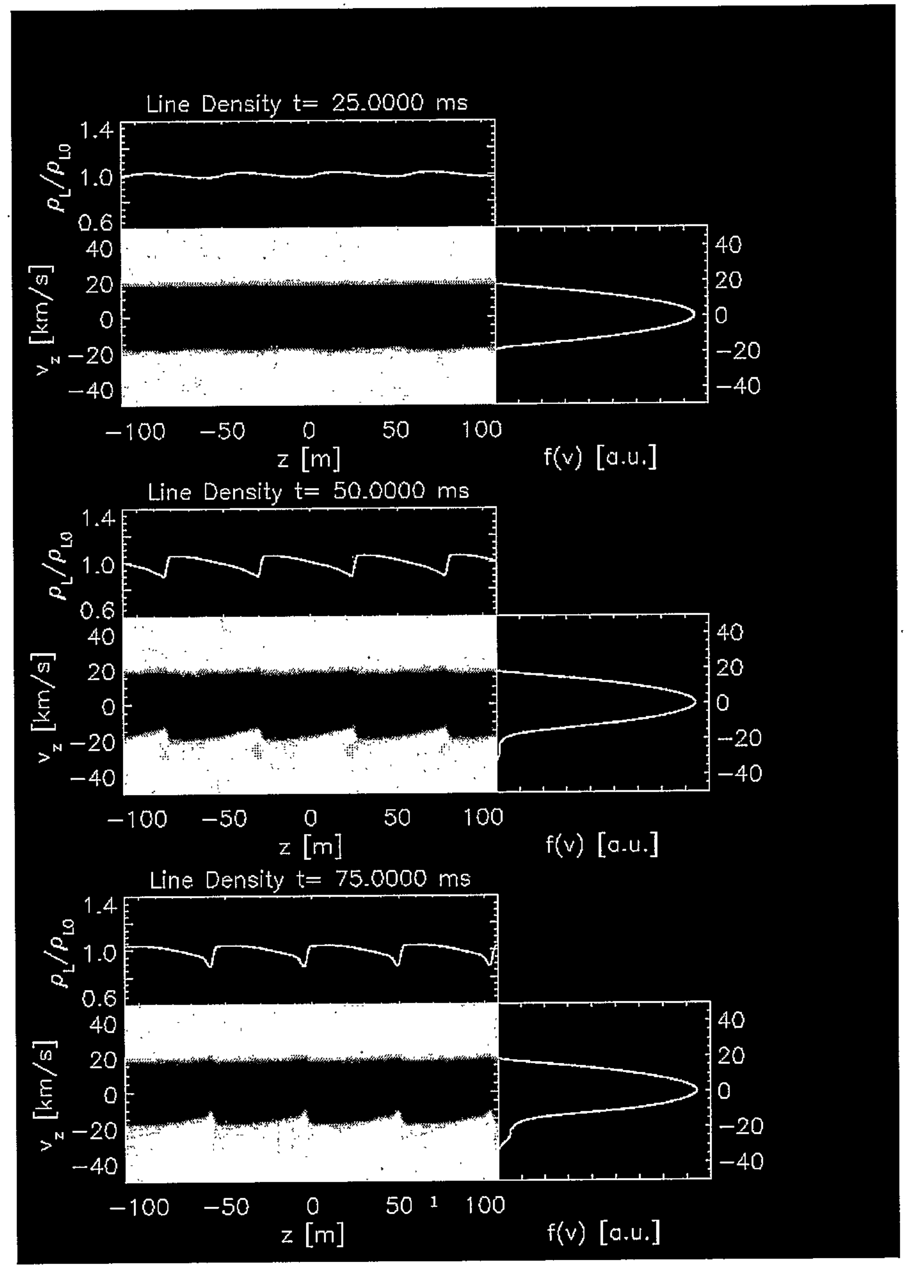
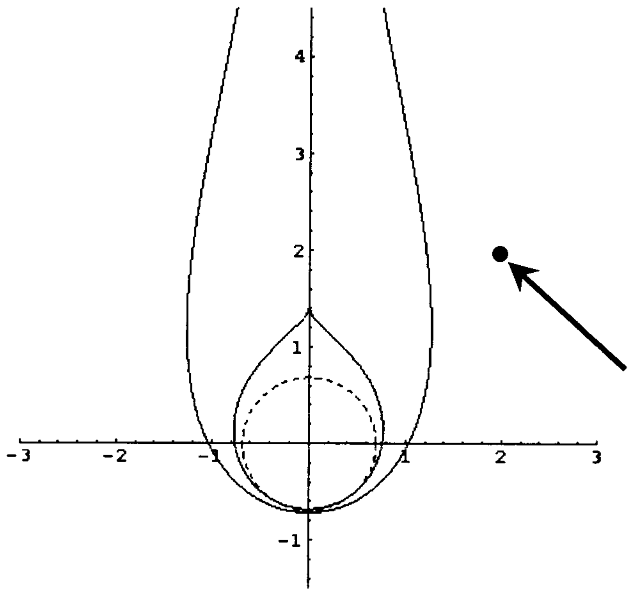


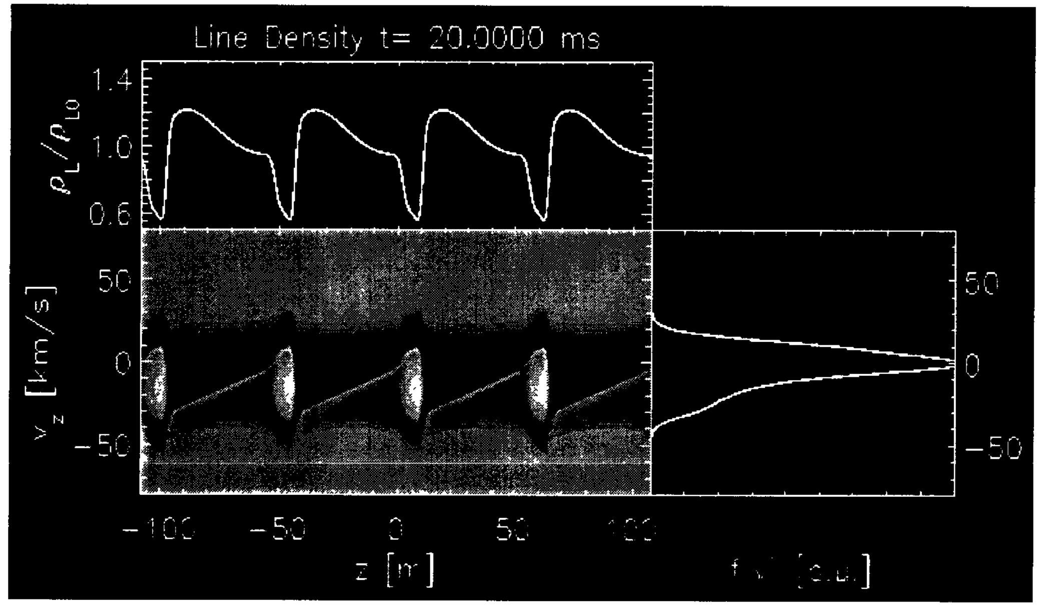
- initially parabolic (unstable)
- stabilizing tail also valid here



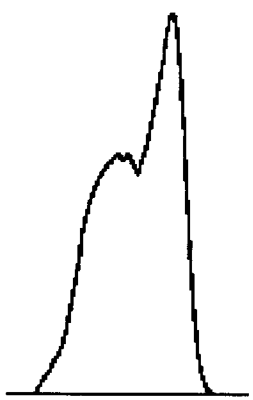


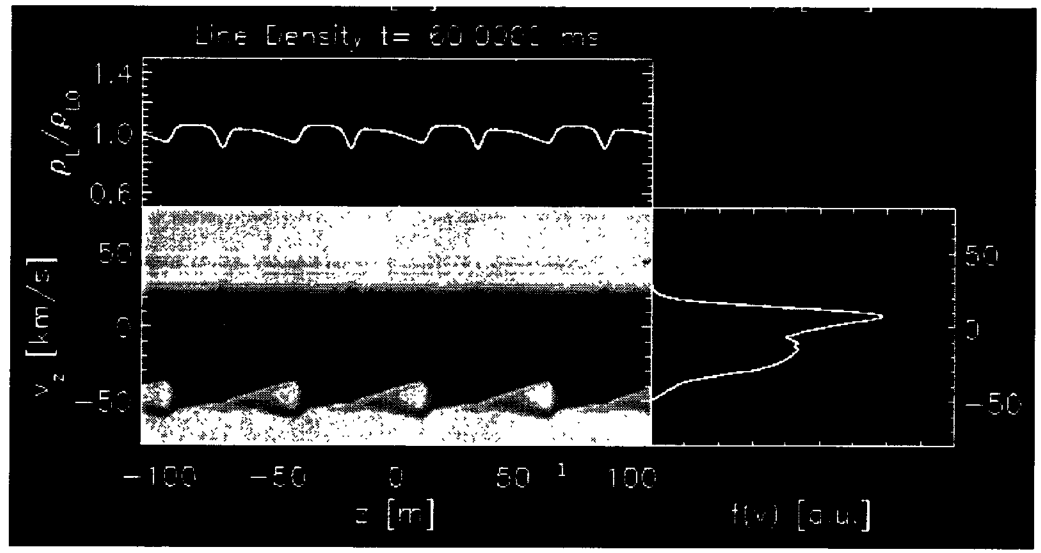
Balanced impedance (ReZ~ImZ)





similar to ESR experiment: layers of holes traveling through momentum space





Nonlinear phase strongly modified by space charge

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in **nonlinear** phase some new features appear:

- nonlinear steepening (faster phase velocity for short waves)
- generation of lower (Fermilab work) and higher harmonics
- overshoot modified by space charge: distribution function not simply broadened
  - only for mainly resistive impedance (or negative mass):

    $$(dp/p)^2_{final} \sim (dp/p)_{initial}(dp/p)_{threshold}$$

  - for balanced impedances $(dp/p)^2_{final}$ can be smaller but slowly growing
  - for dominant space charge impedance: $(dp/p)_{final} \sim (dp/p)_{initial}$ (fwhm) but tails developing towards lower momenta;
- often no thermalization of fluctuations by Landau damping
- close to stability boundary we find notches in line current affecting BTF and Schottky diagnostics - in SIS they dissapear after ~ 200 ms.

Conclusions

- Presently reached good agreement experiment-simulation
  - limited comparison since detailed momentum space information only from simulation
- in nonlinear regime complex behaviour:
  - operation in unstable regime possible for $\mathrm{Re}Z \ll \mathrm{Im}Z$
  - credible long-time simulation not trivial (smoothing by IBS?)
- diagnostics: density fluctuations due to initially unstable behaviour may persist and influence Schottky noise measurements
- more systematic measurements planned