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Coulomb Effects in High Intensity Drivers

Workshop on the Future of High Energy Physics

Snowmass, July 5, 2001

I. Hofmann

GSI Darmstadt

Outline

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- Space Charge & Longitudinal Phase Space
  - Stabilizing effects
  - Measurement issues
  - Compression
- Transverse Space Charge Effects
  - Quadrupolar measurements
  - Space charge resonance
  - Mismatch & Loss

co-workers: R. Bär, O. Boine-Frankenheim, G. Franchetti, G. Rumolo

Experimental Storage Ring for heavy ions at GSI

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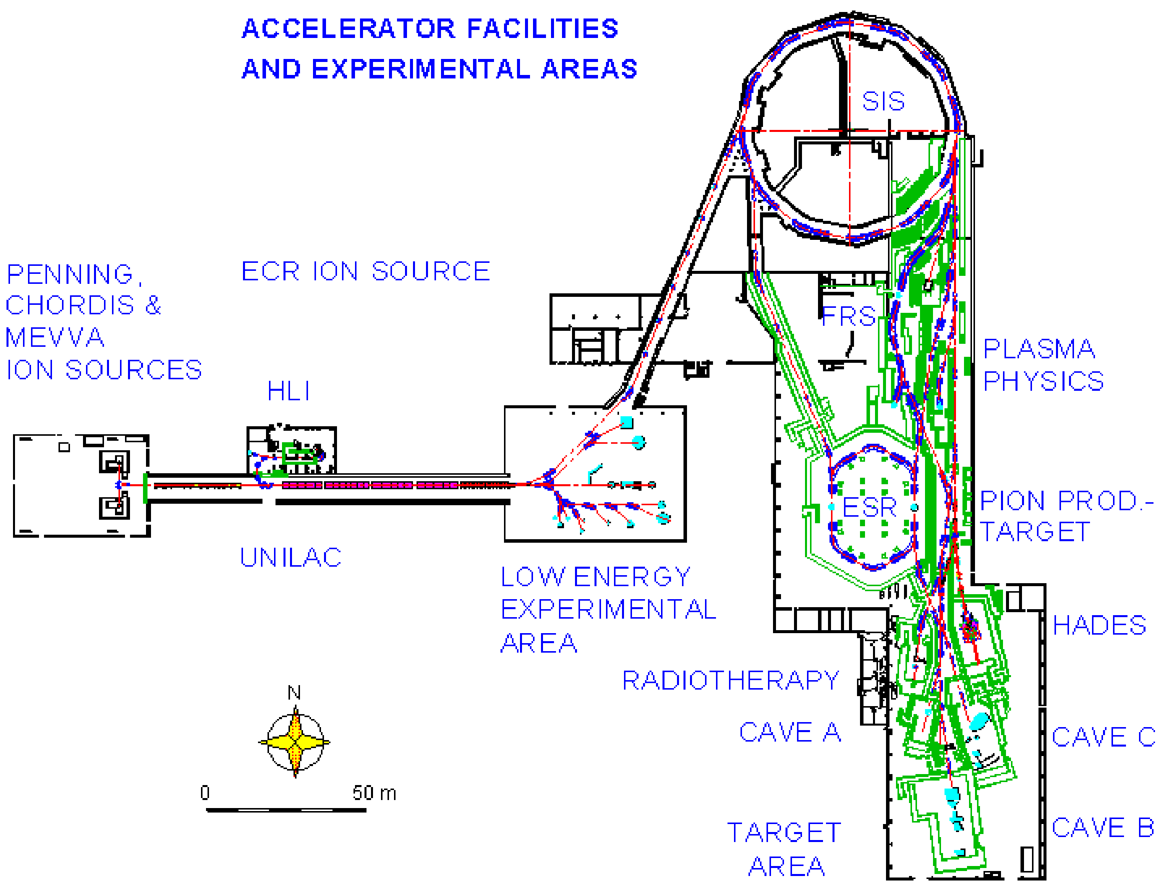
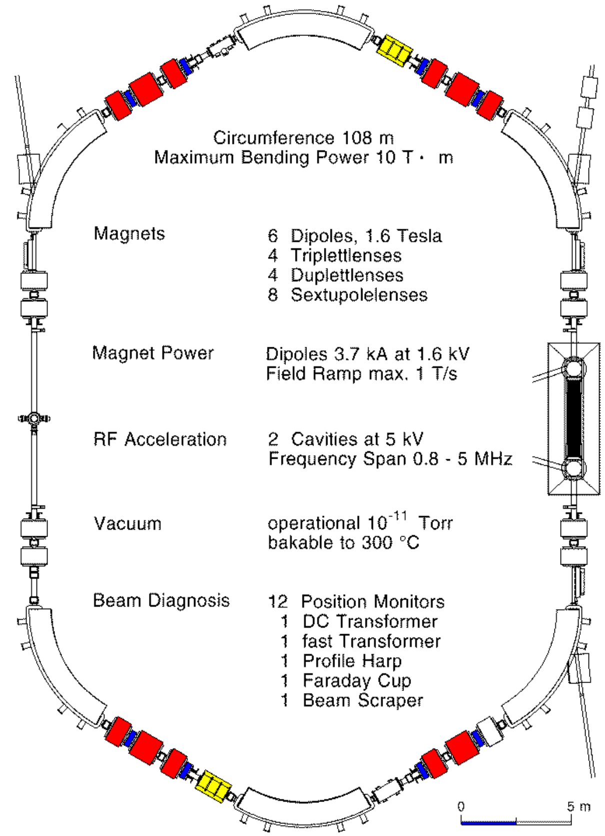




“History” of Longitudinal Instability

Longitudinal (resistive or microwave) instability of coasting beams or long bunches

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.

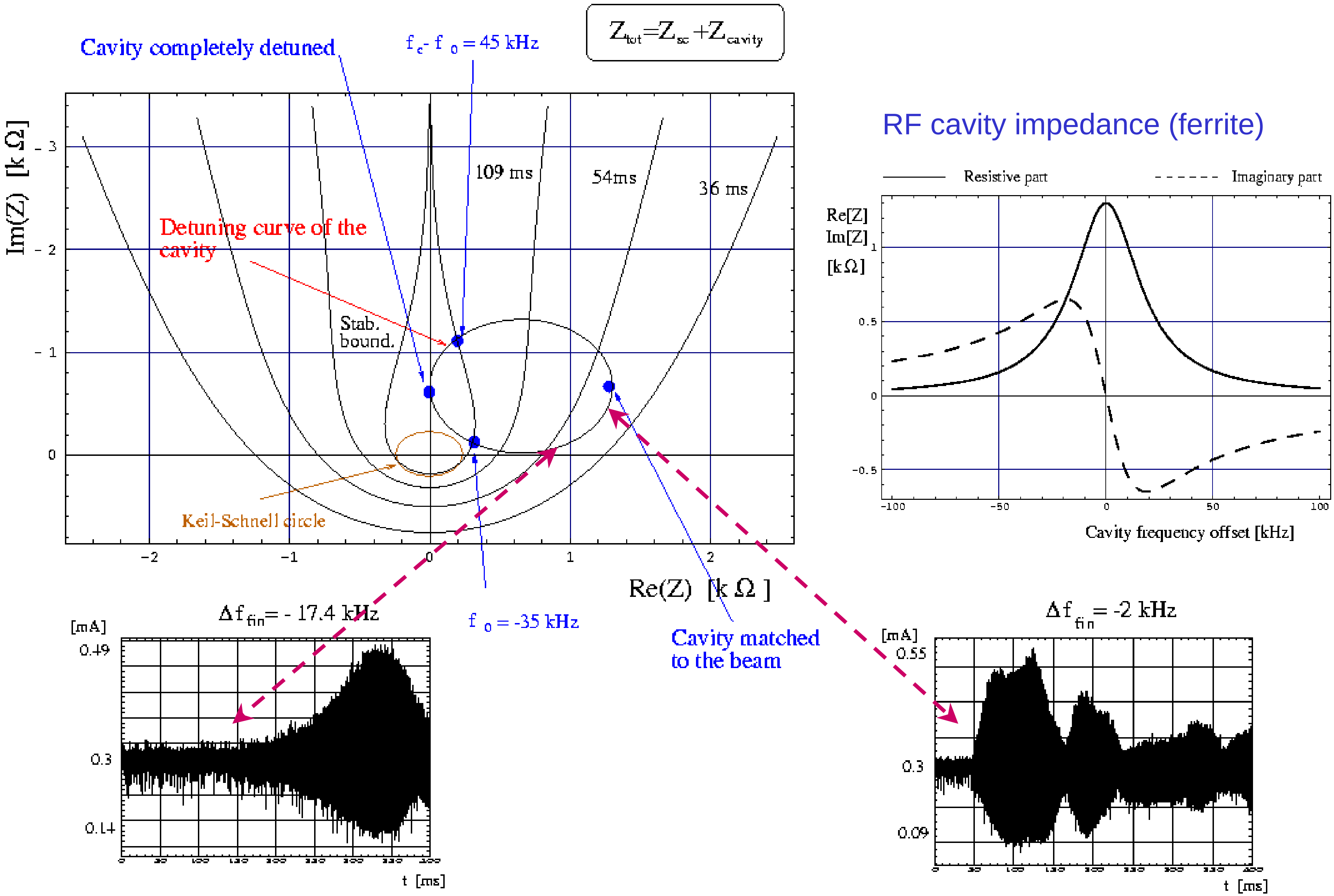
Keil-Schnell circle criterion

In Heavy Ion Fusion drivers, recently also proton drivers interest appeared to operate outside Keil-Schnell circle

in space-charge-dominated regime

Microwave instability measured below transition (CERN-PS) ~ 30 GeV

RF cavity detuning effect on working point

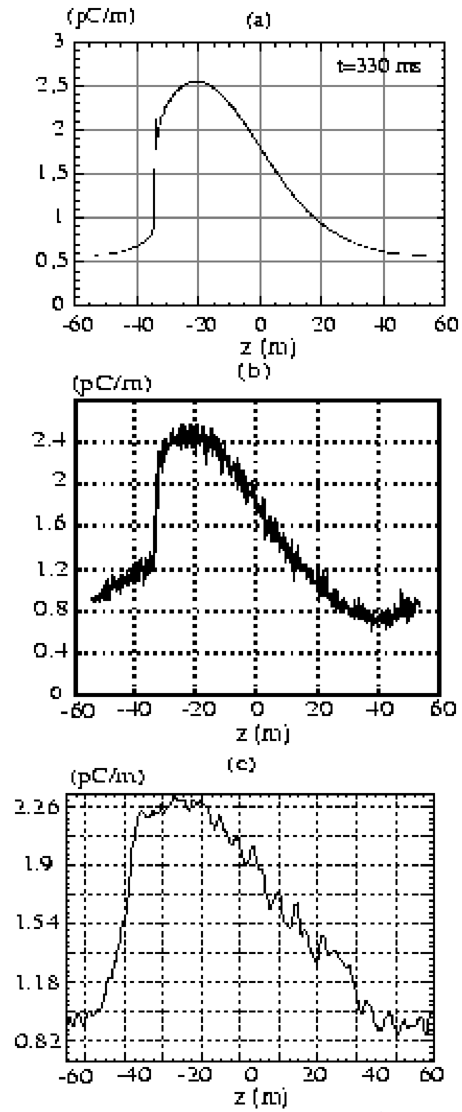


Steepening of resistively driven waves a nonlinear effect

Fluid model (warm)
- no real saturation
  (goes on)

PIC

Measurement



ESR circumference

Comparison: Rumolo et al., Phys. Plasmas **6**, 1999

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

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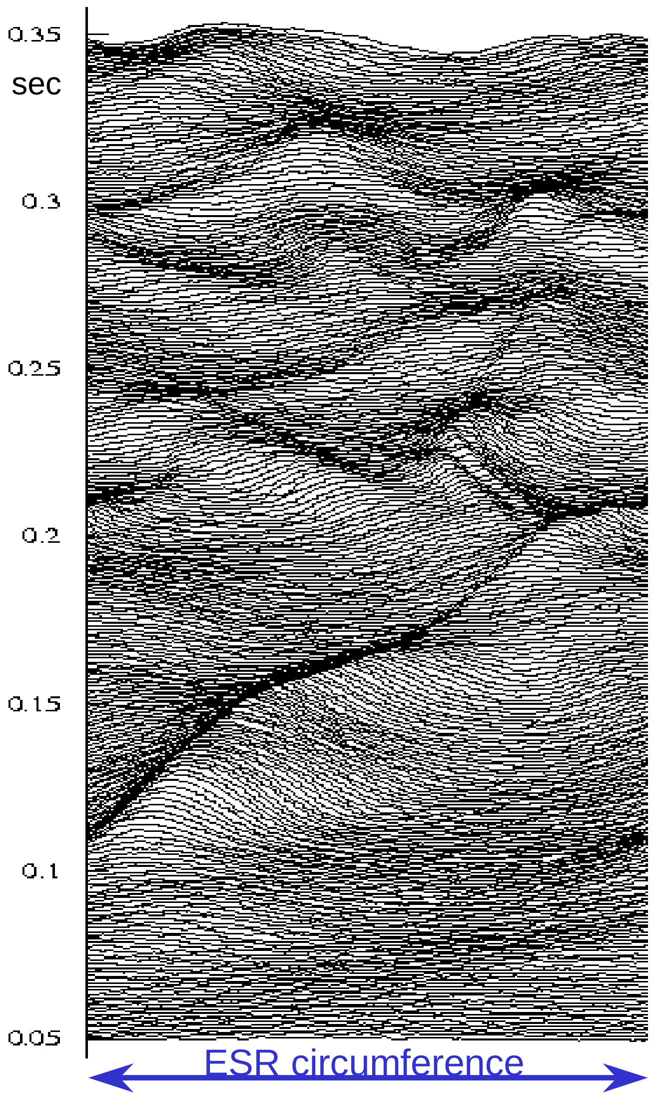
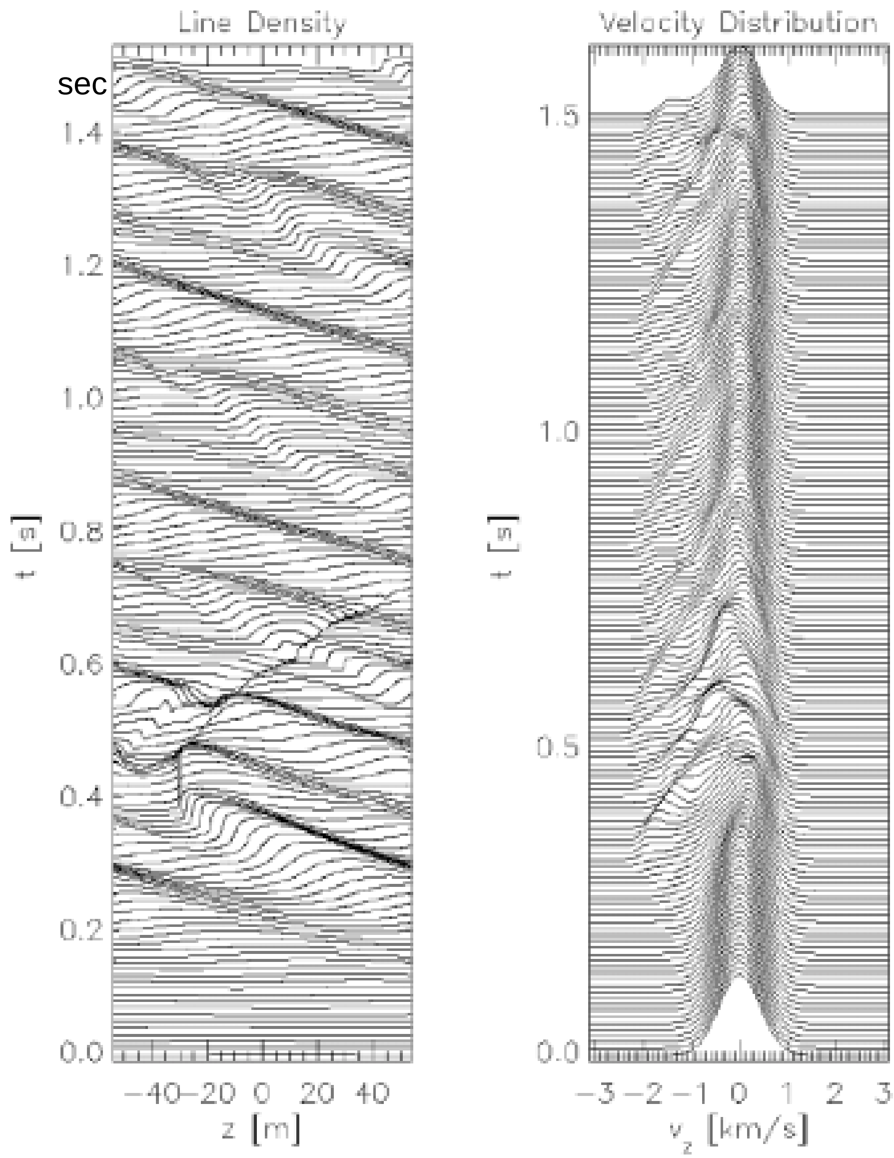
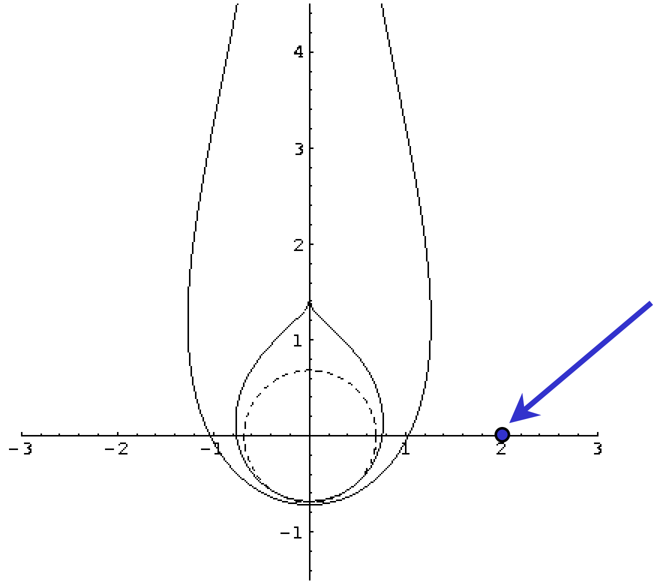
Experiment



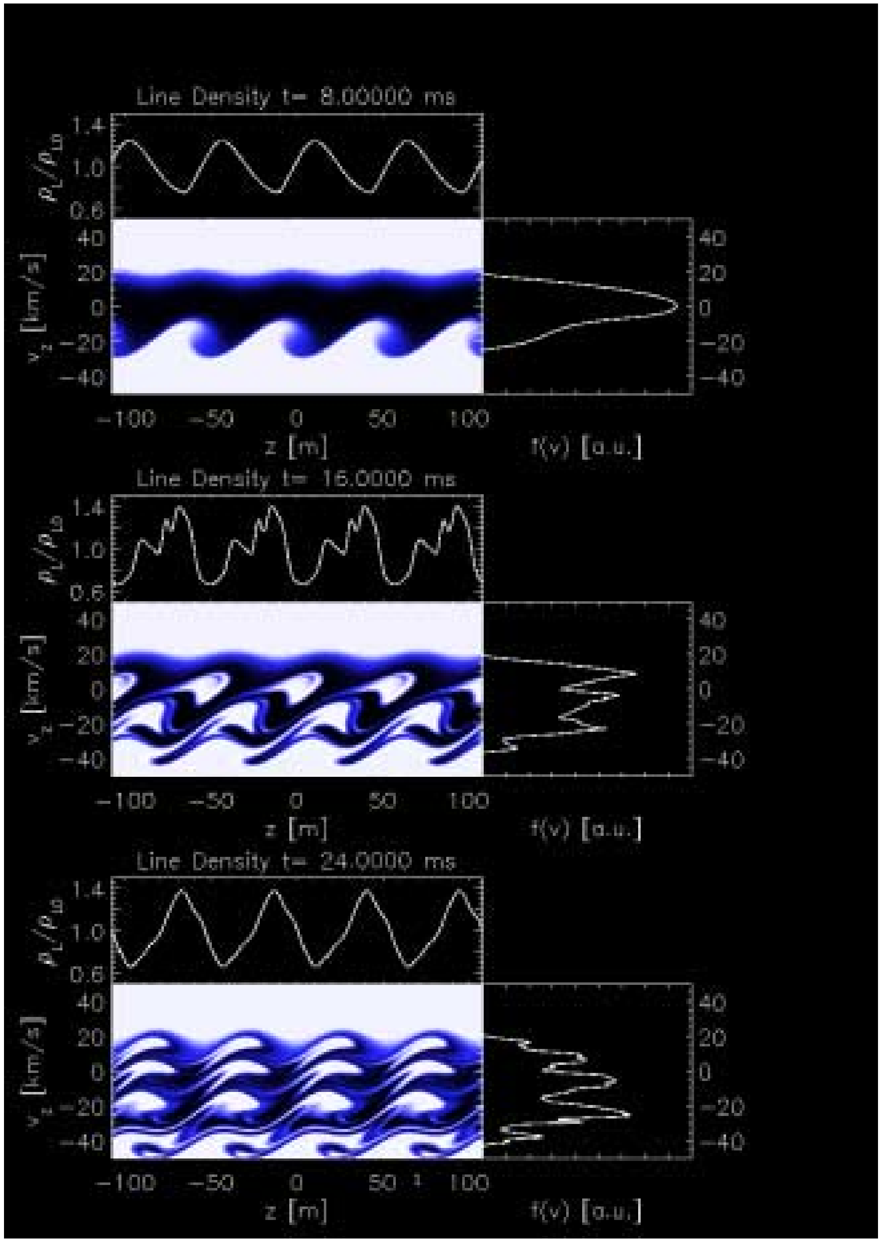
(Direct) Vlasov Simulation



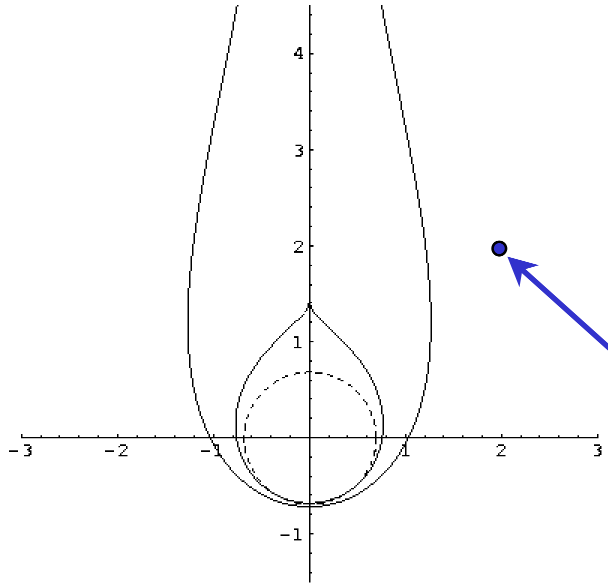
Purely resistive impedance: broadening effect

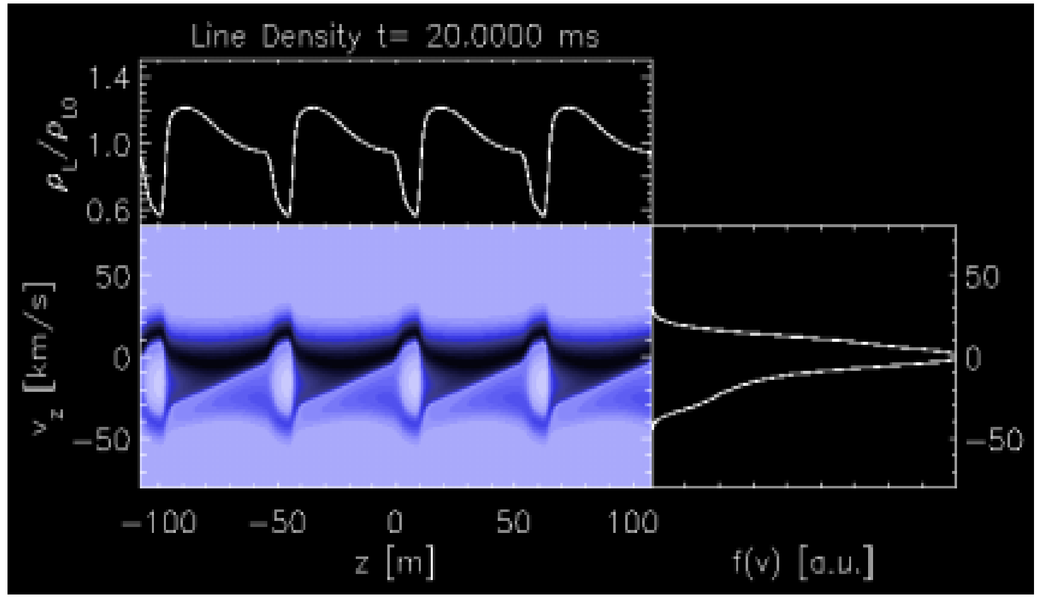


- typical behavior at higher energy
- layers of self-trapped buckets generated at lower edge of momentum space (slow wave) with strong progressive filamentation
- results in broadening (to lower momenta)

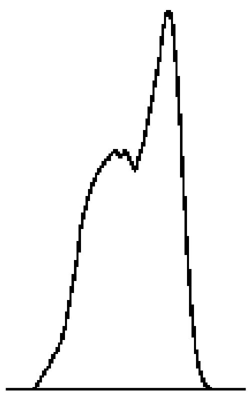


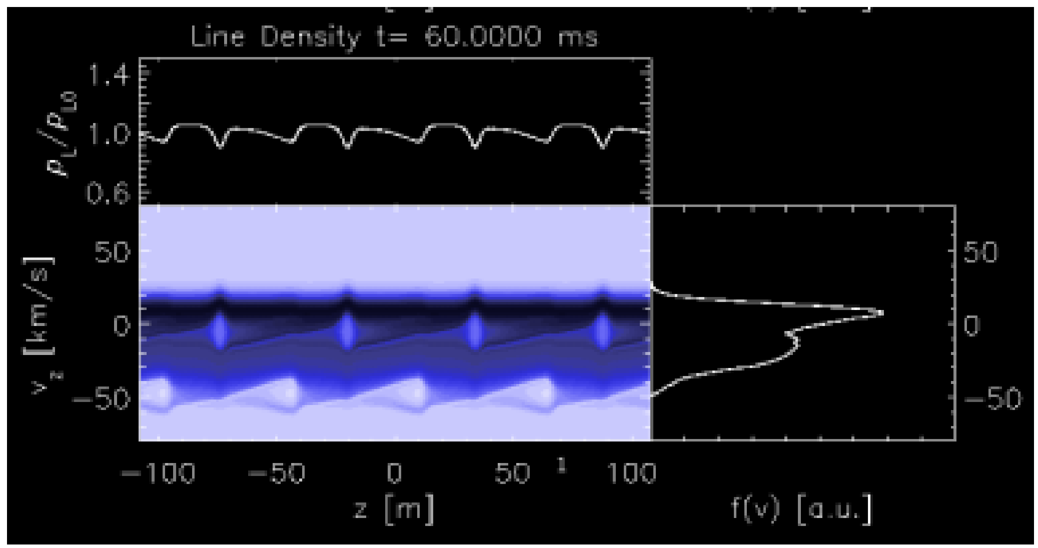
Balanced impedance (ReZ~ImZ)



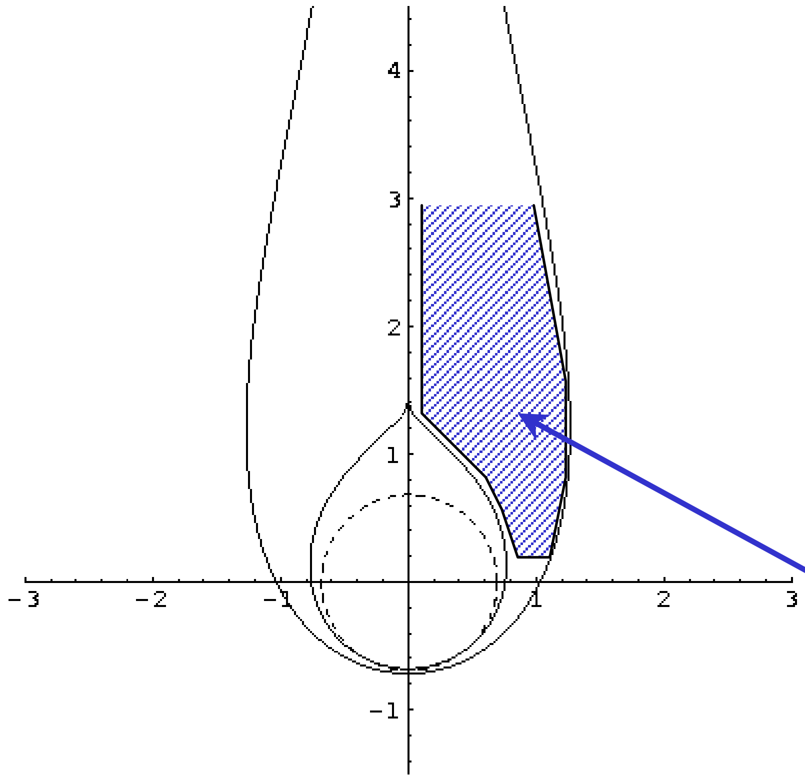


similar to ESR experiment: layers of holes traveling through momentum space and causing broadening of momentum distribution





Near stability boundary



quadratic unstable,
but Gaussian stable

Simulation of marginally unstable distributions

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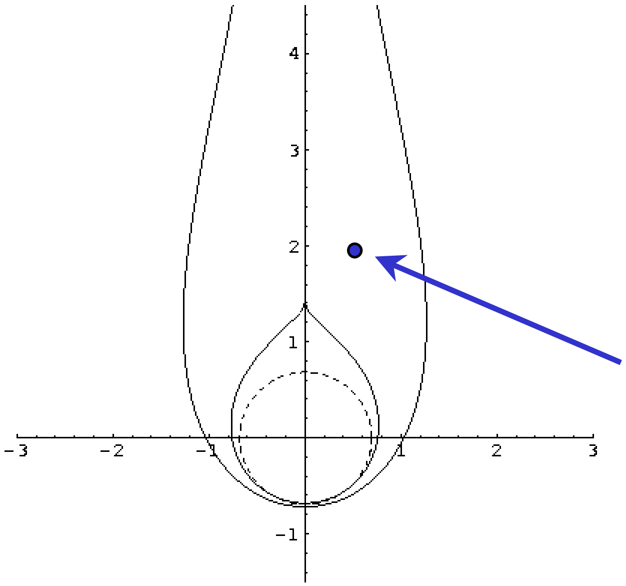
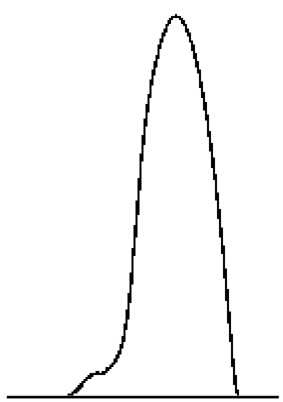
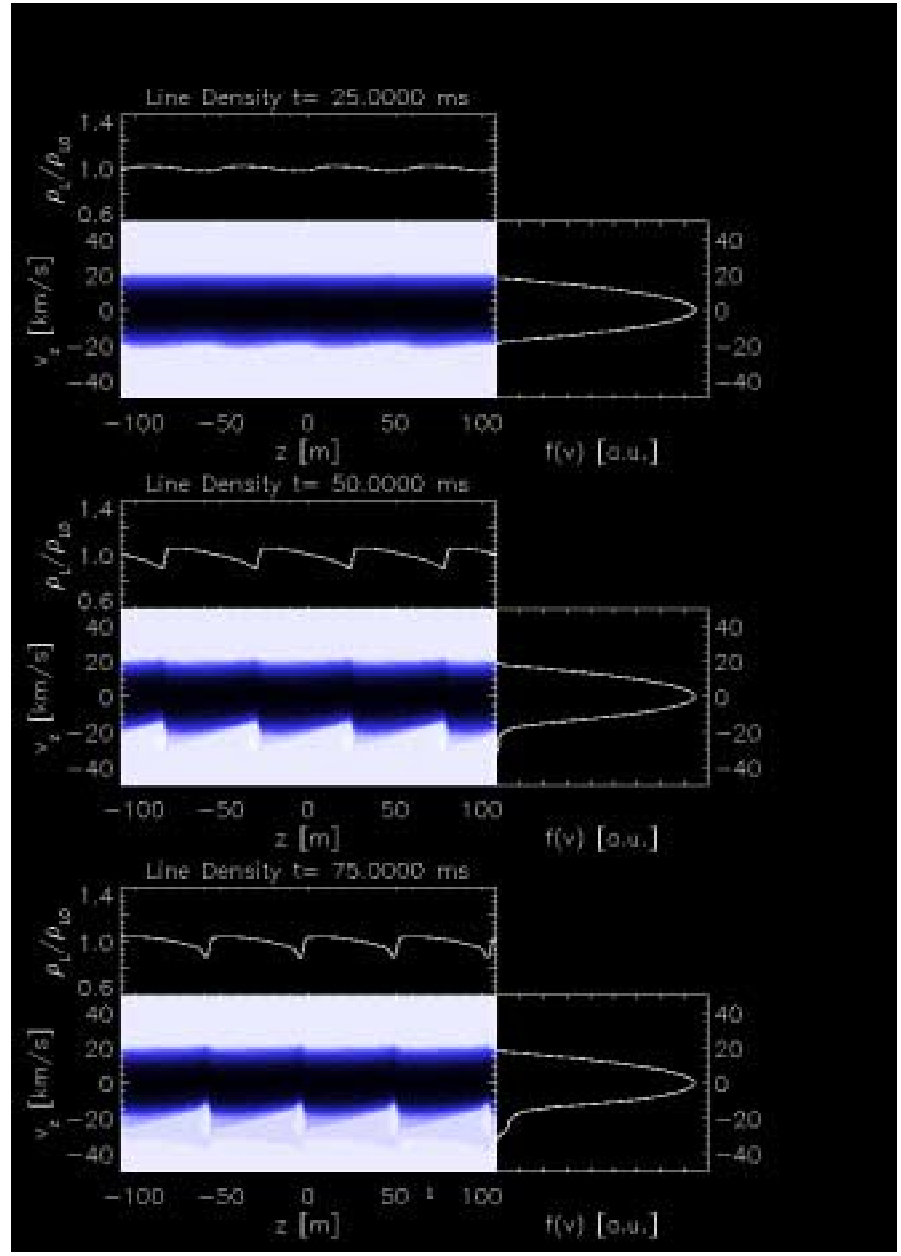
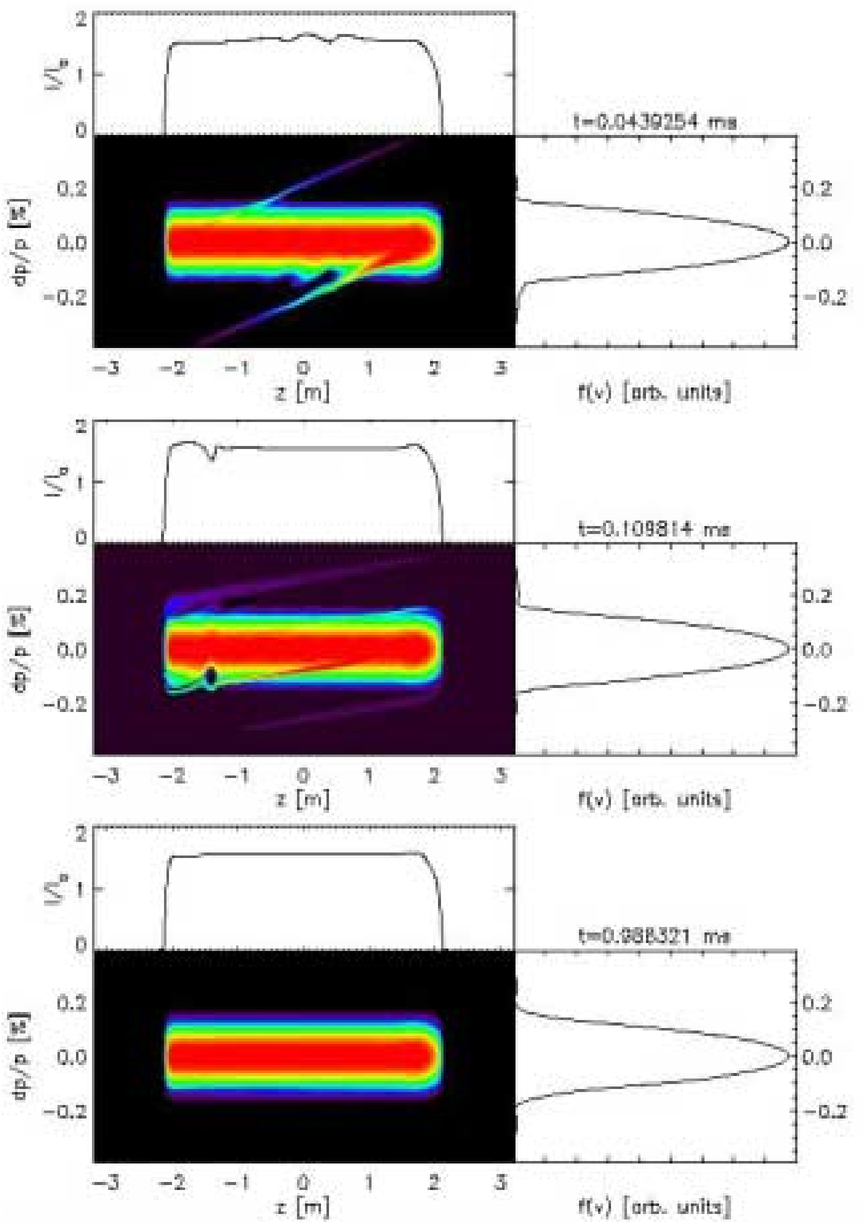


- initially parabolic (unstable)
- stabilizing tail developing here

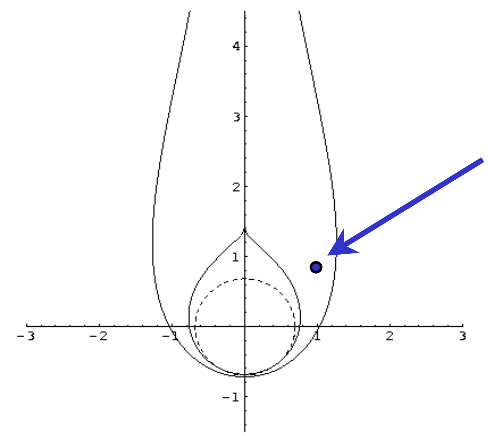




Bunch in ideal barrier bucket with reference to a proton driver

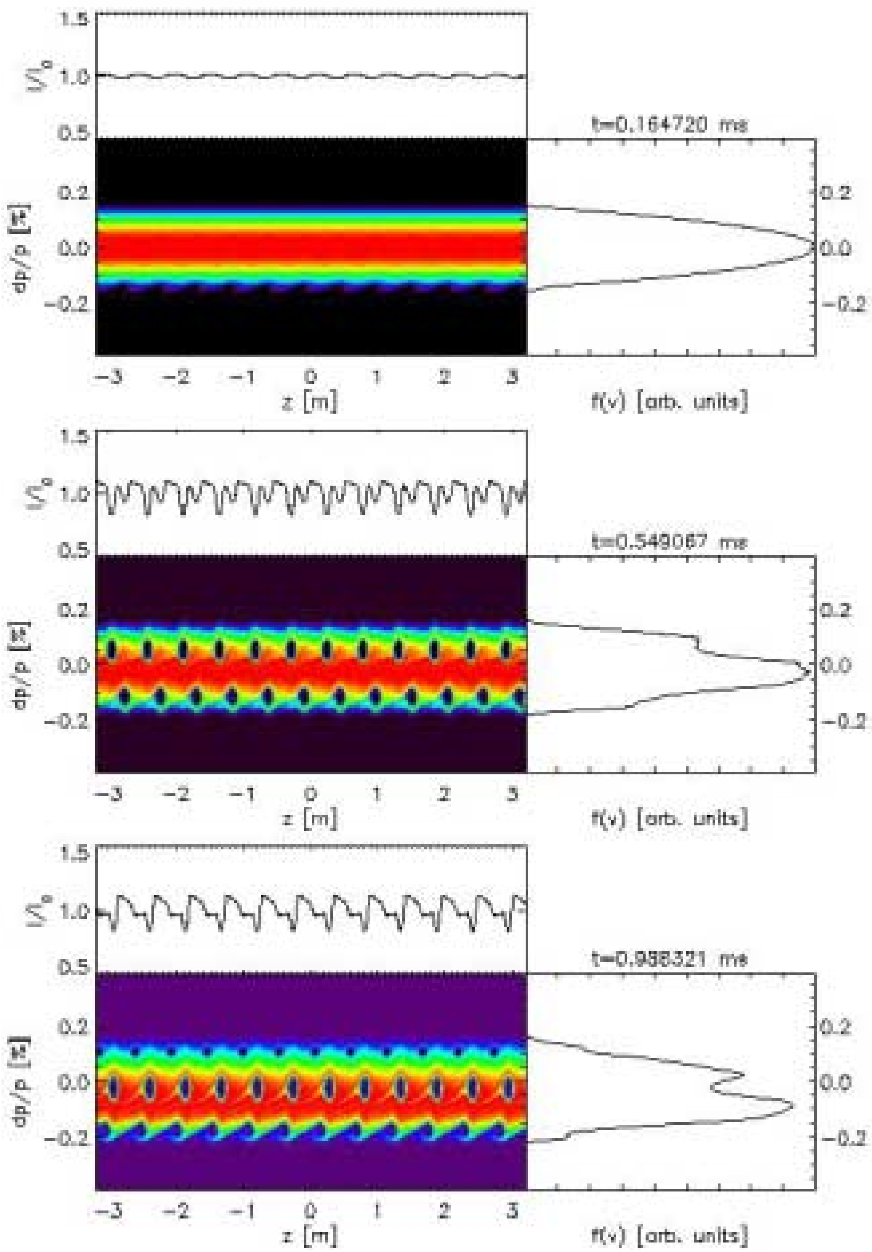


$N_{bunch}=10^{12}$ 2.2 GeV 12 ns
Intially parabolic momentum distribution
Square pulse into ideal barrier
Z/n=70 Ohm space charge
Z/n=50 Ohm broad band

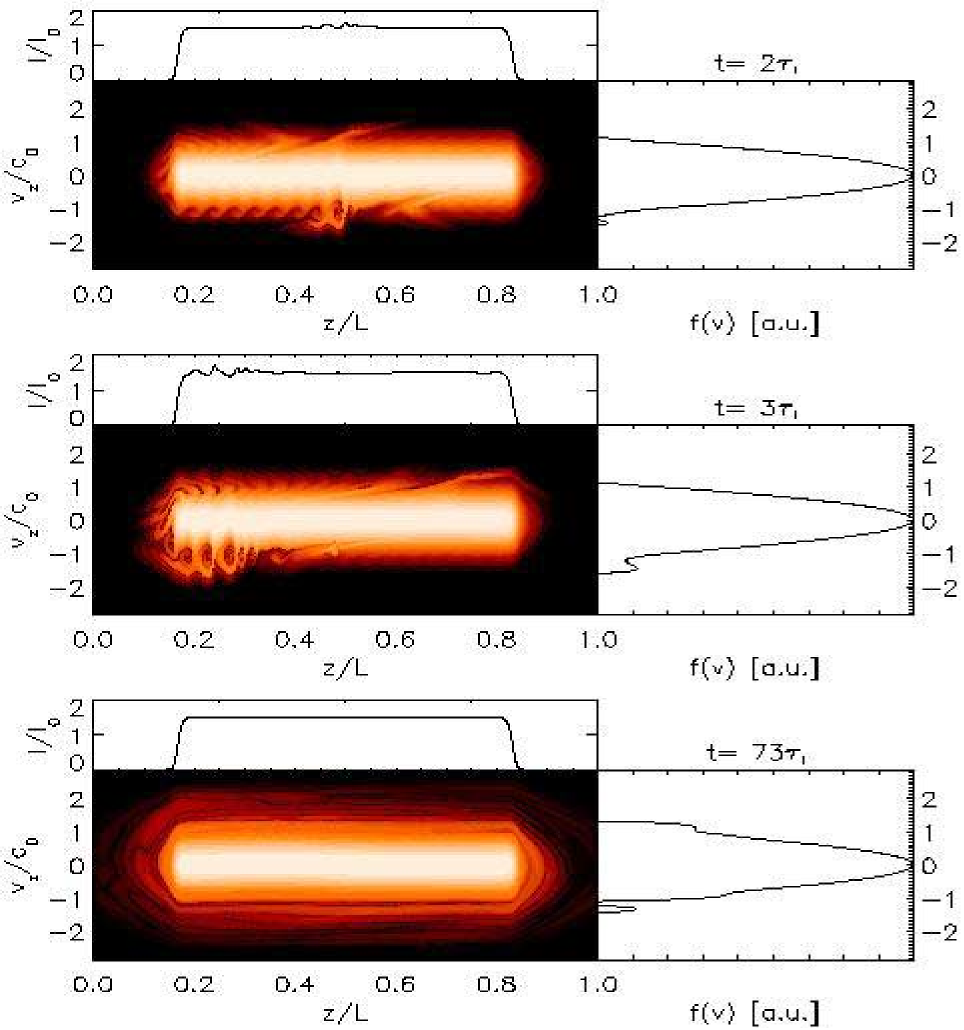


- Perturbations originating at bunch ends
- Finite bunch length can have stabilizing effect for **propagating** unstable waves
- holes trapped in phase space

Locally equivalent coasting beam shows more effect



Even much more space charge dominated bunches remain stable (U=10, V=1, h=24)



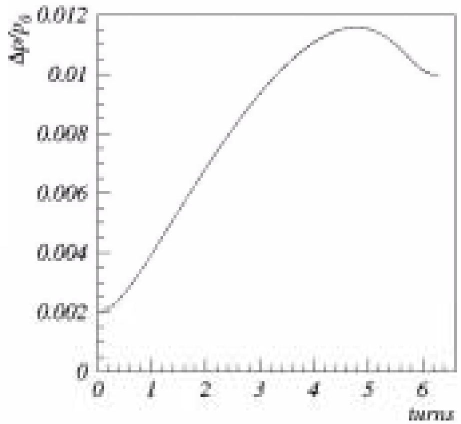
Compression of bunches in p driver *

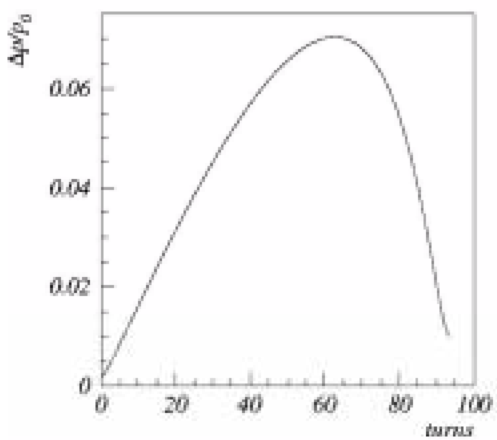
(ignoring higher order effects)

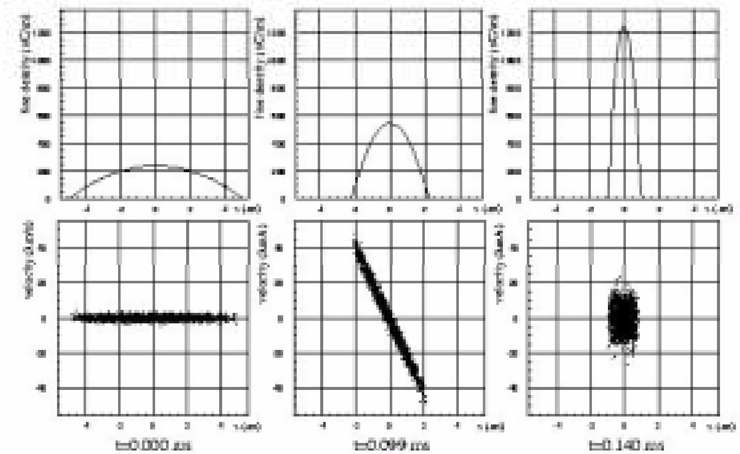
Example: 10^{13} p per bunch, 1.5 GeV, dp/p: 0.002->0.01, dz: 5m->1m

approaching transition:

- RF rotation voltage dominated by space charge
  $V \sim \eta/\chi^2 + (\eta\Sigma_f)/(1+\chi)$
  - χ: compression factor
  - η: slip factor
  - Σ_f : space charge parameter (~U)
    $= 3g_0 N_b r_p / (\beta^2 \gamma^2 \eta\, z_b \delta p/p^2)$
- increasing over-rotation







* G. Franchetti, I. Hofmann and G. Rumolo, PR-STAB (2000)

Above transition „attractive“ effect of space charge *

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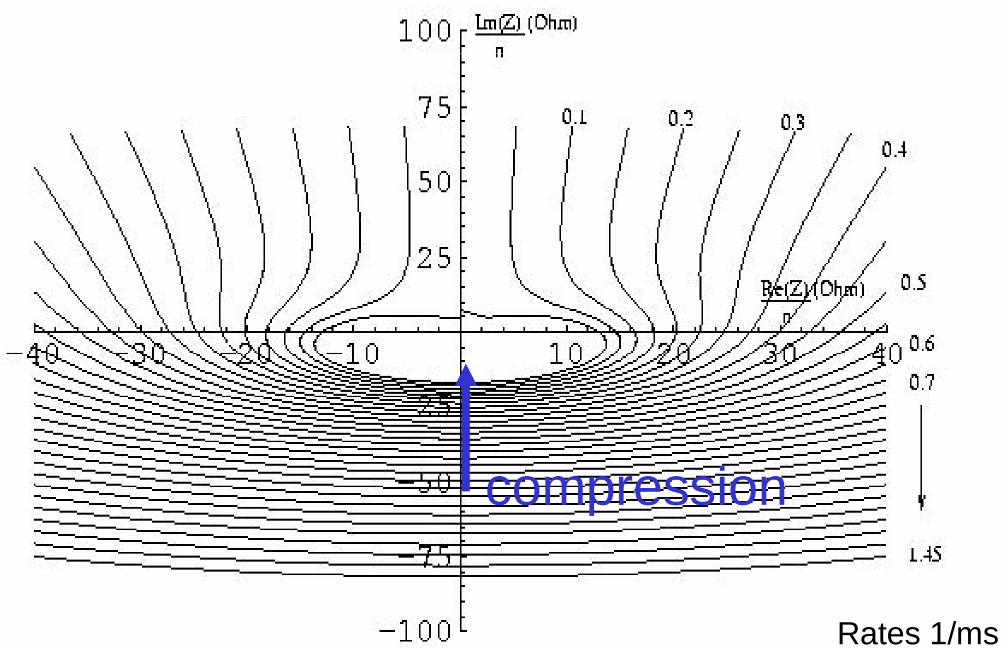
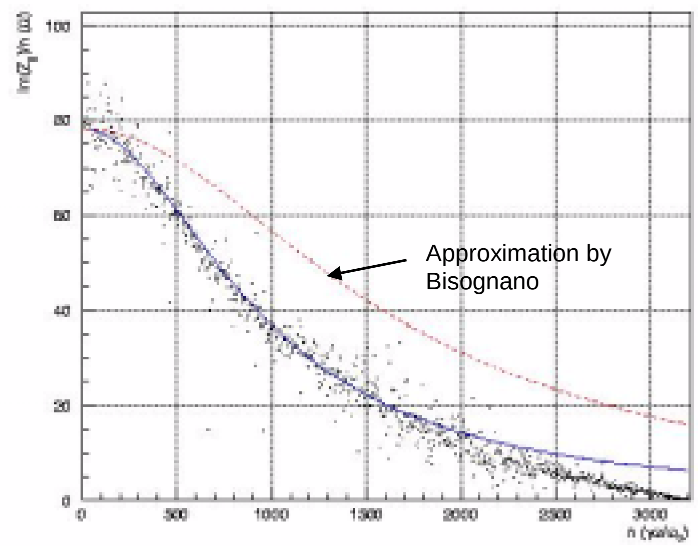
Space charge supports
- envelope rotation
- also growth of higher order modes



Reduced coupling impedance for very short wavelengths:

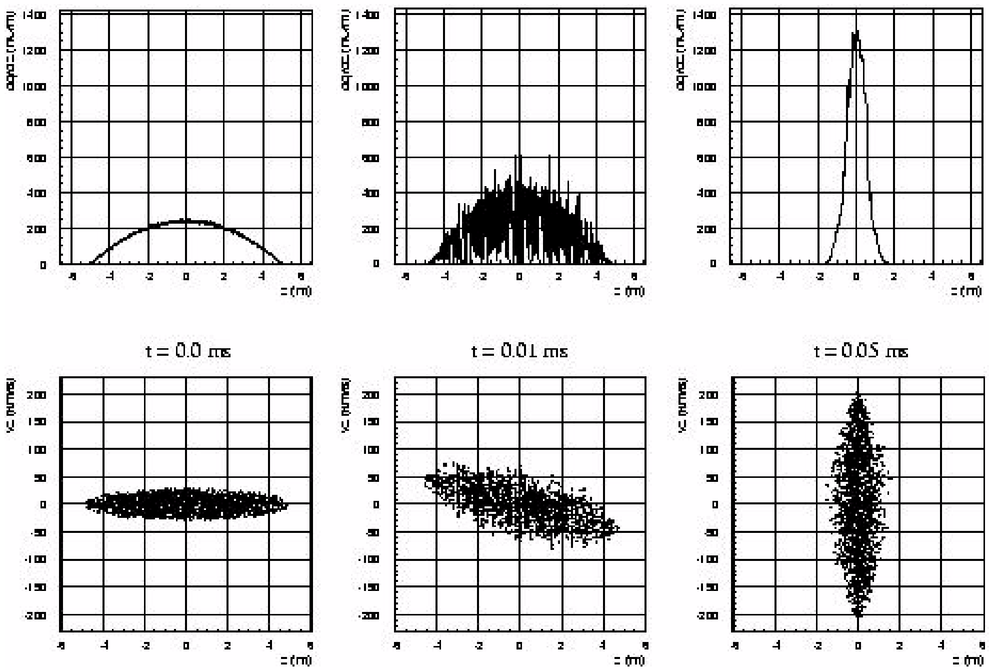


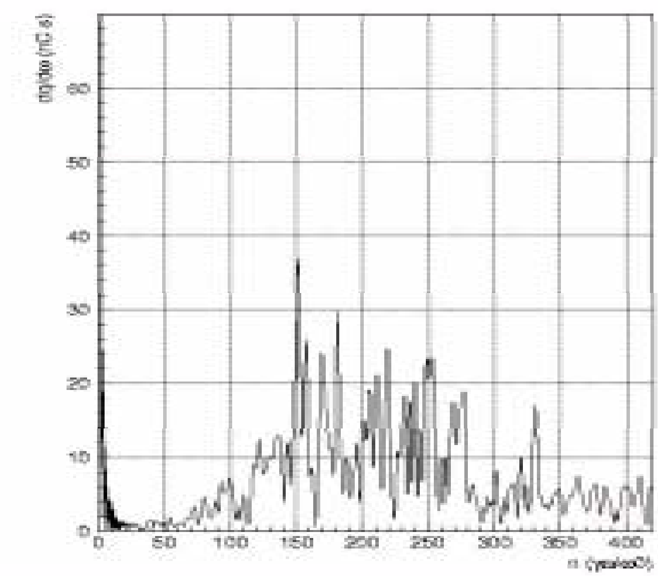
* G. Rumolo and I. Hofmann, PAC01

PIC-simulation in r-z (constant focusing)

• Negative mass modes are non-propagating (Re ω -> Im ω) purely growing

• Rotation must be faster than growth of negative mass modes
  - „mixing of modes“ helps during rotation





spectrum

Approaching transition from above limited by negative mass instability to a space charge parameter $|\Sigma_i|$~5

(final working point inside K.-S. circle)

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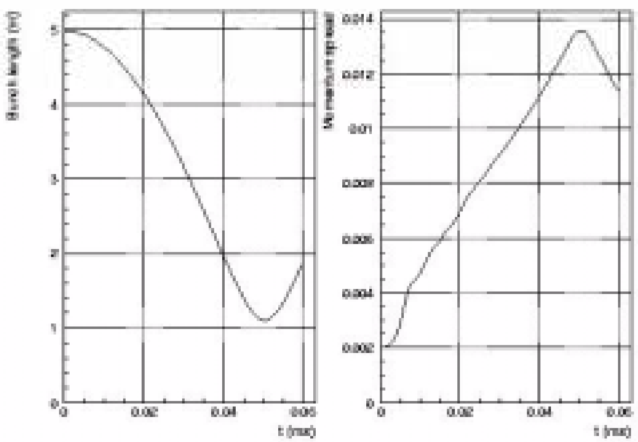
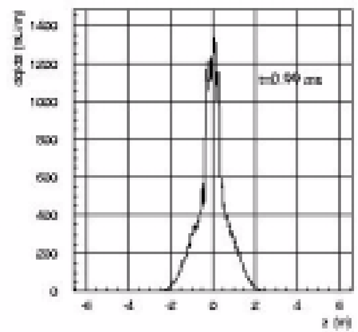
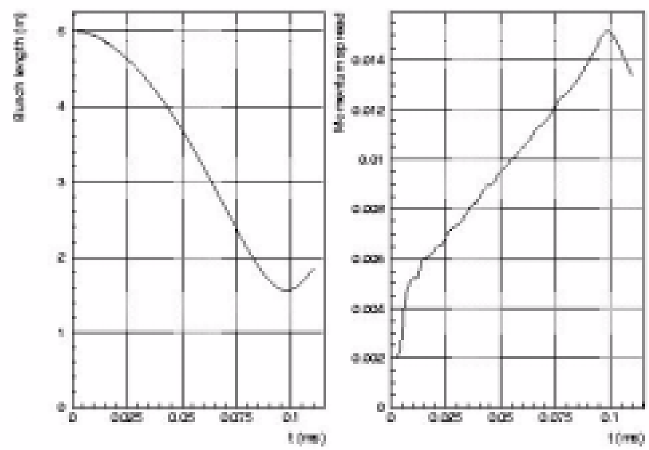
Optimum case: Rf voltage saving ~ 2 above transition



broadend shoulders for ~ 2 times smaller η





Transverse Space Charge Issues

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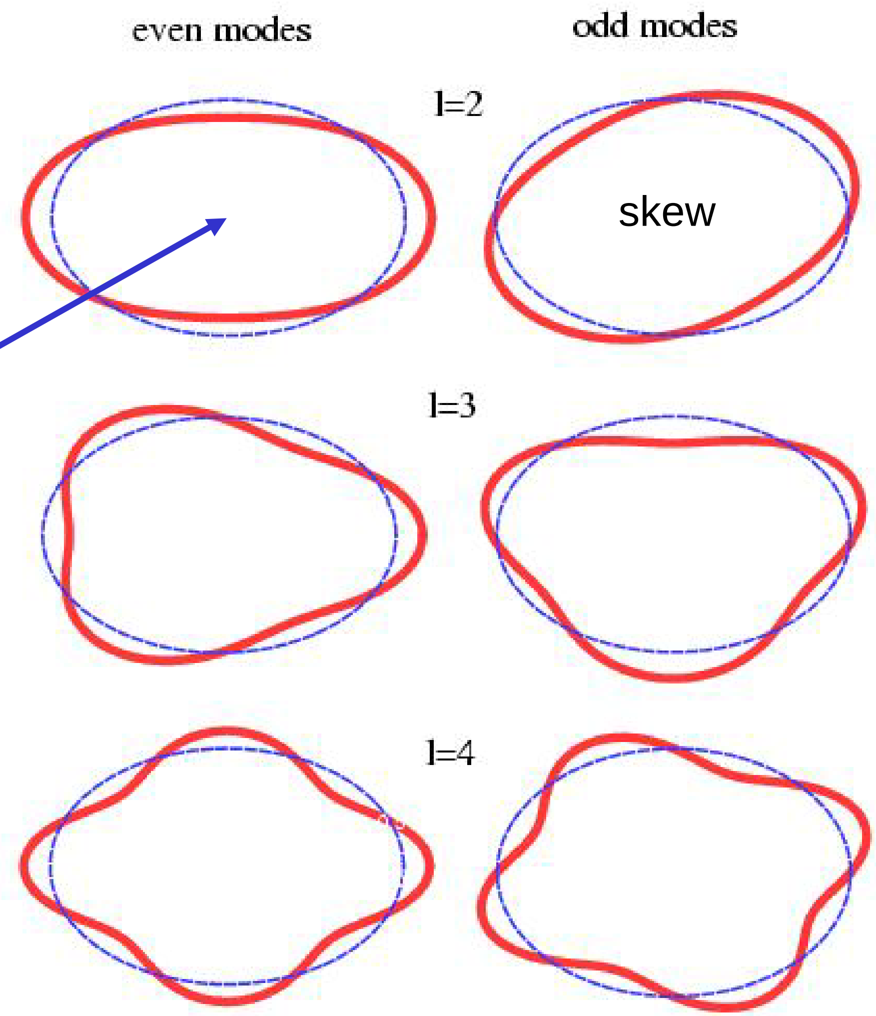
Modes of transverse density oscillations

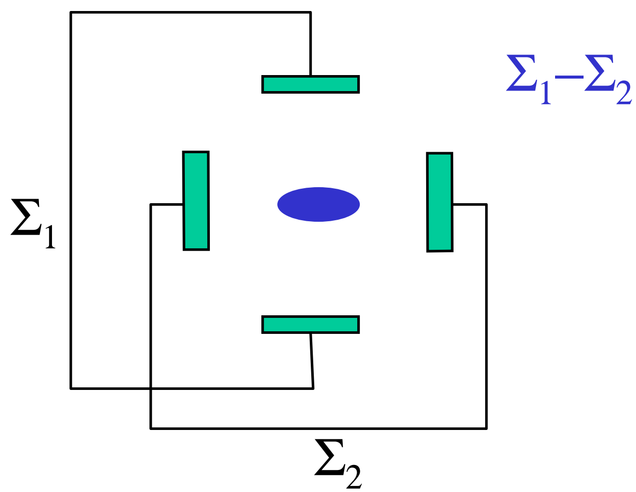
- coherent shift for resonance crossing
- emittance transfer

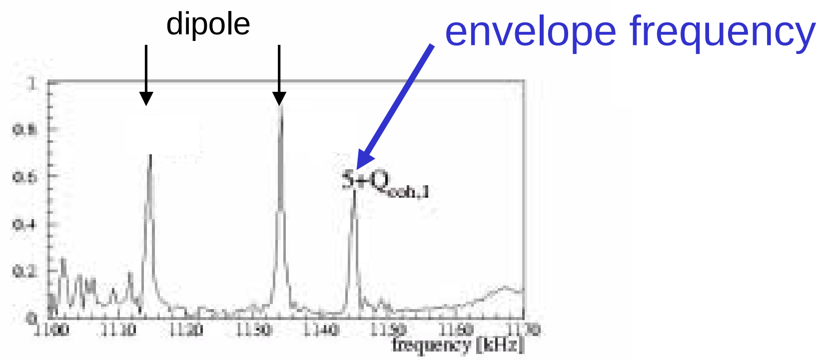


2 envelope modes (breathing and quadrupolar) can be observed with quadrupolar pickup

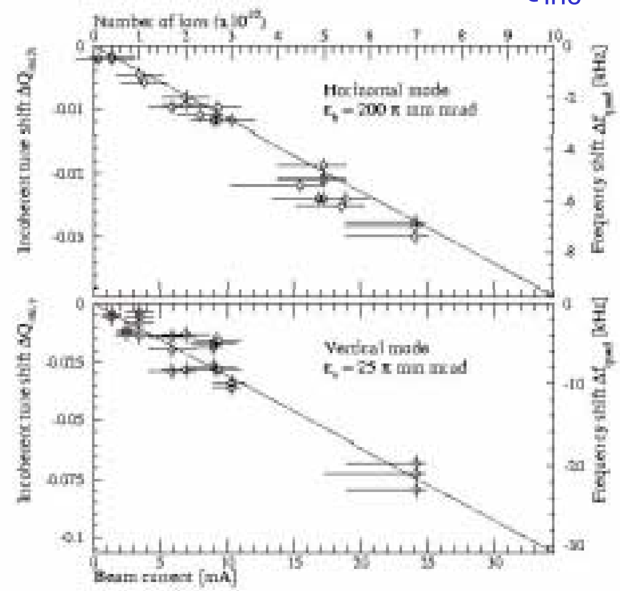
Quadrupolar Pickups to measure coherent envelope frequency shift (coasting beam)

- excited beam with swept frequency
- recorded response





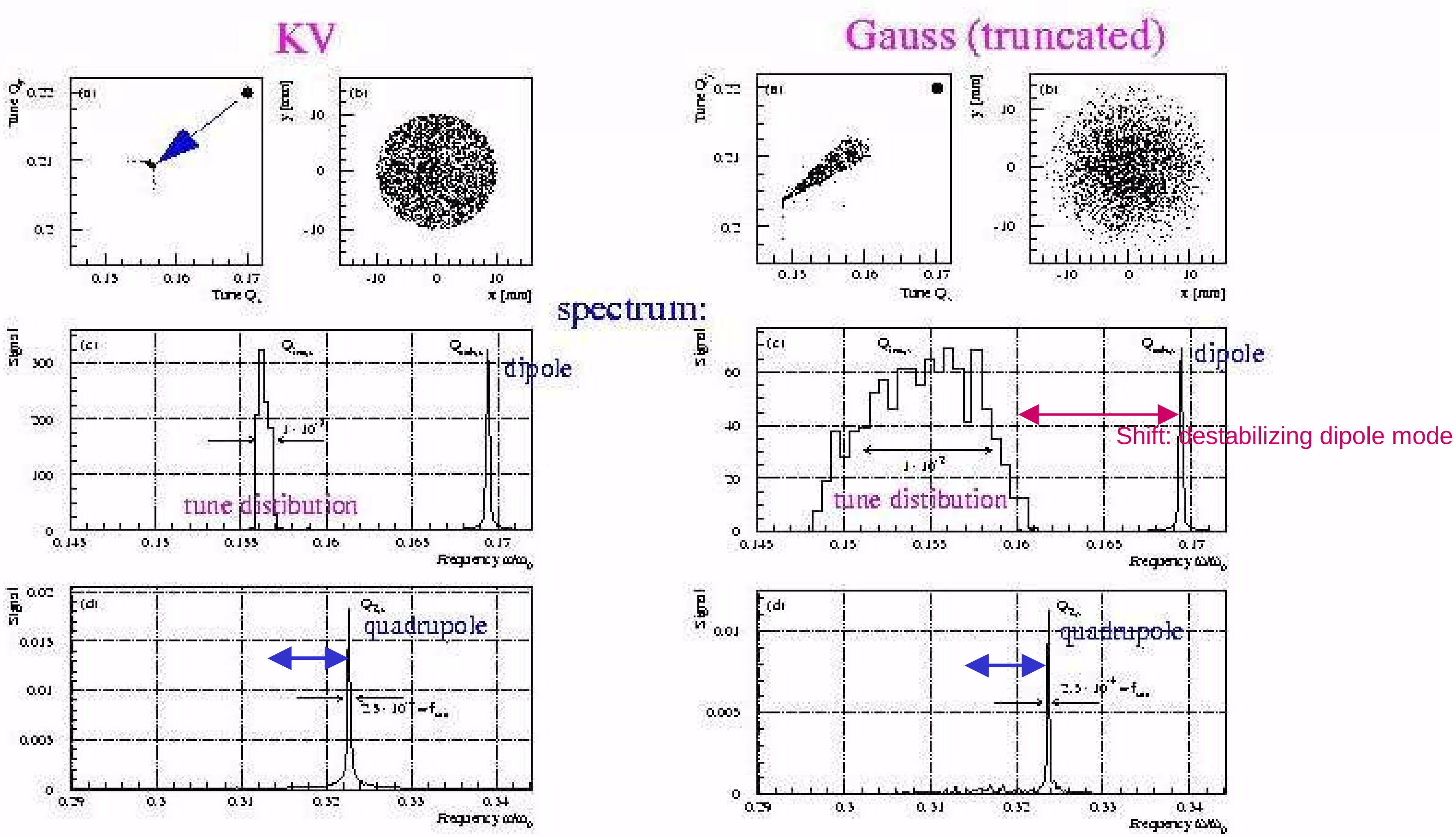
used it to determine ΔQ_{inc} or ε_{rms}



$$Q_{coh,1} - 2Q_{o,x} = (3 - a(a+b))\Delta Q_{inc}$$

Coherent frequency shift - no incoherent signal observed

2D PIC-simulation to analyze noise very useful
- for injection imprint (SNS ring etc.)
- bunched beam effect
- significant sampling times may be needed
- great challenge to parallel computing



Higher – 4th order – known as "Montague-resonance": $Q_{x0} / Q_{y0} \sim 1$

- Montague, 1968 CERN-68/83
- need to split tunes to avoid $2Q_y - 2Q_x = 0$ driven by nonlinear space charge force from non-uniform beam $V_{sc} \sim a(x^2 + y^2) + b(x^4 + x^2 y^2 + y^4) + \ldots$ leading to emittance transfer from horizontal to vertical in *ideal* lattice
- Montagues analysis was *incoherent* – fixed space charge potential – coherent more adequate
- ~ measurement reported at KEK (Sakai et al,. PAC01)

Studied space charge driven 4th order resonance in detail using 2D PIC and $\nu_y/\nu_{y0}=0.8$, $\varepsilon_x/\varepsilon_y=2$ (IH et al., PRL 87/2001)

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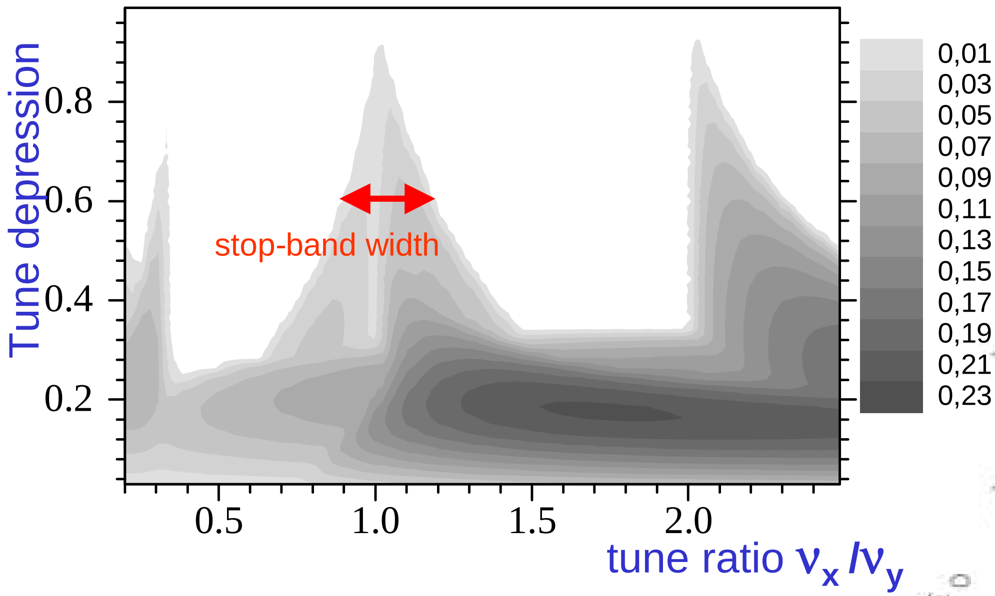
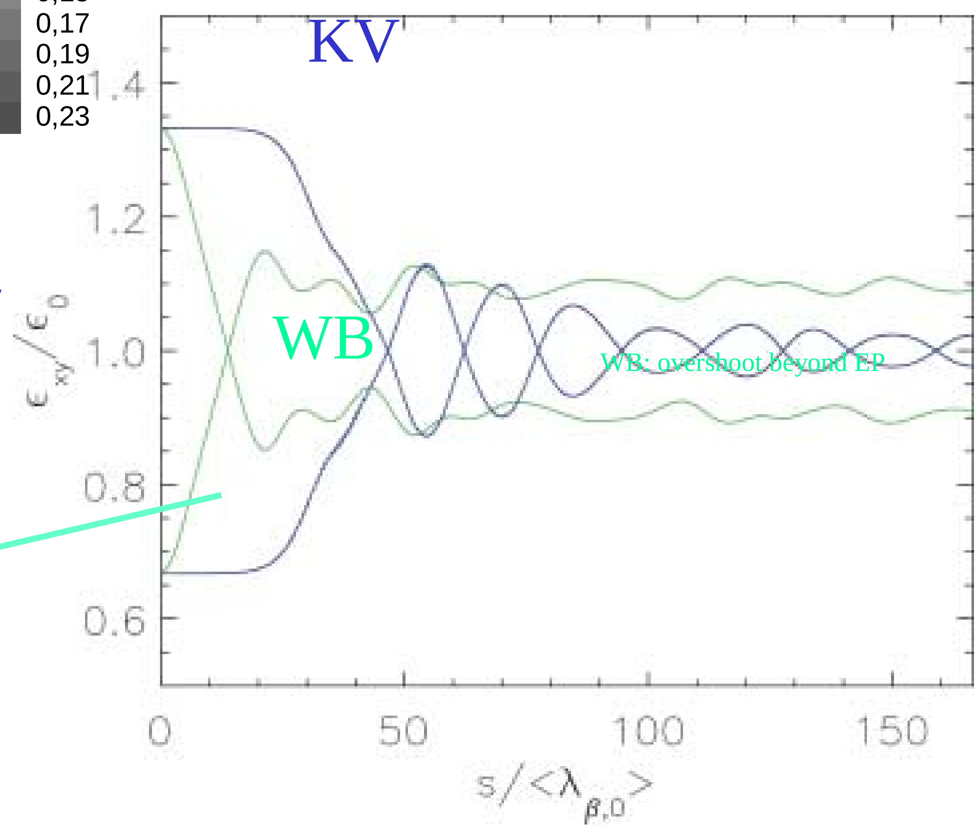
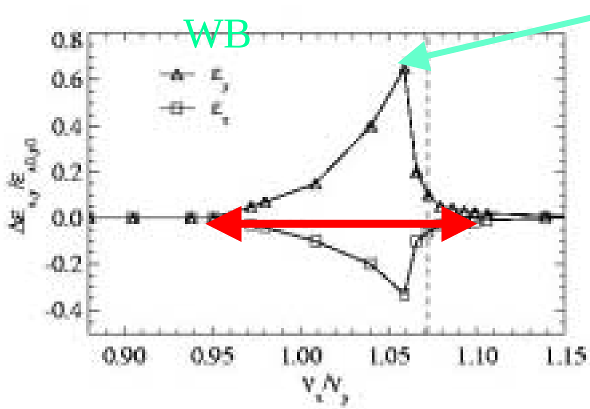
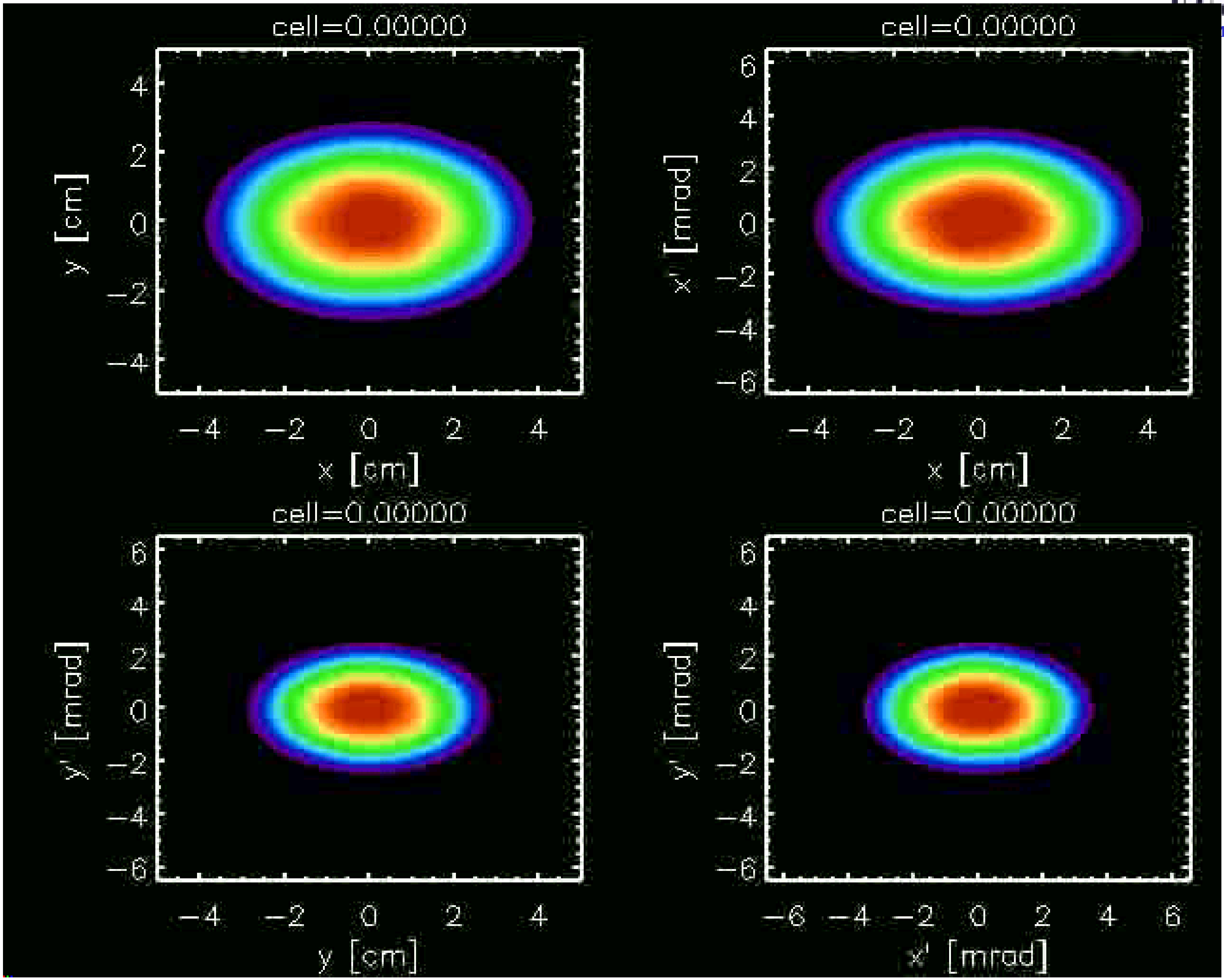






KV: exponential growth takes more time as it grows from noise!



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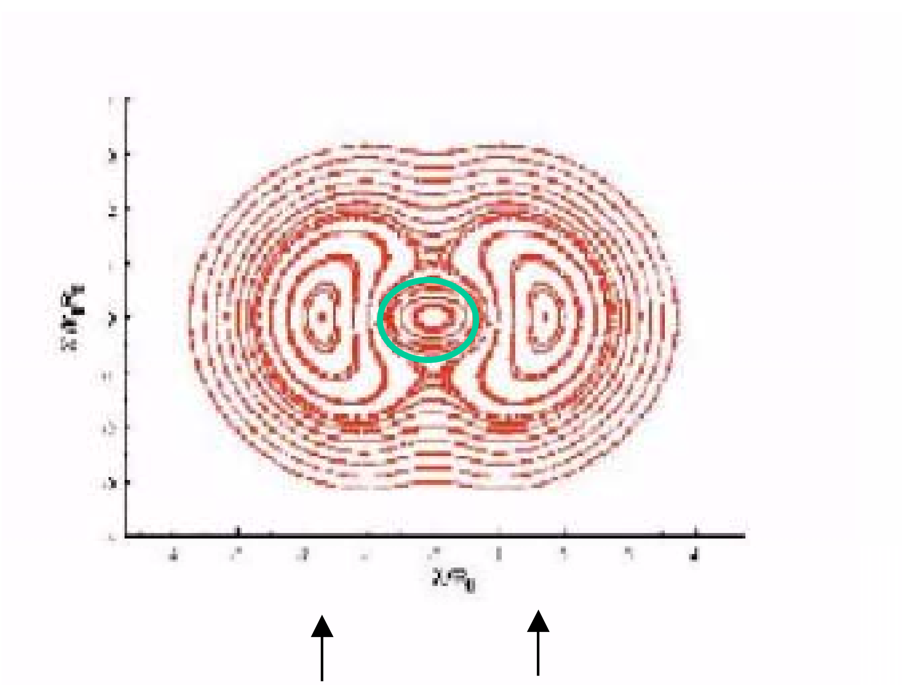
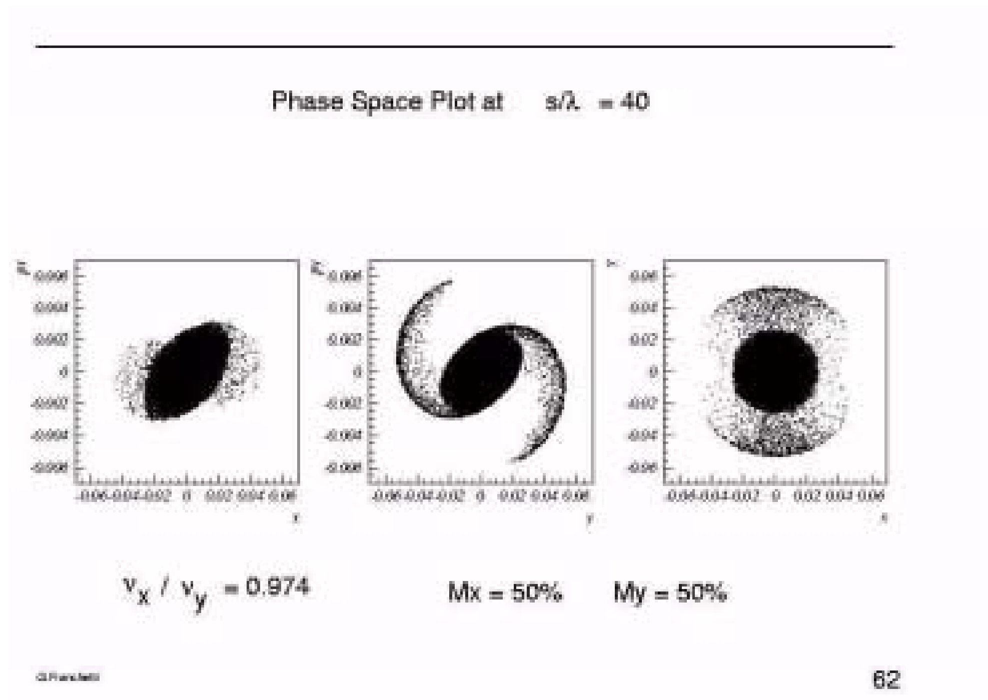
Injection mismatch and halo losses

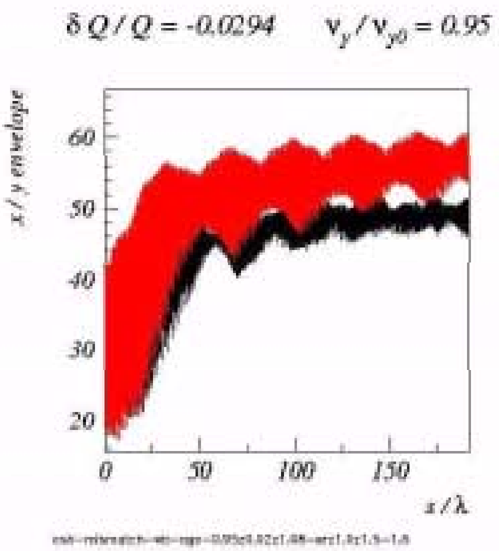
applied in an idealized model as a first step
to model injection loss into AGS at Brookhaven
- to be extended to bunches and full lattice
(G. Franchetti, I.H., A. Luccio)



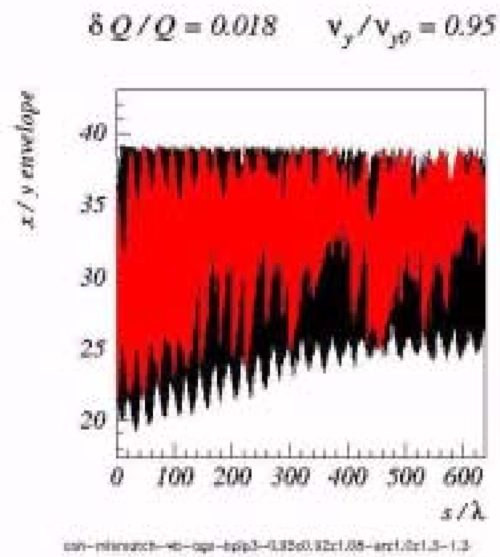
2 fixpoints

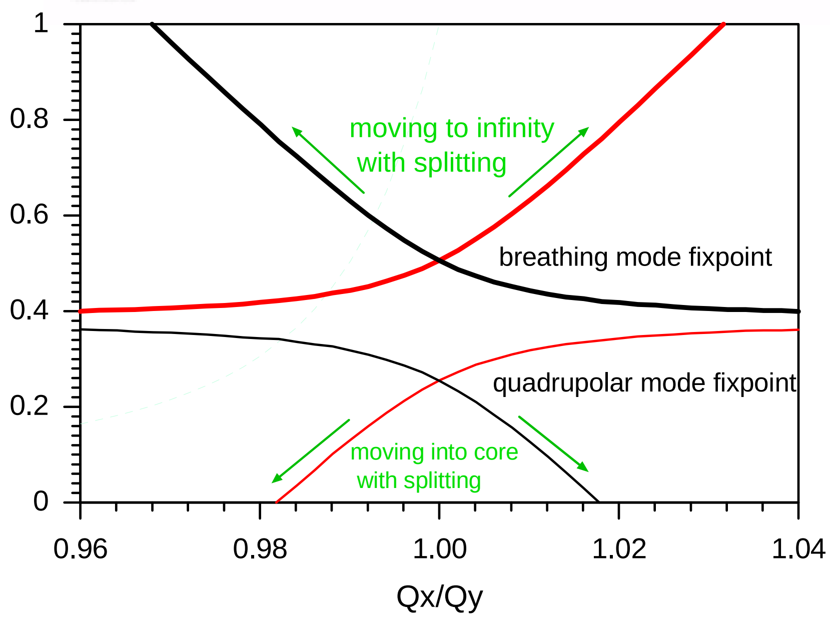


Results on halo growth depend sensitively on tune split



maximum size (mm)





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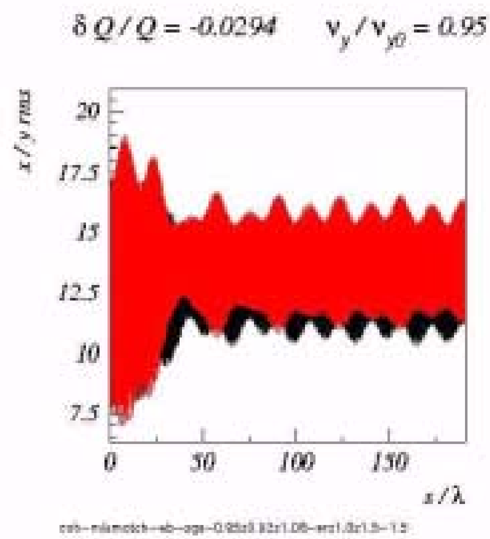
no damping of rms oscillations (function of tune split)



Aperture loss modelling

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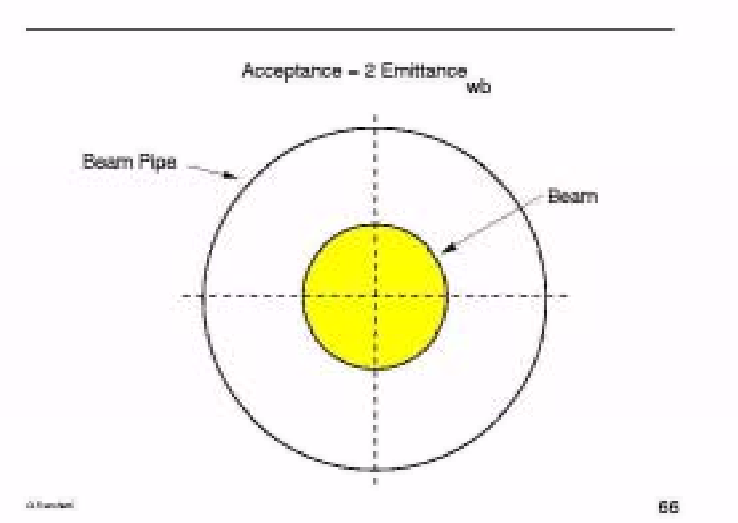

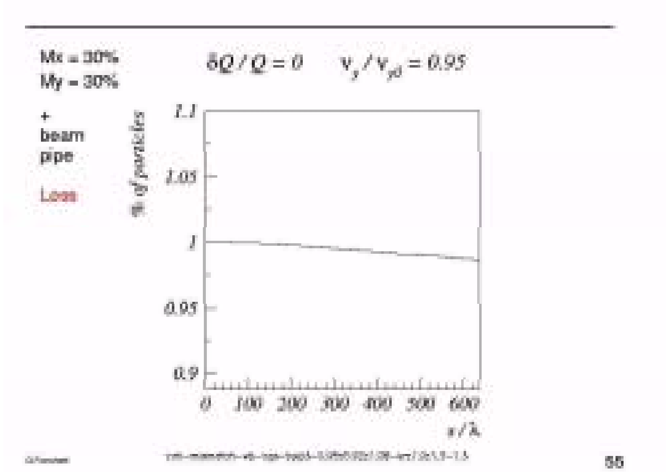

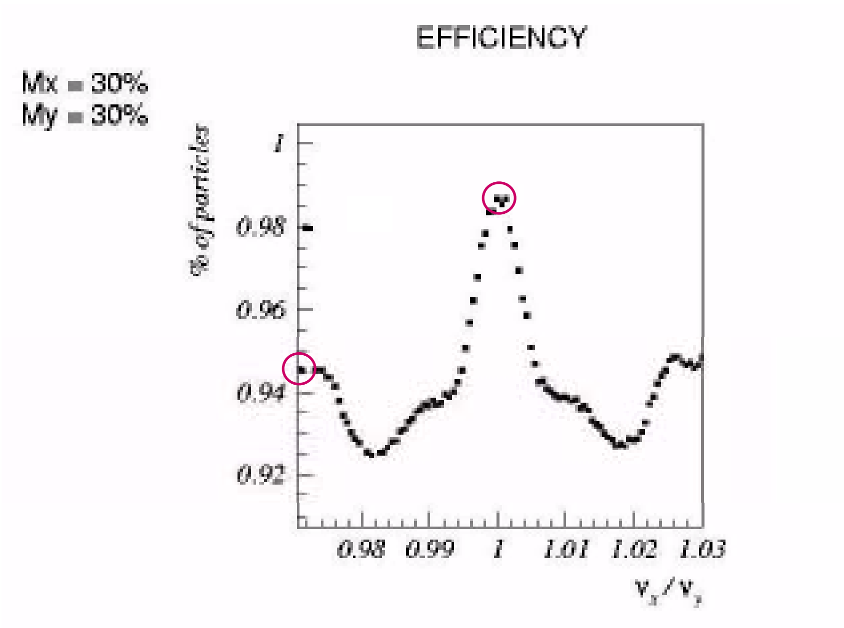

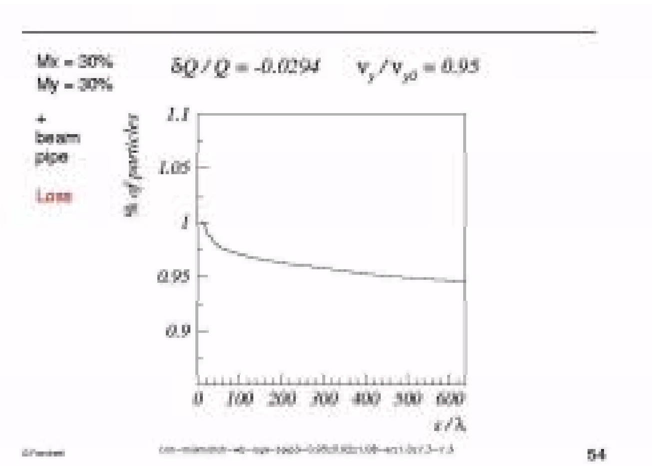

Concluding remarks

- Coherent longitudinal space charge effect may
  - affect Landau damping
  - stabilize or destabilize (*ReZ*/*ImZ*)
  - leave imprint on noise spectrum
- coherent transverse similar
  - dominates quadrupolar spectrum
  - appears in coherent „Montague“
  - mismatch mode damped by halo depending on tune splitting – loss on beam pipe

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

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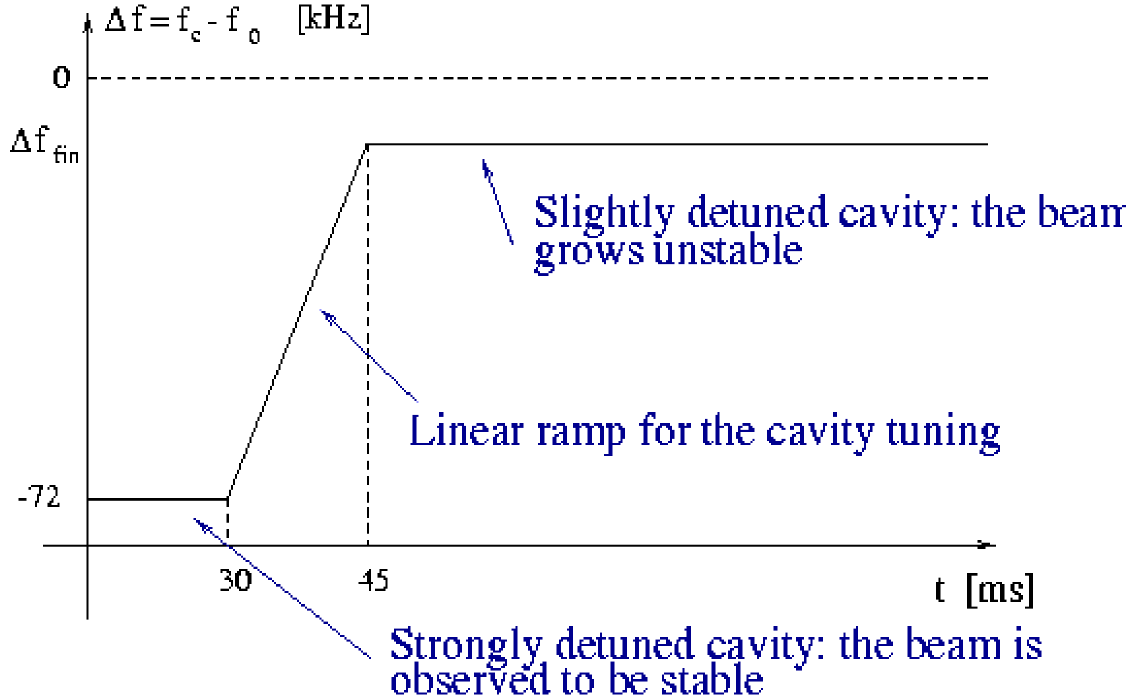
- prior to the onset of instability the beam adopts a very clean Gaussian momentum distribution due to e-cooling
- RF cavity (h=1) destabilizes beam (ecool on or off)
- current signal stored on LeCroy digital analyzer

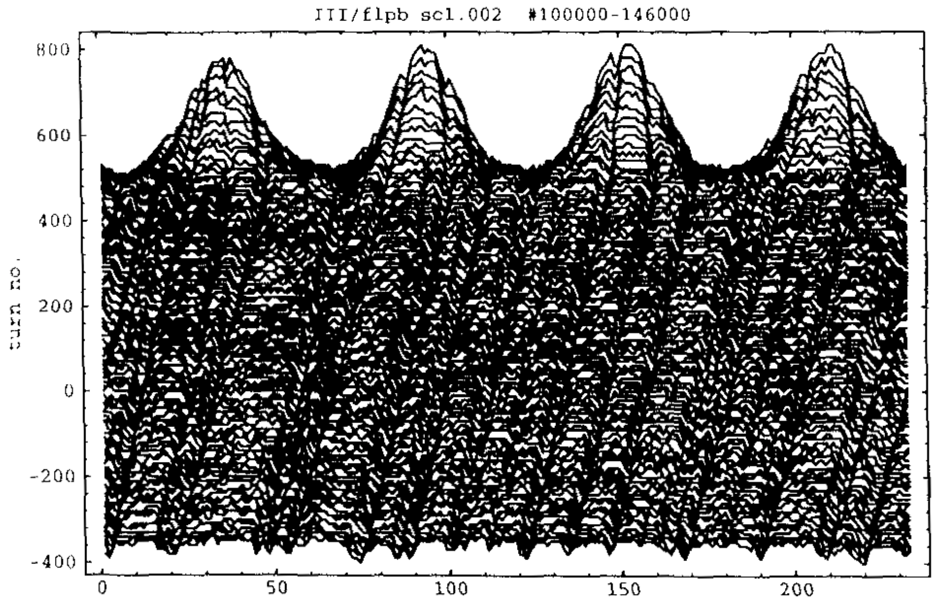


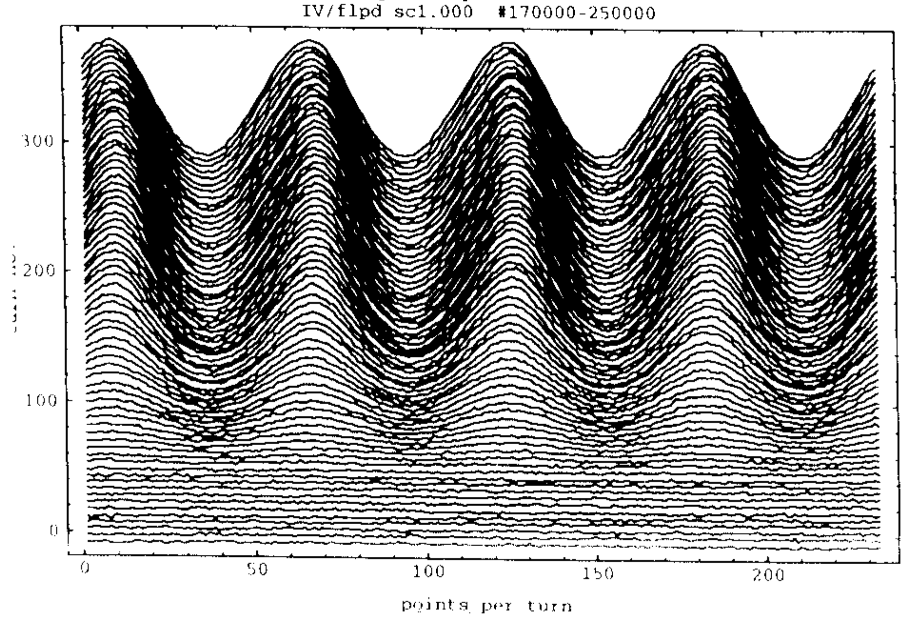
SIS measurement after injection

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 (?)





Holes are continuously trapped in phase space

- 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)