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Beam - Plasma Instabilities

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Beam - Plasma Instabilities

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Background

- Cyclotron maser instability - relevant to Auroral Kilometric radiation (AKR). Theoretical and experimental investigation.
- Programme now being extended to look at more general beam plasma instabilities in a controlled experiment.
- Look at two-stream, Weibel, anomalous Doppler ......

Cyclotron Maser

- Cyclotron resonance when

$$\omega - k_{||} v_{||} = n \frac{\omega_c}{\gamma}$$

γ = usual relativistic factor

n = integer

Small frequency differences matter, so relativistic mass correction is important, even at fairly low energies.

Instability mechanism

- Resonant particles interact strongly with wave.
- Gain or lose energy depending on position with respect to wave phase.
- Produces diffusion in velocity space - down gradient in distribution function.
- Instability if particles lose energy.

Diffusion path

- Particle moves freely along magnetic field.

Interaction with wave changes energy and momentum with

$$\frac{dW}{dp_{||}} = \frac{\omega}{k_{||}}$$

$$W - \frac{\omega}{k_{||}} p_{||} = const$$

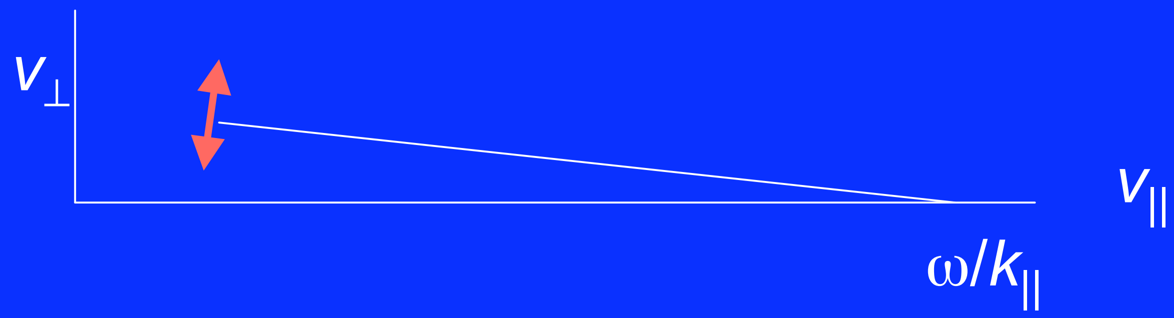
Non-relativistic

$$\left(v_{||} - \frac{\omega}{k_{||}}\right)^2 + v_{\perp}^2 = const$$

For electromagnetic modes

$$\frac{\omega}{k_{||}} >> v_{||}$$

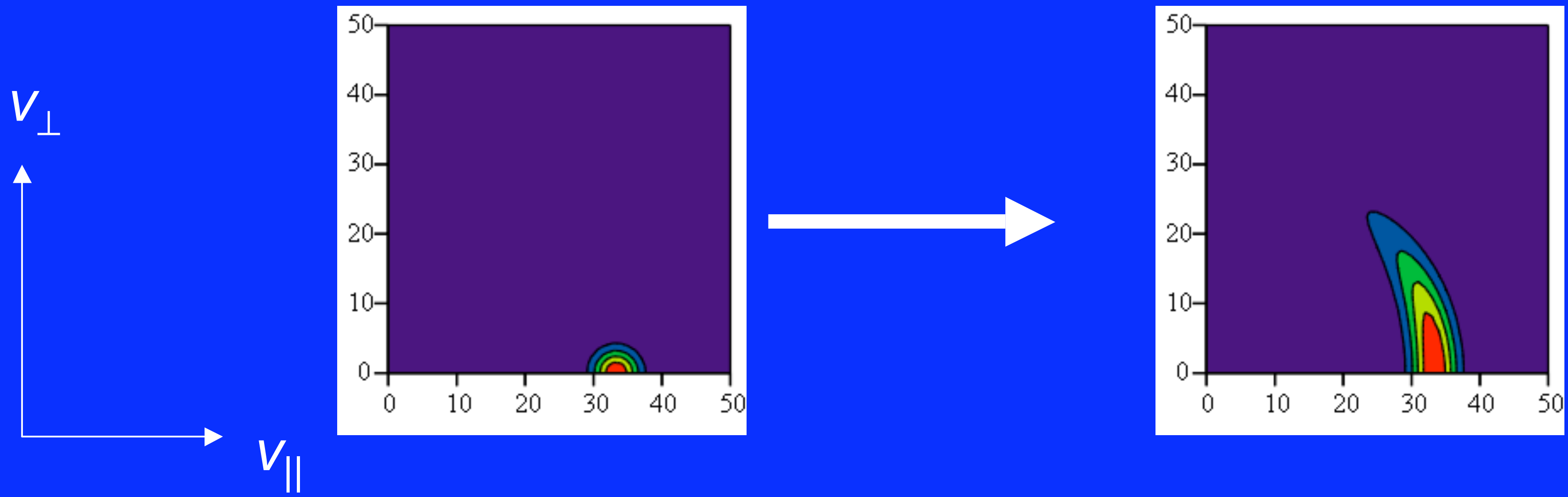
in general, so we have



Diffusion almost perpendicular to magnetic field - instability if there is a population inversion in this direction.

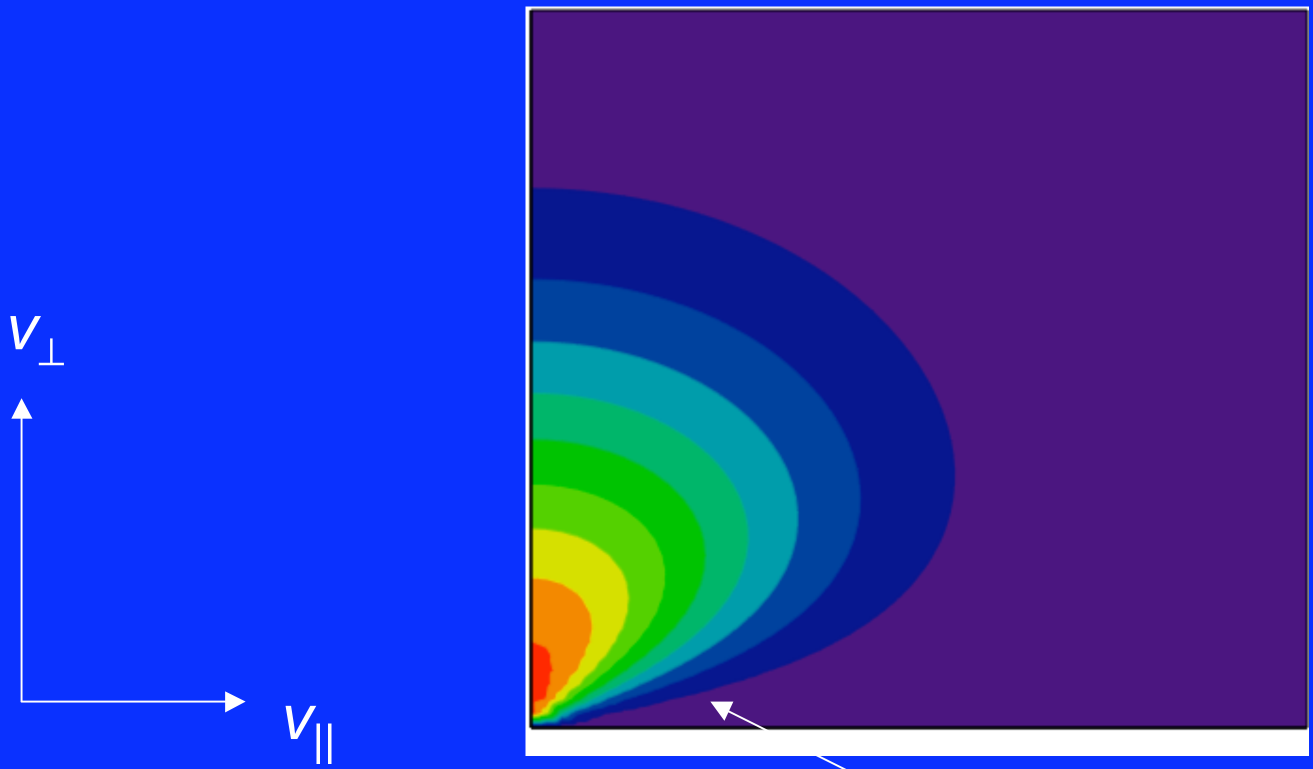
Horseshoe instability

Particle beam moving along converging magnetic field lines.
Conservation of magnetic moment and energy gives



Instability if resonant velocities lie around inside of horseshoe.
Likely source of auroral kilometric radiation.

Loss cone instability



Particles with low perpendicular velocity lost through magnetic mirror.

FAST data - Delory et al, GRL(12), 2069 (1998)

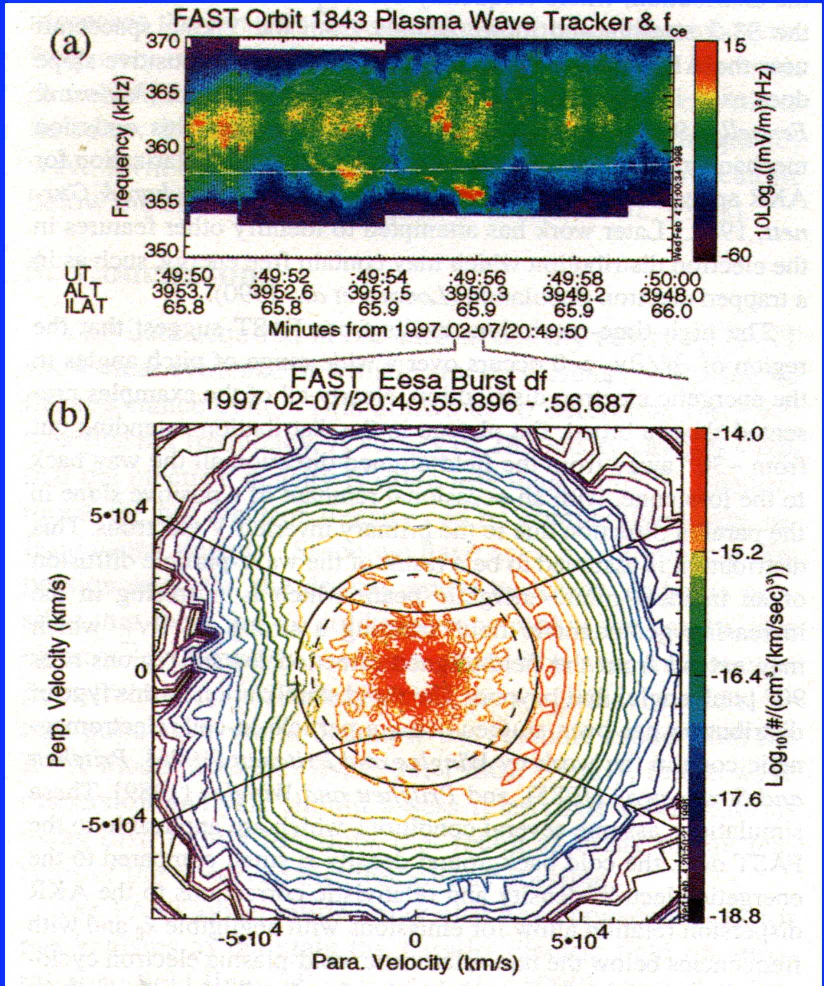
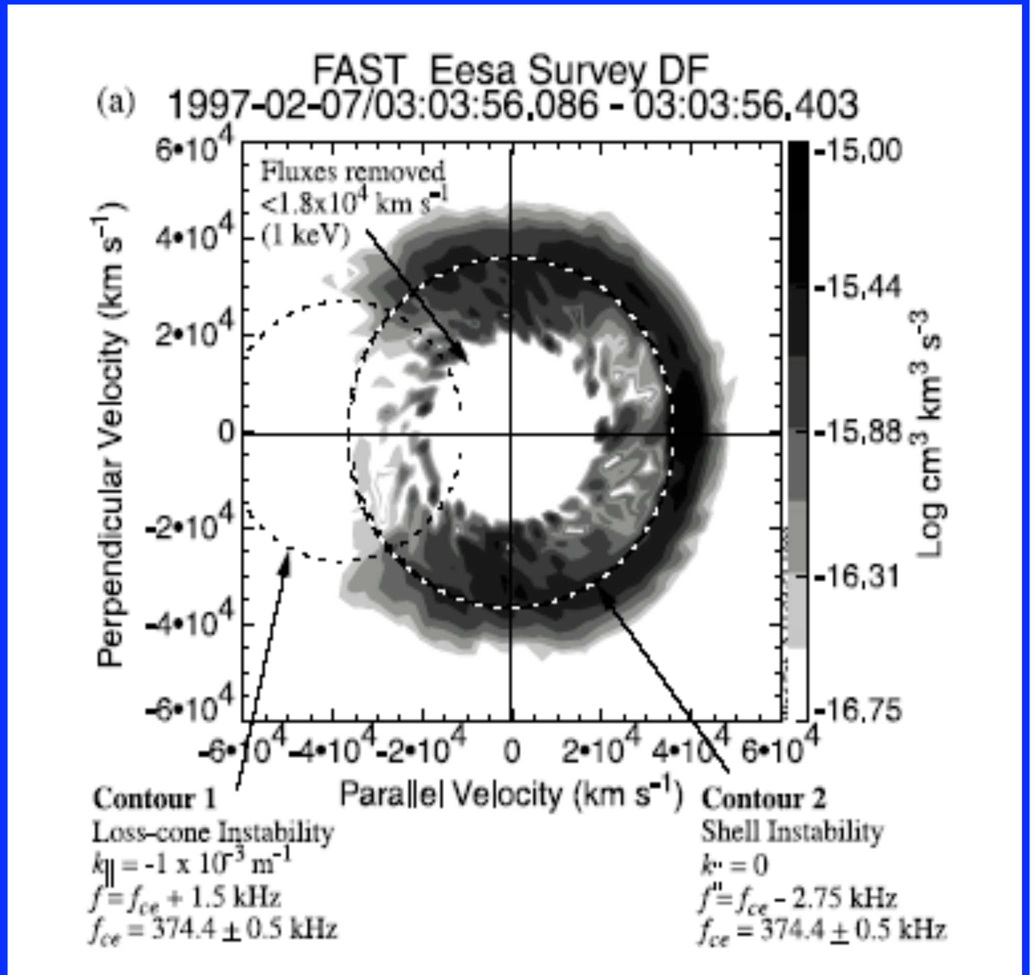
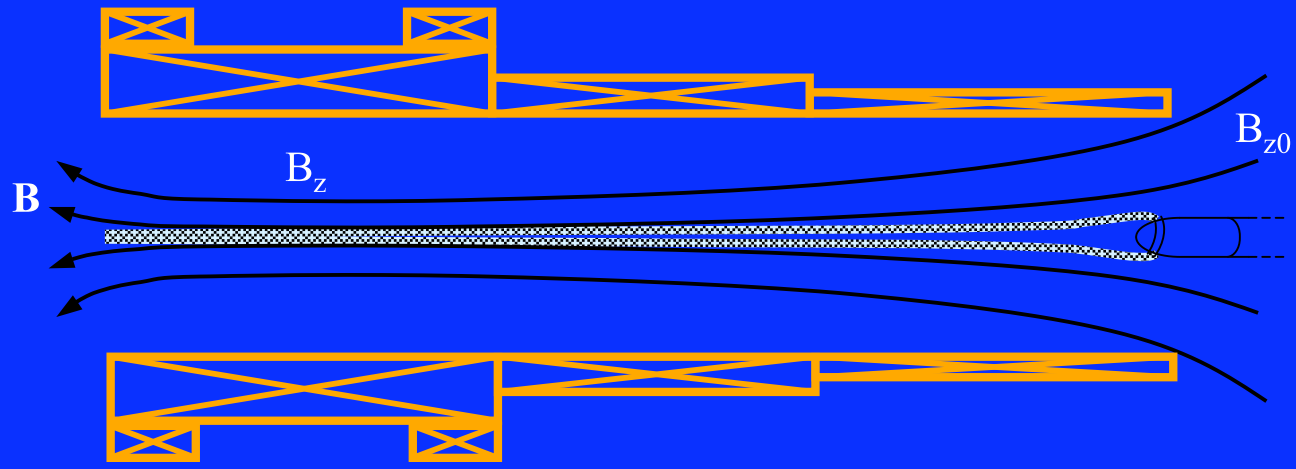


Figure 1. (a) Plasma Wave Tracker data and (b) electron contour plot for orbit 1843. The solid lines represent boundaries for adiabatic motion of electrons (see *Chiu and Schulz* [1978]), while the dotted inner circle shows the resonance condition with $k_{\|} = 0$ in Equation (1) for the AKR burst near ~20:49:56 UT.



The Strathclyde Experiment

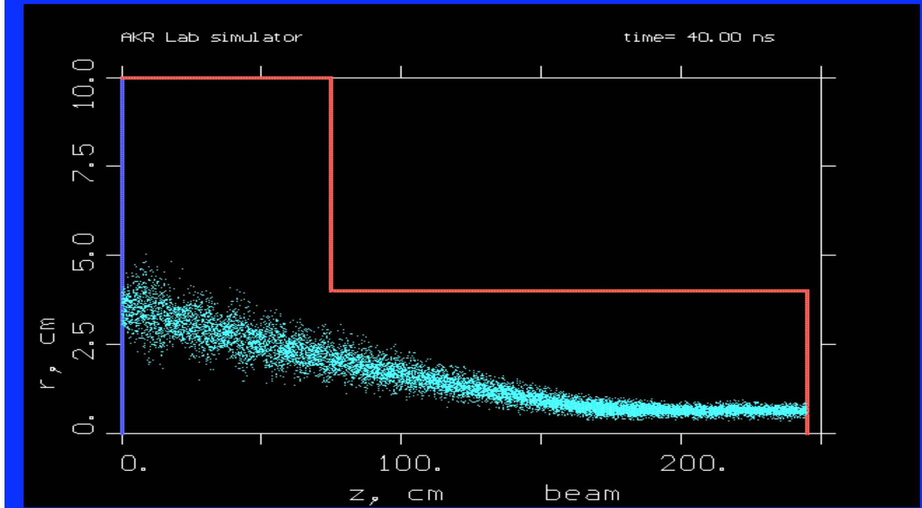


<u>Objectives</u>

- The examination (at GHz frequencies) of the instability attributed to AKR in a laboratory experiment.
- The interaction efficiency, bandwidth, and spectra of emission will be measured.
- A picture of electron velocity distributions will be sought.
- The emission should be mapped with axial position in the experiment.
- A picture of the emission polarisation will be obtained.
- All experimental data will be correlated with results from PIC (particle-in-cell) code simulations.

Results from the PIC code KARAT

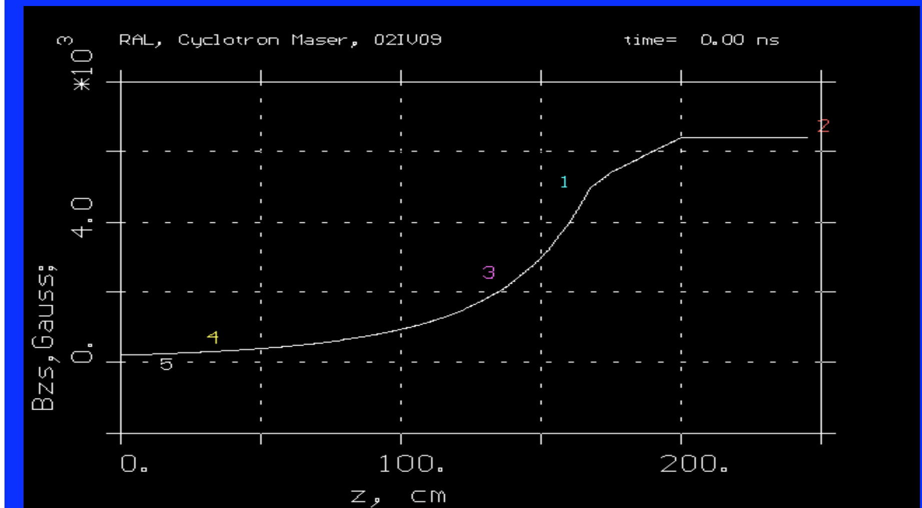
Simplified 40mm bounded simulation (5% energy spread)



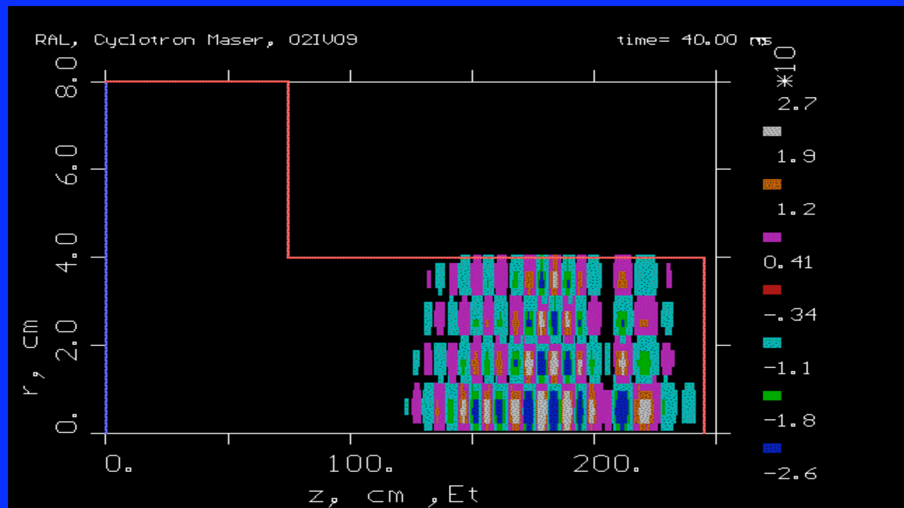
Simulation profile with beam trajectory after a 30ns run.
Anode, cathode and dielectric volumes are depicted

Simulation Parameters:-

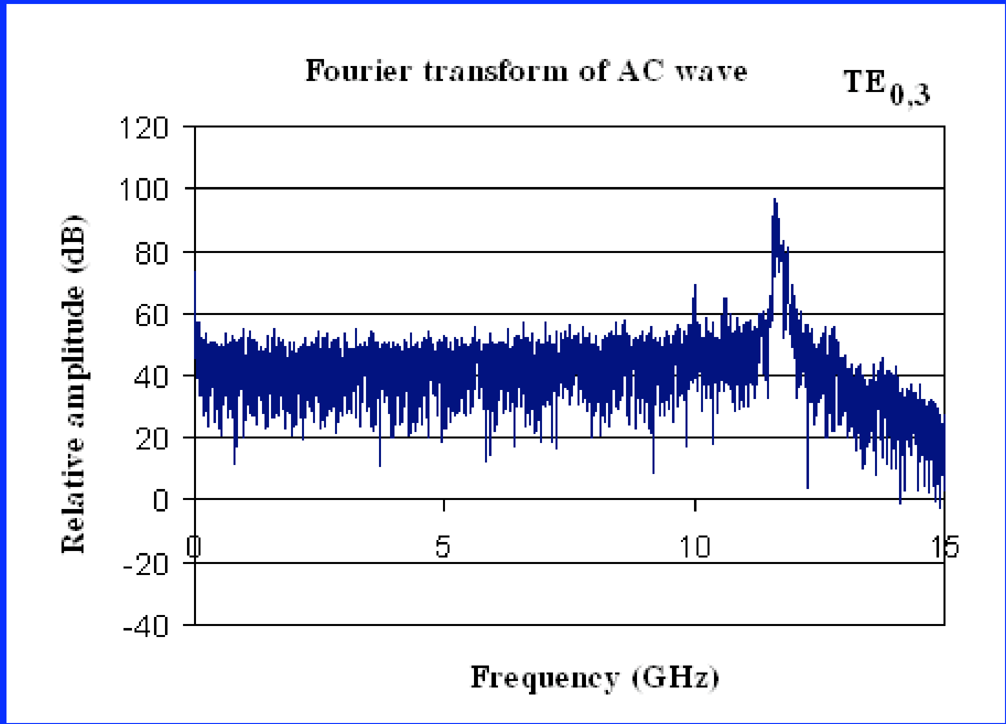
Radial thickness of injected beam = 1cm.
Beam energy = 50keV ; Beam current = 20A
Magnetic mirror ratio $B_z/B_{z0} = 32$ (Bz = 0.016T → 0.52T)



Axial magnetic field profile in simulation. Bz increases steadily from 0.016Tesla at the cathode to 0.52Tesla in the peak region.



Contour plot of transverse electric field E_t inside simulation geometry. The peak in emission is at z = 175cm.



Experimental result - narrow band emission in region of cyclotron frequency.
About 1-2% conversion from beam energy to em radiation - same order of magnitude as in AKR.

Future work

Put Penning trap into waveguide to give background plasma.

Look at effect of this on horseshoe instability.

Vary parameters of beam and background plasma so as to be able to investigate other beam-plasma instabilities in a well-controlled system.

Carry out relevant theoretical and computational analysis.

Relate to problems in magnetically confined plasmas, laser plasmas and space plasmas.

Possible instabilities

1. Anomalous Doppler.

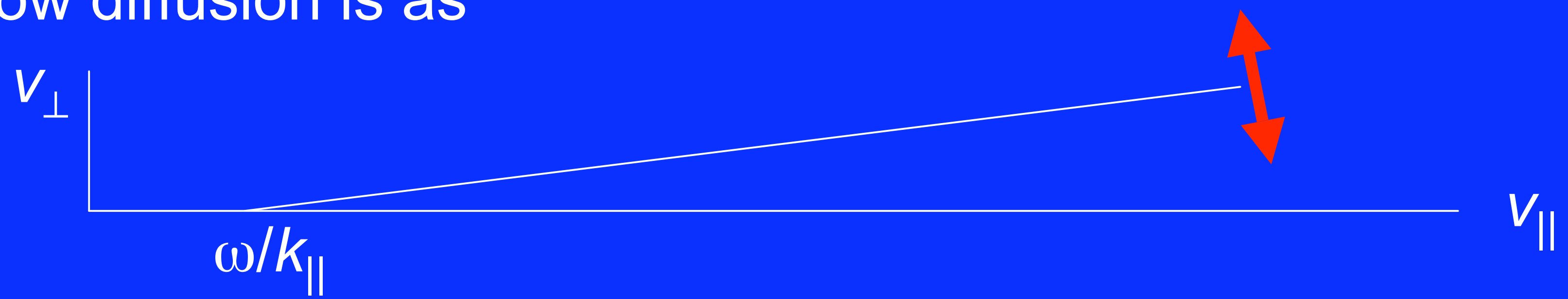
Cyclotron resonance condition with n=-1

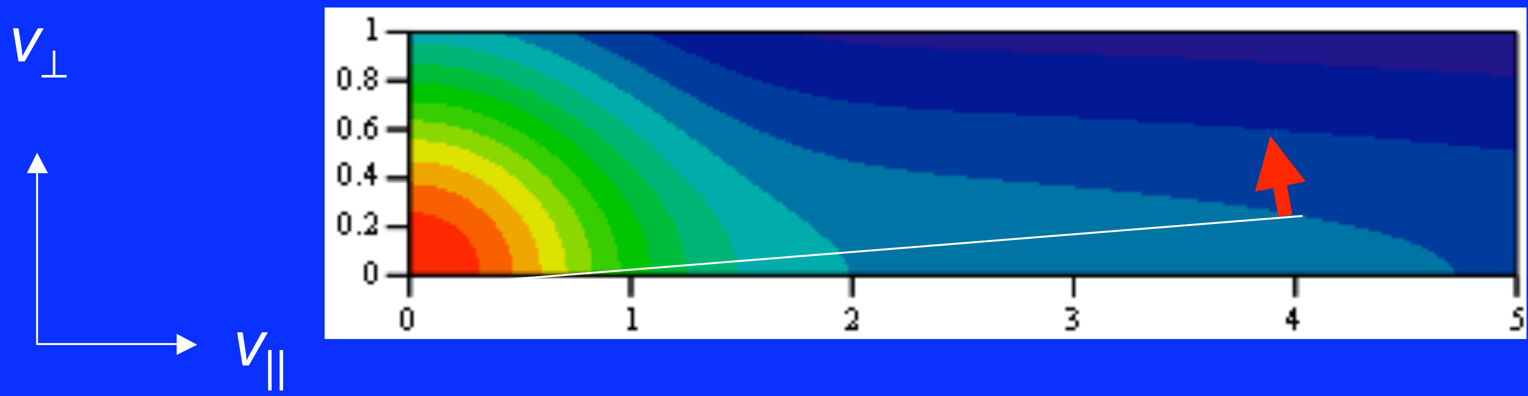
$$\omega = -\omega_c + k_{||} v_{||}$$

$$v_{||} = \frac{\omega + \omega_c}{k_{||}}$$

If $\omega \ll \omega_c$ get slow wave interacting with much faster particle.

Now diffusion is as





Distribution with tail. Diffusion in direction shown - energy decreasing. Destabilises low phase velocity wave.

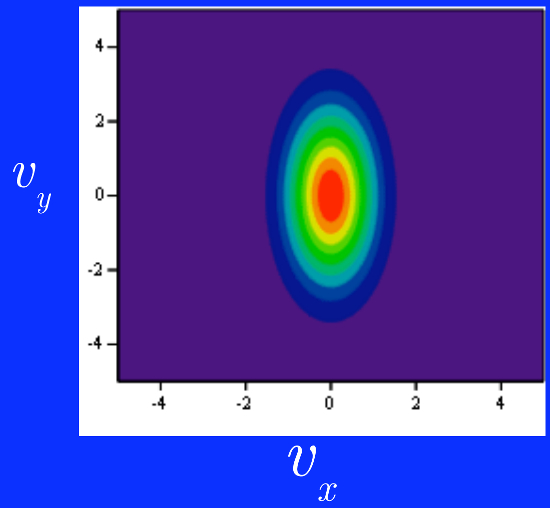
Distributions like this are relevant to lower hybrid current drive in tokamaks.

Instead of producing a tail, a possibility in the experiment could be to make waveguide which can support a slow wave.

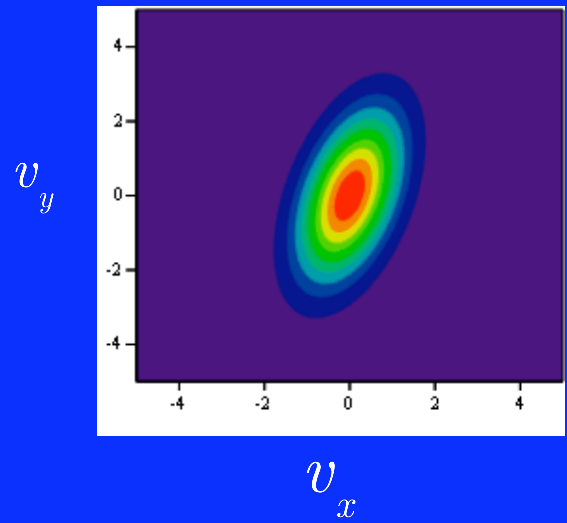
2. Weibel instability

This is an electromagnetic instability generated by an anisotropic electron distribution.

Suppose we have a distribution in the *x*-*y* velocity plane like



B field in z direction rotates this



Particles with +ve v_x have net flux in +ve *y* direction.

Now suppose that a B field oscillating in *x* is set up with a zero at *x*=0.

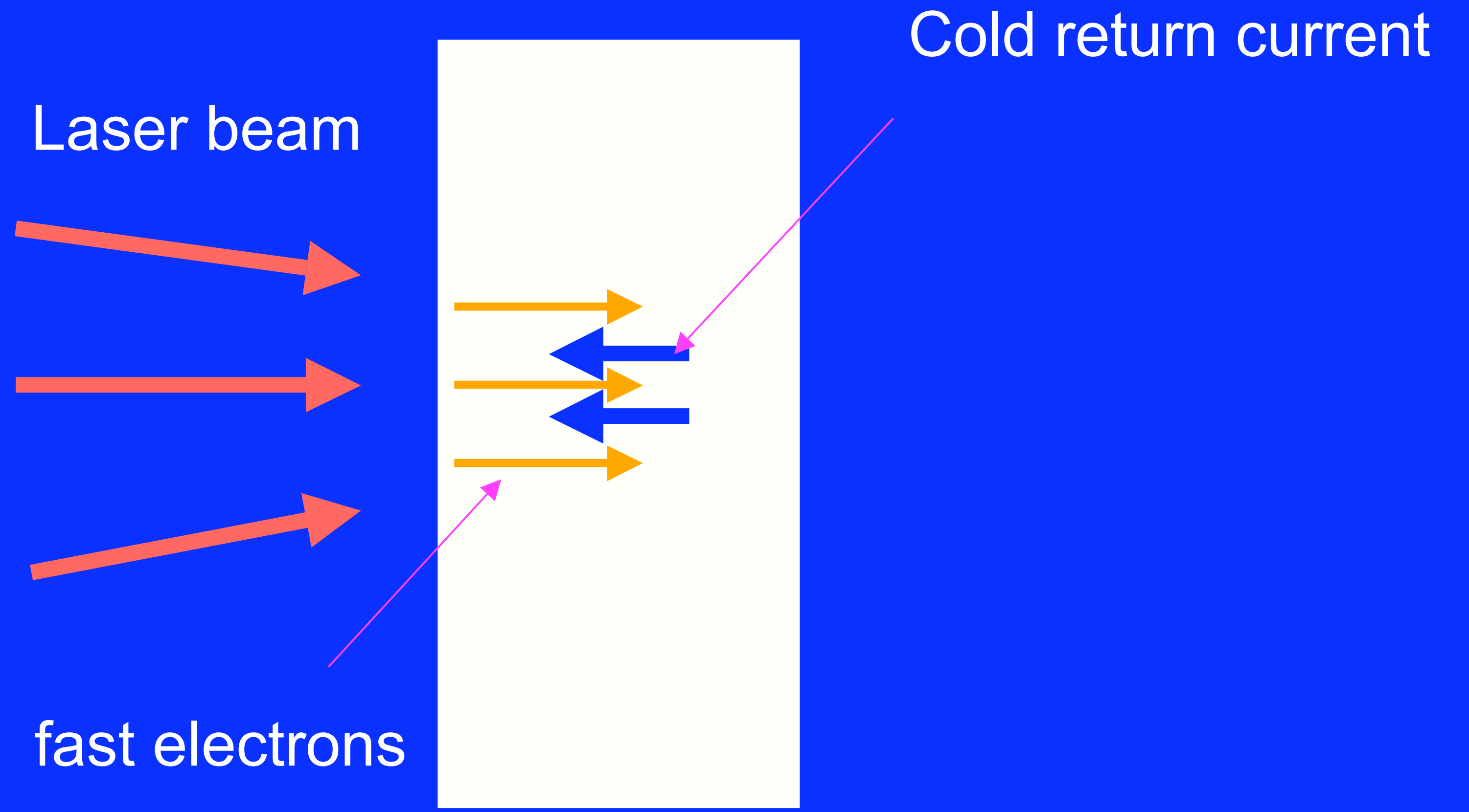
If particles coming from left rotate as shown they produce a positive *y* flux. Particles from other side have negative v_x but rotate in opposite direction since field is reversed - again a +ve *y* flux. Current produced is such as to reinforce magnetic field oscillation - purely transverse growing mode with wavevector perpendicular to long axis of velocity distribution.

In the derivation of the growth rate from the linearized Vlasov equation, the instability is driven by the term

$$\mathbf{v} \times \mathbf{B} . \frac{\partial f_0}{\partial \mathbf{v}}$$

which vanishes if f_0 is isotropic.

Laser plasma.



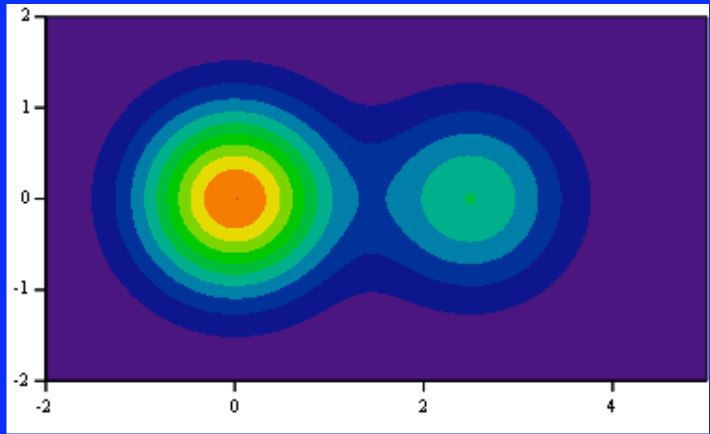
Elongated distribution from superposition of fast electrons and cold return current.

Weibel instability can break current up into filaments.

3. Two stream.

Electrostatic instability produced from interstreaming electron beams.

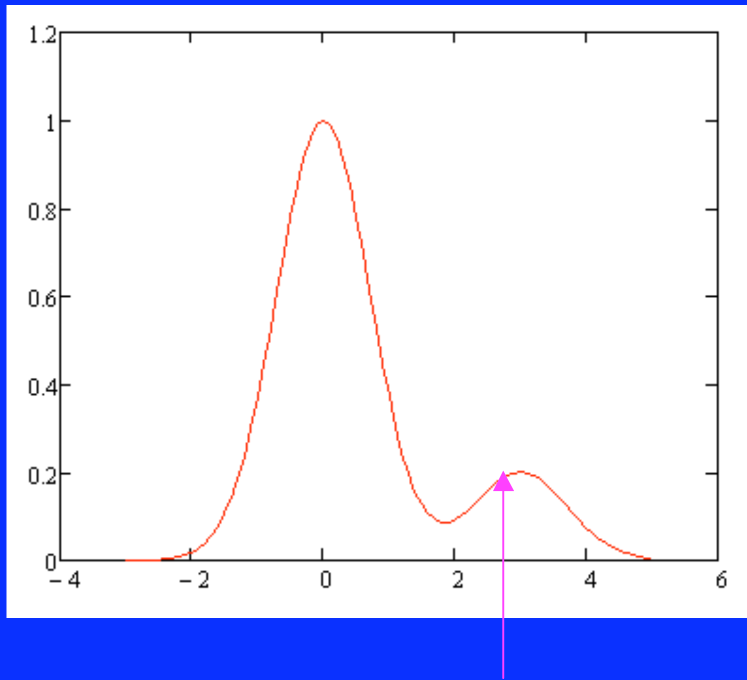
$v_\perp$



$v_{||}$

Diffuse beams - “bump on tail instability” driven by inverse Landau damping.

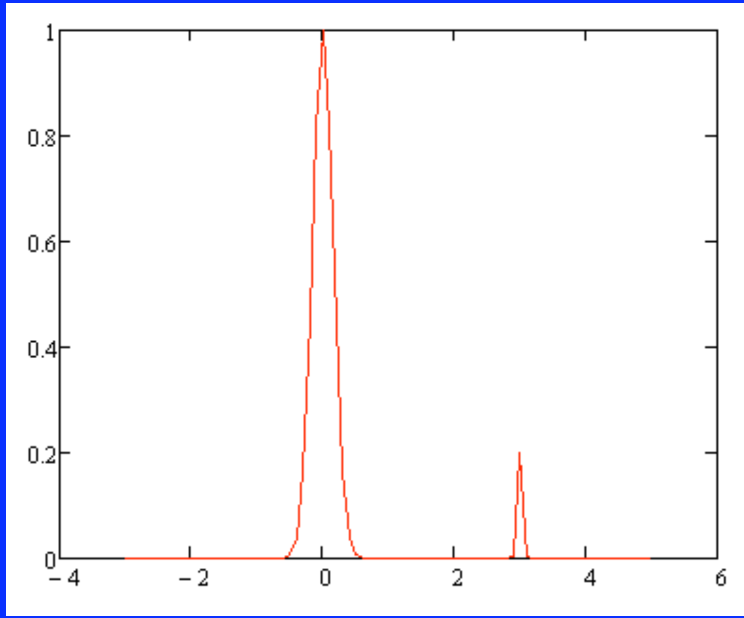
$f(v_{||})$



$v_{||}$

$\frac{\omega}{k_{||}}$

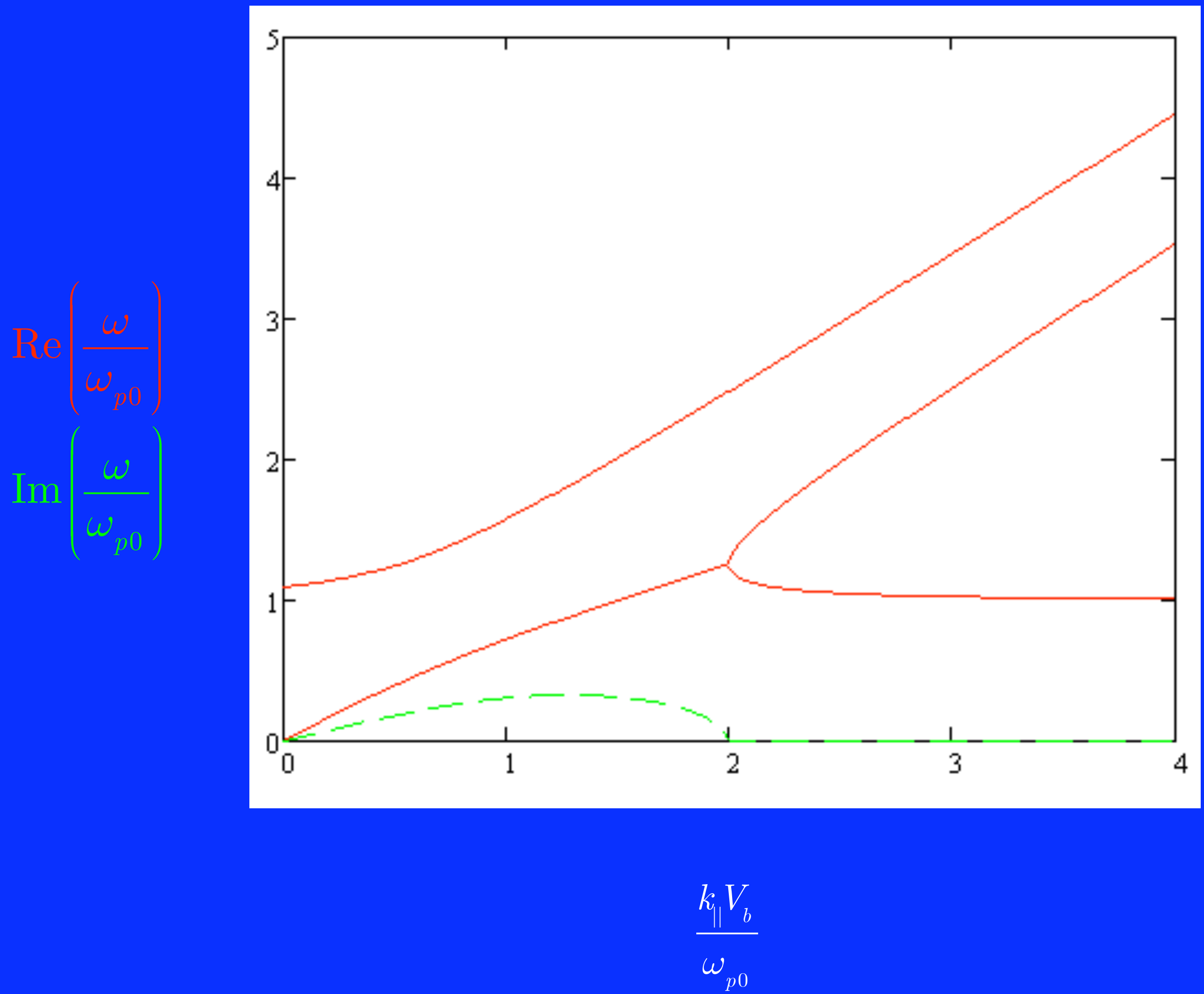
Well separated - two stream driven by interaction between bulk mode and beam mode. Latter is negative energy mode.



$f(v_{||})$

$v_{||}$

Dispersion relation



Beam modes

$\omega \sim \pm\omega_{pb} + k_{||}V$

Bulk mode

$\omega \sim \omega_{p0}$

Conclusions

- Successful experiment on horseshoe instability. Good agreement with theory and simulation.

See McConville et al PPCF **50**, 074010 (2008), Speirs et al PPCF,**50**, 074011 (2008) for further details.

- Extend to include background plasma.
- Challenge for future - identify regimes in which various possible beam instabilities can be generated cleanly.
- Compare experiment with simulations and theory.
- Relate results to situations of interest in laboratory and space plasmas.