Alpha Channeling

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Channeling is enhanced cooling of fusion alpha particles and the removal of this cool ash from the fusion device

Outline

Motivation
ORBIT simulations for ITER
Cyclotron Induced Cooling
Alfvén mode ash removal
Combined cyclotron cooling and Alfvén mode ash removal
Conclusion

Motivation

- Models for channeling have been present for many years, but a full guiding center simulation never performed.

- Models consist of both slab geometry and toroidal geometry diffusion calculations looking for steady state with a source, losses, and a low energy sink representing mode induced ash removal.

- Guiding center simulations can better reveal possible loss mechanisms

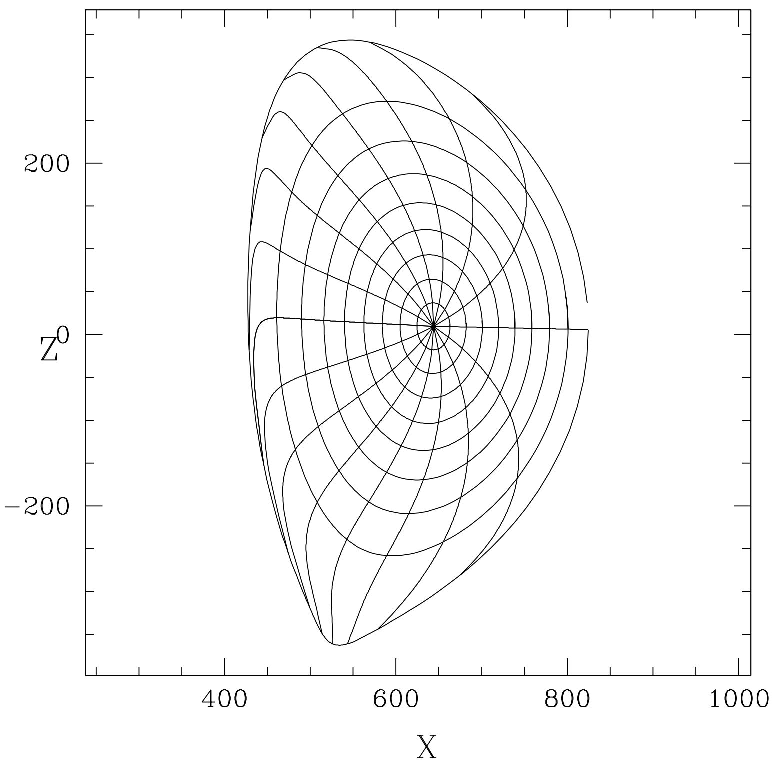
- Perhaps some effect not included in the models can be revealed

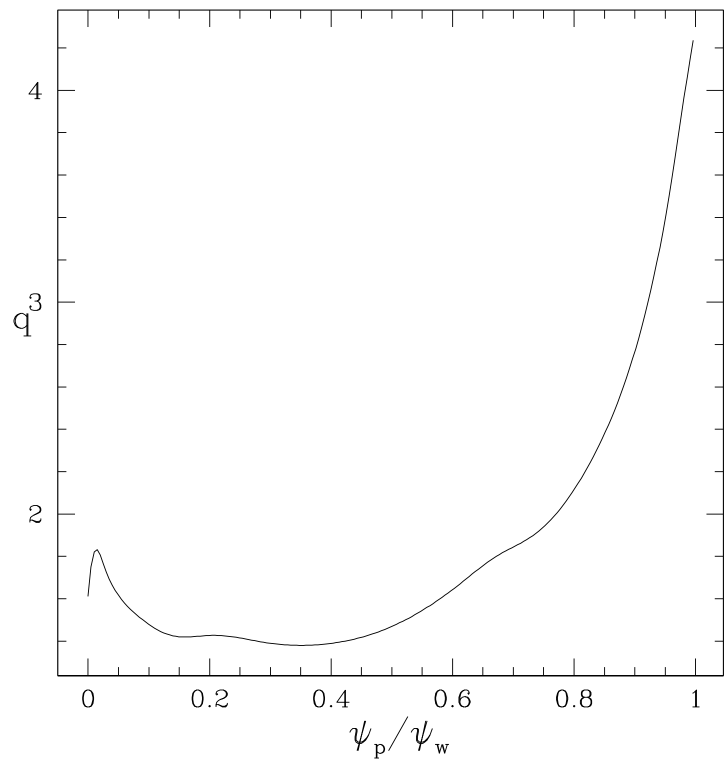
- We choose to follow the full time history of an alpha particle birth profile rather than looking for steady state.

Numerical equilibrium

We consider an equilibrium based on the ITER baseline scenario at Q=10, $q_{95} = 3.0$, type-I ELMY H-mode (inductive plasma). The equilibrium and profile for q for ITER38530D46 at 6 sec.

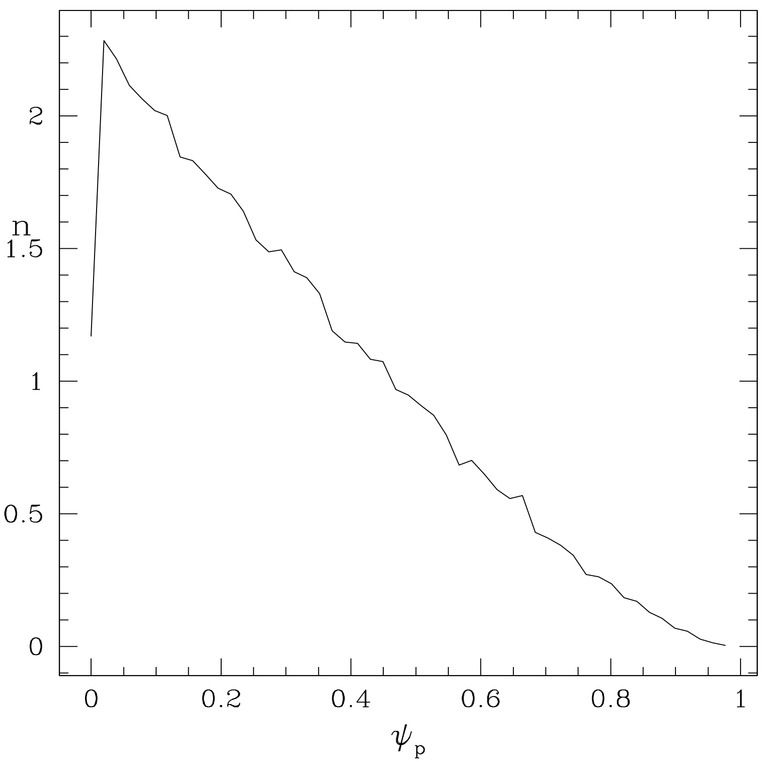
The field on axis was 52.6 kG.

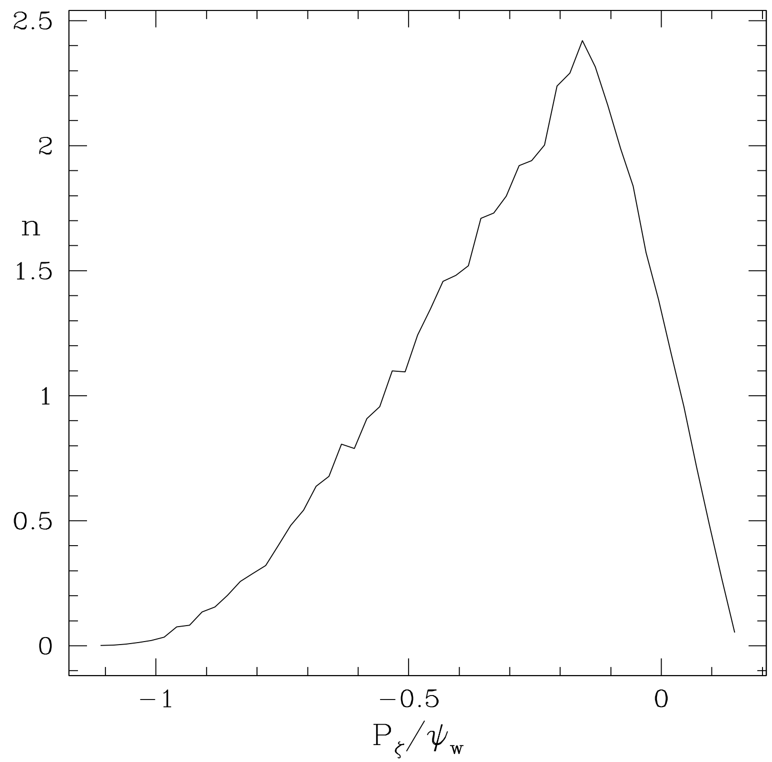




Particle Distribution

Monoenergetic at 3.5 MeV, uniform in pitch, and exponential in poloidal flux, $n \sim e^{-5\psi_p/\psi_w}$ with ψ_w the poloidal flux at the last closed flux surface. This distribution has a prompt loss population of less than 1 percent.





Hamiltonian Guiding Center Code

The Hamiltonian is $H = (\rho_{\|} - \alpha)^2 B^2/2 + \mu B + \Phi$

$$\alpha = \sum_{m,n} A_n \alpha_{m,n}(\psi_p) sin(\Omega_{mn}), \quad \Phi = \sum_{m,n} A_n \Phi_{m,n}(\psi_p) sin(\Omega_{mn}),$$

$\Omega_{mn} = n\zeta - m\theta - \omega_n t - \phi_n,$

Equations of motion

$$\dot{\theta} = \frac{\partial H}{\partial P_\theta} \qquad \dot{P}_\theta = -\frac{\partial H}{\partial \theta}$$
$$\dot{\zeta} = \frac{\partial H}{\partial P_\zeta} \qquad \dot{P}_\zeta = -\frac{\partial H}{\partial \zeta},$$

Canonical momenta

$$P_\zeta = g\rho_{\|} - \psi_p, \qquad P_\theta = \psi + \rho_{\|} I,$$

ψ is the toroidal flux, with $d\psi/d\psi_p = q(\psi_p)$, the field line helicity.
The variable $\rho_{\|} = v_{\|}/B$ is the normalized parallel velocity.

Cyclotron Cooling

Cyclotron mode produces diffusion of particles in a range of major radius X around the cyclotron resonant surface with $X_1 < X < X_2$.

A particle in this domain is given a random step in energy in time dt, resulting in producing diffusion in energy, $D = dE^2/(2dt)$

The magnetic moment μ is stepped with $d\mu B_c = 3dE/2$.
The IBW frequency is chosen to have absorption at the tritium cyclotron frequency $\omega_{cT}/\omega_{c\alpha} = 2/3$. In the narrow layer approximation mode conversion takes place close to the absorption region.
The canonical momentum is stepped according to

$$dP_\zeta = ndE/\omega$$

where ω is the mode frequency and n the toroidal mode number.

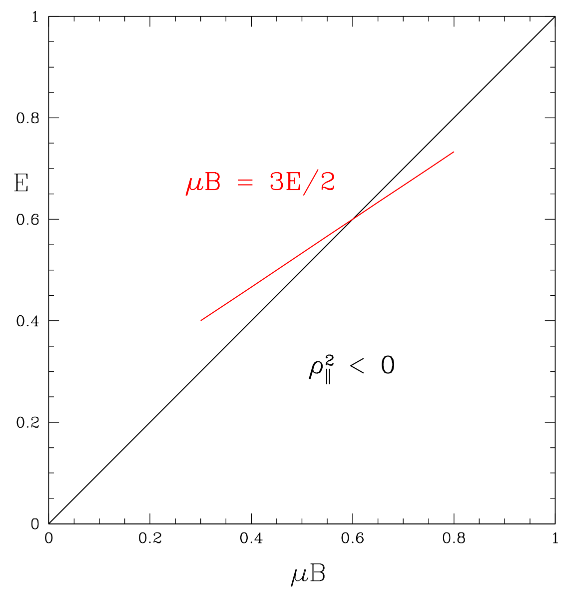
The cyclotron frequency is $\omega_c = 10^8/sec$
toroidal mode number between 30 and 1000.

Cyclotron cooling

How can diffusion in energy produce cooling?

The magnetic moment μ is stepped with $d\mu B_c = 3dE/2$

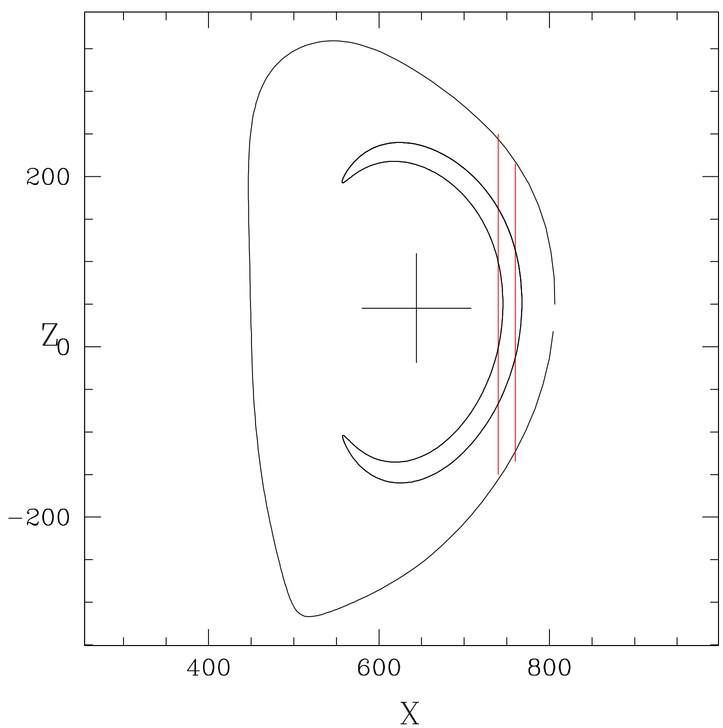
Particles near the boundary $E = \mu B$ can be stepped down in energy with no problem, but they cannot be stepped up in energy if the step crosses the limit $B\mu = E$. This asymmetry produces the cooling.



Radial motion while cooling

$P_\zeta = g\rho_\parallel - \psi_p$ and $ndE = \omega dP_\zeta$ gives $d\psi_p = gd\rho_\parallel - (n/\omega)dE$

From $\rho_\parallel^2 B^2 = 2(E - \mu B)$ and $d\mu B = 3dE/2$ have $d\psi_p = -\left[\frac{g}{2\rho_\parallel B^2} + \frac{n}{\omega}\right] dE$



An orbit when crossing the resonance has $\rho_\parallel$ smaller when negative.

Negative $\rho_\parallel$ acts to cancel the n/ω term

Previous conclusion that particles move out as they cool is not valid.

In fact, simulations show particles remain at same radius or are squeezed toward the magnetic axis while cooling.

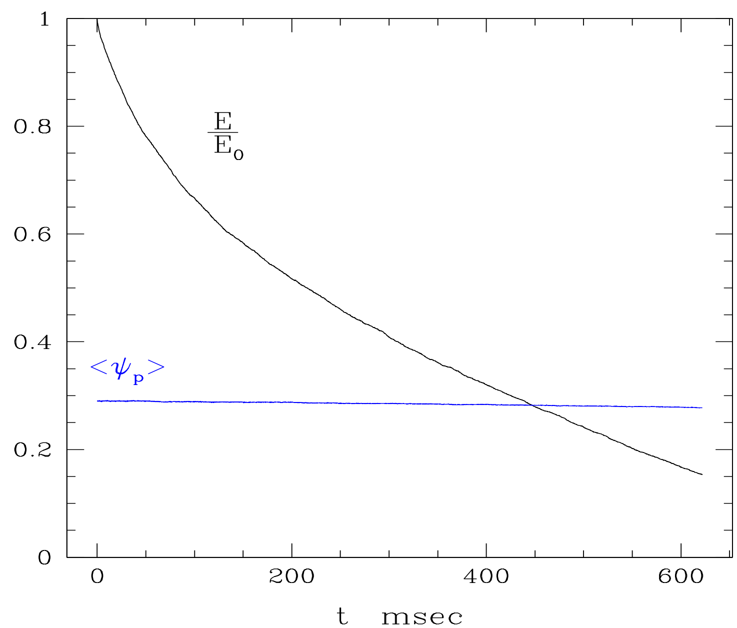
Diffusion models assume ash moves to the plasma edge, where it is easily removed.

Cyclotron Cooling

A cyclotron resonance in the plasma can produce cooling in a time shorter than the one second slowing down on electrons.

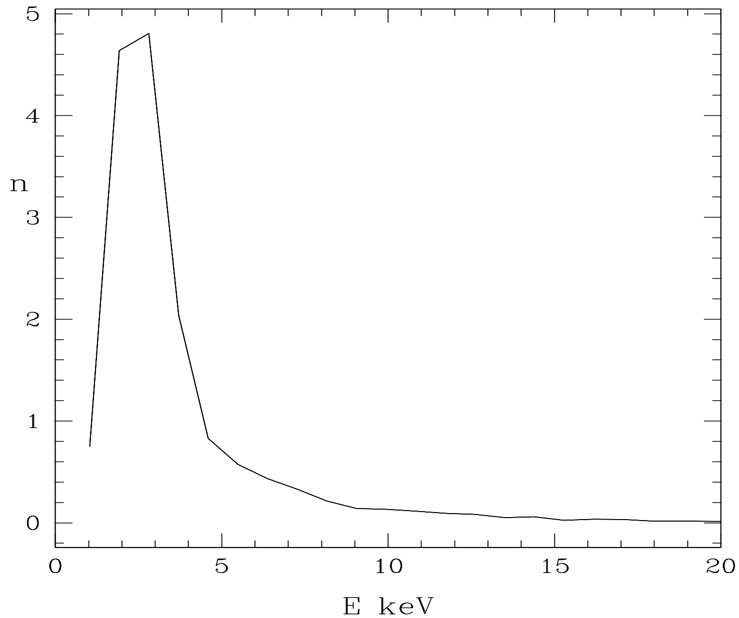
Cyclotron diffusion $D = 300 MeV^2/sec$, and slowing down at $1/sec$.
Resonance for $660 < X < 665$, with $\omega_c = 10^8$, $n = 30$.

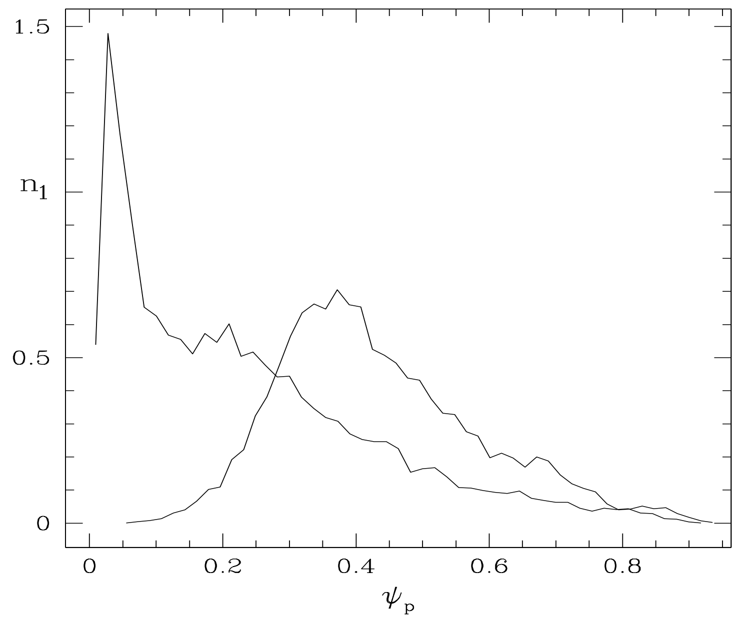
Particle energy and mean location of particles vs time.
There is no transport of particles toward the plasma edge.



Cyclotron Cooling

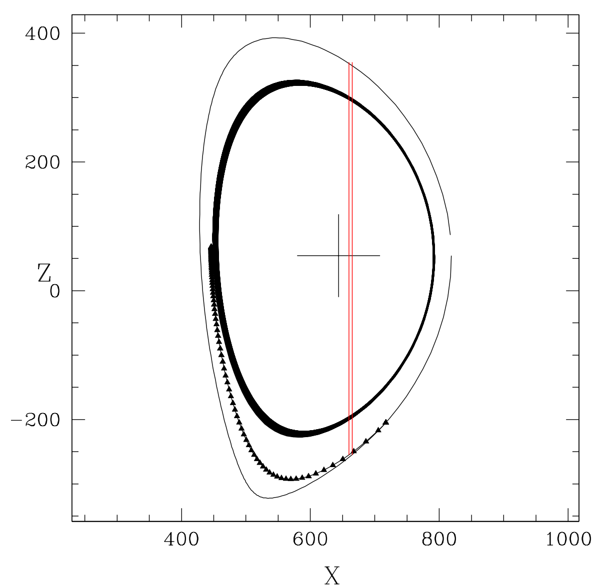
Cyclotron diffusion $D = 300 MeV^2/sec$, and slowing down at $1/sec$.
Resonance for $660 < X < 665$, with $\omega_c = 10^8$, $n = 200$, and 1000.
Lost 0.6 percent, 2/3 passing, 1/3 trapped.
Left - Final confined particle energy distribution at $t = 1 sec$.
Right - Confined cool particle radial distributions, peaked in the center for $n = 200$, and at $\psi_p = 0.4$ for $n = 1000$.

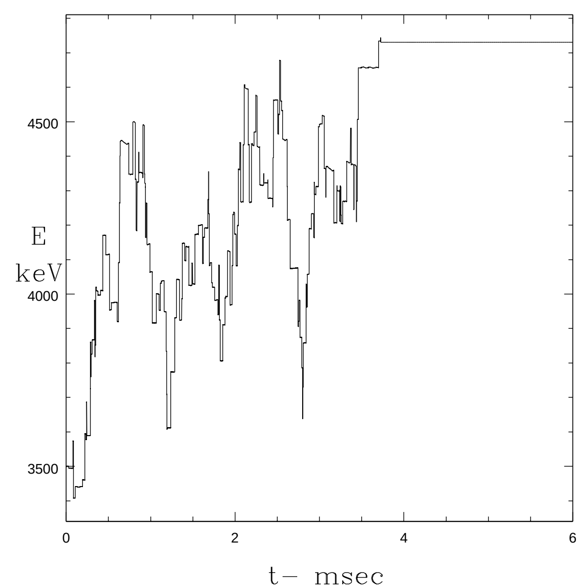




Cyclotron induced loss

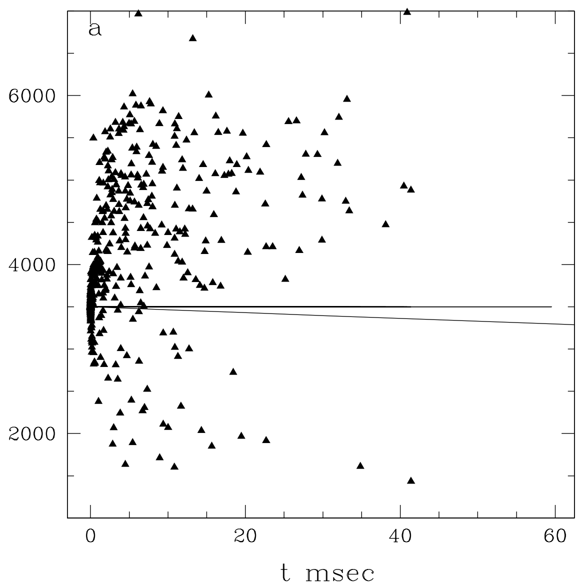
Example of cyclotron resonance induced loss.
Primary loss is due to a particle in a counter moving passing orbit diffusing to higher energy
Energy is increased and the particle in moved inward in poloidal flux, but μ increases even more, causing the particle to transition to a trapped loss orbit

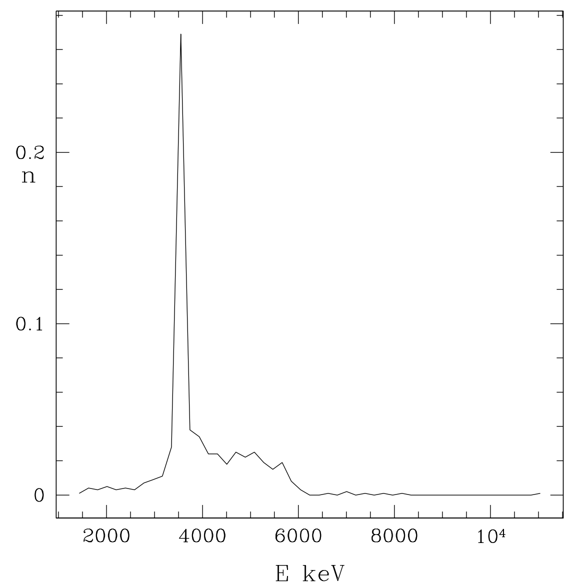




Cyclotron induced loss

Cyclotron diffusion $D_c = 300MeV^2/sec$, and slowing down at $1/sec$.
Resonance for $660 < X < 665$, with $\omega_c = 10^8$, $n = 30$.
Lost particle energy distribution history
$3500e^{-t}$, the slowing down trajectory.
Lost particle energy distribution, mean energy 4 MeV.





Ash removal with Alfvén mode

Must find mode with resonances all across the plasma to remove ash

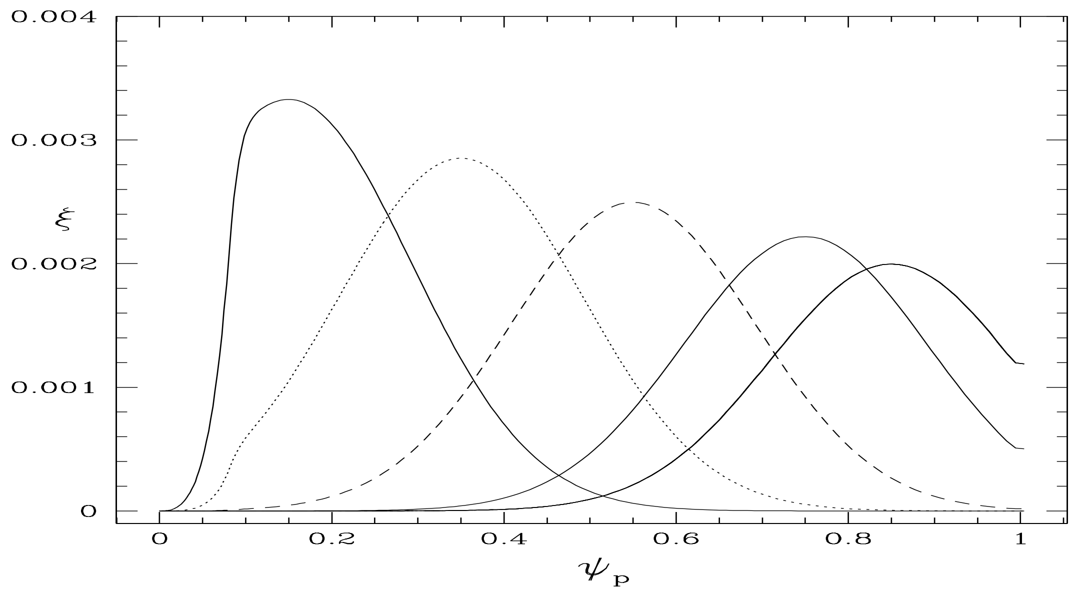
$$\delta\vec{B} = \nabla \times \alpha\vec{B}$$

$$\alpha = \sum_m \alpha_m(\psi_p) sin(n\zeta - m\theta - \omega t)$$

Low frequency, 6 kHz to resonate with low energy

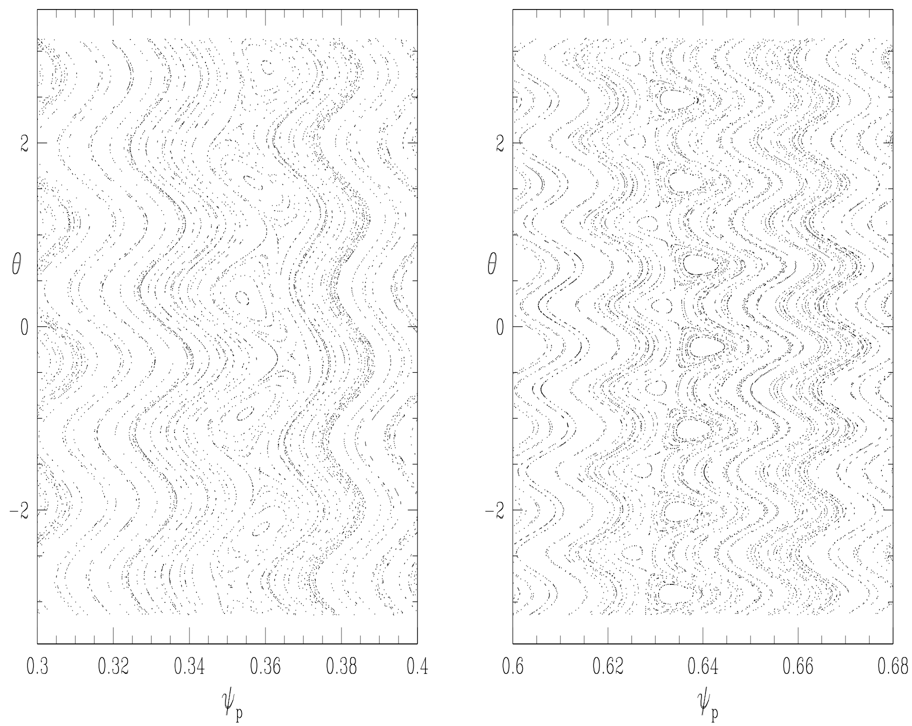
Harmonics of mode used for ash removal

m/n = 4/5, 5/5, 6/5, 7/5, 8/5.



Ash removal resonances

These modes produce a sequence of resonances spanning the plasma
Resonances found using phase vector rotation, and shown with Poincare
$m = 4, 7$



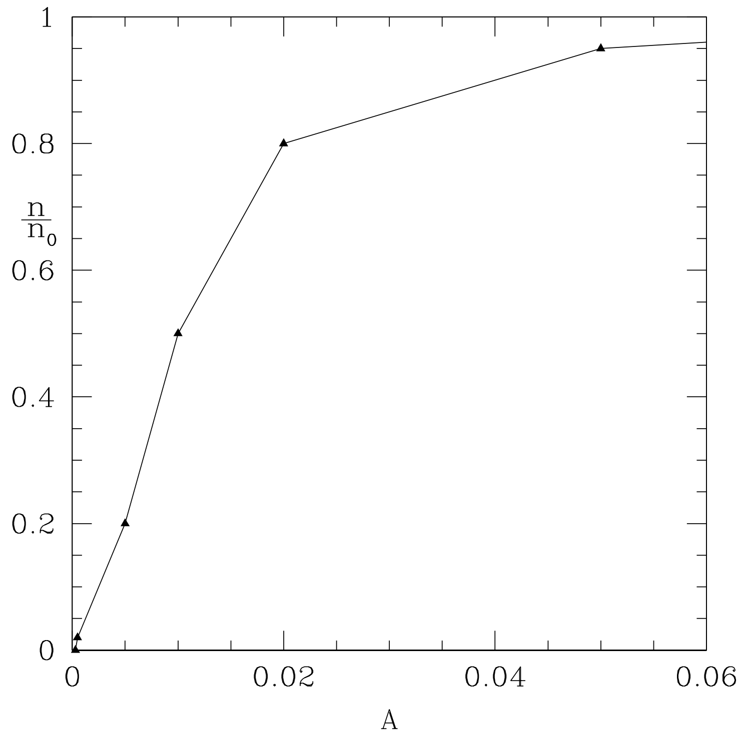
Resonances at $\psi_p = .02, 0.2, 0.39, 0.41, 0.53, 0.55, 0.67, 0.74, 0.81, 0.95$.

Ash removal with Alfvén mode

Loss in 600 msec as a function of mode amplitude.
Initial distribution radially same as alphas, but $E = 10keV$

Threshold for loss at $A = .001$

Faster transport expected with cyclotron resonance also present



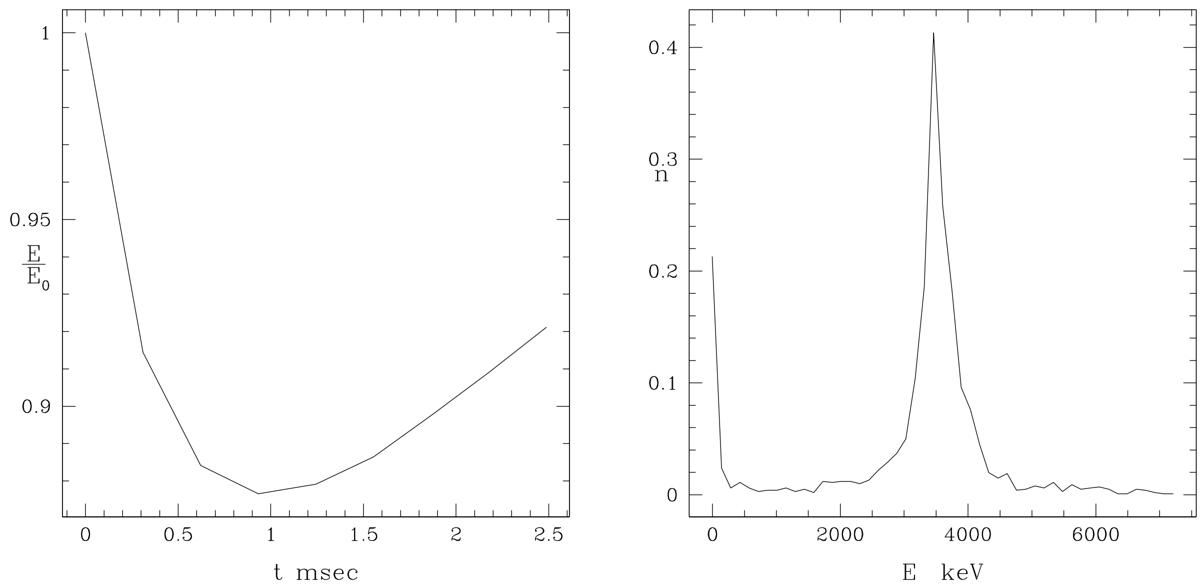
Cyclotron Alfvén Heating

Time evolution of total energy E/E_0 showing initial cooling followed by heating, and the energy distribution at $t = 0.6\ msec$.

Cyclotron $660cm < X < 665cm$, $D = 300Mev^2/sec$, $A = .002$.

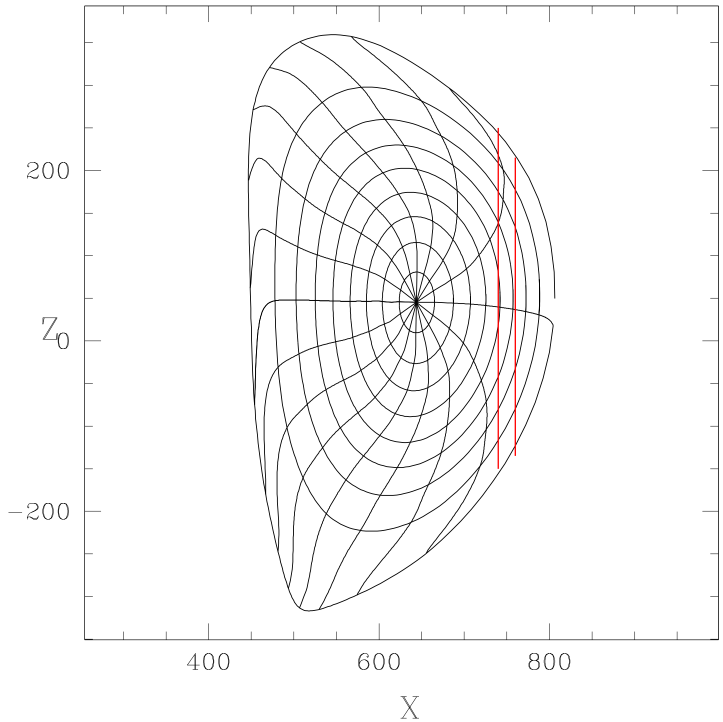
The cyclotron mode produces a strong negative gradient in the energy profile above 3.5 Mev, giving heating and loss of high energy particles.

Alfvén mode must be weak compared to cyclotron



Cyclotron resonance Location

Cyclotron Resonance domain placed close to axis or near the edge.

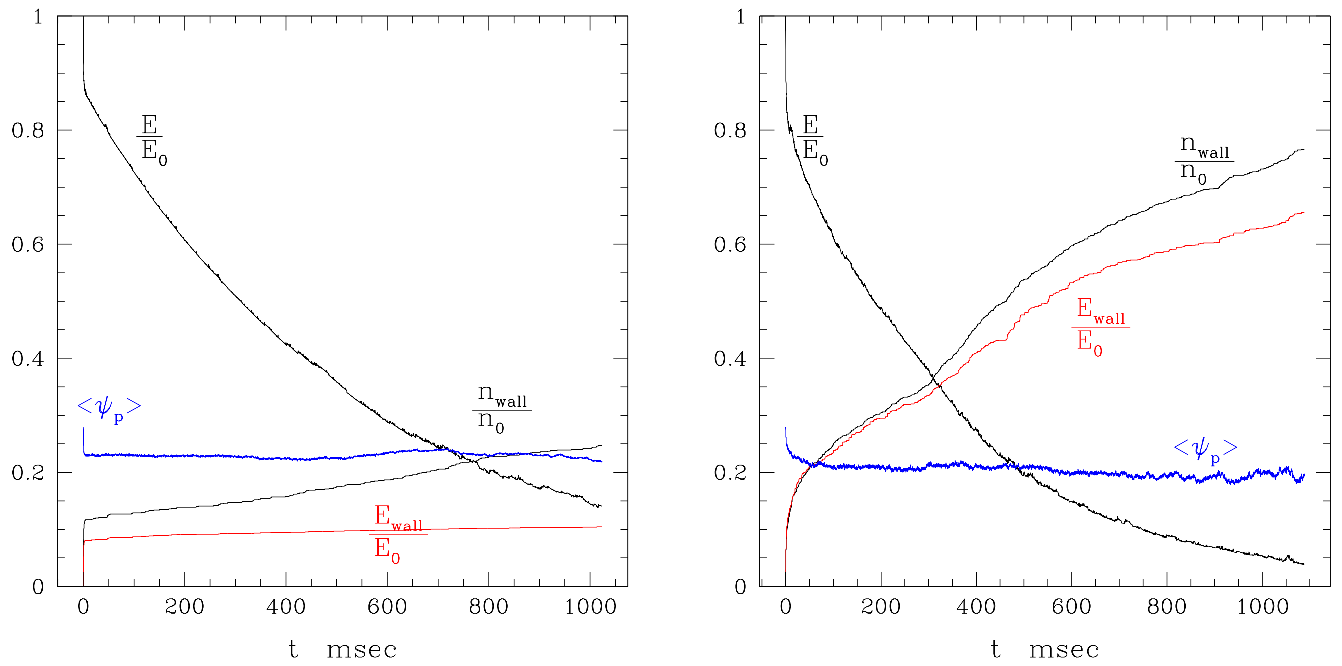


Near axis :
more particles enter resonance,

Near edge :
Alfvén mode causes particles
to move through cyclotron resonance
and cool before exiting.

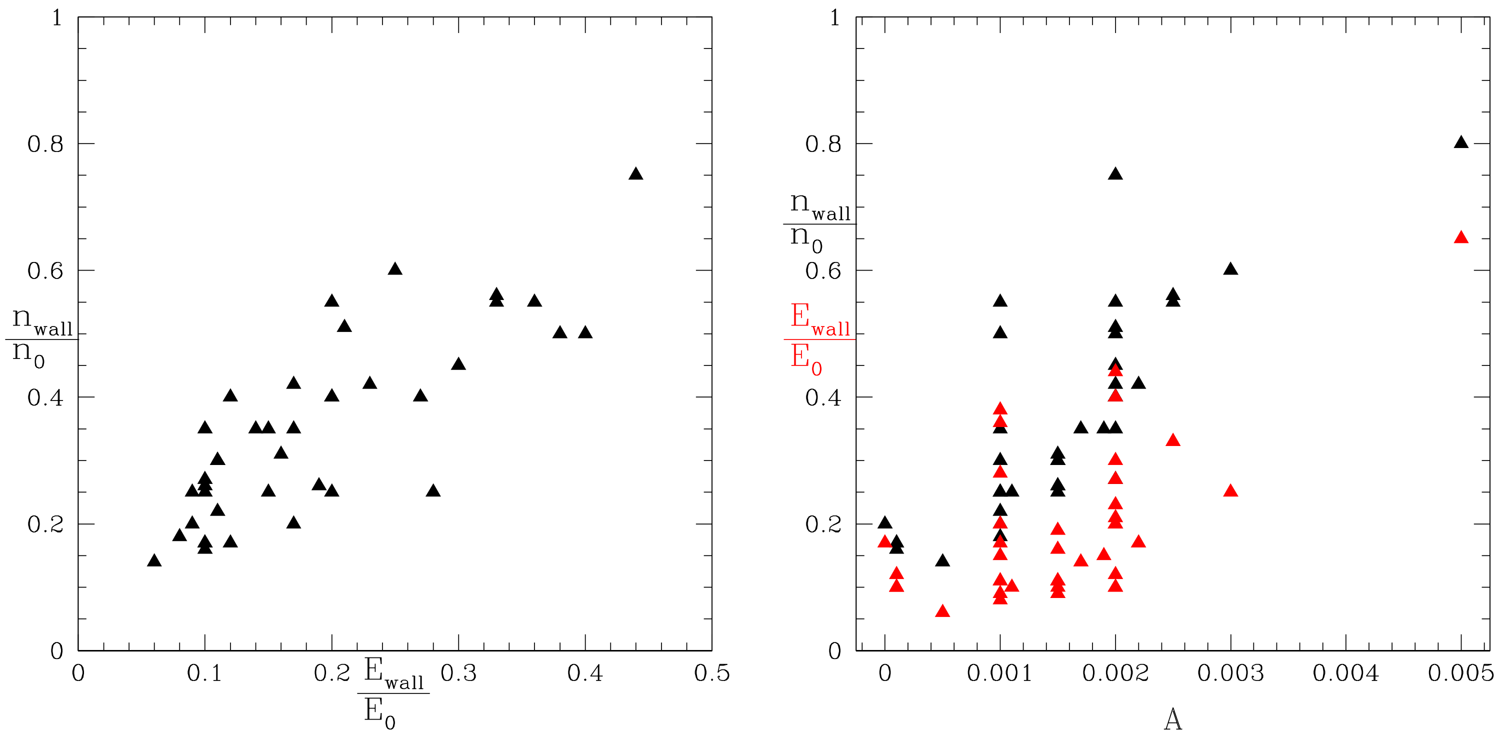
Cyclotron Alfvén Simulation

Time evolution of confined energy showing cooling
fraction of initial energy and of particles lost, mean ψ_p, and lost energy.
Particle loss but also at least ten percent energy loss
Heating by the combination of the cyclotron and the Alfvén mode.
Significant high energy loss before cooling takes place
$A = .0011$, $d = .006$, and $A = .005$, $d = .05$, $dE = \pm d * dt$



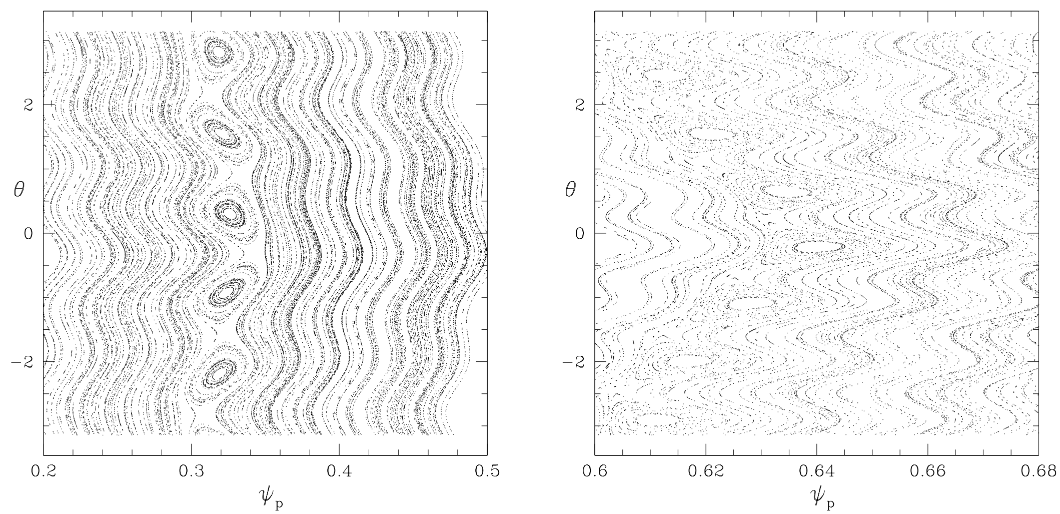
Cooling and induced loss

Fraction of total energy and particles reaching the wall.
Ash removal is small energy loss and large particle loss.
$.0005 < A < .0025$, $300 MeV^2/sec < D < 5000 MeV^2/sec$
$E_{wall}/E_0 > .05$ gives significant wall damage
$E_{wall}/E_0 > .25$ stops ignition



Resonance at High energy

alpha channelling requires ejection of only low energy alpha particles
But if there is a resonance at low energy it exists also at high energy
Resonances due to the 4/5, 7/5, harmonics of the 6 kHz mode
Moving up in energy, the resonances stay at ψ_p except for drift
Poincare plots at 1 MeV



Conclusion

Cooling of alpha particles using cyclotron resonance is feasible.
A cyclotron resonance is capable of producing cooling.
Agrees with previous results.
A cyclotron resonance with toroidal mode number $n = 30$ gives cooling
The cooled distribution is deep in the center of the plasma
Only very large unphysical n can move particles toward the edge

Ash removal with additional Alfvén modes is not successful
Alfvén modes with resonances at low particle energies
also have resonances at high particle energies
high energy particles deposition on the wall cannot be avoided

We find no combination of mode amplitudes producing cooling
and ash removal without also causing a significant fraction of the total
particle energy to be deposited on the walls.