Non-Resonant Particle Heating due to Collisional Separatrix Crossings

F. Anderegg

M. Affolter, D.H.E. Dubin, C. Fred Driscoll

University of California San Diego

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Particle crossing separatrices

Separatrices are barrier in phase space.
=> 2 populations “trapped particle” - “passing particle”
=> Very different orbits near the “X point”
=> Collisions or fluctuations cause dissipation and heating.

• Stellarators
  => with azimuthal (“θ”) asymmetries, separatrix crossings caused particle transport,
     resulting in losses of particle confinement.  (Mynick)

• Tokamaks
  => increased transport  (Galeev, Sagdeev, Furth, Rosenbluth)
  => dissipation of poloidal rotation (Morris et. al.)

• Non-neutral plasmas
  => wave damping and transport due to separatrix crossing (Kabantsev et. al.)
     extensively studied with θ-dependent waves.

  => In this presentation we consider a simple θ-symmetric system.
Overview

• A squeeze voltage $V_{sq}$ creates z-variation in the plasma potential, resulting in a velocity separatrix.

• The plasma is “sloshed” through the separatrix by oscillating the end confinement voltages.

• The slosh-coherent velocity distribution shows trapped particles and passing particles.

• Collisions causes trapped-passing transitions, resulting in irreversible heating.
Magnessium ions

\( B = 3T \)

\( n_0 = 1.6 \times 10^7 \text{ cm}^{-3} \)

\( L_p \sim 12\text{ cm} \)

\( R_p \sim 0.5 \text{ cm} \)
Plasma Density, Temperature profile

Plasma confined in steady state with rotating wall

\[ \text{Mg}^+ \text{ ions} \]
\[ B = 3 \text{T} \]
\[ n = 1.6 \times 10^7 \text{ cm}^{-3} \]
\[ L_p \sim 12 \text{ cm} \]
\[ R_p \sim 0.5 \text{ cm} \]
\[ \lambda_D = 0.24 \text{ cm} \left( \frac{T_{eV}^{1/2}}{n_7^{1/2}} \right) \]

\[ \frac{v_{ii}}{2\pi} < f_{\text{slosh}} < f_{\text{bounce}} < f_{\text{TG wave}} \]

\[ 1 \text{ s}^{-1} \frac{n_7^{1/2}}{2\pi T_{eV}^{3/2}} < \sim 500\text{Hz} < 10\text{kHz} \left( \frac{10 cm}{L_p} \right) T_{eV}^{1/2} < \sim 22\text{kHz} \]
Sloshing plasma through a separatrix

Particle velocity distribution is measured **coherently** with the sloshing oscillations.

Sloshing oscillations move the plasma through separatrix expanding and compressing the trapped particles.

Squeeze voltage
- **Trapped** particle
- **Passing** particle
\[ \Rightarrow \text{velocity separatrix} \]

LIF photon counting

\[ V_{\text{conf}} + V_{\text{slosh}} \]
\[ V_{\text{slosh}} \]
\[ V_{\text{conf}} - V_{\text{slosh}} \]

LIF photon counting

**Right**

**Left**

**Phase**

**Phase**

**Plasma position** (\( V_{\text{slosh}} \))
Phase: 0°
Trapped particles compressed
Passing particles stream away

Phase 180°
Trapped particles expended
Excess passing particles

Photon counting

\( V_{\text{conf}} + V_{\text{slosh}} \)
\( V_{\text{squeeze}} \)
\( V_{\text{conf}} - V_{\text{slosh}} \)

\( V_{\text{conf}} - V_{\text{slosh}} \)
\( V_{\text{squeeze}} \)
\( V_{\text{conf}} + V_{\text{slosh}} \)
Coherent particle velocity distribution

Separatrix “energy” at (z=0, r=0.4cm)

Data collected over 250 oscillation cycles

T = 0.46eV
V_{sq} = 15 V
V_{conf} = 100V
f_{slosh} = 500 Hz
V_{slosh} = 46V_p

Trapped particles are repeatedly compressed and expanded while passing particles stream to partially shield the trapped particles.
The “separatrix energy” varies with $z$ and $r$ in the plasma.

Here we plot the measured "Kinetic particle energy at the laser location required to cross the separatrix".

The measured kinetic energy at the laser location to cross the separatrix is in quantitative agreement with theory.
The coherent change of $F(v)$ measured over 16 phases is:

$$\delta F_{coh}^a(v) = \sum_{j=1}^{\text{phases}} F(v, \theta_j) e^{i \theta_j}$$

=> ± velocity-symmetric:

$$\delta F_{sym}^c(v) = \frac{\delta F_{coh}^c(v) - \delta F_{coh}^c(-v)}{2 F(v = 0)}$$

density and temperature changes

Collisionless theory
=> discontinuity

Data are averaged over a range of radius due to size of laser beam

The anti-symmetric response is small ~ 2% and noisy.

Trapped particles are out of phase with passing particles

Discrepancy in the number of trapped particle not understood at present
Coherent density perturbation

Density perturbation change sign from center to edge of the plasma, in qualitative agreement with the theoretical prediction.

Measured $\delta n_{coh}$ obtained from Maxwellian fit to each phase of the coherent velocity distribution

$T = 0.46eV$
$V_{sq} = 15 V$
$V_{conf} = 100V$
$f_{slosh} = 500 Hz$
$V_{slosh} = 46V_p$
Slow temporal heating

Phase averaged velocity distribution at several times

Slow heating due to separatrix crossing.

Initial heating rate: \( \frac{\Delta T}{\Delta t} \approx 0.4 \text{ eV/s} \)
- Strong heating when particle are forced through a separatrix.
- Heating due to separatrix crossing is larger than viscous heating.
- Negligible heating when particle are sloshed without a separatrix.

!! Too much viscous heating of trapped particle (plasma too cold) !!
Coherent particle velocity distribution

Phase 0°

Phase 180°

larger density

$T = 0.33\text{eV}$

$V_{sq} = -15 \text{ V}$

$V_{conf} = 100\text{V}$

$f_{slosh} = 500 \text{ Hz}$

$V_{slosh} = 46V_p$

=> No separatrix, no X point.
All particles behave the same.

Anti-squeeze has no effect on the velocity distribution.

$F(V, \theta, z=0)$
Anti-squeeze does not create a separatrix and **negligible heating** is observed.
Heating rate due to separatrix crossing

Theory predicts a heating rate due to particle crossing the separatrix as:
(see poster p2-10)

$$\frac{dK}{dt} = 4\sqrt{\pi \omega \nu} \ T \int r dr \ n(r) L \ \exp\left(-\frac{e \phi_s}{T}\right) \left(\frac{\delta L}{L}\right)^2 \left(2 \frac{e \phi_s}{T} + \chi\right)^2$$

- Sloshing frequency
- Collision rate
- Sloshing amplitude
- Separatrix potential in the plasma
- Potential due to trapped particles
- Shielded by passing particles
- Scales roughly as $\phi_s^{1.5}$
Heating rate vs displacement amplitude

Heating rate scaling as $(\delta L)^2$ is consistent with collisional separatrix crossing theory.
Heating rate vs Squeeze voltage

Heating rate scaling as $(V_{\text{squeeze}})^2$ supports the idea of heating due to collisional separatrix crossing.
Heating rate vs sloshing frequency

Heating rate scaling as $(f_{slosh})^{1/2}$ verifies the idea of heating due to collisional separatrix crossing.
The measured **heating rate is in quantitative agreement** (no adjustable parameters) with the theoretical heating due to **collisional separatrix crossing**.

**Theory and experiment**

- $T = 0.46\text{eV}$
- $V_{sq} = 15\text{ V}$
- $V_{\text{conf}} = 100\text{V}$
- $V_{\text{slosh}} = 46V_p$
- $f_{\text{slosh}} = 500\text{ Hz}$
- $\nu_{ii} \approx 2\text{ s}^{-1}$

Calculated heating due to separatrix crossing: **scaling as $\nu_{ii}^{1/2}$**

Calculated viscous heating on trapped particles: **scaling as $\nu_{ii}^1$**
Separatrix crossing
Velocity diffusion to cross separatrix
Small $\Delta v$ required

$\Delta v^2 \sim D_v \cdot t$

$\Delta v \sim \sqrt{D_v \cdot t} \sim \sqrt{v_c \cdot t} \sim \sqrt[4]{v_c f_{sl}}$

$\sim \sqrt[4]{v_c f_{sl}} \cdot \sqrt{f_{sl} v_c}$

$\Delta E \perp \sim \Delta v^2 \sim \bar{v}^2$

$\Delta v^2 \sim D_v \cdot t \sim v_c \cdot t$

$\sim \frac{v_c}{f_{sl}}$ \text{ one cycle}

$\sim \frac{v_c}{f_{sl}} \cdot f_{sl} = v_c \text{ per unit of time}$

Viscous heating

Energy change required for viscous heating
Synthetic collisions

Add a small “tickle” at one end to enhance the velocity diffusion of bouncing particles.

\[ V_{\text{conf}} + V_{\text{slosh}} + V_{\text{tickle}} \]

\[ V_{\text{squeeze}} \]

\[ V_{\text{conf}} - V_{\text{slosh}} \]

\[
\begin{align*}
\dot{T} &= 3 \times 10^{-2} + 3.1 \times 10^{-3} V_{\text{tickle}}^2 \\
\nu_{\text{eff}} &= 3 \frac{\dot{T}}{T_0}
\end{align*}
\]

The effective increased collision rate due end “tickle” is...
Heating rate scales as $\sqrt{f_{sl} \times \nu}$
Summary

• Squeeze voltage creates a velocity separatrix, separating particles into trapped and passing.

• Observe directly trapped and passing particles on slosh-coherent $F(v)$.

• Direct measurements of dissipations due to particle crossing a separatrix.

• Heating rate scales as:

$$\left(\frac{\delta L}{L_p}\right)^2 V_s^2 \sqrt{f_{sl} \times \nu_c}$$

• Separatrix “scars” $F(v)$ so only small velocity diffusion is required for irreversible heating.