The effect of poloidal flow on locked islands

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Plasma flow is observed to "heal" magnetic islands.

Recent work at the Large Helical Device (LHD) indicates that plasma flow plays a primary role in "healing" vacuum magnetic islands in stellarators. An analytic theory to explain this phenomenon has been proposed. [1]

- The model to explain this is reminiscent of 'mode locking/unlocking' physics in tokamaks.
- Governed by a torque balance between viscous and electromagnetic torques:

$$D_A \sin(2\Delta\phi) = D_\Omega$$

where:

$$D_A = \omega_A^2 \frac{m_o^2 k_v^2}{k_f c_r} \frac{(-\rho_0 \Delta_0')}{2m_0} \frac{(t_0')^2 (w^V)^4}{512}$$

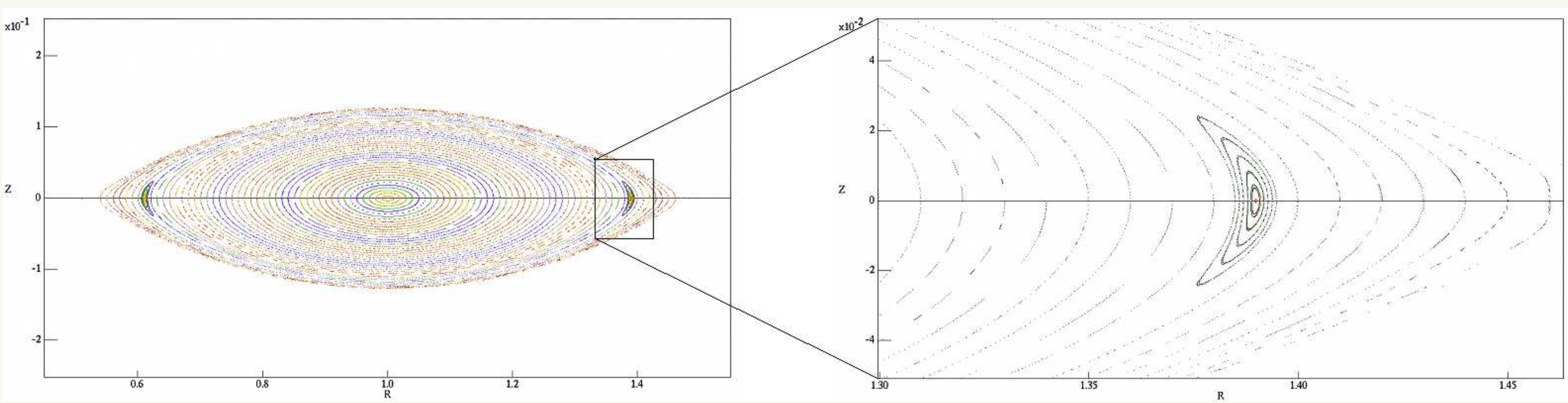
$$D_\Omega = -2\nu_\perp \frac{\rho_0}{\delta_r} \Omega_0^\alpha$$

[1] Hegna, UW-CPTC Report 11-7, 2011.

“Healing” of magnetic islands is investigated with NIMROD.

- A m=2,n=2 straight stellarator vacuum field is created using tools developed for previous work.
- This field is perturbed with m=2,n=5 symmetry-spoiling harmonics which create islands in the vacuum field. Magnetic potential for this situation is given by:

$$\phi = B_0[R\zeta + \epsilon_{22}\frac{2R}{2}I_2\left(\frac{2r}{R}\right)\sin(2\theta - 2\zeta) + \epsilon_{25}\frac{2R}{5}I_2\left(\frac{5r}{R}\right)\sin(2\theta - 5\zeta)]$$



Flow is achieved by using an ad-hoc injection of poloidal momentum.

A source of poloidal momentum is introduced, which is aligned with flux surface projections on the poloidal plane. This alignment is accomplished by:

$$\mathbf{f} \cdot \nabla \psi = 0$$

where

$$\mathbf{f} = f^R \overline{\mathbf{e}_R} + f^Z \overline{\mathbf{e}_Z}$$

is the injected poloidal momentum source.

Specifically,

$$\sqrt{(f^R)^2 + (f^Z)^2} = \text{v\_cent}$$
$$f^R \frac{\partial \psi}{\partial R} + f^Z \frac{\partial \psi}{\partial Z} = 0$$

where v_cent is a parameter specified in nimrod.in and represents the magnitude of the injected poloidal momentum source.

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The poloidal momentum source does indeed produce velocity vectors aligned with the flux surface projection in the poloidal plane.

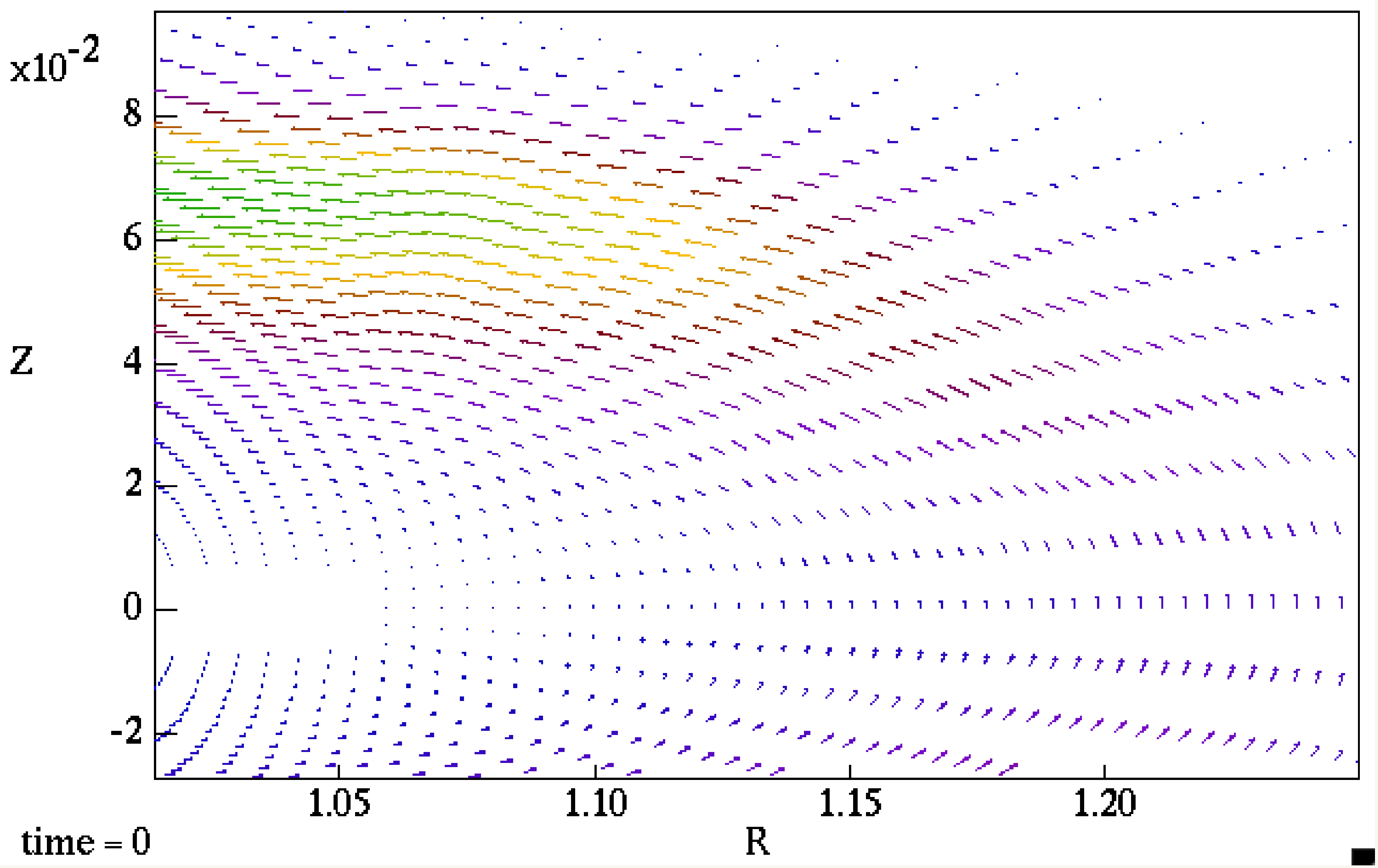

Figure 1: Velocity vectors at t=0.2 ms.

Velocity profiles for the (m=2,n=2,ϵ=0.775) case, slow ramping of injected poloidal momentum.

The island for this case is between R=1.26 and R=1.29.

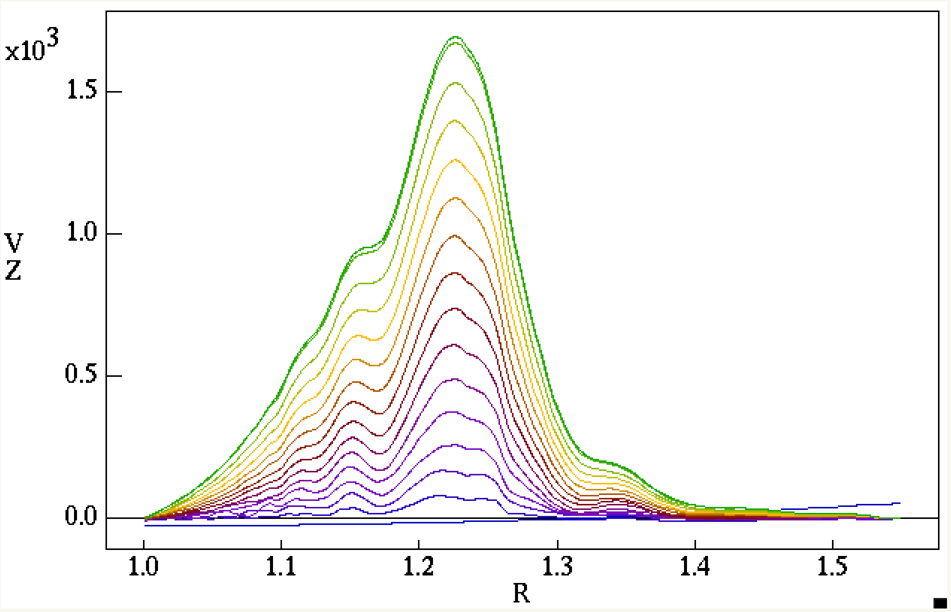

Figure 2: VZ profiles at various times, $\zeta = 0$.

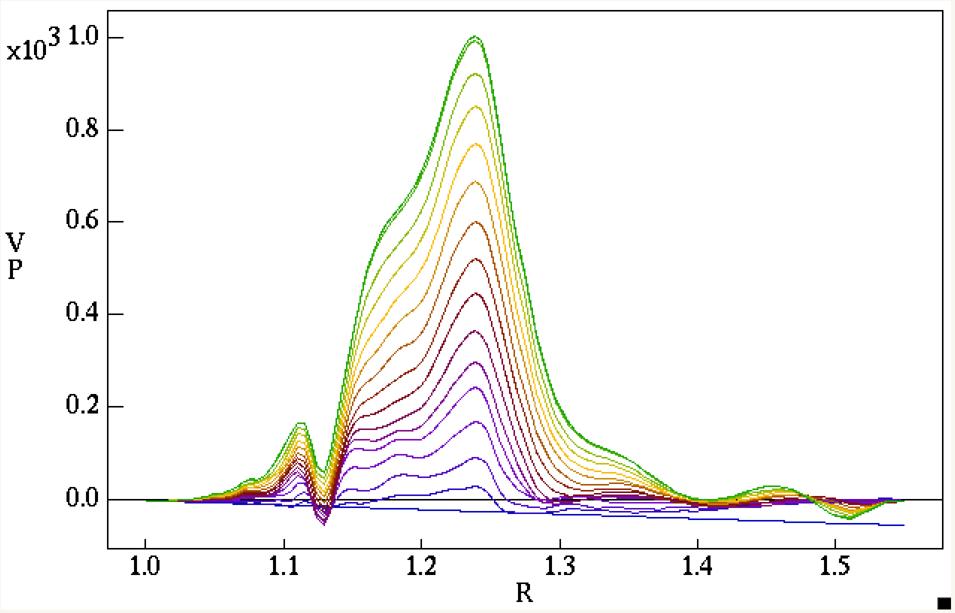

Figure 3: V_ϕ proflies at various times, $\zeta = 0$.

Results for the (m=2,n=2,ϵ=0.775) case, slow ramping of injected poloidal momentum.

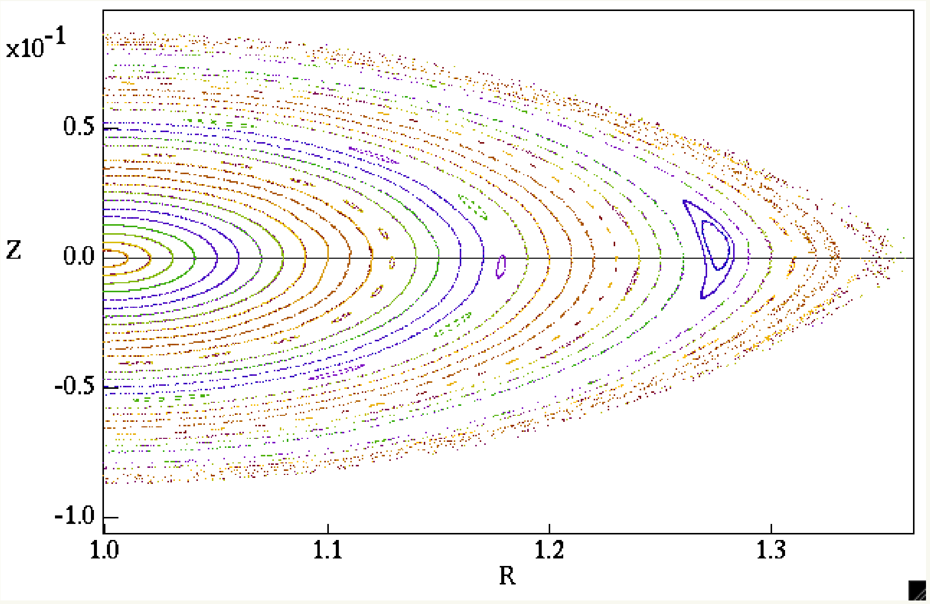

Figure 4: Poincare plot at t=0.061ms, $\zeta = 0$.

Simulation: $\Delta\phi = 1.21°$.
Hegna prediction: $\Delta\phi = 0.4°$.

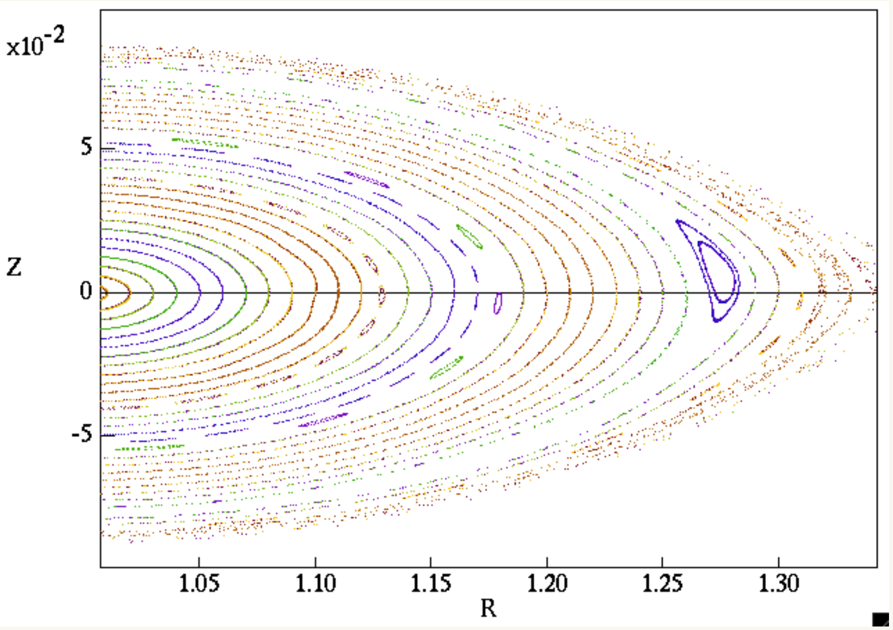

Figure 5: Poincare plot at t=0.152ms, $\zeta = 0$.

Simulation: $\Delta\phi = 1.61°$.
Hegna prediction: $\Delta\phi = 1.0°$.

Velocity profiles for the (m=2,n=2,ϵ=0.775) case, fast ramping of injected poloidal momentum.

The island for this case is between R=1.26 and R=1.29.

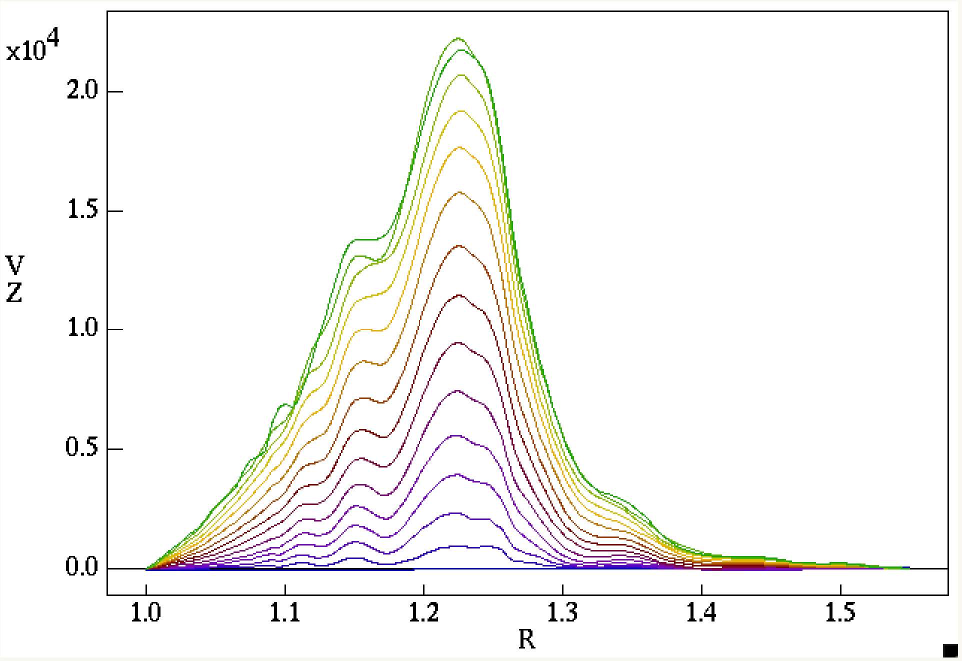

Figure 6: VZ profiles at various times, $\zeta = 0$.

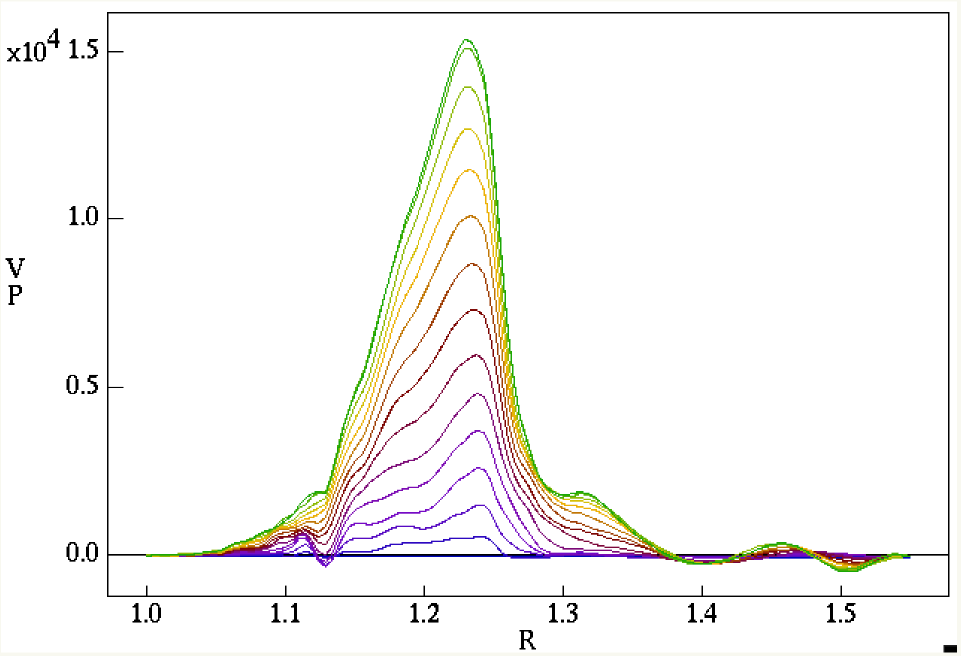

Figure 7: V_ϕ proflies at various times, $\zeta = 0$.

Results for the $(m=2, n=2, \epsilon=0.775)$ case, fast ramping of injected poloidal momentum.

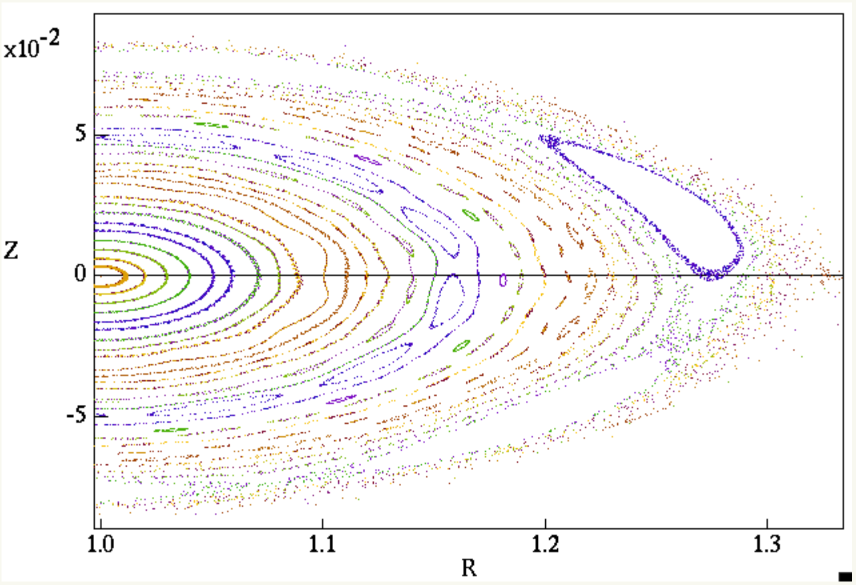

Figure 8: Poincare plot at t=0.089ms, $\zeta = 0$.

Simulation: $\Delta\phi = 6.34°$.
Hegna prediction: $\Delta\phi = 6.3°$.

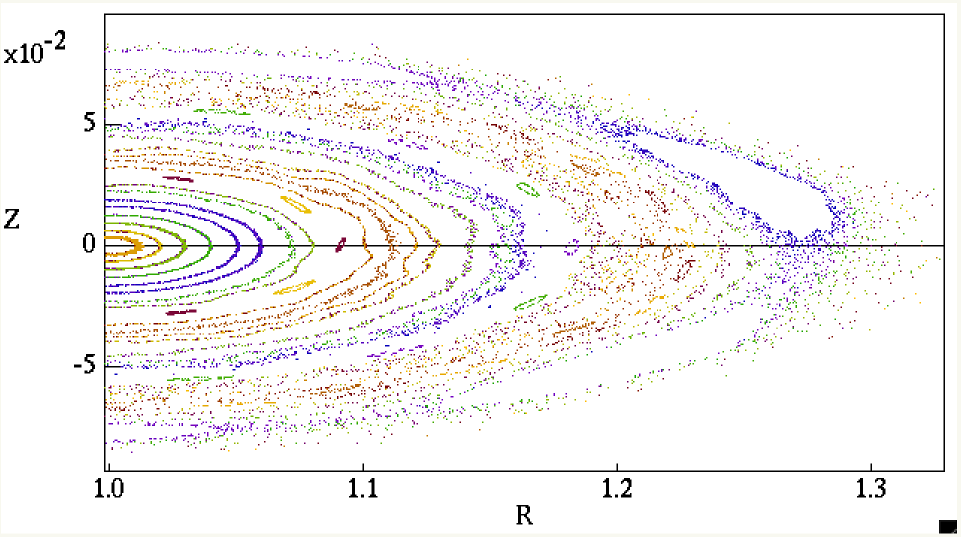

Figure 9: Poincare plot at t=0.214ms, $\zeta = 0$.

Simulation: $\Delta\phi = 6.46°$.
Hegna prediction: $\Delta\phi = 13.8°$.

Results for the (m=2,n=2,ϵ=0.80) case, slow ramping of injected poloidal momentum.

The island for this case is between R=1.22 and R=1.24.

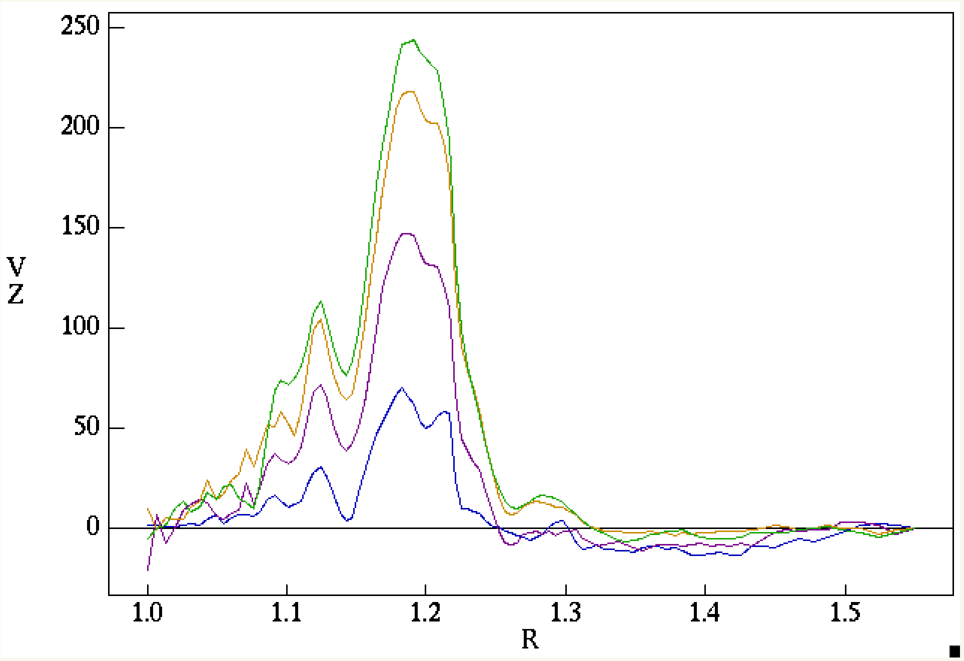

Figure 10: VZ profiles at various times, $\zeta = 0$.

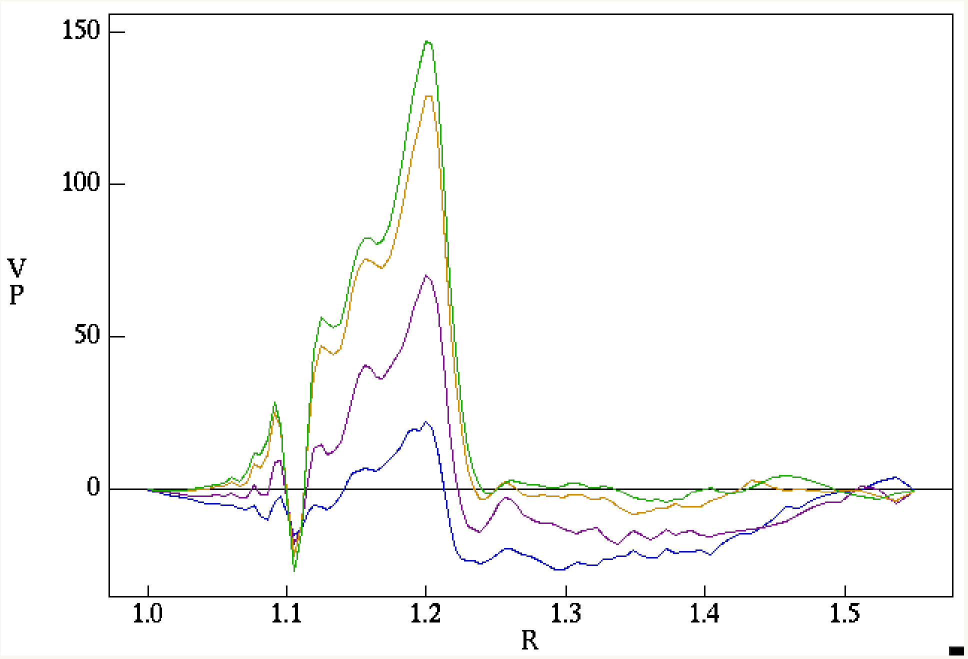

Figure 11: V_ϕ proflies at various times, $\zeta = 0$.

Results for the (m=2,n=2,ϵ=0.80) case, slow ramping of injected poloidal momentum.

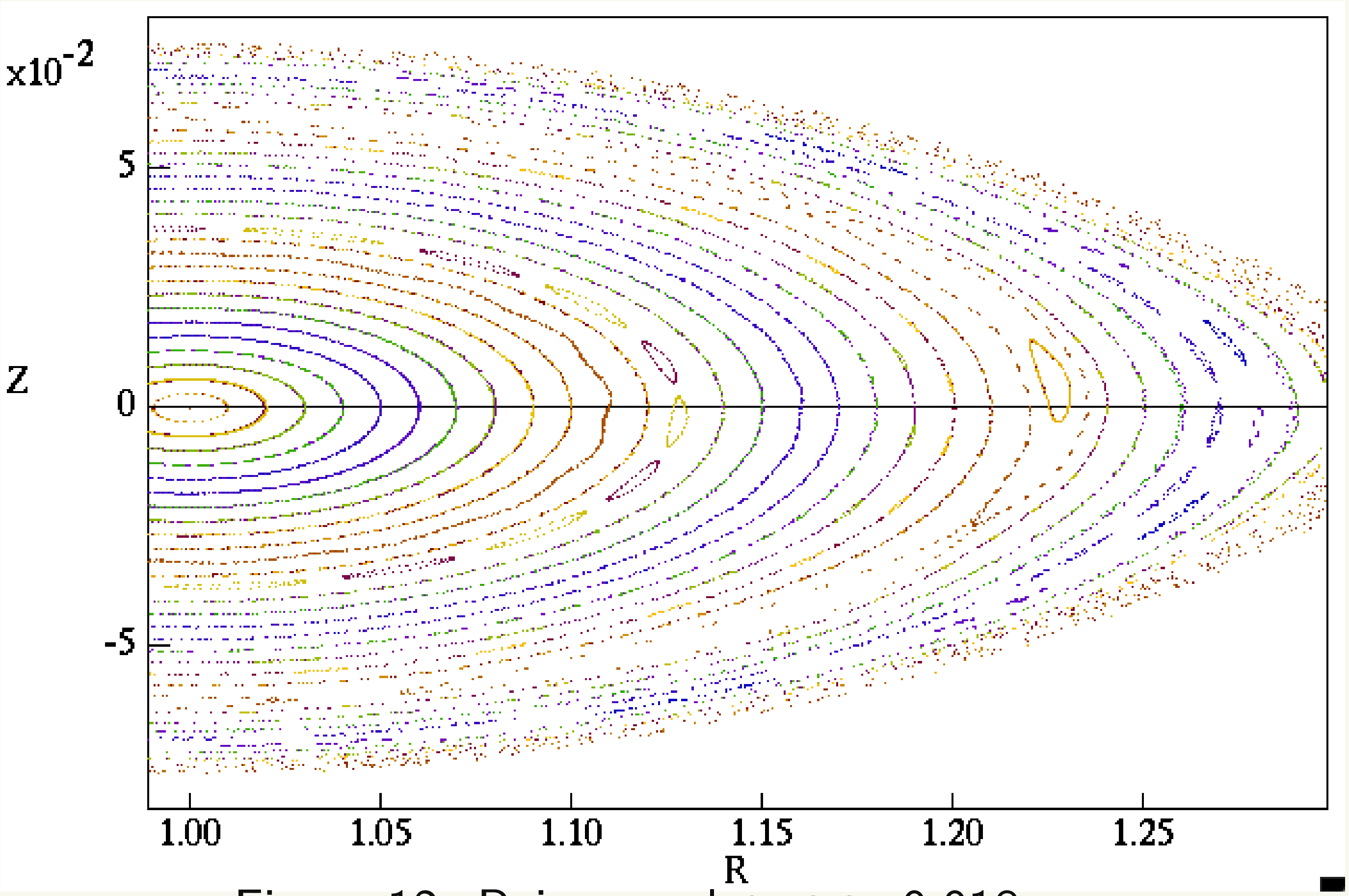

Figure 12: Poincare plot at t=0.018 ms.

Simulation: $\Delta\phi = 1.55°$.
Hegna prediction: $\Delta\phi = 1.1°$.

Results for the (m=2,n=2,ϵ=0.80) case, fast ramping of injected poloidal momentum.

The island for this case is between R=1.22 and R=1.24.

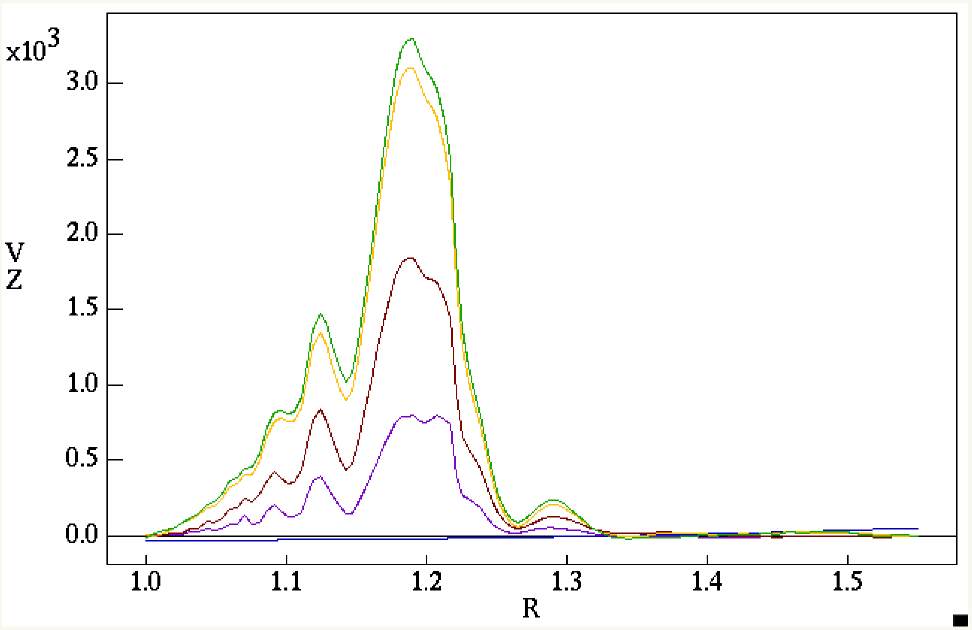

Figure 13: VZ profiles at various times, $\zeta = 0$.

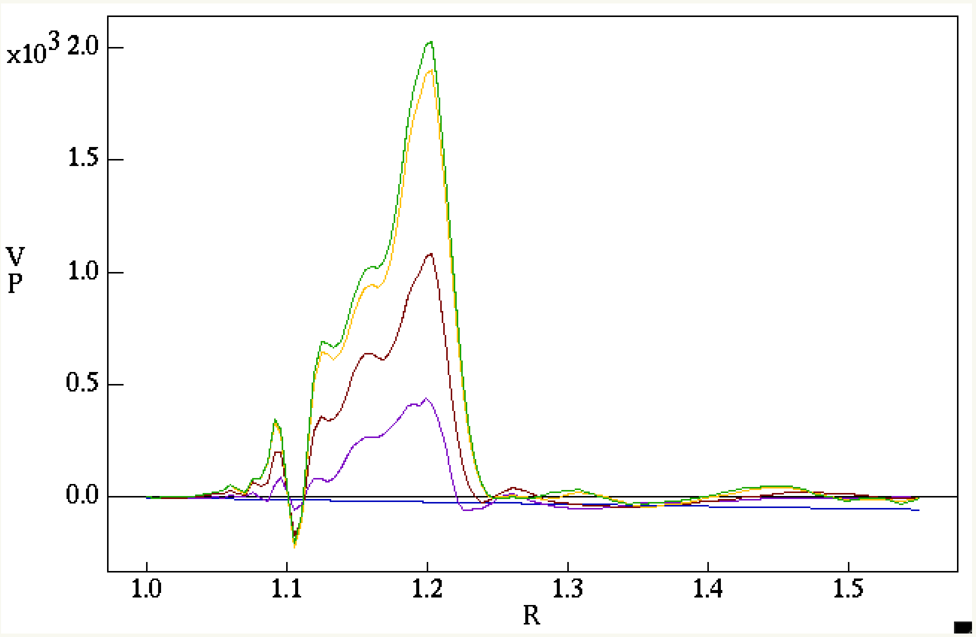

Figure 14: V_ϕ proflies at various times, $\zeta = 0$.

Results for the (m=2,n=2,ϵ=0.80) case, fast ramping of injected poloidal momentum.

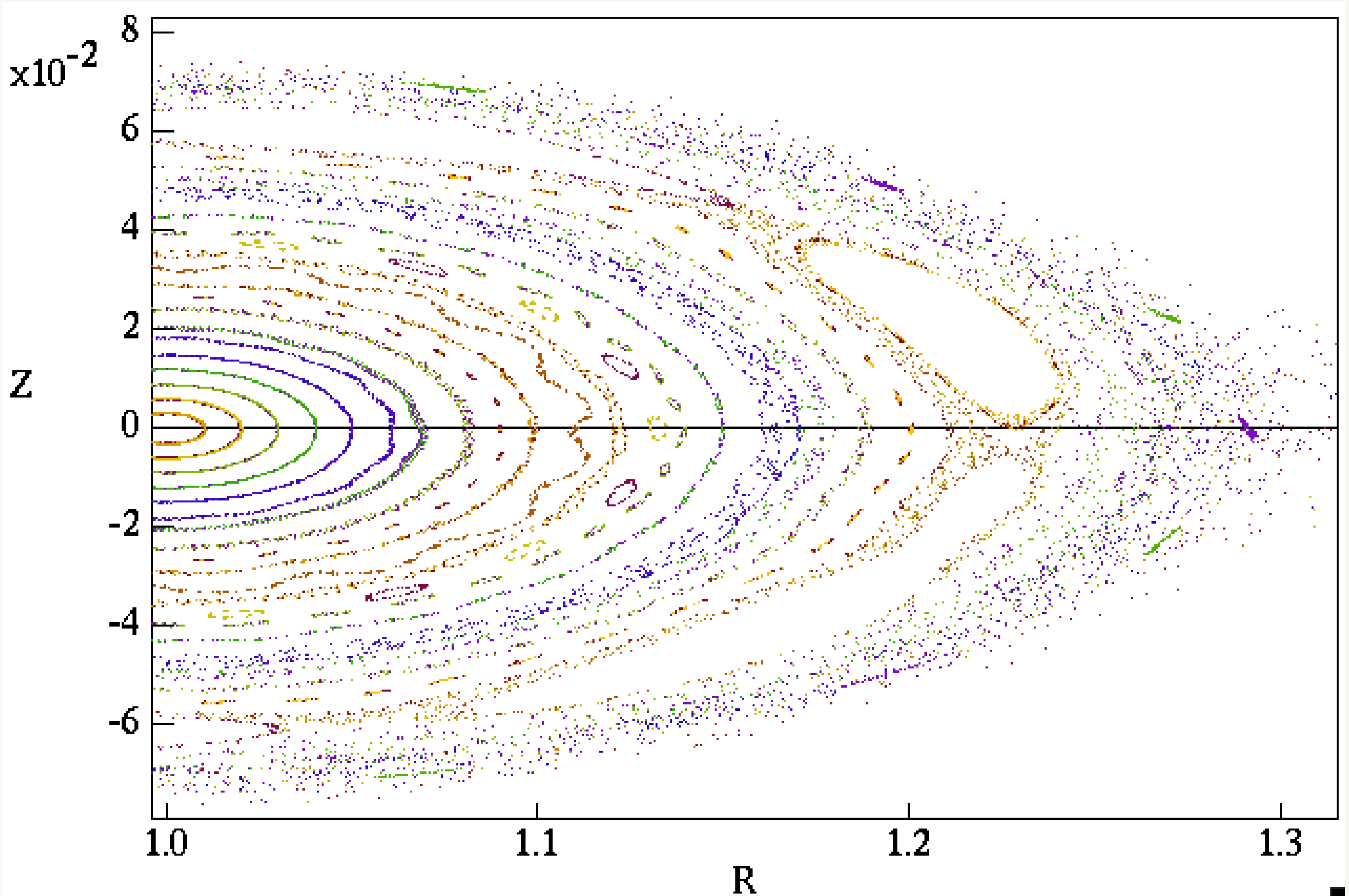

Figure 15: Poincare plot at t=0.025 ms.

Simulation: $\Delta\phi = 6.16°$.

Hegna prediction: $\Delta\phi = 17.2°$.

Summary of results.

- It appears that the simulation and analytic theory are close for small flows. For larger flows, the agreement deteriorates.
- Possible sources of disagreement:
  - Evaluation of geometrical parameters - analytic work is for a cylinder. Flux surfaces in the simulation are not circular.
  - Evaluation of velocities and radii - velocity is not constant on a flux surface projection.
  - Much flux surface destruction is seen in the very high flow cases. Does the model still hold?
  - In the very high flow cases, the flow speeds are exceeding the sound speed in the simulation.

Future work:

- Run cases with the islands placed even further toward the core.
- Increase the background temperature to avoid any shocks.