Simulations of the Compact Toroidal Hybrid using NIMROD

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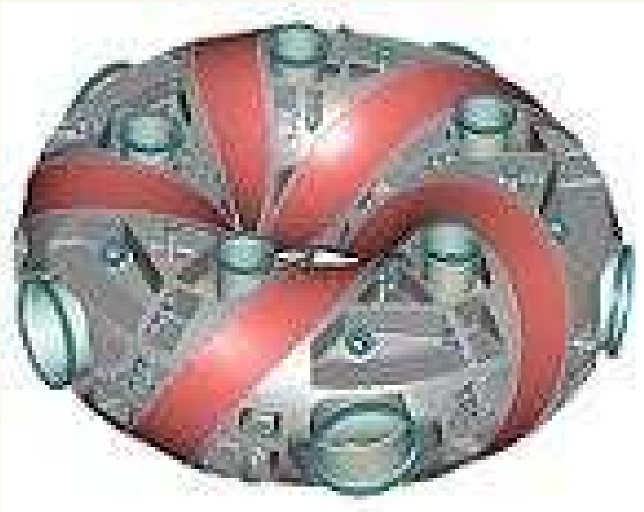
The Compact Toroidal Hybrid is a low aspect ratio stellarator at Auburn University.

- The vessel is axisymmetric (but the magnetic field is non-axisymmetric).
- A substantial fraction of the rotational transform is provided by the plasma current.
- The vacuum rotational transform is flat at about $\iota \approx 0.1$. Toroidal current can raise this value to $\iota \approx 0.5$.
- Five field periods, magnetic field strength of $\sim$ 0.6 T.
- R_0=0.75m, a=0.3m

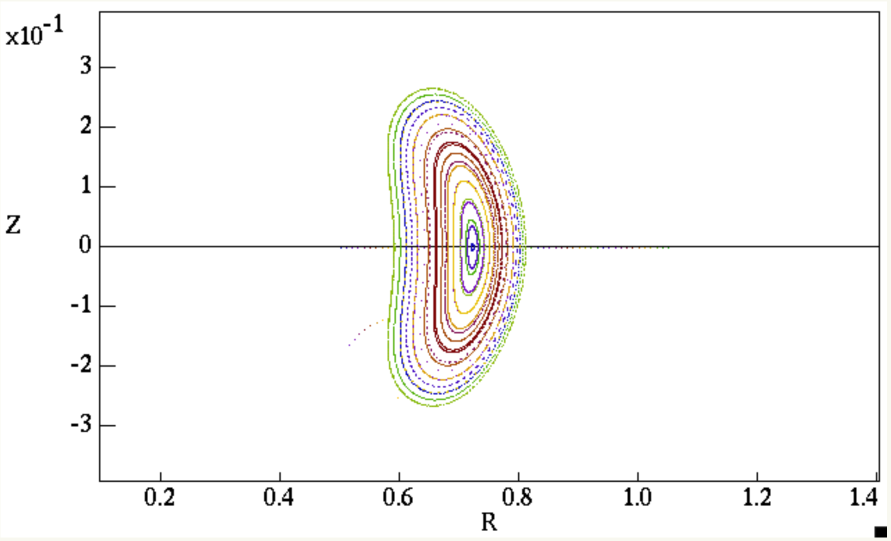


The vacuum magnetic field of the Compact Toroidal Hybrid is modeled with NIMROD.

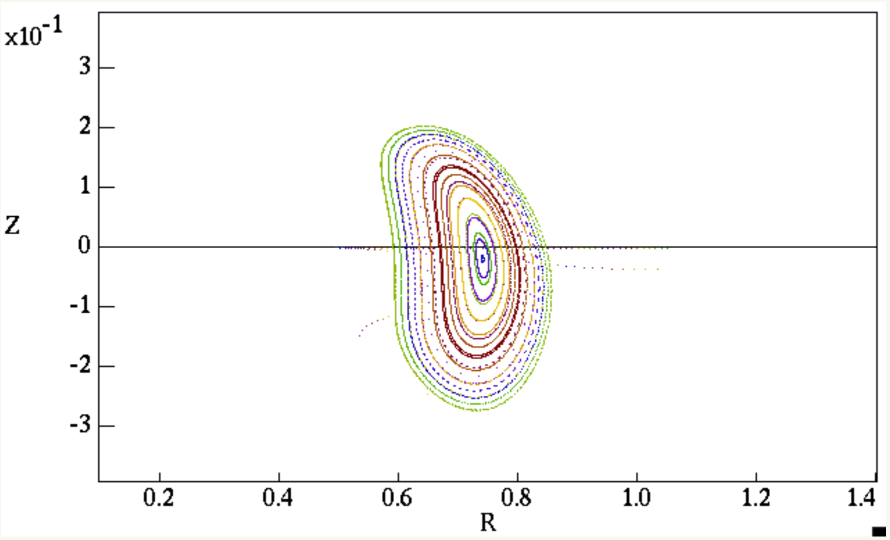
The axisymmetric vessel and non-axisymmetric magnetic field of CTH allow modeling using NIMROD.

- Magnetic field data at the vessel surface have been provided by the CTH team.
- These Fourier-transformed magnetic field data are loaded into the boundary finite element nodes and frozen for all time.
- The magnetic diffusivity is set to a very high value (10^9 m^2/s) and NIMROD is run with very short time steps. The goal is to allow the surface magnetic field to diffuse into the domain in a very short amount of time $\sim 10^{-10}$s.

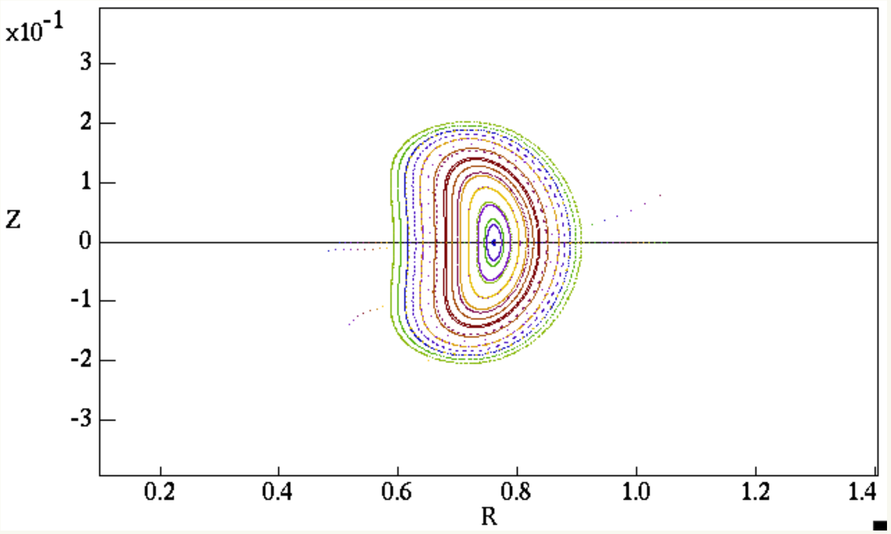
NIMROD-produced Poincaré plots show closed magnetic flux surfaces (vacuum).



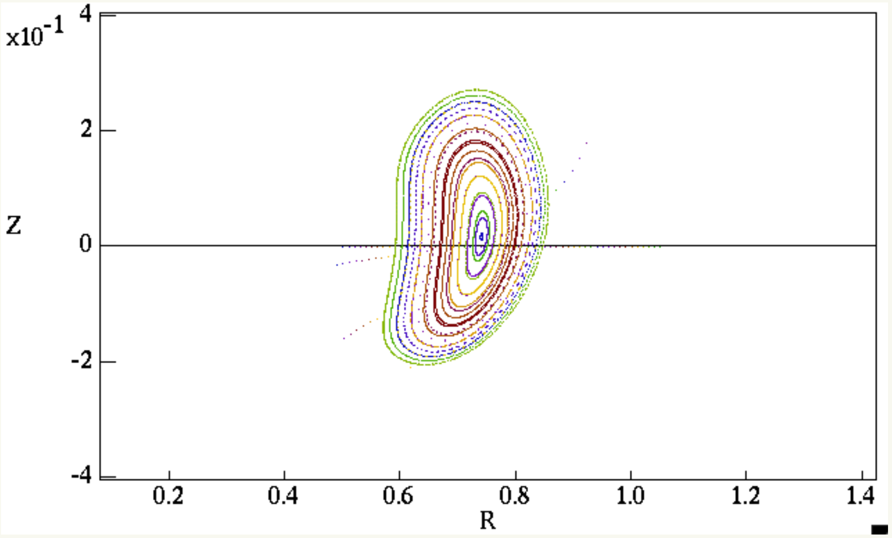
Poincaré plot at $\zeta = 0$.



Poincaré plot at $\zeta = \pi/10$.

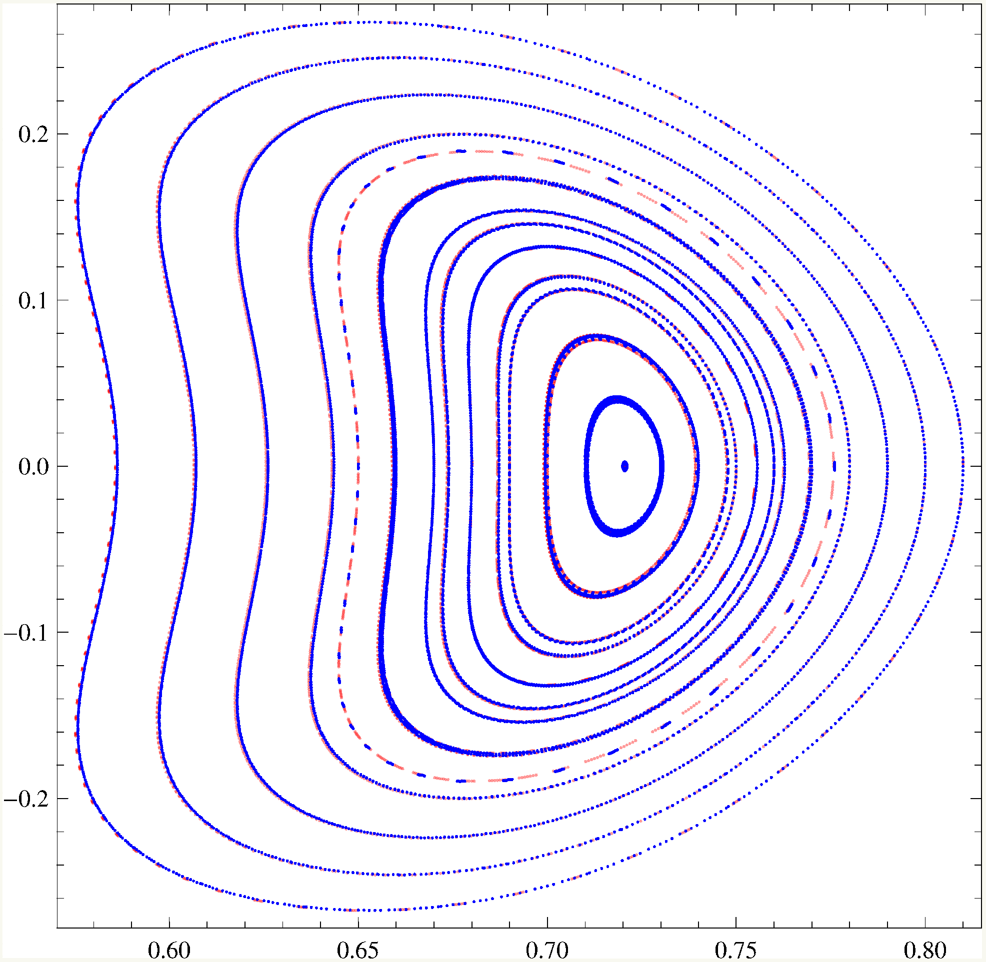


Poincaré plot at $\zeta = 2\pi/10$.



Poincaré plot at $\zeta = 3\pi/10$.

Good agreement is obtained for the vacuum field calculation between NIMROD and Auburn's in-house code, IFT.



Overlay of Poincaré plots as generated by NIMROD (red) and IFT (blue). Graphic courtesy of J. Hebert.

See J. Hebert's poster - Session GP9 (Tuesday morning).

Key parameters for simulation of the Compact Toroidal Hybrid.

Simulation: adding a loop voltage with **zero beta**.

- $S \approx 10^6$

  $=>$ Assume $T_e \approx 100$ eV, to obtain an estimate for resistivity (constant across the closed flux surface region)

  $=>$ Very large resistivity is prescribed in a very narrow layer at the edge of the domain to kill off current outside the LCFS.

- $Pr = 1$

Other CTH parameters of interest:

- $T_e \approx 300$ eV, $T_i \approx 1/3$ eV on axis

  $=>$ Lundquist number $\approx 8 \cdot 10^6$ on axis

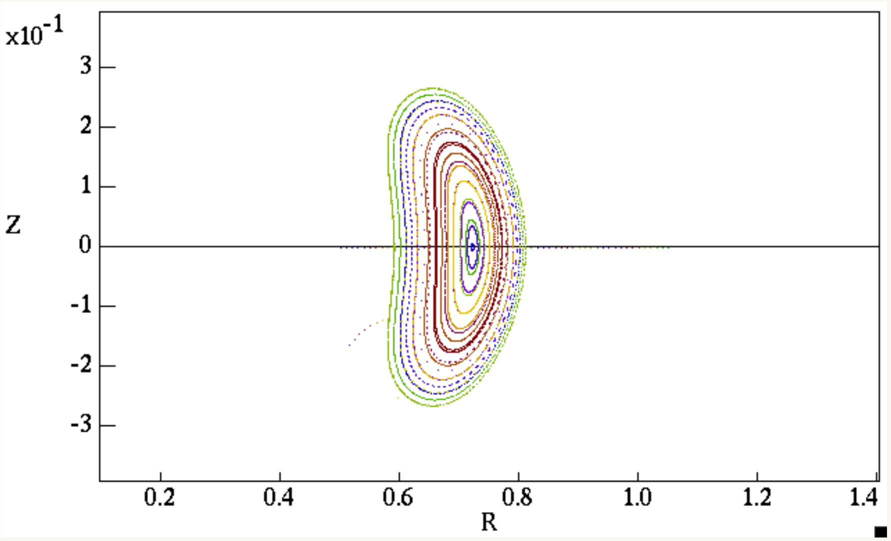
- $n_i = 1.5 \cdot 10^{19}/\text{m}^3$
- $V_A = 3.16 \cdot 10^6 \text{m/s}$
- Confinement time: $\tau_E \approx 0.025\text{s}$.

Simulations performed

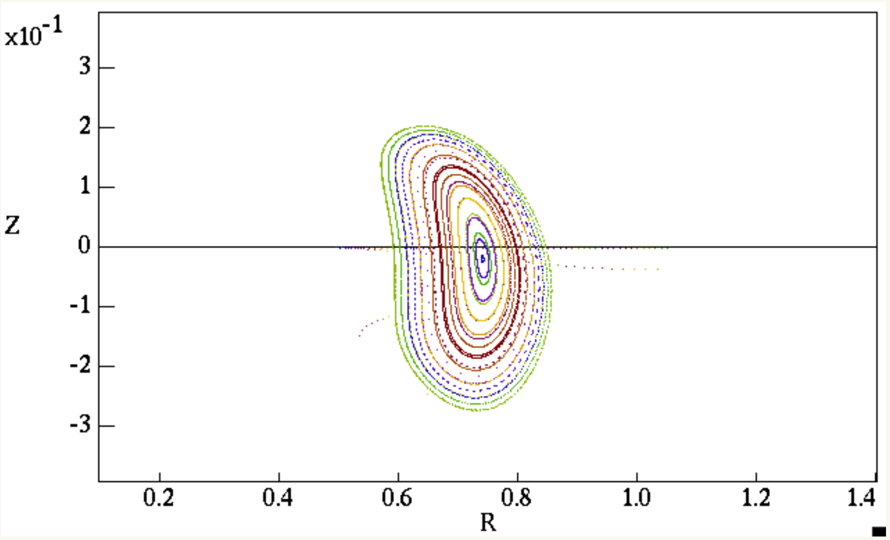
NIMROD simulations are run starting from the vacuum magnetic field. All simulations are zero beta, and current is driven with an applied loop voltage:

- Applied loop voltage = 1V.
- **Applied loop voltage = 4V.**
- Applied loop voltage = 16V.

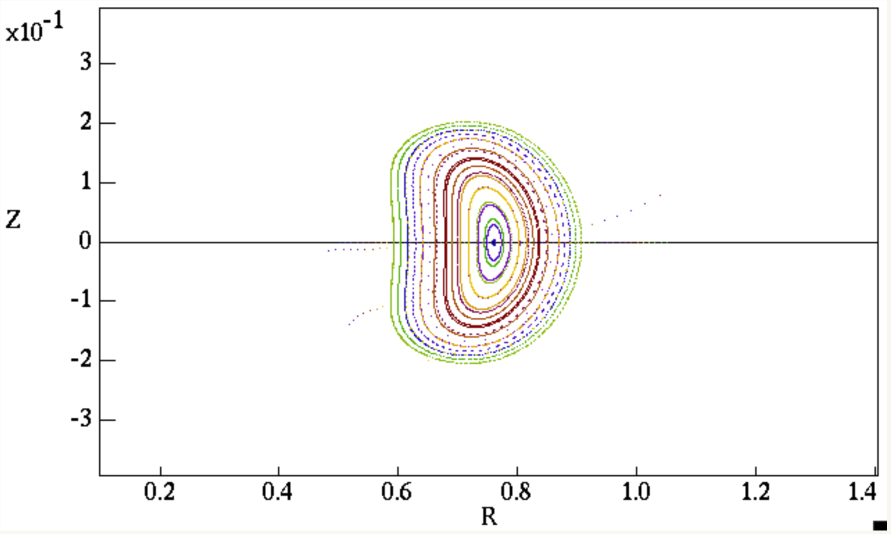
NIMROD-produced Poincaré plots show closed magnetic flux surfaces (vacuum).



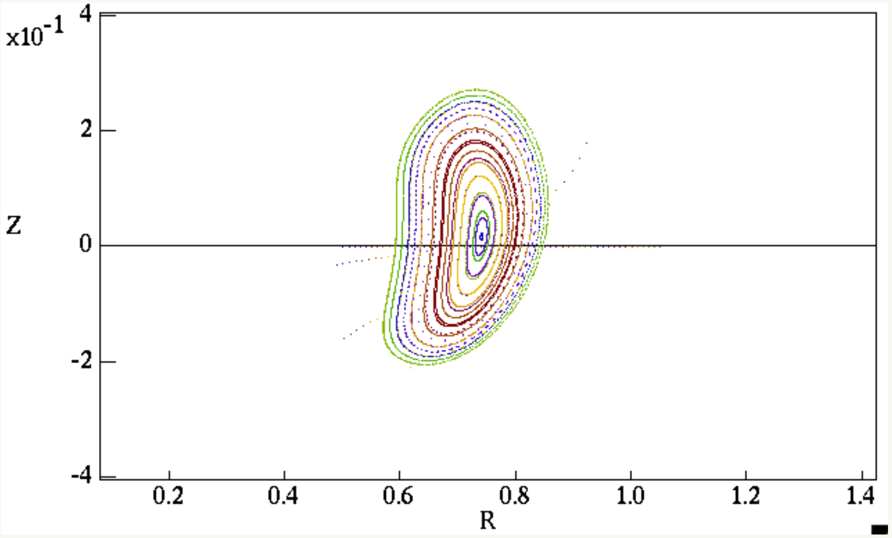
Poincaré plot at $\zeta = 0$.



Poincaré plot at $\zeta = \pi/10$.



Poincaré plot at $\zeta = 2\pi/10$.



Poincaré plot at $\zeta = 3\pi/10$.

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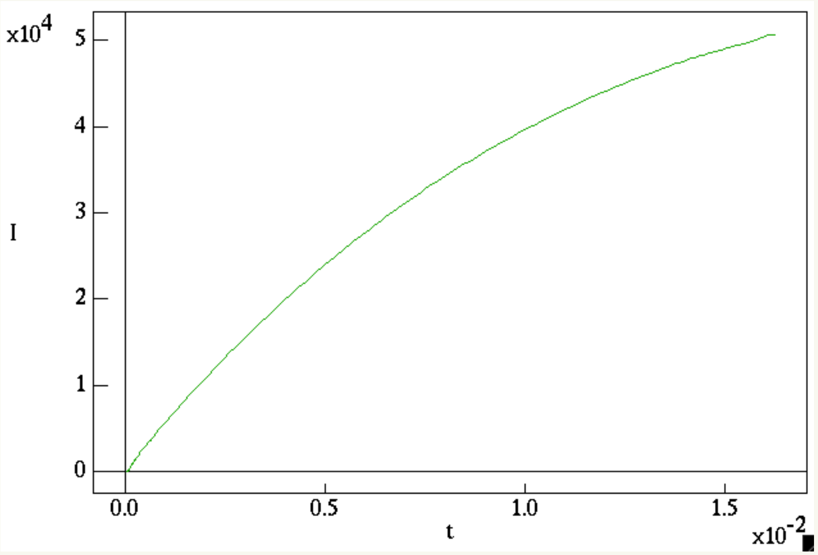
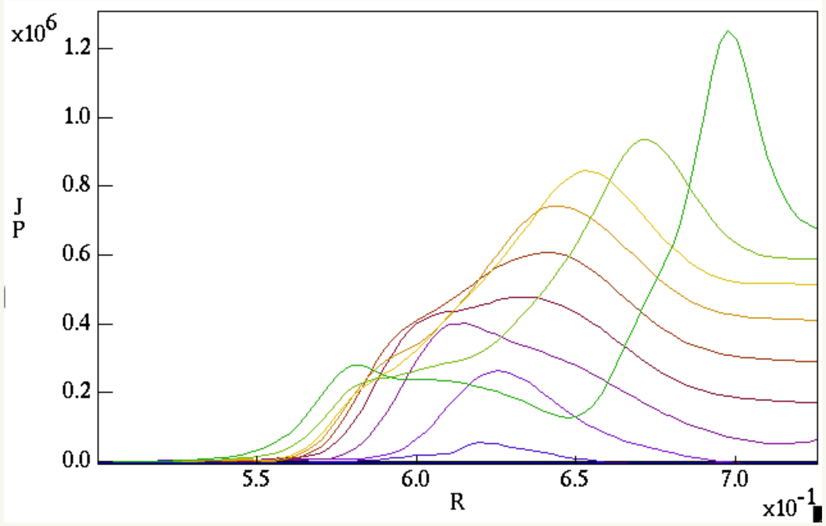
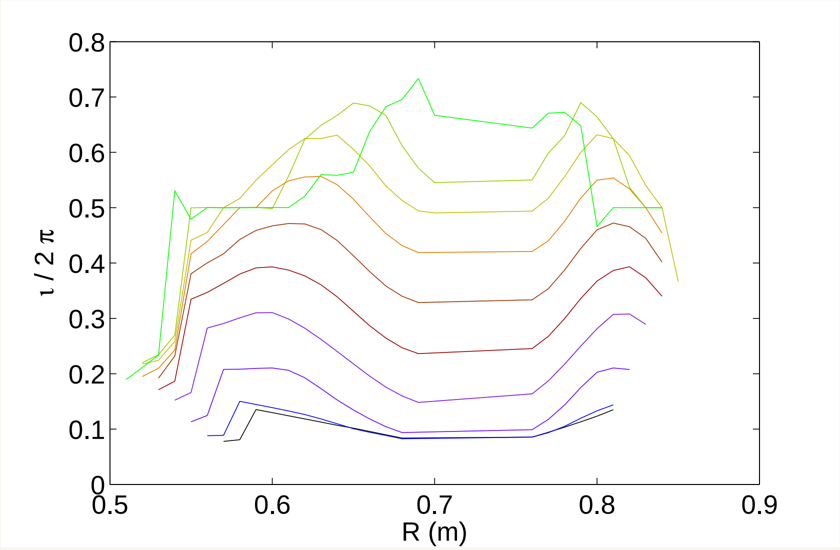
Loop Voltage=4V results in total current of about 50 kA and fast-growing instability.



Total current (A).



Current penetration (ϕ-component) at various times (A/m^2).



Rotational transform profiles at various times.

- Mag axis at 0.725m. Sx from 0.60m (t=0) to 0.54m (t=16ms).
- Hollow current profile.
- Rotational transform profiles become somewhat hollow.
- m=2,n=1 structure forms late in time.

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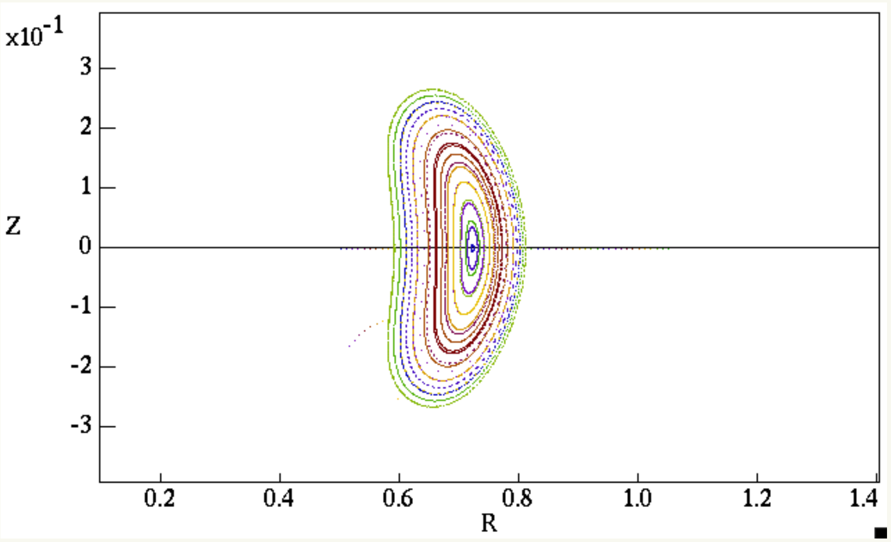
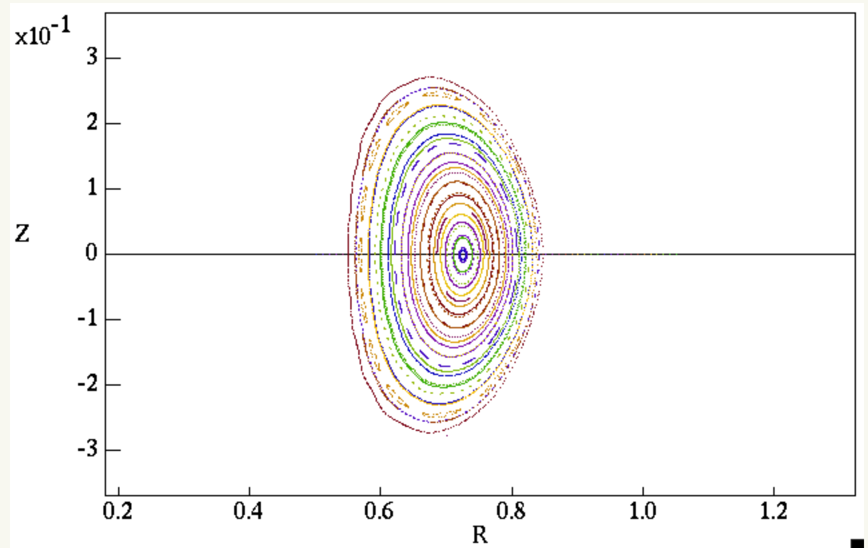
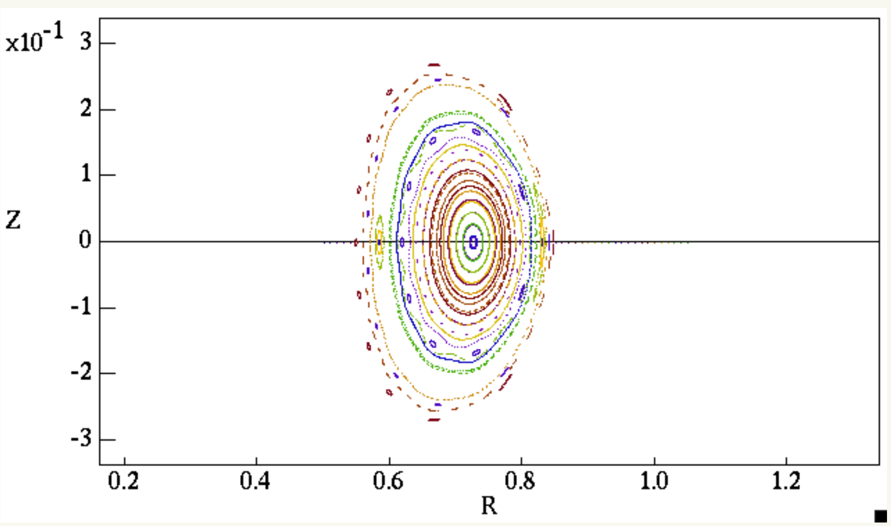
Loop Voltage=4V: Flux surfaces become less elongated, and a m=2,n=1 structure develops.



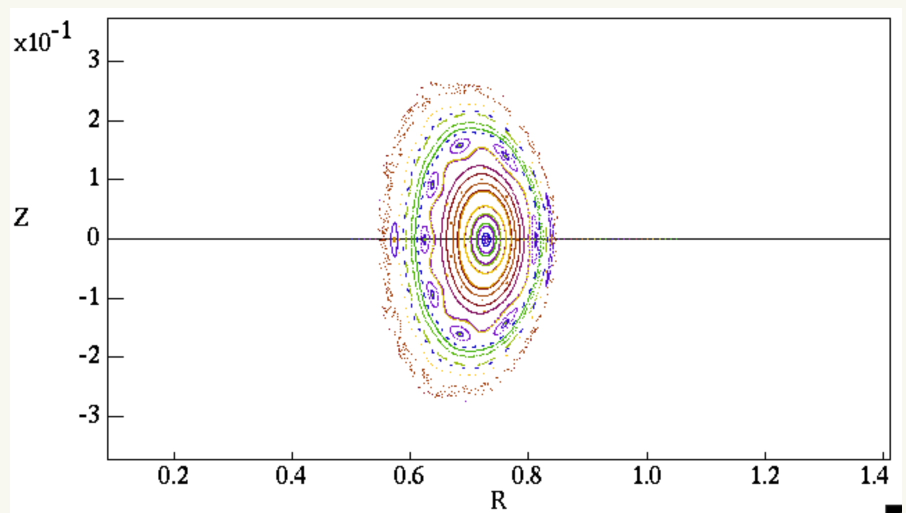
Poincaré plot for t=0.



Poincaré plot for t=9ms.



Poincaré plot for t=12ms.



Poincaré plot for t=14ms.

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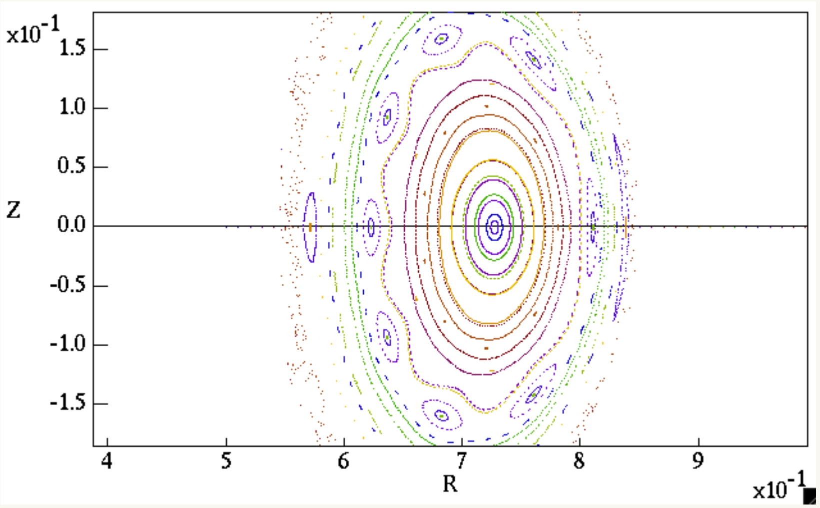
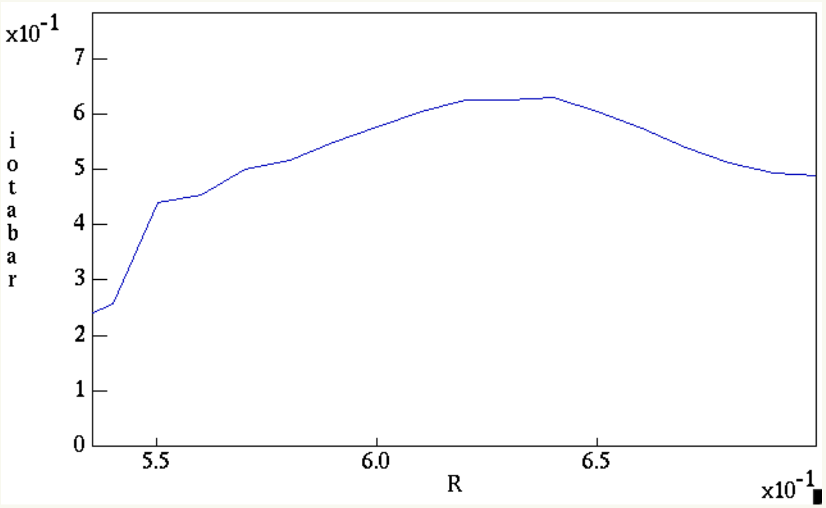
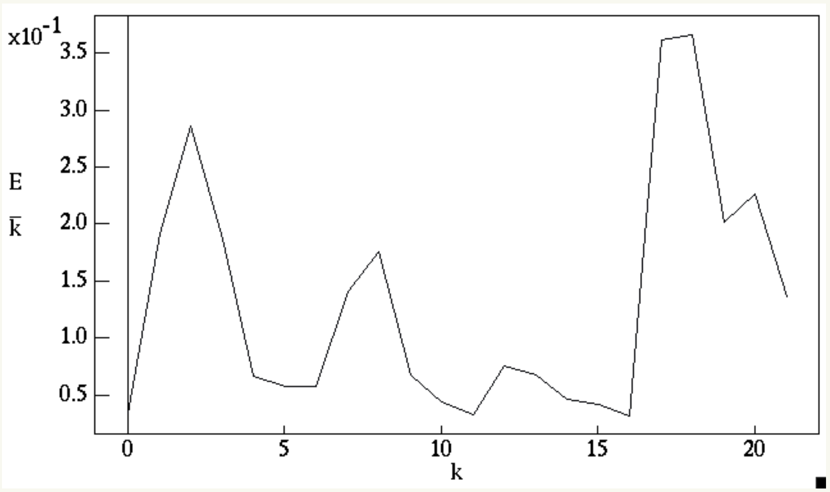
Loop Voltage=4V: m=2,n=1 structure causes loss of flux surfaces.



Poincaré plot at t=14ms.



Rotational transform profile at t=14ms.



Energy spectrum at t$\lesssim$16ms.

- Island structures at $\iota = 1/2$ surface and $\iota = 5/8$.
- All flux surfaces destroyed at t$\gtrsim$ 16ms.

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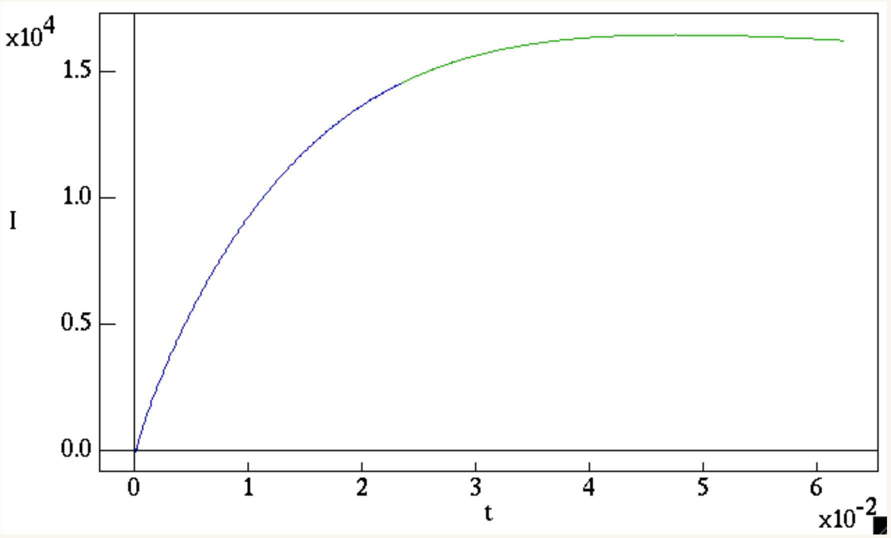
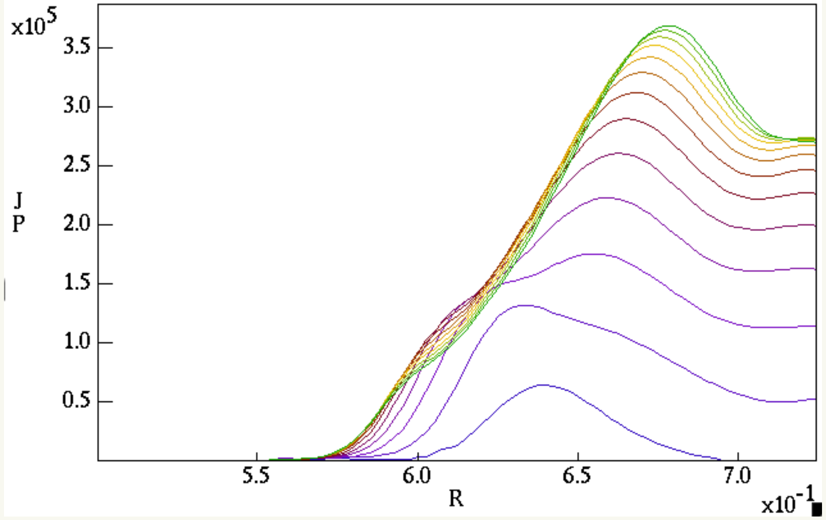
Summary and future work.

- The Compact Toroidal Hybrid has been modeled using NIMROD.
  - The vacuum magnetic field as calculated by NIMROD agrees with calculations from Auburn's IFT.
  - Various loop voltages have been applied, resulting in:
    - Current penetration toward the core, although the profiles remain somewhat hollow.
    - Island formation at low-order rational surfaces. Some double tearing modes observed.
    - Complete flux surface destruction at high values of current drive.
- Future work:
  - Finite beta calculations - J. Hebert, Auburn University.
    - Self-consistent ohmic heating.
    - Temperature-dependent resistivity.
  - Change loop voltage as a function of time to mimic interesting experimental results.

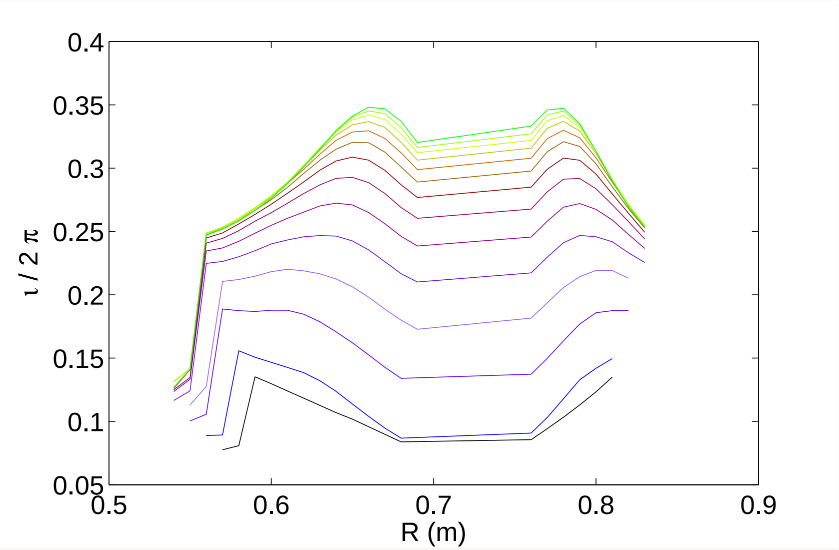
Loop Voltage=1V results in total current of about 15 kA and a stable configuration.



Total current (A).



Current penetration (ϕ-component) (A/m^2).



Rotational transform profiles at various times.

- Magnetic axis at 0.725m. Separatrix from 0.60m (t=0) to 0.56m (t=62ms).
- Hollow current profile.
- Rotational transform a little hollow, but remains relatively flat.

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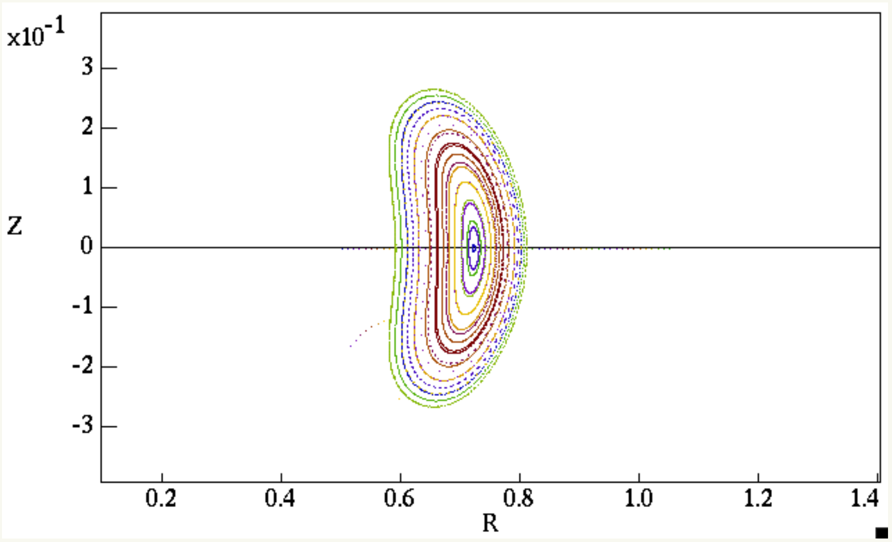
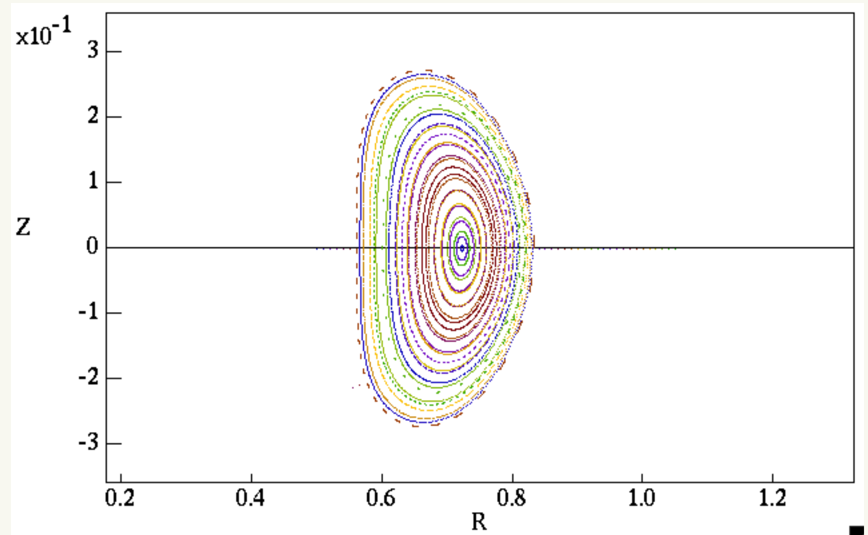
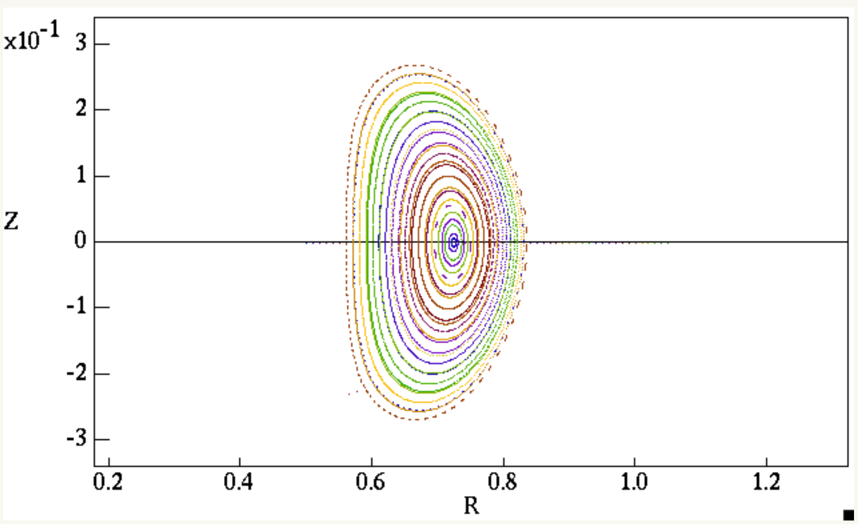
Loop Voltage=1V: Flux surfaces become less elongated.



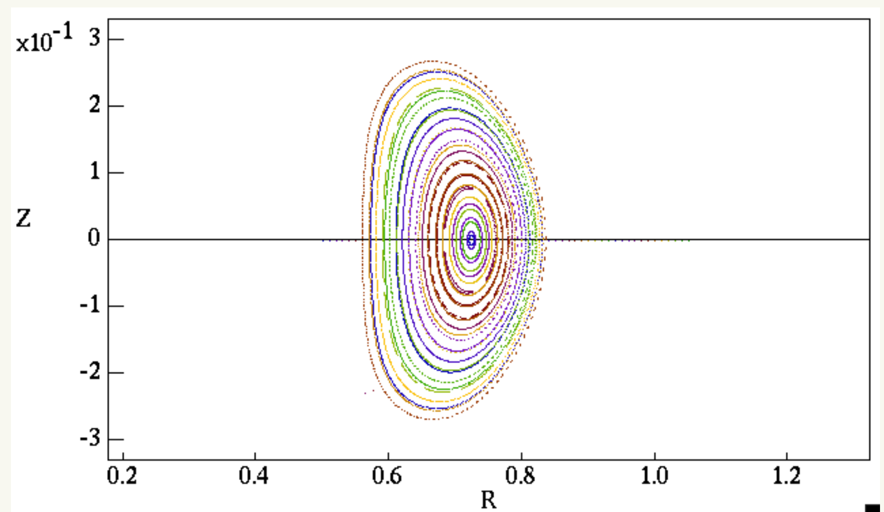
Poincaré plot for t=0.



Poincaré plot for t=17ms.

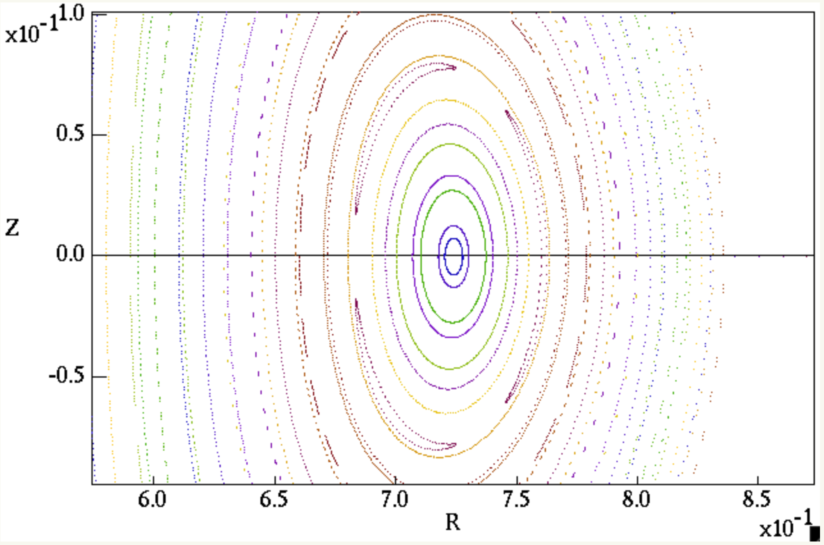


Poincaré plot for t=37ms.

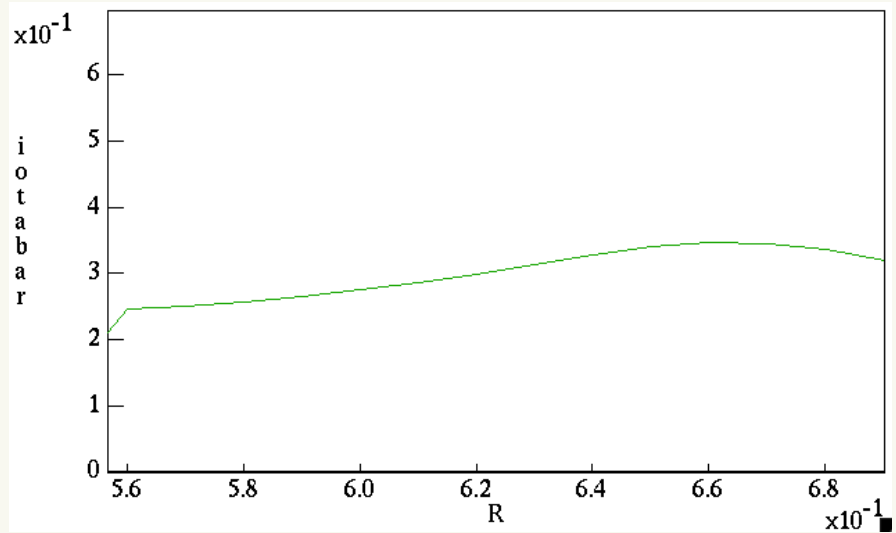


Poincaré plot for t=62ms.

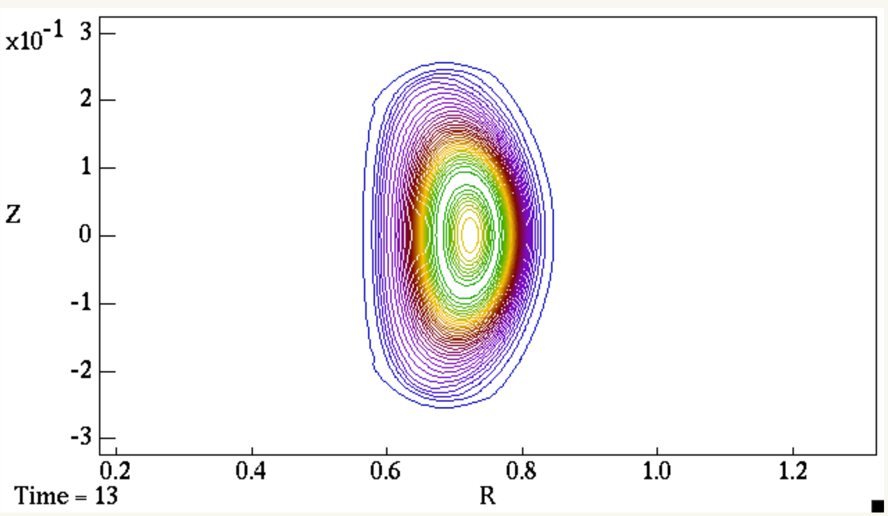
Loop Voltage=1V: No island formation seen until very late in the simulation.



Poincaré plot at t=62ms.



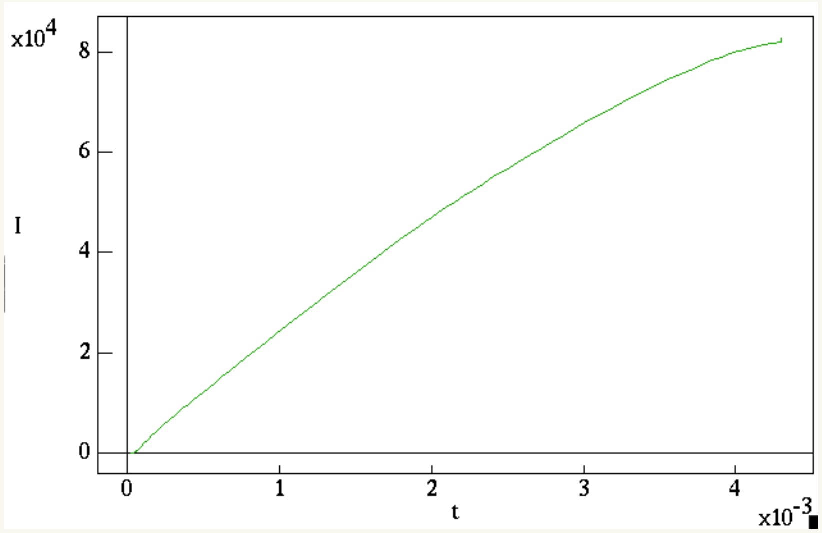
Rotational transform profile at t=62ms.



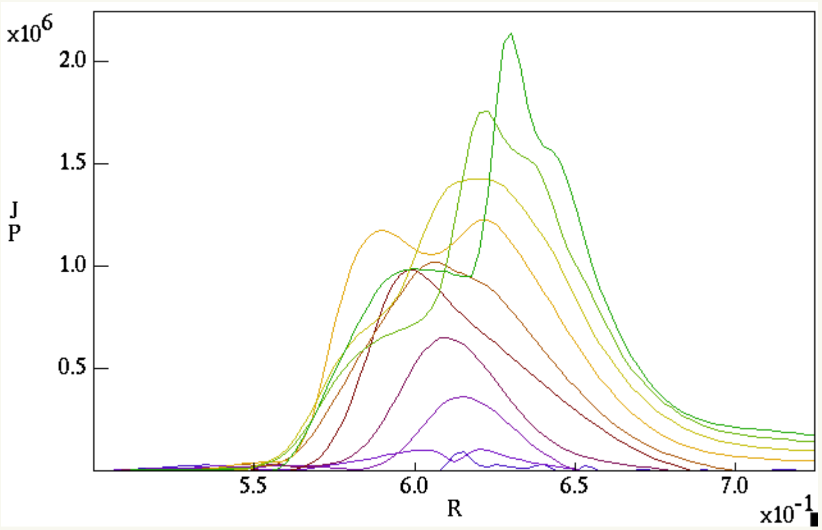
Parallel current contours at t=62ms.

- Island formation at $\iota = 1/3$ surface.

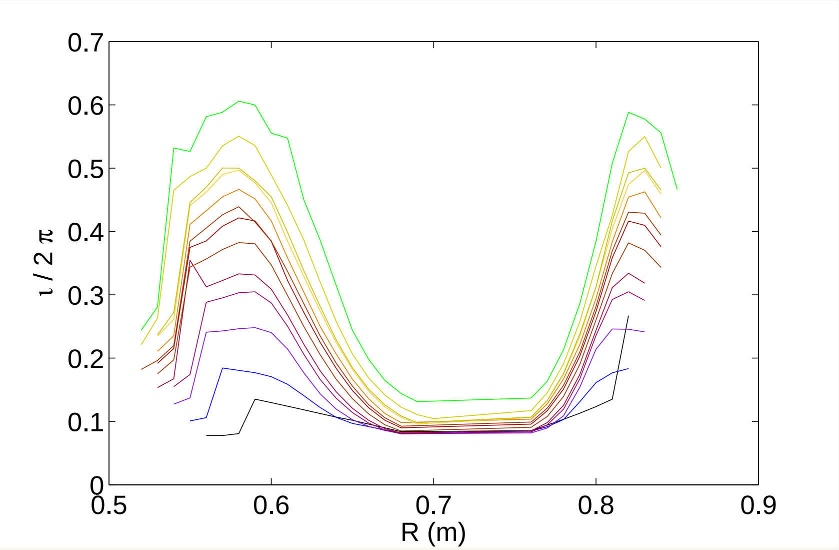
Loop Voltage=16V results in total current of about 80 kA and fast-growing instability.



Total current (A).



Current penetration (ϕ-component) (A/m^2).



Rotational transform profiles at various times.

- Mag axis at 0.725m. Sx at 0.60m (t=0) to 0.54m (t=4ms)
- Hollow current profile.
- Rotational transform profile becomes hollow.

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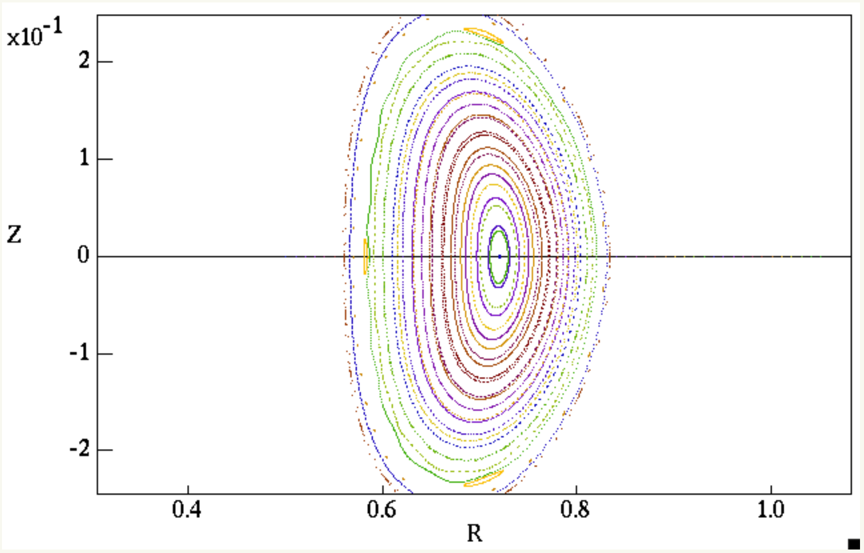
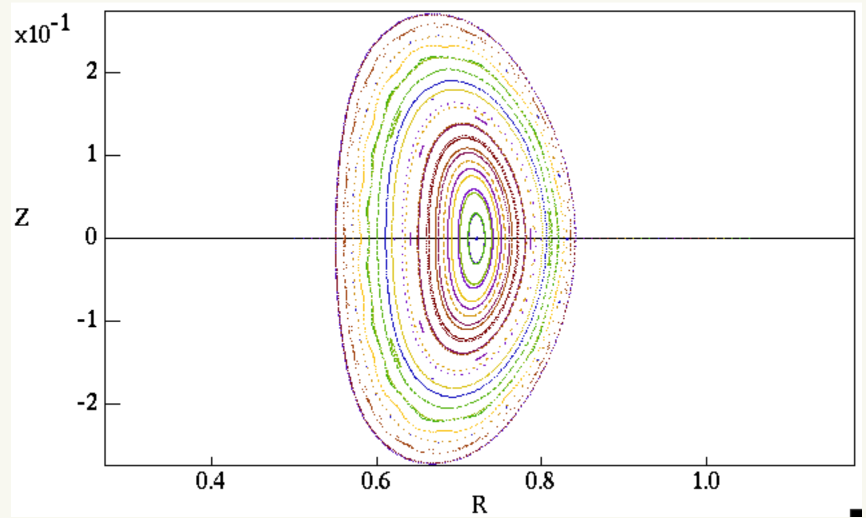
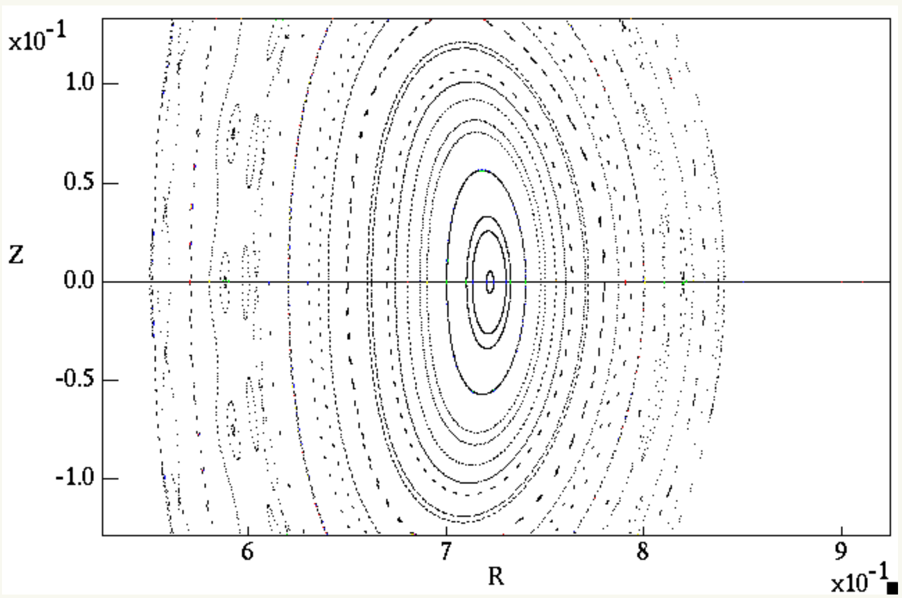
Loop Voltage=16V: 3/1 islands appear then disappear; overlap of 11/5 and 12/5 islands destroys flux surfaces.



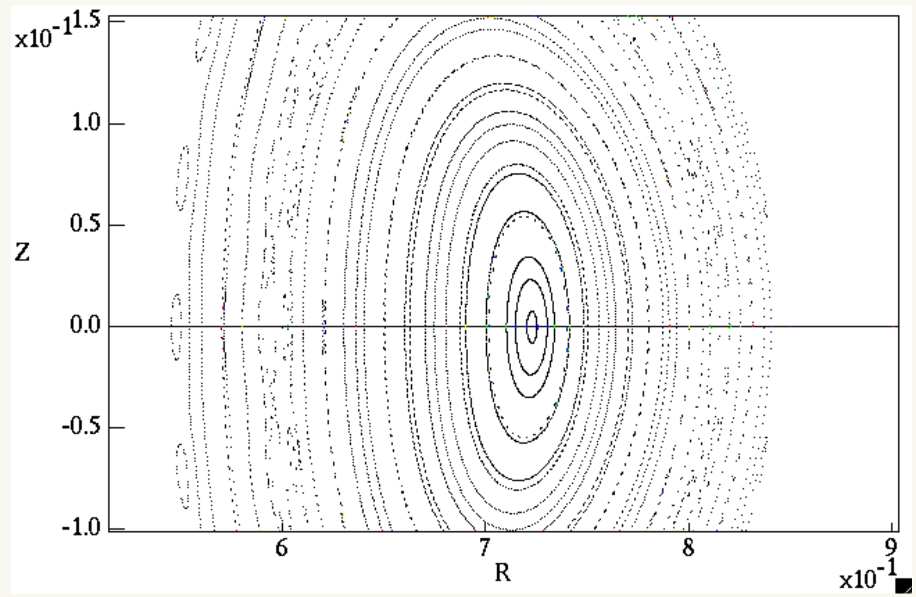
Poincaré plot for t=1.0ms



Poincaré plot for t=1.3ms.

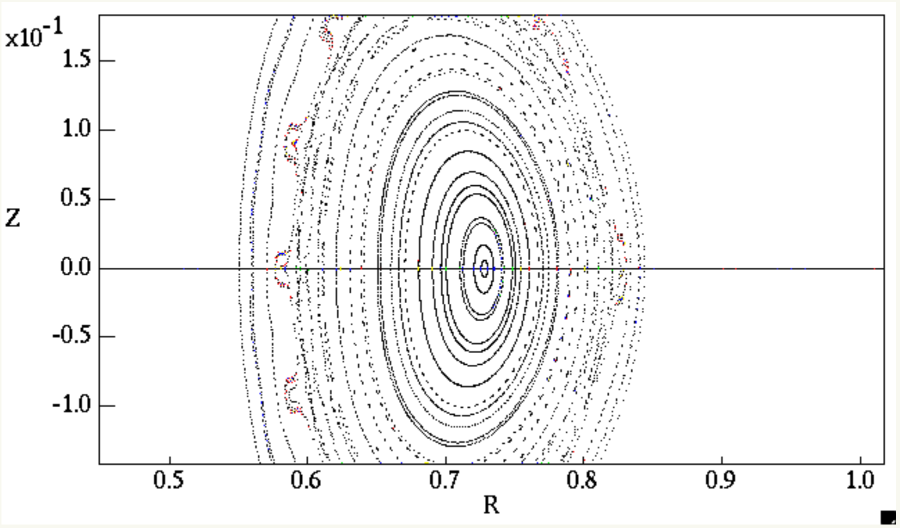


Poincaré plot for t=1.5ms.

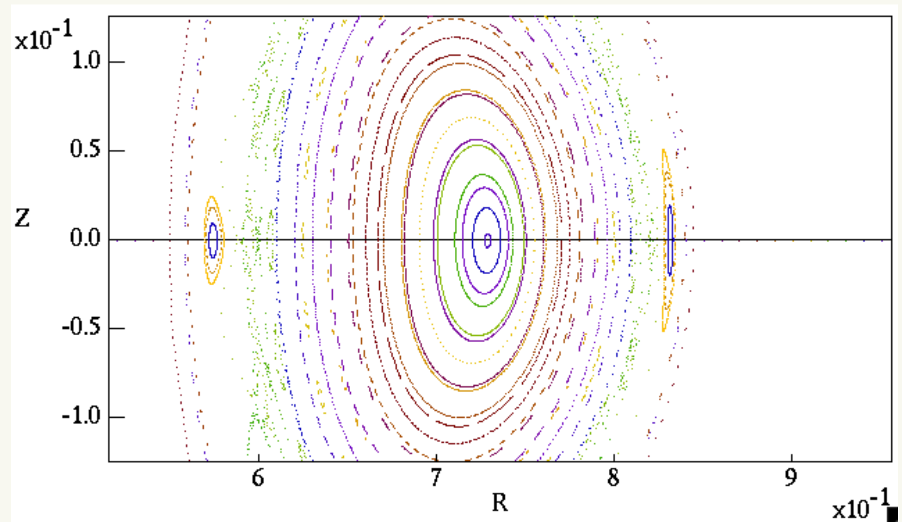


Poincaré plot for t=1.6ms.

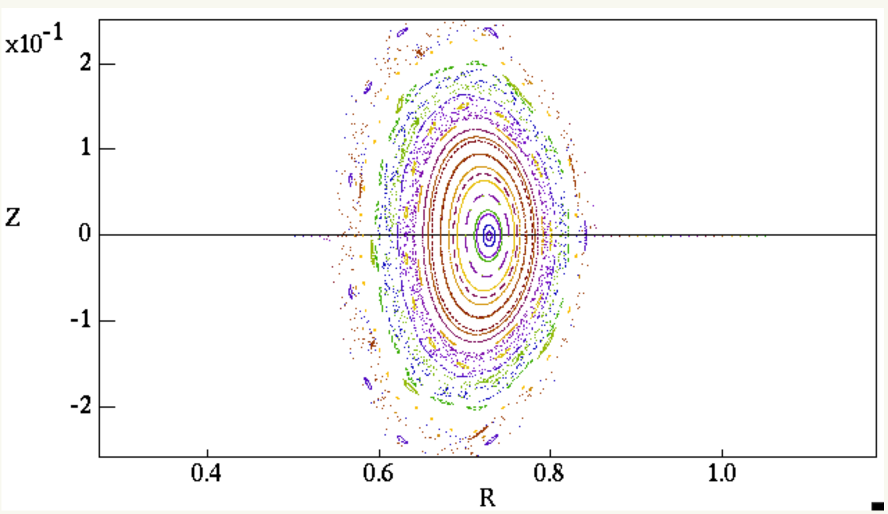
Loop Voltage=16V: A 10/5 structure gives way to a 2/1 structure which grows resulting in complete loss of flux surfaces.



Poincaré plot at t=1.9ms.



Poincaré plot at t=2.0ms.



Poincaré plot at t=2.6ms.

- Possible 10/5 double tearing mode

  => Reconnection & flux surface destruction.

  => 2/1 structure results.

- All flux surfaces lost at t≈ 4ms.

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