Comparing SSPX and NIMROD
The role and physics of reconnection in the spheromak

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with thanks to:
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CEMM Meeting – November 14, 2004

Work performed under the auspices of the U. S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

This work builds on earlier NIMROD spheromak calculations

- Calculations examining formation, equilibria and magnetic chaos

  J. M. Finn, C. R. Sovinec, and D. del-Castillo-Negrete, “Chaotic Scattering and Self-Organization in Spheromak Sustainment,” Phys. Rev. Letters 85, 4538 (2000)

  C. R. Sovinec, J. M. Finn, and D. del-Castillo-Negrete, “Formation and sustainment of electrostatically driven spheromaks in the resistive magnetohydrodynamic model,” Phys. Fluids 8, 475 (2001)

  V. A. Izzo and T. R. Jarboe, “A numerical assessment of the Lundquist number requirement for relaxation current drive,” Phys. Plasmas 10, 2903 (2003)

- Application to specific devices

  V. A. Izzo, 3D MHD simulations of the HIT-SI spheromak experiment, Invited paper this APS meeting (Thursday afternoon)

  C. R. Sovinec, B. I. Cohen, G. A. Cone, E. B. Hooper, and H. S. McLean, “Numerical Investigation of Transients in the SSPX Spheromak,” submitted to Phys. Rev. Letters.

  B. I Cohen, “Spheromak Evolution and Energy Confinement,” Invited paper, this APS meeting (Thursday afternoon)

  E. B. Hooper, et al. “Reconnection in NIMROD and SSPX during spheromak formation,” Poster paper, this APS meeting (Wednesday morning)

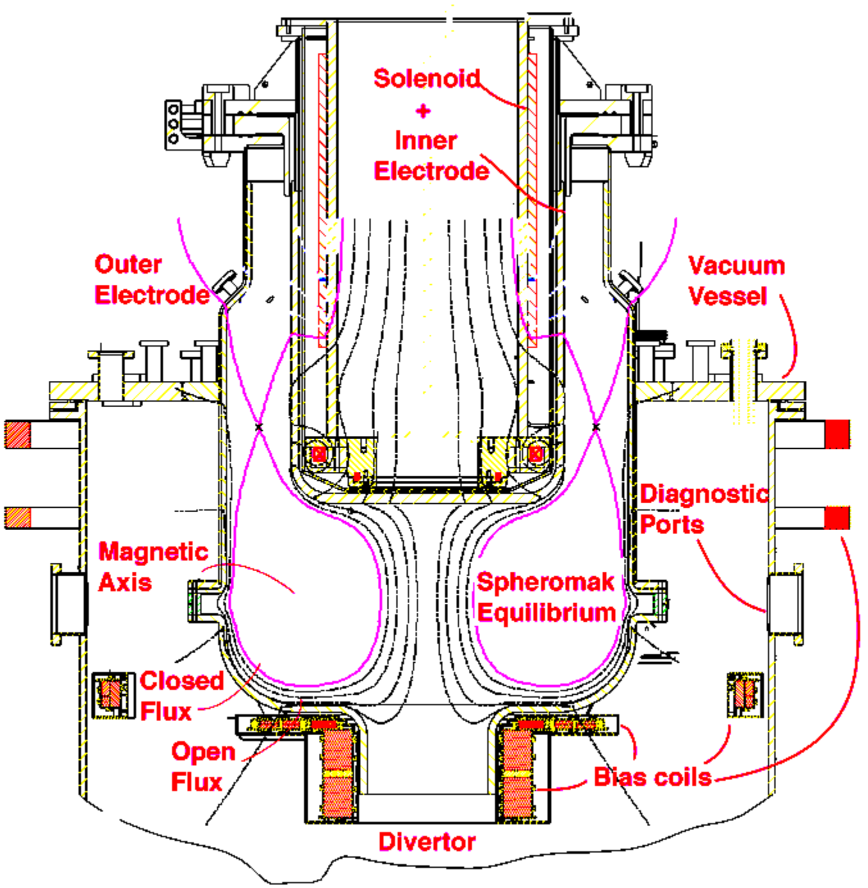
Modeling SSPX has been guided by experiment, contributed to our understanding of the physics, and is starting to help guide experimental runs

NIMROD is now “benchmarked” for the MHD evolution of SSPX — It does a good job reproducing the time histories of fields, temperatures, and injector (“gun”) characteristics

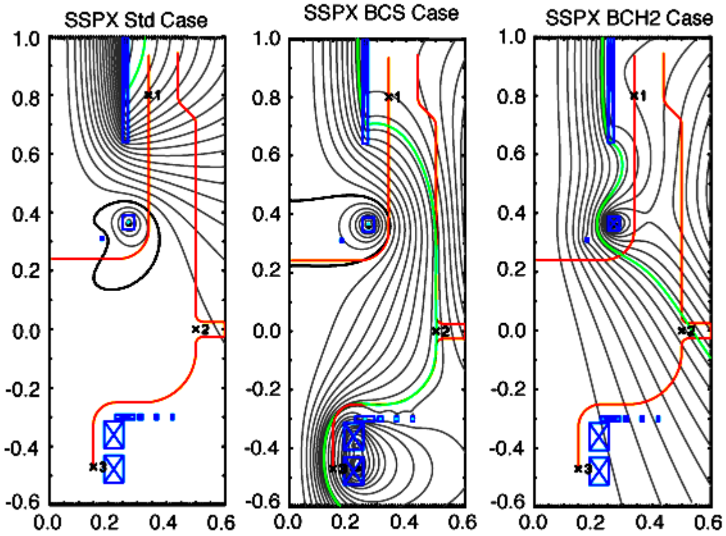
Some detailed MHD characteristics of SSPX — comparing experiment with NIMROD modeling

- **Mode amplitudes** previously examined by Sovinec
  - Drop when the gun is operated at $\lambda_{gun} \approx \lambda_{flux\ conserver}$ as in the experiment
  - Amplitudes about the same as the experiment
  - Mode structure finds the n=1 mode is peaked on the current column — driven by the gun current
- **Mode frequencies**
  - Much lower than experiment
  - Non-MHD physics — e.g. rotation drive — required to explain the frequencies
- **Plasma startup and transition to quasi-steady state**
  - NIMROD — mode growth from "seed amplitude" determines when non-axisymmetric processes become important
  - SSPX — startup is more non-axisymmetric than possible in the code, so non-axisymmetric processes occur earlier
  - SSPX — time evolution during a second current pulse is explained by the growth of modes from an initially small amplitude with the delay of reconnection

Important features of SSPX



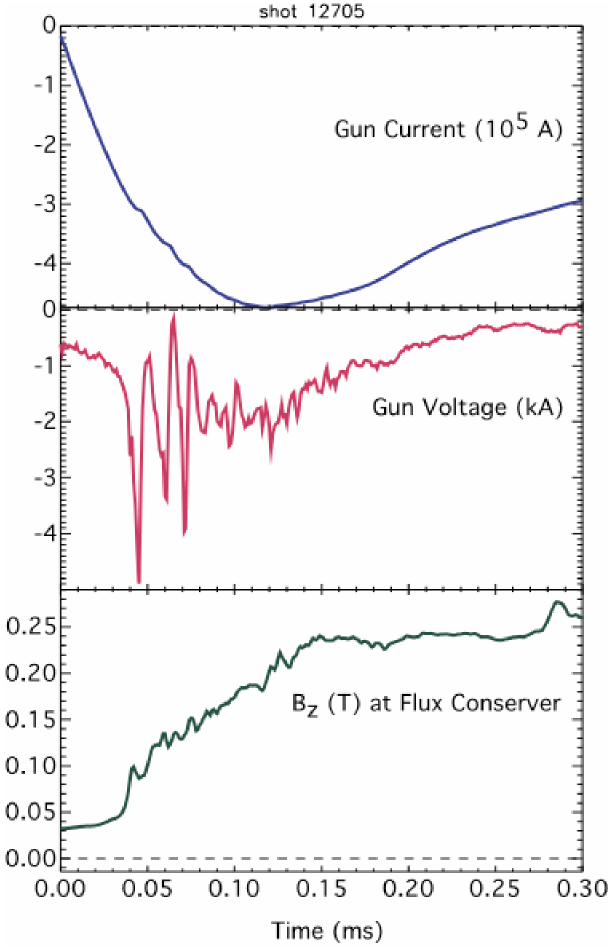
- **Thick wall (~.015 m) copper flux conserver (dia=1 m) minimizes dissipation.**
- **Tungsten coating to reduce sputtering. Ti gettered to reduce impurities**
- **4 msec discharges. 500 kA peak formation, 250 kA sustained**
- **9 solenoidal coils provide flexible vacuum field programming**



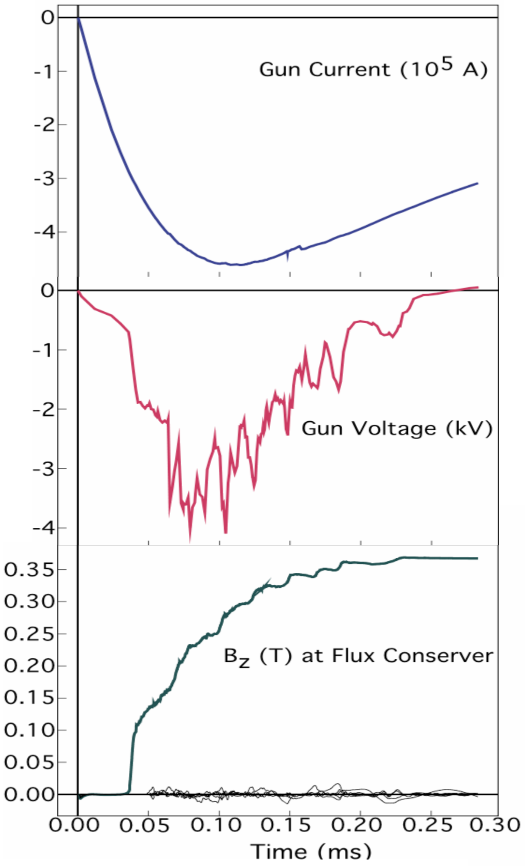
The correct geometry, vacuum flux, and gun current yields good agreement between NIMROD and SSPX

Azimuthally-averaged toroidal flux is generated when the n=1 mode amplitude is large enough to generate n=0 nonlinearly — Reconnection is required for topology change

SSPX

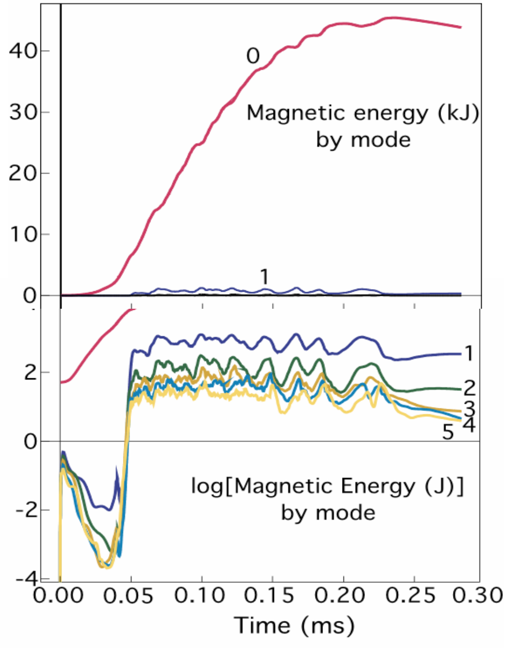


NIMROD

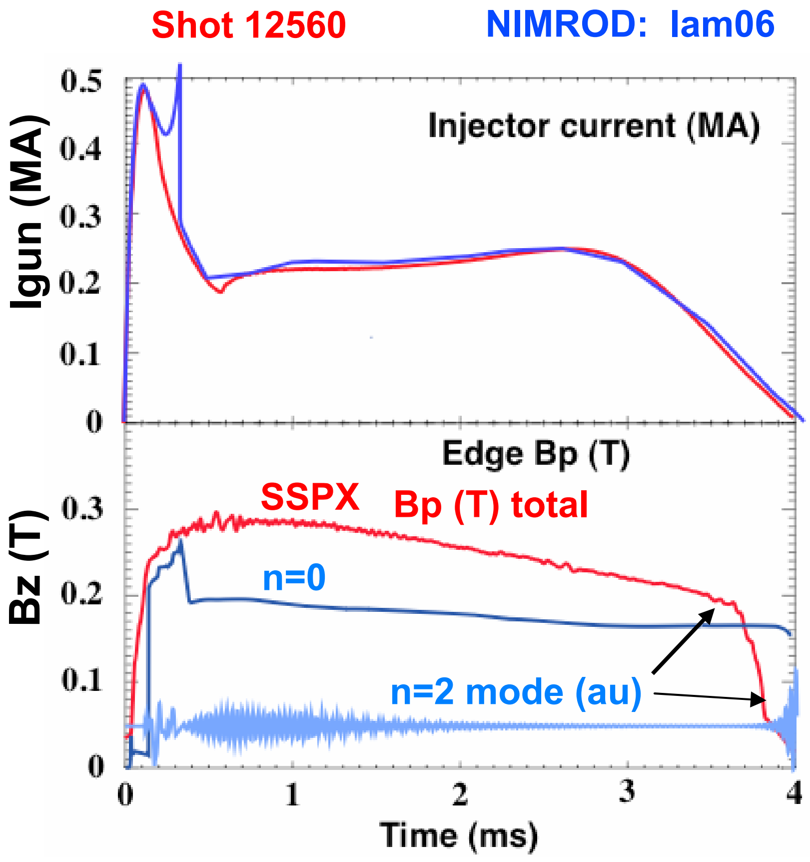


Reconnection when:

- **Gun voltage spikes**
- **B_z steps up**
- **Mode amplitudes drop**

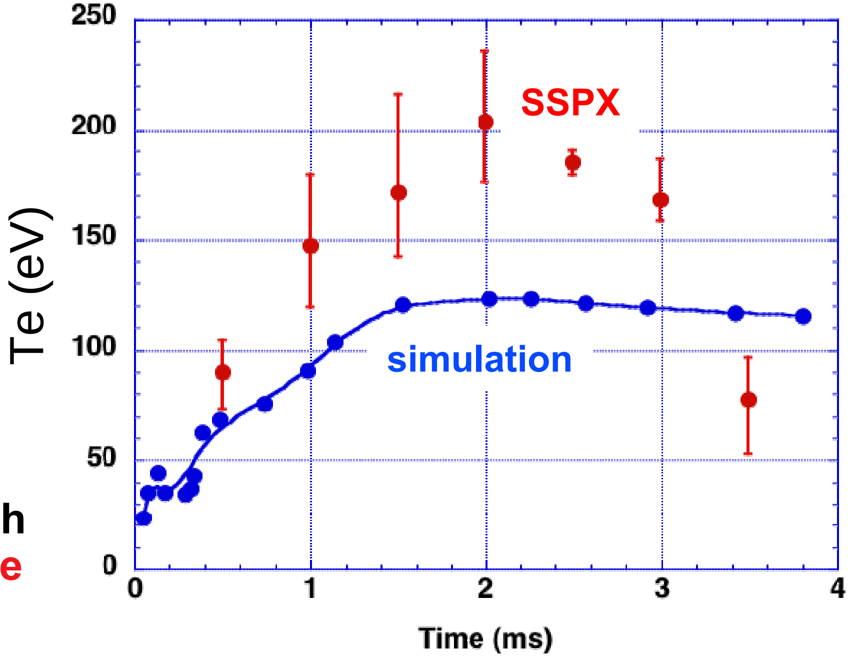


The temperature history of SSPX is reproduced quite well by NIMROD

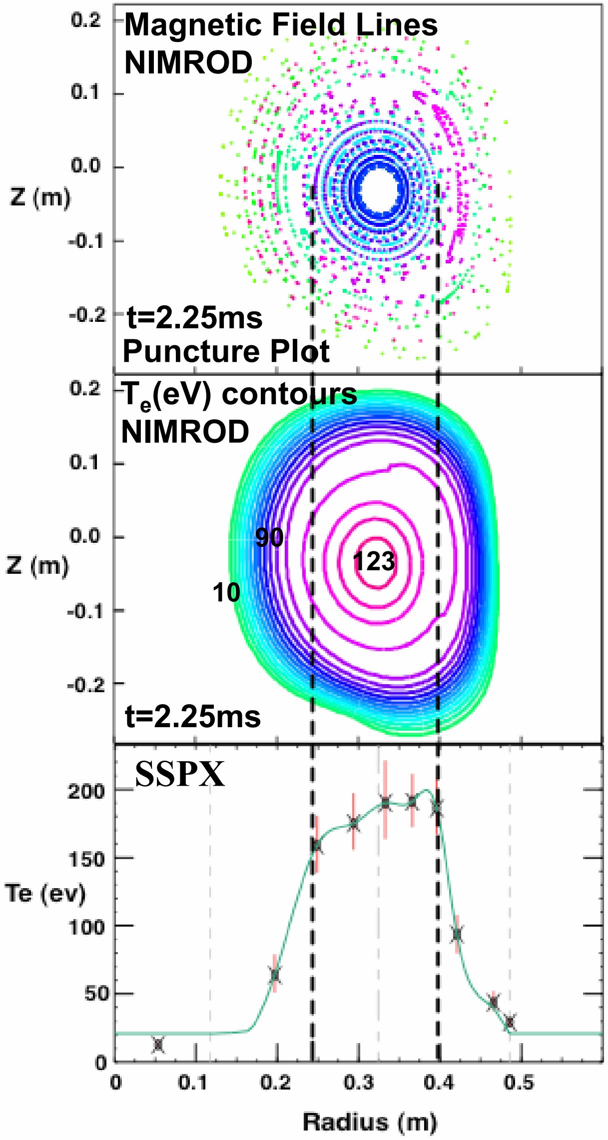


- The n=2 mode at 0.5-2 ms is an island with n/m = 2/1; q=1/2 inside the separatrix – We are examining the effect on flux surfaces
- Plasma dumps at ~ 4 ms with a 2/1 mode

- Improved NIMROD simulations with
  - Spitzer-Braginskii resistivity
  - Parallel thermal conduction
- In NIMROD $T_e = T_i$; in SSPX the energy exchange time is ~ 1 ms after t≈1 ms —> $T_e > T_i$



NIMROD Simulations Show Good Flux Surfaces and Electron Temperatures Similar to SSPX

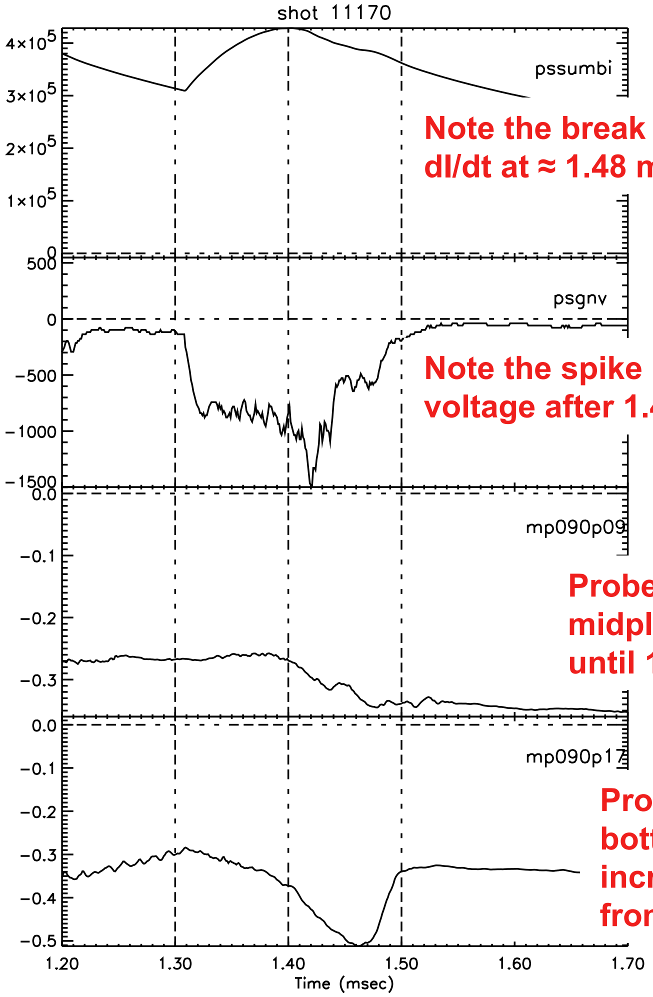


- **"Sustainment" phase: NIMROD simulations show regions of good confinement ($0.25<R<0.4$) surrounded by islands and chaotic lines ($0.15<R<0.25, 0.4<R<0.48$) and then open field lines.**
- **Electron temperature contours align with the magnetic field lines.**
- **Local flattening often seen in the SSPX T_e profile may be due to the presence of islands**
- **Transition from good flux surfaces to chaotic and then open field lines leads to steep drop in T_e**

See Bruce Cohen, Thursday afternoon Paper PI1B for more results

SSPX reconnection — A second current peak into an existing spheromak — B_{poloidal} at the flux conserver midplane does not start to increase until the peak of the second current pulse

I, V, 90° midplane and bottom probes



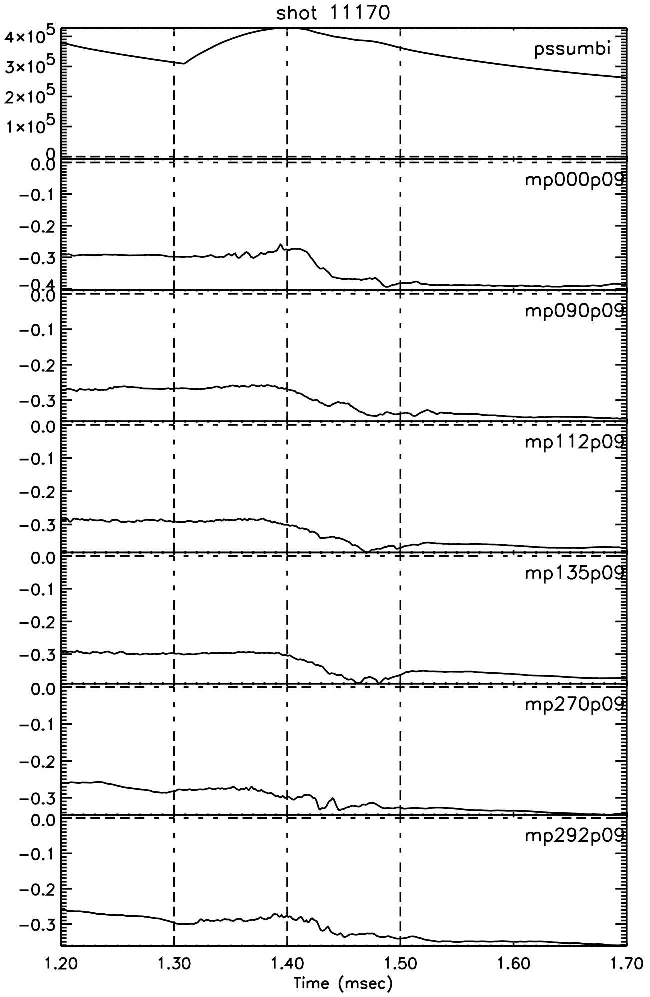
Note the break in dI/dt at ≈ 1.48 ms

Note the spike in voltage after 1.4 ms

Probe p09 (FC midplane) flat until 1.4 ms

Probe p17 (FC bottom) increases from 1.3 ms

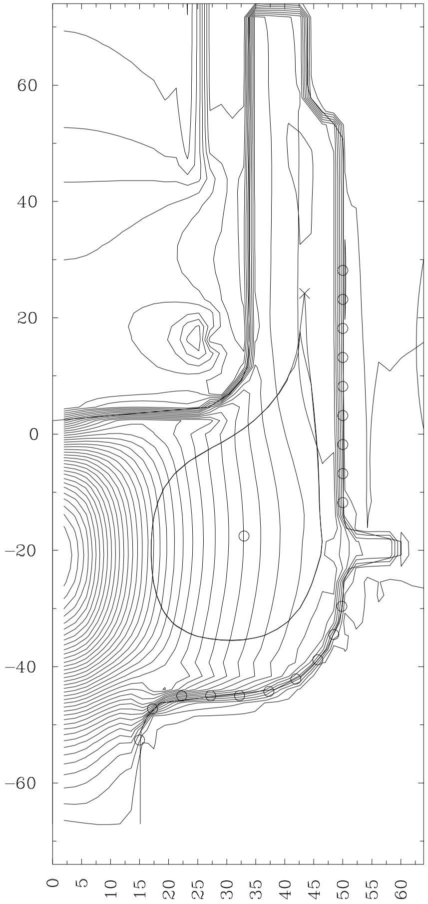
Azimuthal array shows this at all angles



Contours of |B| show the column is pinched during the current rise and relaxes during the event

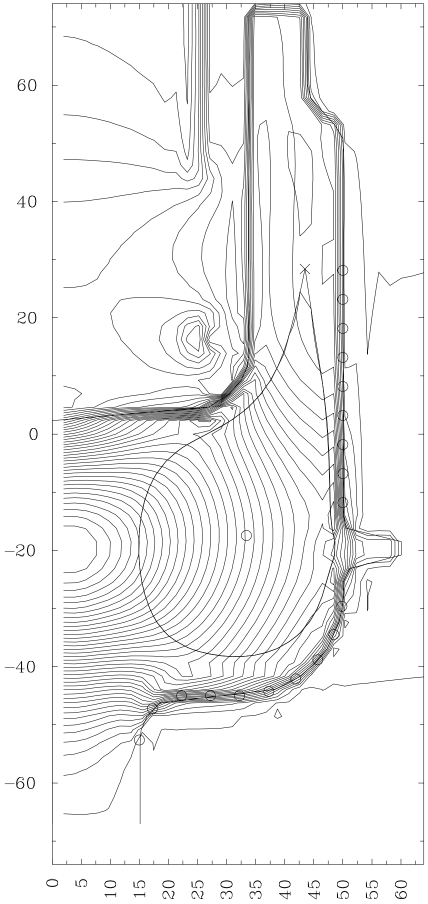
During current rise

t = 1.38 ms



During current decay

t = 1.52 ms



Further evidence for a reconnection event is in my APS poster

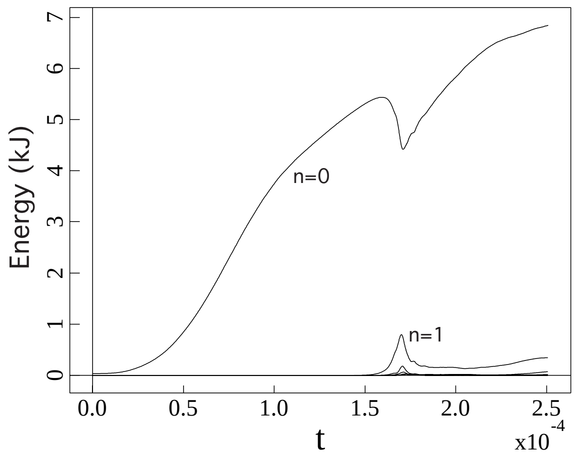
NIMROD
Buildup starting with low amplitude magnetic modes

When NIMROD is started with low amplitude, non-symmetric modes — helicity and magnetic energy injection forms a nearly axisymmetric configuration

- **There is little or no conversion of toroidal flux into poloidal flux until the modes (especially n=1) grow sufficiently large that nonlinear coupling generates an axisymmetric magnetic field**
- **Flux conversion requires a change in field topology — A reconnection event occurs, very similar to that seen in SSPX**
  - **We study this event to gain insight into the physics occurring during reconnection in spheromaks**

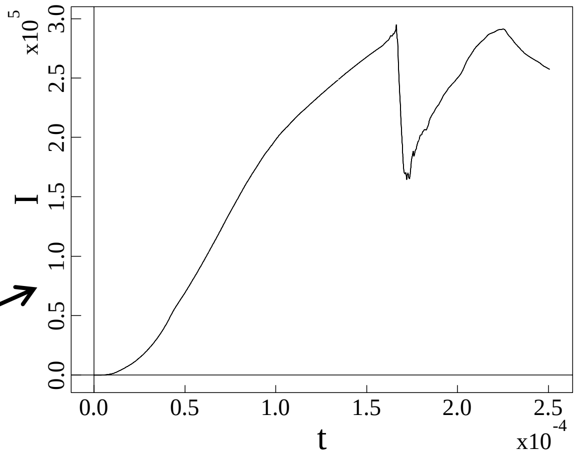
NIMROD — Mode growth from a low “seed” delays initial reconnection processes until after the current peaks

Magnetic Energy vs. t



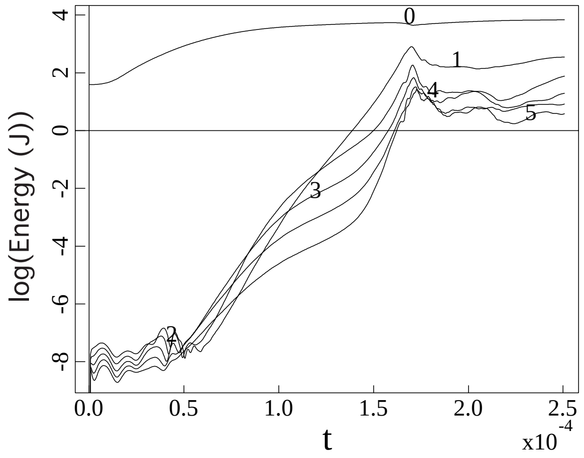
Energy in n=0 grows until higher n modes become large

Total (n=0) Current vs. t



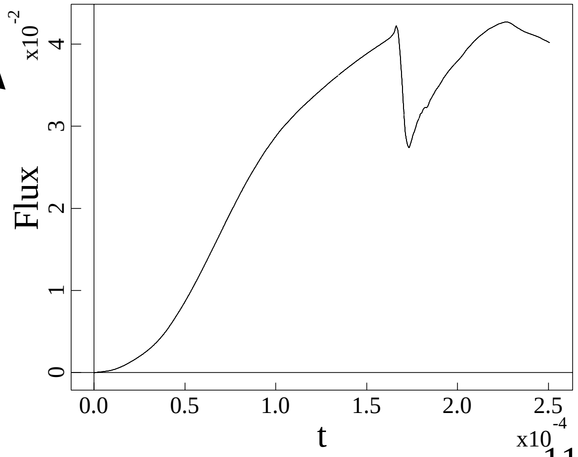
Toroidal current and flux drop during the initial reconnection event

Magnetic Energy vs. t



Mode energy takes 100 μs to grow from 10^{-8} J

Total (n=0) Flux vs. t

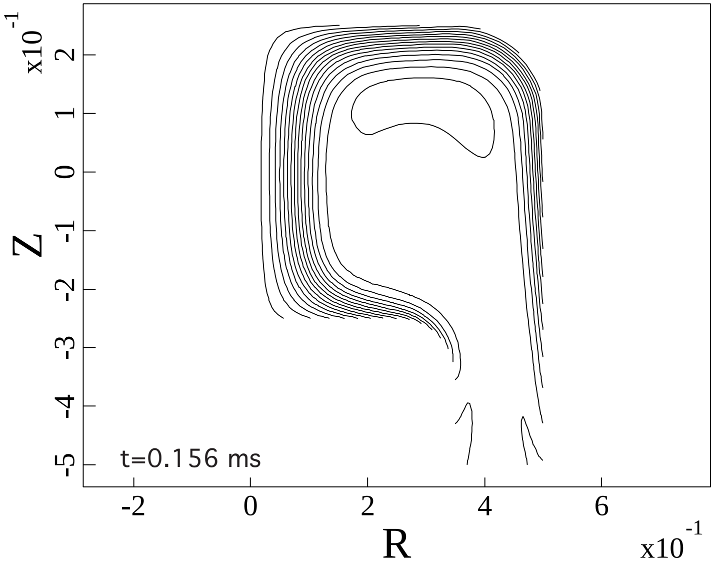


Before the burst of magnetic activity, the fieldlines lie on the open flux resulting from the "bubble-burst" from the gun

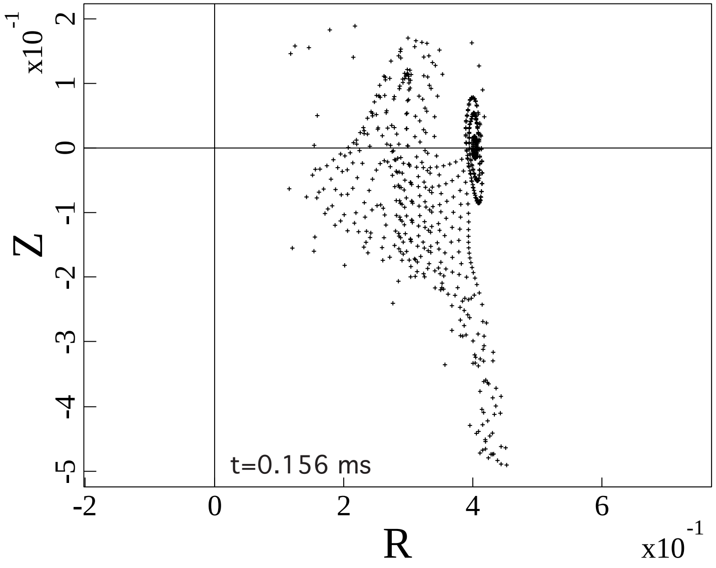
All fieldlines are open (except for a small island near the flux conserver)

— no indication of chaos

- **Puncture plots are smooth**
- **$\lambda = \mu_0 j/B$ peaked on the geometric axis and small on the magnetic axis (not shown)**
- **Small poloidal field near magnetic axis — fieldlines make many toroidal transits**



Poloidal flux



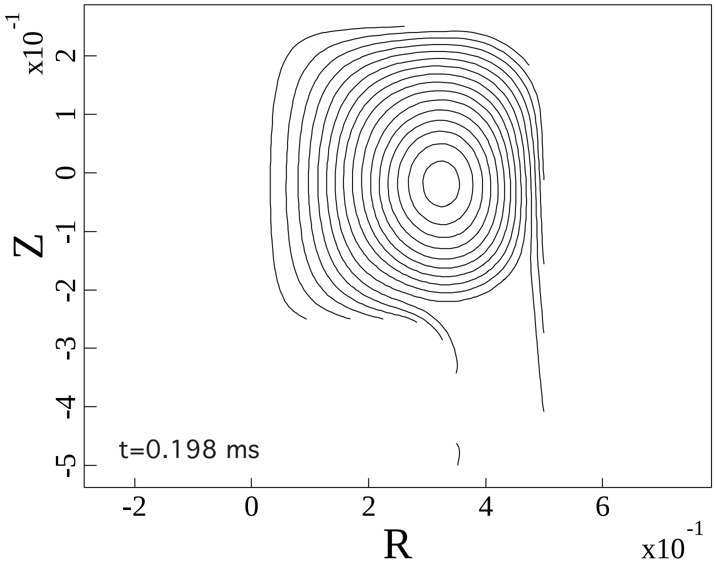
Surface of Section

After the burst of magnetic modes, azimuthally-averaged flux surfaces are formed (a “good” mean-field spheromak) but fieldlines are chaotic

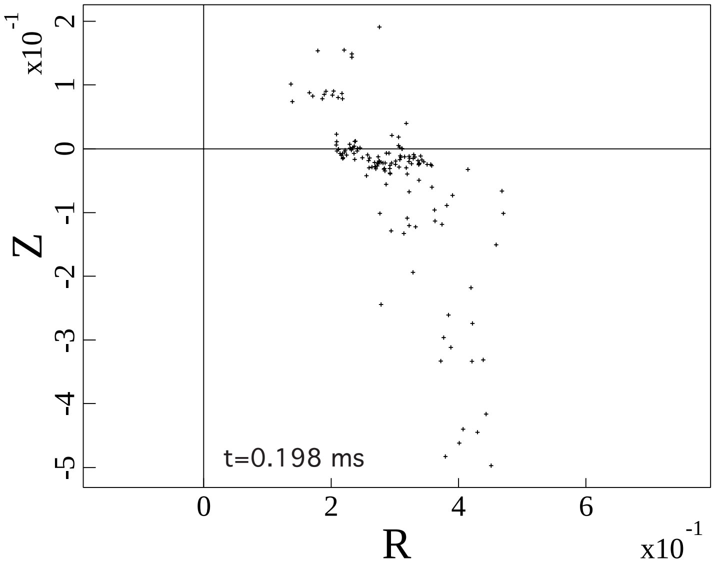
All fieldlines are open — chaos is apparent

- **All fieldlines exit the flux conserver**
- **$\lambda=\mu_0 j/B$ (azimuthally averaged) is patchy and non-monotonic (shown later)**

Poloidal flux



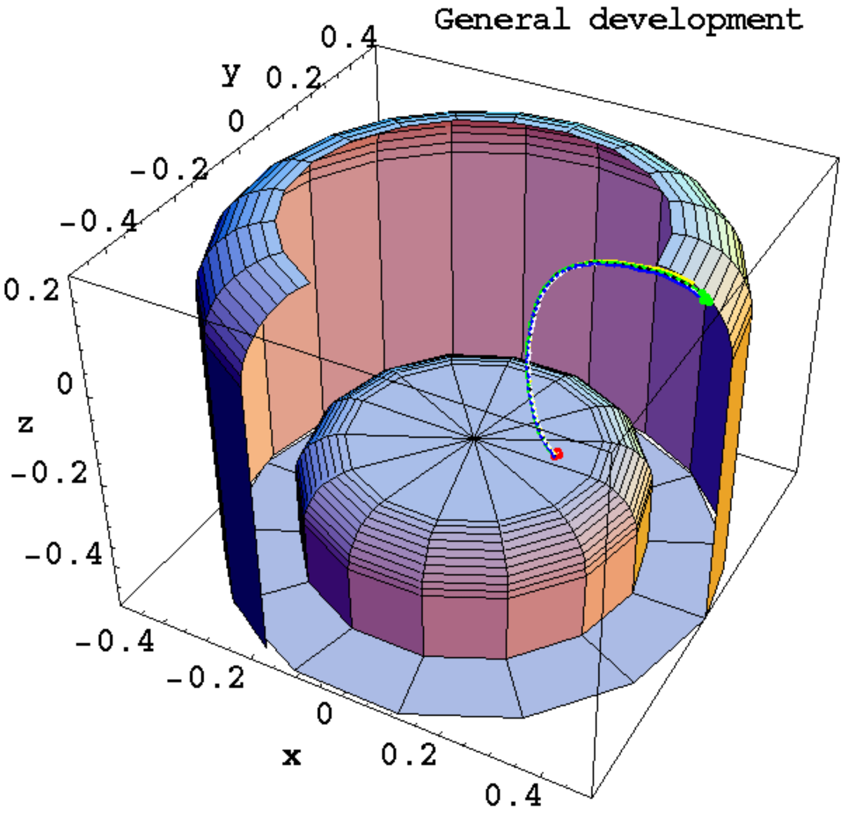
Surface of Section



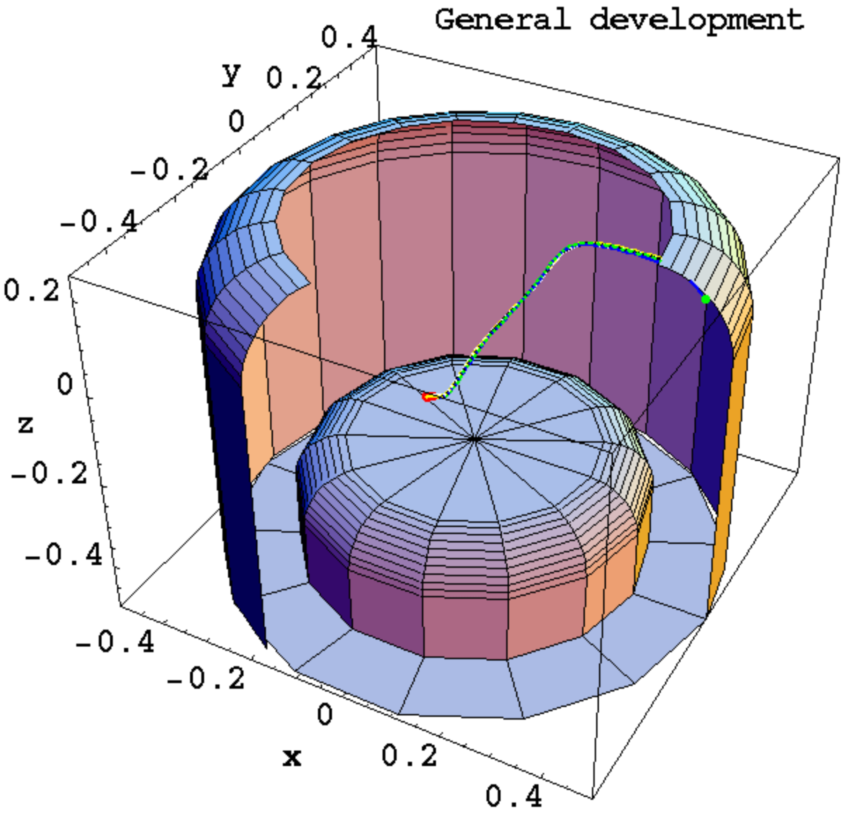
Fieldline evolution as the discharge develops

During early formation stages, the fieldlines evolve without chaos

Initial “bubble blowing”

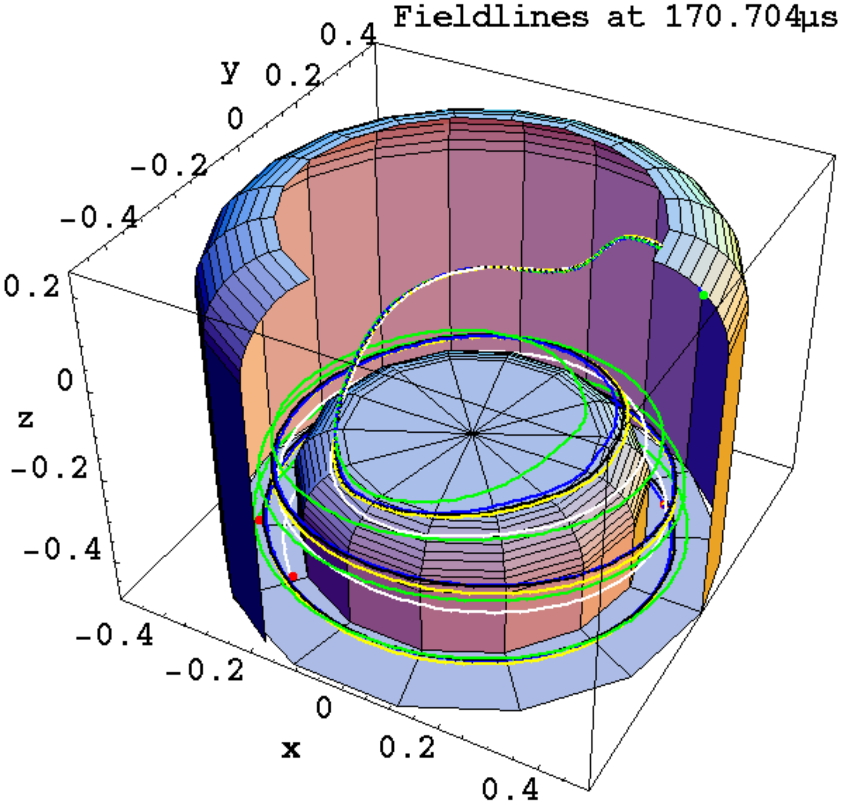


Toroidal field growth

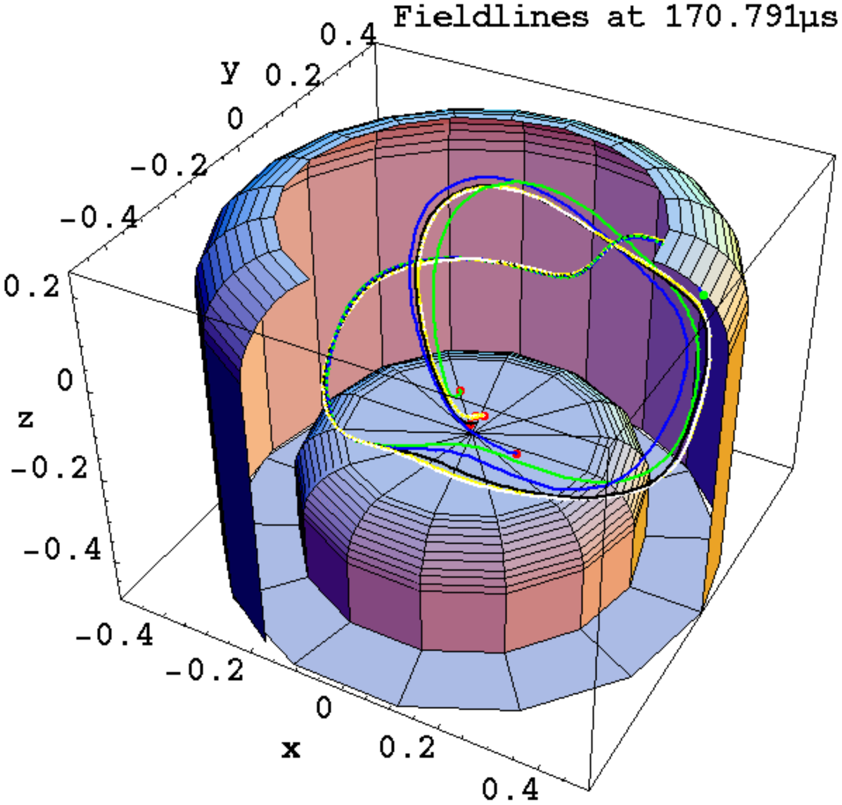


Fieldline evolution (cont.) — reconnection is needed for topology change and generates chaos

Development of chaos

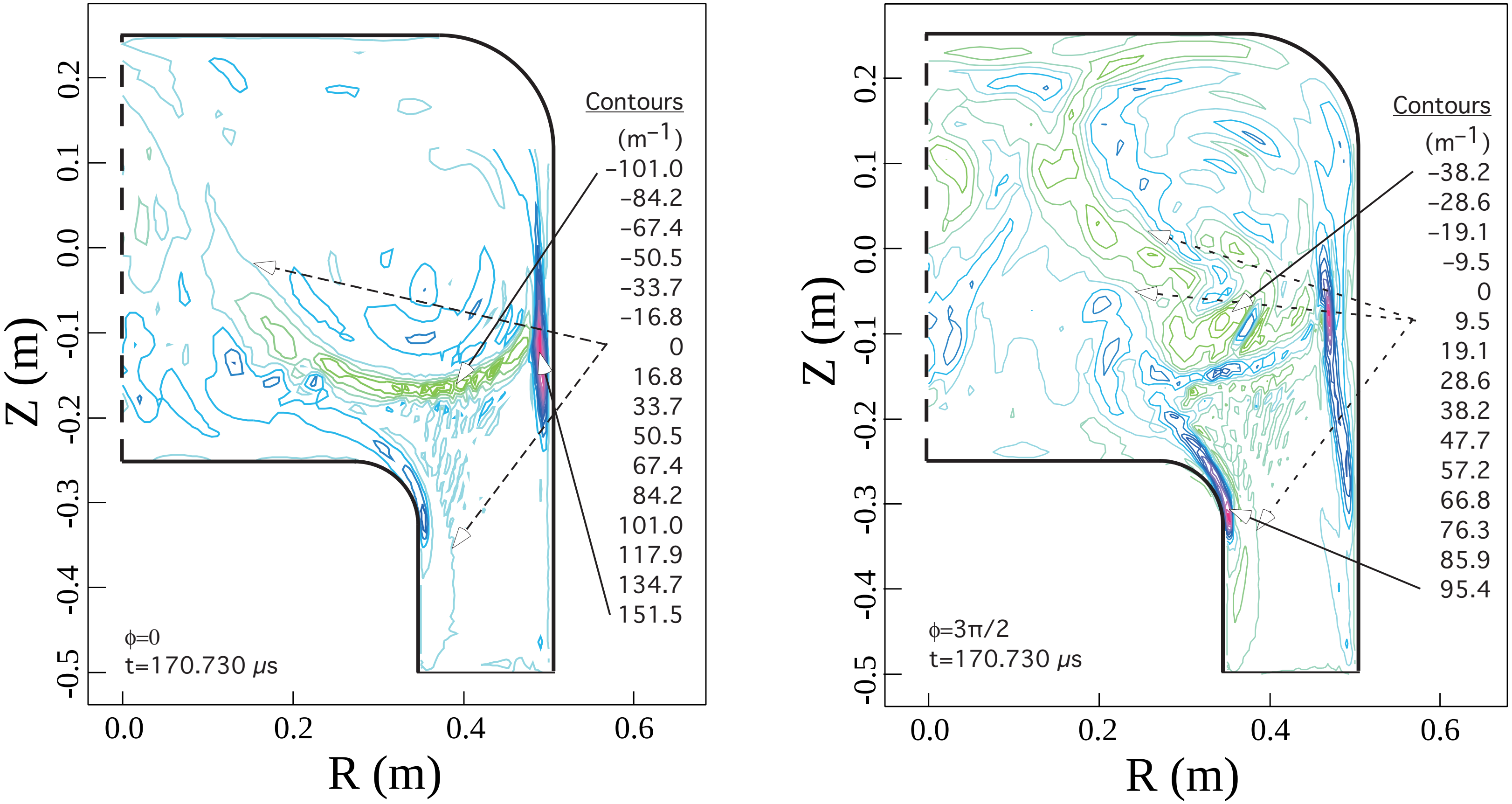


Knots sometimes form – a clear demonstration of topology change



At other times (not shown) the 5 fieldlines (1 cm spaced cross at the flux conserver) diverge significantly from one another

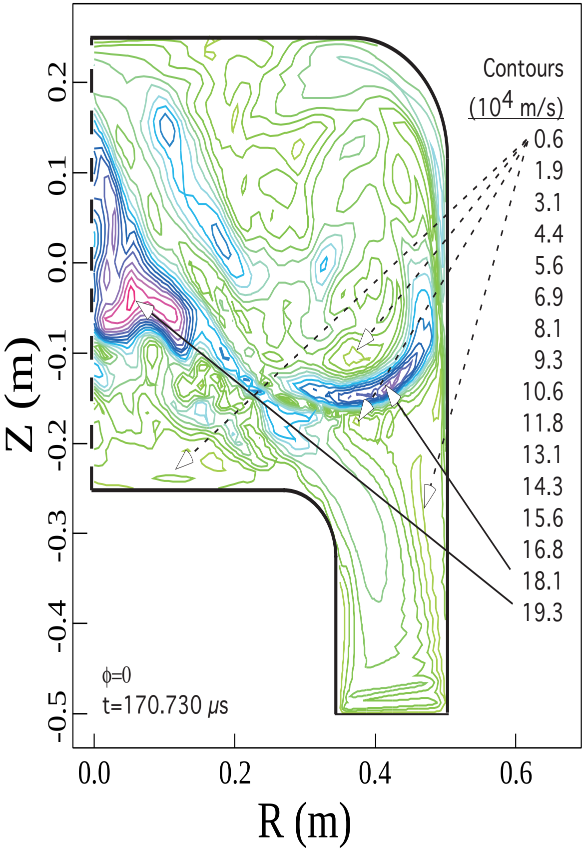
Current sheets with λ < 0 — are associated with reconnection



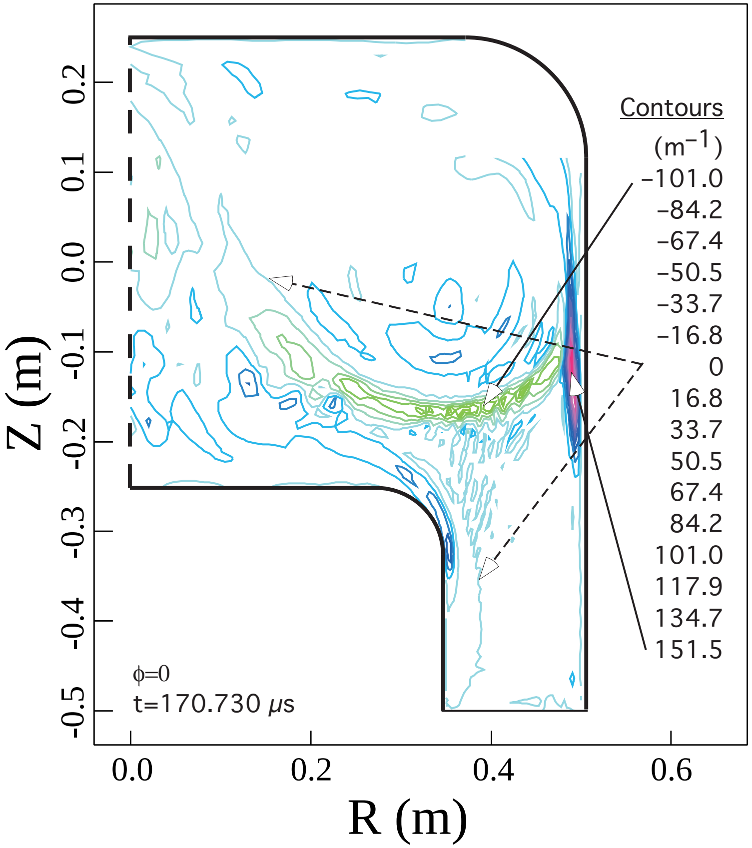
Fieldlines which pass close to the current sheets are very sensitive to their precise location — as expected for generation of chaos

Large velocity flows perpendicular to B are associated with the current layers

Perpendicular speed



λ



Helicity (K) and magnetic energy (W) decay times depend differently on λ

$$\tau_W = \frac{W}{dW/dt} = \frac{\int B^2 dV}{2\int \frac{\eta_\parallel \lambda^2}{\mu_0} B^2 dV + 2\mu_0 \int j_\perp \cdot E_\perp dV}$$

$$\tau_K = \frac{K}{dK/dt} = \frac{\int B^2 dV}{2\int \frac{\eta_\parallel \lambda}{\mu_0 \langle \lambda^{-1} \rangle} B^2 dV}$$ with $\langle \lambda^{-1} \rangle = K/2\mu_0 W$

NIMROD finds large (factor of 10) spatial variations in λ – including sheets of negative current

- **Energy losses depend quadratically on λ — τ_W is reduced significantly by these variations**
- **Helicity losses depend linearly on λ so the variations tend to cancel (“conservation of helicity”) — however, the variations are so large that cancellation is not perfect**

SSPX formation efficiencies [~ 18% (energy) and ~ 33% (helicity)] are likely due to enhanced losses associated with current layers

Summary

- NIMROD does a good job of matching the experiment
- Reconnection is needed to convert toroidal flux to poloidal flux
- In NIMROD we find:
  - Initial injection of current is nearly axisymmetric
  - Non-symmetric modes grow until nonlinearities are large enough to generate n=0 fields
  - Reconnection then occurs with strong effects on topology
- Examination of details in NIMROD identifies current sheets as a major “player” in reconnection
  - Inductive electric fields reverse λ in the current sheets
  - “Collisions” of fieldlines with these sheets generate chaos
  - Ohmic dissipation due to large variations in λ are a candidate for inefficiencies during formation

See Bick Hooper, Poster HP1.070 (Wednesday AM) for more details