# Spectroscopic observation of simultaneous bi-directional outflows in SSX

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with contributions from

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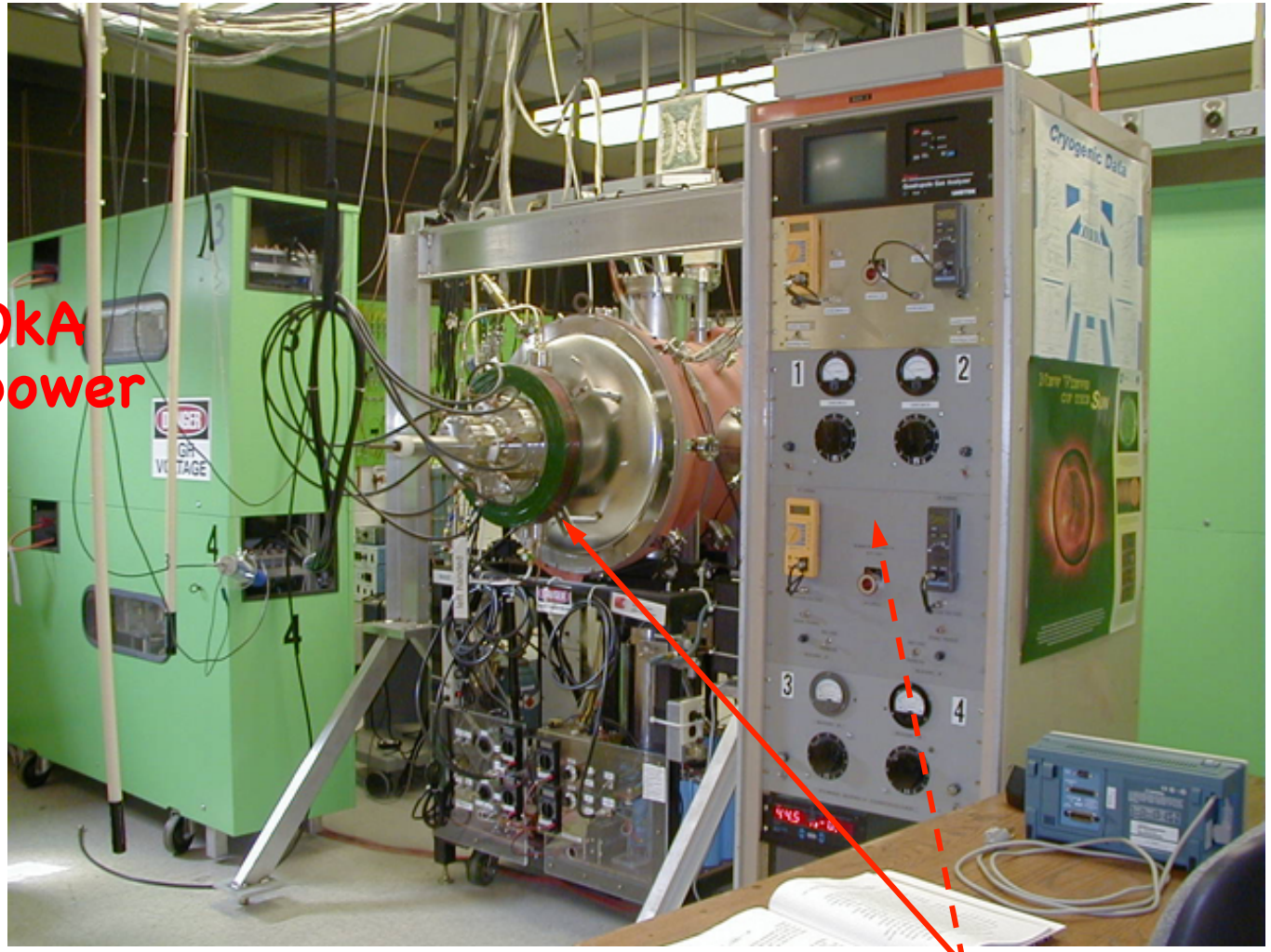
# Outline

- Overview of SSX experiment
- Merging, reconnection and relaxation
- Myers simulation, SSX measurement of outflows
- Tim Gray talk next

# The SSX Laboratory




10kV/100kA
Pulsed power

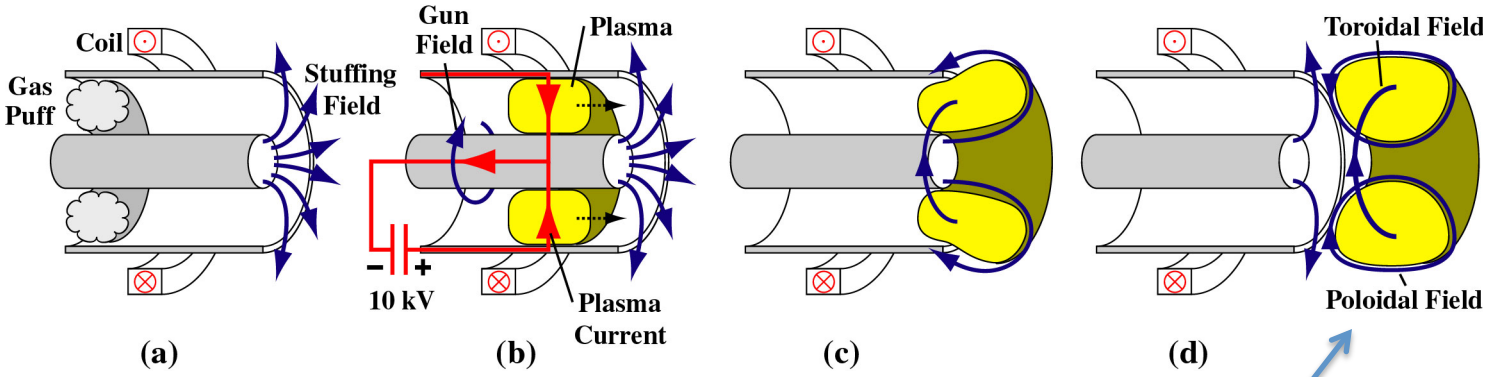
Cylindrical vacuum chamber
(D = 0.5 m, L = 1 m)

High voltage plasma
guns on each end

# SSX parameters

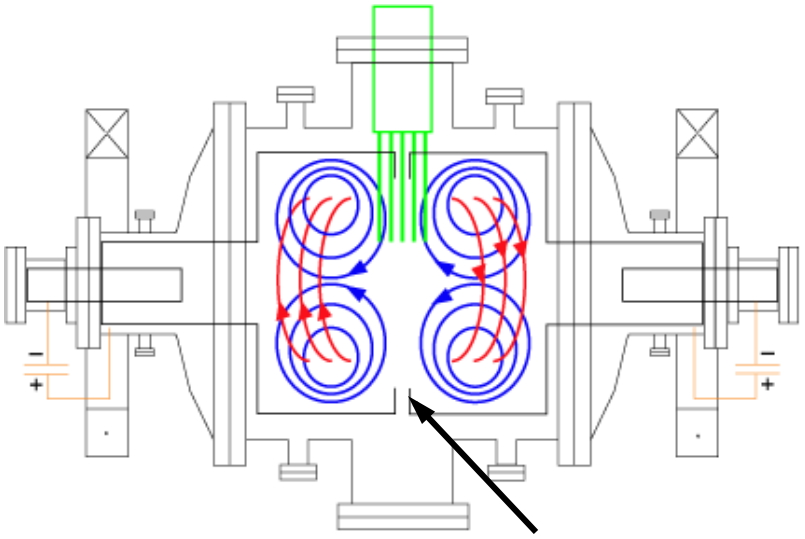
| | |
|---|---|
| Ion Density (protons) | $10^{14}$ -$10^{15}$ $cm^{-3}$ |
| Temperature ($T_e$,$T_i$) | 20 - 80 eV |
| Magnetic Field | 0.1 Tesla |
| Ion gyroradius | 0.5 cm |
| Alfvén speed | 100 km/s |
| S (Lundquist number) | >1000 |
| Plasma β | 10-100% |
| Poloidal flux | 3-4 mWb |

# Spheromak formation

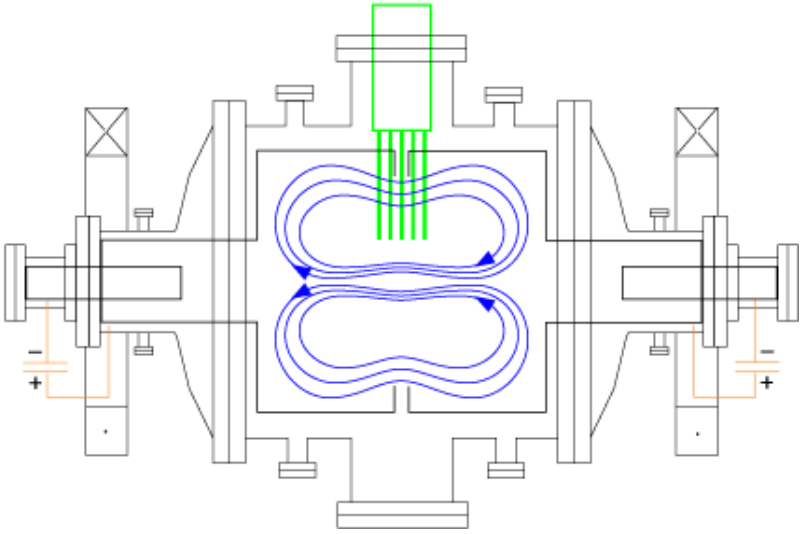



Spheromak

# Plasma merging paradigm

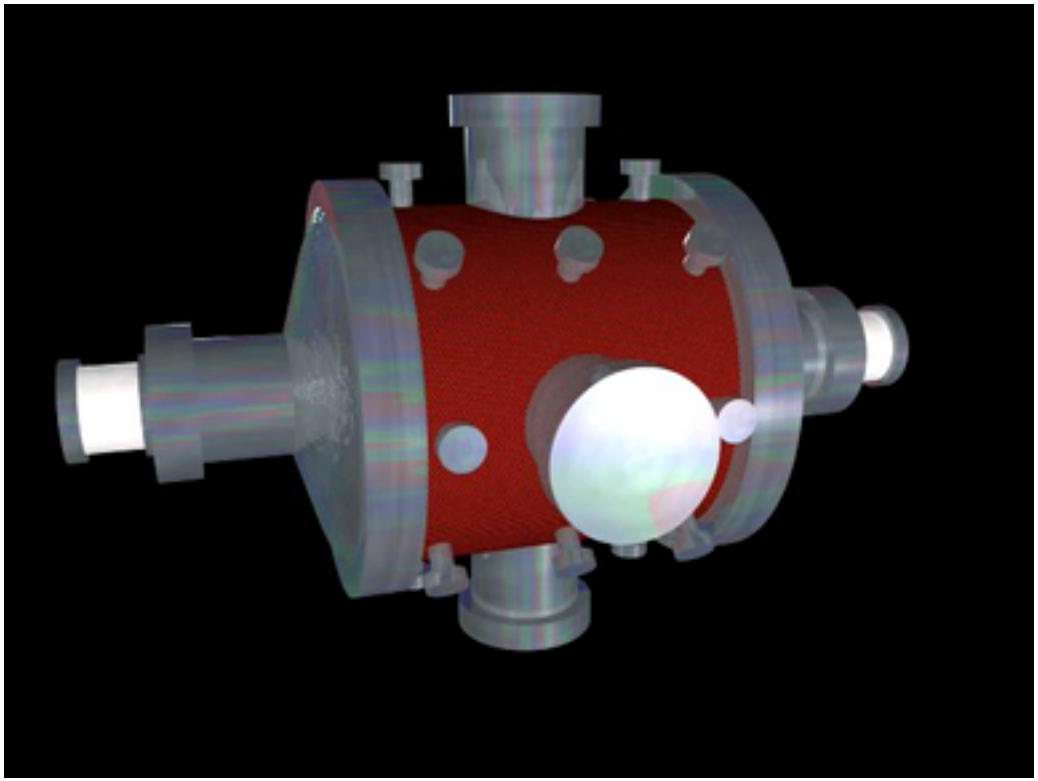


Rapid merging of two rings



Single structure is formed

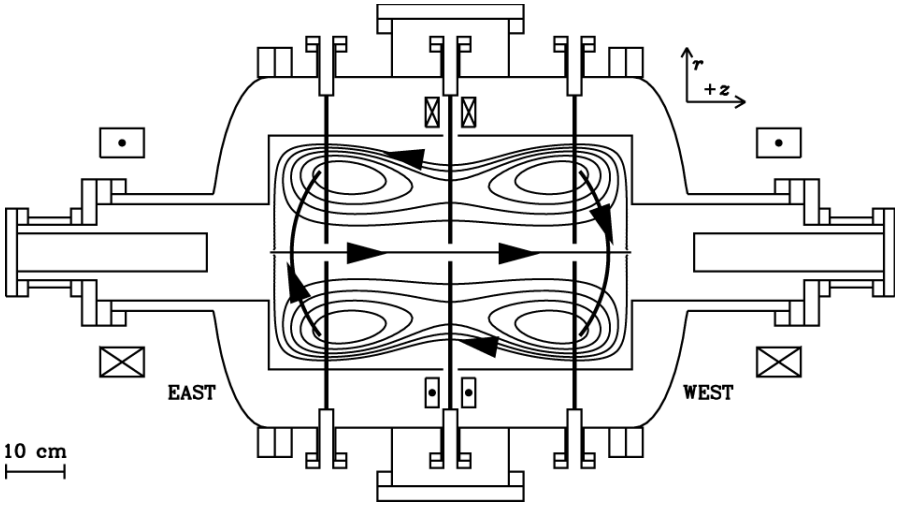
# Spheromak merging

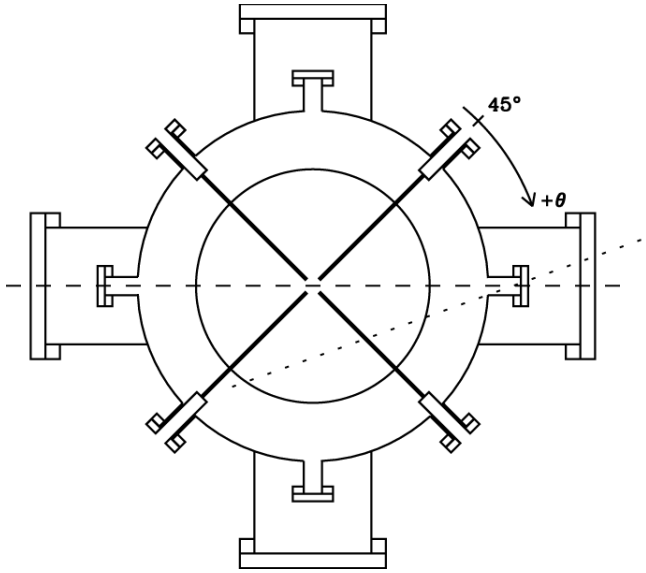


# Counter-helicity merging and relaxation

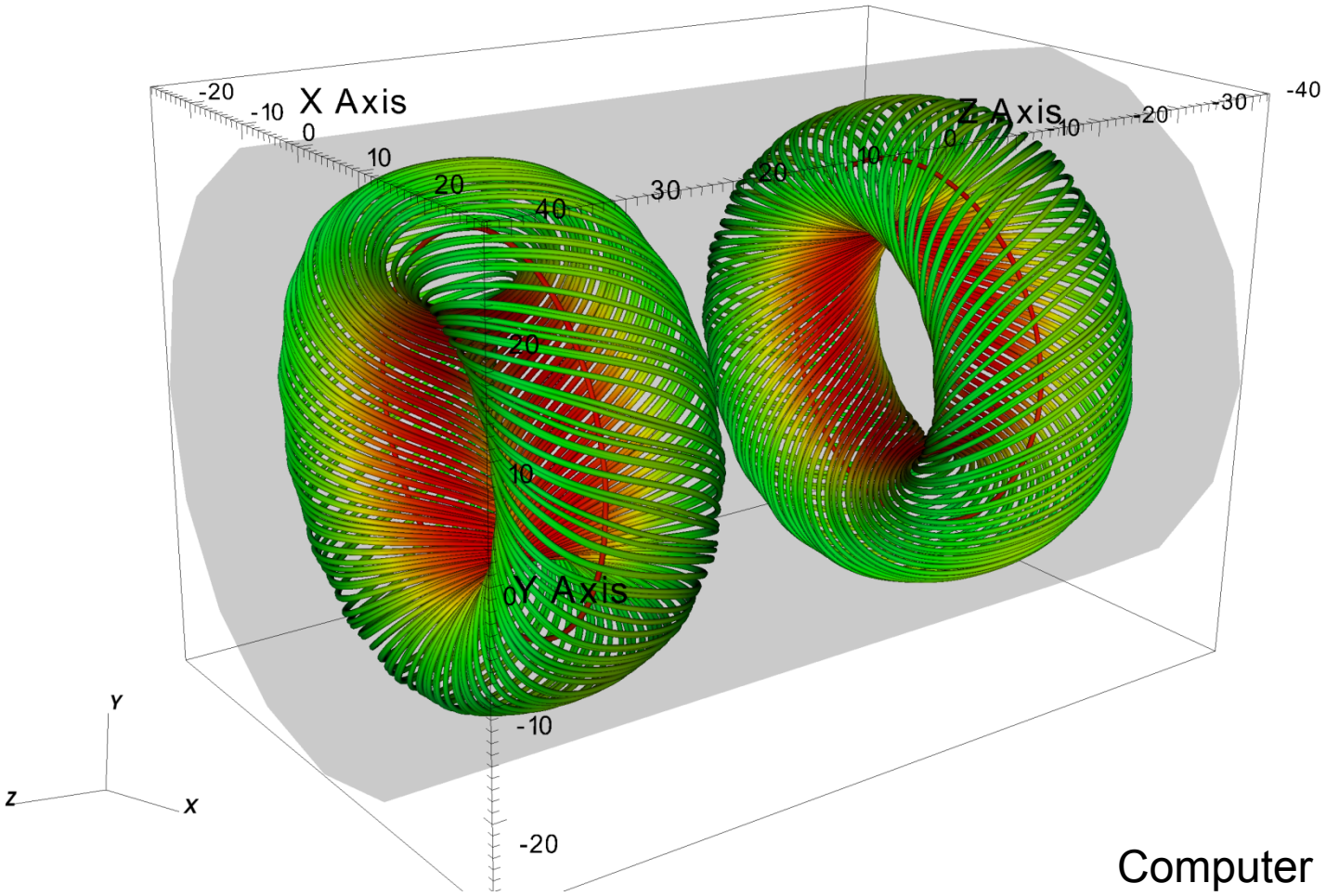
- 3D MHD simulation (HYM) 3:1
- Close comparison to experimental data
- See papers by C. Cothran and C. Myers
- C. Myers, et al, Phys. Plasmas Nov. 2011

# SSX device (counter-helicity)

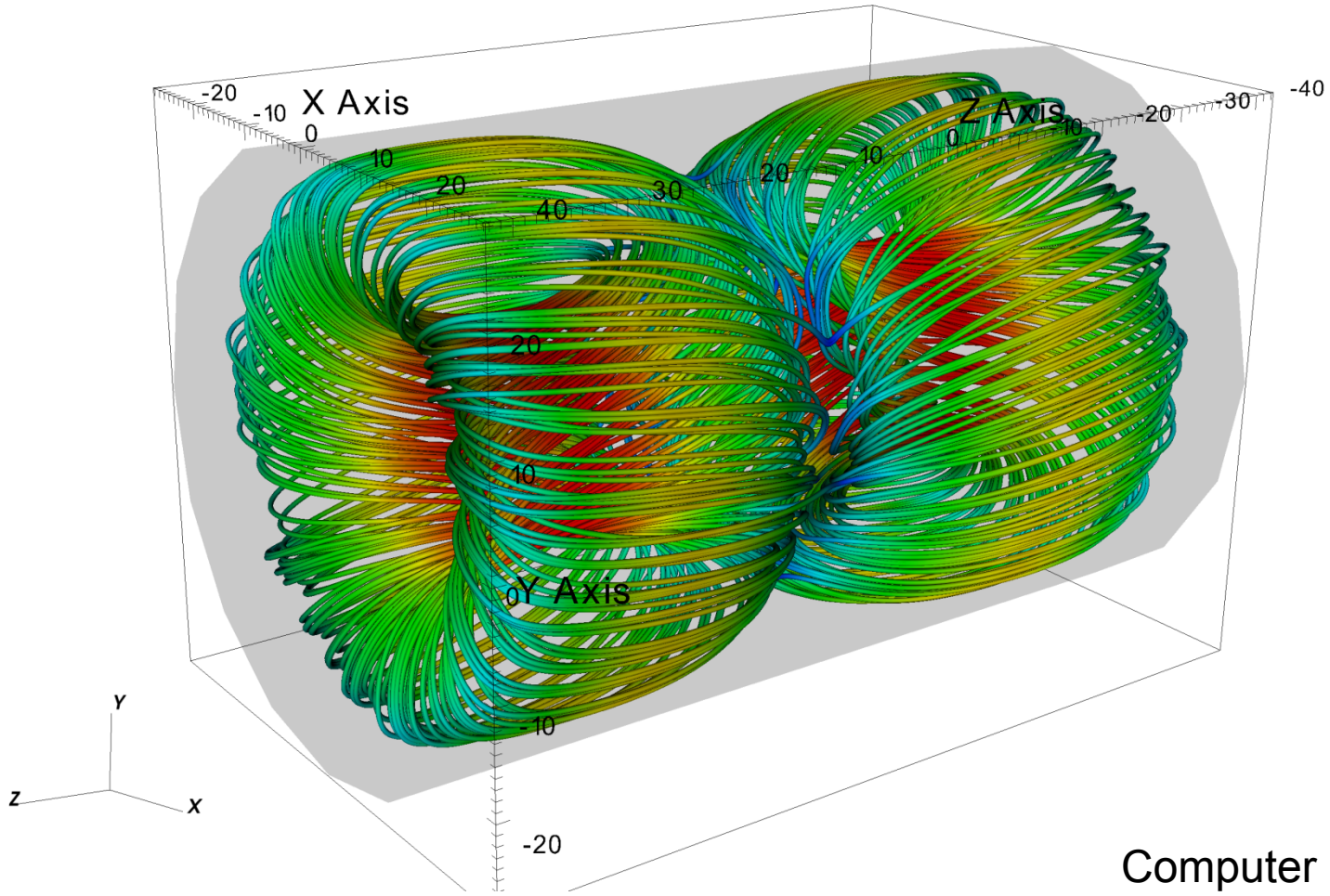


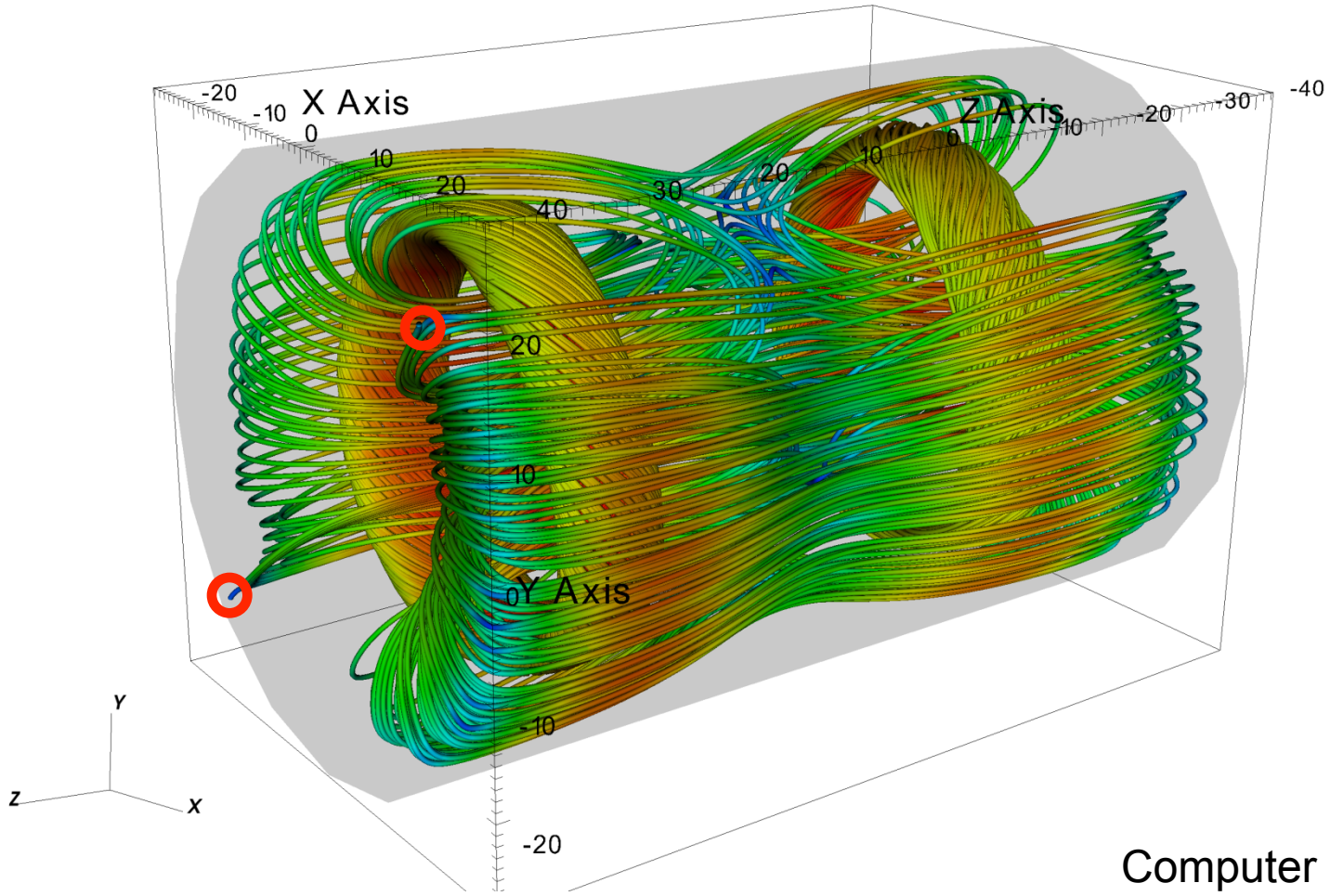

- Opposing magnetized plasma guns
- Prolate flux conserver (L=0.6m, R=0.2m)
- Reconnection at midplane
- Merged state relaxes to minimum energy




Computer simulation
C. Myers, Princeton




Computer simulation
C. Myers, Princeton

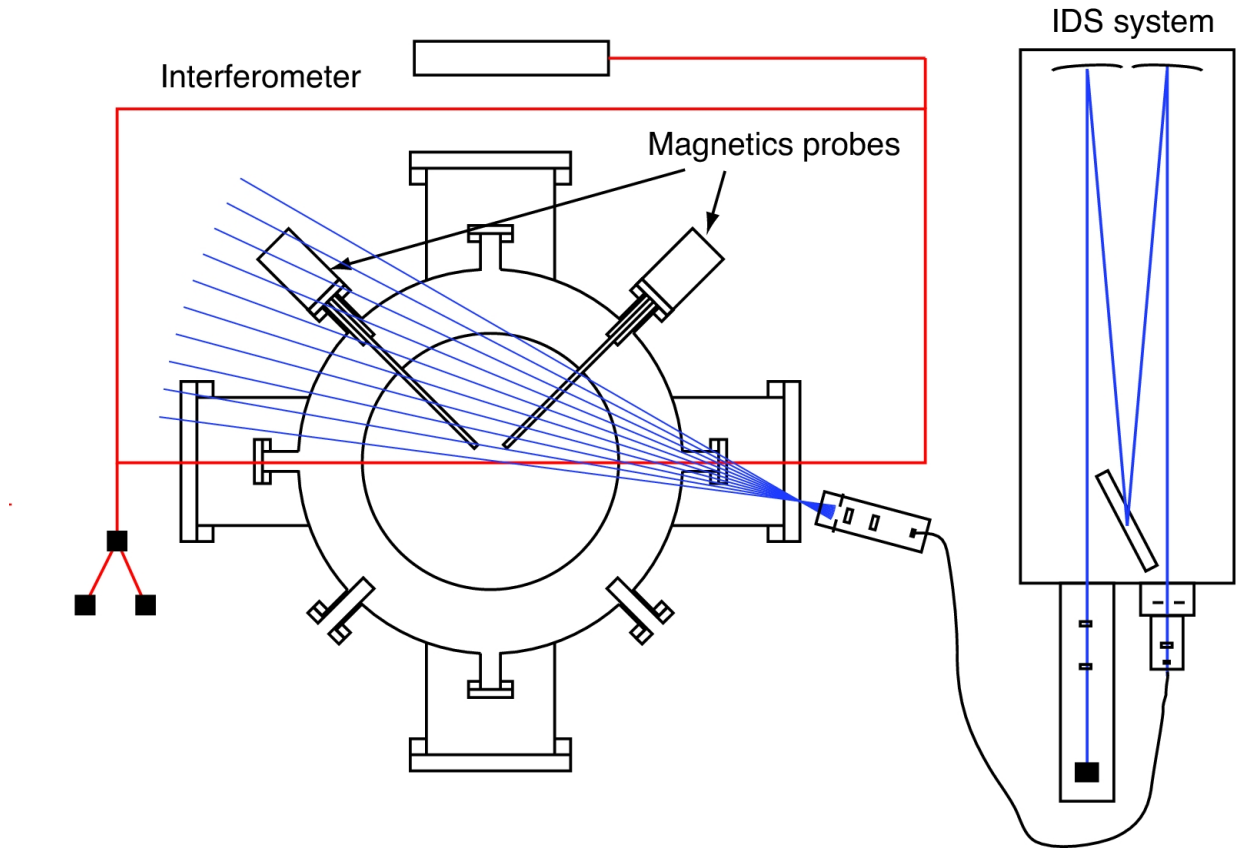



Computer simulation
C. Myers, Princeton

# Ion dynamics during counter-helicity merging and relaxation

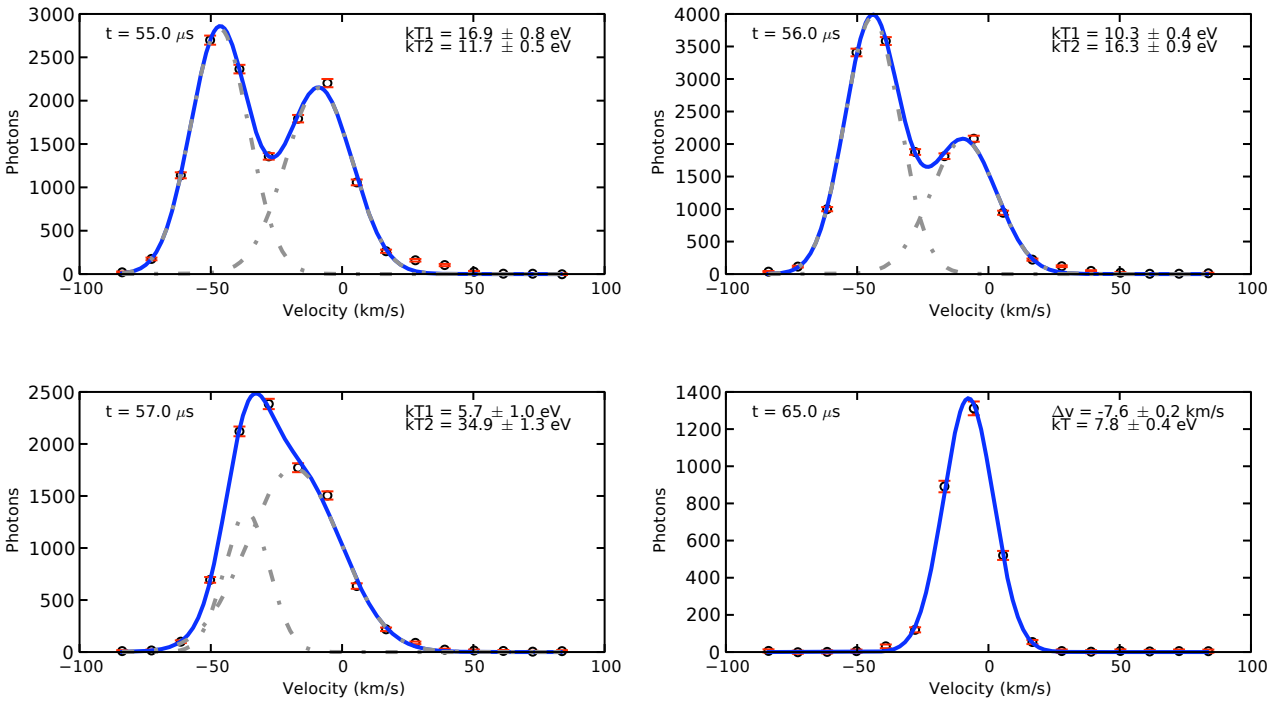
- Heating and complex flows early
- Relaxed state characterized by single temperature Maxwellian

# Ion Doppler spectrometer on SSX



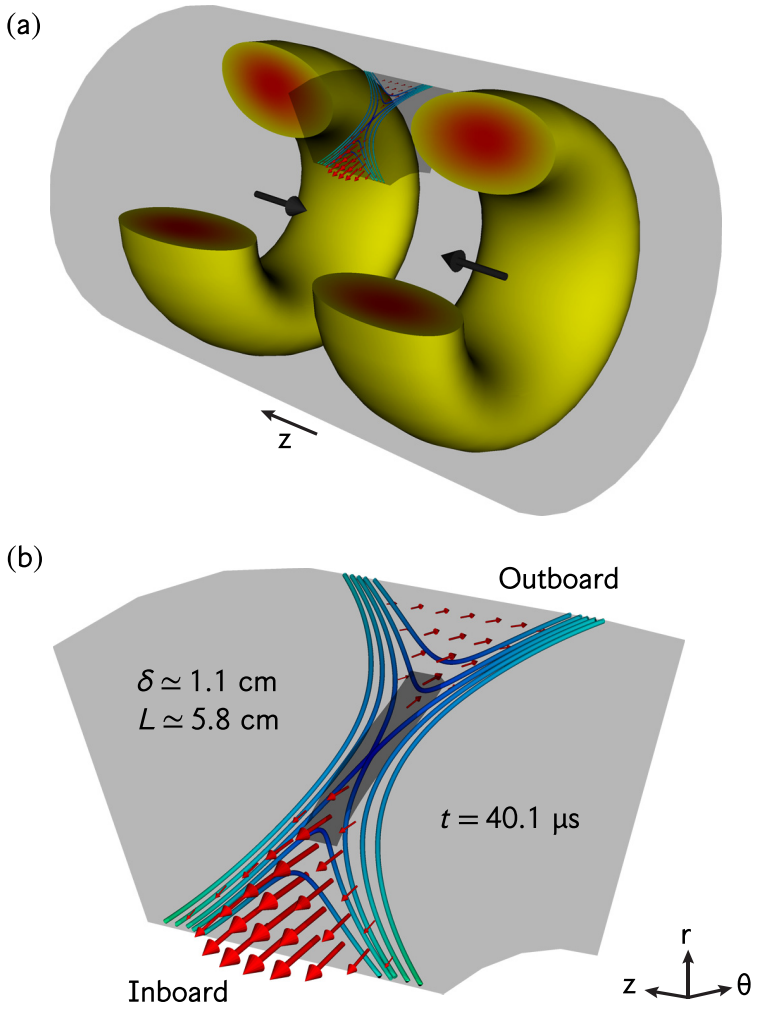

Interferometer chord and two magnetic probes also shown

# Typical Doppler line shapes in SSX during reconnection and relaxation ($C_{III}$ line)

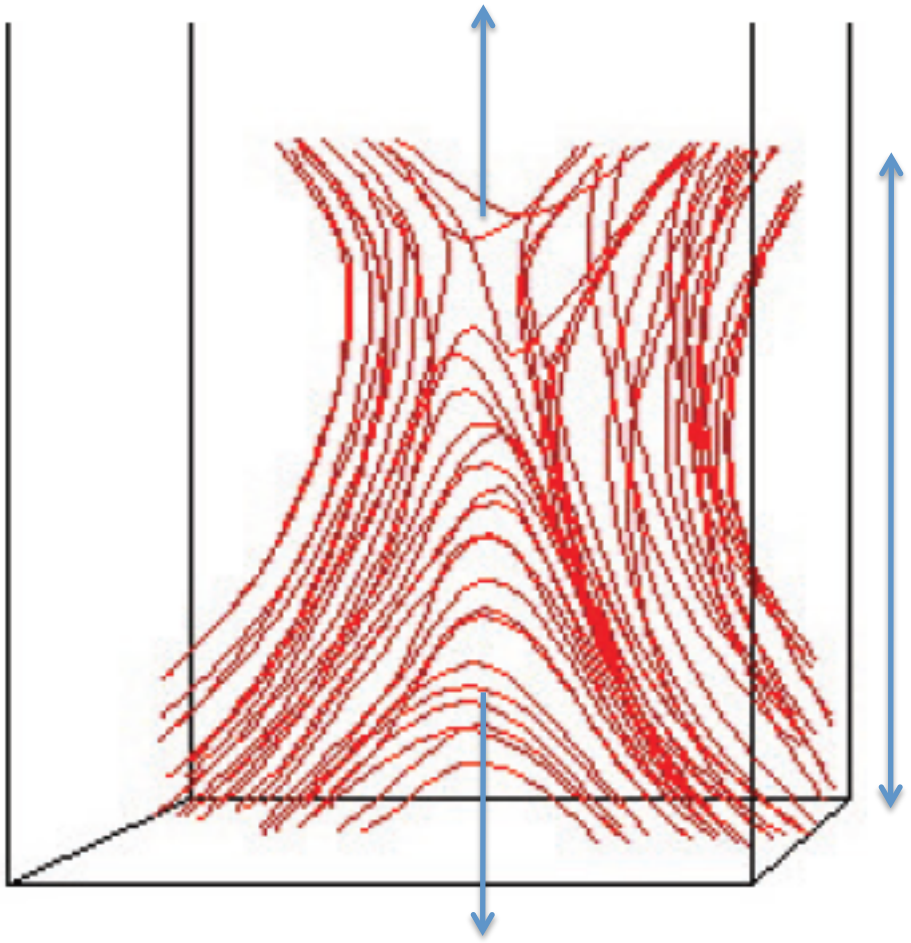



Double Maxwellian line shape early and single Maxwellian late in time

# HYM simulation predicts outflows



# Measurement of 3D structure

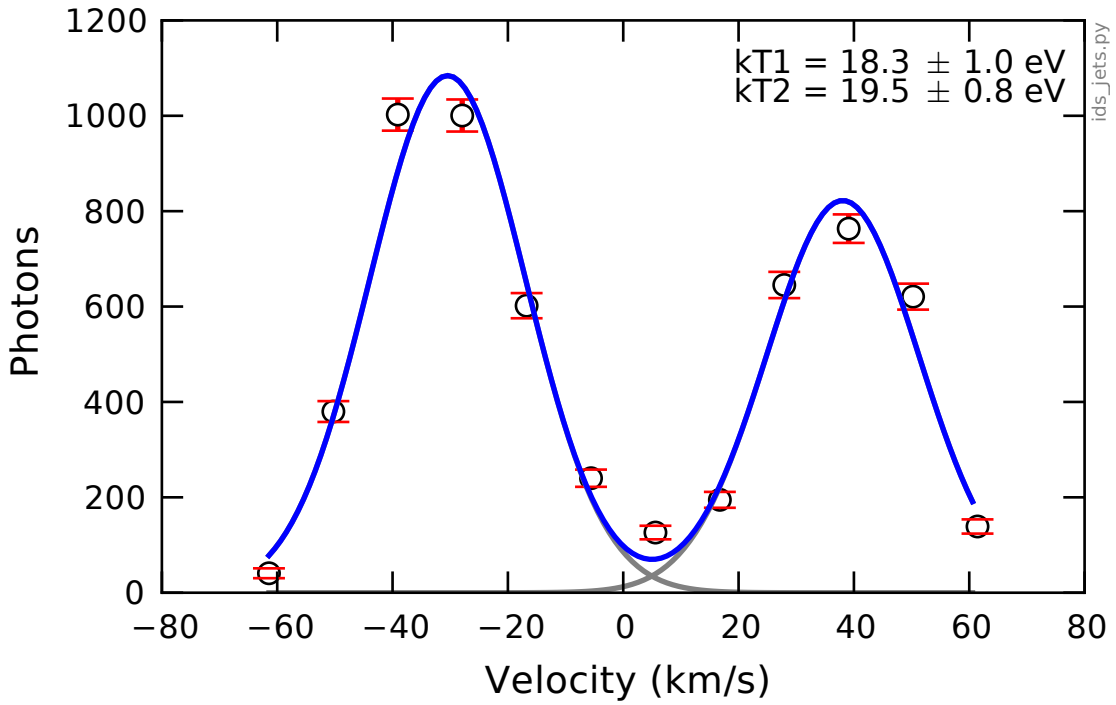


8 cm

Direction of outflows

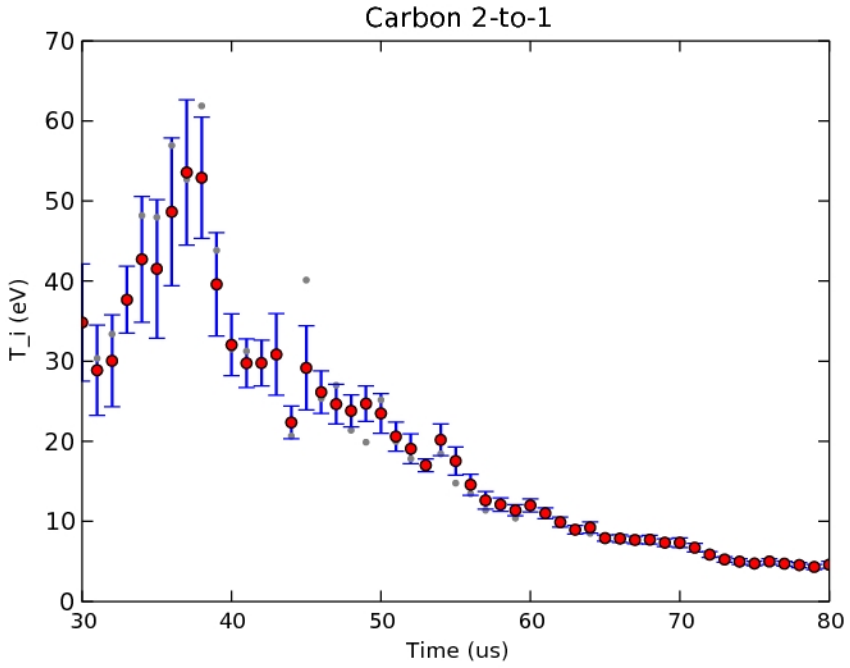
200 triples
2 cm spacing
1 μs cadance, t = 40 μs

# Measured bi-directional outflows




30.4 km/s radially out and 38.1 km/s radially in (+/- 0.3 km/s)… or about 0.5 $V_A$ at 40 μs, external measurements predict internal structure

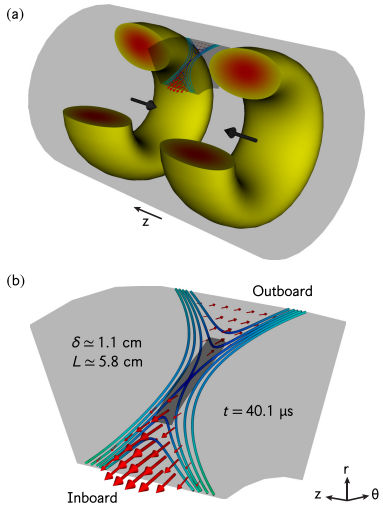
# IDS ion temperature measurement 25 shot average, $C_{III}$ 229.69 nm, prolate



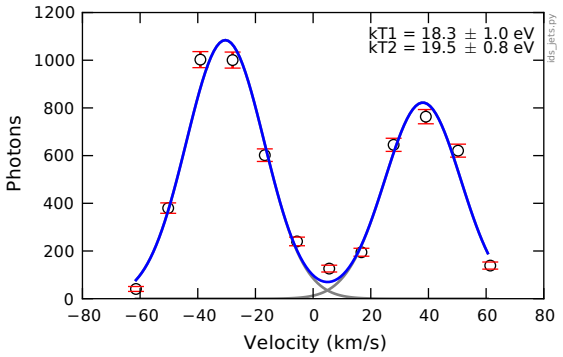

Ion heating evident from 30-40 μs
in the more compact 2:1 flux conserver

# Summary

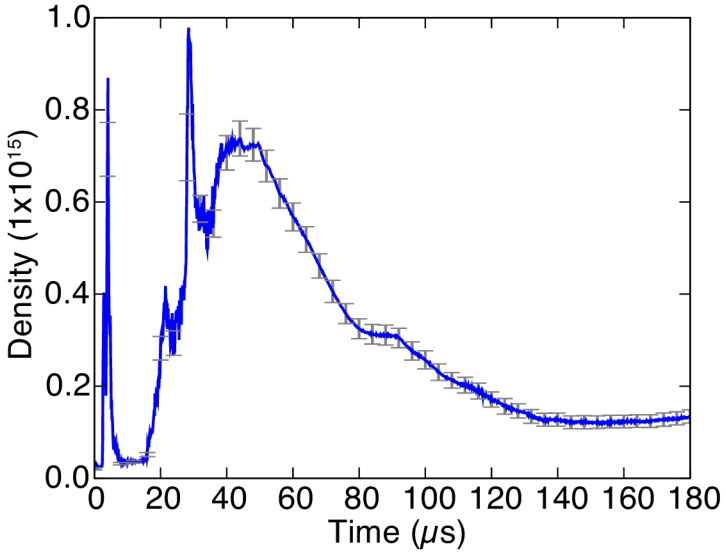
3D MHD simulation shows outflow jets and magnetic structure similar to SSX experiment

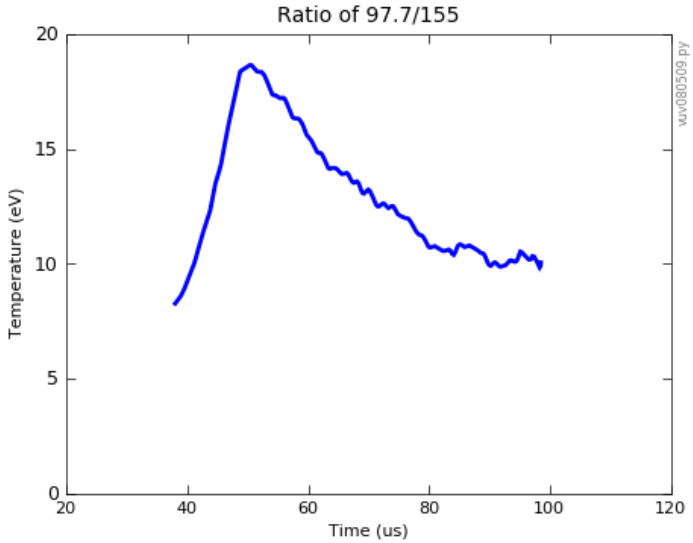



IDS measurement shows simultaneous bi-directional, nearly Alfvenic outflow jets that reveal aspects of internal structure



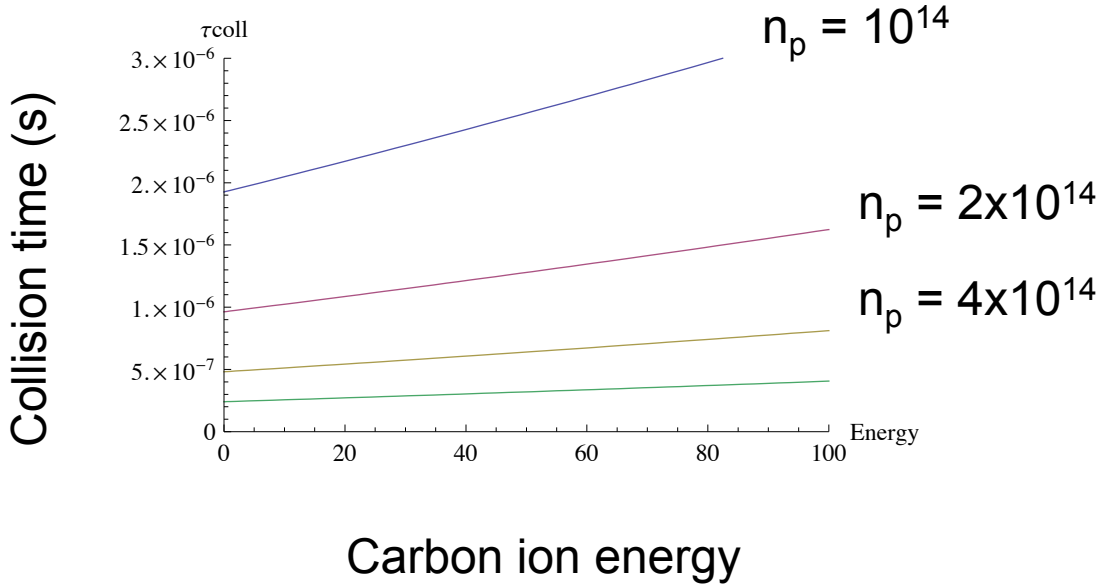
# Mean electron density and temperature for IDS runs (counter-helicity)



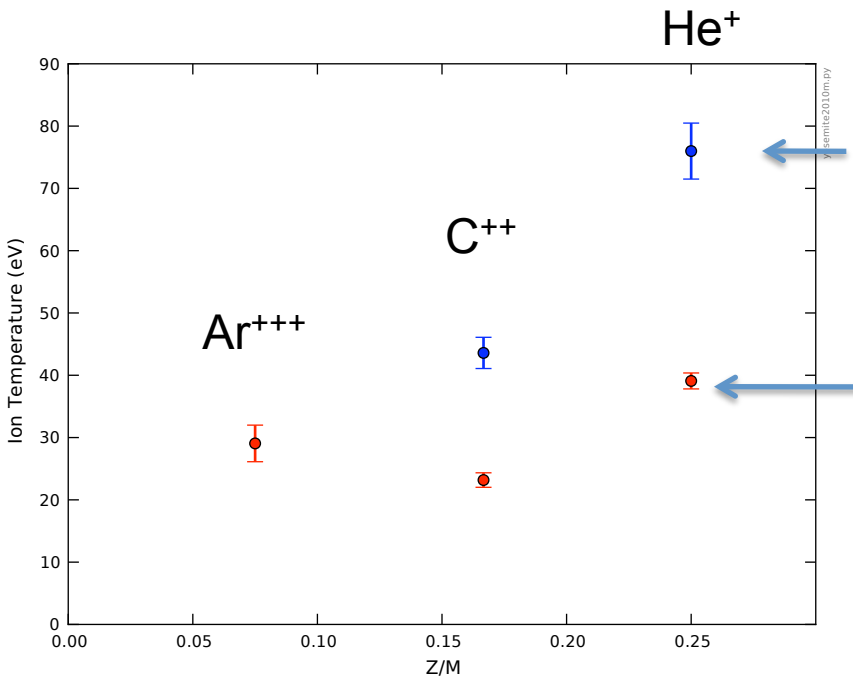




Density measured with HeNe interferometer
$T_e$ measured with VUV spectroscopy (Chaplin, et al)

# Carbon ion collision times (20 eV proton temperature)



# Argon, Carbon, Helium ion temperature vs Z/M




Reconnection heating (blue)

Decay phase (red)

$\omega = qB/M$

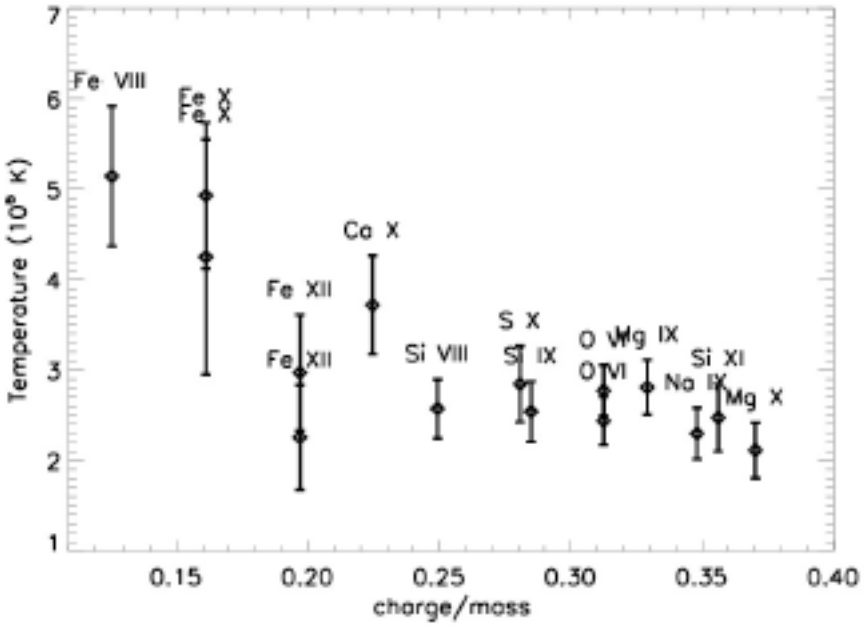
Z/M = 1 ~ 1.5 MHz

2:1 flux conserver

Average over a 5 μs window

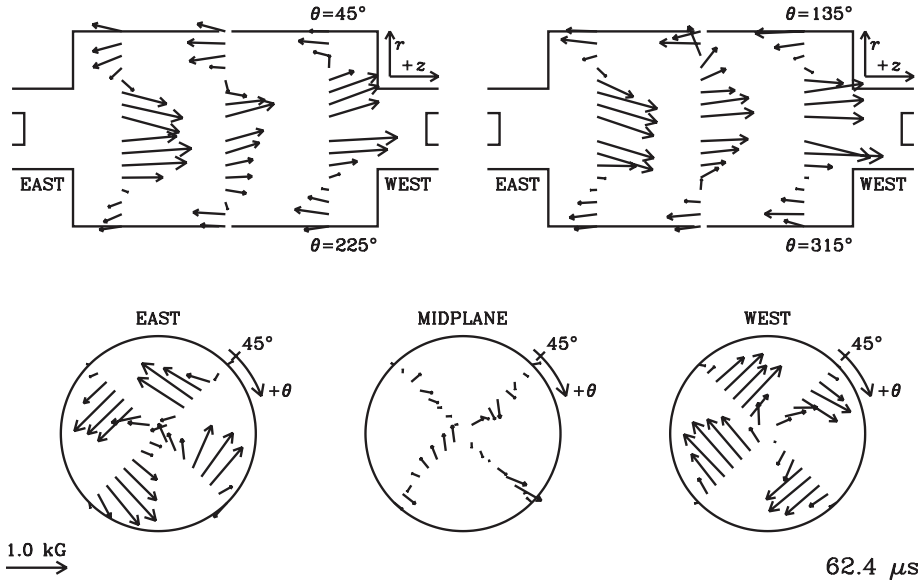
Z/M scaling consistent both early and late in time (He and C)

# Ion temperature in the low corona vs. Z/M



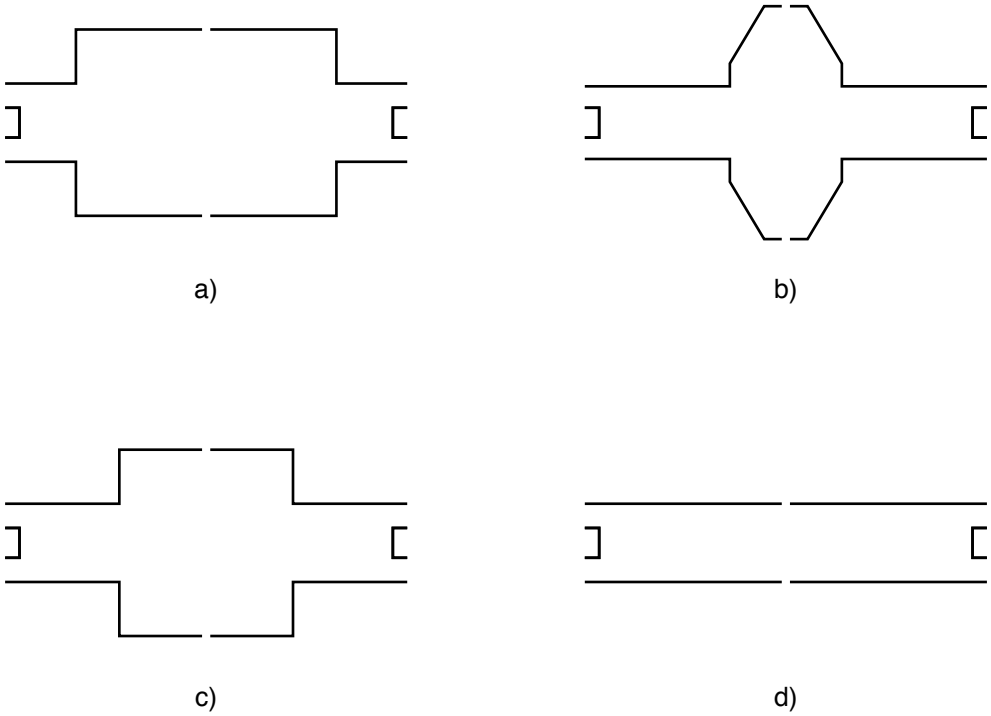

Dolla and Soloman, Ann. Geophys. 2009
40,000 km above the solar surface
Large set of lines, SUMER spectrometer

# Probe data for counter-helicity merging



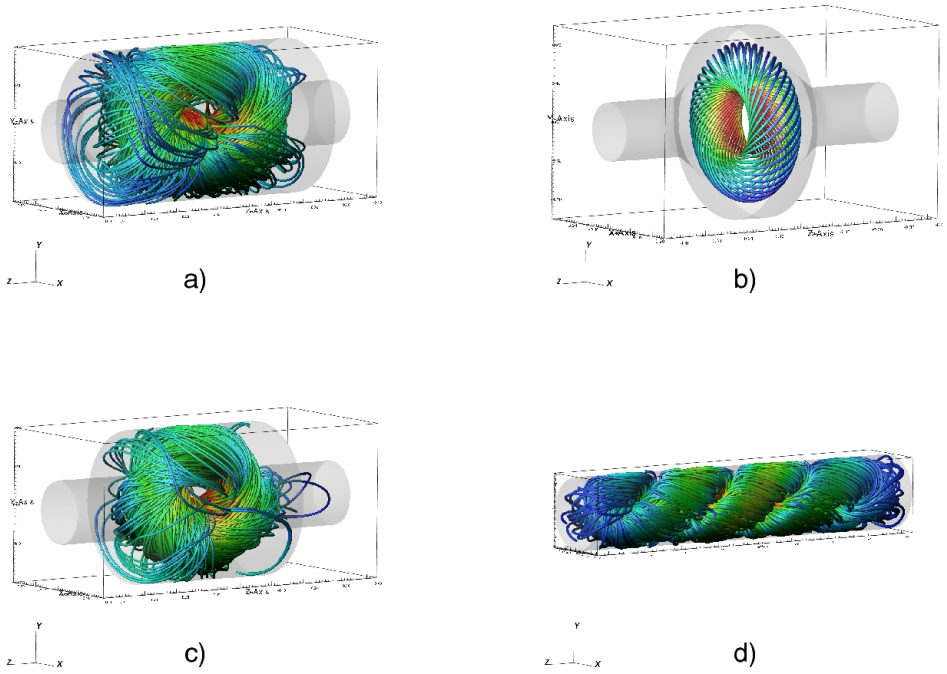

Similar dynamics and final state as seen in simulation

# Aspect ratio scan of SSX flux conservers



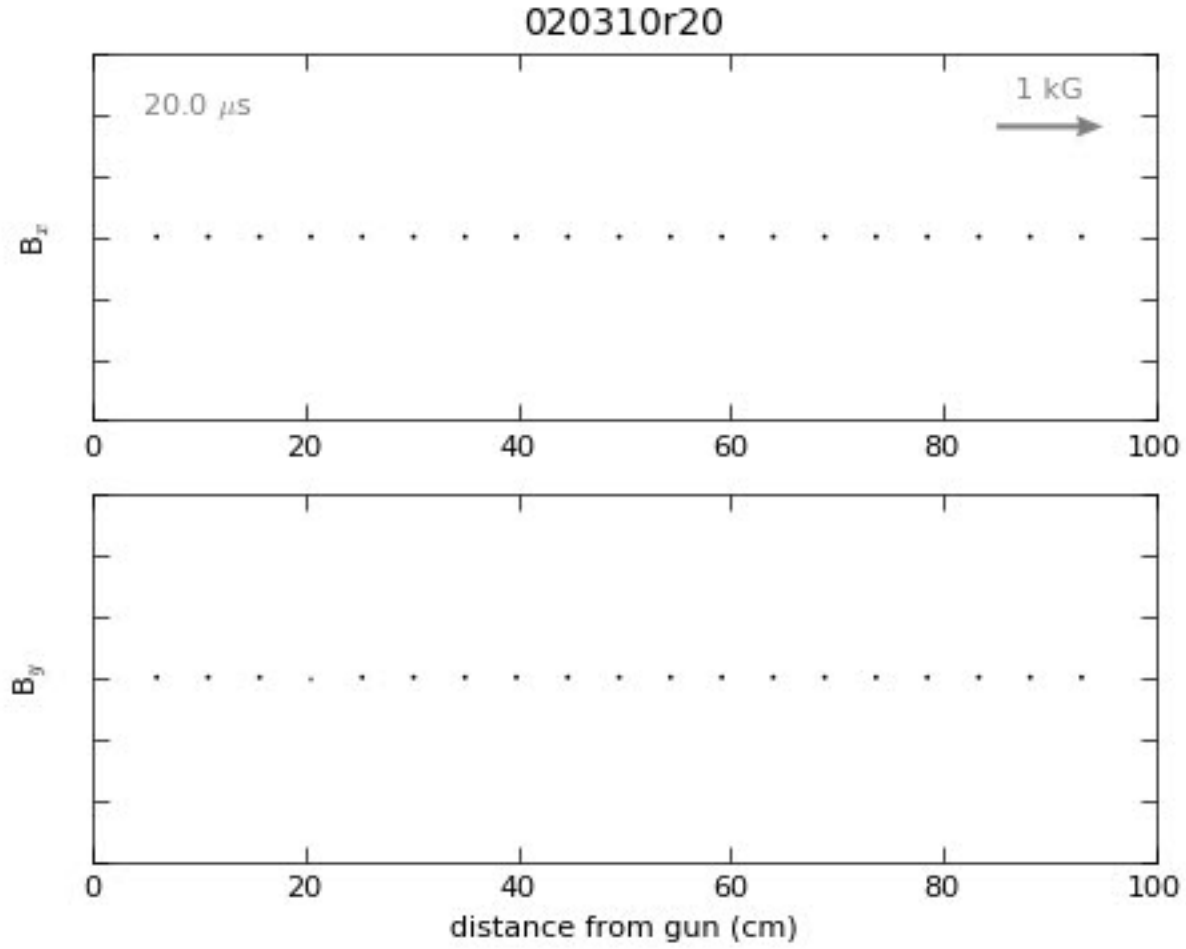

a) prolate 3:1, b) oblate 1:1, c) slightly-prolate 2:1, d) super-prolate 10:1 (MHD wind tunnel)

# Merging studies in several different experimental shapes (co-helicity)

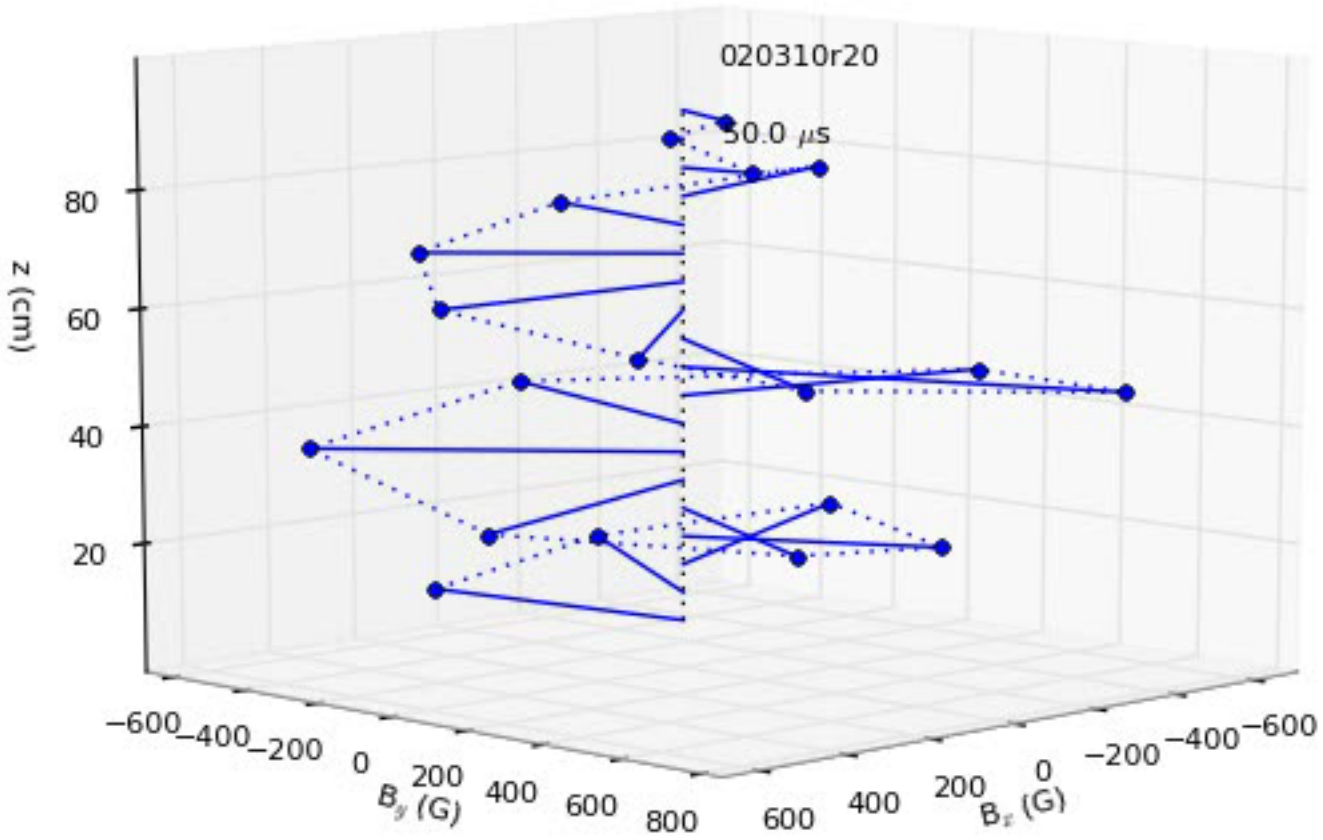



Magnetic field structure measured in 4 different vessels in SSX
(prolate 3:1, oblate 1:1, slightly-prolate 2:1, super-prolate 10:1)

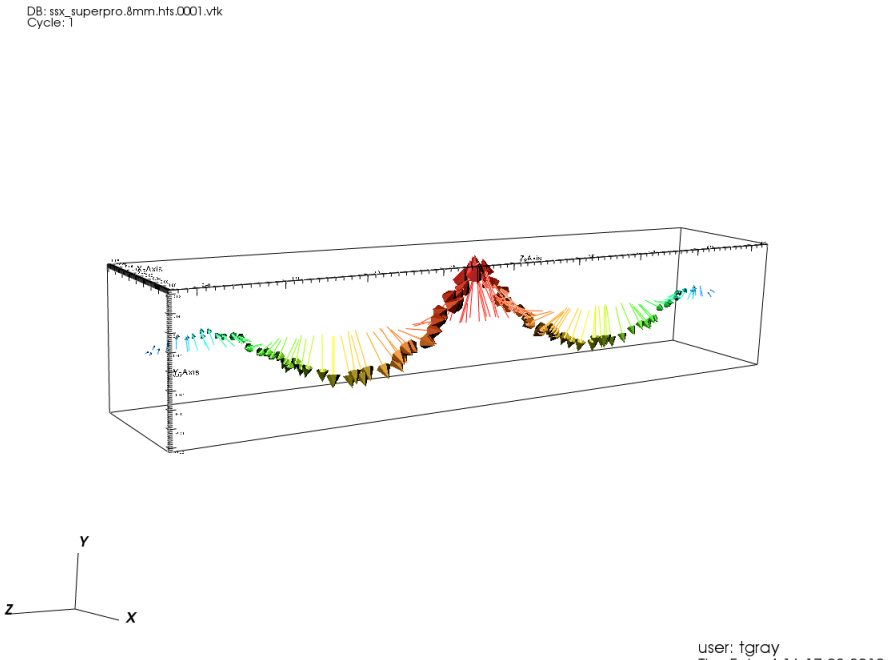
# Initial high velocity flows and fluctuations

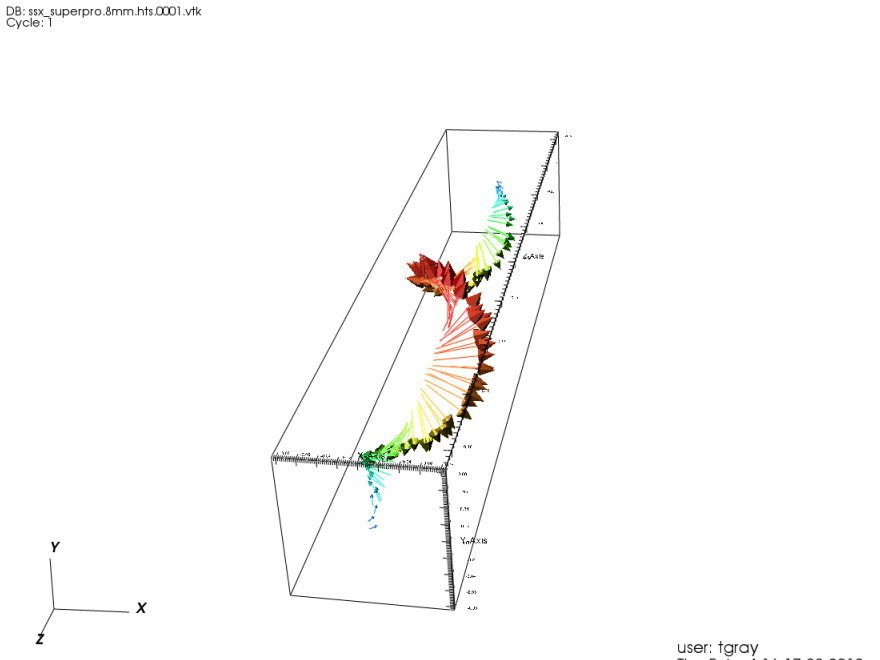


# Relaxed state (Taylor double helix)

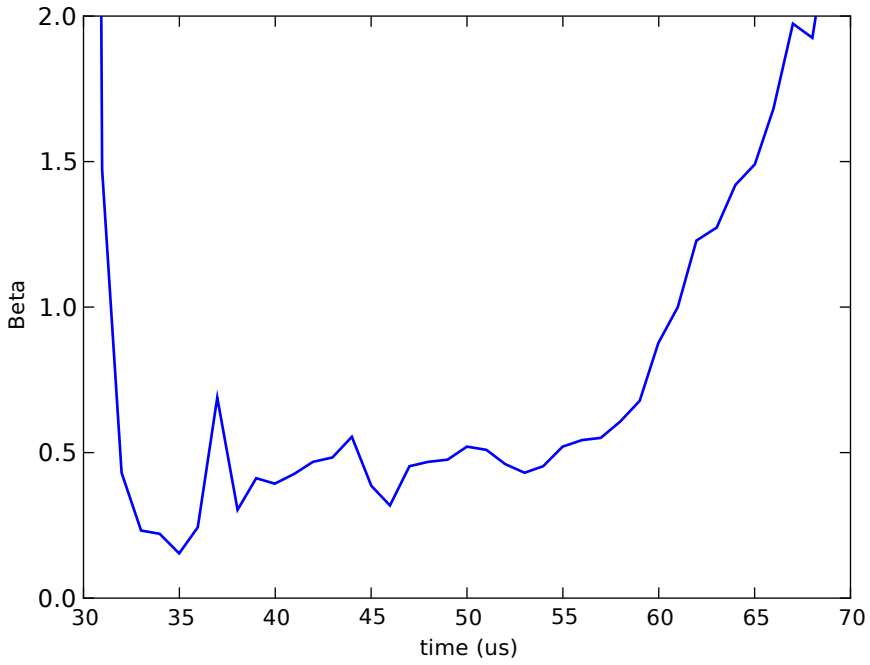


# Compare to predicted Taylor state



# Measured β is high (about 0.5)




Despite high β and large flows, Taylor model fits well

# Other shots show quadrupole