Mass dependent ion heating in counter-helicity merging experiments in SSX

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Outline

• Overview of SSX merging experiment
  • Counter- and Co-helicity merging
  • Ion dynamics during relaxation
• Ion heating (carbon, helium, argon)
**SSX parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Density (protons)</td>
<td>(10^{14}-10^{15}) cm(^{-3})</td>
</tr>
<tr>
<td>Temperature ((T_e, T_i))</td>
<td>20 - 80 eV</td>
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<tr>
<td>Magnetic Field</td>
<td>0.1 Tesla</td>
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<tr>
<td>Ion gyroradius</td>
<td>0.5 cm</td>
</tr>
<tr>
<td>Alfvén speed</td>
<td>100 km/s</td>
</tr>
<tr>
<td>S (Lundquist number)</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Plasma (\beta)</td>
<td>10-100%</td>
</tr>
<tr>
<td>Poloidal flux</td>
<td>3-4 mWb</td>
</tr>
</tbody>
</table>
Spheromak formation
Counter-helicity merging scenario

Right-handed Spheromak

Left-handed spheromak

Reconnected poloidal flux
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
3D reconnection (lab and solar)

one foot tall

5 earth diameters tall
Oblate flux conserver in SSX

- $L = 0.3 \text{ m}$, $R = 0.25 \text{ m}$, tilt stable aspect ratio
Oblate flux conserver in SSX

Conical entrance region
Oblate flux conservers in SSX

Aluminum insert
Oblate flux conserver in SSX

Midplane diagnostic gap
Aspect ratio scan of SSX flux conservers

A) prolate 3:1, B) oblate 1:1, C) slightly-prolate 2:1 (present), D) super-prolate 10:1 (under construction)
Aspect ratio scan of SSX flux conservers (simulation)

Lowest energy eigenmode (self organized Taylor state) calculated for 4 flux conserving boundaries in SSX (prolate 3:1, oblate 1:1, slightly-prolate 2:1, super-prolate 10:1)
Self-organized Taylor state formed by co-helicity merging in SSX (prolate)

(a) SSX magnetic data and (b) calculation of Taylor state
(see T. Gray talk for more details)
Ion dynamics during relaxation

- Complex multi-component flow early
- Relaxed state characterized by single temperature gaussian
Ion doppler spectrometer on SSX

Interferometer chord and two magnetic probes also shown
Typical Doppler line shapes in SSX during reconnection and relaxation (CIII line)

Double gaussian line shape early and single gaussian late in time
Magnetic structure
(unstable! turbulent?)
Mean electron density and temperature for IDS runs (50 shots, oblate)

Density measured with HeNe interferometer
Te measured with VUV spectroscopy (Chaplin, et al)
Carbon ion collision times (20 eV proton temperature)

Collision time (s) vs Carbon ion energy

$\tau_{\text{coll}}$ vs Energy

$n_p = 10^{14}$

$n_p = 2 \times 10^{14}$

$n_p = 4 \times 10^{14}$
Ion heating studies in SSX

- $C_{\text{III}}$, $He_{\text{II}}$, $Ar_{\text{IV}}$ lines
- Studies in oblate and prolate geometries
Solar plasma temperature

Steve Cranmer, APS April 2009
Solar wind plasma not in equilibrium

\[ \begin{align*}
T_{\text{ion}} & \gg T_p > T_e \\
(T_{\text{ion}}/T_p) & > (m_{\text{ion}}/m_p) \\
T_\perp & \gg T_\parallel \\
u_{\text{ion}} & > u_p
\end{align*} \]

...especially in the high-speed wind.

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**WIND** at 1 AU
(Collier et al. 1996)

**Ulysses** at 2–4 AU
(Reisenfeld et al. 2001)

**Helios** at 0.3 AU
(e.g., Marsch et al. 1982)

Steve Cranmer, APS April 2009
IDS ion temperature measurement
50 shot average, CIII 229.69 nm, oblate

Weighted sum and single gaussian
Merging begins at 30 µs
IDS ion temperature measurement
50 shot average, HeII 468.57 nm, oblate

2% Helium doping
\( T_{\text{He}} > T_{\text{C}} \)
IDS ion temperature measurement
50 shot average, HeII 468.57 nm, oblate

Helium oblate

2% Helium doping
\[ T_{\text{He}} > T_c \]
IDS ion temperature measurement
25 shot average, CIII 229.69 nm, prolate

Ion heating evident from 30-40 µs
IDS ion temperature measurement
25 shot average, HeII 468.57 nm, prolate

2% Helium doping
$T_{He} > T_C$
IDS ion temperature measurement
25 shot average, HeII 468.57 nm, prolate

2% Helium doping
\[ T_{\text{He}} > T_{\text{C}} \]
IDS ion temperature measurement
ArIV 219.3 nm, prolate

2% Argon doping (weak signals, no filter)

\[ T_{\text{Ar}} \ll T_{\text{C}}, T_{\text{He}} \] (late in time)
estimate 15 eV maximum during reconnection
Argon, Carbon, Helium ion temperature vs Z/M
Merging in oblate geometry in SSX tends to be unstable... heating mostly the ions

Averaging a large number of shots shows a heating rate scaling like charge to mass ratio $Z/M$
Summary

Merging in SSX is magnetically complex early... but settles into a quiescent final state.

Complex magnetics are associated with complex, multi-component flows... final state is characterized by a single cool Maxwellian.
Additional slides
Self-organized Taylor state formed by co-helicity merging in SSX (prolate)

(a) Flat lambda profile and (b) transition to n=1 state
(see T. Gray talk for more details)
Self-organized Taylor state formed by co-helicity merging in SSX (prolate)

(a) Lambda evolution merging and (b) single spheromak
(see T. Gray talk for more details)
Self-organized Taylor state formed by co-helicity merging in SSX (prolate)

(see T. Gray talk for more details)
Self-organized Taylor state formed by co-helicity merging in SSX (prolate)

(see T. Gray talk for more details)
Collier (1996)
IDS ion temperature measurement
CIII 229.69 nm (single shot)

\[ kT = 39.52 \pm 2.37 \text{ eV} \]
\[ t = 46 \mu s \]
IDS ion temperature measurement
CIII 229.69 nm (16 heating shots)
IDS ion temperature measurement
CIII 229.69 nm (50 shot average)
IDS ion temperature measurement
HeII 468.57 nm (single shot, 2%)
IDS ion temperature measurement
HeII 468.57 nm (50 shot average, 2%)
IDS ion temperature comparison

CIII 229.69 nm

HeII 468.57 nm