Relaxation of flux ropes and magnetic reconnection in RSX

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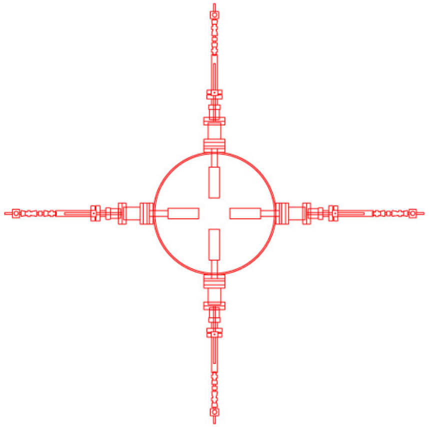
Outline



1. Motivations
2. The RSX device and diagnostics
3. Experimental measurements
   - Single flux rope
   - Two flux ropes
4. Conclusions and discussion

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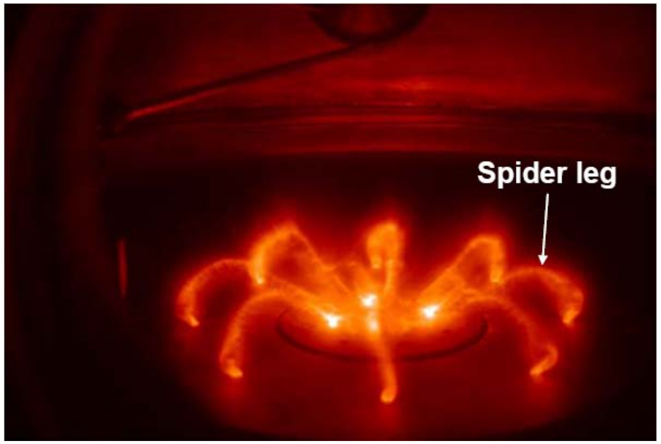
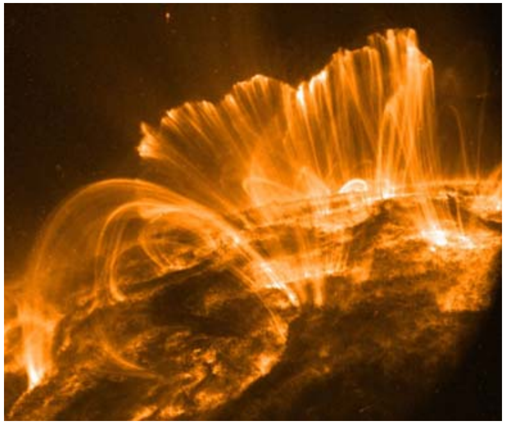
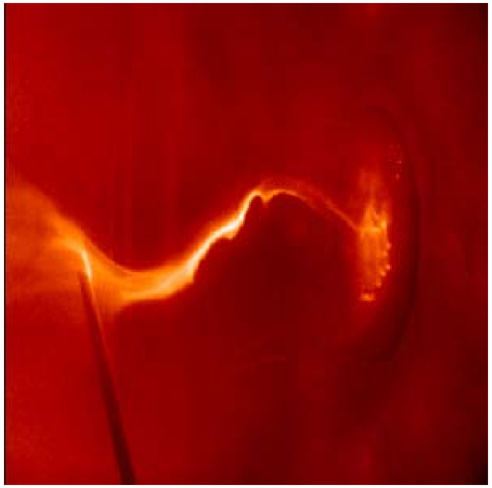
Flux ropes are ubiquitous in Nature

Early stage of spheromak formation
P.M. Bellan, this workshop





Solar arcades
Solar flares



Formation of spheromak through kink instability
S. Hsu and P.M. Bellan, PRL **90**, 2003

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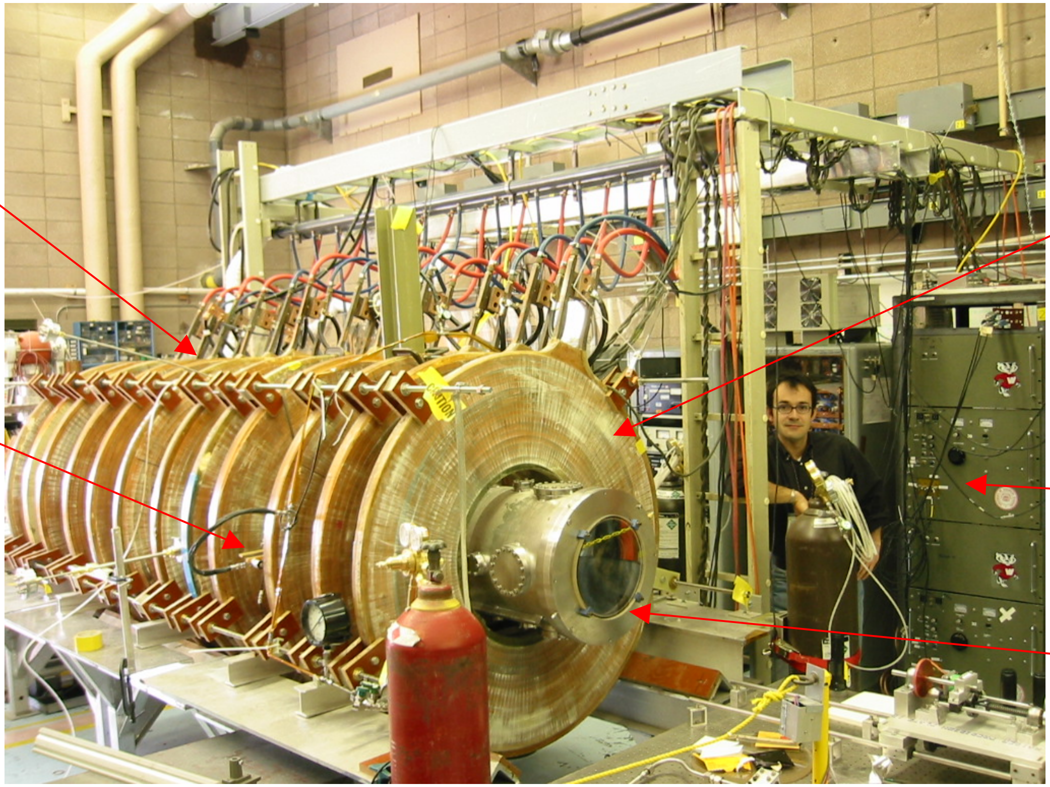
RSX device

External anode

Plasma gun



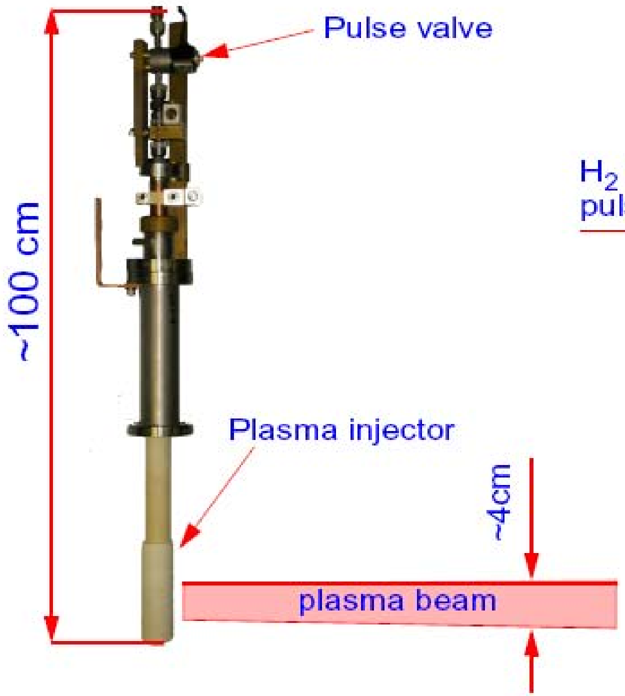
Magnet coils

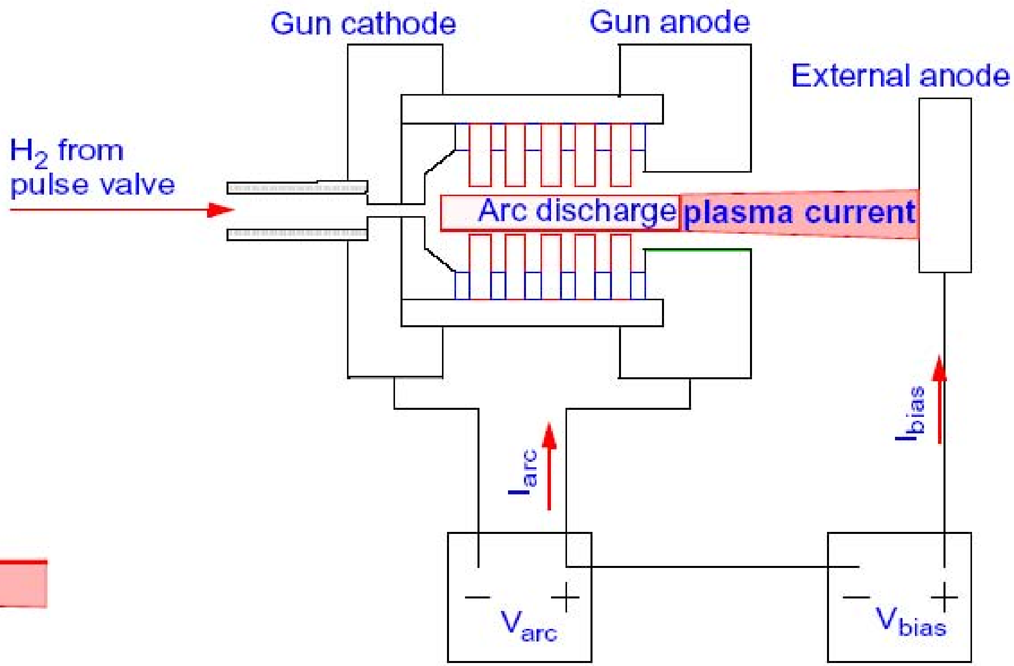
Capacitor bank

Vessel

Reconnection Scaling Experiment: a new device for three-dimensional magnetic reconnection studies, I. Furno, et al., *Review of Scientific Instruments*, **74**, 2324 (2003)

The plasma source: the plasma gun

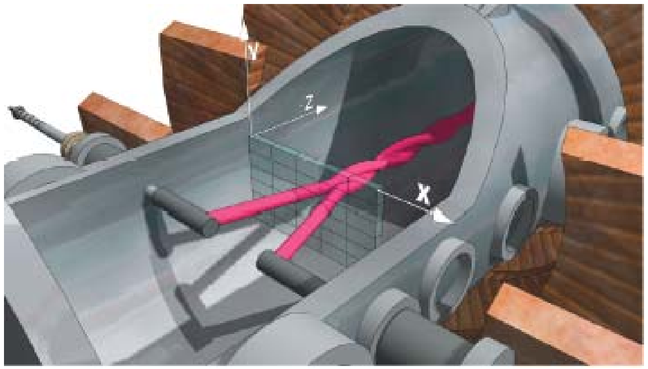


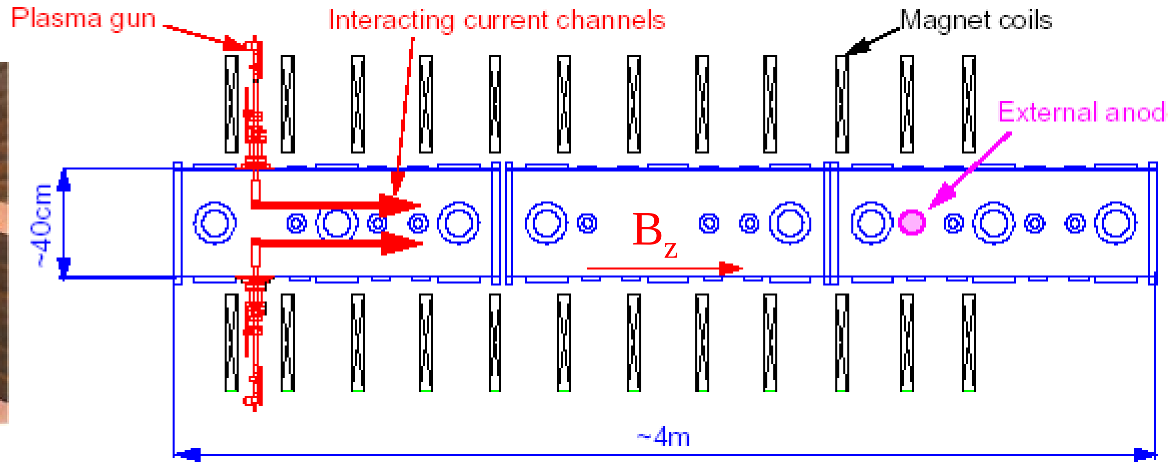


- V_{bias}~300V, I_{bias}~600kA, V_{arc}~100V, I_{arc}~1kA.

Schematics of RSX

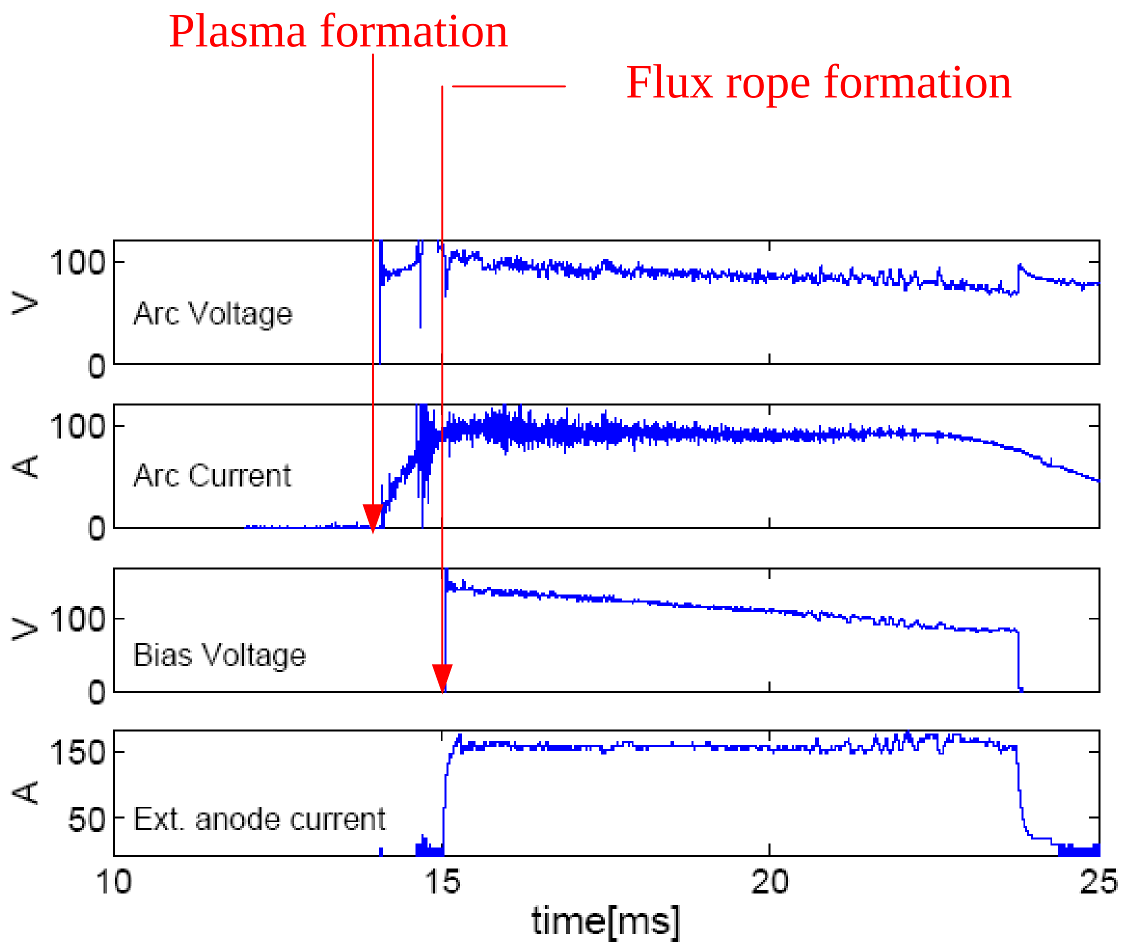
3D schematic view of RSX





- linear vacuum vessel ⇒ easy of diagnostics, 3D experiment
- 12 magnet coils: B_z= 0-1000 Gauss ⇒ can be varied independently
- 4 movable plasma guns ⇒ single and multiple flux rope interaction

Discharge sequence

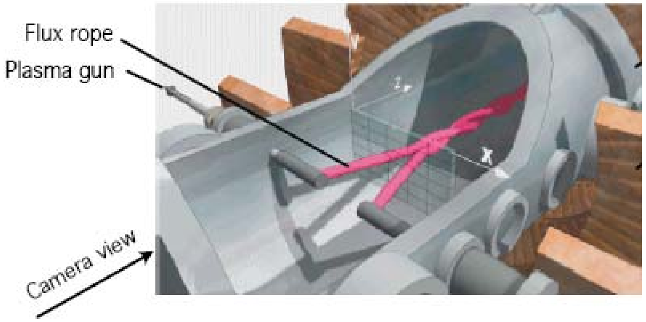


Plasma parameters and diagnostics

Density	n_e~10^{12}-10^{14} cm^{-3}
El. Temperature	T_e~3-15eV
Poloidal field	B_{pol}< 50 Gauss
Scale size	d~ 10 cm L~ 30-300 cm
Ion skin depth	$\delta_i=c/\omega_{pi}$~2 cm
electron skin depth	$\delta_i=c/\omega_{pi}$~1.7 mm
Ion gyro radius	r_{Gi}~0.35-1.4 cm
electron gyro radius	r_{Ge}~1-4 mm

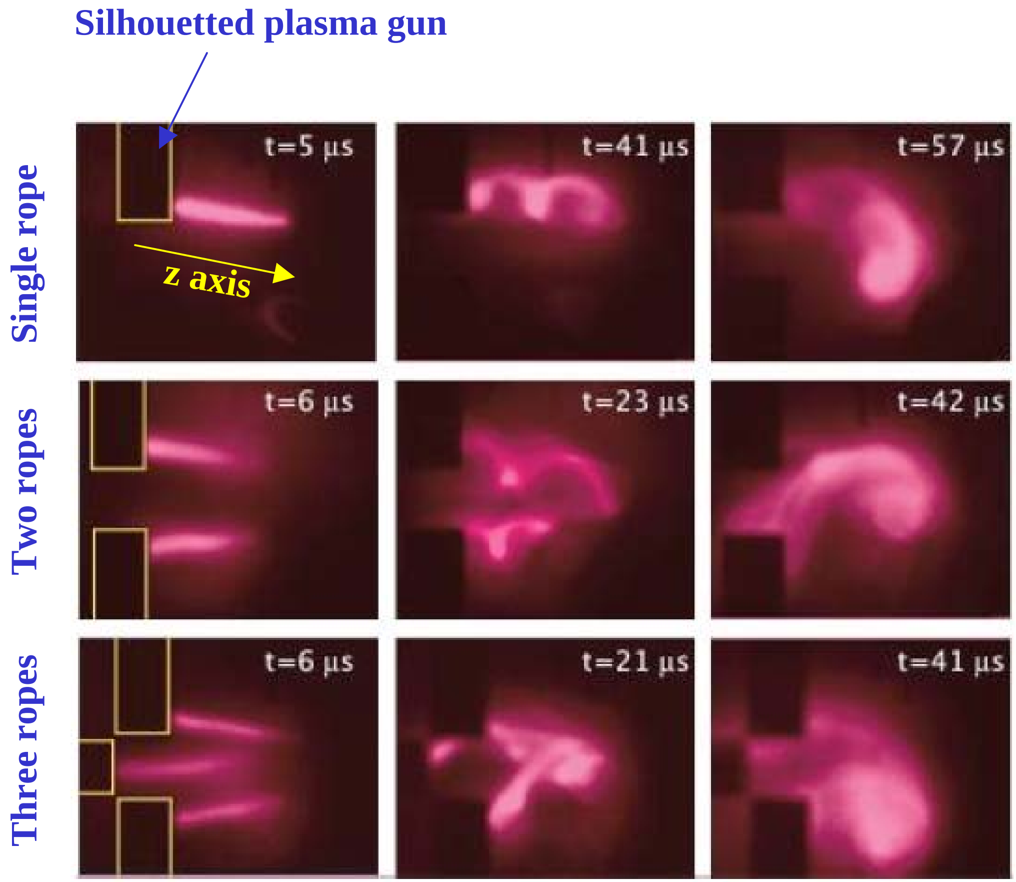
- Gun parameters (current, voltage)
- Multi-2D magnetic probe (2.5mm space resolution, 20MHz acq. Freq.) $\Rightarrow$ B field
- Triple electrostatic probe (2 mm space resolution, 20MHz acq. Freq.) $\Rightarrow$ T_e, n_e
- Poloidal and axial arrays of magnetic probes (8 mm diameter,time response 100 ns) $\Rightarrow$ mode number (m, n)

Cook Dicam, fast gated CCD camera



- visible light emission
- global dynamics

2 frames per shot
1280×1024 pixels, 12bit
40 ns min. exposure ($<t_{Alf}$=0.5-1micro-sec)



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Physics questions we want to address and critical features of RSX

- How does the plasma relaxed state depend on β?

In RSX, β can be scaled (β<< 1 to β~1) by varying plasma density, external magnetic field, and total plasma current.

- How does relaxation depend on the external drive?

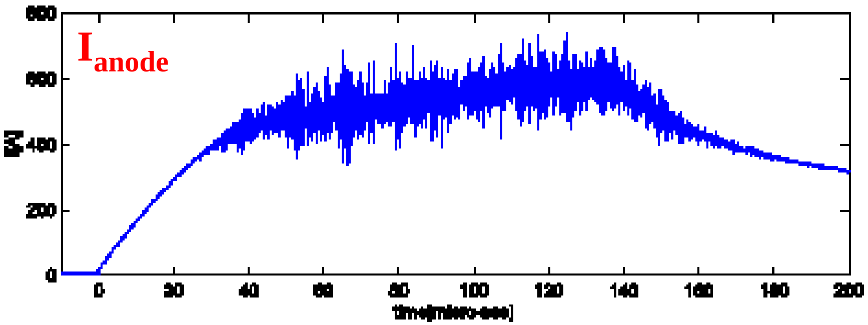
In RSX, the rate of change of V_{bias} can be controlled externally ($dV_{bias}/dt > 0$, $dV_{bias}/dt = 0$, ...)

- How is the relaxed state influenced by boundary conditions (see for example D.D. Ryutov, ICC-2004) ?

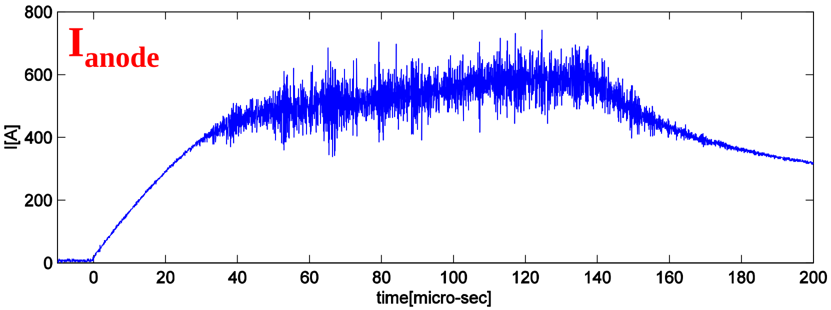
In RSX, it is easy to implement different boundary conditions (i.e. shaped anode, flux conserver).

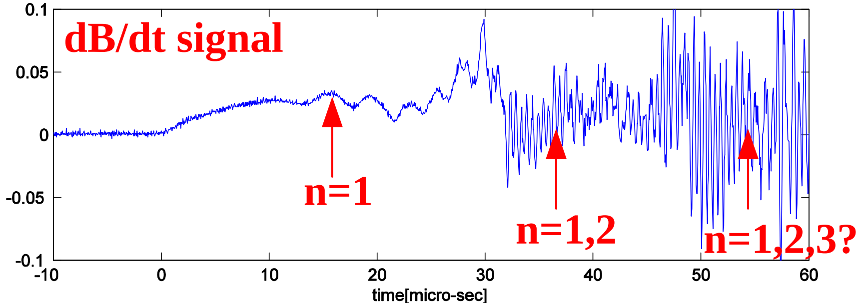
Preliminary studies of single flux rope relaxation

Density	n_e~0.6-3e^{13}cm^{-3}
El. Temperature	T_e~3-15eV
Scale length	L~100 cm r~2 cm
Guide field	B_Z=200 Gauss
Ion skin depth	$\delta_i=c/\omega_{pi}$~2 cm
electron skin depth	$\delta_i=c/\omega_{pi}$~1.7 mm
Ion gyro radius	r_{Gi}~0.35-1.4cm
electron gyro radius	r_{Ge}~1-4mm

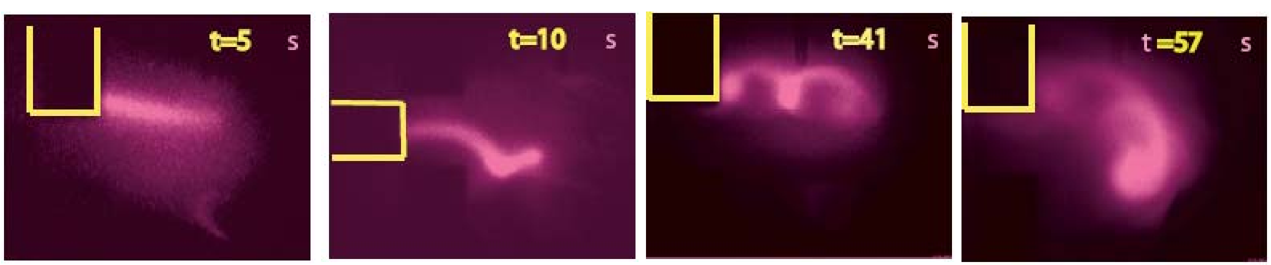


Single and multiple helicity states are observed during current ramp up ($dV_{bias}/dt > 0$)





- Onset of m/n=1/1 consistent with KS limit q_{edge}= 1
- q_{edge}= 2 at onset of n=2 ?
- Saturated state for n=1 and n=2 is observed, no disruption
- Plasma increases its inductance at n=2 onset



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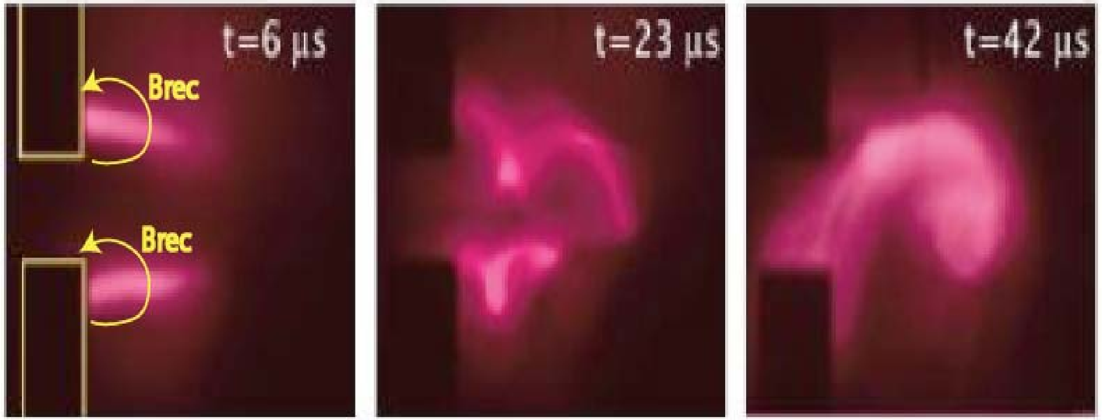
Open questions

- Identify the saturation mechanism (field line bending, wall).
- Non linear mode coupling.
- Influence of external drive on the relaxed state.
- How does relaxation change with β?

Relaxation of two flux ropes and magnetic reconnection

Density	n_e~0.6-3e^{13}cm^{-3}
Guide field	B_Z=100-400Gauss
Reconnection field	B_{rec}~10 Gauss
El. Temperature	T_e~3-15eV
Scale size	d~8 cm L~100 cm

- High guide field (B_z / B_{rec} = 20-60)
- 2 plasma guns at z = 0, spaced by 8 cm
- External anode at z = 1 m
- Measurements in the reconnection plane at z = 0.5m



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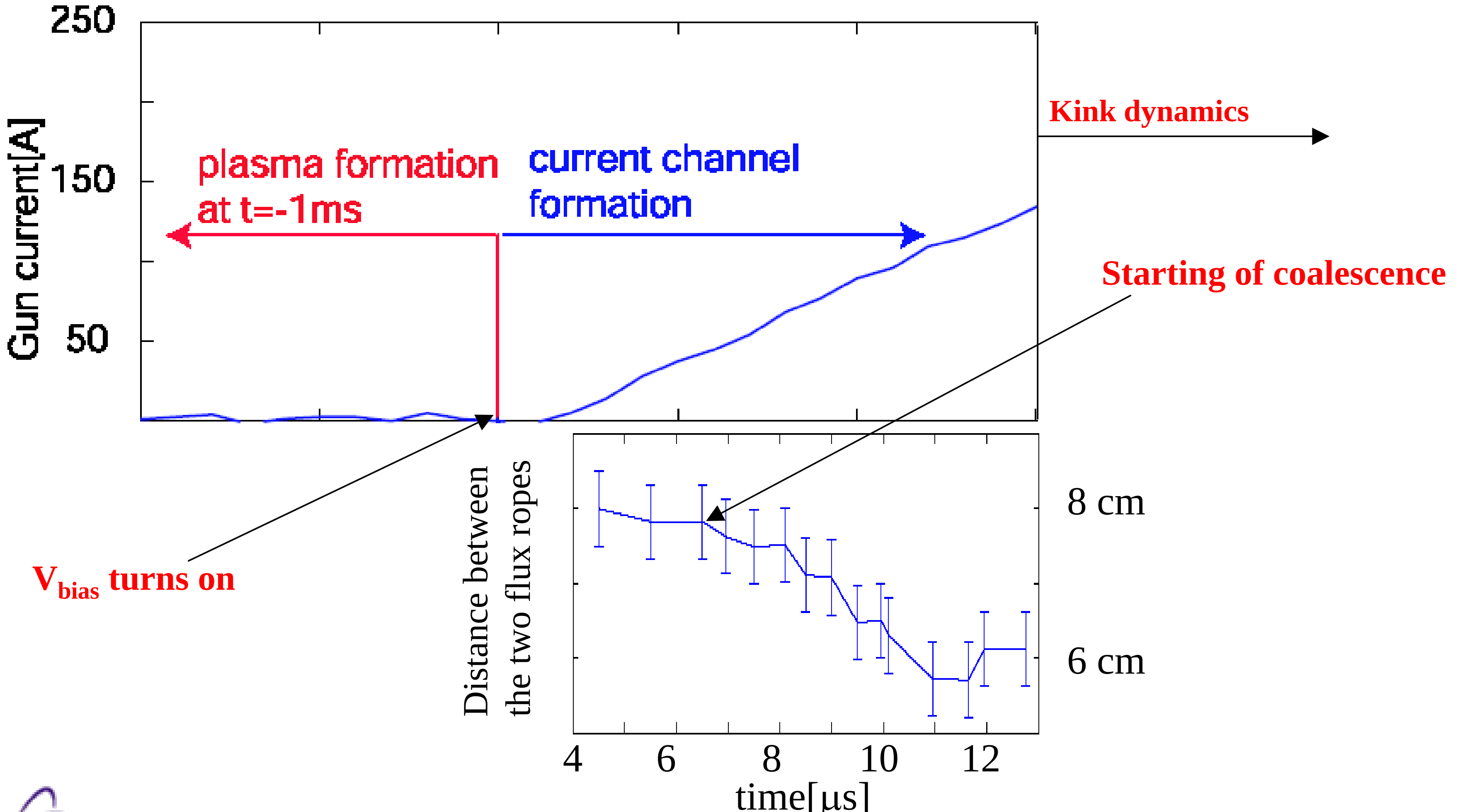
Coalescence of the flux ropes is observed during current ramp-up



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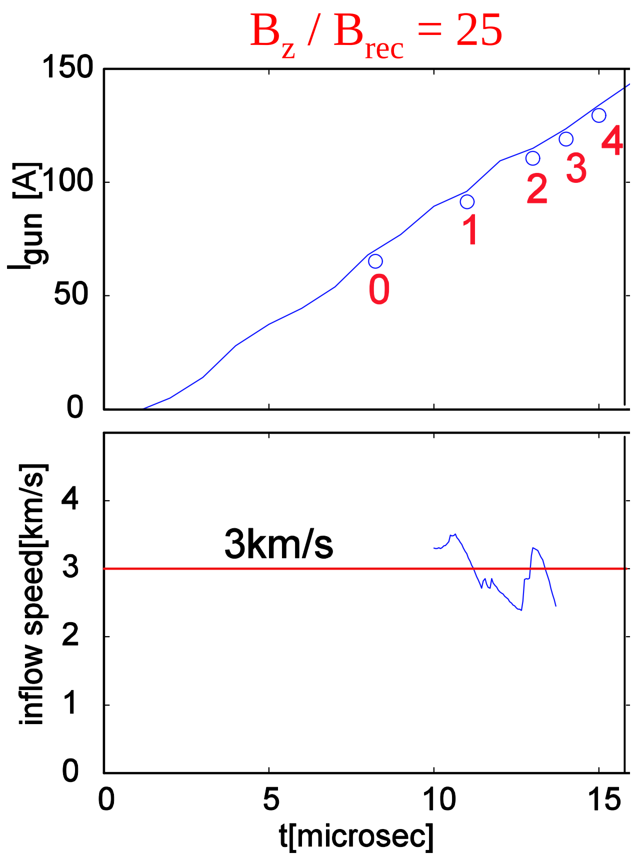
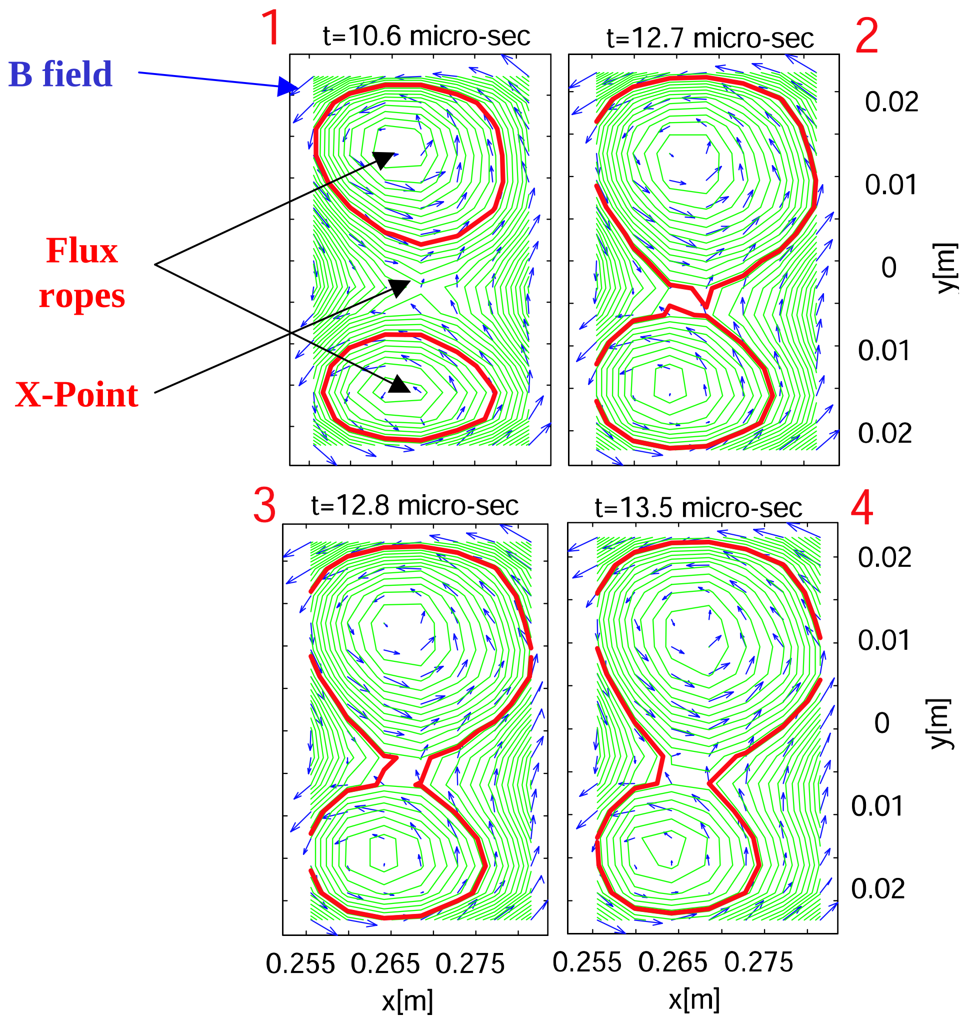
Magnetic reconnection is observed





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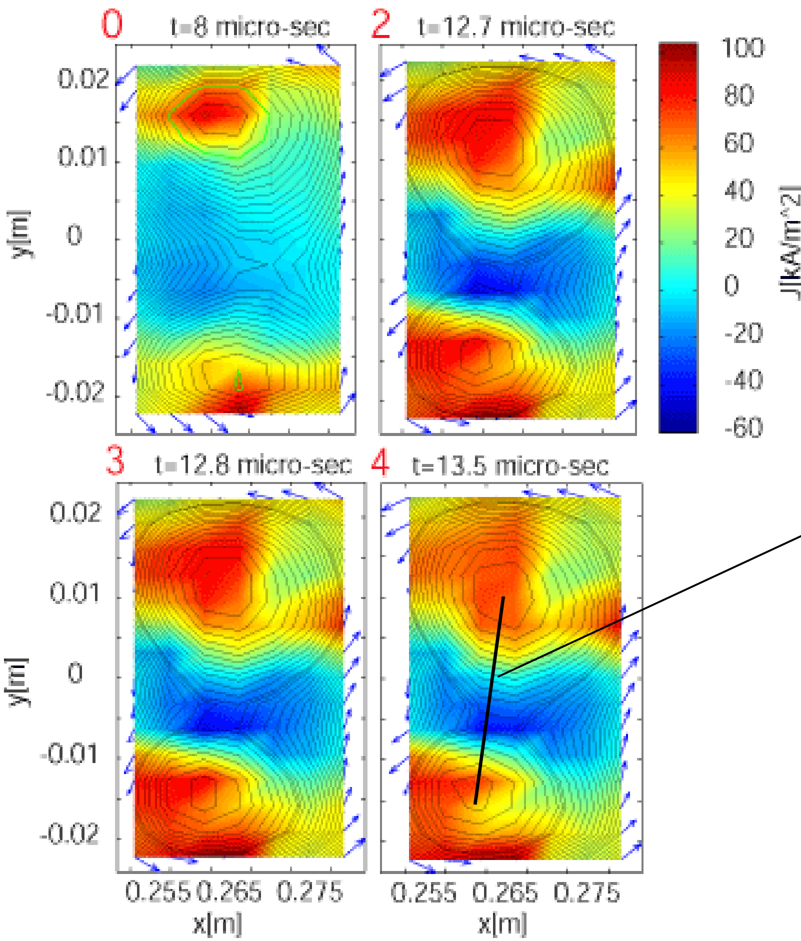
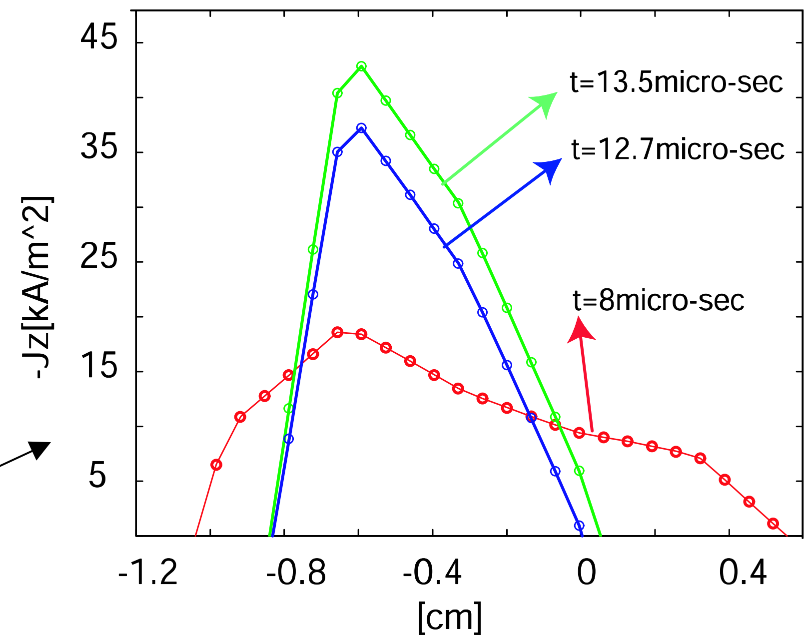
Current sheet shrinks to a size between δ_i and δ_e





- Ion skin depth $\delta_i \approx$9cm
- Electron skin depth $\delta_e \approx$2mm
- Ion Gyroradius $\rho_i \approx$0.7cm
- Ion sound radius $\rho_s \approx$1.7cm

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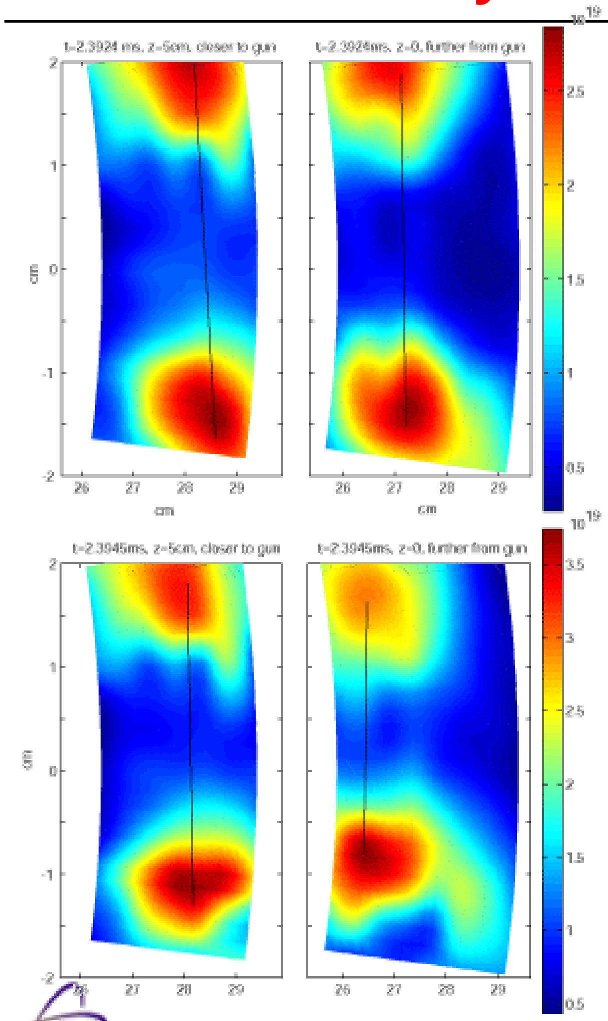
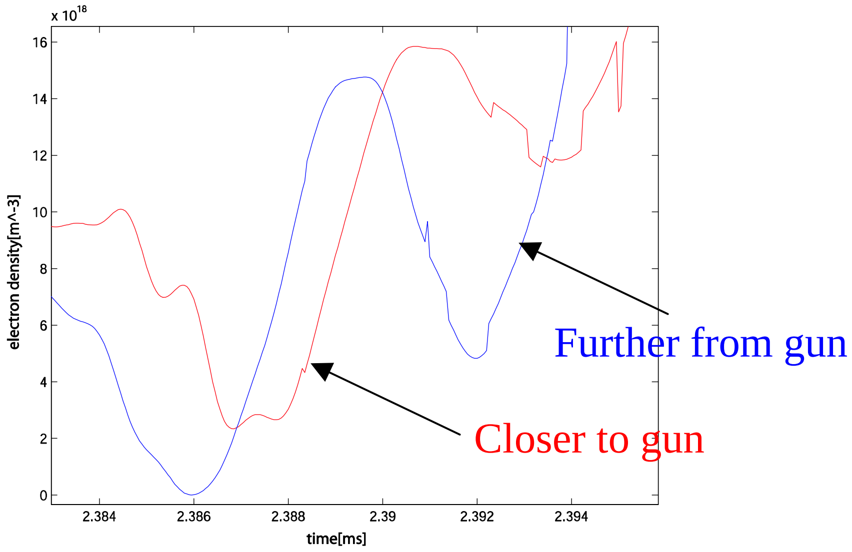
3D effect :observation of zipper effect and density wave in the current sheet





- **Zipper effect**: coalescence and twisting start at the external anode and propagates towards the guns
- A **pressure rarefaction wave** is observed in the current sheet that propagates in the **direction of the electron drift velocity** (from external anode to plasma gun)

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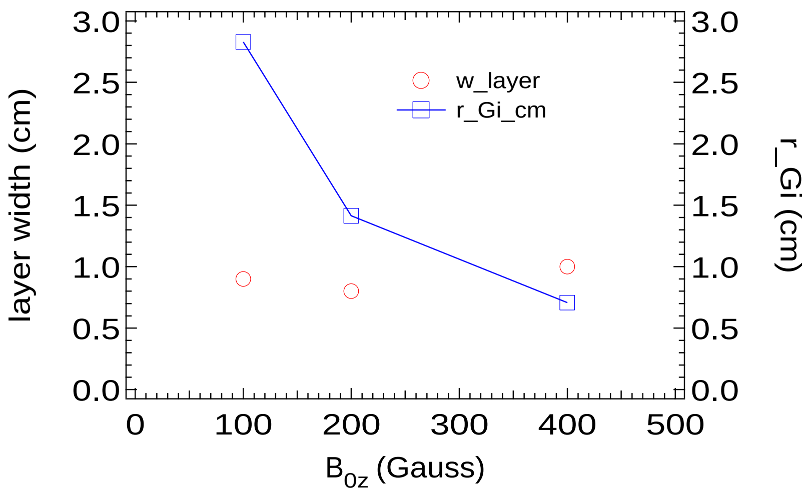
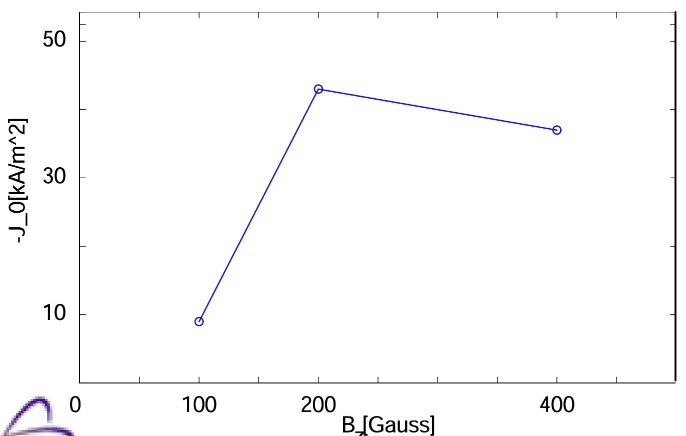
Guide magnetic field scan

Peak current density in the current sheet





- 3 magnetic fields: B_z=100, 200,400 Gauss
- Gun pressure adjusted to have same n_e
- No strong dependence of the current sheet thickness on B_z is observed
- J_0 in the current sheet increases and saturates with B_z
- This observation may be interpreted in terms of increased electron mobility in the *z* direction due to a reduced Larmor radius [Ricci P. et al, *Physics of Plasmas 10, p.3554 (2003)*].

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Summary

• On RSX, relaxation of single and double flux rope is studied in the presence of a high guide magnetic field.

• Single and multiple helicity relaxed state are identified in single flux rope relaxation.

• Magnetic reconnection play an important role in two flux rope relaxation.

• A current sheet is observed on a scale length intermediate between δ_i and δ_e. No strong dependence of the current sheet thickness on $B_{z.}$

• The peak current density in the current sheet increases and saturates with B_z.

• 3D effects:propagation of density wave and zipper effect

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