Study of Magnetic Reconnection and Merging of Compact Toroids

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Norman Rostoker Memorial Symposium

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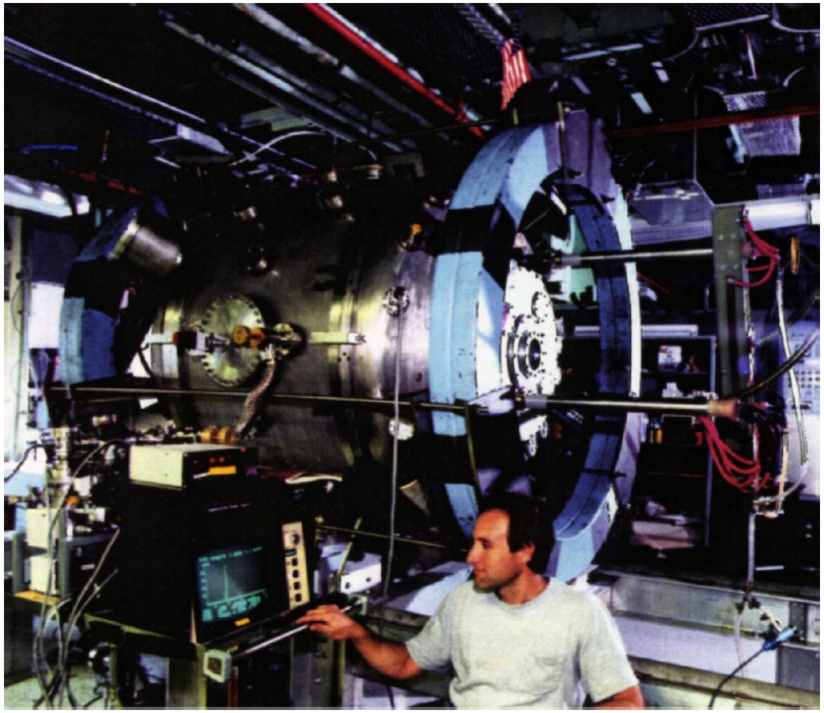
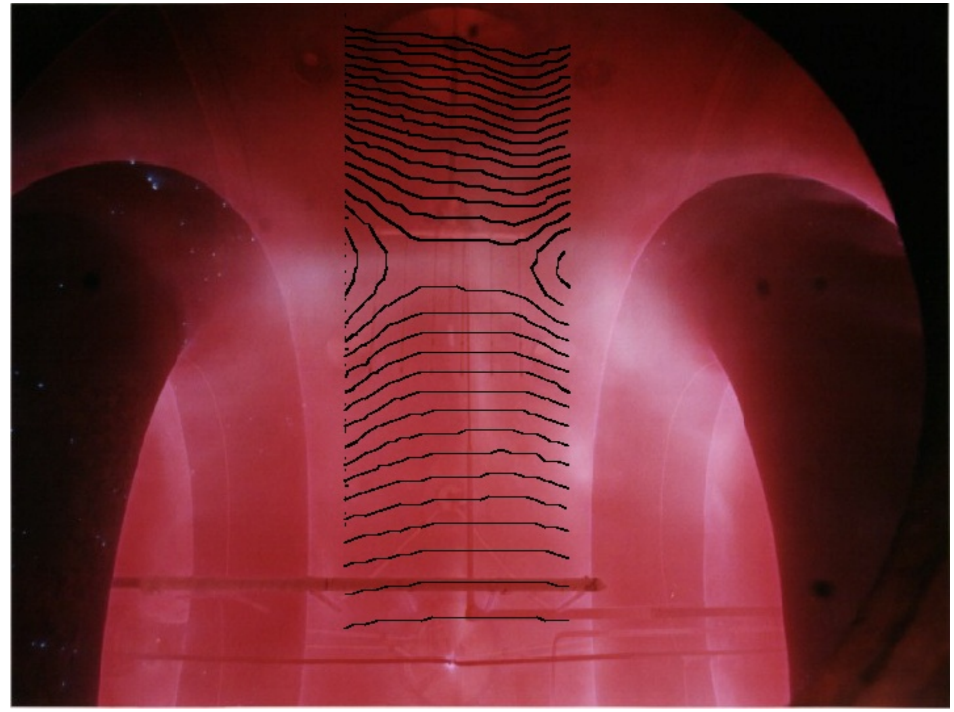
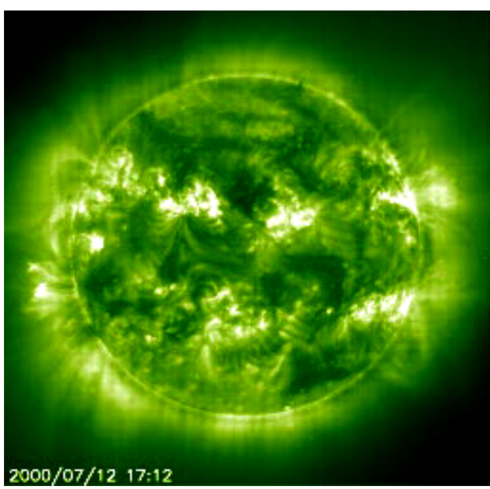
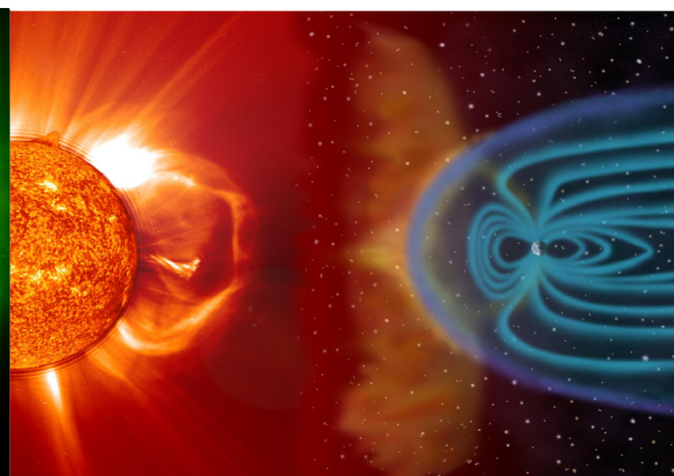
PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Magnetic Reconnection Experiment

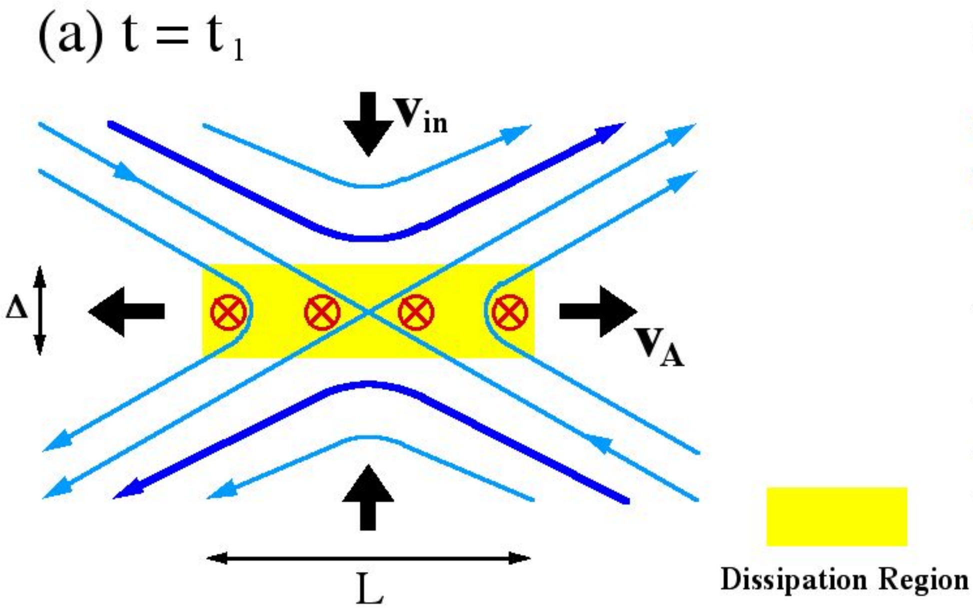








Magnetic reconnection = Fundamental Process



Local view of reconnection: filed line reconnection=> Topology Change

Conversion of magnetic energy to particle heating and acceleration

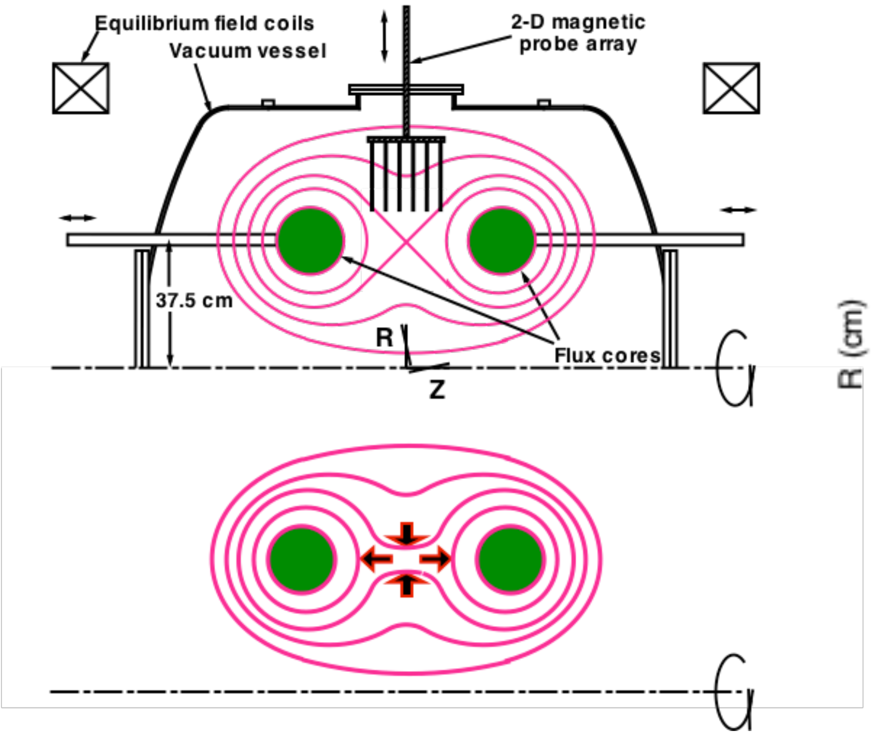
How do we study magnetic reconnection in dedicated lab experiments?

1. We create a proto-typical reconnection layer in a controlled manner and study the fundamental plasma dynamics
2. Cross-validation of experiment and numerical modeling

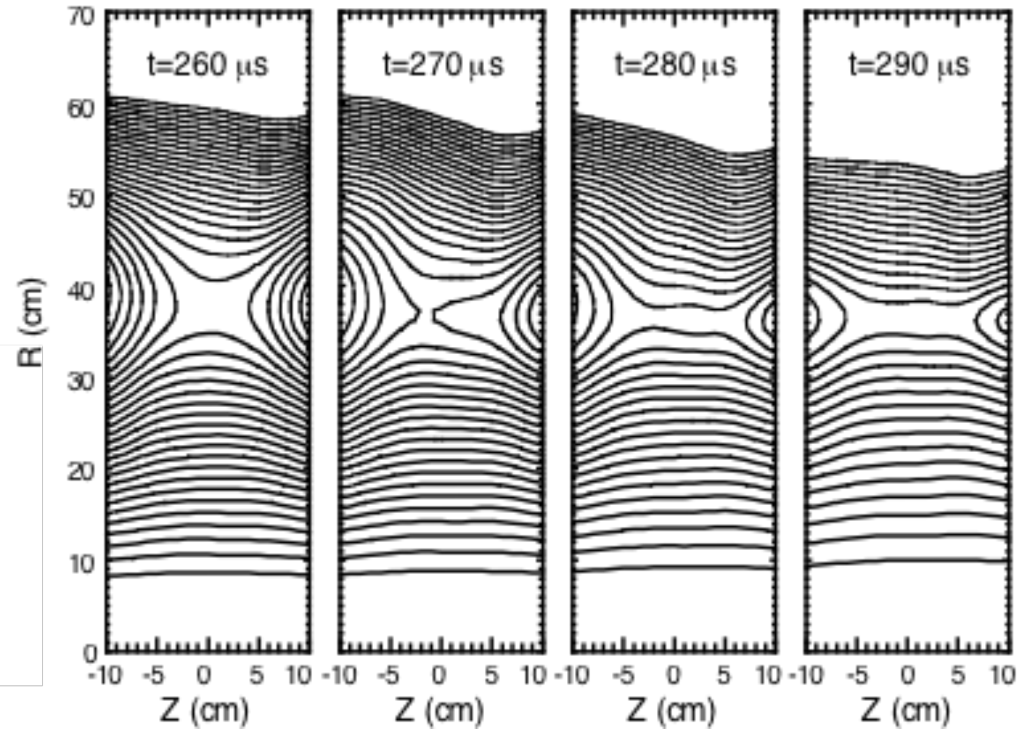
The primary issues/questions;

- Why does reconnection occur so fast?
- Dynamics of electrons and ions
- How does local reconnection determine global phenomena?
- How is magnetic energy converted to plasma flows and thermal energy?

Experimental Setup and Formation of Current Sheet



Experimentally measured flux evolution



n_e= 1-10 x10^{13} cm^{-3},
T_e~5-15 eV,
B~100-500 G,

MRX

Magnetic
Reconnection
Experiment

Poloidal Flux Evolution

Null-helicity Reconnection

Princeton Plasma Physics Laboratory, Princeton University

Local Reconnection Physics

1. MHD analysis
2. **Two-fluid analysis**

Particle dynamics of the two-fluid reconnection layer

Normalized with $x/\Delta \rightarrow x,\ V/V_A \rightarrow V,\ B/B_0 \rightarrow B$

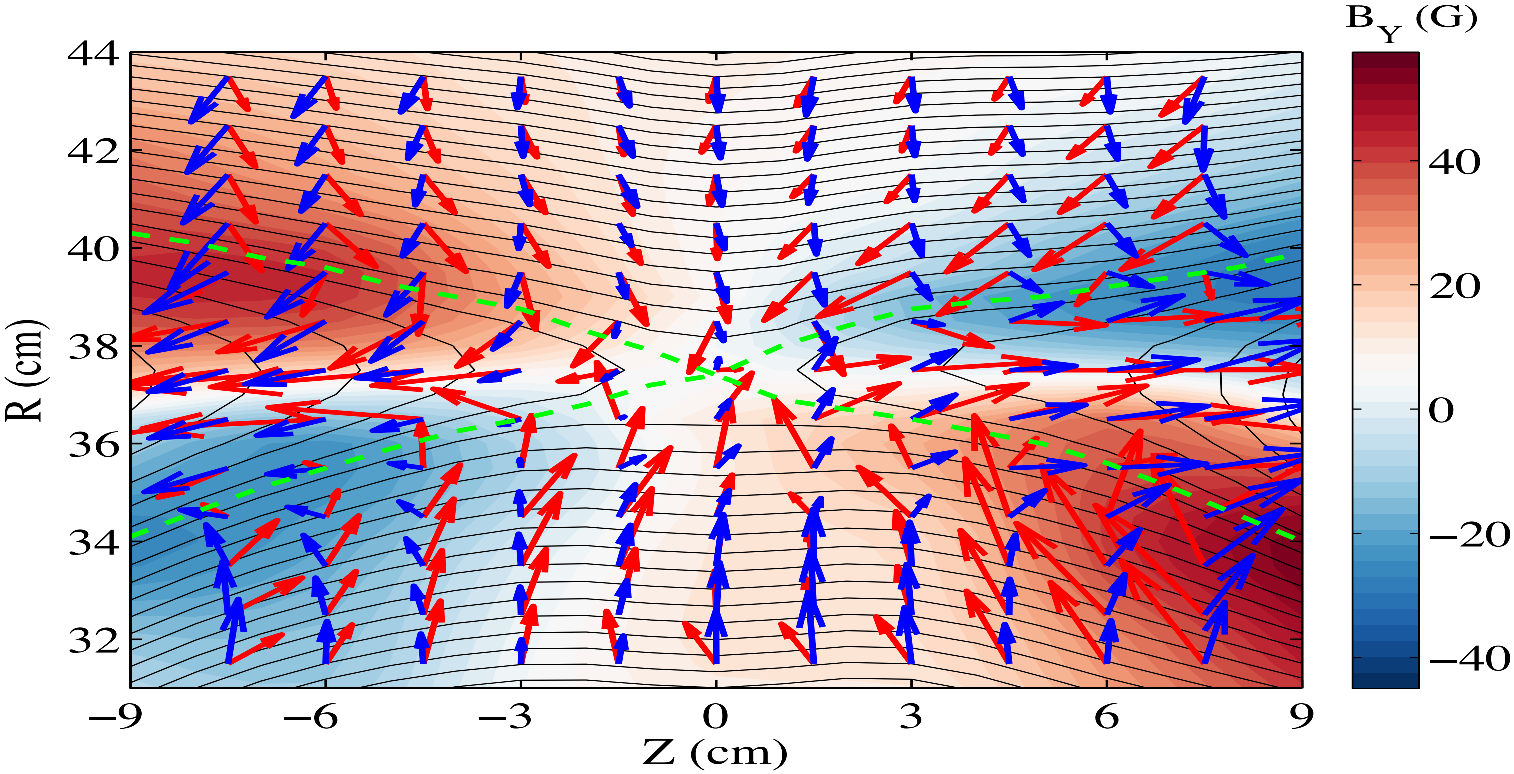
$$E_{rec} + V_{in} \times B_{rec} = 0 + \underbrace{\frac{\delta_i}{\Delta}\frac{j_{in} \times B_{rec}}{n}}_{\text{Hall term}} - \underbrace{\frac{\delta_e^2}{\Delta^2}\frac{1}{n}\frac{dj_{rec}}{dt}}_{\text{Electron inertia term}} + \underbrace{\frac{\delta_i}{\Delta}\frac{(\nabla \cdot P_e)_{off}}{n}}_{\text{Electron pressure term}}$$

Ideal MHD region

Hall term

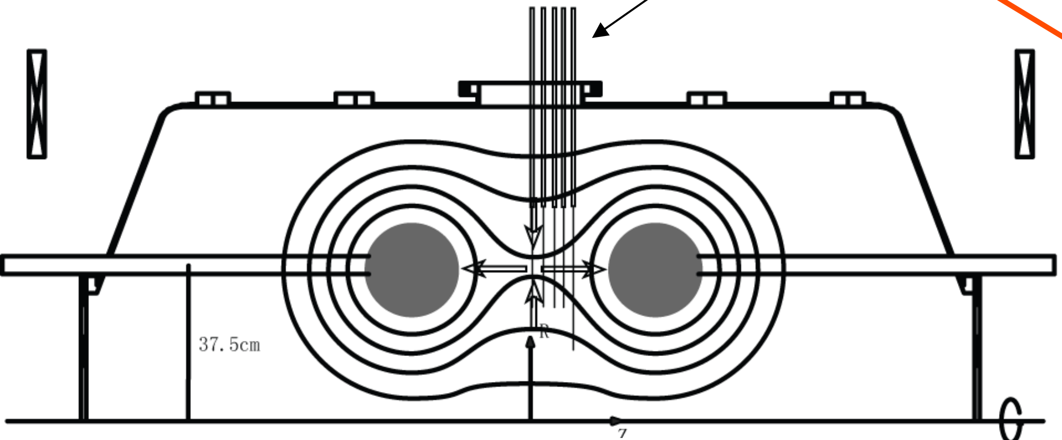
Electron inertia term

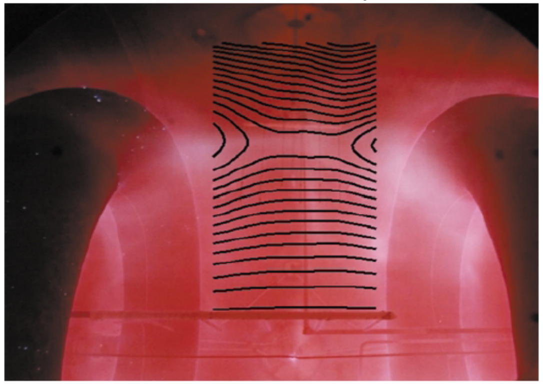
Electron pressure term

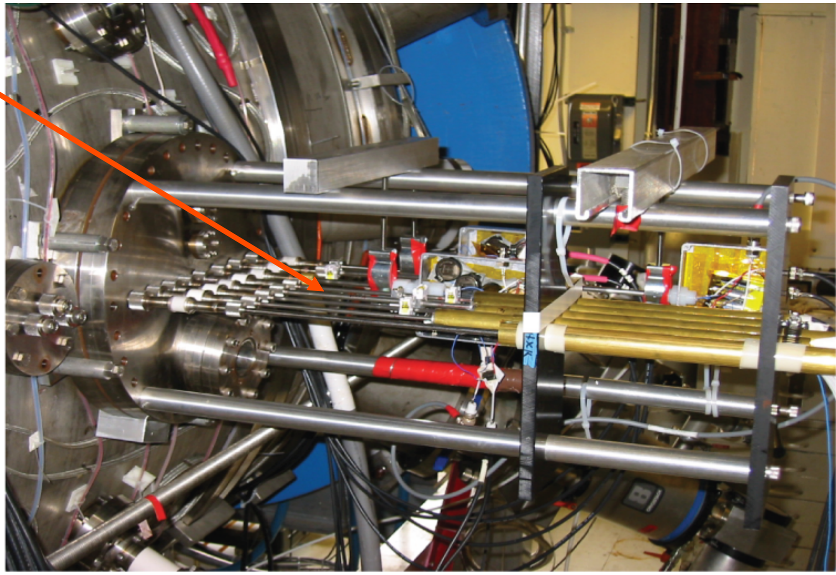


MRX with fine probe arrays

Linear probe arrays

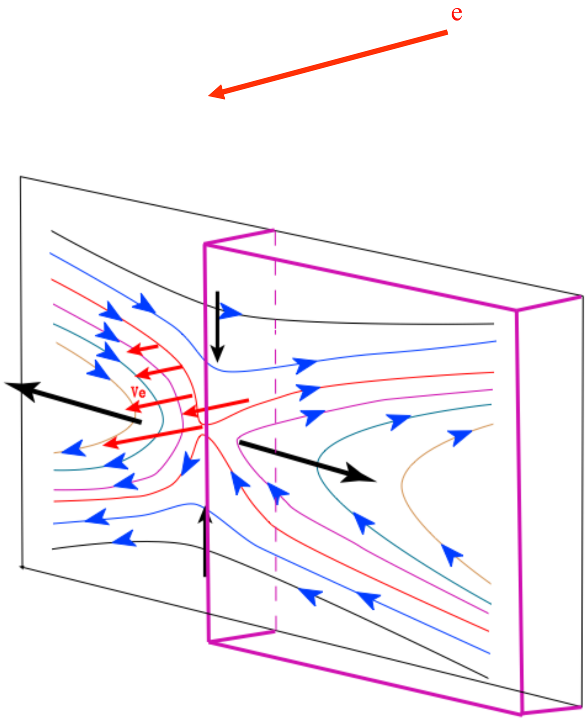




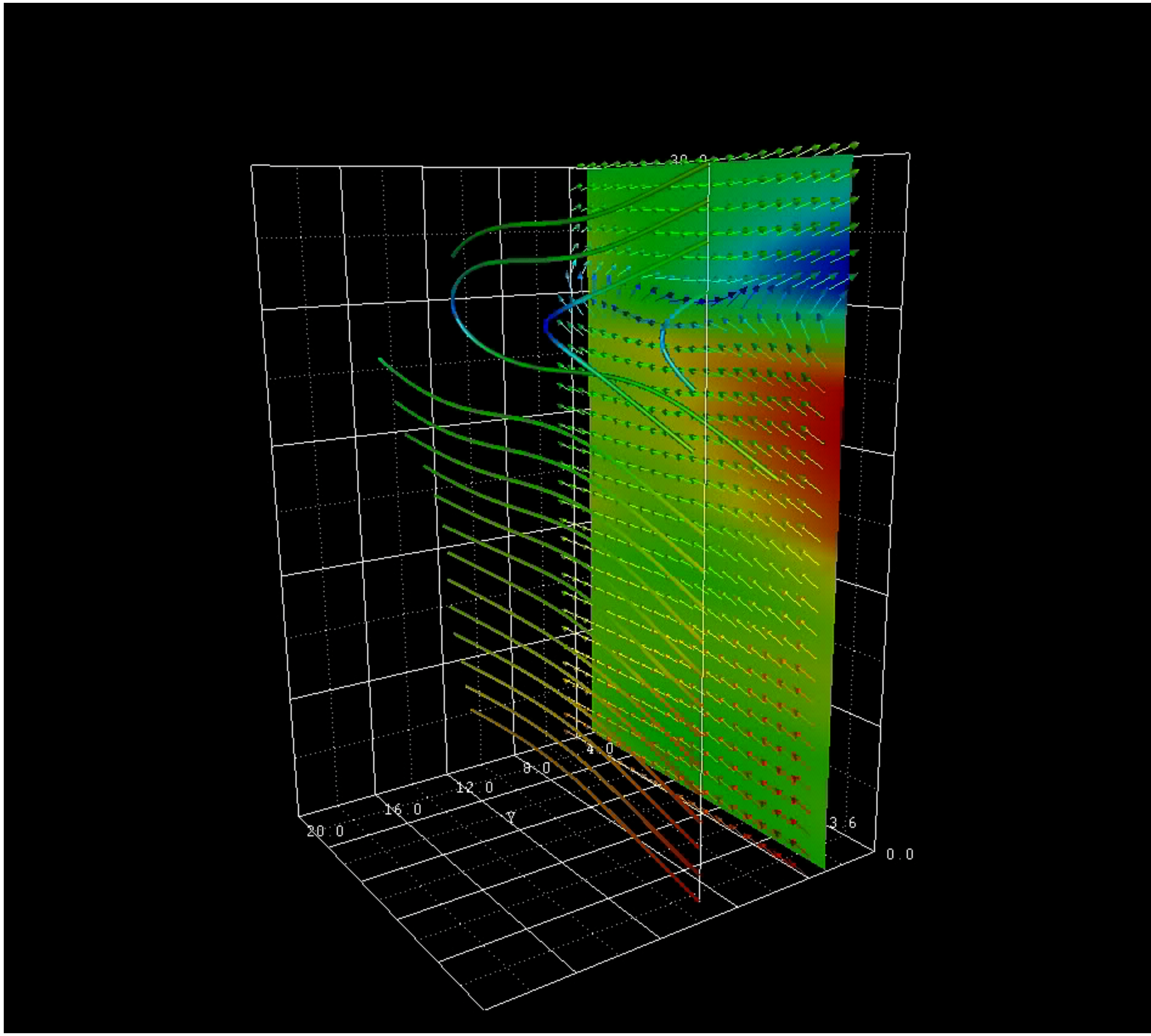


- Five fine structure probe arrays with resolution up to Δx= 2.5 mm in radial direction are placed with separation of Δz= 2-3 cm

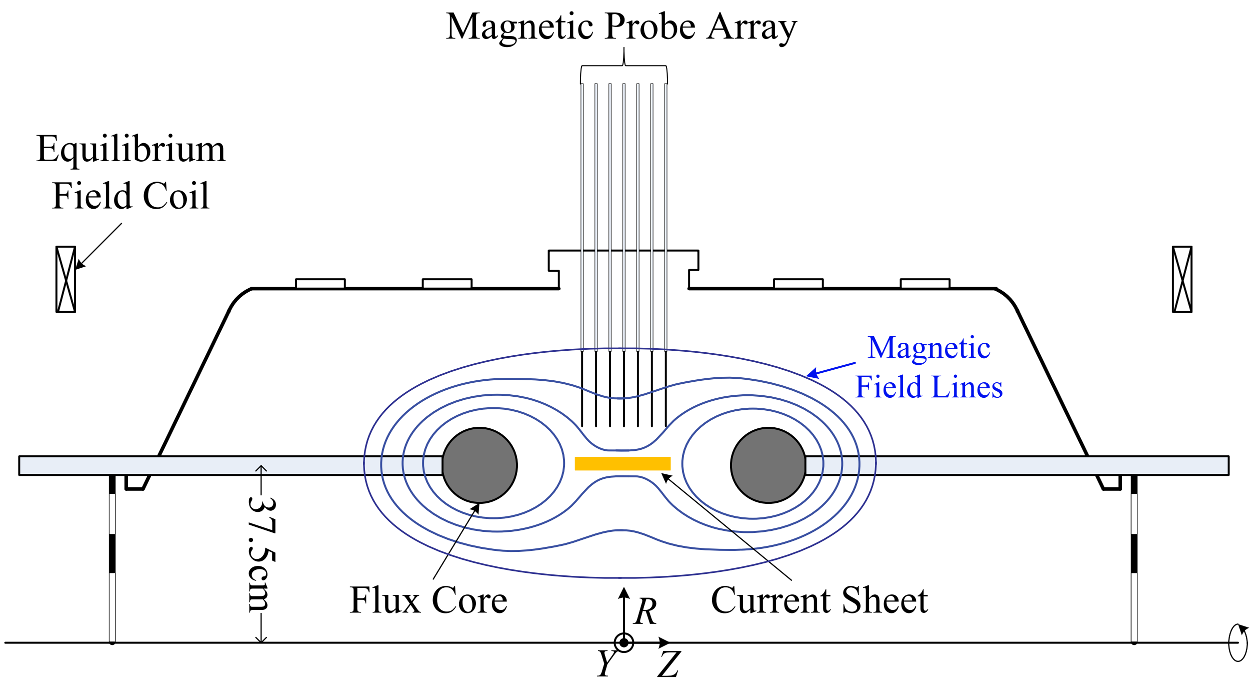
Evolution of magnetic field lines during reconnection in MRX

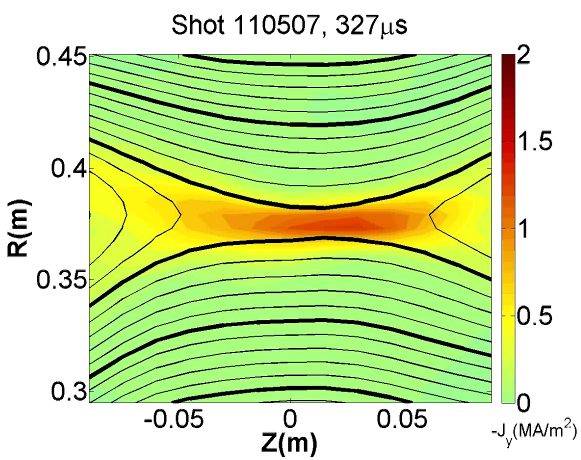


Measured region



Experimental Setup for Energetics Study

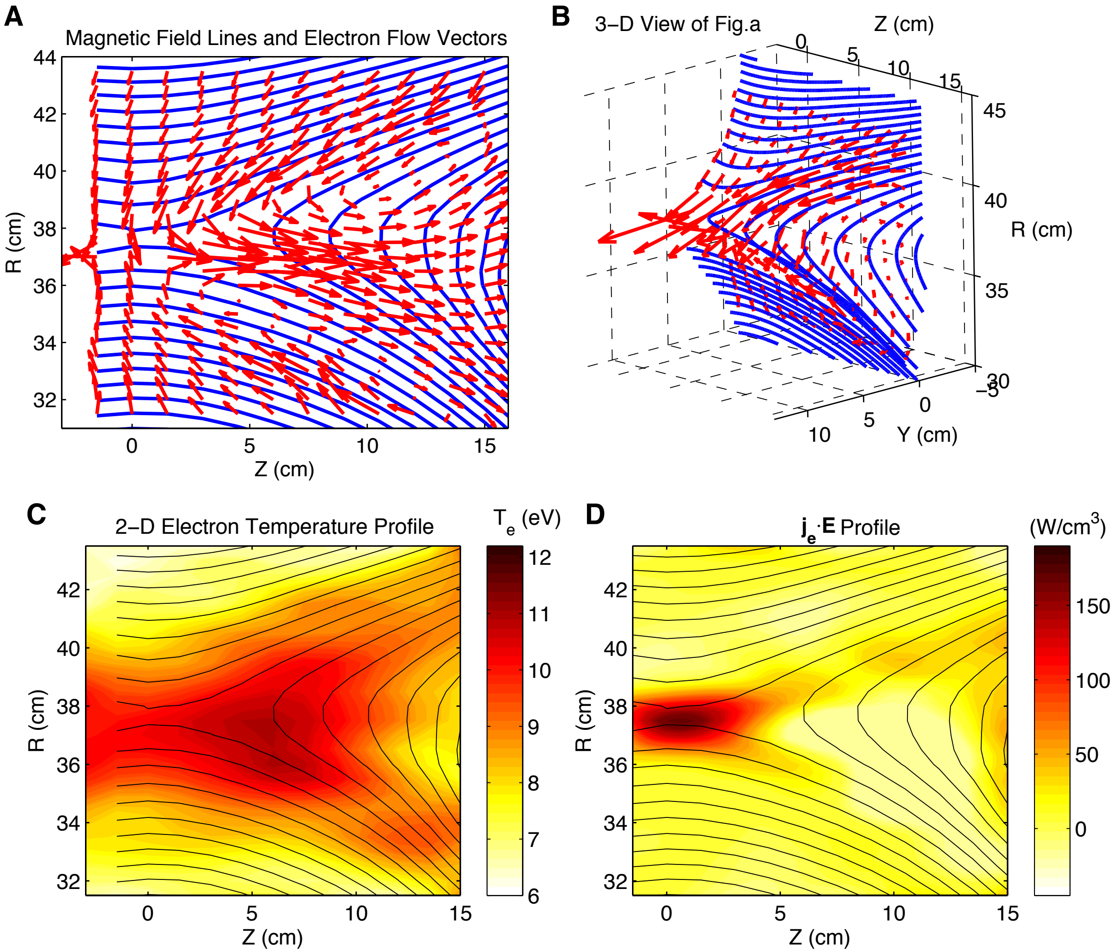




- Helium discharge
- n_e: 2-8×10^{13}/cm^3
- T_e~T_i: 6-15eV
- $\lambda_{mfp,e} \geq c/\omega_{pi} > \delta_{CS}$ (~2cm)
- No guide field.
- IDSP to measure T_i

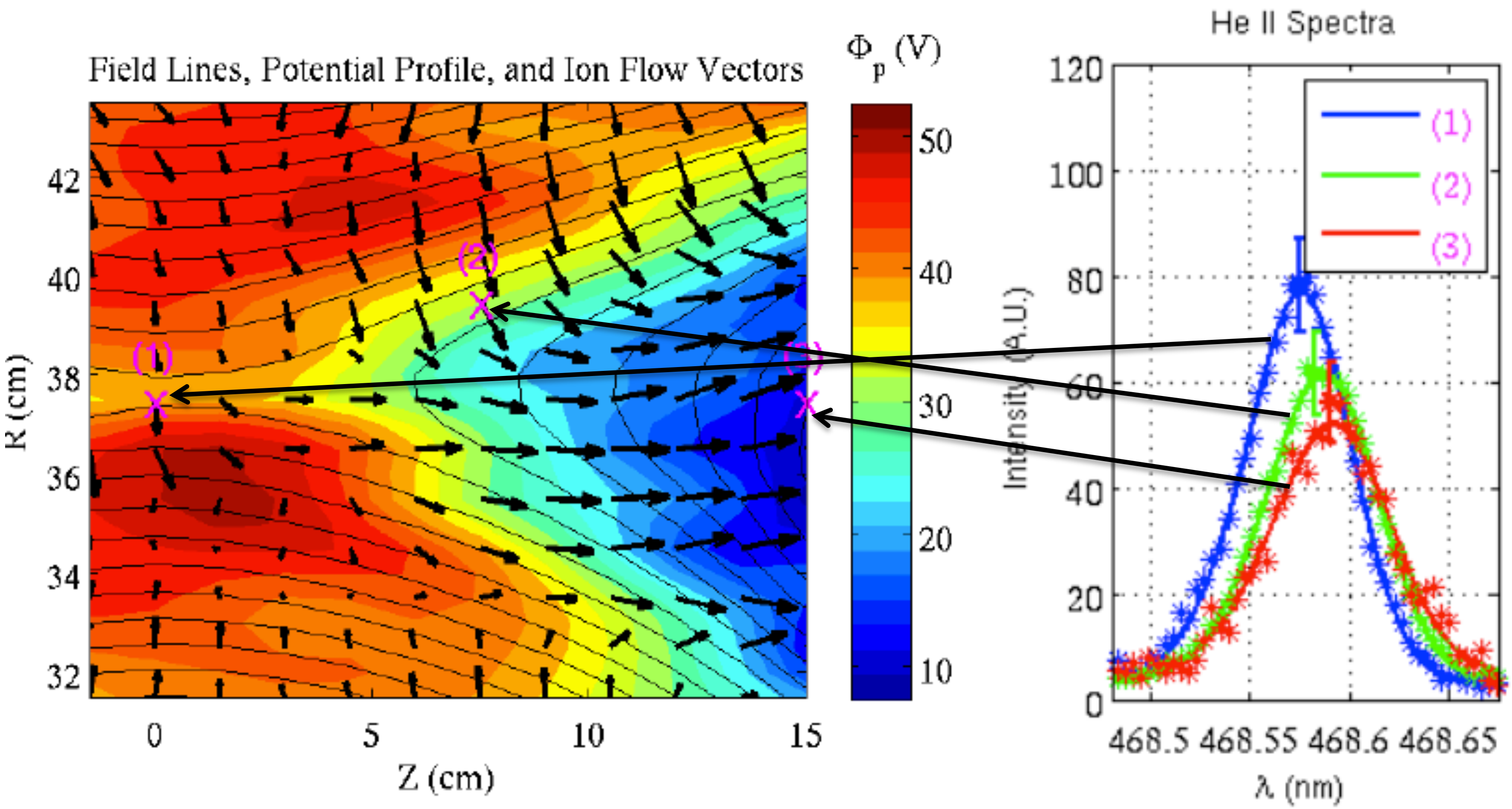
Electron dynamics and strong electron heating observed in the broad exhaust region of MRX

$\mathbf{j} = \mathrm{Curl}\ \mathbf{B}, \ \mathbf{V}_e = \mathbf{j}_e / ne$



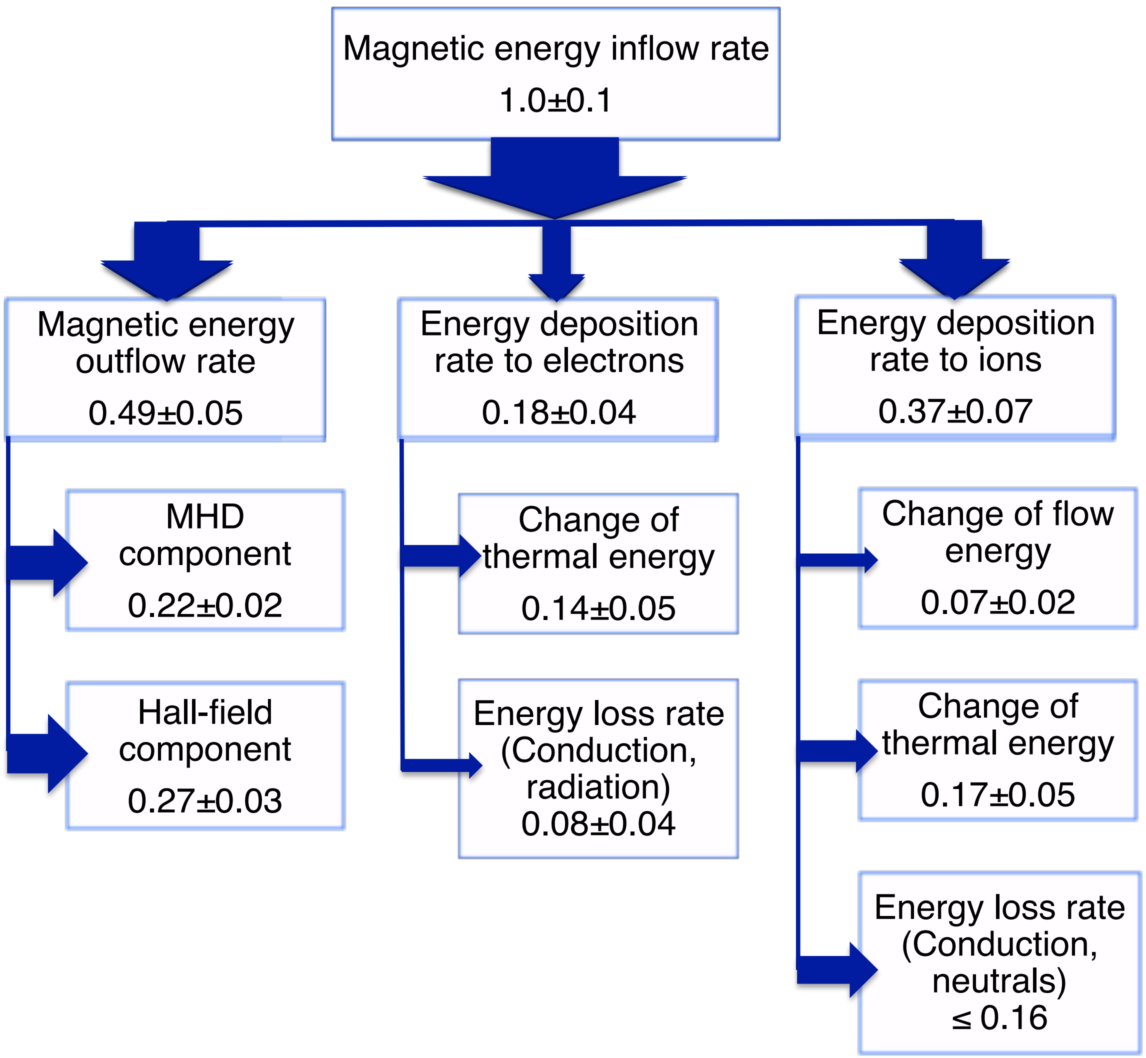
- Electron gain energy mostly near the X-point.
- The energy transported via heat conduction

Ion acceleration and heating in the reconnection layer



Ion heating is attributed to re-magnetization of accelerated ions
We note collisions play a role in ion heating in the exhaust

Inventory of Energy

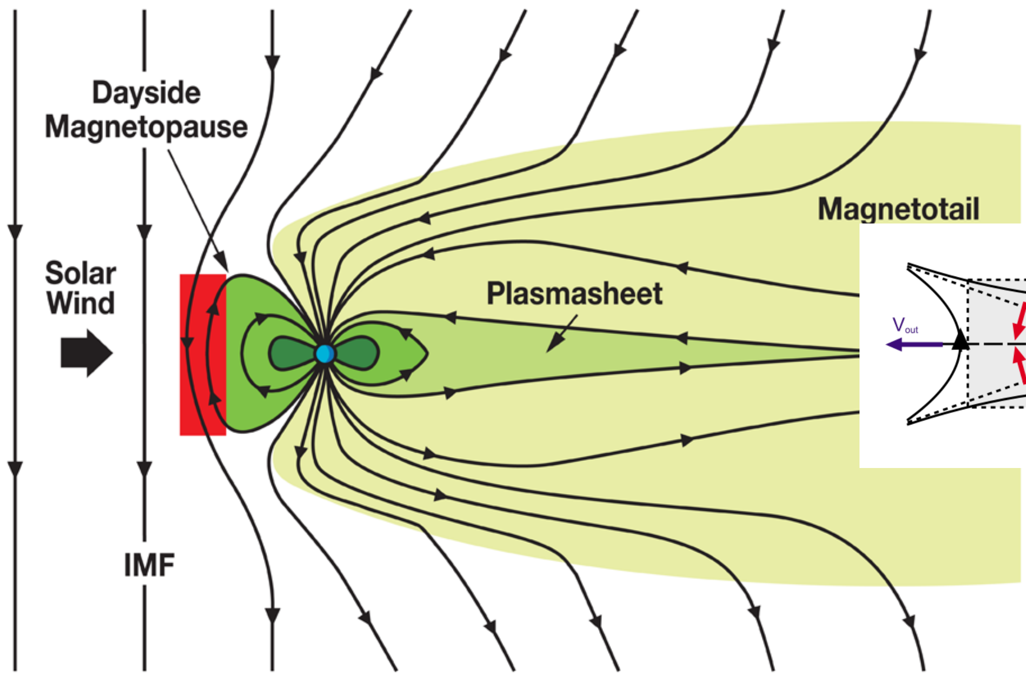


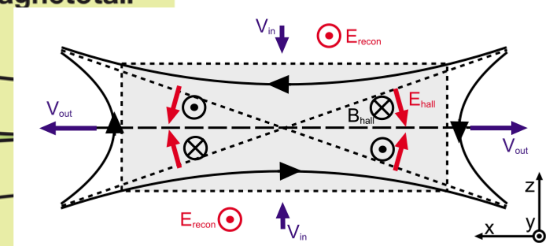
Nature Communications (2014)

Energy conversion during magnetic reconnection

- Significant particle heating and acceleration observed in reconnection events in the magnetosphere, solar flares and laboratory experiments.
- It is generally difficult to identify the inventory and partitioning of energy

- **Our findings on energy partitioning in a reconnection layer is remarkably consistent with the recent space results**





J. Eastwood et al, 2013

Summary of findings on MRX reconnection research

MRX has been very productive; 15 plus PRL, Science, Nature papers et al.

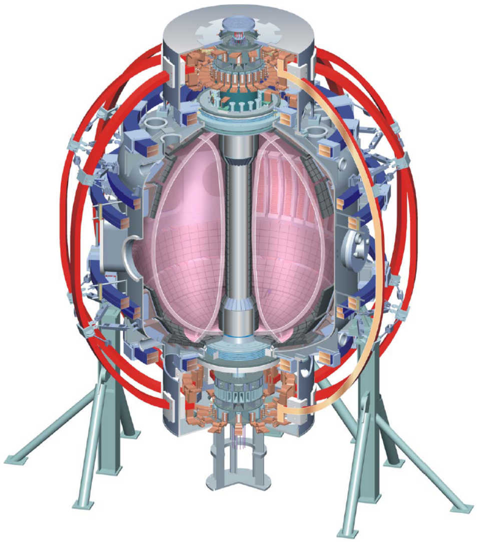
- Verified experimentally the **two-fluid (collision-less) reconnection physics**
  - Verification of Hall effects
  - Validation and verification of numerical simulation codes
  - Identification electron diffusion layer => NASA's MMS Project

- Identified the in-plane electric field which plays a key role for ion acceleration and heating
  - Ions are accelerated electrostatically near the separatrices.
  - Ions are heated downstream by **re-magnetization** and collisions.

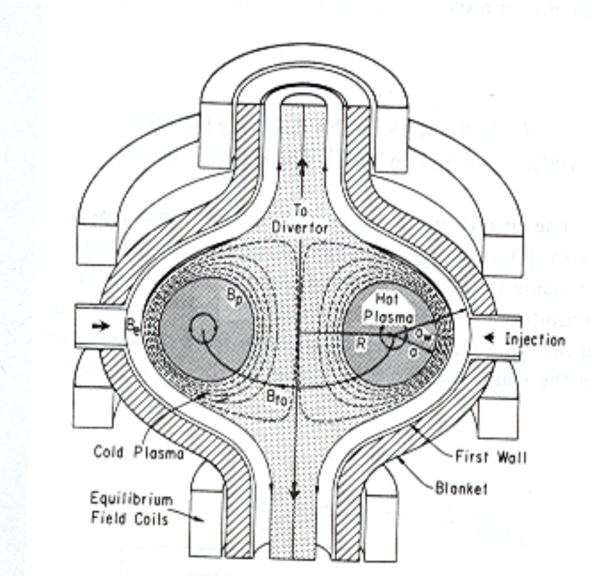
- **Conversion magnetic energy and partitioning is quantitatively analyzed in the reconnection layer**
  - Substantial component of outgoing magnetic energy (~ 50%)
    - **50+% of incoming magnetic energy goes to plasma particles**
      2/3: to ions
      1/3: to electrons

SPIRIT
(Self-organized Plasma by Induction, Reconnection, Injection Techniques)

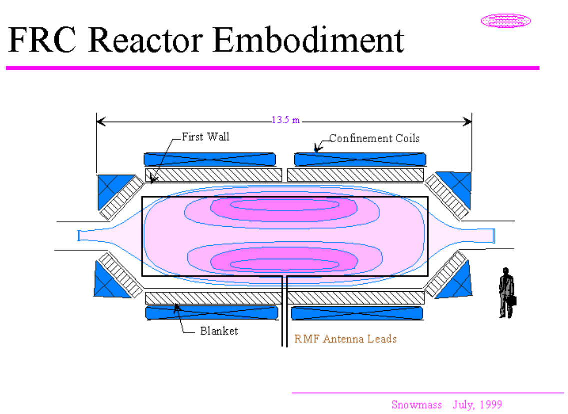
Attempts for simpler reactor core design
=> Compact Toroid Reactor Core



Spherical Torus



Spheromak

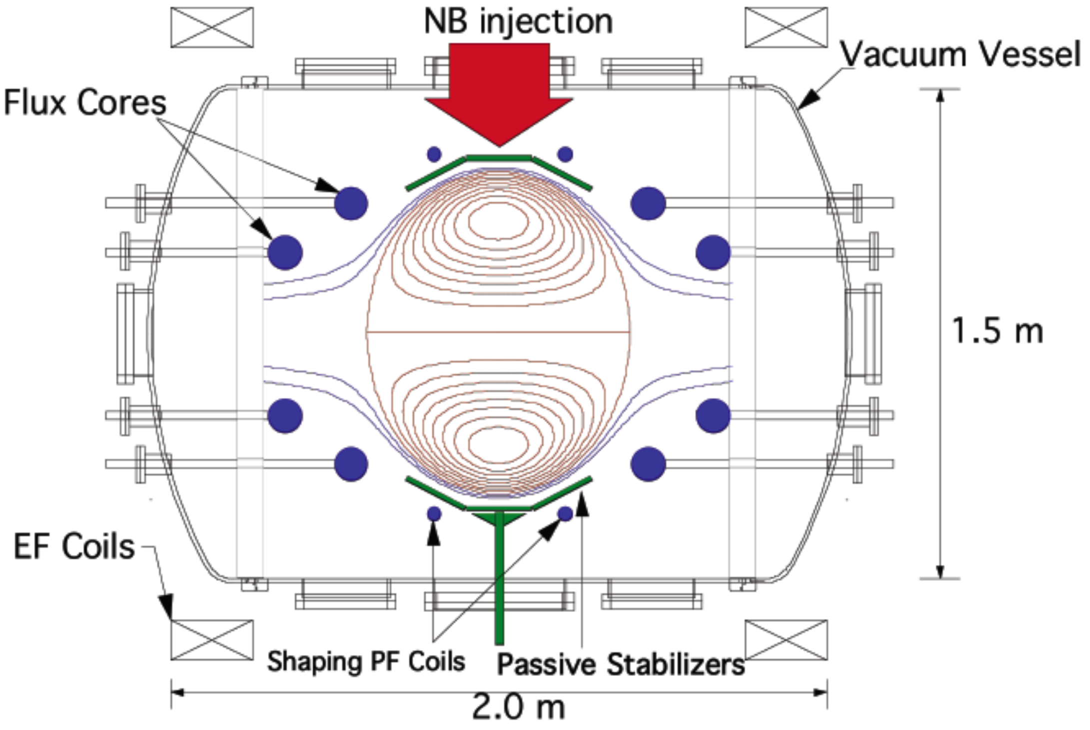


Field Reversed Configuration

SPIRIT Concepts (1997 -)

"Self-organized Plasma
with Induction, Reconnection, and Injection Techniques"

- **Formation of FRC by reconnection of spheromaks**
- **Sustained FRC plasmas with the use of inductive drive**
- **Sustainment of FRC by 10-20 kV NB Injection**
- **<=> N. Rostoker**
  <=> TAE



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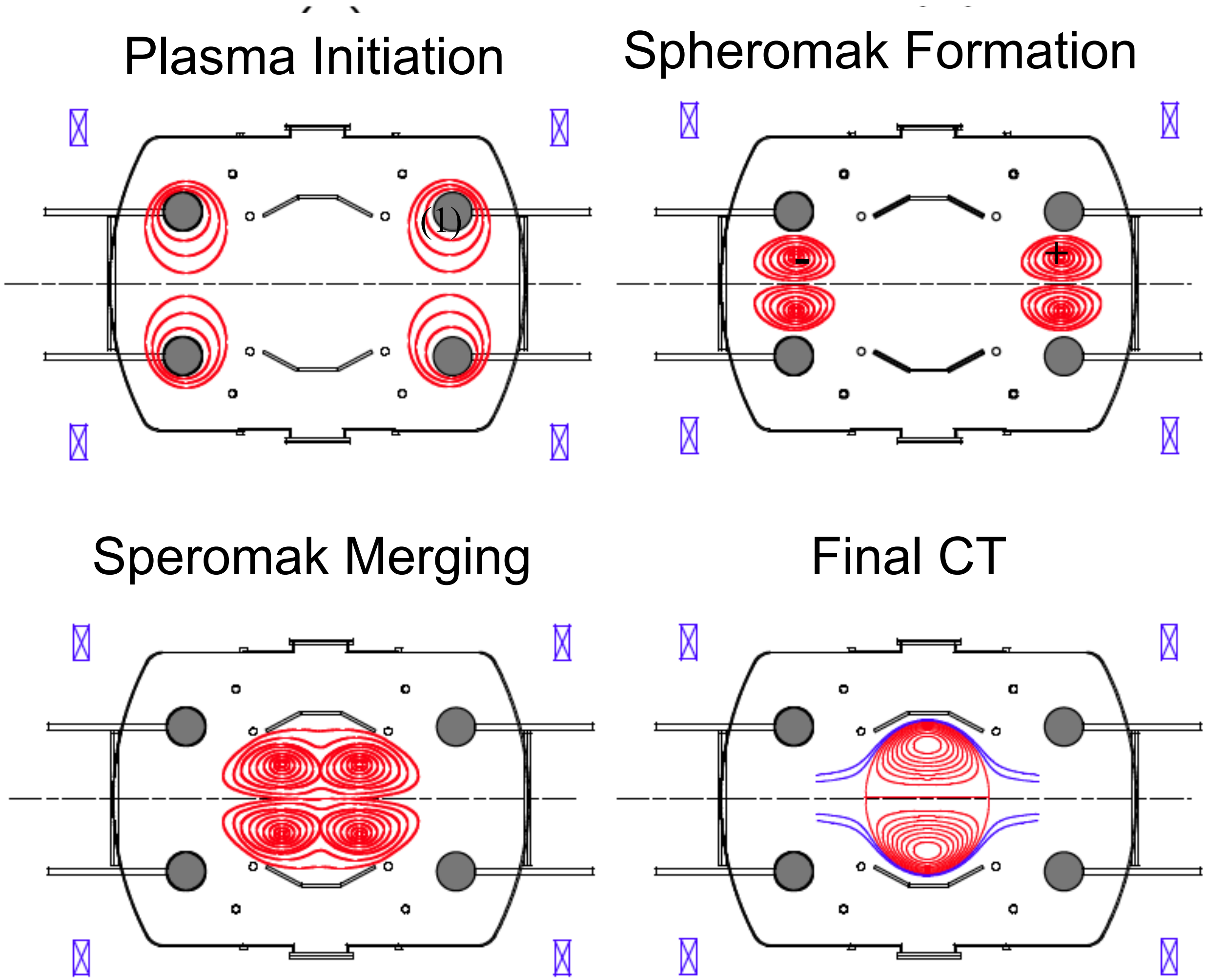
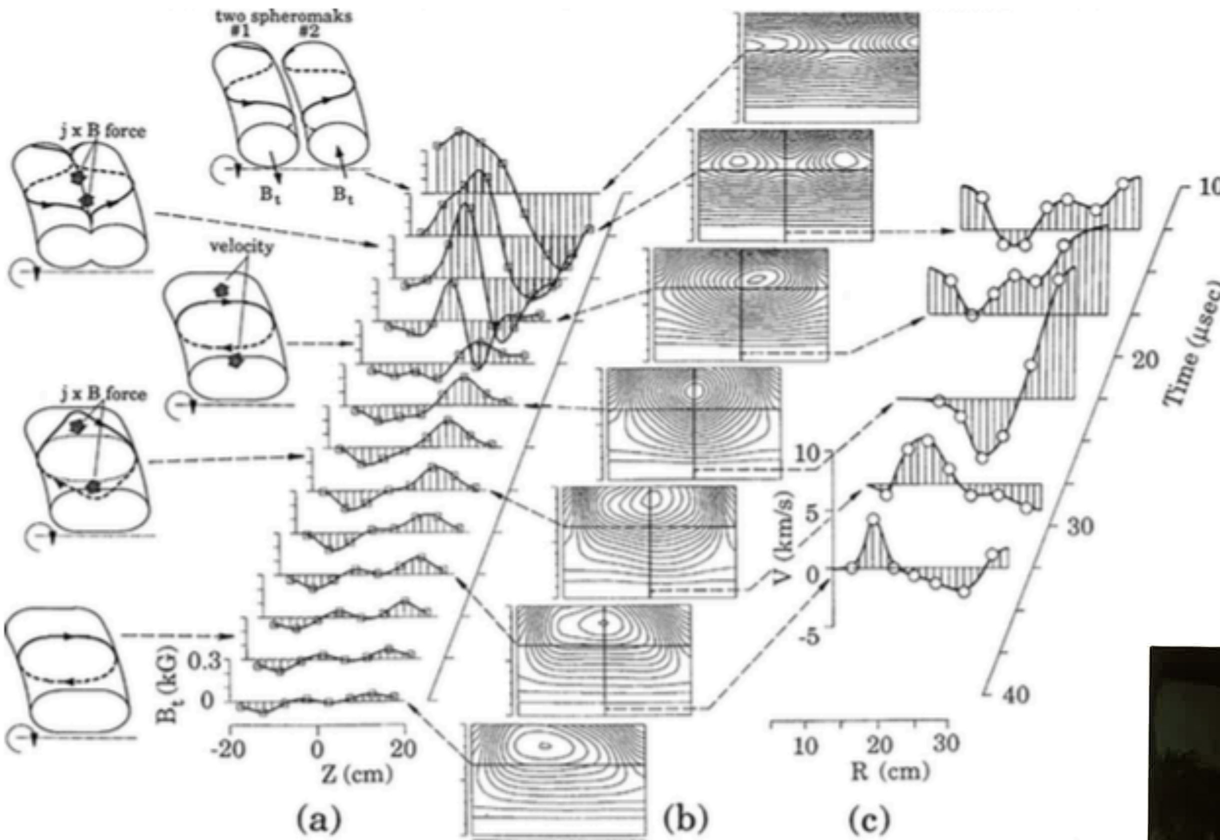
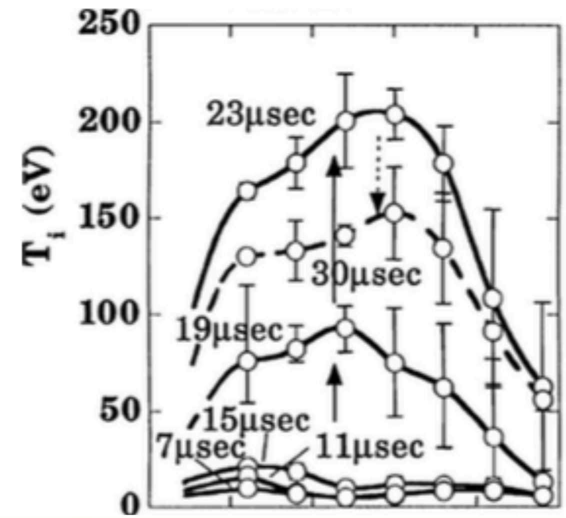
Spheromak Merging Experiments in MRX
(Toroidal Energy => Plasma Kinetic Energy)



(1)

Spheromak Merging Experiments in U. Tokyo
(Toroidal Energy => Plasma Kinetic Energy)



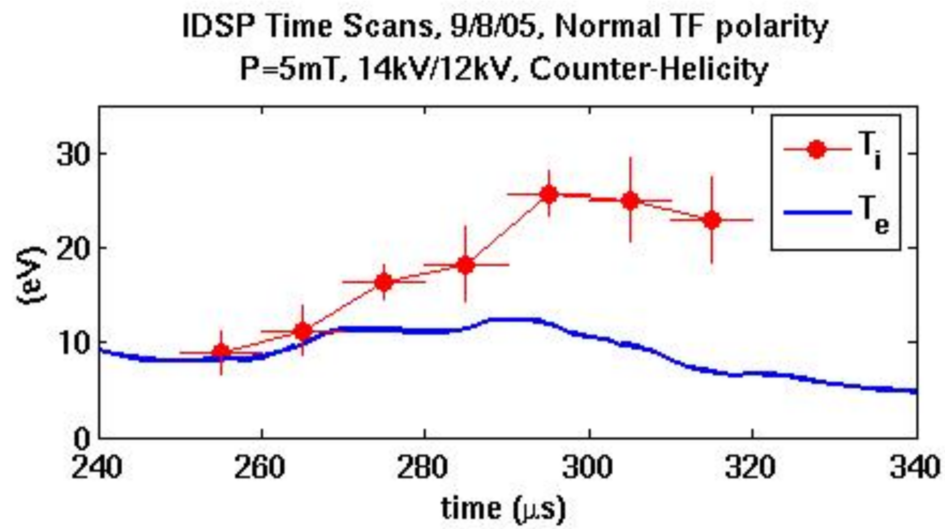


TS-3; Yamada et al PRL (1990)
Ono et al PRL(1996)

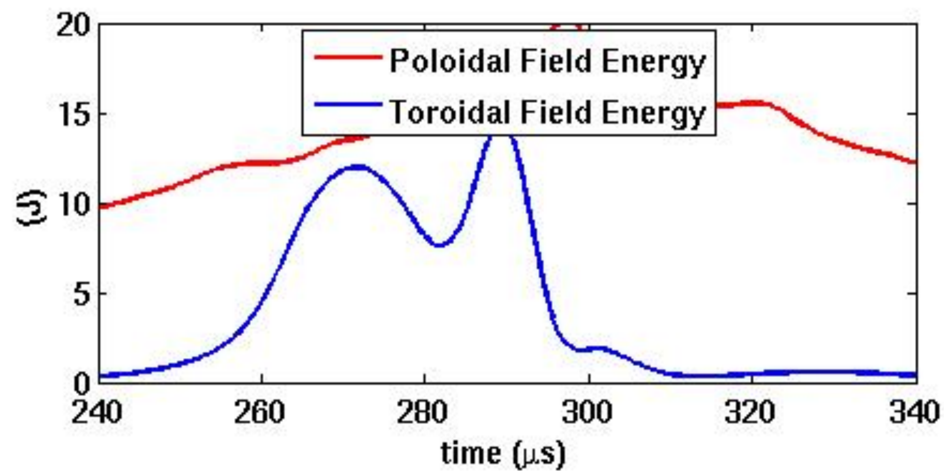
Norman's 70 year Symposium (1995)

Strong ion heating occurs while toroidal field is annihilated

Strongest ion Temperature Rise During Merging Phase (285μs-300μs)



Strong Elimination of Toroidal Field Energy During Merging (285μs-300μs)

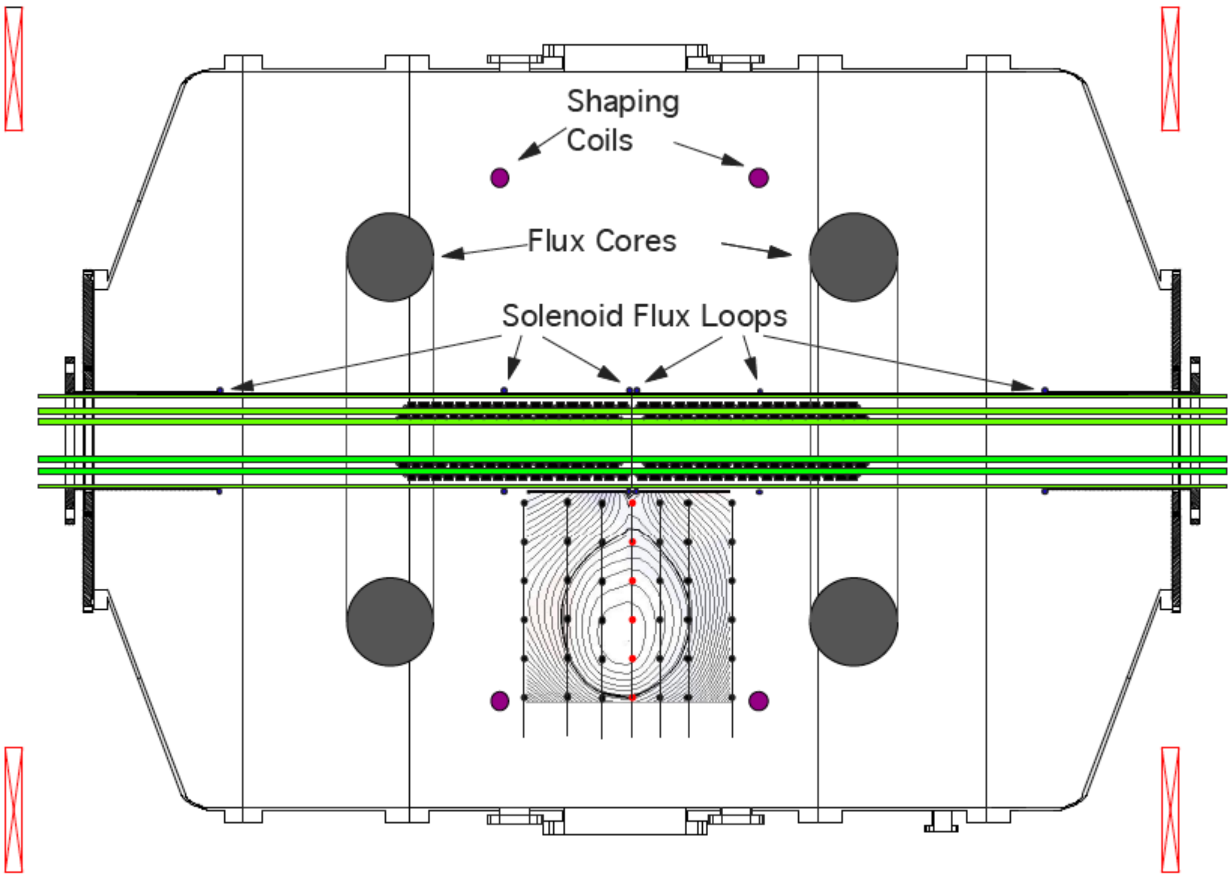


Spheromak Merging is provide a promising option for the TAE project

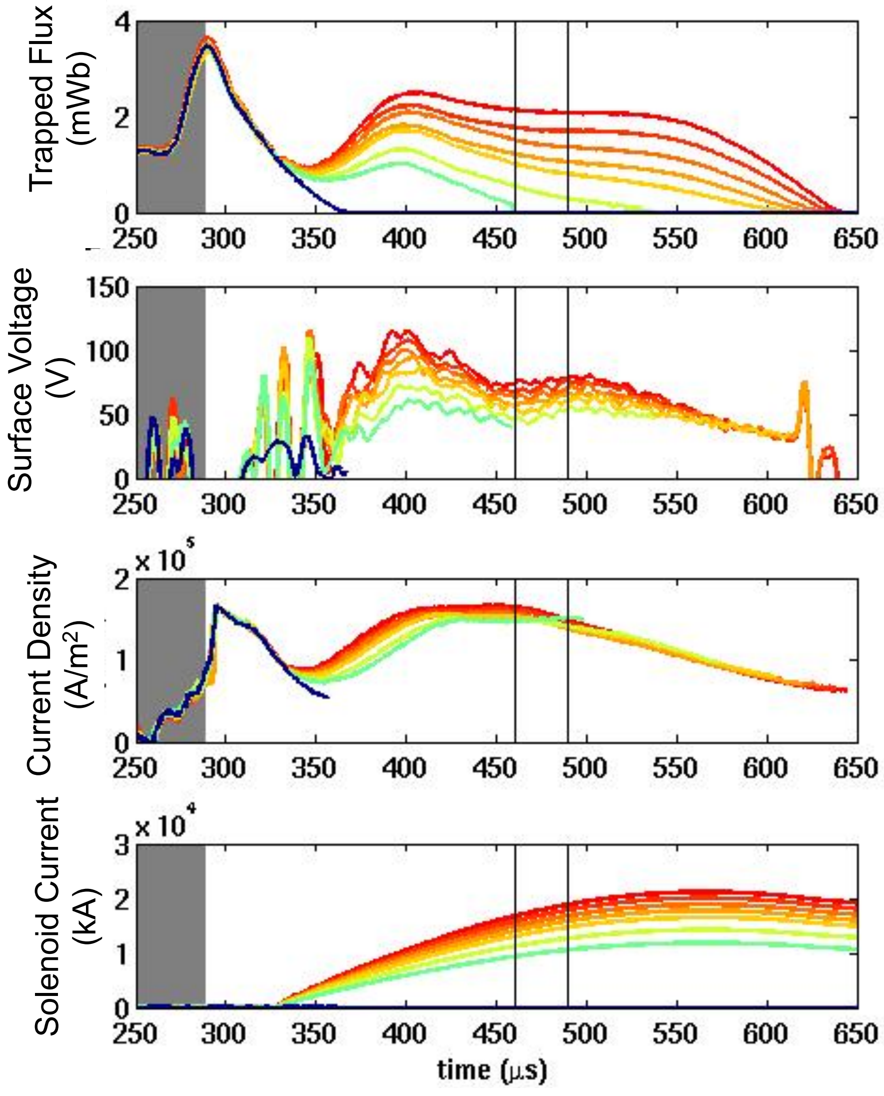
CT Sustainment Campaign on MRX

- 68 turn Ohmic solenoid, Inconel liner
- Three capacitor banks for 4 coils (TF, PF, SF, Ohmic)

New 2D Probe Array

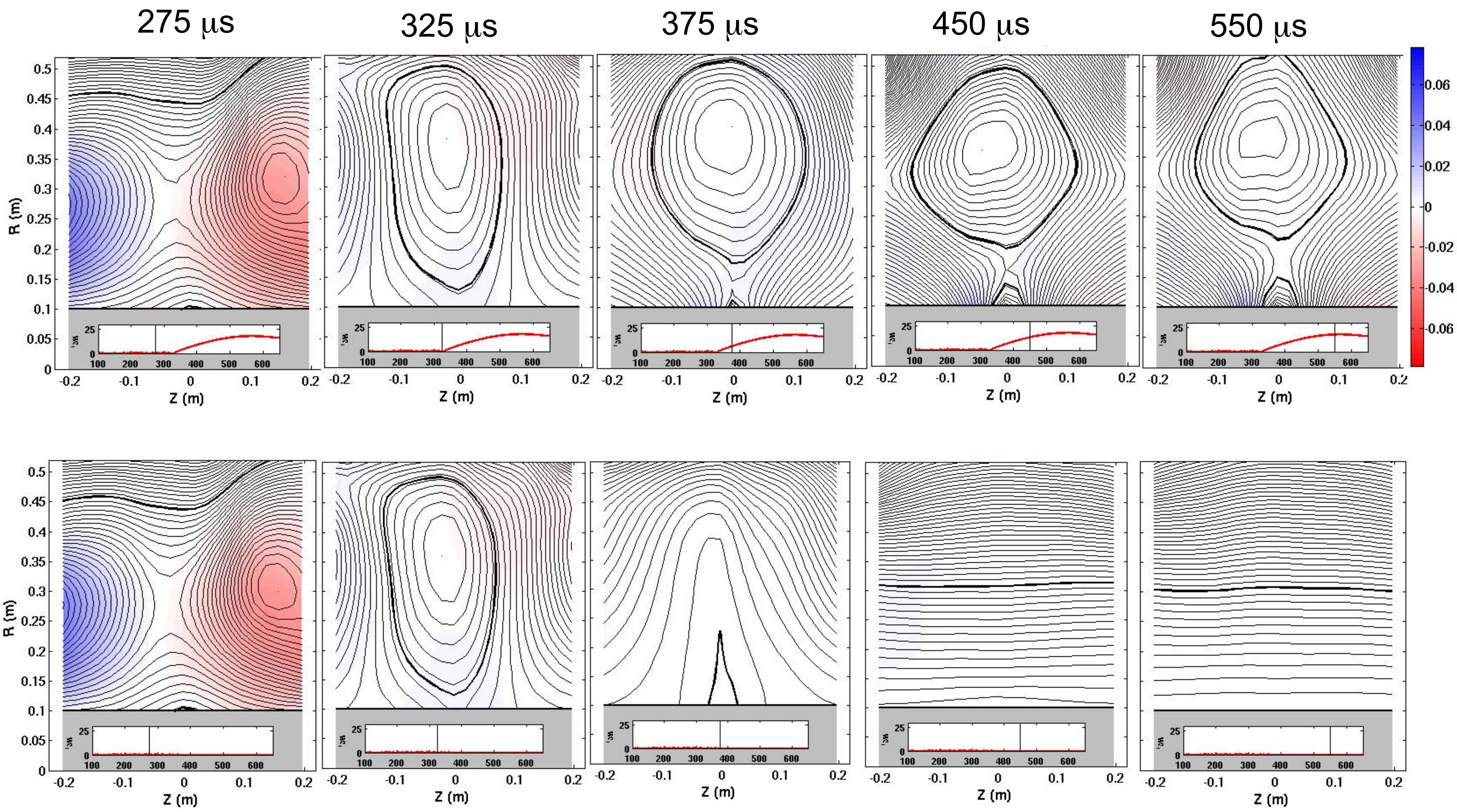


Inductive Drive Generates More Flux, Longer Sustainment



OH Voltages
5kV-9kV
Input Powers:
300-800kW

Ohmic Sustainment for ~300μs Demonstrated



Summary Notes

1) Compact toroid plasma concept to achieve a **small, simple**, **high efficiency, and economical** reactor core.

- Simple geometry
- High power density
- High beta (FRC has highest equilibrium beta)
- Can lead to advanced fuel reactor (P-B^{11}, D-He^{3})

2) Major challenges remain:

- Obtain good confinement of plasma
- **Control of magnetic self-organization**

3) To understand magnetic reconnection is a key

4) TAE is in the forefront to solve these major issues
=> M. Binderbauer's talk