Studies of Particle Heating and Acceleration in the Reconnection Layer

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Mini-Workshop on Magnetic Reconnection
October 25-26, 2012

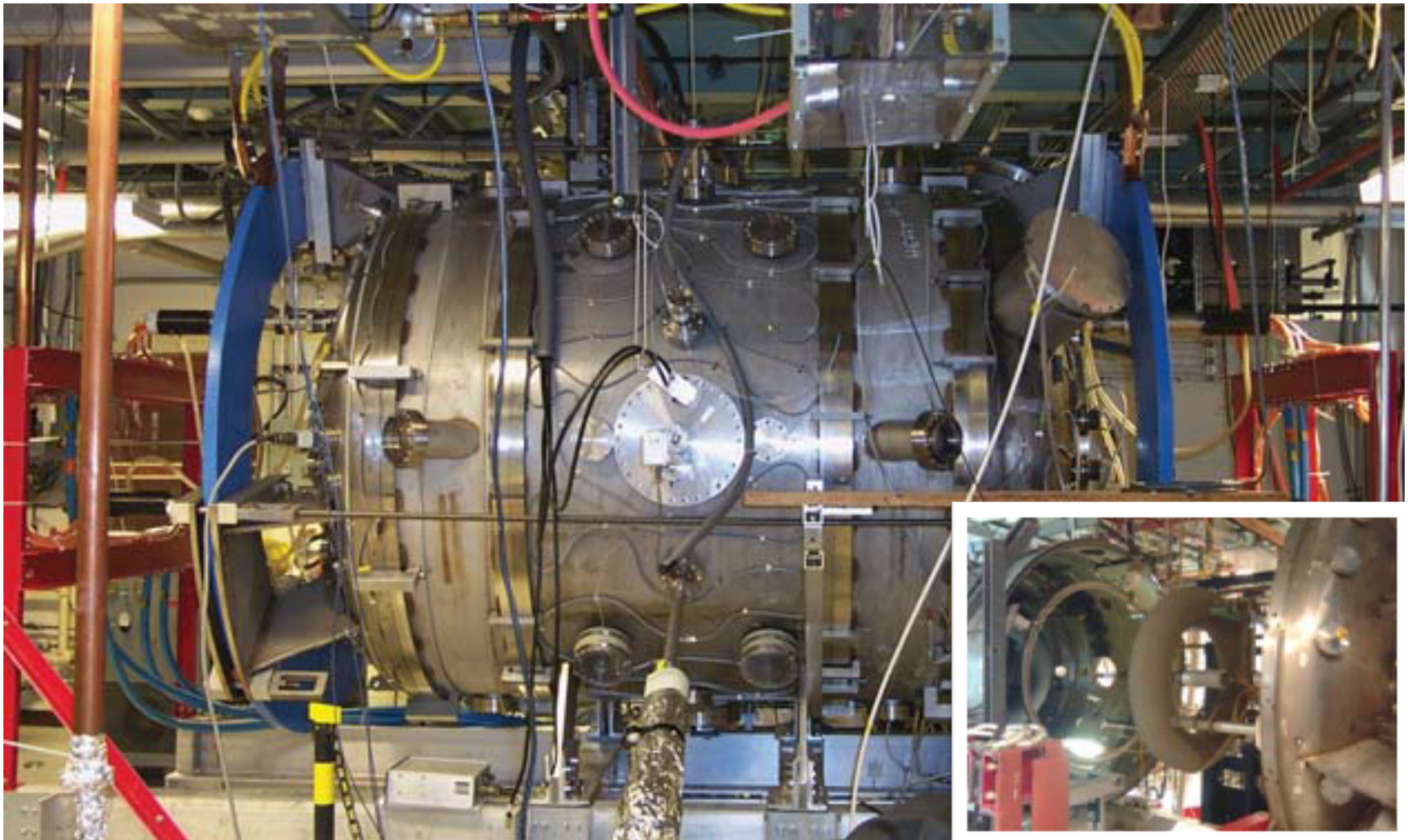
Outline

- Motivation
- Introduction to Experimental Regime
- Diagnostics
- In-plane Potential Profile and Ion Acceleration
- Analysis on Potential Well
- Ion Temperature Profile
- Electron Heating

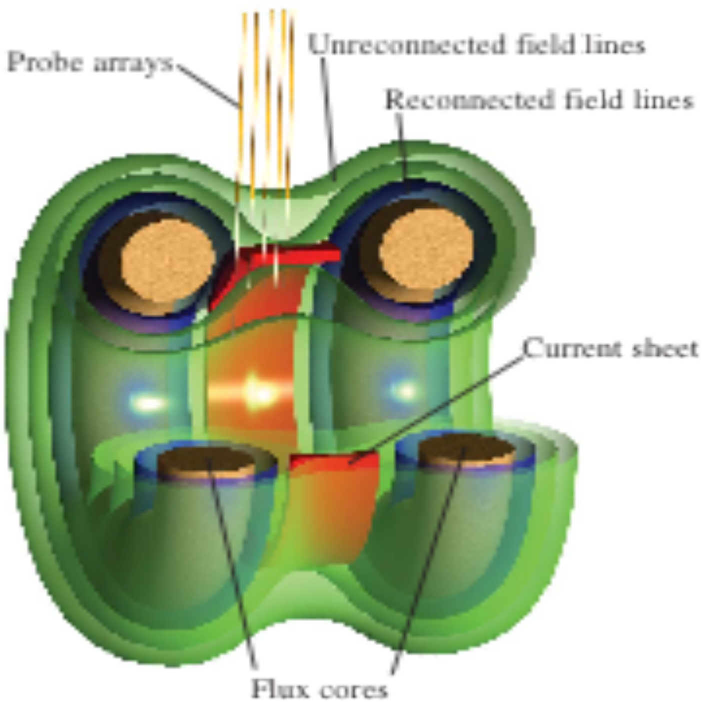
Motivation

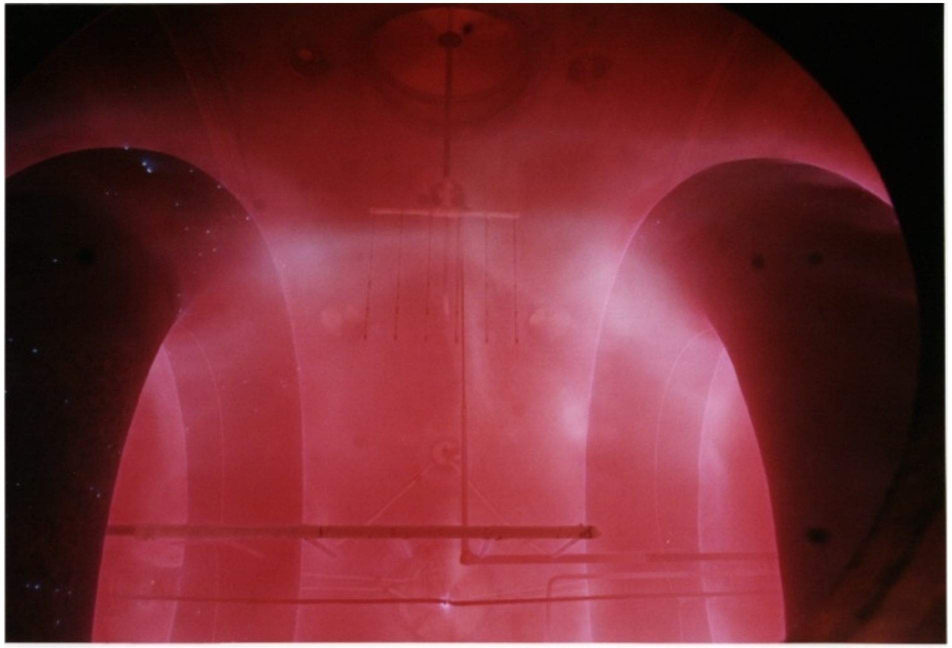
- Magnetic reconnection is known for effective c onversion of magnetic energy into particle ener gy.
- Investigating mechanisms of this energy conve rsion in MRX will improve understanding of magnetic reconnection.

Magnetic Reconnection Experiment



How to Make the MRX plasma

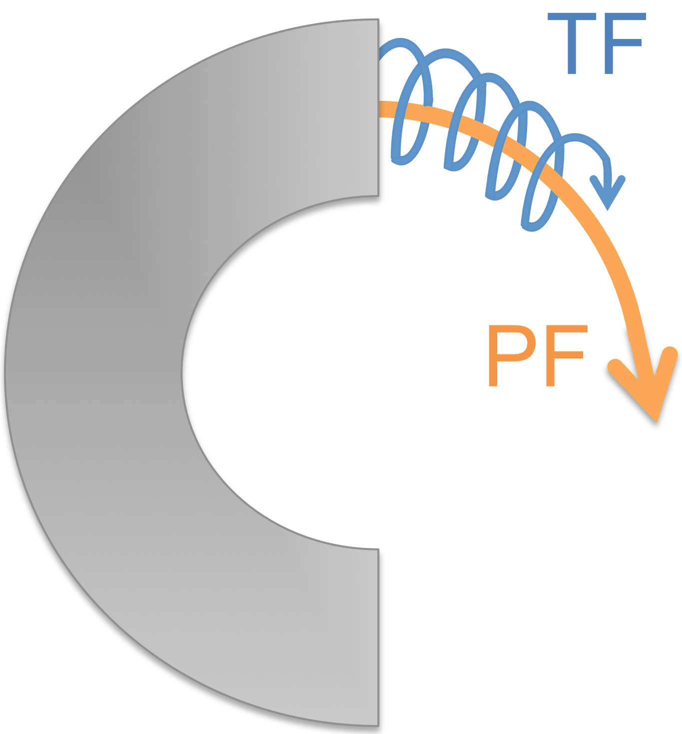




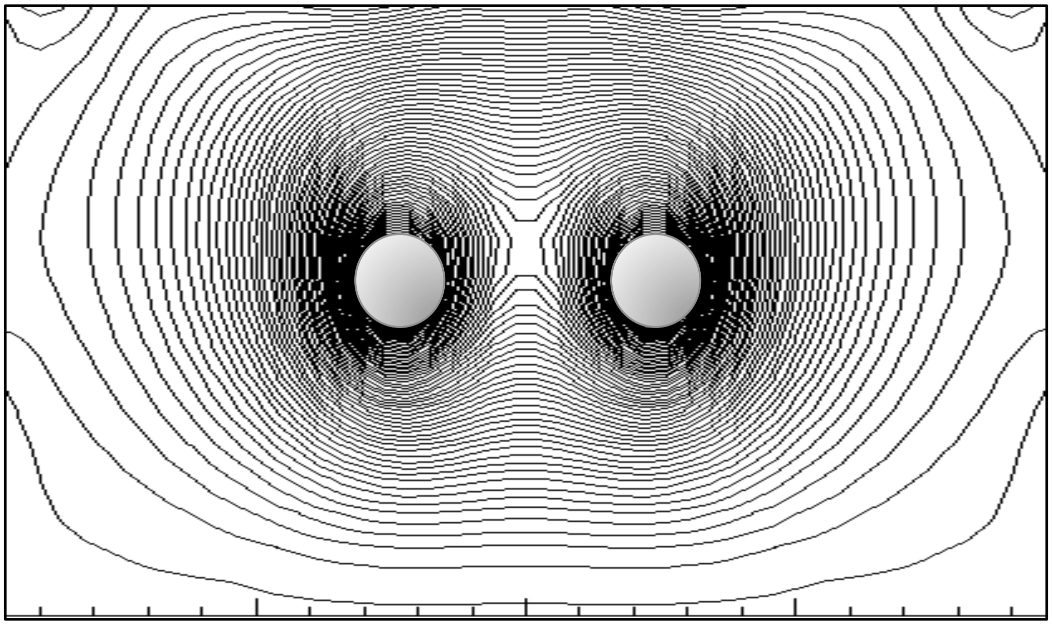
1) Gas is injected into the vacuum vessel.
2) Currents within the “flux cores” ionize plasma and drive reconnection
3) A current sheet develops at the midplane of the device.
4) Probes measure magnetic field, temperature, and density.

Flux Core

Anatomy of a flux core:

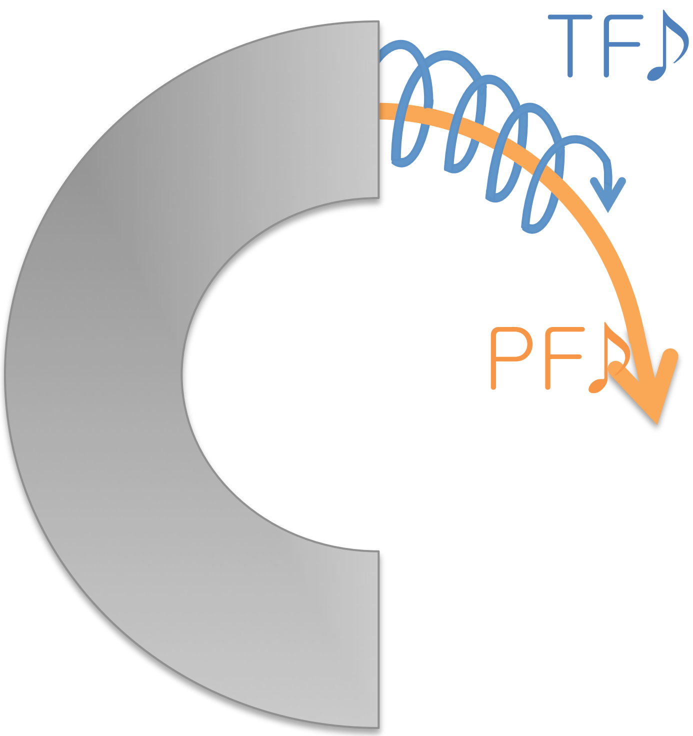


PF produces magnetic field:

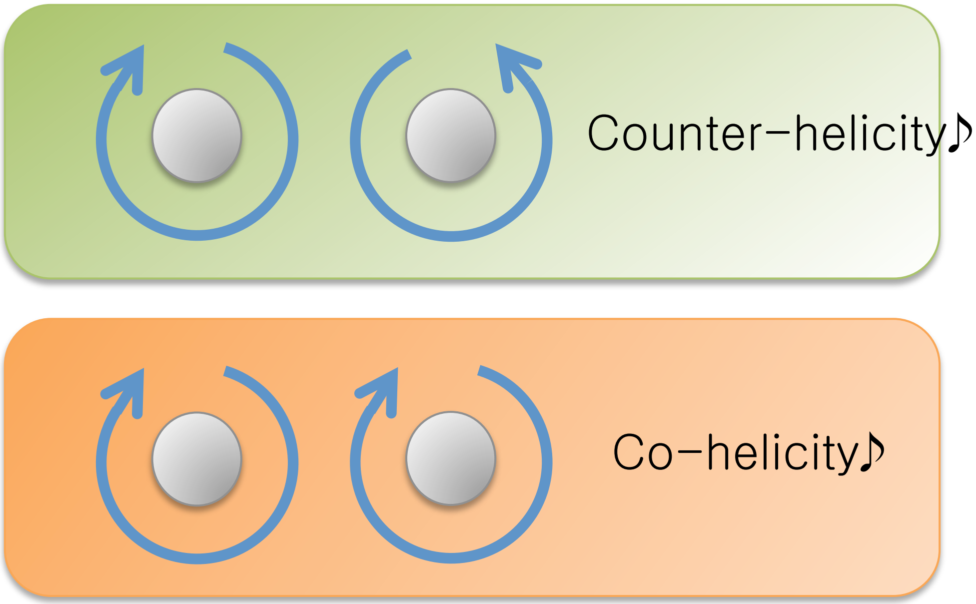


Flux Core (Cont'd)

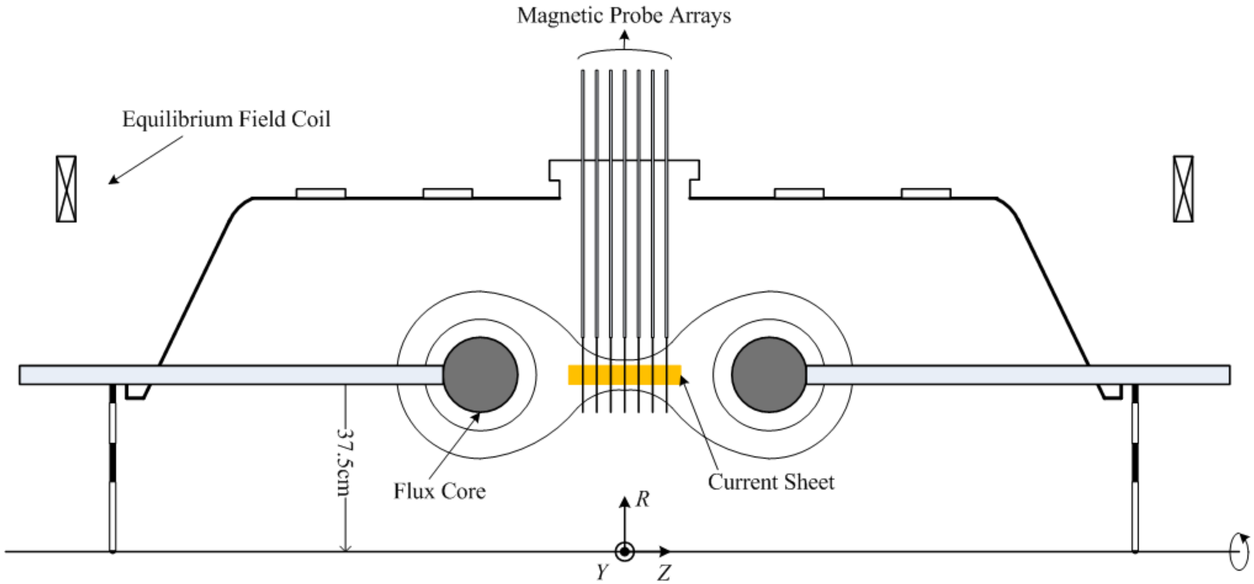
Anatomy of a flux core:

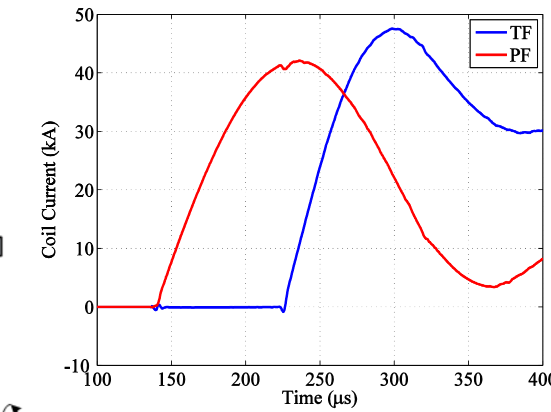


TF produces electric field:
- -creates plasma (good)
- -drives a toroidal magnetic field (bad)



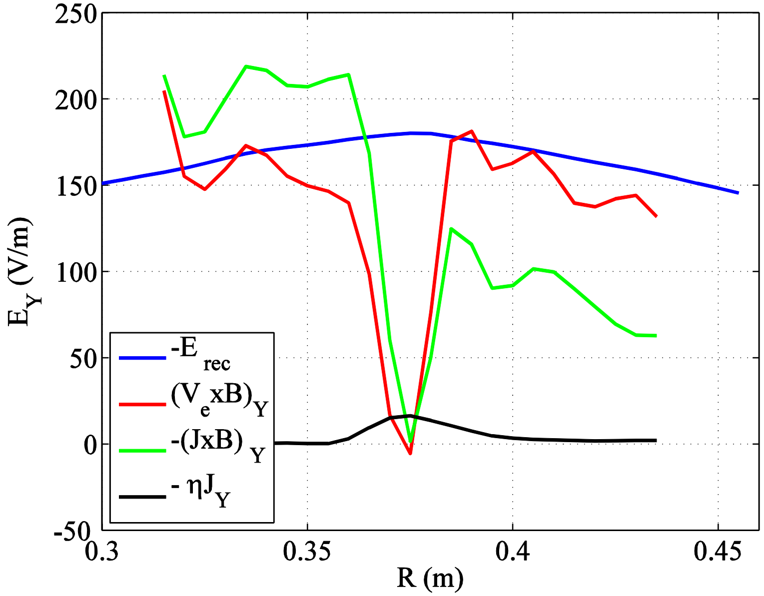
Experimental Setup

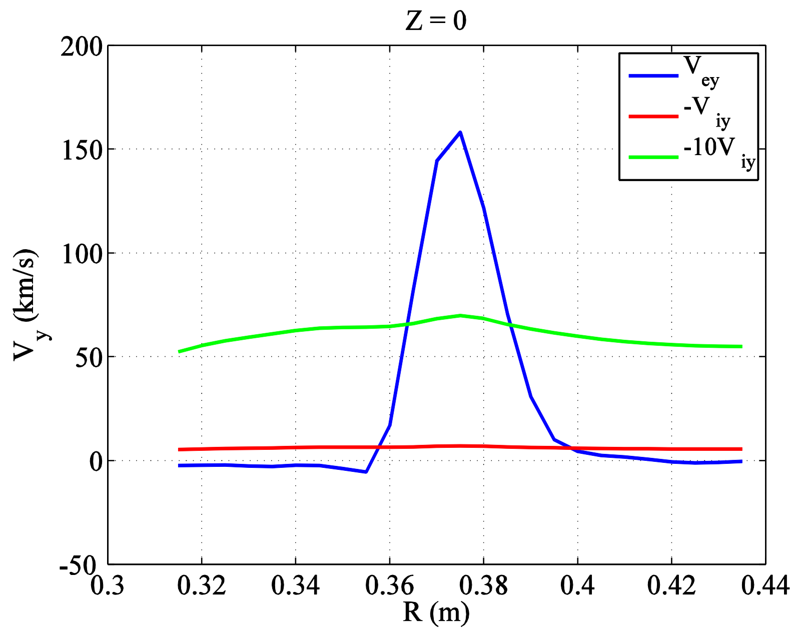




- Helium discharge (4.5 mT → $n_n < 1.4\times10^{14}/cm^3$).
- n_e: $1\text{-}4\times10^{13}/cm^3$ (upstream), $5\text{-}10\times10^{13}/cm^3$ (downstream) .
- T_e: 5-12eV, T_i: 5-14eV.
- Ion inertial length: ~9cm.
- $\lambda_{mpf,e}$: 5-8 cm, δ_{BZ} : ~2cm.
- V_A : ~40km/s.

Collisionless Regime



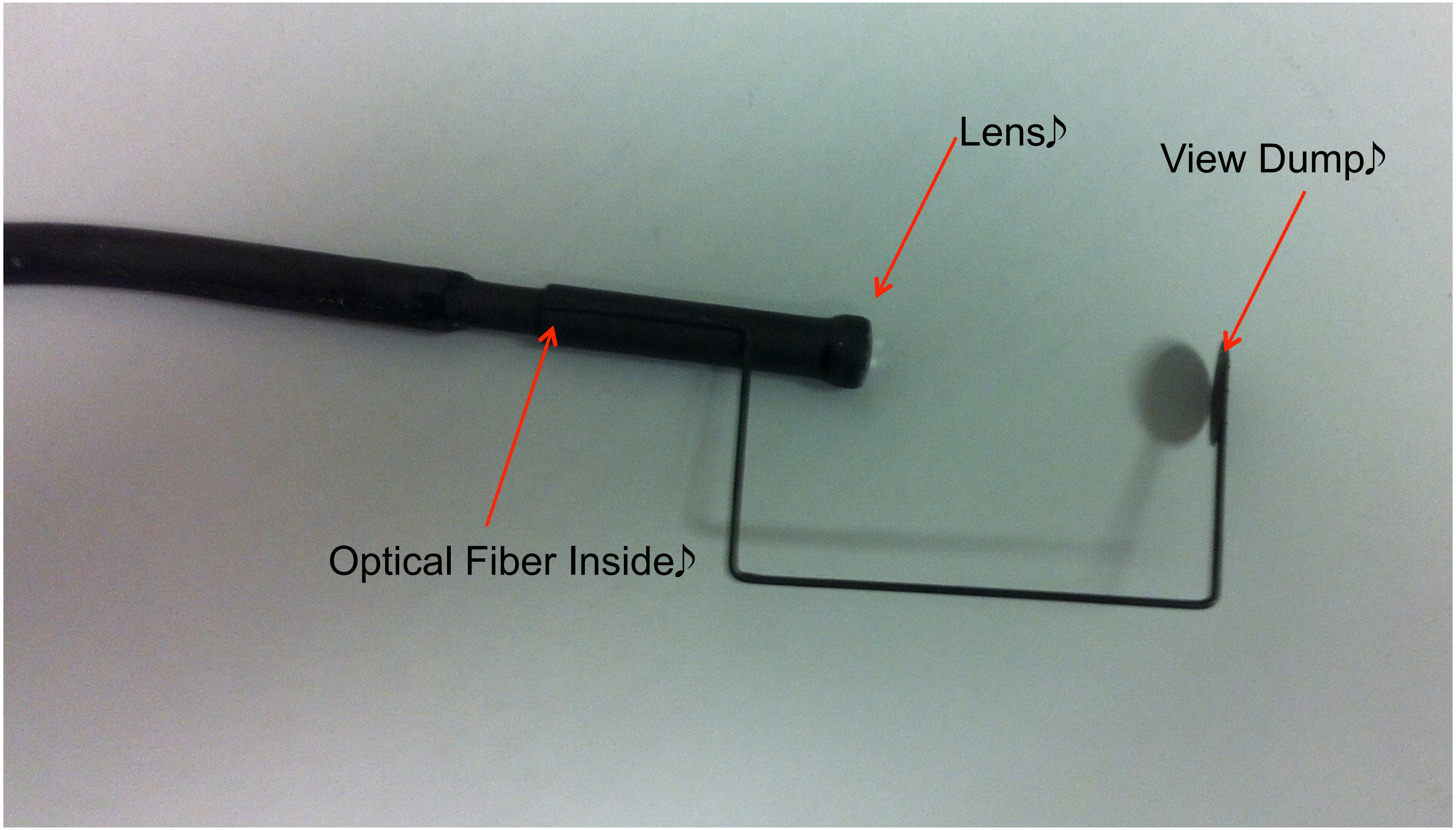


- The resistivity term only accounts for 10% of the reco nnection electric field.
- Outside of the electron diffusion region, $(V_e \times B)$ term balances the reconnection electric field.

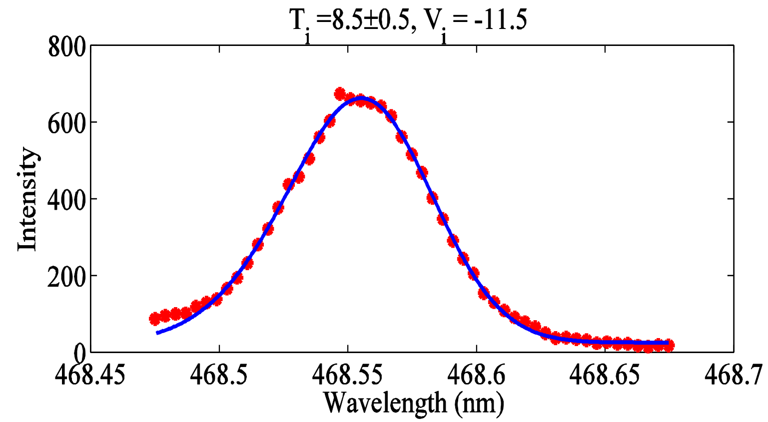
Diagnostics

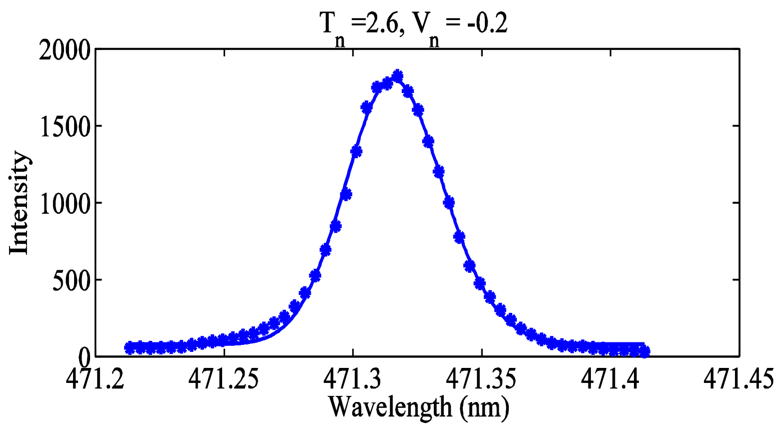
- Magnetic probes
  - 7 probes placed every 3cm along Z, 6mm maximum radial resolution.
- Langmuir probes.
- Mach probes.
  - Calibrated by spectroscopic data.
- Floating potential probe array.
  - 17 radial measurement points, 7mm maximum radial resolution.
- High frequency fluctuation probes.
  - Fluctuations up to ~10MHz.
- Ion Dynamics Spectroscopy Probe (IDSP).
  - 3 different types.

Diagnostics - IDSP



Brief Information on IDSP



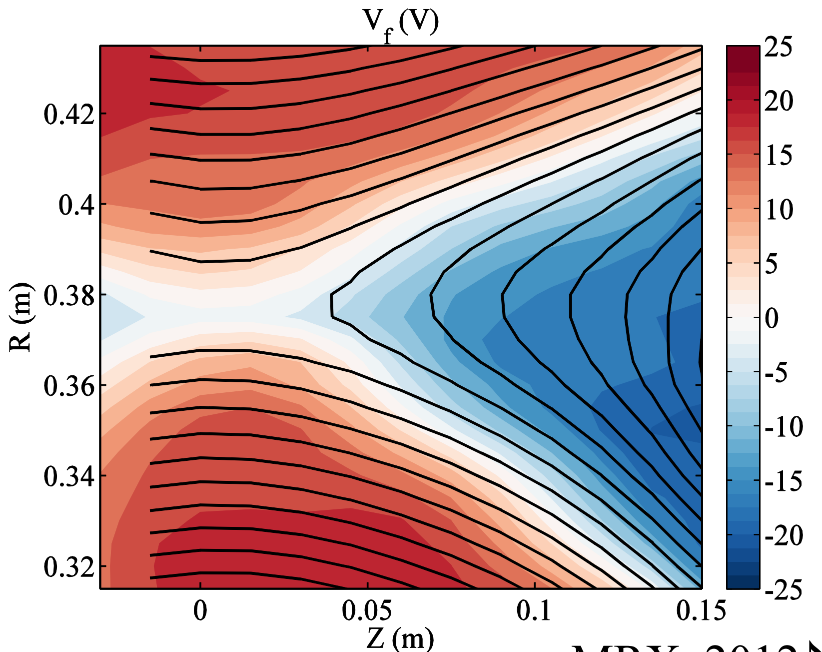


- ICCD camera.
  - Two images per discharge.
  - 5.8 μs gate time.
- Spatial resolution: 3-4 cm.
- He II line (~4685.7Å) and He I line (~4713.4Å) are u sed.
- Both lines have fine struct ure that should be consider ed.

R-Z Scan

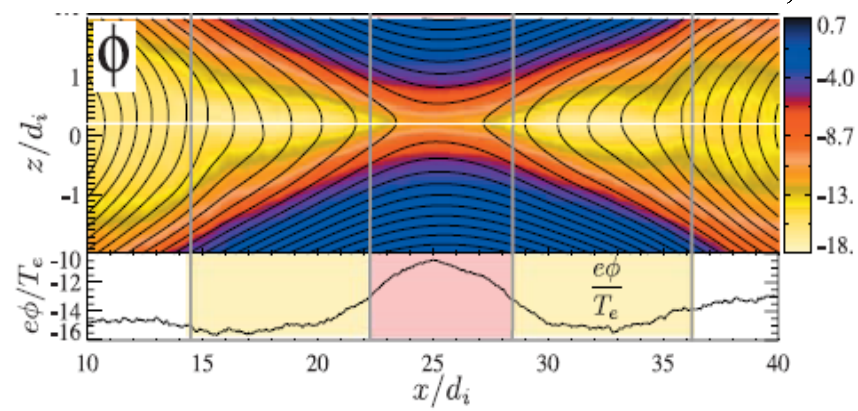
- 6-7 different axial (Z) locations for each probe.
- Langmuir probes, Mach probes – 1cm radial sc an.
- IDSP – 2cm radial scan.
- Over 4200 total discharges.

In-plane Potential Profile

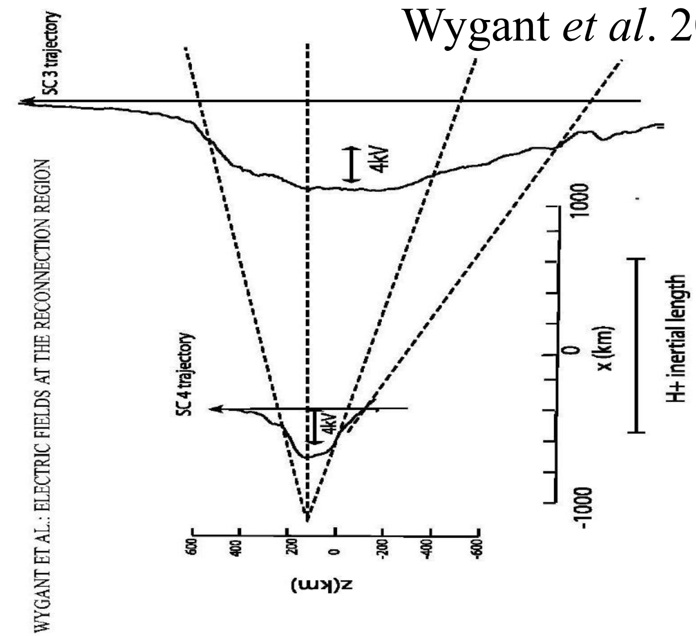


MRX, 2012♪

Karimabadi *et al*, 2007

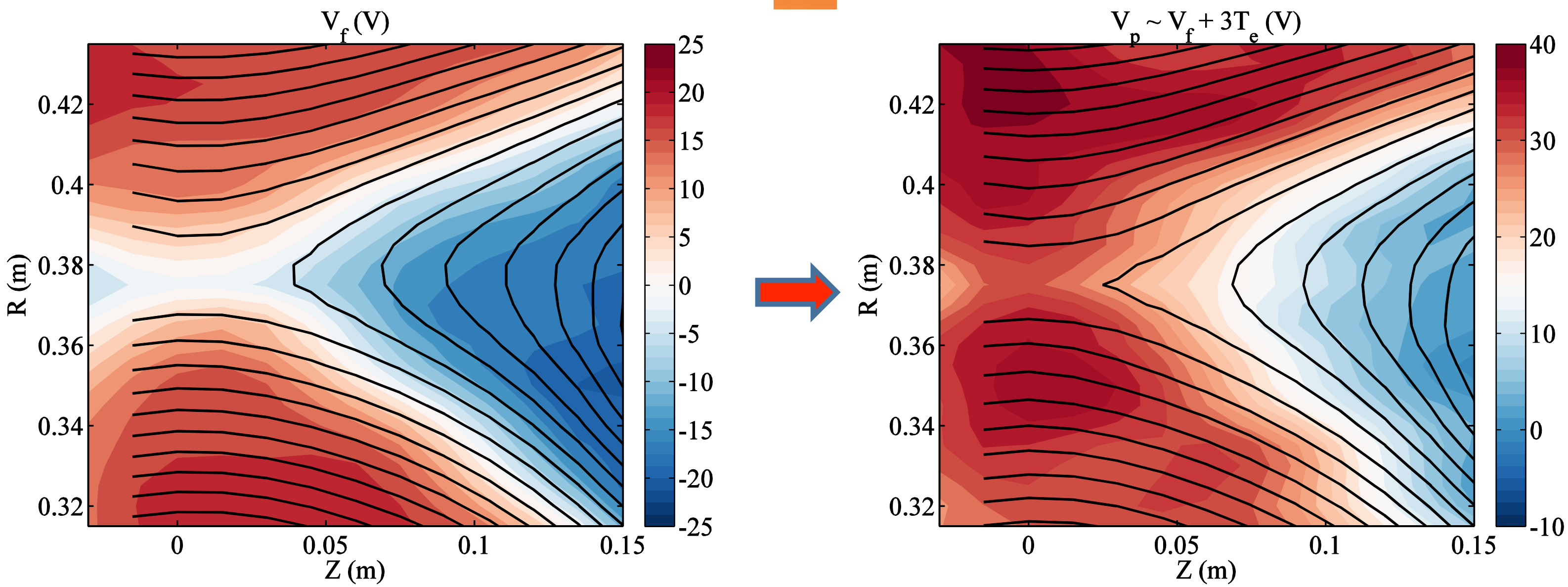


Wygant *et al*. 2005



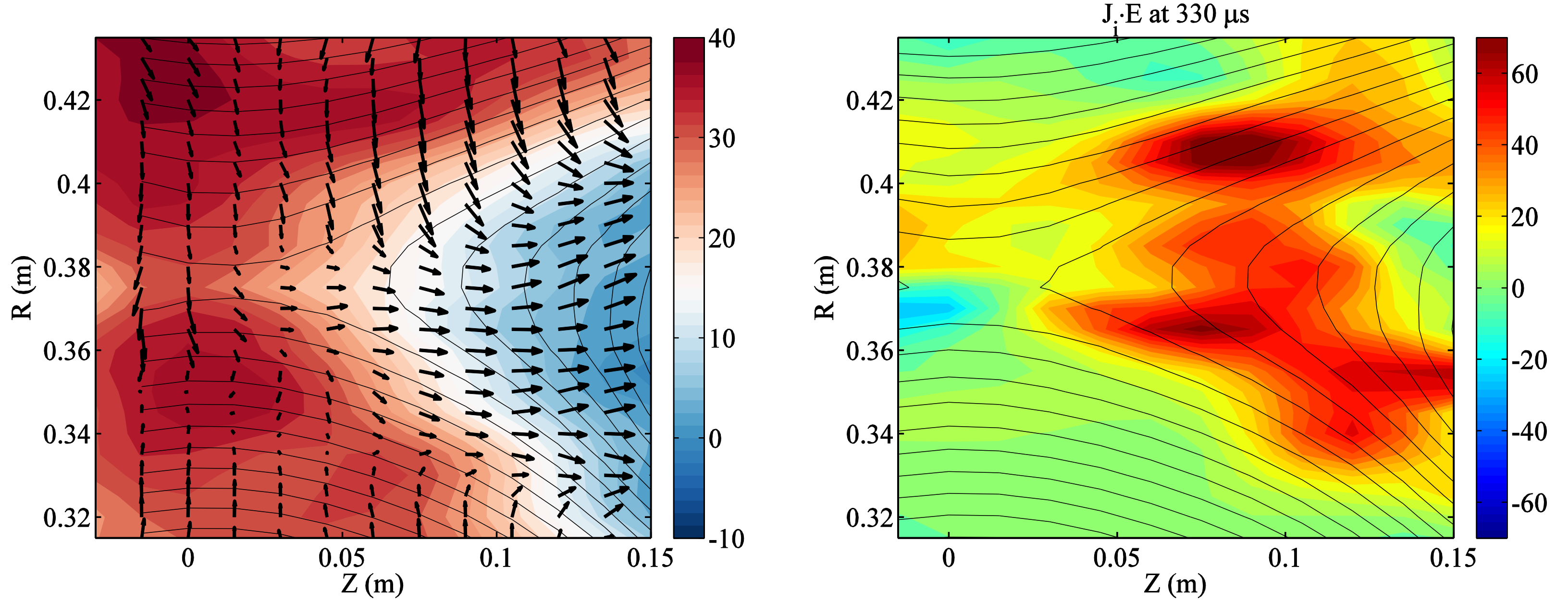
- A large bipolar electrostatic field (BEF) exists in the reconnection layer due to tw o-fluid effects.
- It can accelerate ions generating a pair of counter-streaming ion beams in the diffu sion layer.

Potential Well



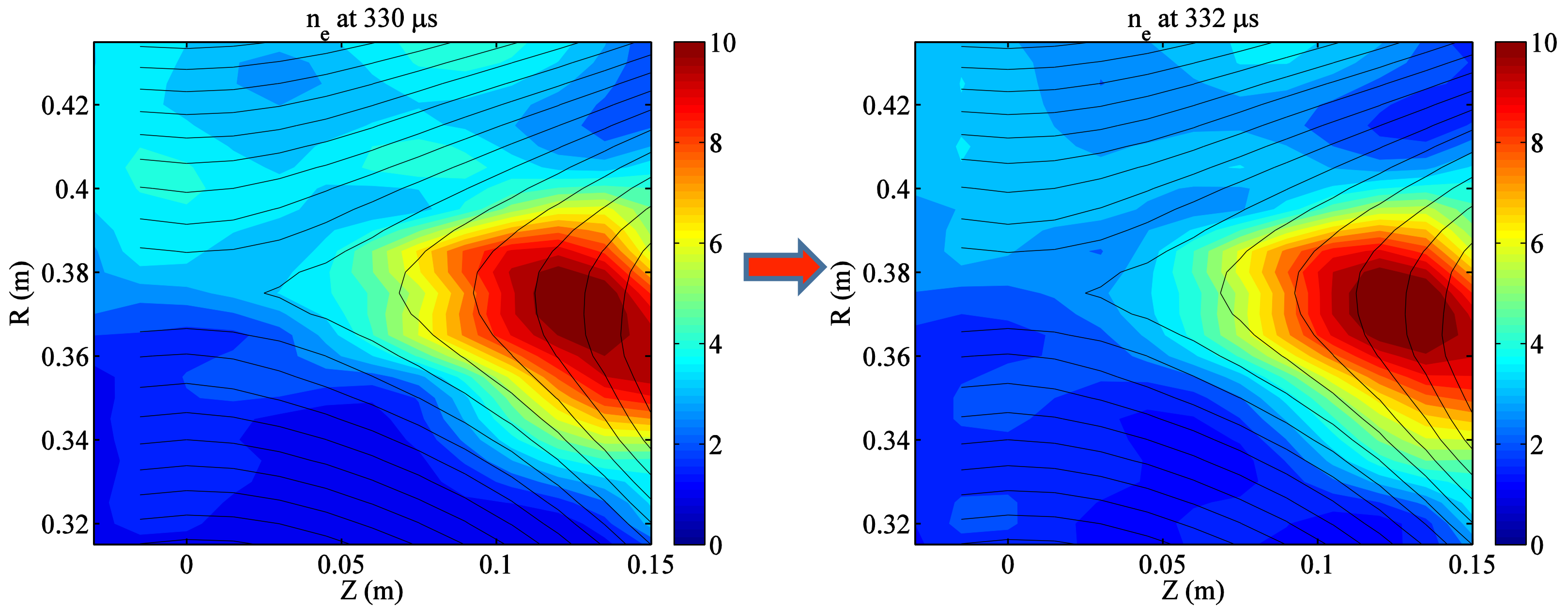
- Magnitude of the potential well is determined by electron dynamics in the e lectron diffusion region.
  - This potential drop is conveyed along the magnetic field.
  - Most of the potential drop occurs near separatrices.
    - It becomes wider downstream.
- It becomes deeper downstream.
  - Electrons are turned toward the outflow direction.
  - The Lorentz force creates further charge separation.

Ion Acceleration



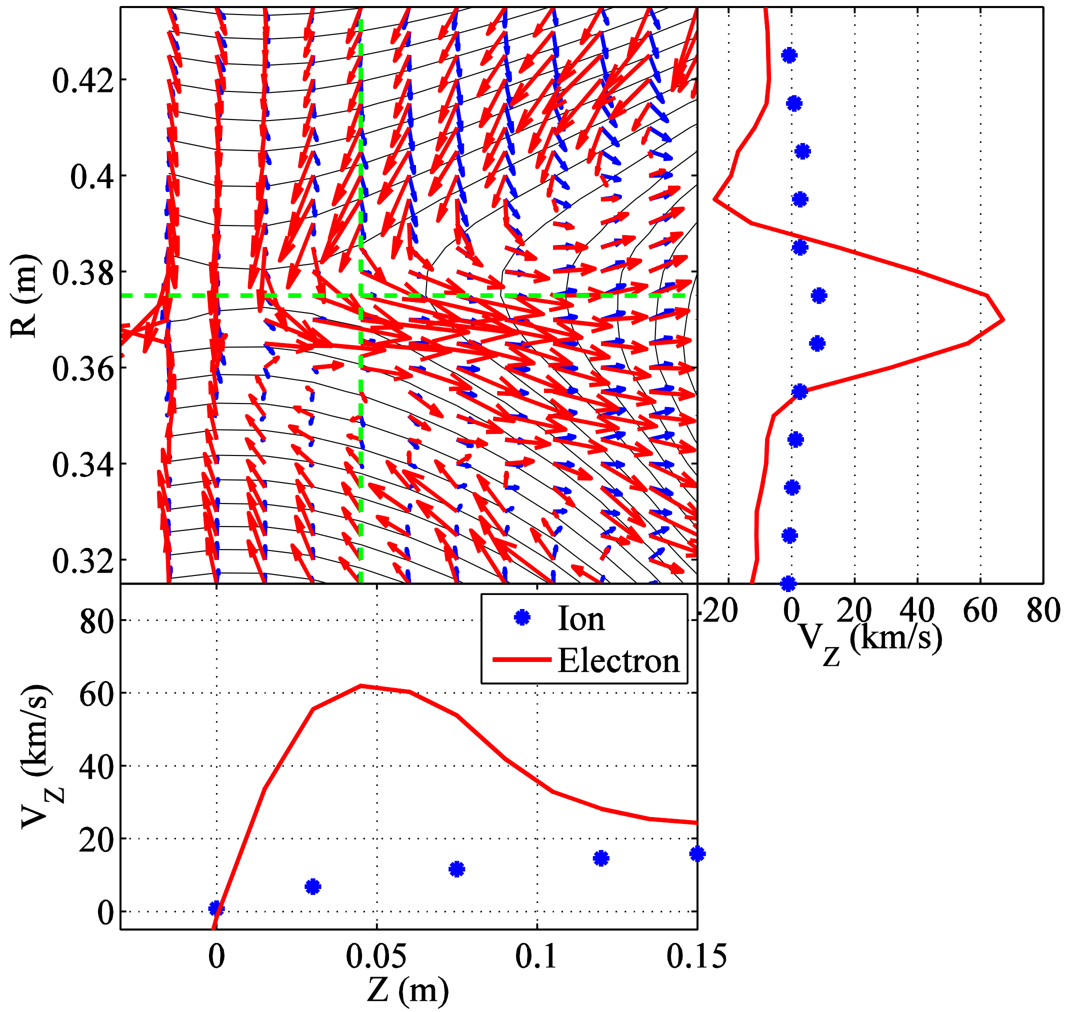
- Clear ion acceleration by the in-plane electric field.
- Asymmetry in the ion inflow is caused by asymmetry in the upstream density.

Asymmetric Upstream Density



- The outboard side (larger R) has higher density.
- During the quasi-steady period, this asymmetry is re duced.

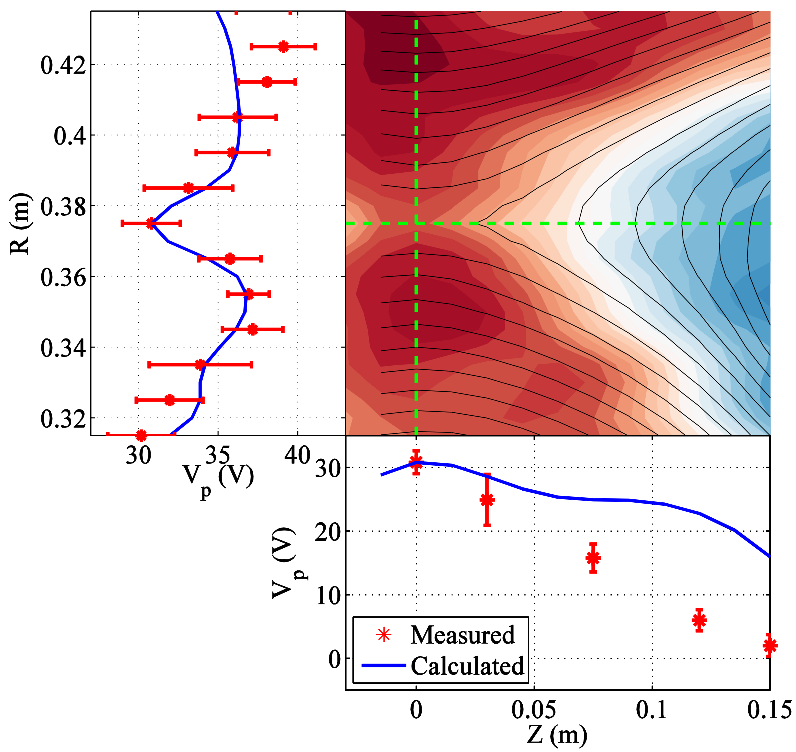
Comparison to Electron Flow



Why not Alfvénic Outflow?

- The maximum ion outflow is only 16 km/s, which is $0.4V_A$.
- The potential drop across the boundary layer is more than 30V such that it can accelerate ions up to V_A.
- High downstream pressure and drag by neutrals are the two main causes of this sub-Alfvénic ion outflow.
  - Ion flow energy increase: 5eV
  - Frictional drag by neutrals: 12eV
  - High downstream pressure: 10~12eV.

Electron Dynamics Controls Potential

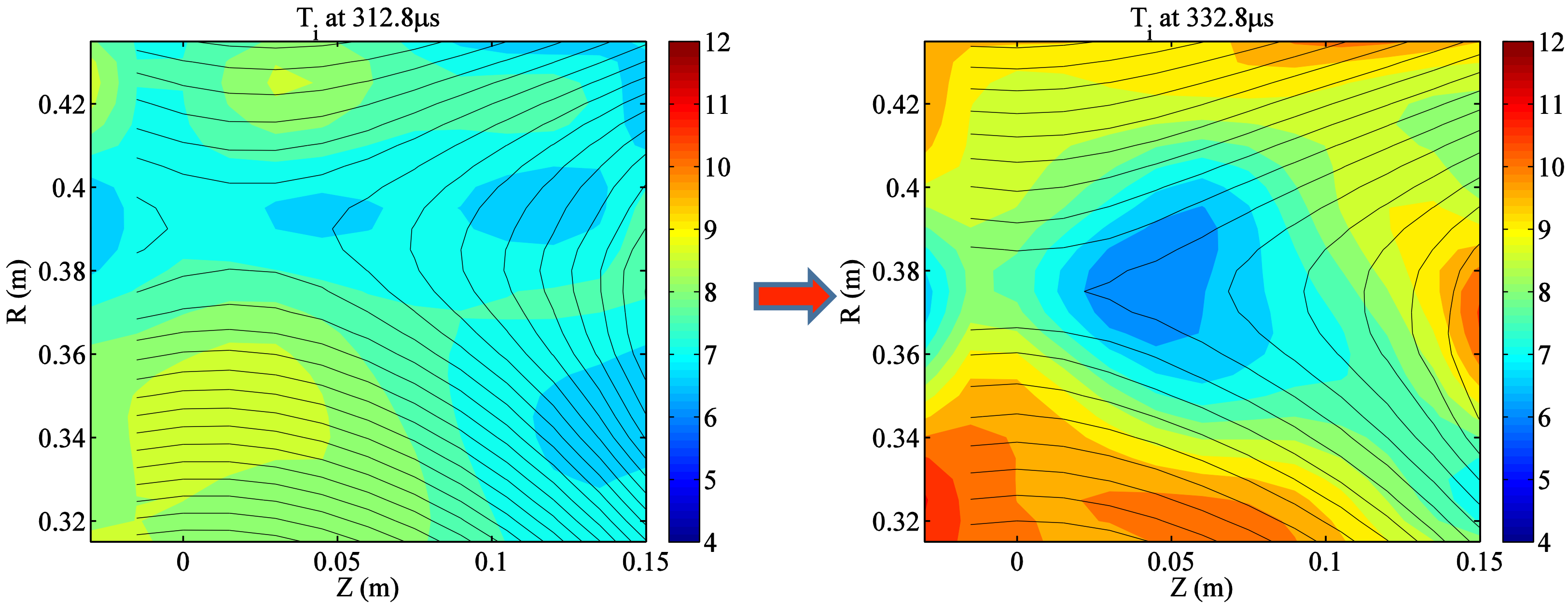


- At Z = 0, assuming an isotropic pr essure tensor,
  $E_R \sim -(V_{ey} - (V_e^*)_y)B_Z$,
  where $(V_e^*)_y \equiv -(1/en_eB_Z)\partial p_e/\partial R$.
- At R=37.5 (current sheet location) ,
  $E_Z \sim (V_{ey} - (V_e^{**})_y)B_R$,
  where $(V_e^{**})_y \equiv -(1/en_eB_R)\partial p_e/\partial Z$.
- By integrating this electric field, w e can independently check the pot ential profile.
  - The radial profile is consistent.
  - The axial profile has larger me asured values.

Magnitude of Potential Well

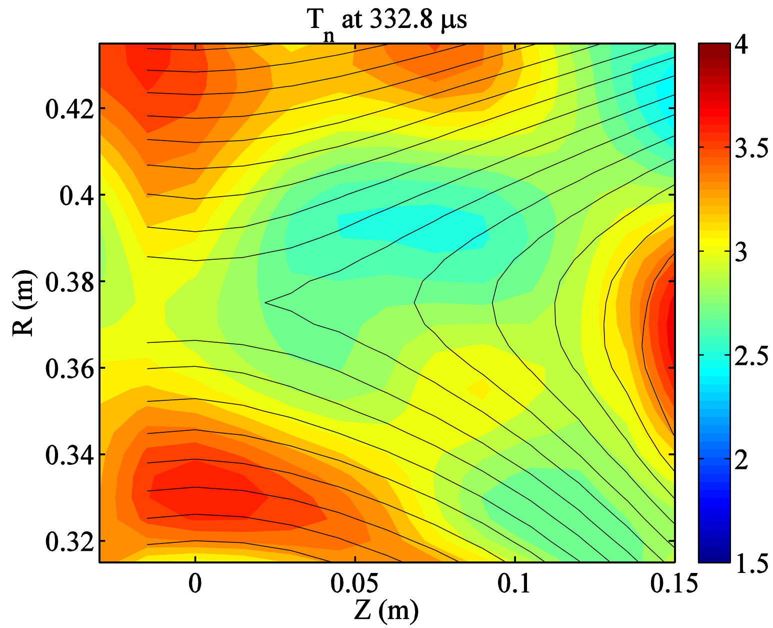
- If there is no contribution from the diamagnetic drift, the maxi mum potential drop across the layer at Z= 0 is $V_{max} \sim p_m/en_e$.= $T_e(eV)/\beta_e$.
  - Collisionless limit.
  - In the collisional limit as in the SP model, there is no potential well.
- If there is a peak in the electron pressure at the center of the la yer, the magnitude decreases as $V_{well} \sim \Delta(p_m + p_e)/en_e$.
  - This is the case for MRX.
  - Indicates the potential well is related to ion pressure increase at the cent er : $\Delta p_i \sim -en_e V_{well}$.
  - Energy conversion process depends on β_e.

Ion Temperature Profile



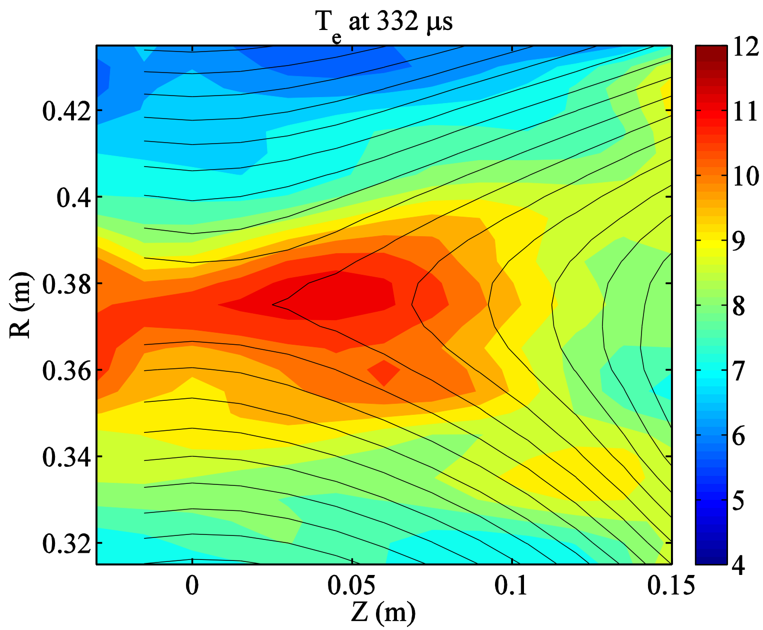
- Overall ion heating during the pull reconnection period.
- However, no strong ion heating is observed at the center.
  - Problem in measurement?
  - Asymmetric upstream density?
- Ions are cooled where they are accelerated.

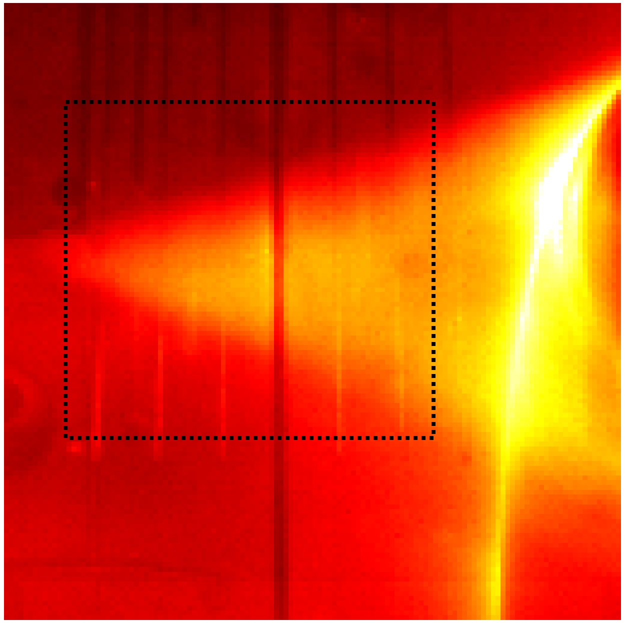
Neutral Temperature



- The neutral temperature profile is qualitatively similar to that of ions.
  - Indicates ion energy loss to neutrals.
  - Neutral drift velocity is negligible – not strongly coupled.
- Ion-neutral collision (charge exchange) frequency is ~20MHz
  .

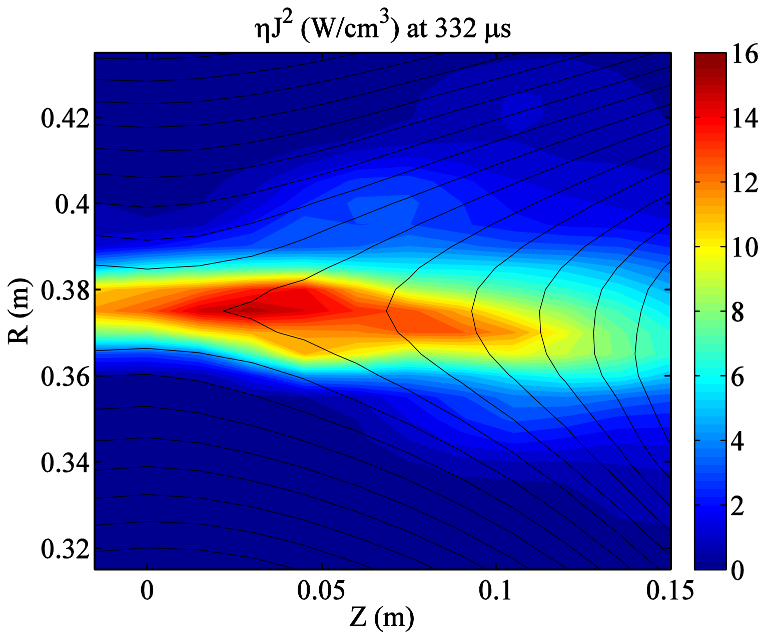
Electron Heating

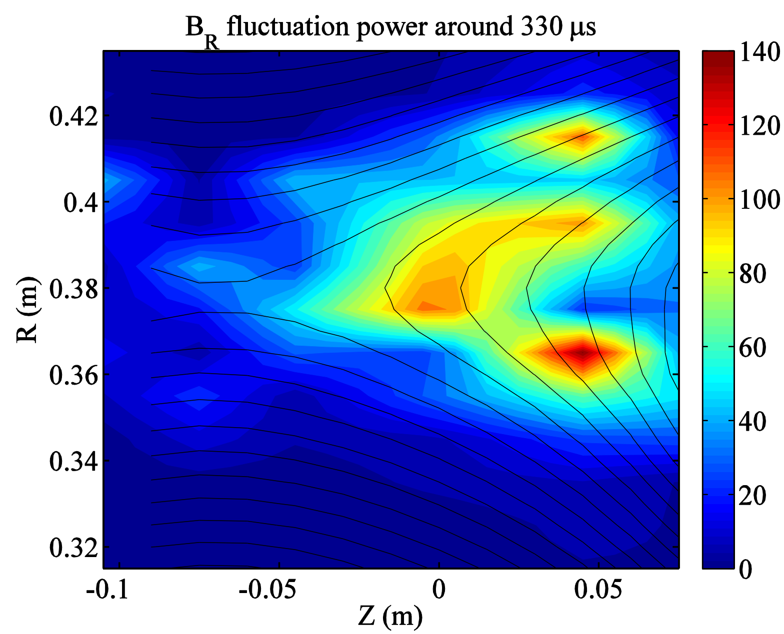




- The electron temperature profile agrees with fast camera ima ges.
  - Sharp increase across the boundary.
  - Brighter regions indicate higher electron temperature.
  - Inboard side has higher electron temperature.

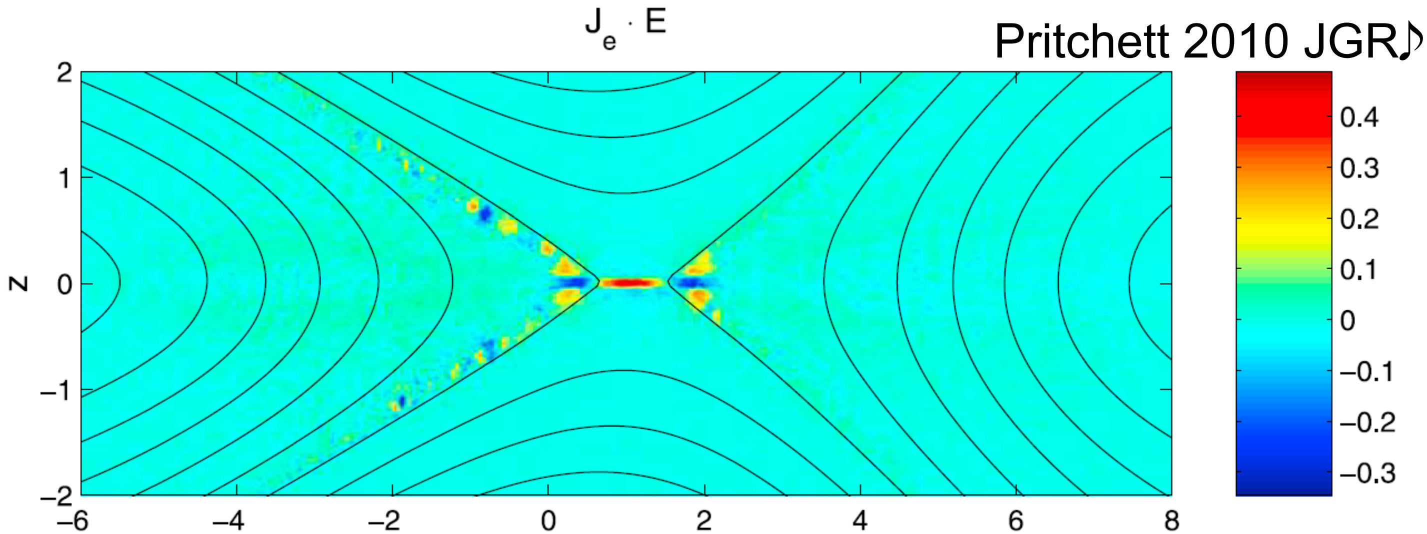
Ohmic Heating or Wave-particle Interaction?

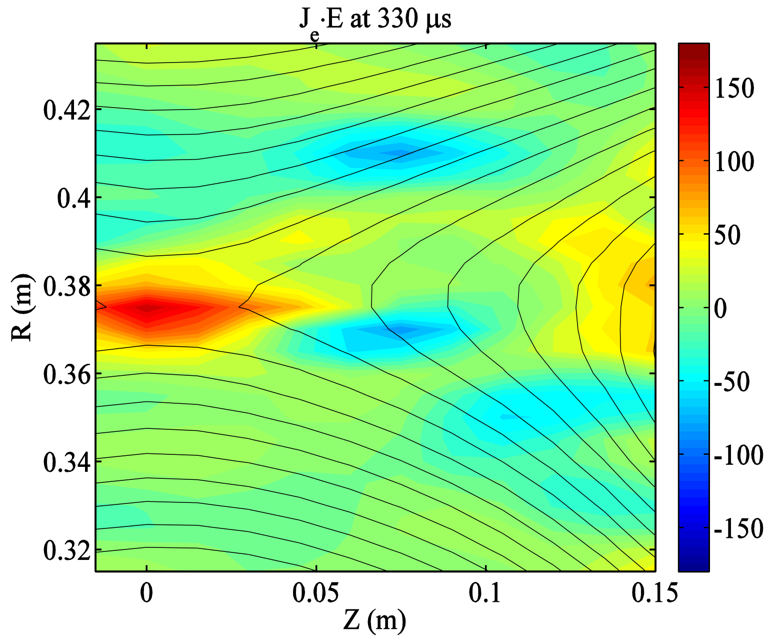




- Is Ohmic heating power enough to explain the observed elect ron heating?
  - More calculation will be conducted to estimate the contribution from Ohmic heating.
- Possible heating by wave-particle interactions indicated by t he high-frequency fluctuation measurements.

Electron Energy Gain





- Electron energy gain is locali zed around the X point. (Elec tron diffusion region.)
- This electron acceleration is t he driving force of the in-plan e potential and contributes io n acceleration.

Summary

- The in-plane potential profile is measured.
  - The radial potential well becomes wider and deeper downstream.
  - Ions are accelerated by the in-plane electric field.
  - The magnitude is related to the dip of the sum of magnetic and electric pressure $V_{well} \sim \Delta(p_m + p_e)/en_e$.
  - It indicates an increase in the ion pressure.
- Ion temperature increases during the pull reconnection period.
  - No ion heating around the X-point.
  - Ion temperature decreases where strong acceleration exists.
  - Neutral temperature profile shows there is some coupling between ions and neutrals by charge exchange collisions.
- Electron temperature sharply rises inside of the separatrix.
  - Ohmic heating – how much contribution?
  - Possible contribution from heating by high-frequency fluctuations.