Magnetic reconnection in the high-energy-density and relativistic regimes

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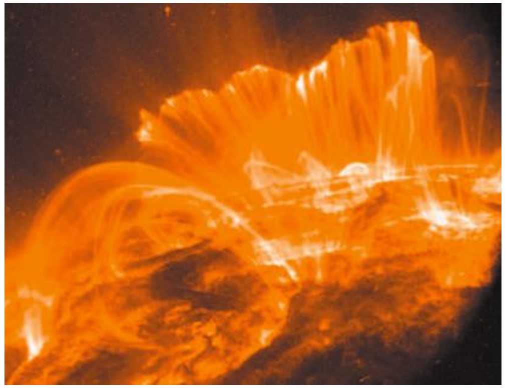
CAPT

Outline

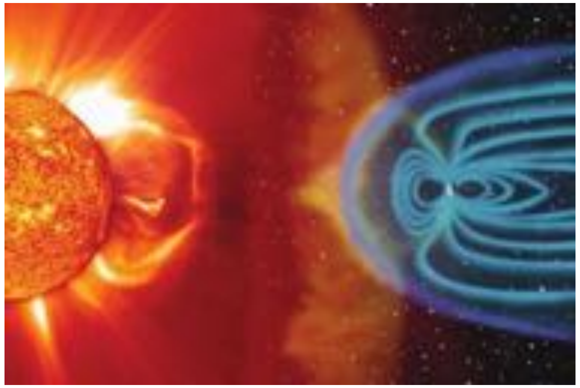
- Introduction
- Magnetic reconnection (MR) in the high-energy-density (strongly-driven, high-β) regime
- MR in the relativistic regime
- Summary

Magnetic reconnection (MR) is a fundamental process in astrophysics, spaces and laboratories

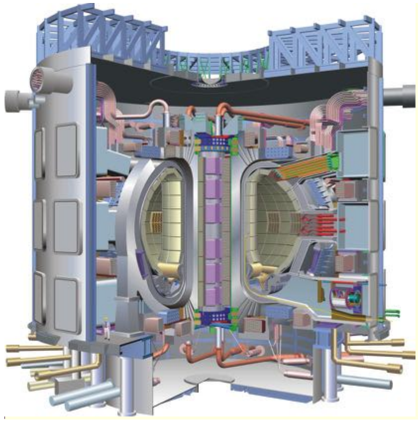
Solar flares



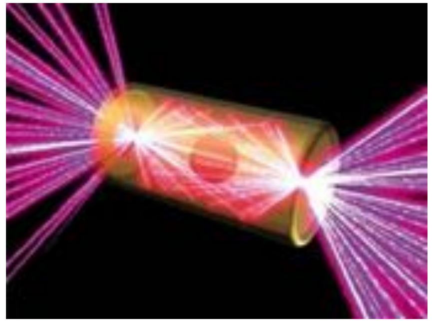
Earth Magnetosphere



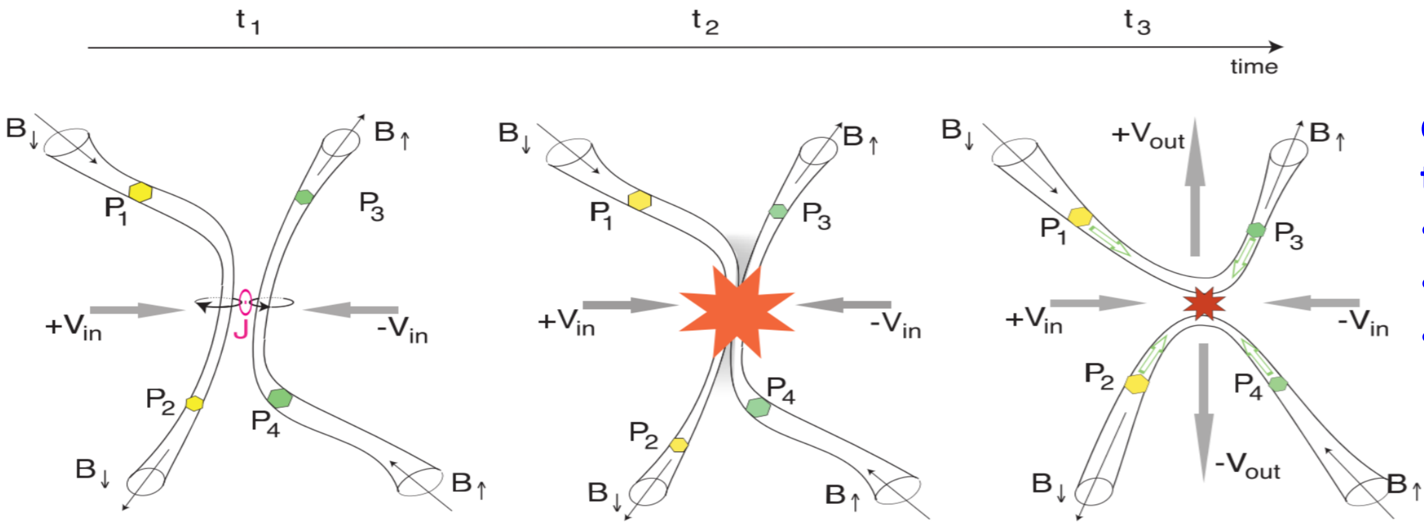
MCF （Tokamk）



ICF



Dramatic topology change



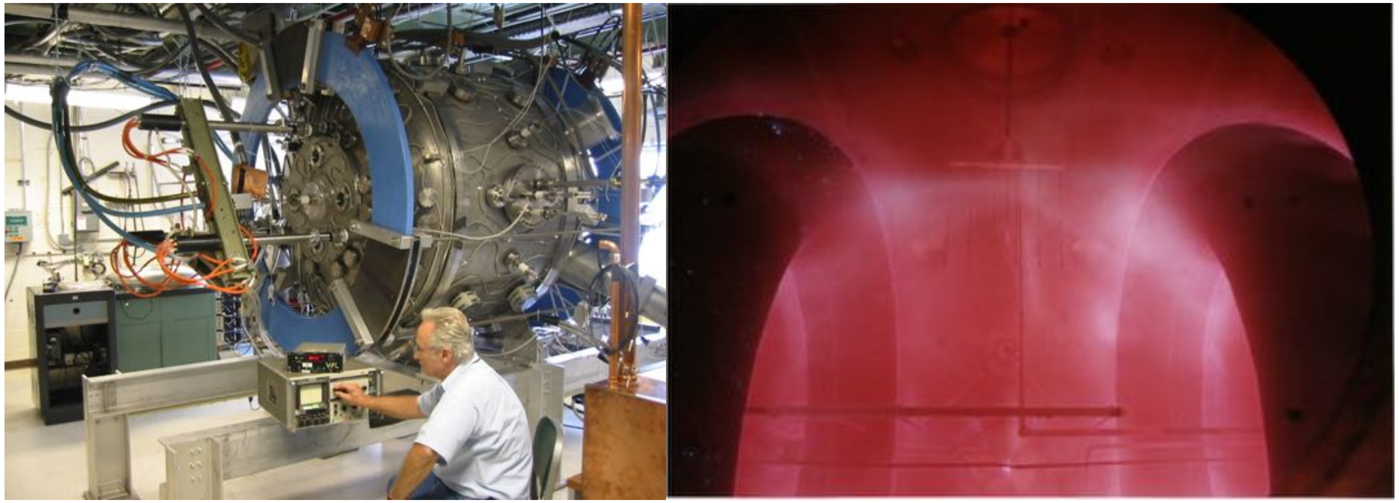
Non-relativistic: $\boldsymbol{E}' = \boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}, \quad \boldsymbol{B}' = \boldsymbol{B}$

Fast release of magnetic energy to plasma kinetic and thermal energy with:

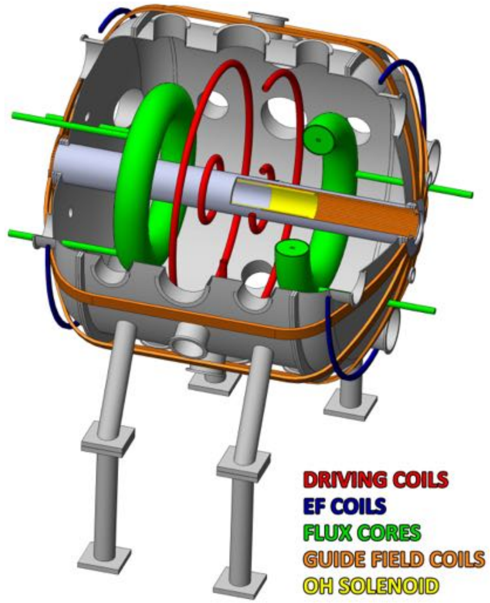
- **Heat of background**
- **Flows (driven)**
- **Jets (explosion)**

MR in tenuous, quasi-steady, cold plasmas has been widely studied

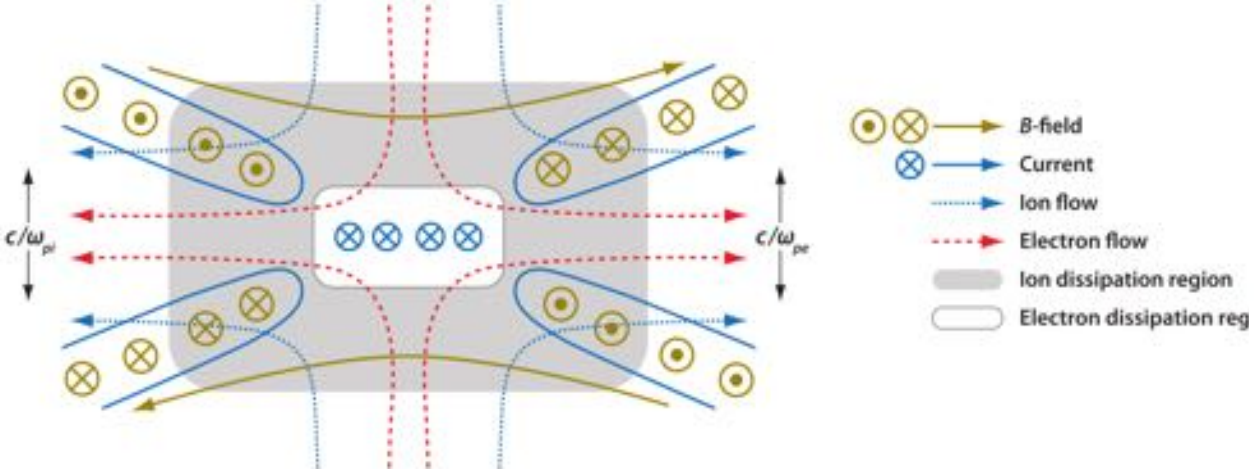
Magnetic Reconnection Experiment (MRX) at PPPL



FLARE at PPPL



Harris current sheet model



$$\beta = 2n_0T_{e0}/B_0^2 < 1$$

thermal pressure < magnetic pressure

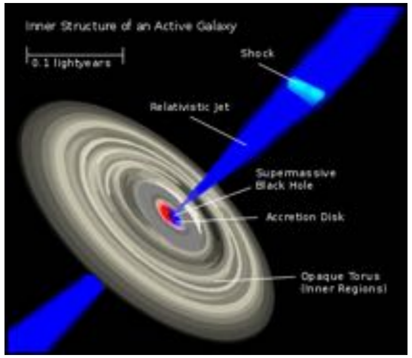
$$nm\frac{d\mathbf{v}_e}{dt} = -\nabla\cdot \mathrm{P}_e - ne(\mathbf{E} + \frac{\mathbf{v}_e\times\mathbf{B}}{c})$$

$$v_{rec}/V_A \sim 0.2$$

Hall effect induces fast MR

MR in the high-energy density (HED) and relativistic plasmas also widely exist in Astrophysics

MR at Active Galactic Nucleus
(heating of AGN, high-β)



MR at supernova explosion
(Supersonic magnetized flows collide, relativistic MR)

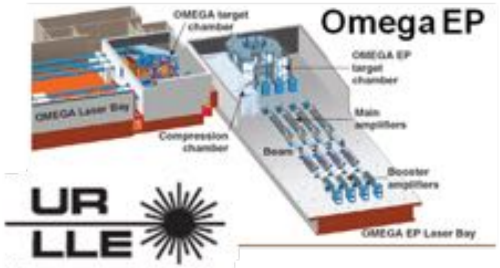
MR at Radio Pulsar
(Relativistic, Magnetic field >10^{12}G)

- Strongly driven: ram pressure > magnetic pressure
- High-β: $\beta = 2n_0T_{e0}/B^2 > 1$, thermal pressure > magnetic pressure
- Relavistic plasmas
- QED regime

→ High-Energy Density regime in high power laser-produced plasma

MR in HED and relativistic plasmas can be accessible by intense laser experiments

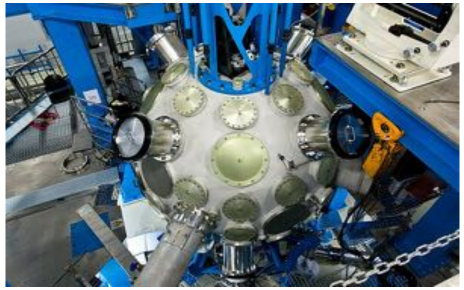
OMEGA (30-40kJ) and OMEGA EP (2.5kJ, 1-10ps)



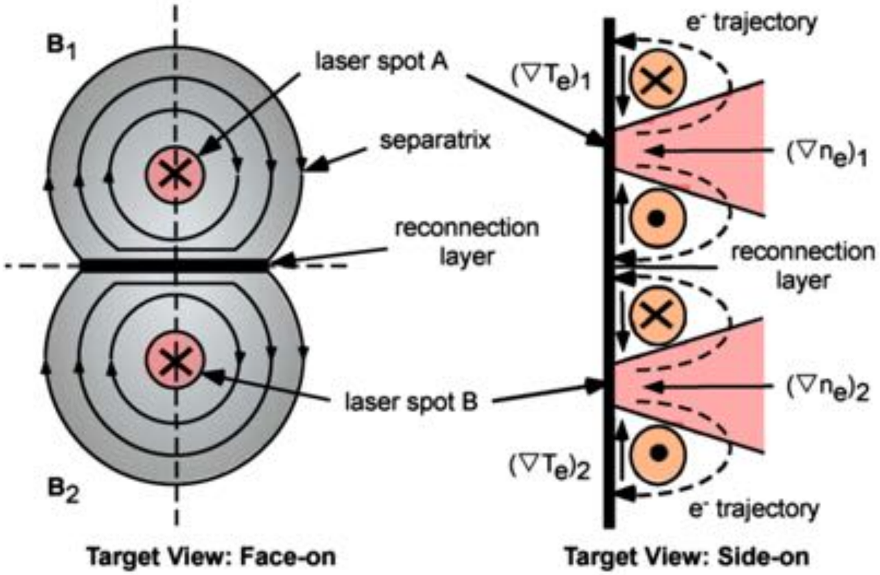
National Ignition Facility (1.8MJ,3-5ns)

Vulcan laser facility (2.6kJ in ns, 1PW in 1ps)

SG-IIU laser facility (3ns, 3kJ, PW beam, 1kJ, 1-10ps)



Configurations



P. Nilson, PRL, 2006

Collision of two laser-produced plasma bubbles with self-generated poloidal magnetic fields:

- B field: Biermann Battery effect $\nabla n \times \nabla T$
- plasma inflow speed: ~ thermal expansion C_s

Summary of HED MR experiments

Experiments Summary

(R) | Nilson (*PRL.* 2006, *POP.* 2008), Willingale (*POP.* 2010)
(O) | Li (*PRL.* 2007), Fiksel (*PRL.* 2014), Rosenberg (*Nat.Comm.* 2015)
(S) | Zhong (*Nat.Phys.* 2010), Dong (*PRL.* 2012)

Experiment Parameter	Rutherford (R)	Omega (O)	SG-II (S)
Ions	Al	CH	Al
Peak density $n_e(\mathrm{cm}^{-3})$	2×10^{20}	9×10^{19}	5×10^{20}
Magnetic field $B(\mathrm{T})$	100	50	200
Temperature $T(\mathrm{ev})$	1000	700	570
Alfvén speed V_A (m/s)	1×10^5	1×10^5	1.2×10^5
Sound speed C_s (m/s)	2×10^5	2.5×10^5	1.5×10^5
Plasma beta β	8	8	2.9

Observation

- jets, plasmoid ejection (probe light beam, ...)
- field evolution (proton probe image)
- temperature (Thomson scattering)

Characteristic

- $\beta \sim 10 - 100$
- $V_{driven} \sim Cs$
- $L/d_i \sim 10 - 100$
- Narrow ribbon
  Finite $L_B < L$

One main concern of MR in the HED regime

Special features of MR in the HED regime:

a) strongly-driven inflow:

hydrodynamic plasma inflow provides a significant source of energy for MR

b) $\beta = 2n_0T_{e0}/B^2 > 1$, hot plasma bubble collision:

compression and amplification of plasma densities and magnetic fields in the interaction center play a significant role.

c) Electrons are magnetized and ions are unmagnetized

two fluid effects

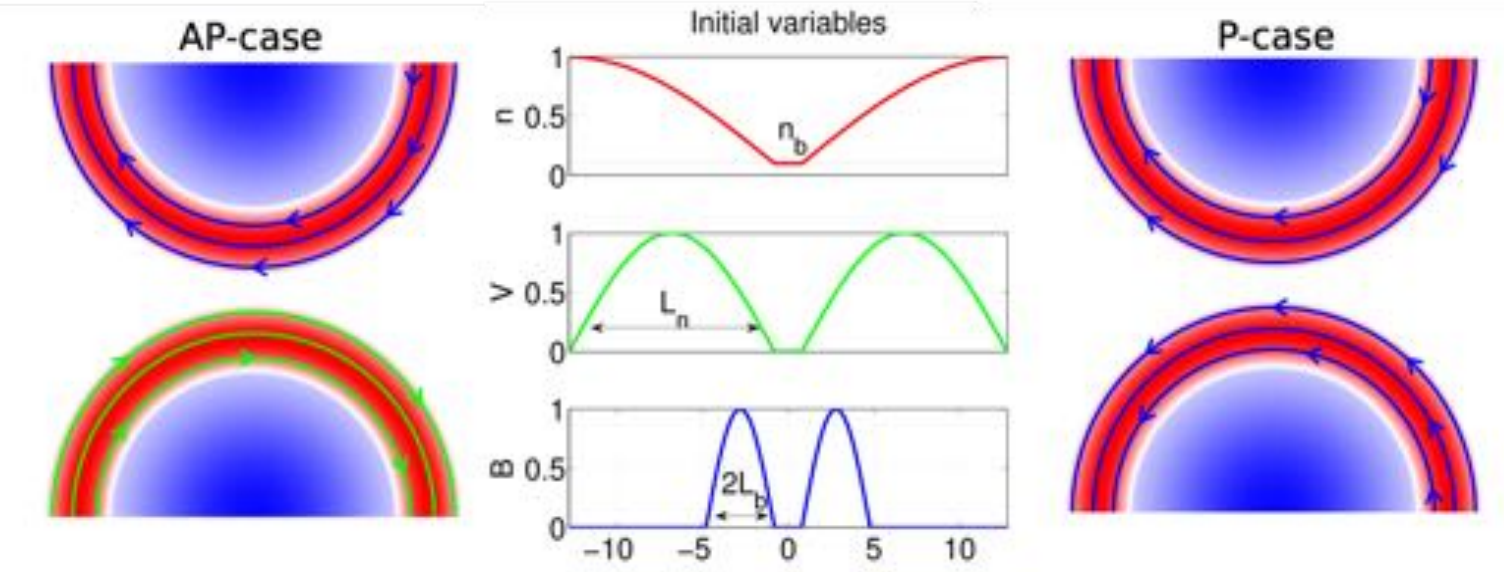
Concern: experimental observations such as heating, jetting, field evolution characteristics are really consequence of MR in the HED regime?

Reexamine and identify the key sign of MR in the HED regime (strongly-driven inflow, **β>1**)

Simulation setup for MR in the HED regime (anti-parallel and parallel cases)

Two cases are employed and compared:

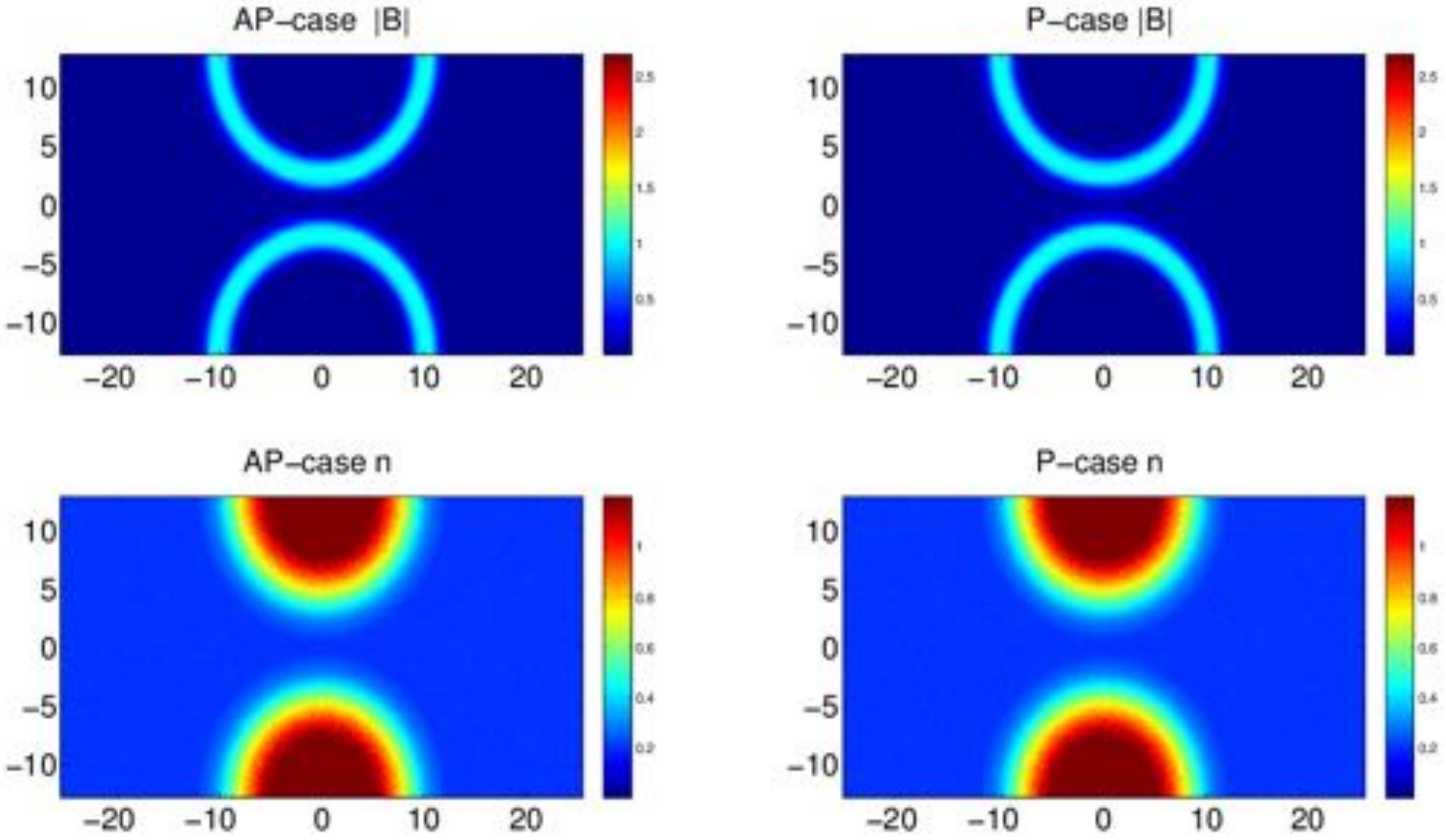
- Anti-Parrallel (AP) - case: plasma bubble collision + MR
- Parralle (P) - case: plasma bubble collision + No MR



- Assume the toroidal magnetic ribbons, neglecting LPI process
- Two bubbles expand radially $V_0 = 2.0C_s, 0.8C_s, 0.2C_s$
- Alfvén speed $V_A = c/100$, $m_i/m_e = 100$
- Plasma beta $\beta = 5$, $n_0/n_b = 10$
- Simulation domain $25.6d_i \times 12.8d_i$, d_i ion skin depth

Z. Xu, B. Qiao*, PRE 93，033206 (2016).

Basic pictures of plasma bubble collision: evolution of magnetic field topologies and plasma density distributions



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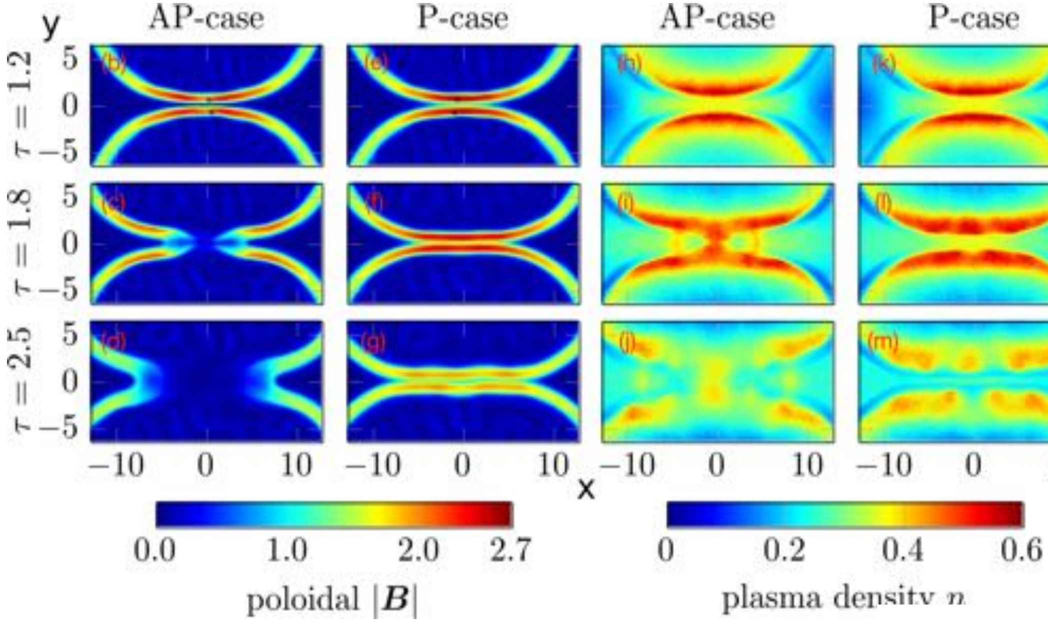
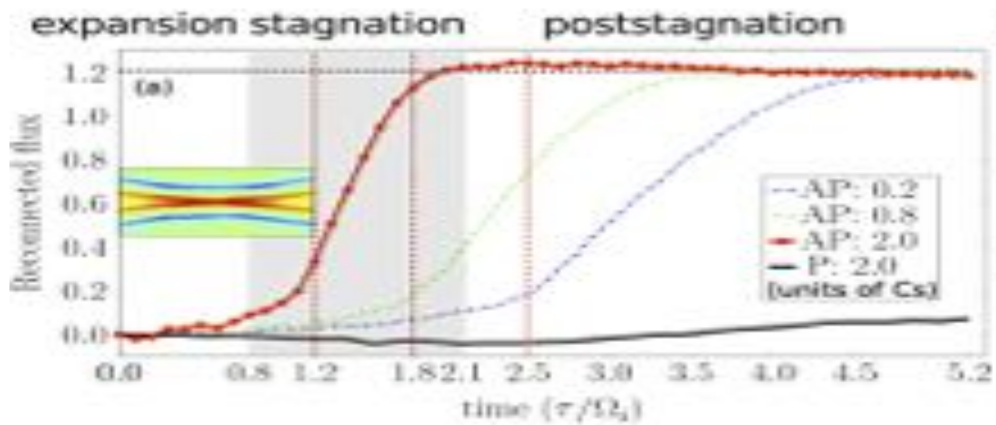


- Bubble squeeze each other enhance B by 2.5× factors and density from 0.1 to 0.6.
- For the AP-case, the current layer in the center becomes too intense, it breaks up through instabilities/turbulence, leading to onset of MR.
- For the P-case, the current in the center cancel out each other, leading to no MR.

The MR reconnection flux evolution:

$$\Psi/B_0 d_i = (\int B \times dl)/B_0 d_i$$

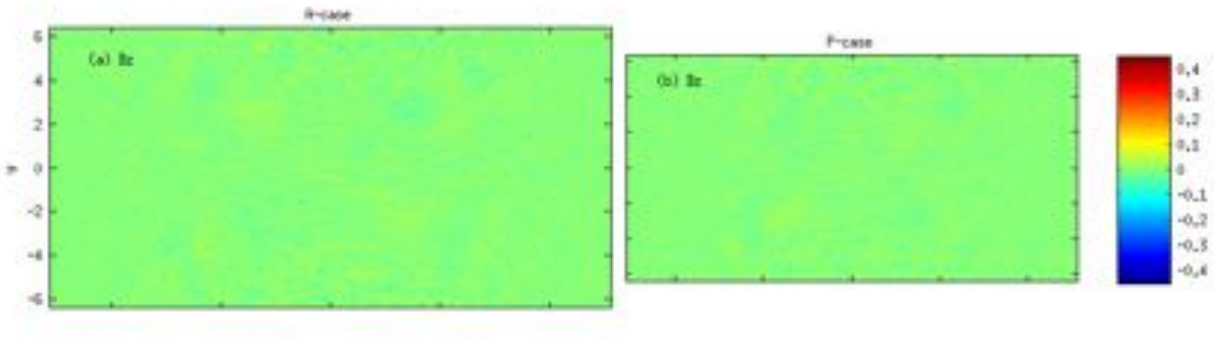


Z. Xu, B. Qiao*, PRE 93，033206 (2016).

Quadrupole magnetic field Bz and bipolar electric field Ey can be induced by merely two plasma bubble collisions.

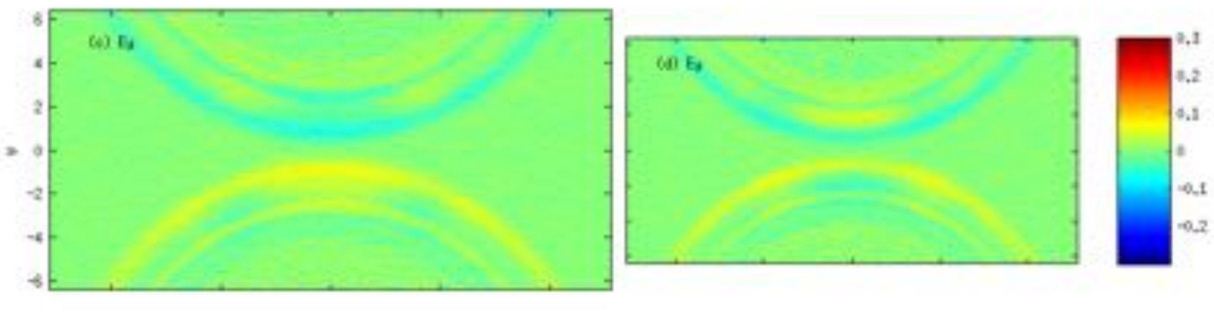
AP-case P-case

B_z (out-of-plane)



AP-case P-case

E_y (in-plane)



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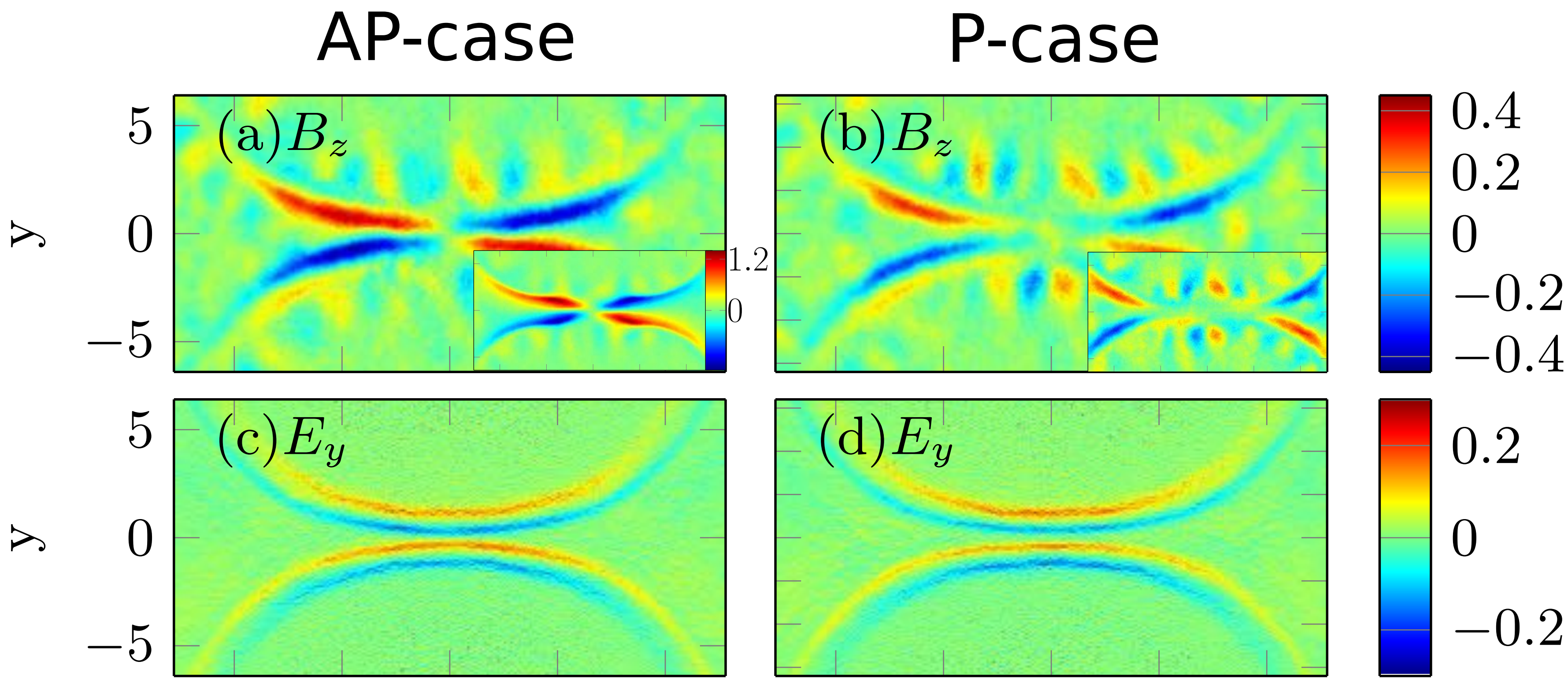
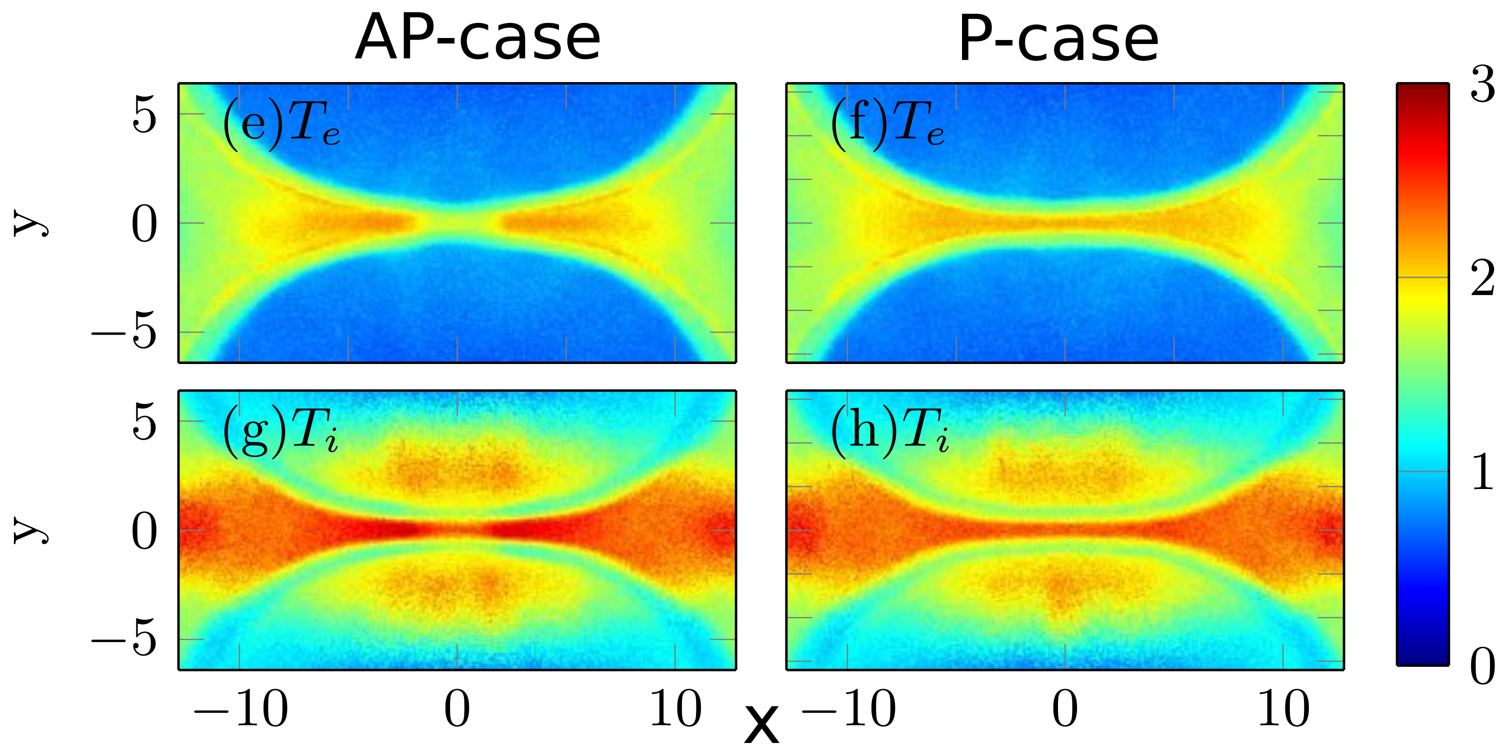


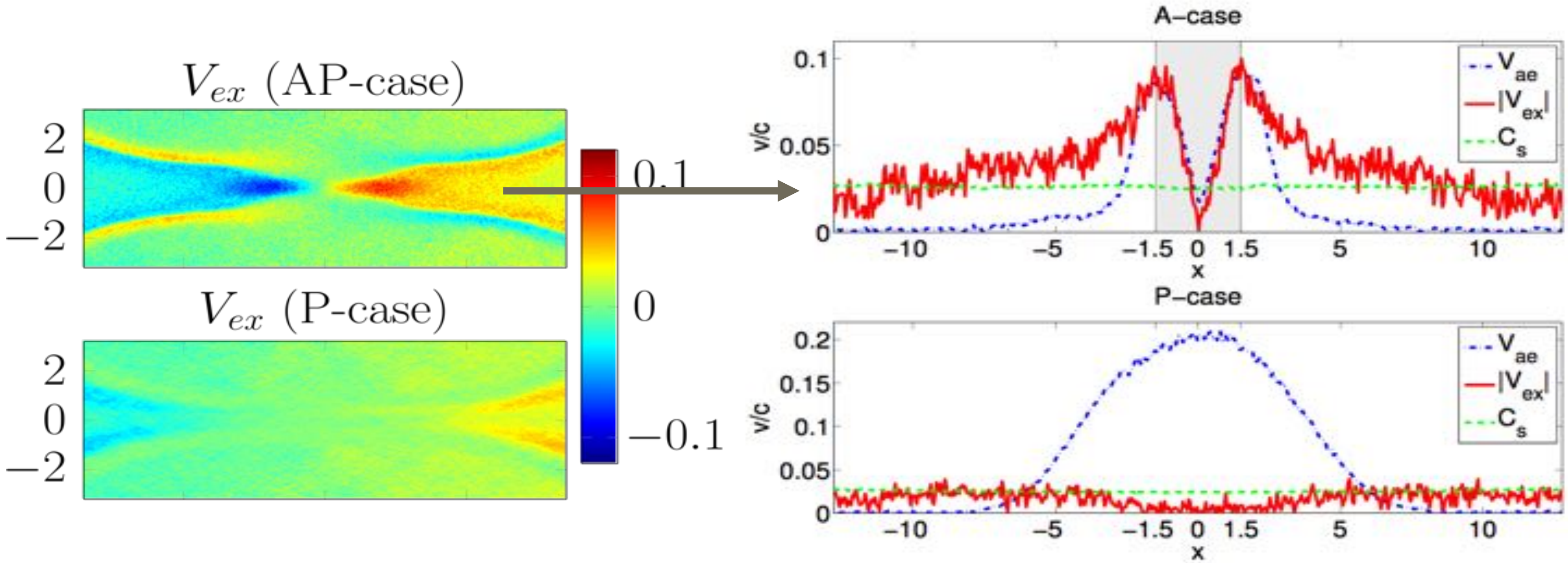
- electrons move from the upper bubble (upstream) down towards the center, and then shift along the magnetic field line going backwards. ---> B_z
- the magnetized electrons are well frozen along the magnetic field line, being pushed deeper than ions towards the interaction center. ----> E_y

Electron and ion heating can also be seen in both cases due to bubble collision and piling up instead of MR



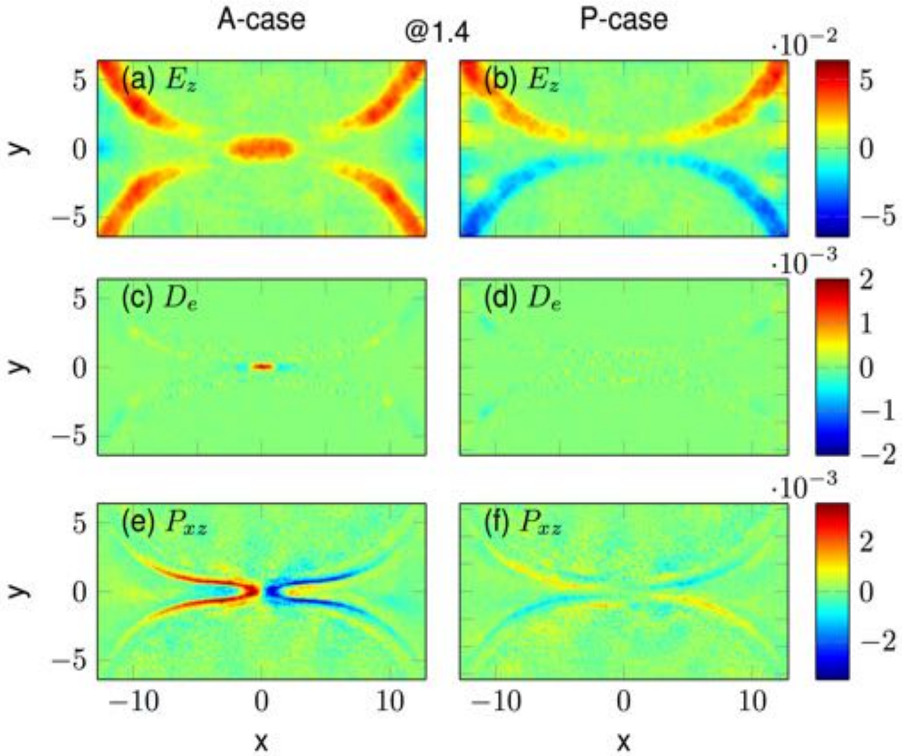
- Temperature profile is similar over whole simulation
- Most area is heated by bubble collision
- The anomalous heating in experiment shall be check

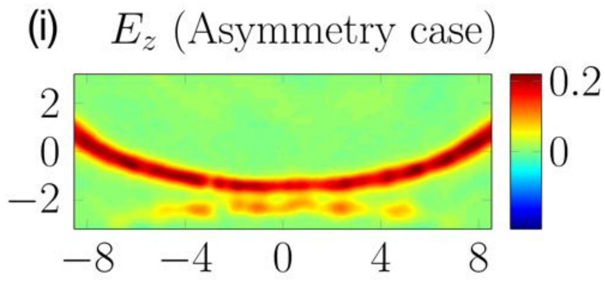
The ratio of jet velocity to the local acoustic speed should be carefully checked to identify MR occurrence



- A-case: electron jets ~ electron Alfvén velocity V_{ae}
- P-case: velocity ~ acoustic speed C_s
- To identify the jets, the parameter $R_v = V_{ae}/C_s \sim 2\sqrt{m_i/\beta m_e}$ should be large enough.

Key sign of MR occurrence in HED regime: the Lorentz-invariant scalar quantity D_e in electron dissipation region





$$E_z \approx -\frac{1}{ne}(\partial_x P_{exz} + \partial_y P_{eyz})$$

$$E_z \sim \partial_x \langle v_{ex} \rangle_d \sqrt{2T_e m_e}/e$$
$$\sim v_{ex}\sqrt{2T_e m_e}/(\delta e)$$

$$BV_A/B_0 c \sim 0.12, \delta \approx 1.0 d_i$$
$$T_e \approx 0.04 m_e c^2 v_{ex} \approx 0.1c$$
$$\Rightarrow E_z/c \sim 0.03 B_0$$

- Electron dissipation region (EDR) [Zenitani 2011 PRL]

the non-ideal Joule dissipation term

$$D_e = J_\mu F^{\mu\nu} u_\nu = \gamma_e [\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v}_e \cdot \boldsymbol{E})]$$

7%

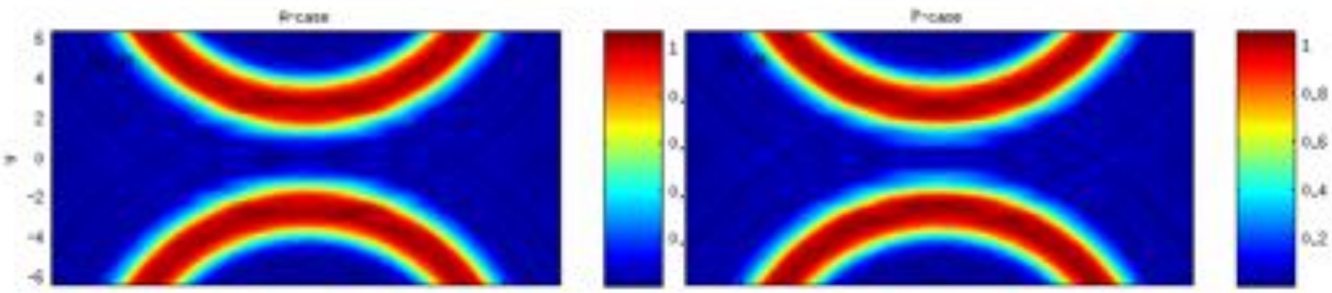
The charge term

- E_z mainly supported by off-diagonal electron pressure $\partial_x P_{xz}$
- No EDR found in P-case

Key sign of MR occurrence in HED regime: the Lorentz-invariant scalar quantity D_e in electron dissipation region

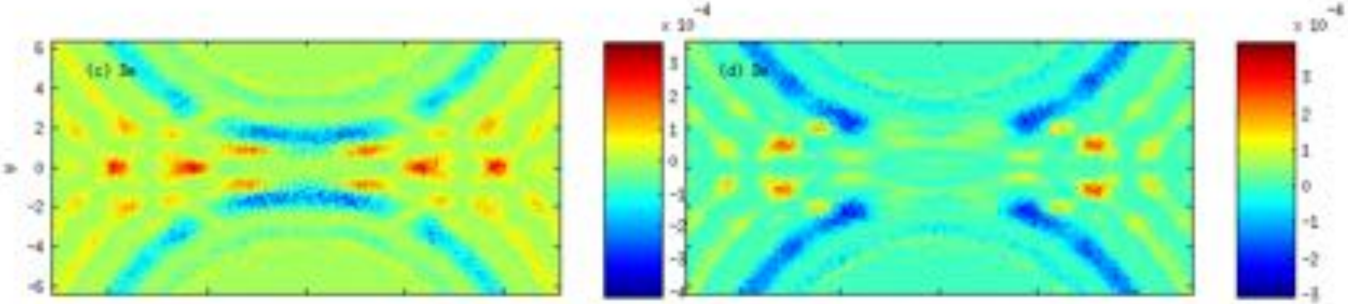
AP-case P-case

B_z

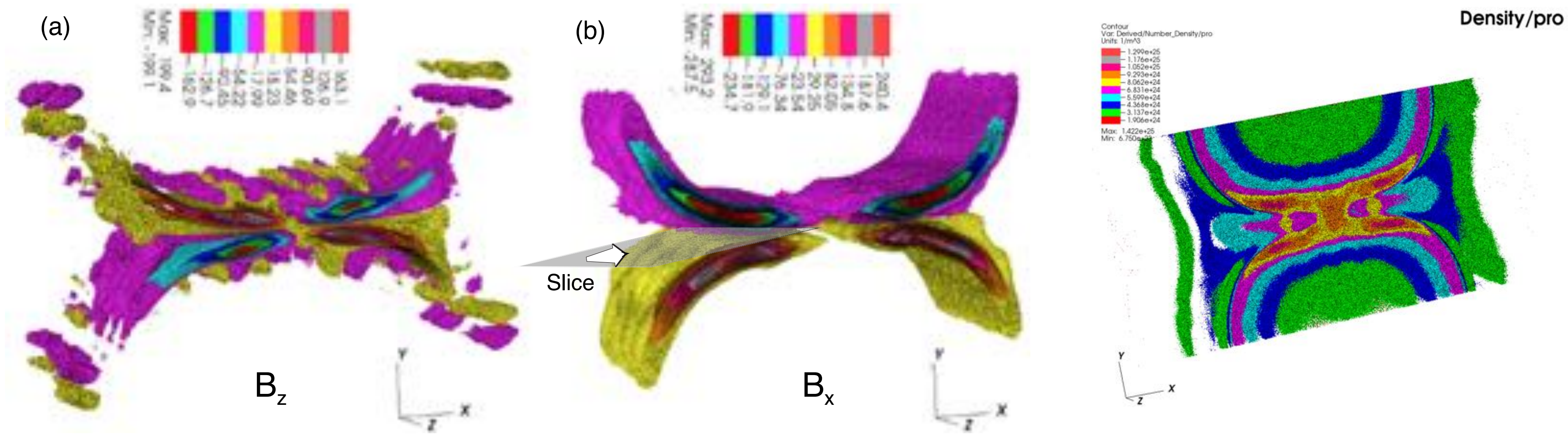


AP-case P-case

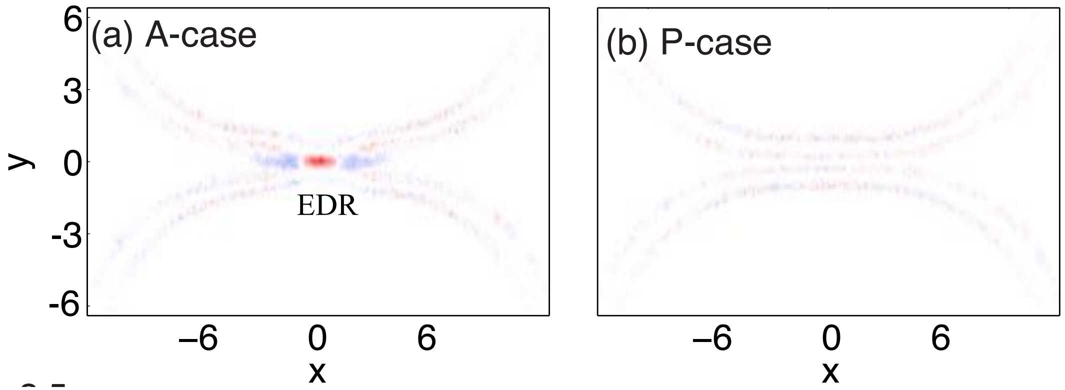
D_e



3D PIC simulations have confirmed the theory



$$D_e = J_\mu F^{\mu\nu} u_\nu = \gamma_e \left[\boldsymbol{j} \cdot (\boldsymbol{E} + \boldsymbol{v}_e \times \boldsymbol{B}) - \rho_c (\boldsymbol{v_e} \cdot \boldsymbol{E}) \right]$$



- many experimental observations observed of MR in the HED regime do not necessarily mean the occurrence of MR
- Electron dissipation region need to find an Lorentz invariant variable as the key sign of MR occurrence: $D_e = \gamma_e j \cdot (\mathbf{E} + \mathbf{v}_e \times \mathbf{B})$

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How to define MR topology in relativistic regime

The Lorentz transformation of magnetic field:

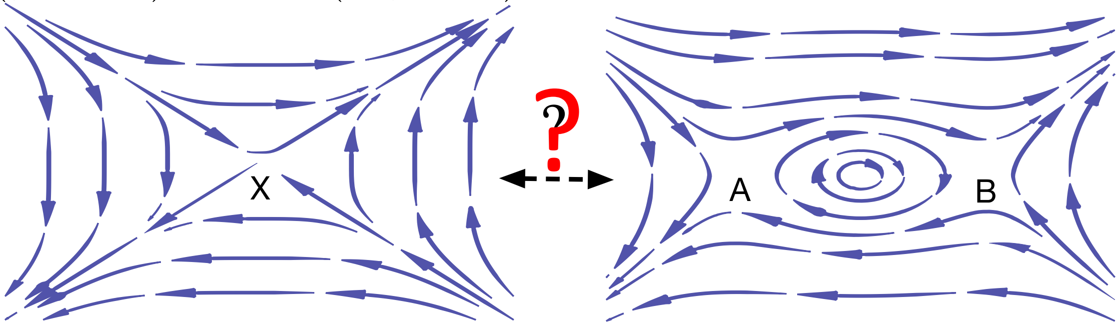
$$\boldsymbol{B}' = \gamma_0\left(\boldsymbol{B} - \frac{\boldsymbol{v}_0}{c^2}\times\boldsymbol{E}\right) + (1-\gamma_0)\frac{\boldsymbol{B}\cdot\boldsymbol{v}_0}{v_0^2}\boldsymbol{v}_0, \quad \boldsymbol{v}_0\text{: the observer's velocity}$$

- in the unrelativistic regime: $\boldsymbol{B}' = \boldsymbol{B} - \frac{\boldsymbol{v}_0}{c^2}\times\boldsymbol{E} \approx \boldsymbol{B}$

The magnetic field configurations is independent of the reference frames

- in the relativistic regime, the magnetic field is coupled with electric field in the Lorentz transformation:

$\boldsymbol{B} = (y^3, x^3, 0)\,, \quad \boldsymbol{E} = (x, y, -2z)$ $\qquad$ $\boldsymbol{B}' = (\gamma_o(y^3 + v_o y), \gamma_o(x^3 - v_o x), 0)$



An observer move with relativistic velocity v_0 in the z-direction

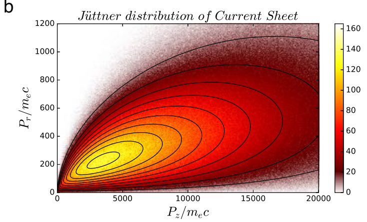
[G. Hornig and K. Schindler, Phys. Plasmas(1996)]

- **The numerous studied singular point "magnetic null" (Pontin et al. 2011; Olshevsky et al. 2016) may not be "stable" for a relativistic observer,**
- **X- and O-point can transform to each other (Hornig & Schindler 1996) (no plasma is considered)**

MR in relativistic regime – X-point check (local view)

Relativistic plasmas: $f_s \propto \mathrm{sech}^2(\frac{y}{w}) \exp\left[-\frac{\gamma_d}{T_s}(\gamma m_s c^2 + m_s V_d u_z)\right]$ Relativistic Harris equilibrium:

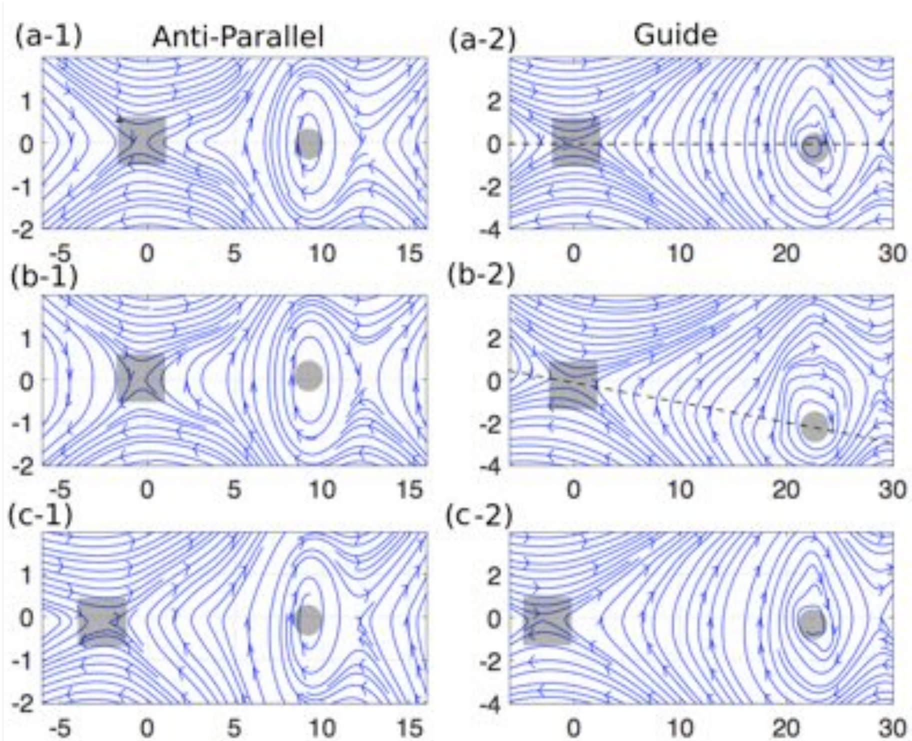
b



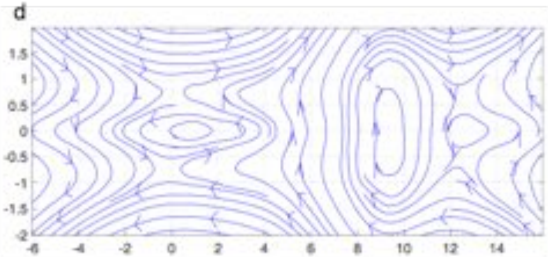
Lab frame

Observer moving along z-direction with γ=10

Observer moving in plane with $-v_x=v_y=0.995c$ (γ=10)



d



Observer moving along z-direction with a pseudo superluminar velocity v_z=3c can only turn x-point to o-point

X-points in relativistic plasmas are generally conserved.

Summary

MR in the HED, relativistic and near-Schwinger QED regimes has been studied:

- Many experimental observations observed of MR in the HED regime do not necessarily mean the occurrence of MR.
- The magnetic nulls (X- and O- points) of MR configuration keep conserved in the relativistic regime, but it will wander in a small region where the Lorentz invariants keeps, when the observer reference frame changes.

Thanks for you attention!