FLARE (Facility for Laboratory Reconnection Experiments): A Major Next-Step for Laboratory Studies of Magnetic Reconnection

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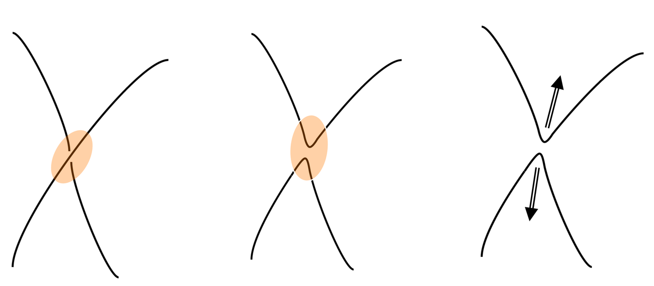
Abstract

A new intermediate-scale plasma experiment, called the Facility for Laboratory Reconnection Experiments or FLARE, is under construction at Princeton as a joint project by five universities and two national labs to study magnetic reconnection in regimes directly relevant to space, solar, astrophysical, and fusion plasmas. The currently existing small-scale experiments have been focusing on the single X-line reconnection process in plasmas either with small effective sizes or at low Lundquist numbers, but both of which are typically very large in natural and fusion plasmas. The design of the FLARE device is motivated to provide experimental access to the new regimes involving multiple X-lines at large effective sizes and high Lundquist numbers. The motivating major physics questions, the construction status, and the planned collaborative research will be discussed.

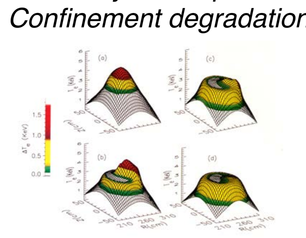
What Is Magnetic Reconnection?



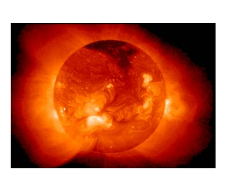
Two Key Features:
- Topological rearrangement of magnetic field lines
- Dissipation of magnetic energy to plasma energy

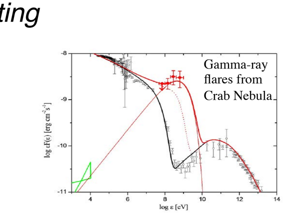
Where Does It Occur and Why Is It Important?

Laboratory fusion plasmas: Confinement degradation



Solar plasma: Flares and corona heating





Magnetospheric plasma: Cause of aurora & substorms

Astrophysical plasmas: Particle energization

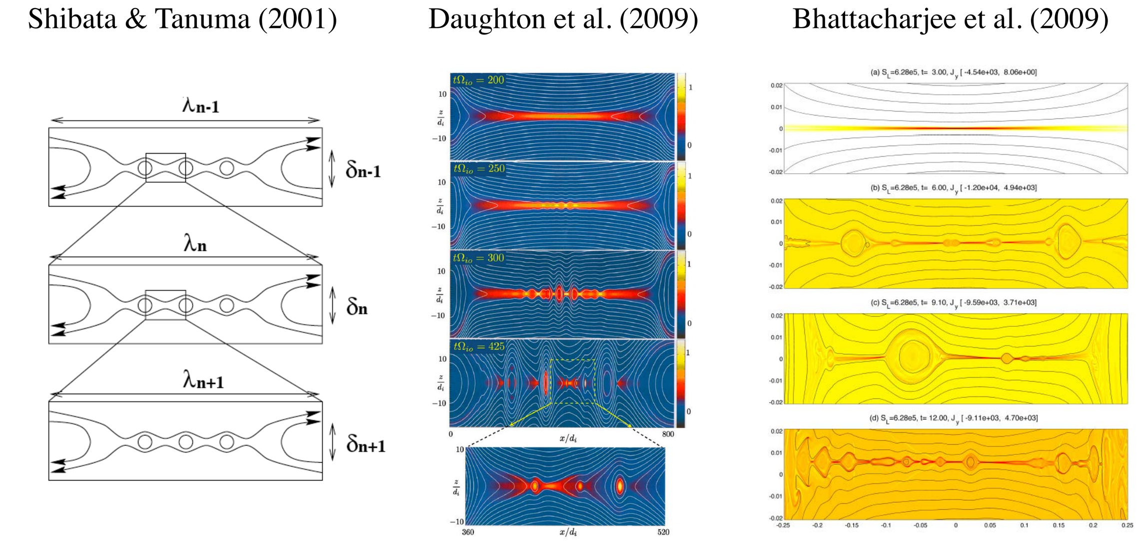
Outstanding Questions & Lab Experiments

- **How is reconnection rate determined? (*The rate problem*)**
- **How does reconnection take place in 3D? (*The 3D problem*)**
- **How does reconnection start? (*The onset problem*)**
- **How does partial ionization affect reconnection? (*The partial ionization problem*)**
- **How do boundary conditions affect reconnection process? (*The boundary problem*)**
- **How are particles energized? (*The energy problem*)**
- **How to apply local reconnection physics to a large system? (*The multi-scale problem*)**

Device	*Where*	*Since*	*Who*	*Geometry*	*Focus*
3D-CS	Russia	1970	Syrovatskii, Frank	Linear	3D, energy
LPD, LAPD	UCLA	1980	Stenzel, Gekelman	Linear	Energy, 3D
TS-3/4	Tokyo	1990	Katsurai, Ono	Merging	Rate, energy
MRX	Princeton	1995	Yamada, Ji	Toroidal, merging	Rate, 3D, energy, partial ionization, boundary, onset
SSX	Swarthmore	1996	Brown	Merging	Energy, 3D
VTF	MIT	1998	Fasoli, Egedal	Toroidal	Onset, 3D
Caltech exp	Caltech	1998	Bellan	Planar	Onset, 3D
RSX	Los Alamos	2002	Intrator	Linear	Boundary, 3D
RWX	Wisconsin	2002	Forest	Linear	Boundary
Lasers plasmas	UK, China, Rochester	2006	Nilson, Li, Zhong, Dong, Fox, Fiksel, Gao, Ji…	Planar	Flow-driven
VINETA II	Max-Planck	2012	Grulke, Klinger	Linear	3D
TREX	Wisconsin	2013	Egedal, Forest	Toroidal	Energy
FLARE	Princeton	2013	Ji +	Toroidal	All

Why FLARE?

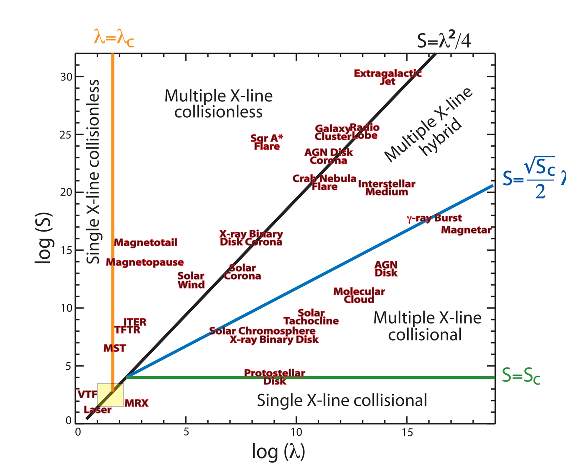
Plasmoid Dynamics May Solve Scale Separation Problem



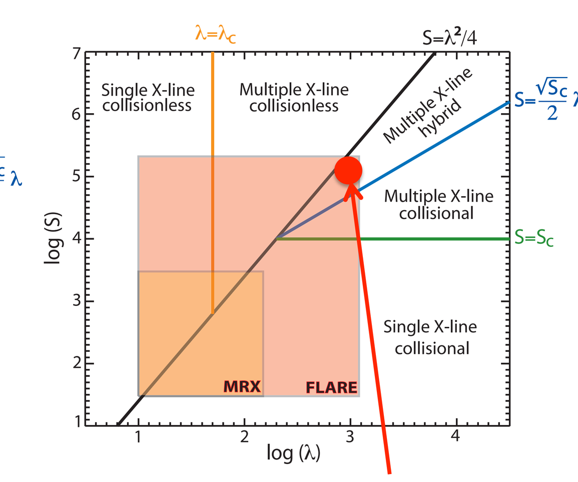
Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….

"Phase Diagram*" for Different Coupling Mechanisms

*H. Ji & W. Daughton, PoP **18**, 111207 (2011) $S = \mu_0 L_{CS} V_A / \eta_S$; $L_{CS} = L/4$; $\lambda = L/\rho_S$



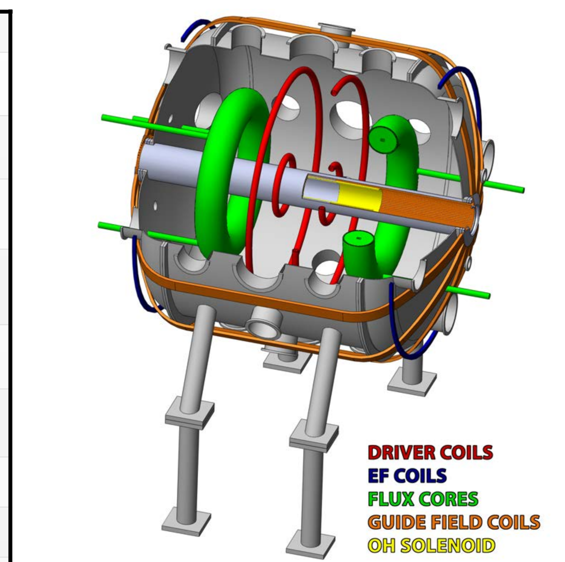
Nearly all reconnection phenomena fall into multiple X-line phases



Design target for FLARE to access all reconnection phases

FLARE Design Based on MRX

Parameters	MRX	FLARE
Device diameter	1.5 m	3 m
Device length	2 m	3.6 m
Flux core major diameters	0.75 m	1.5 m
Flux core minor diameter	0.2 m	0.3 m
Stored energy	25 kJ	4 MJ
Ohmic heating/ drive	No	0.3 V-s
Outer driving coil	Yes	Yes
Inner driving coil	No	Yes
S (anti-parallel)	600-1,400	5,000-16,000
$\lambda = (Z/\delta_i)$	35-10	100-30
S (guide field)	2900	100,000
$\lambda = (Z/\rho_S)$	180	1,000



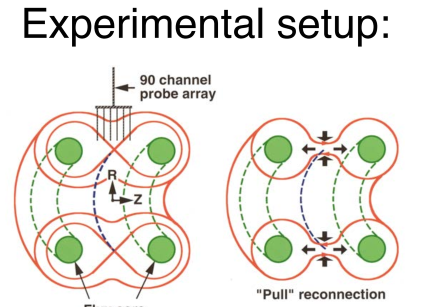
$$S = 1.09\times 10^5 \left(\frac{L}{1.6m}\right)\left(\frac{B_{rec}}{0.1T}\right)\left(\frac{n}{10^{19}}\right)^{-1/2}\left(\frac{T_e}{30eV}\right)^{3/2}$$

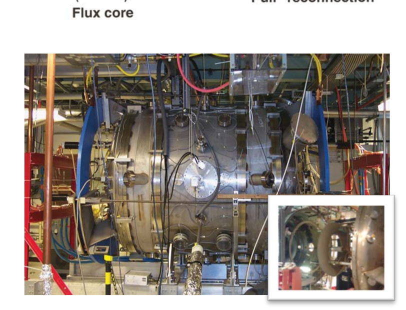
$$\lambda = 1.01\times 10^3 \left(\frac{L}{1.6m}\right)\left(\frac{B_{guide}}{0.5T}\right)\left(\frac{T_e+T_i}{60eV}\right)^{-1/2}$$

MRX*(Magnetic Reconnection Experiment) Operational Since 1995

*http://mrx.pppl.gov

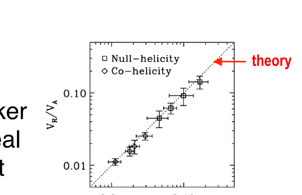
Experimental setup:

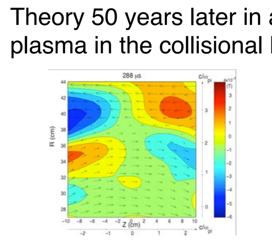




Key results:

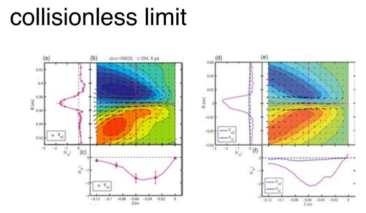
Proved classical Sweet-Parker Theory 50 years later in a real plasma in the collisional limit

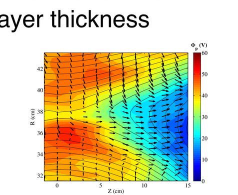




Confirmed two-fluid effects for fast reconnection in the collisionless limit

Challenged numerical simulations on electron layer thickness



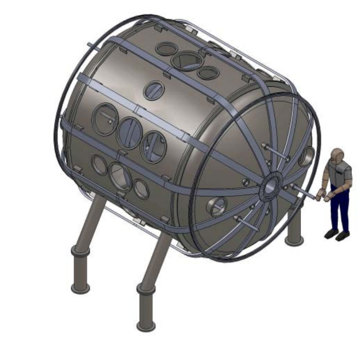


Evaluated energy conversion efficiency and electron/ion partition

Also: solar flux rope dynamics, guide field dependence, and partial ionization effects…

Status of FLARE Construction Project

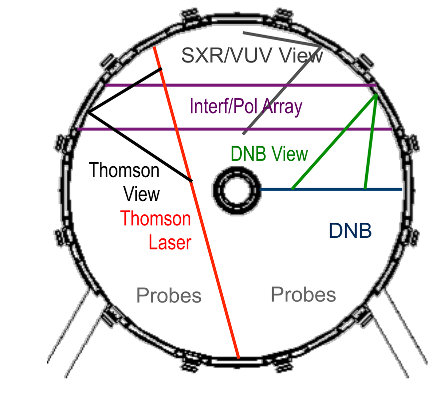
Phase 1 (Optimization): FY14 complete
Phase 1 (Design): FY15 largely complete
Phase 2 (Procurement): FY15
Phase 2 (Manufacturing): FY15 & 16
Phase 2 (Assembly): FY16
Phase 2 (Installation): FY16
Operation and Research: FY17



Complete: optimization of port allocations considering accessibility of future possible advanced diagnostics

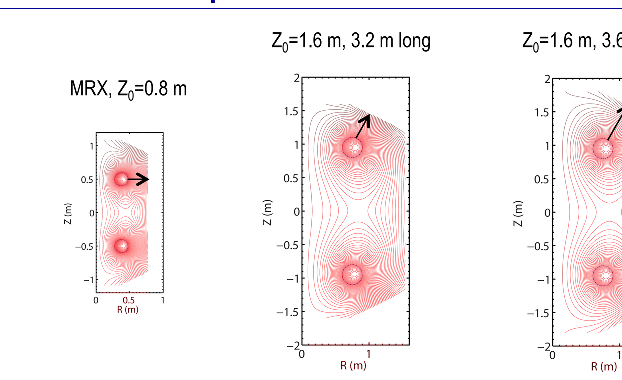
- Potential future diagnostics:
  - Thomson Scattering
  - Vacuum Ultra-violet & Soft X-ray detectors
  - Neutral beam diagnostics. e.g.:
    - charge exchange recombination spectroscopy
    - beam emission spectroscopy
    - motional stark effect
  - Multichannel interferometer/polarimeter
  - Microwave scattering
- Midplane access desirable for many diagnostics
  - Combined diagnostic layout requires careful planning to avoid mutual obstructions
  - free operation zone needed for probes
  - Off-midplane ports simplify problem

Hypothetical layout assuming *no out-of-midplane views*



No boxports due to increased EF current from 13kA to 18.5 kA/turn, error fields and costs

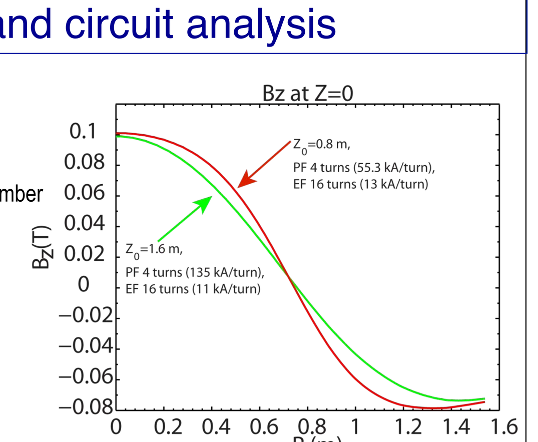
Complete: vacuum vessel length optimization



A 13 % increase in vessel length from 3.2 m to 3.6 m leads to an 50% increase in the distance between flux core surface and vacuum vessel

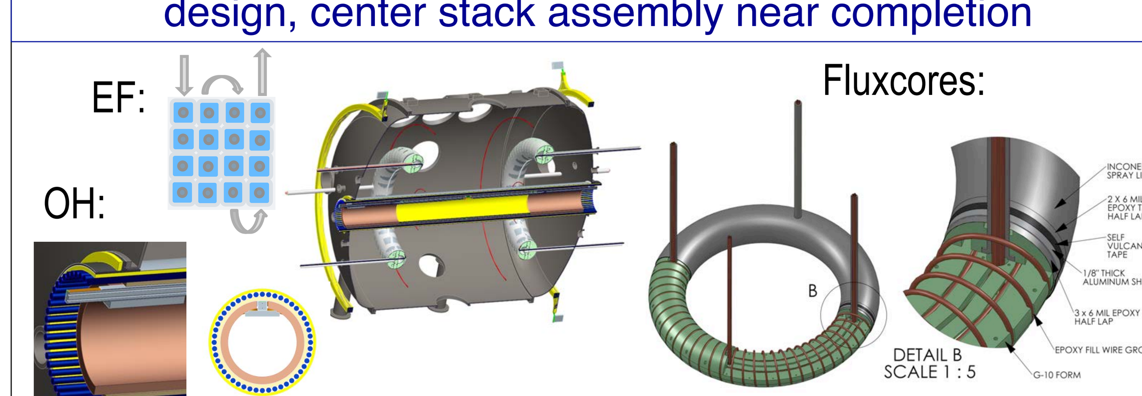
Complete: coil system specifications
Complete: power supply system specifications
Complete: EM, thermal and circuit analysis

- The field requirements and the corresponding locations
  - B_z=1 kG at R=0
  - B_T= 1 T inside the fluxcore
- X point should be at R=0.75 m (using EF to adjust)
- Z_0 ranges from 0.8 m to 1.6 m, with eddy current in the vacuum chamber
  - Z_0=0.8 m case
    - Total fluxcore PF current: 221 kA = 4 turns * 55.3 kA
    - Total EF current 208 kA = 16 turns * 13 kA
  - Z_0=1.6 m case
    - Total fluxcore PF current: 540 kA = 4 turns * 135kA
    - Total EF current 176 kA = 16 turns * 11 kA
- 4 PF coil turns for each flux core
  - All 8 turns in parallel for shortest rise time (cycle/4)
- 60 TF coil turns for each flux core, divided into 4 sections
  - All 8 sections in parallel for shortest rise time (cycle/4)



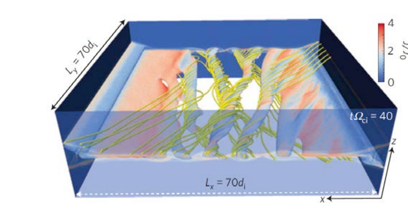
Coil System	Ohmic Heating (OH)	Equilibrium Field (EF)	Guide Field (GF)	Fluxcore PF Coil	Fluxcore TF Coil	Inner Driving Coil	Outer Driving Coil
# of Coils	2	2	1 system	2	2	2	2
Turns / coil	25	16	48	4x1	4 x 15	2	2
Circuit connection	Series/ Parallel	Parallel	Series	8 x 1 Parallel	8 x 15 parallel	Parallel	Parallel
Current (kA)	100	13	40	135	62.5	25	25
Capacitor Bank (mF) / kV	5.04/20	420/1.4	44/14	3.9/20	1.25/20	0.0625/10.2	0.0875/20
Bank energy (MJ)	1.01	0.41	4.3	0.78	0.25	0.0033	0.018
Rise time (ms)	1.2 /0.6	30	19	0.11	0.08	0.02	0.06

Complete: EF coil design, OH coil design, preliminary fluxcore design, center stack assembly near completion

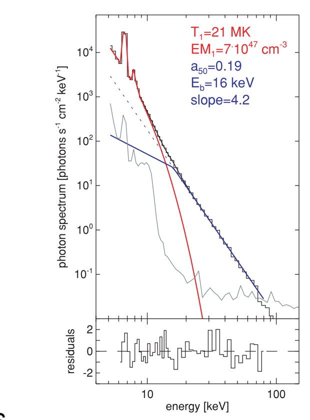


Initially Planned Research Topics

- Multiple-scale
  - Plasmoid instability in MHD
  - Scaling of multiple X-lines in MHD
  - Transition from MHD to kinetic
  - Scaling of kinetic X-lines
  - Guide filed dependence of multiple scale reconnection
- Reconnection rate
  - Reconnection rate in multiple X-line in MHD
  - Reconnection rate in multiple X-line in MHD and kinetic
  - Can asymmetry with a guide field reduce or even suppress reconnection?
- 3D
  - Plasmoid instability in 3D: flux ropes?
  - Third dimension scaling of multiple X-line reconnection: towards turbulent reconnection?
  - Externally driven tearing mode reconnection
  - Interaction of multiple tearing modes: magnetic stochasity?
  - Line-tied effects in the third direction
- Onset
  - Is reconnection onset local or global?
  - Is reconnection onset 2D or 3D?
- Particle acceleration
  - Ion acceleration in large system
  - Electron acceleration in large system
  - Scaling of ion heating and acceleration
  - Scaling of electron heating and acceleration
- Partial ionization
  - Modification of multiple-scale reconnection by neutral particles
  - Neutral particle heating and acceleration



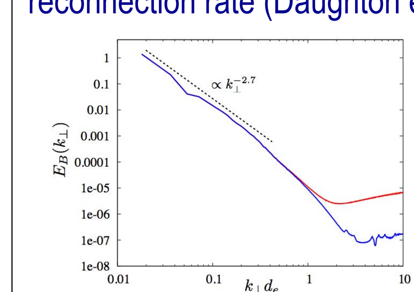
Daughton et al. (2011)

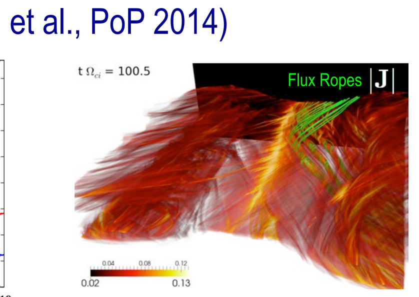


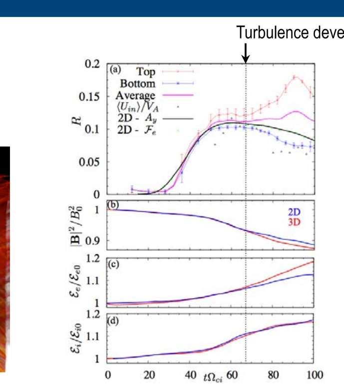
Krucker et al. (2010)

Some New Ideas…

First indication that 3D turbulence may influence reconnection rate (Daughton et al., PoP 2014)



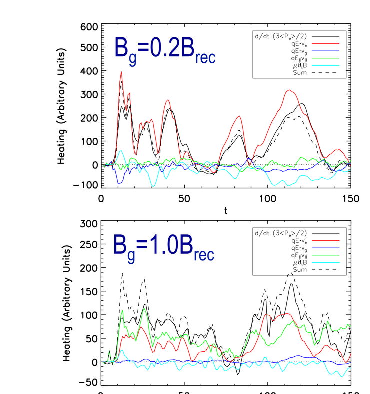




Mechanisms for electron heating and acceleration during reconnection (J. Drake et al., 2014)

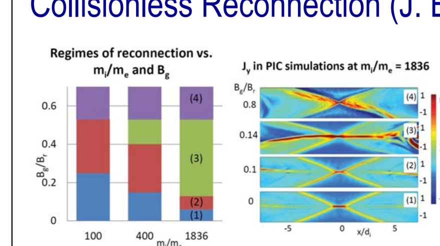
$$\frac{d\varepsilon}{dt} = \frac{\mu}{\gamma}\frac{\partial B}{\partial t} + qv_\parallel E_\parallel + q\vec{v}_c \bullet \vec{E} + q\vec{v}_B \bullet \vec{E} \quad v_c = \frac{v_\parallel^2}{\Omega}\vec{b}\times(\vec{b}\bullet\vec{\nabla}\vec{b}) \quad v_B = \frac{\gamma v_\perp^2}{2\Omega}\vec{b}\times\frac{\vec{\nabla}B}{B} \quad \mu = \frac{m\gamma^2 v_\perp^2}{2B}$$

Mechanism	Term in drift kinetic Equation	2D PIC (B_g=0.2B_{rec})	2D PIC (B_g=1.0B_{rec})
Parallel electric field	$qv_\parallel E_\parallel$	small	dominate
Curvature drift: Slingshot term (Fermi acceleration) increases the parallel energy	$q\vec{v}_c \bullet \vec{E}$	dominate	dominate
Grad B drift: Betatron acceleration increases/ decreases perpendicular energy	$q\vec{v}_B \bullet \vec{E}$	Energy sink	small
Magnetic moment	$\frac{\mu}{\gamma}\frac{\partial B}{\partial t}$	Energy sink	small

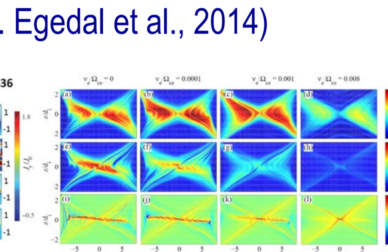


Dahlin et al., 2014

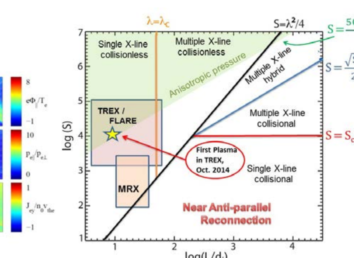
Regimes of the Electron Diffusion Region in Collisionless Reconnection (J. Egedal et al., 2014)



Le et al., PRL 2013



Effects of collisions at B_g=0.28B_{rec}



Le et al., 2014

Proposed Research Program

- Operate as a DoE Office of Science user facility
  - Open to all interested users regardless nationality or institutional affiliation
  - Allocation of facility resources determined by merit review of proposed work
  - No user fees unless proprietary work
  - Support for user safety and efficiency
  - Support a formal user organization for representing users, sharing information, forming collaborations etc.
- Program governed by Steering Committee comprised of PI, 4 co-PIs, PPPL director, User Organization chair, 2 senior physicists
- Funding proposals submitted to and selected by funding agencies
- Collaborate and coordinate with other intermediate-scale experiments

Acknowledgements: NSF Major Research Instrument Program and DoE Fusion Energy Sciences Office