The Status and Plans for the Upcoming FLARE (Facility for Laboratory Reconnection Experiments) Project [http://flare.pppl.gov]

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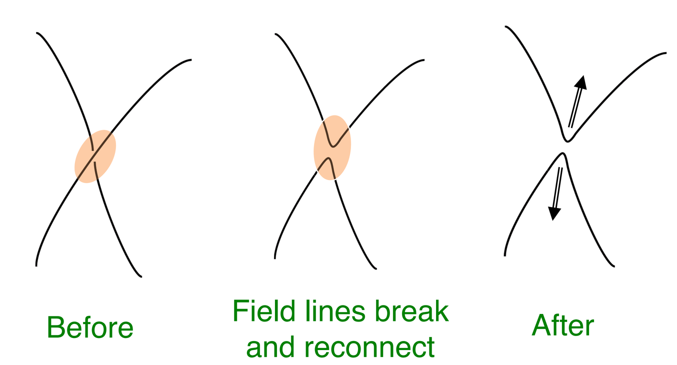
Abstract

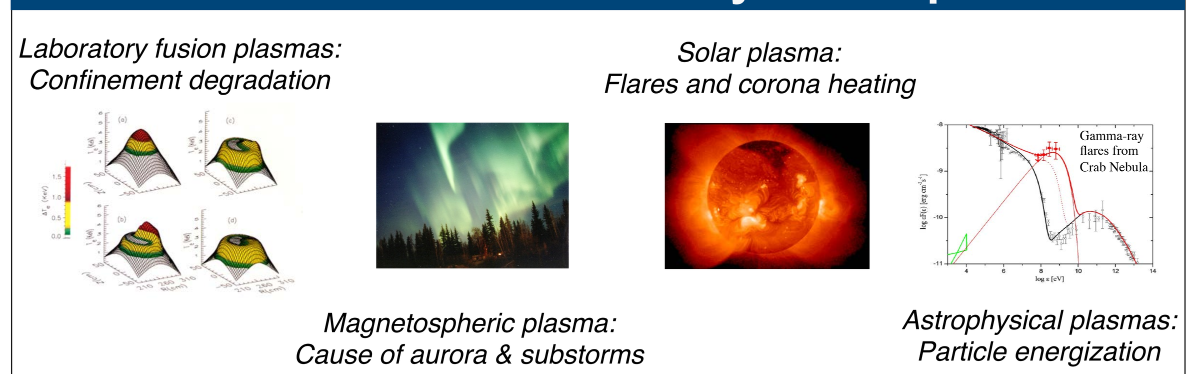
The FLARE device (http://flare.pppl.gov) is a new intermediate-scale plasma experiment under construction at Princeton to study magnetic reconnection in regimes directly relevant to space, solar, and astrophysical plasmas. The existing small-scale experiments have been focusing on the single X-line reconnection process either with small effective sizes or at low Lundquist numbers, but both of which are typically very large in natural plasmas. The configuration of the FLARE device is designed to provide experimental access to the new regimes involving multiple X-lines. All major mechanical components of the FLARE device have been designed and are under construction. The device will be assembled and installed in 2016, followed by commissioning and operation in 2017. The FLARE will be operated as a user facility open to all users regardless their nationalities or institutions, only subject to merit reviews.

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?



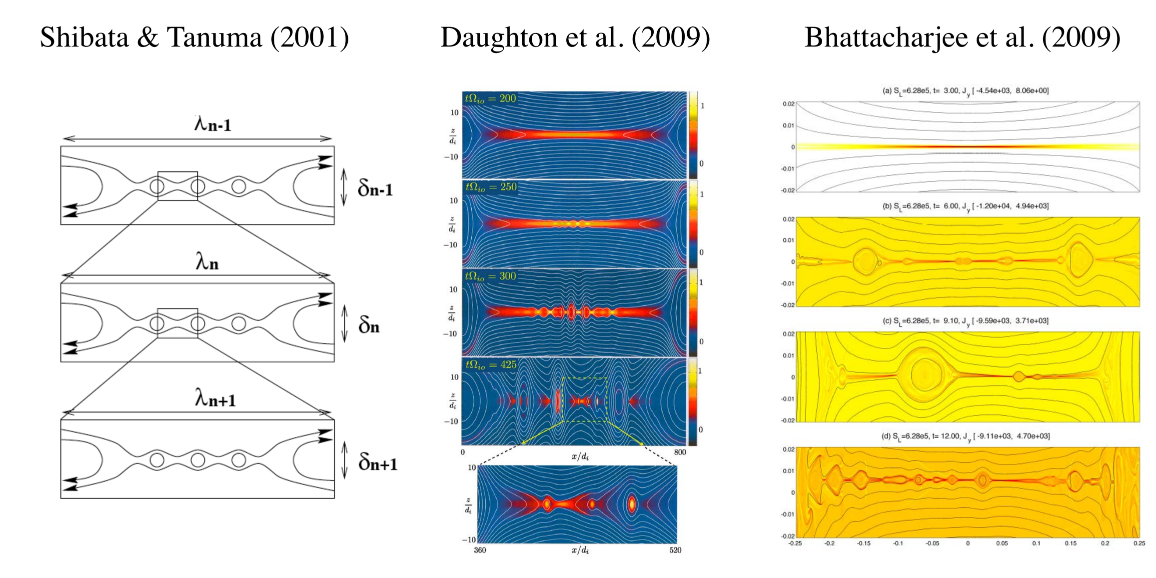
Outstanding Questions & Lab Experiments

- **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)*
- **What roles reconnection plays in flow-driven systems?** (**The flow-driven problem**)
- **How does reconnection take place under extreme conditions?** (**The extreme 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, MAST	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
Laser plasmas	UK, China, Rochester	2006	Nilson, Li, Zhong, Dong, Fox, Fiksel	Planar	Flow-driven, extreme
VINETA II	Max-Planck	2012	Grulke, Klinger	Linear	3D
TREX	Wisconsin	2013	Egedal, Forest	Toroidal	Energy
FLARE	Princeton	2013	Ji +	Toroidal	All
HRX	Harbin, China	2015	Ren +	3D	3D, energy

Why FLARE?

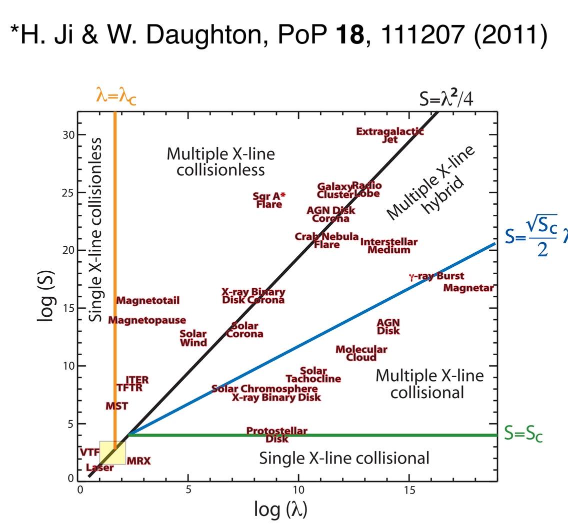
Plasmoid Dynamics May Solve Scale Separation Problem



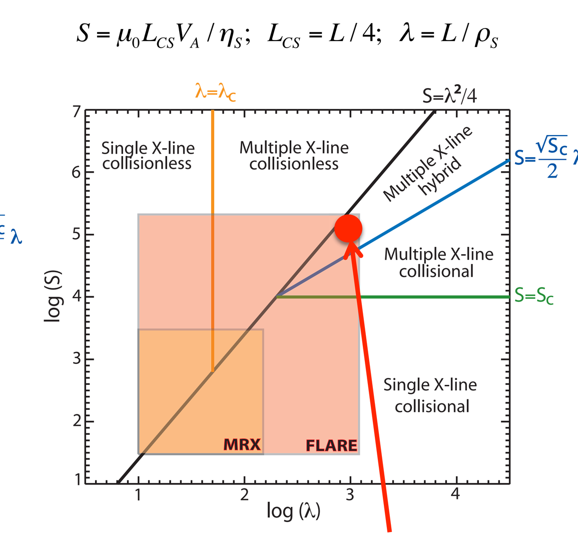
Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….

"Phase Diagram*" for Different Coupling Mechanisms

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



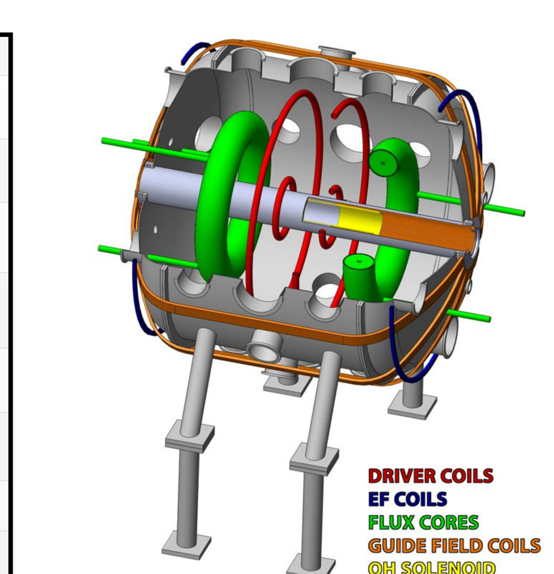
Nearly all reconnection phenomena fall into multiple X-line phases



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	Yes	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



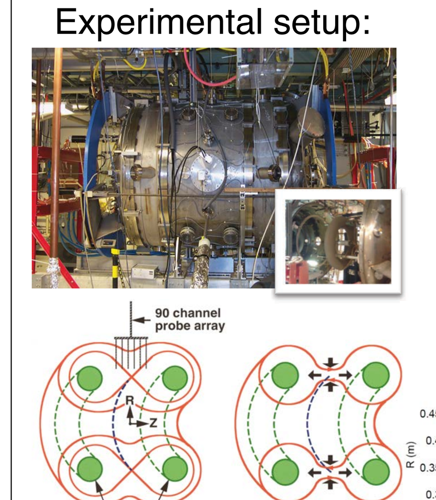
$$S = 1.09\times 10^5 \left(\frac{L}{1.6m}\right)\left(\frac{B_{rec}}{0.1T}\right)\left(\frac{n}{10^{19}}\right)^{-1/2}\left(\frac{T_e}{30eV}\right)^{3/2}$$

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

MRX*(Magnetic Reconnection Experiment) Operational Since 1995

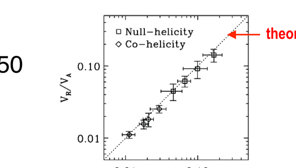
*http://mrx.pppl.gov

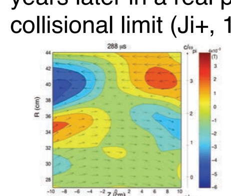
Experimental setup:



Key results:

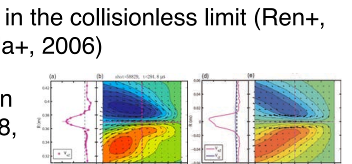
Proved classical Sweet-Parker theory 50 years later in a real plasma in the collisional limit (Ji+, 1998, 1999)

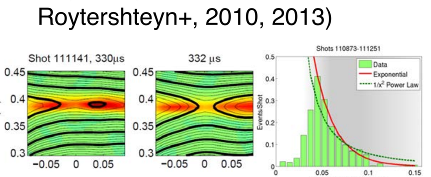




Confirmed two-fluid effects for fast reconnection in the collisionless limit (Ren+, 2006, Yamada+, 2006)

Challenged numerical simulations on electron layer thickness (Ren+, 2008, Ji+, 2008, Dorfman+, 2008, Roytershteyn+, 2010, 2013)



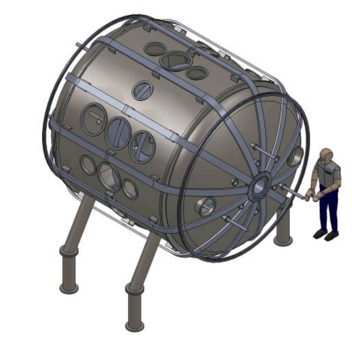


Impulsive reconnection during collisionless plasmoid/flux rope ejection (Dorfman+, 2013, 2014)

Also: (1) lower-hybrid waves (Carter+, 2001,2002, Ji+, 2004, Roytershteyn+, 2013); (2) guide field effects (Tharp+, 2012, 2013); (3) partial ionization effects (Lawrence+, 2013); (4) ion flow generation/heating, energy conversion efficiency and partition (Yoo+, 2013, 2014, Yamada+, 2014, 2015); (5) asymmetric reconnection (Yoo+, 2014); (6) line-tied flux rope equilibrium and stability (Oz+, 2012, Myers+, 2015)…

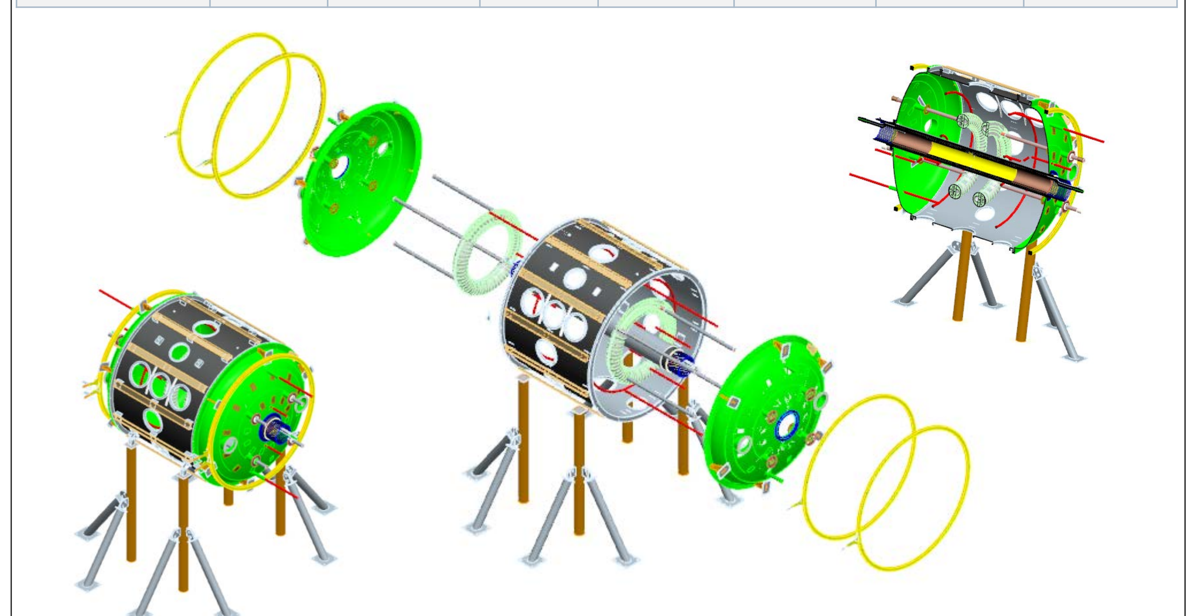
Status of FLARE Construction Project

Design optimization: complete
Engineering design: complete
Procurement: ongoing
Fabrication: ongoing
Assembly: FY2016
Installation: FY2016-17
Operation and Research: FY2017

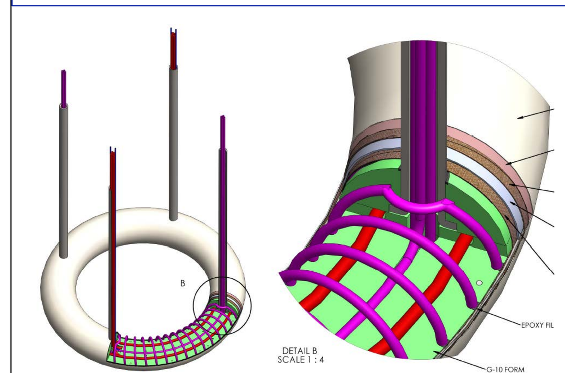


Complete: optimization of vacuum chamber and coil designs
Complete: coil system specifications
Complete: power system specifications

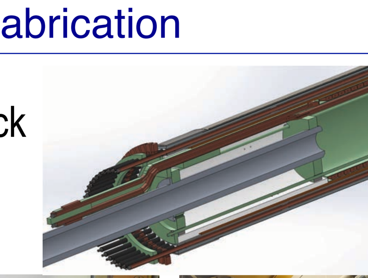
Coil System	Ohmic Heating (OH)	Equilibrium Field (EF)	Guide Field (GF)	Fluxcore PF Coil	Fluxcore TF Coil	Inner Driving Coil	Outer Driving Coil
# of Coils	2	2	1 system	2	2	2	2
Turns / coil	25	16	48	4x1	4 x 15	2	2
Circuit connection	Parallel	Parallel	Series	8 x 1 Parallel	8 x 15 parallel	Parallel	Parallel
Current (kA)	90	13	40	135	62.5	25	25
Capacitor Bank (mF) / (kV)	3.00/20	420/1.4	44/14	3.9/20	1.25/20	0.038/10.2	0.050/20
Bank energy (MJ)	1.01	0.41	4.3	0.78	0.25	0.0033	0.018
Rise time (ms)	0.45	30	19	0.11	0.08	0.01	0.03



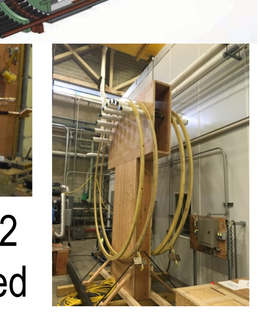
Complete: fluxcore, EF, OH, GF/center stack design
Complete: EF and OH coil fabrication



Fluxcore design completed



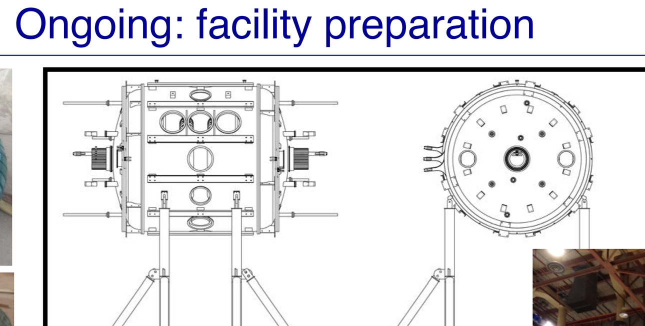
Center stack design completed



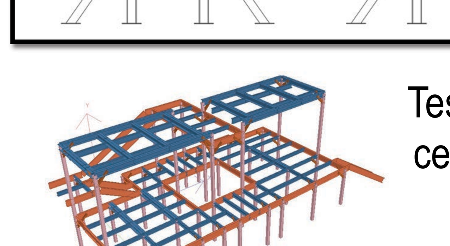
All 4 EF coils & 2 OH coils delivered

Ongoing: fluxcore fabrication
Ongoing: vacuum chamber fabrication
Ongoing: power system design
Ongoing: facility preparation

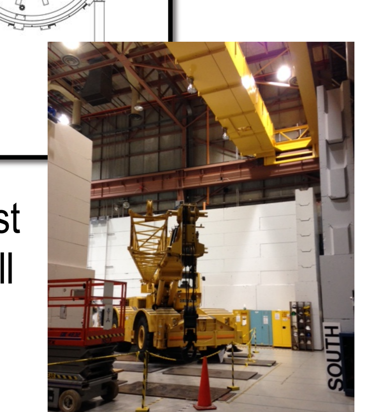
Fluxcore G10 pieces completed



Vacuum chamber



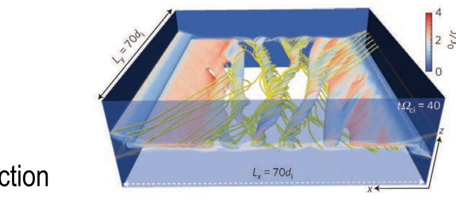
Platform



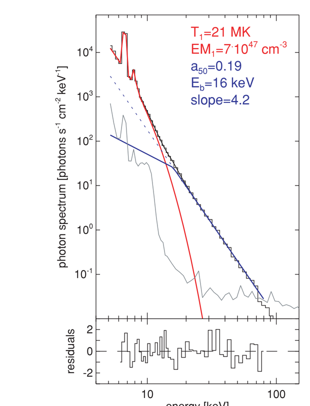
Test cell

An Initial List of Possible 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 field dependence of multiple-scale reconnection
- Reconnection rate
  - Reconnection rate for multiple X-lines in MHD
  - Reconnection rate for multiple X-lines in both MHD and kinetic
  - Will upstream 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 and heating in large system
  - Electron acceleration and heating 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



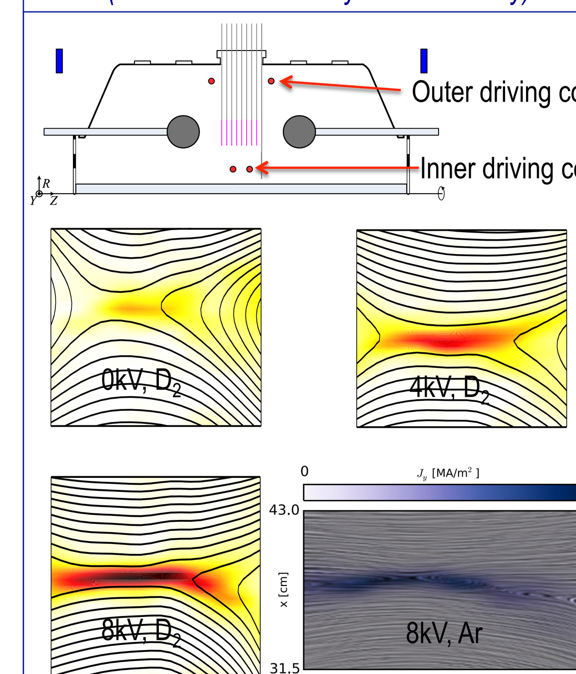
Daughton et al. (2011)



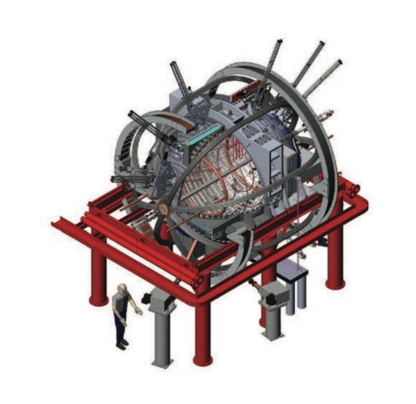
Krucker et al. (2010)

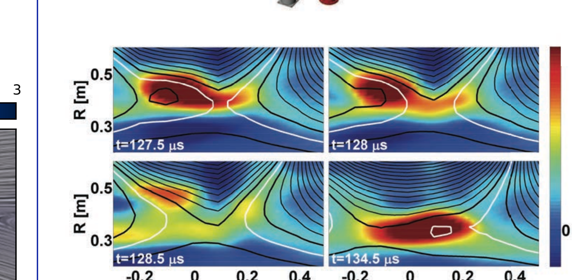
Driving Coils Drive Reconnection Effectively with Plasmoids

Collisional Plasmoids on MRX
(Princeton Plasma Physics Laboratory)



Collisionless Plasmoids on TREX
(University of Wisconsin – Madison)

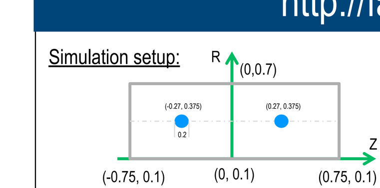




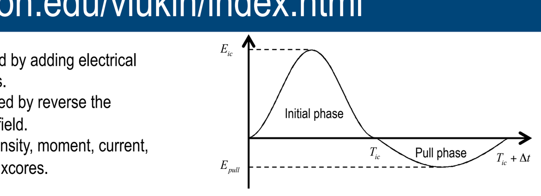
Modeling using HiFi code* by Y. Chen, V.S. Lukin, E. Meier +

*http://faculty.washington.edu/vlukin/index.html

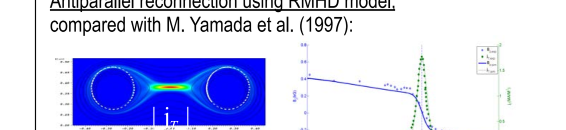
Simulation setup:



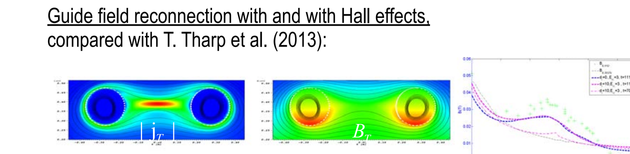
- Magnetic field generated by adding electrical field inside the fluxcores.
- Pull reconnection realized by reverse the direction of the electric field.
- Sink/source used for density, moment, current, and pressure around fluxcores.



Antiparallel reconnection using RMHD model, compared with M. Yamada et al. (1997):



Guide field reconnection with and with Hall effects, compared with T. Tharp et al. (2013):



Proposed Research Program

- Operate as a DoE Office of Science user facility
  - Does not compete with private sectors
  - Open to all interested users regardless nationality or institutional affiliation
  - Allocation of facility times determined by merit review of proposed experiments
  - No user fees unless proprietary work
  - Support user safety and use efficiency
  - Support a formal User Organization for representing users, sharing information, forming collaborations, future diagnostics and upgrades etc.
- Governed by PI and Steering Committee (4 Co-PIs, PPPL director, User Organization chair, 2 senior physicists)
- Users submit funding proposals to funding agencies
- Collaborate and coordinate with other intermediate-scale laboratory experiments

Fabrication is funded by NSF, Princeton U., U. Wisconsin, and U. Maryland. Facility support is provided by DoE Fusion Energy Sciences Office