FLARE: A New User Facility to Study Multiple-Scale Physics of Magnetic Reconnection through *in-situ* Measurements

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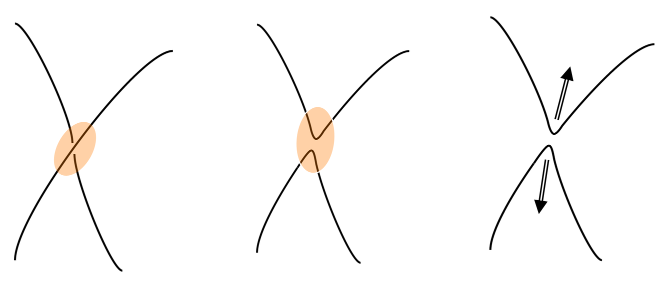
What Is Magnetic Reconnection?

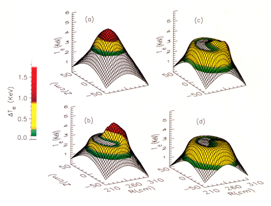
Local picture:



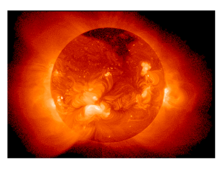
Two Key Features:
- Topological rearrangement of magnetic field lines
- Dissipation of magnetic energy to plasma energy

Where Does It Occur and Why Is It Important?

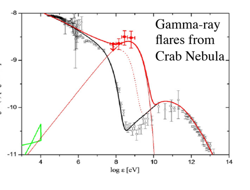
Laboratory fusion plasmas: Confinement degradation



Solar plasma: Flares and corona heating



Magnetospheric plasma: Cause of aurora & substorms



Astrophysical plasmas: Particle energization

Outstanding Major Scientifc Questions

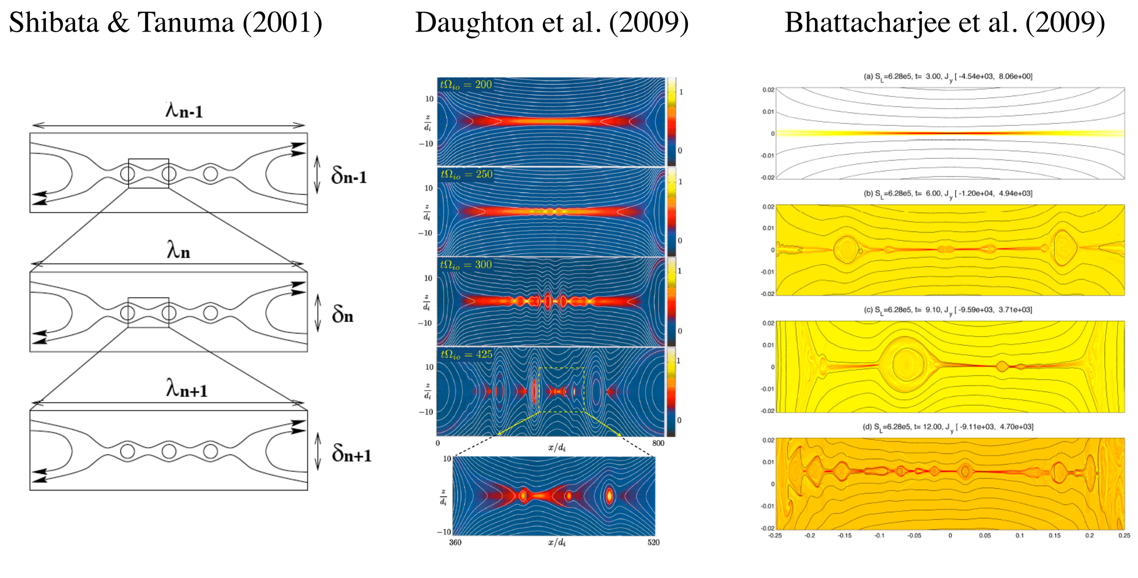
- **How is reconnection rate determined?** (*The rate problem*)
- **How does reconnection take place in 3D?** (*The 3D problem*)
- **How does reconnection start?** (*The onset problem*)
- **How does partial ionization affect reconnection?** (*The partial ionization problem*)
- **How do boundary conditions 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*)

Past, Present, and Future Lab Experiments

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, multiple-scale
MAGPIE Z-pinch	London	2015	Lebedev	Linear	Energy
KRX	Hefei, China	2017	Xie, Lu	Linear	Electron diffusion region
TS-U	Tokyo	2017	Ono	Toroidal	Energy
FLARE	Princeton	2017	Ji +	Toroidal	All
AREX-3D	Harbin, China	2019	E, Mao, Ren +	3D	3D, energy

Why FLARE?

Plasmoid Dynamics May Solve Scale Separation Problem

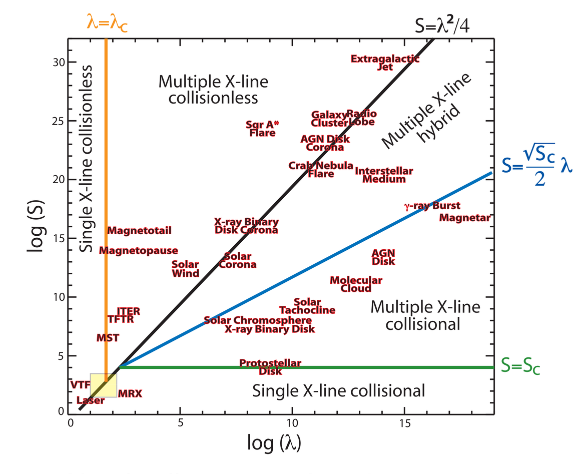


Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….

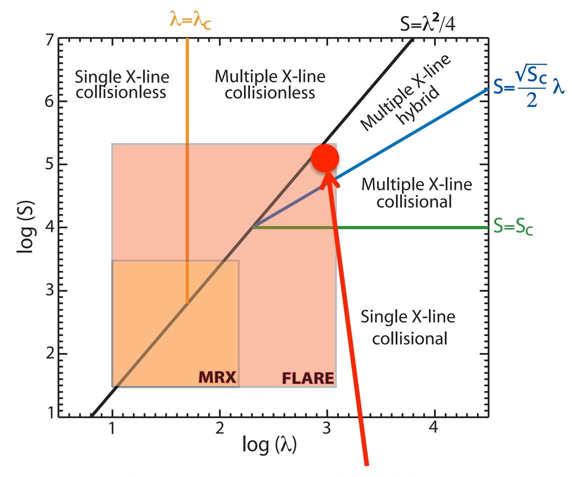
"Phase Diagram*" for Different Coupling Mechanisms

*H. Ji & W. Daughton, PoP **18**, 111207 (2011)

$S = \mu_0 L_{CS} V_A / \eta_S$; $L_{CS} = L/4$; $\lambda = L/\rho_S$



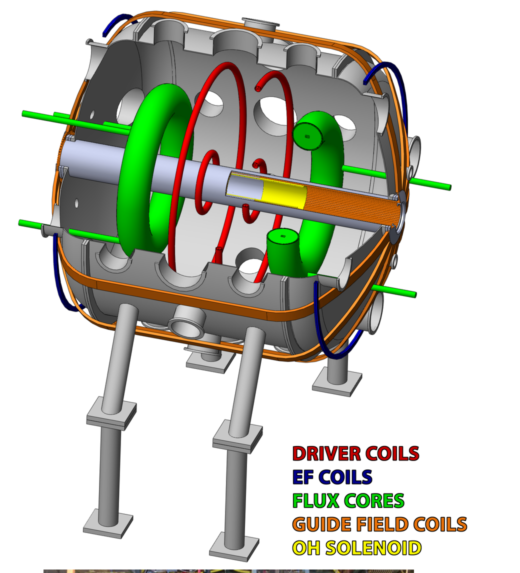
Nearly all reconnection phenomena fall into multiple X-line phases

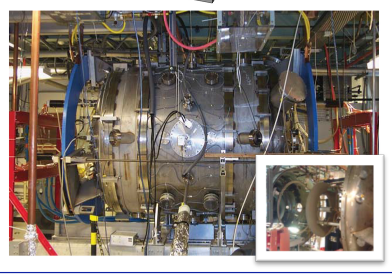


Design target for FLARE to access all reconnection phases

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	5.4 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





MRX(Magnetic Reconnection Experiment, mrx.pppl.gov)
Operational Since 1995 at Princeton

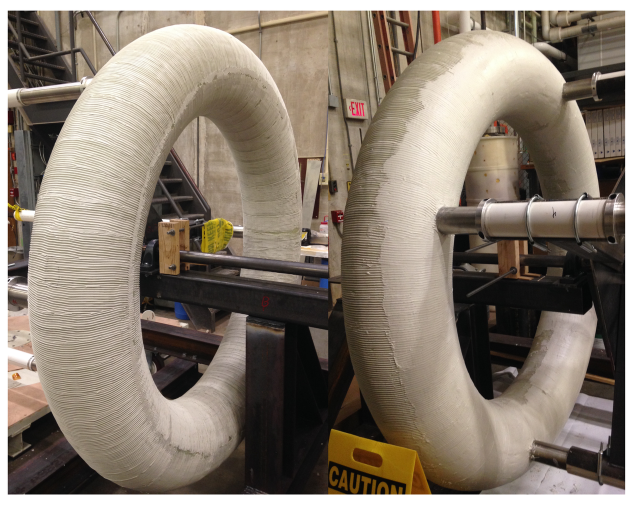
Status of FLARE Project

- Hardware design optimization & finalization: complete
- Major hardware components (EF coils, OH coils, flux cores, center stack, and vacuum vessel): delivered
- Hardware assembly and testing complete by April 2017
- Power system: design completed
- Power system for first plasma: installation by March 2017
- First plasma: predicted in summer 2017
- Installation at Princeton Plasma Physics Lab (PPPL) in 2017
- Power system and facility upgrade for full capabilities
- Commissioning of operation and diagnostics
- User research begins in 2018

Pictures, Pictures, Pictures….

Vacuum chamber

4 EF coils



2 flux cores

2 OH coils

Center stack

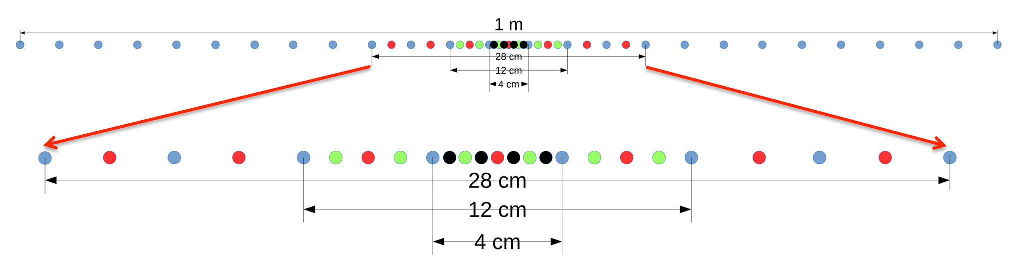
Krucker et al. (2010)

Why You Should Use FLARE?

- If you are a basic plasma physicist or a fusion plasma physicist, FLARE can provide a state-of-the-art platform for laboratory research on reconnection and related phenomena with in-situ coverage over multiple scales (MHD, ion and electrons).
- If you are a space plasma physicist,
  - FLARE can test and contribute on local kinetic physics.
  - FLARE can also provide global MHD physics that is missing from your in-situ measurements, but needed to study external causes and global consequences.
- If you are a solar physicist or an astrophysicist,
  - FLARE can test and contribute on global MHD physics.
  - FLARE can also provide local kinetic physics that is missing from your remote-sensing measurements, but needed to explain the observed energetic particles.

FLARE Research Diagnostics

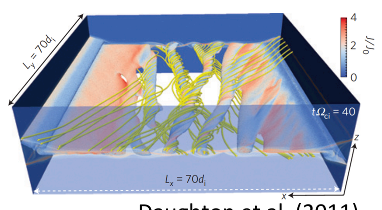
- The main diagnostics: a massive magnetic probe array to cover 1 m and maximum resolution of 5 mm. (MHD scale: ~ 1m; Ion scale: 2-12 cm; Electron scale: 0.5-3 mm)
  - 129 coils in one probe; 15 axial locations: 129 × 15 = 1935 total coils.
  - Covers 42 cm (84 cm) in axial direction with 3 cm (6 cm) resolution.
- Users will be able to select the 1024 coils to digitize at 50MHz (>2 f_{LH}).



Other diagnostics: Langmuir/Mach probe, ion/neutral spectroscopy, high-f probe,…
Possible future advanced diganostics: Thomson scattering, turbulence imaging, …

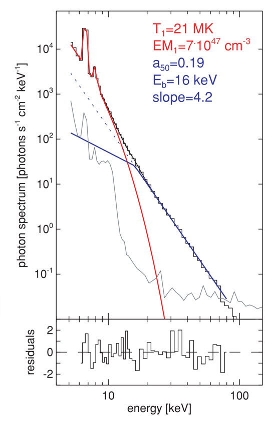
An Initial List of Possible Research Topics

- 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



Daughton et al. (2011)

- 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 stochasticity?
  - 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



Krucker et al. (2010)

- Partial ionization
  - Modification of multiple-scale reconnection by neutral particles
  - Neutral particle heating and acceleration

FLARE as a DoE Office of Science User Facility

- Open to all interested users regardless nationality or institutional affiliation.
- Allocation of facility times through merit review of proposed experiments.
- No user fees unless proprietary work.
- Provide sufficient resources for experimental efficiency and user safety.
- Support a formal User Organization (UO) for representing users, sharing information, forming collaborations, future diagnostics and upgrades etc.
- Science Advisory Committee to advise on science goals, priorities and opportunities.
- Facility Scheduling Committee to review machine time proposals and allocate time.
- Users: (1) submit a Notice of Intent, (2) receive feedback, (3) submit machine time proposal, (4) review by Fac. Sch. Com., (5) time allocation, (6) perform experiment.
- Initial operation: to commission the facility to develop and demonstrate operational and diagnostics capabilities, involving users as much as possible.
- Collaborate and coordinate with other intermediate-scale laboratory experiments.

FLARE is a best project demonstrating the partnership spirit between NSF and DoE in plasma physics:

Fabrication is funded by NSF, Princeton U., U. Wisconsin, and U. Maryland. Facility support, diagnostics, and operation is/will be provided by DoE Fusion Energy Sciences.

20TH ANNIVERSARY WORKSHOP FOR THE NSF/DOE PARTNERSHIP IN BASIC PLASMA SCIENCE AND ENGINEERING, January, 2017