FLARE: A Collaborative User Facility to Study Magnetic Reconnection and Related Phenomena

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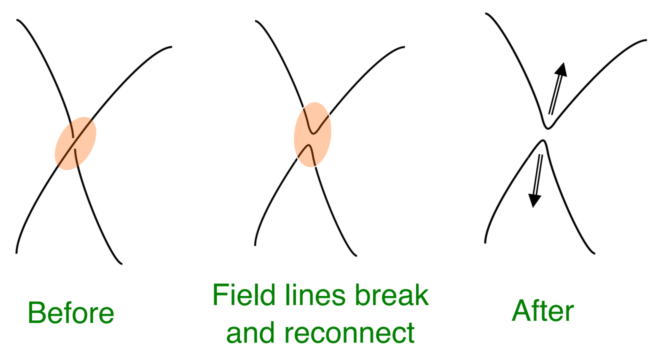
Abstract

The FLARE device (Facility for Laboratory Reconnection Experiments; http://flare.pppl.gov) is a new experiment constructed at Princeton University for the study of magnetic reconnection in the multiple X-line regimes, directly relevant to space, solar, astrophysical, and fusion plasmas. The first plasma operation was successfully conducted to validate the engineering design and to demonstrate access to parameter space beyond its predecessor, Magnetic Reconnection Experiment (MRX). The device has been relocated to PPPL to be installed while the power supplies are being upgraded to access new multiple X-line regimes in the reconnection phase diagram [Ji & Daughton, Phys. Plasmas **18,** 111207 (2011)]. A progress update including available diagnostics and the operation plan as a DoE collaborative user facility will be presented.

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

Major Scientific Challenges*

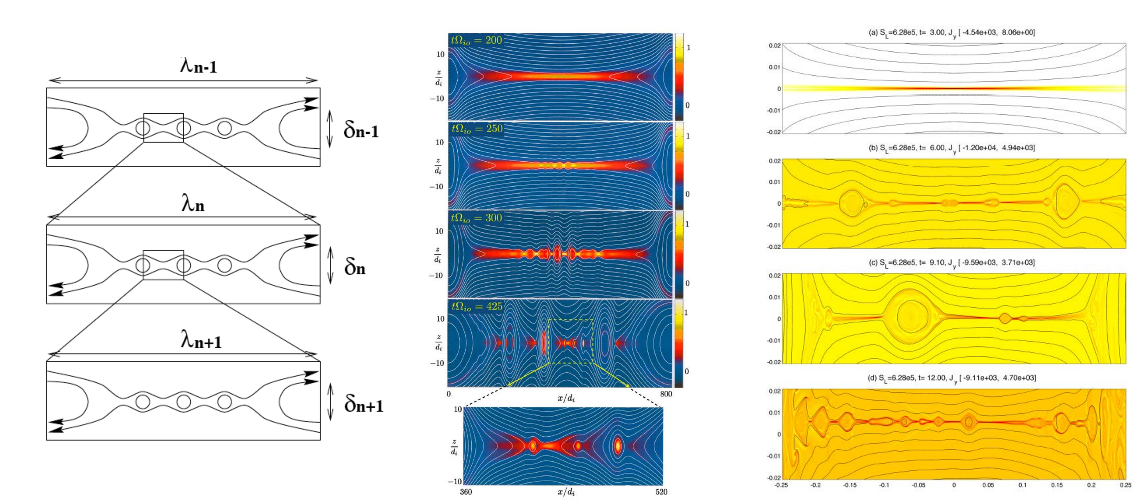
1. The multi-scale problem: How does the local reconnection physics, often on the kinetic scales, couple to the global MHD scales? What roles does turbulence via plasmoid instability of reconnecting current sheet play?
2. The 3D problem: How does reconnection take place in 3D? What roles do complex intertwining "flux ropes" in the large-scale current sheet play? How fast reconnection is related self-organization phenomena, such as Taylor relaxation?
3. The energy conversion problem: How are charged and neutral particles heated at the expense of magnetic energy, and how are they accelerated to non-thermal energies?
4. The boundary problem: How do boundary conditions affect reconnection process? Do the line-tying and driving from the boundaries, including their symmetries, fundamentally alter reconnection physics in the periodic systems?
5. The onset problem: How does reconnection start? Is the onset mechanism a 2D or 3D phenomena? Does it occur locally and spontaneously or driven globally?
6. The partial ionization problem: How does partial ionization affect reconnection? Does it accelerate or slow done the reconnection process?
7. The flow-driven problem: What roles reconnection plays in flow-driven systems in terms of turbulence and transport?
8. The extreme problem: How does reconnection take place under extreme conditions, such as intense radiation and strong magnetic, near compact astrophysical objects?
9. The multi-process problem: How do the multiple plasma processes, such as turbulence, shock, and reconnection, are interconnected to change magnetic topology, release energy from large scale field and flow, and heat the plasma?
10. The explosive phenomena problem: How, and under what conditions, explosive phenomena take place through both linear and nonlinear global MHD instabilities?

* H. Ji, et all., "Major scientific challenges and opportunities in Understanding Magnetic Reconnection and Related Explosive Phenomena throughout the Universe", white paper submitted to Plasma 2020 and Astro 2020 Decadal Surveys (2019).

Why FLARE?

Plasmoid Dynamics May Solve Scale Separation Problem

Shibata & Tanuma (2001) — Daughton et al. (2009) — Bhattacharjee et al. (2009)

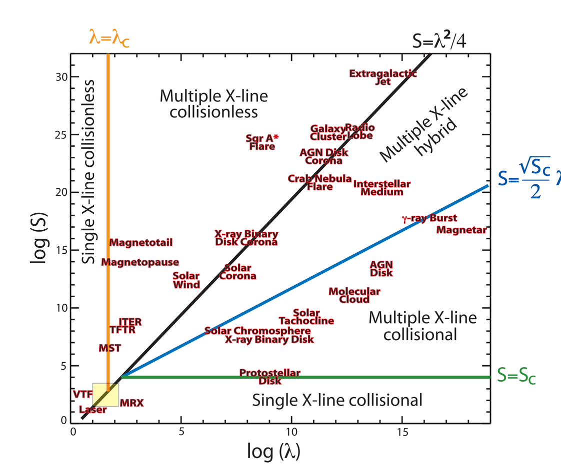


Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….

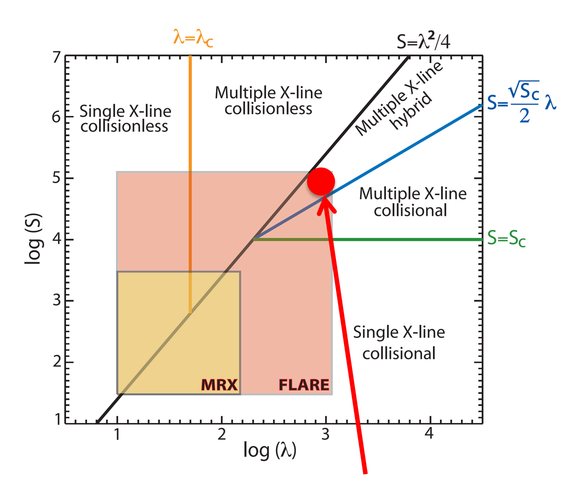
"Phase Diagram*" for Different Coupling Mechanisms

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

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



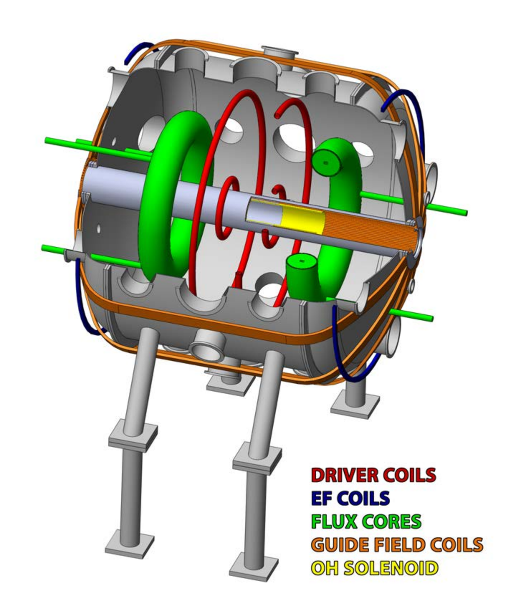
Nearly all reconnection phenomena fall into multiple X-line phases



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	~30 kJ	~6 MJ
Ohmic heating/drive	No	0.3 V-s
Guide field	0.1 T	0.5 T
S (anti-parallel)	600-1,400	5,000-16,000
$\lambda=(Z/\delta_i)$	35-10	100-30
S (guide field)	2,900	100,000
$\lambda=(Z/\rho_S)$	140	1,000



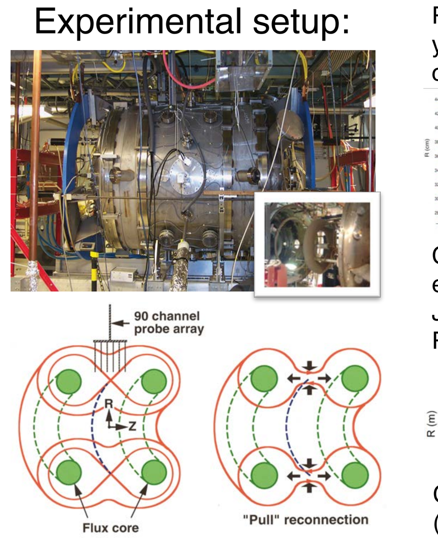
$$S = 1.09\times 10^5 \left(\frac{L}{1.6m}\right)\left(\frac{B_{rec}}{0.1T}\right)\left(\frac{n}{10^{19}}\right)^{-1/2}\left(\frac{T_e}{30eV}\right)^{3/2}$$

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

MRX*(Magnetic Reconnection Experiment) Since 1995

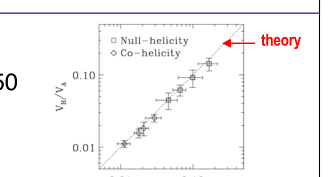
*http://mrx.pppl.gov

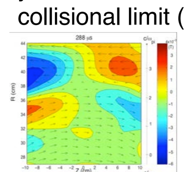
Experimental setup:



Key results:

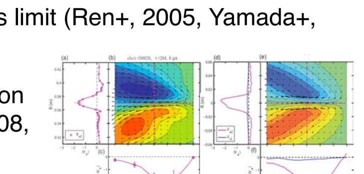
Proved classical Sweet-Parker theory 50 years later in a real plasma in the collisional limit (Ji+, 1998, 1999)

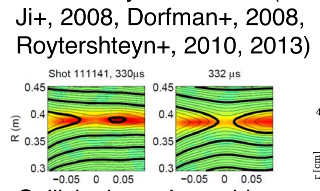




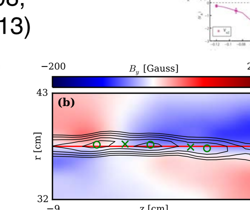
Confirmed two-fluid effects for fast reconnection in the collisionless limit (Ren+, 2005, Yamada+, 2006)

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





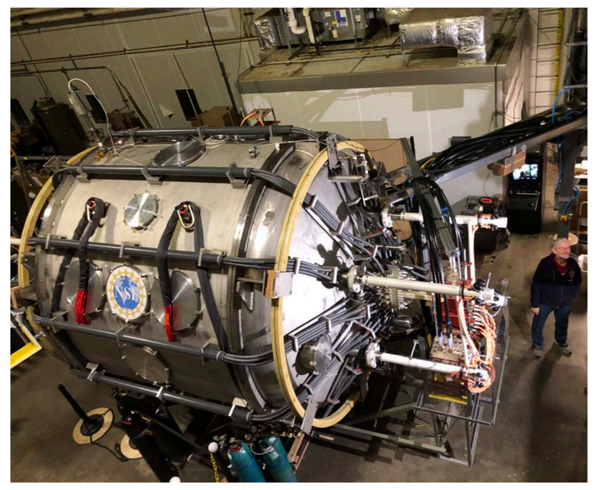
Collisionless plasmoids (Dorfman+, 2013, 2014)



Collisional electron-scale plasmoids (Jara-Almonte+, 2016)

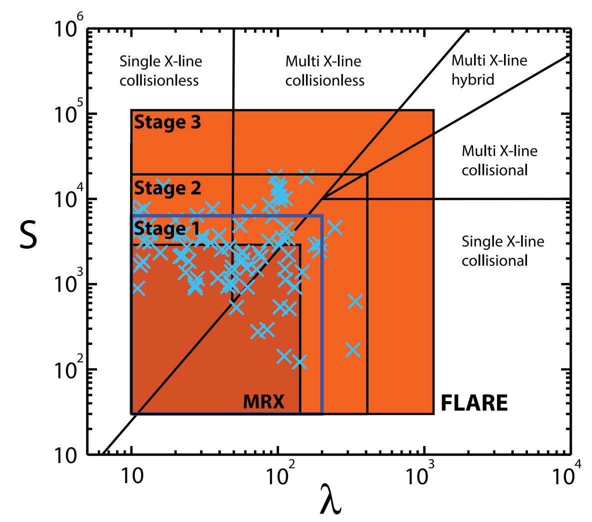
Also: (1) lower-hybrid waves (Carter+ 2001,2002, Ji+ 2004, Roytershteyn+ 2013); (2) guide field effects (Tharp+ 2012, 2013); (3) partial ionization (Lawrence+ 2013); (4) ion heating, energy conversion and partition (Yoo+ 2013, 2014, Yamada+ 2014, 2015); (5) asymmetric reconnection (Yoo+ 2014); (6) Arched flux rope stability (Oz+ 2012, Myers+ 2015); (7) Two-fluid effects during fast guide field reconnection (Fox+ 2017)

FLARE Successfully Constructed and Operated



- Vessel and vacuum systems
- A pair of flux cores including Toroidal Field (TF) and Poloidal Field (PF) coils, a Guide Field (GF) coil system, a pair of Ohmic Heating (OH) coils, and two pairs of Equilibrium Field (EF) coils
- Stage-1 power supplies: one capacitor bank for each of EF, GF, TF and PF coil systems
- Control and safety systems

- Explored a wide parameter space (H_2, D_2, & He gases at different fill pressures, with & without guide field)
- Validated FLARE design principles (flux cores, guide field coil, capacitor banks, operational sequences etc).
- Exceeded predicted performance of Stage-1 power supplies (capacitor banks)



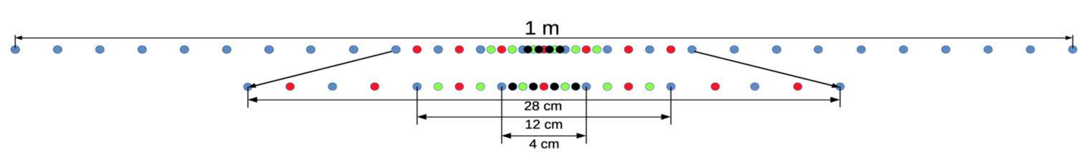
FLARE Installation at PPPL with Upgrades

- Relocate and install FLARE device at PPPL
- Upgrade power supplies (capacitor banks and control) with Stage-3 capabilities
- Provide infrastructure (platform, control room, enclosures, cooling water, network etc)
- Install and test initial set of diagnostics (more below)
- Scheduled to finish ready for research between November 1, 2020 and April 1, 2021.

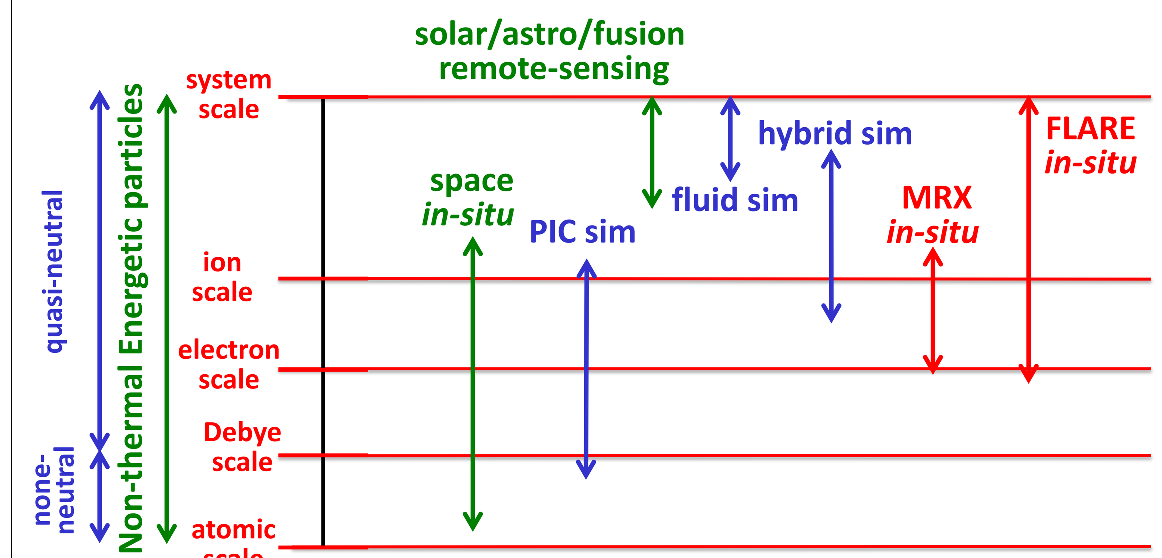
FLARE at C-S high-bay of PPPL August 29, 2019

Unique *in-situ* Diagnostics Over Multiple Scales: System MHD Scale, Ion Scale, & Electron Scale

- 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}).

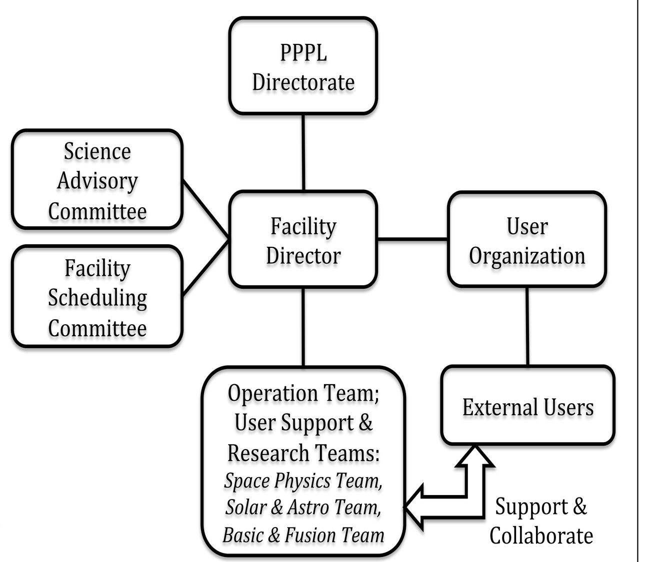


- Other diagnostics: Langmuir/Mach probe, spectroscopy, high-f probe…



FLARE Operation and Organization

- FLARE will be operated as a collaborative user facility.
- Open to all users regardless nationality or institution.
- Steps by users: (1) submit a Notice of Intent, (2) receive feedback, (3) submit machine time proposal, (4) review by Facility Scheduling Committee based on merits and feasibilities, (5) time allocation, (6) perform experiment.

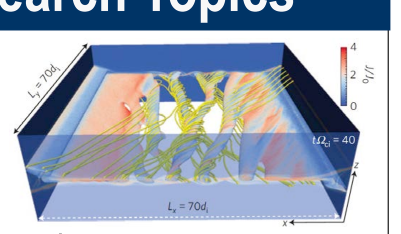


- Science Advisory Committee advise on goals, priorities & opportunities.
- Support a formal User Organization for representing users, sharing information, forming collaborations, future diagnostics and upgrades.
- Three User Support & Research Teams, each engaging users from corresponding field(s):
  1. Space Physics Team (Jongsoo Yoo, jyoo@pppl.gov)
  2. Solar & Astrophysics Team (Jon Jara-Almonte, jjaraalm@pppl.gov)
  3. Basic & Fusion Plasma Physics Team (Yang Ren, yren@pppl.gov)
- Closely associated with a Theory and Simulation Team.
- Potential users can visit http://flare.pppl.gov & email to hji@pppl.gov or any other FLARE team members.

Why Should You 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).
  - Supported by the Basic & Fusion Plasma Physics Team
- If you are a space 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.
  - Supported by the Space Physics Team
- 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.
  - Supported by Solar & Astrophysics Team

An Initial List of Possible Research Topics



Daughton et al. (2011)

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

Krucker et al. (2010)