

The FLARE Device and Its First Plasma Operation

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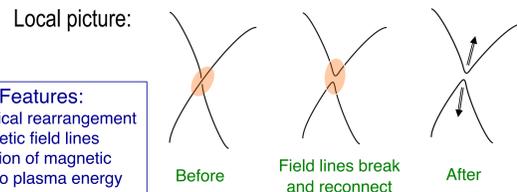
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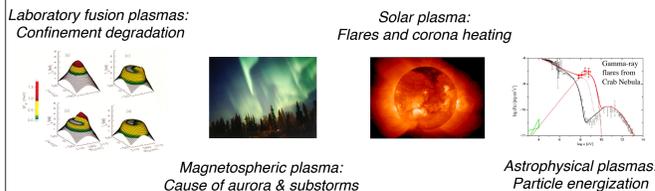
Abstract

The FLARE device (Facility for Laboratory Reconnection Experiments; <http://flare.pppl.gov>) is a new laboratory experiment constructed at Princeton for the studies of magnetic reconnection in the multiple X-line regimes directly relevant to space, solar, astrophysical, and fusion plasmas, as guided by a reconnection phase diagram [Ji & Daughton (2011)]. The first plasma operation was successfully conducted to validate its engineering design and to demonstrate its experimental access to the parameter space beyond its predecessor, MRX (Magnetic Reconnection eXperiment; <http://mrx.pppl.gov>). Details on construction completion and first plasma results will be presented; future operation plans - possibly as a user facility - and research plans will be discussed.

What Is Magnetic Reconnection?



Where Does It Occur and Why Is It Important?



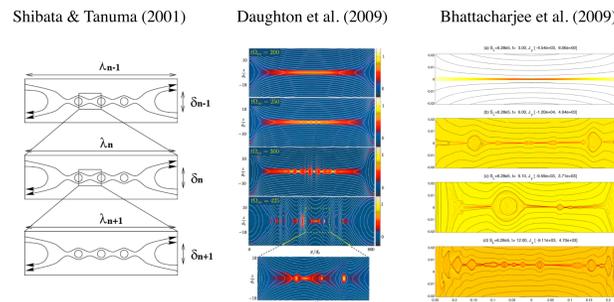
Outstanding Questions & Lab Experiments

- 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	2013	Gruelke, Klinger	Linear	3D
TREX	Wisconsin	2014	Egedal, Forest	Toroidal	Energy, multiple-scale
MAGPIE Z-pinch	London	2015	Lebedev	Linear	Energy
Mirror, KRX	Hefei, China	2017	Sun/Xie +	Linear	Electron diffusion region
TS-U	Tokyo	2017	Ono	Toroidal	Energy
FLARE	Princeton	2018	Ji +	Toroidal	All
AREX-3D	Harbin, China	2019	E. Ren, Mao +	3D	3D, energy

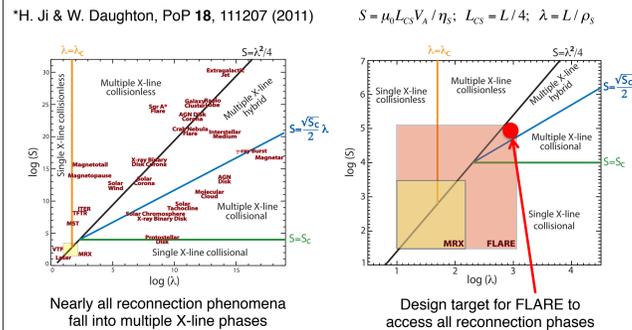
Why FLARE?

Plasmoid Dynamics May Solve Scale Separation Problem



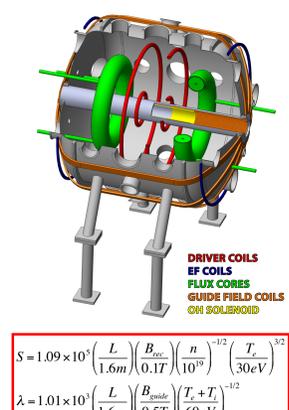
Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ...

"Phase Diagram*" for Different Coupling Mechanisms



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
$\lambda = (Z/\delta)$	35-10	100-30
S (guide field)	2,900	100,000
$\lambda = (Z/\rho_s)$	140	1,000



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

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

MRX* (Magnetic Reconnection Experiment) Since 1995

*<http://mrx.pppl.gov>

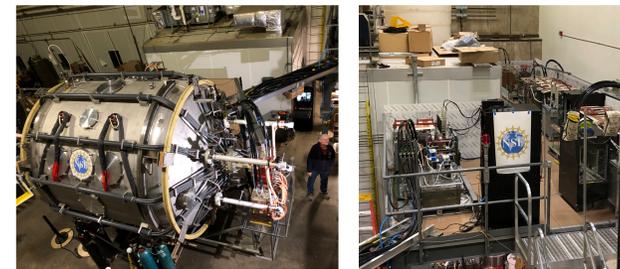
Experimental setup:

Key results:

- Proved classical Sweet-Parker theory 50 years later in a real plasma in the collisionless 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)

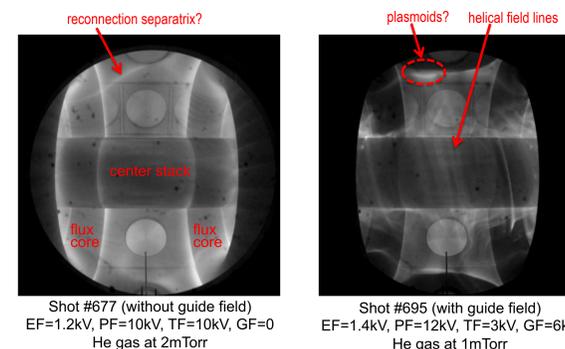
FLARE Successfully Constructed



- Vessel and vacuum systems
- Coil 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

FLARE First Plasma Operation

- A period of 6 days (March 4-9, 2018) after thorough preparations
- Total 100 hour operation with >700 shots, over 2 shifts each day
- First plasma successfully generated on Sunday, March 4 at 8:13pm
- Visible light image of Shot #320, EF=0.8kV, PF=7kV, TF=7kV, GF=0, with He gas at 4mTorr



Operation Parameters Exceeded Targeted Stage-1 Physics Capabilities

- Explored a wide parameter space (H₂, D₂, & He gases at different fill pressures, with & without guide field)
- Validated FLARE design principles (flux cores, guide field coil, capacitor banks, operational sequences etc).
- Established confidence on access of Stage-3 physics capabilities by adding more capacitor banks.
- Example:

Shot #874 (without guide field)
EF=0, PF=13kV, TF=10kV, GF=0
Hydrogen gas at 3mTorr

PF & TF Current Waveforms:

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_{UH}).
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- Other diagnostics: Langmuir/Mach probe, spectroscopy, high-f probe...

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)**.
- 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.
- 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.

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

FLARE Installation, Operation & Research

- Proposed to DoE to move FLARE from storage and install at PPPL with upgraded capacitor banks and diagnostics capabilities.
- Operate for research either as a user facility or a research project.
- If user facility, open to all users regardless nationality or institution.
- Facility Scheduling Committee review machine time proposals and to allocate time based on merit review of proposed experiments.
- 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: (1) Space Physics Team, (2) Solar & Astrophysics Team, and (3) Basic & Fusion Plasma Physics Team, each engaging users from corresponding field(s).
- Potential users can visit <http://flare.pppl.gov> & email to hi@pppl.gov