

Introducing a New DoE Collaborative Research Facility: FLARE

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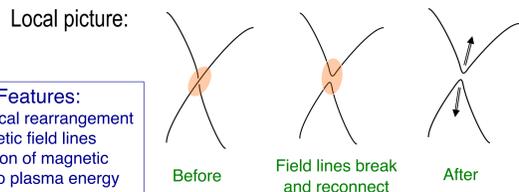
Overview

The FLARE (Facility for Laboratory Reconnection Experiments; www.pppl.gov/FLARE)^{*} is a new experiment for the study of magnetic reconnection in the multiple X-line regimes in the reconnection phase diagram [1], directly relevant to space, solar, astrophysical, and fusion plasmas. The design is based on the highly successful predecessor, MRX (Magnetic Reconnection Experiment; mrx.pppl.gov). The original device was constructed and tested on the main campus of Princeton University and was subsequently installed at PPPL with a major upgrade of the power suppliers and a full set of initial diagnostics. The first plasmas were successfully generated on April 14, 2025 and initial operations began on June 1, 2025. Detailed facility capability, initial results, and research topics are presented.

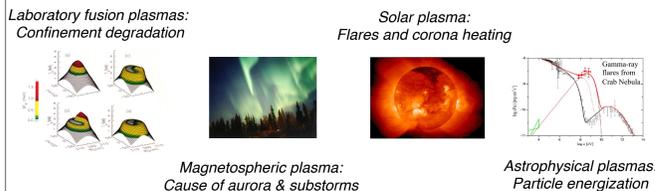
^{*} FLARE was developed through funding from DOE under contract # DE-AC02-09CH11466 and Princeton University. The initial FLARE instrument construction was funded by the National Science Foundation Major Research Instrument grant PHY-1337831 and Princeton University, as well as contributions from the University of Wisconsin-Madison and the University of Maryland. Initial operation is supported by DOE under contract #DE-AC02-09CH11466.

[1] H. Ji and W. Daughton, *Physics of Plasmas* **18**, 111207 (2011).

What Is Magnetic Reconnection?



Where Does It Occur and Why Is It Important?



Progress in Magnetic Reconnection Research^{*}

- Phase I (1950s-1990s)**
 - Focus on MHD/fluid physics – **reconnection rate**
 - Sweet-Parker model vs Petschek model
 - Solar observations (e.g. Yokohoh), MHD modeling, laboratory fusion (e.g. tokamaks) and basic plasma experiments (e.g. LAPD, MRX)
- Phase II (1990s-2020s)**
 - Focus on physics beyond MHD – **rate and dynamics**
 - In-situ observations (e.g. Cluster, MMS), Hall MHD/2-fluid/kinetic modeling, laboratory basic plasma experiments (e.g. MRX, VTF/TREX)
- Phase III (2020s-)**
 - Physics across MHD and kinetic scales – **multiscale, energy and onset**
 - Multiscale observations (e.g. Plasma Observatory, multiscale computing, and multiscale laboratory experiments (e.g. FLARE))

^{*} H. Ji, W. Daughton, J. Jara-Almonte, A. Le, A. Stanier, J. Yoo, *Nature Reviews Physics* **4**, 263 (2022).

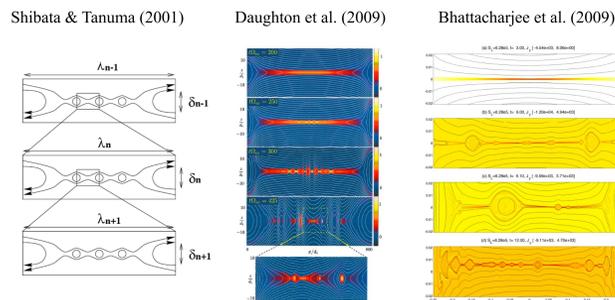
Major Scientific Challenges^{*}

- Multi-scale problem:** How does reconnection couple global fluid scales to local kinetic scales?
- 3D problem:** How does reconnection take place in 3D?
- Energy problem:** How are charged and neutral particles heated and accelerated?
- Boundary problem:** How do boundary conditions affect reconnection process?
- Onset problem:** How does reconnection start?
- Partial ionization problem:** How does partial ionization affect reconnection?
- Flow-driven problem:** What roles does reconnection plays in flow-driven systems which sometimes generate magnetic fields themselves?
- Turbulence and shock problem:** What role does reconnection play in related processes such as turbulence, shocks and transport?
- Related explosive phenomena:** How does magnetic reconnection act either as a driver or as a consequence of explosive phenomena such as solar flares and coronal mass ejections?
- Extreme condition problem:** How does reconnection take place under extreme astrophysical conditions such as intense radiation and relativistic velocities?

^{*} H. Ji, et al., "Major scientific challenges and opportunities in Understanding Magnetic Reconnection and Related Explosive Phenomena throughout the Universe", white paper submitted to *Plasma* 2020, *Astro* 2020, *Heliophysics* 2024 Decadal Surveys.

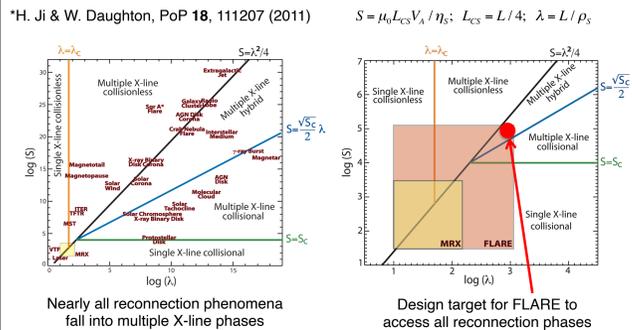
Why FLARE?

Plasmoid Dynamics May Solve Scale Separation Problem



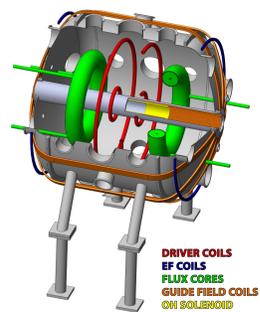
Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ...

"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	~0.2 MJ	~6.5 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
λ=(Z/δ)	35-10	100-30
S (guide field)	2,900	100,000
λ=(Z/ρs)	140	1,000



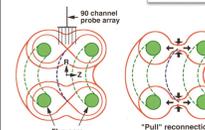
$$S = 1.09 \times 10^3 \left(\frac{L}{1.6m} \right) \left(\frac{B_{vc}}{0.1T} \right) \left(\frac{n}{10^{20}} \right) \left(\frac{T_e}{30eV} \right)^{3/2}$$

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

MRX* (Magnetic Reconnection Experiment) (1995-present)

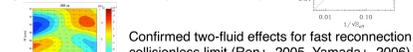
^{*} <http://mrx.pppl.gov>

Experimental setup:



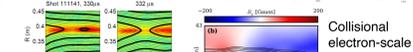
Key results:

Proved the classical Sweet-Parker theory 50 years after it was proposed, using a real plasma in collisional limit (Ji+, 1998, 1999)



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

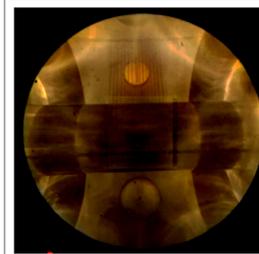
Challenged numerical simulations on electron layer thickness (Ren+, 2008, Ji+, 2008, Dorfman+, 2008, Roytershteyn+, 2010, 2013)



Collisionless plasmoids (Dorfman+, 2013, 2014)

Also: (1) lower-hybrid waves (Carter+ 2001, 2002, Ji+ 2004, Roytershteyn+ 2013, Yoo+ 2024); (2) guide field effects (Tharp+ 2012, 2013; Fox+ 2017, 2018); (3) partial ionization (Lawrence+ 2013); (4) ion heating, energy conversion and partition (Yoo+ 2013, 2014, Yamada+ 2014, 2015, Goodman+ 2023, Bose+ 2024); (5) asymmetric reconnection (Yoo+ 2014); (6) Arched flux rope stability (Oz+ 2012, Myers+ 2015, Alt+ 2023)

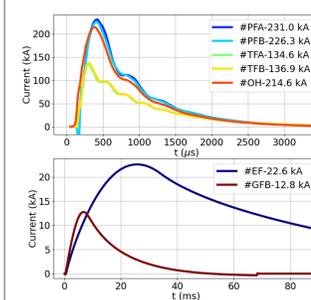
FLARE Successfully Commissioned



First plasmas achieved at PPPL on April 14, 2025:

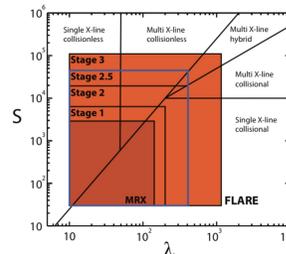
- Helium (fill pressure = 1.5 mTorr)
- Coil currents: PF=160 kA, TF=110 kA, EF=1.6 kA
- Camera exposure time: 1 μs
- Flux core separation (surface-to-surface): 1 m
- Coil connection: counter-helicity
- Filaments along TF windings visible

Current Key Device Capability



- Maximal coil currents:**
 - PF: 480 kA ($B_z \sim 1 \text{ kG}$ @ $Z=0\text{cm}$)
 - TF: 220 kA
 - EF: 23 kA ($B_z \sim 0.34 \text{ kG}$ @ $R=75\text{cm}$)
 - GF: 13 kA ($B_z \sim 1.6 \text{ kG}$ @ $R=75\text{cm}$)
 - OH: 170 kA (flux ~ 0.3 Weber)
- Available Operational Modes:**
 - Push vs pull vs merging reconnection
 - Anti-parallel vs guide field reconnection
 - Co- vs counter-helicity reconnection
 - Spheromak vs tokamak/ST merging
 - Field-Reversed Configuration (FRC)
 - Symmetries and boundary conditions

- Experimental flexibilities:**
 - Independently controllable PF/TF currents enables downstream asymmetry for pull reconnection
 - OH coils can heat plasma and/or aid reconnection drive.
- Plasma compositions**
 - Vacuum base pressure 6×10^{-7} Torr
 - Working gas: H_2 , D_2 , He, Ne, Ar
- Data acquisition:**
 - 1248 Ch with 40 MSamples/s
 - HSDS data server



Current capabilities at Stage 2.5 with total energy of ~3.6 MJ

- Compared with MRX (~0.2 MJ) and Stage 1 (~0.8 MJ)
- Stage 3 will be available with ~6.5 MJ by installing drive coils and guide field coil bracing after initial operations.

Available Diagnostics

A Massive Array of Magnetic Probes

- 128 coils in one probe; 15 axial locations: $128 \times 15 = 1920$ 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 40MS/s ($>2 f_{LH}$).

- Langmuir probes** for electron density & temperature; **Mach probes** for flow; **energy analyzers** for nonthermal electrons; **high-f fluctuation probes** (future)
- Interferometry** based on fiber at 1550-nm diode laser
- Optical diagnostics:** **fast camera**, **soft X-ray tomography** (future), **ion Doppler spectroscopy**, **Thomson scattering** (future)

Initial Operation & Research since June 1, 2025

- Establish reliable operational and diagnostics capabilities
- Focus on physics of multiple X-line kinetic reconnection
- Study of effects of downstream asymmetry directly relevant to magnetotail and solar flare reconnection
- Theoretical and numerical tools via collaborations
 - Kinetic simulations by VPIC
 - Fluid simulations by Gkeyll multi-moment, multi-fluid model
 - Hybrid (kinetic ions + fluid electrons)
 - MHD with embedded PIC (MHD-AEPIC)

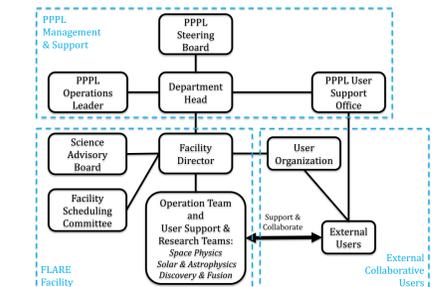
Initial Results Highlights

- In the process of establishing reliable operation/diagnostics capabilities
 - Record-long current sheets ($>45\text{cm}$) with ion-scale plasmoids observed
-

Near-term and Proposed Long-term Plans

- Until Nov 2026: Initial operations and research
- Dec 2026 - May 2027: Install drive coils and guide field structure bracing for Stage 3; Thomson scattering for thermal and nonthermal electrons, probe positioner, flux core mover, end bell removal; Major maintenance
- From Jun 2027: Operations and research at Stage 3 to uncover new multi-scale physics; establish external collaborative user program

FLARE Operation and Organization



- FLARE is a Collaborative Research Facility open to public/private users
- Run-time proposals selected based on merits and feasibilities
- Science Advisory Board advise on goals, priorities & opportunities.
- Support a formal User Organization for representing users.
- Three User Support & Research Teams, engaging different users:
 - Space Physics Team (Jongsoo Yoo, jyoo@pppl.gov)
 - Solar & Astrophysics Team (Sayak Bose, sbose@pppl.gov)
 - Discovery & Fusion Team (Peiyun Shi, pshi@pppl.gov)
- Closely associated with a Theory and Simulation Team.
- Potential users can visit <http://www.pppl.gov/FLARE> and/or email hji@pppl.gov or any other FLARE team members.

An Initial List of Possible Research Topics

- Multiple-scale**
 - Plasmoid instability and its scaling in MHD^{*}
 - Transition from MHD to kinetic^{*}
 - Scaling of kinetic X-lines
 - Guide field dependence of multiple-scale physics
- Reconnection rate**
 - Reconnection rate for multiple X-lines in MHD^{*}
 - Reconnection rate for multiple X-lines in kinetic
 - Reconnection rate for multiple X-lines in both MHD and kinetic^{*}
 - Upstream and/or downstream asymmetry effects
 - Guide field effects
- 3D**
 - Plasmoid instability in 3D: flux ropes?
 - Third dimension scaling: 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
 - Partition between electrons and ions
- Partial ionization**
 - Modification of multiple-scale reconnection by neutral particles
 - Neutral particle heating and acceleration

^{*} Feasible at Stage 3 after installing drive coils and GF structure bracing