# FLARE: A New User Facility for Studies of Multiple-Scale Physics of Magnetic Reconnection Through *in-situ* Measurements

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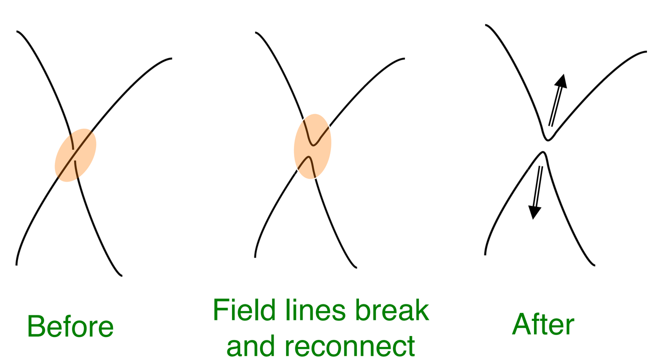
## Abstract

The FLARE device (Facility for Laboratory Reconnection Experiments; http://flare.pppl.gov) is a new laboratory experiment under construction 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 whole device have been assembled with first plasmas expected in the fall of 2017. The main diagnostics is an extensive set of magnetic probe arrays, currently under construction, to cover multiple scales from local electron scales (~2 mm), to intermediate ion scales (~10 cm), and global MHD scales (~1 m), simultaneously providing *in-situ* measurements over all these relevant scales. The plans and example topics as a user facility will be discussed.

## 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?


## 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*)**

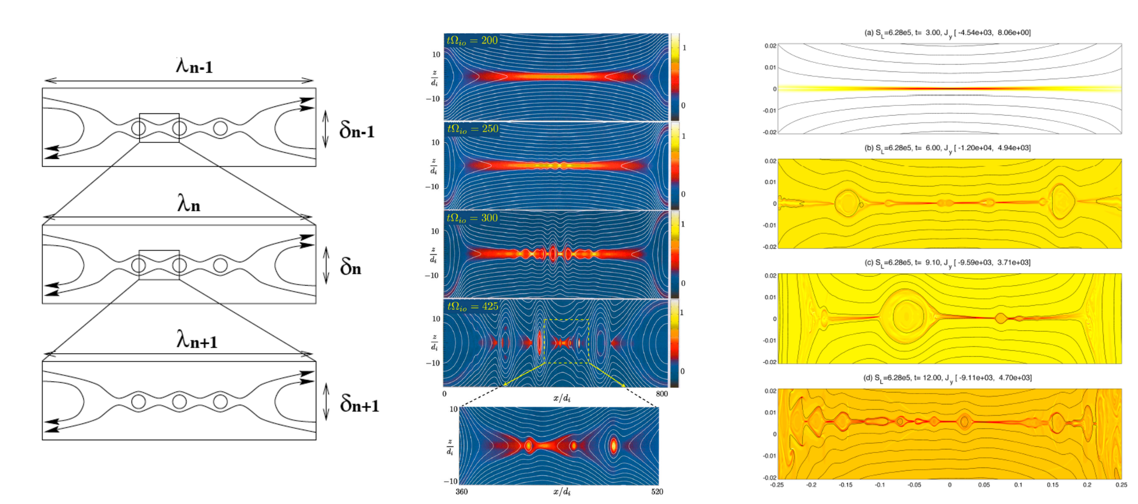
| *Device* | *Where* | *Since* | *Who* | *Geometry* | *Focus* |
|---|---|---|---|---|---|
| 3D-CS | Russia | 1970 | Syrovatskii, Frank | Linear | 3D, energy |
| LPD, LAPD | UCLA | 1980 | Stenzel, Gekelman | Linear | Energy, 3D |
| TS-3/4, MAST | Tokyo | 1990 | Katsurai, Ono | Merging | Rate, energy |
| 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 | Grulke, 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 | 2017 | Ji + | Toroidal | All |
| AREX-3D | Harbin, China | 2019 | E, Ren, Mao + | 3D | 3D, energy |



## Why FLARE?

### Plasmoid Dynamics May Solve Scale Separation Problem

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

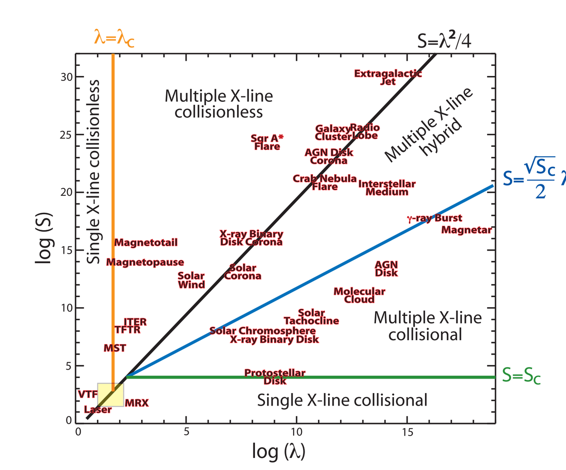


Many theoretical works: Loureiro et al. (2007); Cassak et al. (2009); Uzdensky et al. (2010) ….

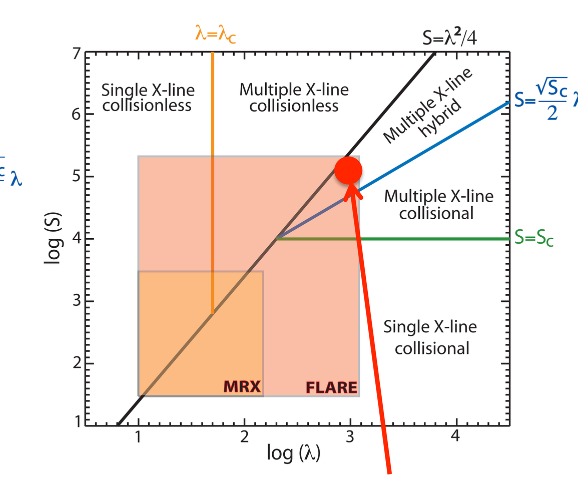
### "Phase Diagram*" for Different Coupling Mechanisms

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

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



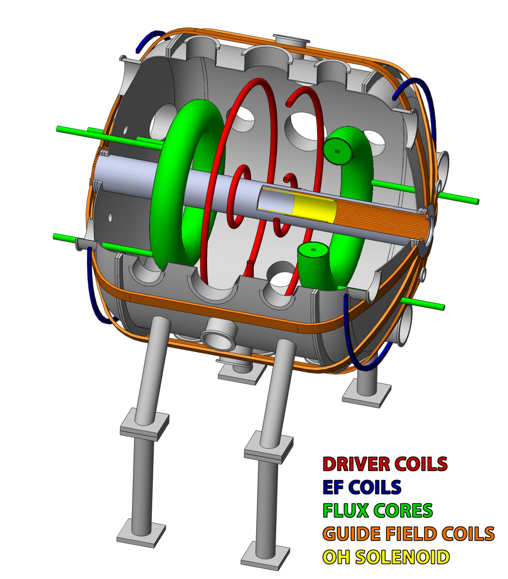
Nearly all reconnection phenomena fall into multiple X-line phases



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 | 25 kJ | 5.4 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$_i$) | 35-10 | 100-30 |
| S (guide field) | 3,000 | 100,000 |
| λ=(Z/ρ$_S$) | 200 | 1,000 |



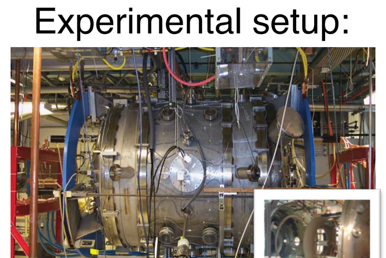

$$S = 1.09\times10^5 \left(\frac{L}{1.6m}\right)\left(\frac{B_{rec}}{0.1T}\right)\left(\frac{n}{10^{19}}\right)^{-1/2}\left(\frac{T_e}{30eV}\right)^{3/2}$$

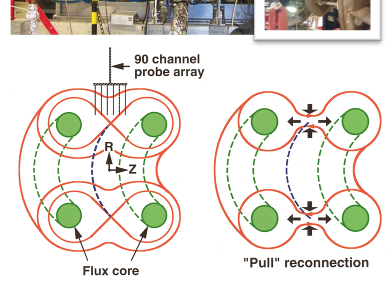
$$\lambda = 1.01\times10^3 \left(\frac{L}{1.6m}\right)\left(\frac{B_{guide}}{0.5T}\right)\left(\frac{T_e+T_i}{60eV}\right)^{-1/2}$$

### MRX*(Magnetic Reconnection Experiment) Operational Since 1995

*http://mrx.pppl.gov

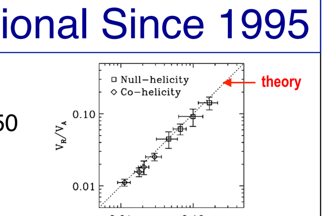
Experimental setup:

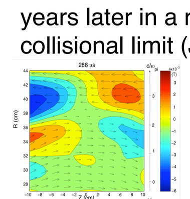





Key results:

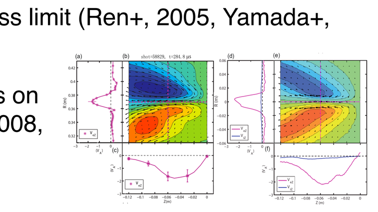
Proved classical Sweet-Parker theory 50 years later in a real plasma in the collisional limit (Ji+, 1998, 1999)

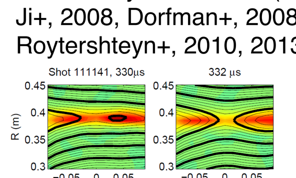


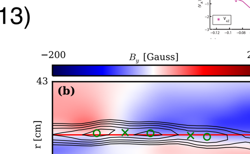
Confirmed two-fluid effects for fast reconnection in the collisionless limit (Ren+, 2005, Yamada+, 2006)

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





Collisionless plasmoids (Dorfman+, 2013, 2014)

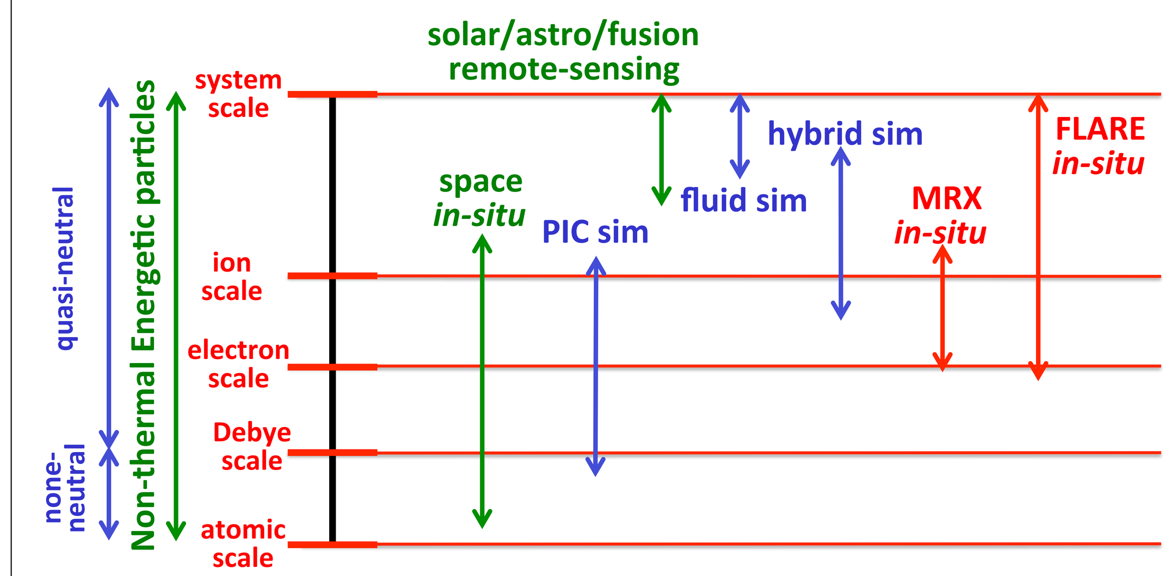


Collisional electron-scale plasmoids (Jara-Almonte+, 2016)

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, line-tied flux rope stability (Oz+ 2012, Myers+ 2015); (7) Two-fluid effects during fast guide field reconnection (Fox+ 2017)

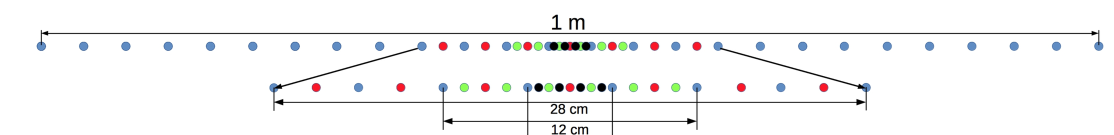
## *in-situ* Measurements Over Multiple Scales: System MHD Scale, Ion Scale, & Electron Scale

- Magnetic field
  - Local singularities: X-line, O-line, 3D null point, separatrix, separators…
  - Global properties: magnetic flux and helicity conservation, magnetic field line stochasticity…
- Thermal plasma
  - Global MHD physics
  - Local ion kinetic physics
  - Local electron kinetic physics
  - Microscopic Debye scale physics
- Non-thermal energetic particles
  - Integrate physics on all scales kinetically
  - A complete understanding requires physics on all scales



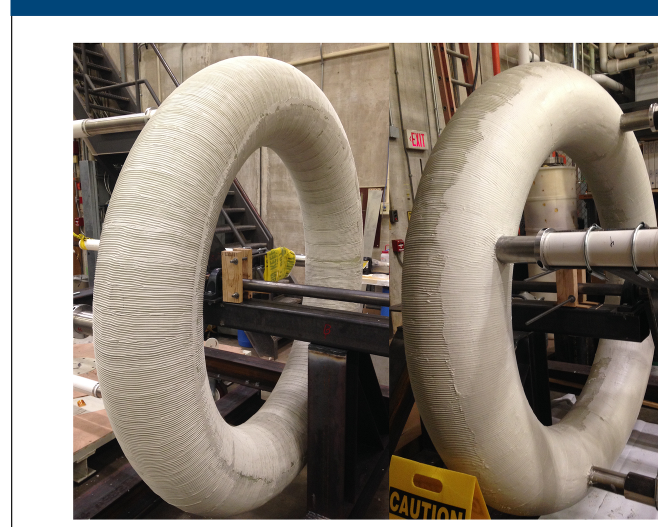

## FLARE Research Diagnostics

- 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 $f_{LH}$).

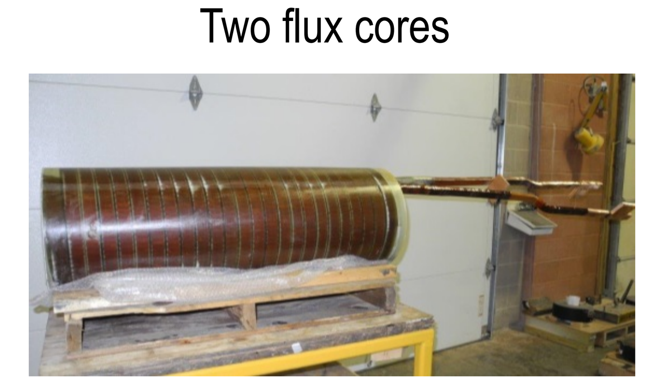



- Other diagnostics:
  - Langmuir/Mach probe, ion/neutral spectroscopy, high-f probe…
- Advanced diagnostics in the future:
  - Thomson scattering, tomographic ion Doppler spectroscopy…

## Internal Coil Systems



Two flux cores

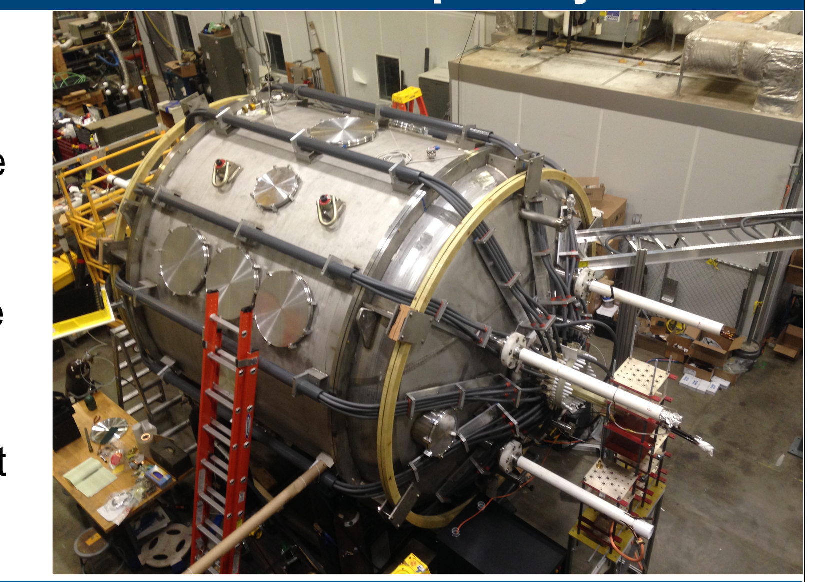


One of two OH coils

Center stack

## First Plasmas Are One Step Away!

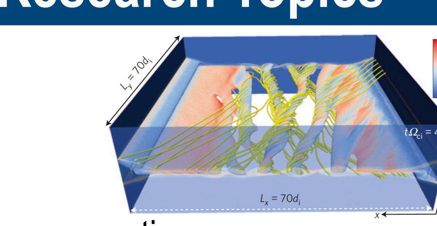
- Research quality vacuum achieved
- Capacitor banks are being tested
- Power cables and safety interlocks are being installed
- First plasmas are expected in the next months



## 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.

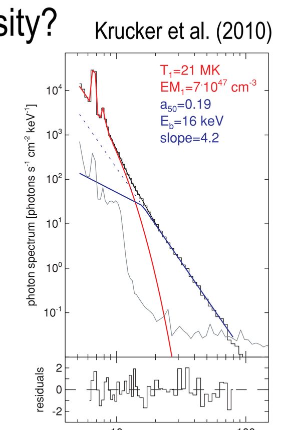
## An Initial List of Possible Research Topics



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

Krucker et al. (2010)




## FLARE Proposed as a DoE User Facility

- Open to all users regardless nationality or institutional affiliation.
- Steps by users: (1) submit a Notice of Intent, (2) receive feedback, (3) submit machine time proposal, (4) review by Facility Scheduling Committee, (5) time allocation, (6) perform experiment.
- 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 hji@pppl.gov