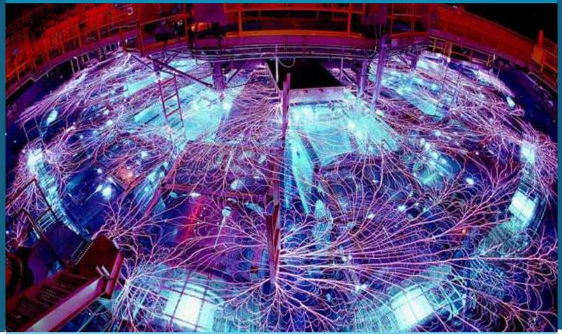
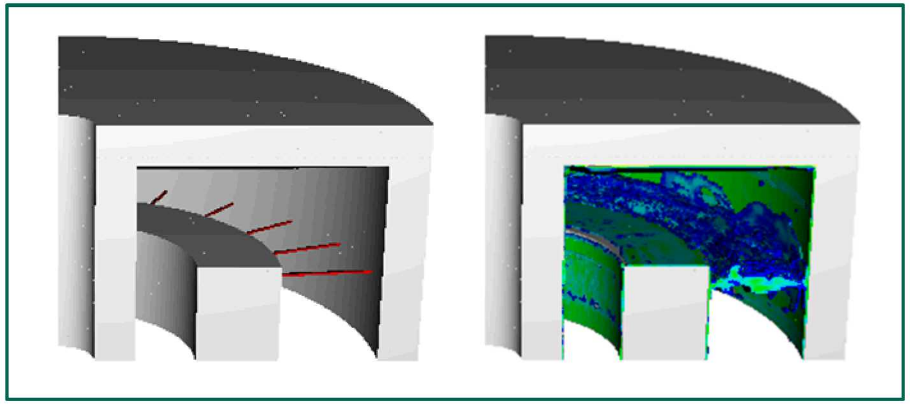
SAND2019-8437C

A magnetic reconnection fundamental science platform for Z





PRESENTED BY

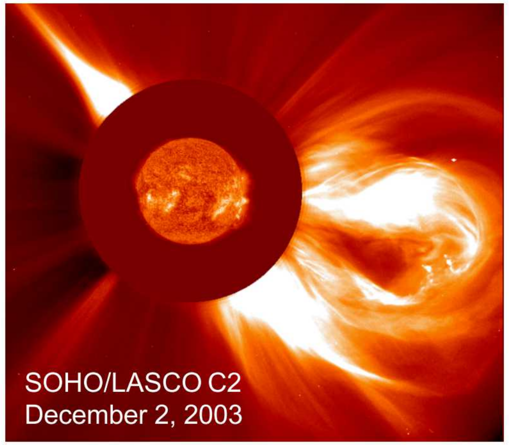
Clayton Myers and Chris Jennings

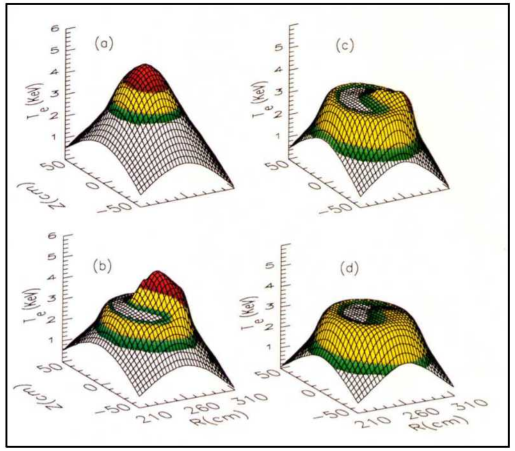
July 23, 2019

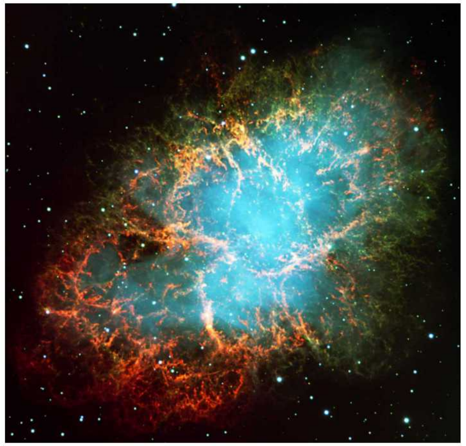
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

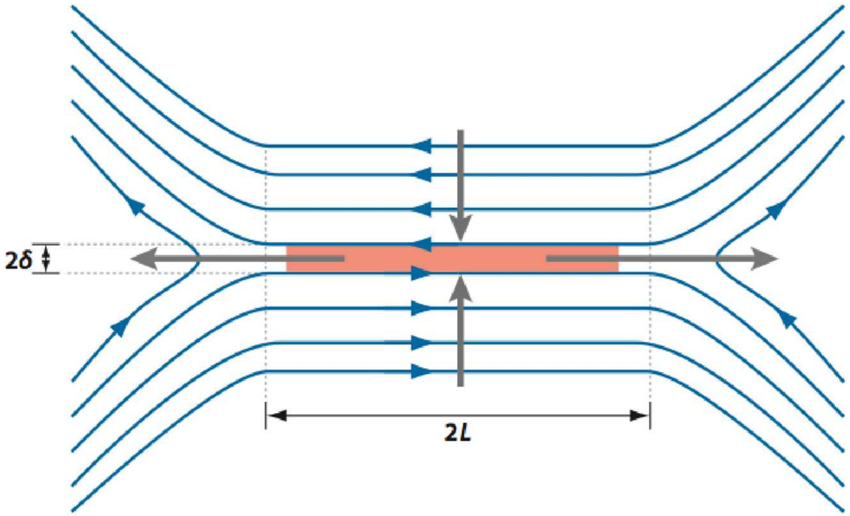
SAND2017-9564 A

Magnetic reconnection is a fundamental process that controls topological change and energy conversion in magnetized plasmas









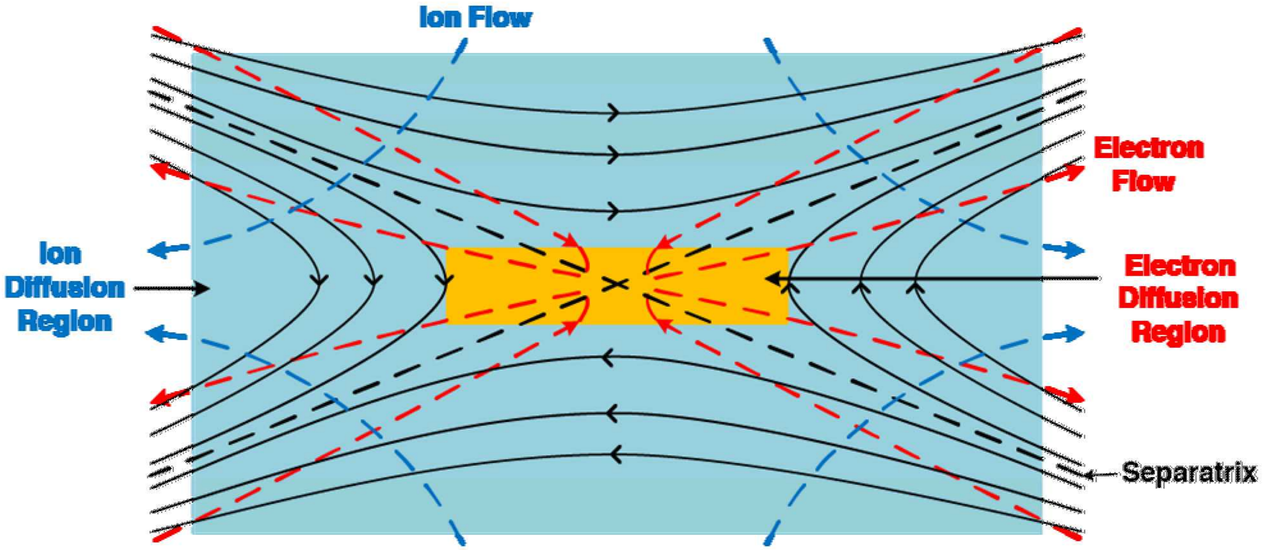
- MHD reconnection theory was developed in the 1950's by Peter Sweet and Eugene Parker
- Predicts a thinner sheet and slower reconnection with increasing *S*:

$$\delta = L/\sqrt{S} \qquad \tau_{\mathrm{rec}} = \sqrt{S}\,\tau_A$$

- According to MHD, solar flares should take way too long!

$$\tau_{\mathrm{rec}} \sim 10^6 \cdot (100 \text{ sec}) = \text{many months}$$
$$\tau_{\mathrm{flare}} \sim 15 \text{ minutes}$$

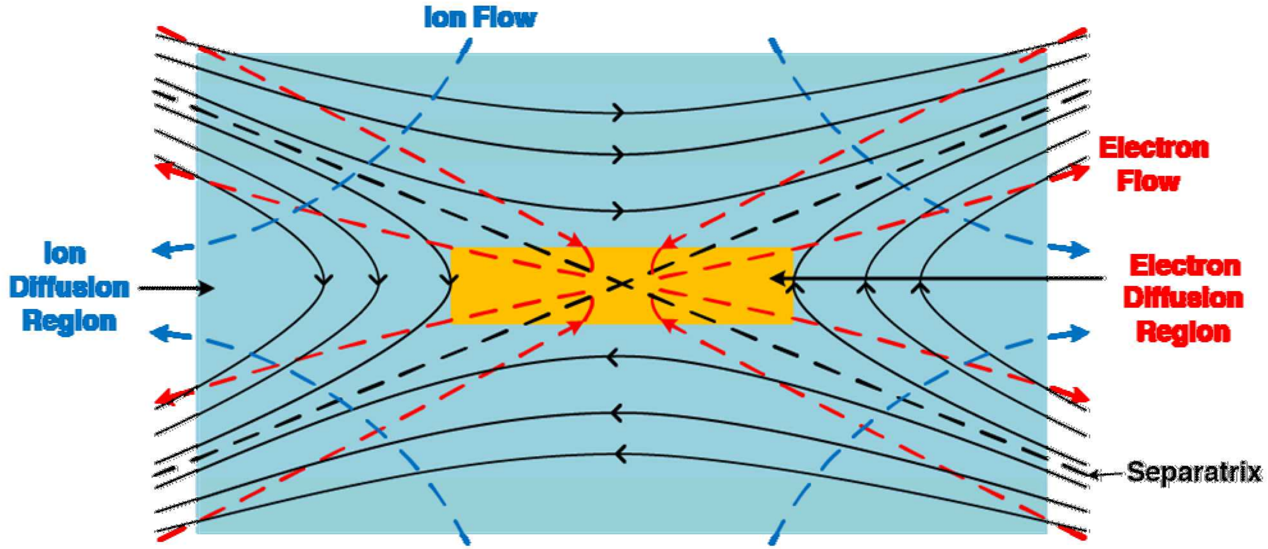
Numerous theories have been developed to explain fast reconnection rates that exceed the Sweet-Parker MHD limit



Collisionless / Hall / two-fluid reconnection:

- The current sheet can't keep thinning forever
- Since the magnetic field goes to zero at the X-point, particles will detach from the field at small scales
- Ions detach at the ion skin depth: $\delta_{SP} < d_i$
- In two-fluid reconnection, the reconnection rate is set by electron processes rather by ion processes

Numerous theories have been developed to explain fast reconnection rates that exceed the Sweet-Parker MHD limit

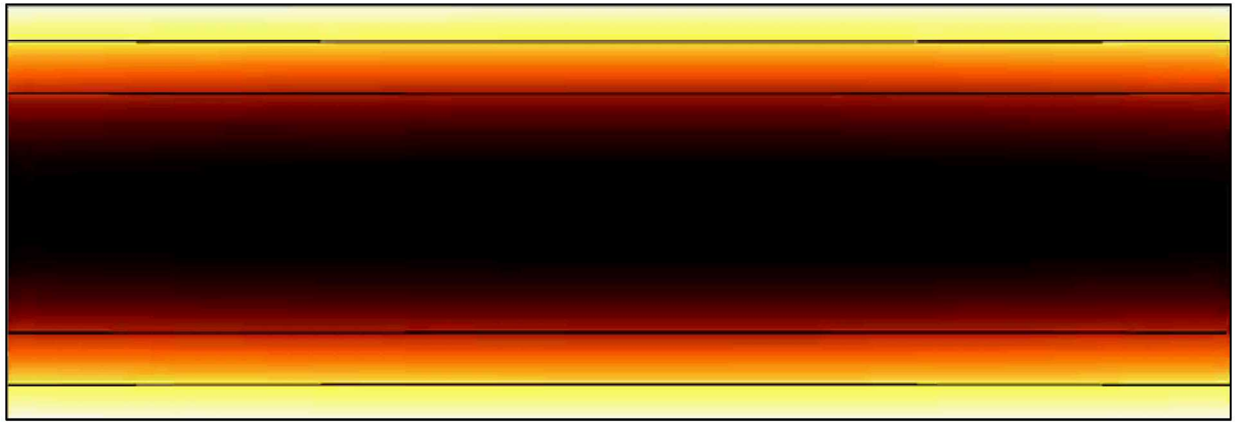


Collisionless / Hall / two-fluid reconnection:

- The current sheet can't keep thinning forever
- Since the magnetic field goes to zero at the X-point, particles will detach from the field at small scales
- Ions detach at the ion skin depth: $\delta_{SP} < d_i$
- In two-fluid reconnection, the reconnection rate is set by electron processes rather by ion processes

Plasmoid-mediated reconnection:

- Large MHD systems will have a large-aspect-ratio Sweet-Parker current sheet: $\delta = L/\sqrt{S}$
- Above a critical Lundquist number, the long, thin current sheet will break up into many X- and O-points
- The underlying mechanism is the 'plasmoid' instability
- The numerous smaller current sheets that result have a faster aggregate reconnection rate



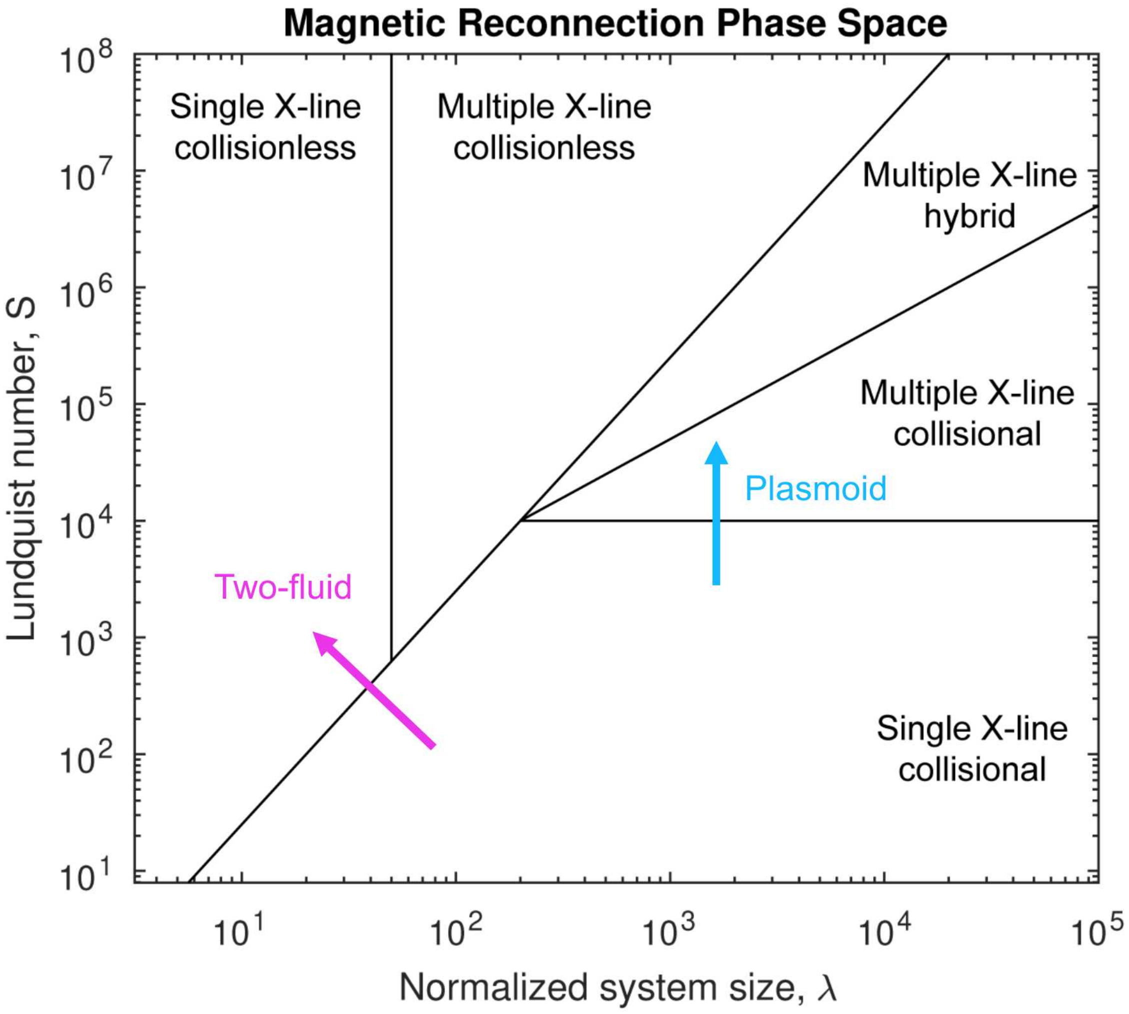
Huang & Bhattacharjee *Phys. Plasmas* 2010

The various reconnection regimes can be synthesized in a 2D dimensionless 'reconnection phase space'

- The reconnection phase space defines theoretical boundaries between different reconnection regimes
- The key parameters are the Lundquist number, S, and the normalized system size, λ:

$$S = \frac{\mu_0 v_A L}{\eta} \propto \frac{BLT_e^{3/2}}{\sqrt{\rho}} \qquad \lambda = \frac{L}{d_i} \propto L\sqrt{n_i}$$

- The collisional-to-collisionless transition at $\delta_{SP} \sim d_i$ is shown in magenta
- The laminar-to-plasmoid transition at $S = S_c \sim 10^4$ is shown in cyan



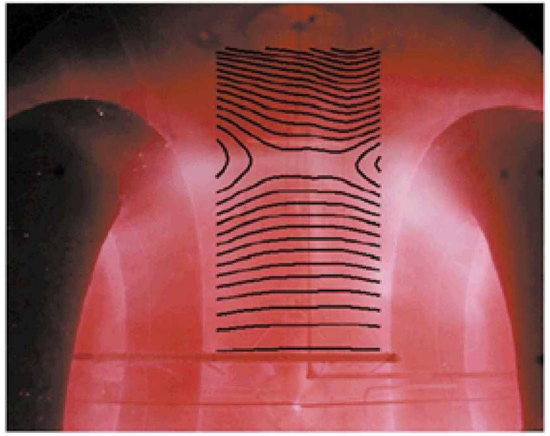
Adapted from Ji & Daughton *Phys. Plasmas* 2011

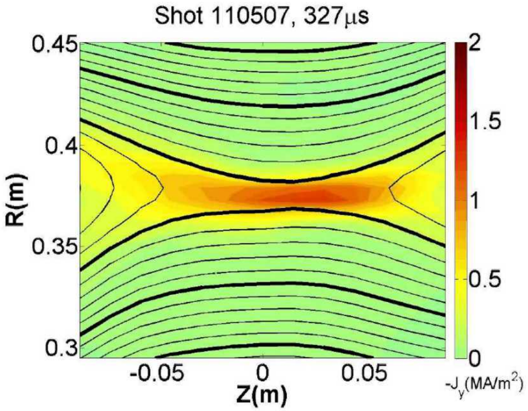
Gas discharge experiments such as MRX at Princeton are the workhorses of laboratory reconnection research

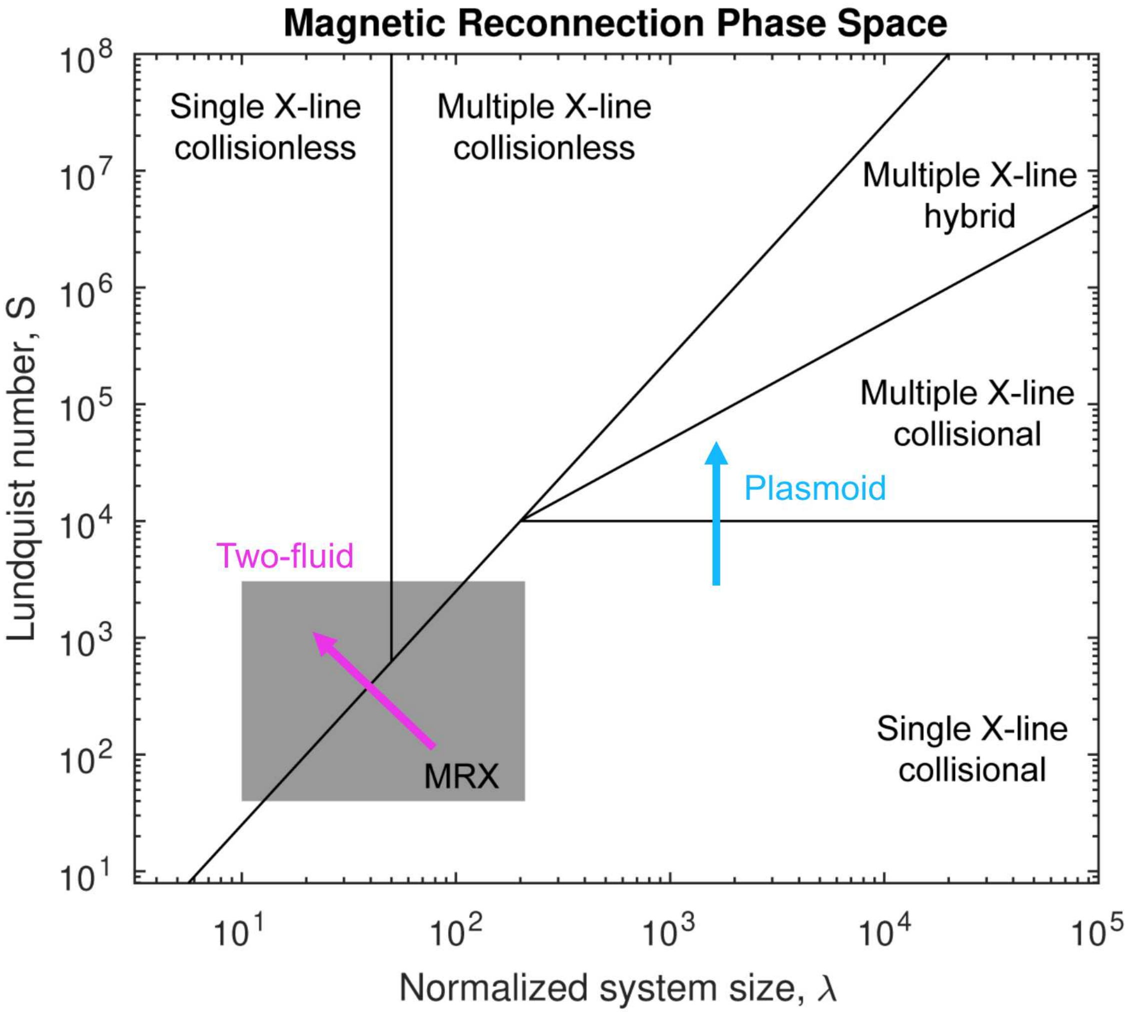
Gas discharge experiments are exploring the magnetic reconnection phase space in the low-energy-density regime:

- MRX (PPPL)
- TREX (UW Madison)
- LAPD (UCLA)
- SSX (Swarthmore)

MRX = Magnetic Reconnection Experiment:





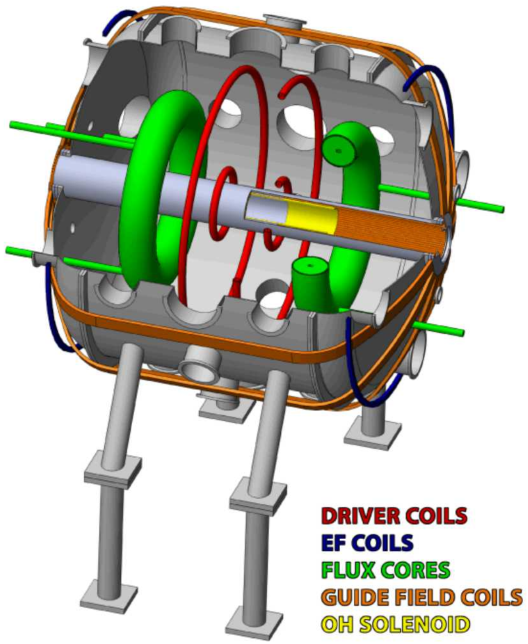


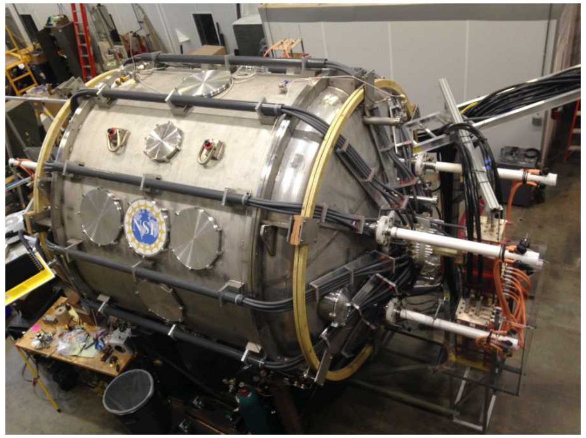
Adapted from Ji & Daughton *Phys. Plasmas* 2011

Next generation gas discharge experiments such as FLARE will access new reconnection parameter regimes

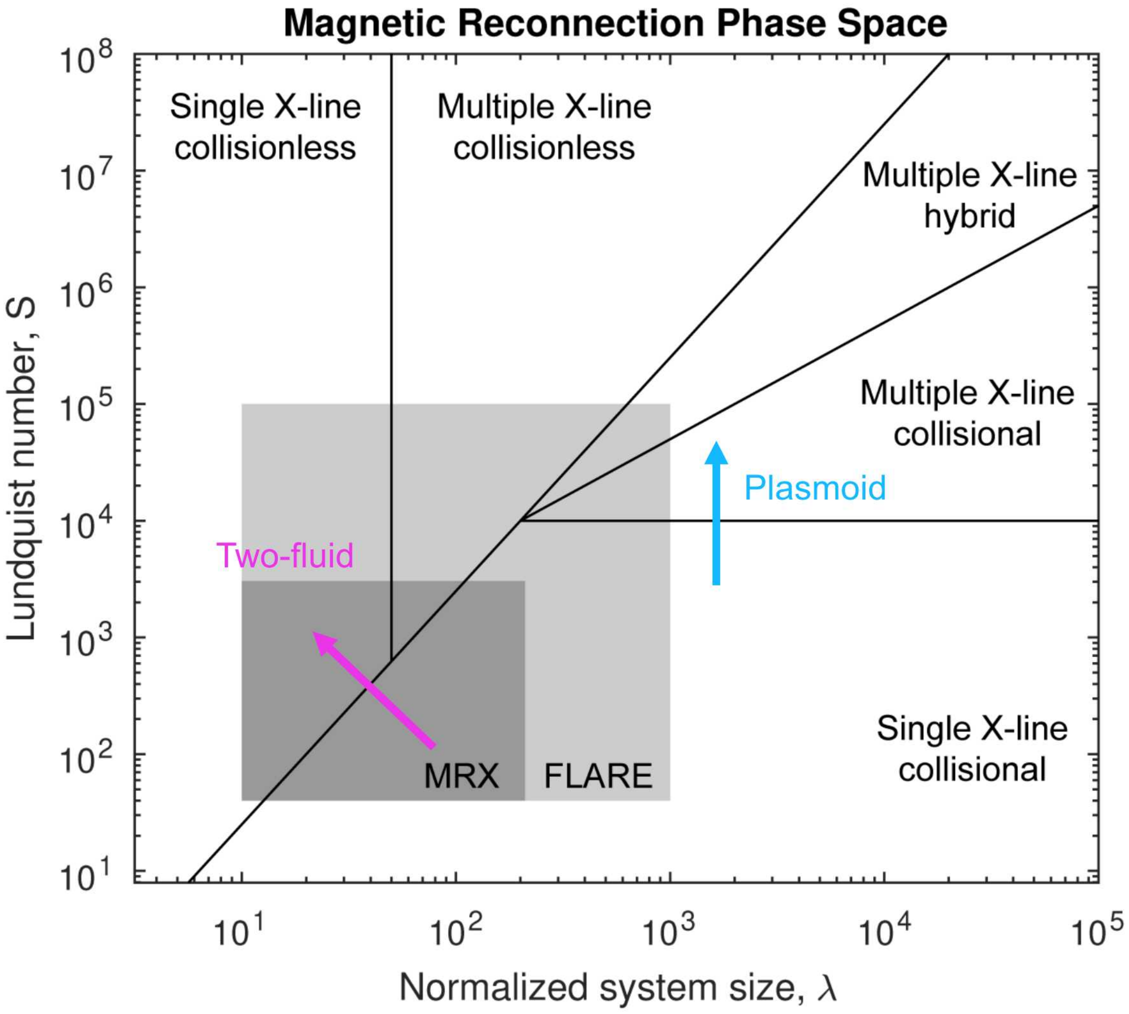
FLARE = Facility for Laboratory Reconnection Experiments

Vacuum vessel = 3 m diameter, Stored energy = 4 MJ



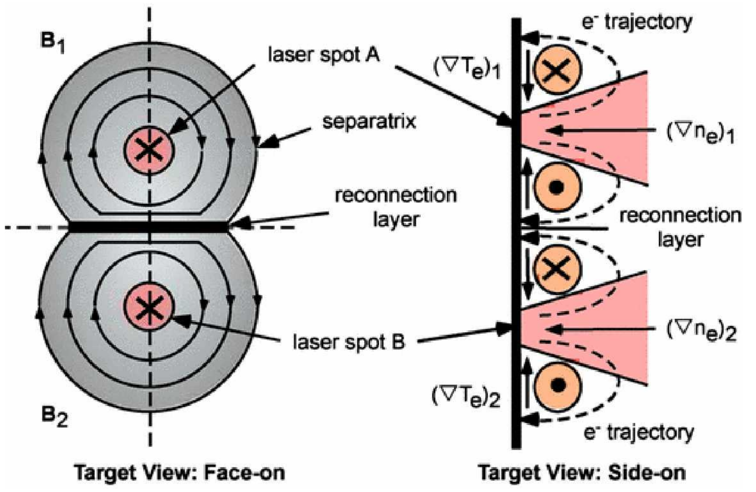


FLARE construction completed in March 2018. Awaiting DoE funding for operations.

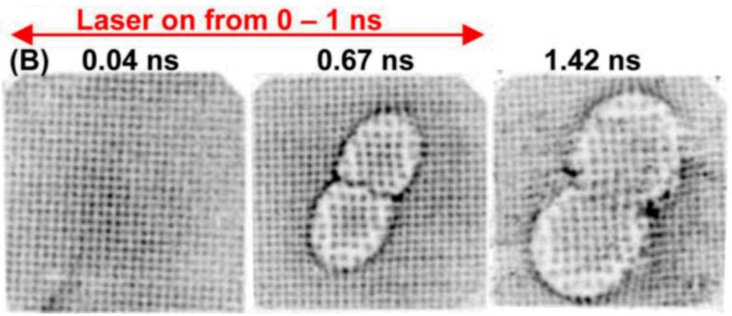


Adapted from Ji & Daughton *Phys. Plasmas* 2011

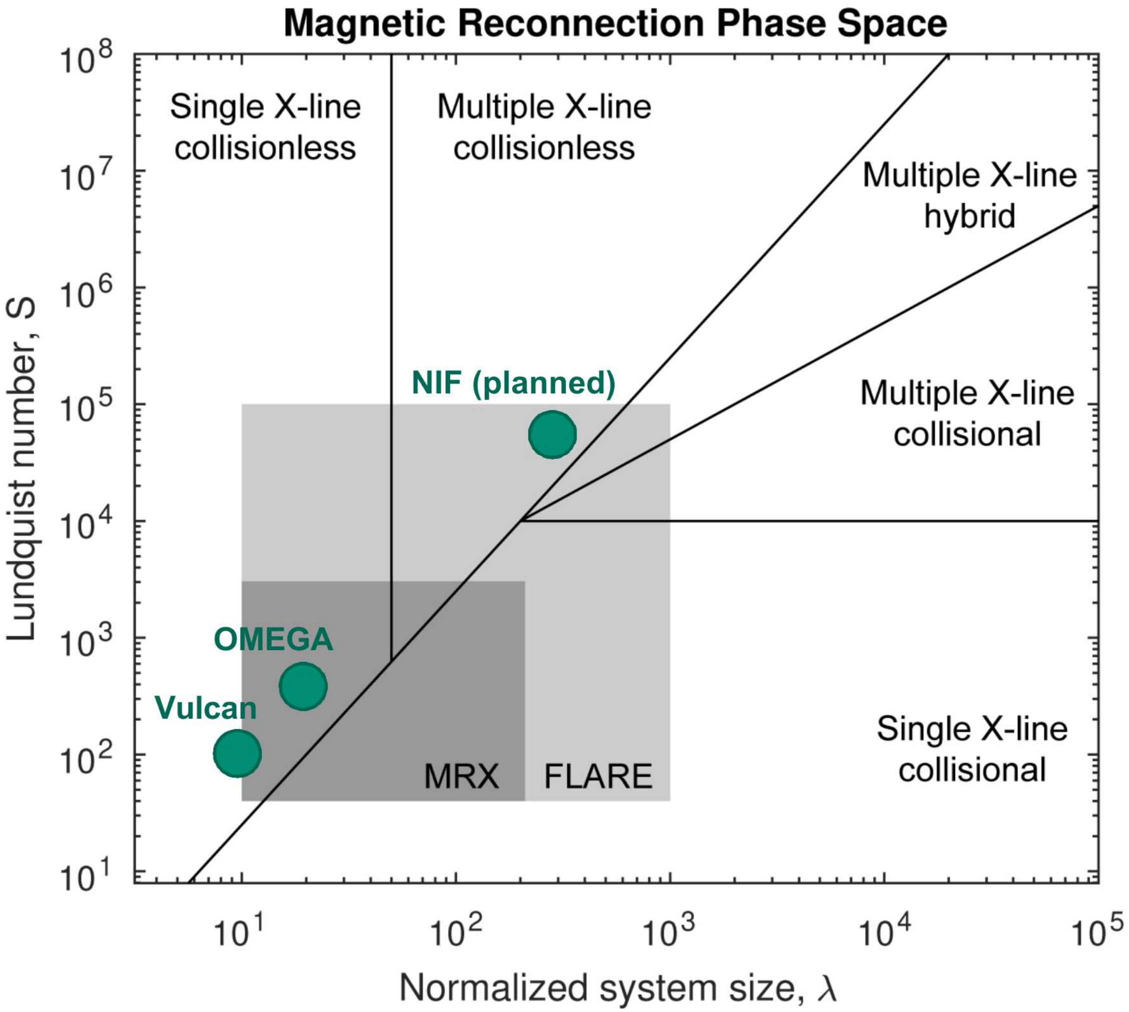
Laser experiments can produce HED reconnection by merging two plasma bubbles → magnetic fields generated by the Biermann battery



Nilson et al., *Phys. Rev. Lett.* 2006 (Vulcan laser)

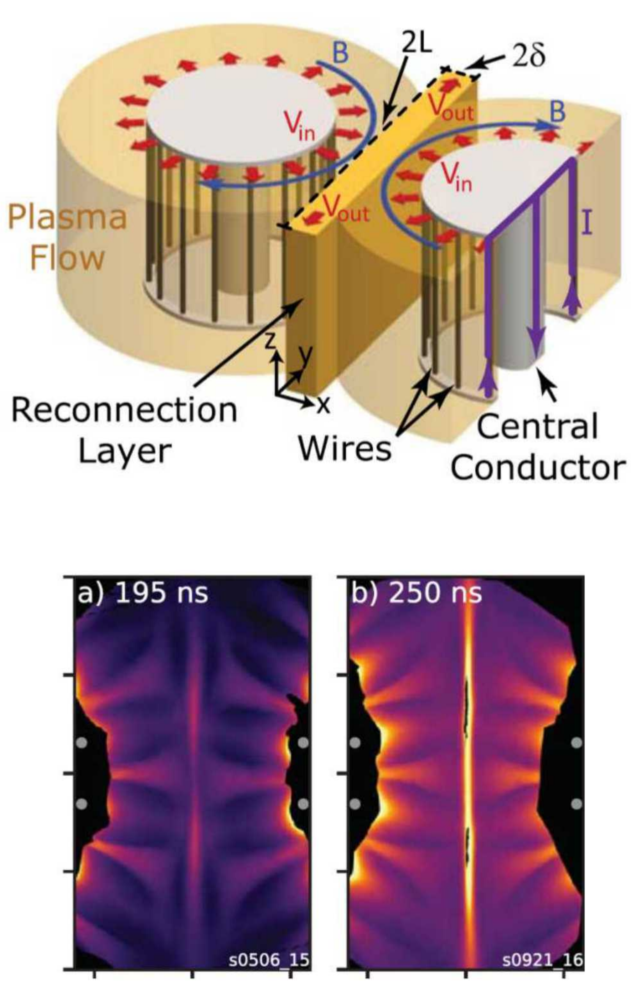


Li et al., *Phys. Rev. Lett.* 2007 (OMEGA)

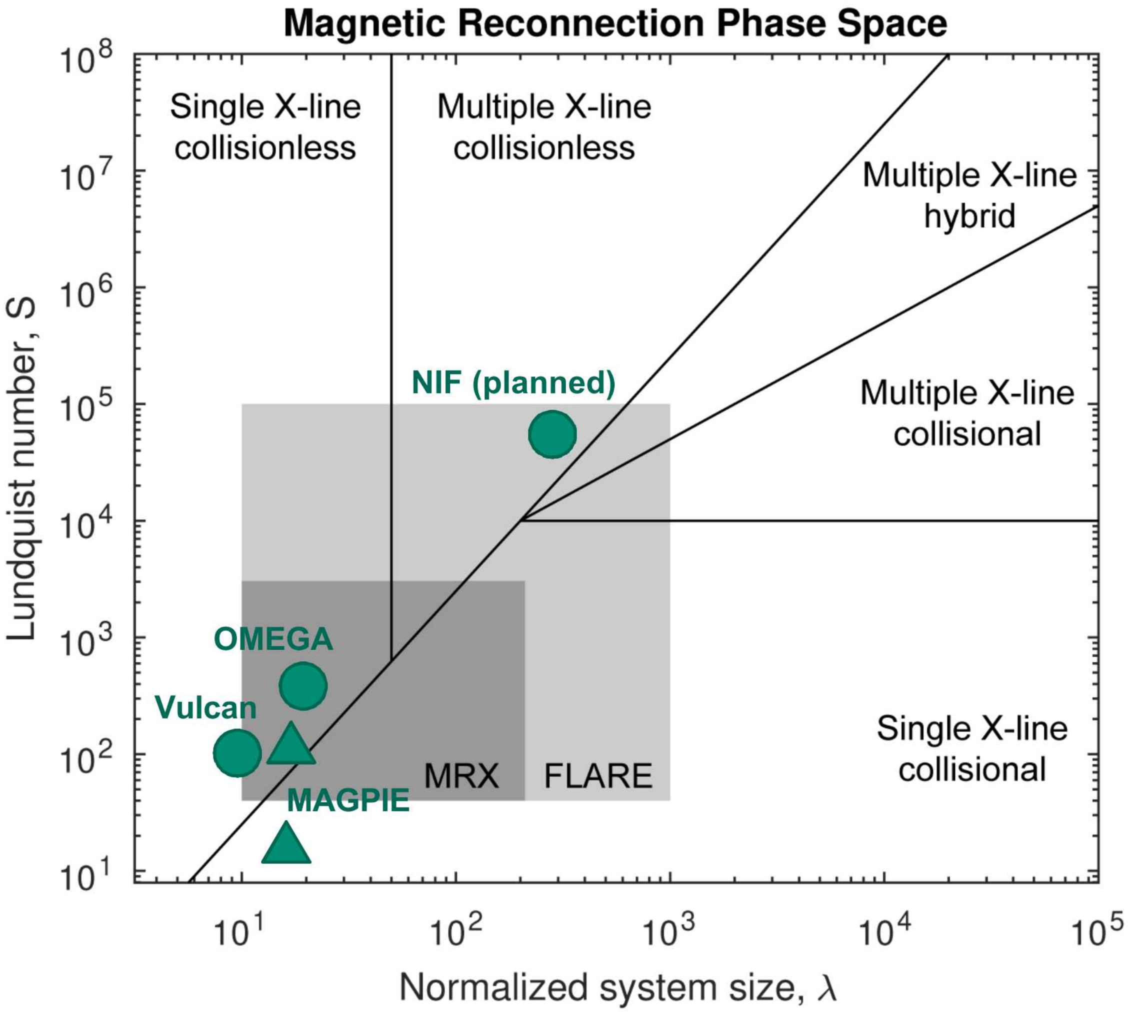


Adapted from Ji & Daughton *Phys. Plasmas* 2011

Pulsed-power reconnection studies have been pioneered using side-by-side inverted wire arrays on MAGPIE



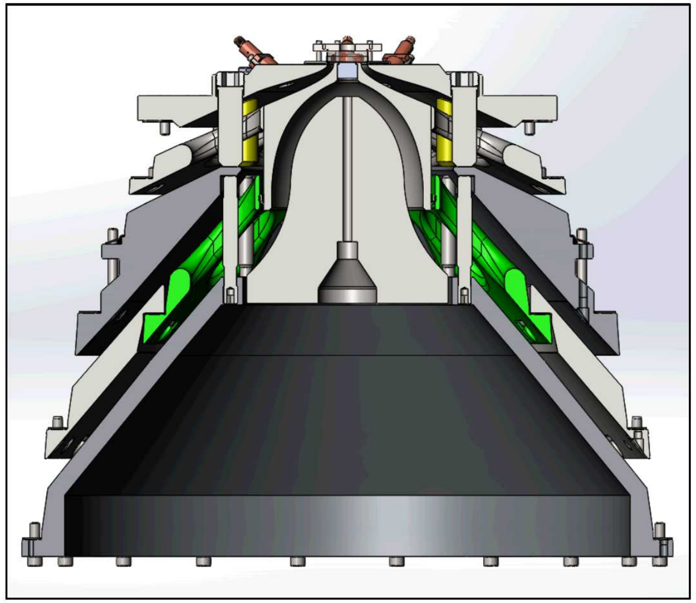
Hare et al., *Phys. Plasmas* 2018

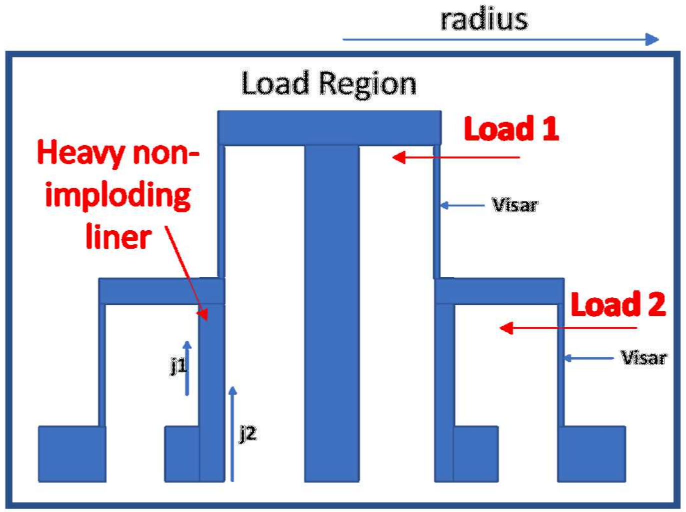


Adapted from Ji & Daughton *Phys. Plasmas* 2011

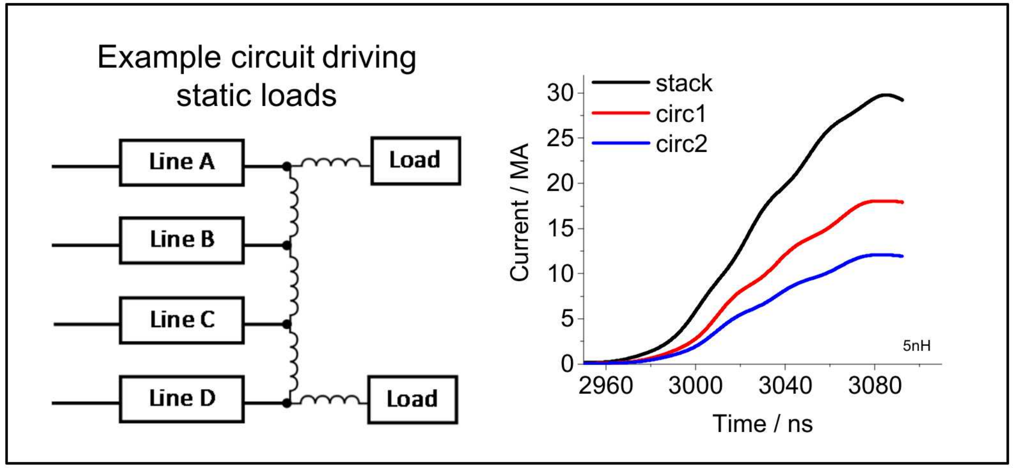
A magnetic reconnection platform for Z
(Let’s set some records)

The split inner MITL that Chris presented at the CY19 shot proposal forum is the key enabling technology for magnetic reconnection on Z





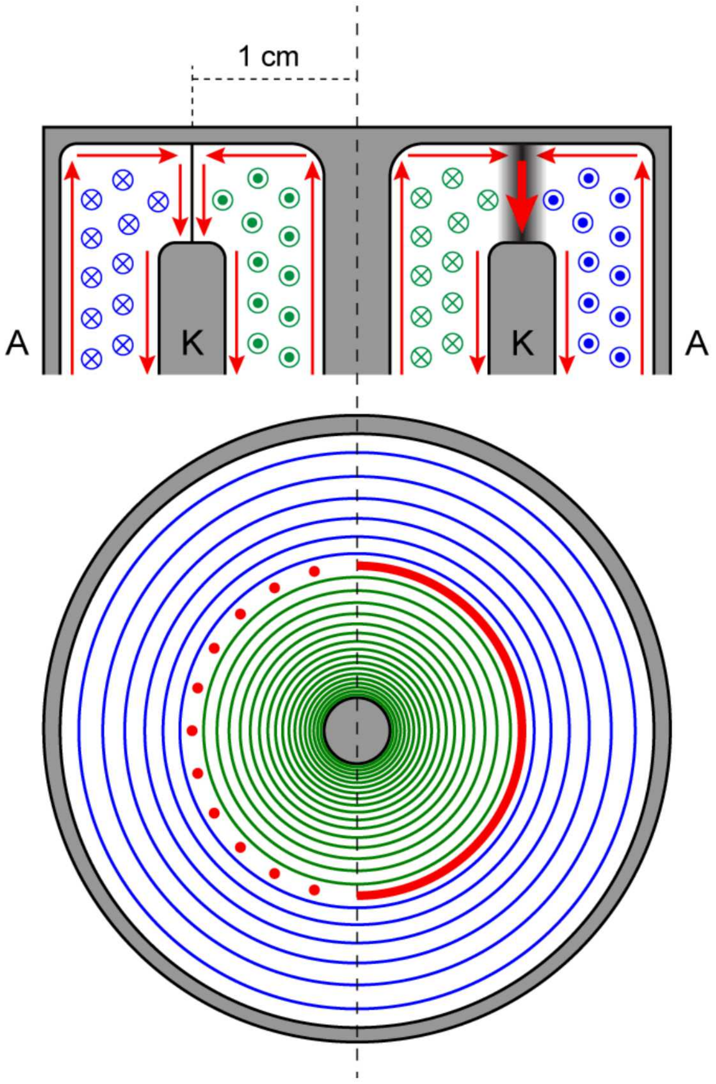
- Dual circuit operation of Z could be achieved with minimal convolute re-design.
- Gaps and inductances are comparable to those already routinely fielded.
- Retaining both connections enables selective partitioning of current between loads.

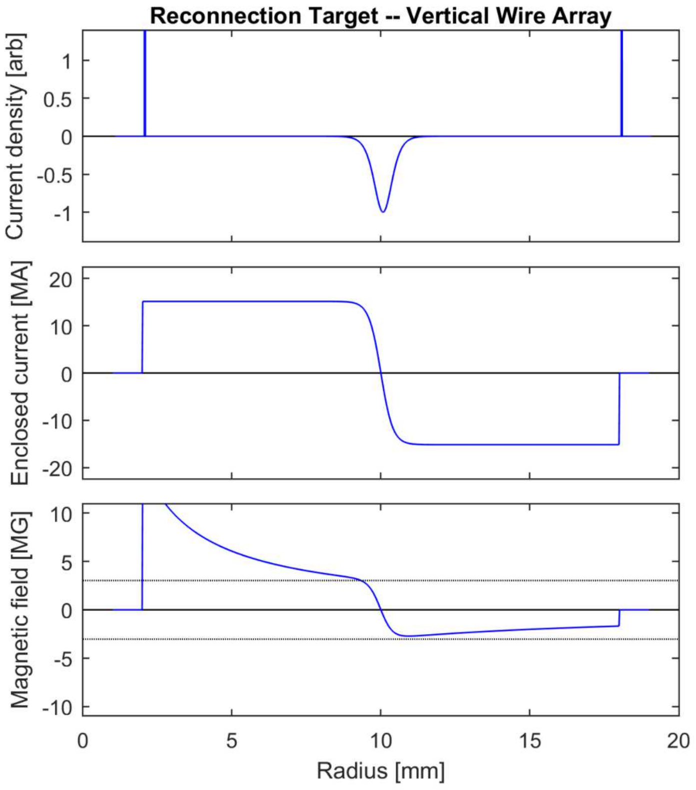


- We propose to simultaneously field two static loads and use return can velocimetry to assess the current delivered to each load.
- The target would be a solid rod target inside a heavy non-imploding liner target to enable VISAR access to both current paths.
- **The key feature for reconnection is that the current in the two nested loads flows in opposite directions → set up opposing B-fields to reconnect**

We have designed a novel pulsed-power-driven reconnection target that can access entirely new reconnection parameter regimes

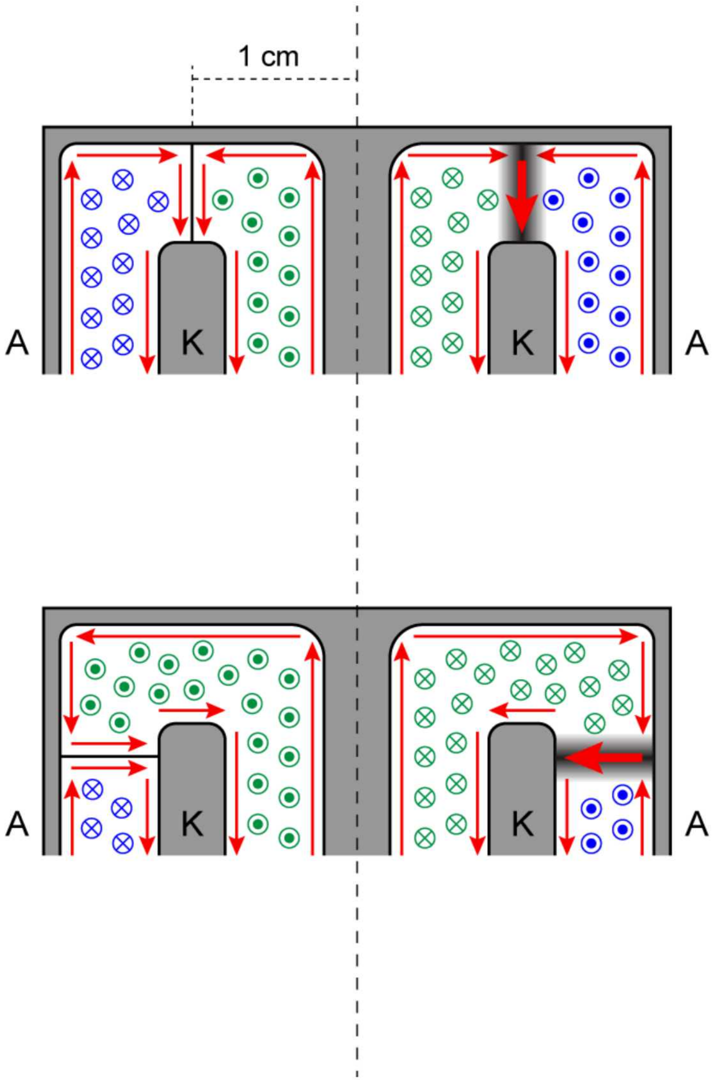
- Dual 6-mm inner MITLs connect to nested current paths within the target
- Azimuthal fields of opposite polarity converge on a 6-mm tall vertical wire array (or gas puff)
- The wire mass compresses and smears out into a ring of plasma
- The target is low-inductance due to its large-radius, non-imploding nature (~15 MA to each side, negative L-dot!)



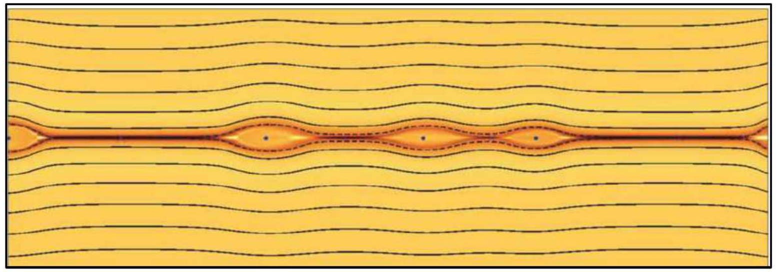


We have designed a novel pulsed-power-driven reconnection target that can access entirely new reconnection parameter regimes

- Dual 6-mm inner MITLs connect to nested current paths within the target
- Azimuthal fields of opposite polarity converge on a 6-mm tall vertical wire array (or gas puff)
- The wire mass compresses and smears out into a ring of plasma
- The target is low-inductance due to its large-radius, non-imploding nature (~15 MA to each side, negative L-dot!)
- The wire array / gas puff can be moved from a vertical to a radial configuration to improve diagnostic access

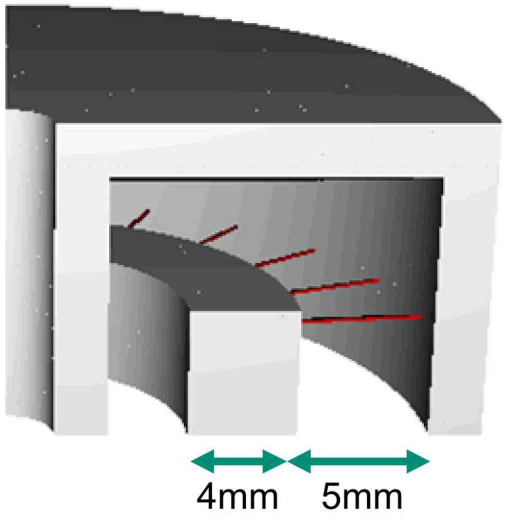


Plasmoids viewed from top

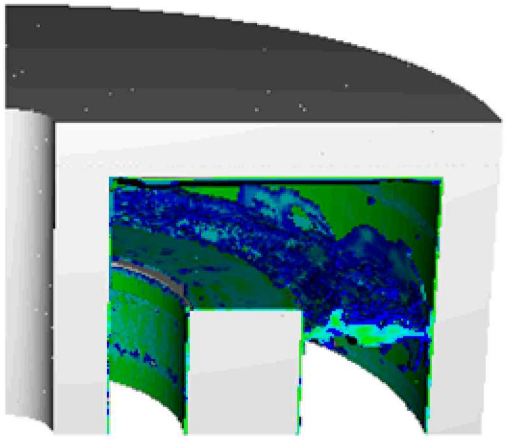


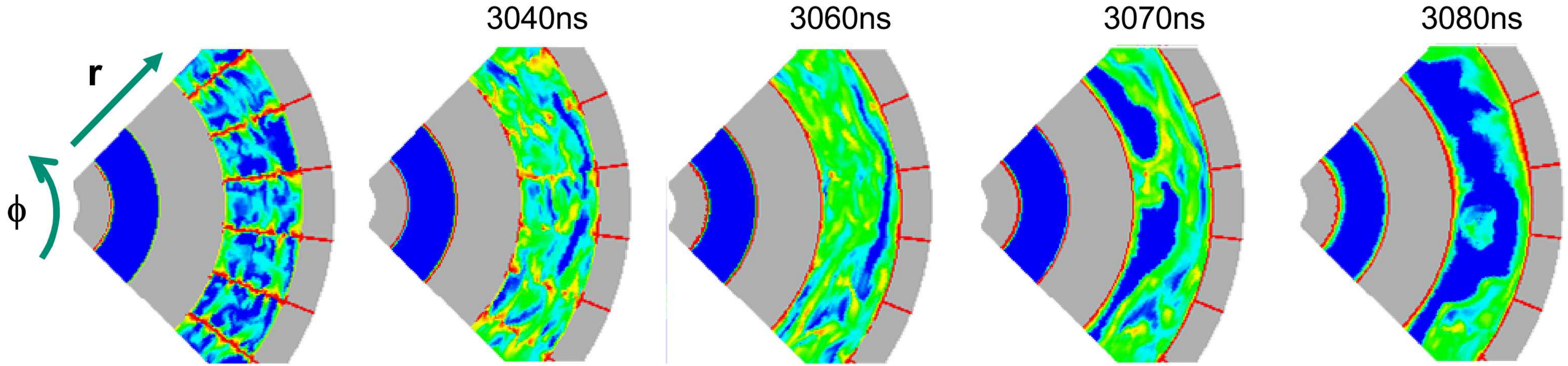
Plasmoids viewed from side

Scoping simulations from GORGON indicate that the wires smooth out into a reconnecting current sheet



Discrete wires merge into a confined current sheet





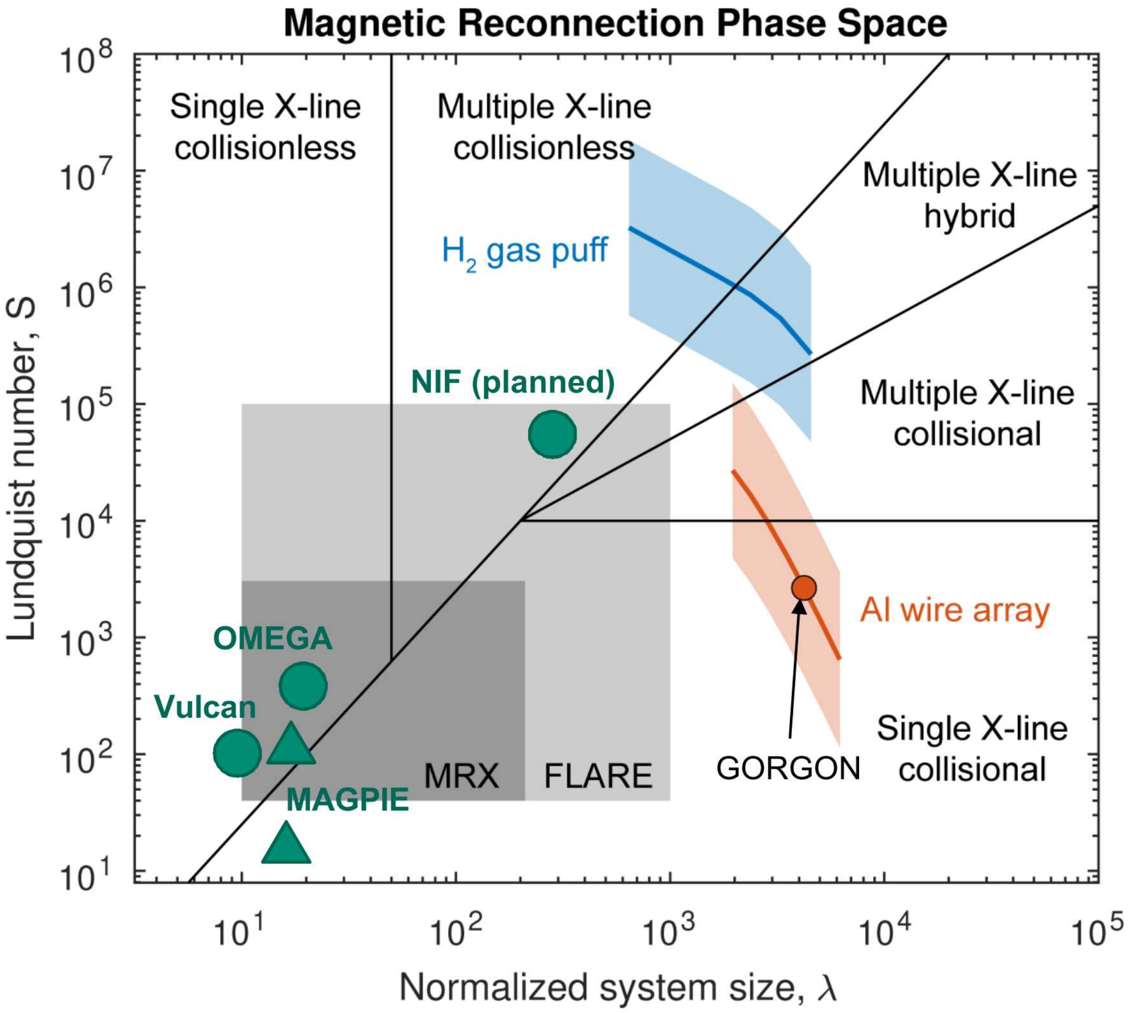
Later in time current sheet is unstable to radial redistribution of mass

When driven with Z, this split-inner-MITL reconnection target can readily achieve world-record laboratory reconnection parameters

Z is an energy-rich device that can create multi-MG magnetic fields at centimeter scales.

We could readily achieve world-record laboratory reconnection parameters!

Parameter	Al wire array	H_2 gas puff
Current [MA] / B-field [MG]	15 / 2.2	15 / 2.2
Mass density [mg/cc]	0.2−2	5e-4−0.2
Electron density [#/cc]	5e19−6e20	3e18−1e20
Temperature [eV]	500−70	1000−500
Alfvén velocity, v_A [km/s]	450−140	2800−450
Alfvén transit time, τ_A [ns]	200−600	30−200
Sweet-Parker width, δ_{SP} [μm]	200−1600	14−60
Ion skin depth, d_i [μm]	45−14	130−20
Lundquist number, S	4e7−7e2	1e7−5e5
System size, λ	2e3−6e3	6e2−4e3
Plasma β	0.3−0.4	0.04−1



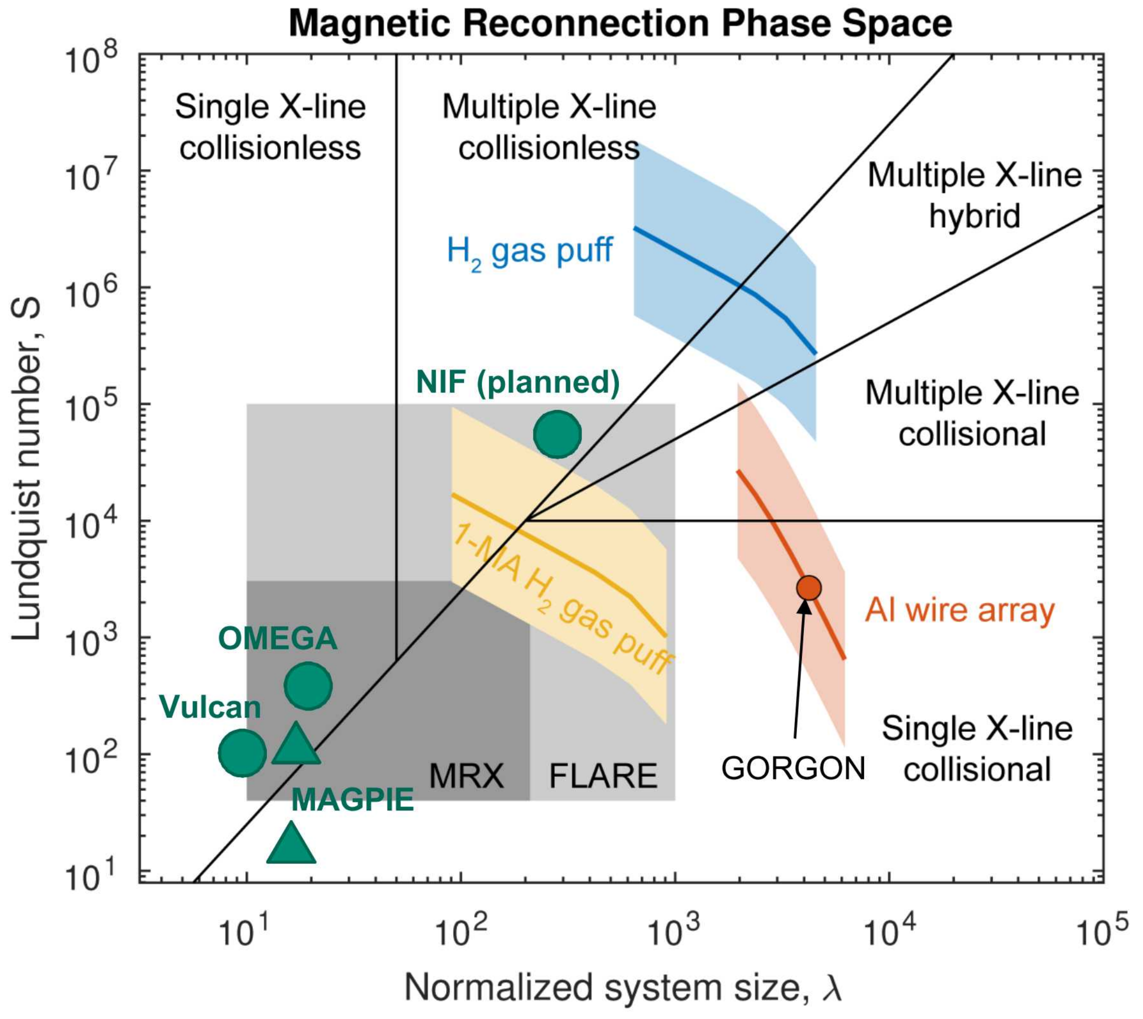
Adapted from Ji & Daughton *Phys. Plasmas* 2011

Initial testing of the pulsed-power reconnection target on a 1-MA driver could quickly achieve interesting reconnection parameters

A 1-MA driver could access parameter regimes that are close to the design points for FLARE and NIF

This would also provide a 1-MA platform development opportunity before moving these targets to Z

Parameter	H_2 gas puff	1-MA H_2 GP
Current [MA] / B-field [MG]	15 / 2.2	0.75 / 0.1
Mass density [mg/cc]	5e-3−0.2	1e-4−0.01
Electron density [#/cc]	3e18−1e20	7e16−6e19
Temperature [eV]	1000−500	30
Alfvén velocity, v_A [km/s]	2800−450	1000−100
Alfvén transit time, τ_A [ns]	30−200	85−850
Sweet-Parker width, δ_{SP} [μm]	14−60	325−1300
Ion skin depth, d_i [μm]	130−20	930−90
Lundquist number, S	1e7−5e5	2e4−1e3
System size, λ	6e2−4e3	90−900
Plasma β	0.04−1	0.01−0.4



Adapted from Ji & Daughton *Phys. Plasmas* 2011

A major challenge is how to diagnose these experiments

Magnetic field / reconnection rate:

- Return-can velocimetry
- Micro B-dots?
- Line VISAR?
- Chordal Faraday rotation?
- Chordal Zeeman splitting?

Density and temperature:

- Chordal and/or axial spectroscopy
- Volumetric dopants
- Visible interferometry?
- Thomson scattering?

Morphology:

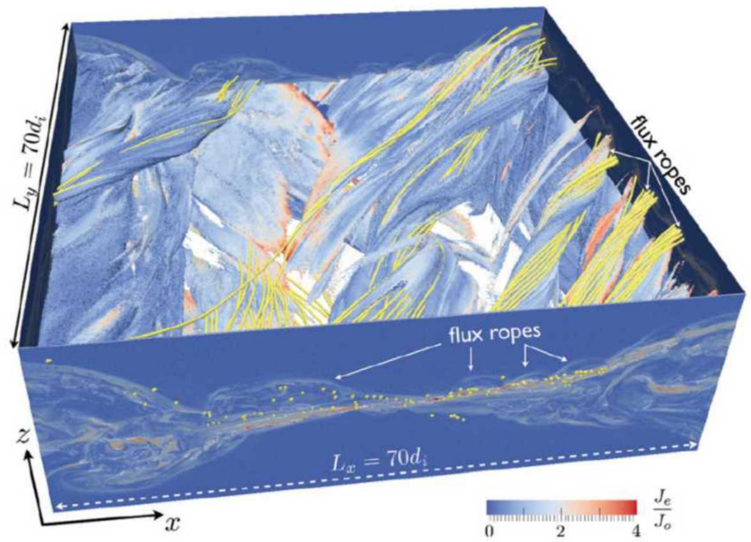
- Gated self-emission imaging
- Apertured PCDs / XRDs
- ???

Heating and/or particle acceleration:

- Chordal spectroscopy (bi-directional azimuthal flows)
- Surface dopants (beam-target interaction)
- ???

Pulsed-power (and Z in particular) can help to unravel multiple fundamental problems in magnetic reconnection

- How does reconnection proceed so quickly? *(The rate problem)*
- Why is reconnection so impulsive? *(The onset problem)*
- How does reconnection take place in 3D? *(The 3D problem)*
- How does weak ionization affect reconnection? (*The partial ionization problem*)
- How do boundary conditions affect reconnection? *(The boundary problem)*
- How are particles energized by reconnection? *(The energy problem)*
- How to apply local reconnection physics to a large system? *(The multi-scale problem)*



W. Daughton et al. *Nat. Phys.* 2011
3D guide field reconnection with VPIC