PRINCETON PLASMA PHYSICS LABORATORY

Magnetic Reconnection Plasma Thruster

Fatima Ebrahimi (Princeton University/PPPL)

2024 IPELS-16 Workshop

Gharching, August 7, 2024

PRINCETON UNIVERSITY

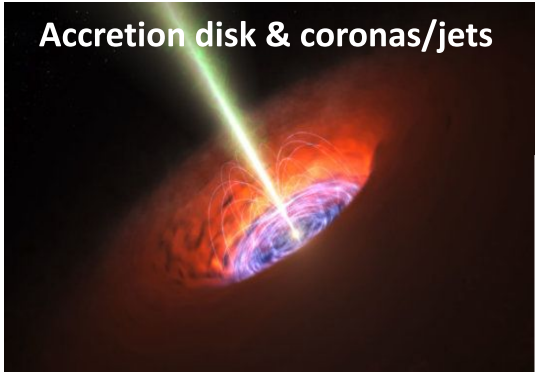
Thanks

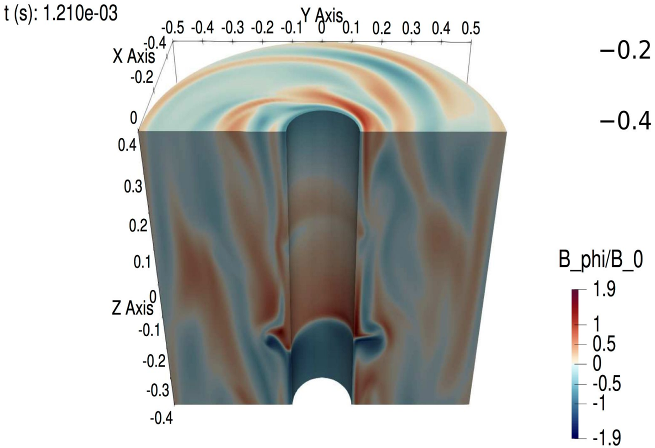
- LDRD team

  Art. Brook, Robert Lunsford, Nicholas O’Gorman, Peter Titus, Jiawen Wang, Andrew Yard

- Philip Efthimion, Jon Menard, Roger Raman

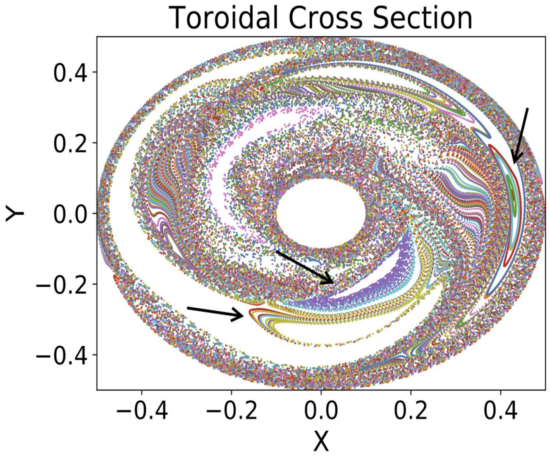
Magnetic reconnection energizes many processes in laboratory and astrophysical plasmas





I -In astrophysical disks

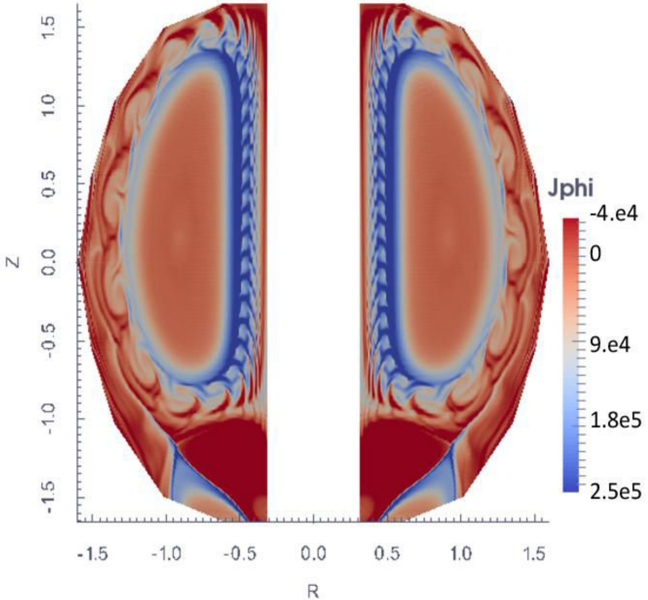
Magnetic islands in accretion flows



Rosenberg & Ebrahimi ApJL 2021

II- In a tokamak

ELM nonlinear dynamics

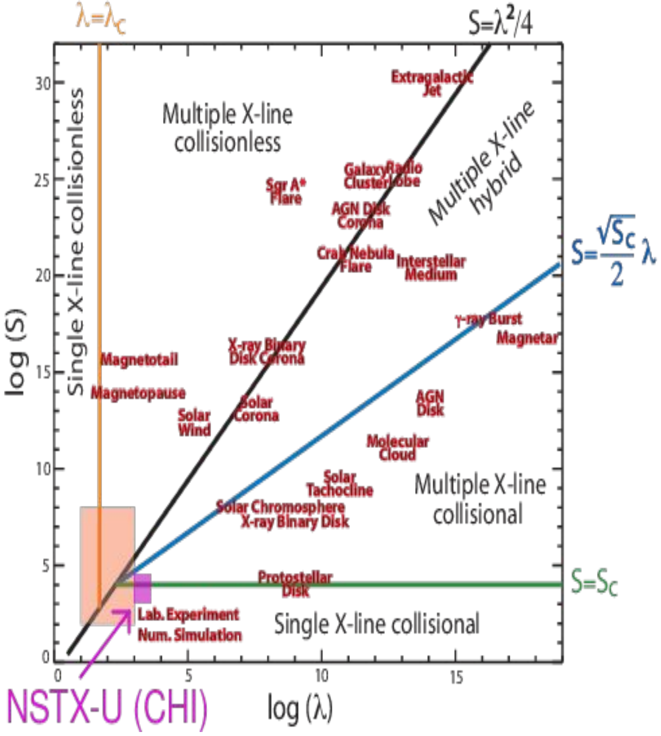


Onset and relaxation of SOL currents.

Ebrahimi PoP 2017,
Ebrahimi & Bhattacharjee NF 2023

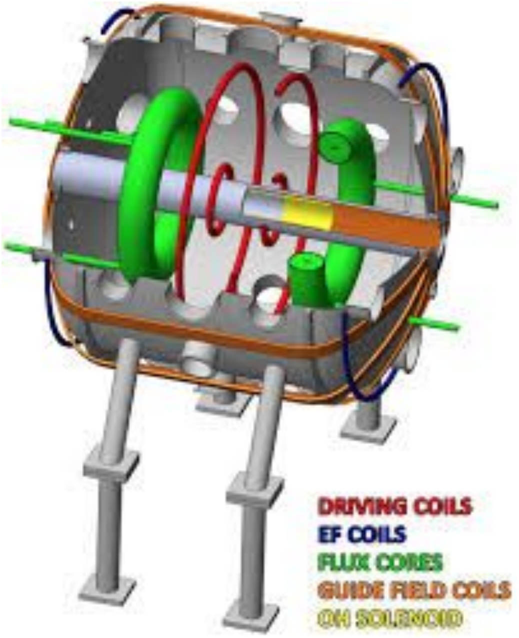
From laboratory to large-scale fusion experiments (to explore multi-scale reconnection problem)

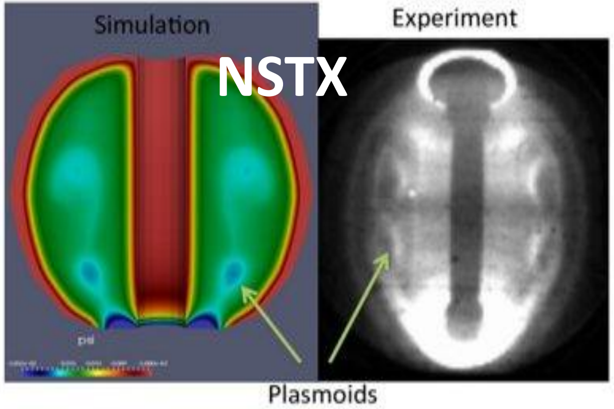
Reconnection phase diagram

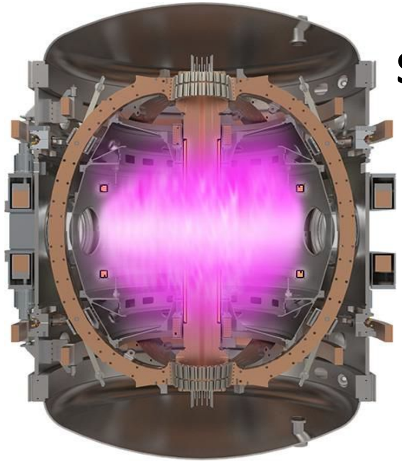


Ji & Daughton 2011

Flare reconnection experiment (PPPL)







ST40 MC

How could current sheets form?

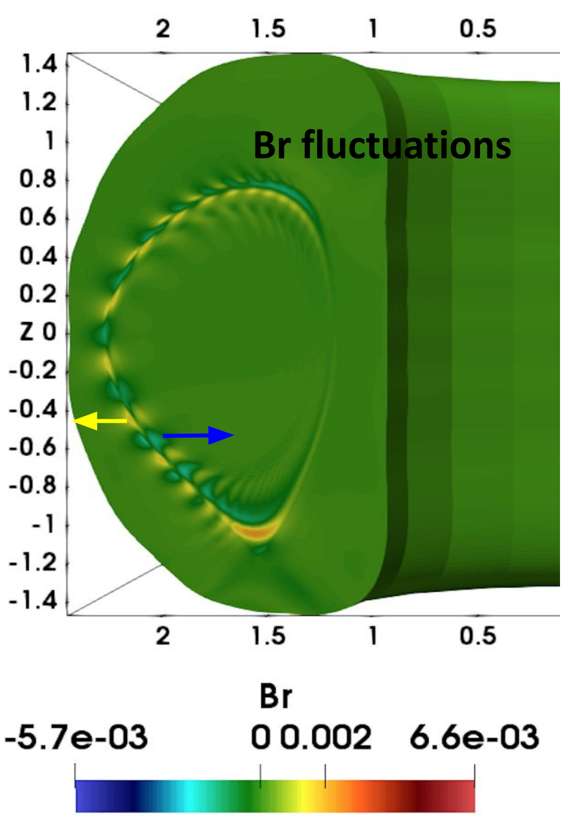
1- Due to a primary instability

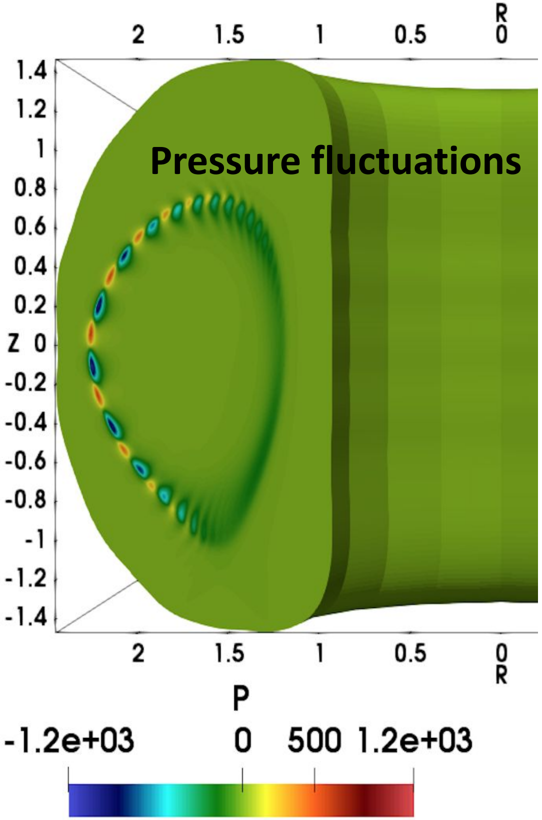
2- Nonlinear dynamics - turbulence (dynamical vortices)

3- Externally forced reconnection to provide reconnection sites inductively or via helicity injection

4- During flux expansion or due to strong current ramp up

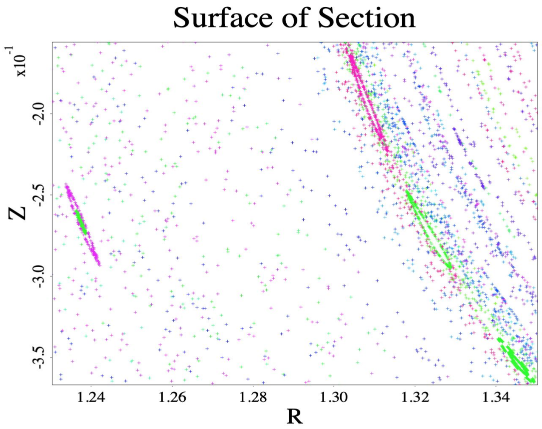
1) Nonlinear edge P-B modes do generate current sheets.





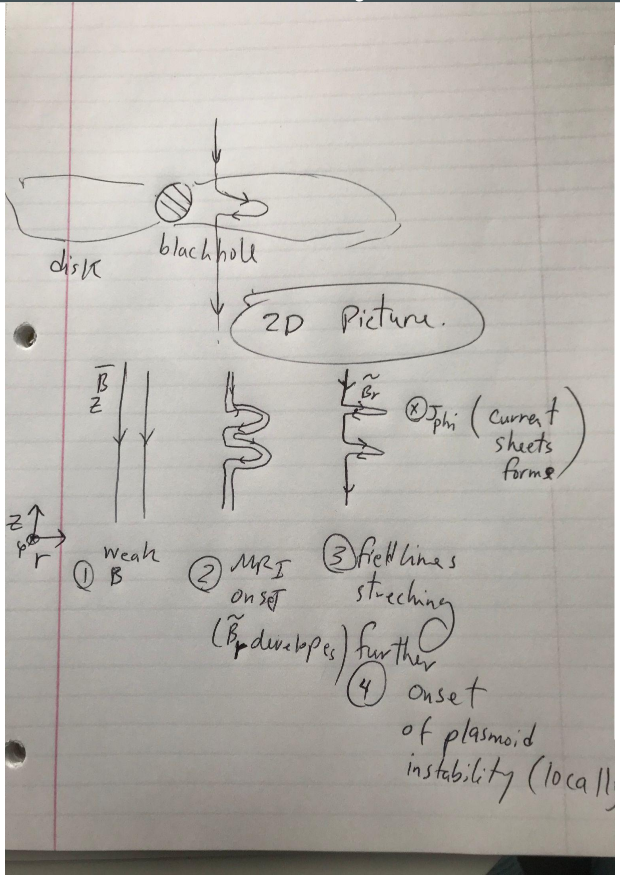
- As edge plasma interchangeably is displaced by the ballooning modes, local edge current sheet could form.

ELM crash: Reconnection physics via full extended MHD is needed for correct relaxation dynamics.

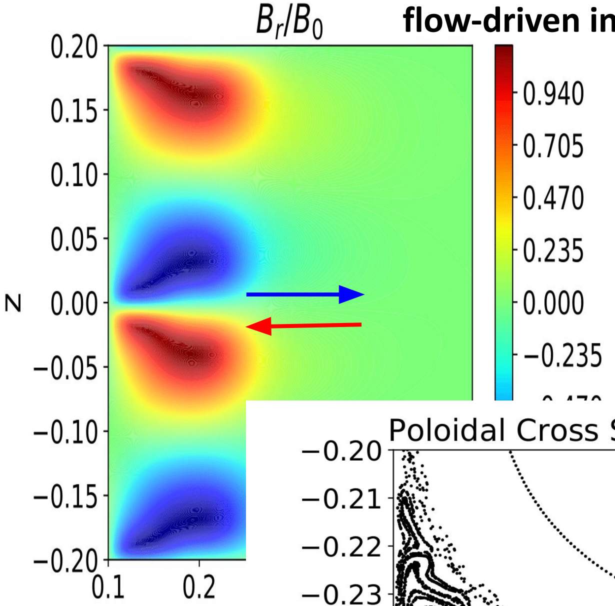


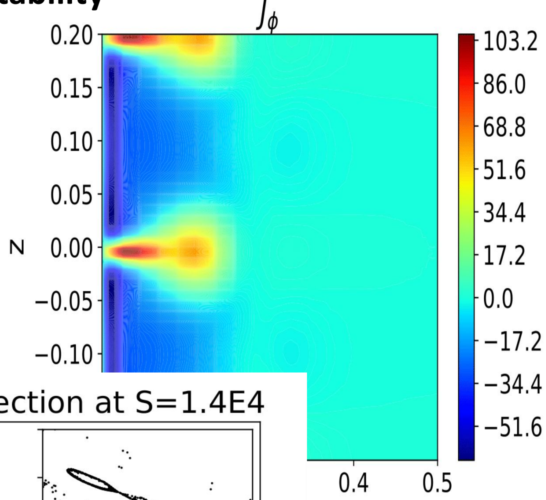
Ebrahimi & Bhattacharjee, Nucl. Fusion 2023
Ebrahimi PoP 2017

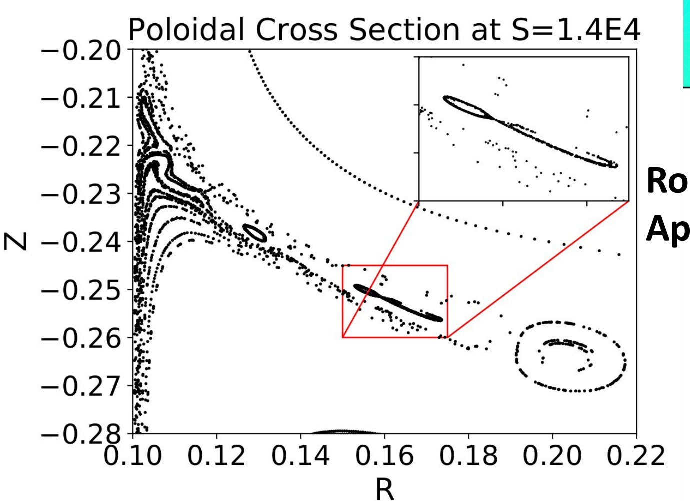
1) How about current sheet formation due to a primary instability? (and cause secondary reconnection)



Primary fluctuations from flow-driven instability

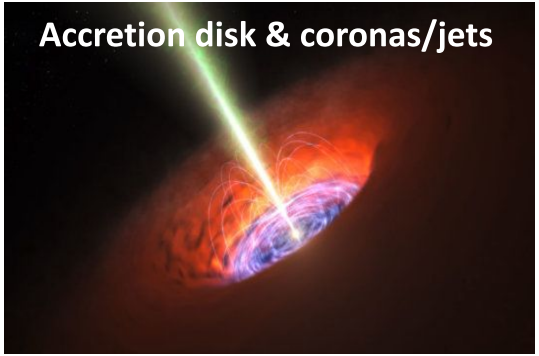


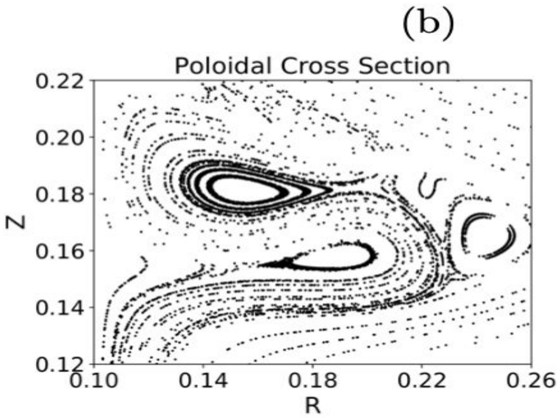




Rosenberg & Ebrahimi ApJL 2021

2- Magnetic reconnection sites are formed via 3D turbulence (dynamical vortices)





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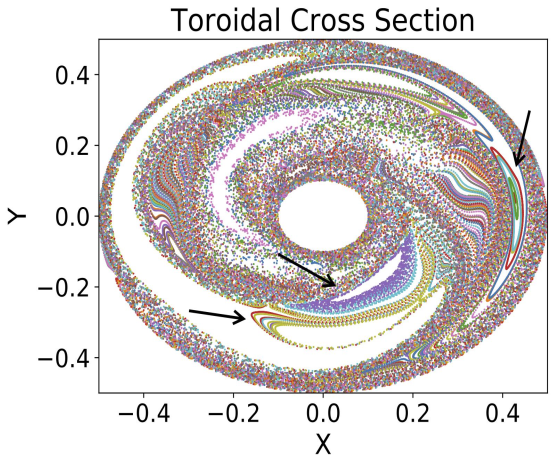
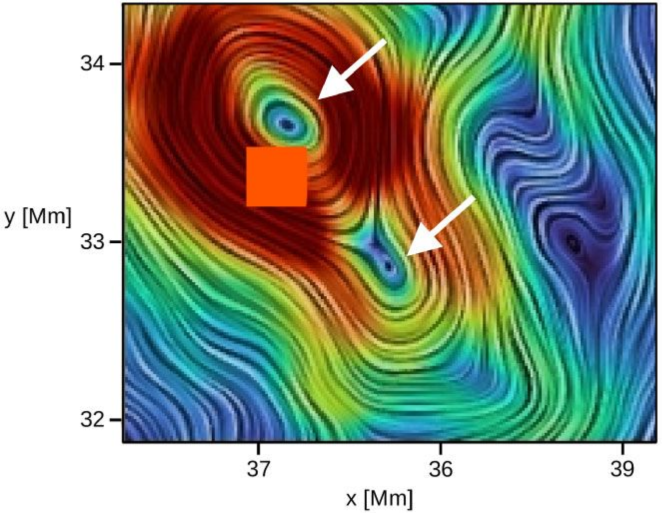


Rosenberg & Ebrahimi ApJL 2021
Ebrahimi & Pharr ApJ 2022

II- Observation: Surface of the sun



Chian et al. MNRAS 2023

Merging current-sheets in 3D form plasmoids

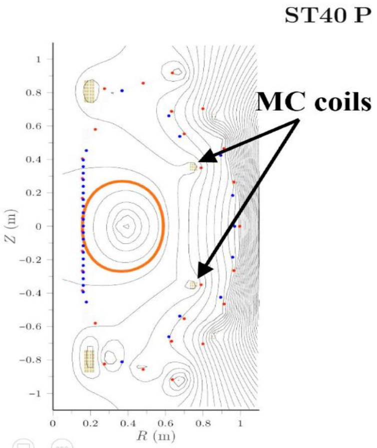
3- Externally forced methods would provide reconnection sites

Compact ST-based fusion reactors require innovative plasma startup

- **Merging compression on START, MAST, UTST, and recent ST40 experiments**

- **Transient coaxial helicity injection on HIT-II and NSTX**
  (This talk)

- **Sustained and local helicity injection on HIT-II and Pegasus**



Fundamental reconnection physics, including plasmoid physics, has been demonstrated during plasma start-up in NSTX

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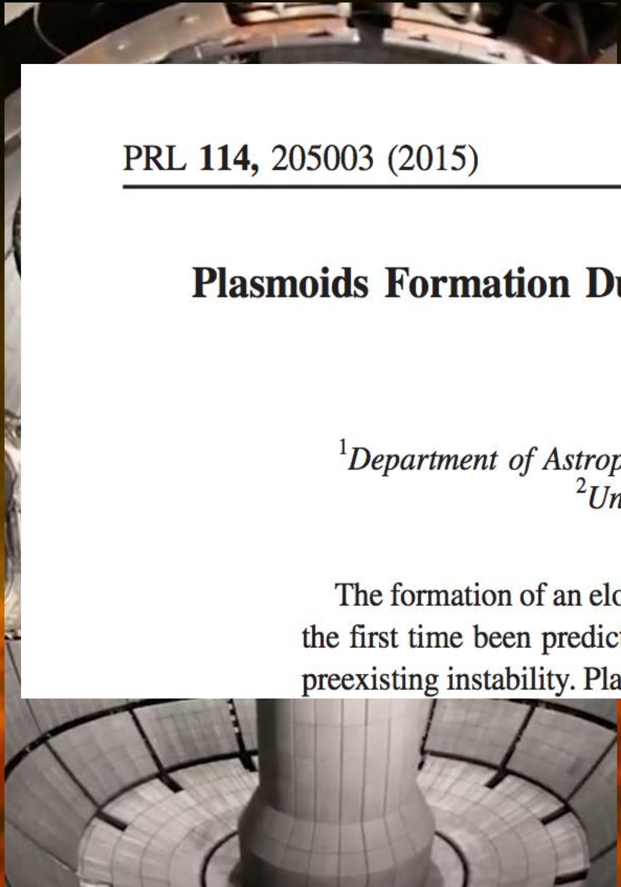


PRL **114**, 205003 (2015) PHYSICAL REVIEW LETTERS week ending 22 MAY 2015

Plasmoids Formation During Simulations of Coaxial Helicity Injection in the National Spherical Torus Experiment

F. Ebrahimi[1] and R. Raman[2]
[1]*Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08543, USA*
[2]*University of Washington, Seattle, Washington 98195, USA*
(Received 2 March 2015; published 20 May 2015)

The formation of an elongated Sweet-Parker current sheet and a transition to plasmoid instability has for the first time been predicted by simulations in a large-scale toroidal fusion plasma in the absence of any preexisting instability. Plasmoid instability is demonstrated through resistive MHD simulations of transient

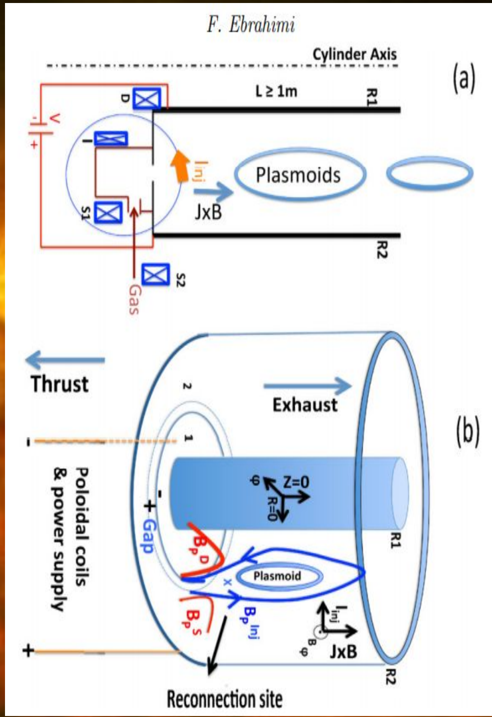
New concept for plasma rocket exploits the mechanism behind solar flares

The magnetic reconnection plasma drive

Princeton plasma physics experiment and simulations show evidence of new acceleration method

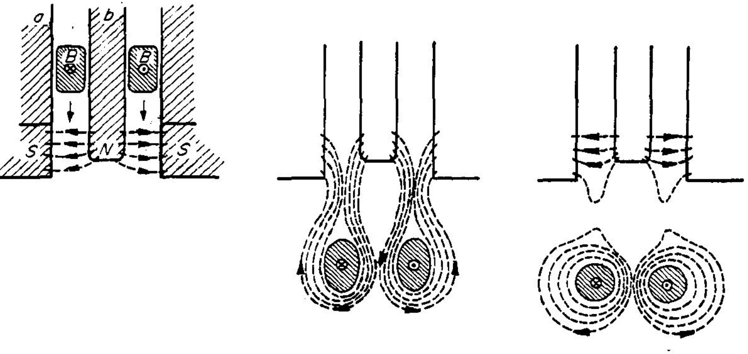
Ebrahimi/Princeton University patent pending USPTO No. 63/085,660

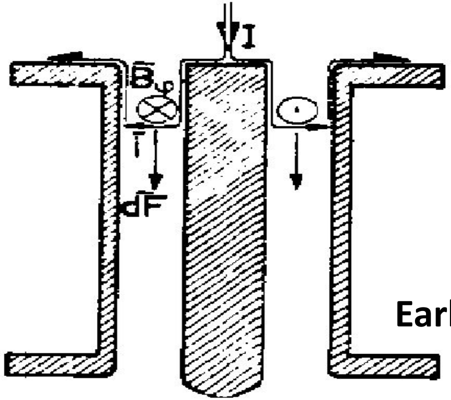
Ebrahimi JPP 2020



Magnetic helicity injection is combined with axisymmetric fast magnetic reconnection

Experiments with plasma rings



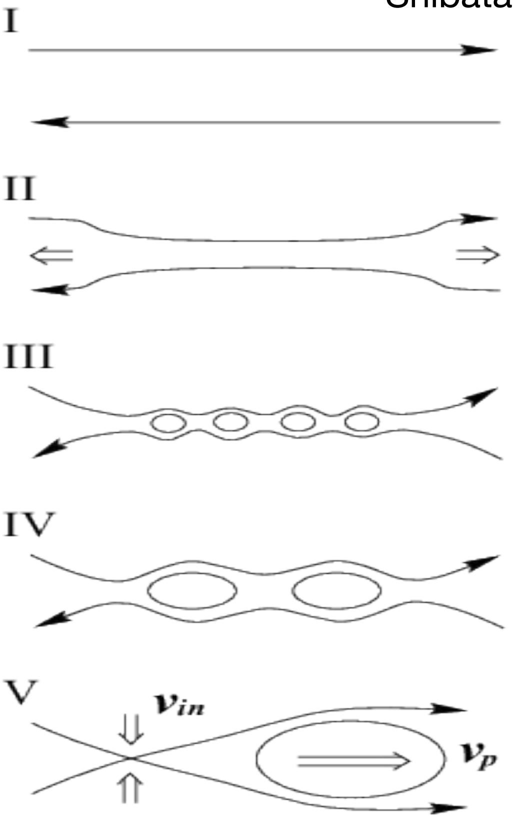


$$d\bar{F} = \bar{I} dv \times \bar{B}_{\varphi}$$

$$\bar{B}_{\varphi} = \mu_0 \frac{I}{2\pi r}$$

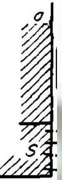
Early experiments of plasma rings

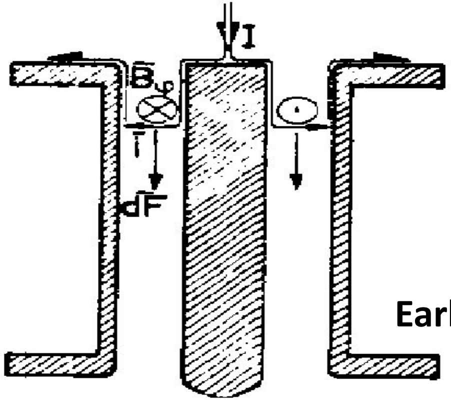
Shibata & Tanuma 2001



Plasmoid reconnection in a current sheet

Magnetic helicity injection is combined with axisymmetric fast magnetic reconnection





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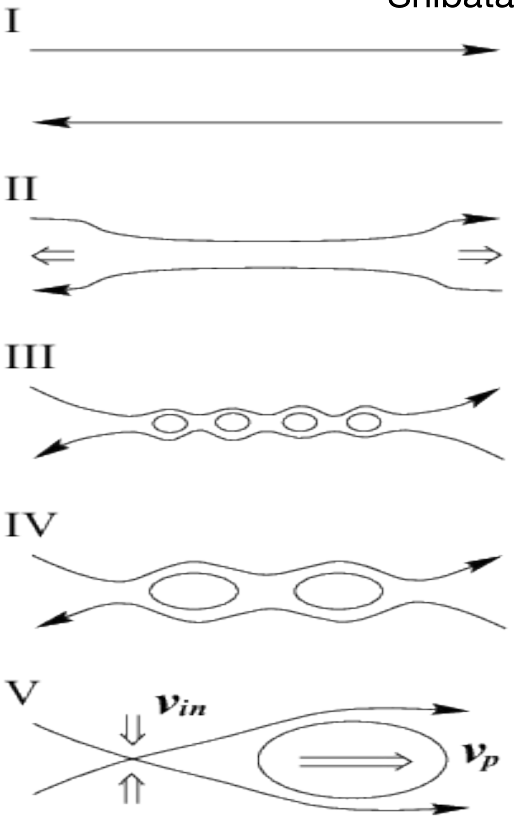


Plasmoid reconnection in a current sheet

Simulations are performed using extended MHD NIMROD code

- Solves the linear and nonlinear MHD equations

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} + \kappa_{divb}\nabla\nabla.\mathbf{B}$$

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{ne}\mathbf{J} \times \mathbf{B}$$

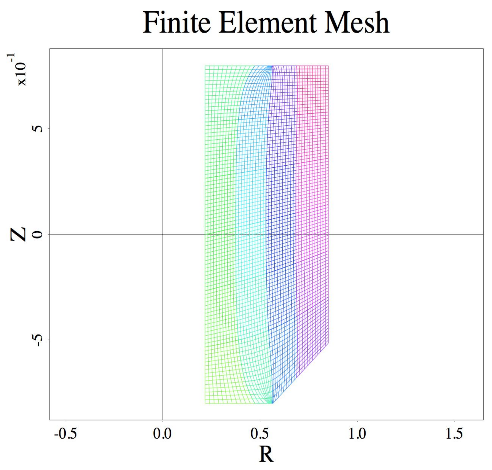
$$\mathbf{J} = \nabla \times \mathbf{B}$$

$$\frac{\partial n}{\partial t} + \nabla.(n\mathbf{V}) = \nabla.D\nabla n$$

$$\rho(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}.\nabla\mathbf{V}) = \mathbf{J} \times \mathbf{B} - \nabla P - \nabla.\Pi$$

$$\frac{n}{(\Gamma - 1)}(\frac{\partial T_\alpha}{\partial t} + \mathbf{V}.\nabla T_\alpha) = -p_\alpha \nabla.\mathbf{V} - \nabla.\mathbf{q}_\alpha + Q$$

- $\mathbf{q} = -n[(\kappa_{||} - \kappa_\perp)\hat{b}\hat{b} + \kappa_\perp \mathbf{I}] \cdot \nabla T$
- Π is the stress tensor (also includes numerical $\rho\nu\nabla V$)



- Poloidal grid 45 x 90 fifth/sixth order finite elements, 2-D (n=0) and 3-D (up to n= 22 toroidal modes)

- Voltage is applied across the injector gap (V_{inj}) *Ex B* normal flows at the gaps

[Bayliss, Sovinec & Redd 2011; Hooper et al. 2012;Ebrahimi et al. 2013; Hooper et al. 2013]

Sweet-Parker current-sheet scaling needs to be incorporated in the classical tearing model

Now **a** (current sheet width) must be replaced with the S-P scaling **a** $\sim L/\sqrt{(S_L)}$

$\tau_A = a/V_A ==> L/(\sqrt{(S_L)}V_A ==> 1/\sqrt{S_L}\tau_A$
$S = aV_A/\eta ==> L/(\sqrt{(S_L)}V_A/\eta ==> S_L^{1/2}$
Replacing above into the maximum growth rate eq. gives:

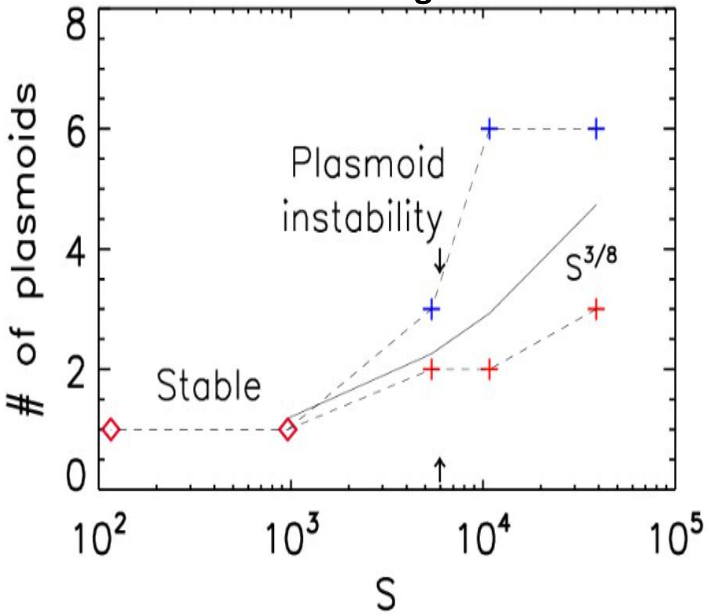
$$\gamma_{max}\tau_A \sim S_L^{1/4} \quad \text{at} \quad (k_{max}L \sim S_L^{3/8})$$

(Tajima & Shibata 1997 Plasma Astrophysics, Loureiro et al. 2007) & Bhattacharjee et al. 2009

Here : $\tau_A = L/V_A$ and $S_L = LV_A/\eta$
(L is the length of the current sheet)

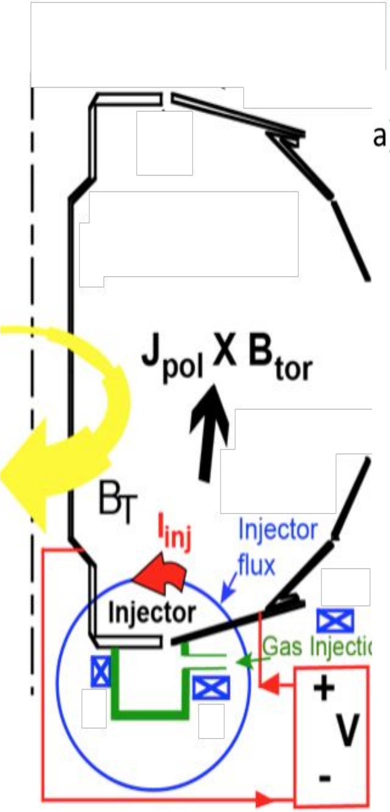
Now the growth rate has a positive exponent S scaling

Simulations with guide field

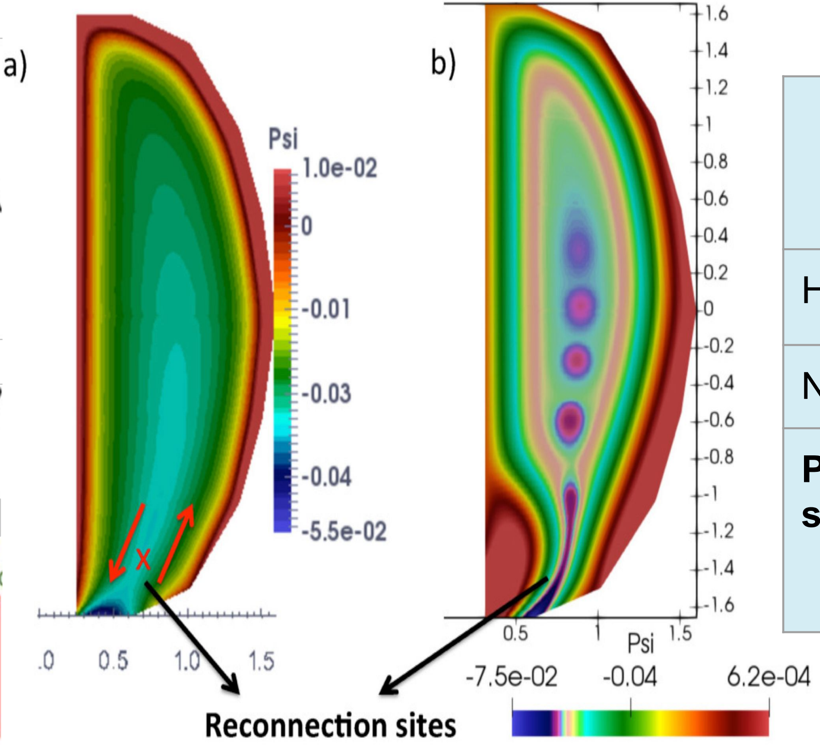


Number of plasmoids is an increasing func#on of S. Blue: small sized transient plasmoids Red: large scale and persistent plasmoids.
Ebrahimi&Raman PRL 2015

Experiments and simulations in NSTX have proven the Transient Coaxial Helicity Injection (CHI) as a primary and scalable candidate for solenoid- free startup in STs



During decay (Vinj =0) **During injection (Vinj on)**



	BT [T]	Injected flux (Wb)	Startup current (MA)
HIT-II	0.4	0.03	0.1
NSTX	0.6	0.06	0.2
Projected simulation	**4**	**0.3**	**1**

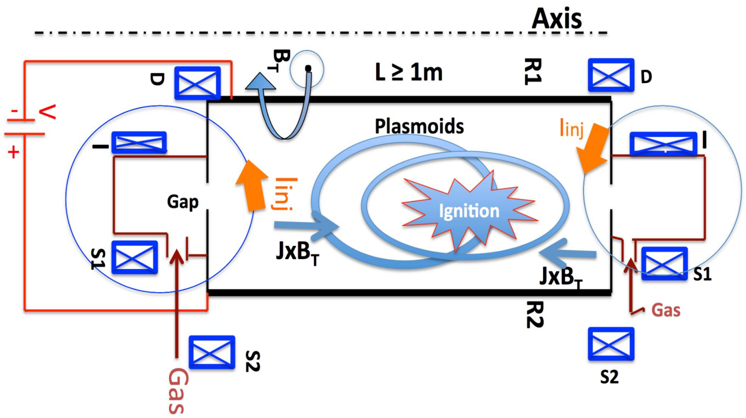
(NSTX plasma volume is ~30x HIT-II)

[Experiments: Raman et al. PRL 2003, 2006]

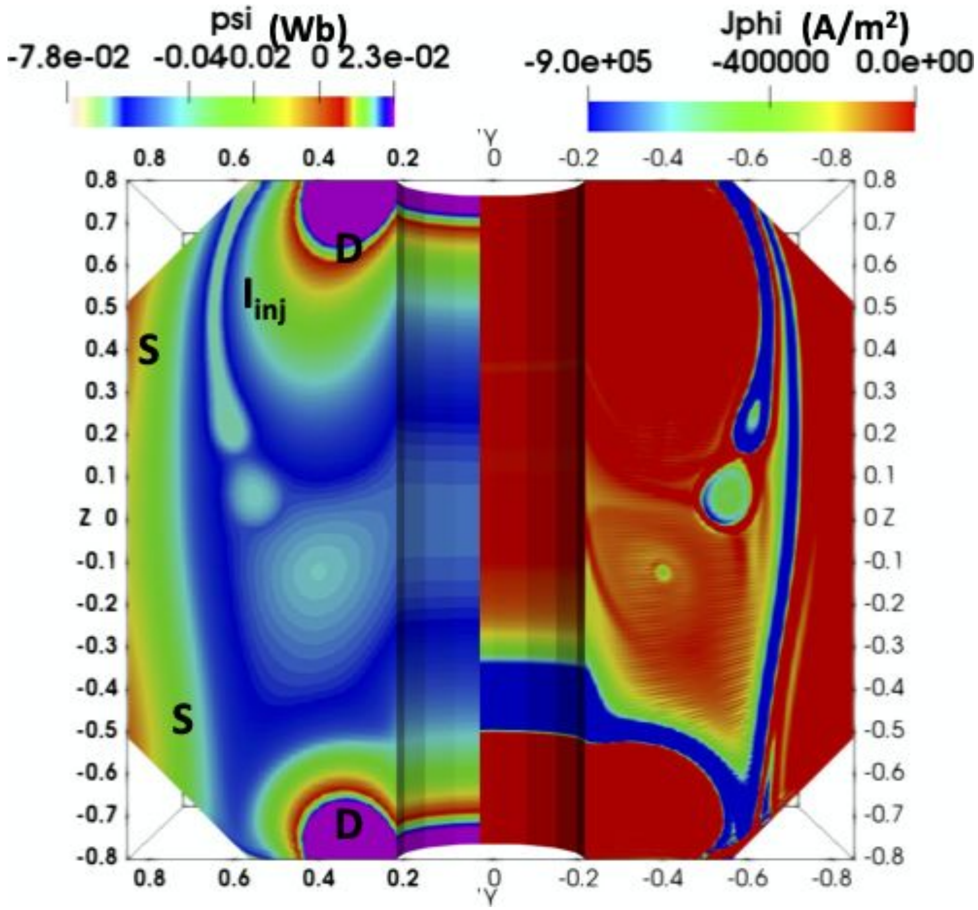
[Simulations: Ebrahimi PoP 2019,2016, Ebrahimi et al. PoP 2013, Ebrahimi&Raman PRL 2105, NF 2016]

Novel fusion concept using plasmoid reconnection (a double null configuration)

Plasmoid reconnection fusion concept.
Princeton University (USPTO No. 63/085,660)
Ebrahimi



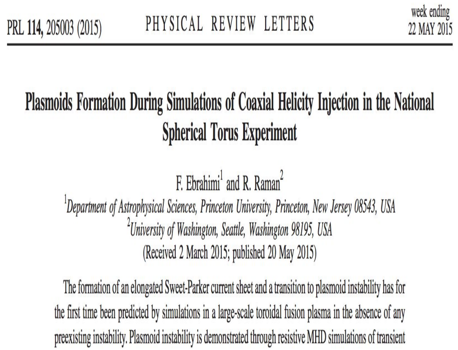
Continuous merging using helicity injection plasmoids. All the fueling and heating is done by plasmoid reconnection.



“Nuclear Fusion Inspires New Rocket Plasma Thruster Design”

2015 -2016 — **2017** — idea — **2018-2019** — **2020-2021** — **2022-2023**

Proof of Principle (foundation)
State-of the art simulations
+NSTX experiment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Ebrahimi&Raman PRL 2015
Ebrahimi &Raman NF 2016, FE PoP2016

➢ **Fast magnetic reconnection creates non-inductive current for fusion**

Propulsion idea

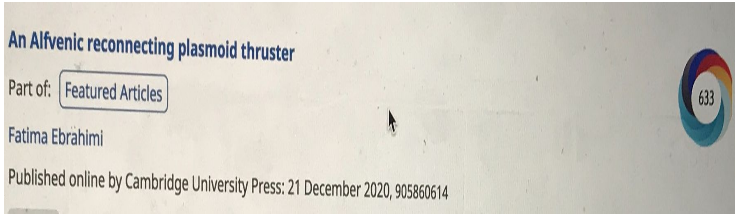
Original invention disclosure filed with Princeton University on June 27, 2017

Favorable current scaling:
for high fusion current (possible for ohmic ignition)
Ebrahimi PoP 2019

Provisional patent filing
September 29 2021
Submitted peer-review paper Feb 6 2020

Ebrahimi JPP 2020

DOE internal funding - Team Engineering design/2022 -

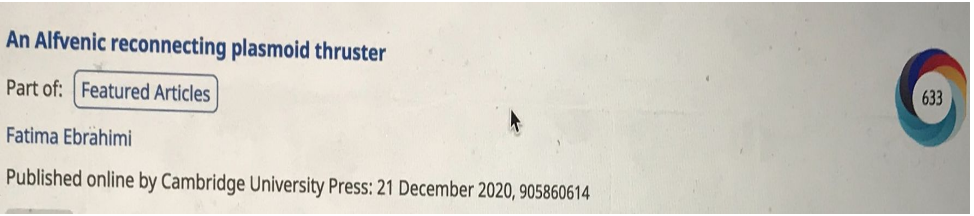


➢ **New propulsion concept based on fast magnetic reconnection proposed**

An Alfvenic Reconnecting Plasmoid Thruster

Princeton University (USPTO No. 63/085,660)

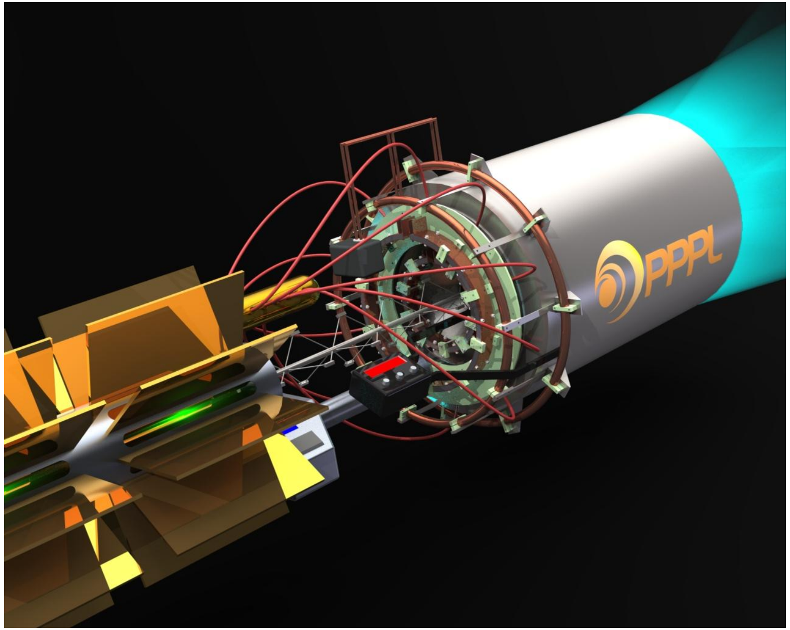
- We are in the design/build stage of a magnetic reconnection thruster at PPPL using a 3-year internal lab funds.


An Alfvenic reconnecting plasmoid thruster

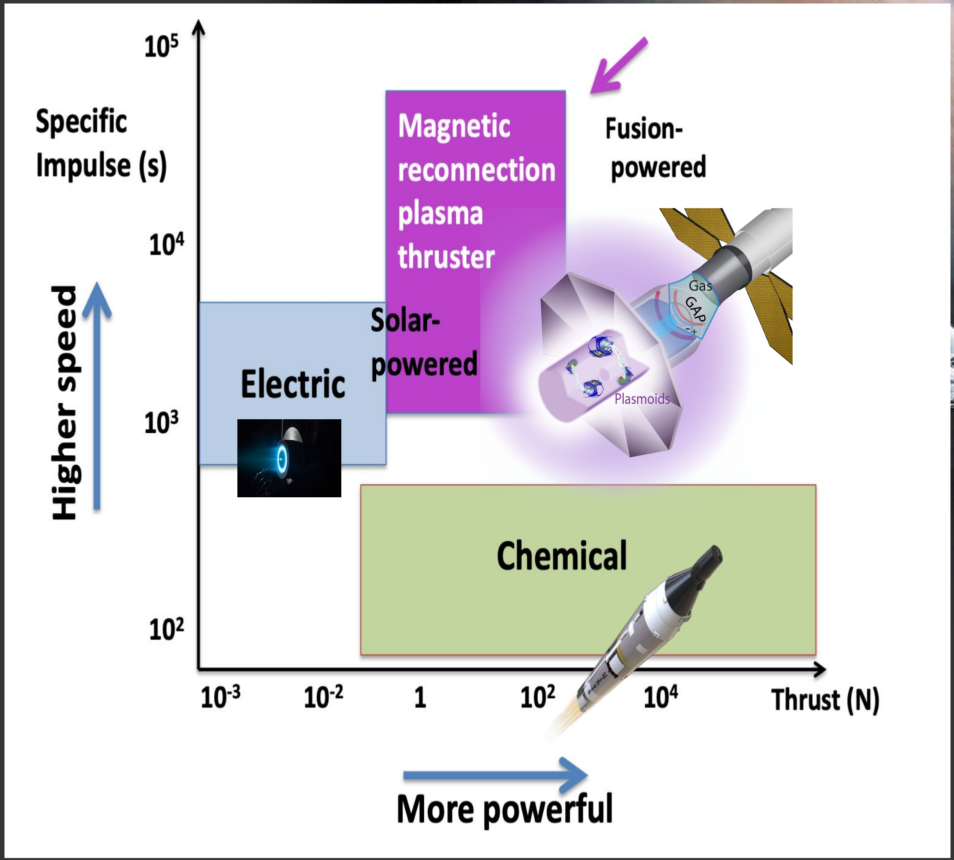
Part of: Featured Articles

Fatima Ebrahimi

Published online by Cambridge University Press: 21 December 2020, 905860614



Plasma MRT occupies the current gap for deep space travel



- **Easier refueling:** Flexible propellant
- **Efficient:** Accelerate plasma ions to high velocity
- **Powerful:** Large, continuous, and adjustable thrust

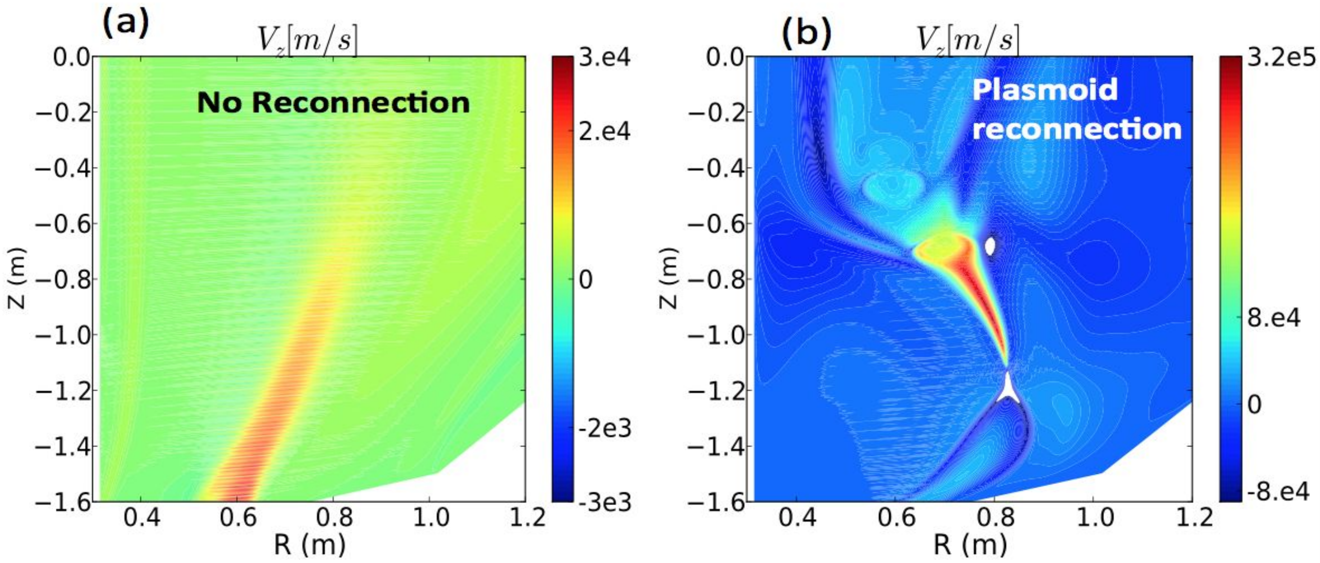
$$\Delta v = v_{ex} \ln (m_0/m_f)$$

$$T = \dot{m}\, v_{ex}$$

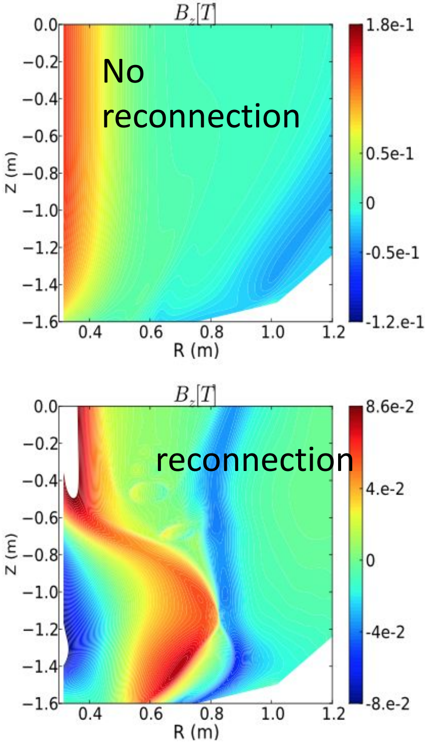
$$I_{sp} = v_{ex} / g_0$$

S. Burg

Magnetic reconnection is essential for high exhaust velocity

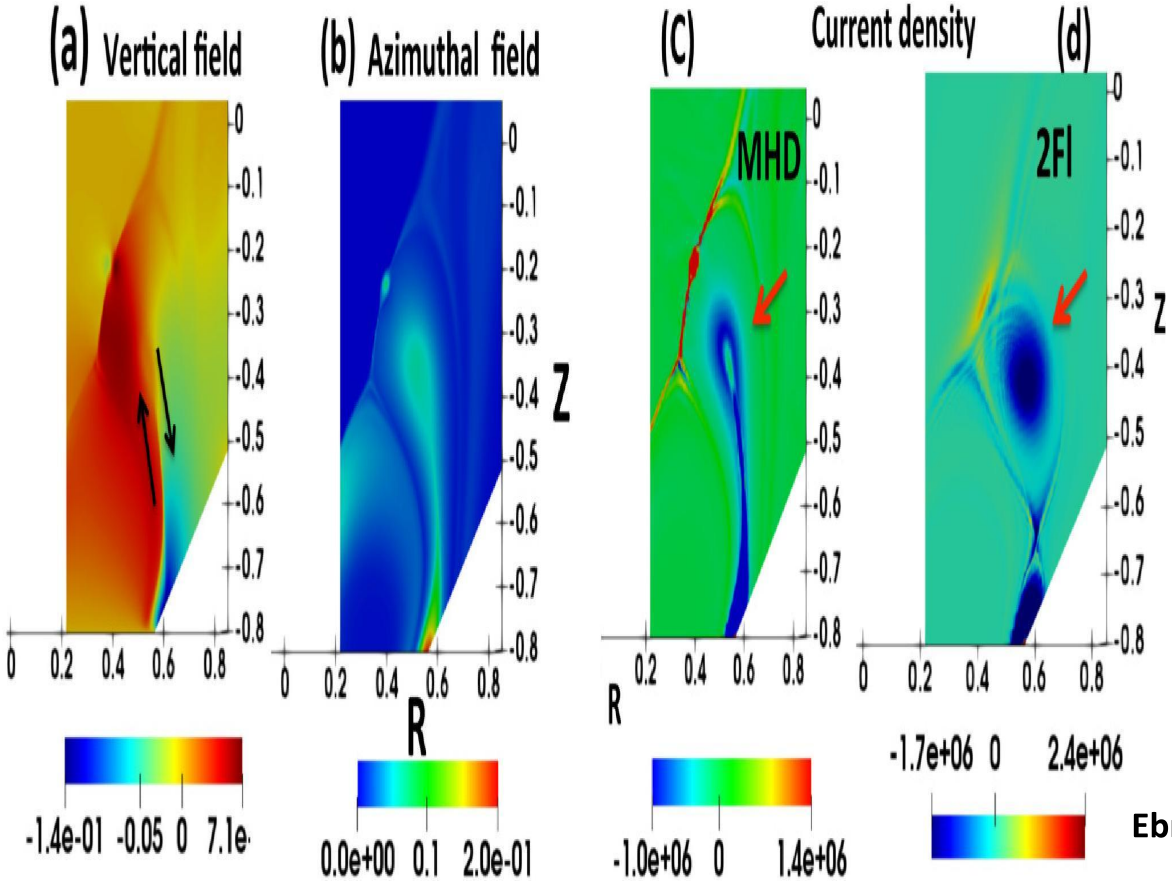


Vertical fields



- Outflow velocities obtained in the simulations
- Magnetic configuration has essential role in inducing reconnection in this thruster

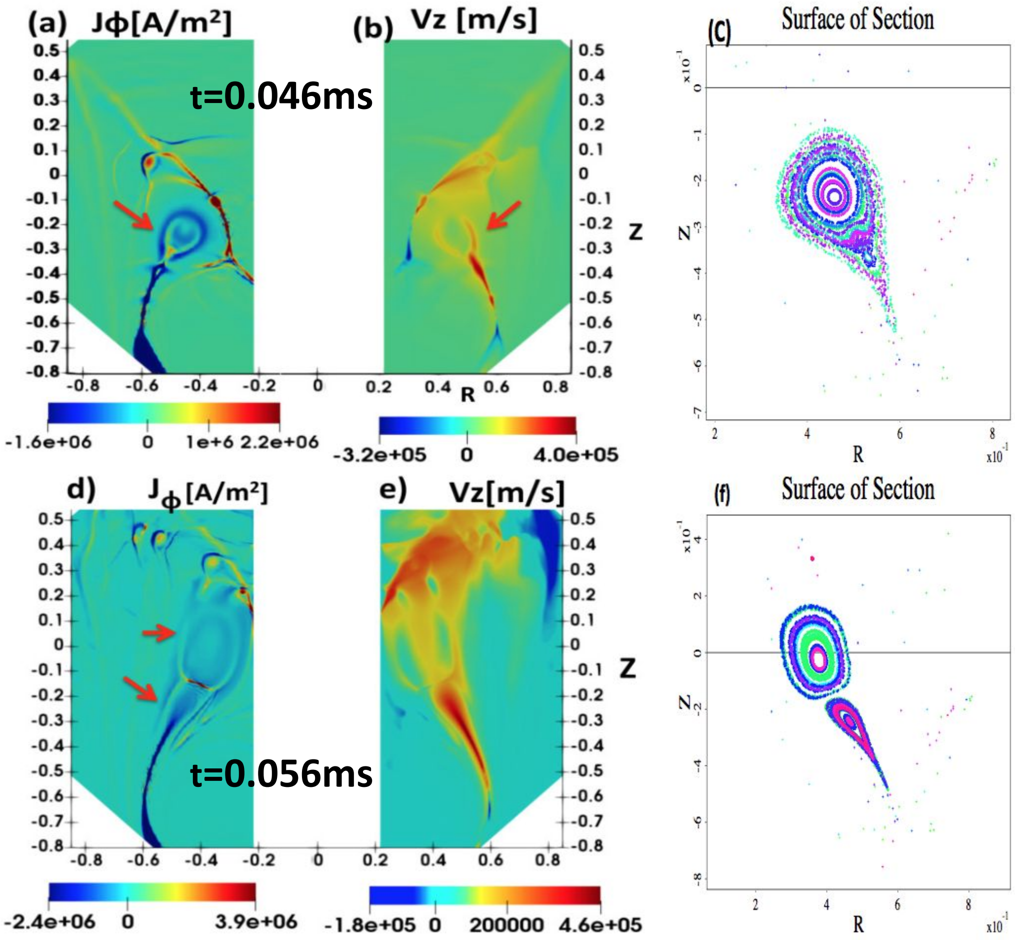
The plasmoid instability is triggered



- The static fields B_p^D and B_p^S radially pinch the injector field around the injector gap to form a primary exhaust reconnecting current sheet
- The plasmoid instability is here triggered at local Lundquist number S ~ 12 000 (based on Bz ~ 500 G, L = 0.5 m and η = 16 m2 s−1).

Ebrahimi JPP 2020

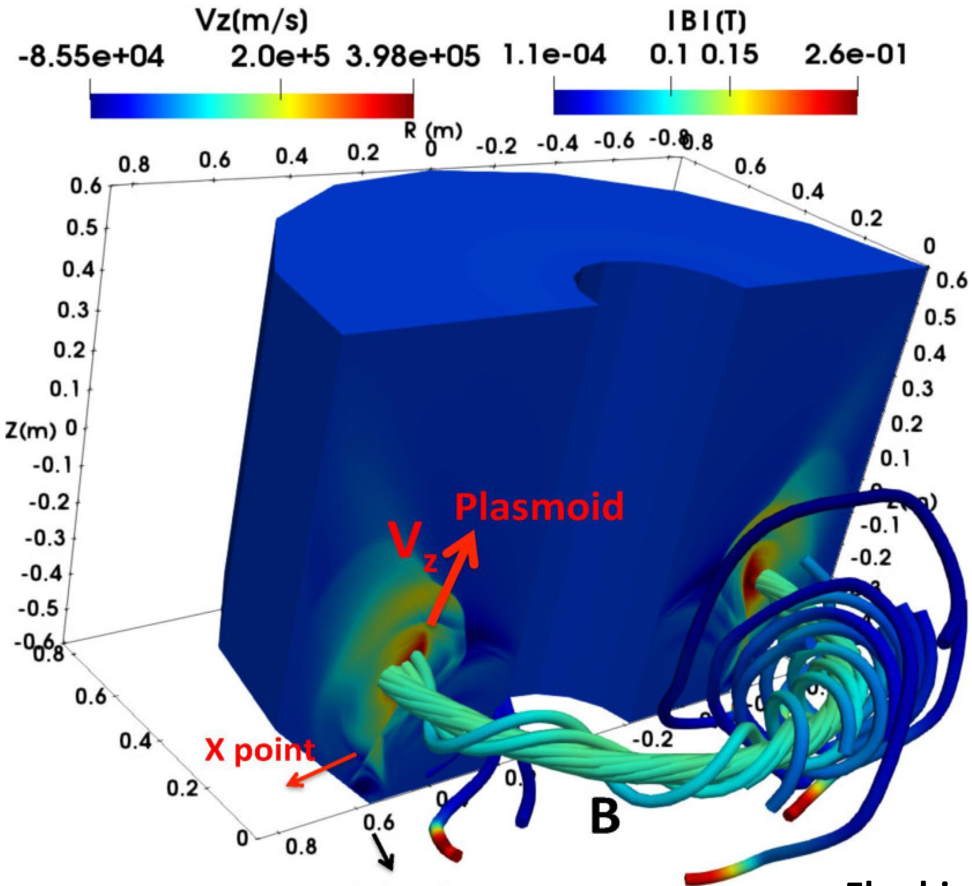
Cyclic ejection of large-scale axisymmetric plasmoids is observed



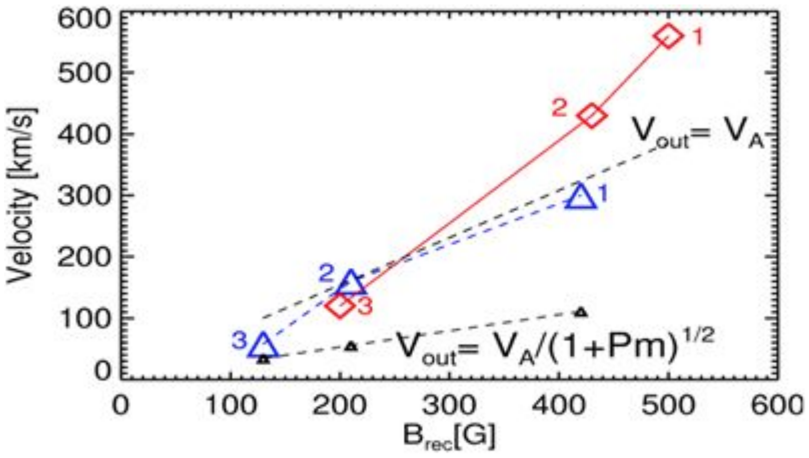
- As the first plasmoid is already ejected, the open field lines start to close again and a large-volume closed field line in the form of a second plasmoid is formed and departs the device with a high outflow velocity of about 460 km s−1.
- The maximum outflows are both along the exhaust current sheets in the form of outflow jets, as well as along the plasmoids.
- Cyclic ejection of large-scale axisymmetric plasmoids is around 10 μs (4–5 Alfven transit times).

Ebrahimi JPP 2020

Momentum-carrying plasmoids are formed during three-dimensional global MHD simulations



Exhaust velocity scales with magnetic field



- $V_{exhaust} \sim V_{A(pol)} = B_{in(z)} / \sqrt{(\mu_0 \rho)}$.
- $F = \rho V^2{}_A A$ <--- **Thrust**

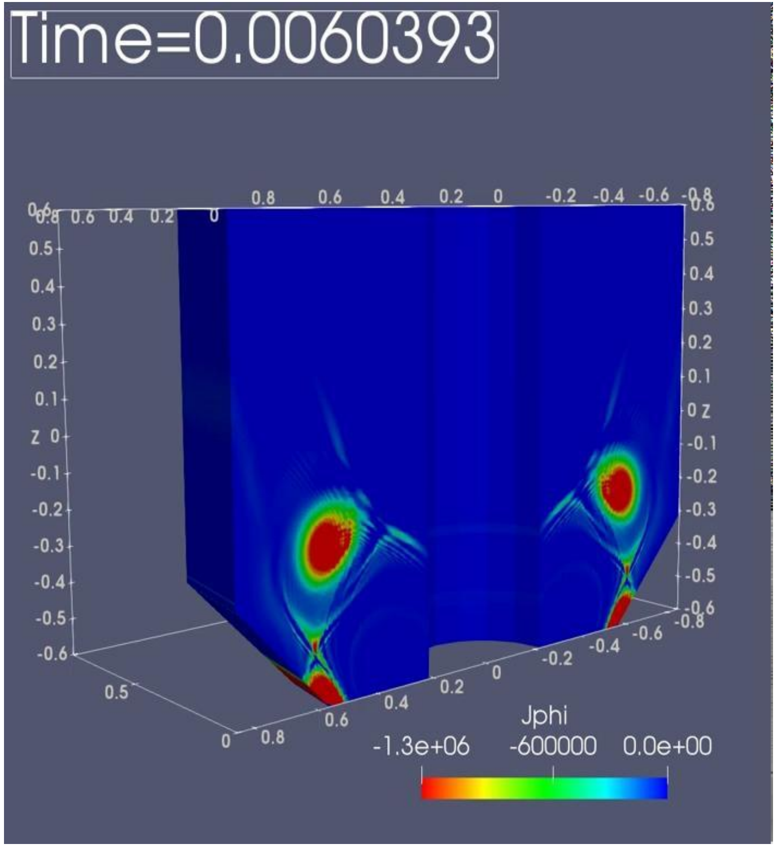
➢ ISP ~ 2,000 - 50,000 s
➢ Thrust ~ 1 - 100 N (Power 0.1 - 10 MW)
➢ For the high-power case that corresponds to about 5-10 mN/kW.

Ebrahimi JPP 2020

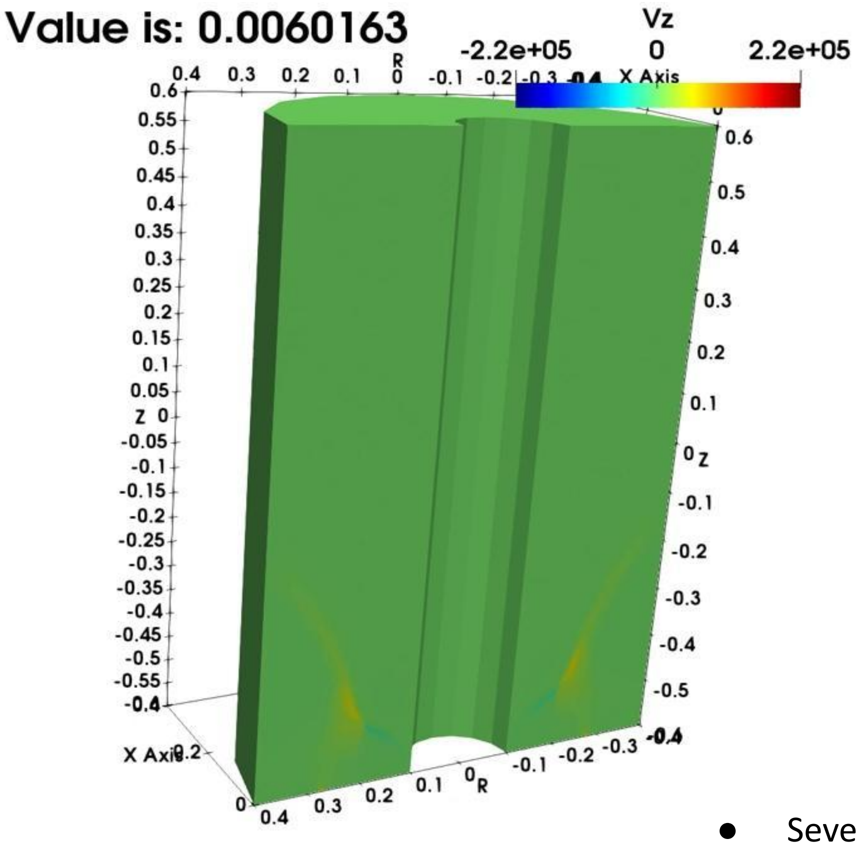
Subsequent ejection of a large plasmoid durig Hall reconnection with large exhaust velocity

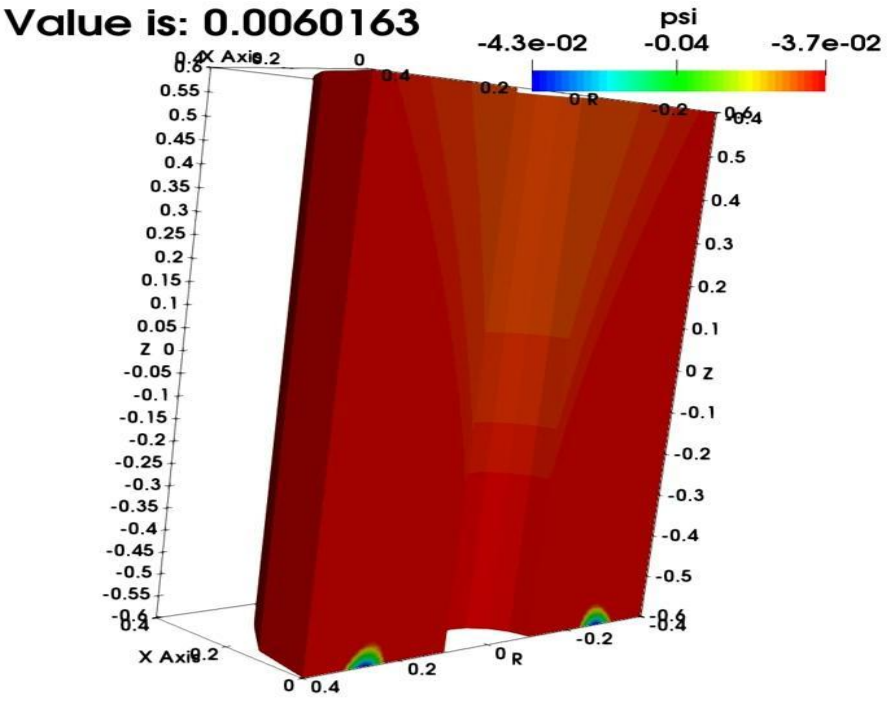
Current density

Exhaust velocity



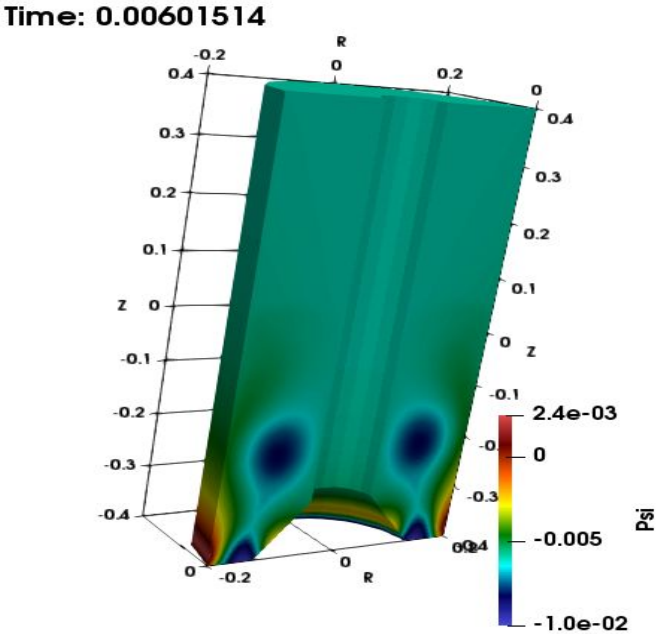
MHD simulations for a small-scale device

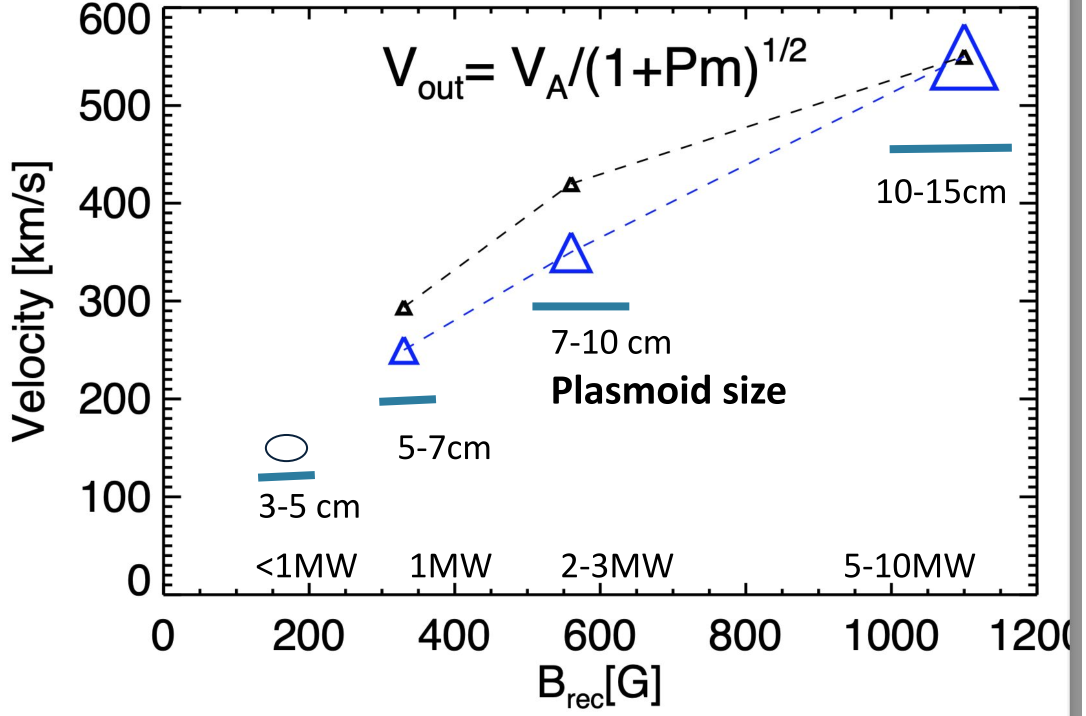




- Several magnetic configurations for smaller scale device performed.

Favorable magnetic field scaling also obtained





- The size of the large plasmoid is for the high power case.

- Plasmoid size as well as **average** speed increases (up to ISP of 50000 s) with the reconnecting field. No guide field here.

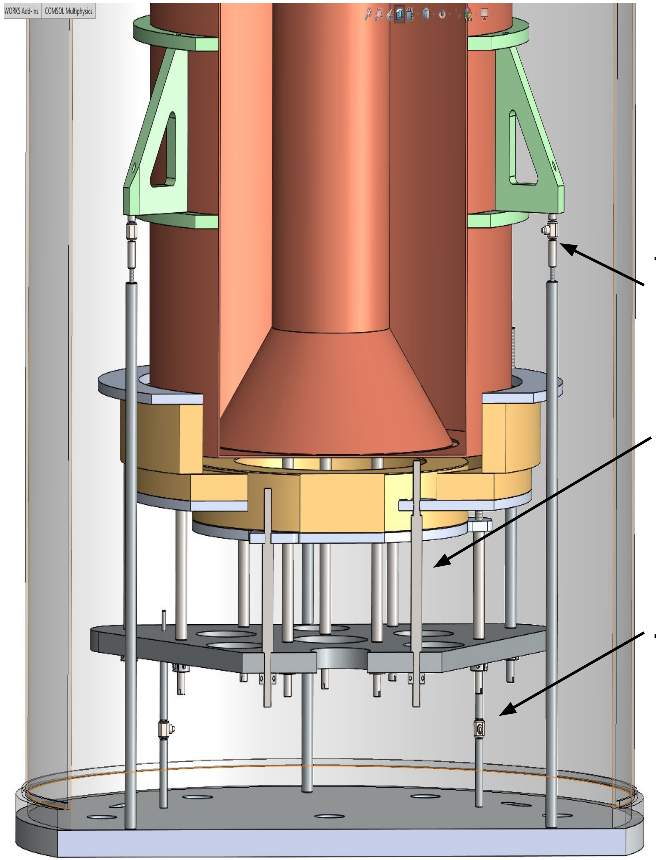
PMRT System Design (building at PPPL)

Simple structure, low-cost in manufacturing/assembling

- ❑ **Vacuum Vessel:**
  40" × 70" 5-mm Stainless steel

- ❑ **Plasma Chamber:**
  ID: 0.1-m – OD: 0.3-m – Length: 1.2-m
  Copper (Glidcop) with tungsten coating

- ❑ Thrust measurement:
  - ❑ Can be changed to horizontal arrangement by adding supporting structure



Force sensor integrated to supporting structure

All coil locations adjustable by adjustment screws

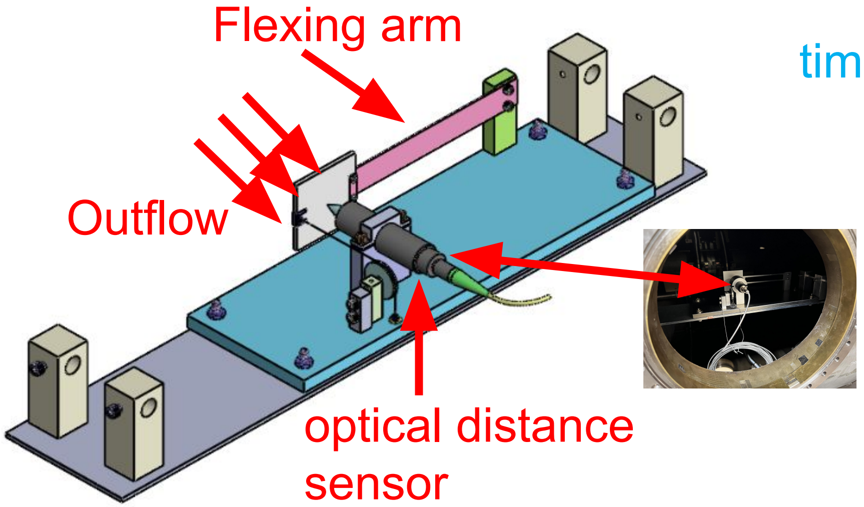
1. Multiple sensors for measuring asymmetrical force

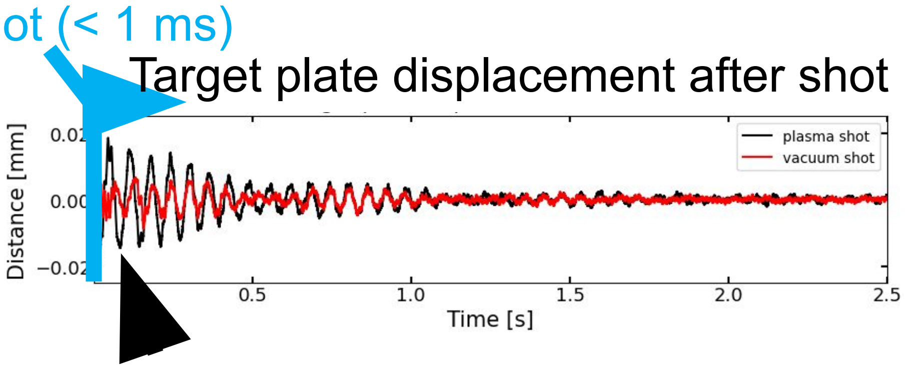
Measurements in existing experiments

- No electrodes for lower electrode erosion
- Generate asymmetry using outflow direction **B** pressure gradient
- Initial displacement measurement data (for thrust) on MRX is promising

Kush Maheshwari+ poster

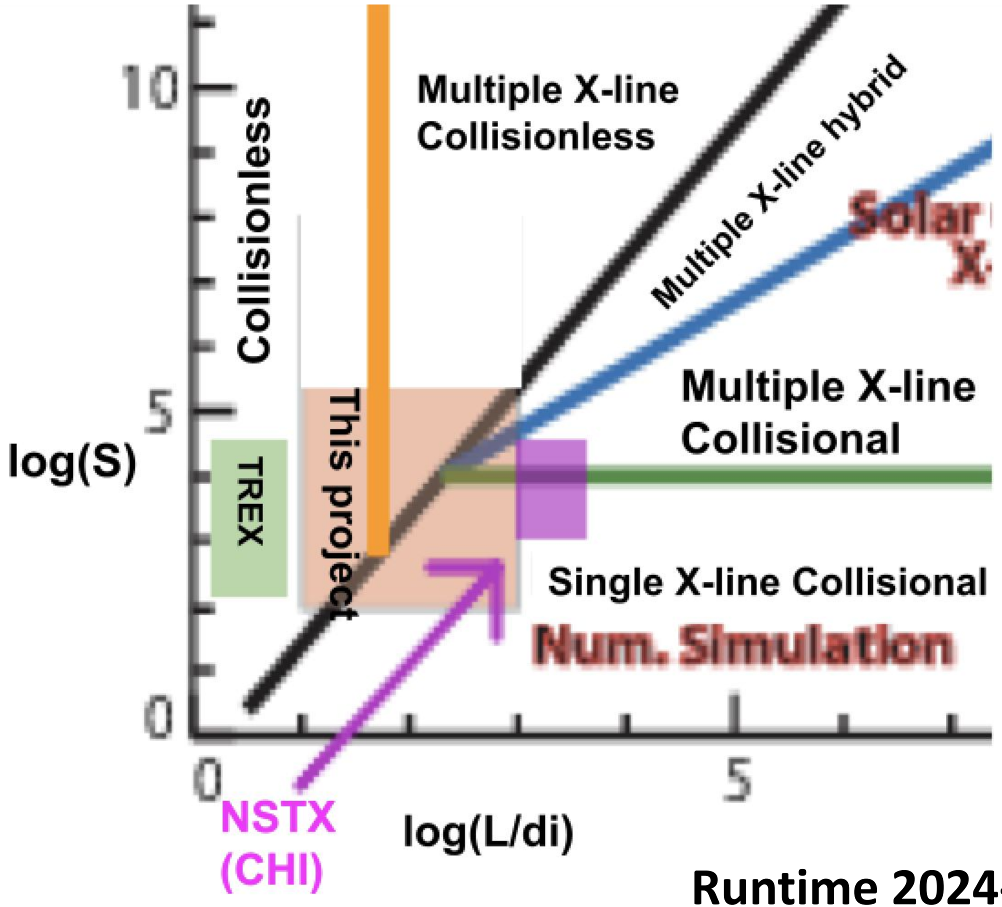
Displacement/thrust measurement apparatus





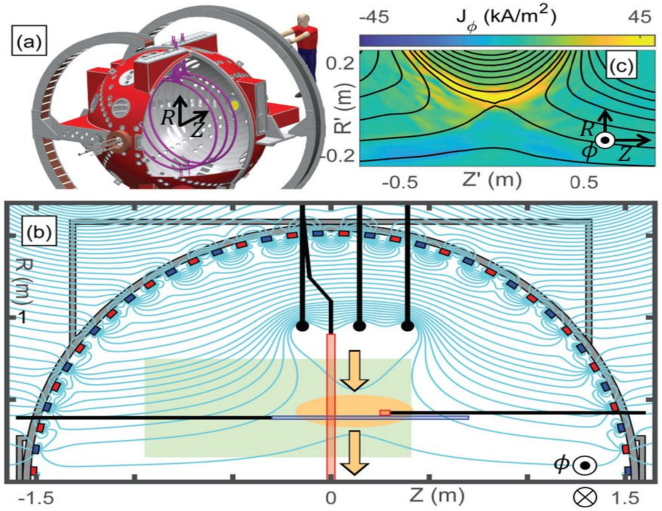
Plasma shot >2x amplitude compared to vacuum shot

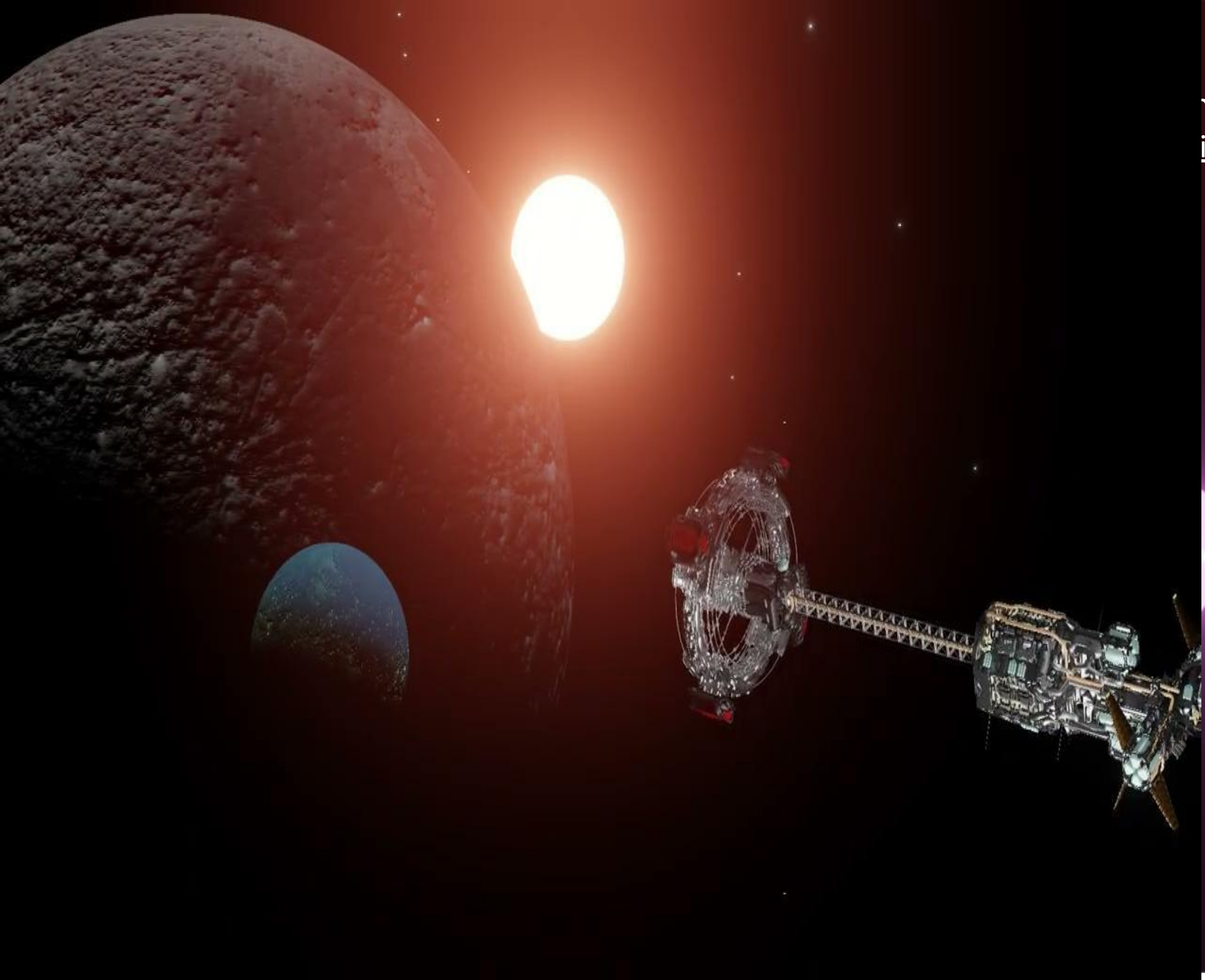
Measurements of Magnetic Reconnection Ion Propulsion on WiPPL



Runtime 2024-2026

- **Orange box: desired operational regime,** approaching the MHD collisional limit ions contribute in the reconnection process for propulsion **λ ~ > 40**





oid reconnection thruster concept
nclude a unique fusion concept.
ity (USPTO No. 63/085,660)

Graphics by
SciVista

Summary

- **Understand and predict** 3-D MHD simulations have shown that system-size plasmoid formation can produce large plasma startup current in spherical tokamaks and a large-fraction conversion of injected open flux to closed flux.

- **Explore** Continuous plasmoid injection due to spontaneous reconnection could be the key for steady-state current-drive. New magnetic configuration is being investigated.

A reconnecting plasmoid thruster is highly scalable

- **Exploits magnetic reconnection to convert magnetic energy to kinetic energy with high exhaust velocity**
    - Experiments at NSTX and simulations using state-of-the-art 3D computational models running on NERSC supercomputers provide a firm scientific foundation for the propulsion concept