May 24th, 7:30 AM

Magnetic Reconnection Propulsion

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Magnetic Reconnection Propulsion

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Space Congress 2016

**“The Journey:
Further Exploration
for
Universal Opportunities”**

“...showcase the evolution of our industry... to meet the challenges of the future.”

***Better, Faster,
Cheaper***

Faster?

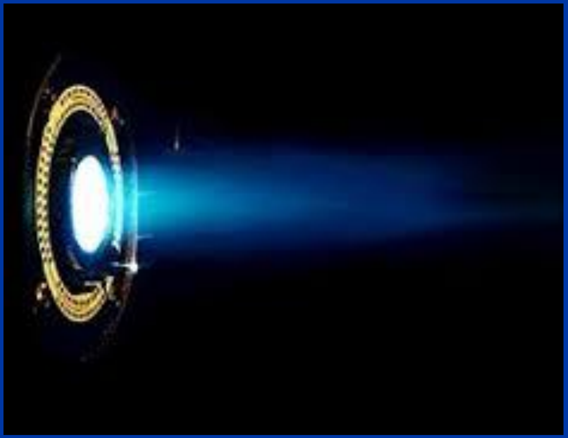
Chemical
Propulsion

Faster? How?

Increase Thrust

$$T = u_{ex}\dot{m}$$

Alternative → Plasma Propulsion



Chemical vs. Plasma Propulsion

Specific Impulse

$$I_{sp} = \frac{u_{ex}}{g_0}$$

Thrust

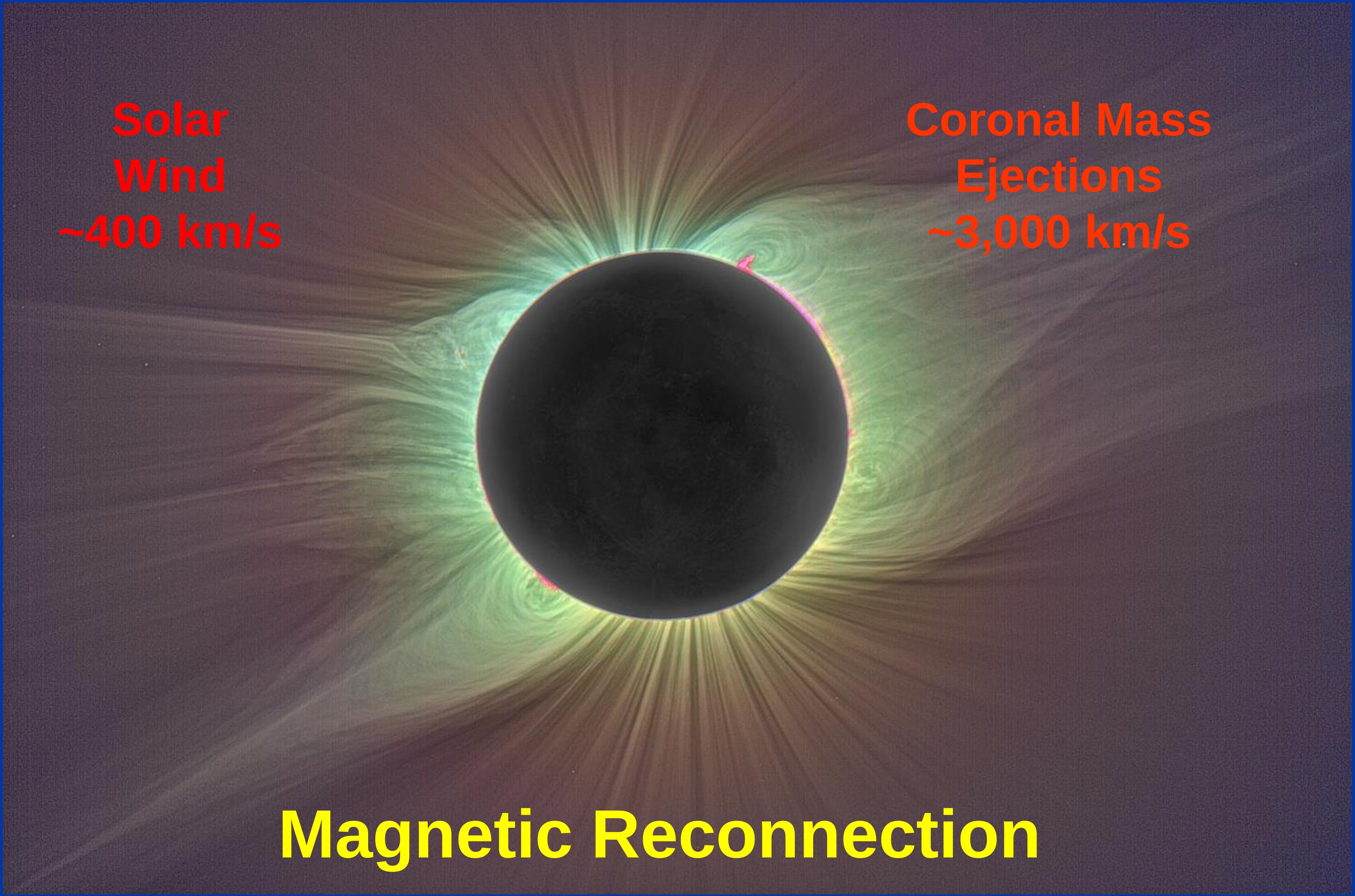
$$T = u_{ex}\dot{m}$$

Chemical (hypergolic)
- I_{sp} = 250-450 s
- u_{ex} = 5-10 km s^{-1}
- Thrusts of ~1 N per unit input mass

Plasma (Hall thrusters, ion, *SEP*)
- I_{sp} = 2000-5000 s
- u_{ex} = ~30 km s^{-1}
- Thrusts of ~0.01 N per unit input mass

Maximize u_{ex}!

Sources of High-speed Particles

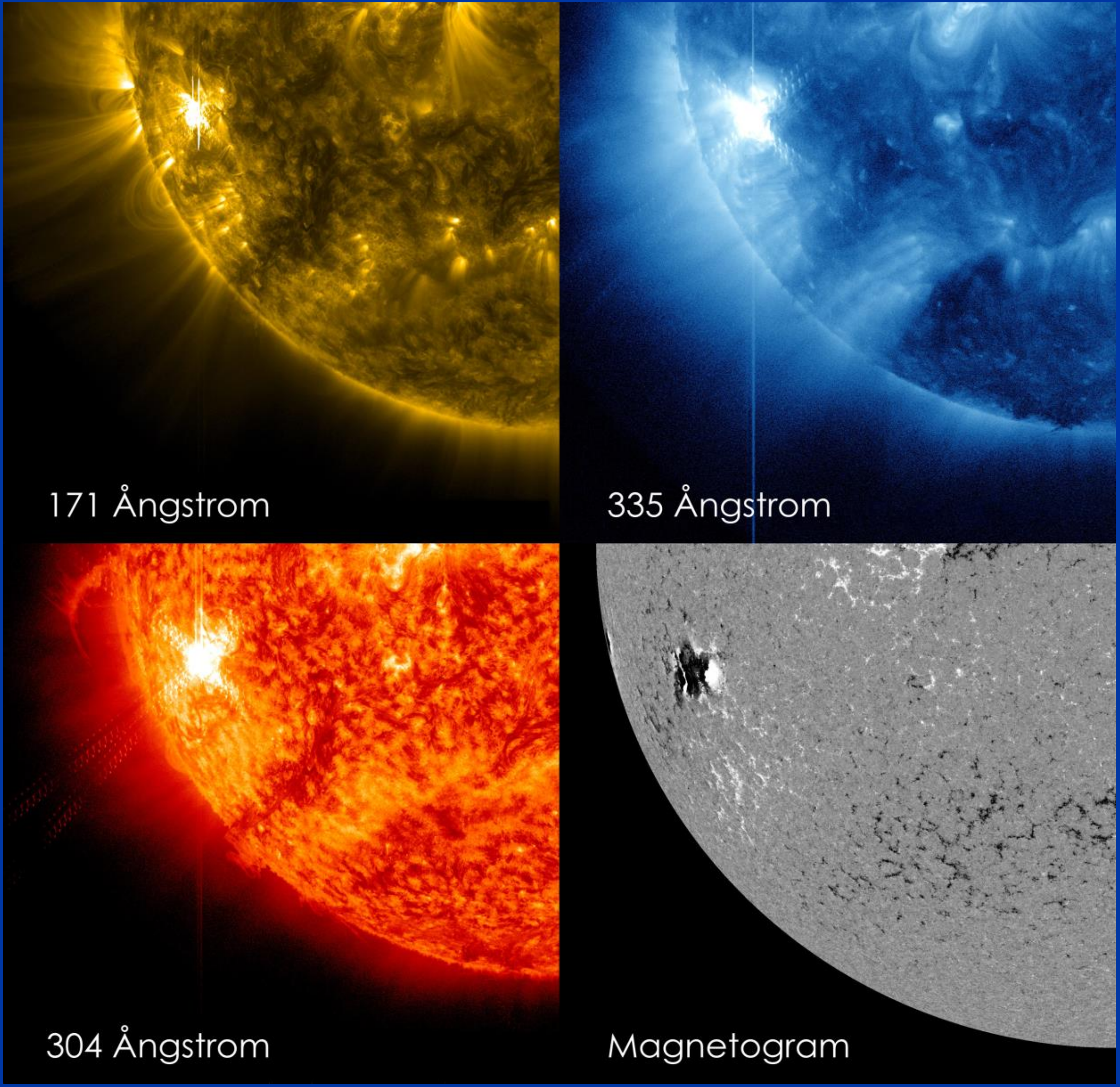


Solar Wind ~400 km/s

Coronal Mass Ejections ~3,000 km/s

Magnetic Reconnection

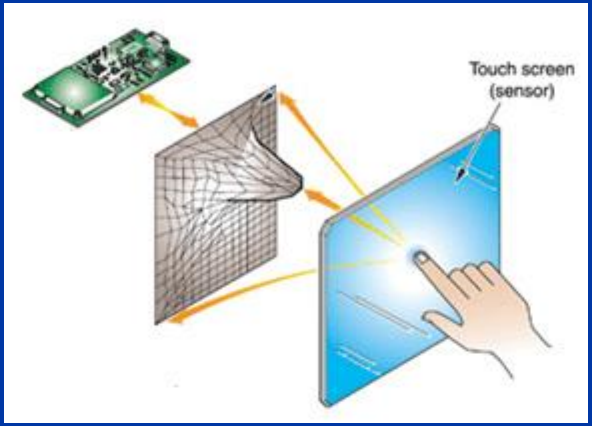
Sources of High Speed Particles



Translate Theory to Engineering

Example: Smartphone touchscreens!

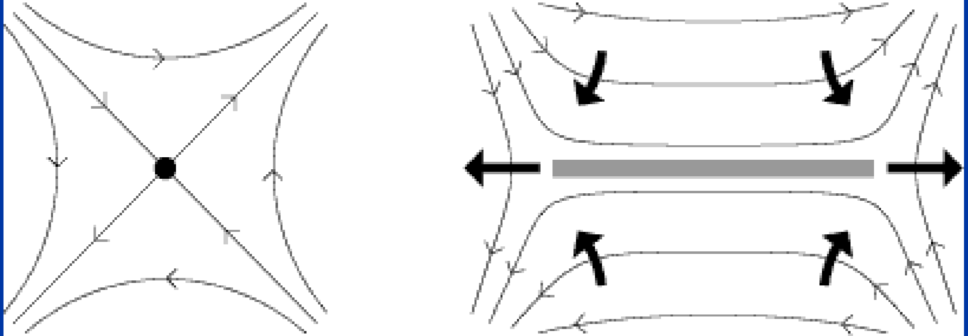
$$C = \epsilon_r \frac{A}{4\pi d} \qquad \Delta V = \frac{Q}{C}$$

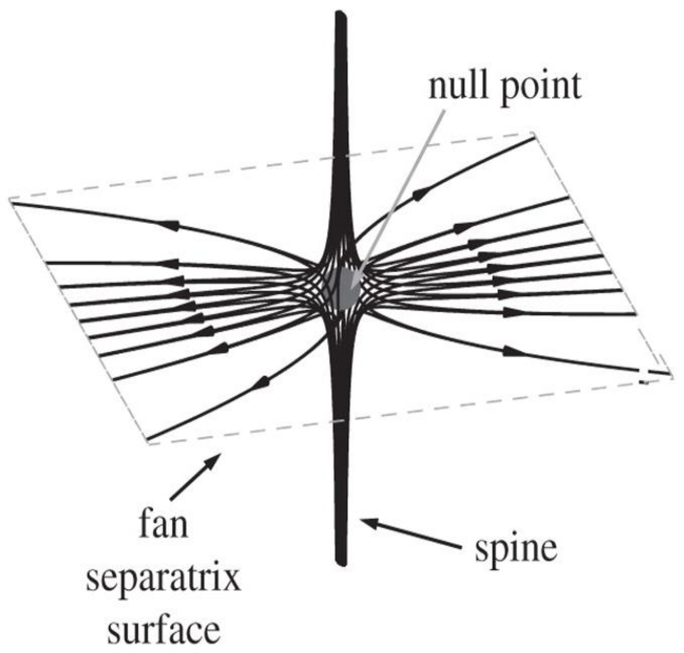


Magnetic Reconnection

2D

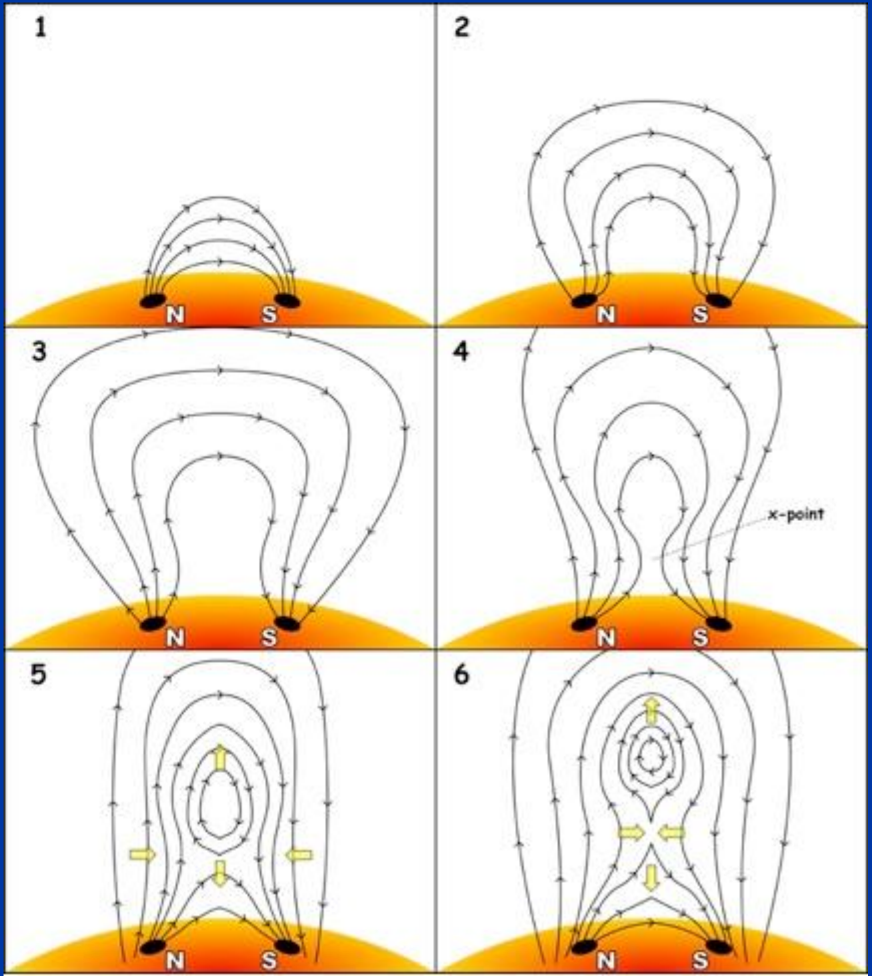
3D

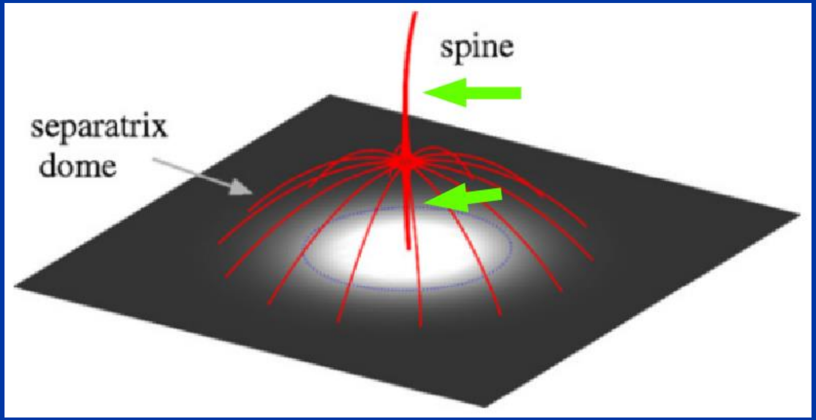


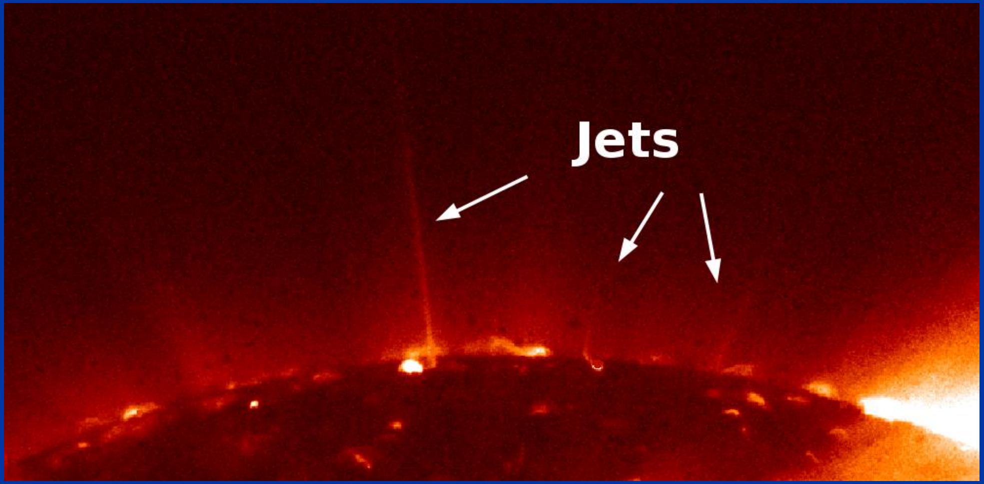


Diffusion-dominated process

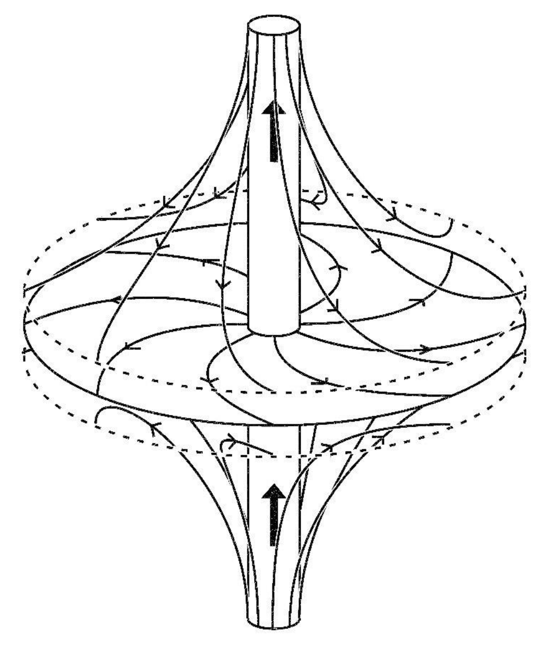
Reconnection in the Solar Atmosphere



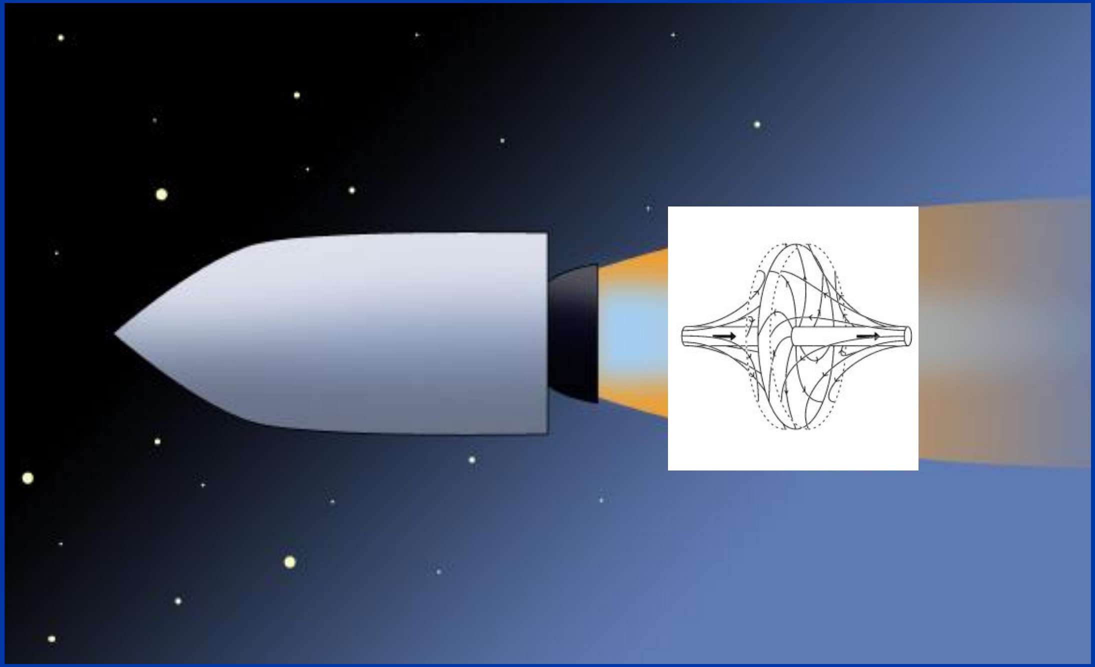




Application to Propulsion?



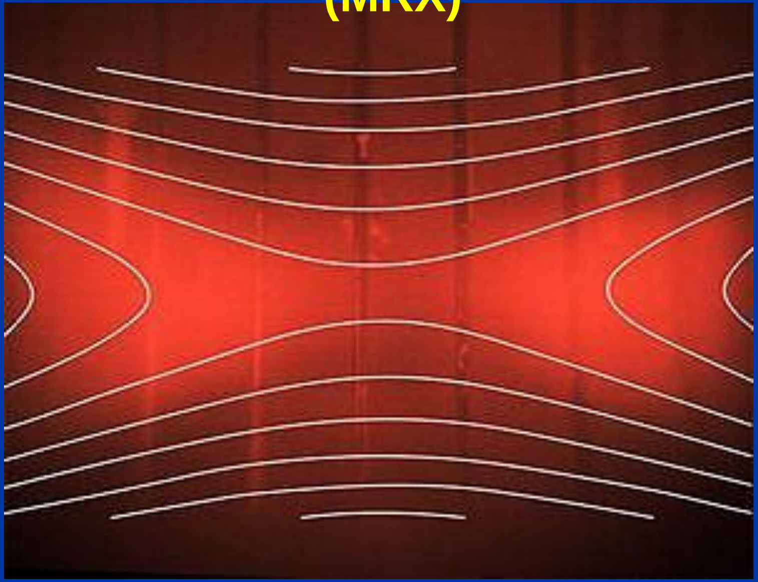
Intense spine current



Reconnection on Earth

MIT
Versatile Toroidal Facility

PPPL
Magnetic Reconnection Experiment (MRX)



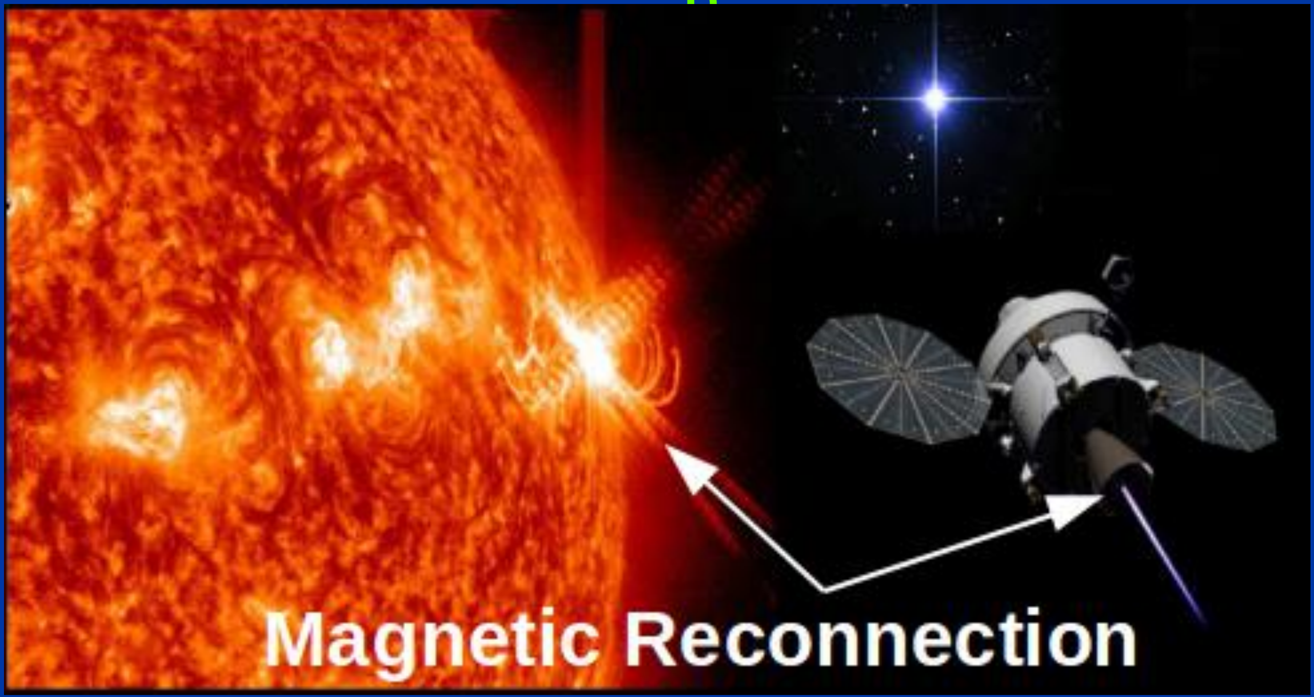
2D manifestations only

Innovate?

State-of-the-art → Better, Faster, Cheaper

Reconnection Devices → Better, Smaller, Cheaper

3
D



From Theory to Practice

Magnetohydrodynamics
(MHD)

-Apply field parameters

-Predict timescales

-Predict particle velocities (u_{ex})

Kinetic Reconnection

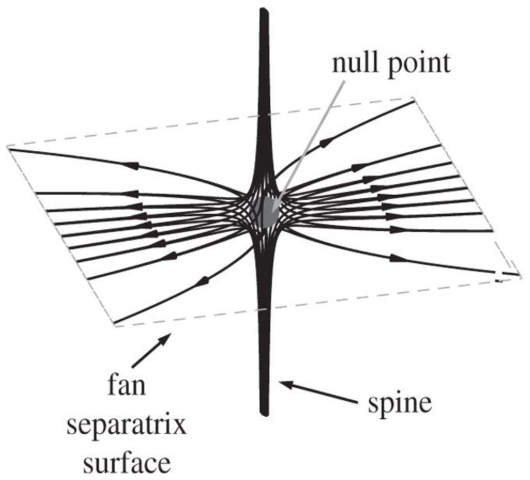
-Perturbations

-Time-dependent field evolution

Engineering

-Enabling components

MHD Modeling



$$\vec{B} = \vec{M} \cdot \vec{r}$$

$$\vec{M} = \begin{vmatrix} 1 & \frac{1}{2}(q - j_{\|}) & 0 \\ \frac{1}{2}(q + j_{\|}) & p & 0 \\ 0 & j_{\perp} & -(p+1) \end{vmatrix}$$

Parnell et al. (1996)

Parnell et al. (2007): Perturb field so that current is induced along spine

$$\mathbf{B} = \mathrm{B}_0 \left(\mathrm{x} - \epsilon \mathrm{e}^{\omega \mathrm{t}} \frac{\mathrm{p}}{\mathrm{p}-1} \mathrm{j}_{\|} \mathrm{y}, -\epsilon \mathrm{e}^{\omega \mathrm{t}} \frac{1}{\mathrm{p}-1} \mathrm{j}_{\|} \mathrm{x} + \mathrm{py}, -(\mathrm{p}+1)\mathrm{z} \right) /\mathrm{l}$$

$$\mathbf{v} = \epsilon \mathrm{v}_{\mathrm{A}} \mathrm{e}^{\omega \mathrm{t}} \left(-\frac{\mathrm{p}}{|\mathrm{p}-1|} \mathrm{j}_{\|} \mathrm{y}, \frac{1}{|\mathrm{p}-1|} \mathrm{j}_{\|} \mathrm{x}, 0 \right) /\mathrm{l}$$

$$\mathbf{J} = \mathrm{B}_0 \epsilon \mathrm{e}^{\omega \mathrm{t}} (0, 0, \mathrm{j}_{\|})/\mathrm{l}$$

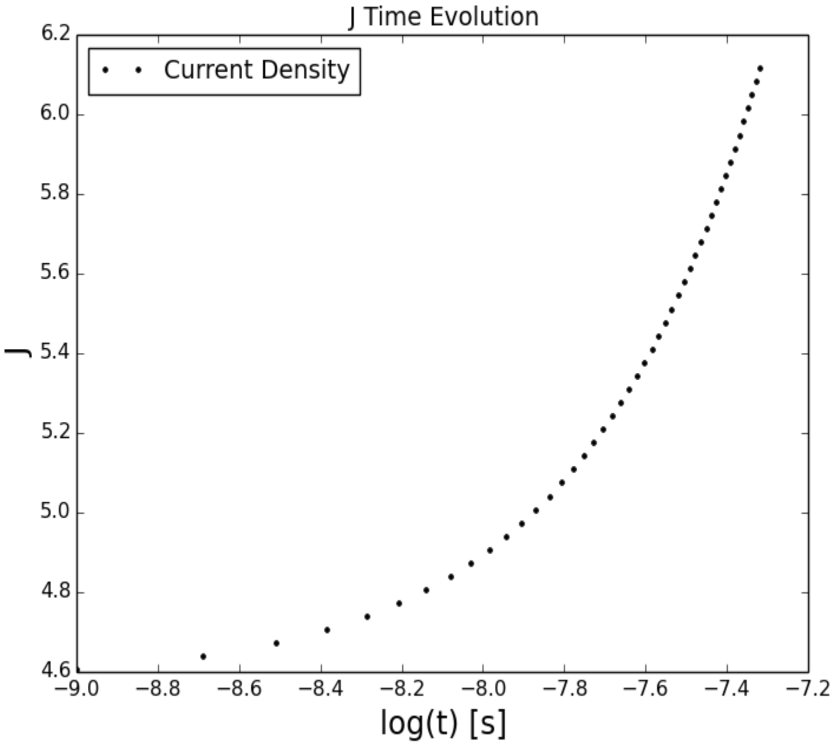
$$\omega = |p - 1| \, v_A / l$$

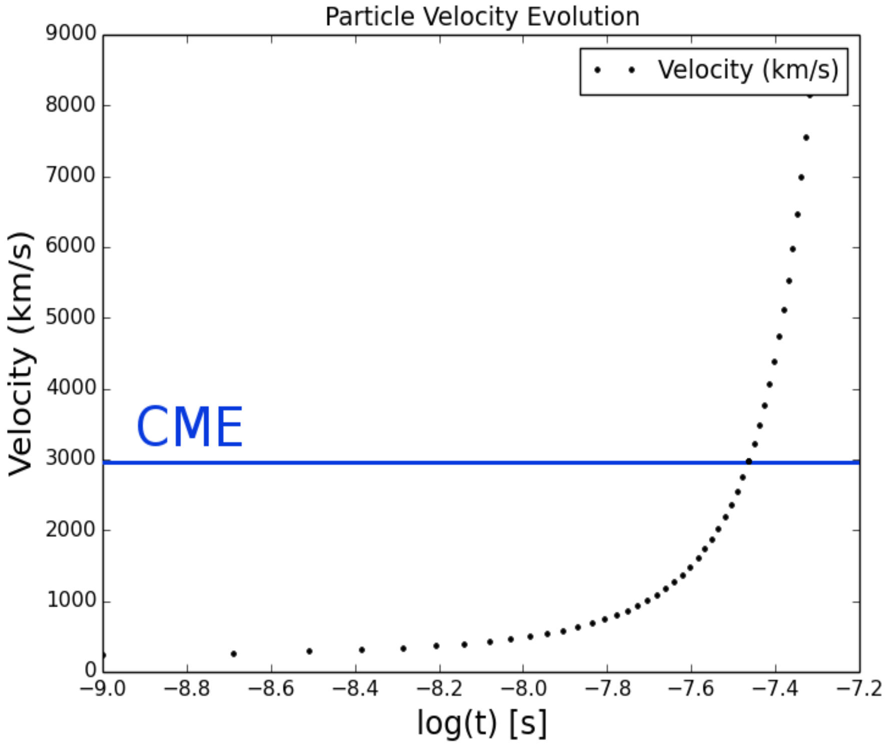
MHD Modeling

Solve with physical parameters:

$m = 2\ m_H$
$B_0 = 1$ T
$l = 1$ m
$n = 10^{18}\ m^{-3}$

$v_A = 10^7$ m/s
$\omega_A = 10^7\ s^{-1}$





limits: $\varepsilon j_z e^{\omega t} < 1$; $S \sim 10^2$

Reconnection will occur on very short timescales

Kinetic Modeling

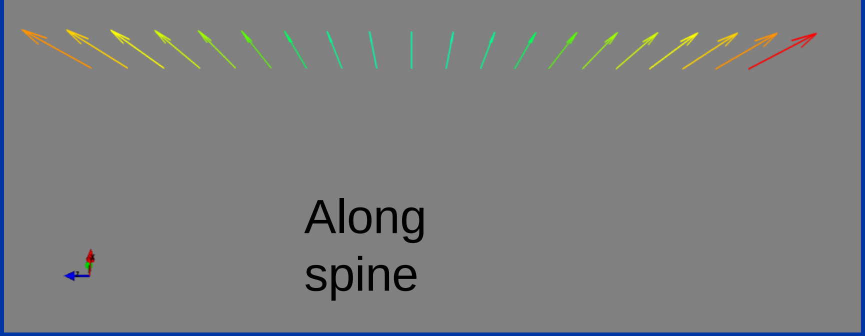
How do charged particles respond to externally imposed boundary conditions?

Plasma flow along spine must be driven by driven perturbation

Produce Initial Magnetic Field

Parnell et al. (1996)

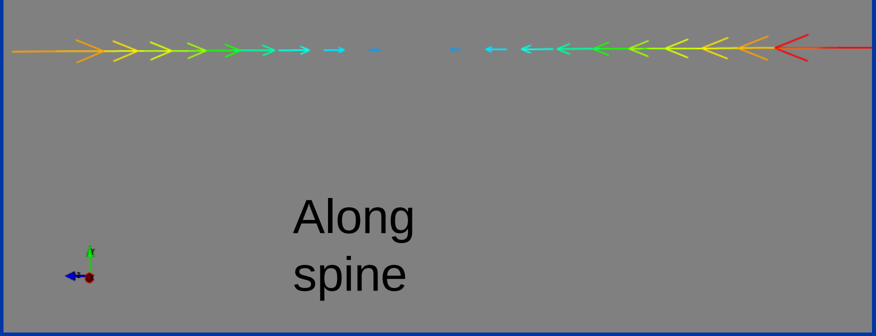
$$\vec{B} = \vec{M} \cdot \vec{r}$$



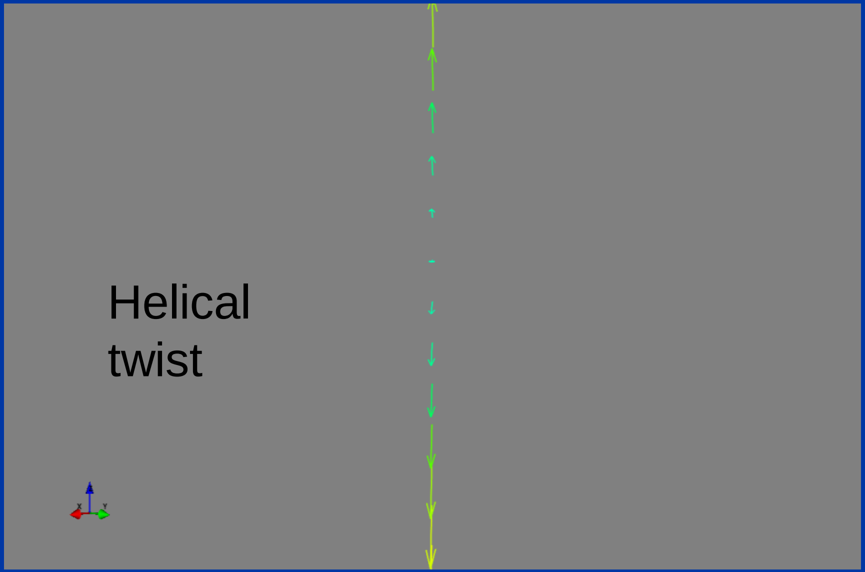
Along spine

Pontin et al. (2011)

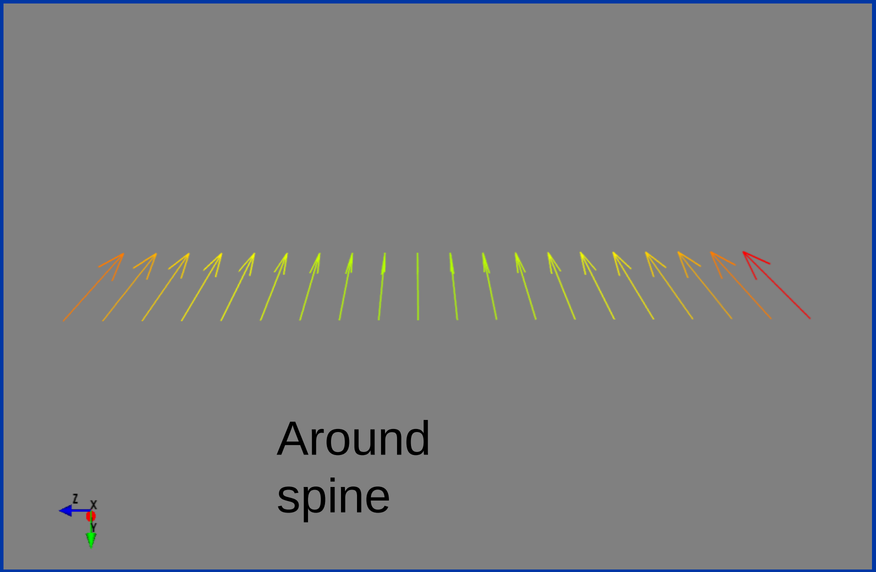
$$\vec{B} = \left[\frac{2}{p+1}x, \frac{2p}{p+1}y, -2z\right]$$



Along spine



Helical twist



Around spine

Produce Initial NP Field

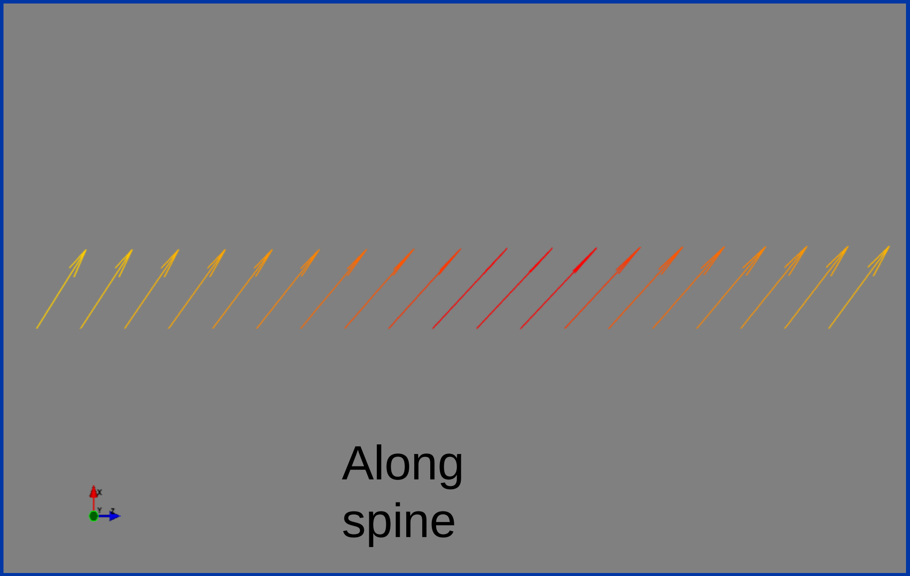
Field we want

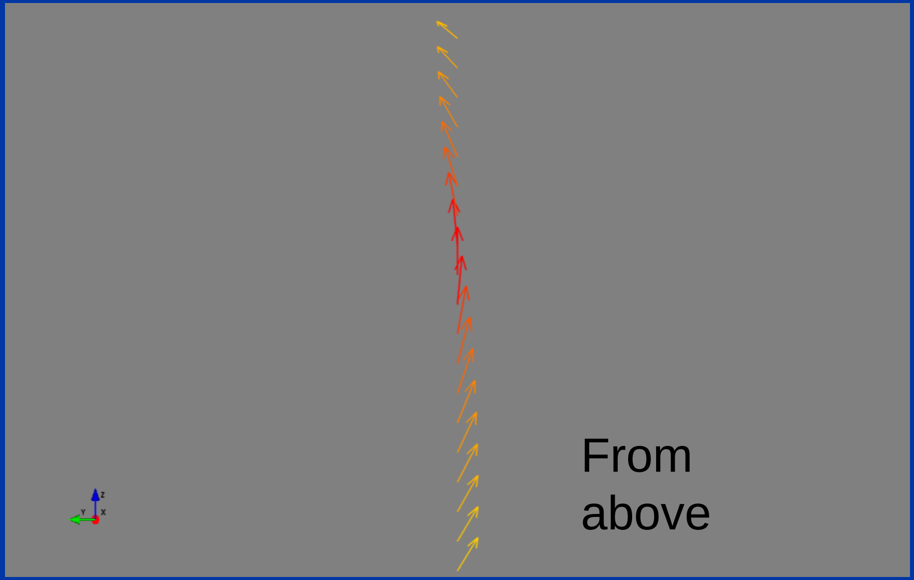
Ampère's Law

Source currents

$$\vec{B} = \vec{M}\cdot\vec{r} \longrightarrow \nabla\times\vec{B} = \mu_0\vec{J} \longrightarrow \boxed{\vec{J} = \frac{1}{\mu_0}(j_\perp, 0, j_\parallel)}$$

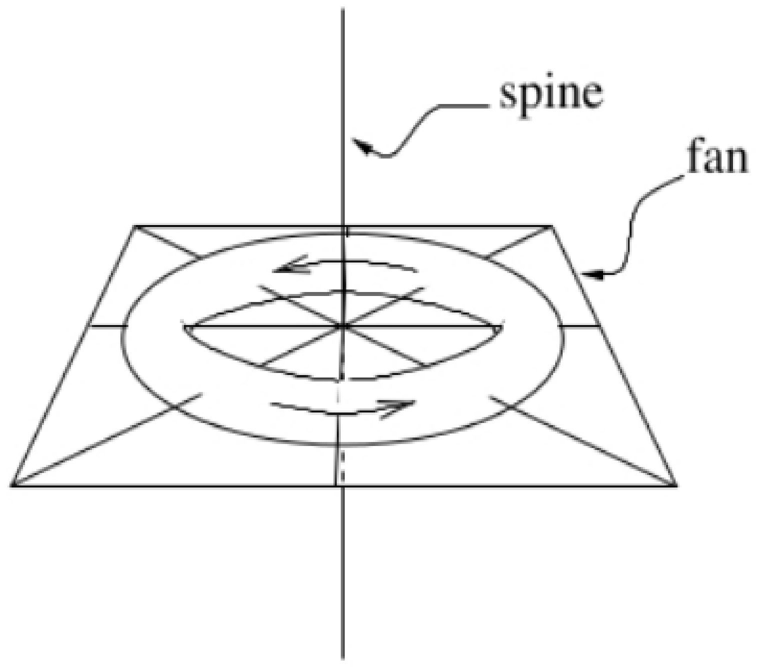
perpendicular

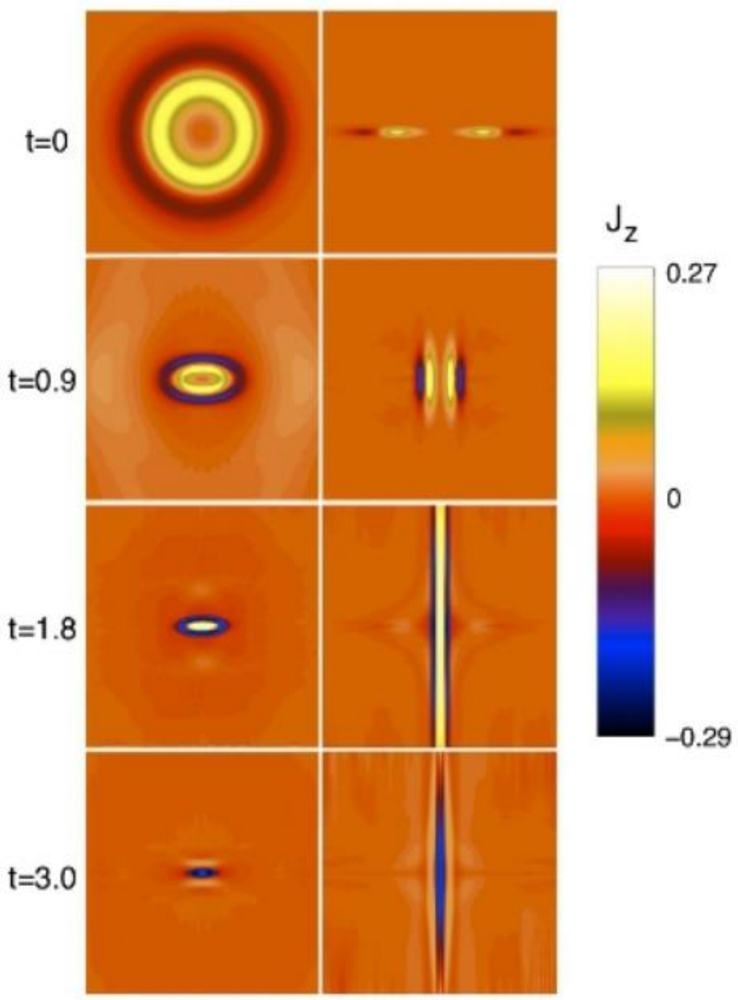




Is there an existing technology that can produce such fields?

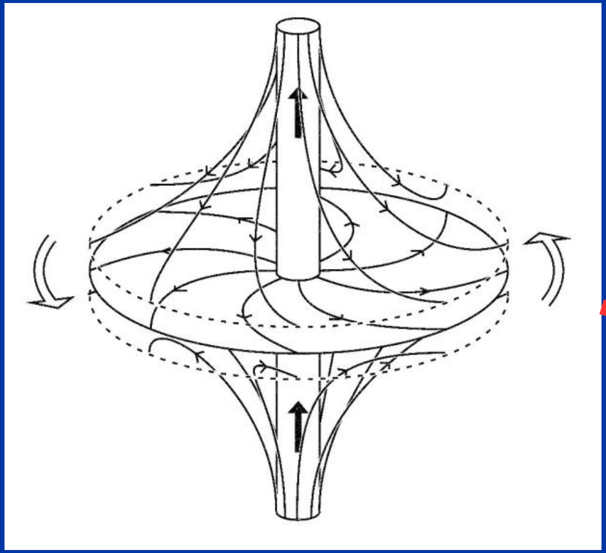
Perturbation Driving Plasma Flow





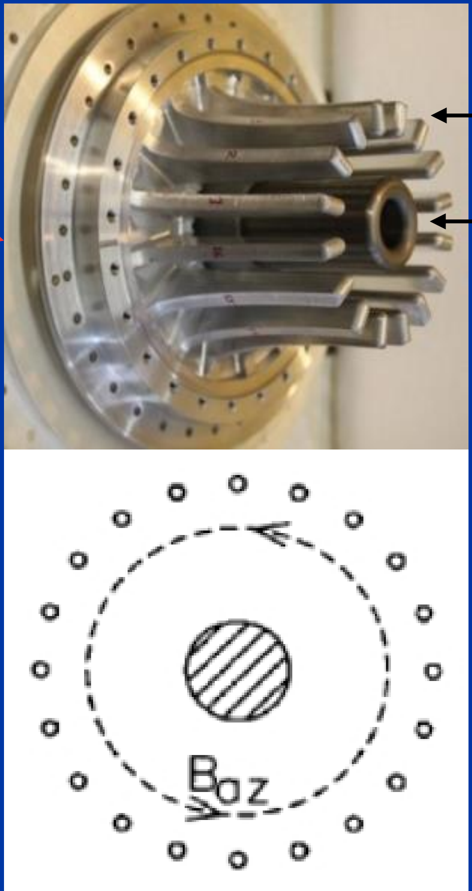
Pontin et al. (2011) applied circular magnetic field perturbation to existing neutral point potential field

Enabling Technology



Theory

Engineering



Krishnan et al. (2010)

outer electrodes
(cathode)

inner electrode
(anode)

Dense Plasma Focus

Creates plasma sheath with circular magnetic field!

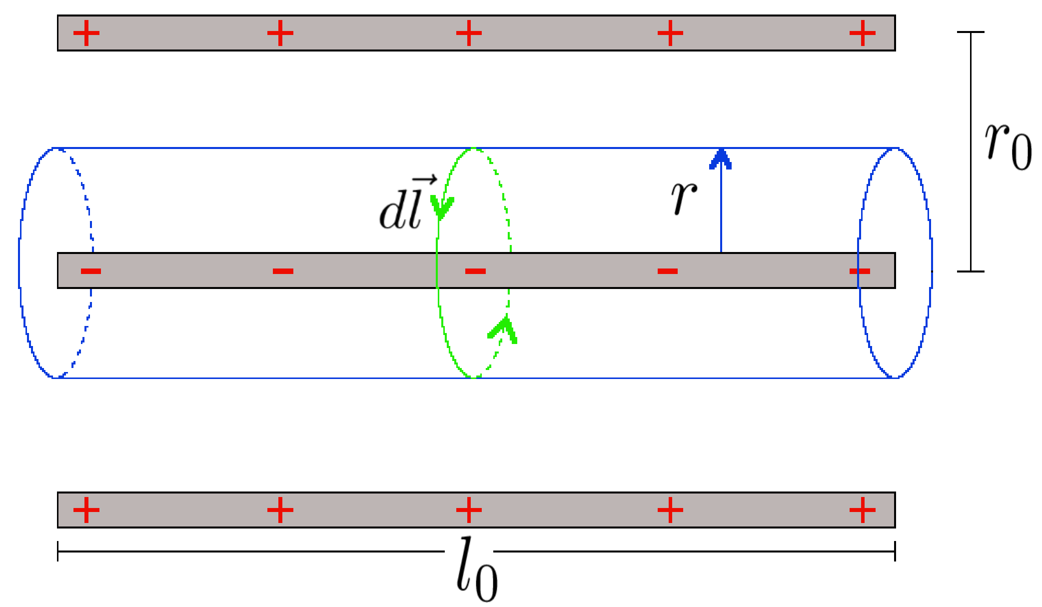
Operate at 100 Hz

Enabling Technology

Dense Plasma Focus
Plasma Sheath
(Toroid)

DPF Fields

$$\oint_C \vec{B}\cdot d\vec{l} = \mu_0\epsilon_0 \frac{d}{dt}\int_S \vec{E}\cdot\hat{n}\,da$$



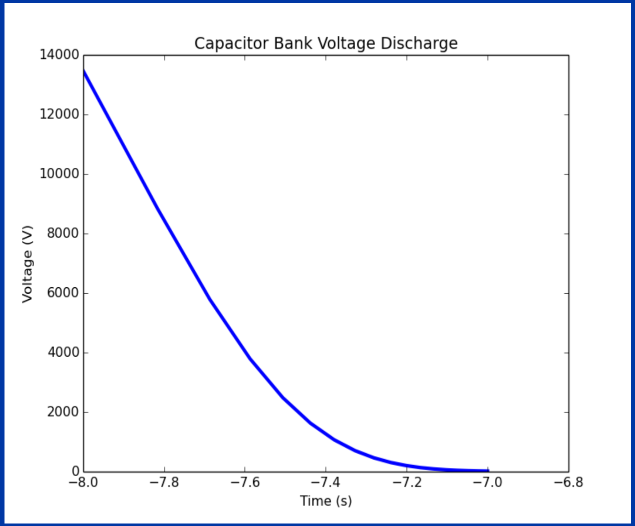
$$Q(t) = C\Delta V e^{-\frac{t}{RC}}$$

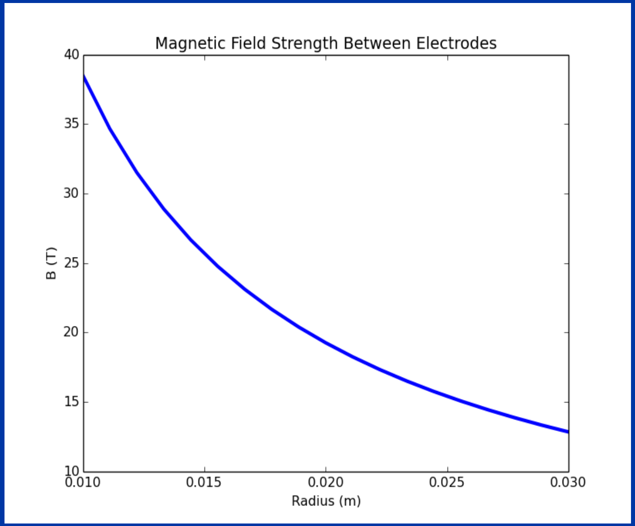
$$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$B(r) = -\frac{\mu_0\Delta V}{2\pi R}\frac{l}{rl_0}e^{-\frac{t}{RC}}$$

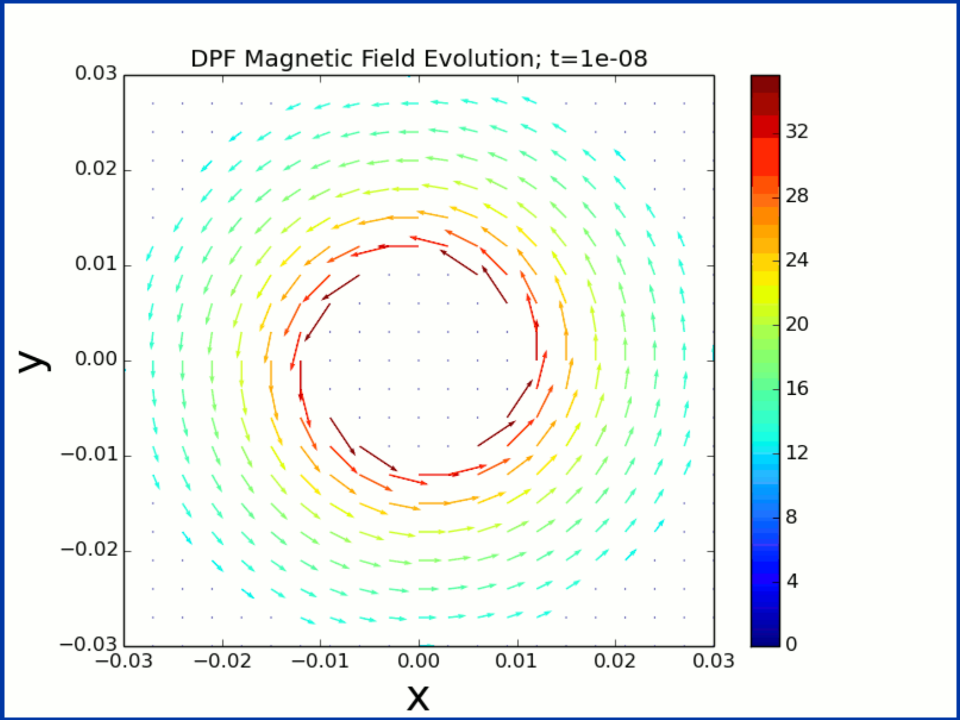
$$E(r) = \frac{\mu_0\Delta V}{2\pi R^2 C}\frac{l}{l_0}\ln(r)e^{-\frac{t}{RC}}$$

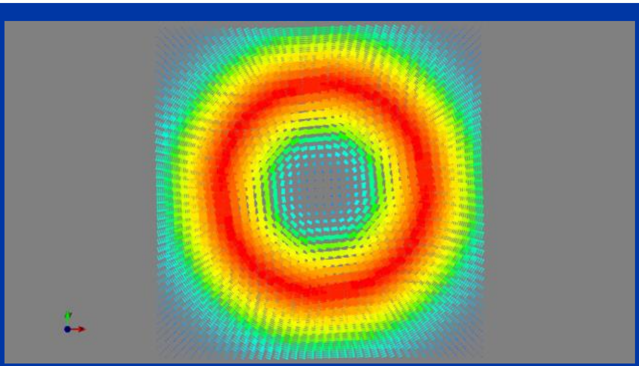
Magnetic Field Evolution





$t = 1x10^{-8} \longrightarrow 1x10^{-7}$ s

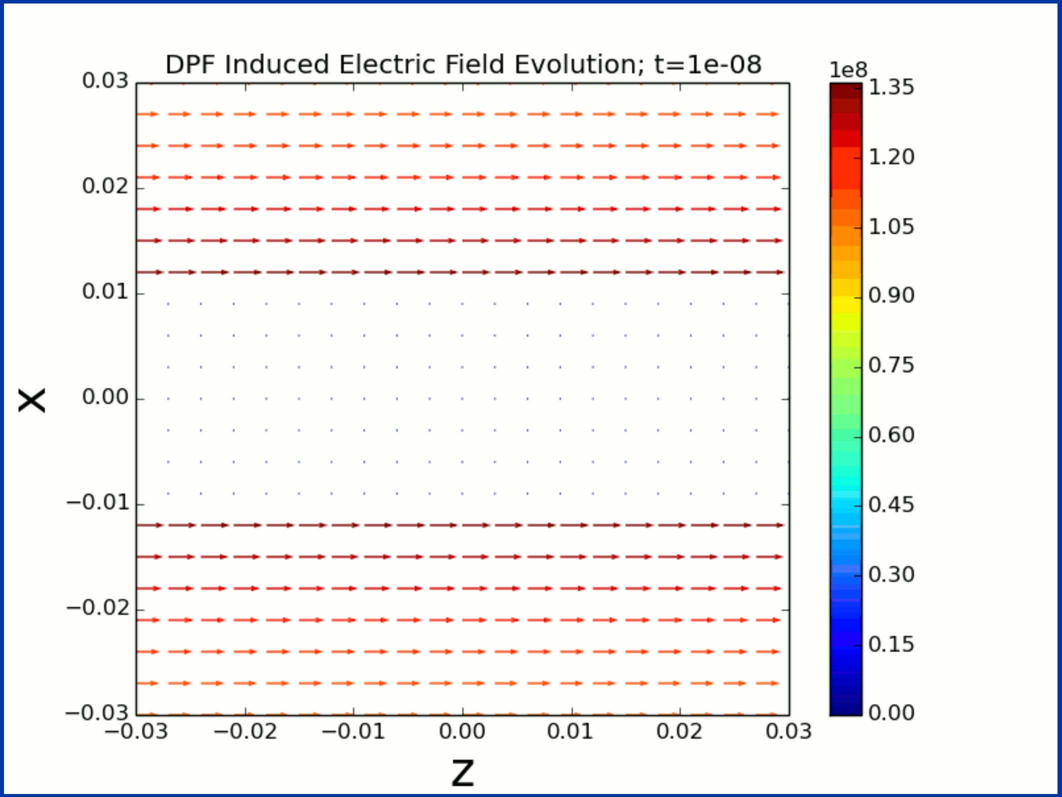




Theoretical Perturbation

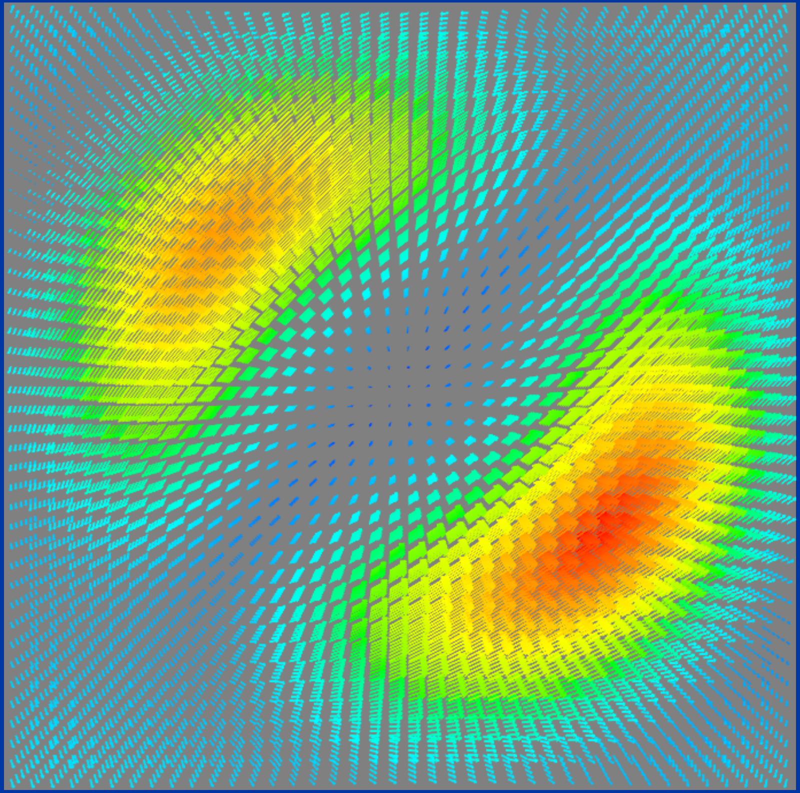
Induced Electric Field Evolution

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

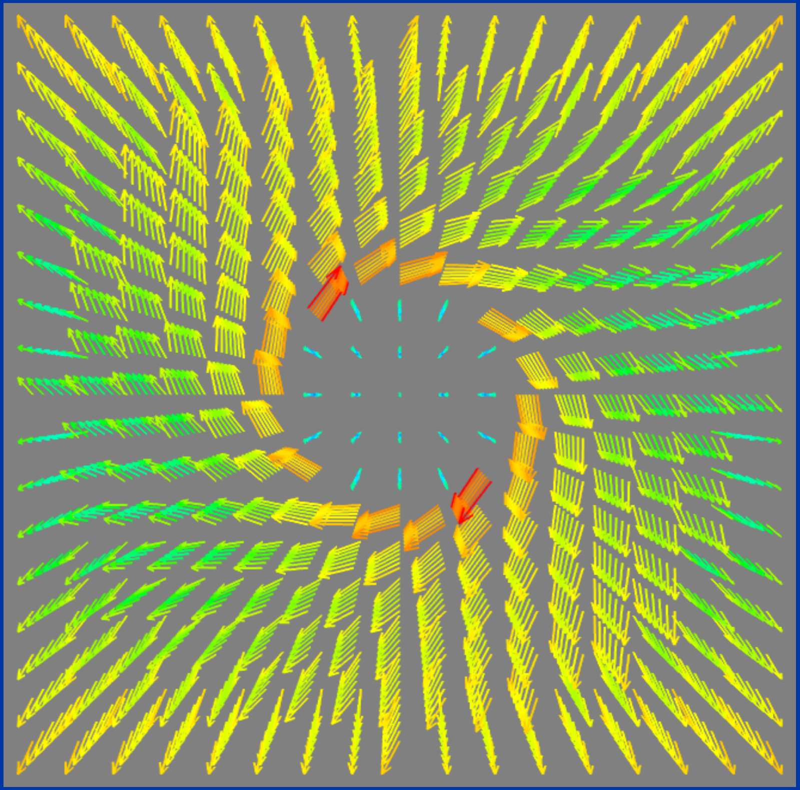


Acts to initialize plasma motions

Kinetic Modeling



Theoretical
Potential field PLUS
Perturbation



Experimental
Potential field PLUS **DPF**
Perturbation

Kinetic Modeling

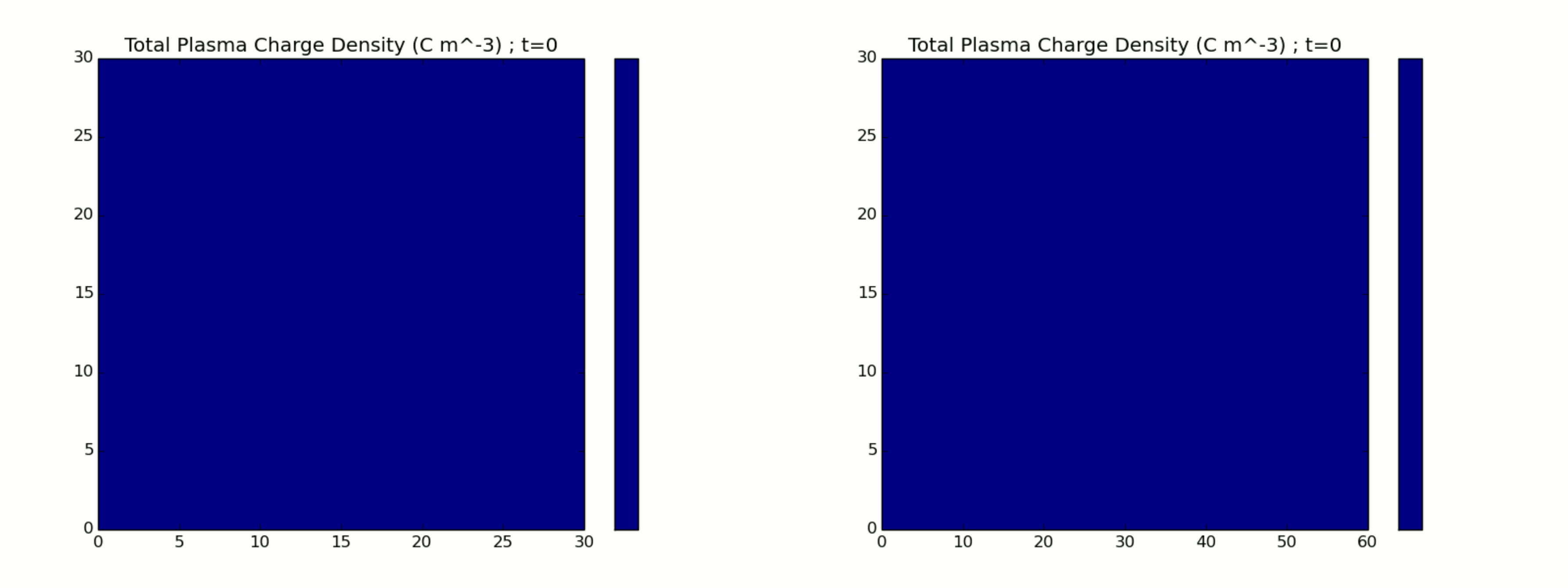
Particle-in-cell (PIC) simulations

Solves plasma motion in charge density space

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

y=0 Plane ; spine up/down

z=0 Plane ; spine in/out

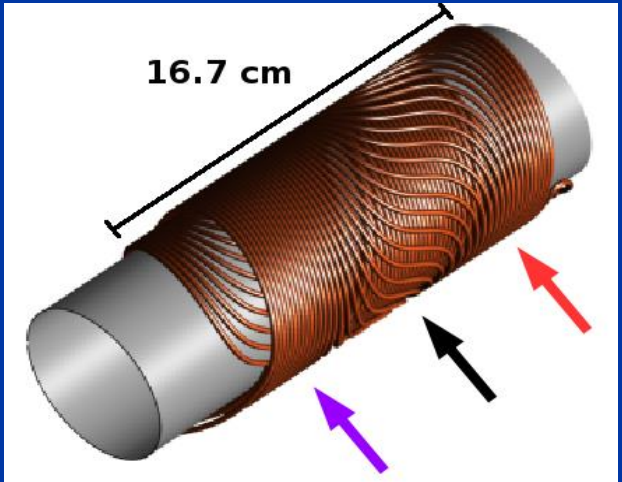


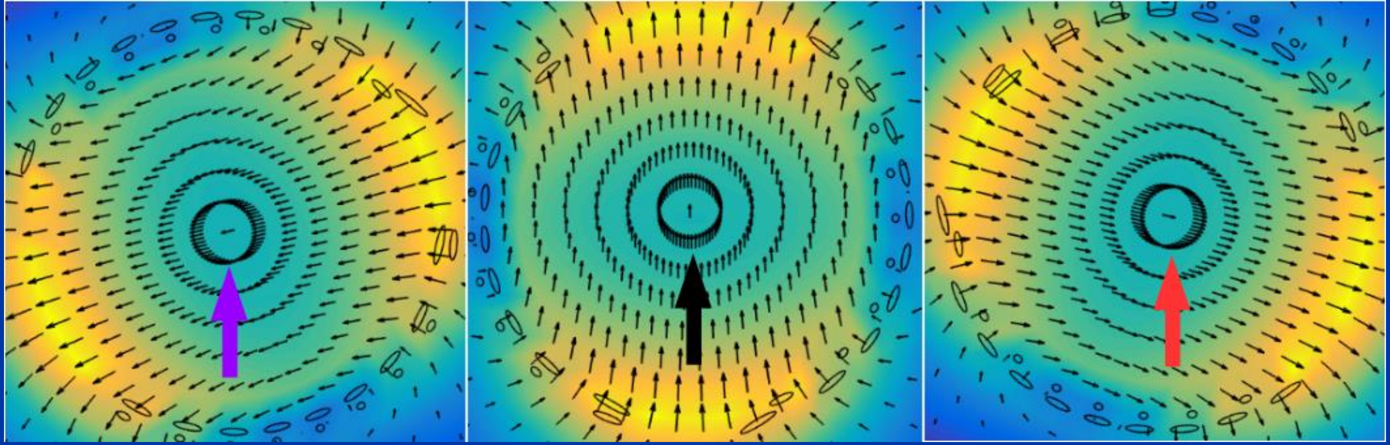
Engineering Considerations

Engineering – Potential Field

“Twisted dipole”

-Copper
-Non-superconducting





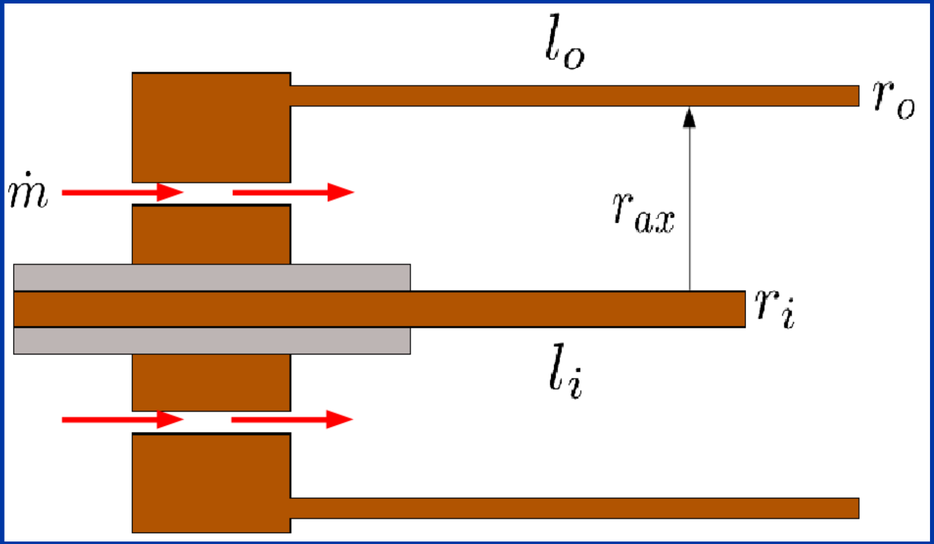
Engineering - DPF

DPF Specifications

- -Mather/Fillipov design
- -Inner electrode (anode) radius
- -Outer electrode (cathode) radius
- -Axial radius
  - (anode-cathode offset distance)
- -Anode length
- -Cathode length
- -Optimal conducting material
- -Optimal insulating material
- -Optimal plasma generation surface

Fuel input

- -Number of feeds
- -Radius of feeds
- -Feed rate and pressure
- **-Determines thrust** $\dot{m}$



Engineering - Thermodynamics

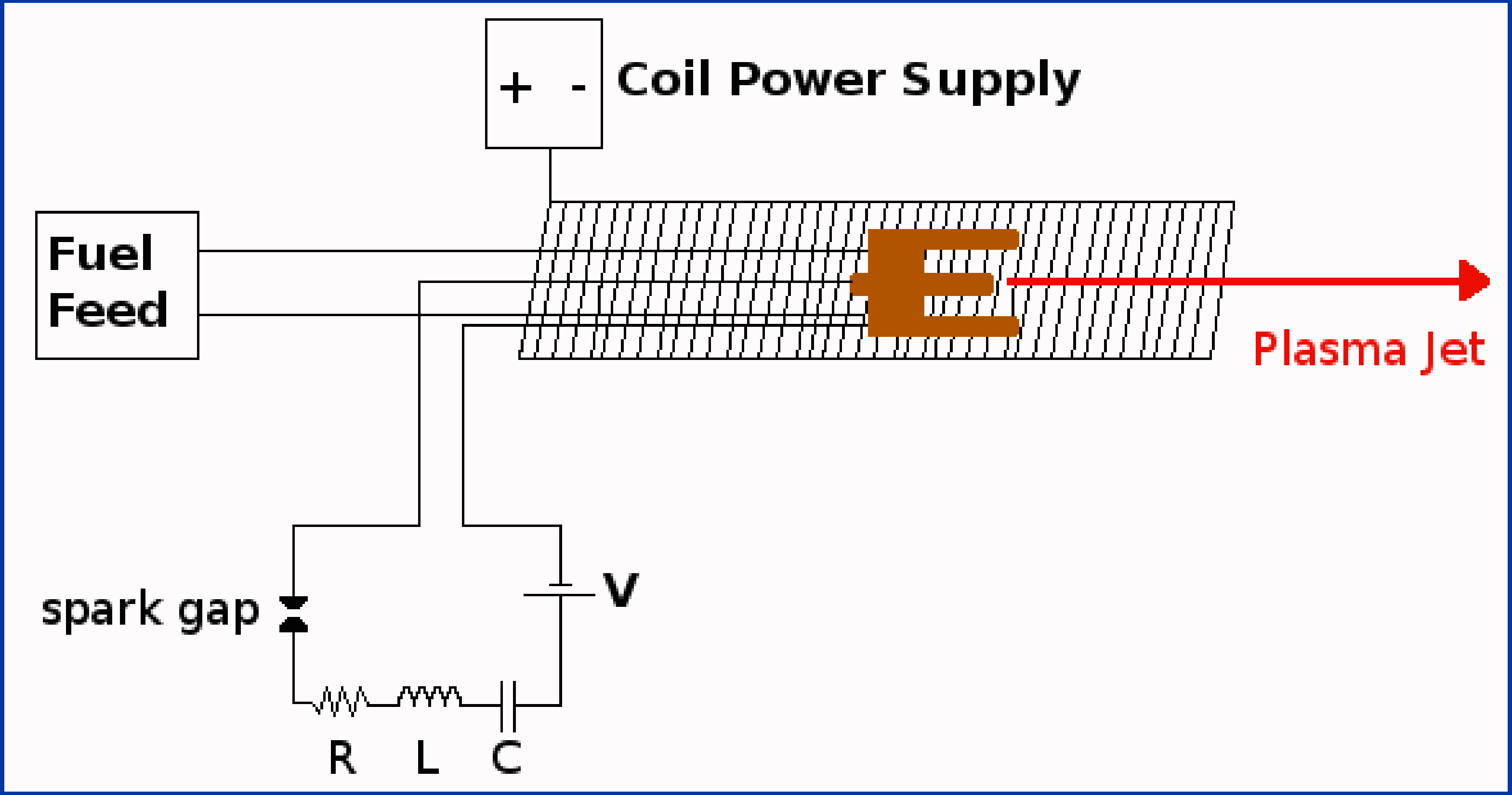
Electrode **degradation** due to charged particle bombardment

- DPF anode decay from fusion reactions
- After 10^3 shots

Thermal analysis

- Heat losses
- Inefficiencies

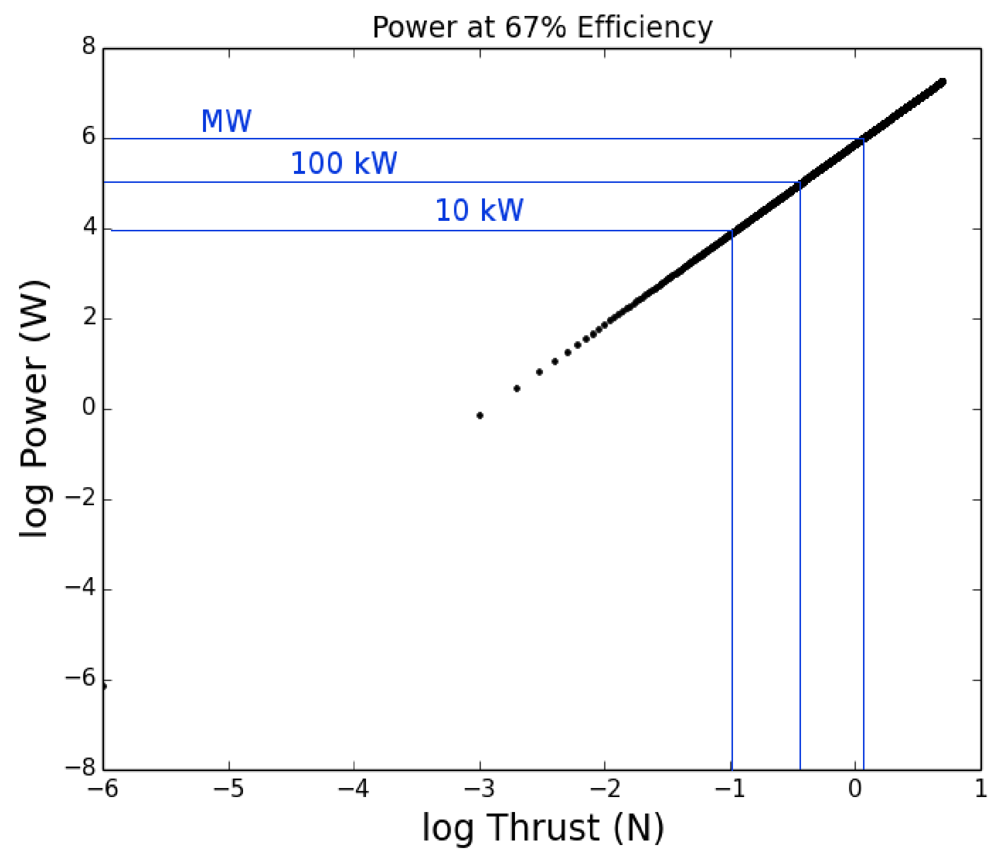
Engineering - System



Engineering – Power

$$P = \frac{1}{2}\dot{m}u_{ex}^2$$

10 MW – nuclear
200 kW – SAFE-2 fission
100 kW – ISS module


Power at 67% Efficiency

Summary

- Show feasibility

- Demonstrate proof-of-concept

- Working towards first publication
  - MHD, kinetic models, engineering

- Grant writing
  - FSGC, Space Technology Research, NIAC

Thank You