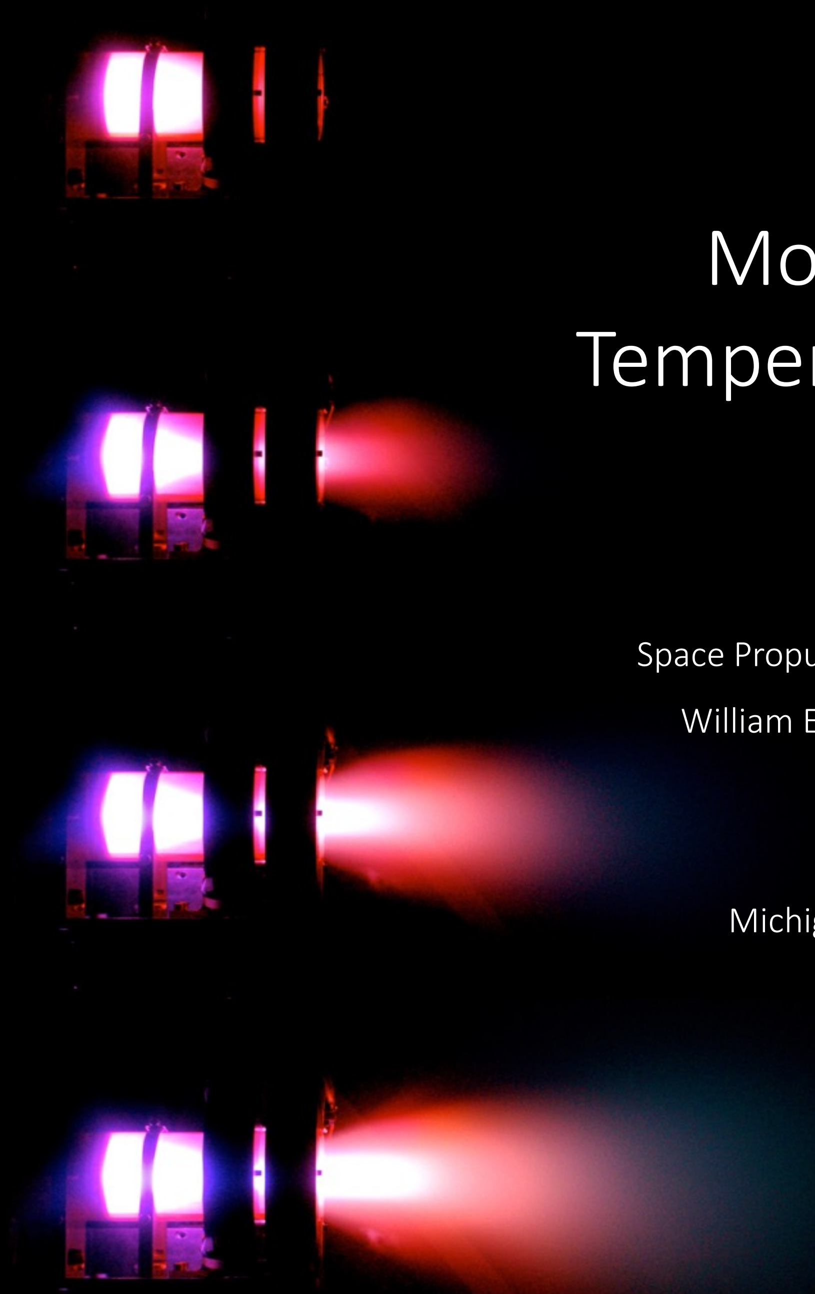


Mode Transitions in Low-Temperature Aerospace Plasmas

Prof. Justin Little

Space Propulsion and Advanced Concepts Engineering (SPACE) Lab

William E. Boeing Department of Aeronautics & Astronautics

University of Washington

Michigan Institute for Plasma Science and Engineering

Early Career Lecture

03/31/21

Video

Plasma Mode Transitions

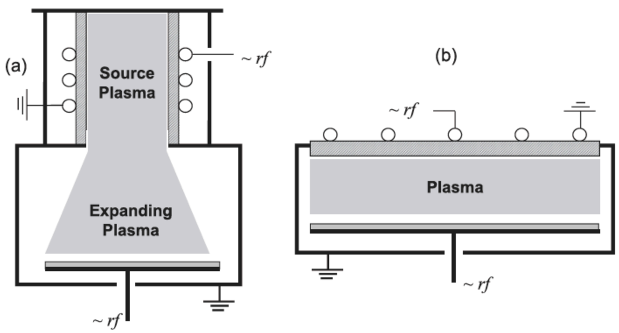
mode transition

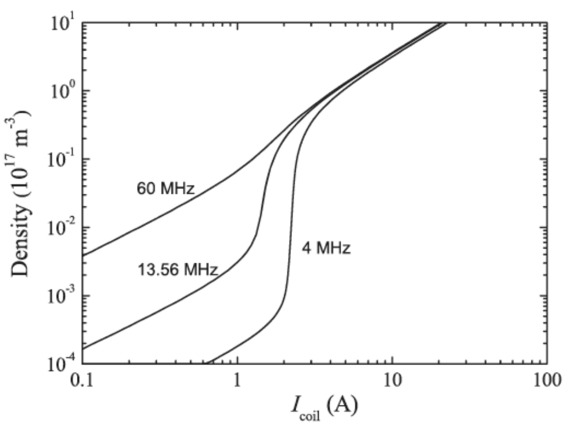
noun

a sudden, major transformation of the structure and/or dynamics of a plasma in response to a minor change to its operating conditions

Plasma Mode Transitions

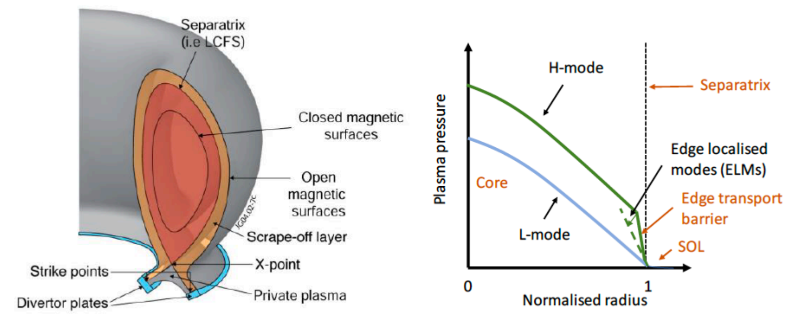
Plasma Processing



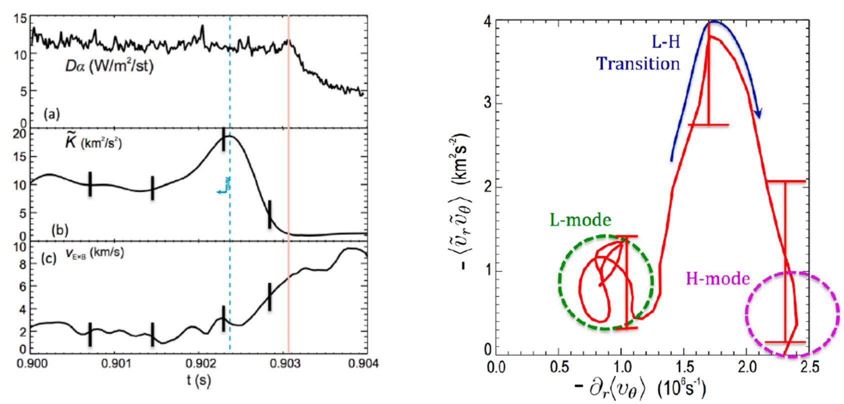


Chabert et. al., *Plasma Sources Sci. Tech.* 30.2 (2021): 024001

Fusion Energy



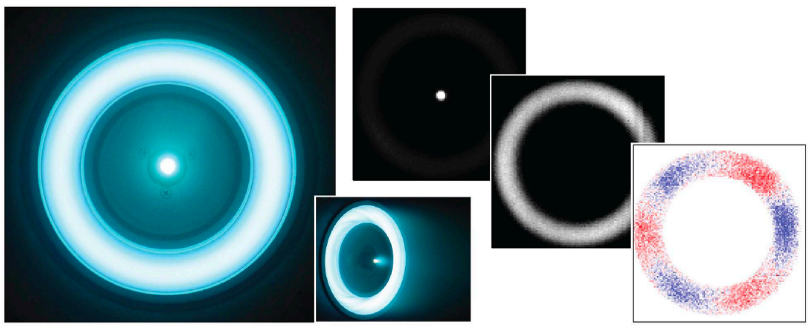
Ham et al. *Nature Reviews Physics* 2.3 (2020): 159-167.



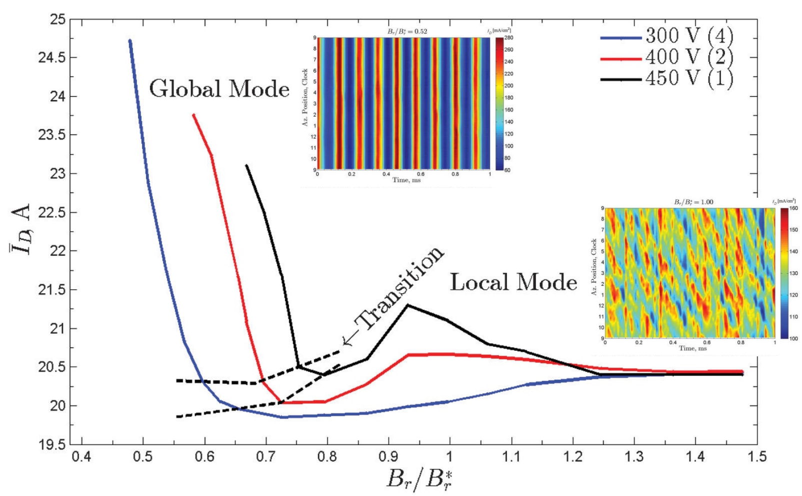
Tynan et al. *Plasma Phys. Controlled Fusion* 58.4 (2016): 044003.

Plasma Mode Transitions

Hall Thrusters

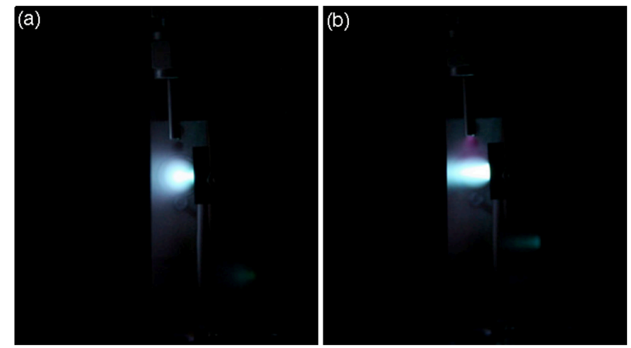


McDonald and Gallimore. *IEEE Trans. Plasma Sci.* 39.11 (2011): 2952-2953.

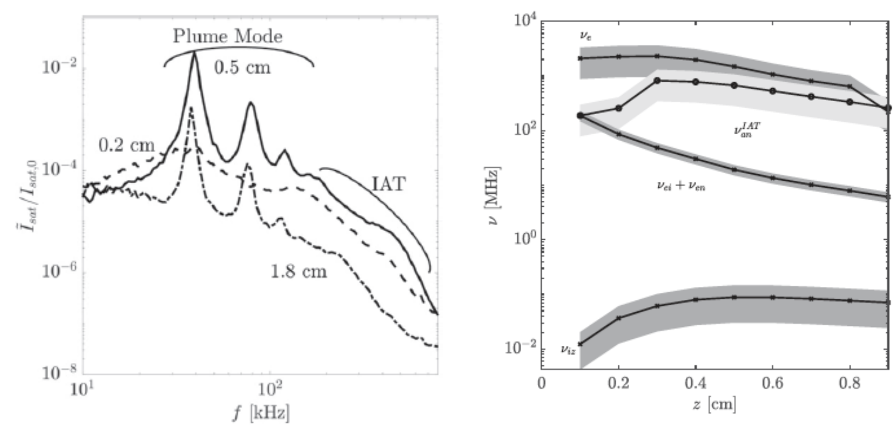


Sekerak et al. *J. Propul. Power* 32.4 (2016): 903-917.

Hollow Cathodes

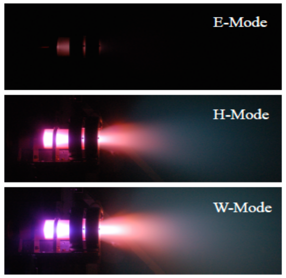


Goebel et al. *30th International Electric Propulsion Conference*. 2007.



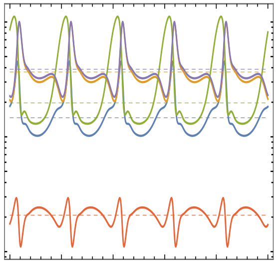
Georgin, Jorns, and Gallimore. *Plasma Sources Sci. Tech.* 29.10 (2020): 105010.

Mode Transitions in Aerospace Plasmas



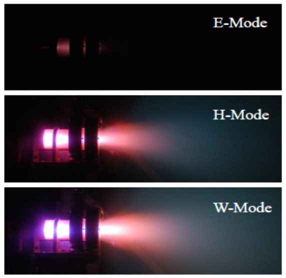
Topic 1: Mode transitions in helicon thrusters

Topic 2: Critical velocities for plasma aerocapture



Topic 3: Data-driven discovery of mode transition physics

Mode Transitions in Aerospace Plasmas



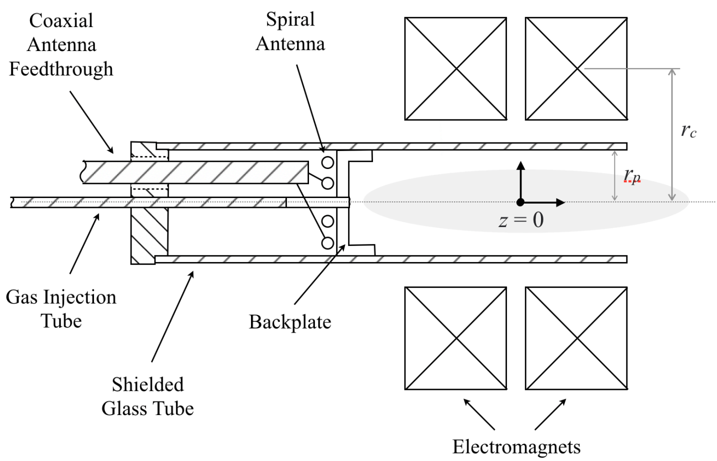
Topic 1: Mode transitions in helicon thrusters

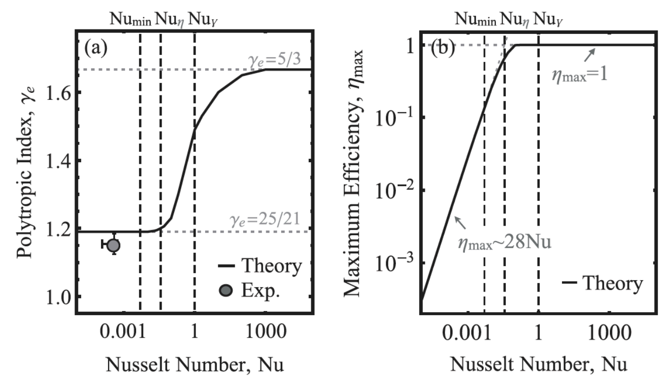
Topic 2: Critical velocities for plasma aerocapture

Topic 3: Data-driven discovery of mode transition physics

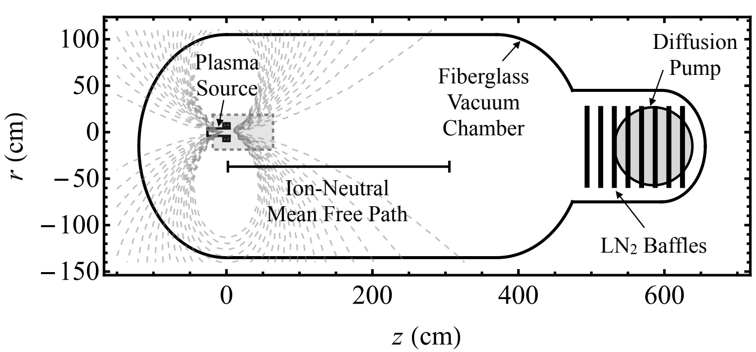
Magnetic Nozzle Experiment (Princeton University)

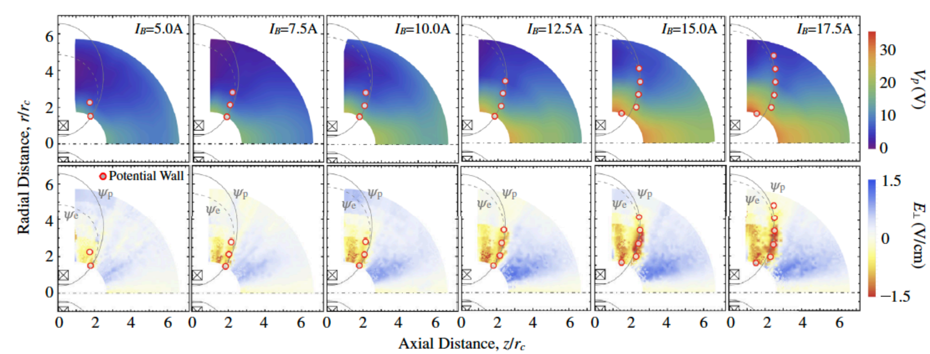
Goal: Understand plasma expansion and detachment from magnetic nozzle





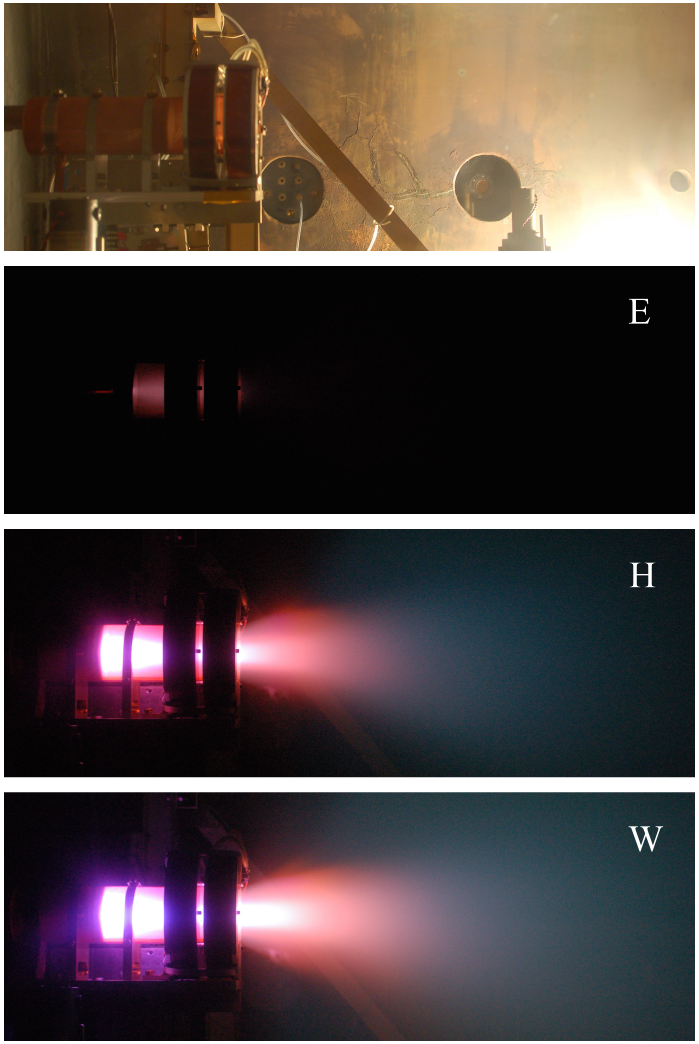
Little and Choueiri. *Phys. Rev. Lett.* 117.22 (2016): 225003.

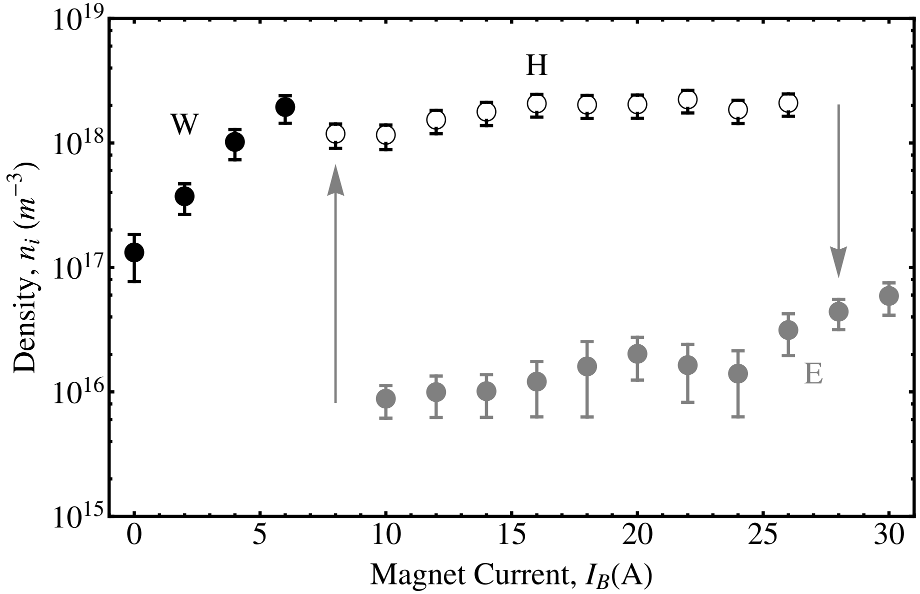




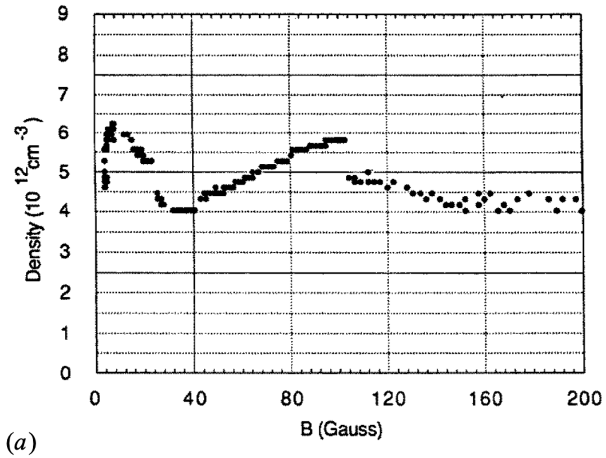
Little and Choueiri. *Phys. Rev. Lett.* 123.14 (2019): 145001.

Mode Transitions

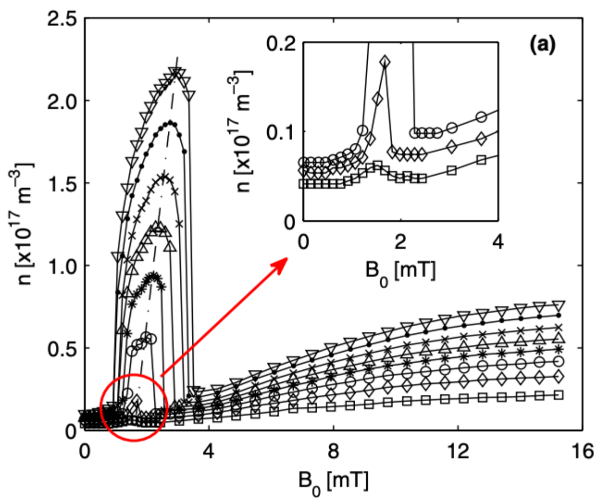




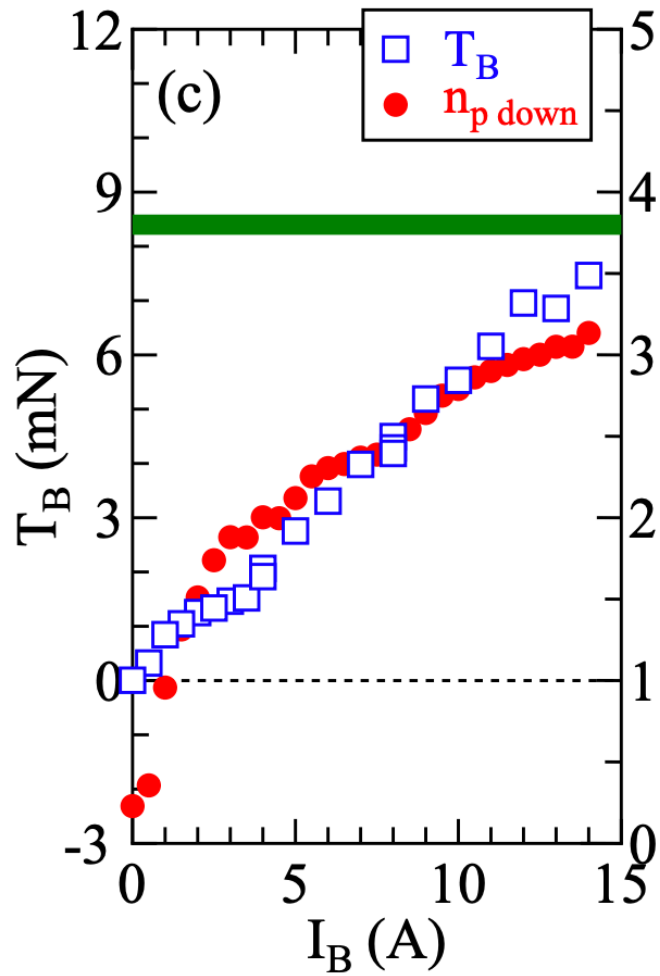
Low-Field Mode Transition (LFMT)



Chen, F. F., et al. "Low-field helicon discharges." *Plasma Physics and Controlled Fusion* 39.5A (1997): A411.



Lafleur, T., Charles, C., and R. W. Boswell. "Characterization of a helicon plasma source in low diverging magnetic fields." *Journal of Physics D: Applied Physics* 44.5 (2011): 055202.



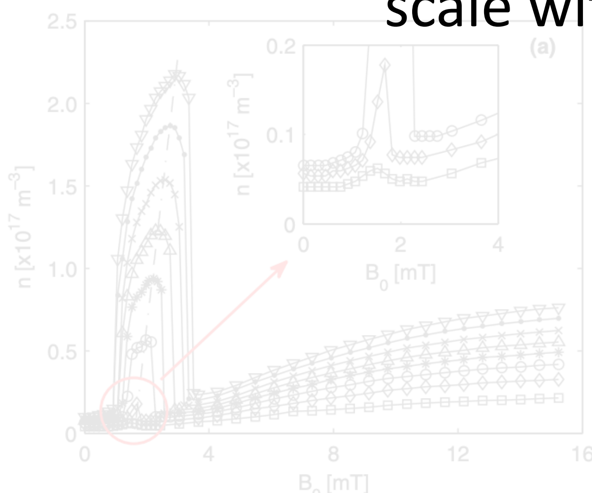
Takahashi, Kazunori, et al. "Effect of magnetic and physical nozzles on plasma thruster performance." *Plasma Sources Science and Technology* 23.4 (2014): 044004.

Low-Field Mode Transition (LFMT)

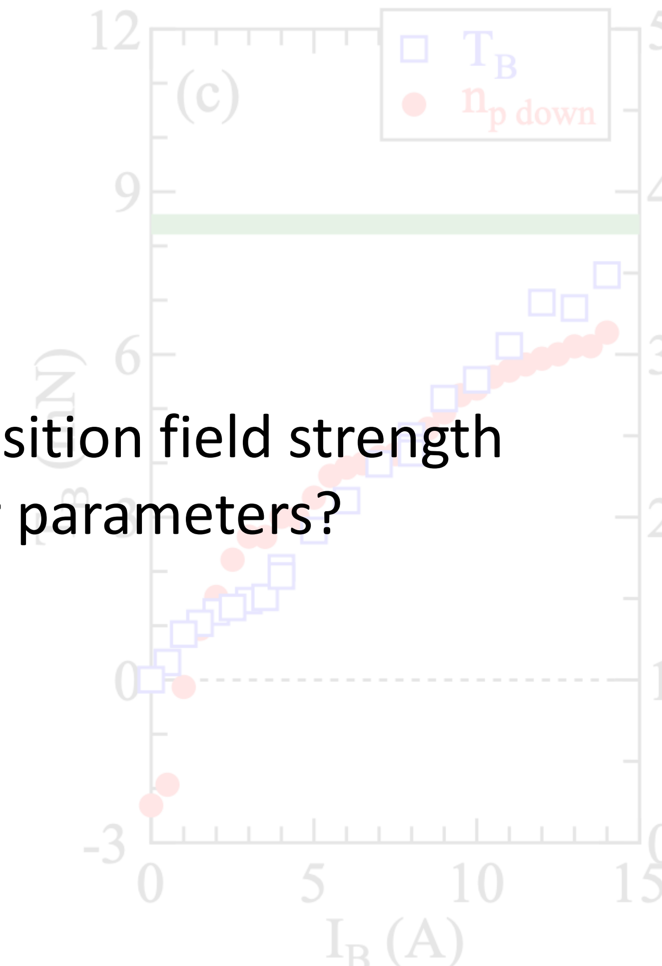
(a)

Chen, F. F., et al. "Low-field helicon discharges." *Plasma Physics and Controlled Fusion* 39.5A (1997): A411.

How does the mode transition field strength scale with thruster parameters?

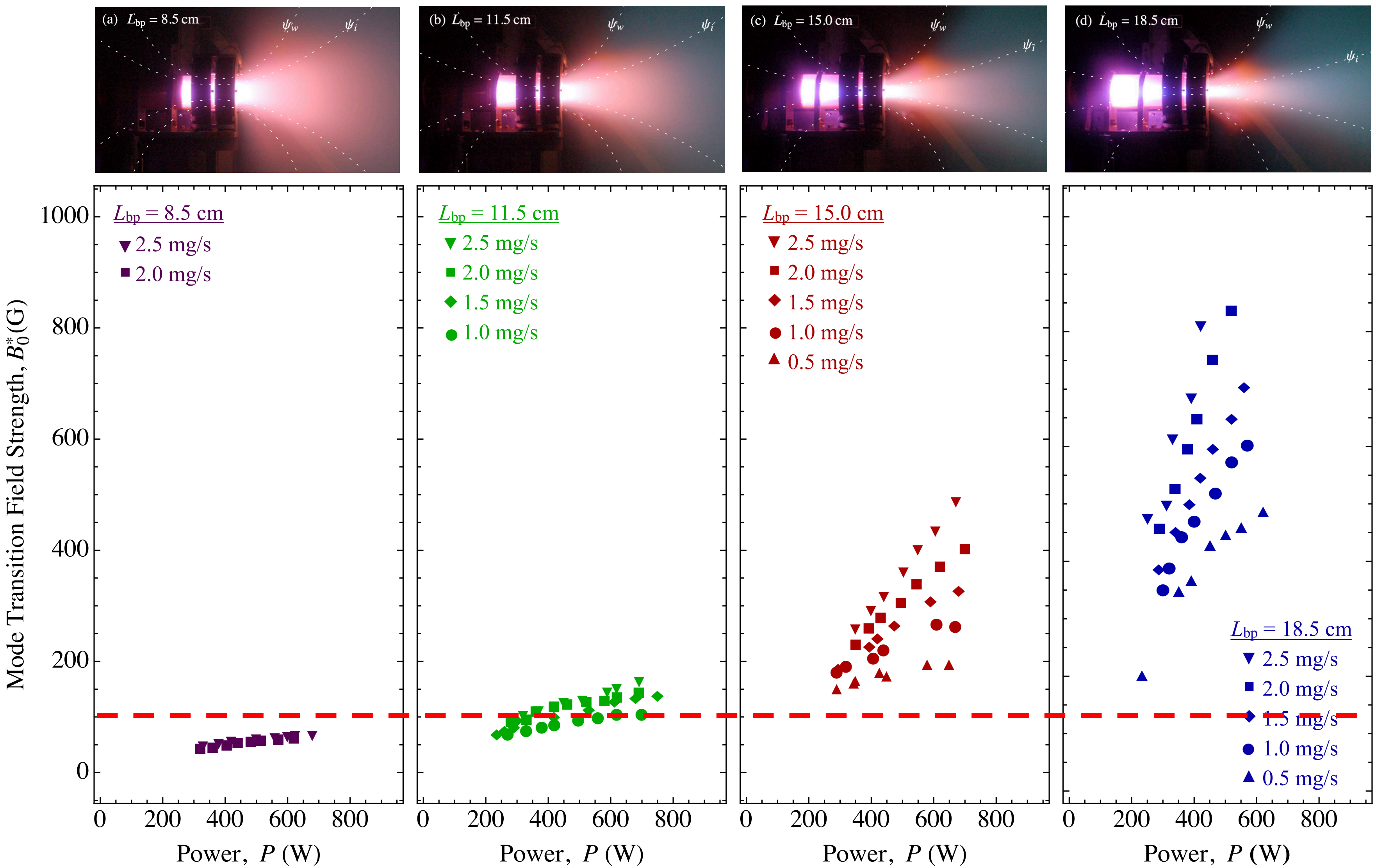


Lafleur, T., Charles, C., and R. W. Boswell. "Characterization of a helicon plasma source in low diverging magnetic fields." *Journal of Physics D: Applied Physics* 44.5 (2011): 055202.

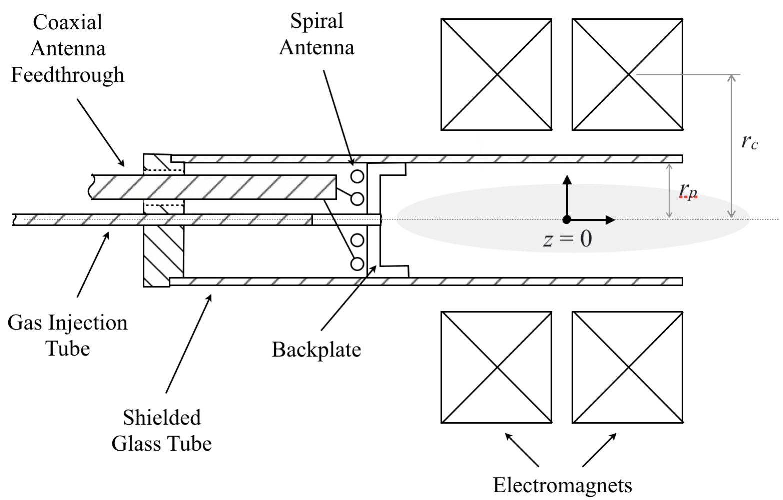


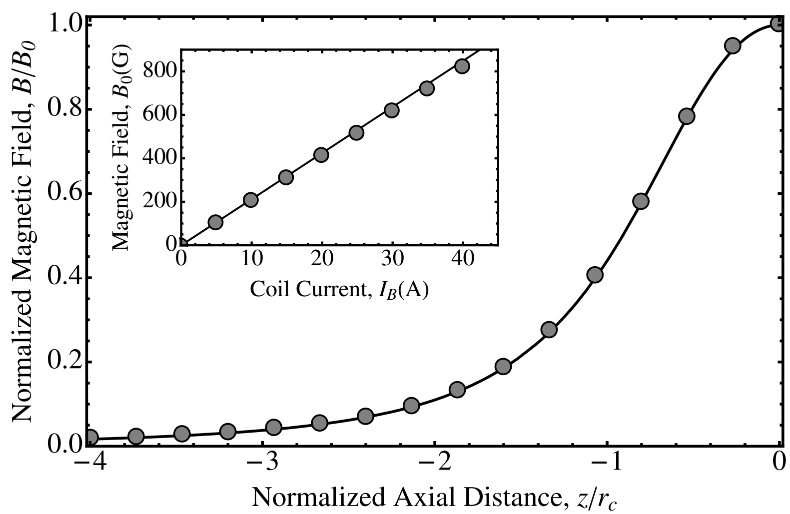
Takahashi, Kazunori, et al. "Effect of magnetic and physical nozzles on plasma thruster performance." *Plasma Sources Science and Technology* 23.4 (2014): 044004.

LMFT Measurements



LMFT Measurements



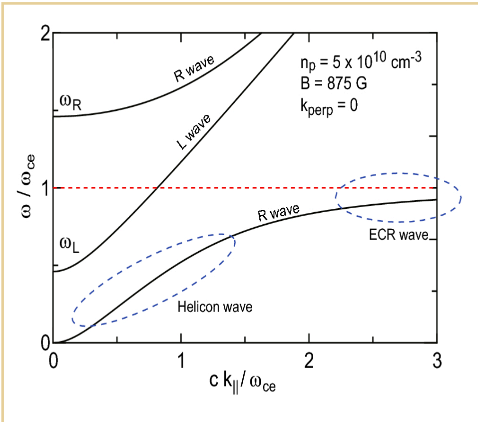


More specifically…

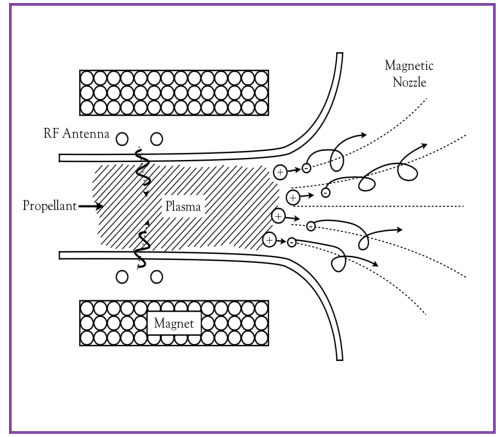
How does the mode transition field strength scale for a converging B-field and m=0 spiral antenna?

Theoretical Model of the LMFT

RF Absorption



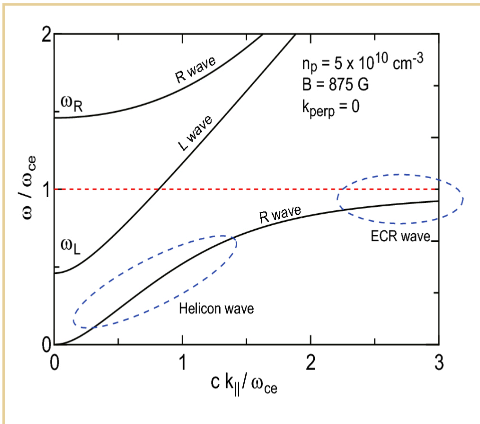
Thruster Global Model



Chabert, Pascal, and Nicholas Braithwaite. *Physics of radio-frequency plasmas*. Cambridge University Press, 2011.

Theoretical Model of the LMFT

RF Absorption

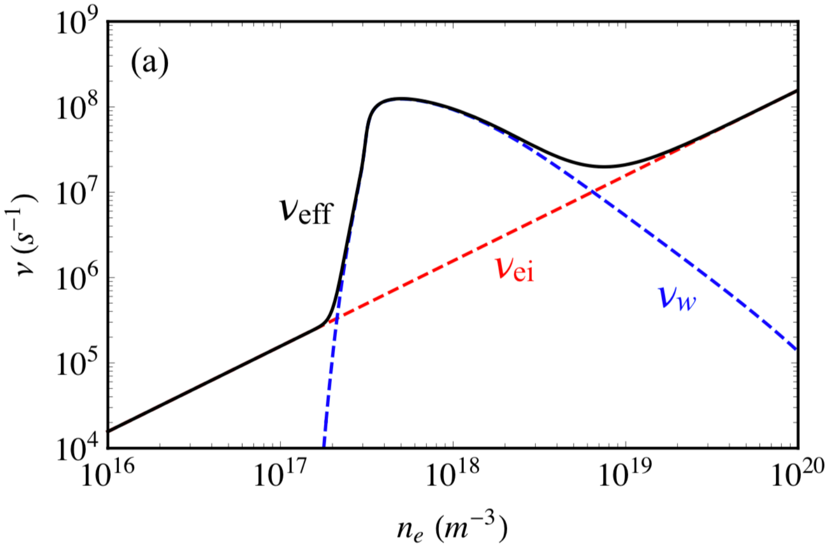


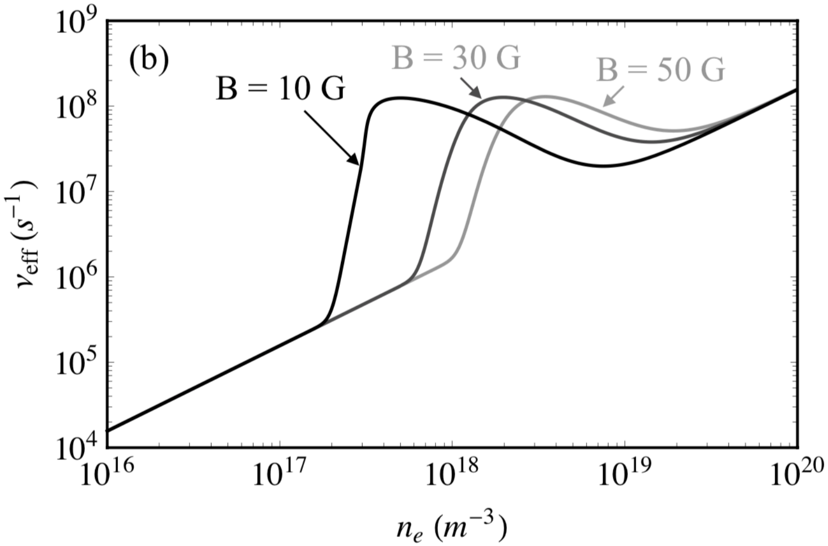
Thruster Global Model

Chabert, Pascal, and Nicholas Braithwaite. *Physics of radio-frequency plasmas*. Cambridge University Press, 2011.

Theoretical Model of the LMFT

$$kk_z = \frac{\omega\omega_{\mathrm{pe}}^2}{c^2\omega_{\mathrm{ce}}}\left(1 - \frac{i\nu_{\mathrm{eff}}k}{\omega_{\mathrm{ce}}k_z}\right)$$

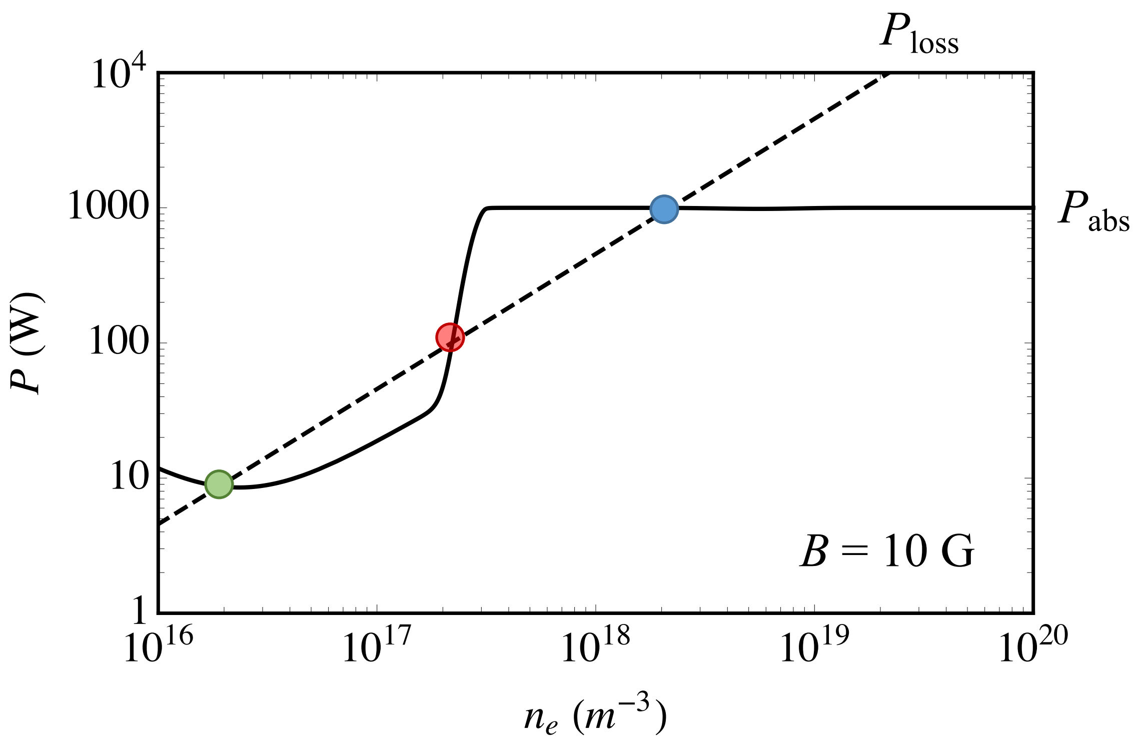




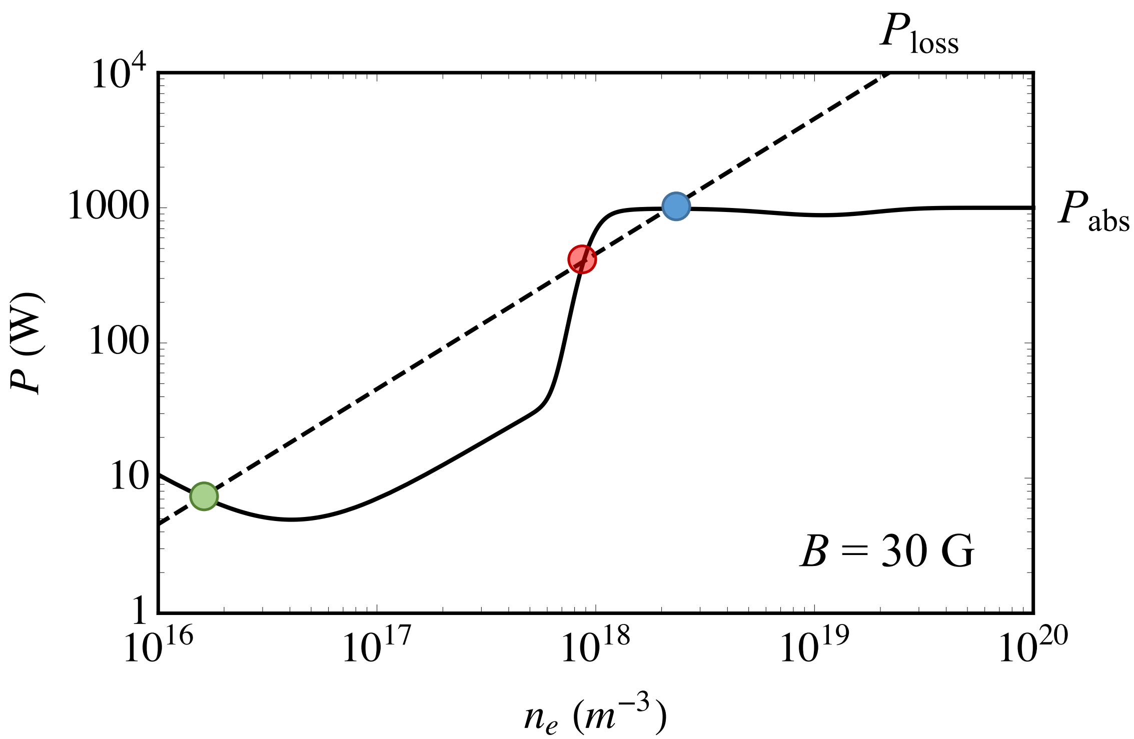
$$\nu_{\mathrm{eff}} = \nu_{\mathrm{ei}} + \nu_w$$

Chen, Francis F. "Plasma ionization by helicon waves." *Plasma Physics and Controlled Fusion* 33.4 (1991): 339.

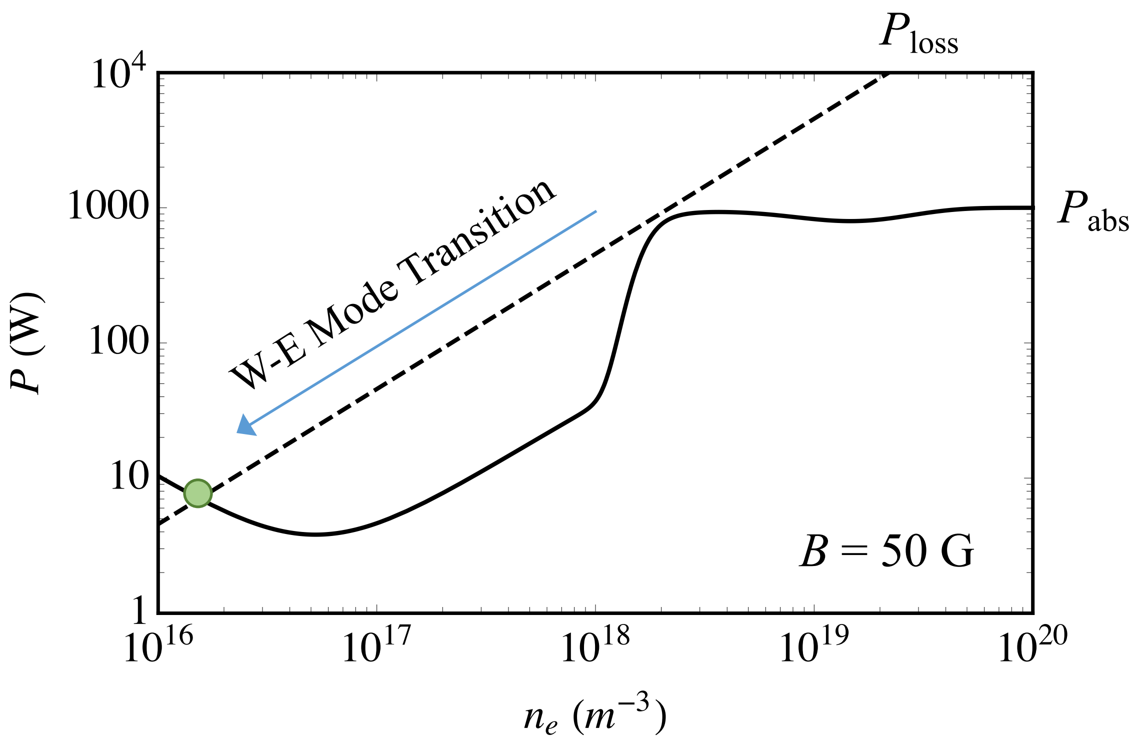
Theoretical Model of the LMFT



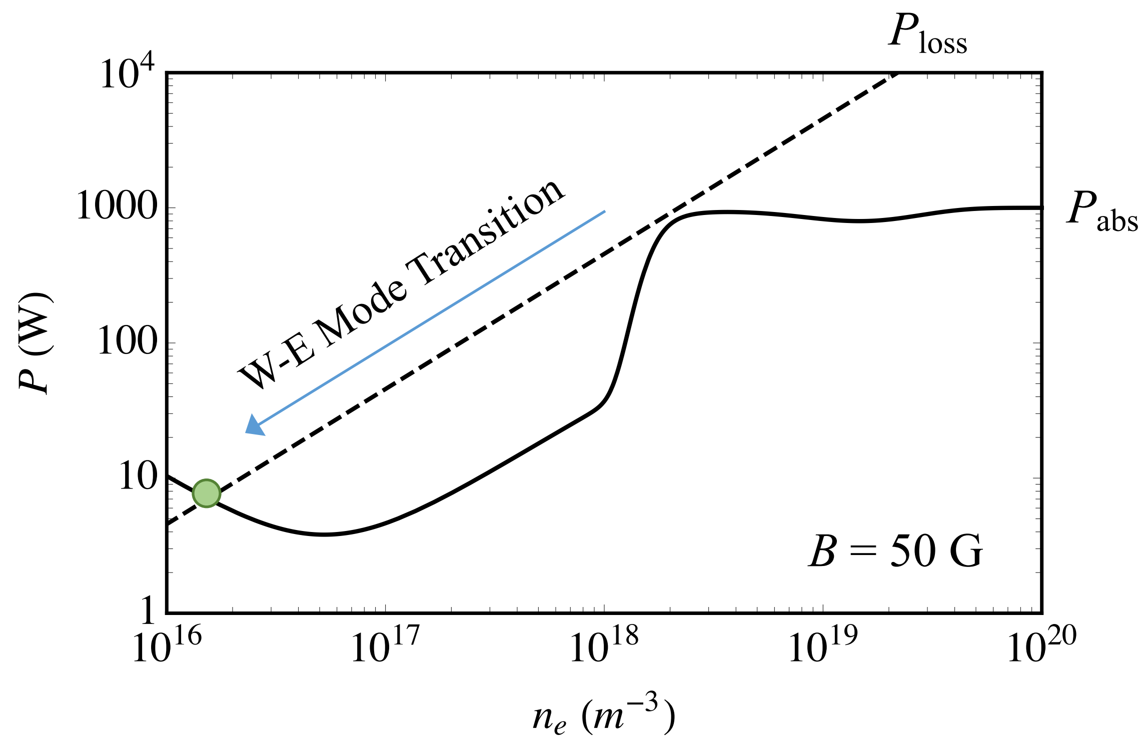
Theoretical Model of the LMFT



Theoretical Model of the LMFT

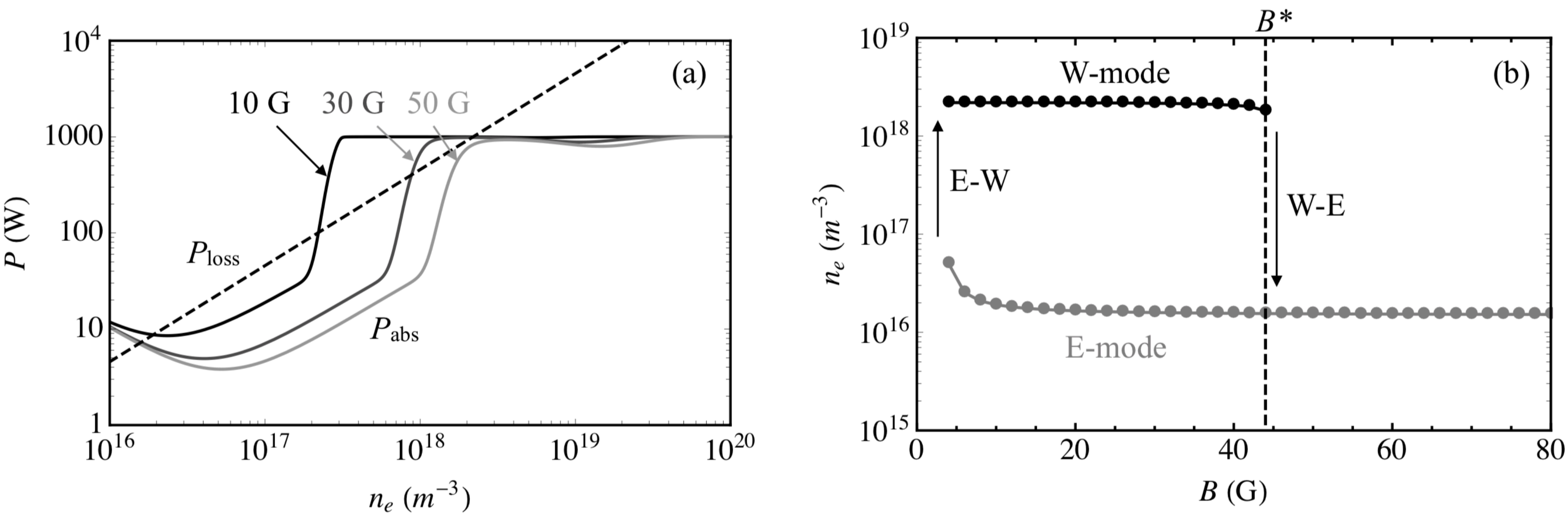


Theoretical Model of the LMFT



wave phase velocity $\gg$ electron thermal velocity

Theoretical Model of the LMFT



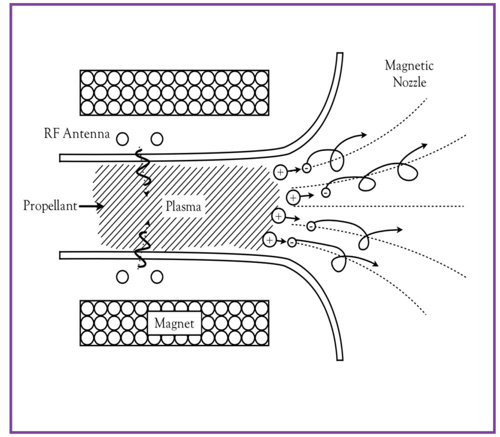
Wave absorption maximum at: $B_m = b_0 r_p n_e T_{\text{ev}}^{1/2}$

Using above plot: $B^* \approx \chi B_m$

Theoretical Model of the LMFT

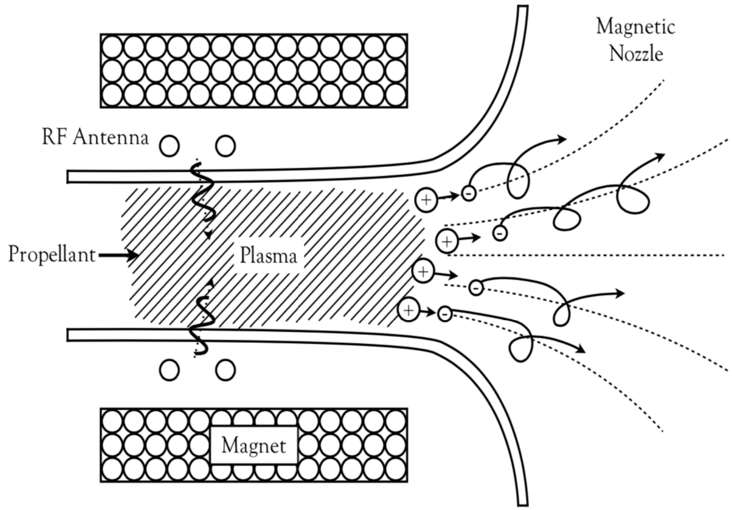
RF Absorption

Thruster Global Model



Chabert, Pascal, and Nicholas Braithwaite. *Physics of radio-frequency plasmas*. Cambridge University Press, 2011.

Theoretical Model of the LMFT

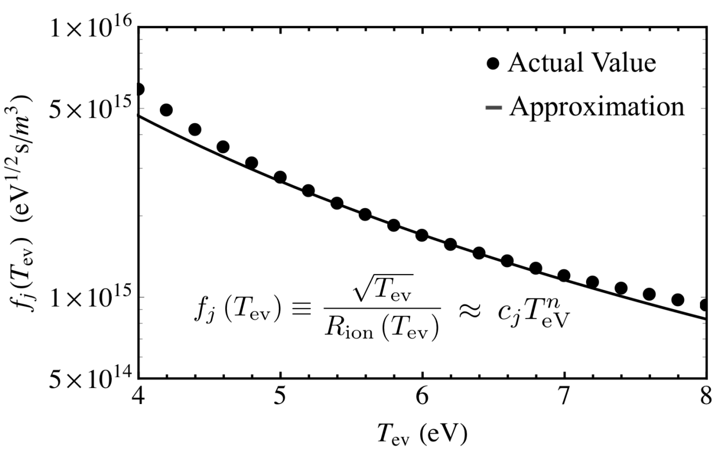


(exhaust kinetic power) (power lost to wall)

$$P_{\text{loss}} = n_e u_i \pi r_p^2 \left(\epsilon_{\text{ke}} + \epsilon_w + \epsilon'_{\text{ion}}\right)$$

(power lost to ionization)

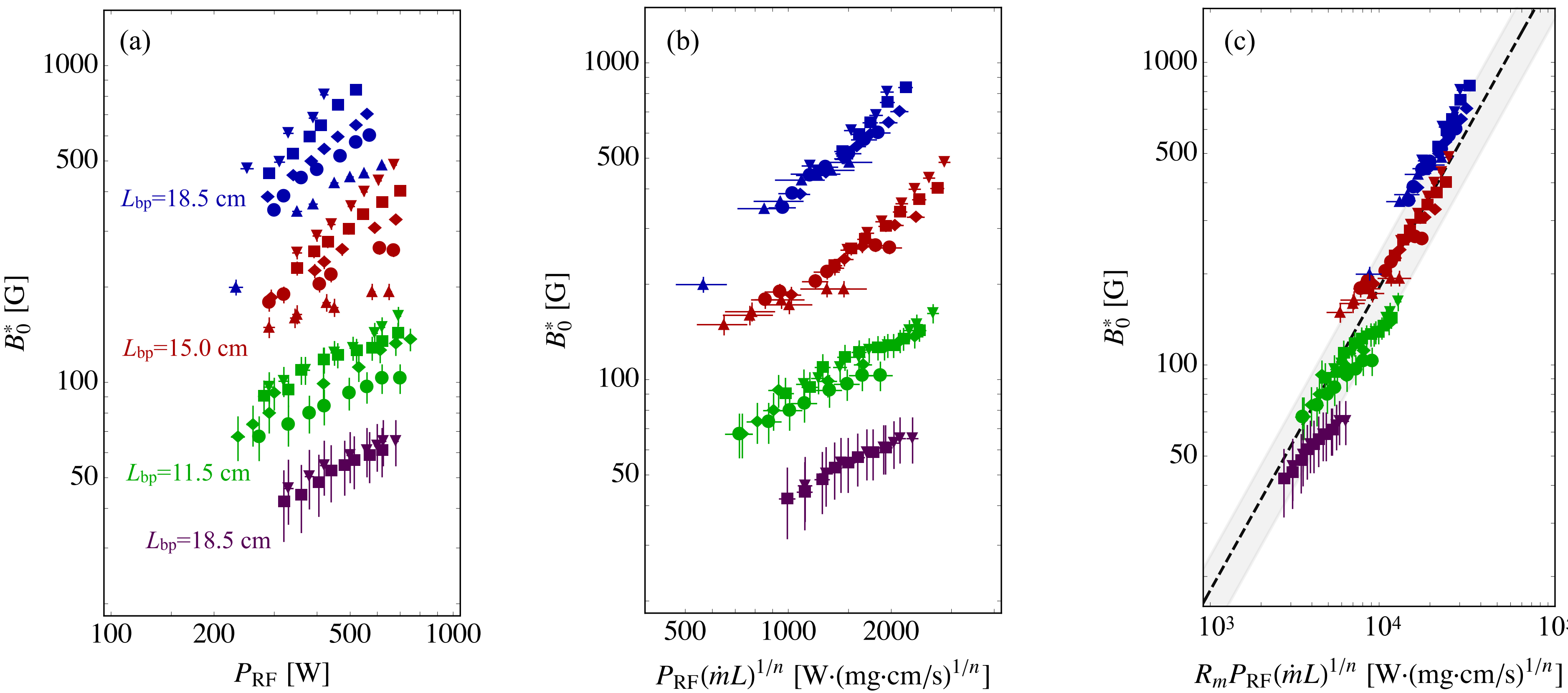
Power balance: $$B^* = \frac{\chi b_1 \eta_c P_{\text{RF}}}{2 r_p \mu(\gamma) e T_{\text{ev}} \sqrt{\gamma m_i}}$$



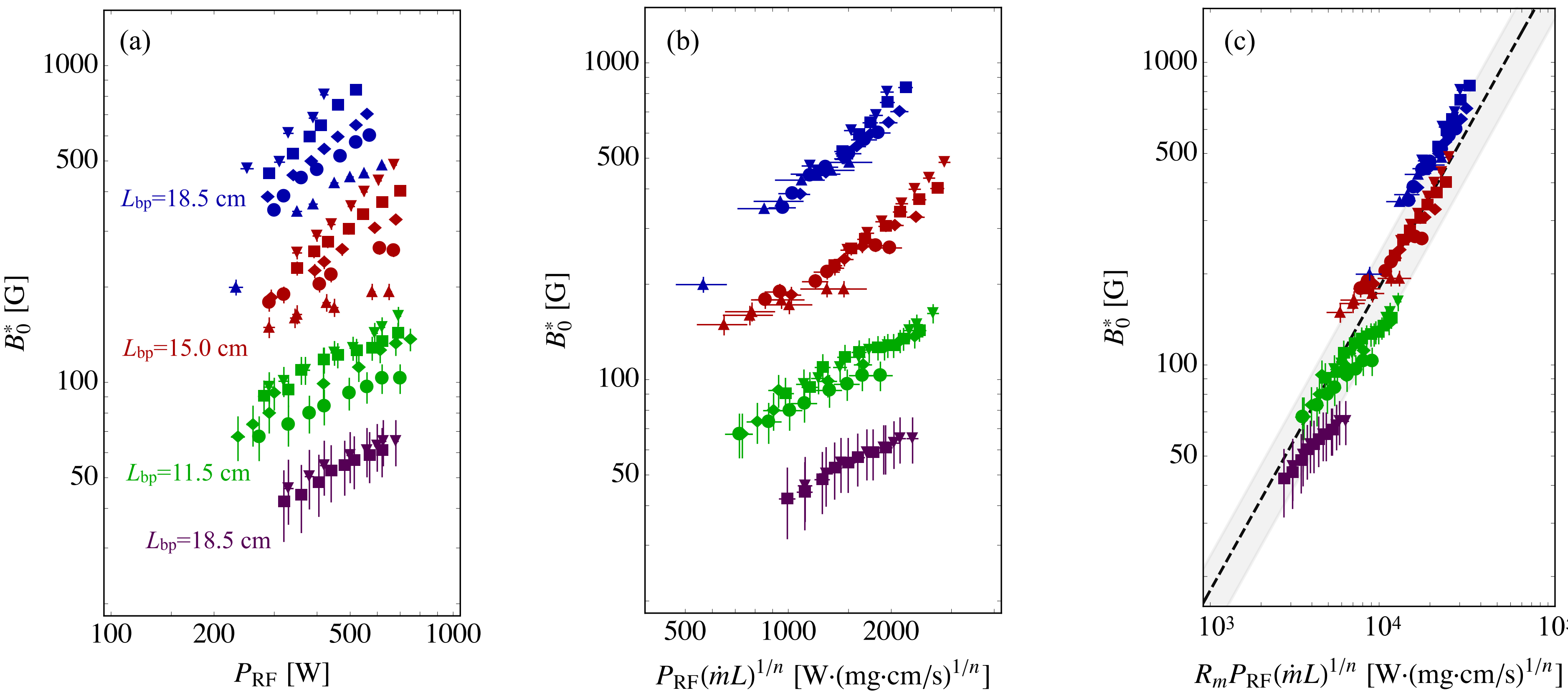
Mass balance: $$T_{\text{ev}} \approx \left(\frac{b_0 c_j u_n r_p^2 \sqrt{m_i/\gamma}}{b_1 \dot{m} L}\right)^{1/n}$$

$$\boxed{B^* = C_1 \frac{P_{\text{RF}}}{r_p \sqrt{m_i}} \left(\frac{\dot{m} L}{c_j r_p^2}\right)^{1/n}}$$

LMFT Scaling with Thruster Parameters



LMFT Scaling with Thruster Parameters



Transition occurs when Landau damping of wave energy can longer sustain plasma

Mode Transitions in Aerospace Plasmas

Topic 1: Mode transitions in helicon thrusters

Topic 2: Critical velocities for plasma aerocapture

Topic 3: Data-driven discovery of mode transition physics

Generating Forces using Magnetic Fields in Space

Magnetic Sail

Zubrin and Andrews. *J. Spacecraft and Rockets* 28.2 (1991): 197-203.

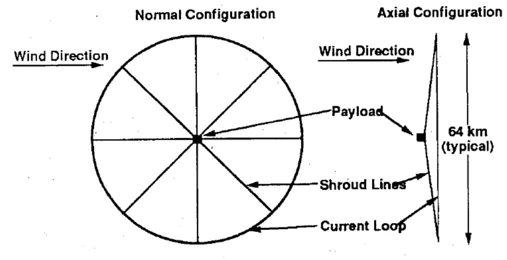
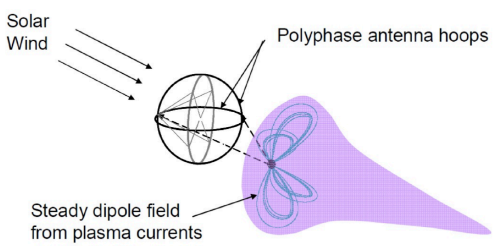


Fig. 1 Magsail deployed with payload.

Plasma Magnetic Sail (M2P2)

Winglee et al. *AIP Conference Proceedings*. Vol. 504. No. 1. American Institute of Physics, 2000.

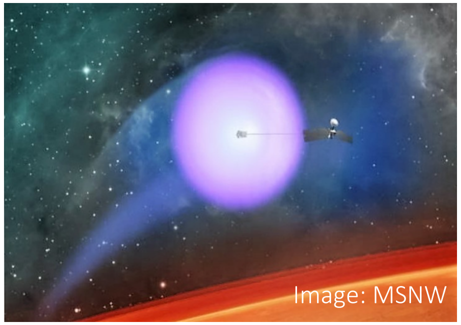
Slough. *30th International Electric Propulsion Conference, Florence, Italy, IEPC-2007-15*. 2007.



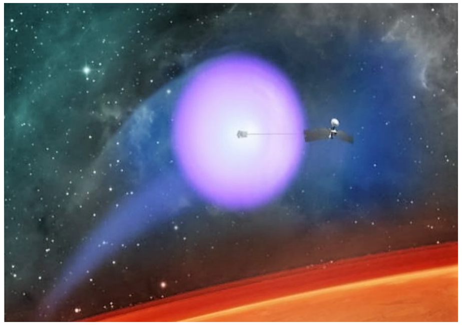
Plasma Magnetoshell

Slough, Kirtley, and Pancotti. *32nd International Electric Propulsion Conference*. 2011.

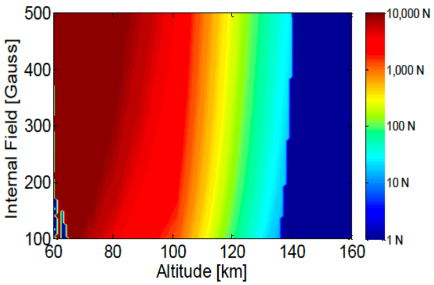
Kirtley. NIAC Phase I, NNX12AR12G Final Report (2012).

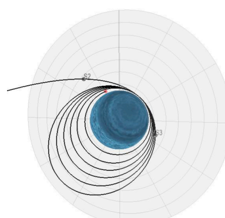


Plasma Magnetoshell Aerocapture



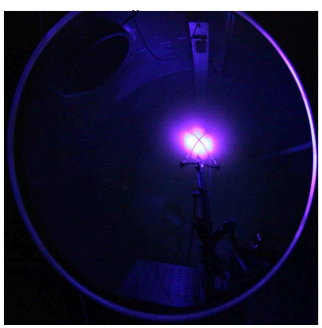
“Plasma parachute” enables high-velocity aerocapture at lower densities compared to aeroshells





Theoretical modeling and mission analysis:

- Neptune: enables 1,000 kg orbiter spacecraft
- Mars: enables orbit insertion of 60 MT payload
- Significant reduction in TPS requirements

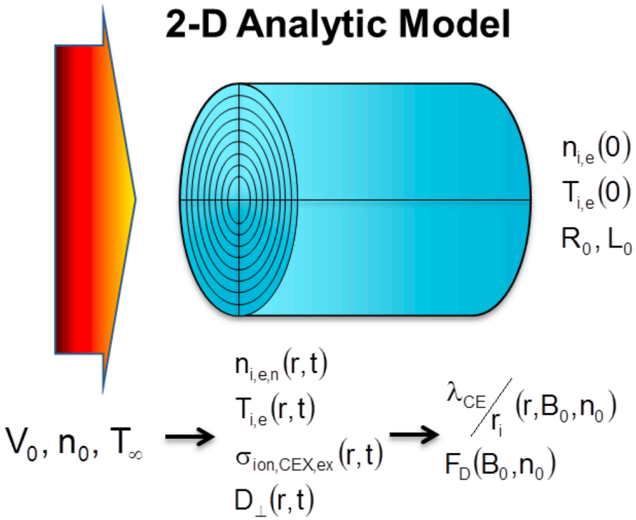


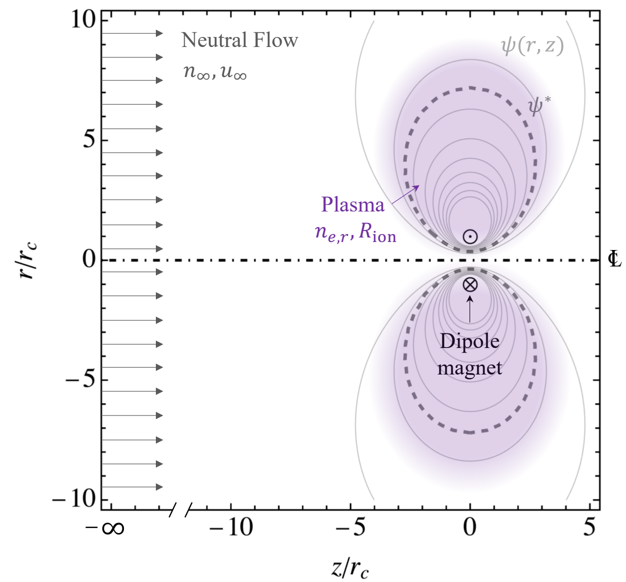
Proof-of-concept tests using pulsed MPDT exhaust plume

- Thrust stand → 1,000X increase in drag over aerodynamic

Kirtley. NIAC Phase I, NNX12AR12G Final Report (2012).

Magnetoshell Analytical Model





Original Model (Kirtley, 2012):

- Magnetic "layers"
- Cylindrical plasma
- No particle trajectories
- *Ad hoc* drag-area
- Partial mass/energy transfer

Our Model (Kelly and Little, 2019):

- Dipole magnetic field
- Plasma dipole equilibrium
- Particle trajectories
- Self-consistent drag area
- Full mass/energy transfer

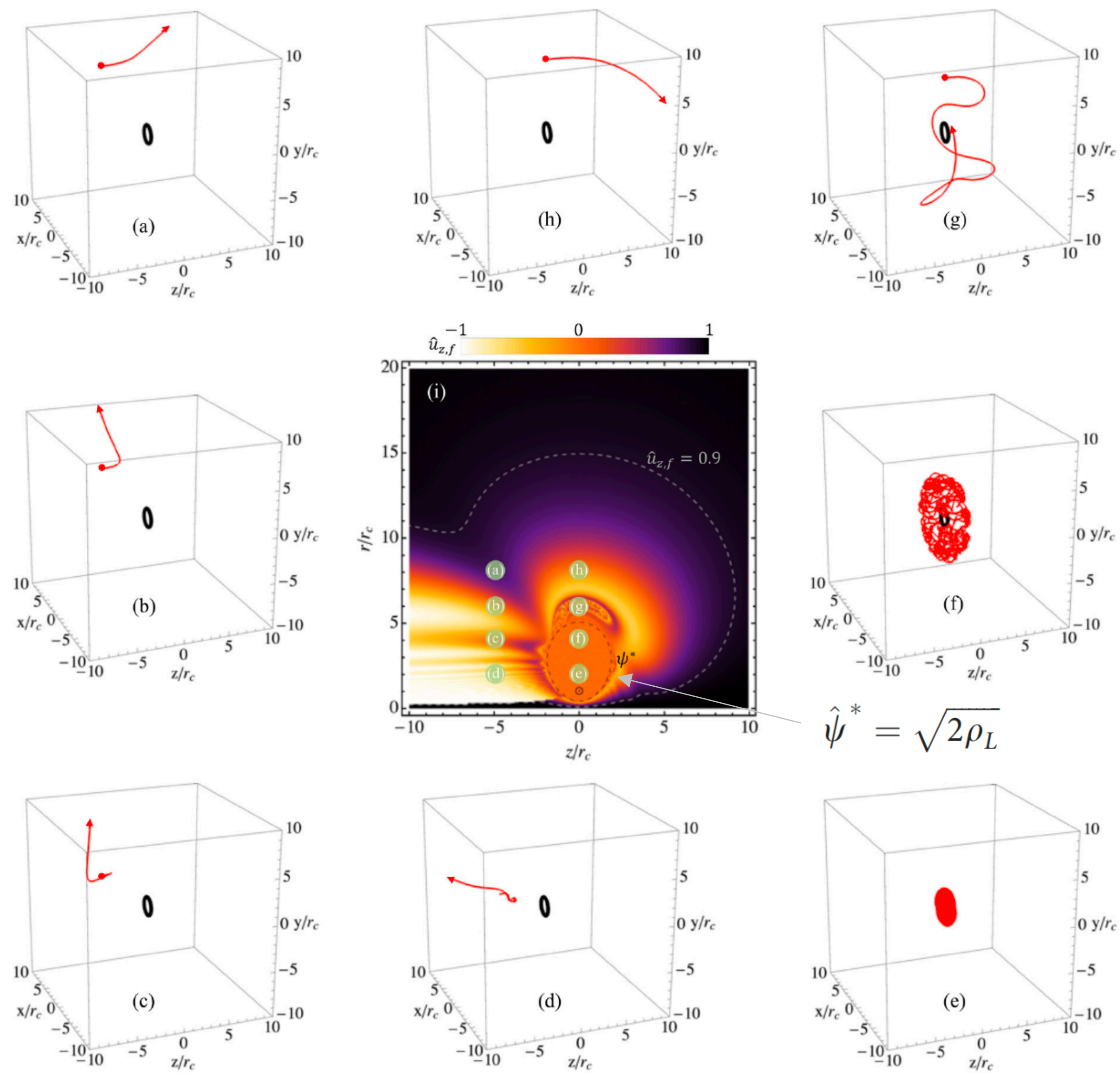
How well does the magnetoshell utilize mass/energy from the flow?

Behavior of Newly Ionized Flow Particles

$$\frac{d\hat{\mathbf{u}}}{d\hat{t}} = \frac{1}{\rho_L}\hat{\mathbf{u}} \times \hat{\mathbf{B}}$$

$$\frac{d\hat{\mathbf{r}}}{d\hat{t}} = \hat{\mathbf{u}}$$

$$\boxed{\rho_L = \frac{m_i u_\infty}{q_i B_0 r_c}}$$



$$\hat{\psi}^* = \sqrt{2\rho_L}$$

Little and Kelly. *Physics of Plasmas* 27.11 (2020): 113512.

Wake Formation and Flow Utilization

“Stream” neutral continuity:

$$\nabla \cdot (n_{sn}\mathbf{u}_{sn}) = -R_{\text{tot}} n_{sn} n_e$$

$$R_{\text{tot}} = R_{\text{ion}} + R_{\text{cx}}$$ (ionization + charge exchange)

$$\hat{n}_{sn} = \exp(-\zeta_{\text{tot}} I_n)$$

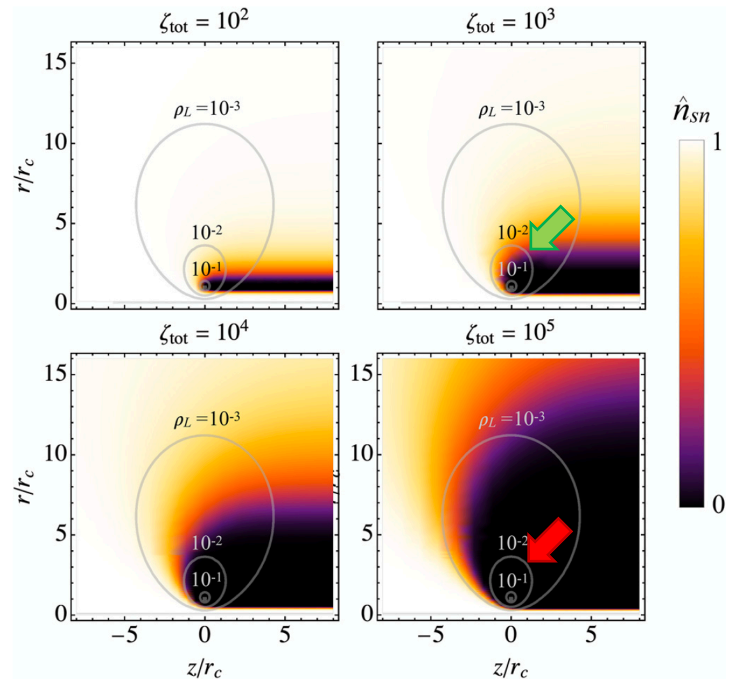
$$I_n = \int_{-\infty}^{\hat{z}} \left(\frac{\hat{\psi}}{\hat{\psi}_r}\right)^{\alpha} d\hat{z}$$ (magnetic topology + n_e-distribution)

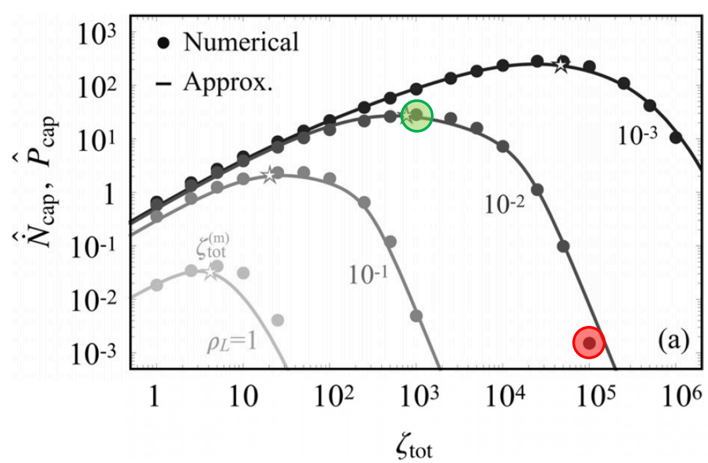
$$\boxed{\zeta_{\text{tot}} \equiv \frac{R_{\text{tot}} n_{e,r}}{u_\infty / r_c}} \sim \frac{\text{(Ionization frequency)}}{\text{(Neutral transit frequency)}}$$

$$\dot{N}_{\text{cap}} = \oint_{\psi>\psi^*} R_{\text{tot}} n_{sn} n_e dV \qquad P_{\text{cap}} = \frac{1}{2} m_{sn} u_\infty^2 \dot{N}_{\text{cap}}$$

$$\hat{\dot{N}}_{\text{cap}} = \hat{P}_{\text{cap}} = \zeta_{\text{tot}} I_{sn}(\rho_L, \zeta_{\text{tot}})$$

$$\boxed{\rho_L = \frac{m_i u_\infty}{q_i B_0 r_c}} \sim \frac{\text{(Characteristic Larmor radius)}}{\text{(Magnetic coil radius)}}$$





Little and Kelly. *Physics of Plasmas* 27.11 (2020): 113512.

Flow Utilization and Mode Transition

How well does the magnetoshell utilize mass/energy from the flow?

Power (and mass) balance in ψ^*:

$$\overbrace{\hat{P}_{\text{cap}} + \hat{P}_{\text{inj}}}^{\hat{P}_{\text{in}}} = \overbrace{\frac{\hat{N}_i}{\hat{\tau}_e}\left(\hat{T}_e + \hat{\varepsilon}_{\text{ion}}\right) + \hat{\dot{N}}_{\text{cap}}\hat{T}_i}^{\hat{P}_{\text{out}}}$$

(Net diffusion of ion + 2n thermal power)

(Ionization power loss)

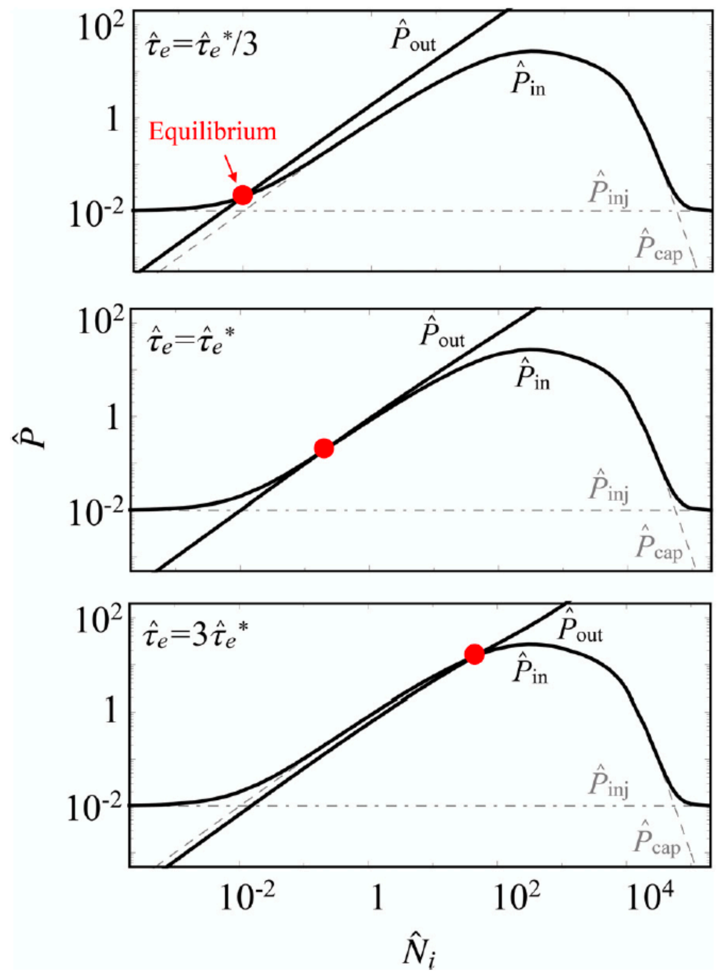
(Diffusion of electron thermal power)

(Power injected into dipole plasma)

(Power captured from the stream neutrals)

$$\boxed{\hat{\tau}_e^* = \left(\frac{\hat{T}_e + \hat{\varepsilon}_{\text{ion}}}{1 - \hat{T}_i}\right)\hat{\tau}_{\text{cap}}} \qquad \hat{\tau}_{\text{cap}} = \frac{u_\infty / r_c}{R_{\text{tot}} n_\infty}$$

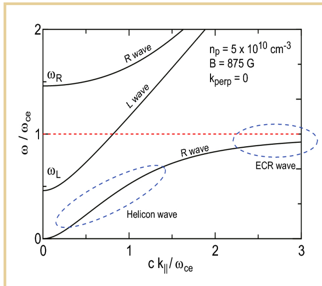
*Critical condition on electron confinement time



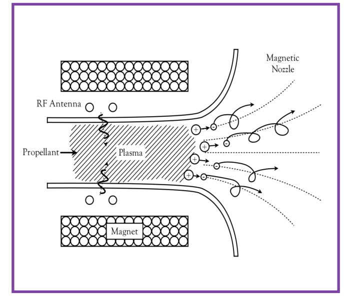
Little and Kelly. *Physics of Plasmas* 27.11 (2020): 113512.

Mode Transitions in Aerospace Plasmas

RF Absorption

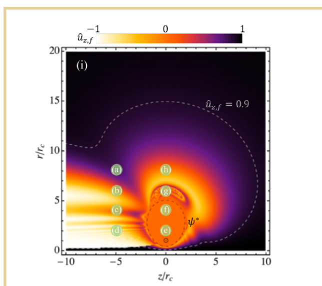


Thruster Global Model

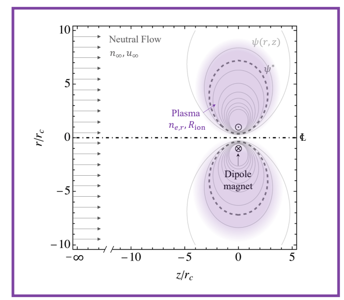


MODE TRANSITION

Flow Absorption



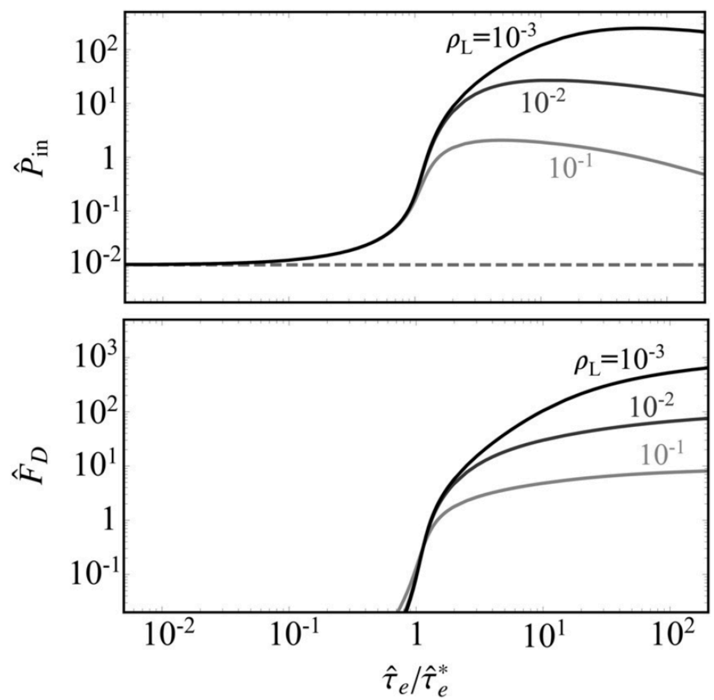
Magnetoshell Global Model

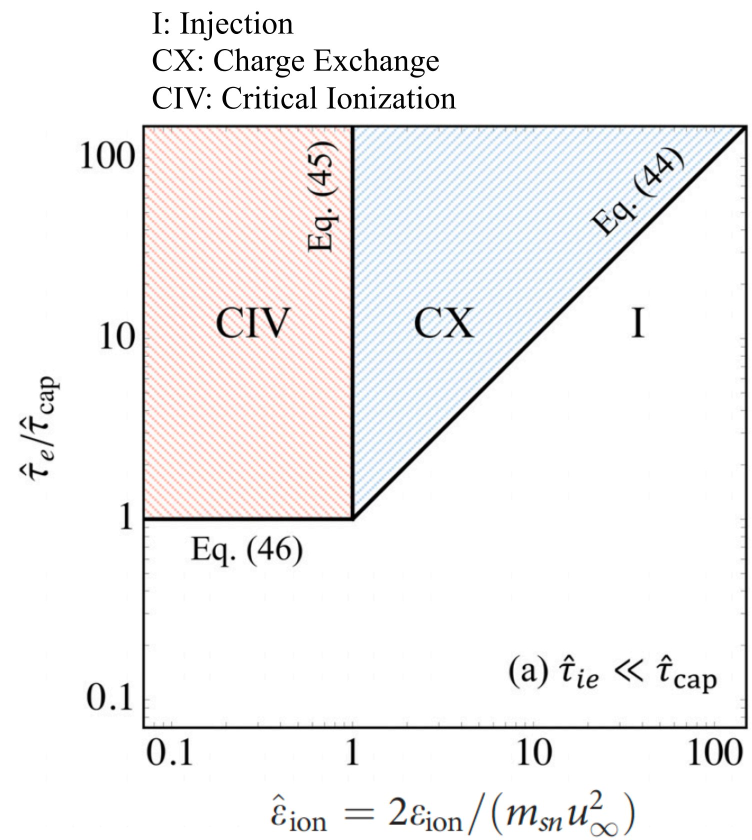


S·P·A·C·E

Little and Kelly. *Physics of Plasmas* 27.11 (2020): 113512.

Influence of Mode Transition on Performance



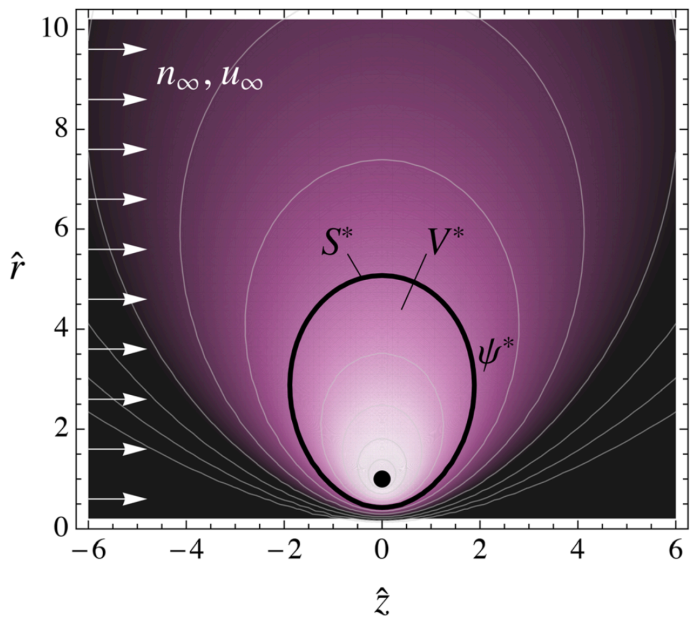


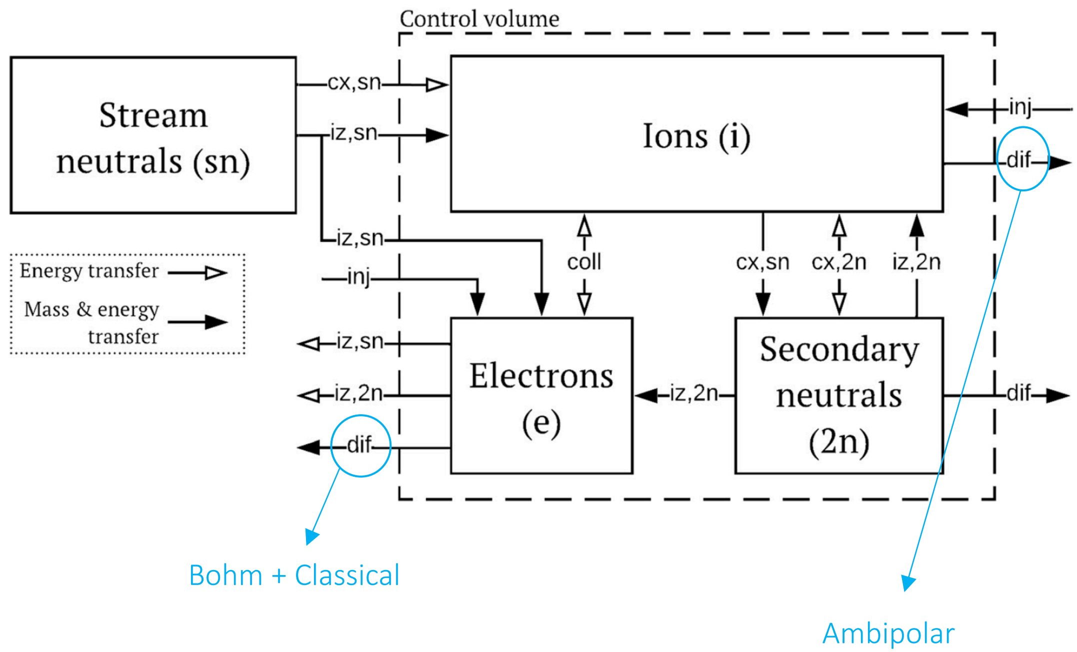
Increasing electron energy confinement time critical to performance!

Little and Kelly. *Physics of Plasmas* 27.11 (2020): 113512.

Magnetoshell Global Model

Do our predictions hold for “standard” diffusion models?



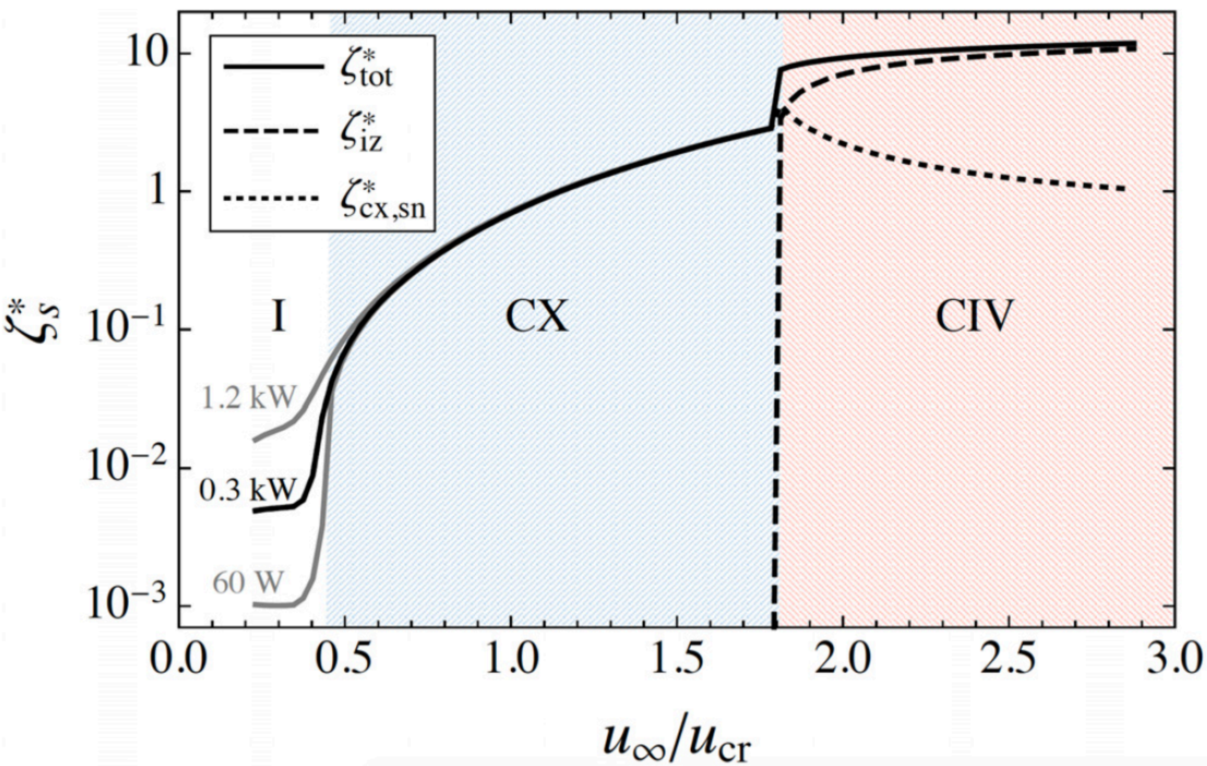


Kelly and Little. *Physics of Plasmas* 27.11 (2020): 113511.

Mode Transition with Increasing Flow Velocity

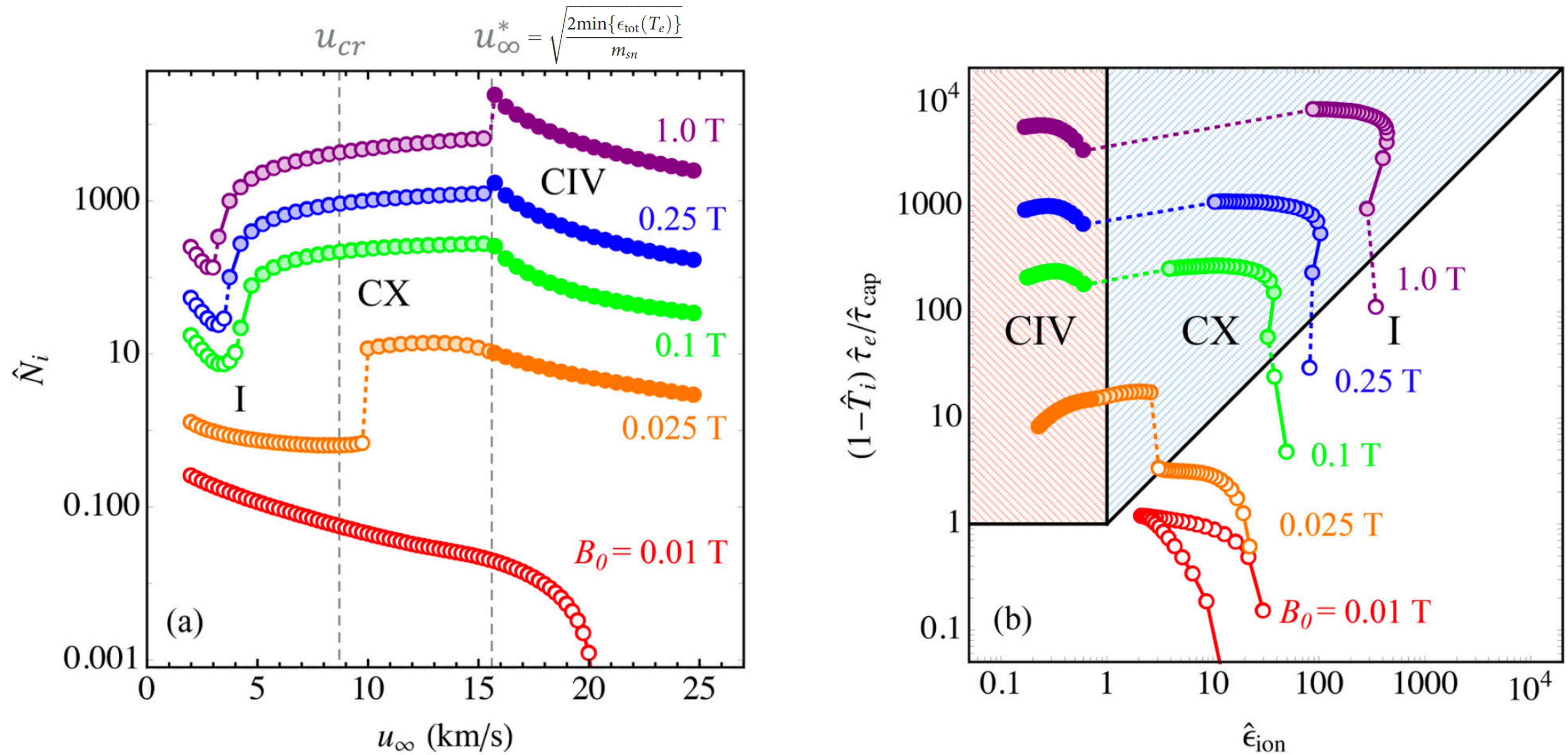
$$\zeta_s^* = \frac{R_s n_e^*}{u_\infty / r_c}$$

(Interaction Strength)



Kelly and Little. *Physics of Plasmas* 27.11 (2020): 113511.

Map of Magnetoshell Operating Modes



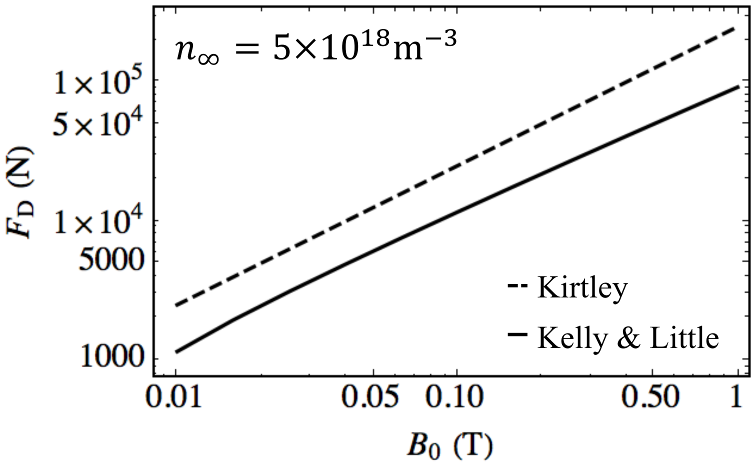
How does the performance compare to the original model?

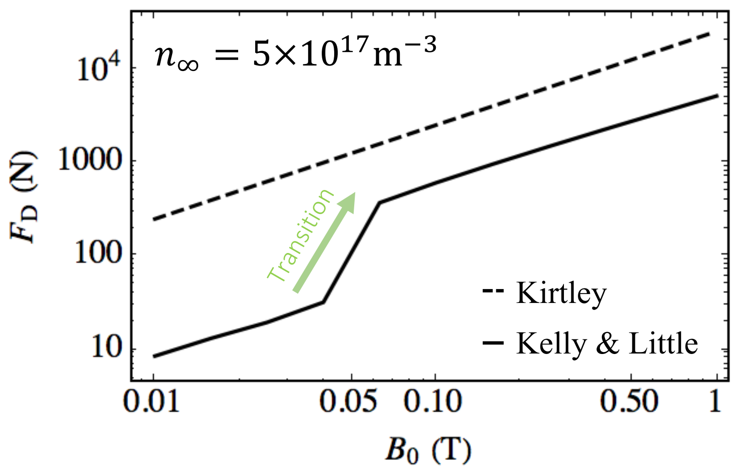
Kelly and Little. *Physics of Plasmas* 27.11 (2020): 113511.

Performance Comparison

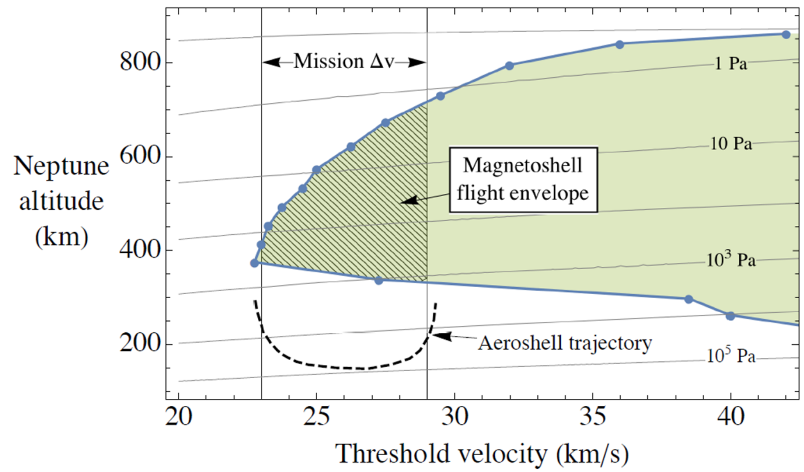
Neptune Orbiter: $r_c = 2$ meters

$u_\infty = 25$ km/s





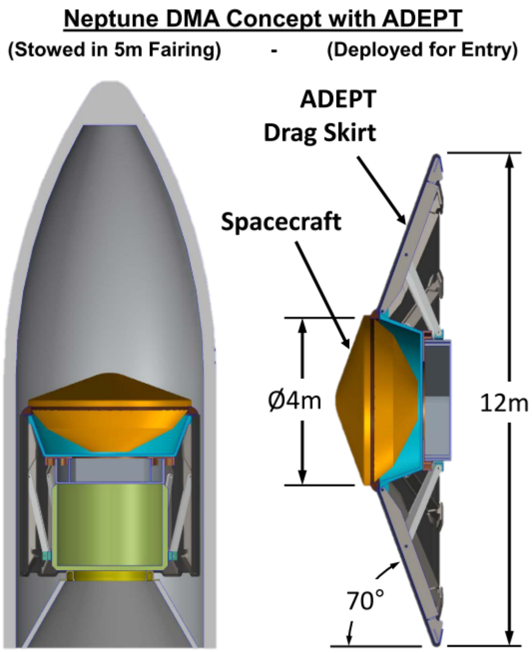
Flight envelope of magnetoshell viability at Neptune

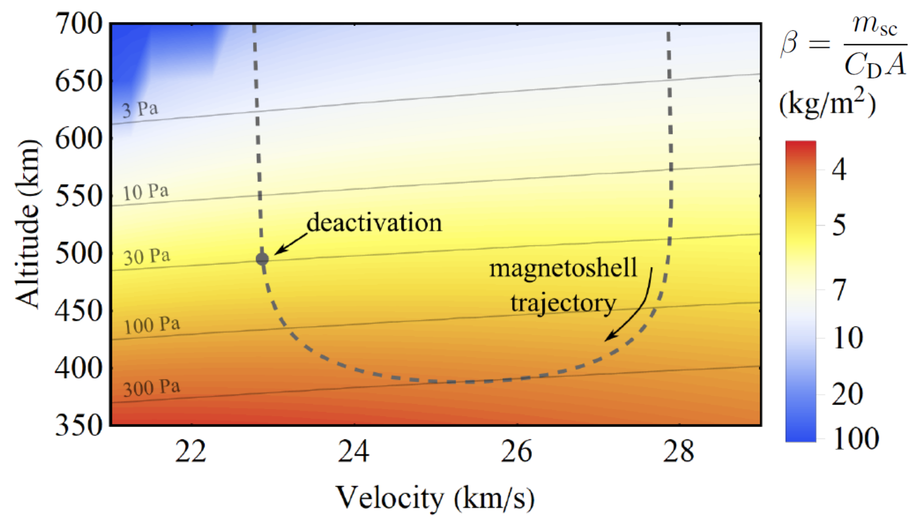


Kelly and Little. 36th International Electric Propulsion Conference, Vienna, Austria, IEPC Paper 2019-202. 2019.

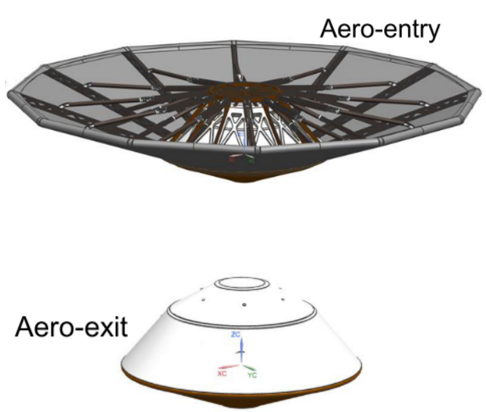
Do the benefits still outweigh the added mass/complexity?

Magnetoshell Aerocapture for Neptune Orbiter Mission





Kelly and Little. 42nd IEEE Aerospace Conference, 2.0304, 2021.



+70% payload mass

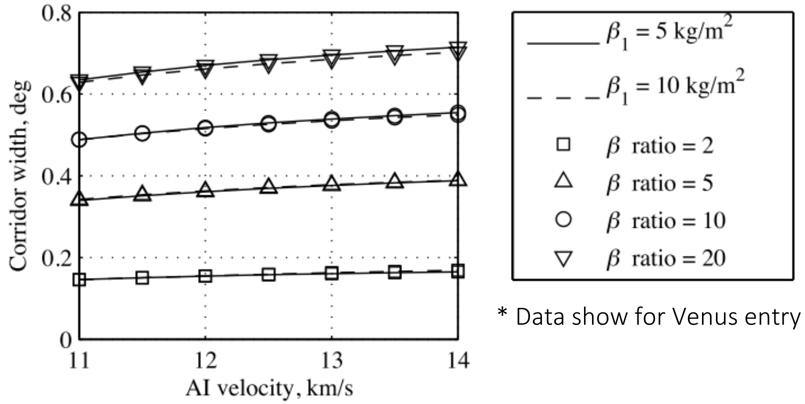
-30% aerocapture system mass

-30% peak heat flux , -45% total heat load

16x improvement in variable drag control

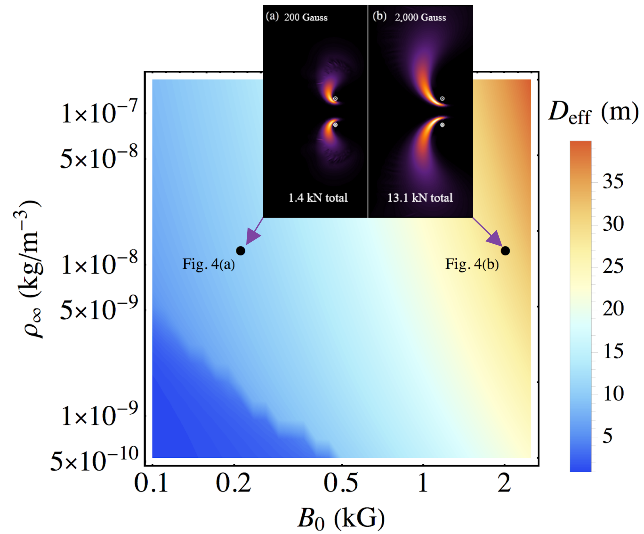
Magnetoshell Aerocapture for Neptune Orbiter Mission

Variable drag increases entry corridor width

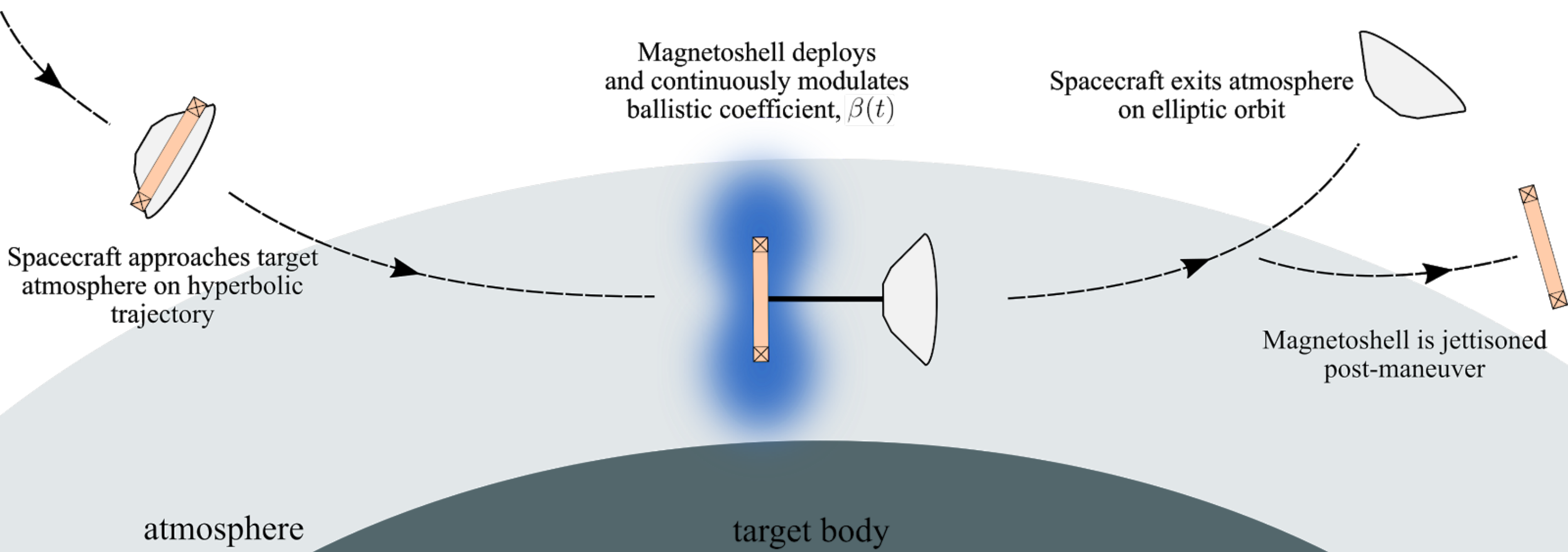


* Data show for Venus entry

Putnam and Braun, J. Spacecr. Rockets **51**, 139 (2014)



Kelly and Little. 42nd IEEE Aerospace Conference, 2.0304, 2021.



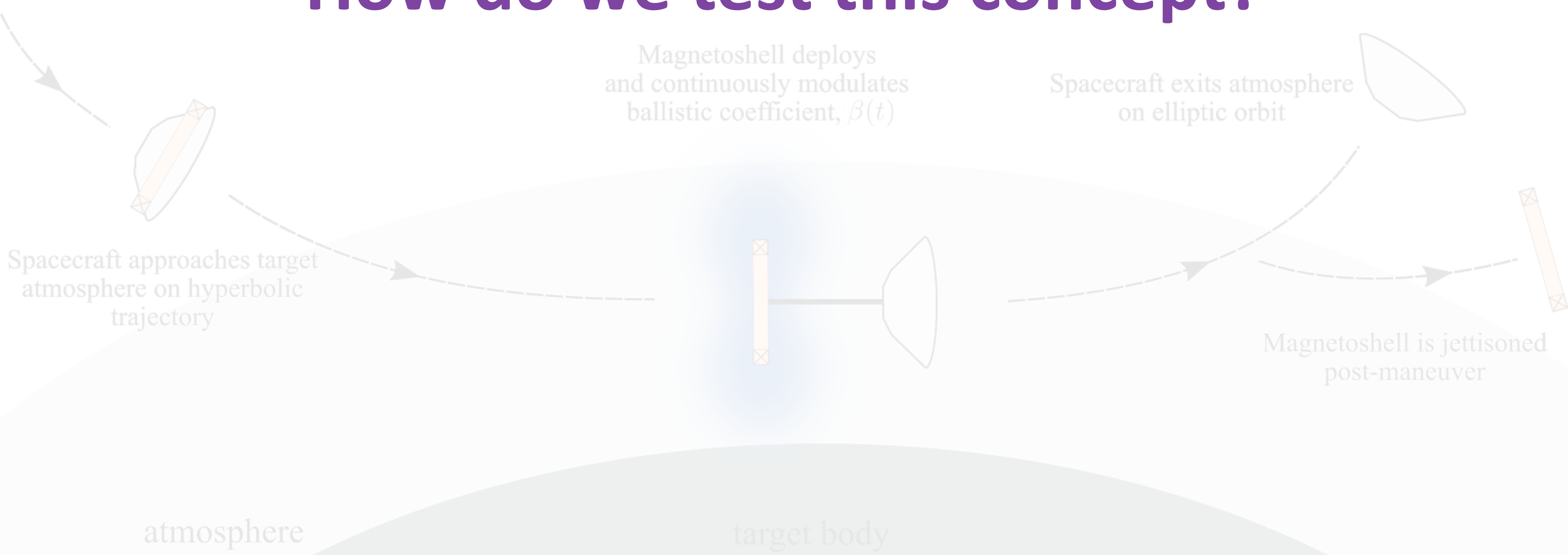
Magnetoshell Aerocapture for Neptune Orbiter Mission

Variable drag increases entry corridor width

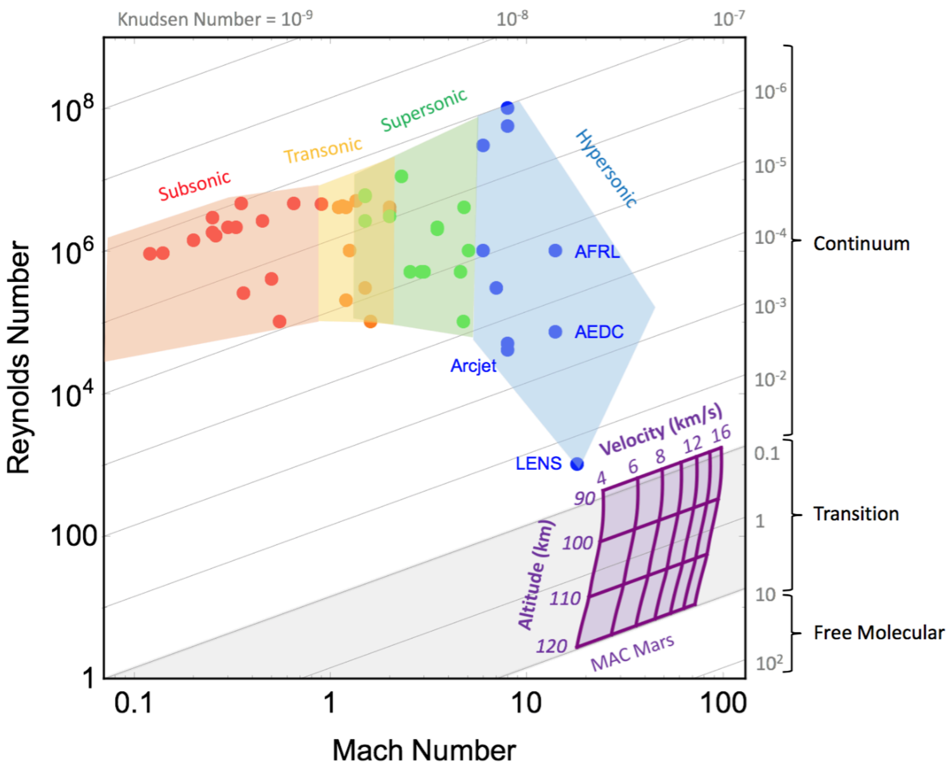
* Data show for Venus entry

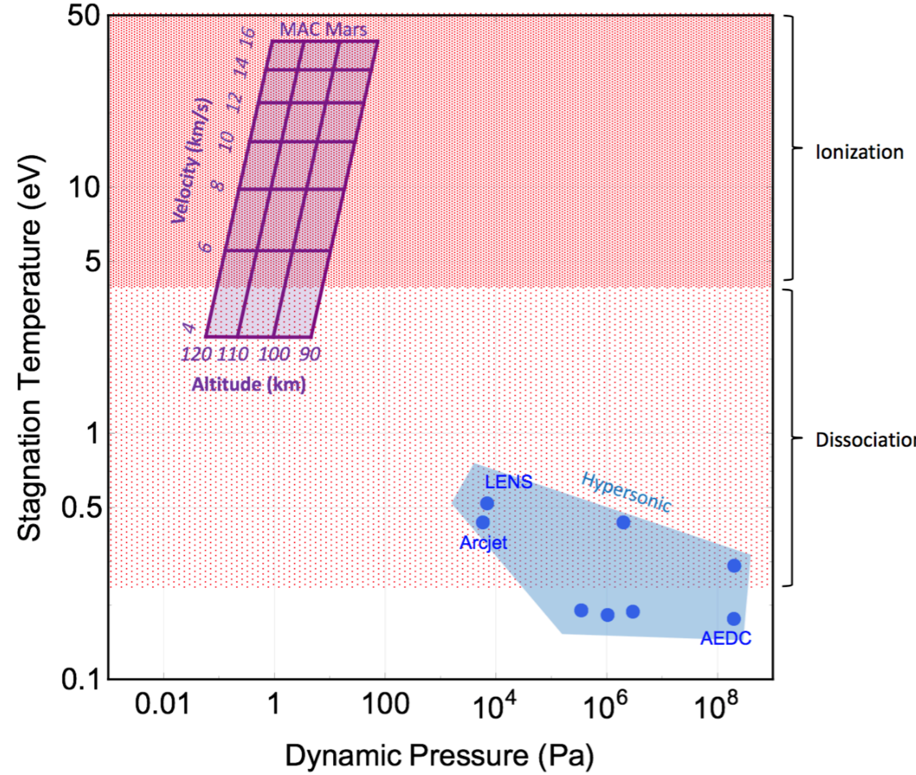
Putnam and Braun, J. Spacecr. Rockets 51, 139 (2014)

How do we test this concept?



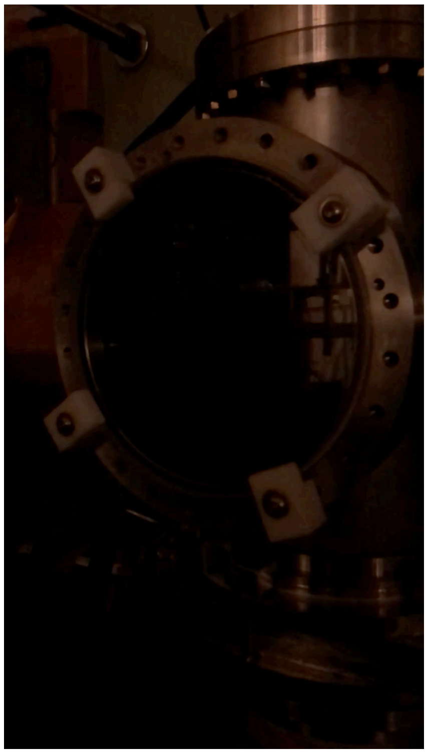
Flow Requirements of Magnetoshell Experiments

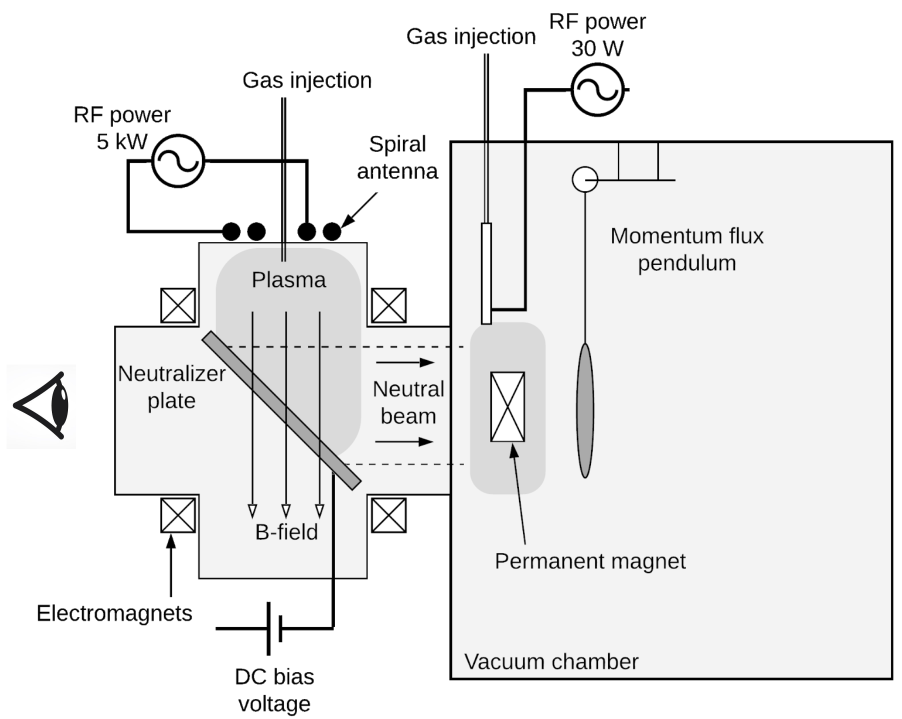


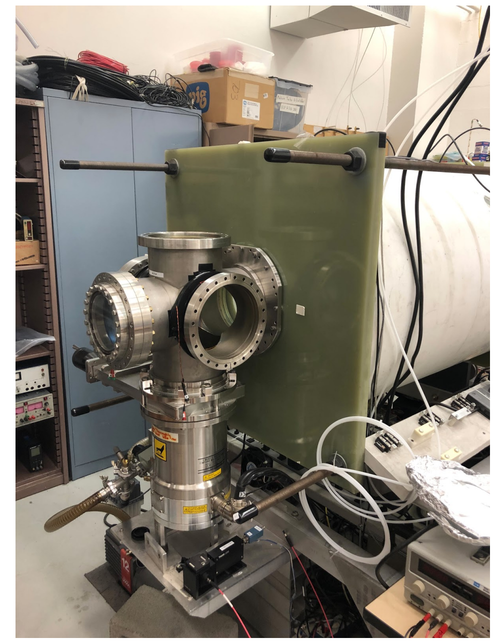


Wind tunnels unable to produce relevant flow regime!

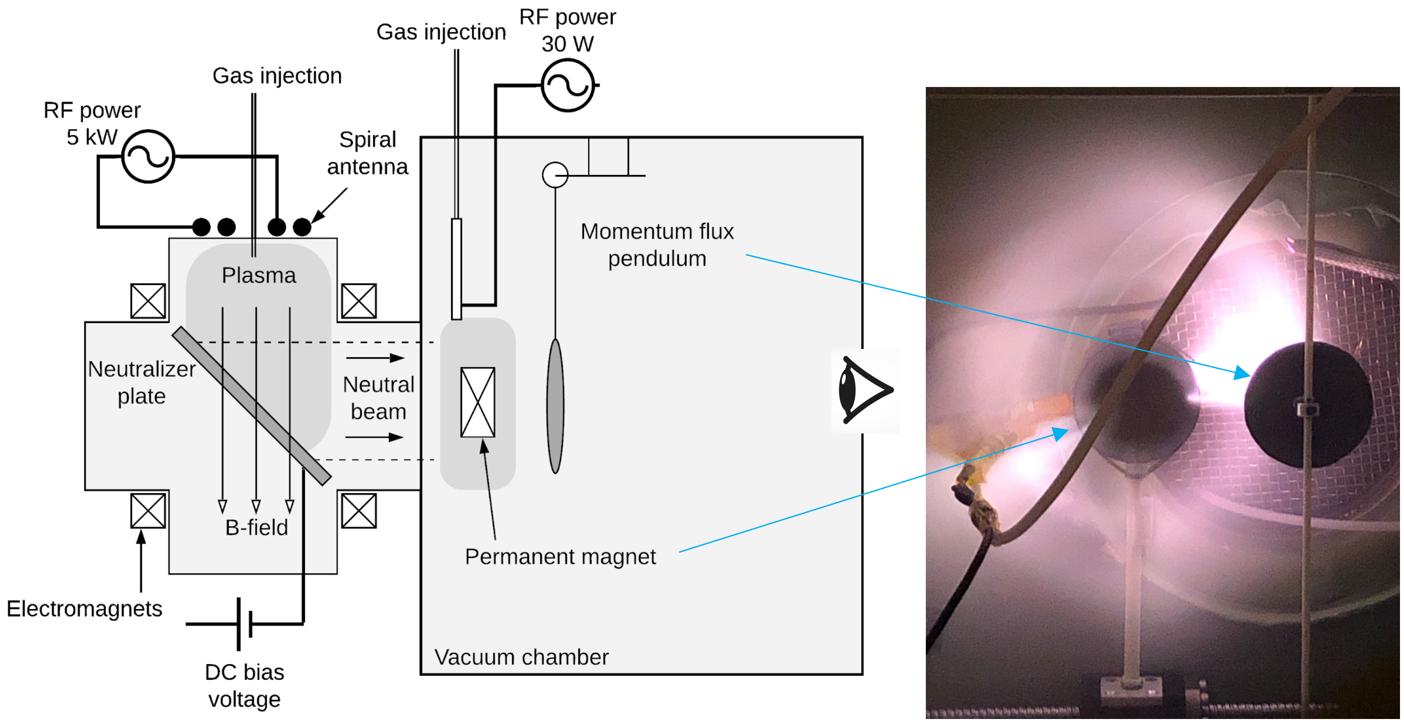
UW Plasma Magnetoshell Aerocapture Experiment





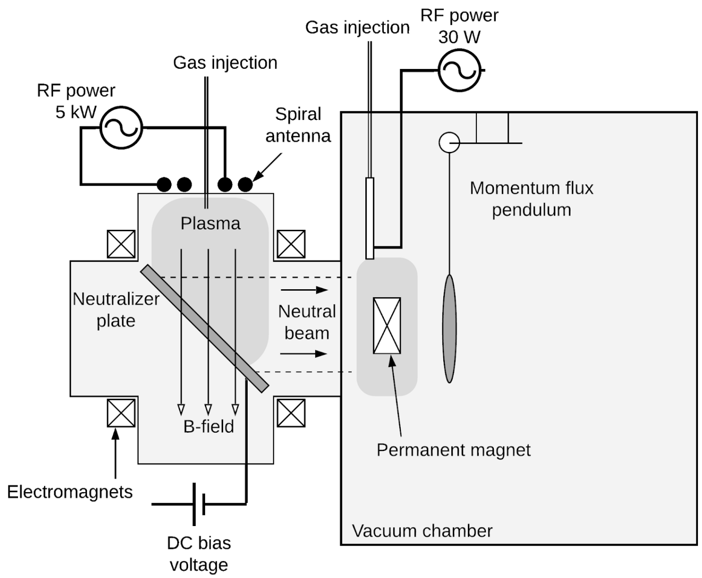


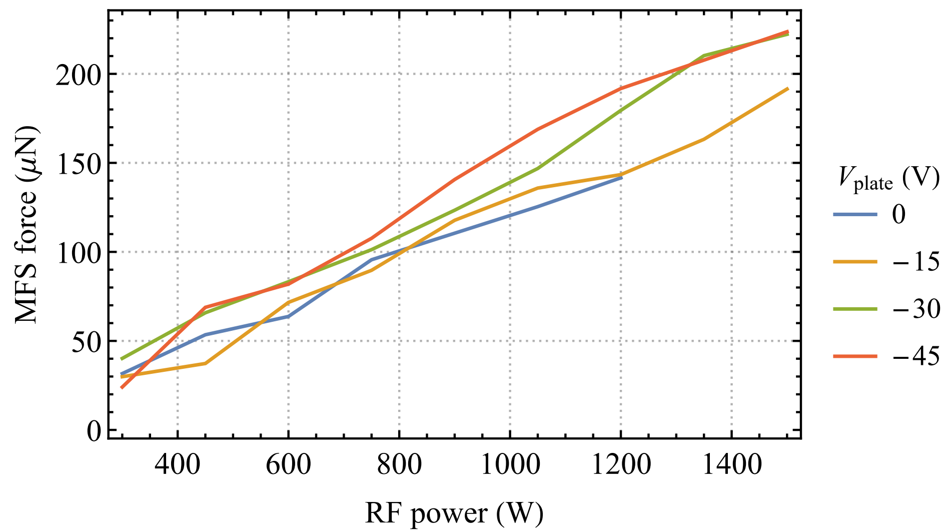
UW Plasma Magnetoshell Aerocapture Experiment



UW Plasma Magnetoshell Aerocapture Experiment

UW Plasma Magnetoshell Aerocapture Experiment

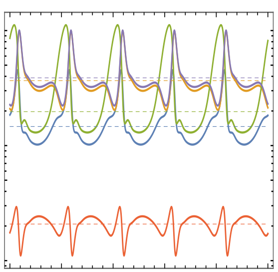




Mode Transitions in Aerospace Plasmas

Topic 1: Mode transitions in helicon thrusters

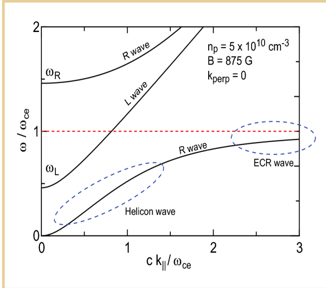
Topic 2: Critical velocities for plasma aerocapture



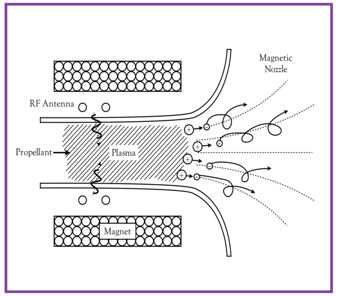
Topic 3: Data-driven discovery of mode transition physics

Mode Transitions in Aerospace Plasmas

RF Absorption

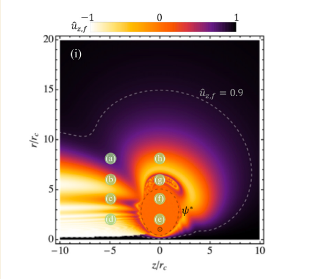


Thruster Global Model

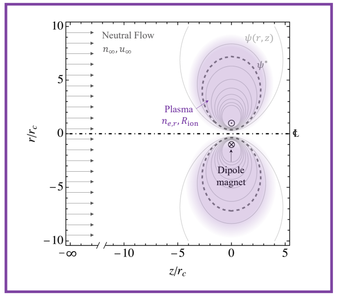


MODE TRANSITION

Flow Absorption



Magnetoshell Global Model



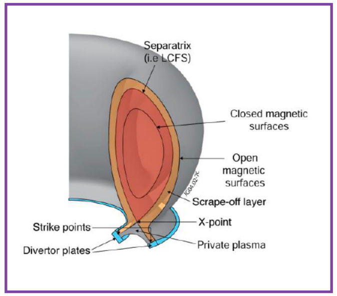
MICROSCOPIC PROCESSES

MACROSCOPIC ORGANIZATION

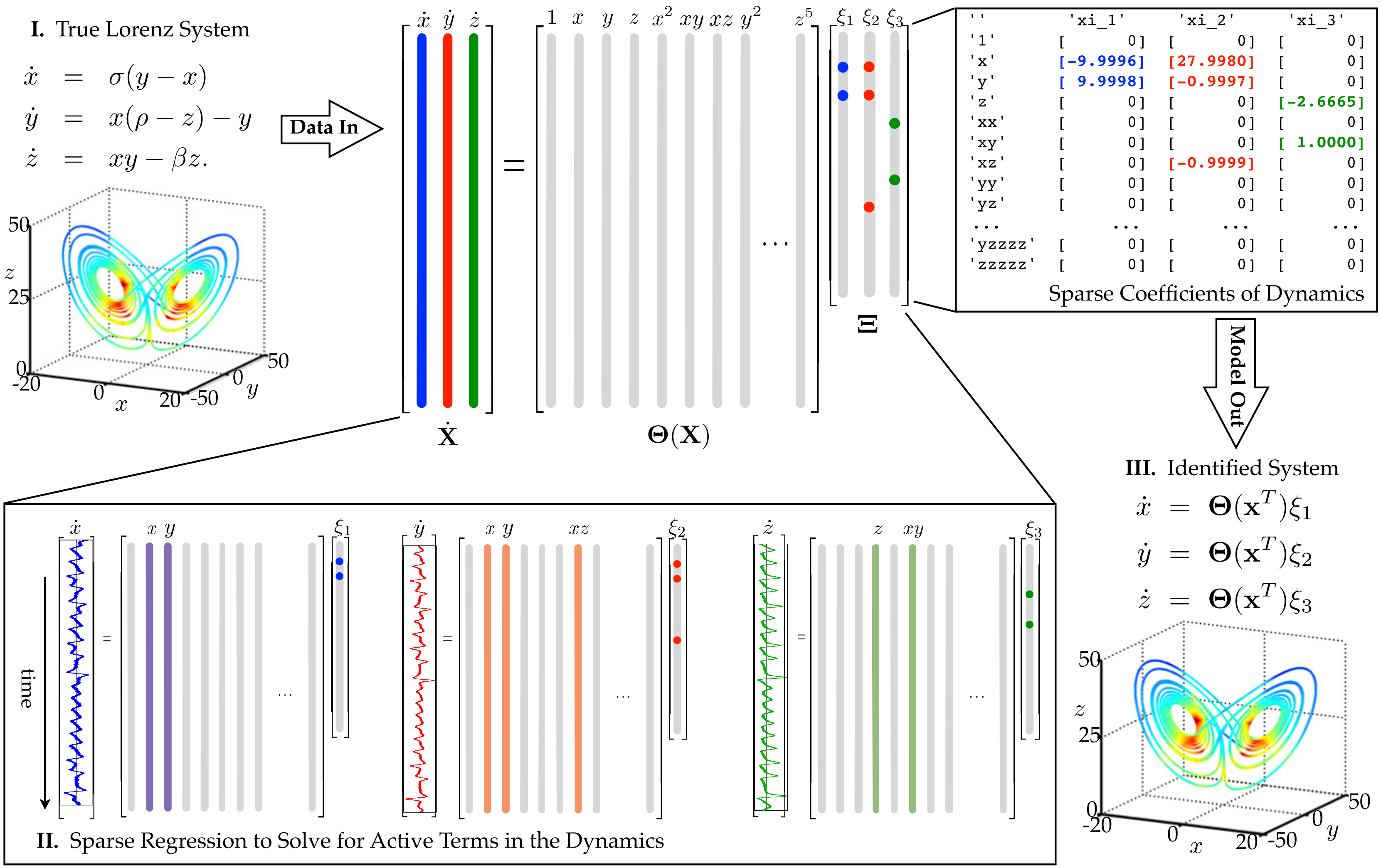
Driving Physics

?

Plasma Configuration

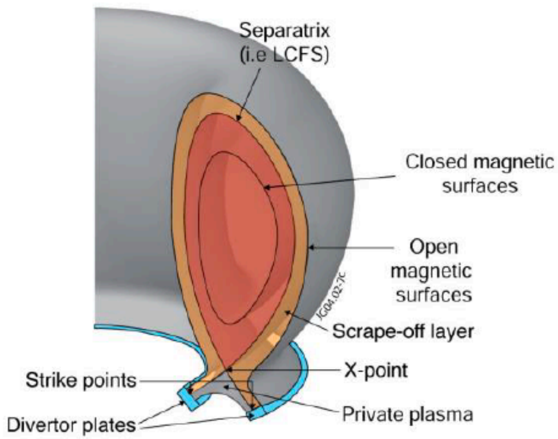


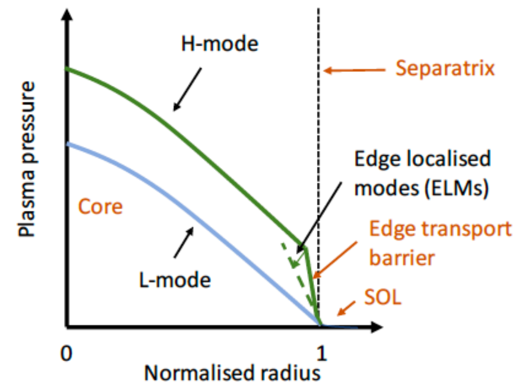
Sparse Identification of Nonlinear Dynamics (SINDy)



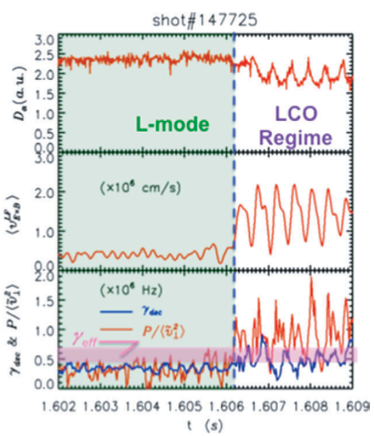
Brunton, Proctor, and Kutz. *Proceedings of the national academy of sciences* 113.15 (2016): 3932-3937.

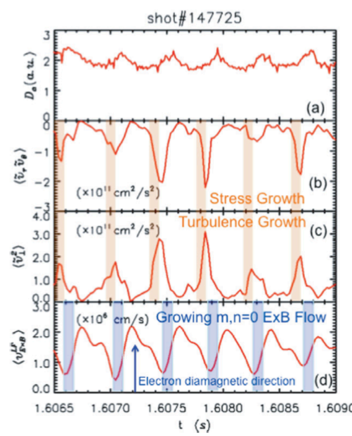
L-H Mode Transition in Magnetically-Confined Plasma



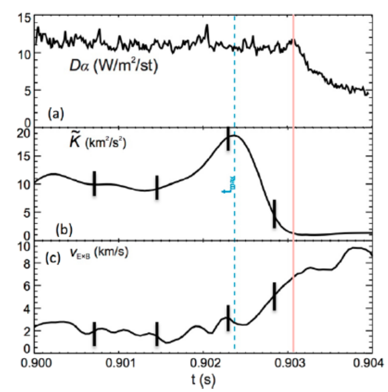


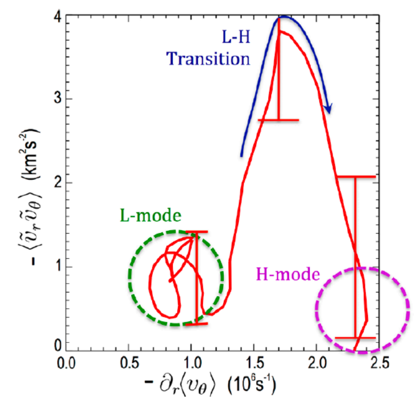
Ham et al. *Nature Reviews Physics* 2.3 (2020): 159-167.





Tynan et al. *Nuclear Fusion* 53 (2013): 073053.

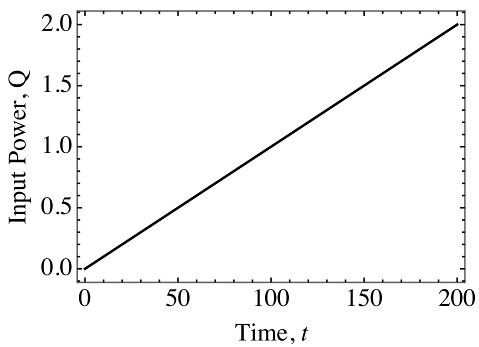




Tynan et al. *Plasma Phys. Controlled Fusion* 58.4 (2016): 044003.

Dynamical Model of the L-H Transition

Turbulence envelope equations in 0D provide dynamical model for L-H transition



$$Q = 0.01t$$

$$a_1 = 0.2$$

$$a_2 = a_3 = 0.7$$

$$b_1 = 1.5$$

$$b_2 = b_3 = 1.0$$

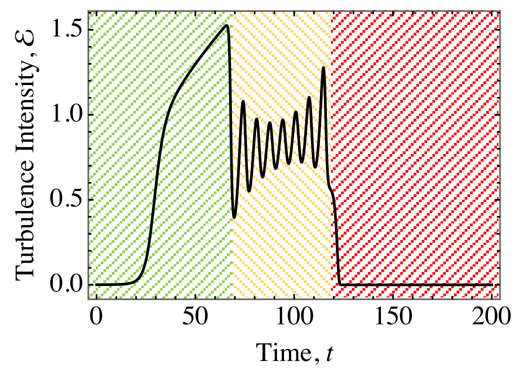
$$c_1 = 1.0$$

$$c_2 = 0.5$$

$$d = 1.0$$

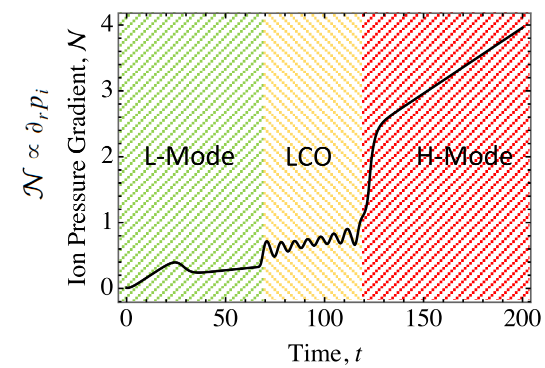
Linear instability | Non-linear saturation | Shear suppression

$$\partial_t \mathcal{E} = \mathcal{E}\mathcal{N} - a_1 \mathcal{E}^2 - \underbrace{a_2 V^2 \mathcal{E} - a_3 V_{\mathrm{ZF}}^2 \mathcal{E}}_{\text{Shear suppression}}$$



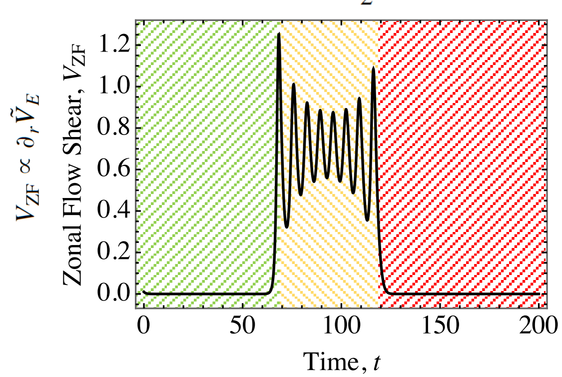
Turbulent diffusion | Neoclassical transport

$$\partial_t \mathcal{N} = -c_1 \mathcal{E}\mathcal{N} - c_2 \mathcal{N} + Q$$



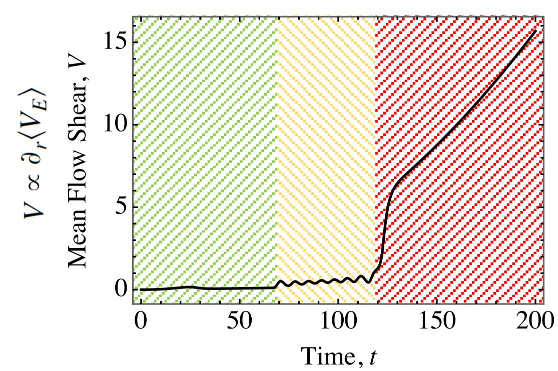
Reynolds stress | Damping

$$\partial_t V_{\mathrm{ZF}} = b_1 \frac{\mathcal{E} V_{\mathrm{ZF}}}{1 + b_2 V^2} - b_3 V_{\mathrm{ZF}}$$



Force balance

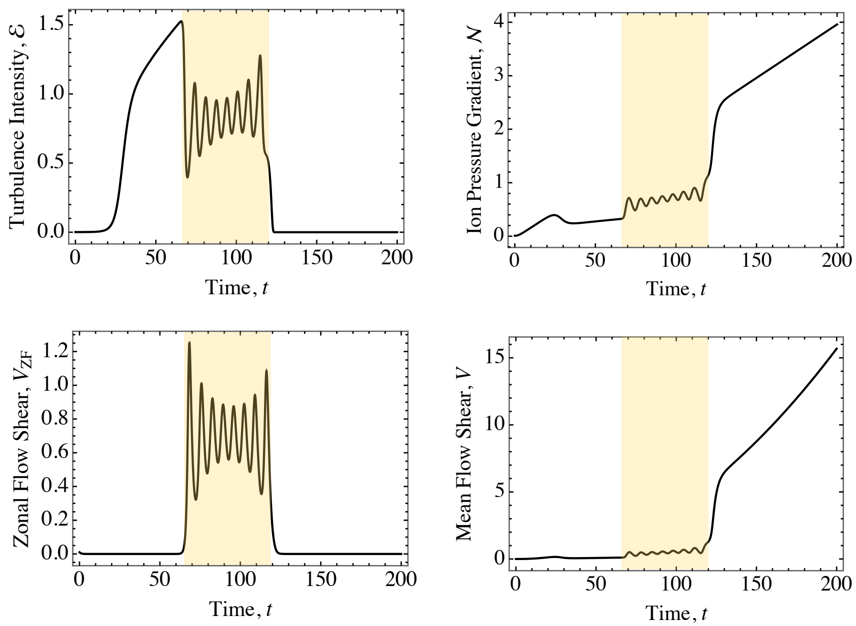
$$V = d\mathcal{N}^2$$



Kim and Diamond. *Phys. Rev. Lett.* 90.18 (2003): 185006.

Application of SINDy to L-H Mode Transition

Can SINDy find coefficients using LCO data?



$Q = 0.01t$

$a_1 = 0.2$

$a_2 = a_3 = 0.7$

$b_1 = 1.5$

$b_2 = b_3 = 1.0$

$c_1 = 1.0$

$c_2 = 0.5$

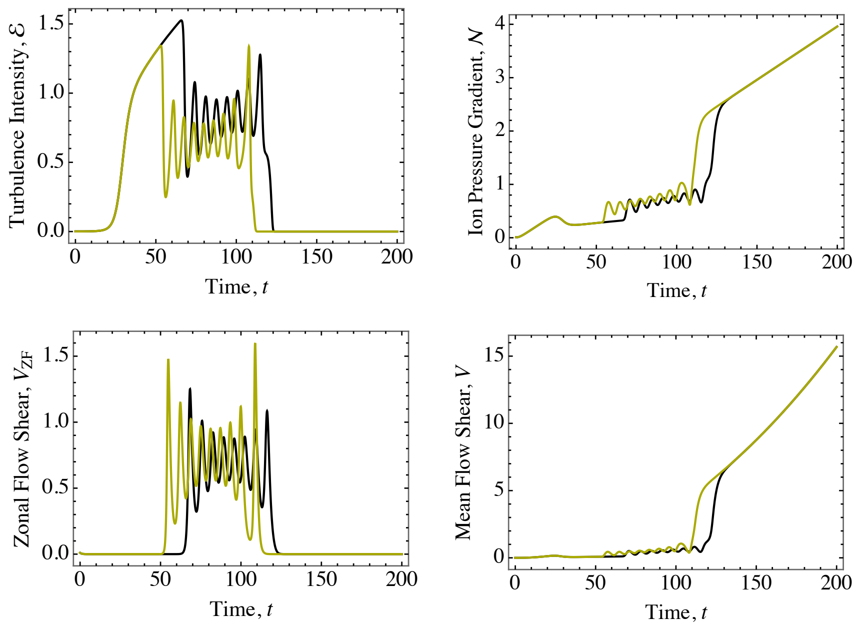
$d = 1.0$

$$\partial_t \mathcal{N} = \boxed{-c_1 \mathcal{E}\mathcal{N}} \boxed{- c_2 \mathcal{N}} + \boxed{Q}$$

	$\dot{\mathcal{E}}$	$\dot{V}_{ZF}$	$\dot{\mathcal{N}}$
t	0	0	0.01
$\mathcal{E}$	0	0	0
V_{ZF}	0	-0.979254	0
$\mathcal{N}$	0	0	-0.5
$\mathcal{E}^2$	-0.2	0	0
$\mathcal{E}V_{ZF}$	0	0	0
$\mathcal{E}\mathcal{N}$	1.	0	-1.
V_{ZF}^2	0	0	0
$V_{ZF}\mathcal{N}$	0	0	0
$\mathcal{N}^2$	0	0	0
$\mathcal{E}^3$	0	0	0
$\mathcal{E}^2 V_{ZF}$	0	0	0
$\mathcal{E}^2\mathcal{N}$	0	0	0
$\mathcal{E}V_{ZF}^2$	-0.7	0	0
$\mathcal{E}\mathcal{N}^2$	0	0	0
$\mathcal{E}\mathcal{N}^4$	-0.7	0	0
V_{ZF}^3	0	0	0
$V_{ZF}^2\mathcal{N}$	0	0	0
$V_{ZF}\mathcal{N}^2$	0	0	0
$\mathcal{N}^3$	0	0	0
$\frac{\mathcal{E}V_{ZF}}{1+\mathcal{N}^4}$	0	1.57443	0

Application of SINDy to L-H Mode Transition

What if we add “unknown” physics?

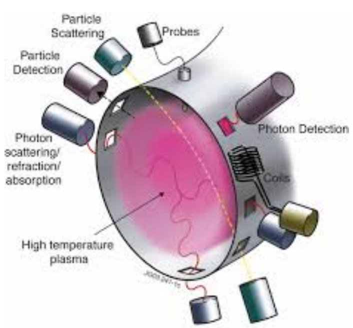


	$\dot{\mathcal{E}}$	$\dot{V}_{ZF}$	$\dot{\mathcal{N}}$
t	0	0	0.01
$\mathcal{E}$	0	0	0
V_{ZF}	0	-1.01465	0
$\mathcal{N}$	0	0	-0.5
$\mathcal{E}^2$	-0.2	0	0
$\mathcal{E}V_{ZF}$	0	0	0
$\mathcal{E}\mathcal{N}$	1.	0	-1.
V_{ZF}^2	0	0	0
$V_{ZF}\mathcal{N}$	0	0	0
$\mathcal{N}^2$	0	0	0
$\mathcal{E}^3$	0	0	0
$\mathcal{E}^2V_{ZF}$	0	0.484106	0
$\mathcal{E}^2\mathcal{N}$	0	0	0
$\mathcal{E}V_{ZF}^2$	-0.7	0	0
$\mathcal{E}\mathcal{N}^2$	0	0	0
$\mathcal{E}\mathcal{N}^4$	-0.7	0	0
V_{ZF}^3	0	0	0
$V_{ZF}^2\mathcal{N}$	0	0	0
$V_{ZF}\mathcal{N}^2$	0	0	0
$\mathcal{N}^3$	0	0	0
$\frac{\mathcal{E}V_{ZF}}{1+\mathcal{N}^4}$	0	1.6598	0

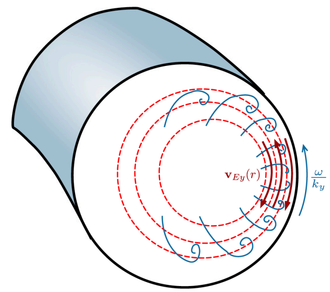
$$\partial_t V_{ZF} = b_1 \frac{\mathcal{E}V_{ZF}}{1 + b_2 V^2} - b_3 V_{ZF} + b_4 \mathcal{E}^2 V_{ZF}$$

$$b_4 = 0.5$$

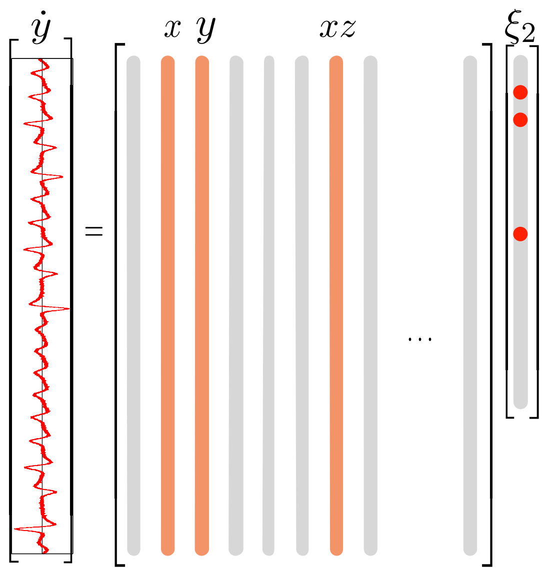
Application of SINDy to Mode Transitions

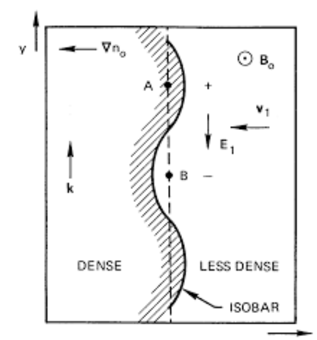


1. Diagnostic advances → more data, higher quality



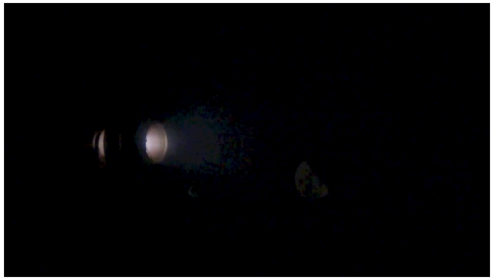
2. Identification of "macro"— scale physical drivers



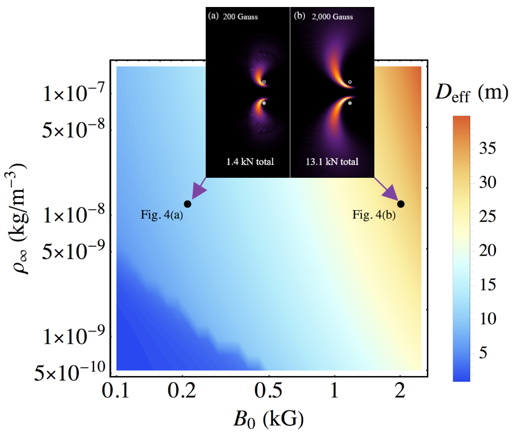


3. Characterization of link between "macro" and "micro" scale physics

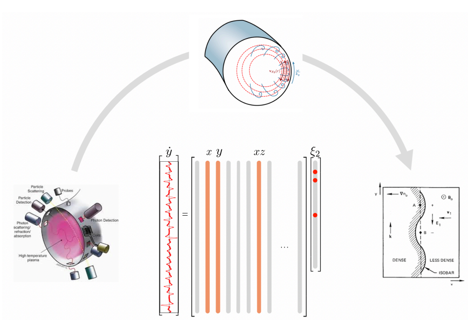
Conclusions



- Plasmas exhibit bizarre, oftentimes unexpected behavior



- Understanding "non-ideal" physics critical for space technology



- Exciting new methods on the horizon enabled by "big data"

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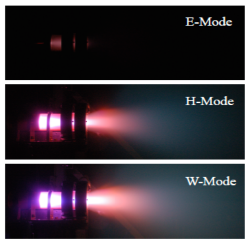

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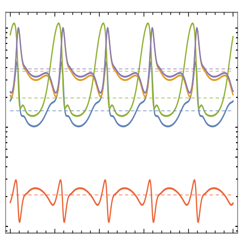

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QUESTIONS?