Turbulence and Transport in Magnetized Plasmas

Troy Carter
Department of Physics and Astronomy, UCLA

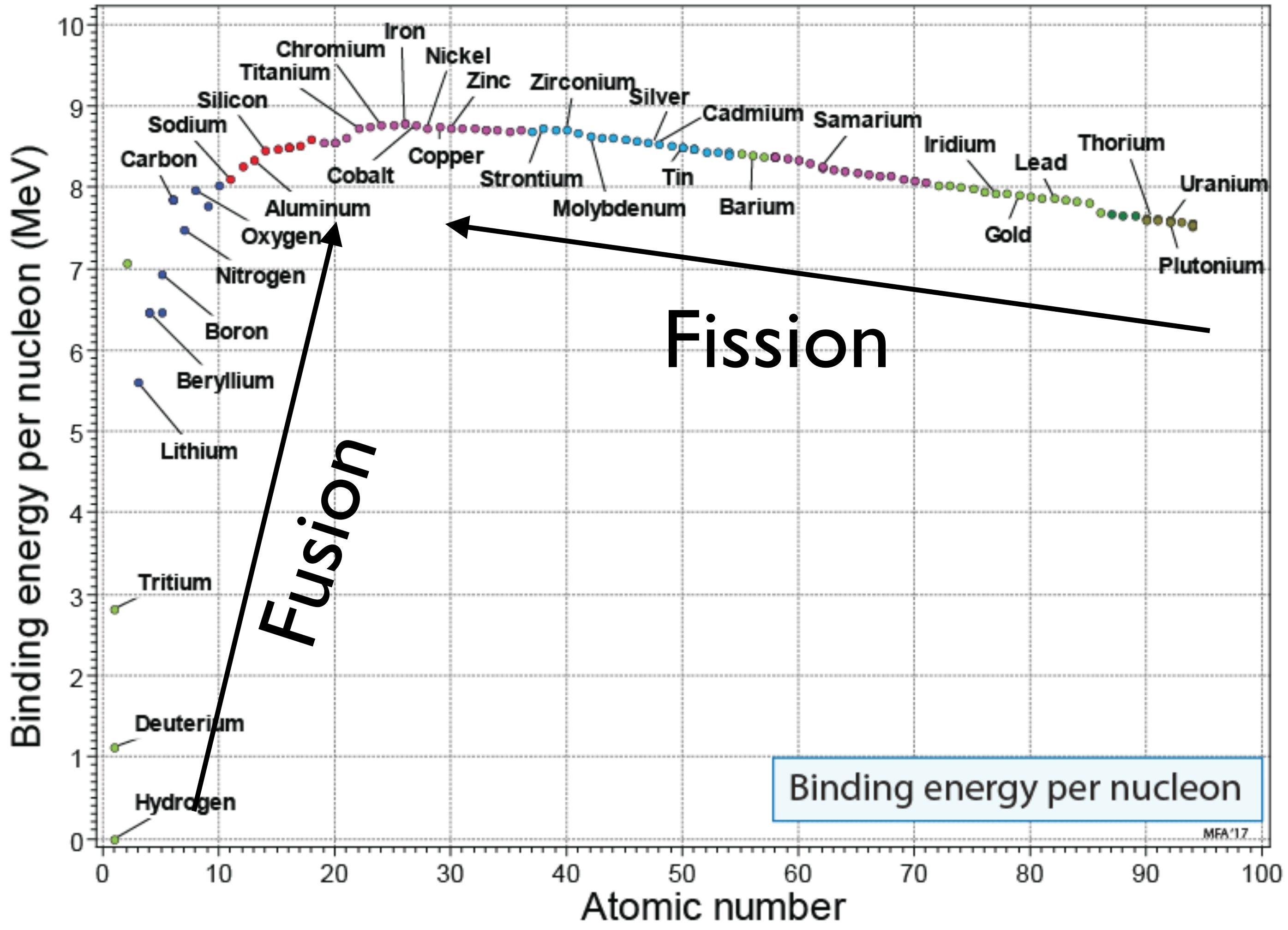
ICTP/IAEA Fusion School 2024

BaPSF

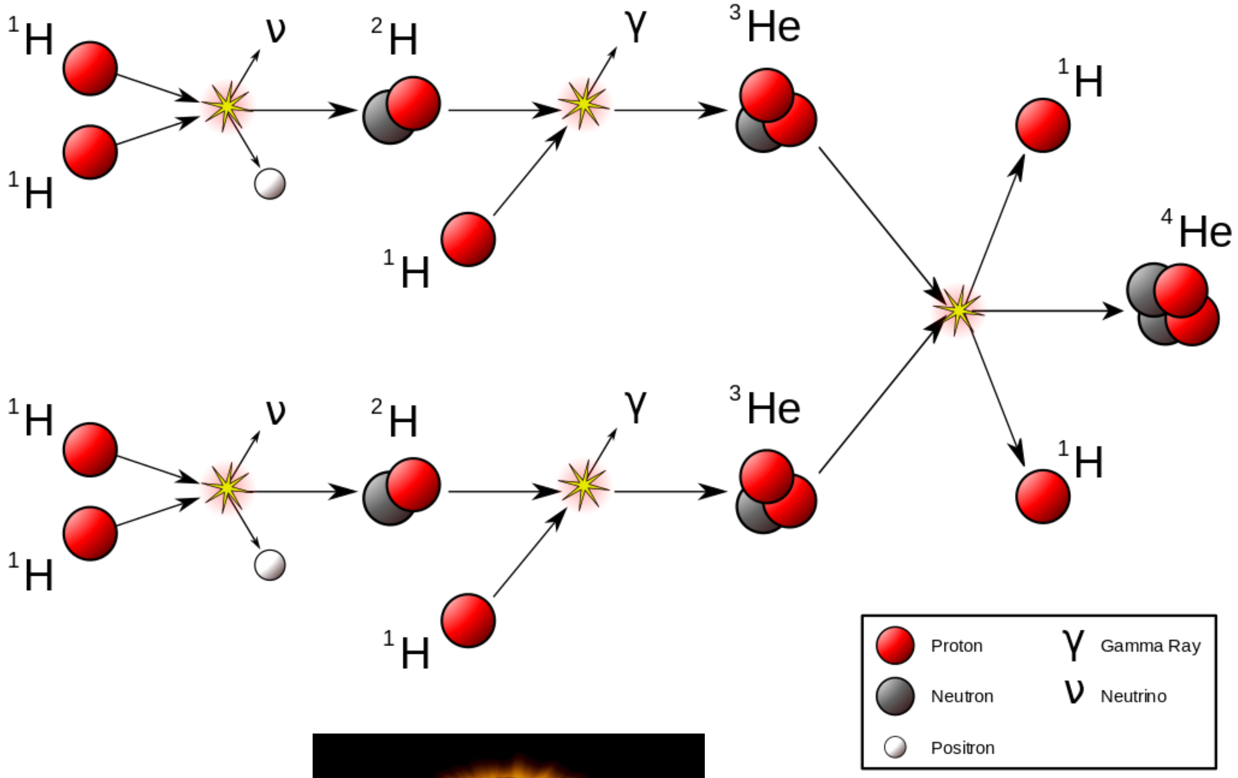
UCLA

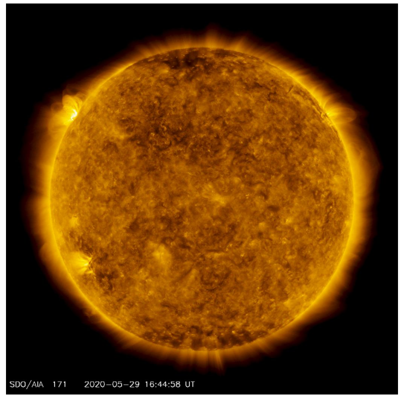
PSTI UCLA
Plasma Science and Technology Institute

Fusion: merging of light nuclei to form heavier nuclei



p-p fusion in Stars

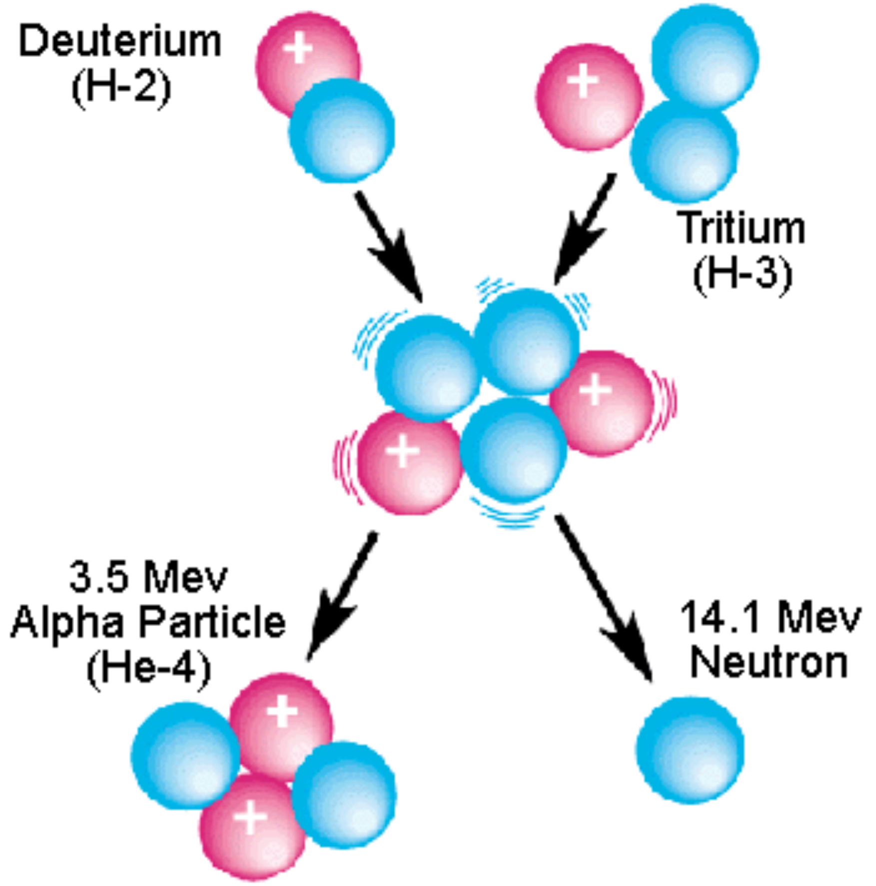




Fusion releases energy by creating “more tightly bound” nuclei: said another way, the reaction products have less mass than the reactants (that missing mass is the released energy: $E=mc^2$)

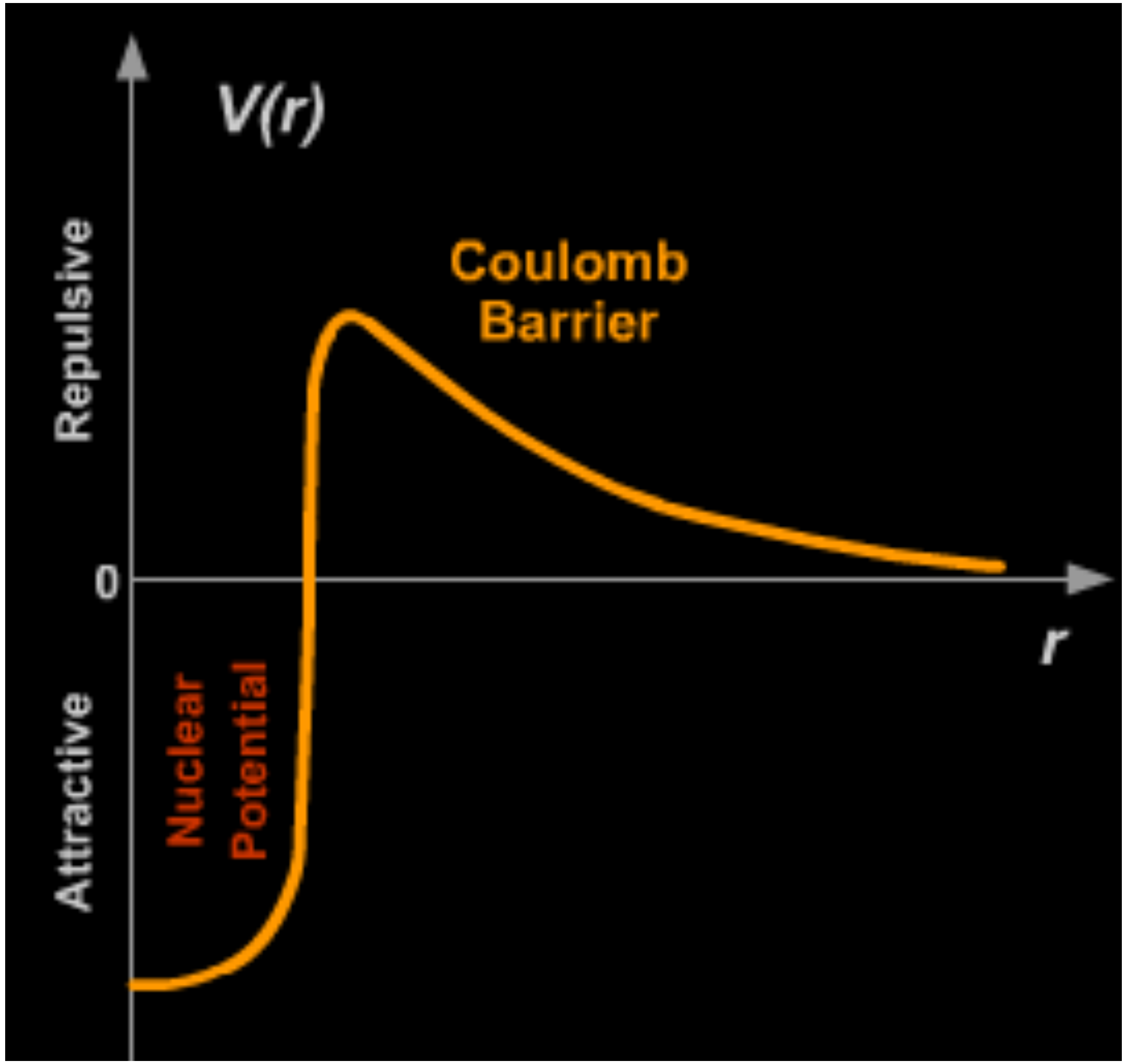
Heavy hydrogen isotopes more suitable for terrestrial fusion

- Deuterium (abundant in seawater) and tritium (unstable, must be manufactured from, e.g. Li) have highest fusion cross-section/probability of fusion reaction occurring
- Reaction products: He nucleus (“alpha-particle”) and a neutron
- Energy carried away in “kinetic energy” of reaction products – they fly off from the reaction at very high speed



Deuterium-Tritium Fusion Reaction

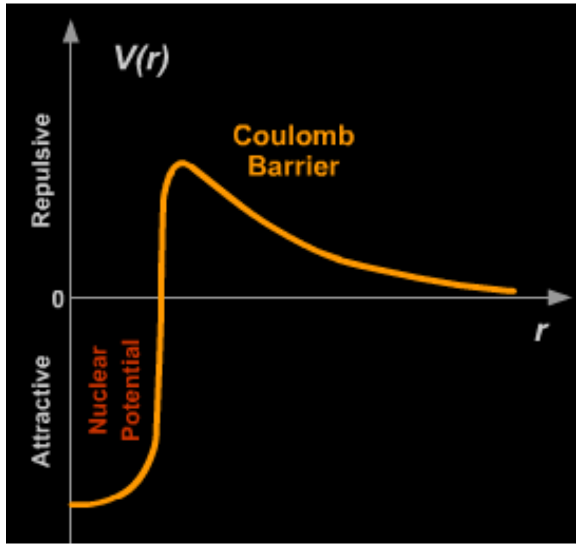
Fusing nuclei must enough energy to overcome "Coulomb Barrier"



- Need enough energy to get "up the hill" associated with electric repulsion
- Strong nuclear force is short ranged but very strong! Once nuclei are close enough, "fall down a steep hole" releasing lots of energy

➡ Need energy equivalent to 100 million degree temperature (~10 keV) to overcome Coulomb barrier

“Scattering” much more likely than fusion reactions!

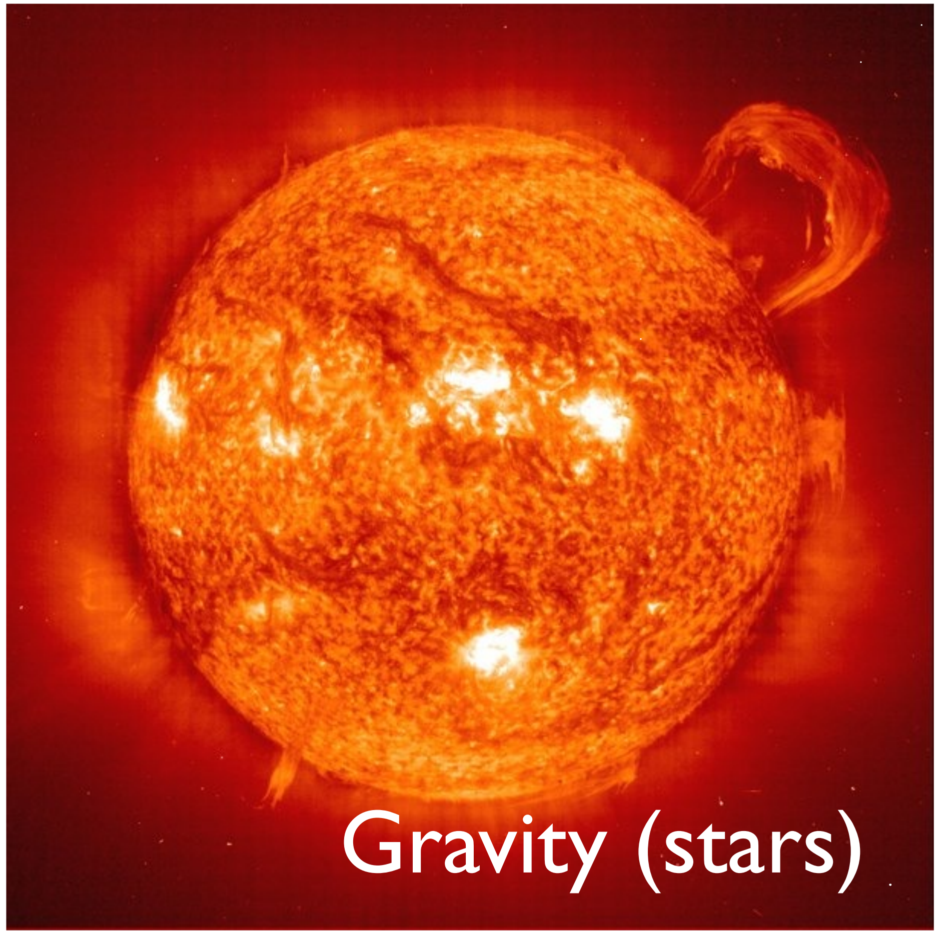


- “Hole” you go down during fusion event is tiny compared to “base of the Coulomb hill” - like trying to get a marble to roll into the (very tiny) crater of a volcano (without aiming!)

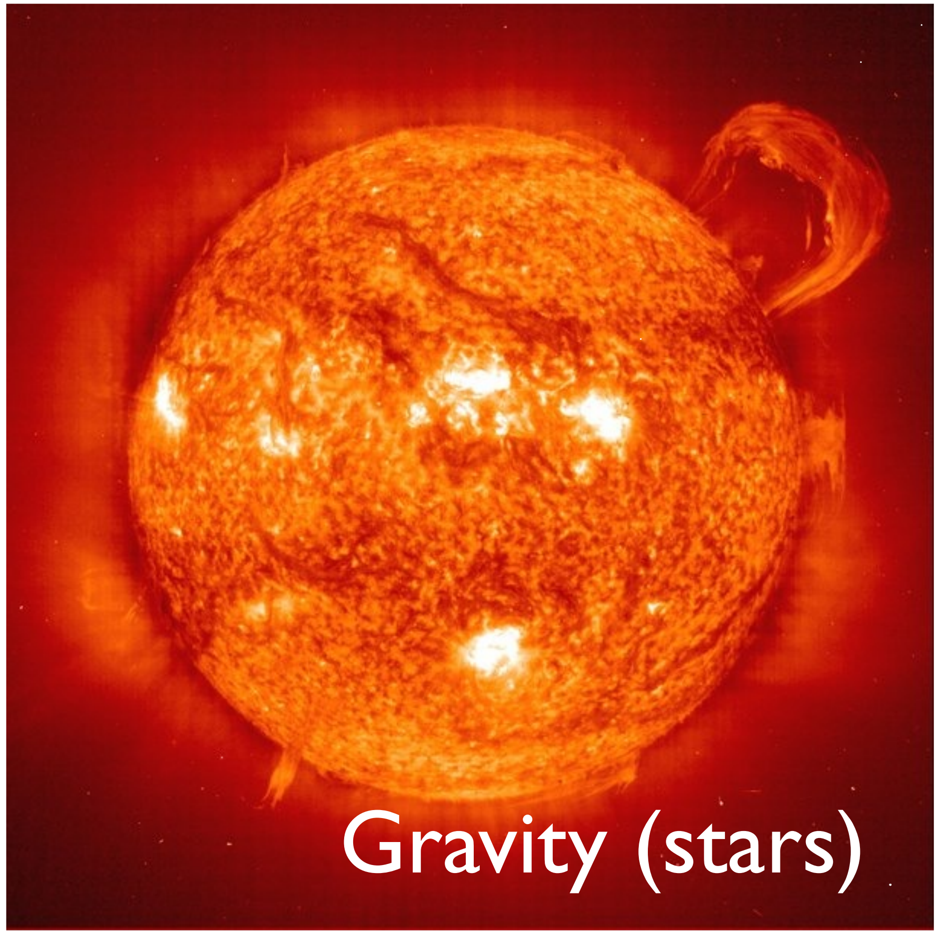
- Most nuclei “roll off the side of the volcano” — this is scattering

➡ Typical nuclei undergoes billions of scattering events before ultimately fusing. Need to “confine” particles to let them interact many, many, many times — means you need a very hot, confined plasma

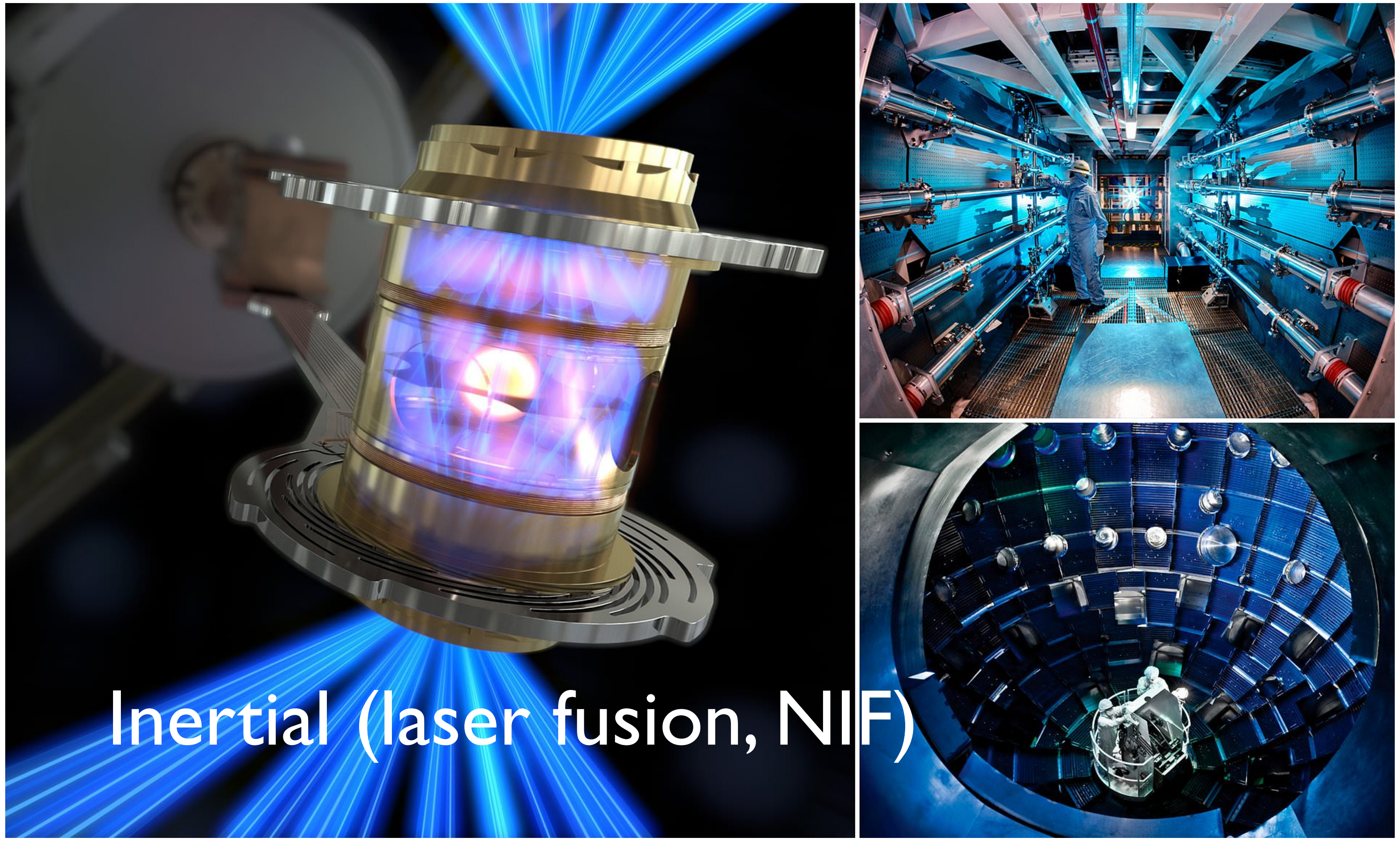
How do you confine a hot plasma?!?


Gravity (stars)

How do you confine a hot plasma?!?

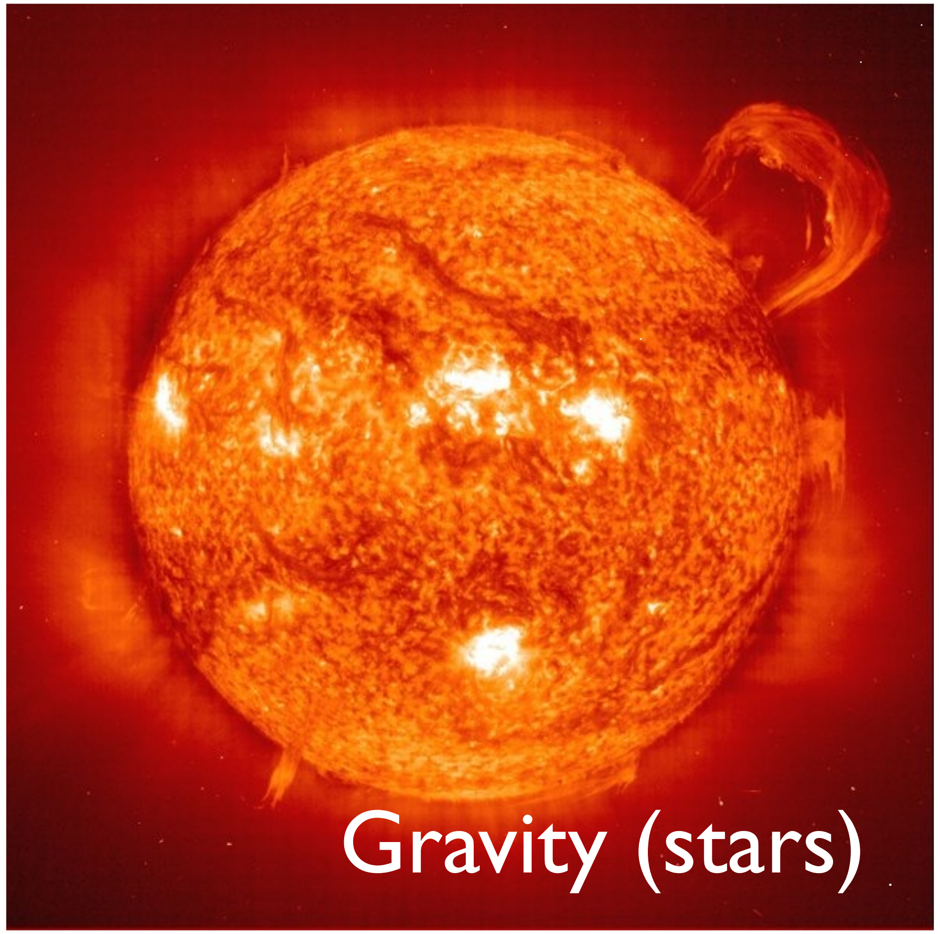


Gravity (stars)

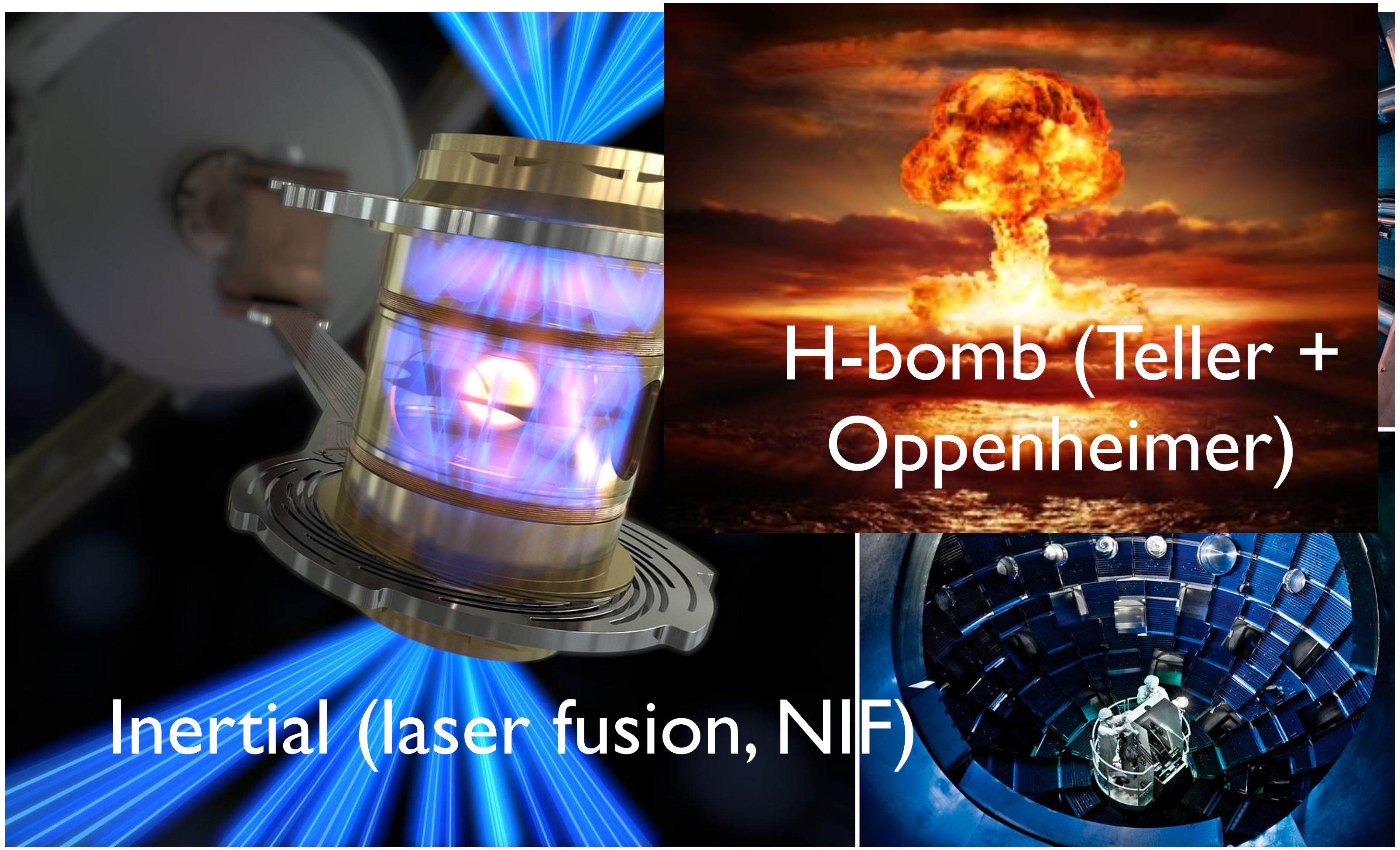


Inertial (laser fusion, NIF)

How do you confine a hot plasma?!?



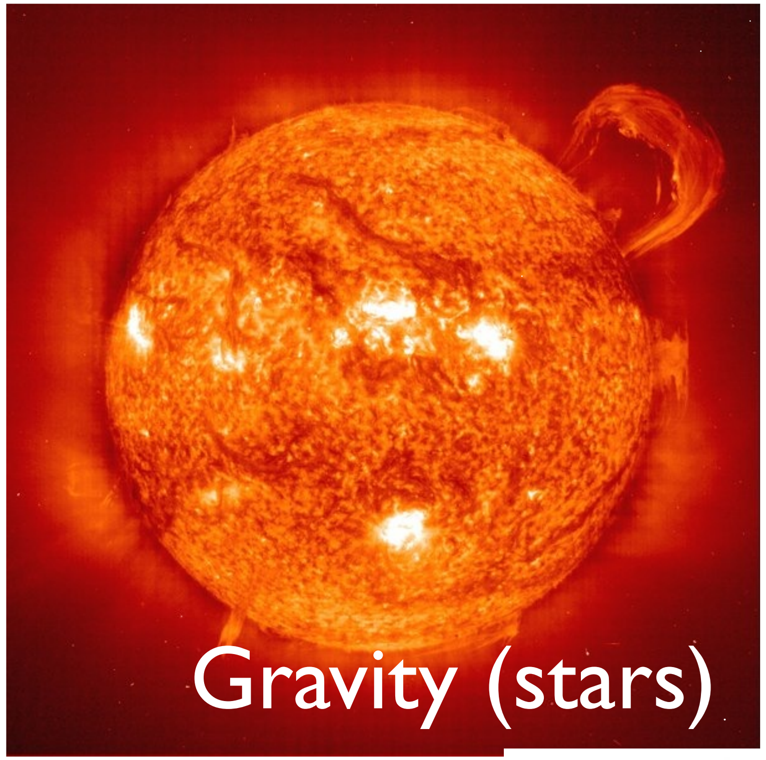
Gravity (stars)



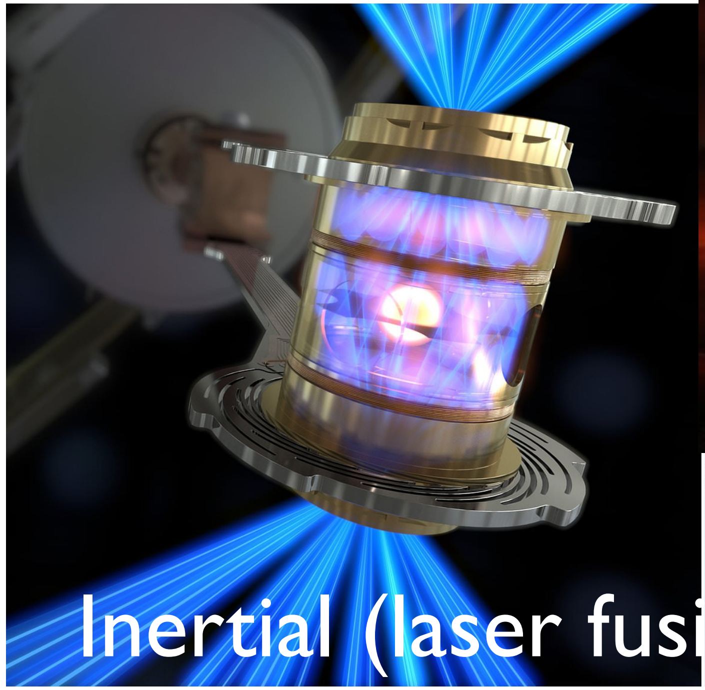
H-bomb (Teller + Oppenheimer)

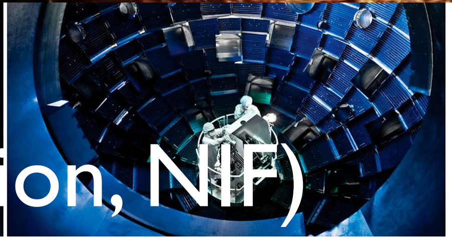
Inertial (laser fusion, NIF)

How do you confine a hot plasma?!?



Gravity (stars)

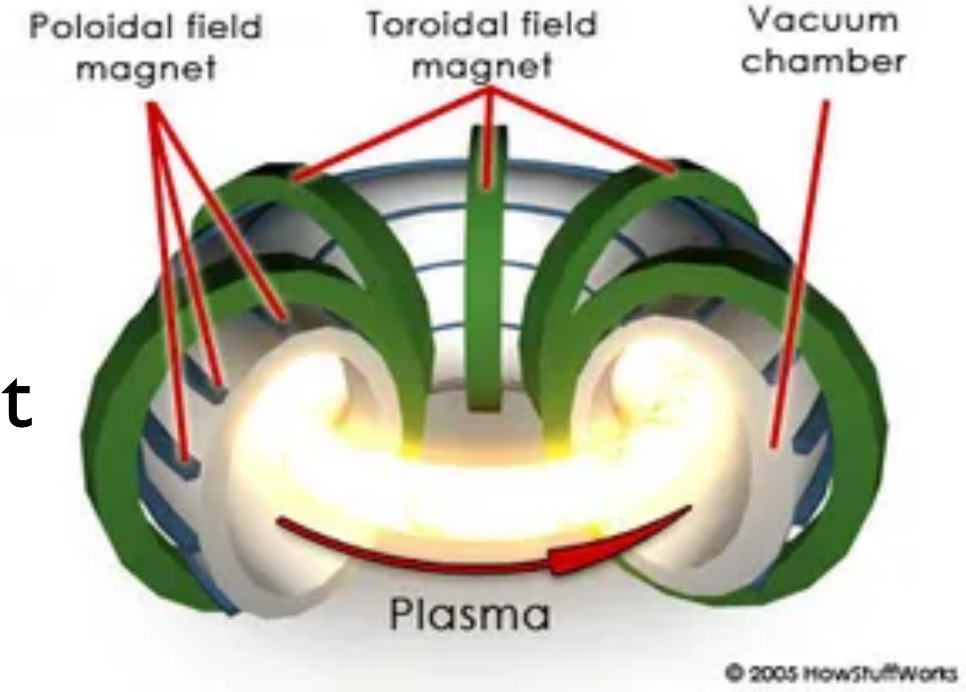




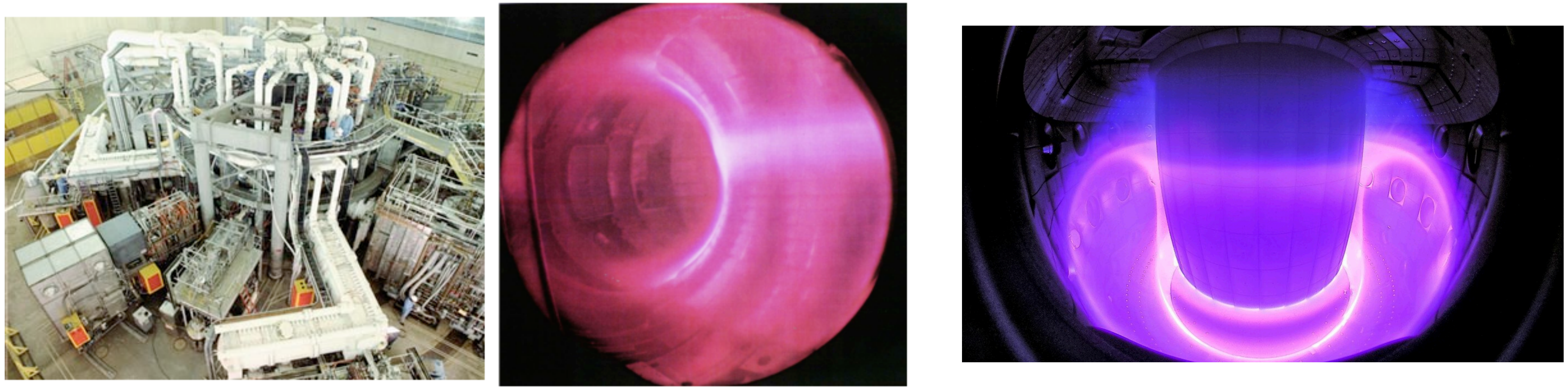
Inertial (laser fusion, NIF)

H-bomb (Teller + Oppenheimer)

Magnetic Confinement



Heating a plasma to 100 Million Degrees



- Initial heating is “Ohmic”, just like heating up the elements in your toaster oven: run current through the plasma (can get you to ~1keV (10 million degrees))
- To get to fusion temperatures (100 million degrees+), use “neutral beam injection” (NBI, directly inject accelerated particles) or “RF” heating (EM waves heat the plasma, not too different from your microwave oven!)
- TFTR, Princeton Plasma Physics Lab (above left) used NBI to reach 500 million degrees: hottest spot in solar system (maybe the galaxy except for near Sag. A*)

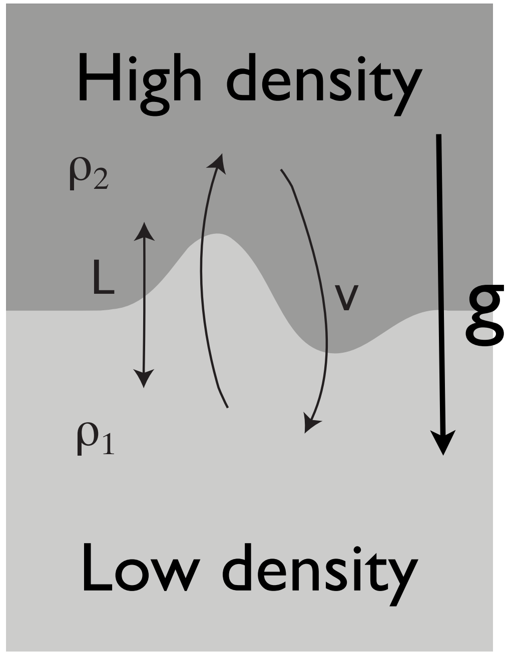
Confinement challenge: Instabilities & turbulence can make our "magnetic bottles" leak

Confined high temperature plasmas are unstable! Instabilities cause convection/mixing — causes hot plasma in the core to "trade places" with cold plasma in the edge

Confinement challenge: Instabilities & turbulence can make our "magnetic bottles" leak

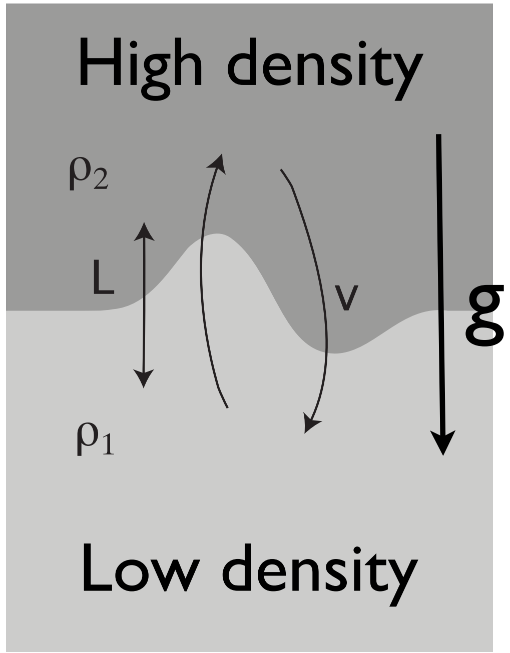
Confined high temperature plasmas are unstable! Instabilities cause convection/mixing — causes hot plasma in the core to "trade places" with cold plasma in the edge

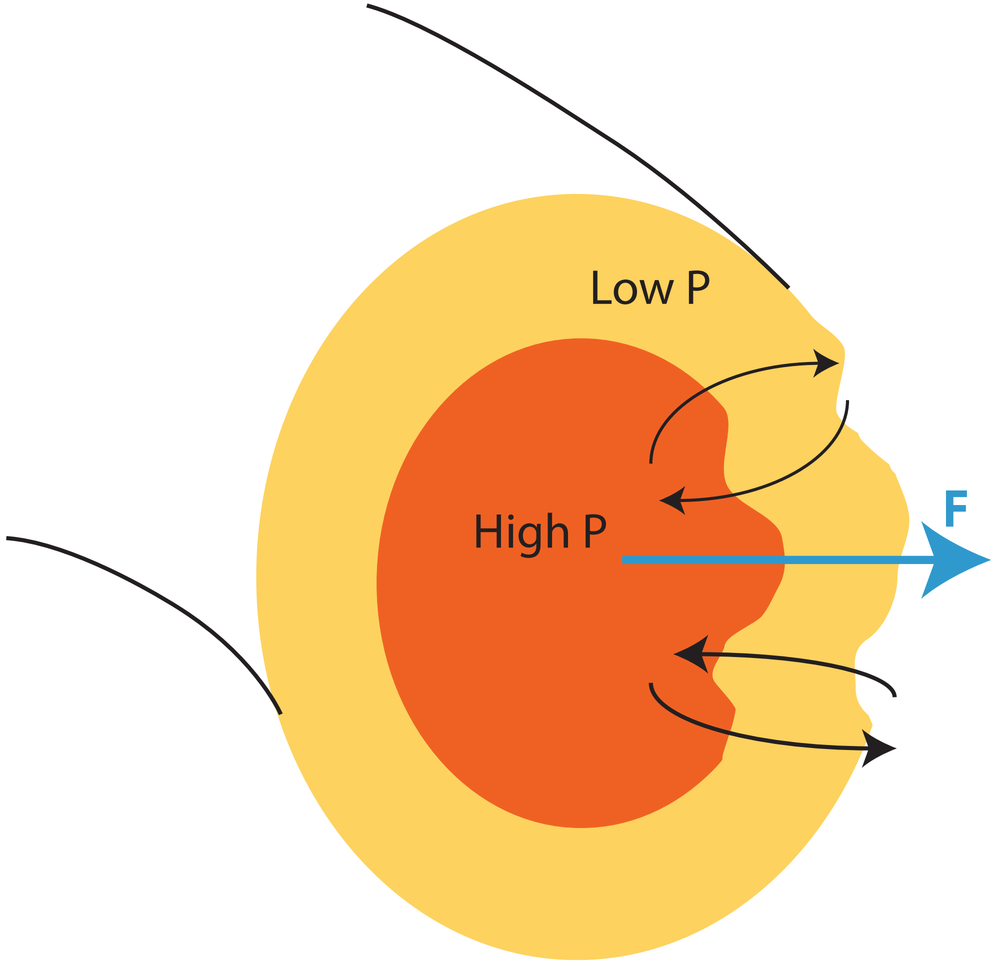
Related instability that you can see in everyday life: "Rayleigh-Taylor" instability. Heavy/dense fluid (e.g. water) sitting on top of less dense fluid (e.g. canola oil) - will spontaneously mix (oil "wants" to be on top)

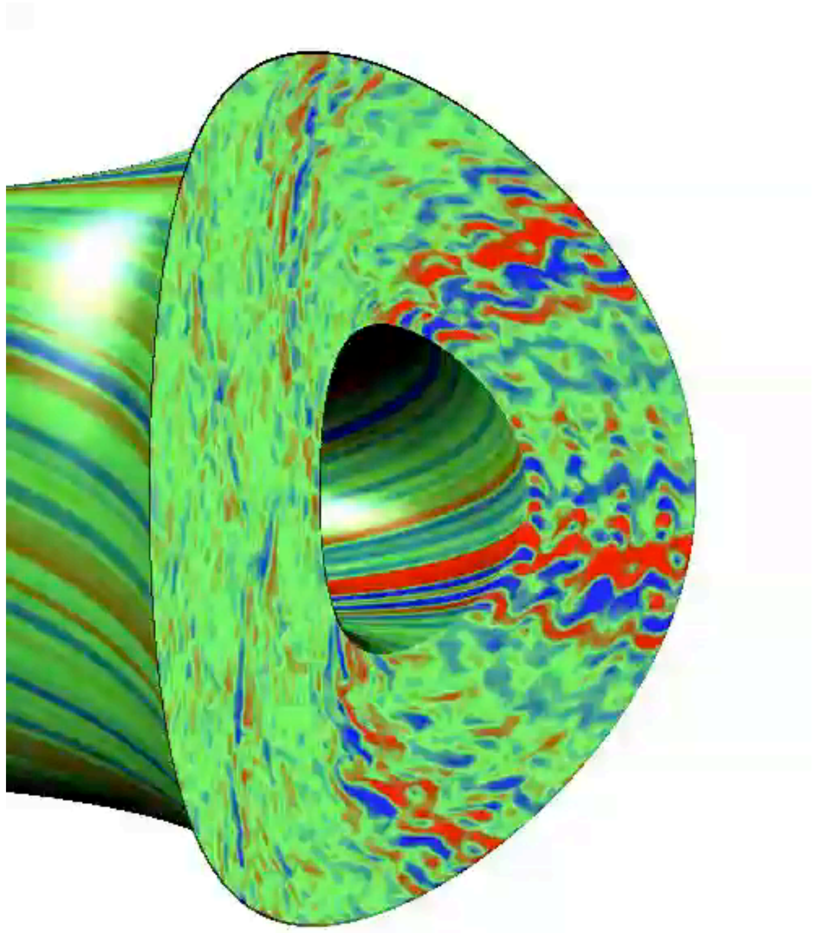


Fusion is hard!: Instabilities & turbulence can make our “magnetic bottles” leak

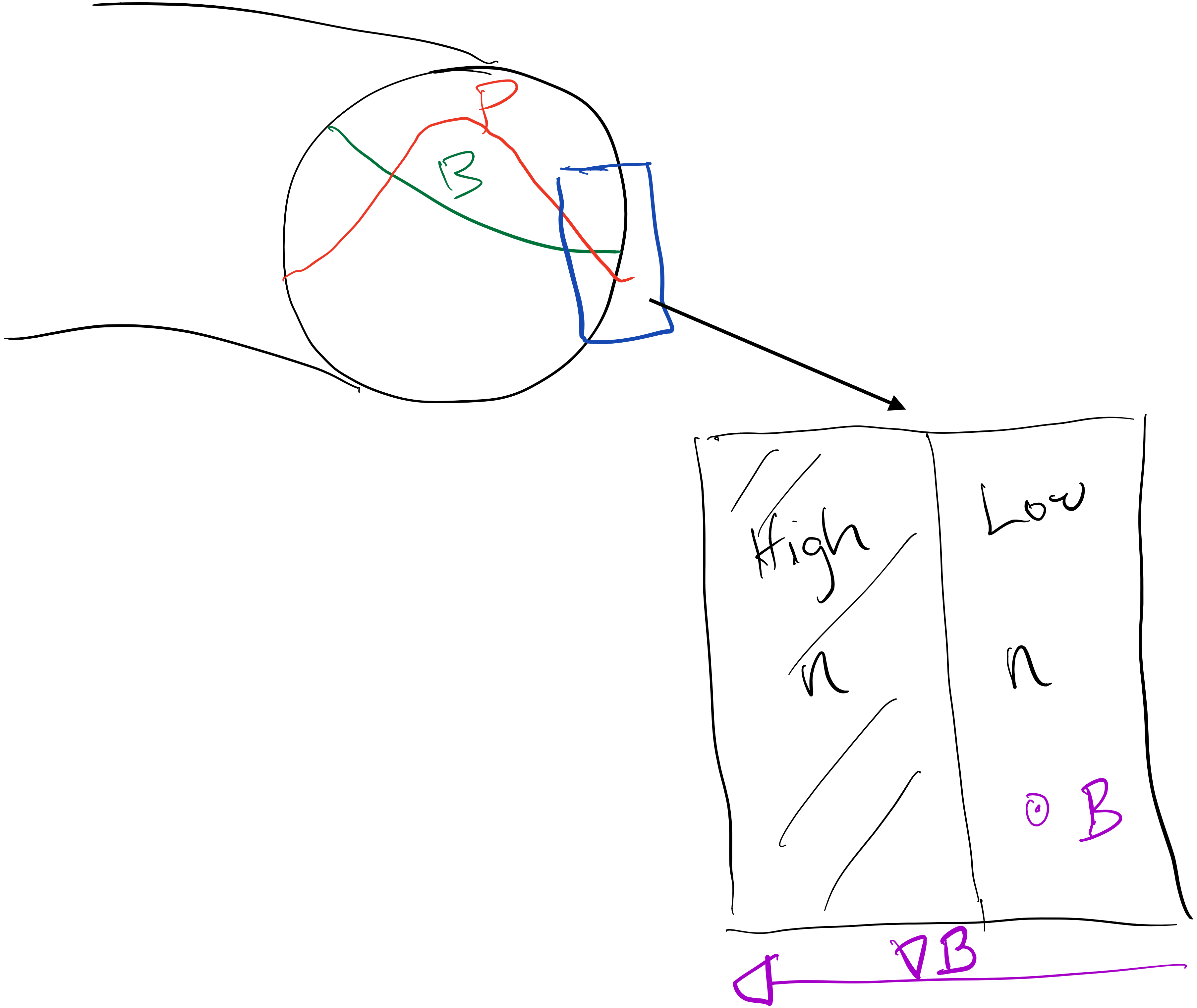
It’s more complicated in a hot, magnetized plasma, but this “interchange instability” causes spontaneous mixing of hot plasma with cold plasma/ outward flow of heat



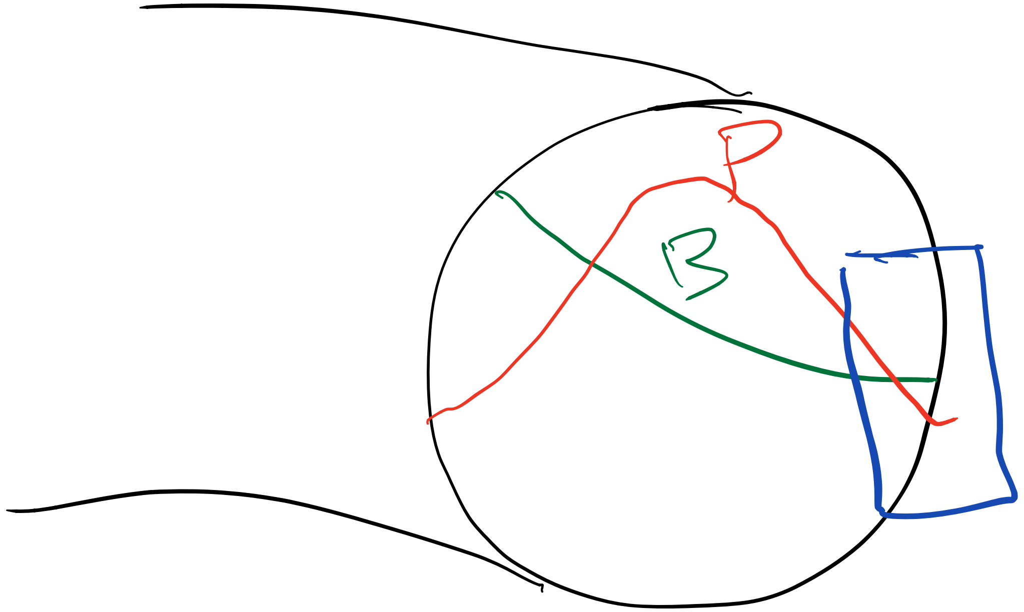




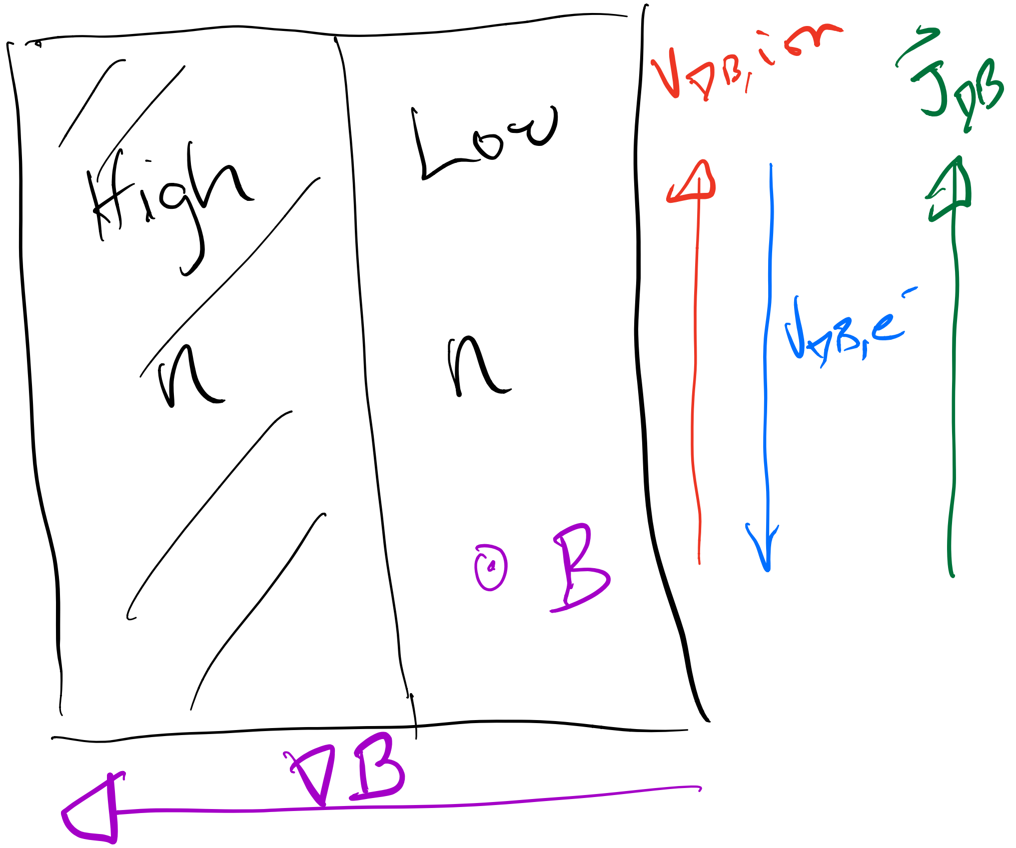
Single particle picture of interchange instability



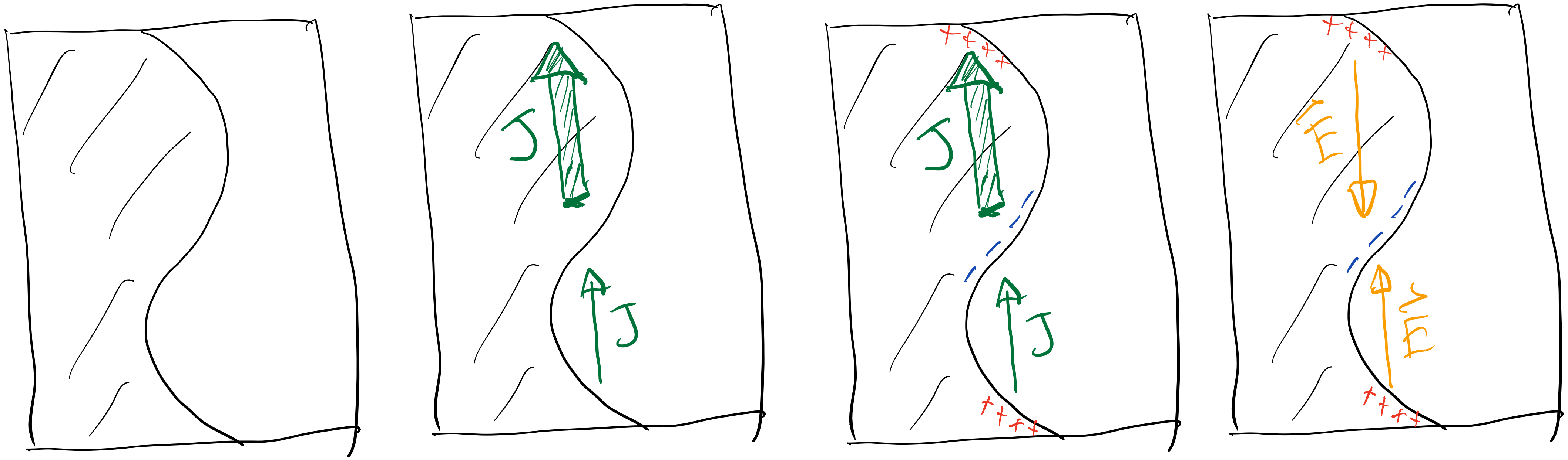
Single particle picture of interchange instability



due to ∇B, get currents due to ∇B drifts

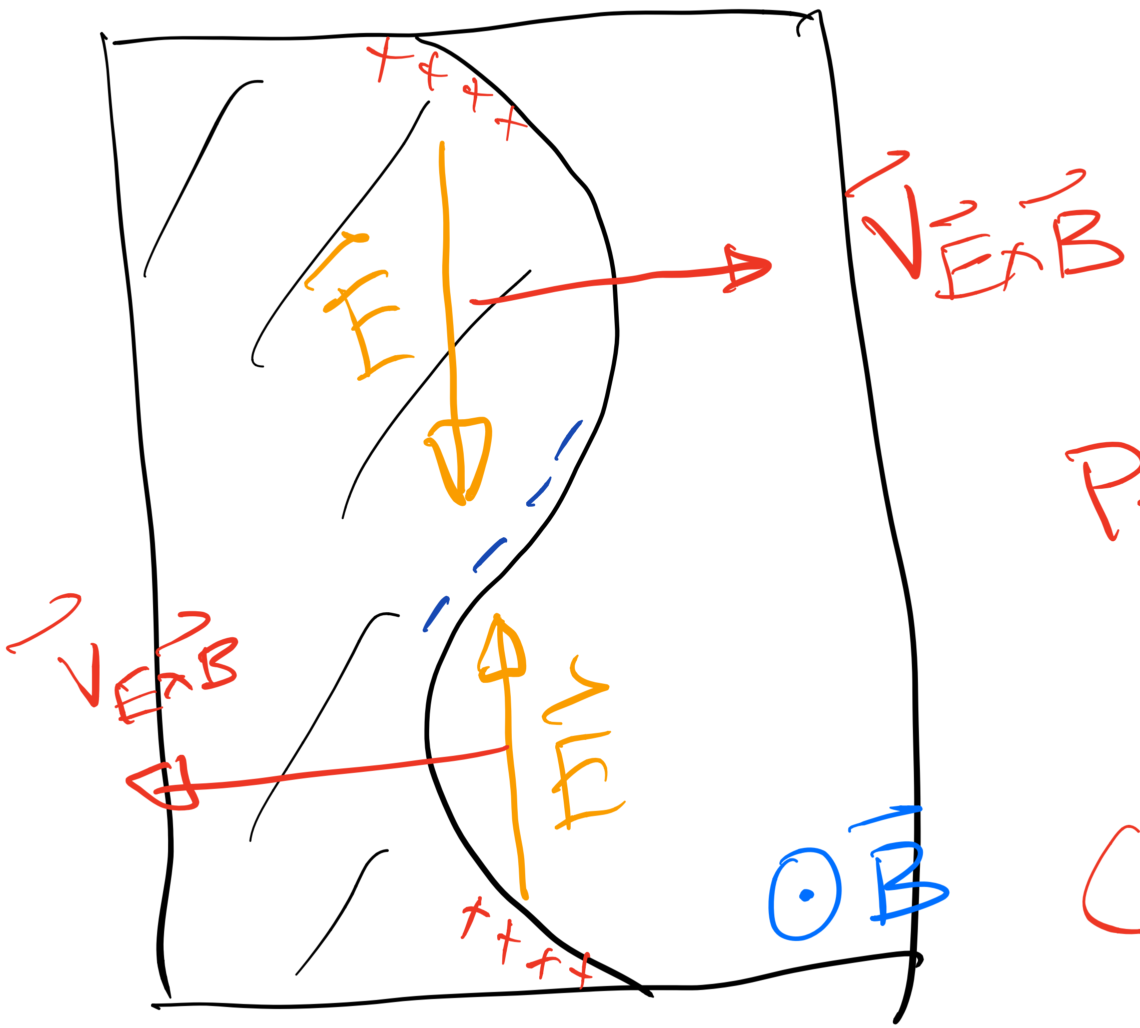


Single particle picture of interchange instability



- Imagine perturbing density as above (can arise spontaneously due to very small thermal fluctuations)
- Causes Grad-B currents to lead to charging of surface of perturbation, leading to E-field

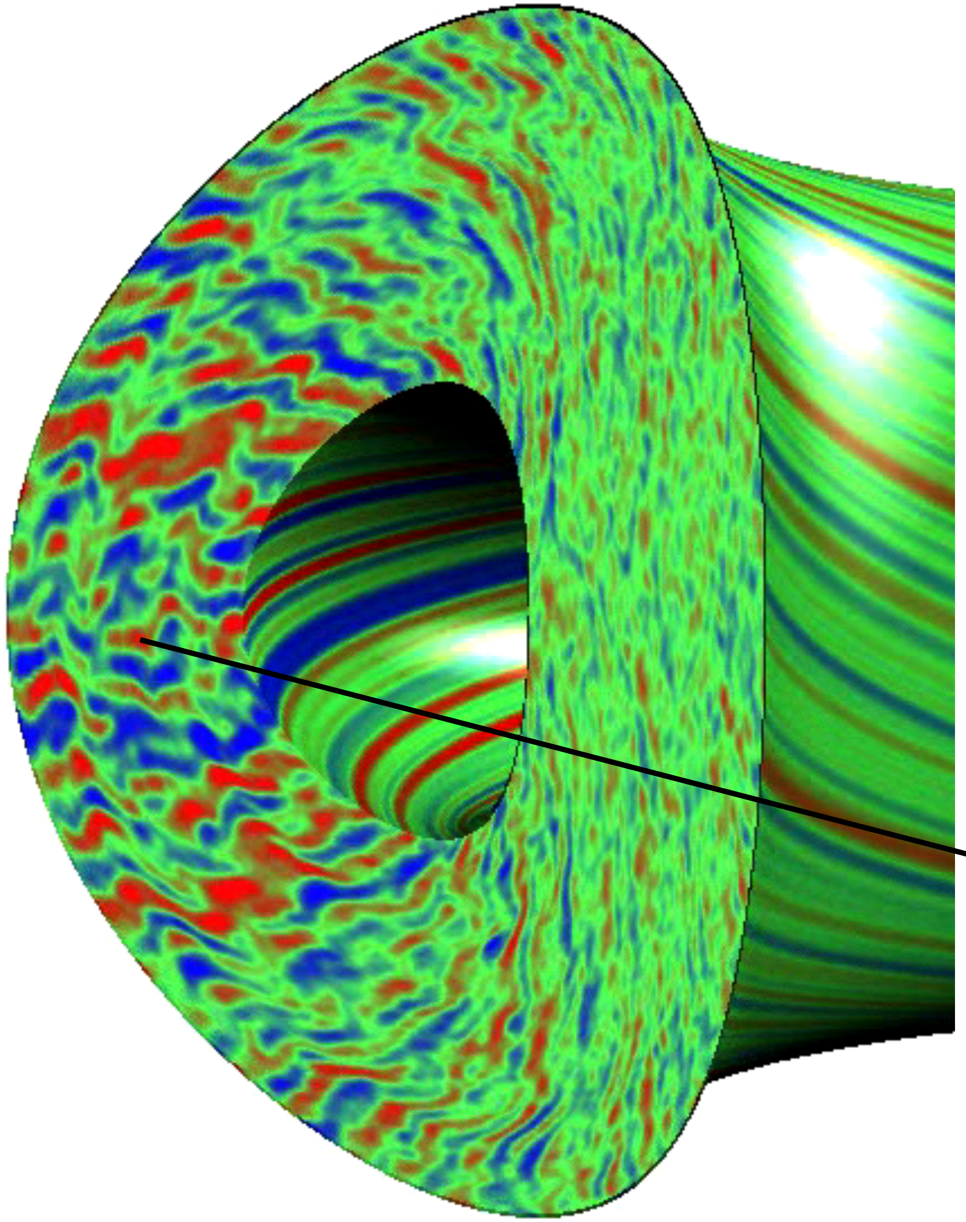
Single particle picture of interchange instability



Perturbation grows!

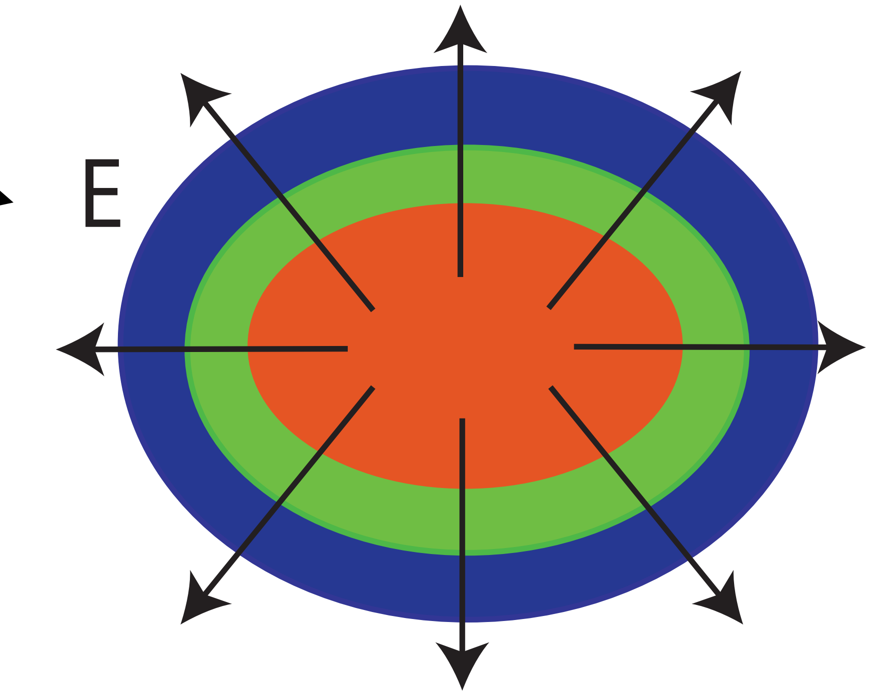
(not on "inboard side")

Turbulent Transport by “Eddies”



Gyrokinetic simulation by Jeff Candy, Ron Waltz (GA)

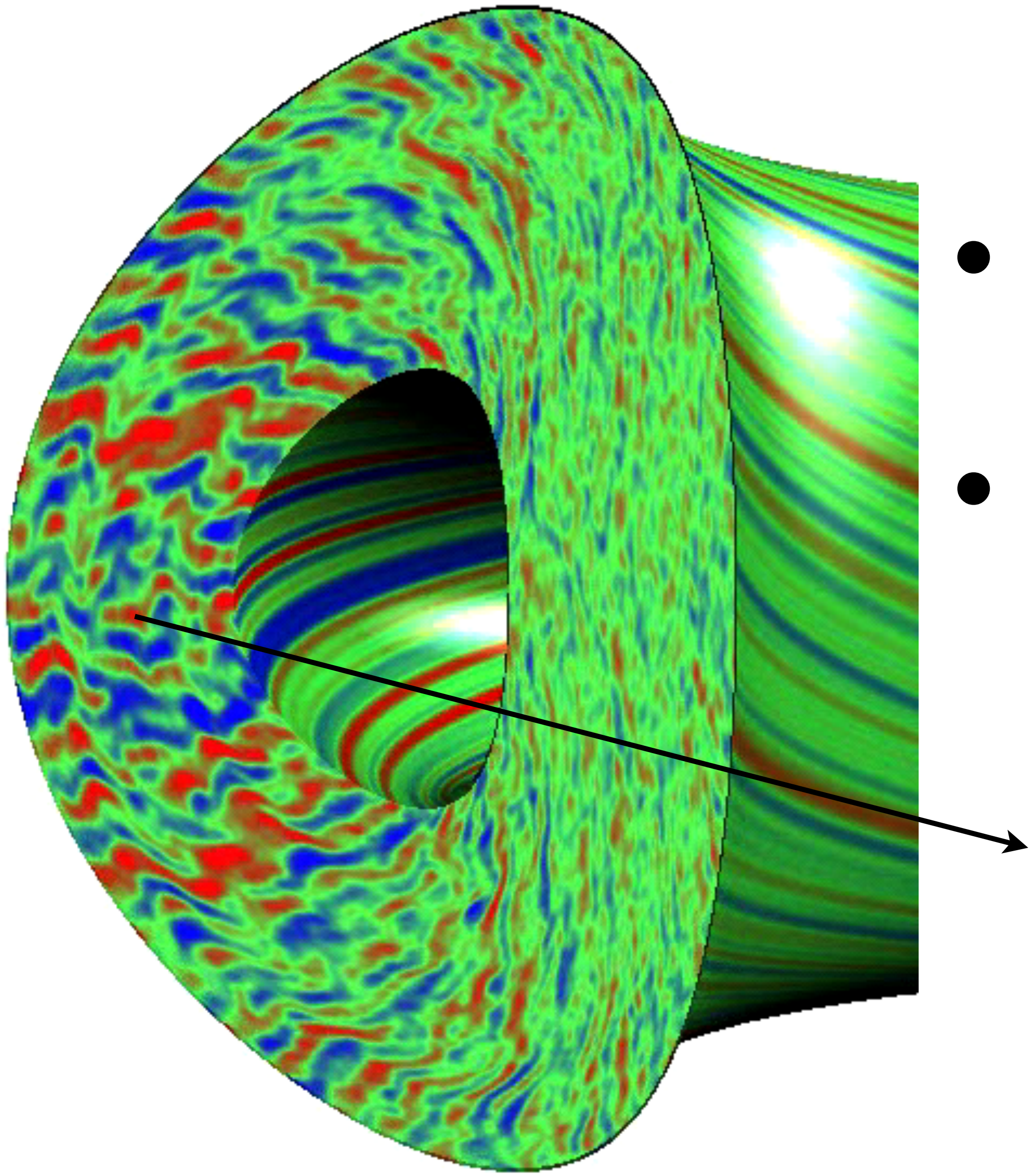
- Movie shows electrostatic potential
- Contours of potential are contours of ExB flow



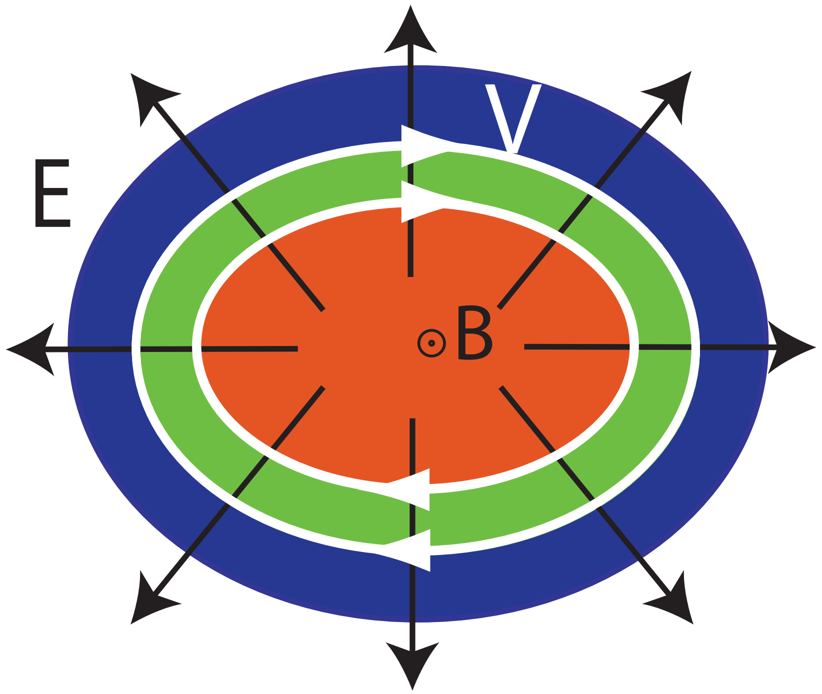
Turbulent Transport by “Eddies”

$$v_{\mathrm{drift}} = \frac{\vec{E} \times \vec{B}}{B^2}$$

- Movie shows electrostatic potential
- Contours of potential are contours of ExB flow

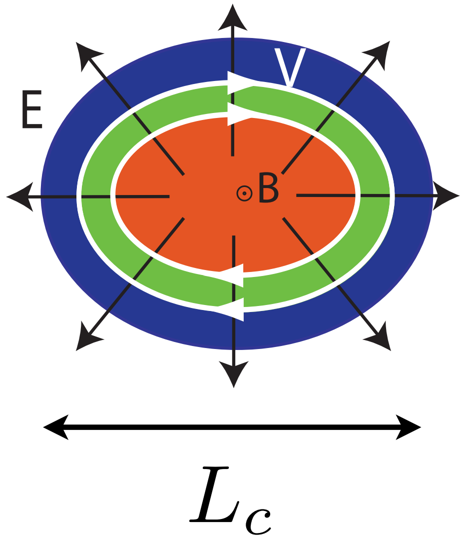


Gyrokinetic simulation by Jeff Candy, Ron Waltz (GA)



Turbulent Transport by "Eddies"

- Turbulent diffusion: random walk by eddy decorrelation



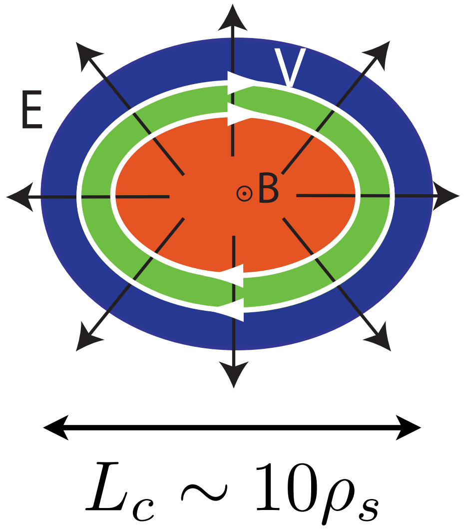
$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

Eddy size

Eddy "turnover" time

Turbulent Transport by "Eddies"

- Turbulent diffusion: random walk by eddy decorrelation



$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

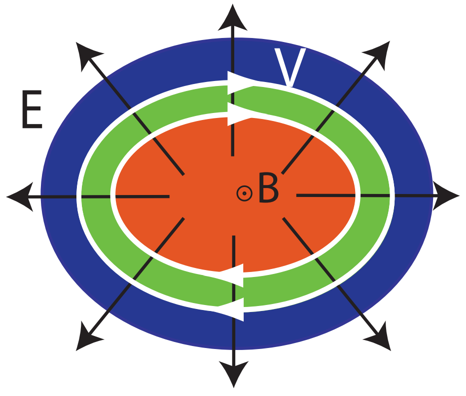
Eddy size

Eddy "turnover" time

$$\tau_c \sim \frac{L_c}{v} \qquad v \sim \frac{E}{B} \sim \frac{\phi}{L_c}\frac{1}{B}$$

Turbulent Transport by “Eddies”

- Turbulent diffusion: random walk by eddy decorrelation



$L_c \sim 10\rho_s$

$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

Eddy size

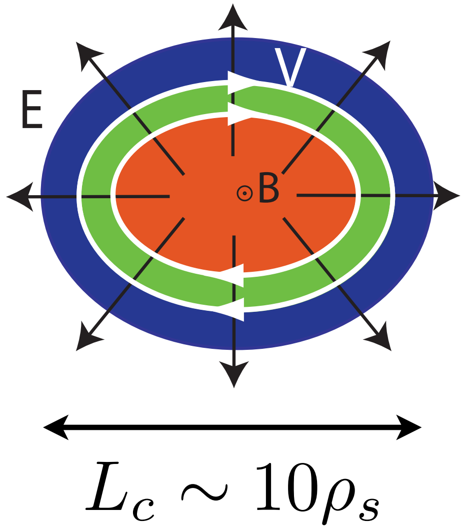
Eddy “turnover” time

$$\tau_c \sim \frac{L_c}{v} \qquad v \sim \frac{E}{B} \sim \frac{\phi}{L_c}\frac{1}{B}$$

$$\boxed{D \sim \frac{\phi}{B} \sim \frac{T}{B}}$$

Bohm diffusion

Turbulent Transport by “Eddies”



$L_c \sim 10\rho_s$

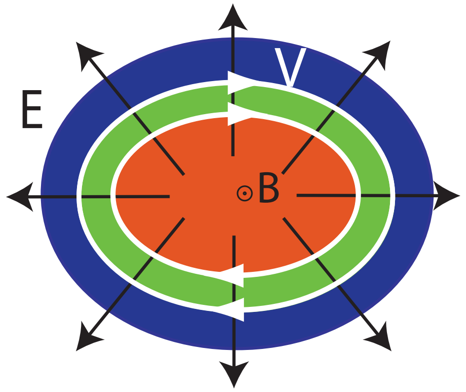
$$\boxed{D \sim \frac{\phi}{B} \sim \frac{T}{B}}$$

Bohm diffusion

Classical diffusion: $D_{\text{class}} \sim \rho^2\nu \sim T^{-1/2} \quad (\nu \sim T^{-3/2})$

Collisional diffusion weaker as plasma gets hotter (hot plasmas are “collisionless”)

Turbulent Transport by "Eddies"



$L_c \sim 10\rho_s$

$$\boxed{D \sim \frac{\phi}{B} \sim \frac{T}{B}}$$

Bohm diffusion

Classical diffusion: $D_{\text{class}} \sim \rho^2\nu \sim T^{-1/2} \quad (\nu \sim T^{-3/2})$

- Turbulent diffusion coefficient orders of magnitude larger than classical (not shown here)
- More importantly: scaling with T is opposite. As T goes up (more heating power is added) confinement degrades. Consistent with so-called "low-confinement" mode or L-mode in experiments.

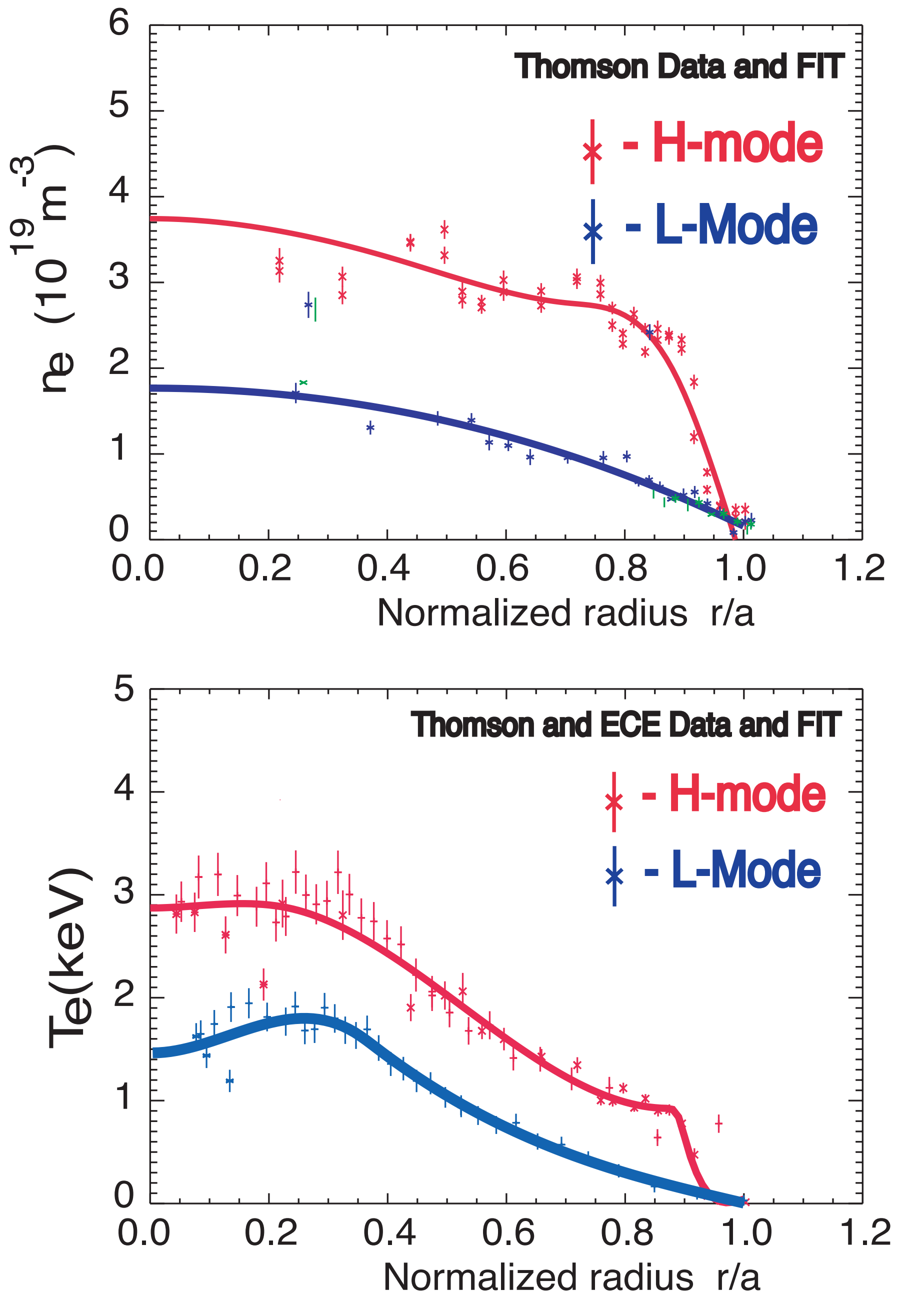
Fusion is hard!: Instabilities & turbulence can make our "magnetic bottles" leak

It's more complicated in a hot, magnetized plasma, but this "interchange instability" causes spontaneous mixing of hot plasma with cold plasma/ outward flow of heat

This breakdown of our "magnetic insulation" means we have to turn the "burner to high" to reach and maintain the high temp needed for fusion reactions to occur

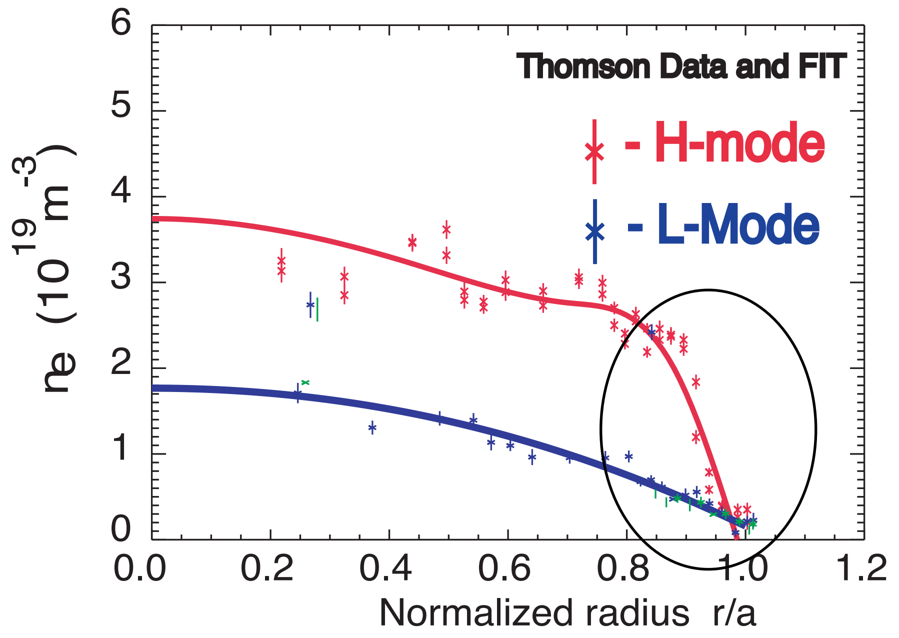
E.g. in experiments on TFTR: succeeded in getting plasmas to fusion temperature (500 million degrees!) with 40MW of heating — but only produced 10MW of fusion power (like burning wet wood)

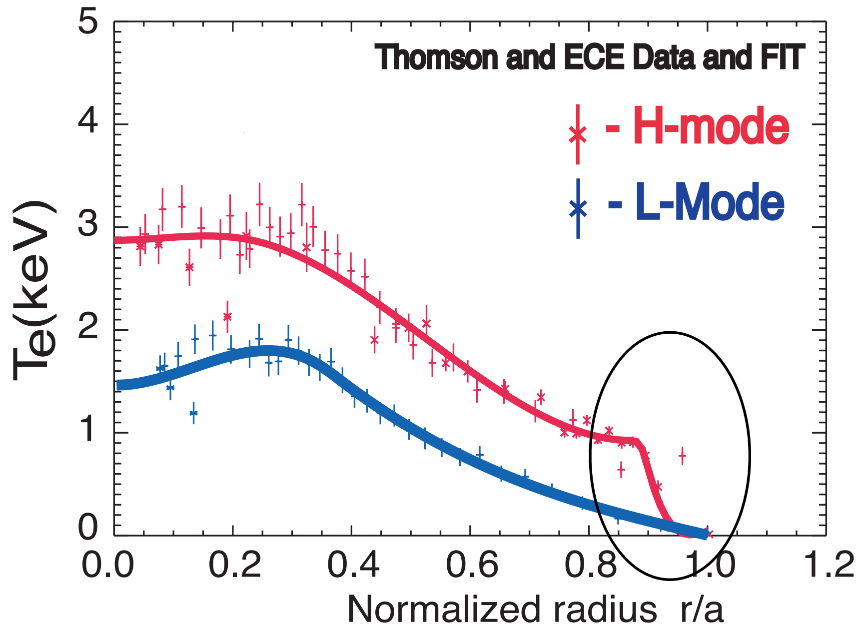
Improved confinement (“H-mode”) due to suppression of transport by sheared flow



- In tokamaks, as heating power increases, can see spontaneous confinement improvement - “H-mode”

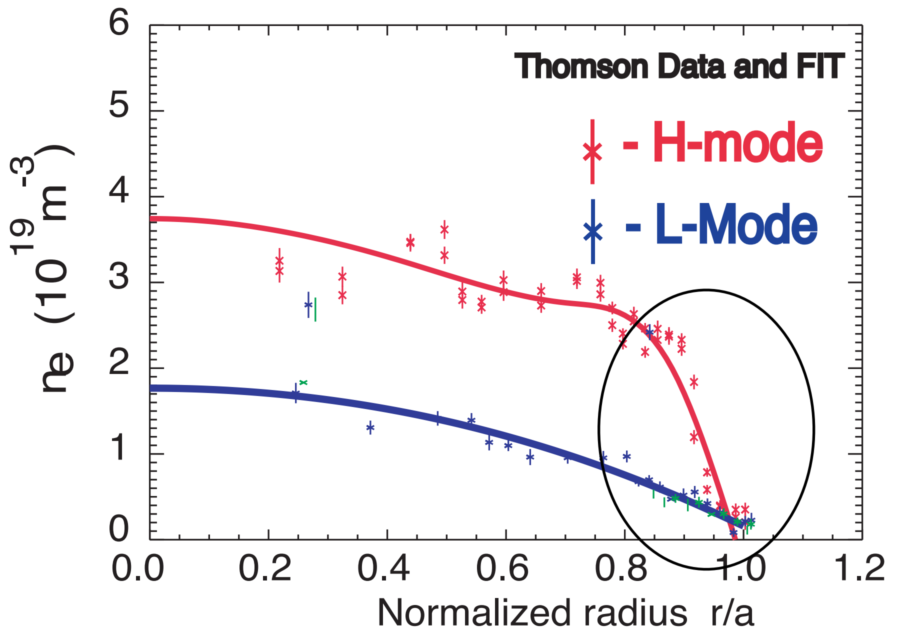
Improved confinement (“H-mode”) due to suppression of transport by sheared flow

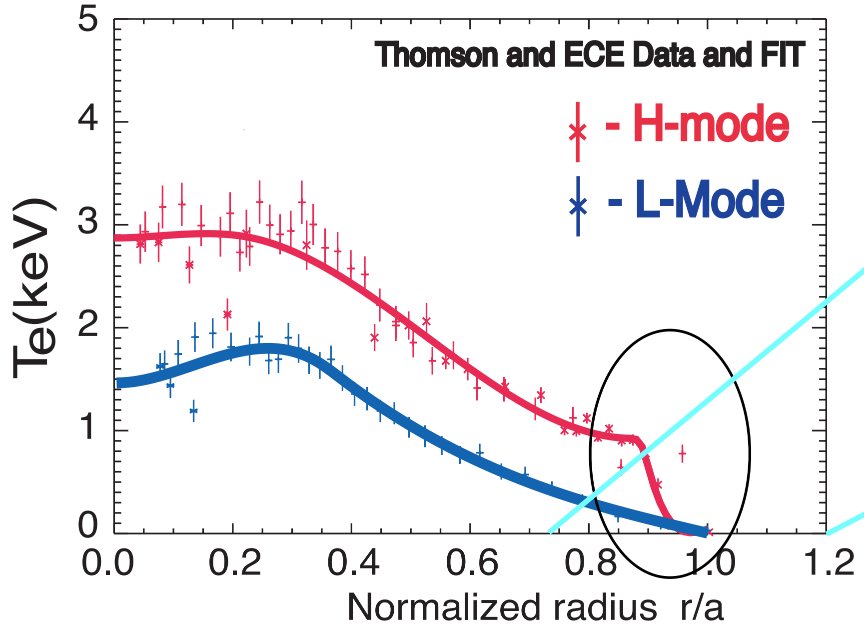


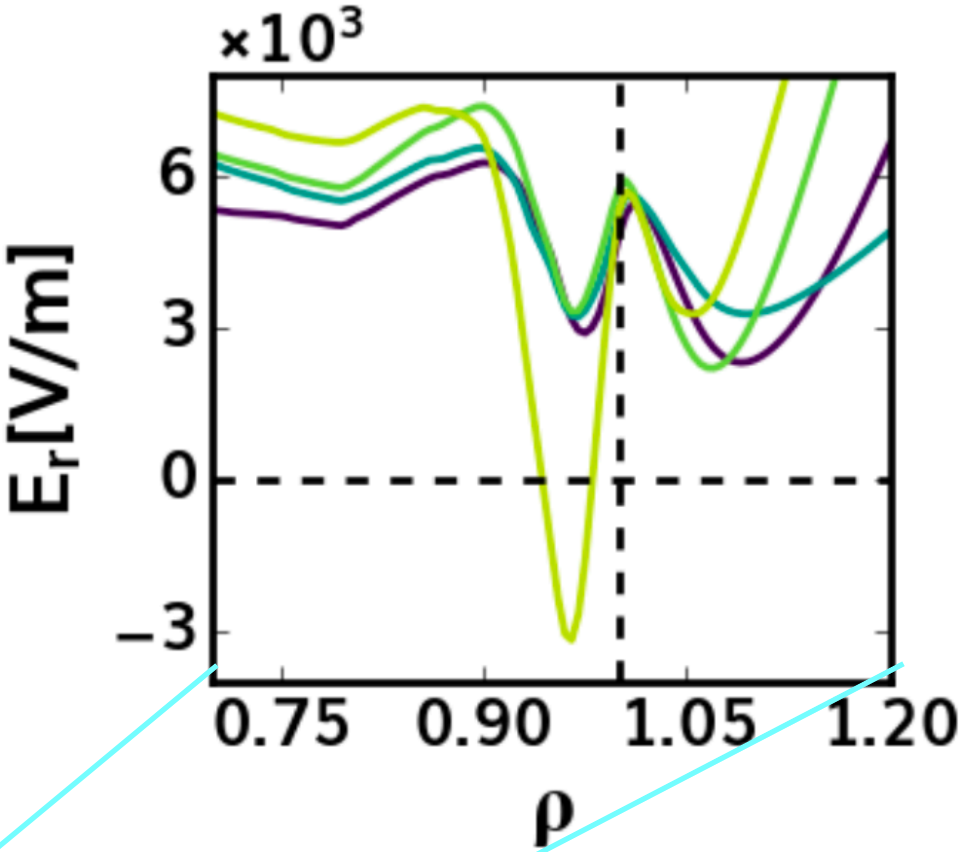


- In tokamaks, as heating power increases, can see spontaneous confinement improvement - “H-mode”
- See formation of “edge transport barrier” (or “pedestal”), core T, n increase as a result (get factor of ~2 improvement in “confinement time”)

Improved confinement (“H-mode”) due to suppression of transport by sheared flow







Kyle Callahan

Key Pedestal feature: flow layer (“Er well”). with strong flow shear

H-mode has been fundamental to progress in fusion, but still poorly understood

- JET's record 16MW D-T shot in the 90s and more recent fusion energy record result was in H-mode: came close to break-even, $Q=P_{fus}/P_{heat}\sim0.66$

H-mode has been fundamental to progress in fusion, but still poorly understood

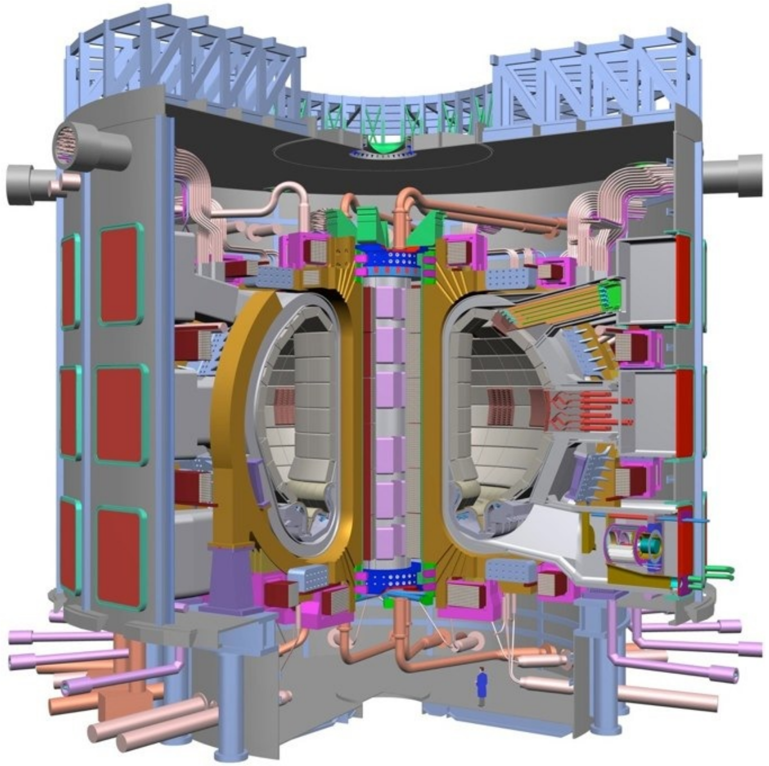
- JET's record 16MW D-T shot in the 90s and more recent fusion energy record result was in H-mode: came close to break-even, $Q=P_{fus}/P_{heat}\sim0.66$
- Important advances in understanding changes in turbulence and turbulent transport in H-mode (more on this later), but a lot of work remains
  - e.g. don't know mechanism for H-mode trigger, what determines height of "pedestal", what sets residual transport in H-mode....

H-mode has been fundamental to progress in fusion, but still poorly understood

- JET's record 16MW D-T shot in the 90s and more recent fusion energy record result was in H-mode: came close to break-even, $Q=P_{fus}/P_{heat}\sim0.66$
- Important advances in understanding changes in turbulence and turbulent transport in H-mode (more on this later), but a lot of work remains
  - e.g. don't know mechanism for H-mode trigger, what determines height of "pedestal", what sets residual transport in H-mode....

➡ To move beyond JET and design the next step experiment, must rely on projections using empirical transport scaling laws

Into the era of burning plasmas



- ITER: Huge device, R~6.2m, a~2m
- Superconducting coils, 400s pulse
- 500MW fusion power, Q=5-10
- Under construction (Cadarache, France)

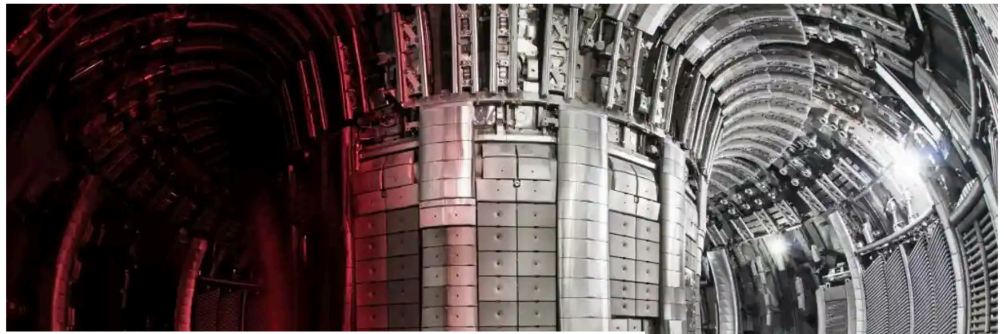
- Fusion plasma in which alpha particle heating will dominate external heating (burning plasma)
- Not a demonstration reactor, but a physics experiment to understand and control burning plasmas

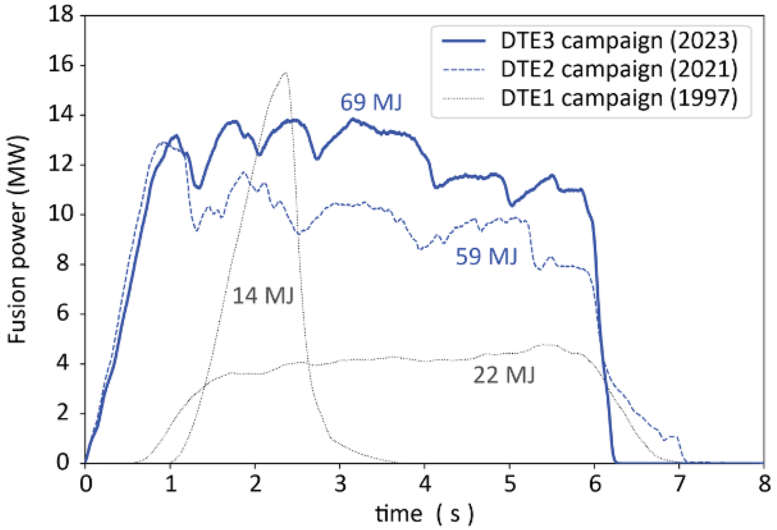
Steady progress has led to recent breakthroughs: sustained fusion power on JET, ignition on NIF

Nuclear fusion heat record a ‘huge step’ in quest for new energy source

2022/2023

Oxfordshire scientists’ feat raises hopes of using reactions that power sun for low-carbon energy





egajoules of heat, beating the 1997

has moved a step closer to
unt of energy released in a

The New York Times

A Laser Fusion Breakthrough Gets a Bigger Burst of Energy

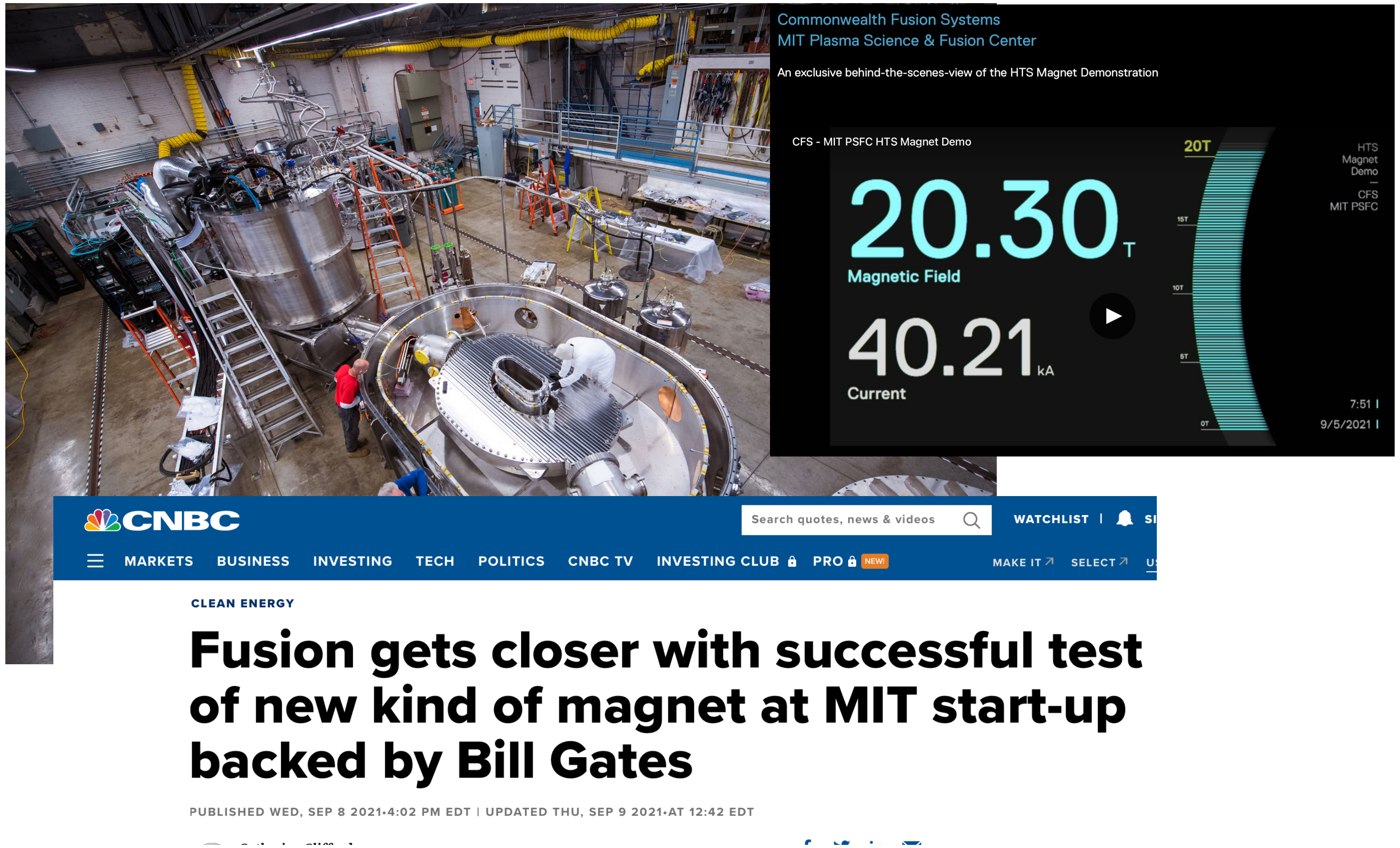
2022/2023

By Kenneth Chang

Sept. 25, 2023

Scientific understanding of high temperature plasmas (importantly controlling instabilities), led to record fusion energy production in JET, Ignition (burning plasma, more energy out than laser than laser energy in) in the National Ignition Facility

Recent technological breakthroughs point the way to economical fusion power



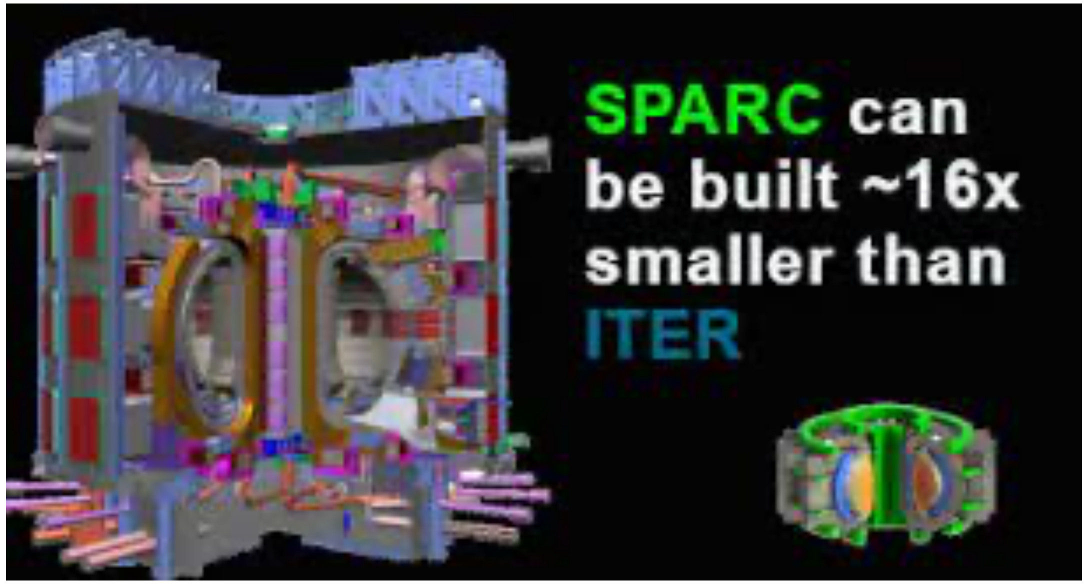
Commonwealth Fusion Systems
MIT Plasma Science & Fusion Center

An exclusive behind-the-scenes-view of the HTS Magnet Demonstration

CLEAN ENERGY

Fusion gets closer with successful test of new kind of magnet at MIT start-up backed by Bill Gates

PUBLISHED WED, SEP 8 2021·4:02 PM EDT | UPDATED THU, SEP 9 2021·AT 12:42 EDT



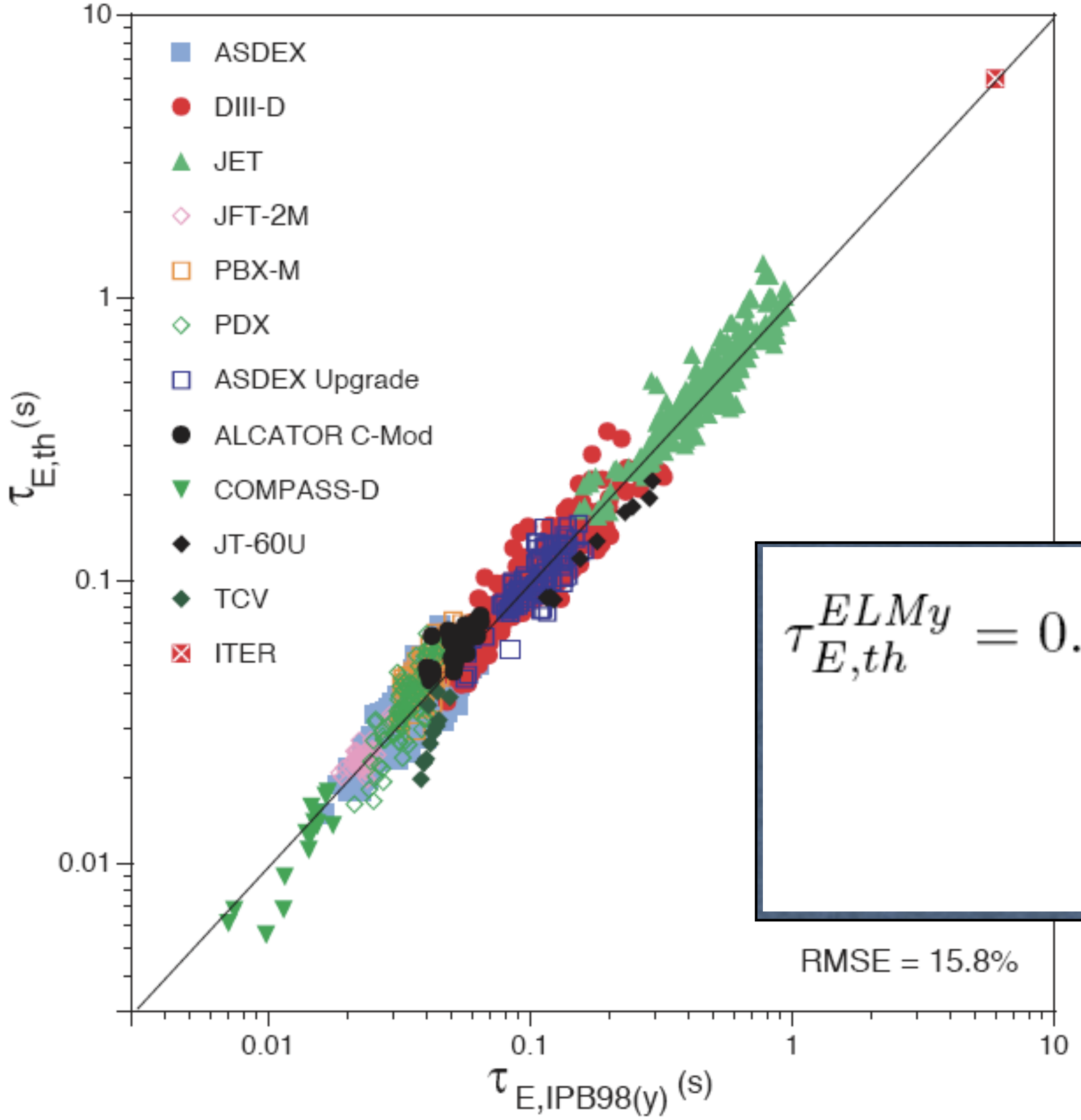
~$50B

~$1B

High-Temp Superconducting magnets enable much higher field, making it possible to build a more compact, economical fusion device

Transport in ITER

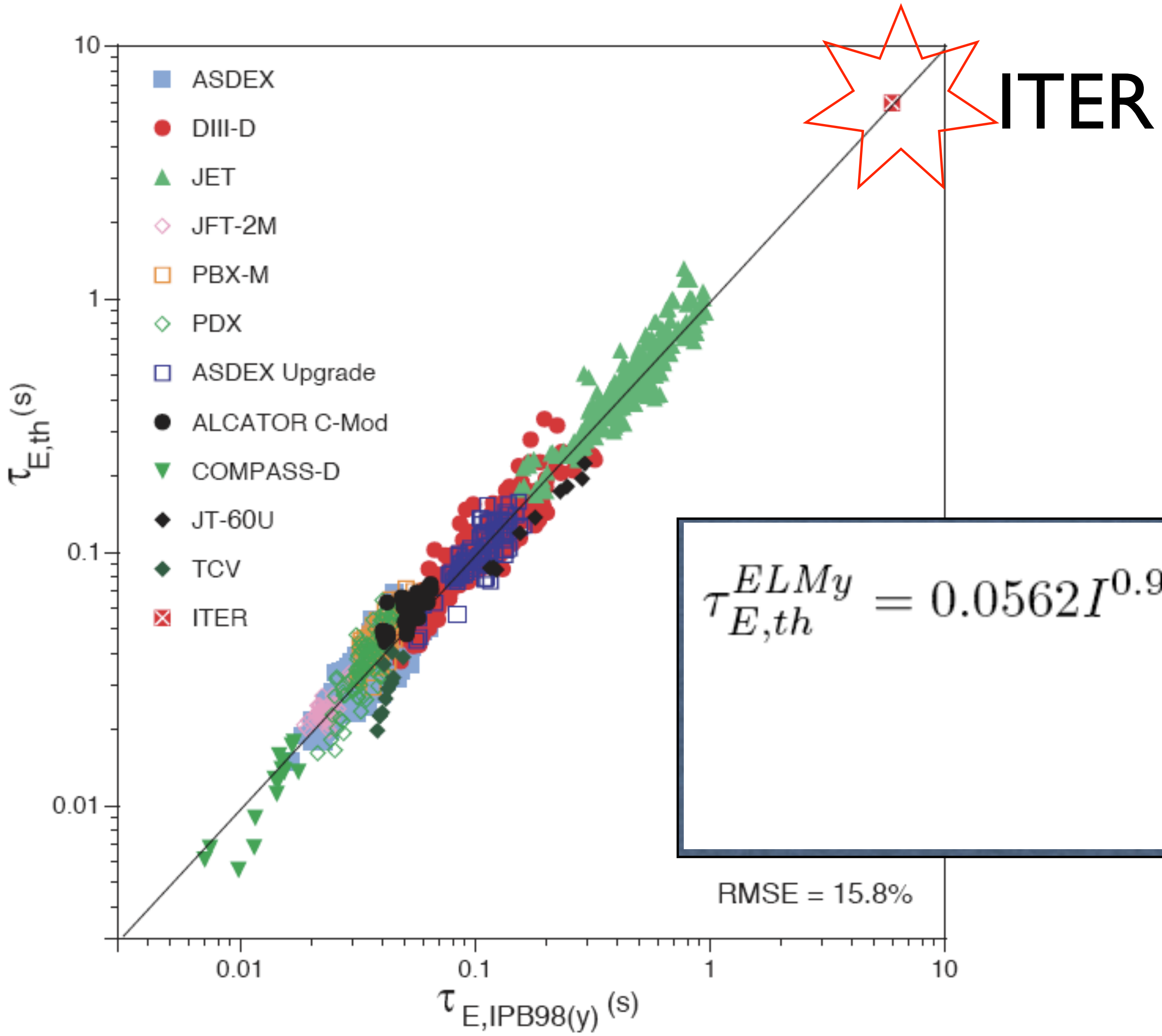
- ITER baseline operation uses H-mode for improved confinement, transport predictions are largely based on empirical scaling laws:



$$\tau_{E,th}^{ELMy} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} \times M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} \quad (20)$$

Transport in ITER

- ITER baseline operation uses H-mode for improved confinement, transport predictions are largely based on empirical scaling laws:



$$\tau_{E,th}^{ELMy} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} \times M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78} \quad (20)$$

Transport in ITER

- ITER baseline operation uses H-mode for improved confinement, transport predictions are largely based on empirical scaling
  - To get beyond JET-level performance, ITER had to be made very large
  - Large extrapolation required from present experiments: can we trust the scaling prediction?

Transport in ITER

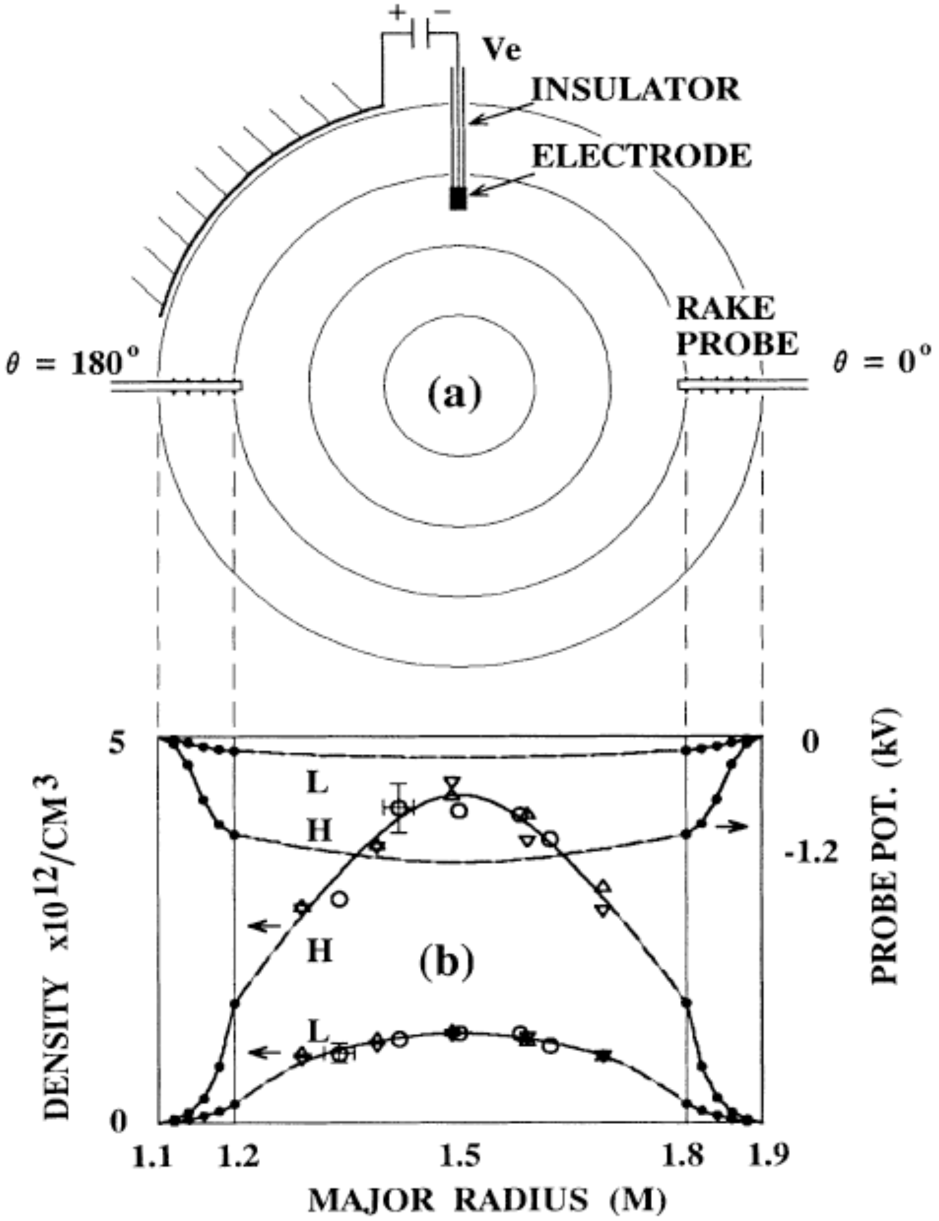
- ITER baseline operation uses H-mode for improved confinement, transport predictions are largely based on empirical scaling
    - To get beyond JET-level performance, ITER had to be made very large
    - Large extrapolation required from present experiments: can we trust the scaling prediction?
- To ensure success in ITER, we need transport prediction capabilities based on first-principles understanding
- Need to accomplish this now, using existing facilities

Transport in ITER

- ITER baseline operation uses H-mode for improved confinement, transport predictions are largely based on empirical scaling
  - To get beyond JET-level performance, ITER had to be made very large
  - Large extrapolation required from present experiments: can we trust the scaling prediction?
- To ensure success in ITER, we need transport prediction capabilities based on first-principles understanding
- Need to accomplish this now, using existing facilities

➡ Motivation for detailed studies of basic physics of turbulence and transport in magnetized plasmas

UCLA tokamak biasing experiments linked H-mode confinement transition to edge flow

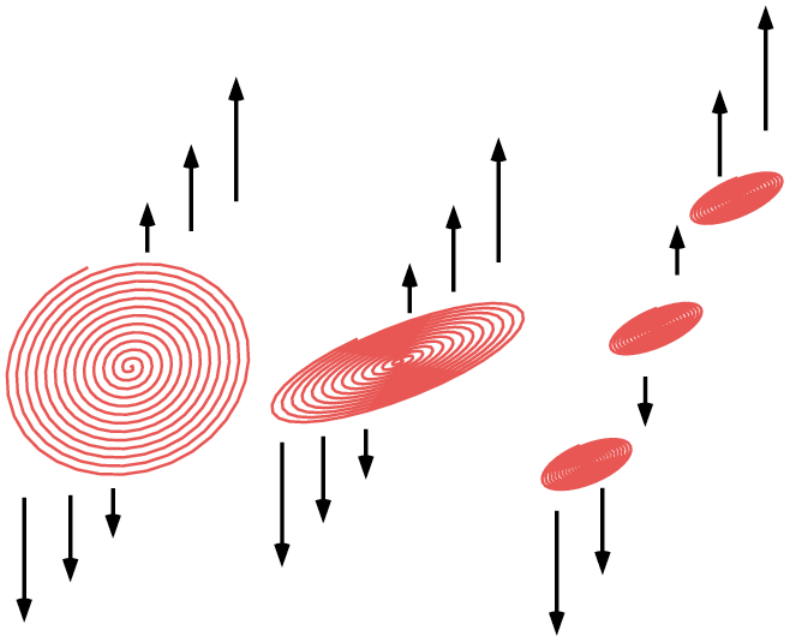


- Research by UCLA tokamak group (Bob Taylor) in the late 80's
- Triggered H-mode not with increased power, but by directly driving edge flow
- Established that edge flow is cause, not effect, of H-mode transition

Taylor, et al., Phys. Rev. Lett. 63, 2365 (1989)

Progress in explaining H-mode: shear suppression of turbulent transport

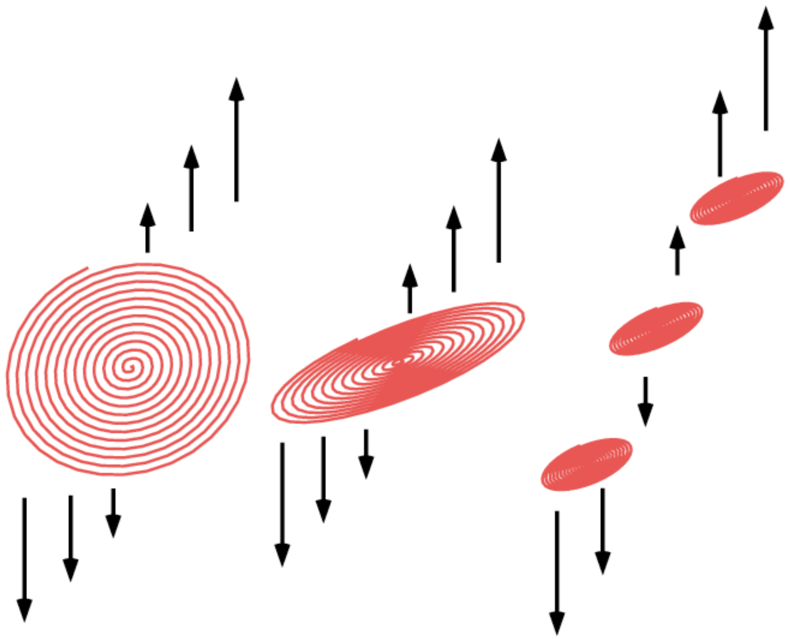
- Transport barrier due to presence of significant shear in edge flow
- Heuristic argument: Sheared flow "breaks up" turbulent eddies, smaller eddies means smaller transport [Biglari, Diamond, Terry]



Review: P. W. Terry, Rev. Mod. Phys. 72, 109 (2000)

Progress in explaining H-mode: shear suppression of turbulent transport

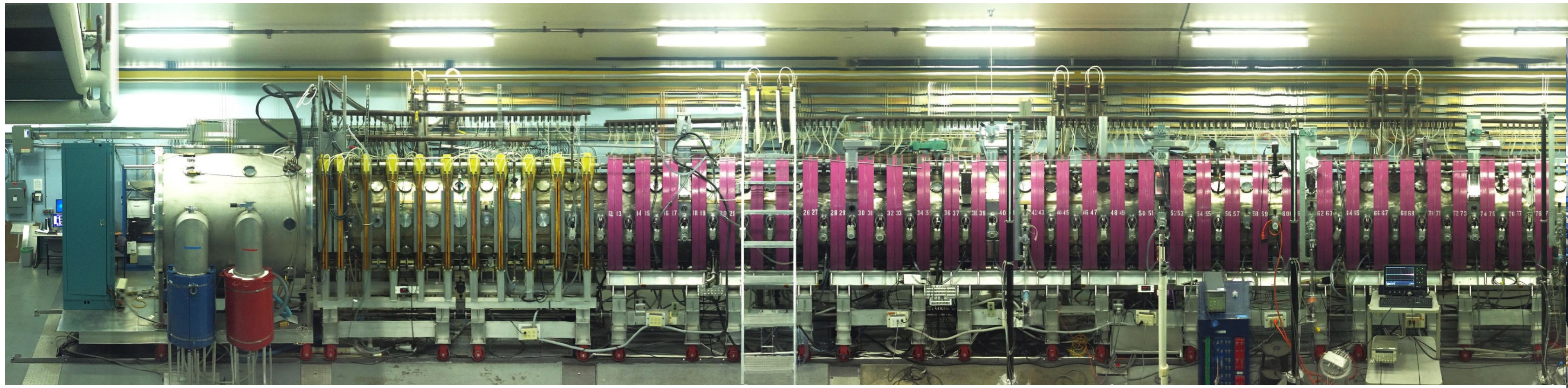
- Transport barrier due to presence of significant shear in edge flow
- Heuristic argument: Sheared flow “breaks up” turbulent eddies, smaller eddies means smaller transport [Biglari, Diamond, Terry]



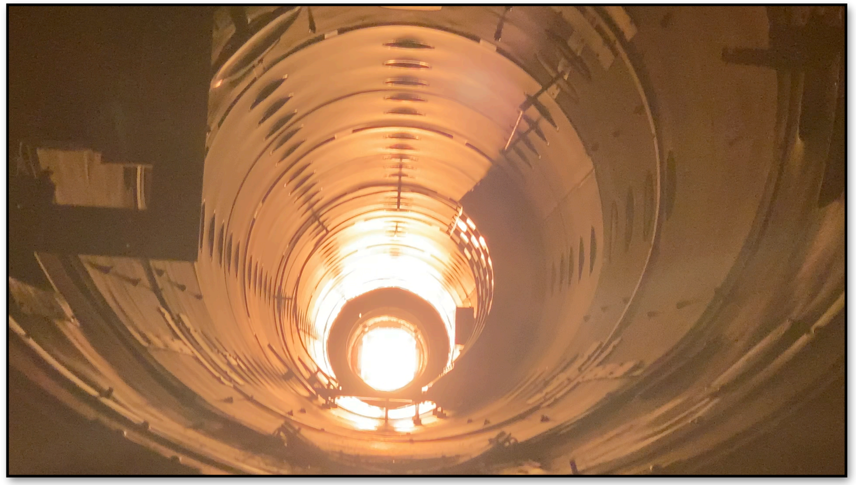
But still no first-principles understanding of H-mode, questions remain about details of flow-shear stabilization (motivates experiments in our laboratory)

Review: P. W. Terry, Rev. Mod. Phys. 72, 109 (2000)

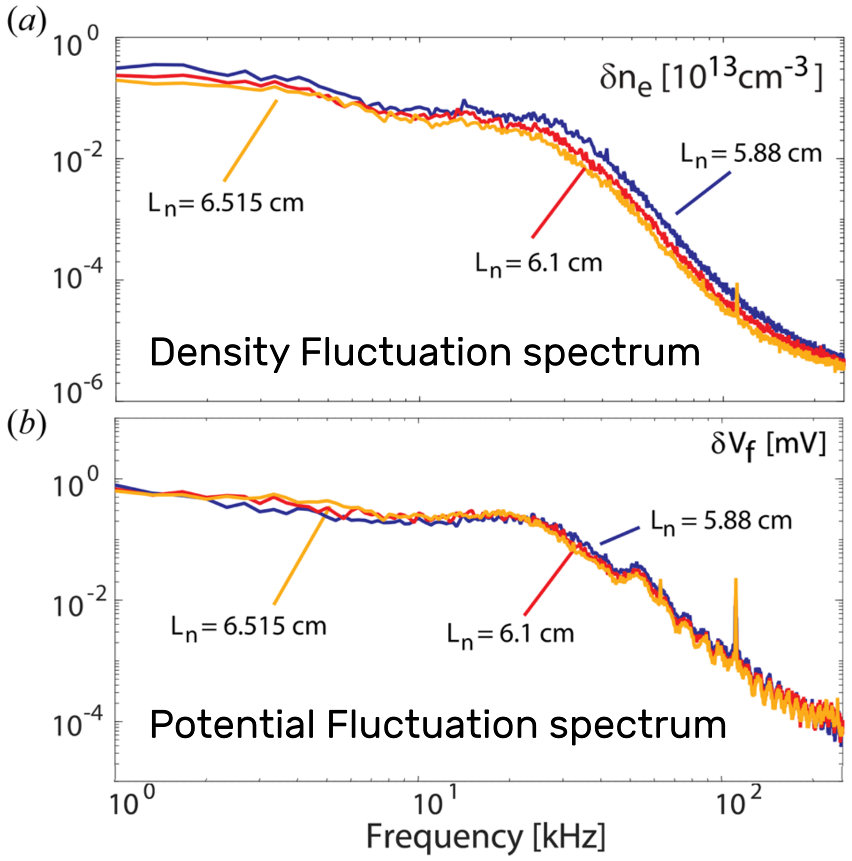
The Large Plasma Device (LAPD): a flexible experimental platform



- 20m long, 1m diameter vacuum chamber; emissive cathode discharge
- LaB_6 Cathode produced plasma: $n \sim 1 \times 10^{13}\ cm^{-3}$, $T_e \sim 10–15$ eV, $T_i \sim 6–10$ eV
- B up to 3.5kG (with control of axial field profile)
- High repetition rate: 1 Hz
- US DOE & NSF Sponsored Collaborative Research Facility @ UCLA

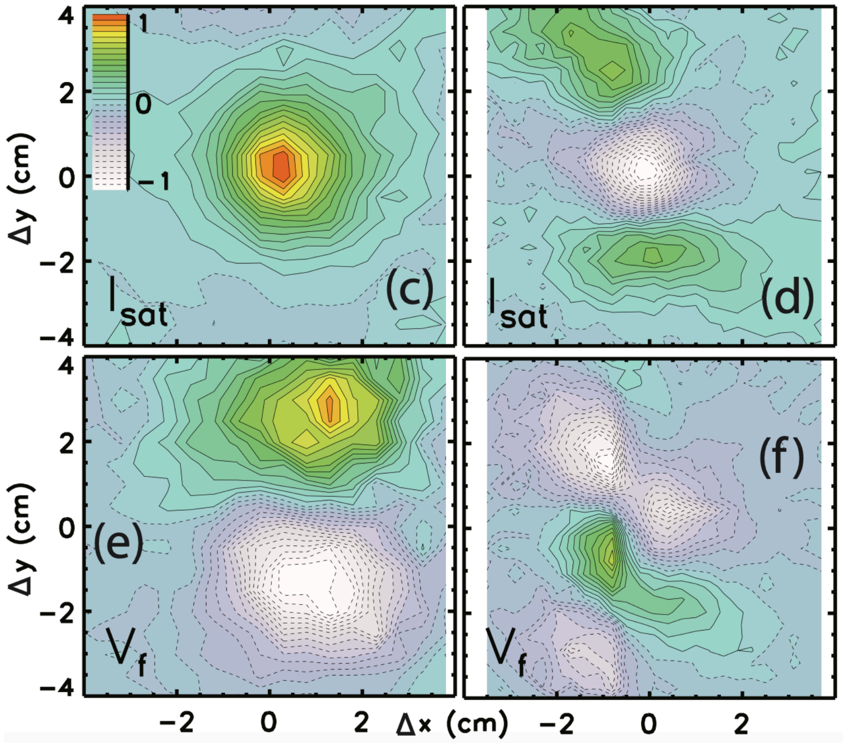


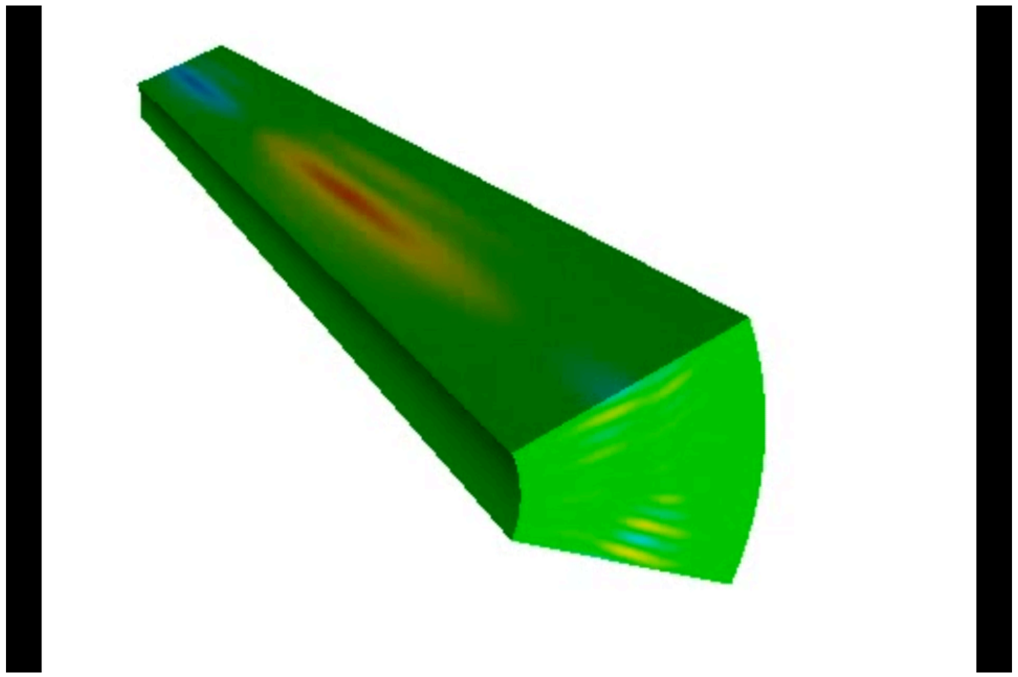
Turbulence & particle transport in LAPD



C. Perks, et al., JPP 88, 905880405 (2022)

T.A. Carter, PoP 13, 010701 (2006)

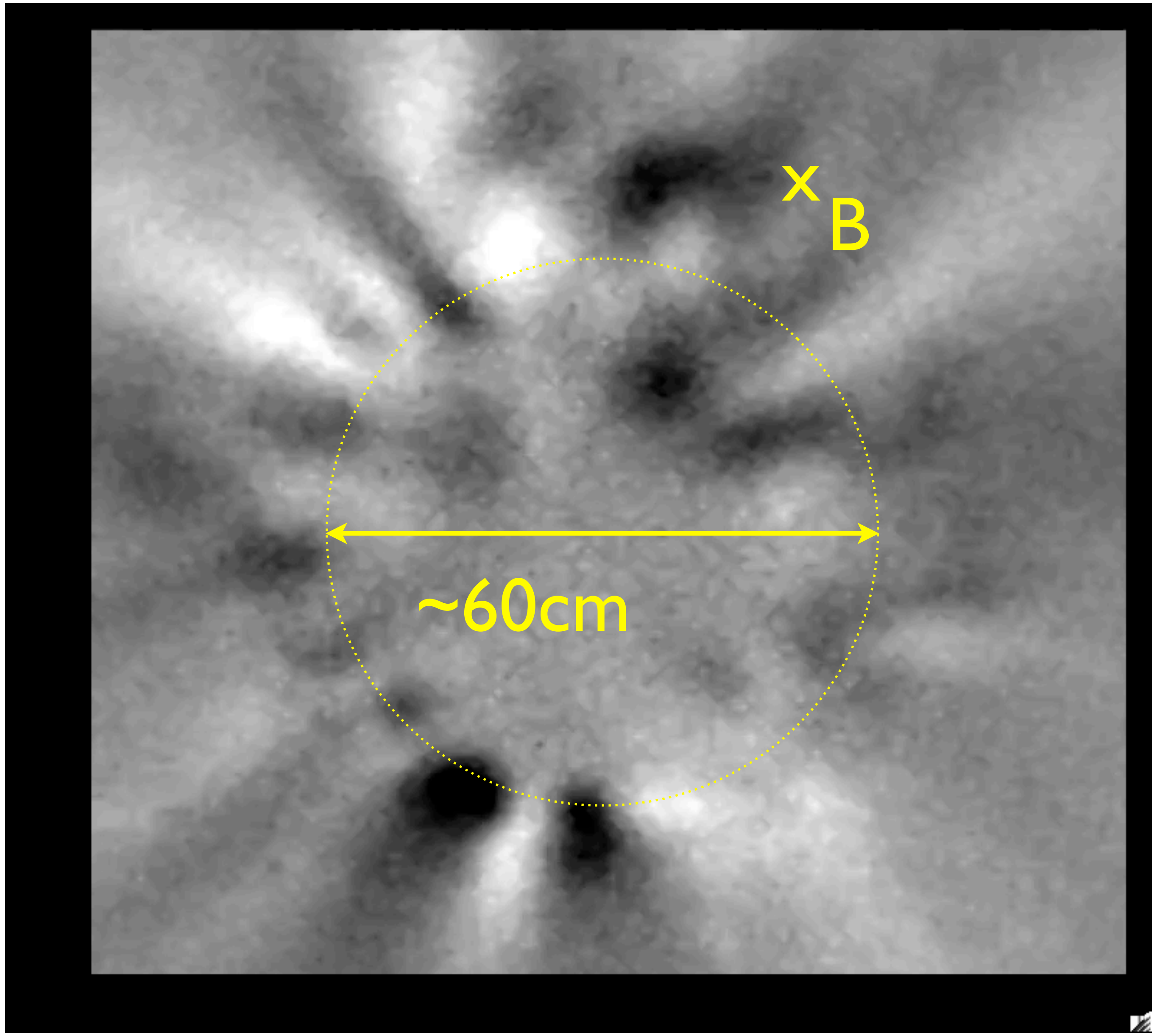




B. Friedman, et al., PoP 19, 102307 (2012)
B. Friedman & T.A. Carter, PRL 113, 025003 (2013)

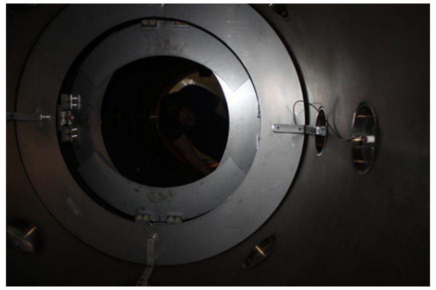
- LAPD plasmas unstable to resistive drift waves as well as rotational interchange (and other flow driven modes) — strong fluctuations in plasma edge
- Broadband fluctuations observed in edge, turbulent particle transport (due to "blobs") in edge. Simulations using BOUT++ reproduce observations

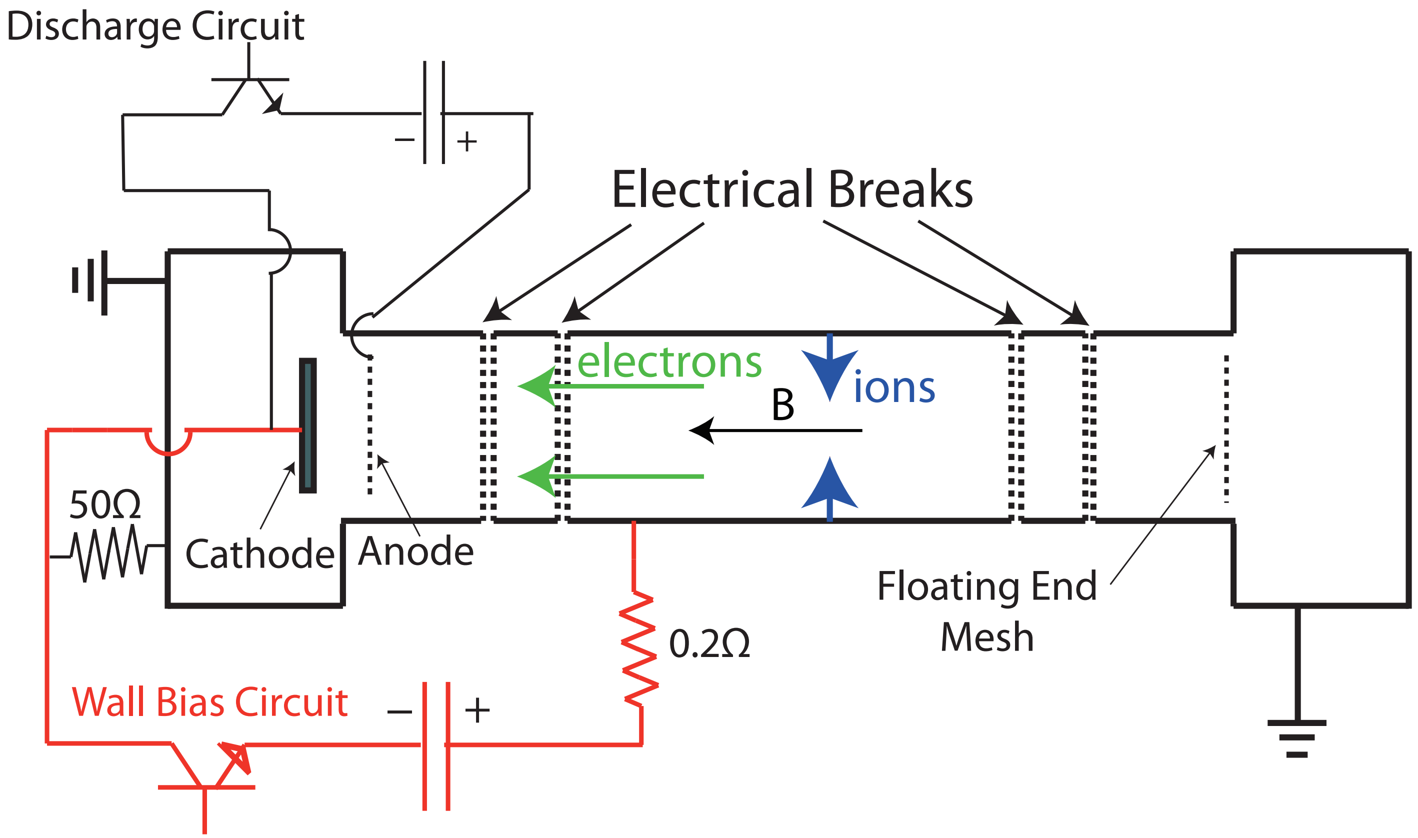
Visible light imaging of LAPD turbulence

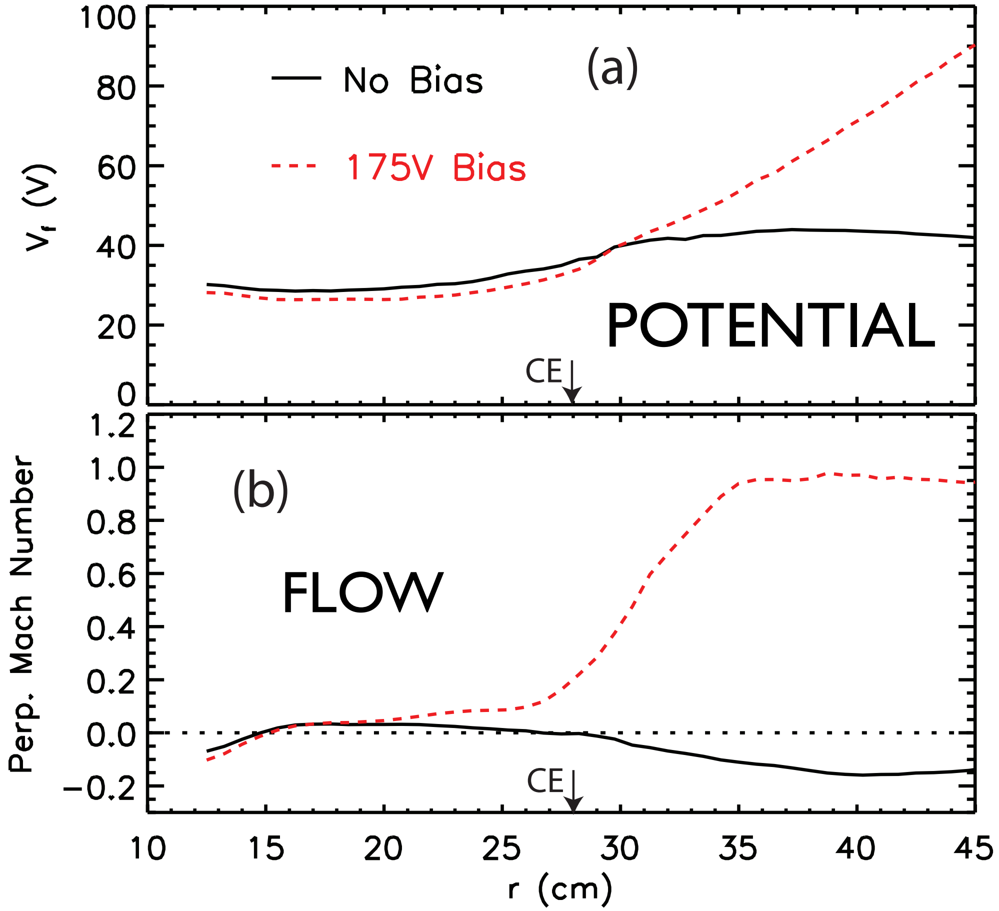


Fast framing camera (~50k frames per second, ~10ms total time),
visible light (neutral He), viewed along B

Controlling plasma flow (rotation) with biasing

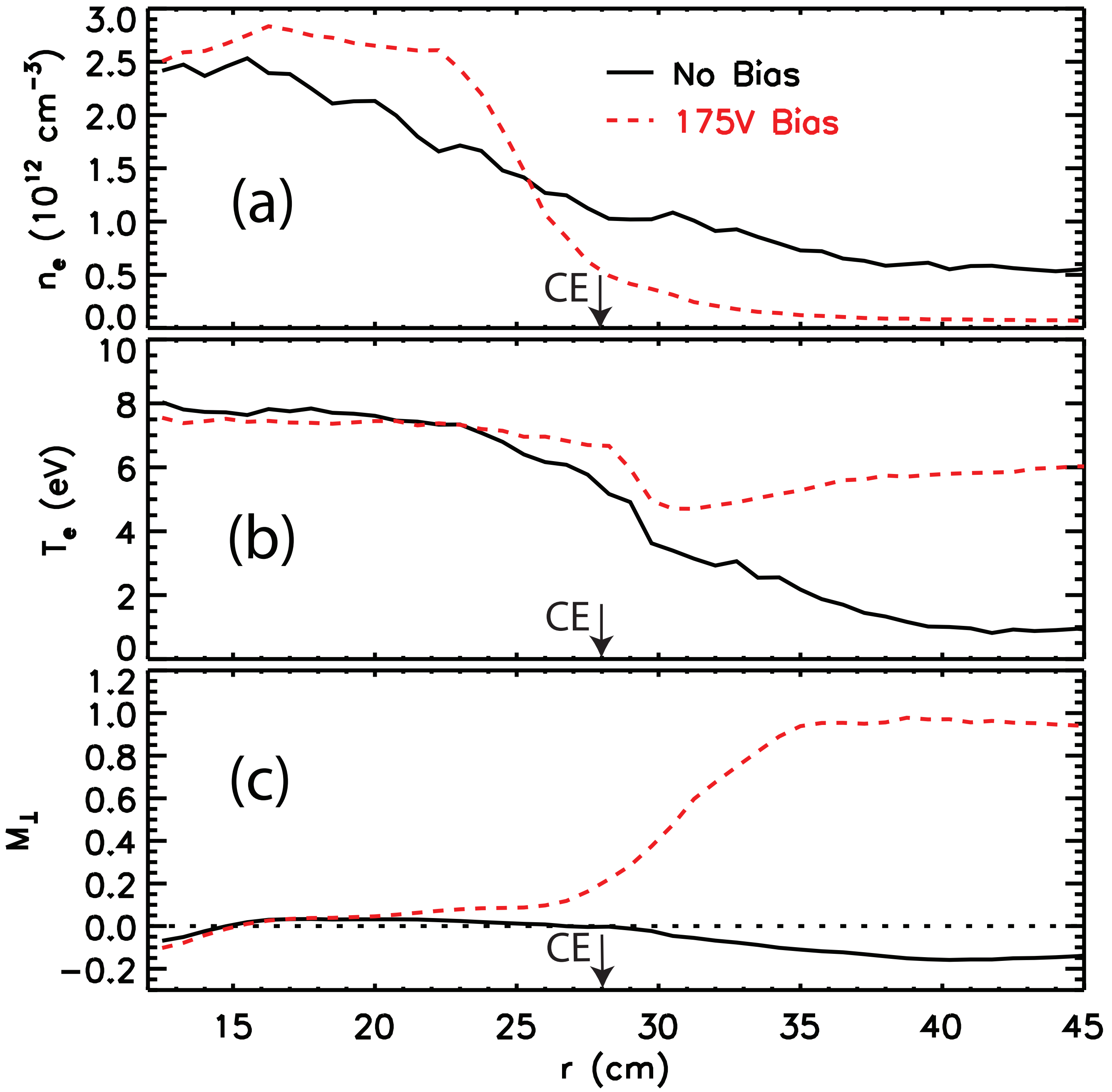






- Apply voltage to (floating) wall of chamber or limiter relative to cathode
- Radial current in response to applied potential (cross-field ion current due to ion-neutral collisions) provides torque to spin up plasma, generates radial electric field & flow in plasma edge

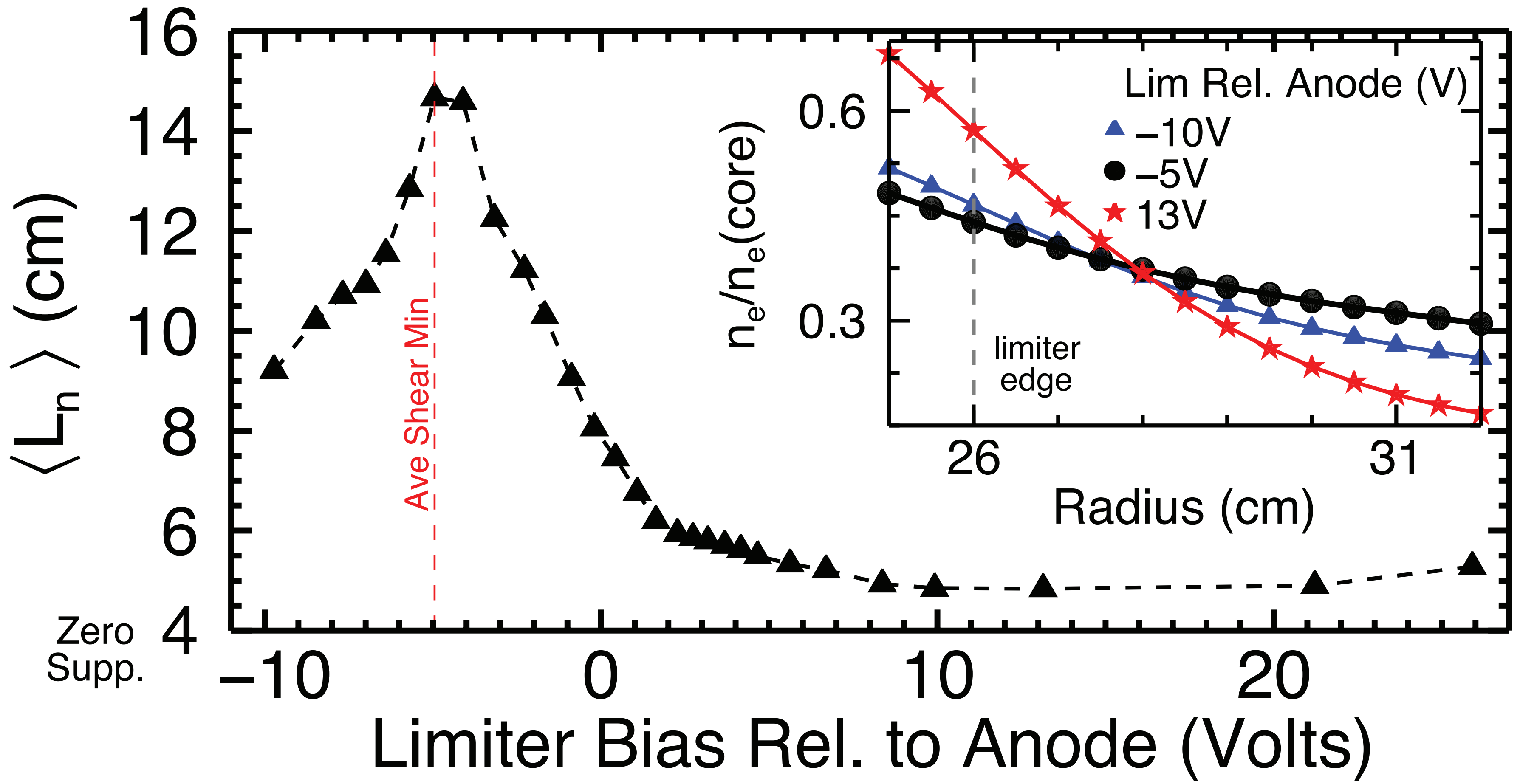
Transport barrier/profile steepening observed with biasing: H-mode in LAPD

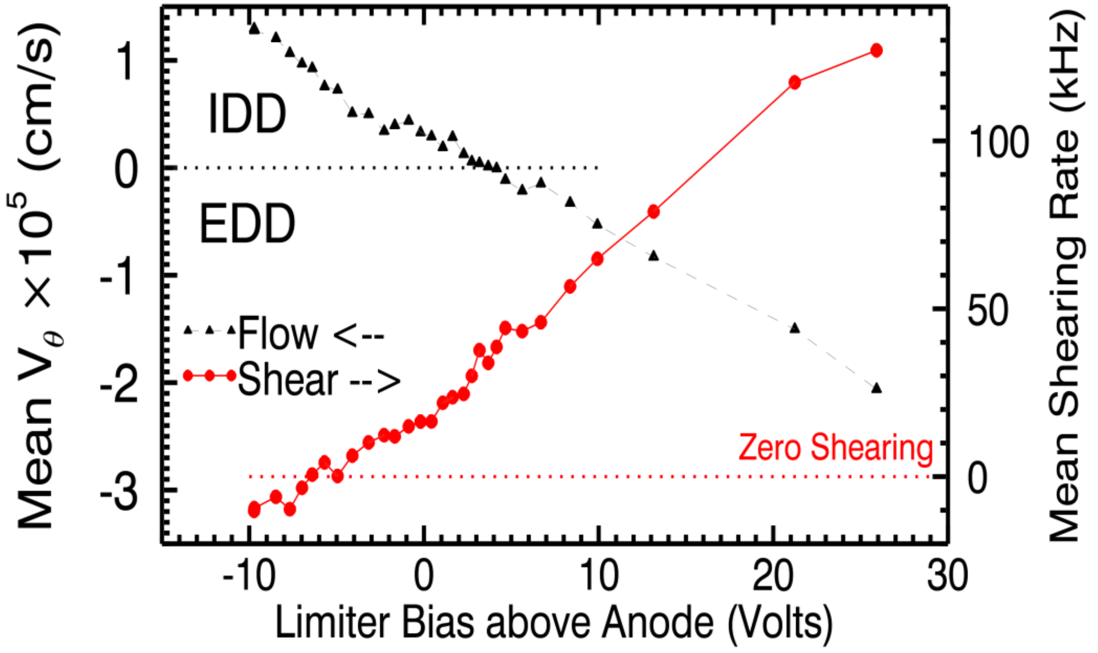


- As bias/flow exceeds a threshold, confinement transition observed ("H-mode" in LAPD)
  - Density profile steepens, edge density drops (source was turbulent transport)
- Detailed transport modeling shows that transport is reduced to classical levels during biasing (consistent with Bohm prior to rotation) [T.A. Carter, et al., PoP 16, 012304 (2009), J.E. Maggs, et al., PoP (2007)]

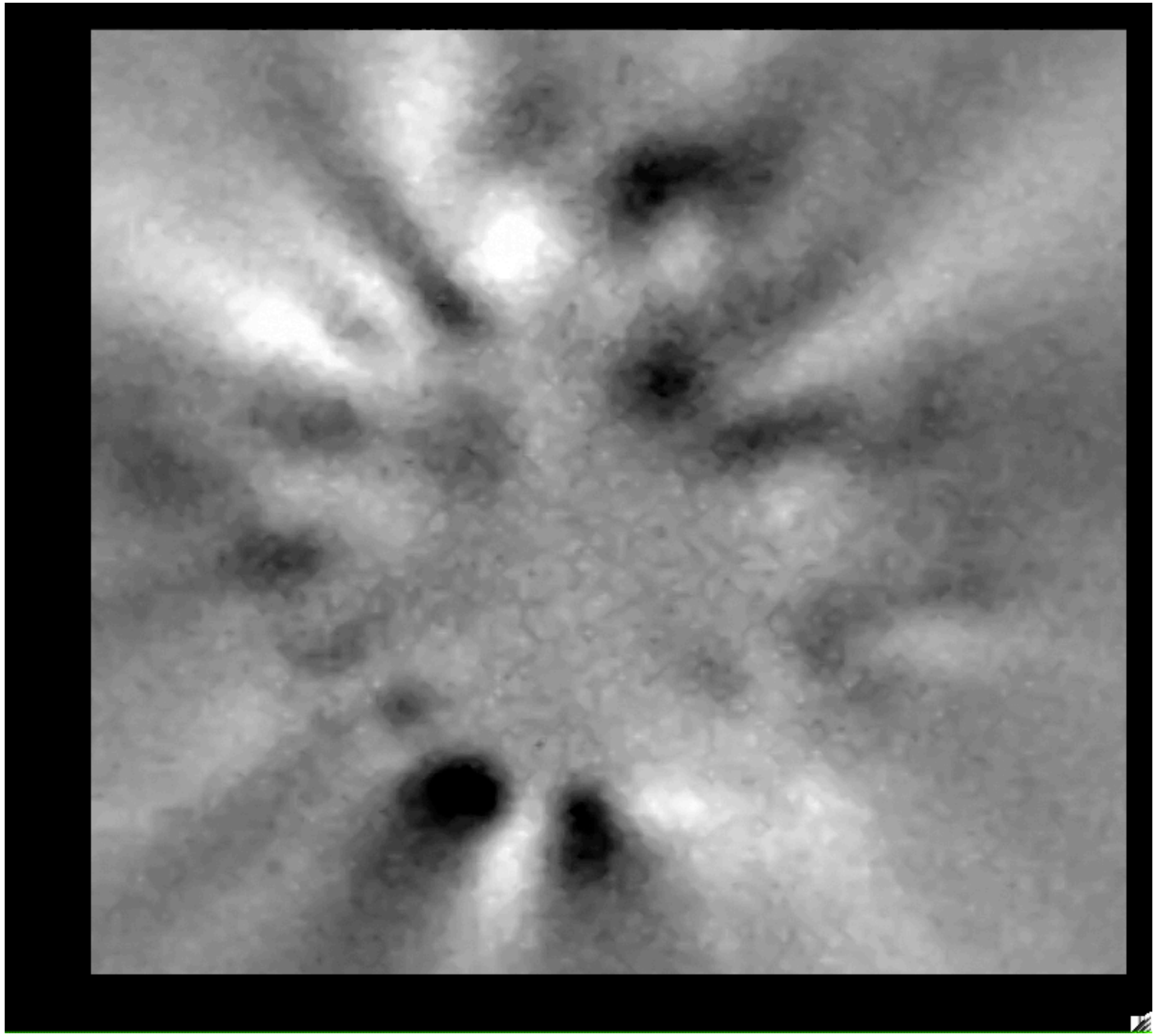
Continuous improvement of confinement/profile steepness with flow shear (independent of sign of rotation)

$$L_n = |\ln \frac{dn}{dr}|^{-1}$$

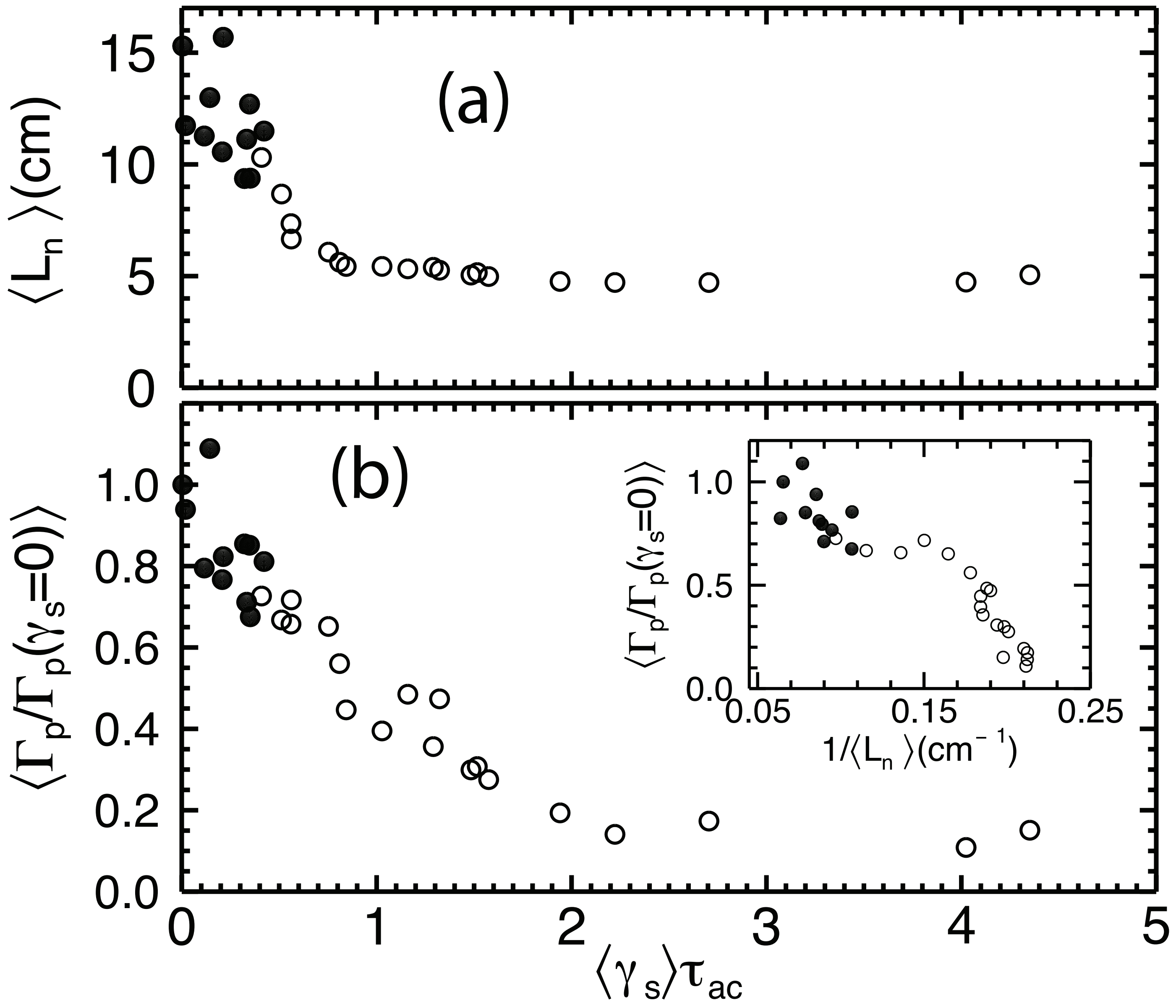




Effect of driven rotation on turbulence: visible imaging



Suppression of turbulent particle flux with flow shear

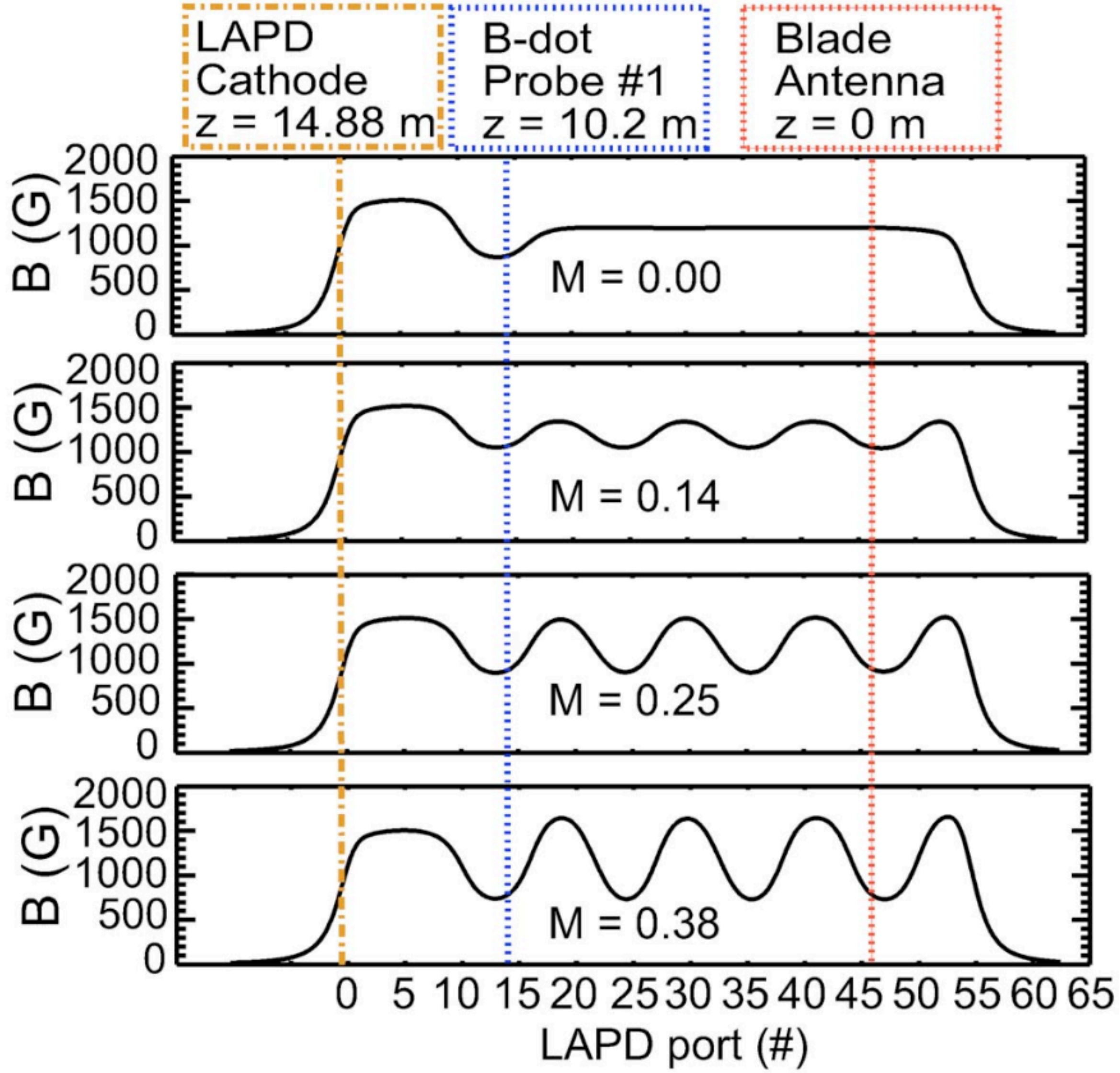


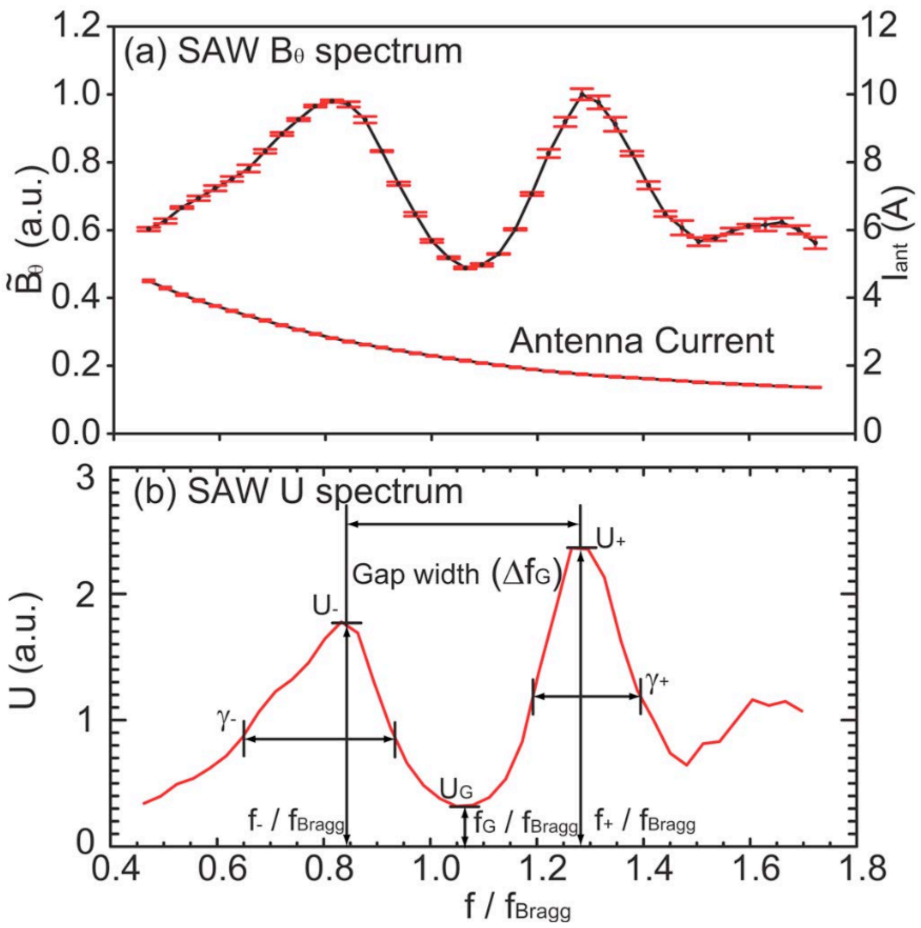
Prof. David Schaffner (Bryn Mawr)

Schaffner et al., PRL 109, 135002 (2012)

Schaffner et al., PoP 20, 055907 (2013)

Flexible magnetic geometry: mirror configurations in LAPD

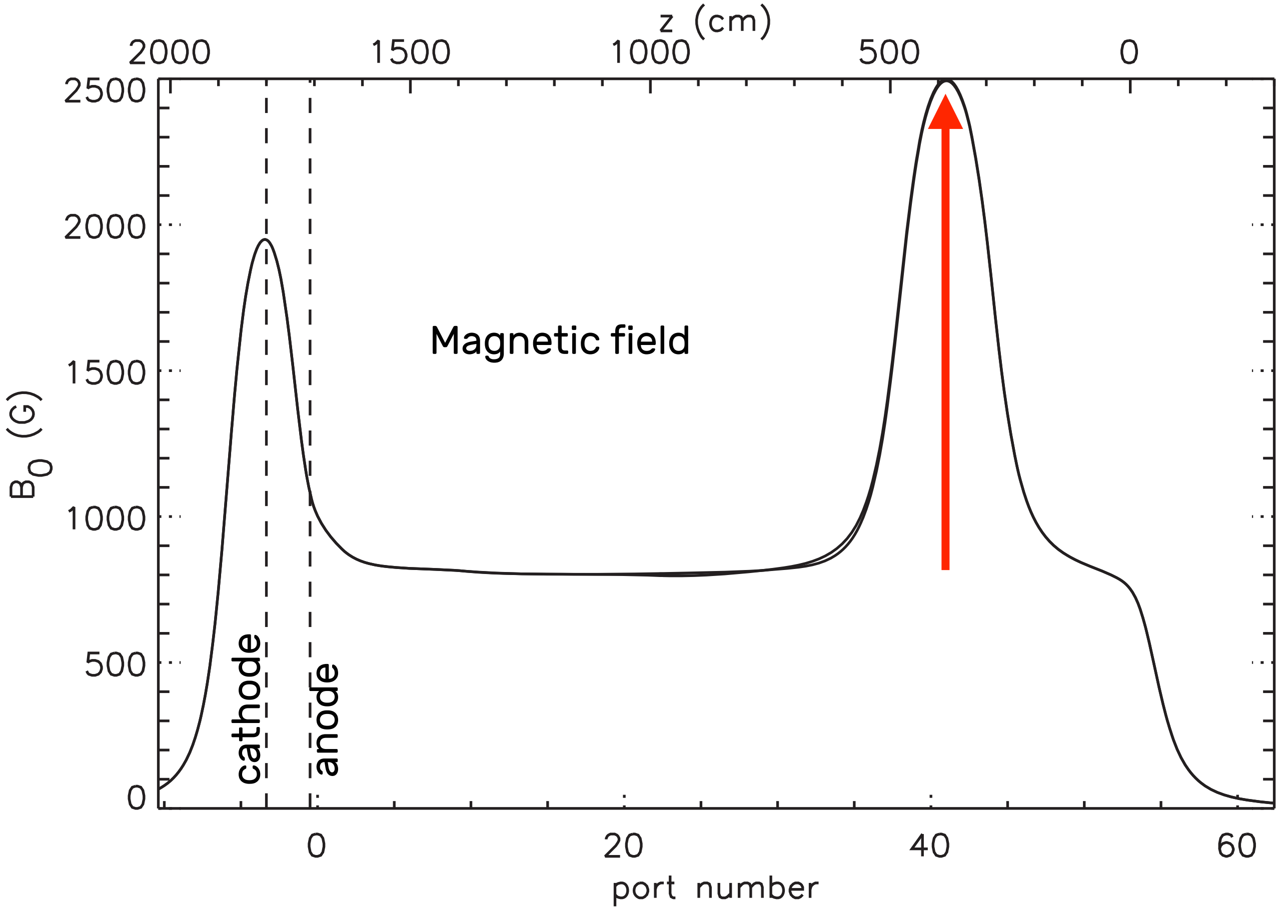


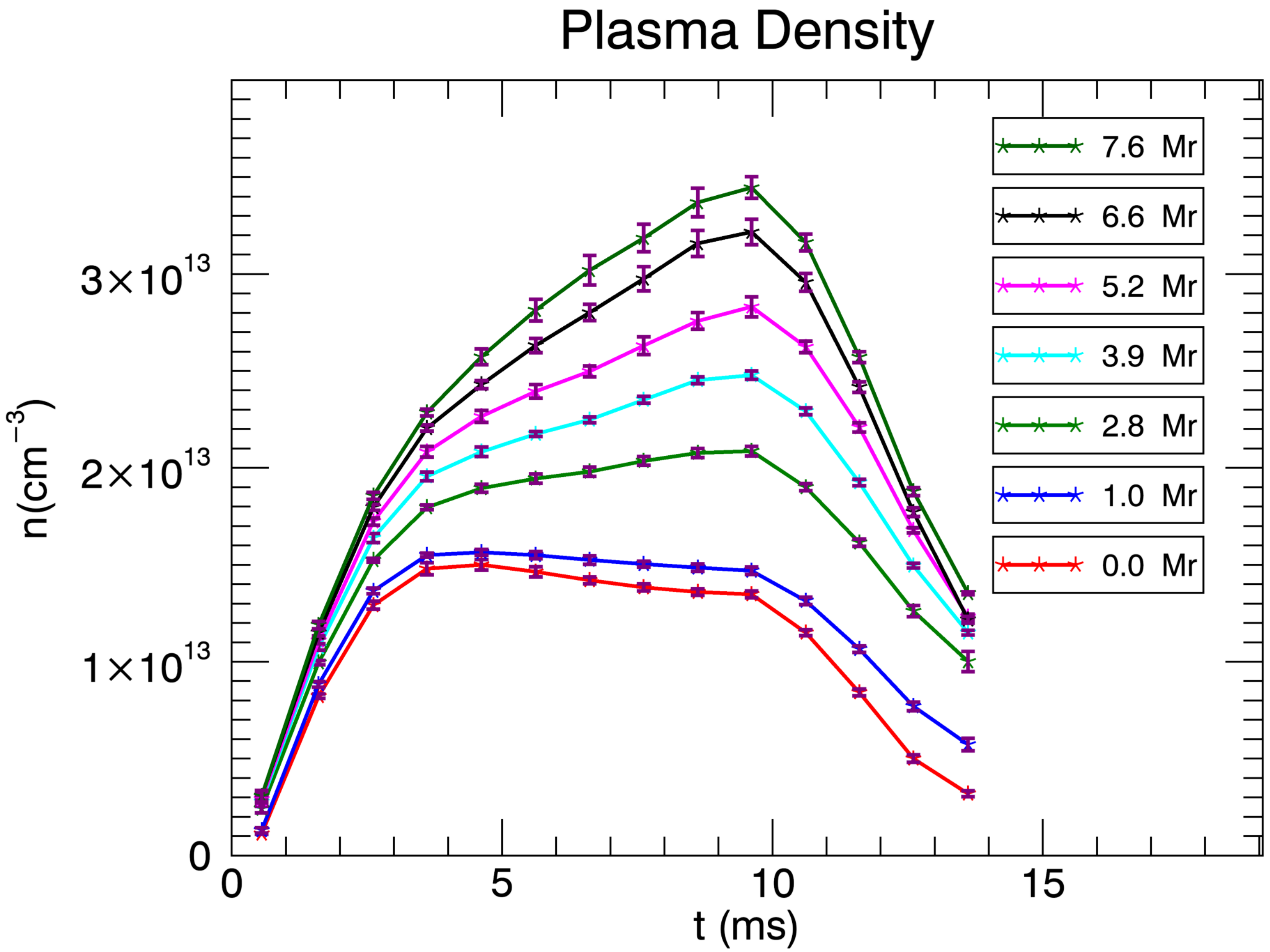


Zhang, Heidbrink, et al., Phys. Plasmas 15, 012103 (2008)

- Flexible magnet system: 10 independently controllable magnet groups, can form a range of mirror configurations. **Example: Periodic mirrors for studies of shear wave propagation, demonstrating spectral gap**

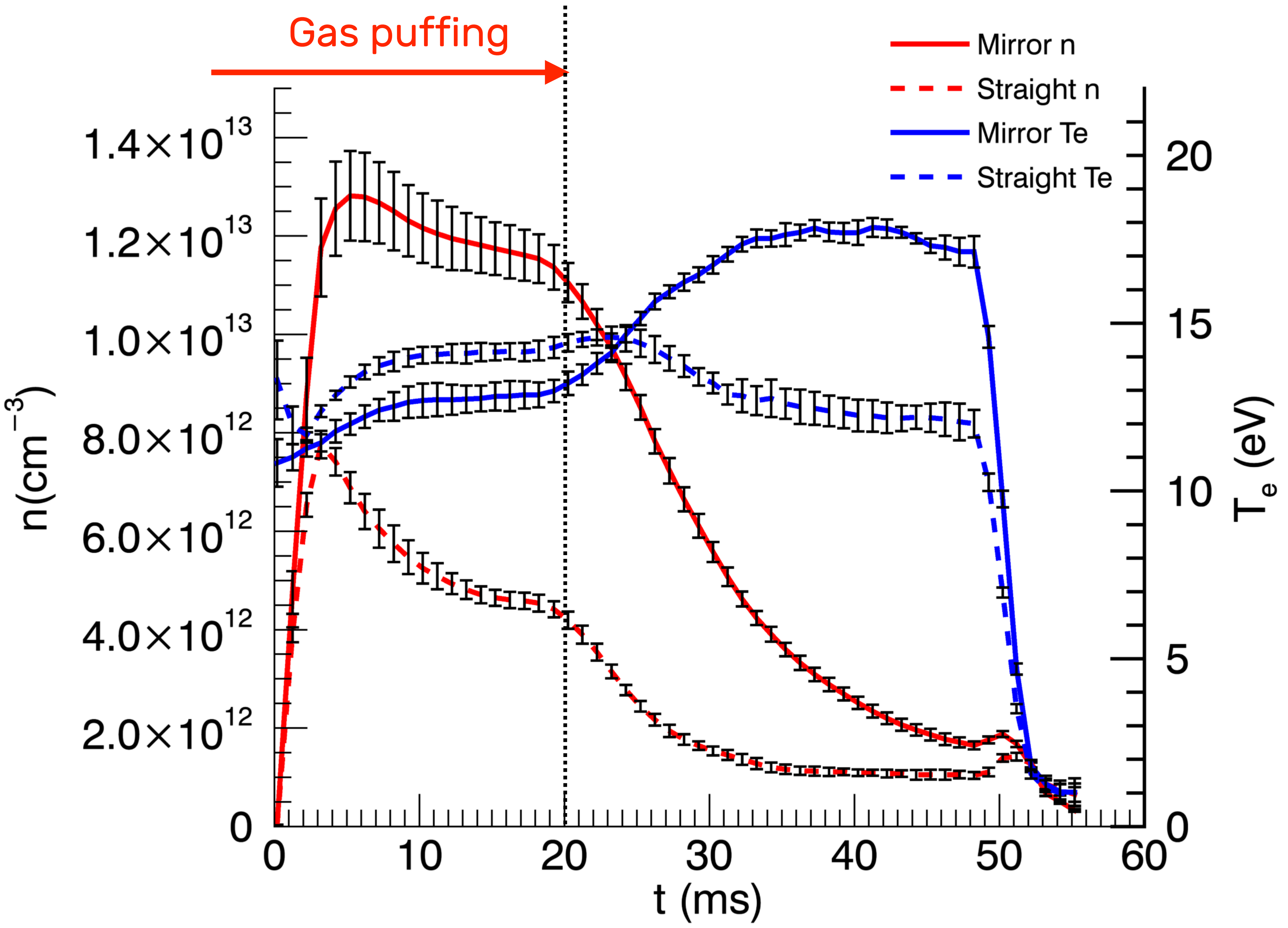
Confinement improvement seen with mirror geometry




Plasma Density

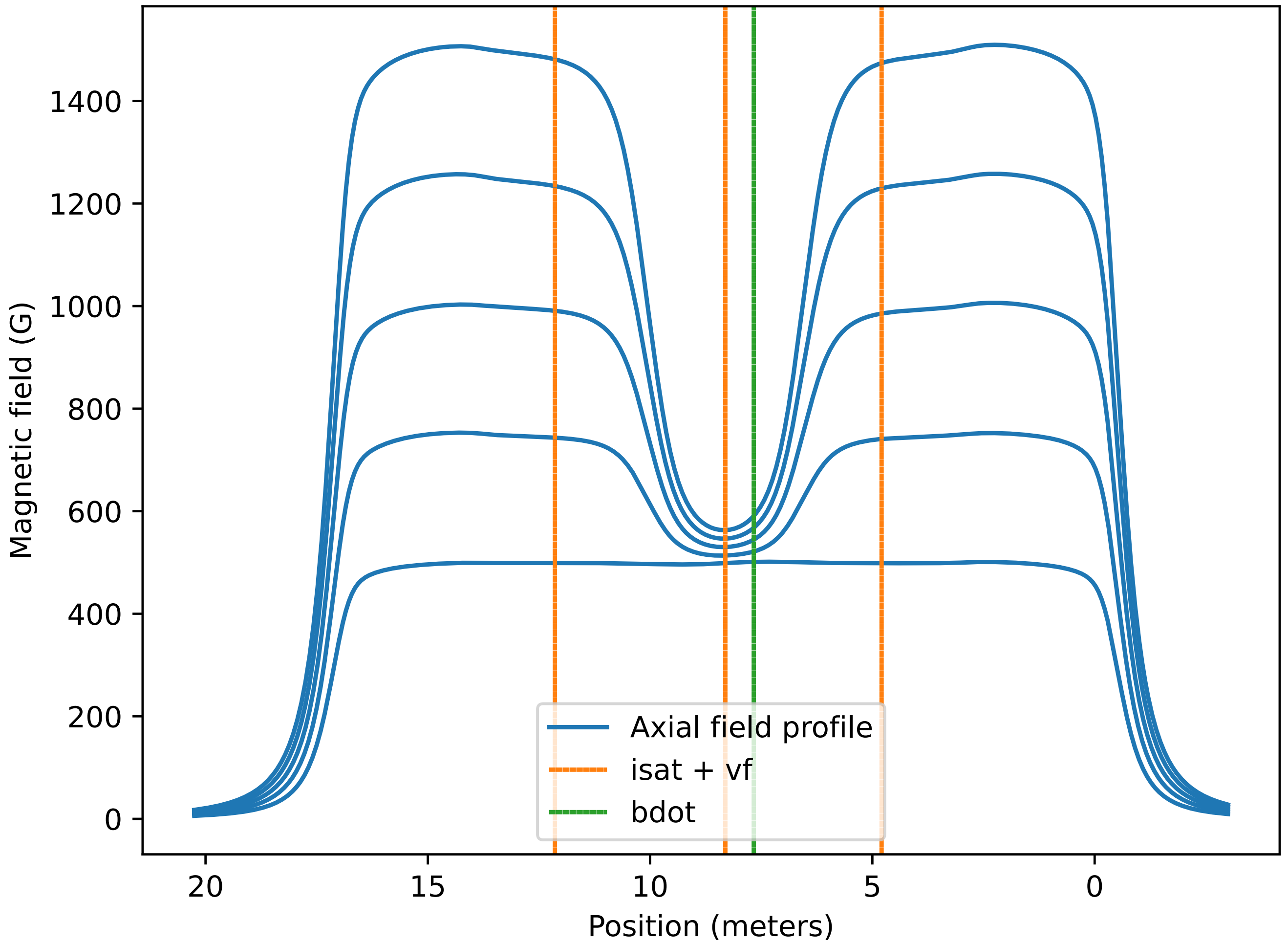
- Core density increase with “half mirror” configuration (mirror ratio up to ~8)
- Evidence that even higher densities are possible with longer discharge/ extended gas puffing (slower density rise consistent with longer particle confinement time)

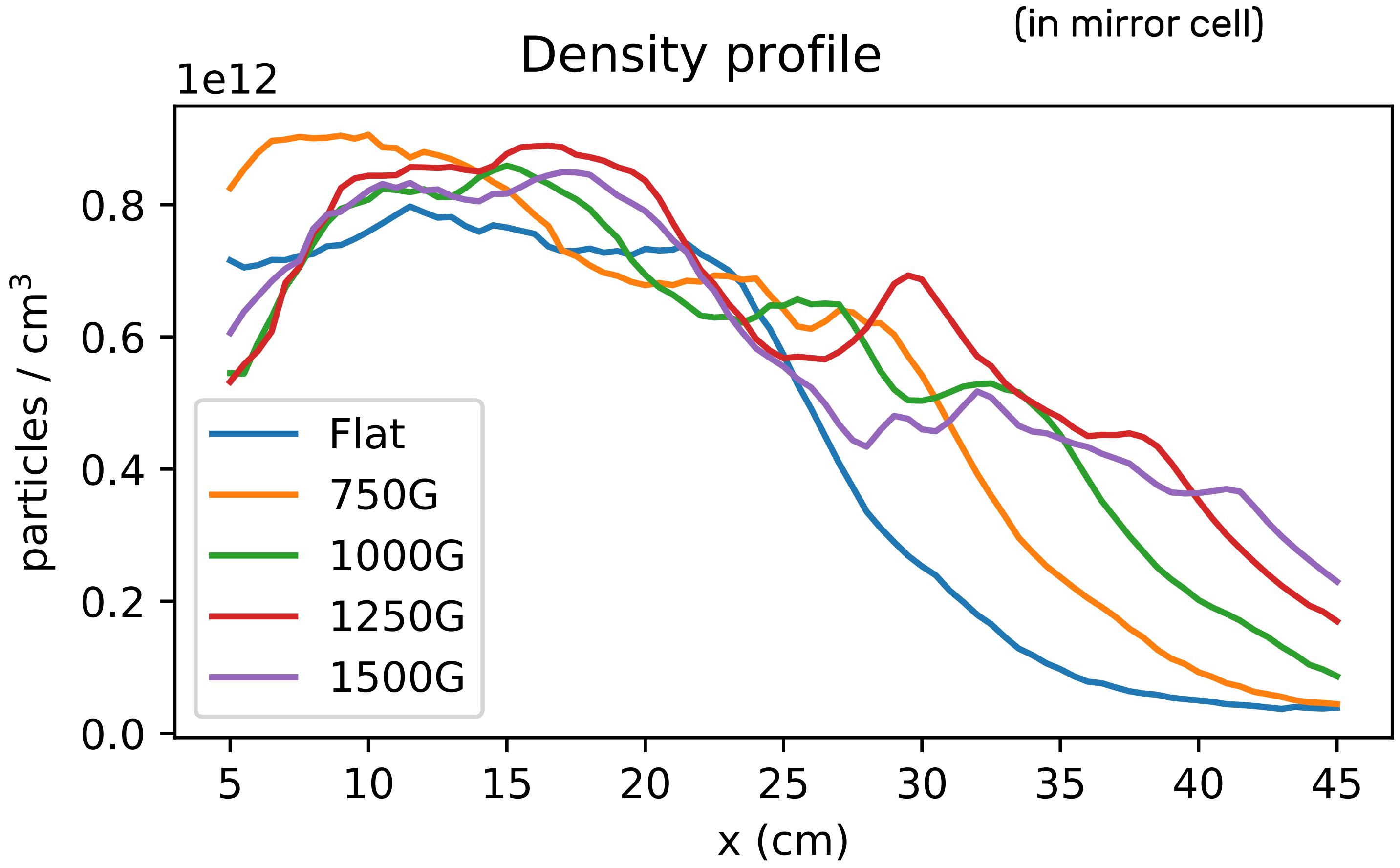
Can create high density or high temperature/collisionless plasmas with control of fueling



- Figure: moderate density, warm plasma with gas puffing initially, hot (record Te in LAPD), lower density plasma with reduced fueling (low collisionality plasmas)
- Not shown: Can create very dense (5×10^{13} cm^{-3}), but cold (~1eV) with high mirror ratio and strong fueling (good for, e.g. collisionless shock studies)

Studies of changes in turbulence with mirror geometry

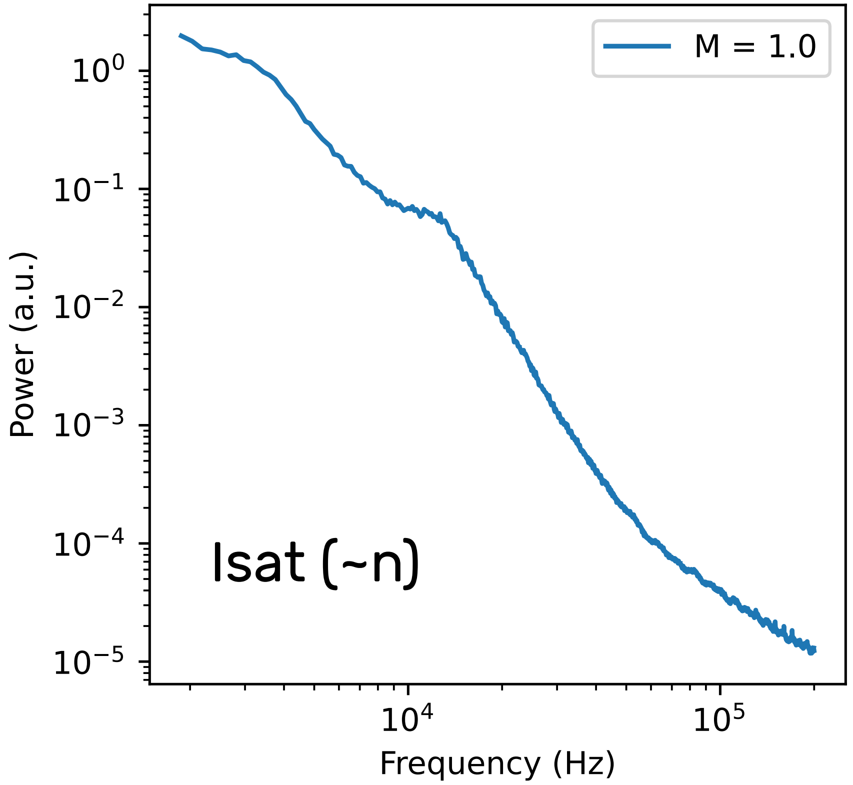




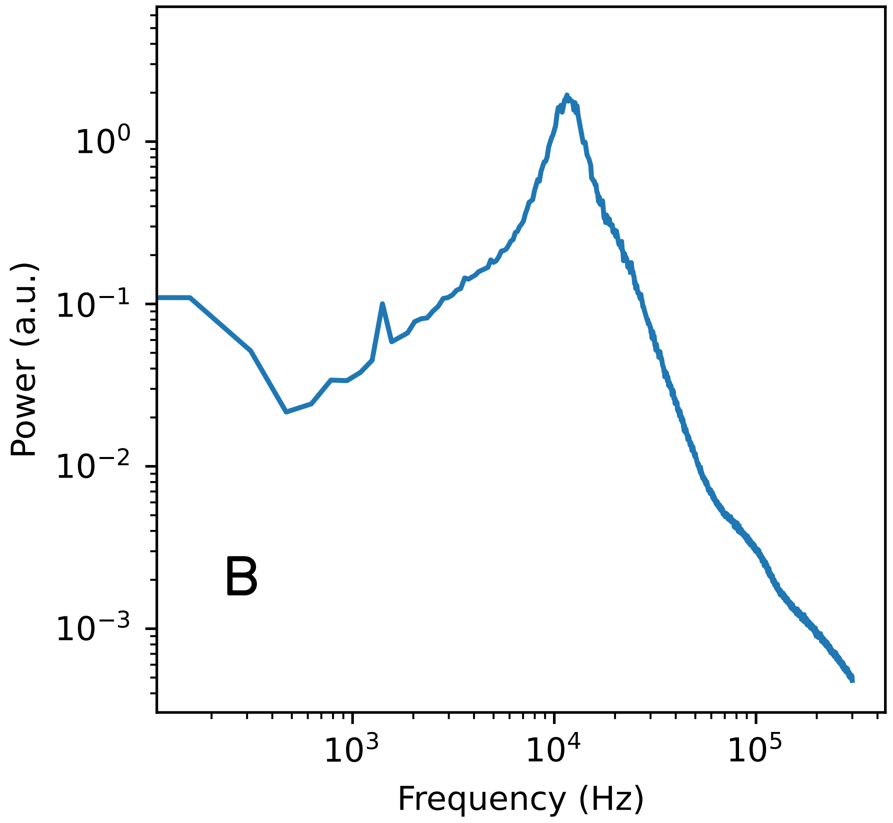
- Initial study: short mirror cell, mirror ratio 1 to 3, lower density plasma
- Plasma source edge maps to increasingly larger radius as mirror ratio increases (magnetic expansion)

Drift-Alfvén turbulence dominates straight-field case

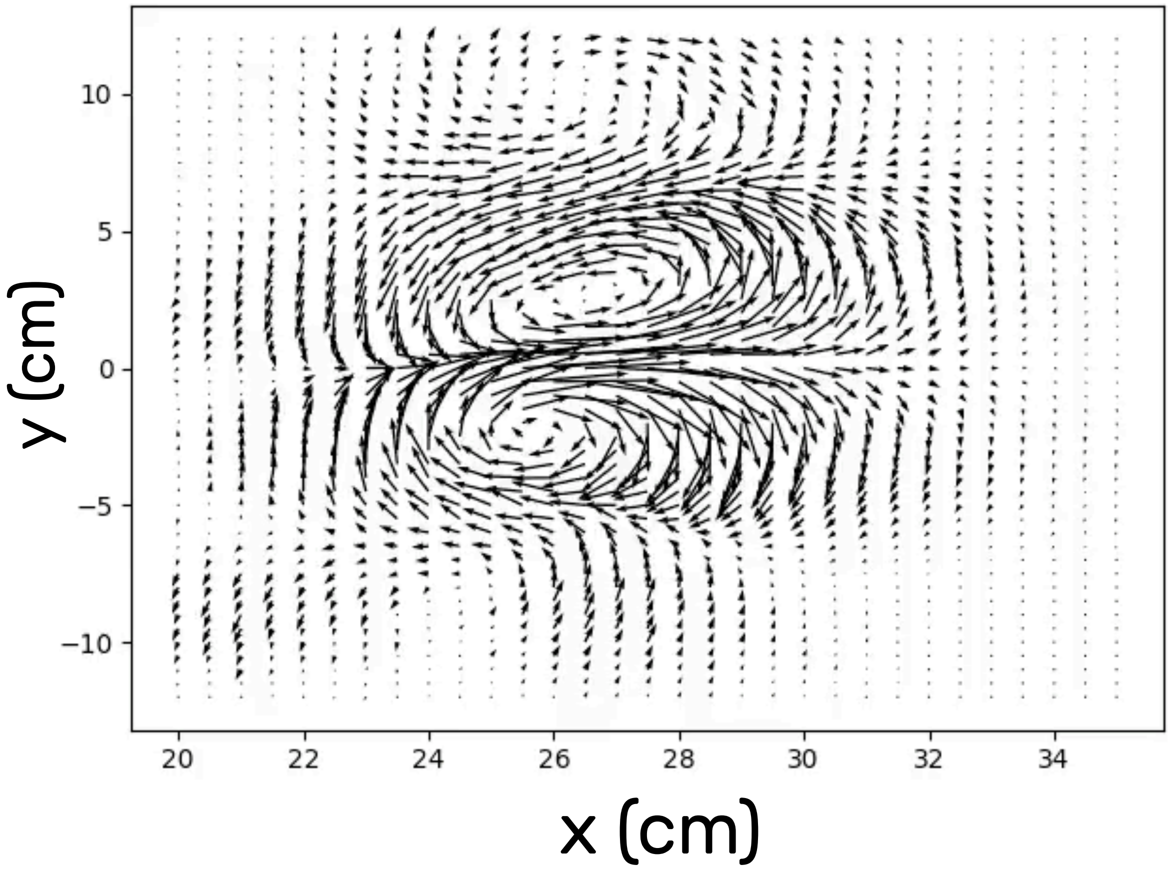
isat fluctuation power



$B_\perp$ fluctuation power

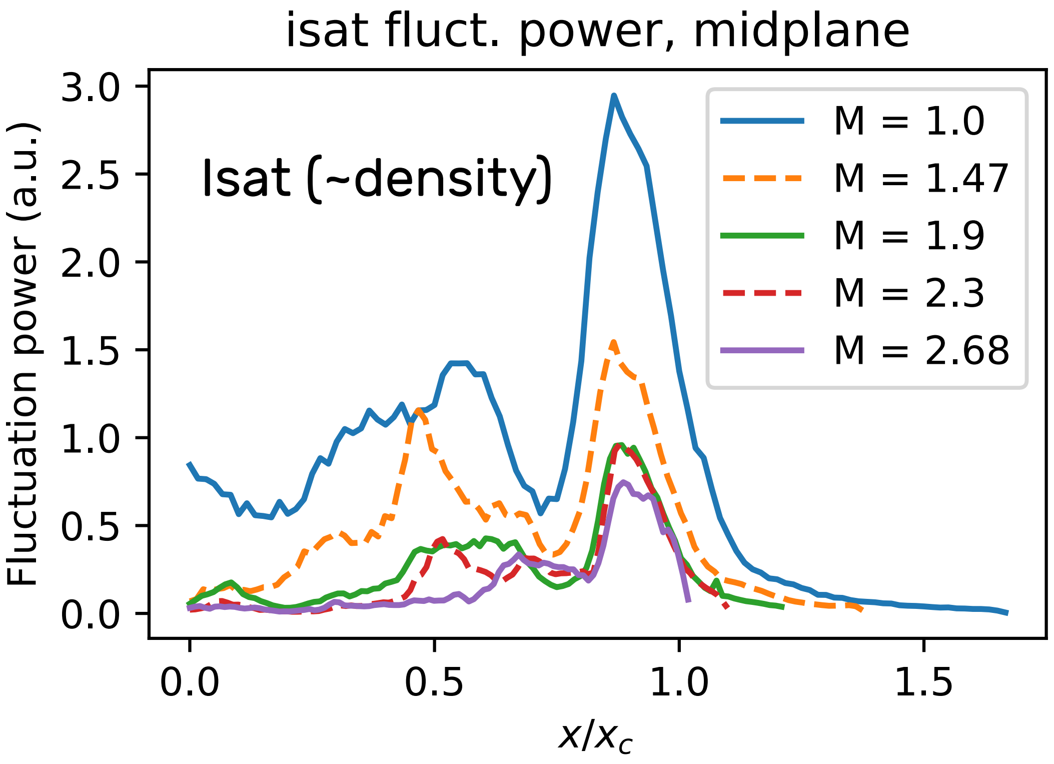


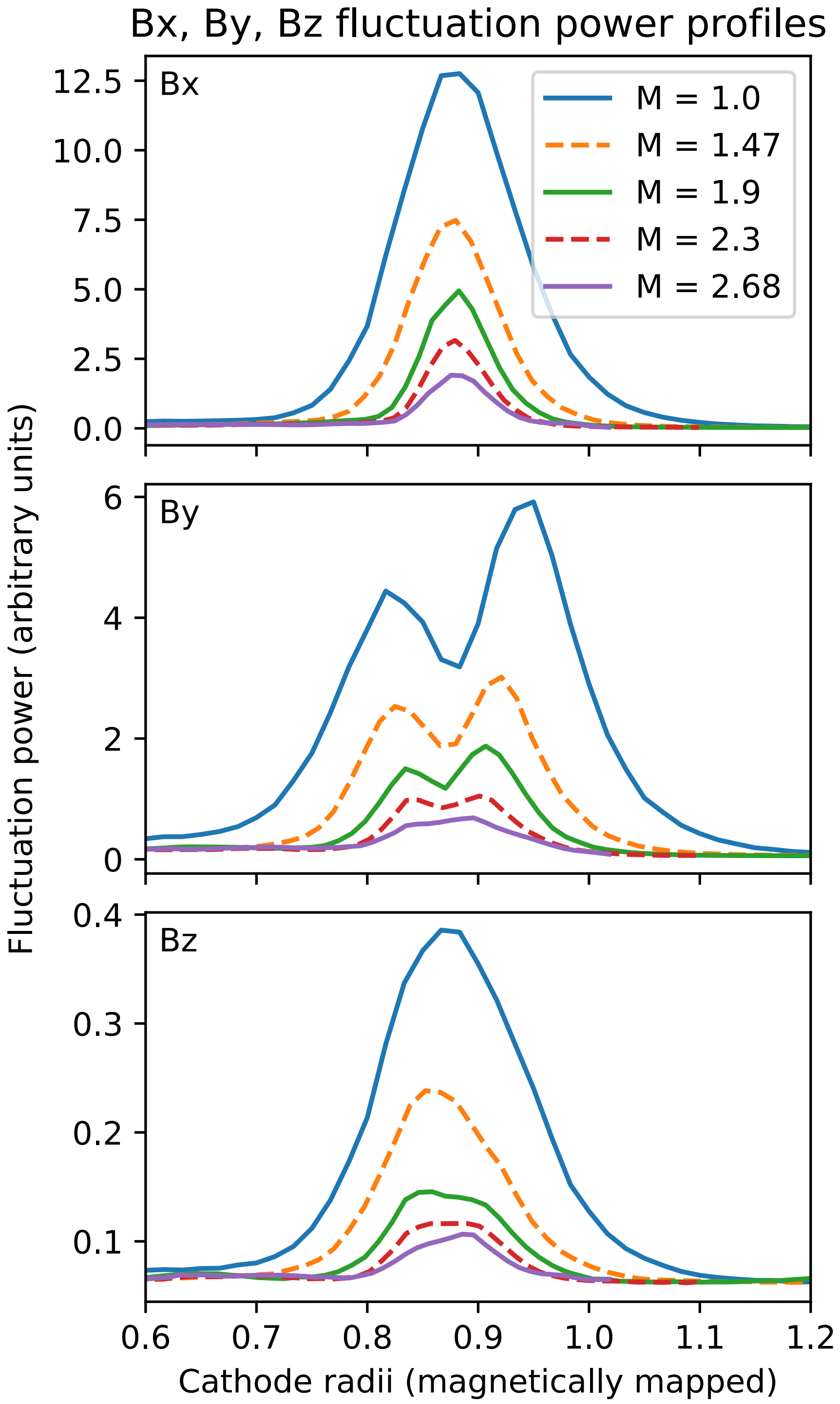
B-n cross correlation

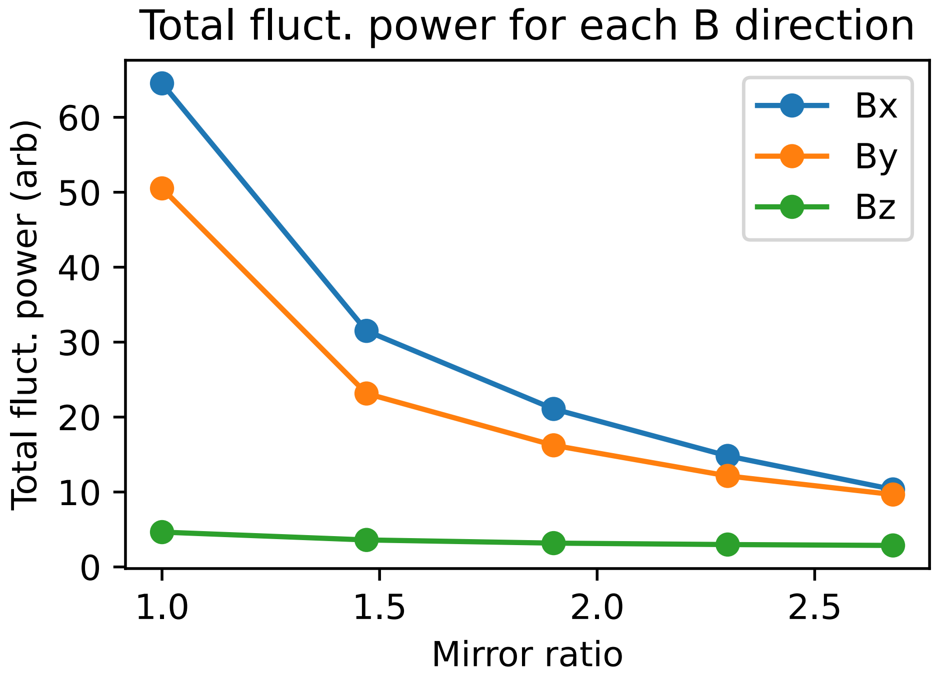


- Resistive drift-wave instability generally dominates in standard LAPD discharges (other sources of free energy: azimuthal flow/rotational interchange) [e.g. Schaffner, et al., PoP 2013]

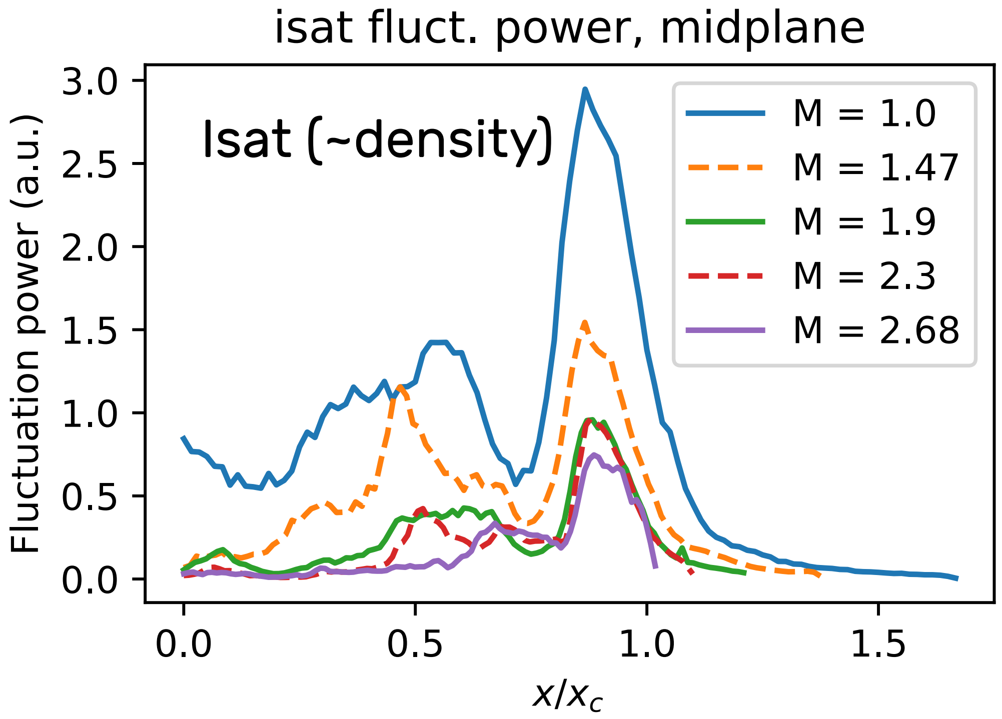
Density, magnetic fluctuation amplitude decrease with increasing mirror ratio

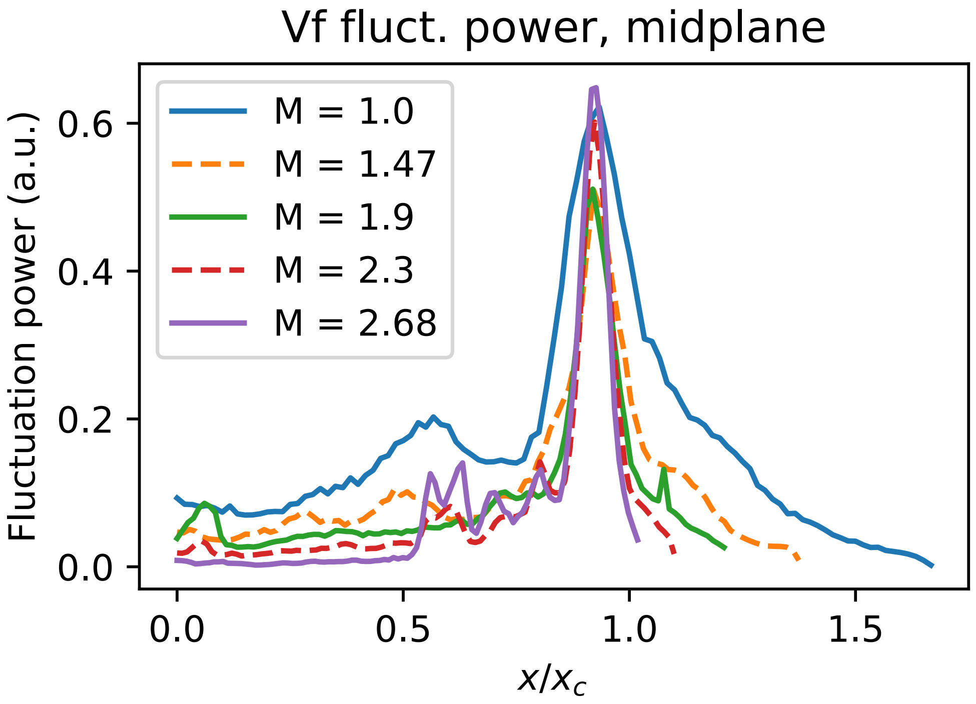


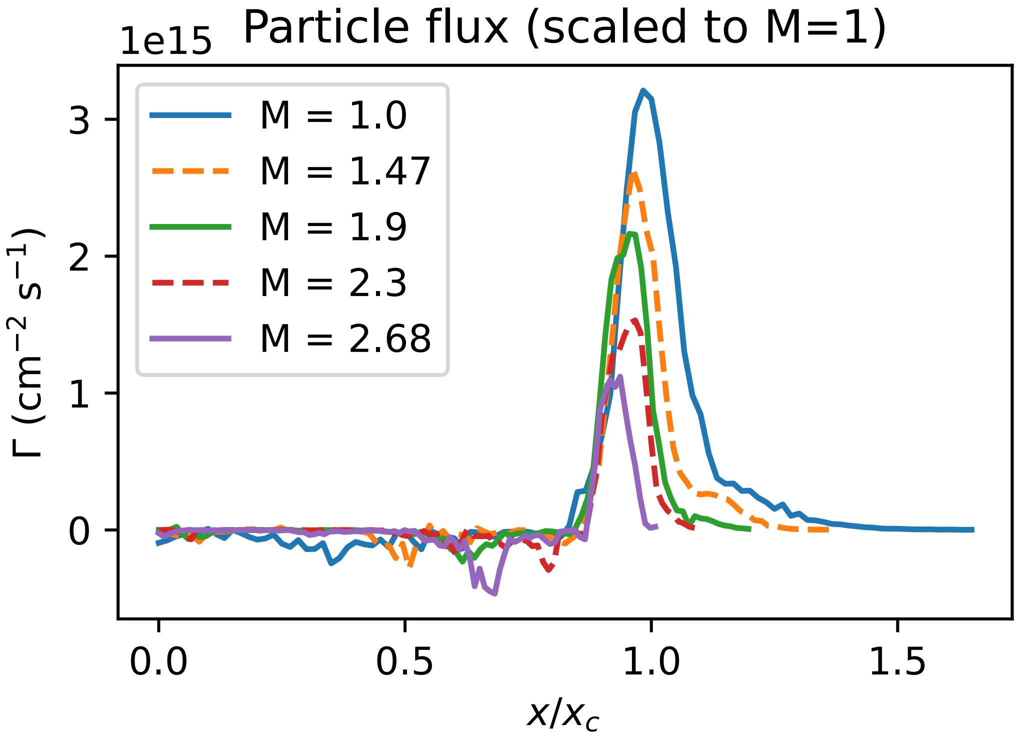




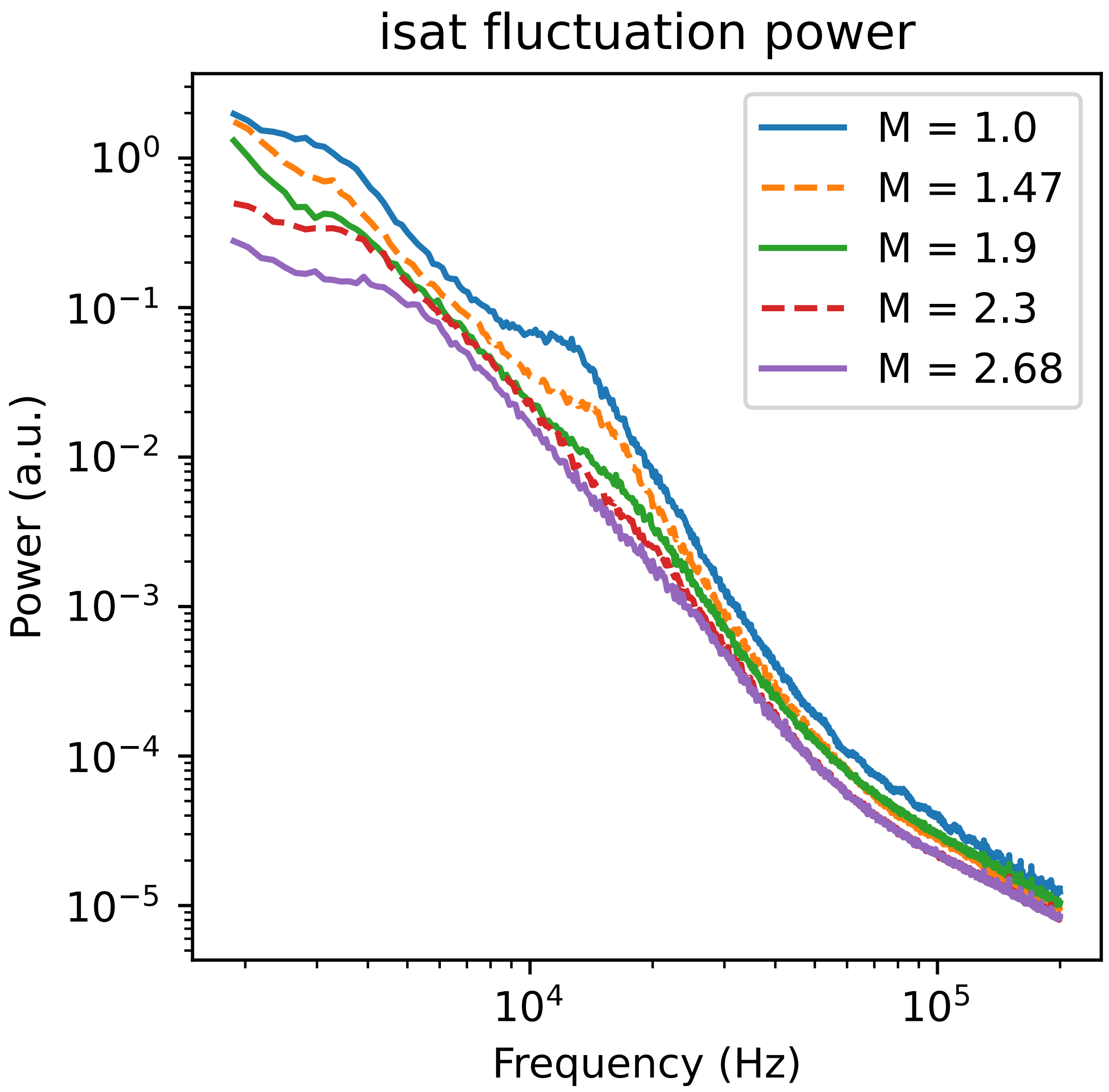
Potential fluctuations do not decrease, but particle flux decreases with mirror ratio

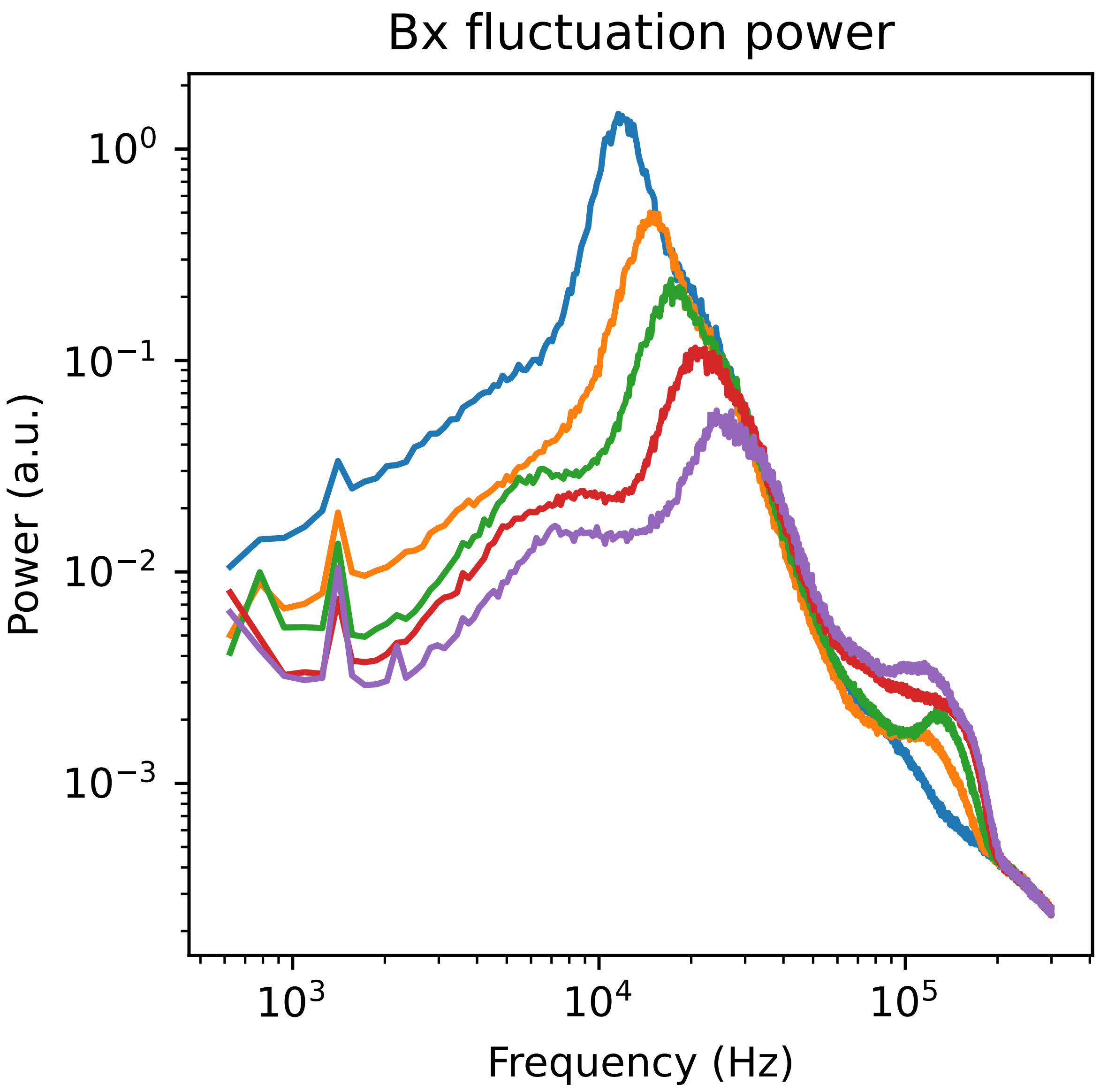

isat fluct. power, midplane


Vf fluct. power, midplane

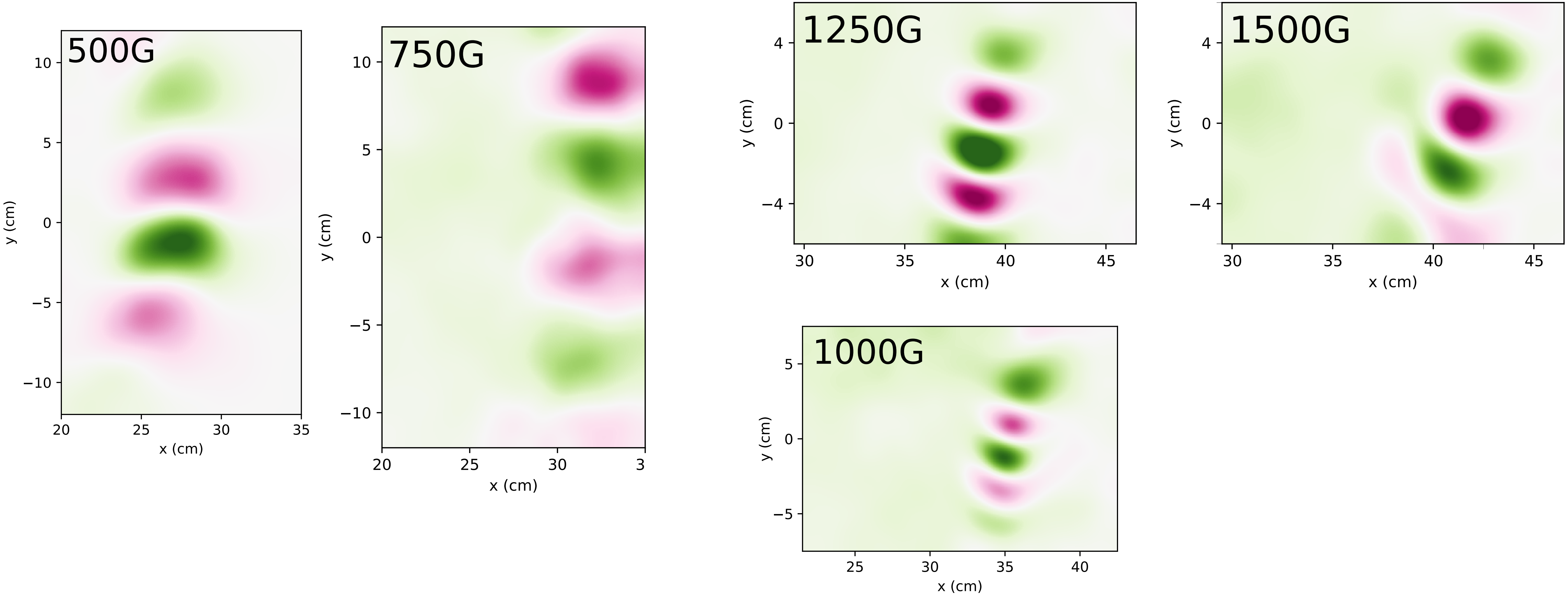

Particle flux (scaled to M=1)

Spectral behavior: overall reduction (except at very high frequency) and upward shift in dominant mode frequency


isat fluctuation power

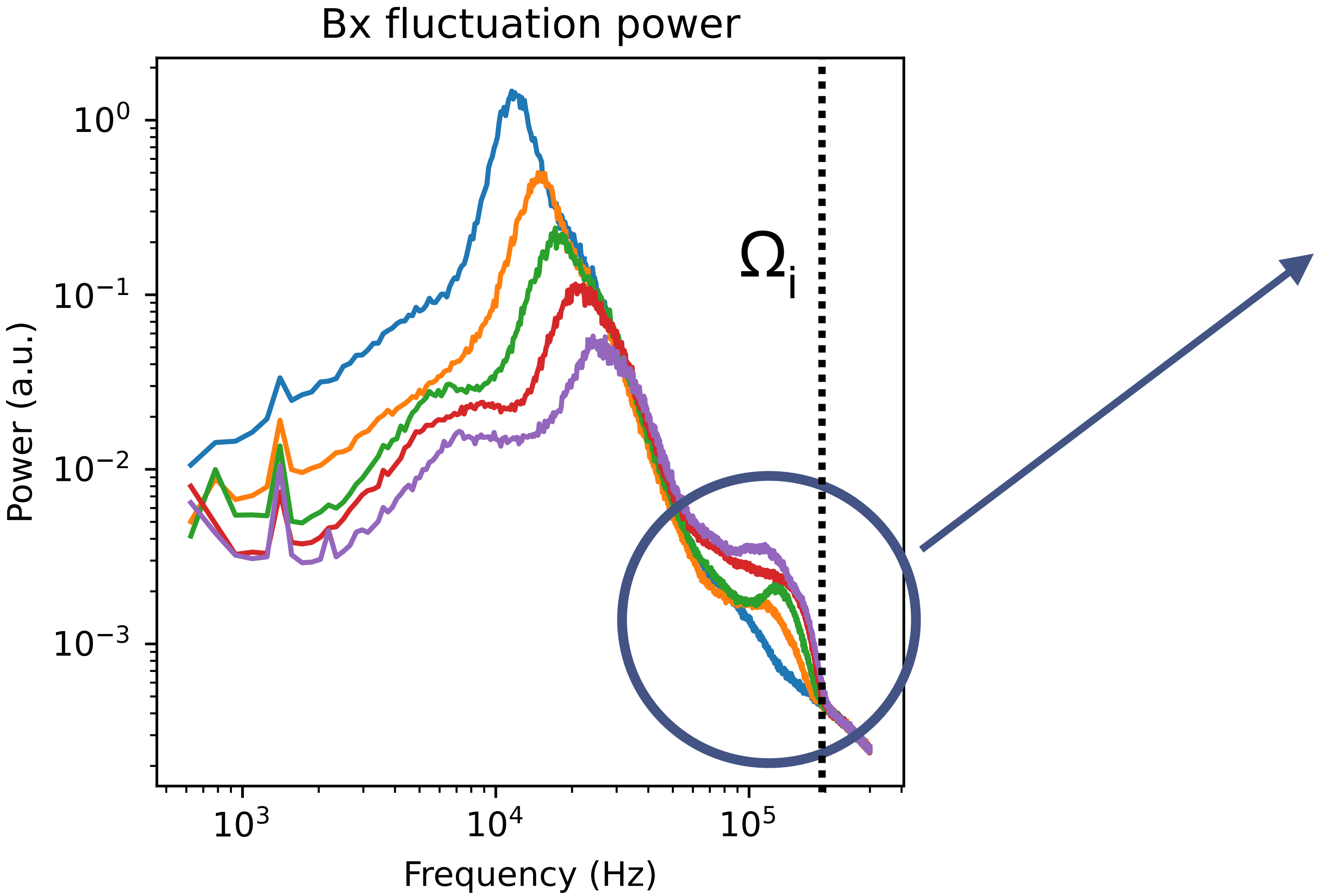

Bx fluctuation power

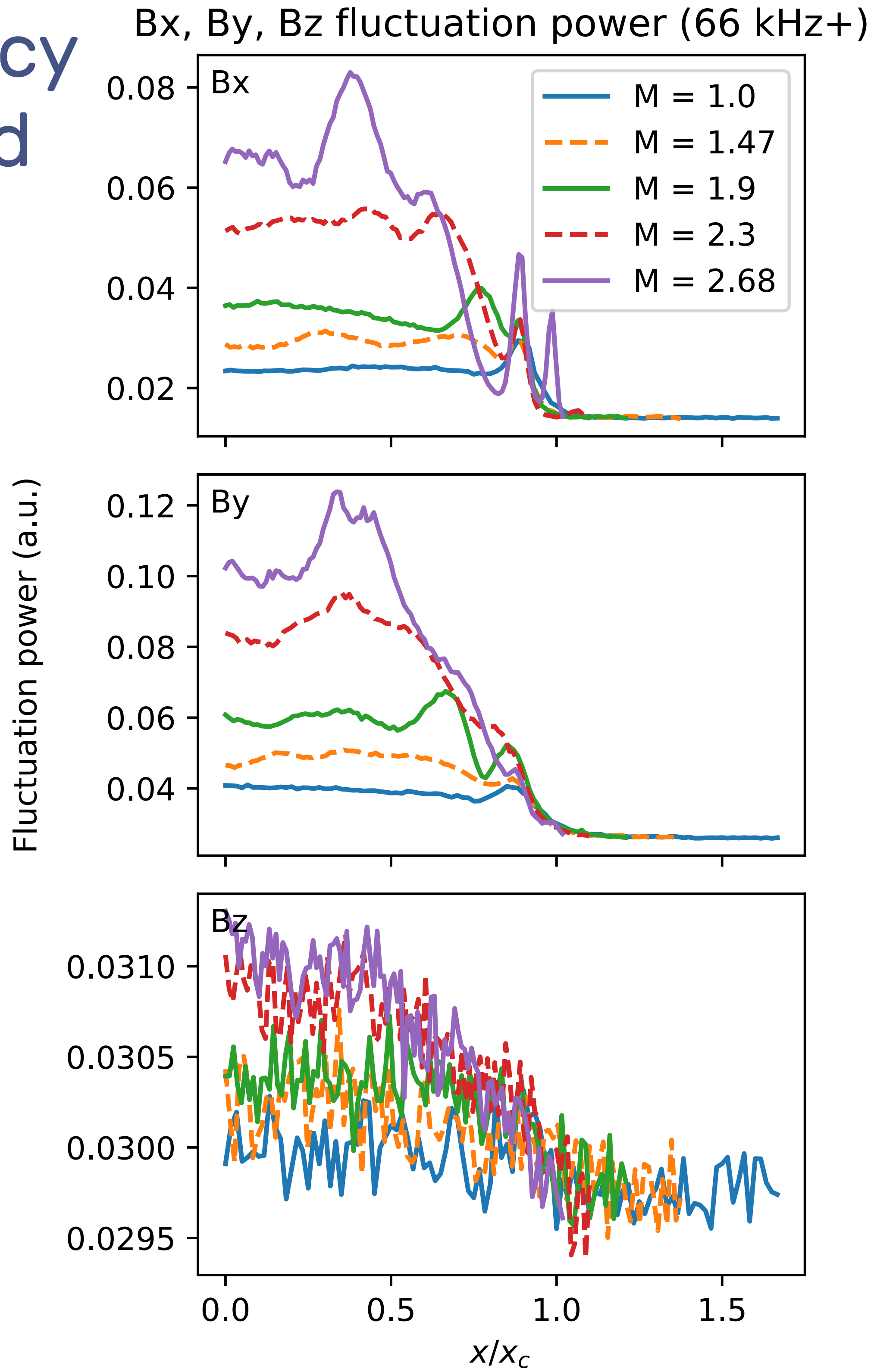
Increase in m number of dominant mode observed (consistent with frequency shift)



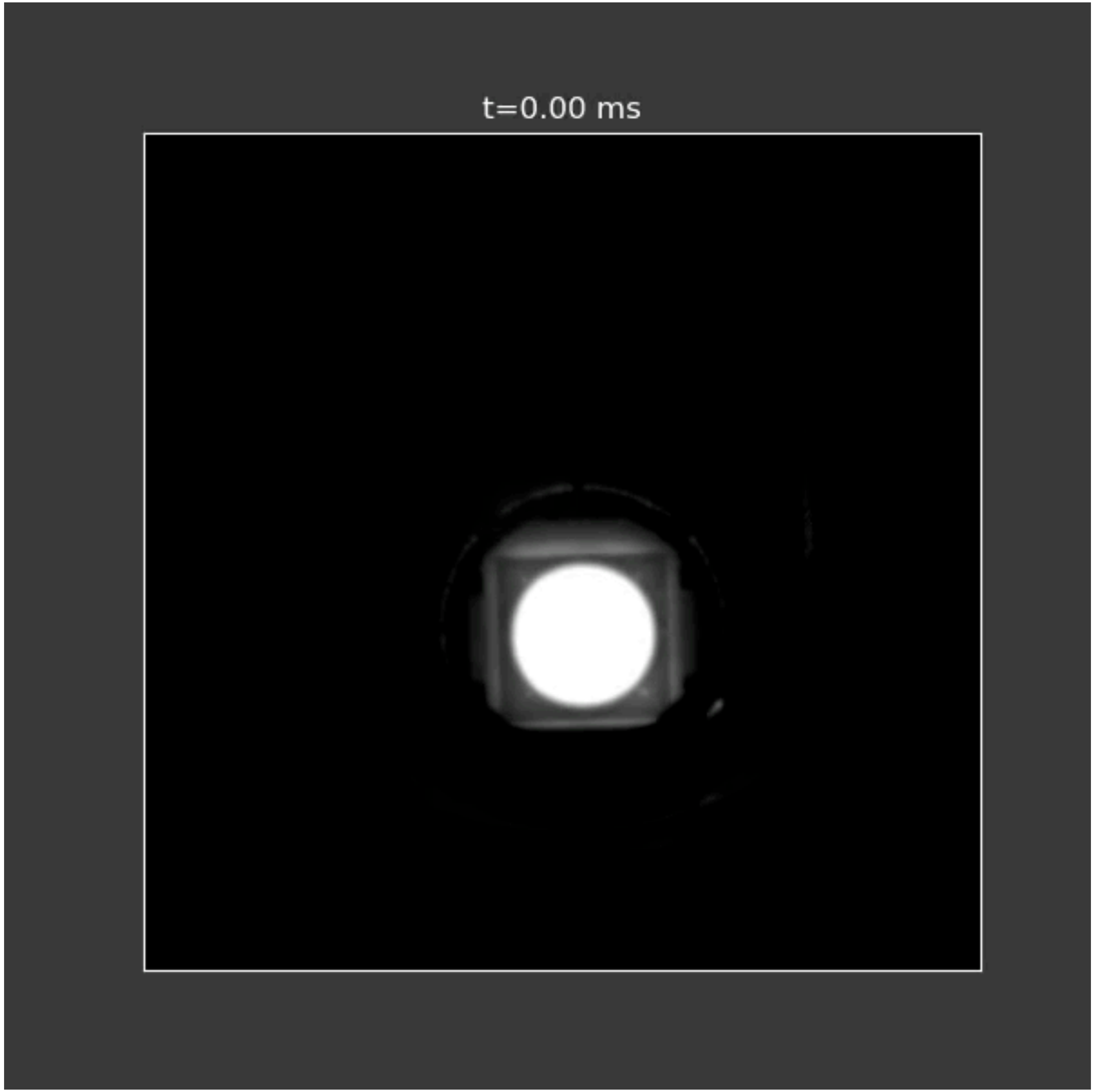
No change in B at measurement location – increasing m number & frequency caused by increasing mirror field

Growth in magnetic fluctuations at high frequency is near cyclotron frequency and is core localized





Fluctuations dominantly shear Alfven wave polarization. Too collisional for DCLC? Perhaps we are creating a cavity and trapping SAWs generated by the discharge source (fast electron driven)?



Visible light imaging: interesting dynamics observed

- Mirror ratio ~6 (600G -> 3500G)
- Bright, structured emission near mirror throat
- Work to do to characterize instabilities/axial variation in LAPD mirror configurations! (we welcome user research proposals!)