U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Comparison of Compressional Alfvén Eigenmodes in NSTX-U with Simulation Using the CAE3B Eigenmode Solver

Nicholas Geiser, Fordham University

N. A. Crocker (UCLA), H. Smith (MP-IPP, Greifswald), E. D. Fredrickson (PPPL)

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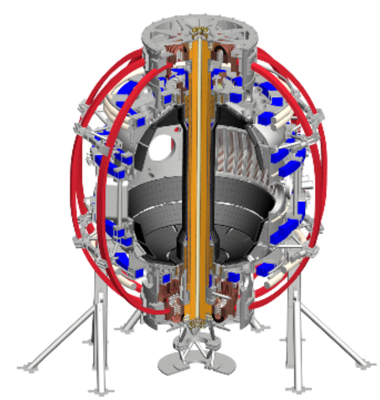
IPP

PPPL



Overview

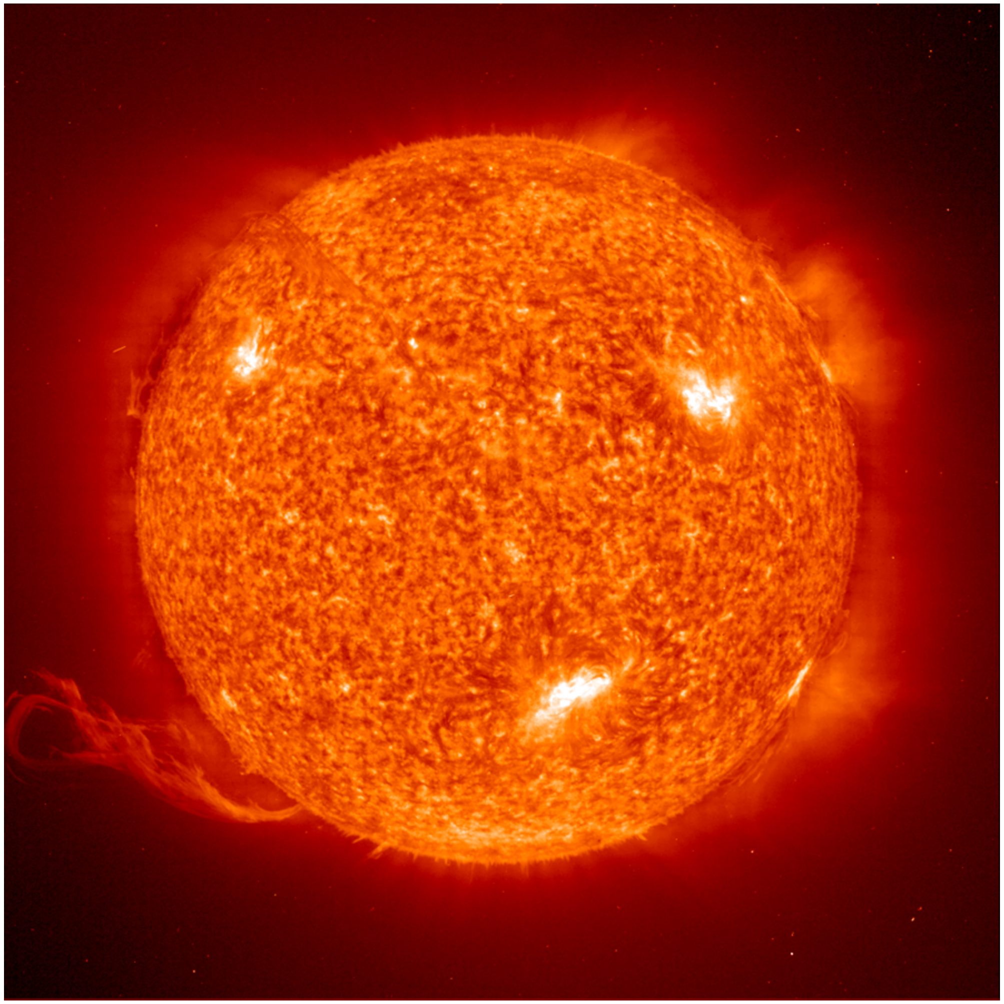
- Nuclear Fusion
- Tokamaks and the NSTX
- Alfvén Eigenmodes
- CAE3B Eigenmode Solver
- Comparisons
- Conclusions

The world needs better energy sources

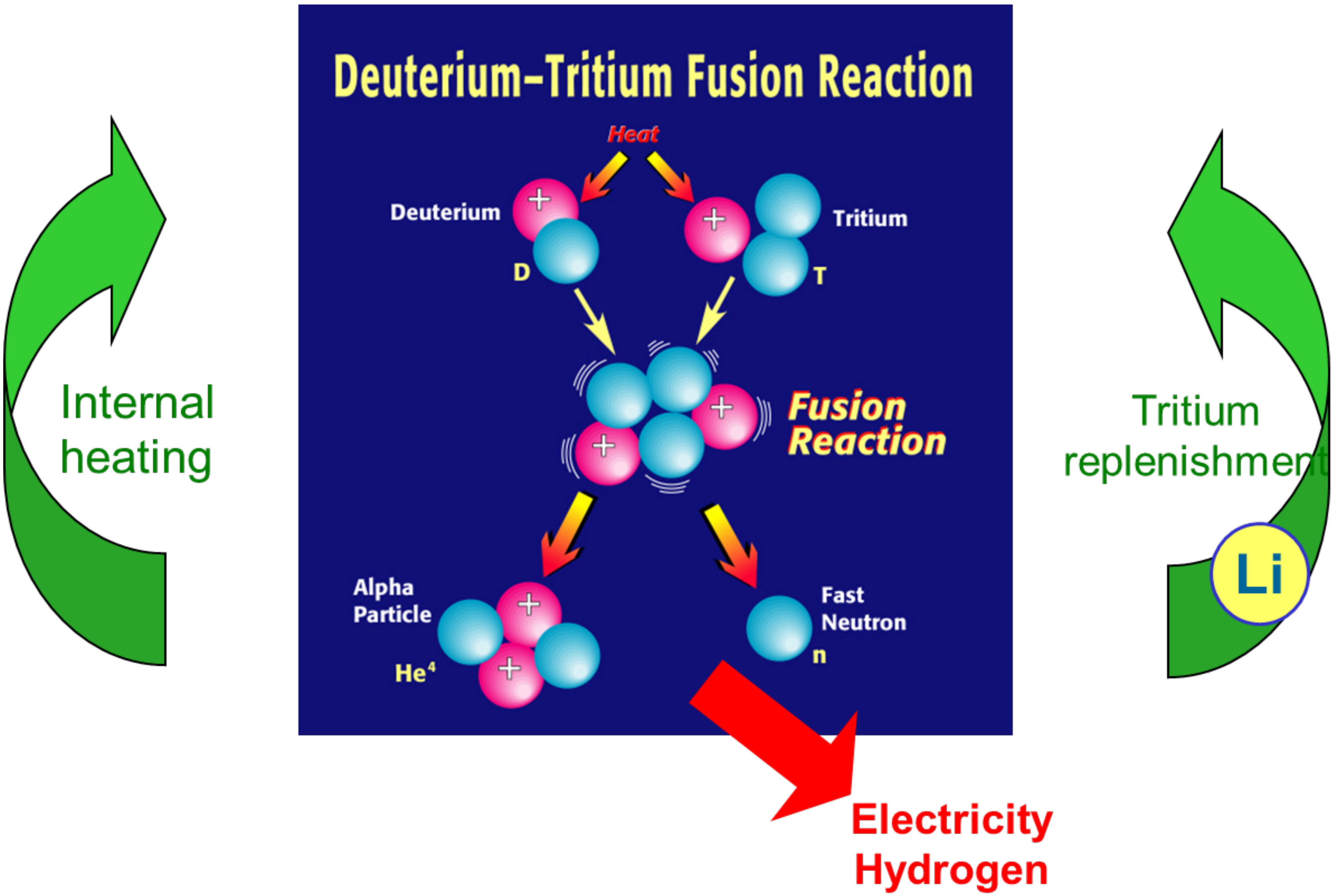
- World energy use will double by ~2045
- Continued reliance on fossil fuel will likely cause unacceptable climate changes
- A substantial R&D program is needed to develop alternative sources of energy
  - NSTX(-U) and PPPL

Nuclear Fusion: Light nuclei fuse into heavier ones

- Fusion powers the sun
- Heavier nuclei are lighter than their constituents, releasing energy
  - $E = mc^2$
- The most simple nuclear processes combine isotopes of Hydrogen into Helium



D-T Fusion



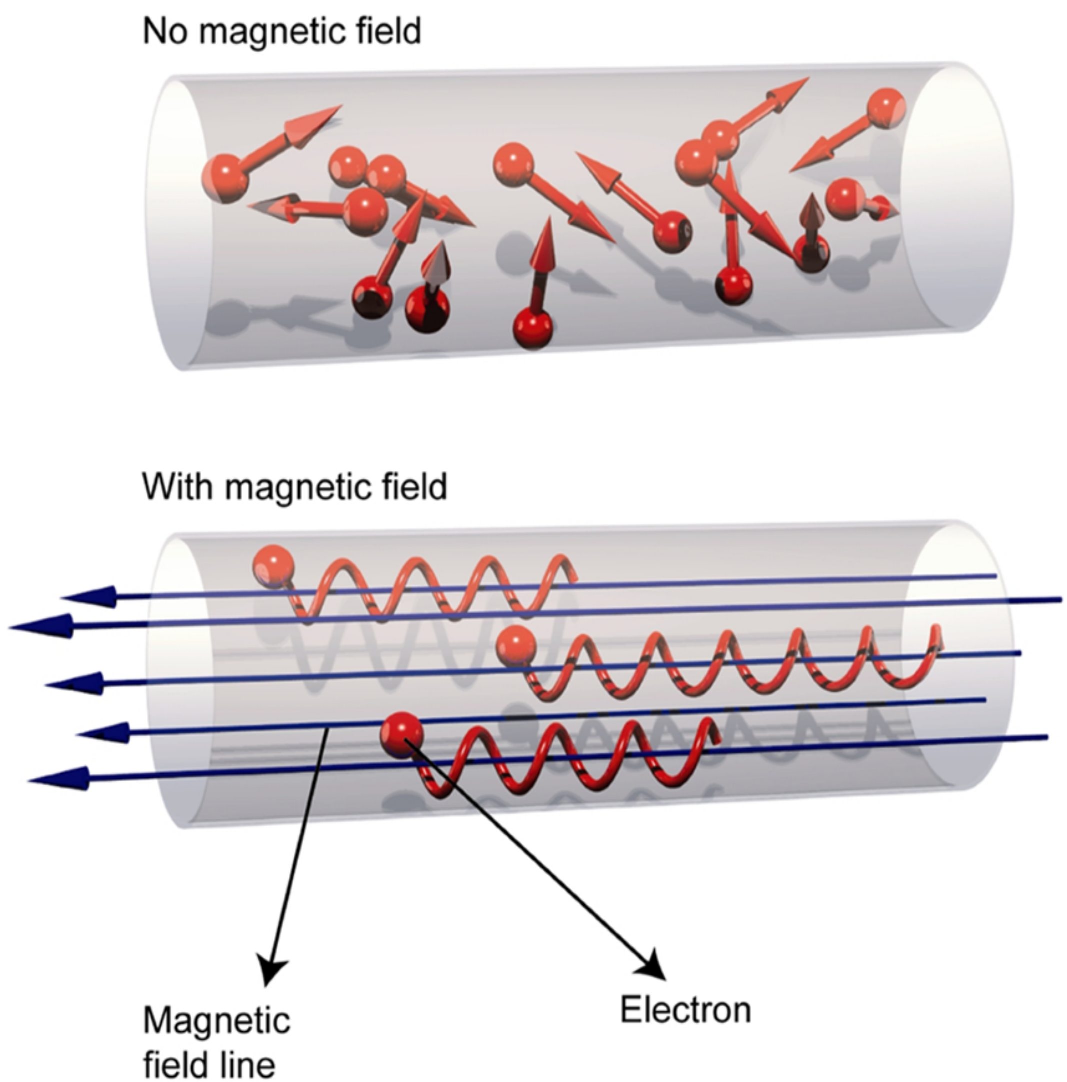
Deuterium–Tritium Fusion Reaction
Heat
Deuterium
D
Tritium
T
Fusion Reaction
Alpha Particle
He4
Fast Neutron
n
Internal heating
Tritium replenishment
Li
Electricity
Hydrogen

Terrestrial Fusion

- First create plasma
  - Hot ionized gas
    - Electrons separate from their nuclei
  - **Easy**

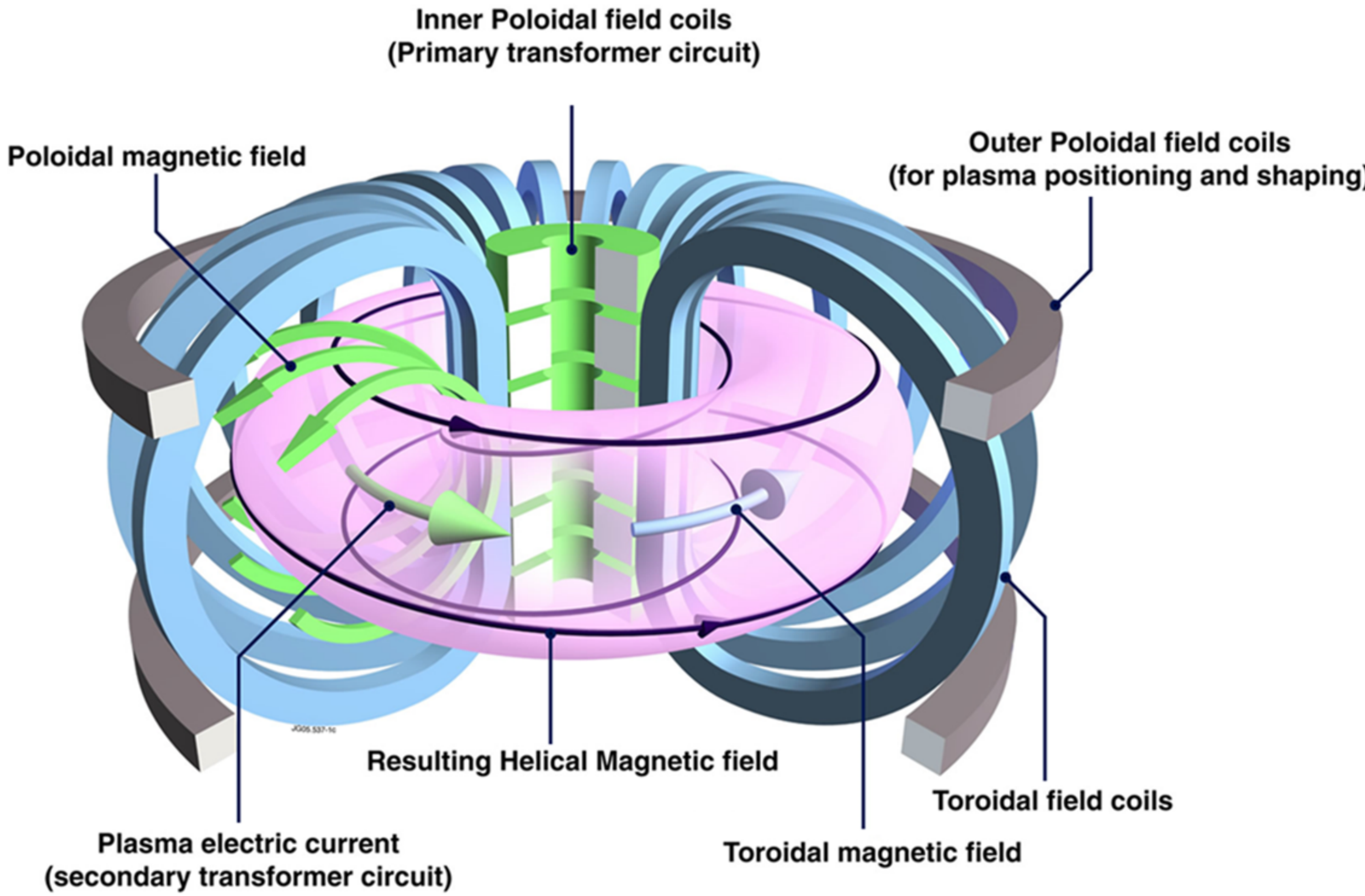
- Plasma must be hot enough to overcome electric repulsion force between nuclei
  - **Easy**

- Then confine the plasma
  - Simplest method of plasma confinement: magnetic fields
  - Lorentz Force: $\boldsymbol{F} = q(\boldsymbol{v} \times \boldsymbol{B})$
  - Charged particles will swirl around magnetic field lines
  - **Hard**



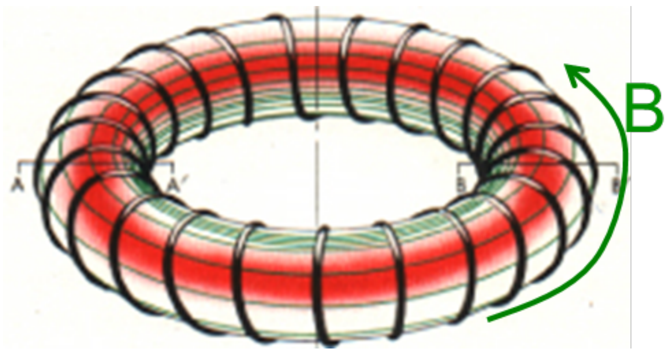
Tokamaks confine plasma into the shape of a torus

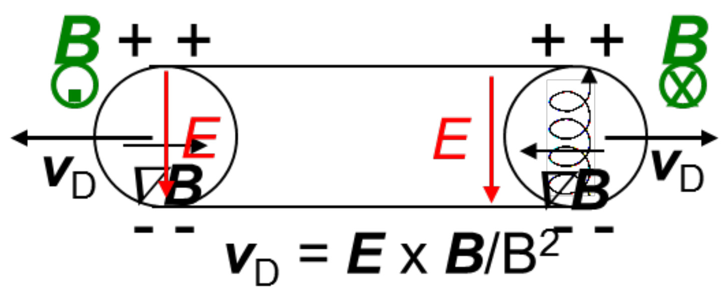
- Addition of toroidal (donut shaped) and poloidal magnetic fields results in closed, helical field lines



Why not use simple toroidal field lines?

- Several effects would cause plasma drift
  - Curvature and gradient in $\boldsymbol{B}$ cause single particles to drift vertically
  - Charge separation at the edges produces a downward $\boldsymbol{E}$ field that drives outward drift of plasma

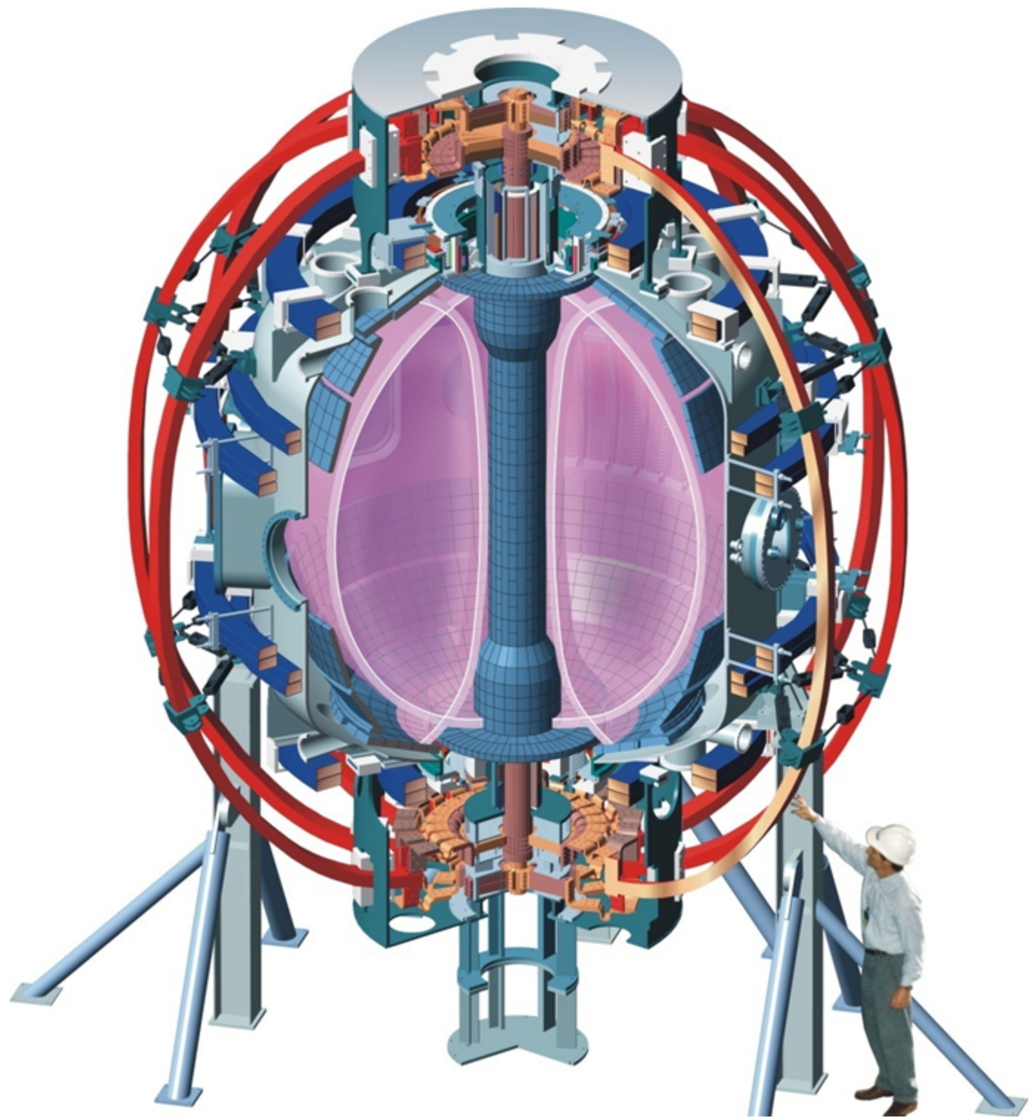




- Introduce rotational transform (helical twist from poloidal field) to field lines, so drifts are compensated over several transits
- Particles then never touch the device walls

NSTX designed to study high-temperature toroidal plasmas

- National Spherical Torus eXperiment
  - Recent upgrade (2015): NSTX-U
- Located at Princeton Plasma Physics Lab (PPPL)
- Spherical Tokamak
  - Squishes plasma
  - Higher temperatures
  - Better shaped plasmas



Magnetic confinement not perfect: plasmas “leak”

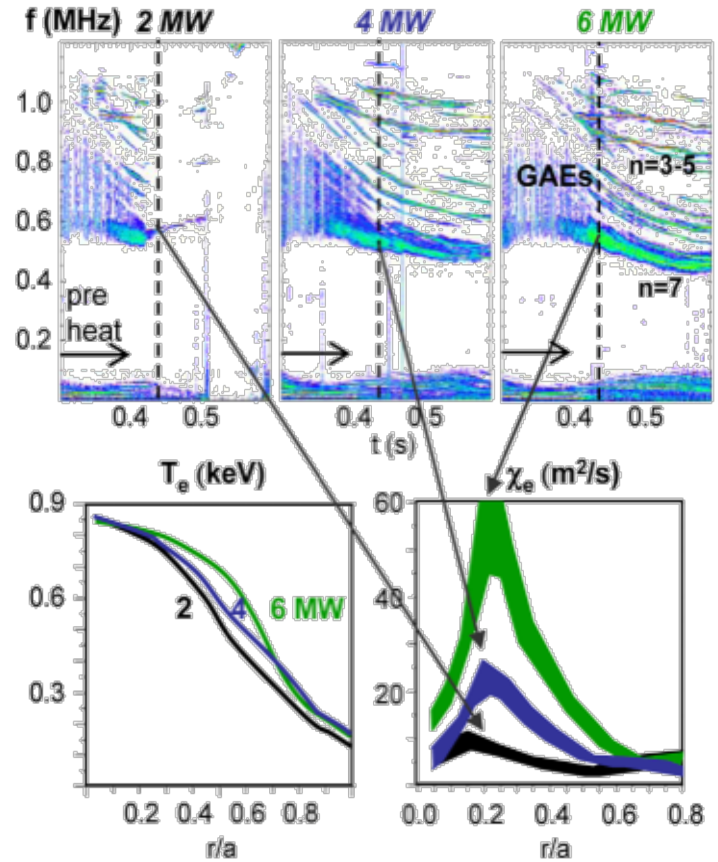
- Understanding this thermal transport in magnetized plasmas will lead to better energy sources

- A type of magnetohydrodynamic wave—compressional Alfvén eigenmodes (CAEs)—may contribute to thermal transport in tokamaks
  - Stochastization of resonant electron orbits?
  - Electromagnetic channeling of beam energy to plasma edge?

- Goals: better understand CAEs
  - Frequency and toroidal mode number of experimentally observed CAEs can be measured
  - CAE3B eigenmode solver numerically simulates CAEs in experimental plasmas
  - CAE3B simulations can be compared with observed modes in an NSTX discharge to verify the physics of CAE3B and further our understanding of CAEs

CAEs candidates for core electron thermal transport in NSTX

- Anomalous heat diffusivity (χ_e) observed in core of NSTX beam heated plasmas
- CAEs excited by Doppler-shifted cyclotron resonance with beam ions
  [N. N. Gorelenkov, NF 2003]
- CAE activity correlates with enhanced χ_e in core NSTX beam heated plasmas
  - Modes originally identified as GAEs
    [D. Stutman, PRL 2009;
    K. Tritz, APS DPP 2010 Invited Talk]
  - later shown to include CAEs
    [N. A. Crocker, PPCF 2011]



[D. Stutman PRL 102, 2009]

Alfvén waves are propagating distortions of magnetic field

- Magnetic field approximately "frozen" into plasma
  - Plasma motion distorts field
  - Field provides restoring force
  - Oscillations and wave propagation

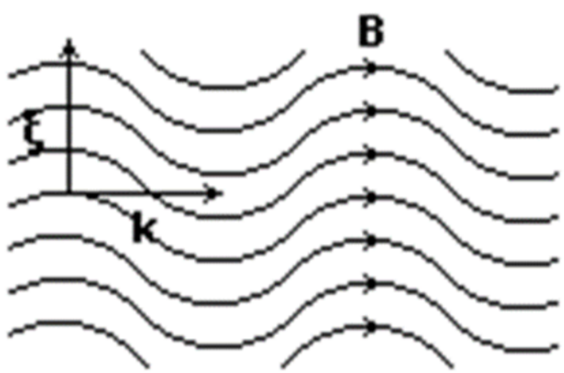
- Eigenmodes: global coherent oscillations at discrete set of frequencies
  - Alfvén eigenmodes (AEs) are Alfvén waves confined within plasma
  - AEs appear as solutions to an eigenmode equation
    - Can be solved using existing numerical techniques

- AEs excited by energetic ions from neutral beam heating of plasma
  - Only *unstable* AEs are observed in any given plasma
    - Not every AE solution appears in a plasma

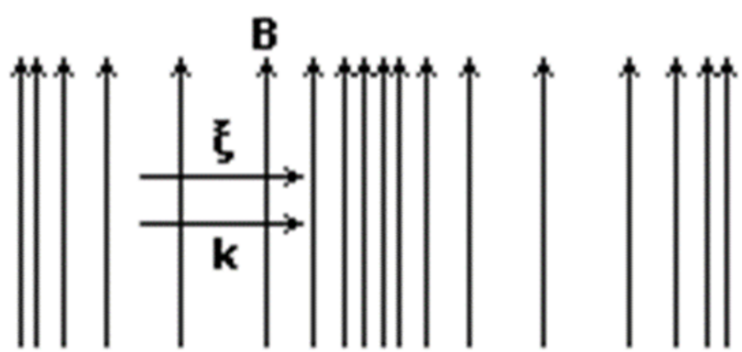
- Each AE has a characteristic frequency

Two Kinds of AEs

- Shear: global Alfvén eigenmodes (GAEs)
  - Motion transverse to k
- Compressional: compressional Alfvén eigenmodes (CAEs)
  - Motion parallel to k
  - Characterized by toroidal (n), poloidal (m), and radial (s) mode numbers
    - CAEs in a perfectly toroidal tokamak would be toroidal harmonics in n, m, and s
    - Behave similarly to quantum numbers of Hydrogen atom



Shear



Compressional

CAEs and GAEs in the NSTX can be identified with array of edge magnetic sensing coils

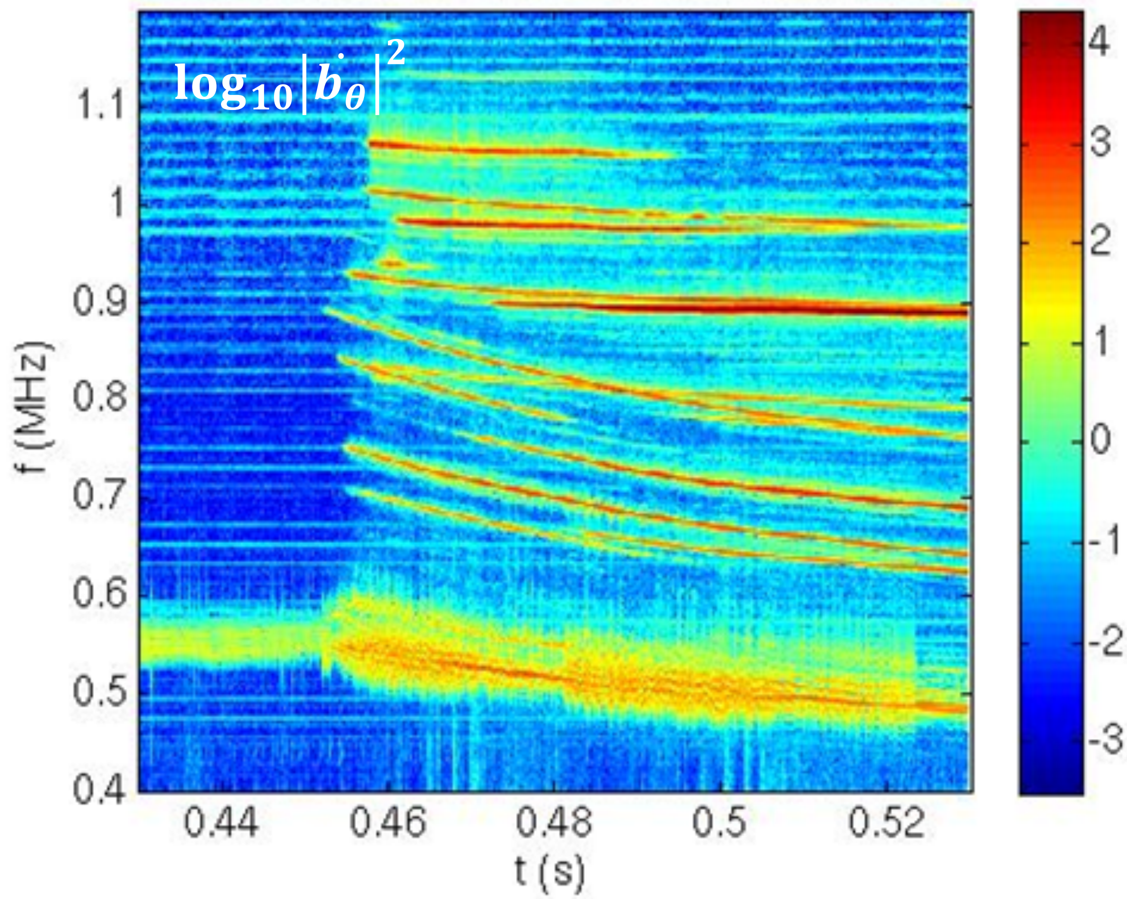
- Faraday's Law measures the time rate-of-change of the toroidal magnetic flux through each coil:

$$\mathcal{E} = \left|\frac{d\Phi_B}{dt}\right|$$

- Short-time FFT raw data into frequency-time space
  - Regions of *high* $|\dot{b_\theta}|^2$, *narrow-band in* f and *temporally extended* are experimental modes

- CAEs and GAEs difficult to unambiguously identify by f alone

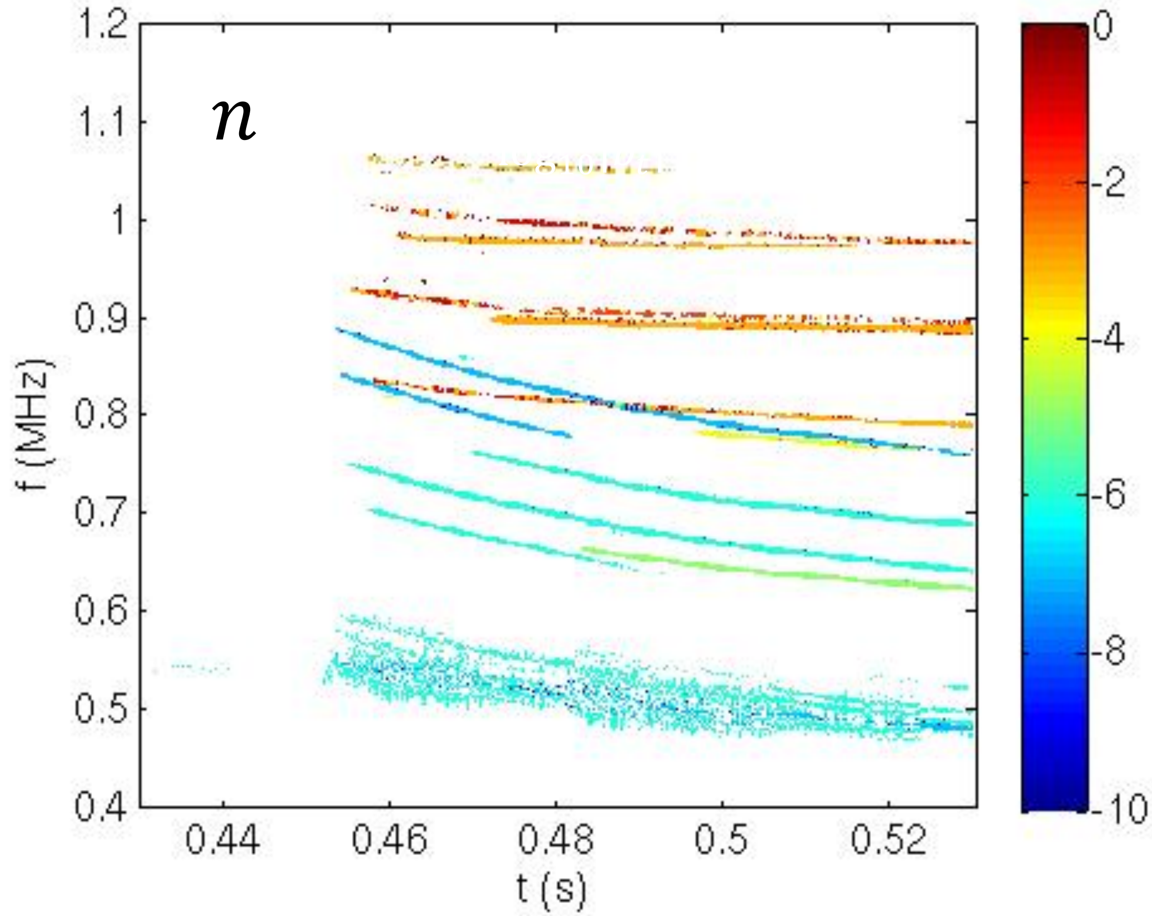
Observed modes in NSTX shot 130335



Toroidal mode number n obtained by best-fitting data to toroidally distributed array

- Facilitates identification and comparison
- Can be complicated by incorrect or ambiguous n determination (e.g. from noise or pickup)
- $n = -3$ and $n = -6$ modes exhibit different behavior
  - These will be compared to simulation

Observed modes in NSTX shot 130335



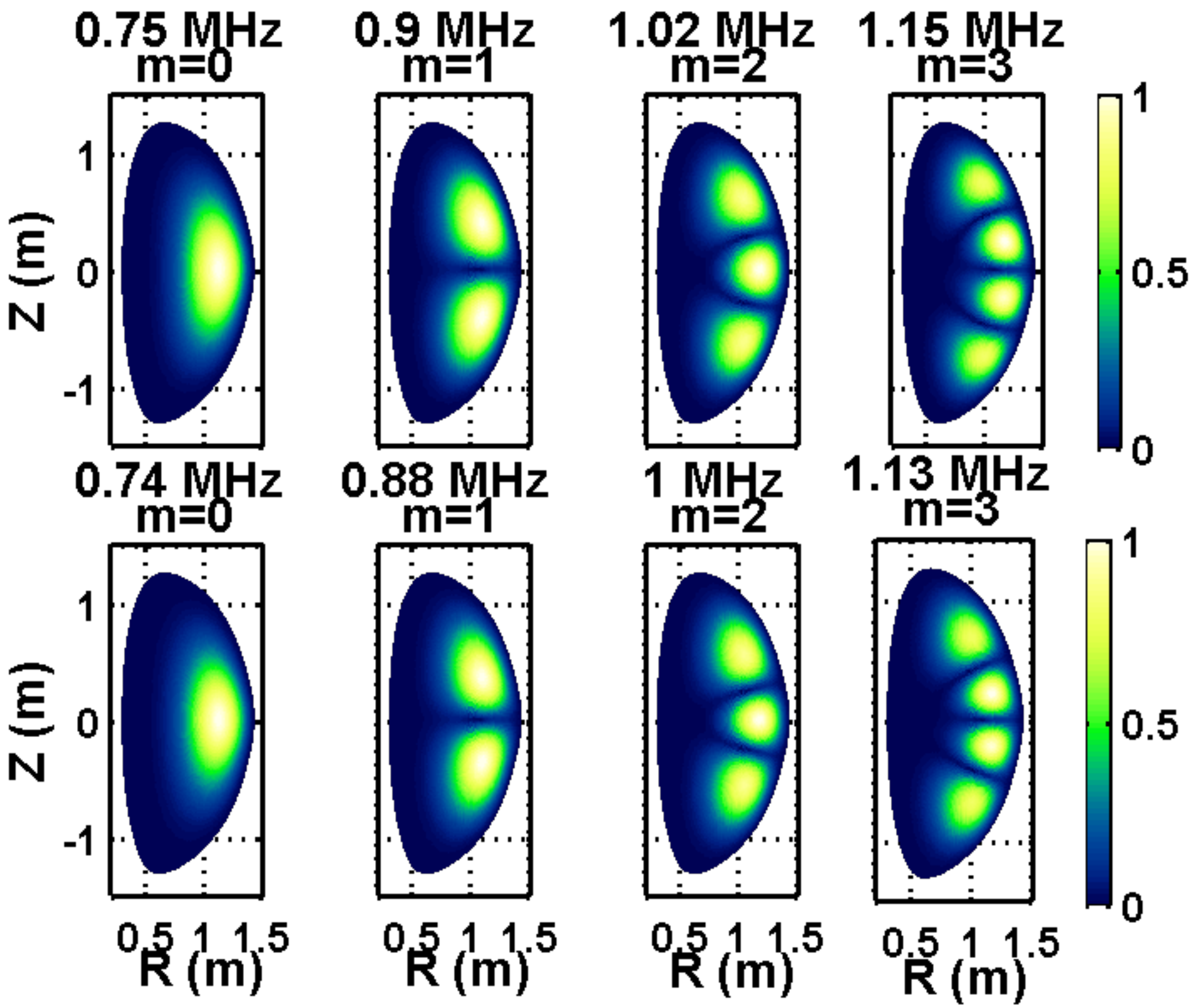
Eigenmode solver CAE3B can be used to simulate CAEs in NSTX plasma

- Simulated CAEs can be compared to observed modes in the NSTX to validate the physics of CAE3B
  - CAE3B finds all CAEs (both stable and unstable) in a plasma shot for a given n and time
- CAE3B uses simplified Hall MHD physics
  - Removes coupling to shear Alfvén waves
    - CAE3B solutions are *only* CAEs
  - No stability physics
- Only compare subsets of observed and simulated modes
  - Observed modes include CAEs and GAEs
  - CAE3B produces only CAEs and spurious solutions
  - CAE3B doesn't predict which CAEs are unstable

$|b_\parallel|$ of simulated CAEs: NSTX shot 130335, $n = -3$

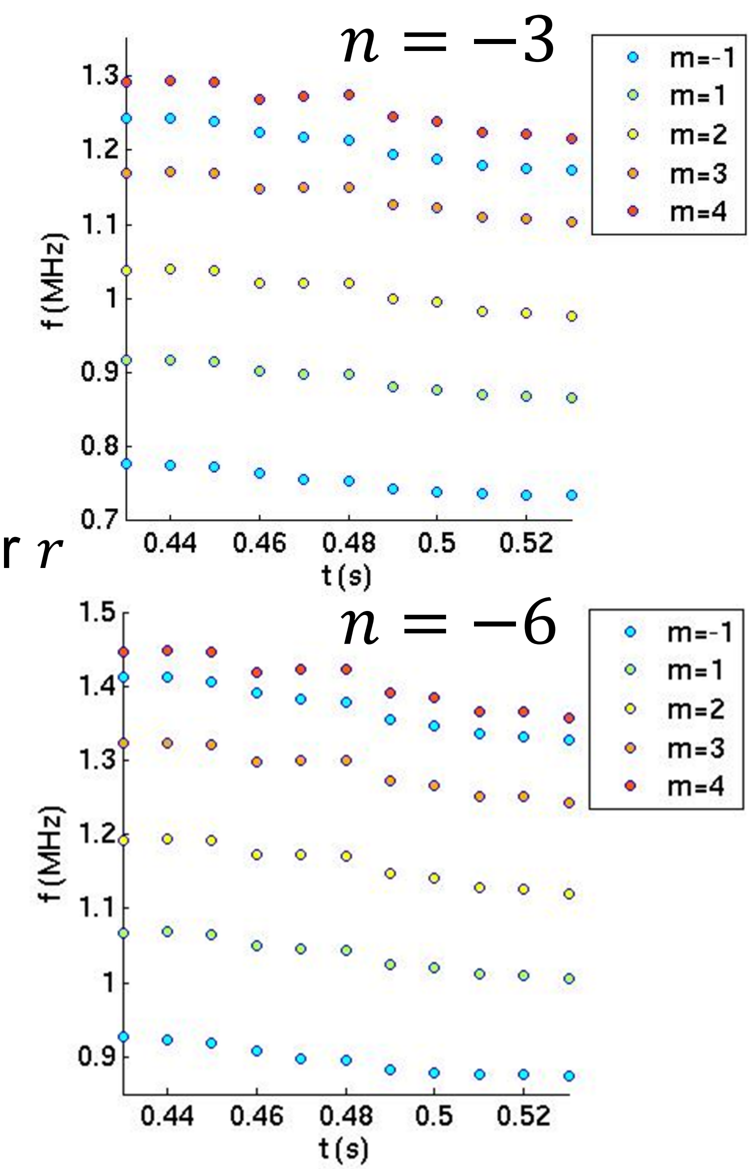
$t = .480s$

$t = .490s$

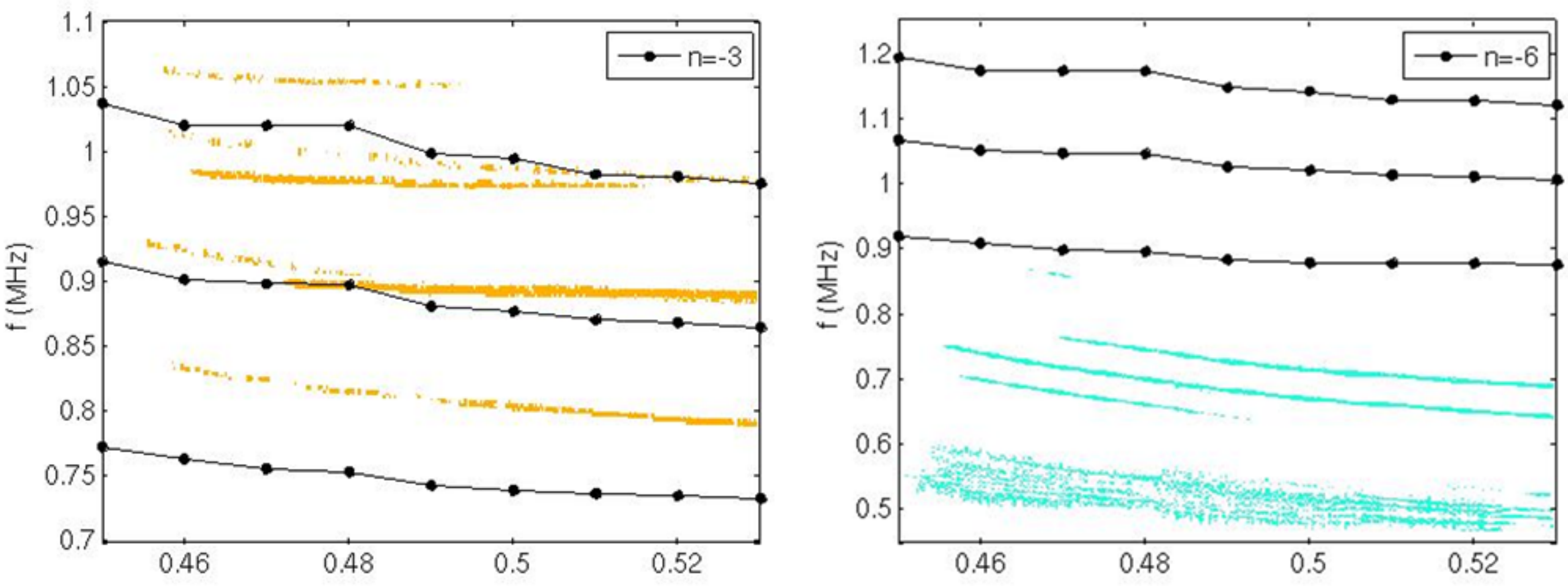


Poloidal mode number m can be used to track CAEs in simulation

- Visual comparison not a tenable method of tracking CAEs
- CAEs adiabatically evolve, conserving mode numbers: (n, m, s)
  - Track CAEs over time with mode numbers
- n is an input parameter in CAE3B
- Quick (and dirty) method for calculating m: poloidal Fourier transform of $b_{||}$; integrate over r
  - Peak in integrated spectrum gives m
  - Does not always correctly identify m
- Cross-coherency calculation resolves misidentifications
  - $\frac{b_{t_1} b_{t_2}^*}{\sqrt{|b_{t_1}|^2 |b_{t_2}|^2}} \approx 1$ for same CAEs



Comparisons of 3 lowest-f simulated CAEs with observed modes ($n = -3$ and $n = -6$)



$n = -3$ observed modes probably CAEs; $n = -6$ probably GAEs

- The $n = -3$ simulated CAEs have $f(t)$ and $\min(f)$ similar to experimental modes → *probably CAEs*
- The $n = -6$ experimental modes have f too low and much higher $|\Delta f/\Delta t|$ than simulation → *probably GAEs*
- Consistent with identification of high-n, low-f modes as GAEs and vice-versa as CAEs in previous research [Crocker, NF 2013]

	$n = -3$		$n = -6$	
	CAE3B	Expt.	CAE3B	Expt.
f_{min} (kHz)	$\sim$750	$\sim$820	$\sim$900	$\sim$500
$\lvert\Delta f/\Delta t\rvert$ (kHz/ms)	$\sim$0.5-0.9	$\sim$0.1-0.7	$\sim$0.6-1.0	$\sim$1.3-1.9
Δf (kHz)	$\sim$80-150	$\sim$80	$\sim$80-150	$\sim$40

CAE3B enhances toolkit for distinguishing CAEs and GAEs in NSTX and NSTX-U plasmas

- Combination of $f(t)$ with $\min(f)$ comparison strengthens identification
  - Powerful comparison tool, but not conclusive: predicted f close but not exact
- f-spacing between modes larger in simulation than experiment; not fully understood, but some effects known
  - Plasma rotation not included in simulations here (under development)
  - Computational domain restricted for numerical reasons, boosting frequencies
- Known effects not expected to largely affect $\Delta f/\Delta t$
  - CAE3B remains a useful tool for distinguishing CAEs and GAEs and can be used for any NSTX or NSTX-U plasma shot

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