Alpha Physics Issues in Compact Stellarators

Don Spong

Oak Ridge National Laboratory

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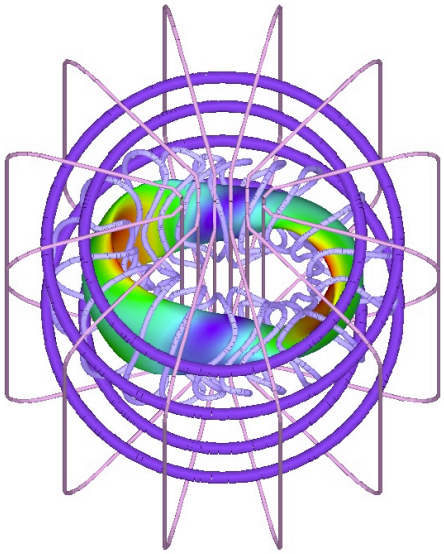
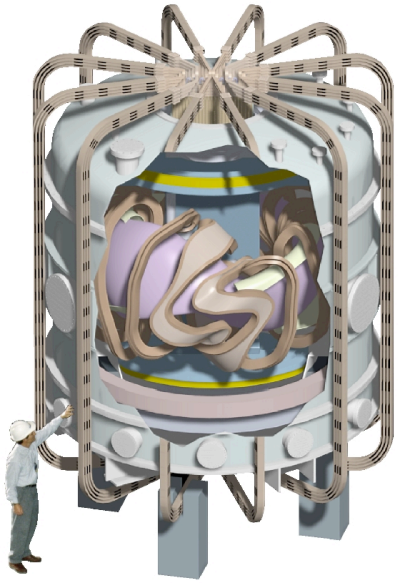




Stellarators and tokamaks share generic burning plasma physics issues:

- Ignition access and maintenance
  - Must go through the “Cordey pass”
    - Density/temperature path that minimizes heating power - determined by
      - confinement scaling
      - alpha loss rates
  - Profile sustainment
    - Pressure profile/bootstrap current/rotational transform coupling
    - Plasma flow/ambipolar electric field - maintenance of enhanced confinement conditions
  - Burn Control
    - Stability depends on temperature scaling of confinement

Generic Burning Plasma Physics Issues (cont'd.)

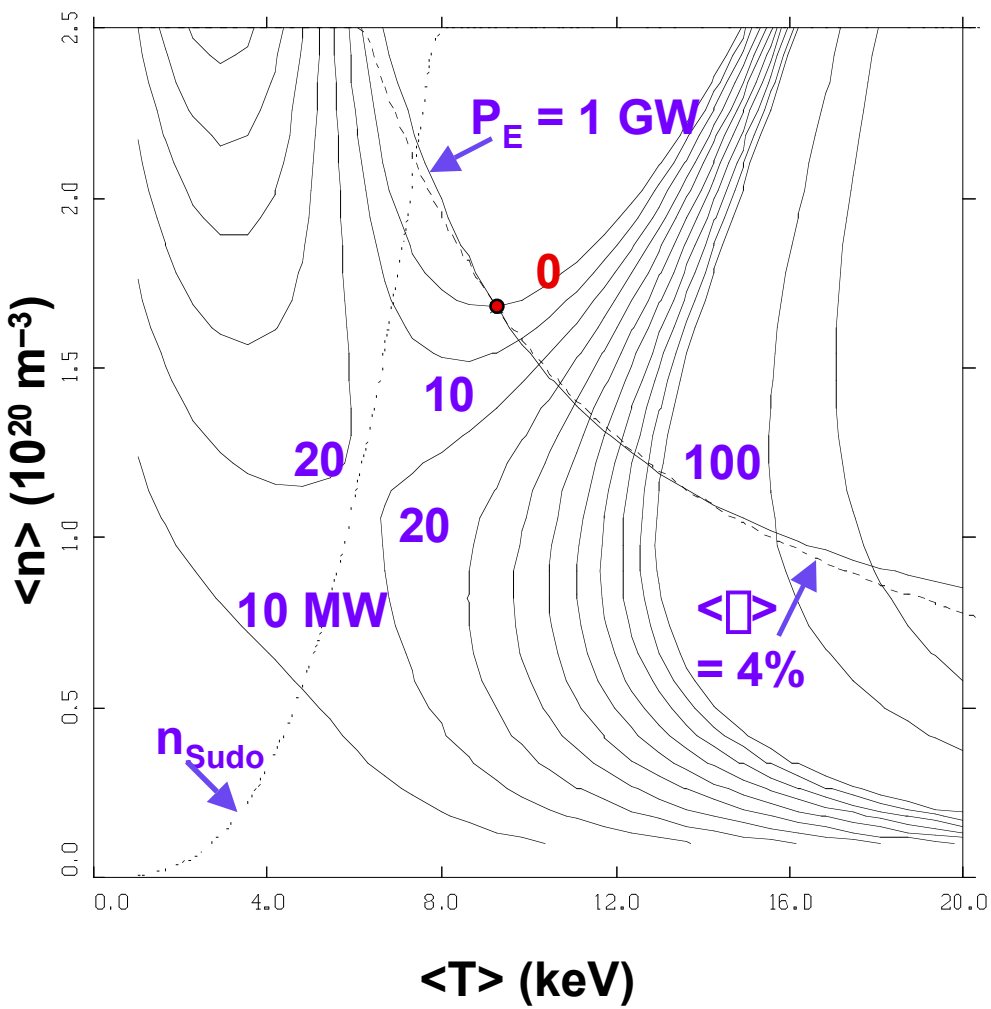
- Alpha particle orbit confinement
  - Losses driven by symmetry breaking
    - Tokamaks - toroidal field ripple
    - Stellarators - deviations from $B = B(\theta,\phi)$ in Boozer coordinates where θ = toroidal, helical or poloidal angles
  - Impact on power balance
  - First wall protection - loss regions, power loading
  - Energy recovery

Generic Burning Plasma Physics Issues (cont'd.)

- Alpha-driven instabilities and collective phenomena
  - Alfvén instabilities (shear/compressional)
  - Fishbones, sawteeth
  - Kinetic ballooning instabilities
  - Interaction with tearing/kink instabilities
  - Ion cyclotron/Loss cone emission
- Nonlinear phenomena
  - Cascades, avalanches, overlapping resonances
  - Chirping, bursting
- Alpha channeling
  - Direct transfers of alpha energy to core ions via waves
  - More efficient use of alpha energy
    - Not vulnerable to orbit losses during long collisional slowing-down time on electrons

Access Path to Ignition: Operating Space for a Quasi-toroidal Stellarator Reactor

(taken from J. Lyon, IAEA 2000 (Sorrento meeting)



- Ignition point (0) is determined by balance between
  - alpha heating power (1/5 of fusion power)
  - plasma energy losses

***R* = 7.1 m, B_0 = 5.4 T**

- **Operating Point**

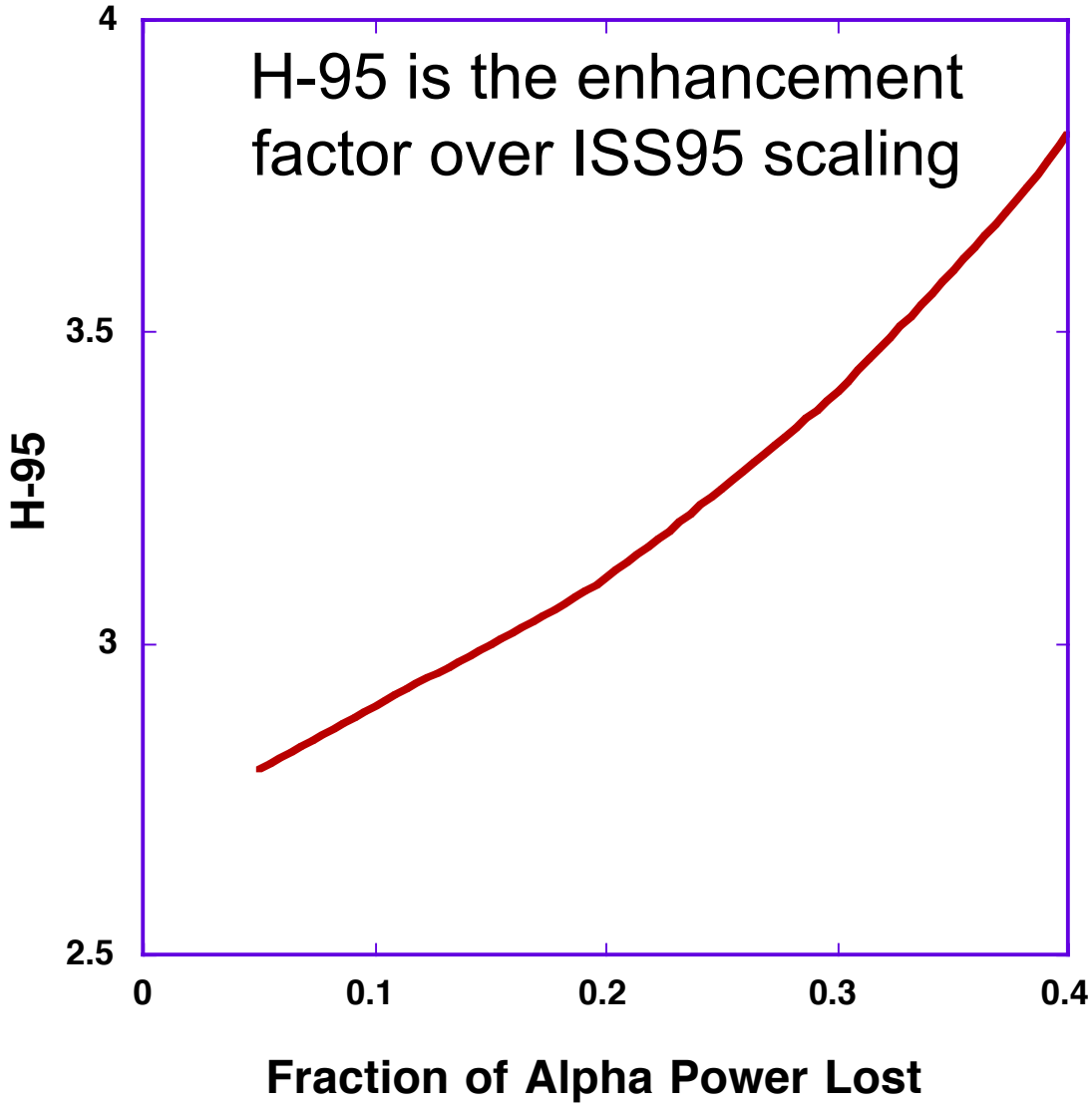
<*n*> = 1.7 x 10^{20} m^{-3}, <*T*> = 9.3 keV
<β> = 4.04%, for H-95 = 2.9
n_{DT}/n_e = 0.82, Z_{eff} = 1.48

- **Saddle Point**

<*n*> = 0.9 x 10^{20} m^{-3}, <*T*> = 5.4 keV
<β> = 1.4 %, and P_{aux} = 20 MW

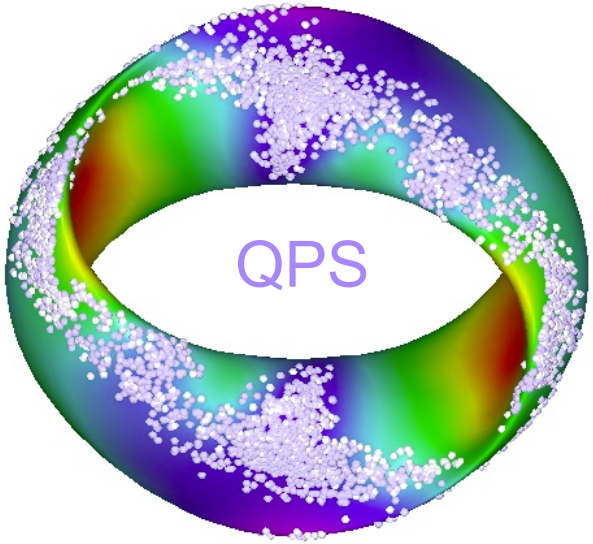
Assumes ARIES-AT *n*(r/a) and *T*(r/a), β losses = 0.1, $\beta_{He}/\beta_{\alpha}$ = 6
B_{max} = 12 T

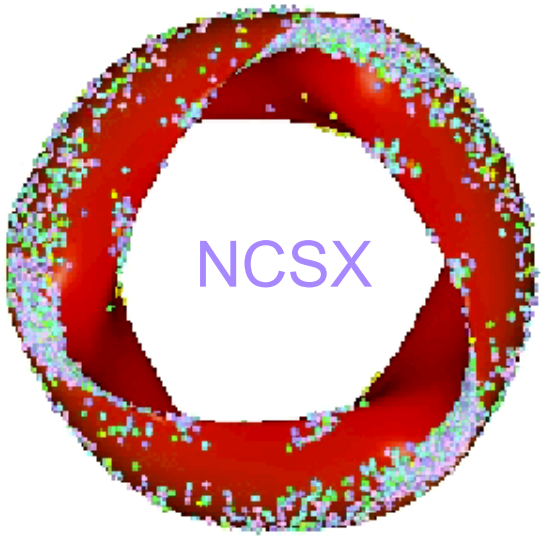
With higher alpha-particle losses (less heating power) confinement must be better to maintain a steady-state power balance [from J. F. Lyon, IAEA 2000 (Sorrento)]



Fast ion losses in toroidal devices are dominated by trapping in local wells:

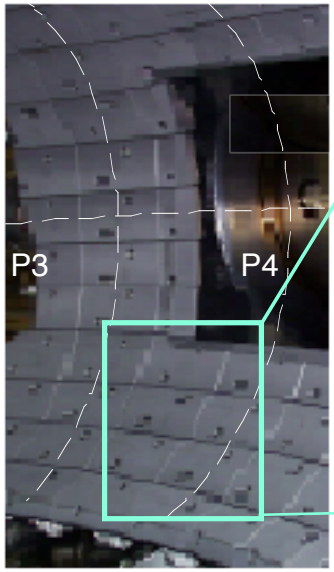
Fast Ion losses In Compact Stellarators

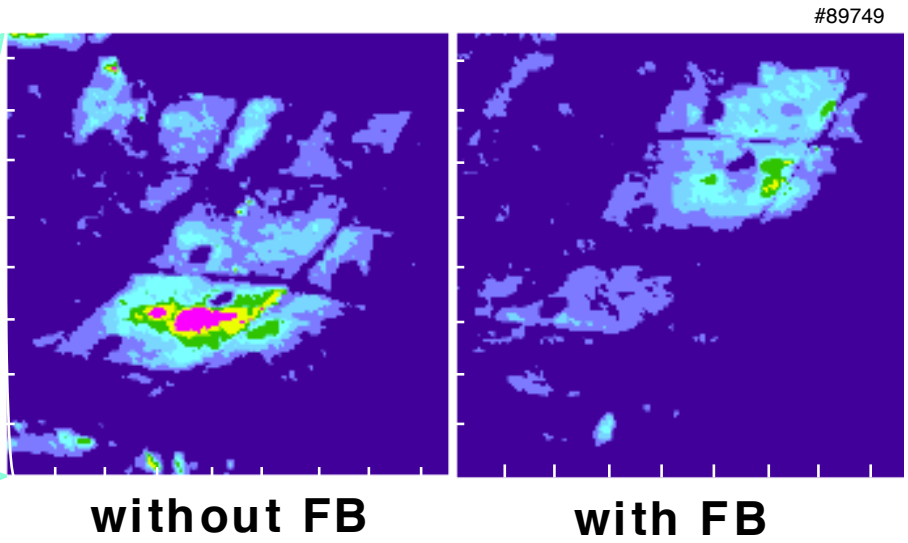




JFT-2M (tokamak)

- Ripple reduced 50% with Ferritic boards (FBs)
- Dramatic reduction in ripple losses - boundary moves out in radius as expected

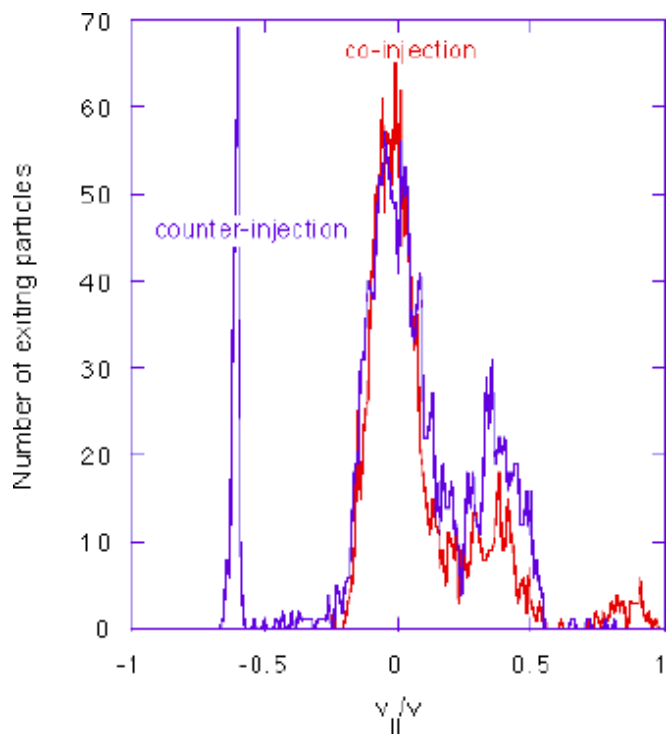




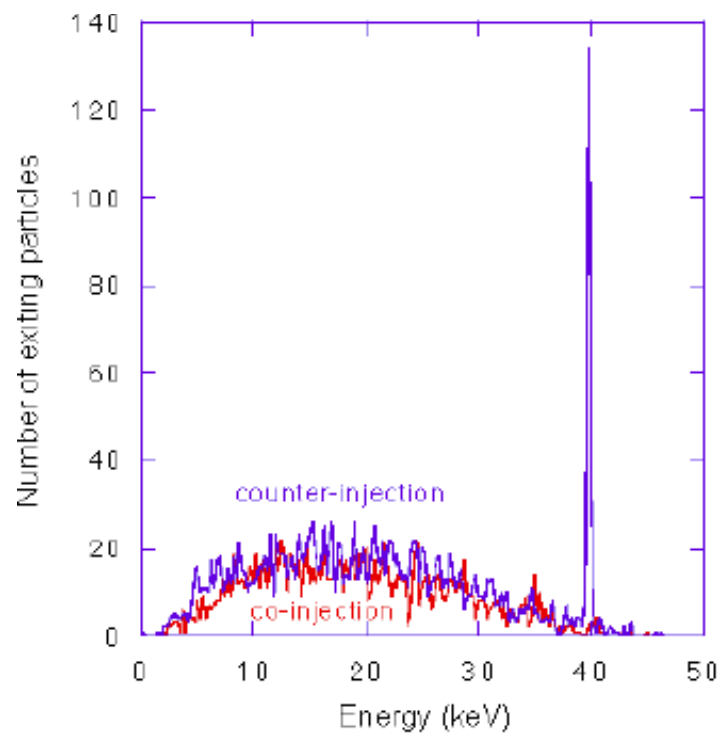
Histograms of escaping fast ions in compact stellarators elucidate the loss mechanisms.

- There are prompt losses for counter-moving particles
- As fast ions slow-down, they pitch angle scatter
- Trapped/transitional orbits lead to a large fraction of the intermediate energy losses

Pitch angle distribution

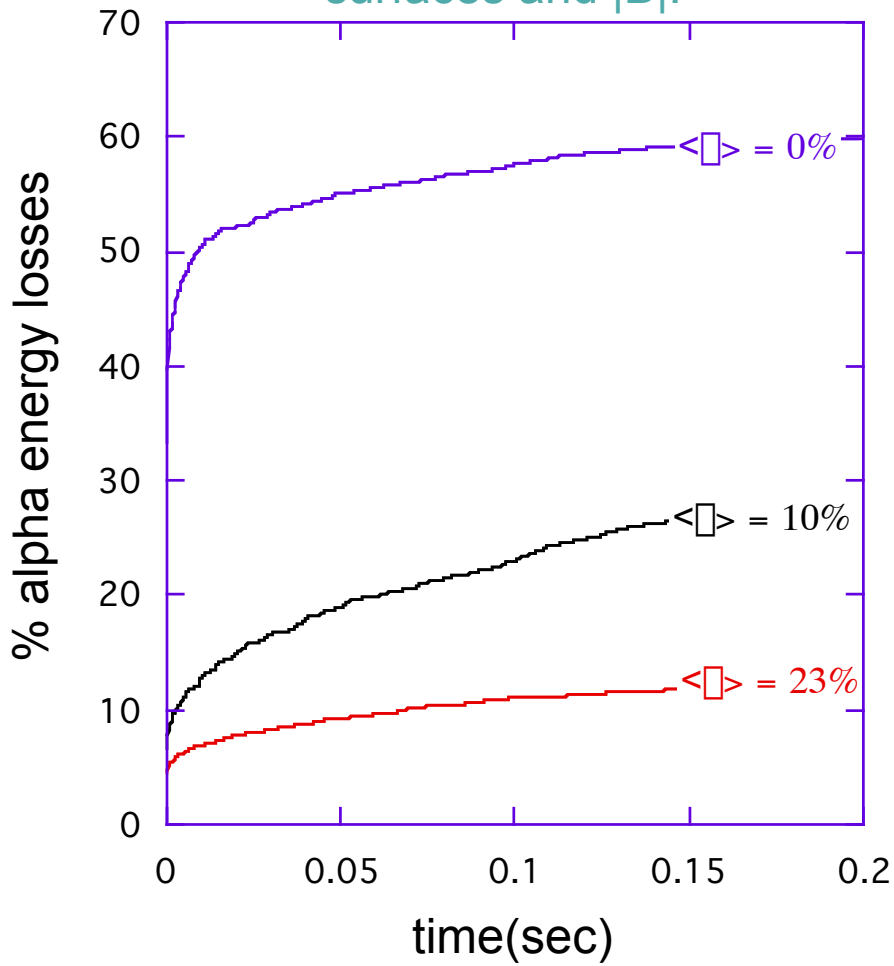


Energy distribution

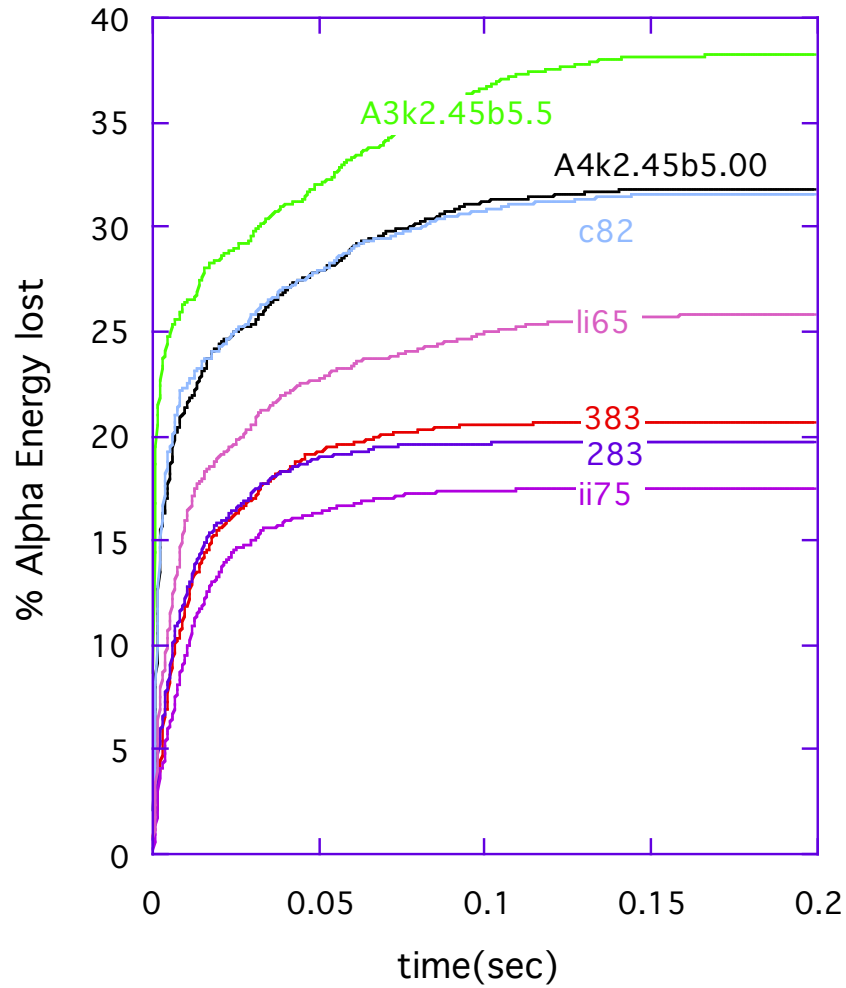


Compact stellarator designs are already achieving tolerable level of alpha loss. Further configuration optimization research is expected to lead to even lower losses.

Alpha loss rates improve in a second stable QPS device as □ is increased. The well formed in |B| aligns flux surfaces and |B|.

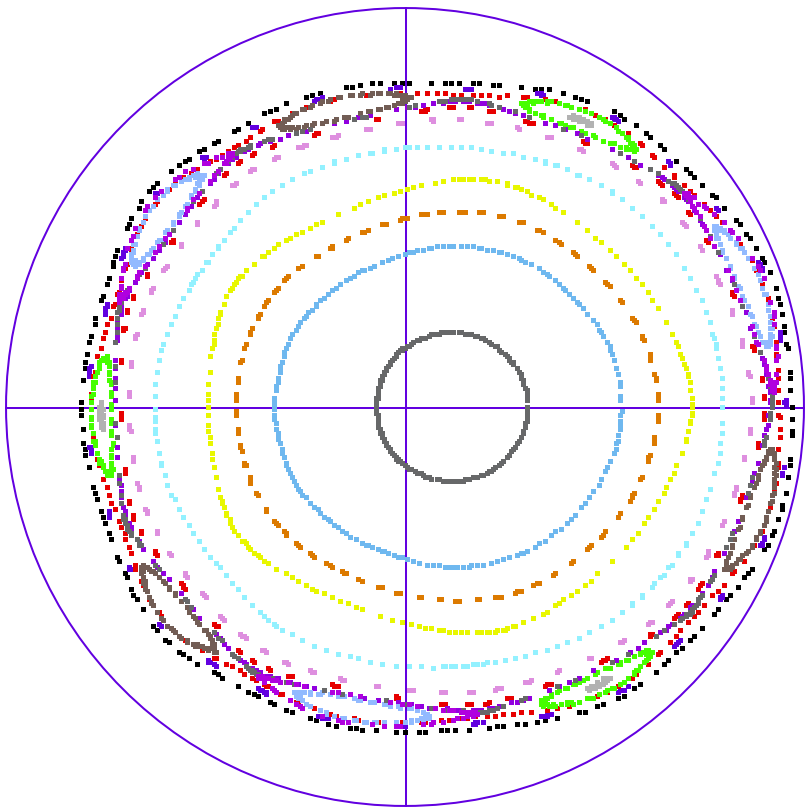


Alpha loss rates improve in a series of QAS devices as the |B| spectrum is made more symmetric.

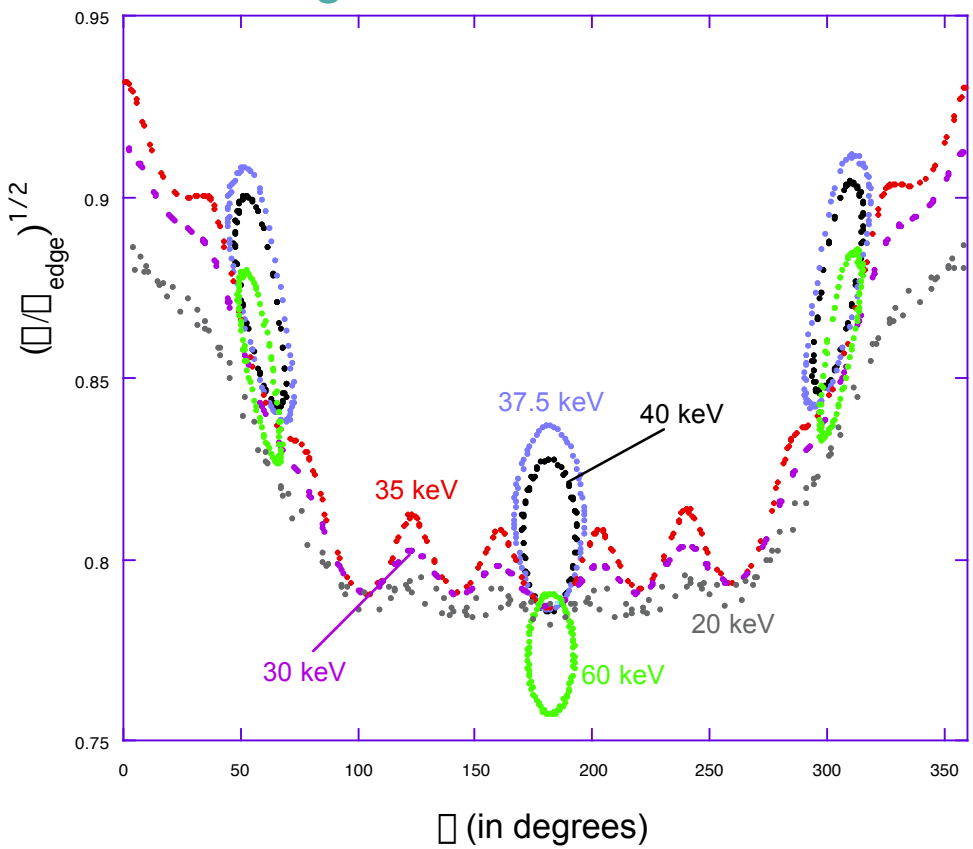


Energetic passing particles in compact stellarators form drift islands over limited regions of phase space. Control of these islands could offer an attractive mechanism for alpha ash removal and/or for burn control.

Drift islands for 40 keV beam ions



Variation in island size/location for energies from 35 to 60 keV



Alpha-destabilized Alfvén modes are an important issue for both stellarator and tokamak reactors

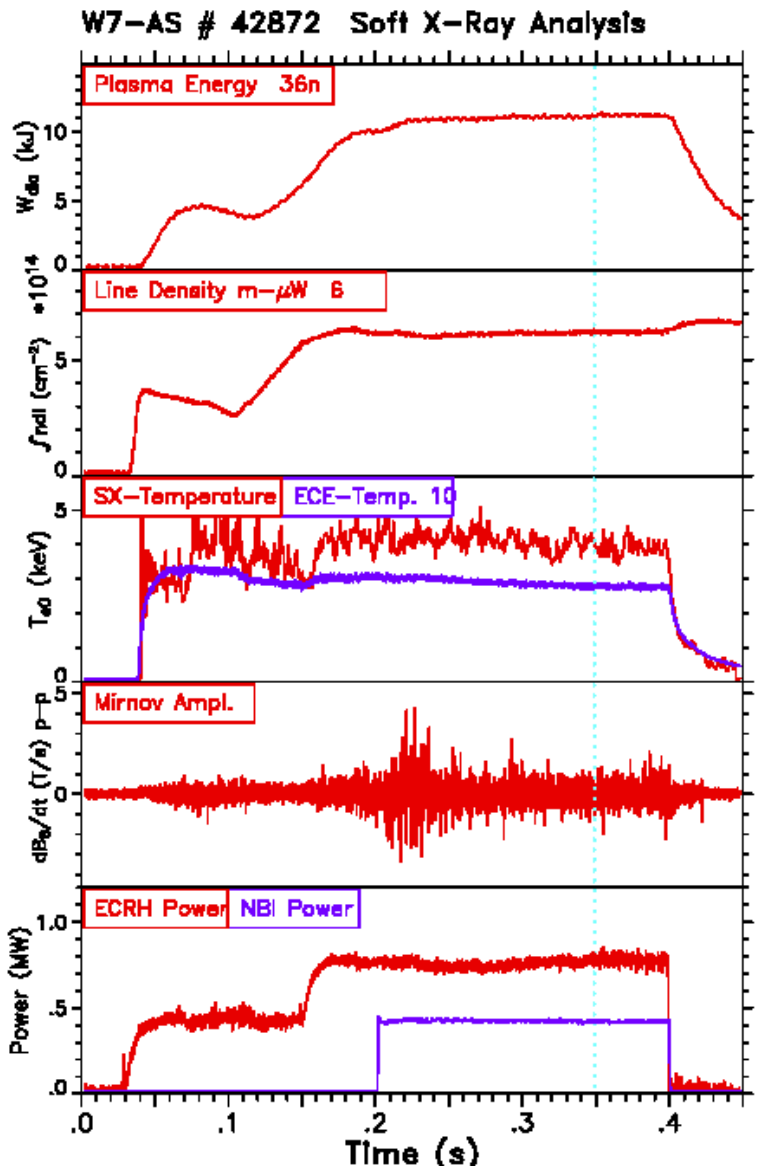
- Motivations for studying Alfvén instabilities in stellarators
  - Readily seen experimentally (W7-AS, CHS, LHD)
    - A. Weller, D. A. Spong, et al., Phys. Rev. Lett. **72**, 1220 (1994); K. Toi, et al., Nucl. Fusion **40**, 149 (2000); A. Weller, et al., Phys. of Plasmas **8** 931(2001)
  - Can lead to enhanced loss of fast ions
  - Potentially useful as a diagnostic (MHD spectroscopy)
  - Possible catalyst for direct channeling of fast ion energy to thermal ions
- Low aspect ratio configurations provide a new environment for Alfvén mode studies
  - Stronger equilibrium mode couplings
  - Lower number of field periods lead to
    - More closely coupled toroidal modes (n_0, $n_0 \pm N_{fp}$, etc.)
    - This results in MAE (Mirror Alfvén), HAE (Helical Alfvén) couplings at lower frequencies

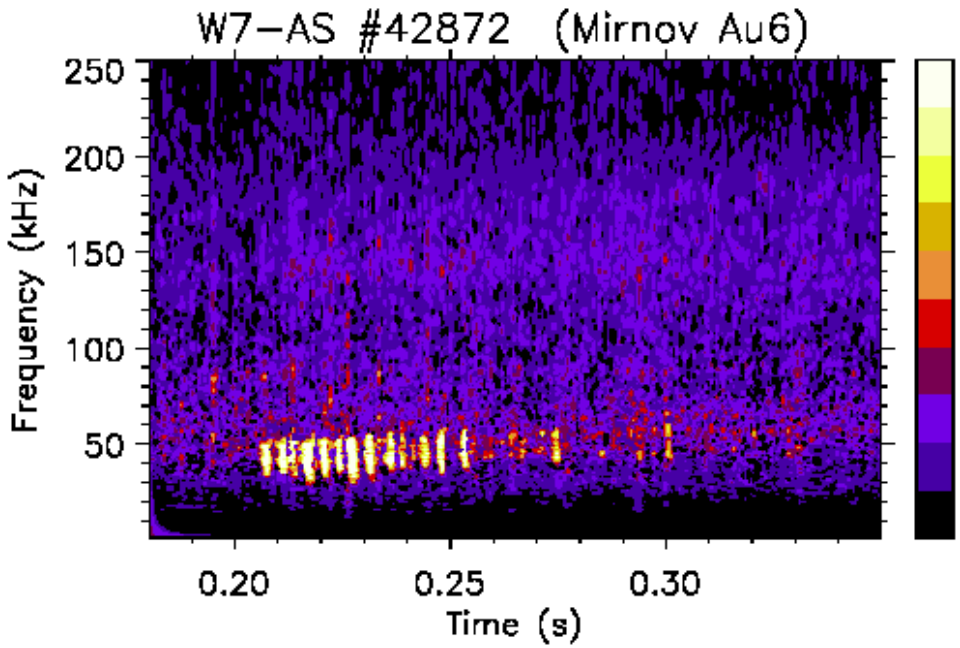
Basic mechanisms of fast-ion destabilized Alfvén waves

- Fast ion (beams, ICH tails, alphas) velocities are a significant fraction of the Alfvén velocity
- Slab or cylinder: the Alfven wave dispersion relation is just $\omega = k_{||} v_A$. However, these modes are singular (in r) and degenerate (different m's and n's) can give the same frequency.
- Strong absorption occurs at these resonances ⇨ such waves cannot be destabilized by fast ions.
- However, in toroidal devices, the dependence of v_A on B results in coupling of different $k_{||}$'s (or m's and n's) leading to the generation of gaps in the dispersion relation where the singular eigenmodes (with their strong absorption) do not exist.
- In these gaps, discrete Alfvén modes exist with a global mode structure.
- These can be readily destabilized by fast ions through inverse Landau damping.
- Since the discrete Alfvén modes generally involve coupling of a number of modes (a range of $k_{||}$'s), they can usually be destabilized even by fast ions whose velocity is only a fraction of v_A (e.g., $v_{fast,\ ion} = v_A/3$ for the classic case of a toroidal Alfvén mode with (m±1) poloidal mode couplings.

Beam-driven Alfvén instabilities dominated by a single frequency are observed on the W7-AS stellarator:

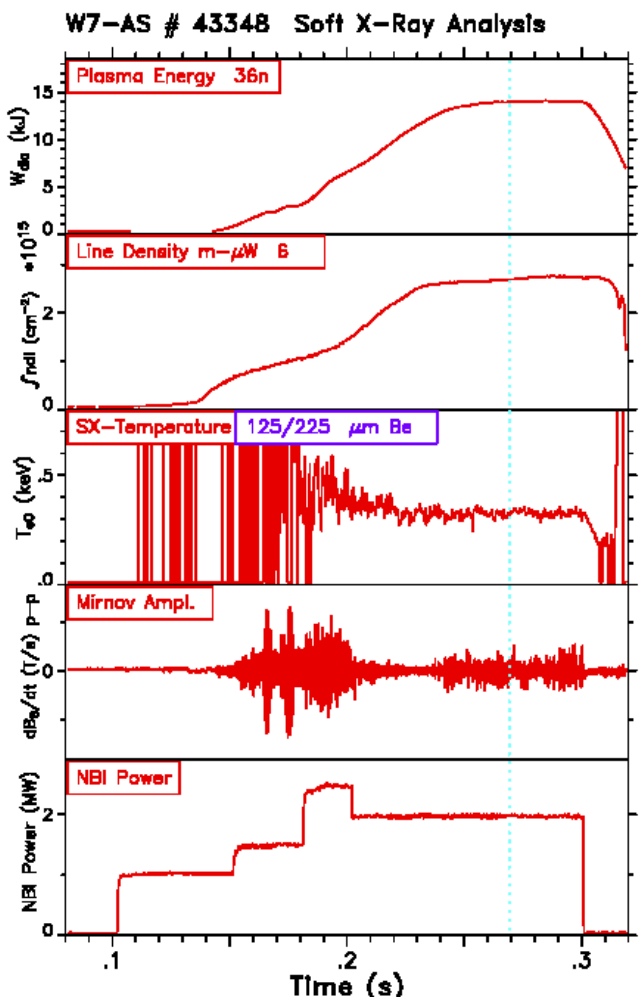
[taken from A. Weller, et al., Phys. Of Plasmas **8** (2001) 931]

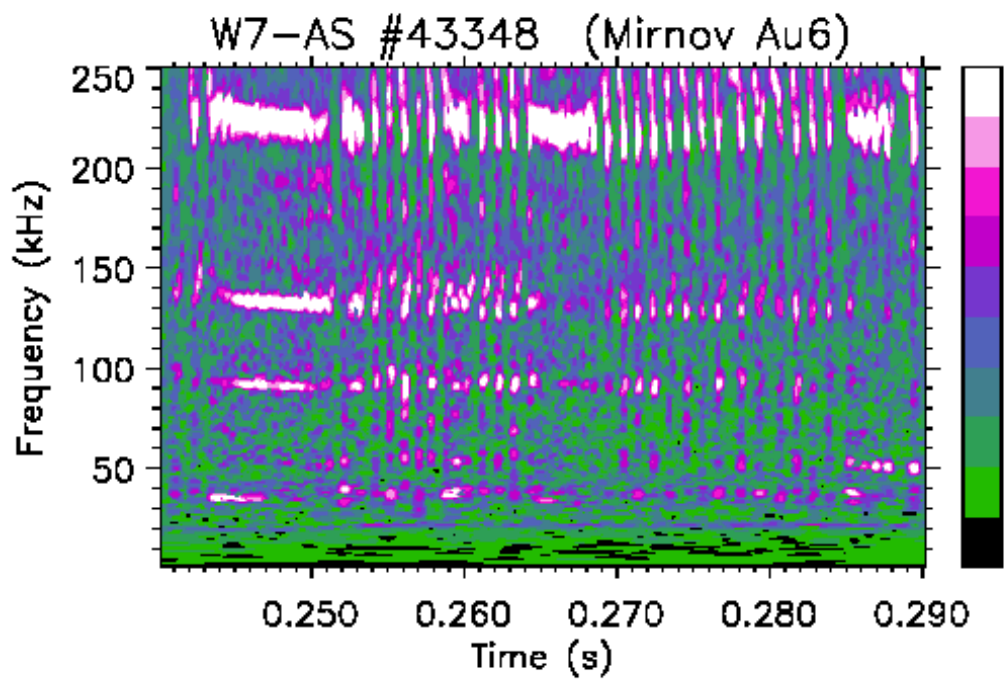




In other regimes, W7-AS sees complex multiple frequency Alfvén instabilities:

[taken from A. Weller, et al., Phys. Of Plasmas **8** (2001) 931]





Comparisons of Alfvén Continuum structure between tokamaks and stellarators

Tokamak

- Equilibrium only couples poloidal mode numbers
  - m and m ± 1, m ± 2, etc.
- Toroidal mode numbers can be examined independently (n is a good quantum number)
  - $n = n_0$, m = 0, 1, 2, ...
- Higher frequency gaps generally closed; lower frequency gaps open
- Low continuum density

Stellarator

- Equilibrium introduces poloidal, toroidal (bumpy), and helical couplings
- Families of modes must be examined
  - $n = \pm n_0, \pm n_0 \pm N_{fp}, \pm n_0 \pm 2N_{fp}, \ldots$ (N_{fp} = field periods in equilibrium) and m = 0, 1, 2, …
- Open gaps present in both high and low frequency ranges
- High continuum density in the case of compact stellarators

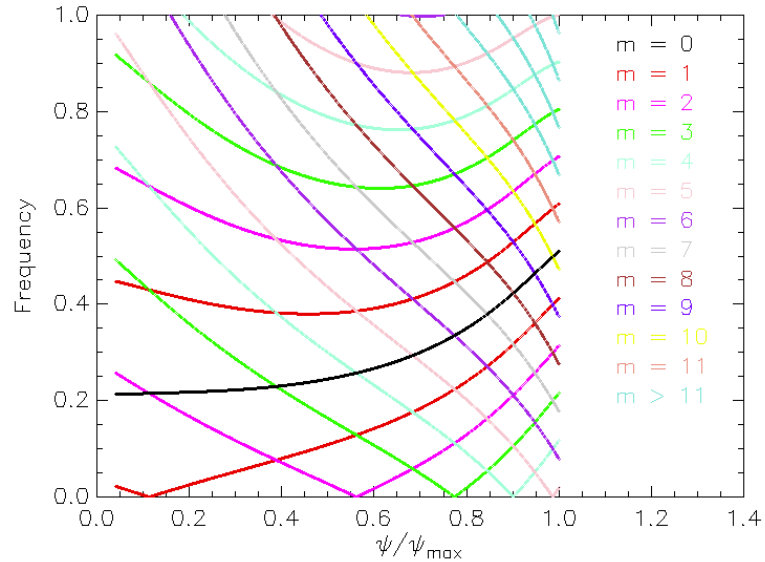
Gaps are opened up in the shear Alfvén continua when B depends on more than one dimension.

- Cylindrical shear Alfvén continua

  $B = B(r)$

  $\omega^2 = k_{||}^2 v_A^2$

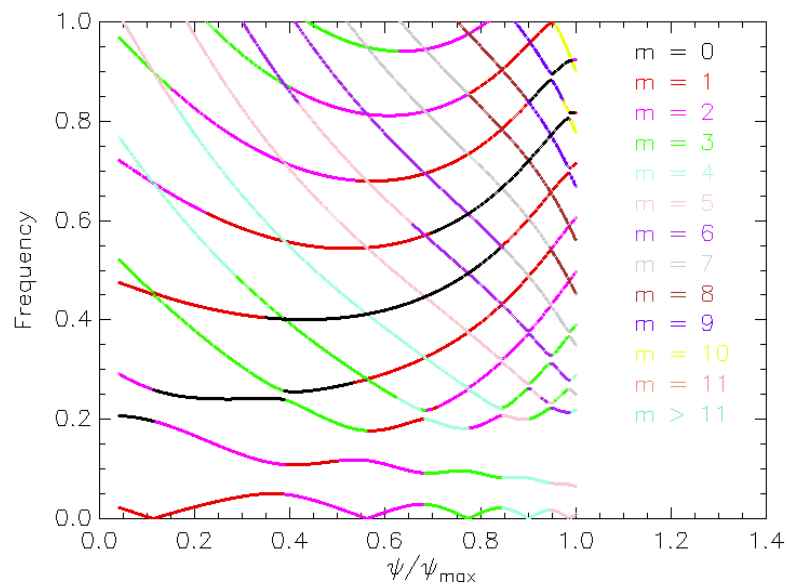
  $= (n - m\iota)^2 v_A^2/R^2$



- Tokamak shear Alfvén continua

  $B = B(\theta,\zeta)$

$$\rho_0 \omega^2 \frac{|\nabla\psi|^2}{B^2}\xi_s + \vec{B}\cdot\nabla\left[\frac{|\nabla\psi|^2}{B^2}(\vec{B}\cdot\nabla)\xi_s\right] = 0$$

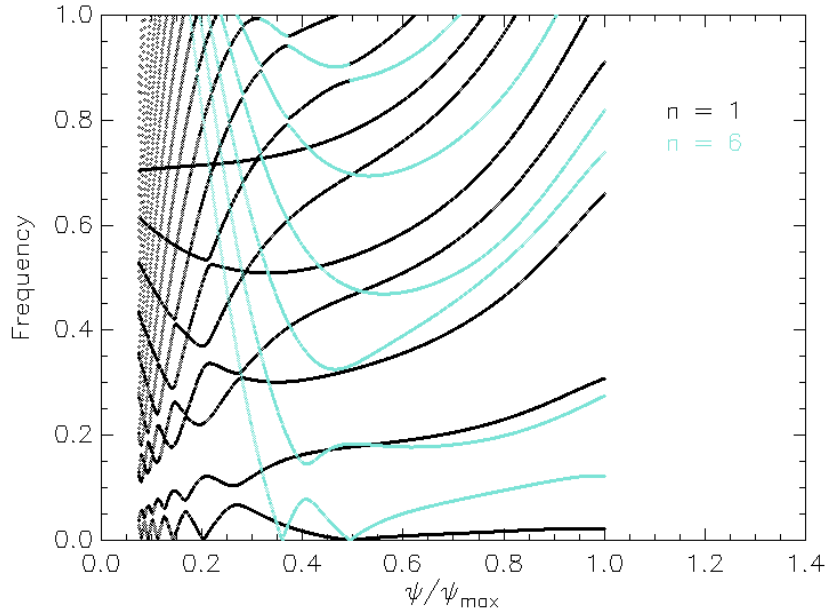


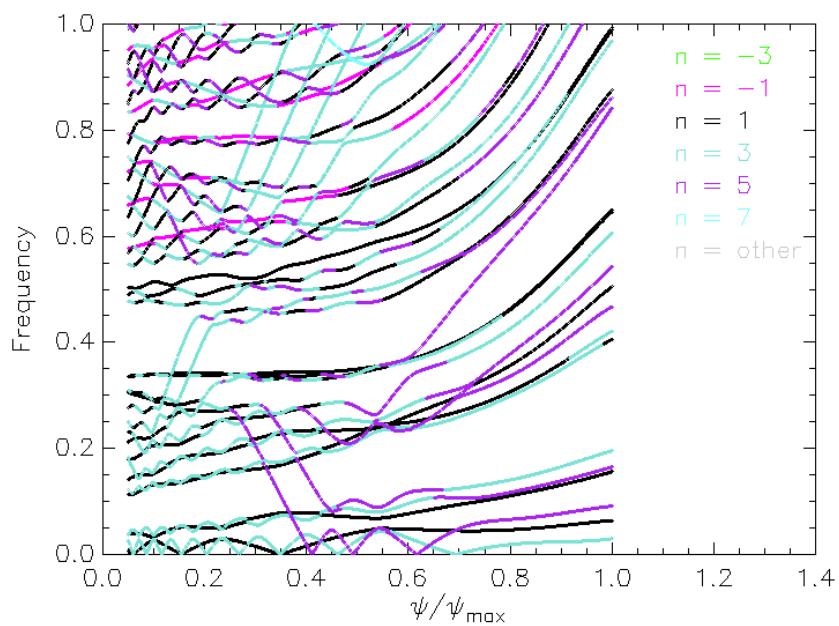
In stellarators, the three dimensional variation of B introduces new couplings into the shear Alfvén continua:

- Large aspect ratio ($R_0/a = 18$) stellarator W7-AS
  - 5 field periods
  - Adjacent toroidal mode numbers (n = 1 and n = 6) only couple at higher frequencies

$$\rho_0 \omega^2 \frac{|\nabla \psi|^2}{B^2} \phi_s + \vec{B} \cdot \nabla \left[\frac{|\nabla \psi|^2}{B^2} (\vec{B} \cdot \nabla) \phi_s \right] = 0$$

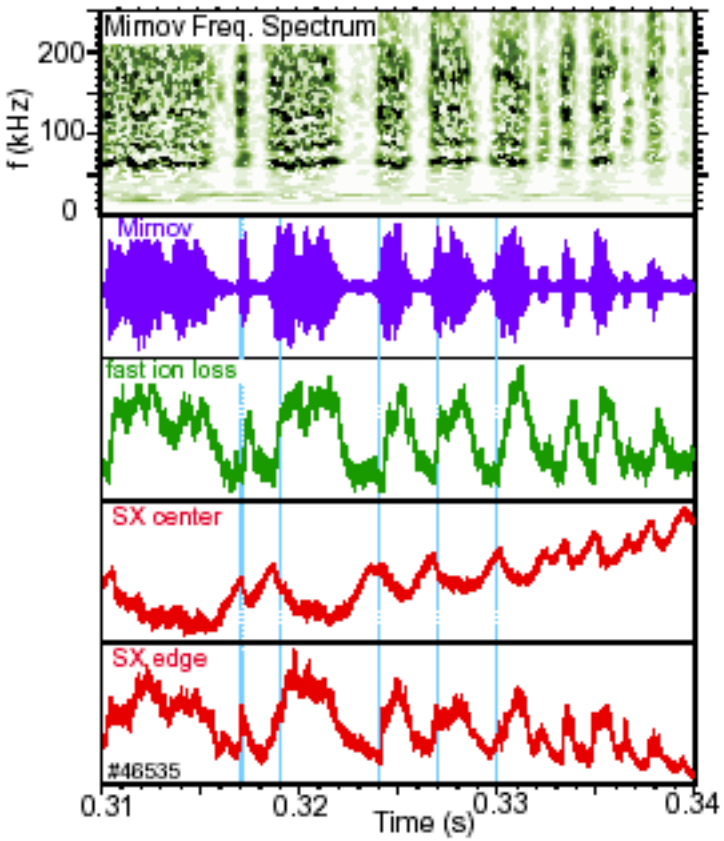
- Low aspect ratio ($R_0/a = 2.7$) QPS stellarator
  - 2 field periods
  - Strong crossover and coupling of adjacent toroidal mode numbers (n = 1, 3, 5, …) even at low frequencies.

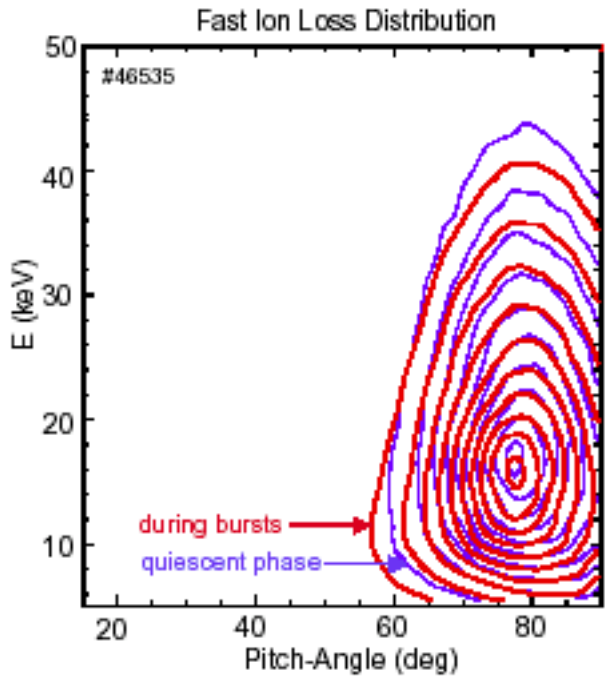




Stellarators (W7-AS discharge #46535) also see complex nonlinear bursting phenomena correlated with fast ion loss and T_e drops:

[taken from A. Weller, et al., Phys. Of Plasmas **8** (2001) 931]





Compact stellarator reactors face many of the same alpha physics issues as tokamaks:

- Access to the ignited state
  - Depends both on a better understanding of alpha loss mechanisms as well as anomalous transport in the core plasma
- Profile maintenance in the ignited state
  - Dynamics and alignment of bootstrap current, plasma shear flow and pressure profiles crucial to burn control
- Prediction of classical alpha loss (driven by symmetry-breaking)
  - Important for first wall protection, power balance, ash removal
- Alpha collective phenomena
  - Complex nonlinear physics
  - Reactor regime (high toroidal mode number) difficult to test in existing devices
  - Important for first wall protection, power balance, burn control

Compact stellarator reactors also offer new possibilities for improved control of several burning plasma physics issues:

- 3D shaping introduces a higher degree of design flexibility
- Bootstrap current levels are naturally reduced (by the magnetic geometry) from axisymmetric levels
- Resilience to disruptions, external kinks
- Can be designed with no instability to neoclassical tearing modes
- May be possible to design-in alpha ash removal and burn control mechanisms through drift islands
- Alfvén continuum damping an mode structure may be influenced through magnetic design