# Alpha Physics Issues in Compact Stellarators

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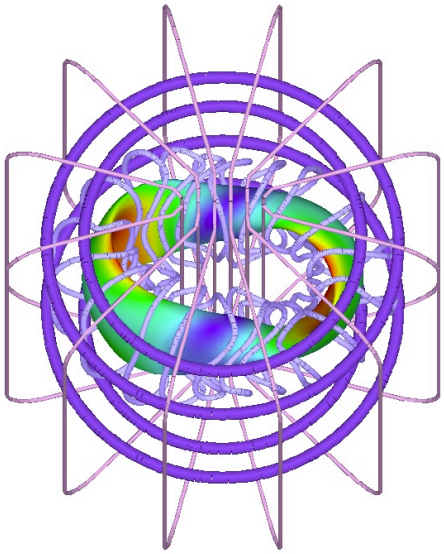
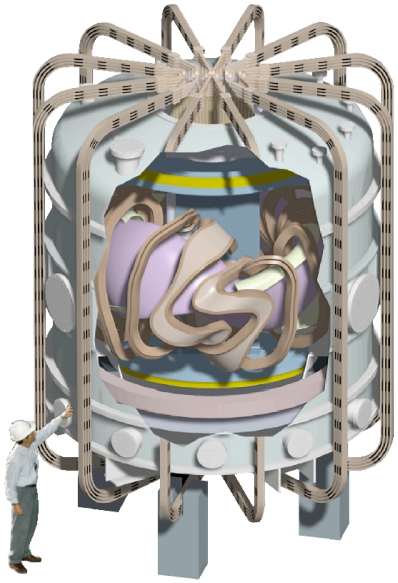




# Stellarators and tokamaks share generic burning plasma physics issues:

- 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.)

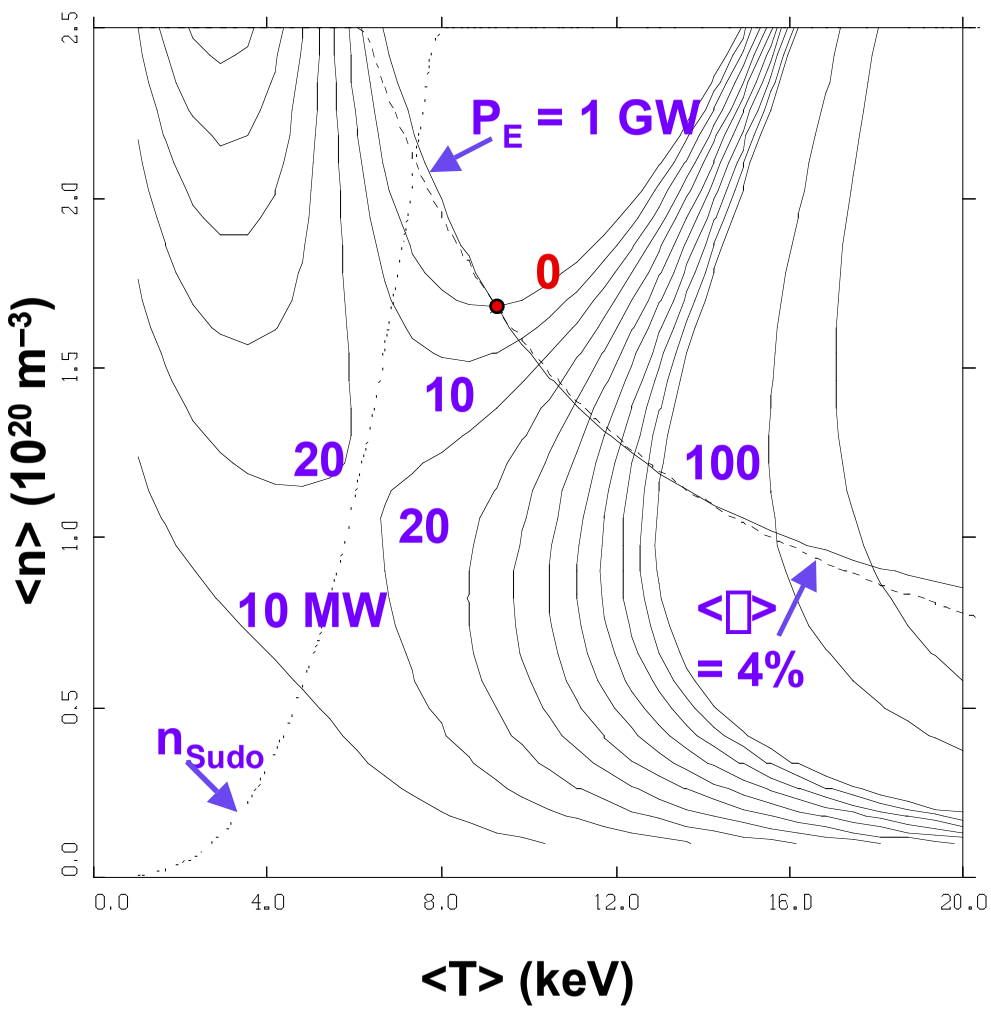
- Alpha particle orbit confinement
  - Losses driven by symmetry breaking
    - Tokamaks - toroidal field ripple
    - Stellarators - deviations from $B = B(\theta,\phi)$ in Boozer coordinates where $\theta$ = toroidal, helical or poloidal angles
  - Impact on power balance
  - First wall protection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

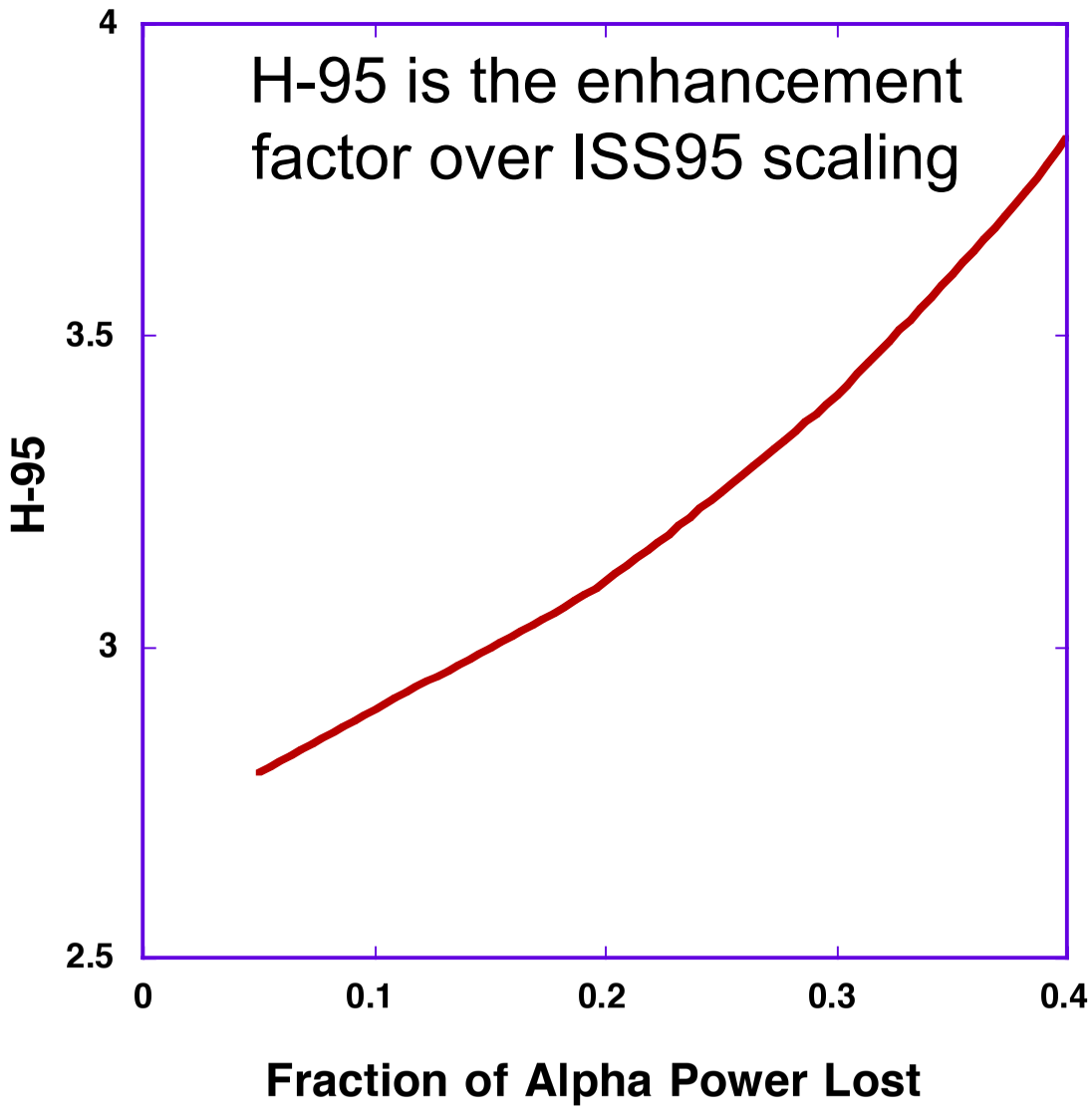
**<*n*> = 1.7 x $10^{20}$ m$^{-3}$, <*T*> = 9.3 keV**
**<β> = 4.04%, for H-95 = 2.9**
**$n_{DT}/n_e$ = 0.82, $Z_{eff}$ = 1.48**

- **Saddle Point**

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

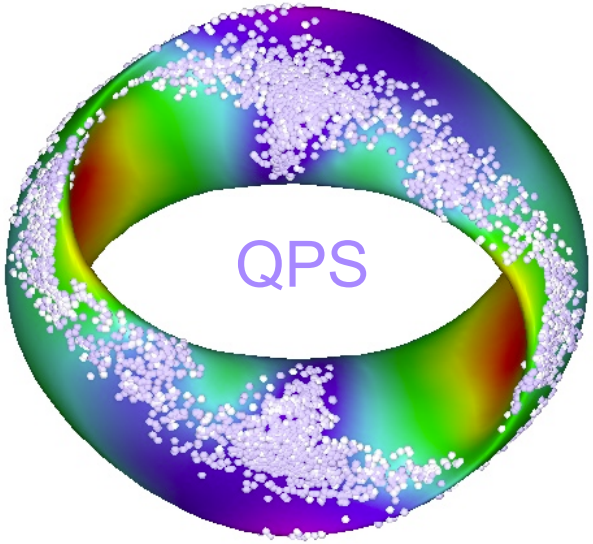
**Assumes ARIES-AT *n*(r/a) and *T*(r/a), β losses = 0.1, $\beta_{He}/\beta_{\alpha}$ = 6**
**$B_{max}$ = 12 T**

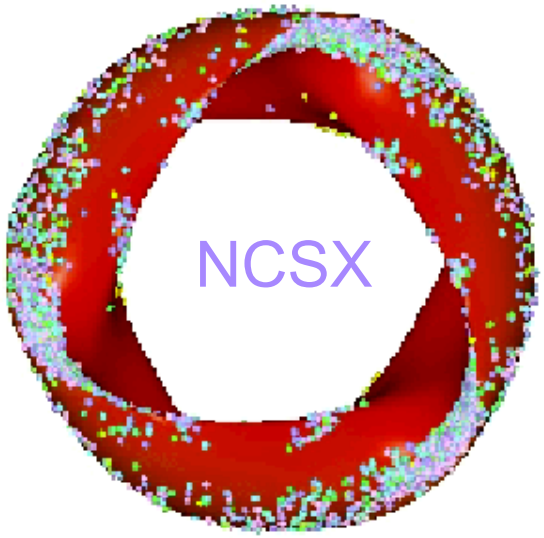
# With higher alpha-particle losses (less heating power) confinement must be better to maintain a steady-state power balance [from J. F. Lyon, IAEA 2000 (Sorrento)]



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

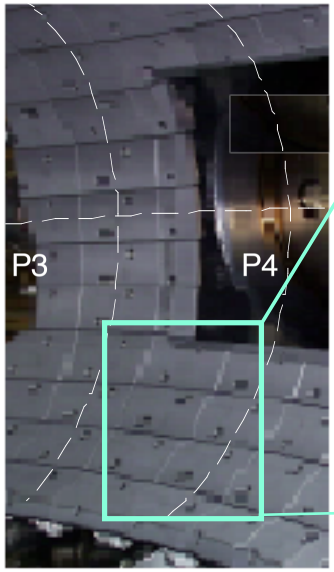
Fast Ion losses In Compact Stellarators

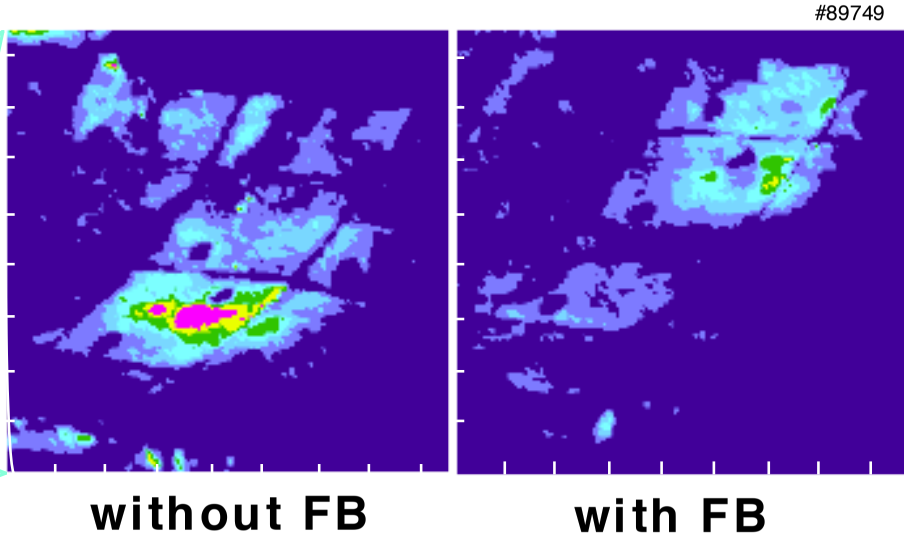



JFT-2M (tokamak)

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

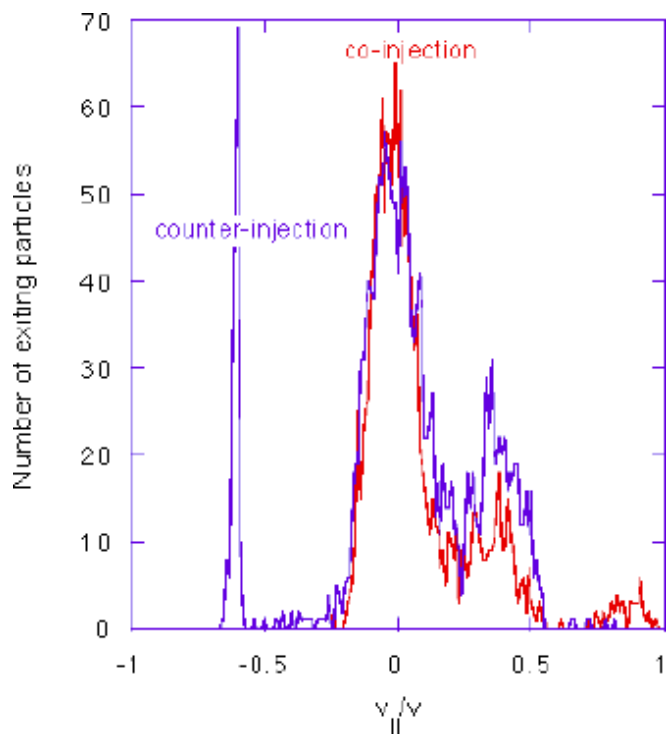


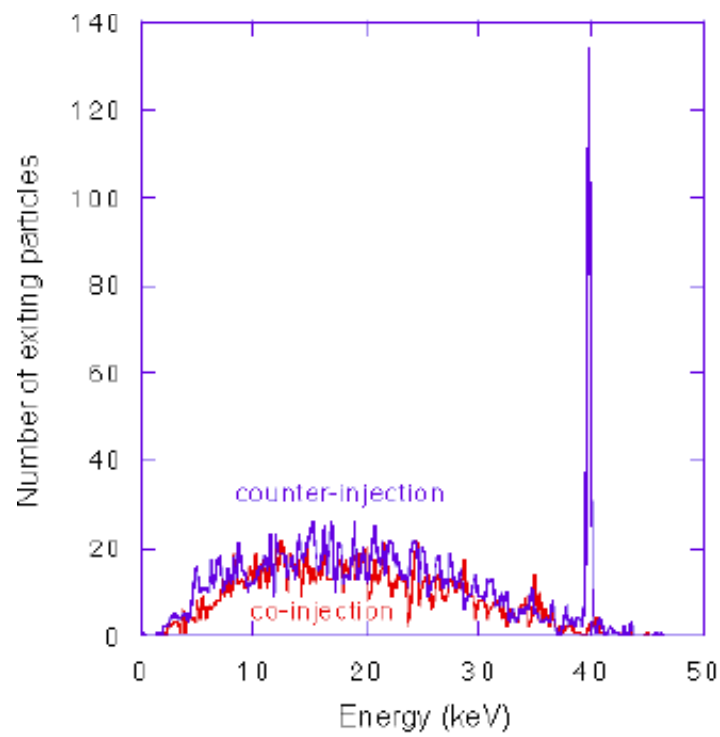
# Histograms of escaping fast ions in compact stellarators elucidate the loss mechanisms.

- 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

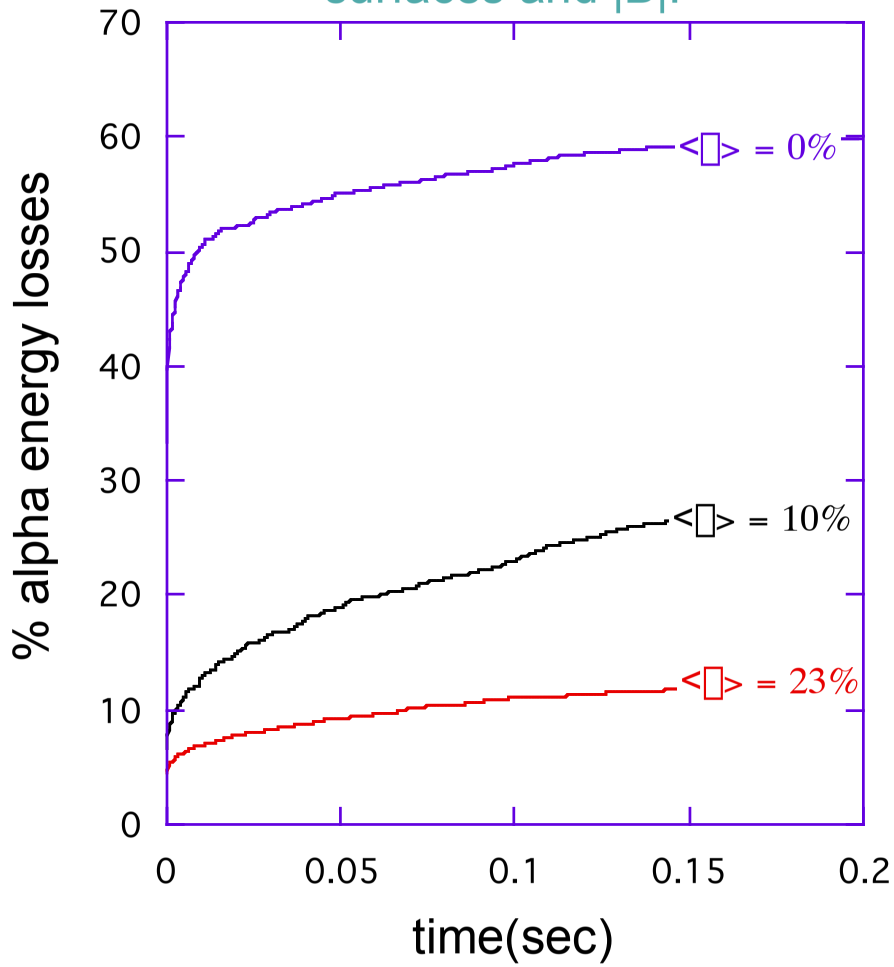



Energy distribution

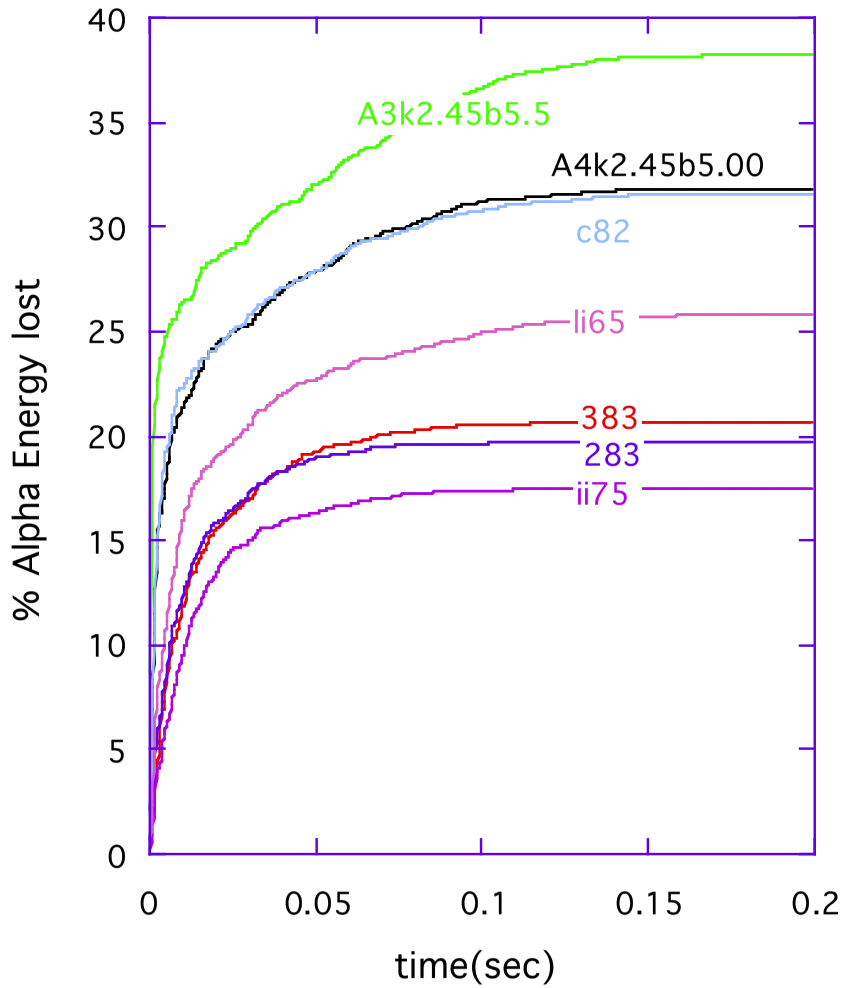


# Compact stellarator designs are already achieving tolerable level of alpha loss. Further configuration optimization research is expected to lead to even lower losses.

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

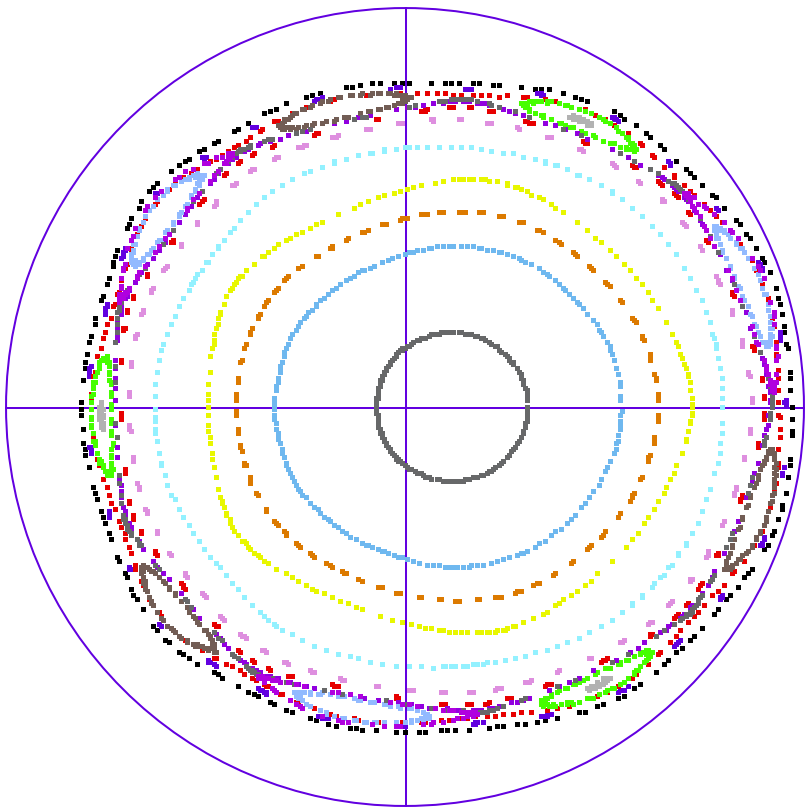



Alpha loss rates improve in a series of QAS devices as the |B| spectrum is made more symmetric.

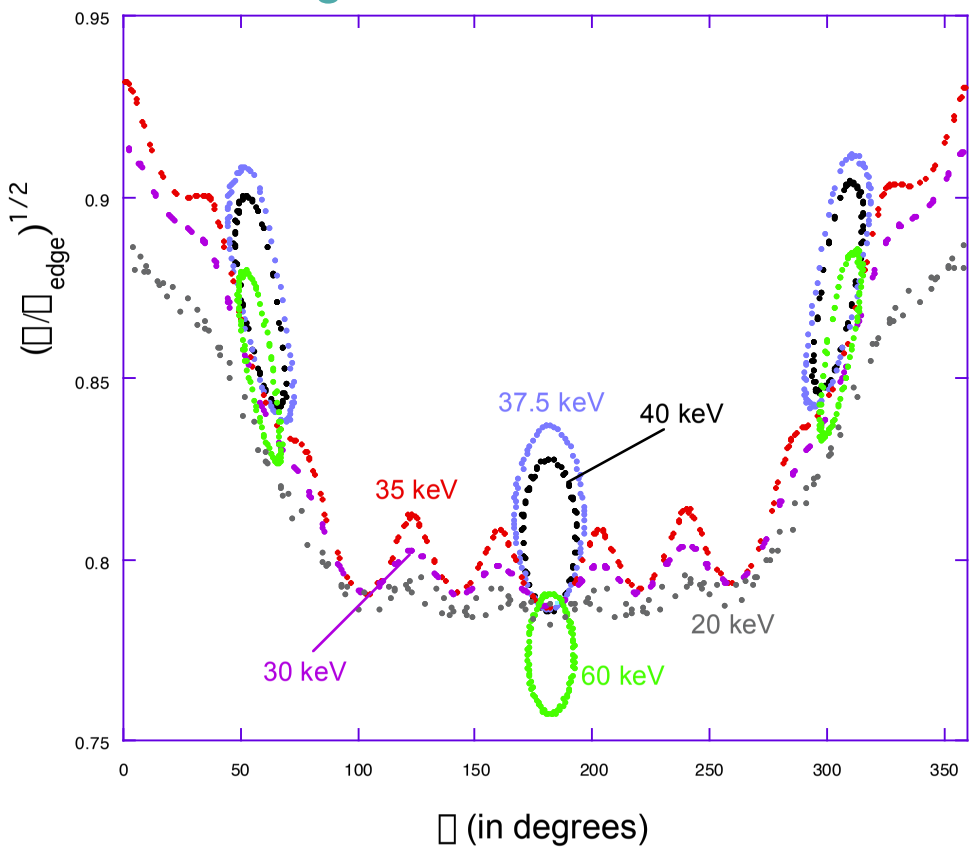


# Energetic passing particles in compact stellarators form drift islands over limited regions of phase space. Control of these islands could offer an attractive mechanism for alpha ash removal and/or for burn control.

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

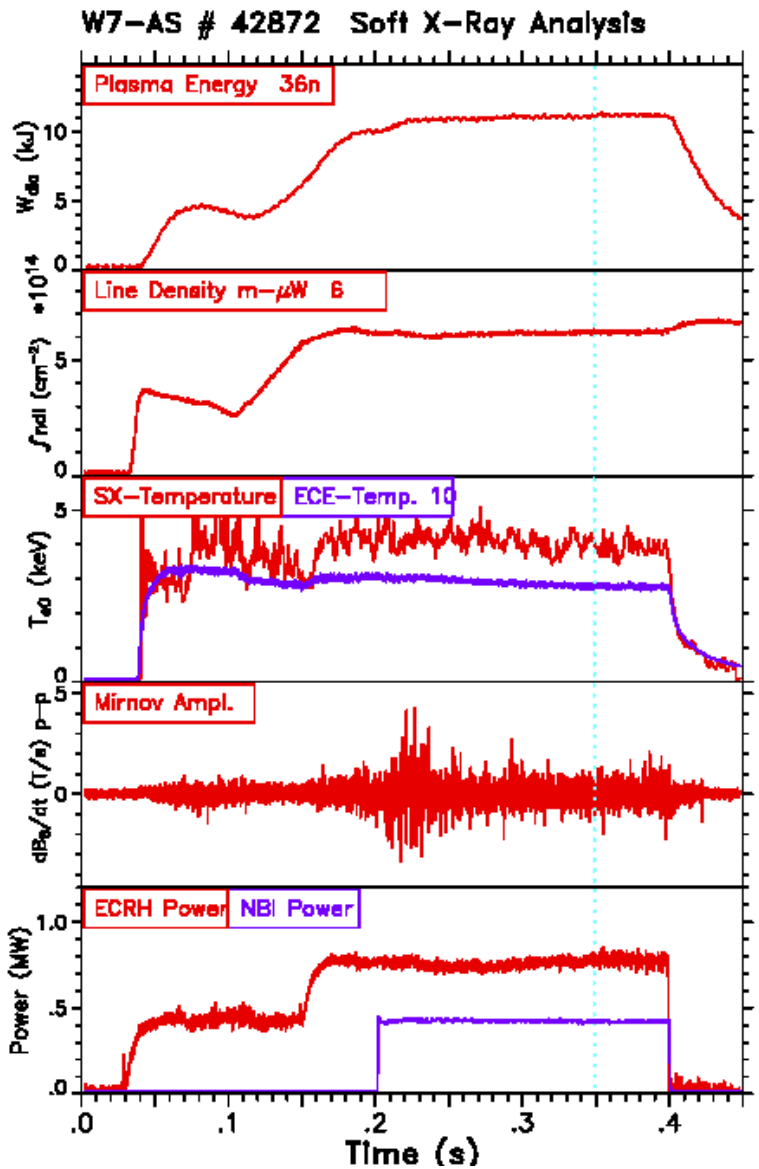
- Motivations for studying Alfvén instabilities in stellarators
  - Readily seen experimentally (W7-AS, CHS, LHD)
    - A. Weller, D. A. Spong, et al., Phys. Rev. Lett. **72**, 1220 (1994); K. Toi, et al., Nucl. Fusion **40**, 149 (2000); A. Weller, et al., Phys. of Plasmas **8** 931(2001)
  - Can lead 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

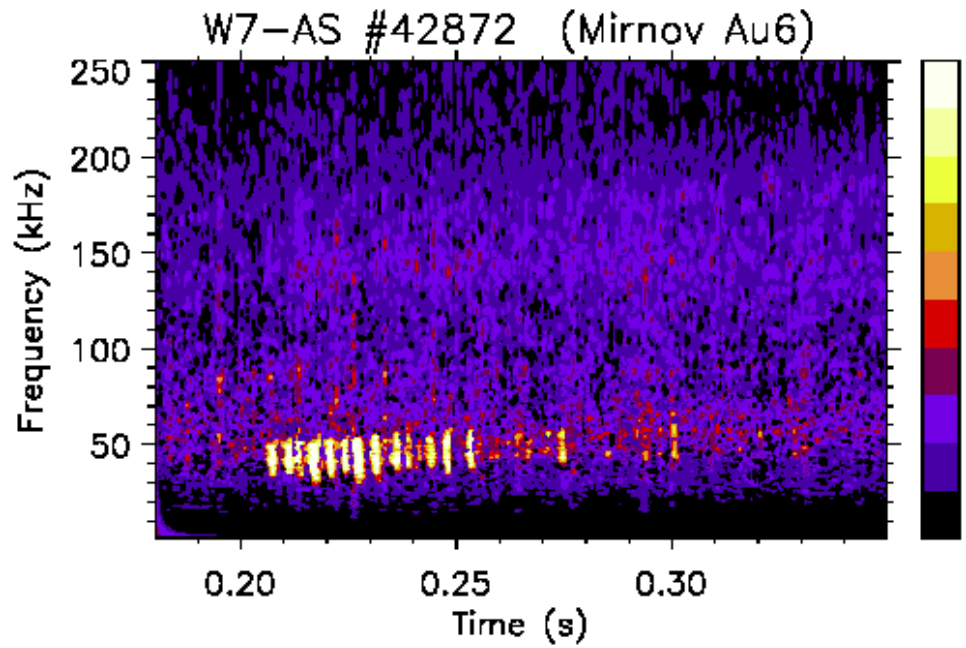
# Basic mechanisms of fast-ion destabilized Alfvén waves

- 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:

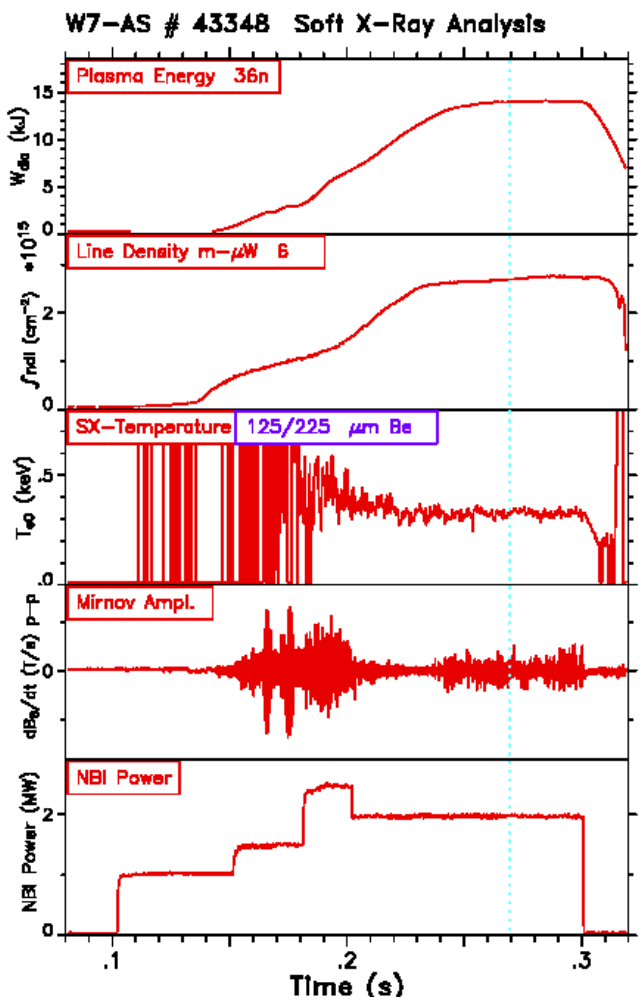
[taken from A. Weller, et al., Phys. Of Plasmas **8** (2001) 931]

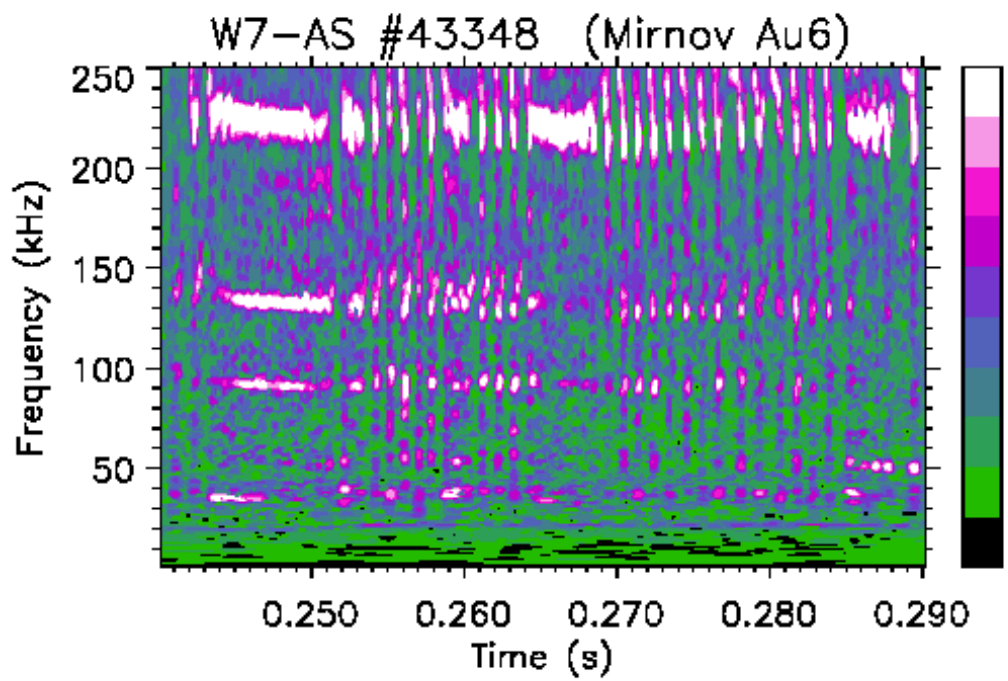


# In other regimes, W7-AS sees complex multiple frequency Alfvén instabilities:

[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

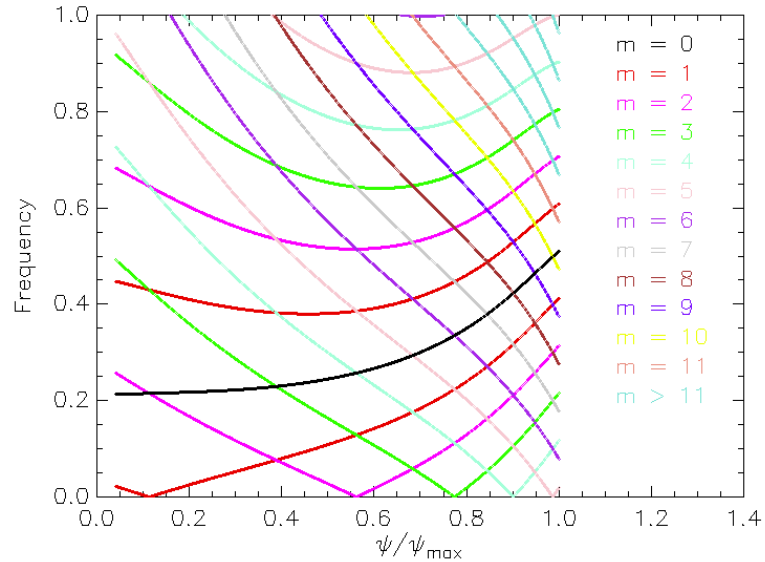
# Gaps are opened up in the shear Alfvén continua when B depends on more than one dimension.

- Cylindrical shear Alfvén continua

  $B = B(r)$

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

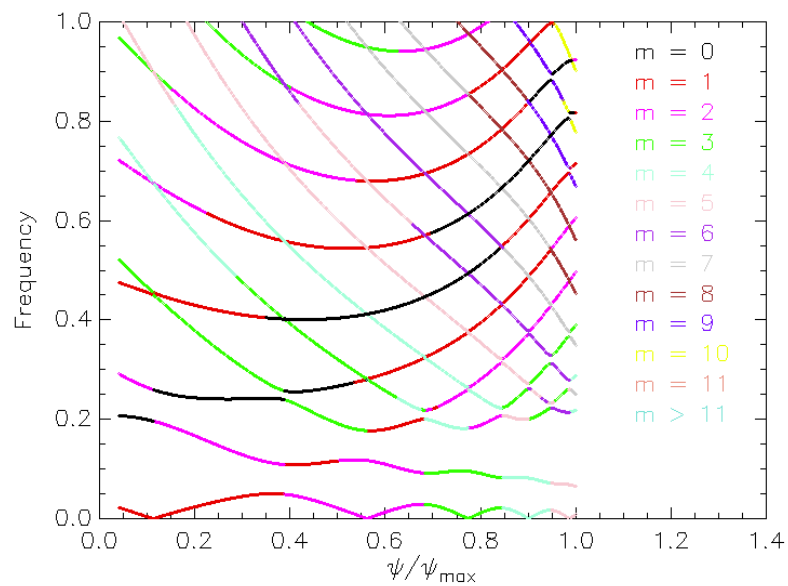
  $= (n - m\iota)^2 v_A^2/R^2$




- Tokamak shear Alfvén continua

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

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

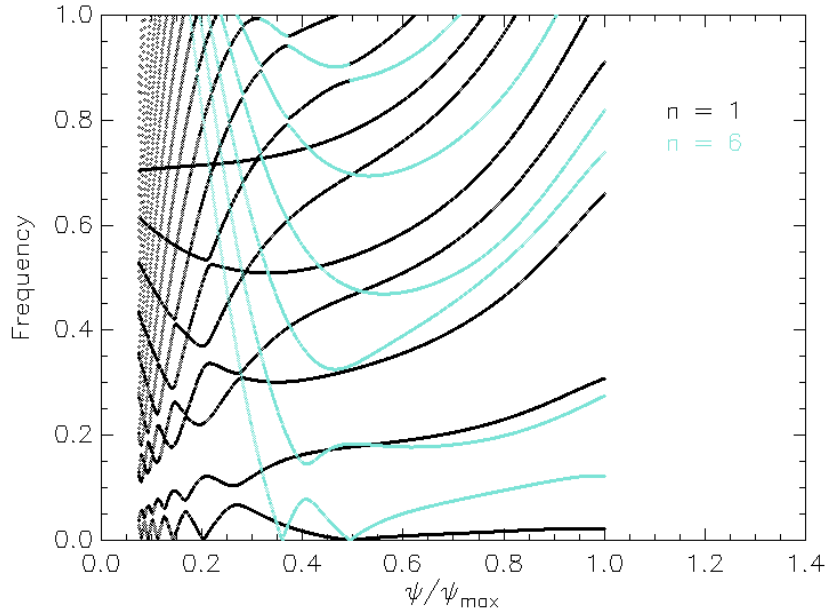


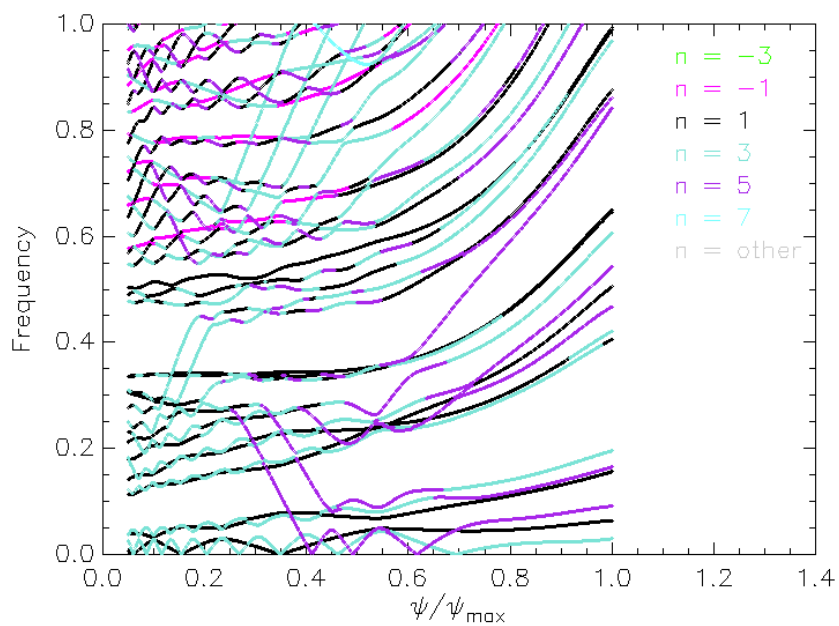
# In stellarators, the three dimensional variation of B introduces new couplings into the shear Alfvén continua:

- 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

$$\omega_0 \omega^2 \frac{|\nabla \psi|^2}{B^2} \phi_s + \vec{B} \cdot \nabla \left[ \frac{|\nabla \psi|^2}{B^2} (\vec{B} \cdot \nabla) \phi_s \right] = 0$$

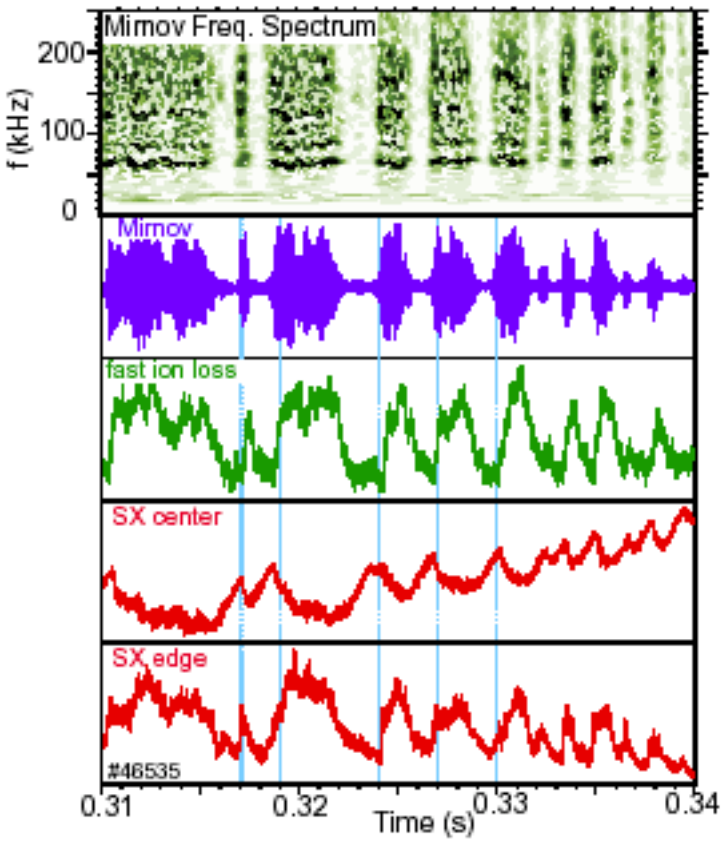
- Low aspect ratio ($R_0/a = 2.7$) QPS stellarator
  - 2 field periods
  - Strong crossover and coupling of adjacent toroidal mode numbers (n = 1, 3, 5, …) even at low frequencies.

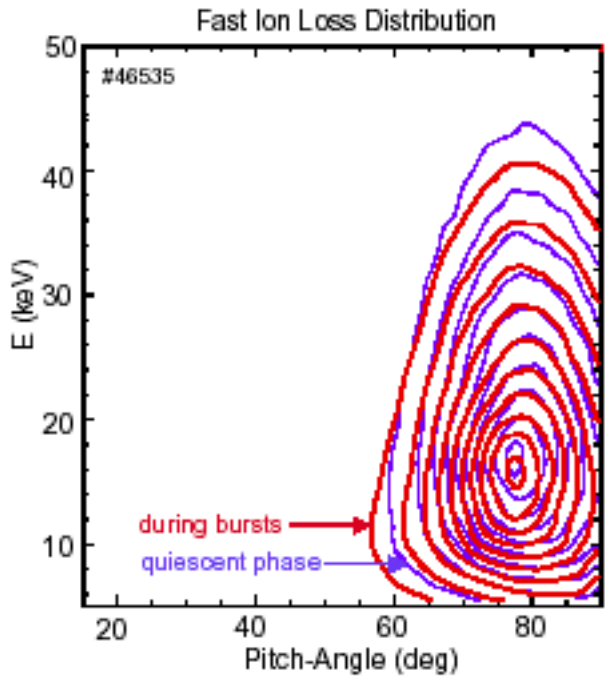


# Stellarators (W7-AS discharge #46535) also see complex nonlinear bursting phenomena correlated with fast ion loss and $T_e$ drops:

[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