ENERGETIC PARTICLE ISSUES FOR COMPACT STELLARATORS

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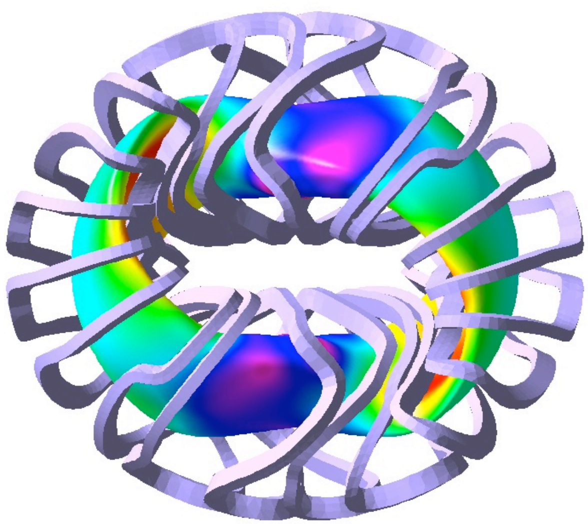
collaborations acknowledged with: J. F. Lyon, S. P. Hirshman, L. A. Berry, A. Weller (IPP), R. Sanchez (Univ. of Madrid), A. Ware (Univ. Mont.)

IAEA Technical Meeting on Energetic Particle Physics October 6 - 8, 2003

General Atomics

San Diego, CA



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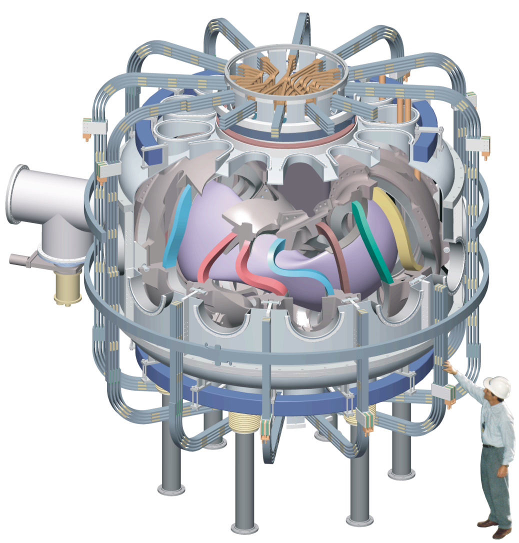
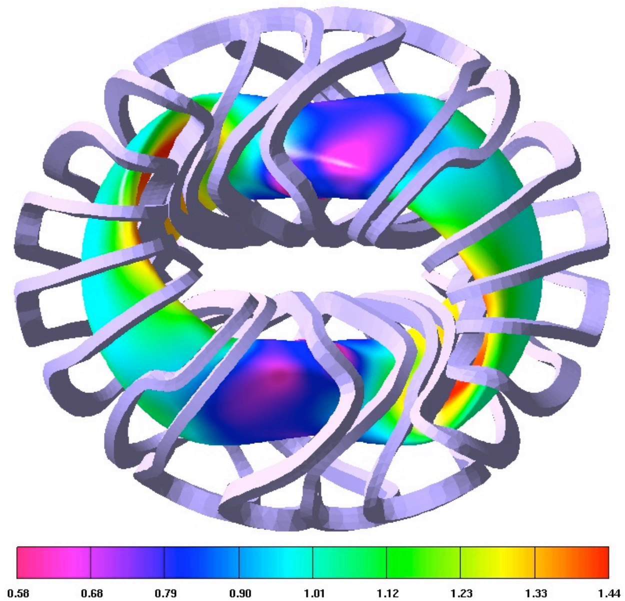


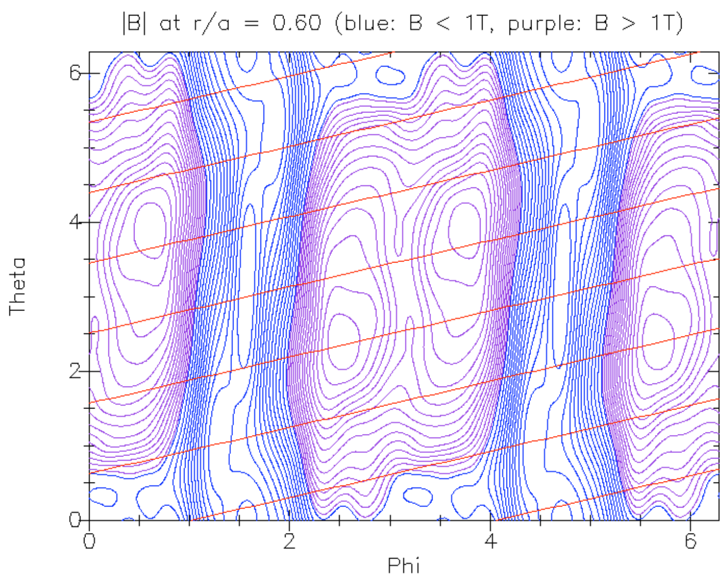
Outline of Talk

- Two low aspect ratio stellarator designs are being pursued in the U.S.
  - QPS (ORNL) - symmetry in the poloidal direction ($R_0/<a> = 2.7$)
  - NCSX (PPPL) - symmetry in the toroidal direction ($R_0/<a> = 4.4$)
  - Compactness lower development cost for fusion, better reactor economics
- Energetic particle issues include:
  - Confinement
    - Beam heating and slowing down
    - Alpha confinement in reactor extrapolations
      - Impact on power balance
      - Wall heat loads
      - Ash removal
    - Impact of energetic particle losses on thermal confinement via ambipolar electric field
    - Runaway, elevated ECH tail generation
  - Alfvén and other collective instabilities/external MHD excitation
    - GAE/TAE/HAE/MAE modes
    - Tearing modes, fishbones
    - Kinetic ballooning

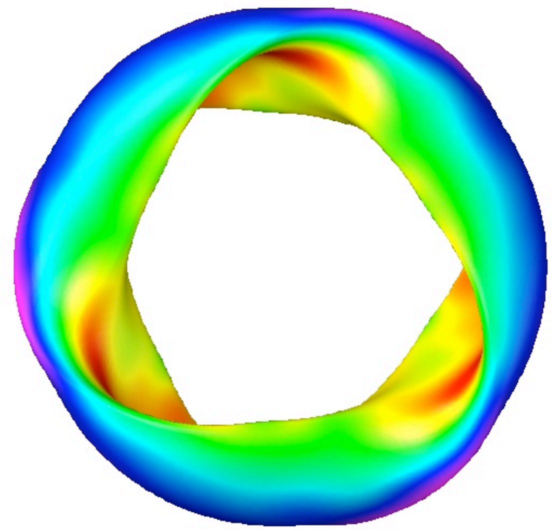
Compact stellarators have been designed with complementary/orthogonal forms of quasi-symmetry:

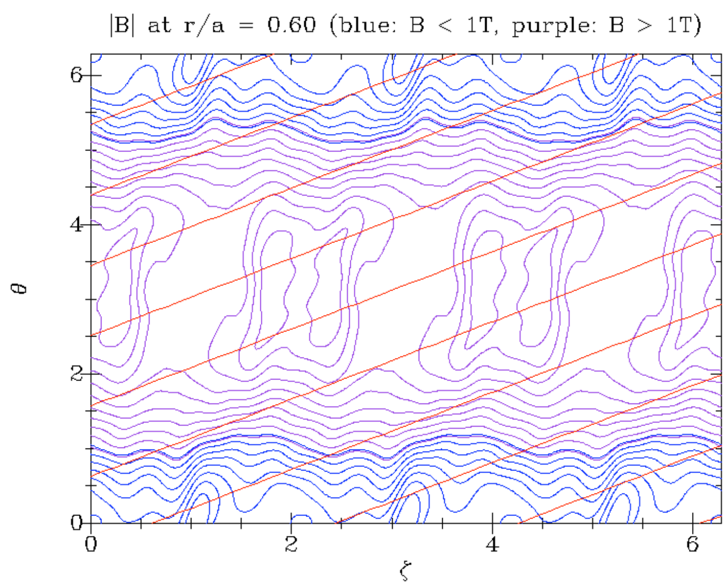
QPS (quasi-poloidal symmetry)



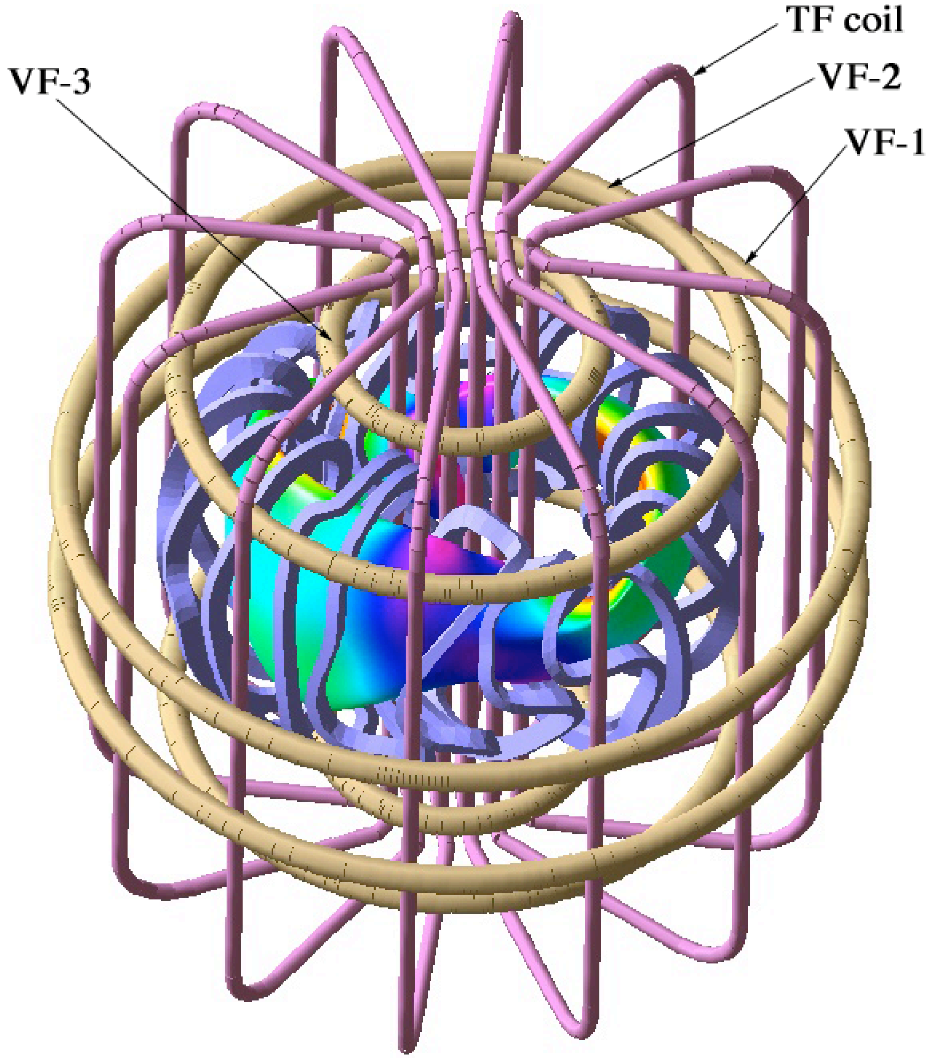


NCSX (quasi-toroidal symmetry)





QPS offers substantial flexibility through 9 independently variable coil currents



- Flexibility is a significant advantage offered by stellarator experiments
- Flexibility will aid scientific understanding in:
  - Flux surface fragility/island avoidance
  - Neoclassical vs. anomalous transport
  - Transport barrier formation
  - Plasma flow dynamics
  - MHD stability
- QPS offers flexibility through:
  - 5 individually powered modular coil groups
  - 3 vertical field coil
  - toroidal field coil set
  - Ohmic solenoid
    - Variable ratios of Ohmic/bootstrap current

Stellarators and tokamaks share generic burning plasma physics issues:

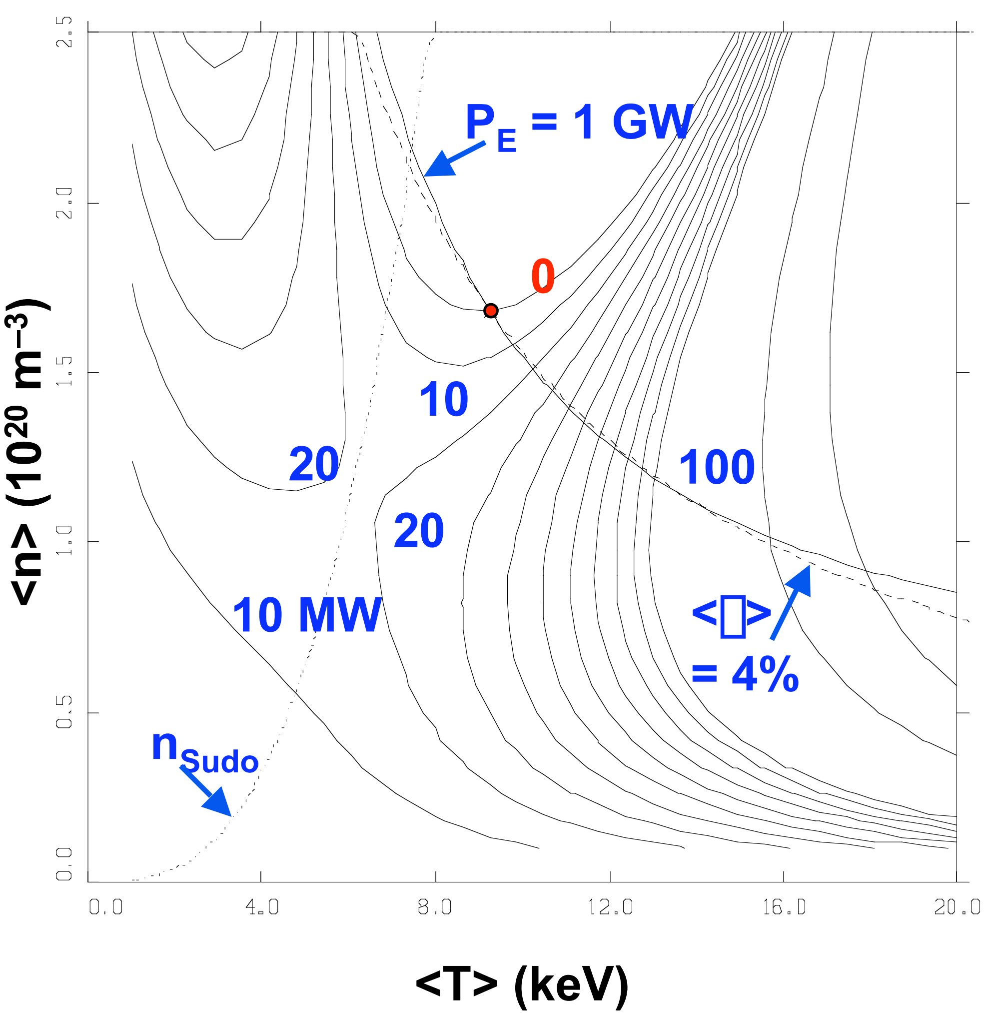
- Ignition access and maintenance
  - Must go through the "Cordey pass"
    - Density/temperature path that minimizes heating power - determined by
      - confinement scaling
      - alpha loss rates
  - Profile sustainment
    - Pressure profile/bootstrap current/rotational transform coupling
    - 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(□,□) in Boozer coordinates where □ = toroidal, helical or poloidal angles
  - Impact on power balance
  - First wall protection - loss regions, power loading
  - Energy recovery

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
<□> = 4.04%, for H-95 = 2.9
n_{DT}/n_e = 0.82, Z_{eff} = 1.48

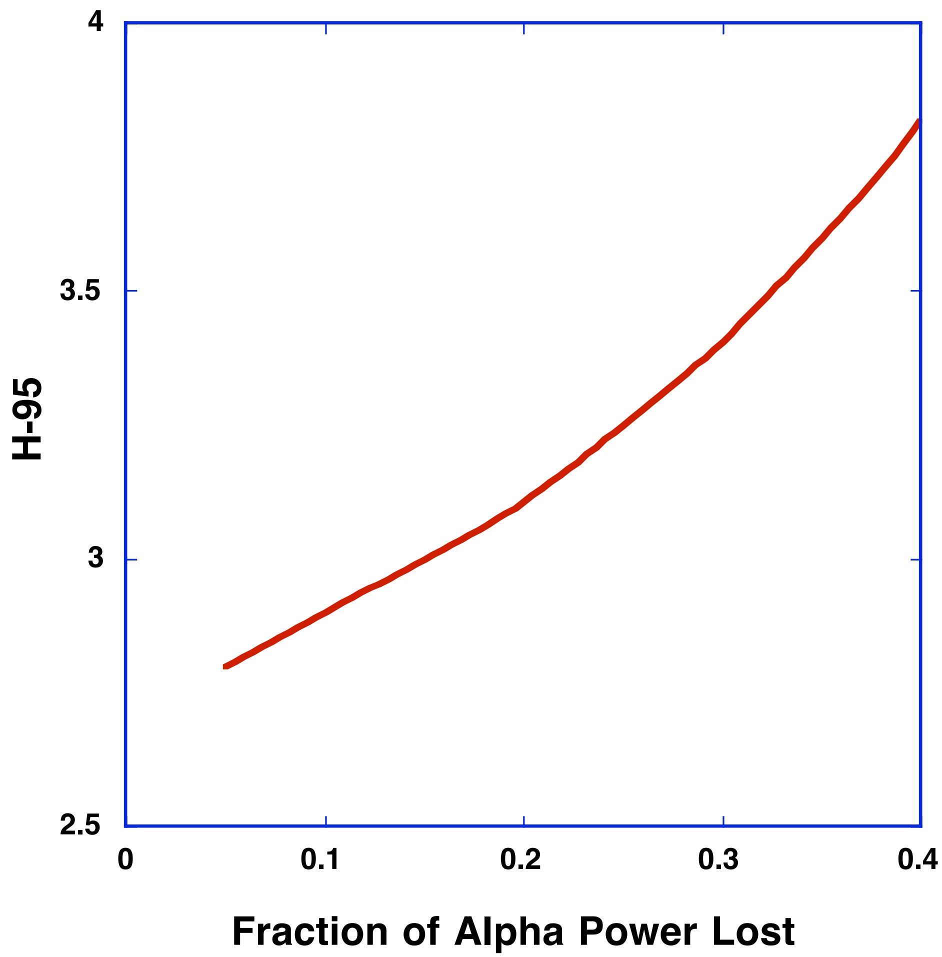
- **Saddle Point**

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

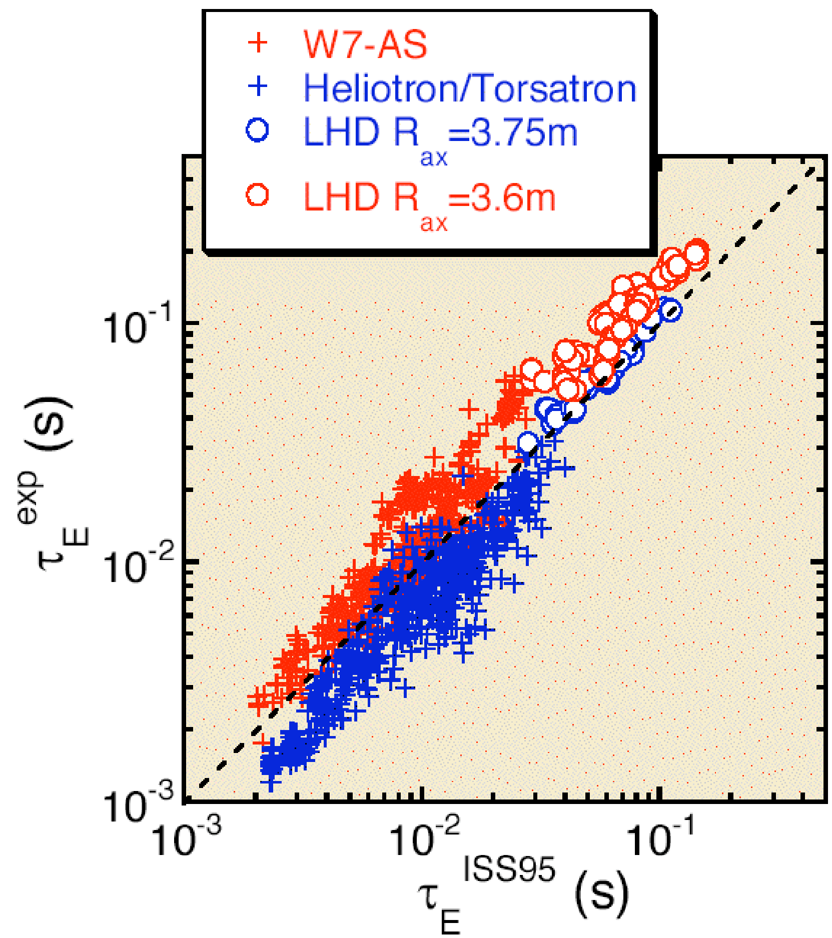
Assumes ARIES-AT n(r/a) and T(r/a), □ losses = 0.1, $□_{He}/□_{□}$ = 6 B_{max} = 12 T

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)]

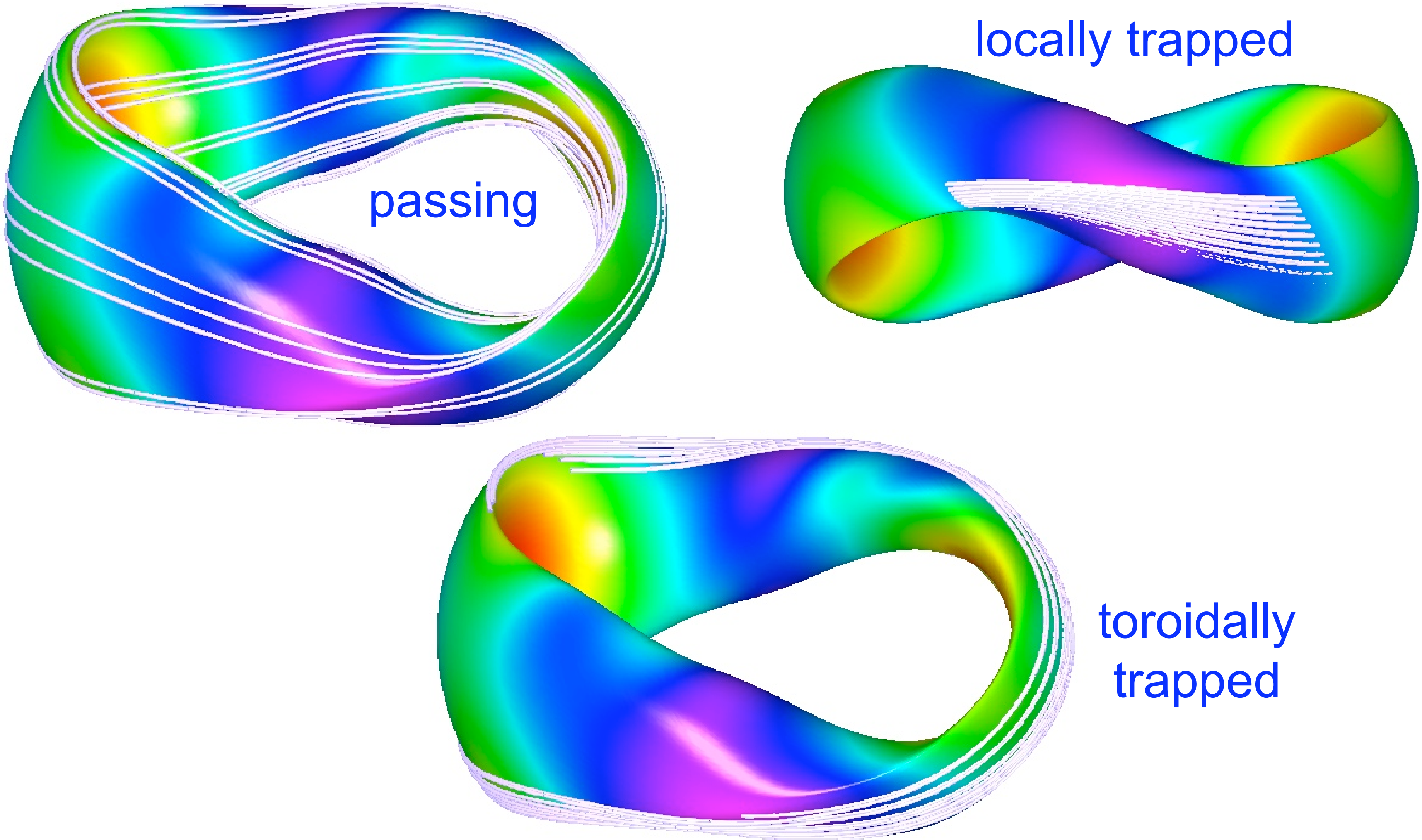
H-95 is the enhancement factor over ISS95 scaling



Confinement data shows H-95 ~ 3 is achieved
(taken from H. Yamada, K. Ida, et al. 14th International Stellarator Workshop)



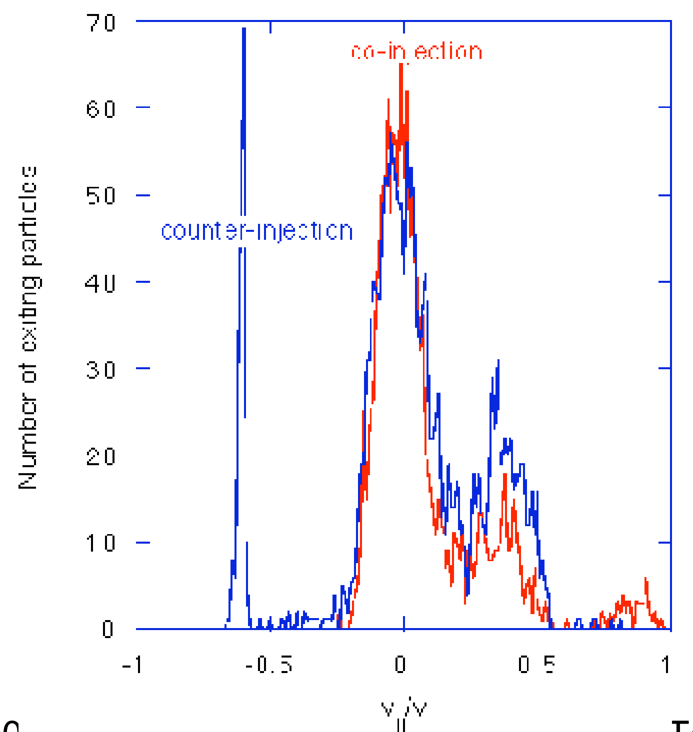
Compact stellarators can have a variety of orbit topologies



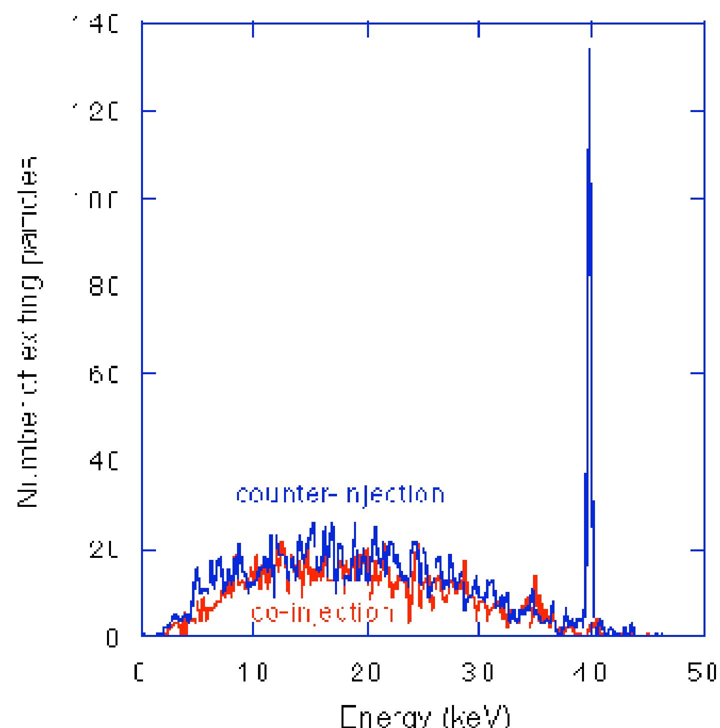
Histograms of escaping fast NBI ions in compact stellarators elucidate the loss mechanisms.

- 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

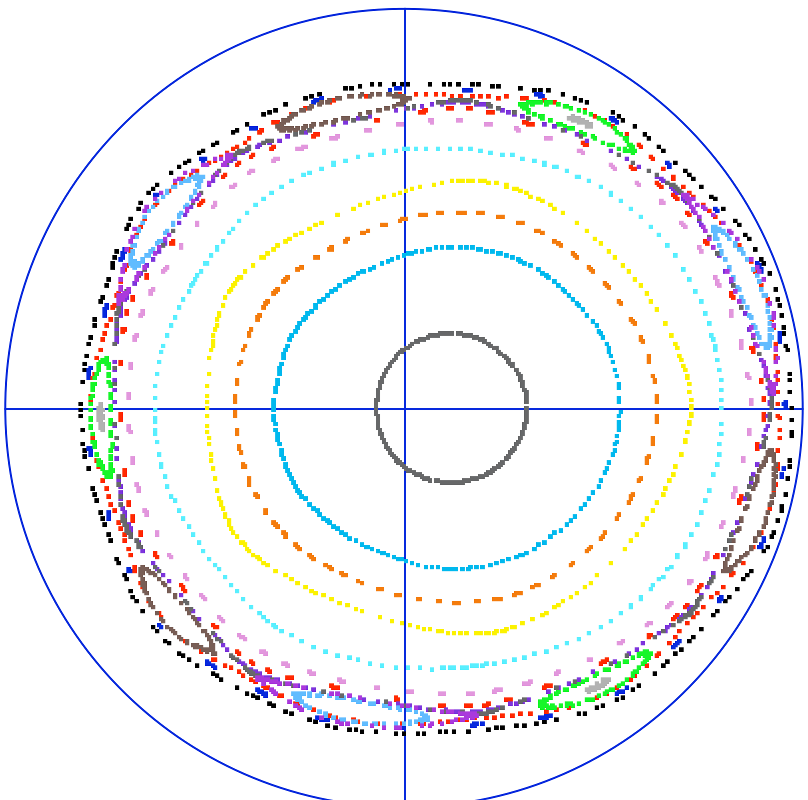


Energy distribution

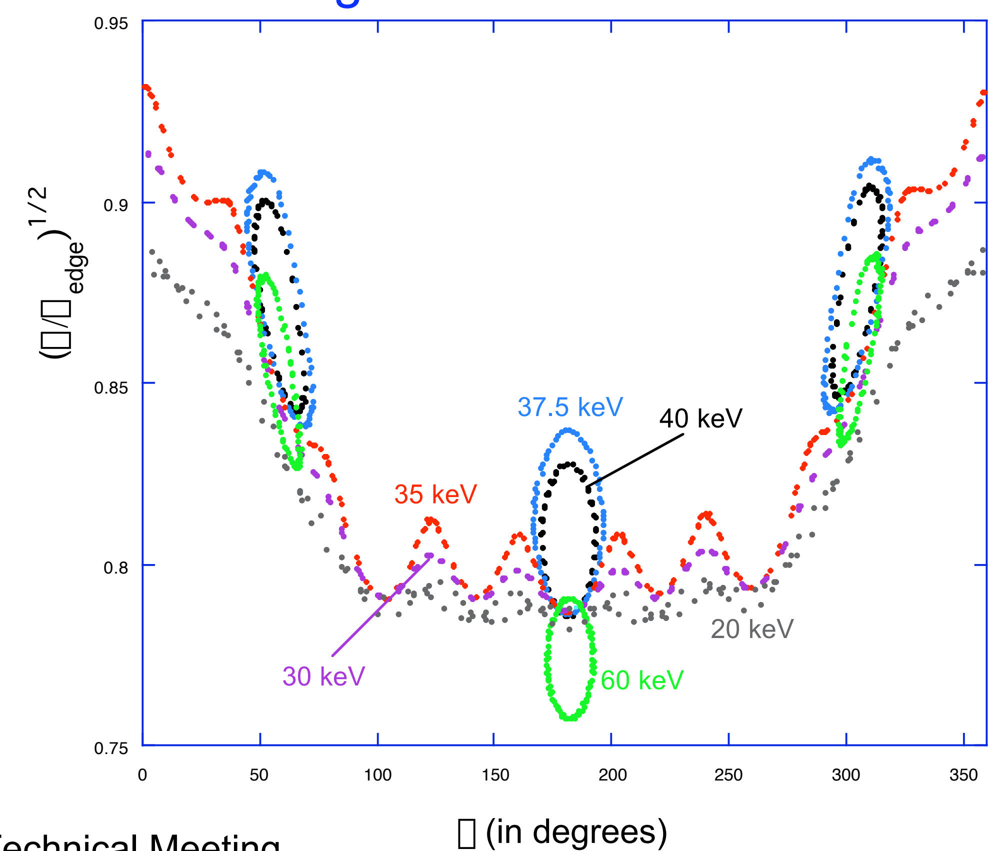


Energetic passing particles in compact stellarators form drift islands over limited regions of phase space. Control of these islands could offer an attractive mechanism for alpha ash removal and/or for burn control.

Drift islands for 40 keV beam ions

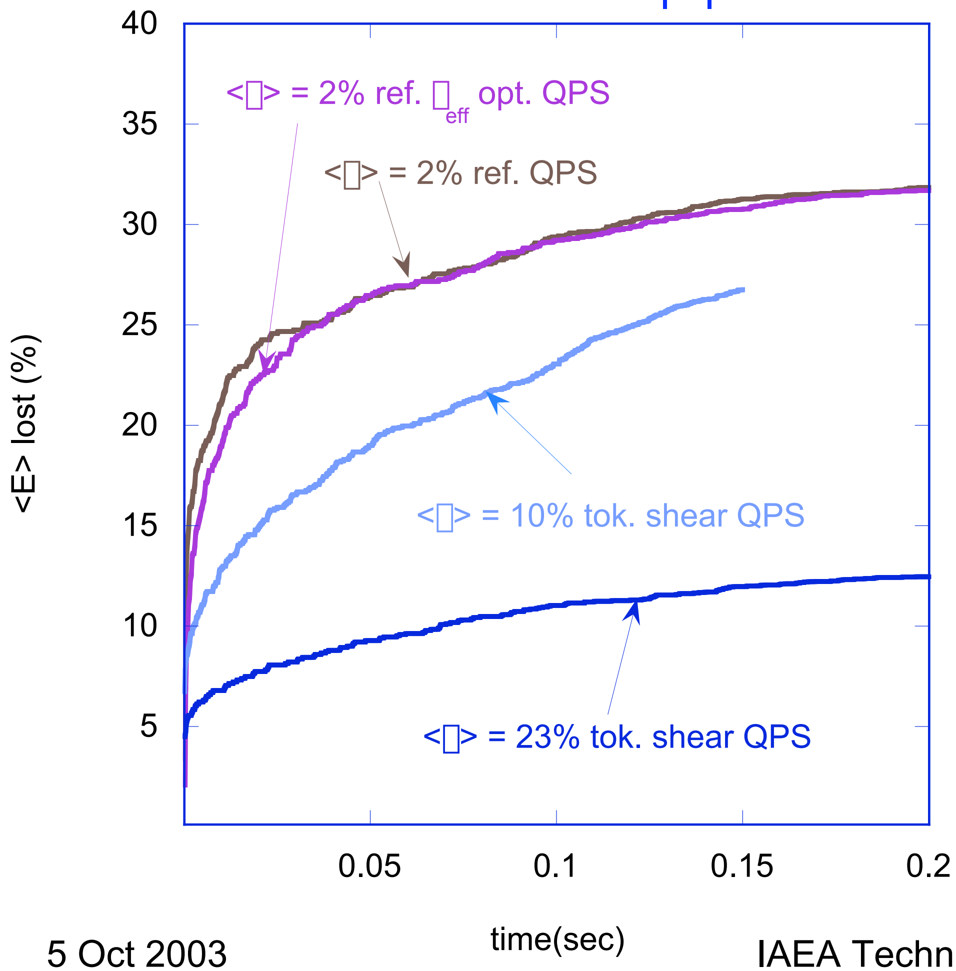


Variation in island size/location for energies from 35 to 60 keV

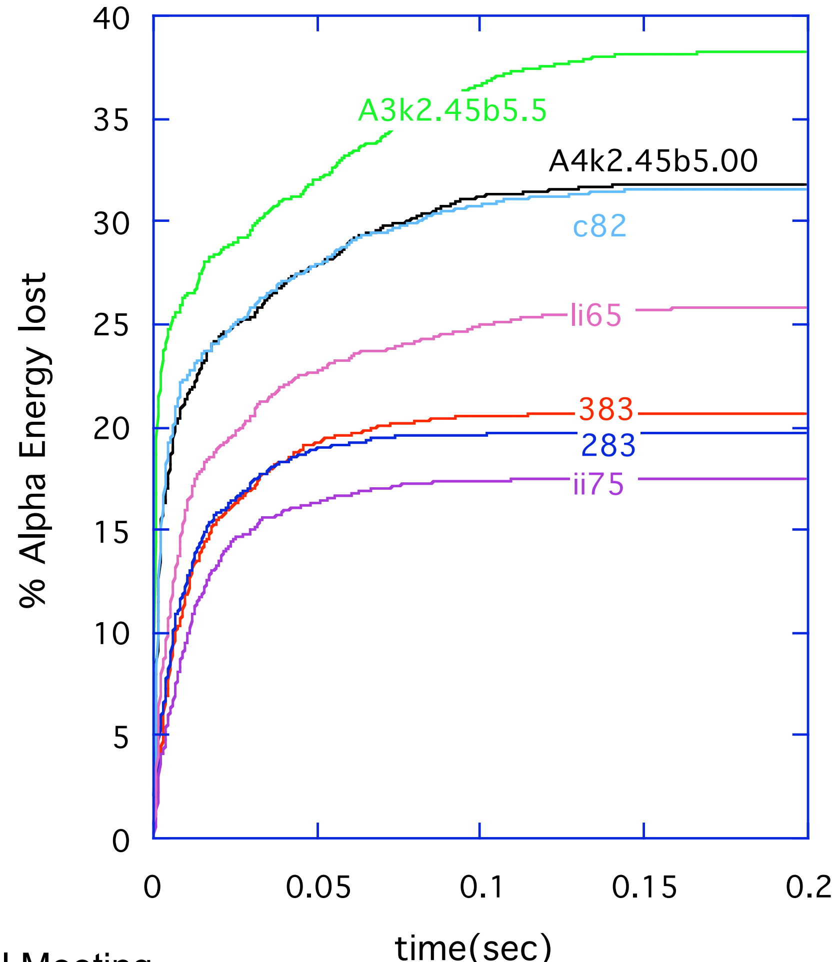


Compact stellarator designs are achieving tolerable level of alpha loss. Further configuration optimization (L.–P. Ku – ARIES CS reactor study) is expected to lead to even lower losses.

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

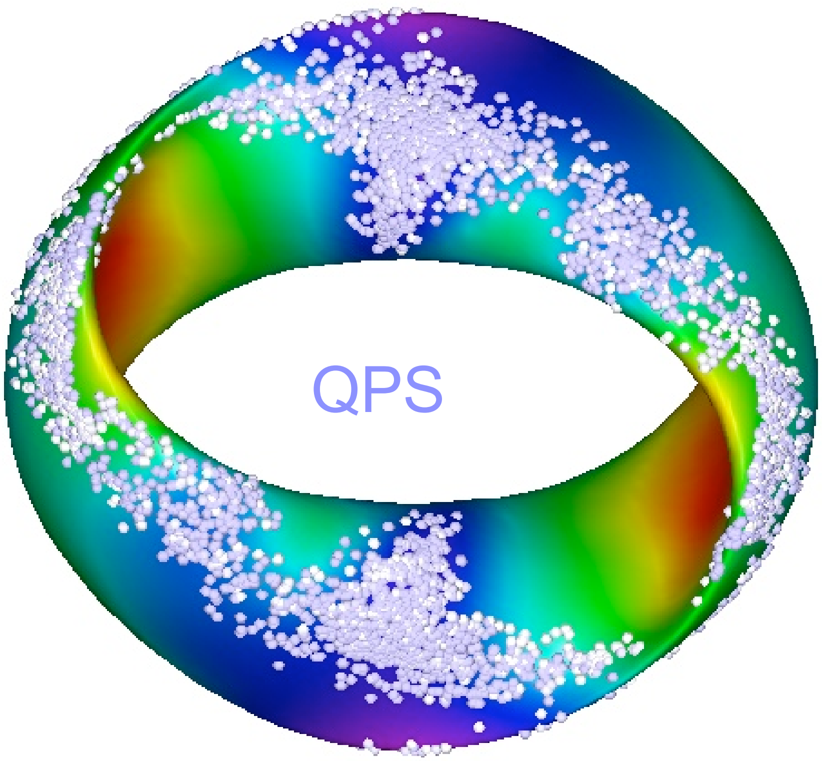


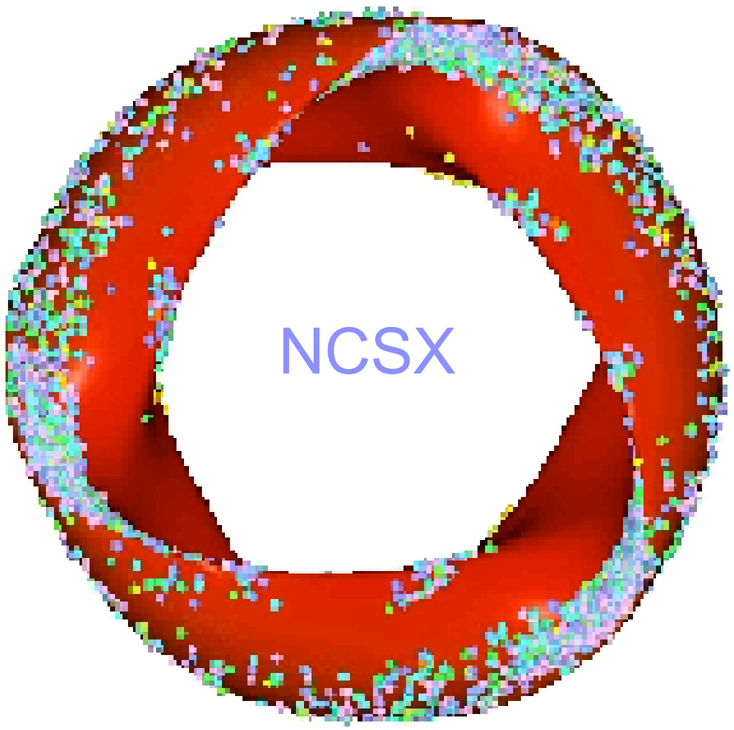
Alpha loss rates improve in a series of NCSX devices as the |B| spectrum is made more symmetric.



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

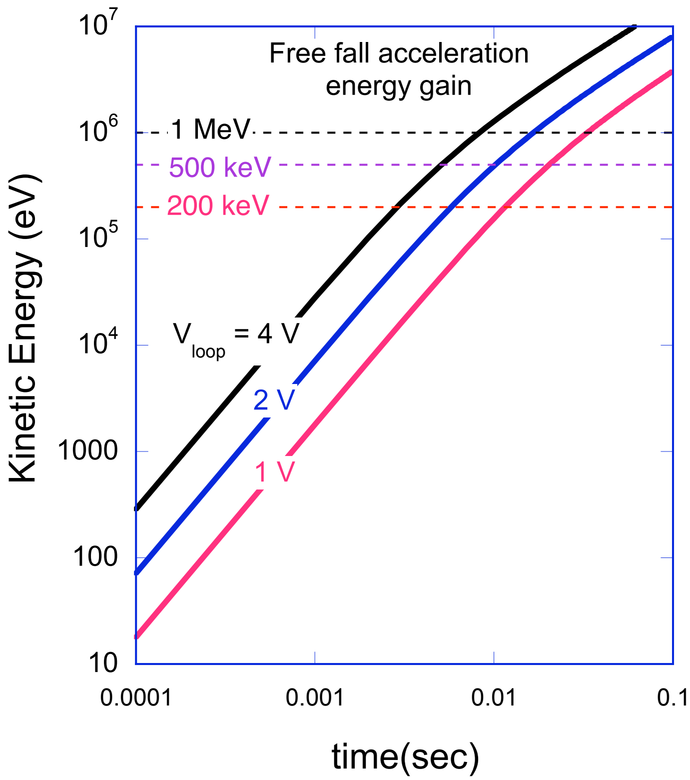
Fast Ion losses In Compact Stellarators

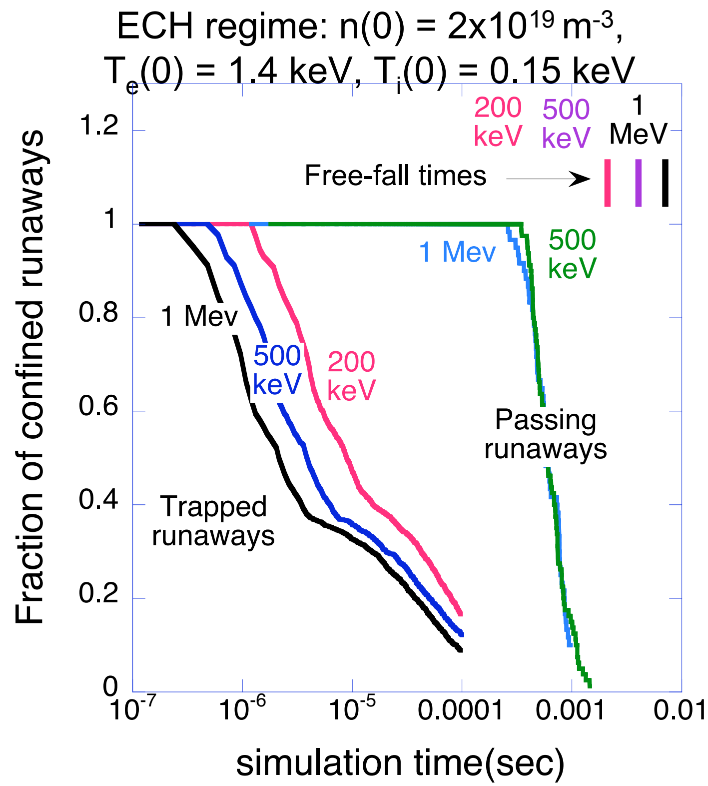


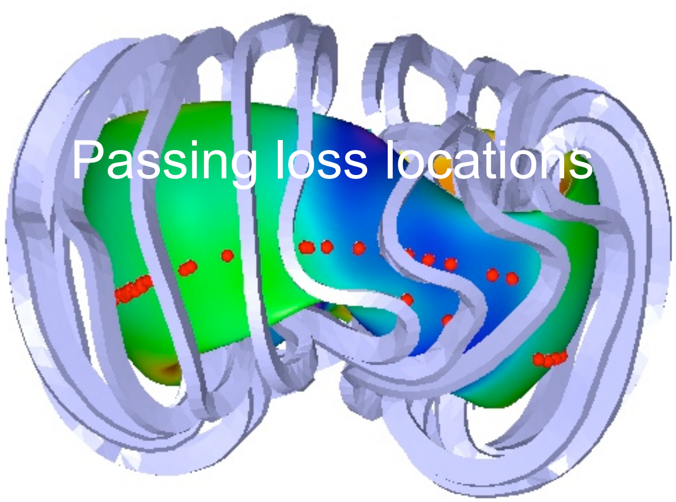


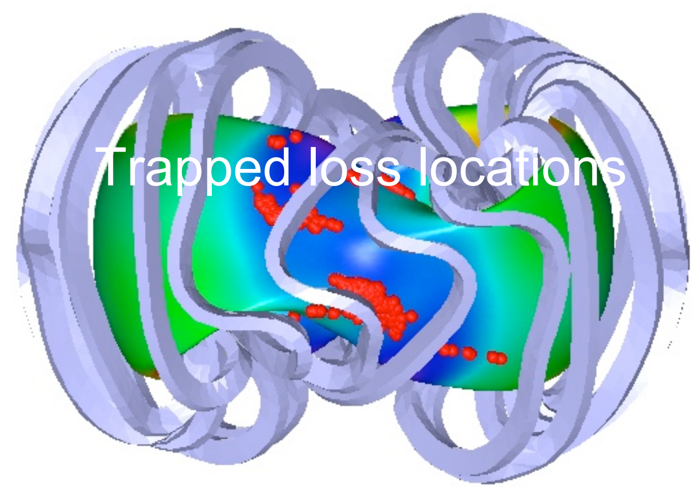
Monte Carlo analysis of runaway electrons provides information about confinement and loss locations

QPS









Controlled runaway electron production can be a useful tool for plasma microturbulence studies

- Work by Kwon, Diamond, et al., Nuclear Fusion (1988) used the decay rate of ~1 MeV runaway electrons in ASDEX to infer:
  - Thermal plasma microturbulence eddy size and electromagnetic fluctuation level
- Compact stellarators offer a more controlled environment than tokamaks for such studies
  - Closed flux surfaces present from t = 0
  - Sawteeth, tearing modes absent
  - Need to tailor Ohmic drive to avoid damaging runaway levels

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
    - Wider spread of bounce and precessional frequencies than in a tokamak

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
- Profile consistency limits variation of q-profile unless special techniques are used.

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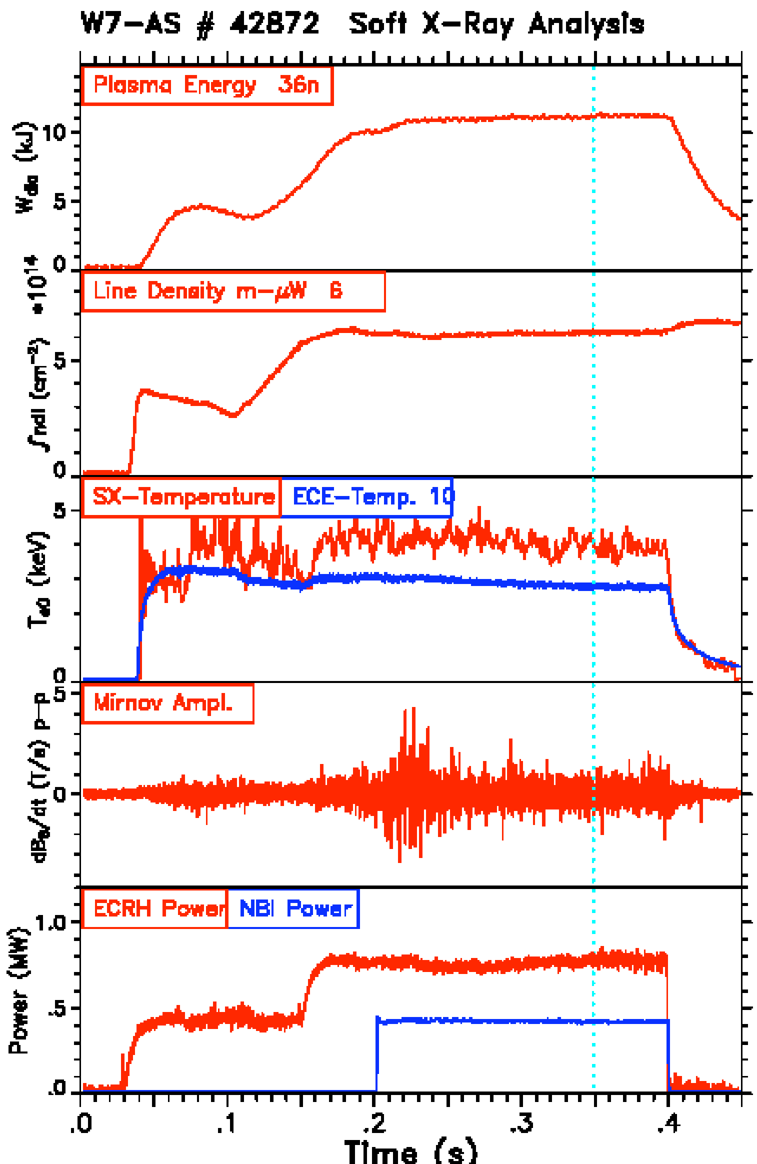
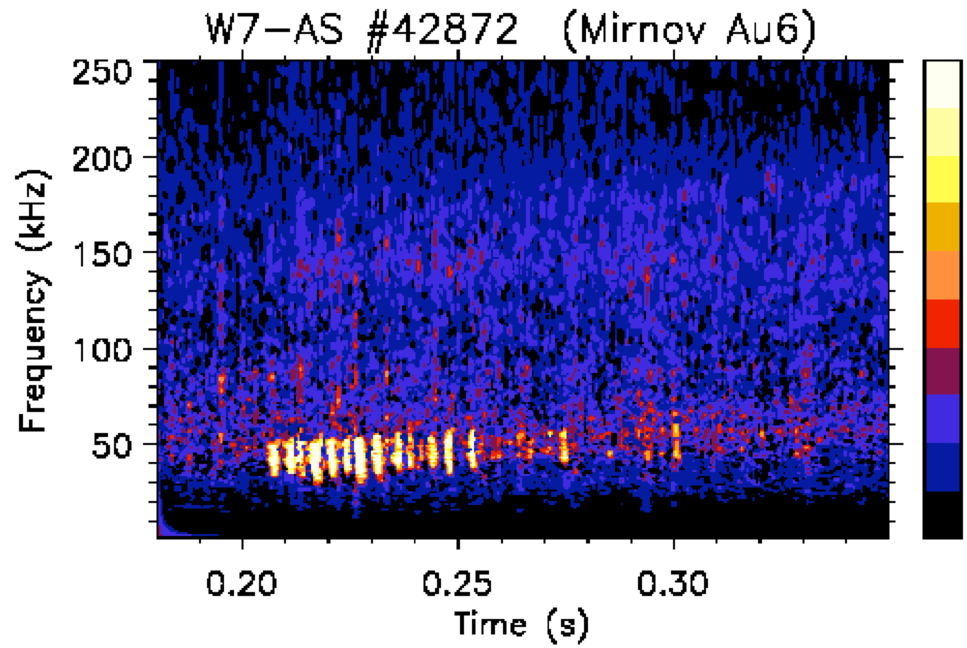
Stellarator

- Equilibrium introduces poloidal, toroidal (bumpy), and helical couplings
- Both g□□ and $|B|^2$ couplings can induce gaps
- 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
- External control of rotational transform profile allows a range of different AE phenomena to be examined

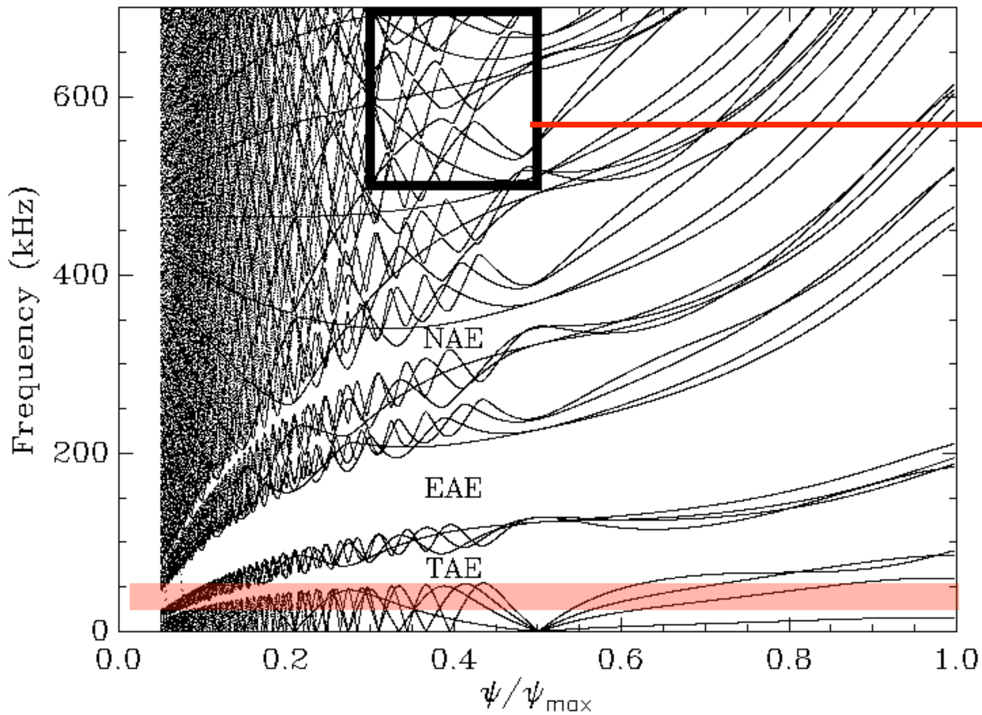
Beam-driven Alfvén instabilities dominated by a single frequency are observed on the W7-AS stellarator:

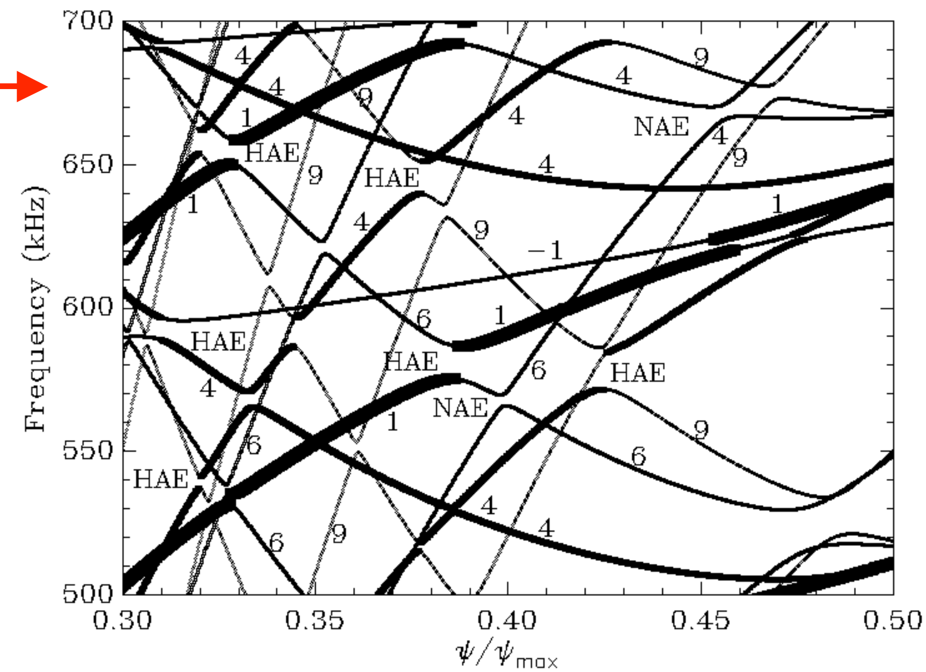
[taken from A. Weller, et al., Phys. Of Plasmas 8 (2001) 931]





STELLGAP[1] code applied to W7-AS case #42872

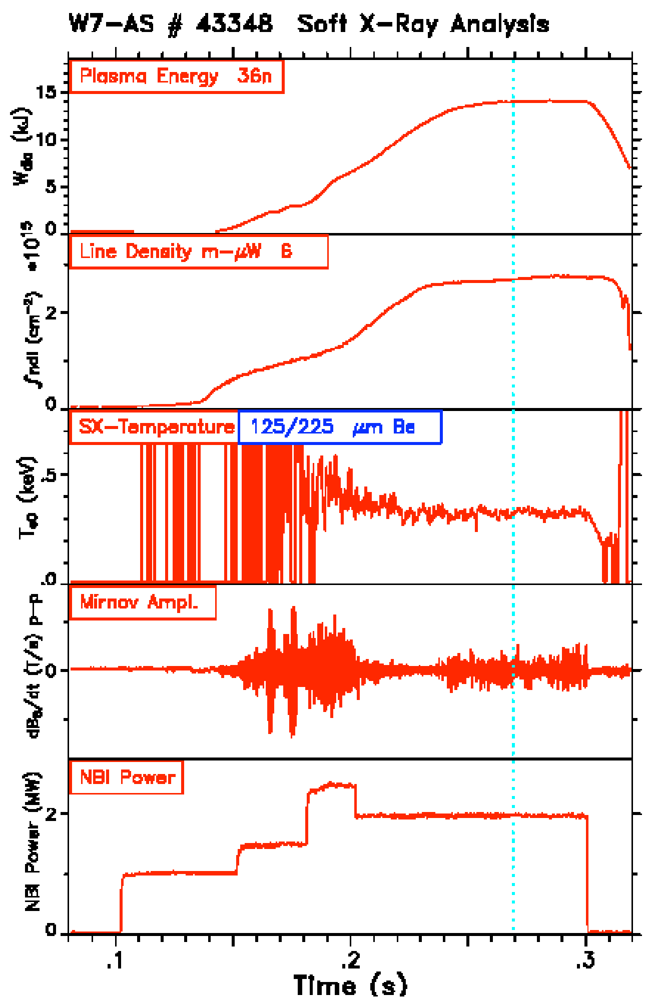


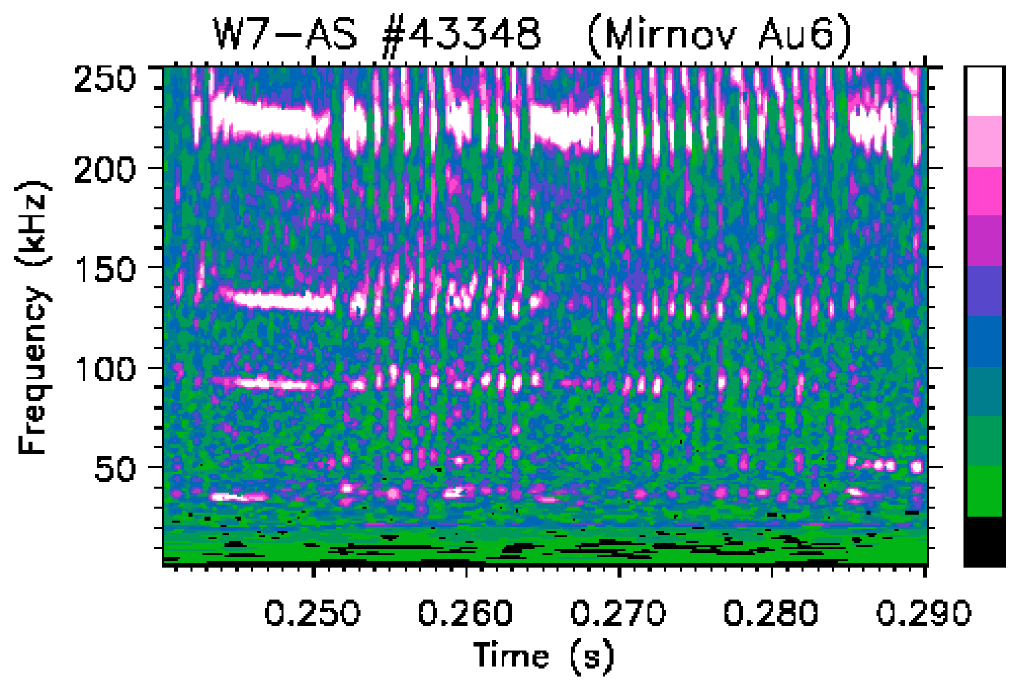


[1]D. A. Spong, et al., Phys. Plasmas **10** (2003) 3217]

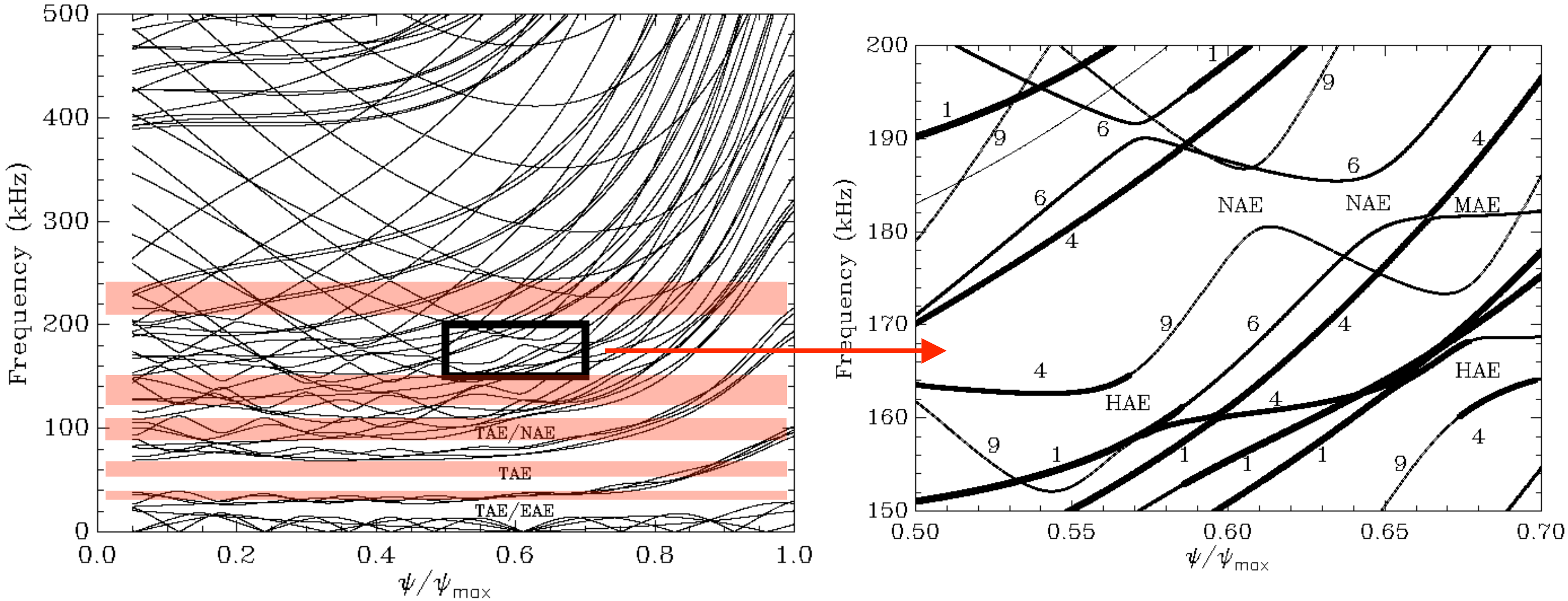
In other regimes, W7-AS sees complex multiple frequency Alfvén instabilities:

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





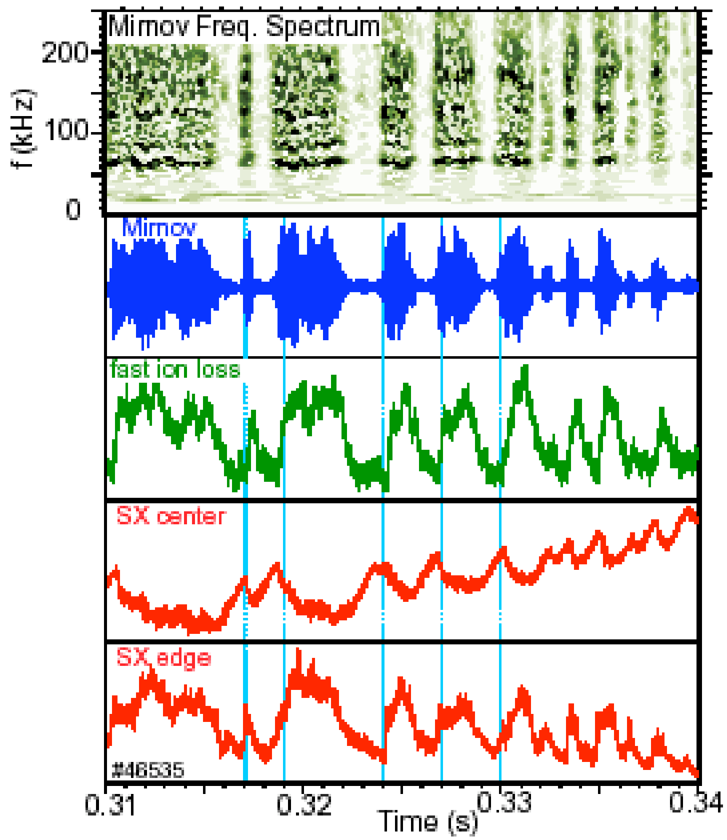
STELLGAP[1] code applied to W7-AS case #43348

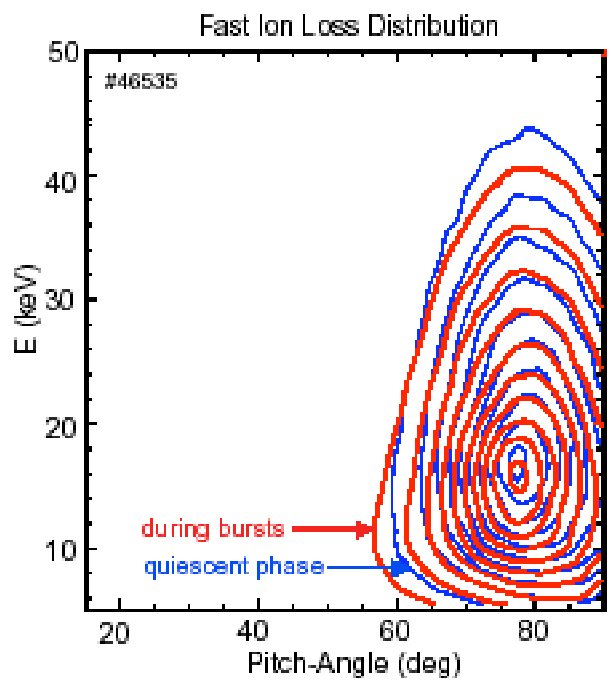


[1]D. A. Spong, et al., Phys. Plasmas **10** (2003) 3217]

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

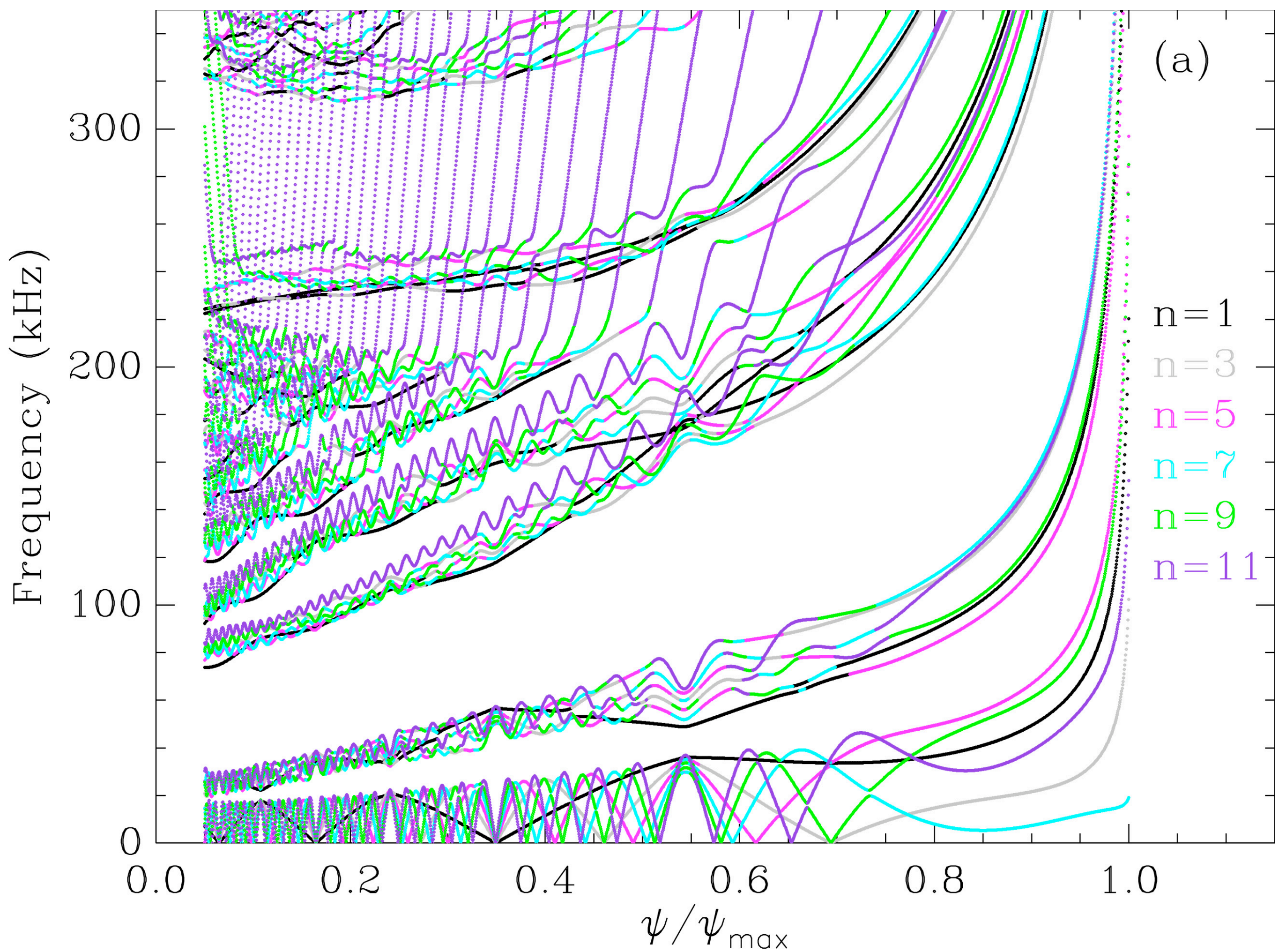
[taken from A. Weller, et al., Phys. Of Plasmas 8 (2001) 931]



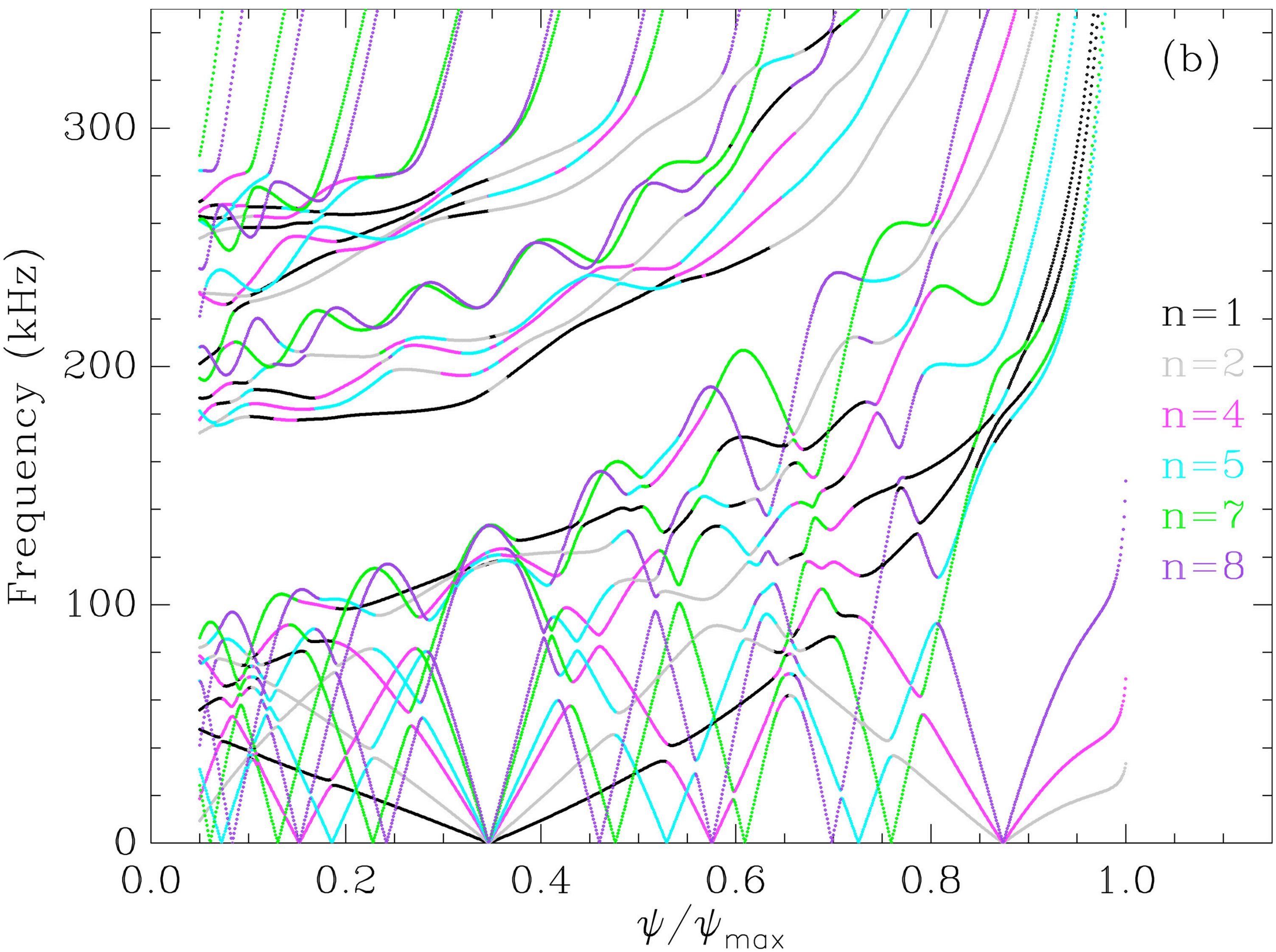


Continuum gap structure for QPS (QA-symmetry) n = 1 mode family using STELLGAP code

QPS



Continuum gap structure for NCSX (QA-symmetry) n = 1 mode family using STELLGAP code



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 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 alpha ash removal and burn control mechanisms that can be externally turned on and off
  - passing particle drift islands
- Alfvén continuum damping and mode structure may be influenced through magnetic design