Energetic Particle Physics in MST Reversed Field Pinch

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RFP provides complementary environment to other toroidal configurations for EP physics

- Fast-ion dynamics in an RFP can be quite different from that in tokamaks and other configurations
  - Weak toroidal field → large fast-ion β and stronger drive
  - Large magnetic shear → increased stability
- Energetic particle driven instabilities observed in MST
  - Multiple bursty modes with fishbone-like temporal dynamics

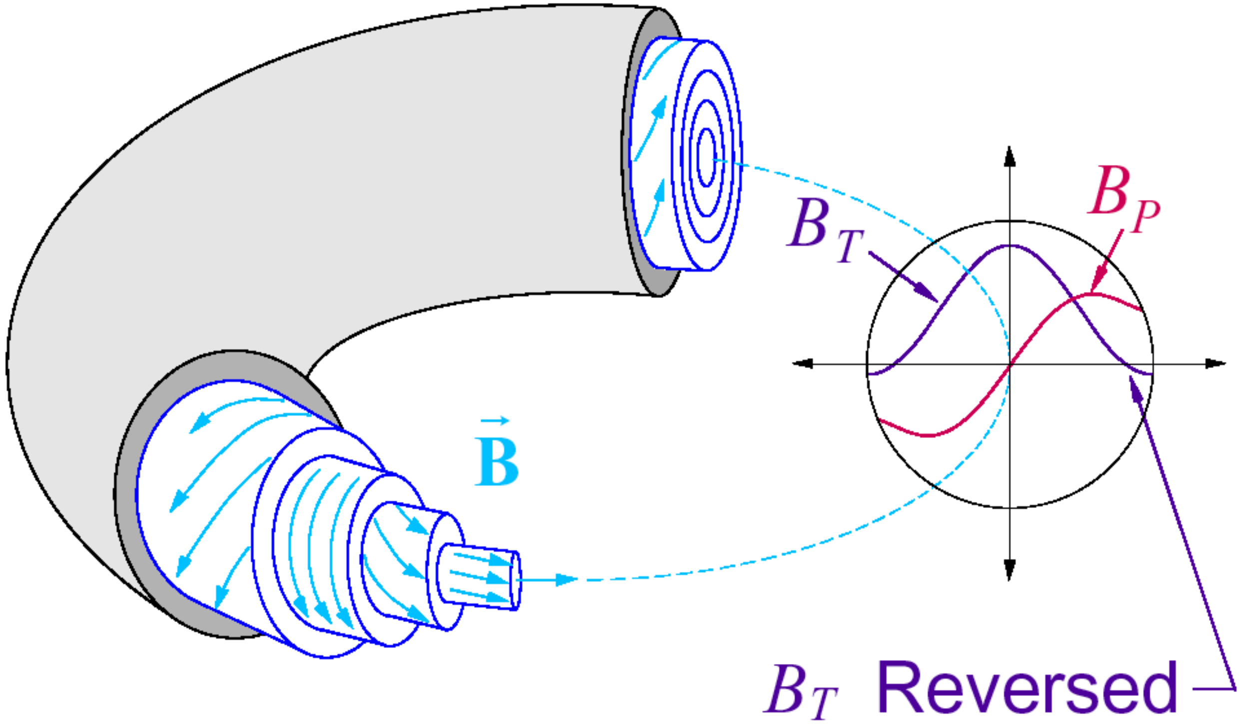
- Opportunity to explore and validate important EP physics!

Outline

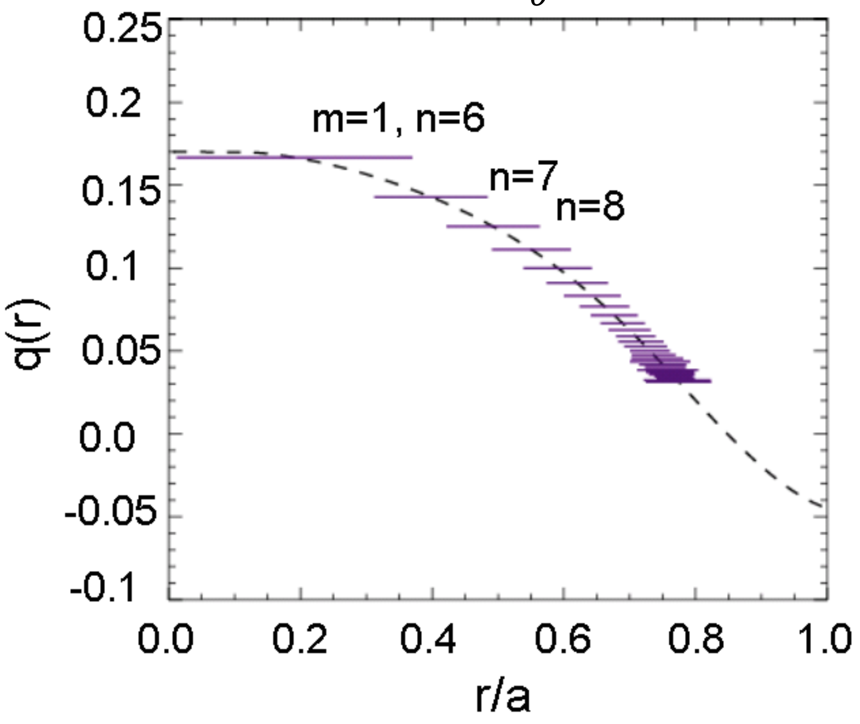
- MST and Neutral Beam Injection
  - TRANSP/NUBEAM modeling of fast-ion distribution
  - Neutral Particle Analyzer diagnostic for fast-ion energy distribution
- Fast particle confinement in 3D fields
  - Stochasticity in presence of multiple islands
  - Helical core of QSH state
- NBI driven bursting modes
  - Well studied EPM
  - Characterization of AE

MST provides complementary environment to study energetic particle physics

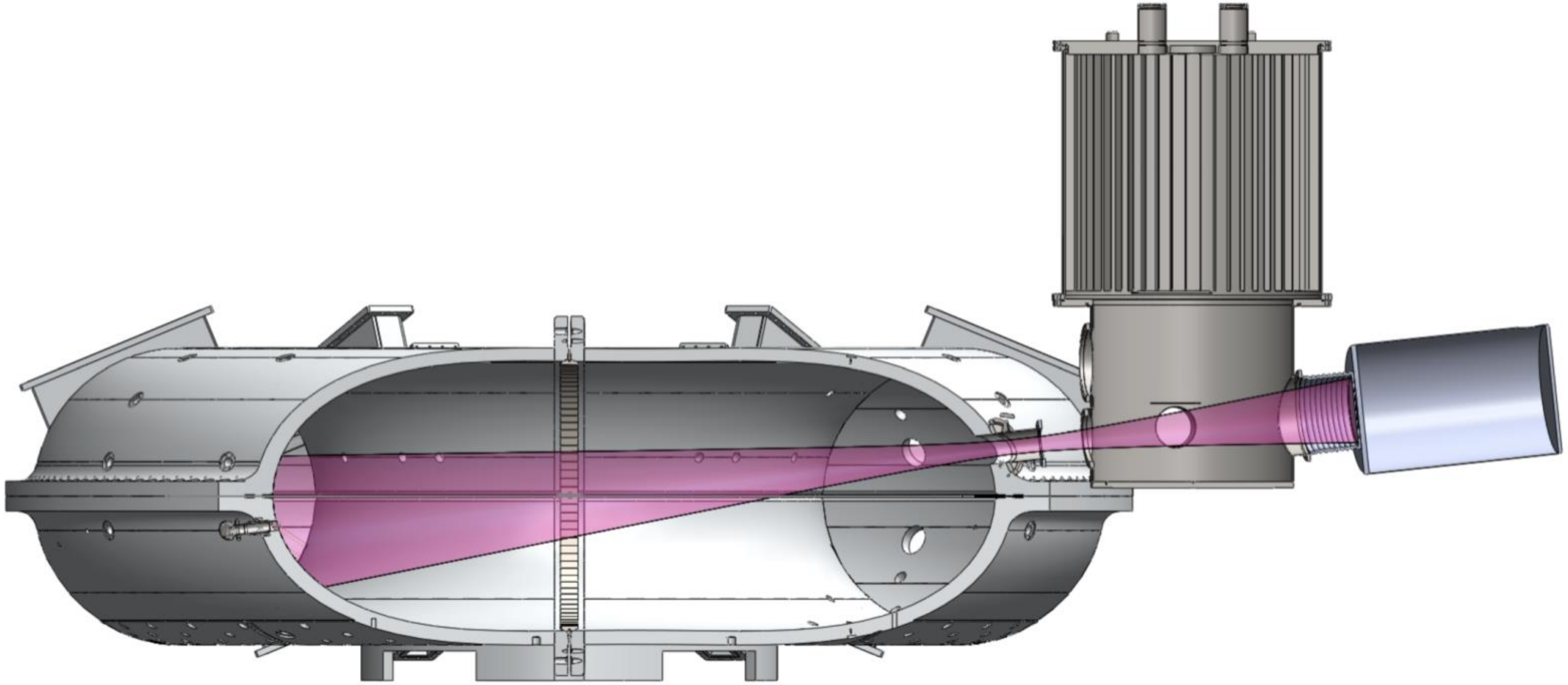
- Comparable B_θ and B_ϕ lead to strongly sheared magnetic field and $q < 1$



$$q(r) = \frac{rB_\phi}{RB_\theta} < 1$$



Tangentially injected neutral beam maximizes fast ion deposition



Madison Symmetric Torus

R=1.5 m; a=0.52 m

$I_p \sim 200 - 500$ kA

$|B| \sim 0.2 - 0.5$ T

$T_e(0) \sim 200 - 2000$ eV

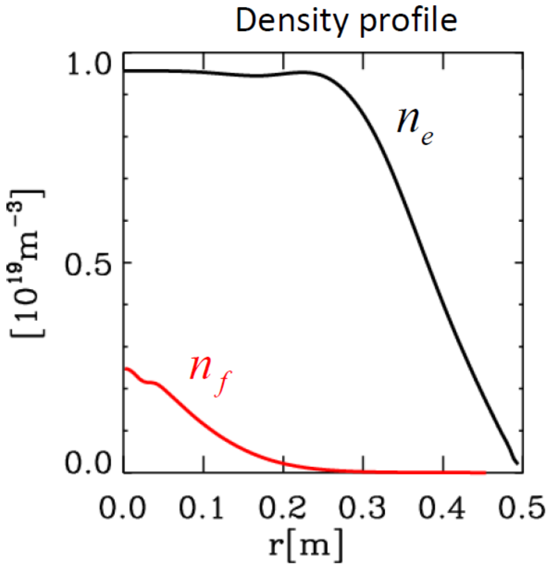
$n_e \sim n_D \sim 10^{13}$ cm^{-3}

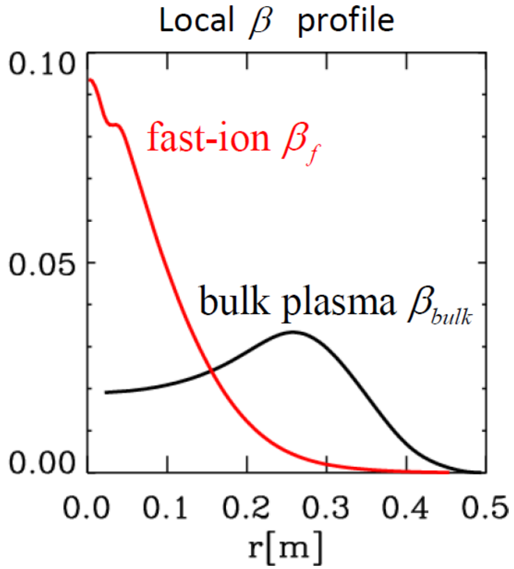
Pulse length ~ 60-100 ms

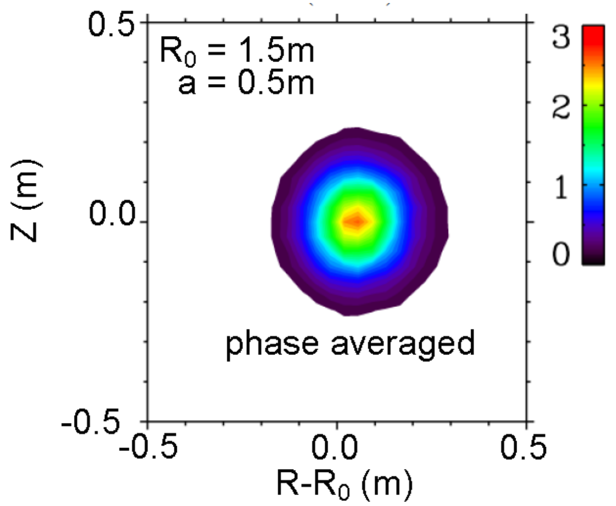
NBI Parameter	Specification
Beam energy	25 keV
Beam power	1 MW
Pulse length	20 ms
Composition	95-97% H, 3-5% D
Energy fraction (E:E/2E/3:E/18)	86%:10%:2%:2%

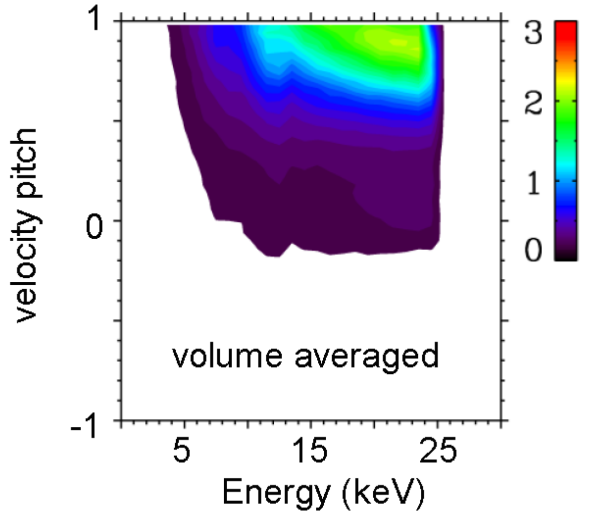
Classical TRANSP/NUBEAM modeling predicts core localized high pitch fast ion population

- Most ions confined near core: $r/a < 0.4$
- Mostly passing particles with pitch: $v_{\parallel}/v > 0.9$
- Classical modeling predicts fast ion beta well in excess of core bulk beta
  - Expected limited by onset of EP driven magnetic activity



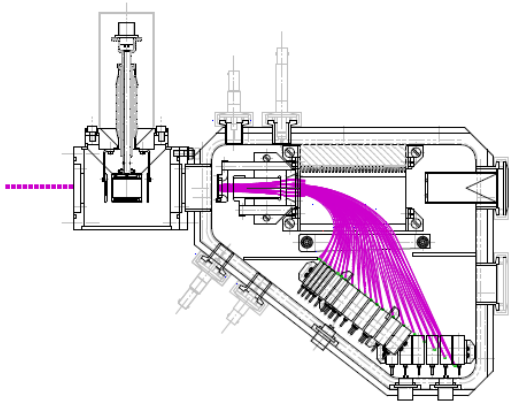


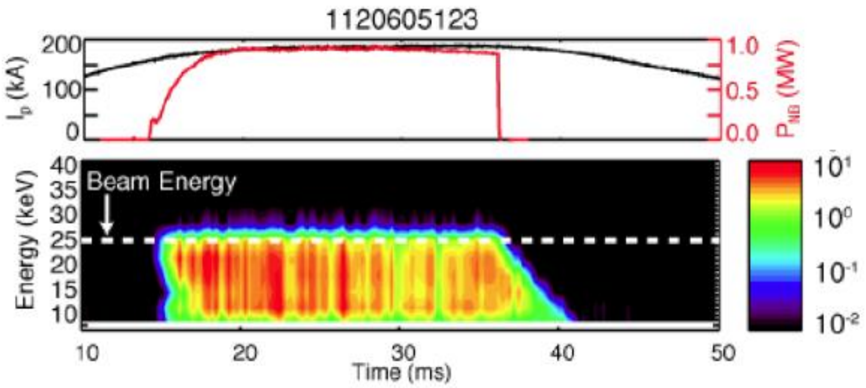


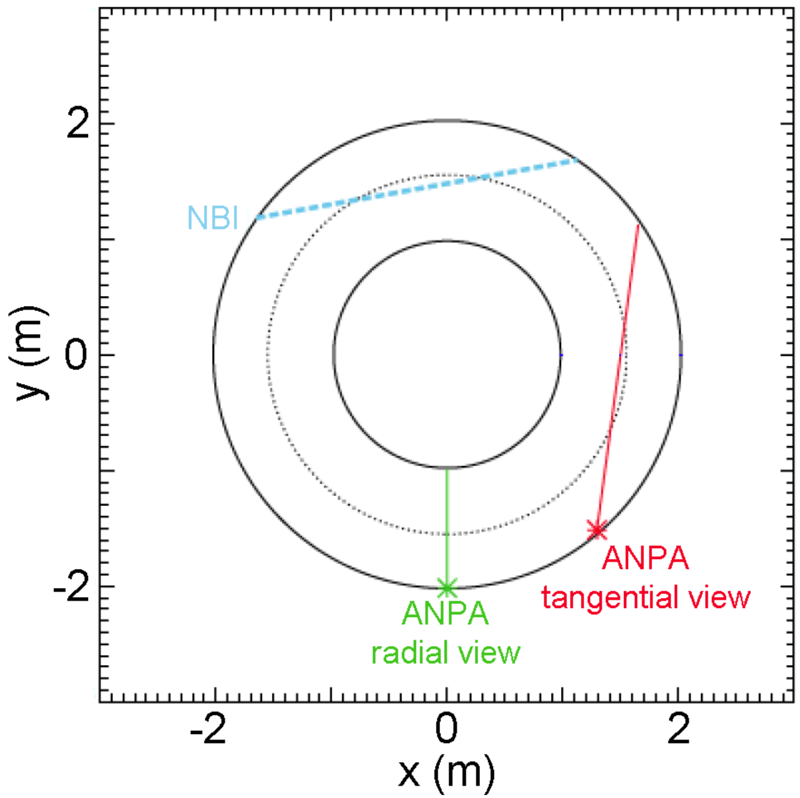


NPA measures fast-ion energy distribution

- Resolves energy distribution of plasma ions (H and D) in 5-40keV range
- Viewing location determines sampled population







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  - Well studied EPM
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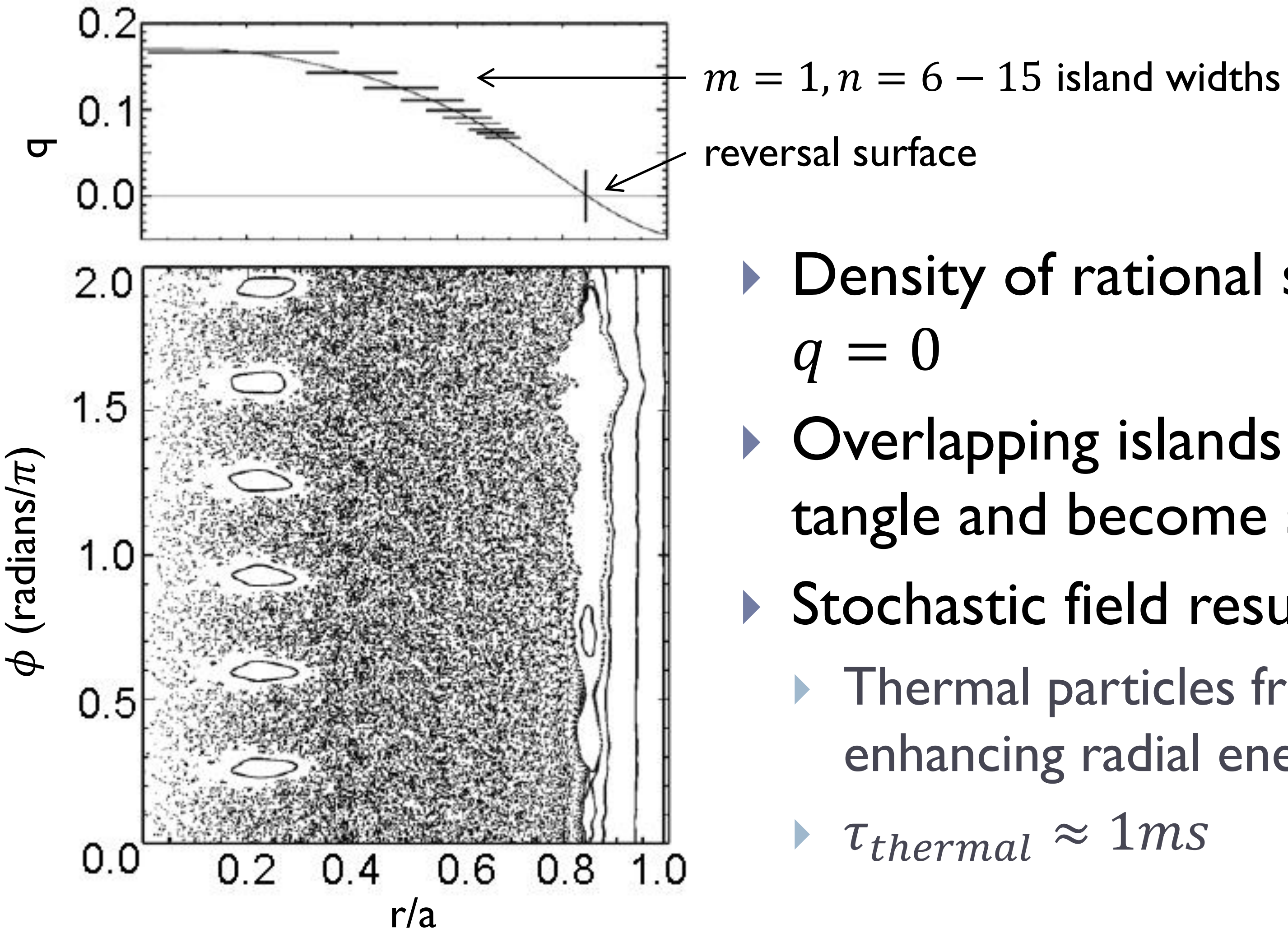
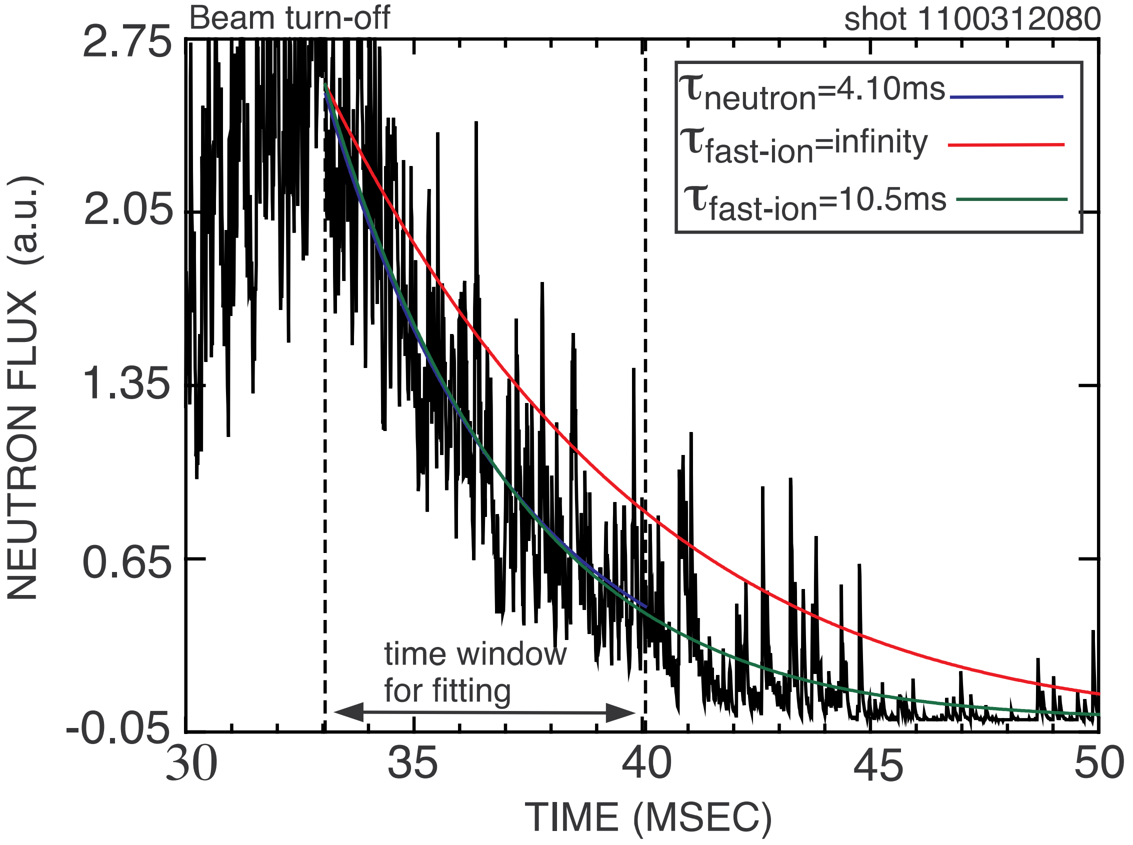
Magnetic island overlap causes field stochasticity

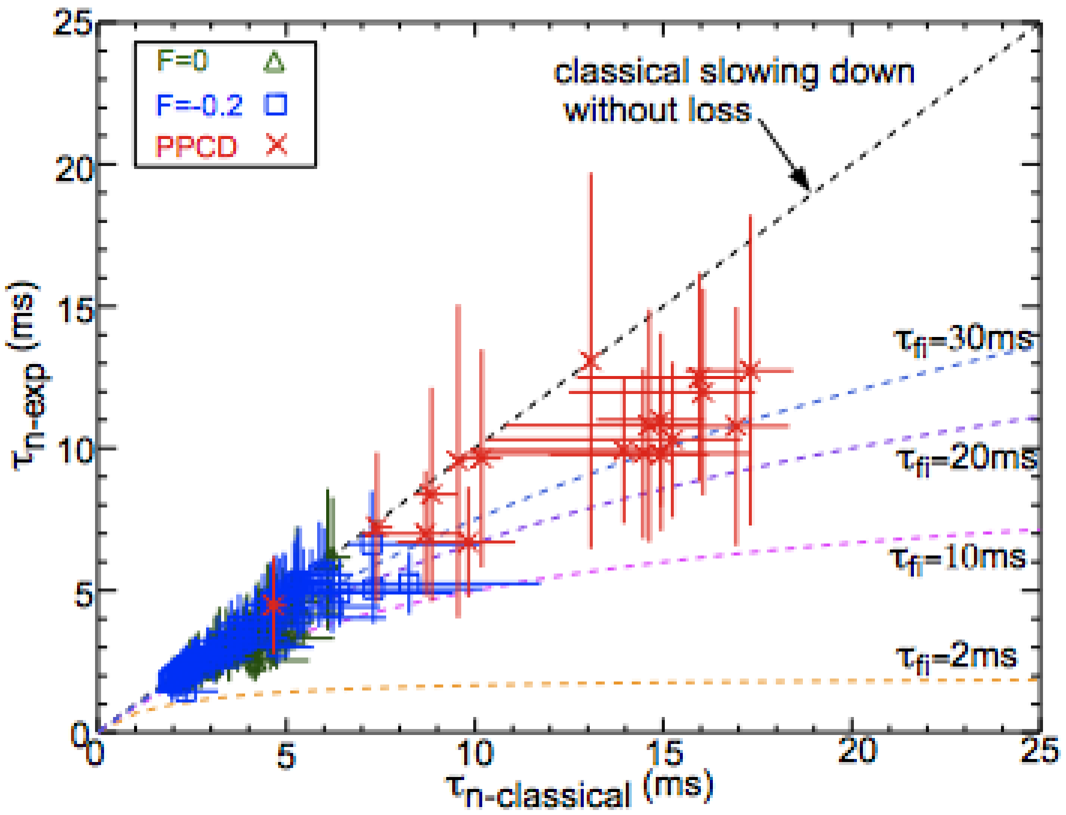


- Density of rational surfaces increases towards $q = 0$
- Overlapping islands cause magnetic field to tangle and become stochastic
- Stochastic field results in rapid radial transport
  - Thermal particles free-stream along field line enhancing radial energy and particle diffusion
  - $\tau_{thermal} \approx 1ms$

Fast ions near classical confinement in stochastic field

- Decay of fusion neutron flux used to measure confinement in beam-blip experiments

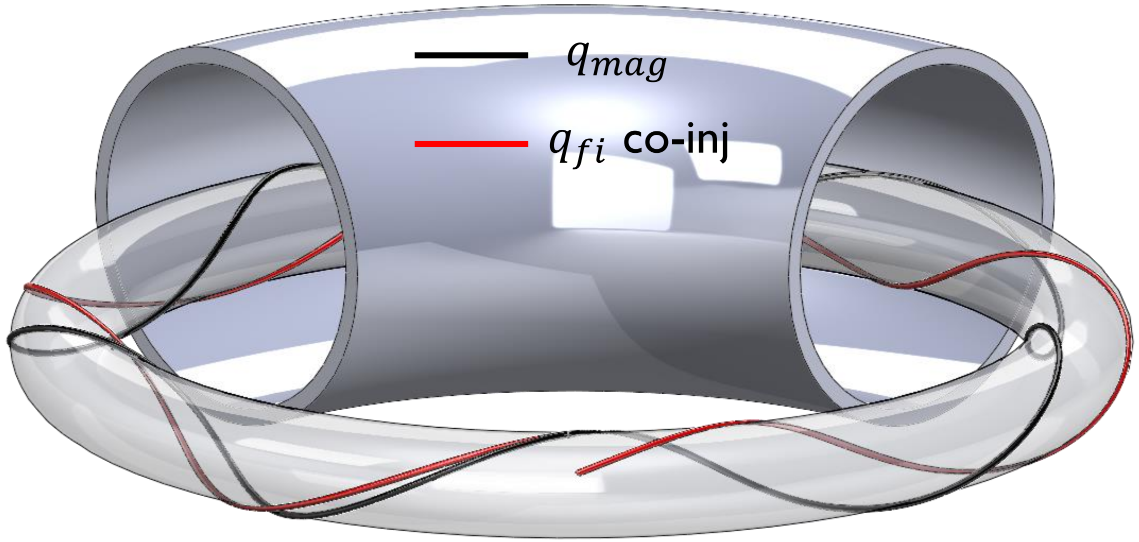




- W.W. Heidbrink and G.J. Sadler 1994 *Nucl. Fusion* **34** 535

RFP field puts fast ion drift in magnetic surface

- $v_{GC} = v_{\parallel}\boldsymbol{b} + \frac{v_{\perp}^2}{2\omega_c}\frac{\boldsymbol{B}\times\nabla\boldsymbol{B}}{|B|^2} + \frac{v_{\parallel}^2}{\omega_c}\frac{\boldsymbol{B}\times\boldsymbol{\kappa}}{|B|} = v_{\parallel}\boldsymbol{b} + \boldsymbol{v}_D$ ($\boldsymbol{E}\times\boldsymbol{B}$ term unimportant)
- $\nabla\boldsymbol{B}$ and $\boldsymbol{\kappa}$ are both dominated by **r** (not **R**)
- $\boldsymbol{v}_D$ is $\perp B$ but in the surface
- Fast-ion rotational transform $q_{fi} = \frac{r v_\phi}{R v_\theta}$ differs from q_{mag}
  - Guiding center motion at substantially different helicity than local magnetic perturbation



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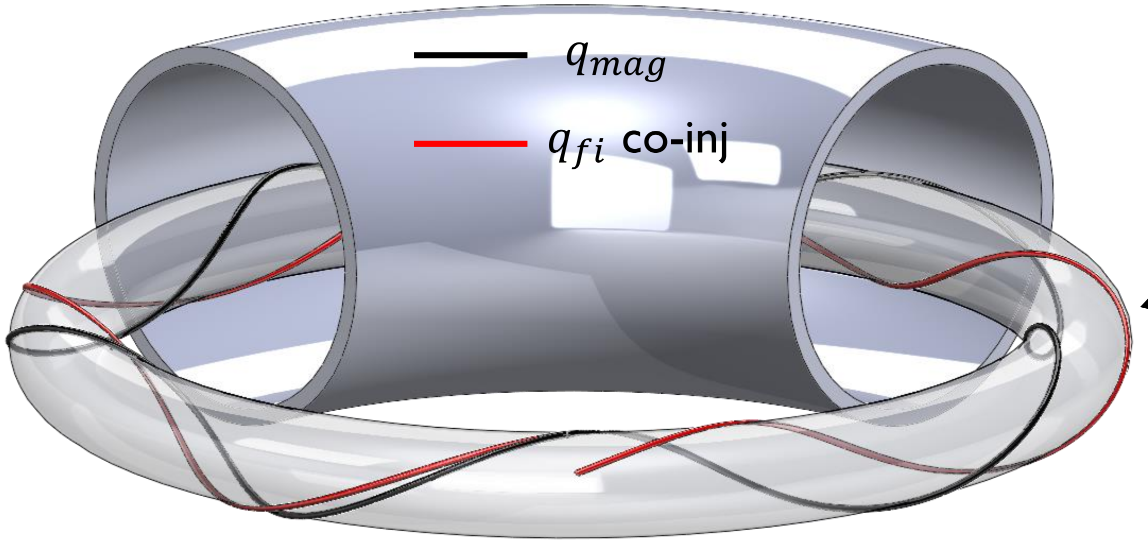
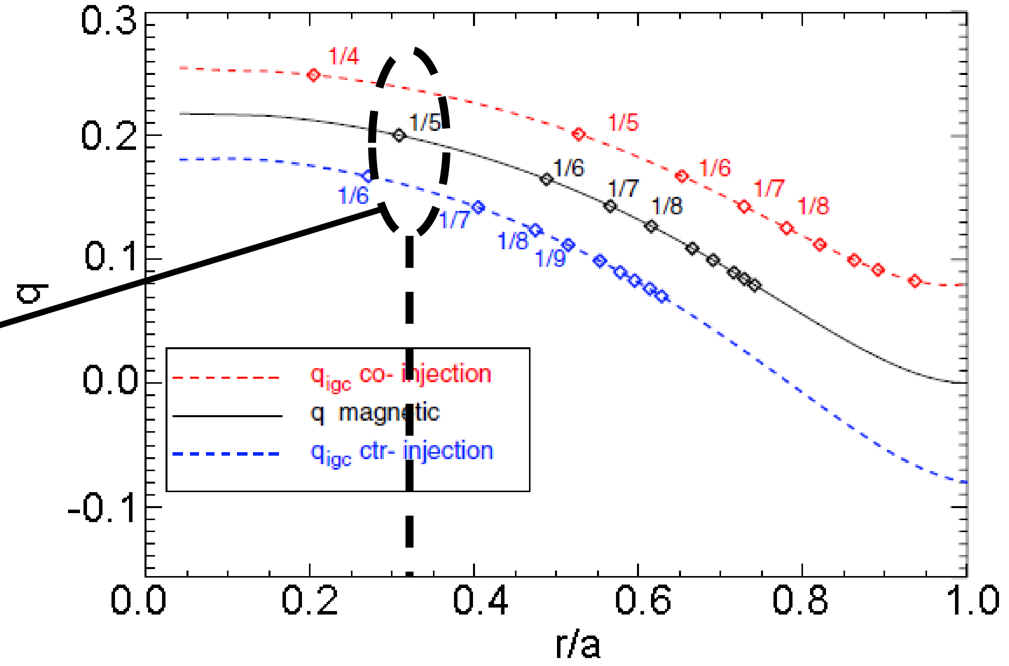


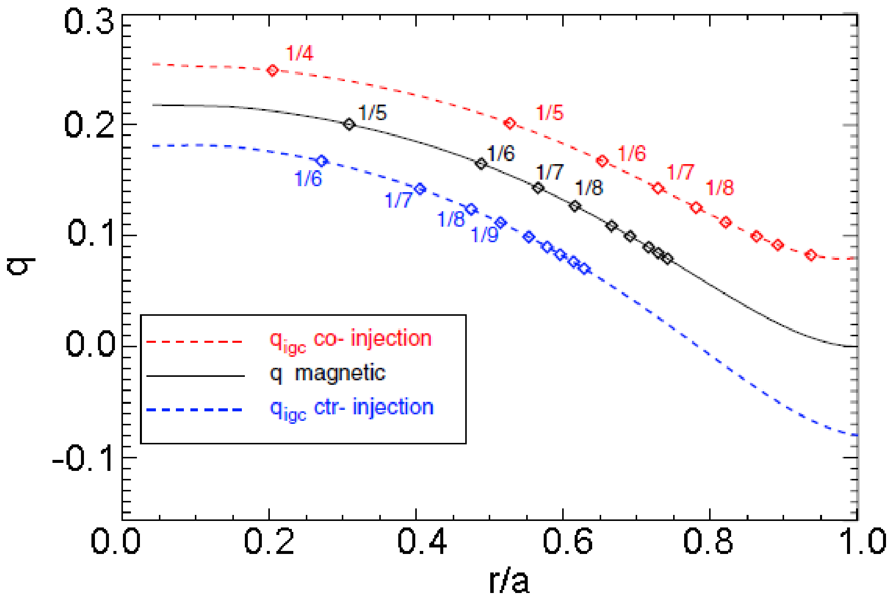
q mag = 0.20
q_{fi} co-inj = 0.24



- $q_{fi} > q_{mag}$ for co-injection, $q_{fi} < q_{mag}$ for counter-injection

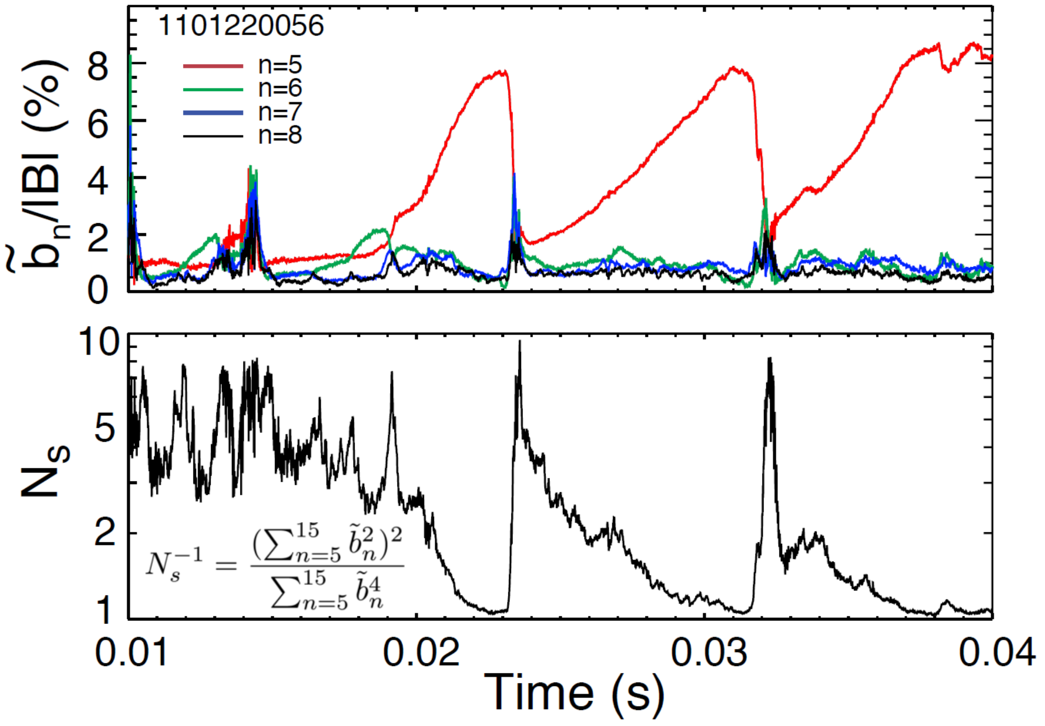
Substantial radial domain exists in core free of ion guiding center resonances for co-injected ions

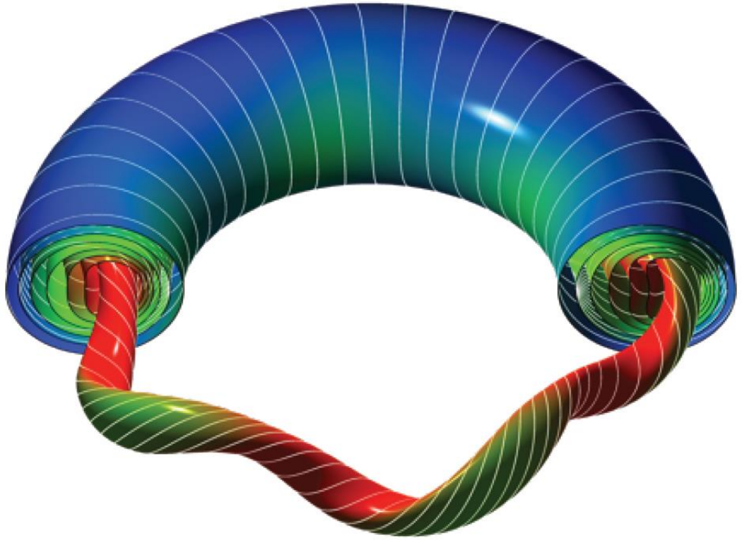
- Fast ion resonant surfaces shifted away from q_{MHD}
- Co-injection:
  - Effective helicity of guiding center motion (m=1,n=4) is without a corresponding magnetic perturbation within the plasma
  - Core localized ions insensitive to stochastic magnetic transport, rendering them nearly classically confined
- Counter-injection:
  - With lowered q_{fi}, helicity of motion does match helicity of magnetic perturbation in plasma
  - $\tau_{f,co} \gg \tau_{f,ctr} \gtrsim \tau_{thermal}$



MST spontaneously transitions from stochastic to QSH

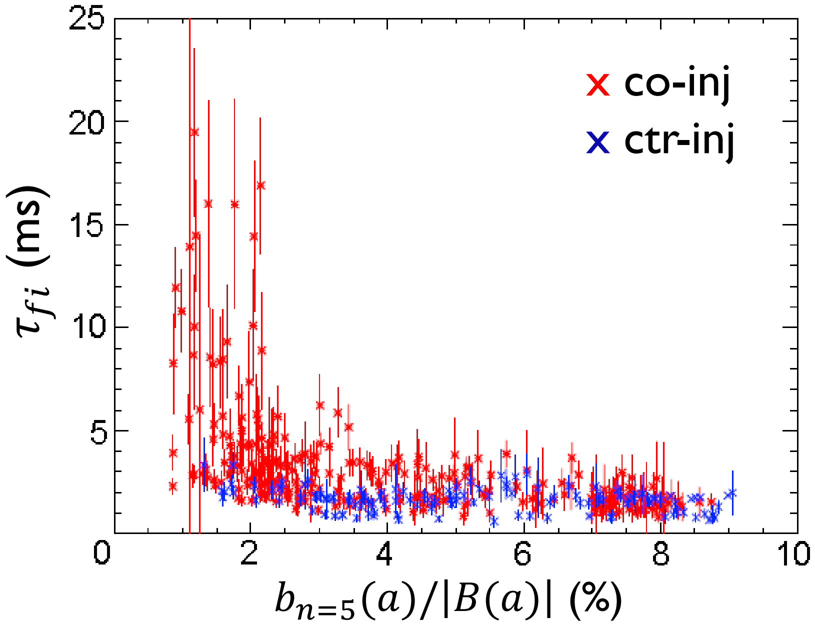
- Quasi-single-helicity equilibrium mainly described by helical core (n=5) in MST with axisymmetric circular surfaces at the edge
  - Occurs with growth of core-most mode and reduction of secondary modes





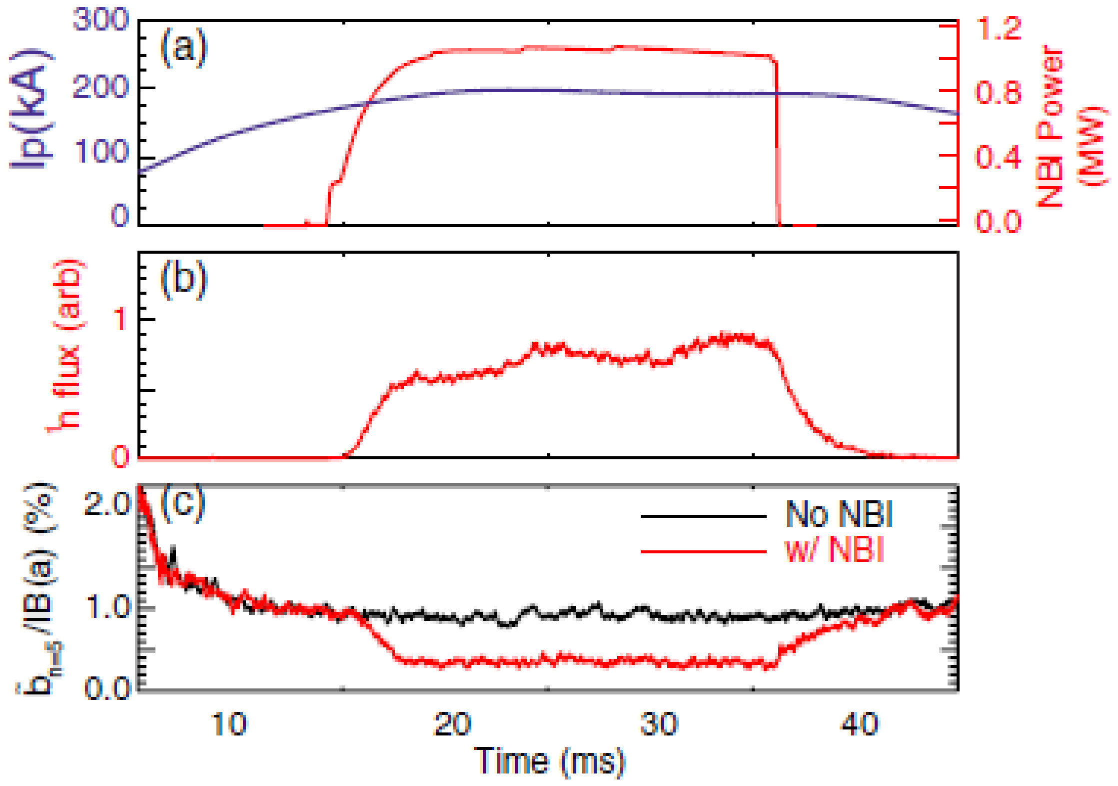
Fast ion confinement decreases with core helical perturbation

- Inverse relation between co-injected confinement and strength of helical perturbation revealed through beam-blip experiment
- Difference between co- and counter-injected ions in stochastic field disappears in QSH state
- Neo-classical effects (even stellarator-like) become important



Fast ion population affects tearing mode amplitudes

- In plasmas with marginal likelihood of QSH, large fast ion content delays transition
- Discharges with no QSH transition show a reduction in core-most tearing mode amplitude
  - Changes in tearing mode amplitude can be used as a proxy for fast-ion content



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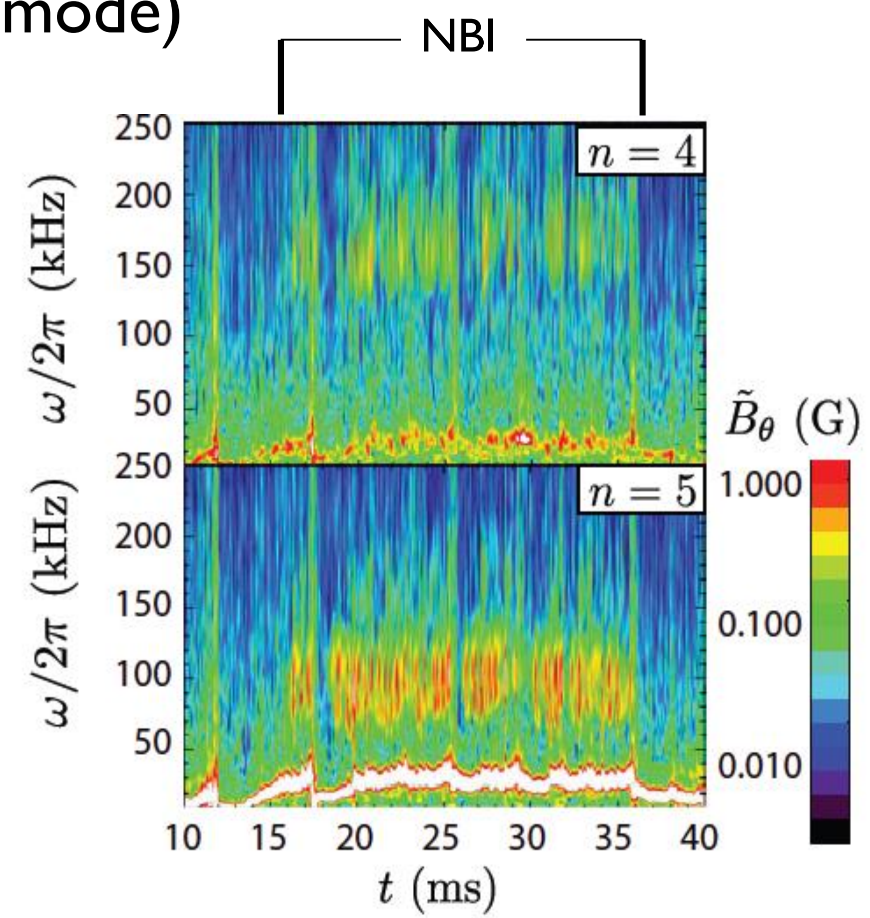
High fast ion concentration drives multiple bursting modes

- Wavelet analysis reveals bursty EP modes
- Prevalent EPM/AE pair (triplet with smaller n=1 mode)
  - Dynamics of triplet well studied
    - Internal $\tilde{n}$ and $\tilde{b}$ structure measured
    - Lin et al. PoP 2014



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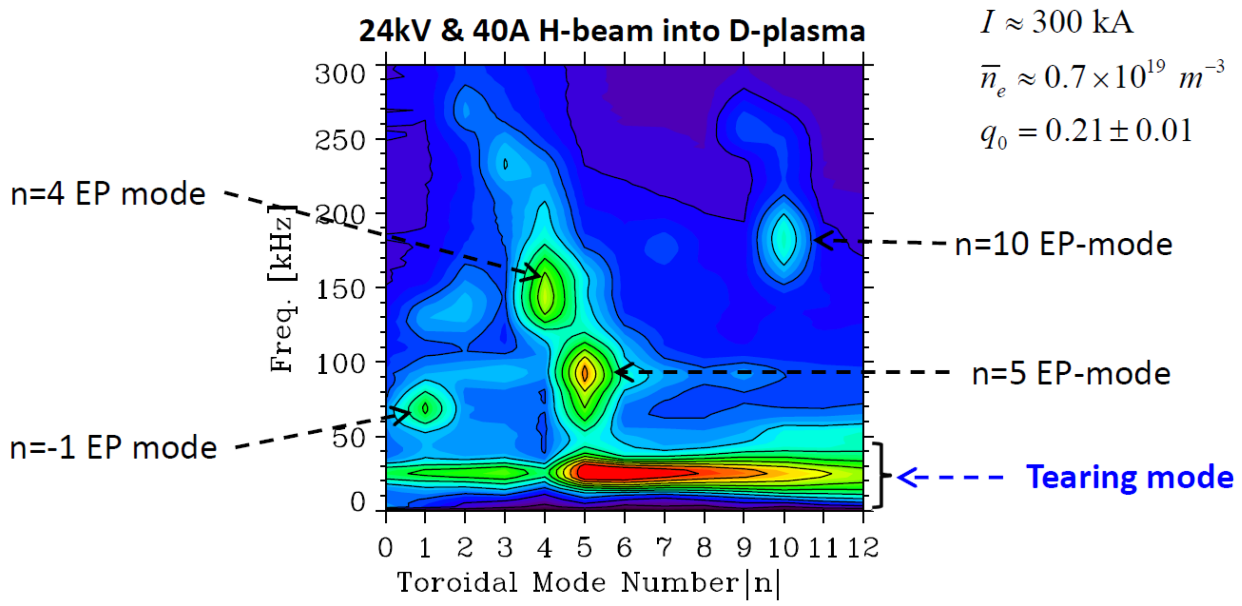
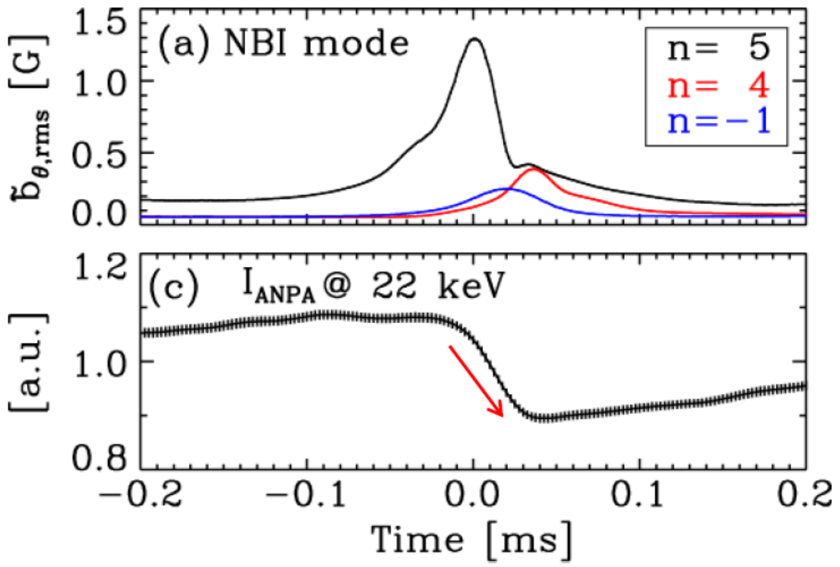
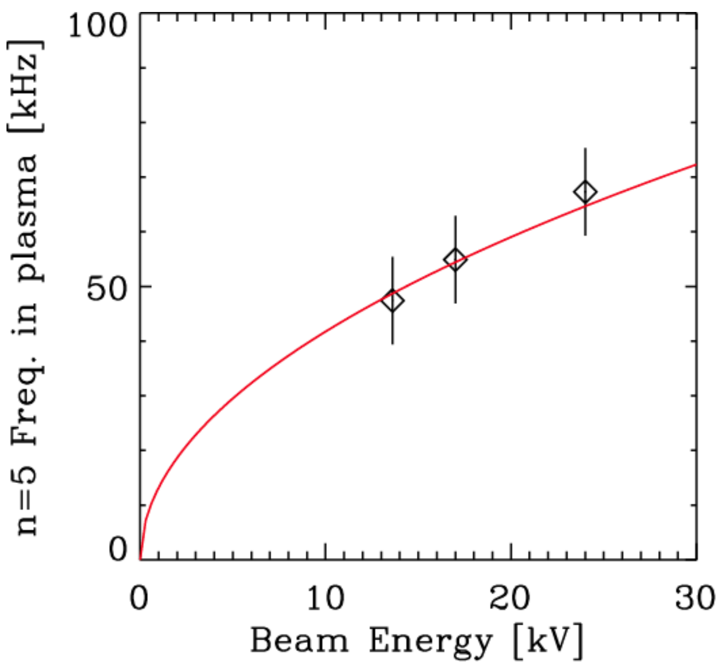
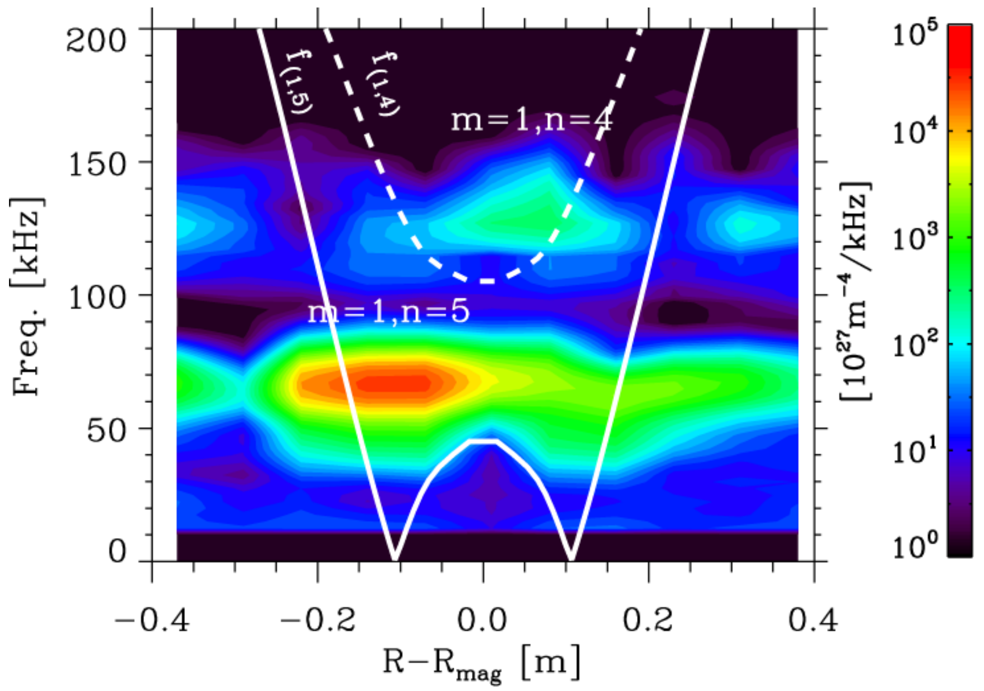




EPM is clearly identified (typically n=5)

- Continuum mode destabilized by strong drive
  - $f \propto v_{beam}$, $\omega \simeq k_{\parallel} v_A$





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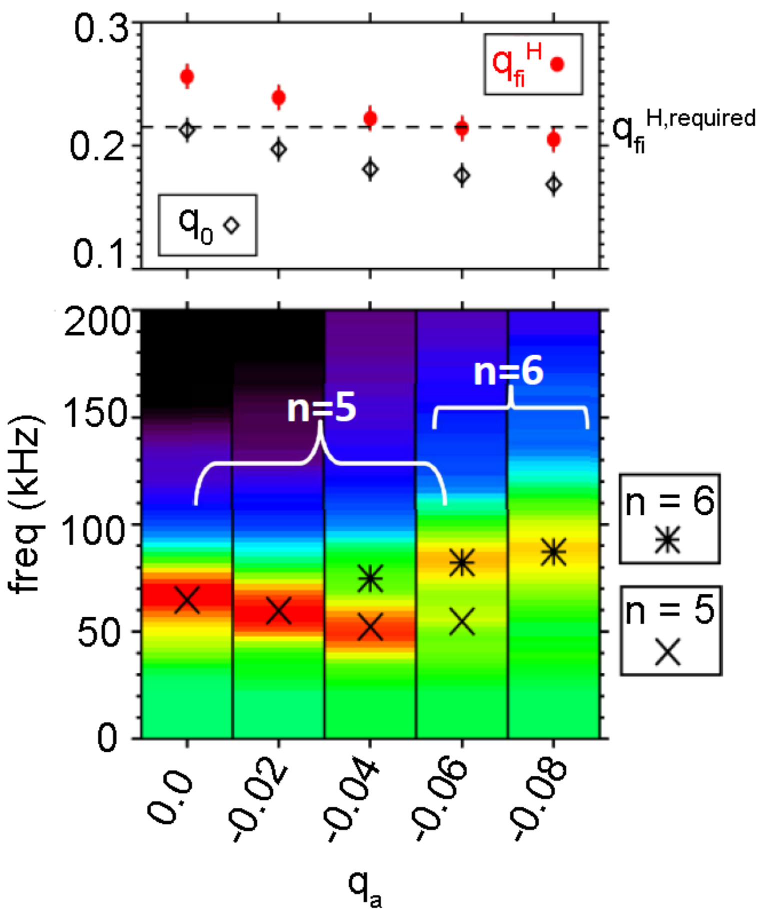
- Resonance condition is understood
  - Can alter toroidal mode number of EPM by varying equilibrium (and Alfvén continuum)
  - $f \simeq nf_{\phi} - (m+l)f_{\theta}$, $q_{fi} = \frac{f_{\phi}}{f_{\theta}}$
  - $q_{fi}^{required} \simeq \frac{m+l}{n-f/f_{\phi}}$

$q_{fi}^{H,required} \simeq 0.215$ for m=1,n=5 at measured frequency
$q_{fi}^{H,required} \simeq 0.18$ for m=1,n=6



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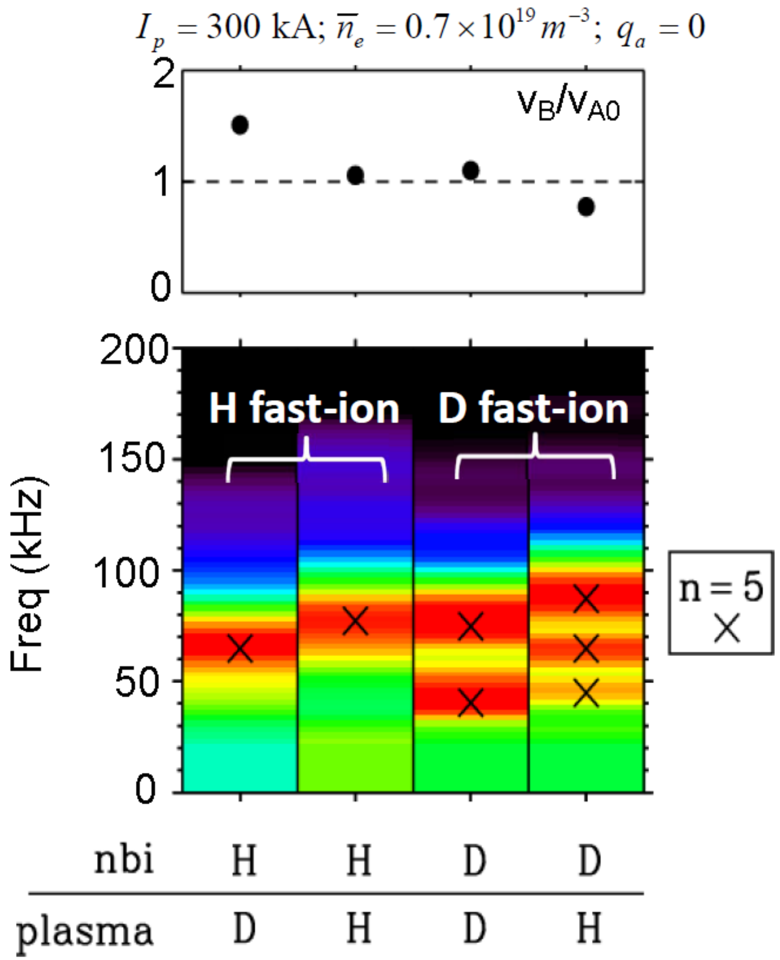
  - Driving mechanism in pressure gradient



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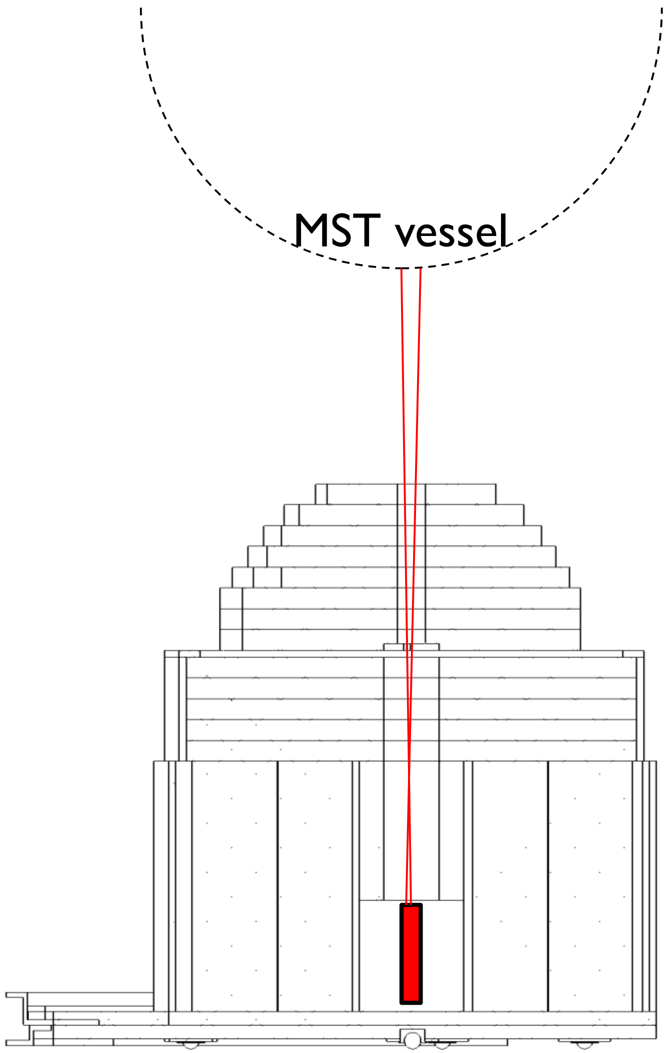
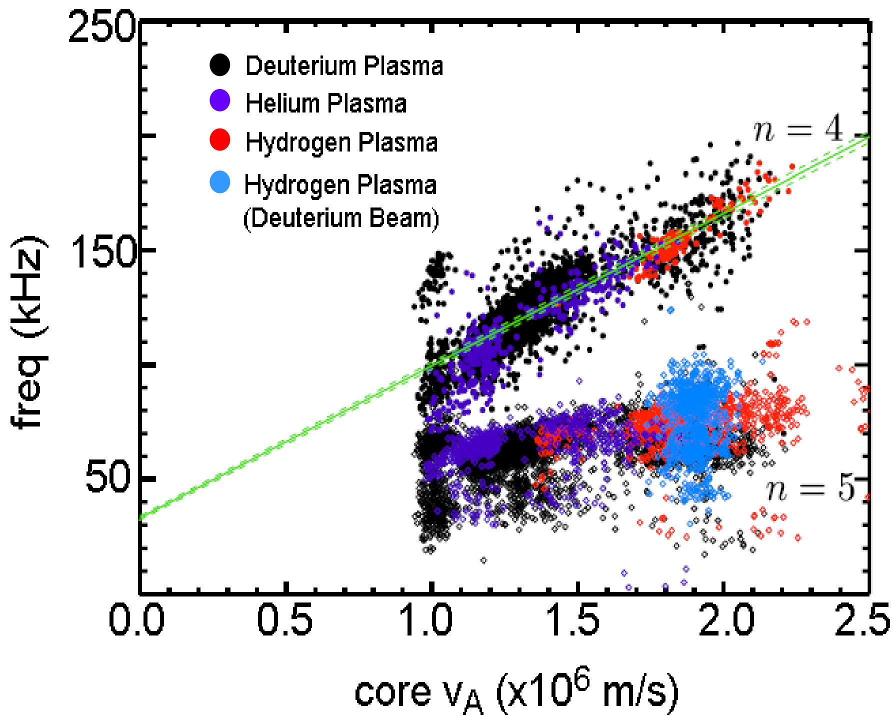
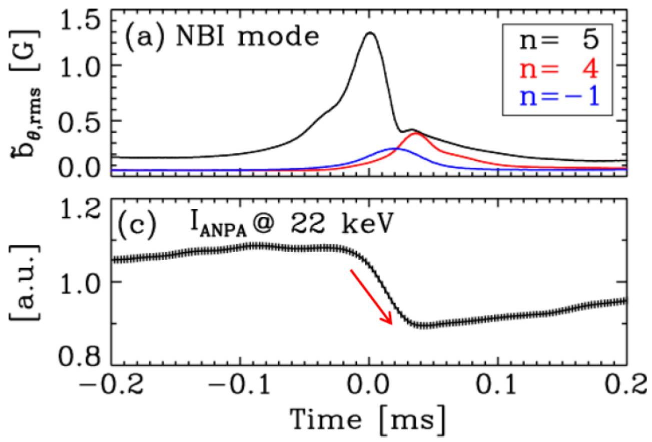
- Critical β_{fi} to destabilize EPM identification is underway

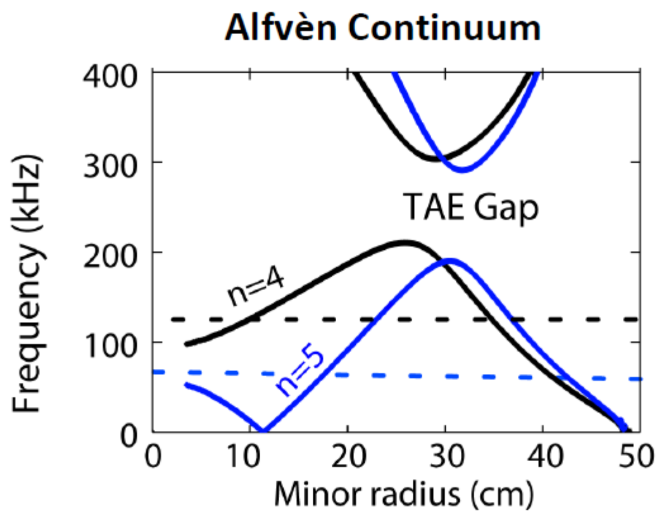


Nature of coincident n=4 AE is becoming clearer

- Alfvén eigenmode excited in continuum gap
  - $f \propto v_A$ (not TAE)







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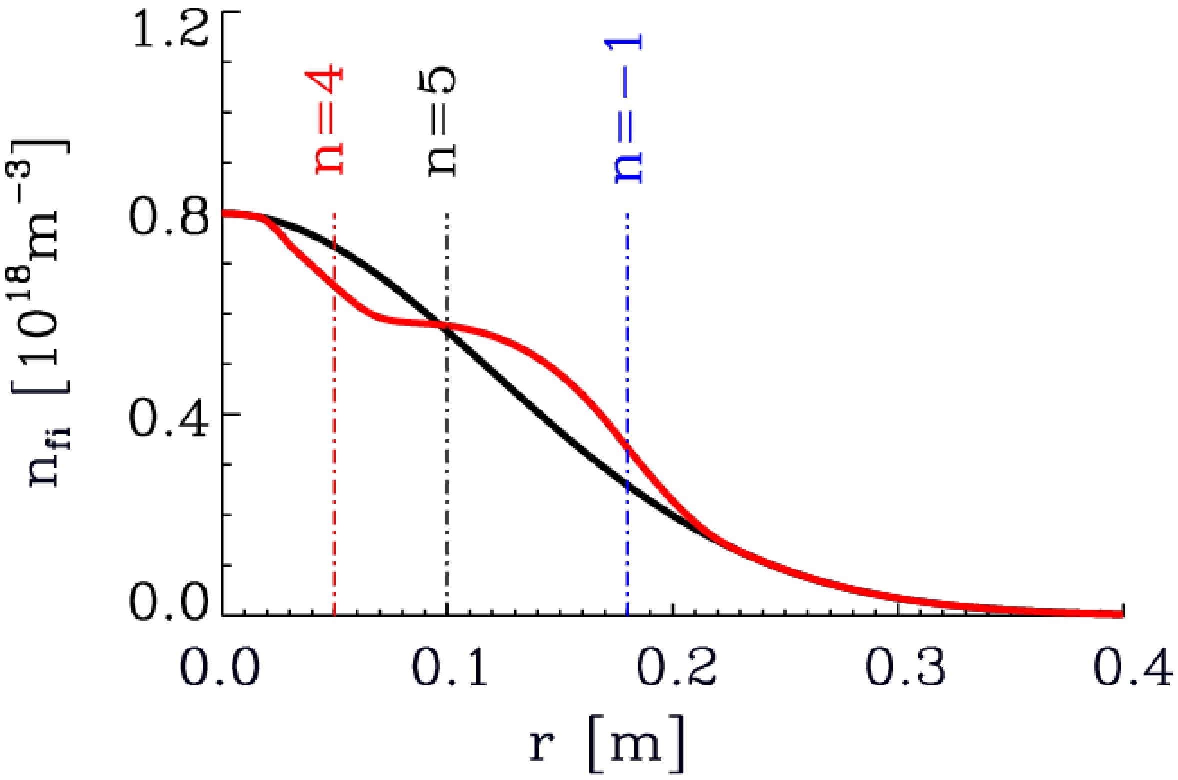

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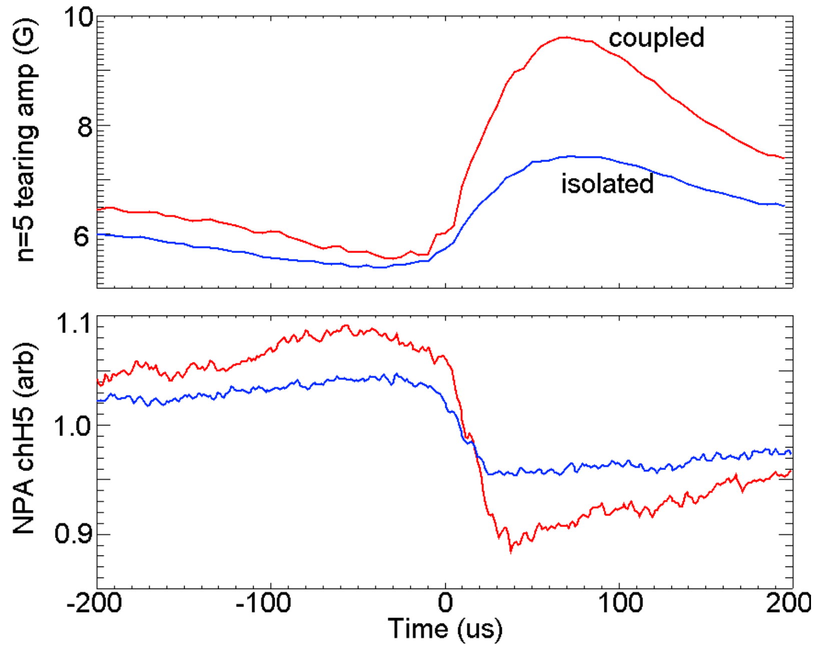
  - Transport effect enhanced by mode coupling



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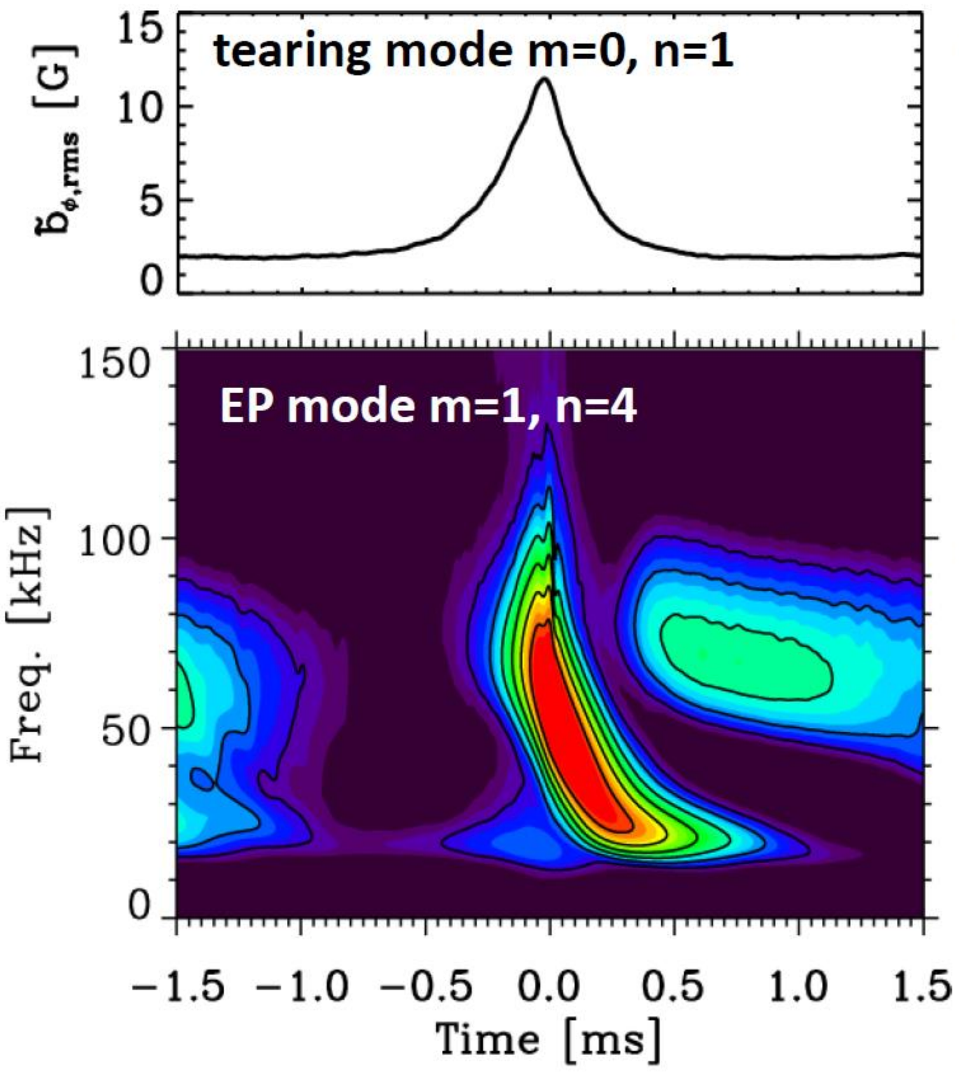
- New theory predicts a magnetic island induced gap in Alfvén continuum
  - Cook, Hegna accepted PoP May 2015
  - Matches mode number and frequency of observed AE

Summary

- Fast-ion confinement in the RFP exhibit:
  - Near neo-classical confinement times for co-injected particles
  - Co- vs counter-injection asymmetry
  - Reduced confinement in QSH state
- EP mode classification is underway
  - Dominant (n=5) EPM shows features of continuum destabilization:
    - Frequency scales with beam velocity, peaking near Alfvén continuum
    - Mode number altered by varying equilibrium (resonance condition)
    - Driven by fast-ion pressure gradient
  - Often present n=4 mode scaling with Alfvén speed implies AE character
    - New theory predicts observed frequencies

Chirping EP mode triggered by tearing mode



- m=1,n=4 chirping mode most robustly observed in 200kA D-plasmas with D-beam injection
- Occurs after the n=1 tearing mode implying necessary triggering mechanism from the fast-ion redistribution induced by the tearing mode

Fast ion population affects QSH transition

- In plasmas with marginal likelihood of QSH, large fast ion content delays transition