Effect of Fast-ion Distribution Function on Beam Driven Instabilities in NSTX

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Abstract

The deuterium beam distribution function is modified from shot to shot while keeping the total injected power to ~2 MW. The experimental ``knobs" are the beam energy (90 keV and 60 keV), the beam tangency radius, and the fraction of trapped beam ions, which is modified at a predetermined time by applying $\geqq 2$ MW of High Harmonic Fast Wave (HHFW) heating.

Neutral particle analysis confirms perpendicular acceleration of the beam ions. The neutral beams are injected into a helium L-mode plasma and produce a rich set of instabilities, including TAE modes, instabilities with rapid frequency sweeps or chirps, and strong, low frequency (10-20 kHz) fishbones. Fishbones are excited when $q_0 < 1$ and when the trapped beam-ion fraction increases; they are always present later in the discharge.

However, TAE modes are excited only early in the discharge and, under some circumstances, they are suppressed by HHFW heating on a collisional time scale. In contrast with a Dipole experiment [1], the cyclotron heating has no effect on the chirping instabilities.

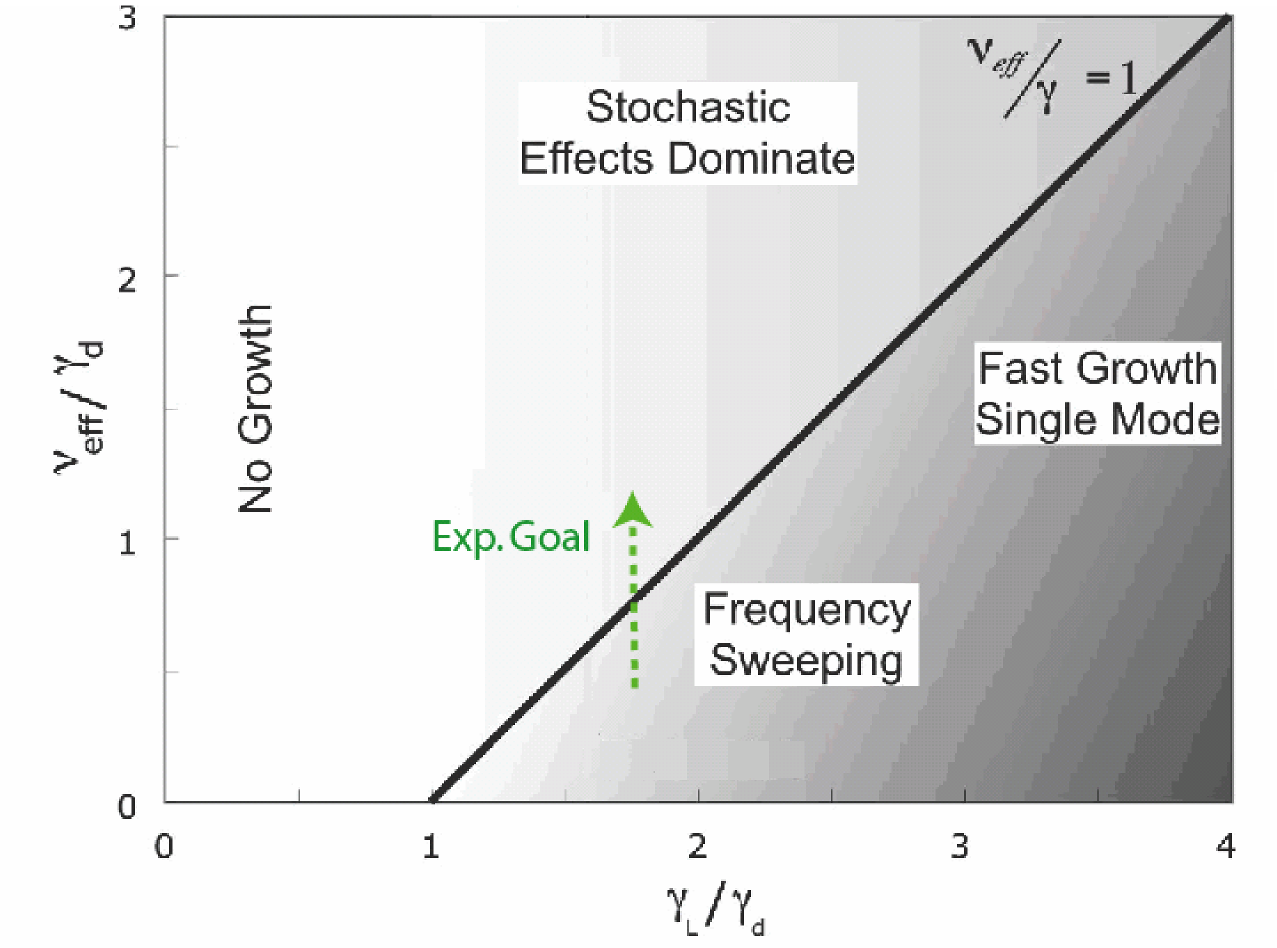
[1] D. Maslovsky, B. Levitt and M. E. Mauel, Phys. Plasmas **10** (2003) 1549

Motivation

- The nonlinear saturation of fast-ion instabilities:
  - determines their ultimate impact on fast-ion transport
  - must be understood in order to predict the effect of alpha driven instabilities in ITER and other burning plasmas
- The experiment was motivated by the Berk-Breizman [1] theory which attributes frequency chirping to the formation of holes and clumps in phase space.
- In the theory, increasing the effective collision frequency of the fast ions that drive the instability can suppress frequency chirping.
- In the experiment, high-power ≧ 2 MW High Harmonic Fast Wave (HHFW) heating accelerates the beam ions in an attempt to alter the effective collision frequency.

[1] H.L. Berk, B.N. Breizman, J. Candy, M. Pekker, N.V. Petviashvili., Phys. Plasmas **6** (1999) 3102

Berk-Breizman Model of Chirping Suppression



γ_L – linear growth rate

γ_d – nonresonant dissipation

ν_{eff} – collisionality parameter

$\gamma = \gamma_L - \gamma_d$

D.Maslovsky *et al.*, Phys.Plasmas **10** (2003) 1549

Typical discharge parameters

- Background gas is Helium, thus:

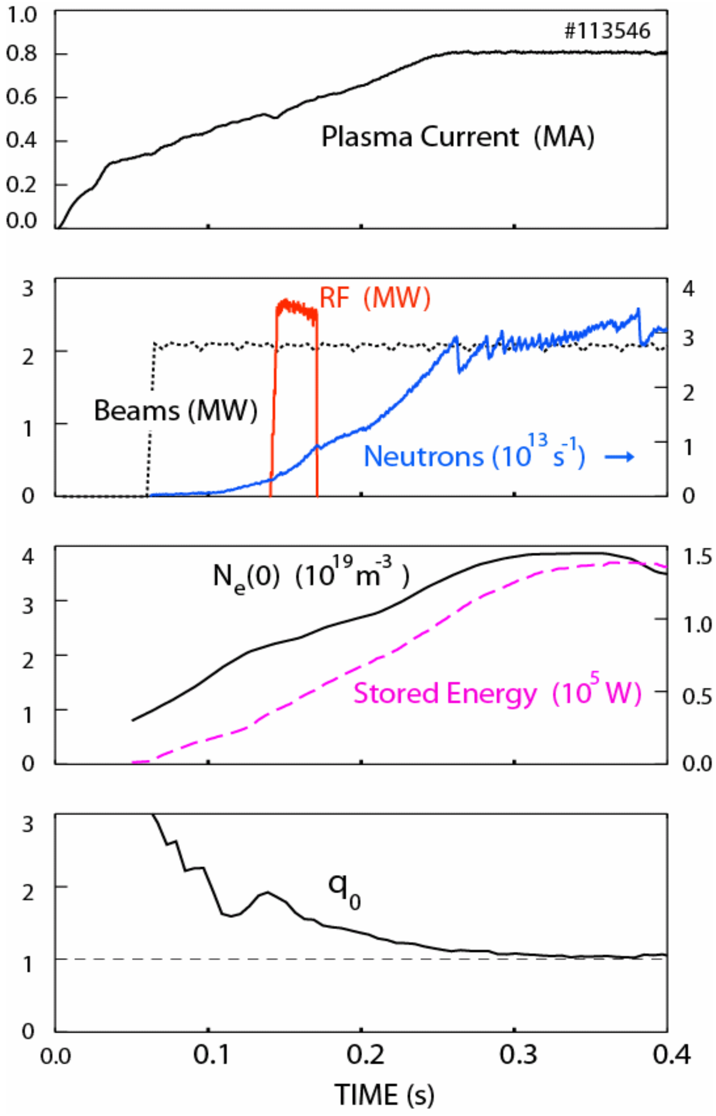
  L –mode plasmas

- I_p and beam power kept constant, resulting in nearly identical discharges:

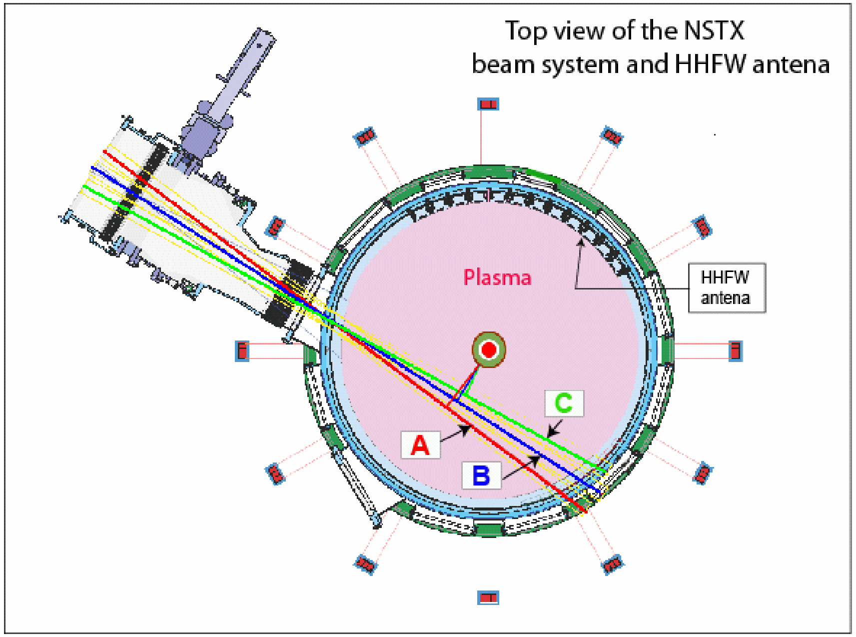
  ~ 10-15% variation of N_e ,T_e

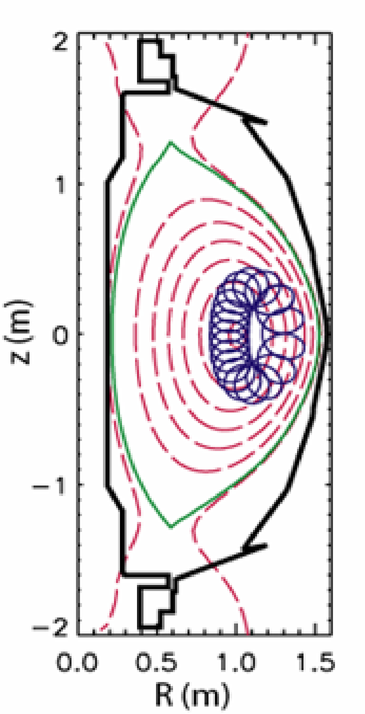
- HHFW heating applied :
  - Early in the shot, during the I_p ramp-up

    or
  - Late in the shot, well into the I_p flat-top phase



Geometry of the experiment



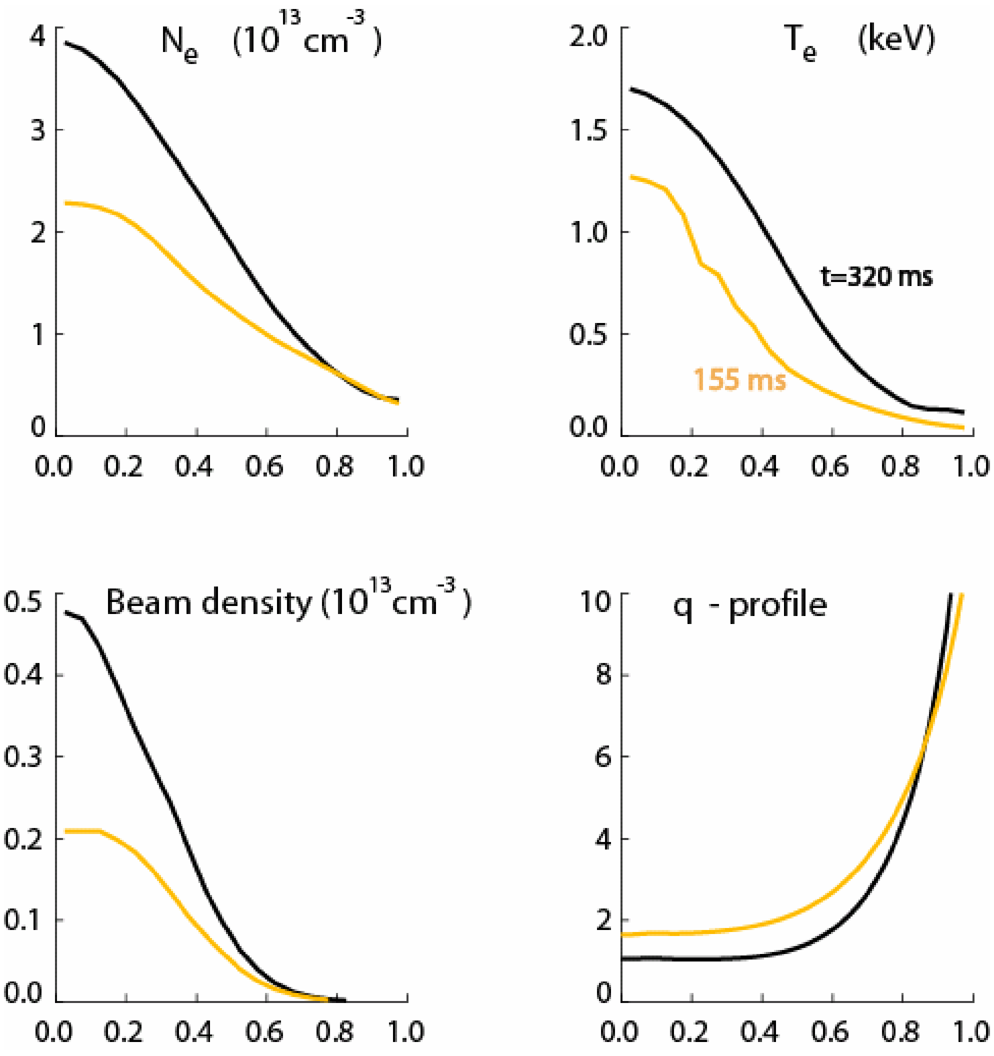


- Tangency radii:
  - Beam-line **A**: 69.4 cm
  - Beam-line **B**: 59.2 cm
  - Beam-line **C**: 48.7 cm

- Vessel cross section and an orbit of a 90 keV deuterium ion born near R=1.3m with pitch = 0.41

Typical plasma profiles

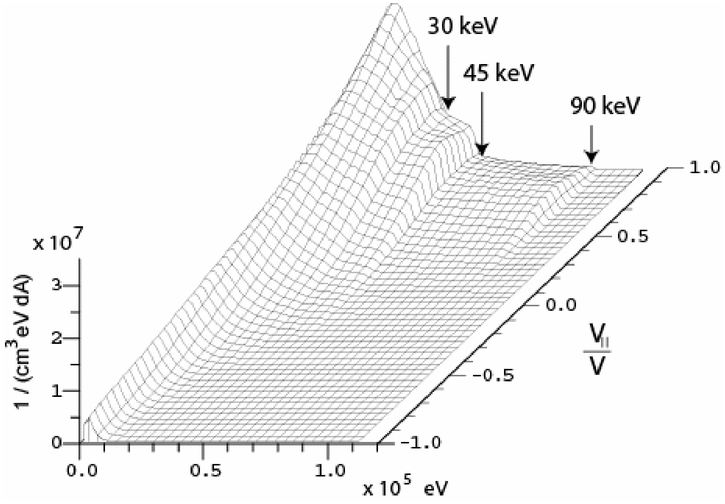
- Favorite times for analysis:
  - Early time: 155ms
  - Late time: 320 ms



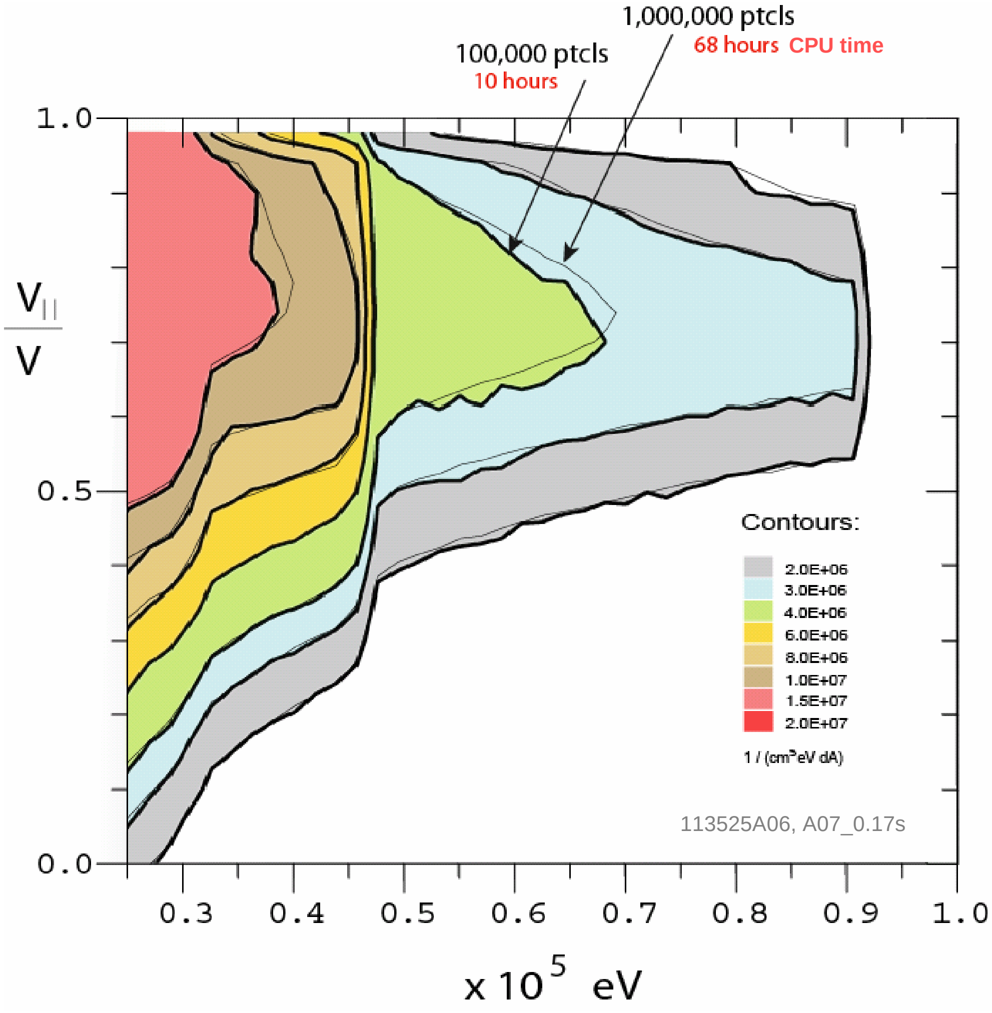
NORMALIZED RADIUS

NORMALIZED RADIUS

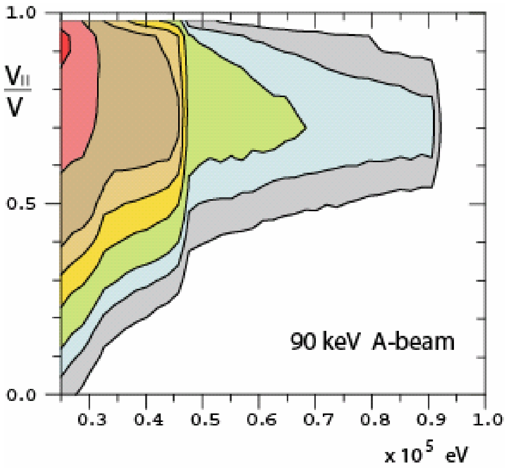
TRANSP code used to calculate the classical beam-ion distribution function

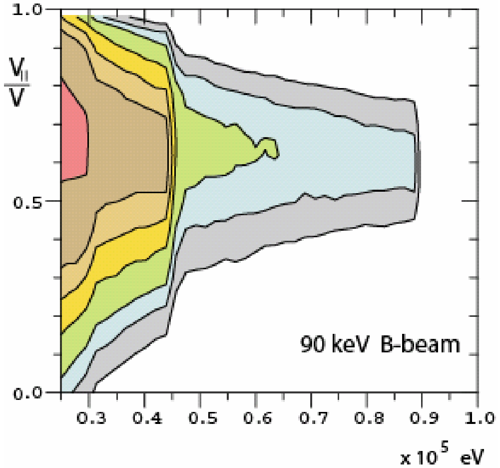


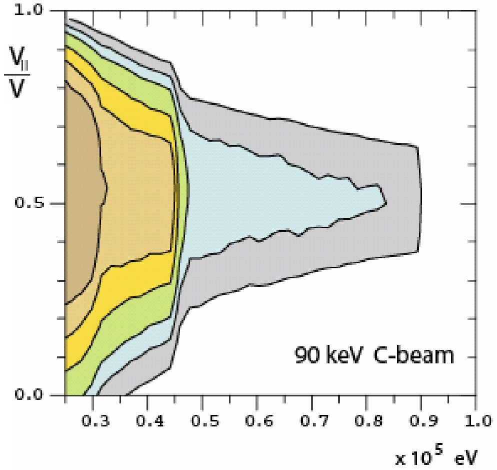
Sufficiently smooth distribution functions obtained with 100,000 Monte Carlo particles.

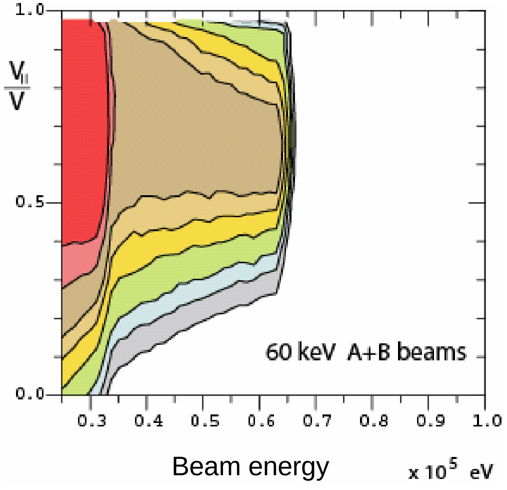


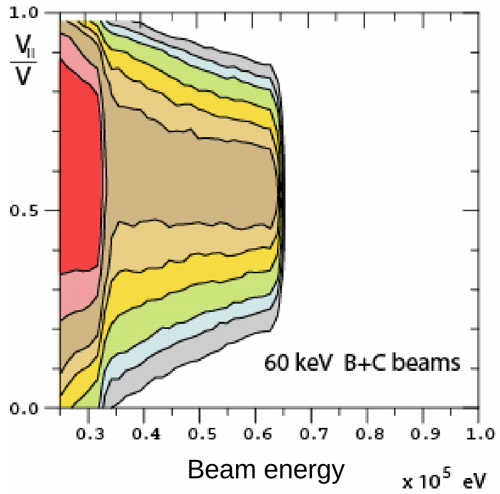
Five distinct beam-ion distribution functions created in the experiment











Contours:

- ⬜ 2.0E+06
- 🟦 3.0E+06
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- 🟧 8.0E+06
- 🟫 1.0E+07
- 🟥 1.5E+07
- 🟥 2.0E+07

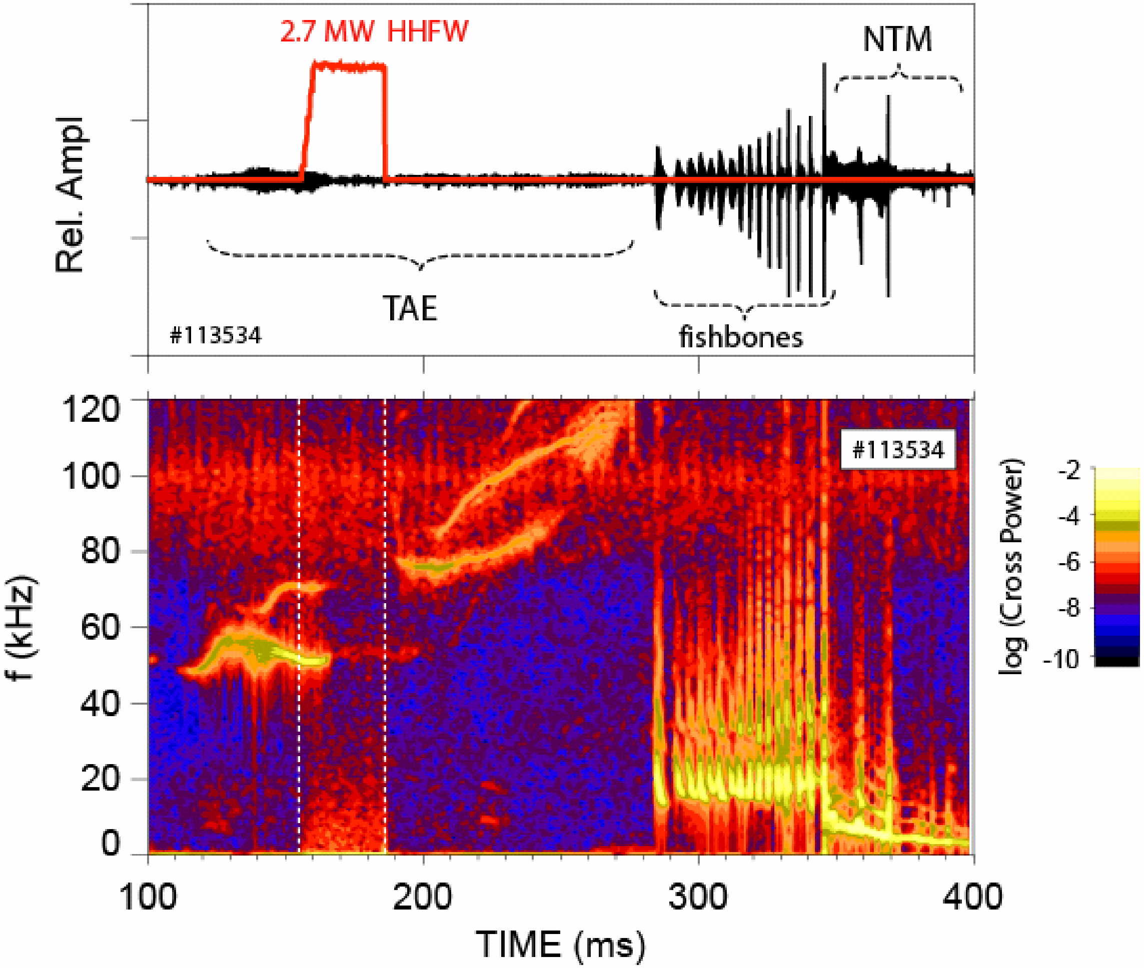
1 / (cm^{3}eV dA)

t=0.17s for the examples shown

Different mode types observed at different times in the discharges

- Early on, TAE modes and/or chirps (Type III fishbones) present
- Type II fishbones dominate the latter part of the discharge
- These plasmas usually terminate with Neoclassical Tearing Modes (NTM)

Note: *Type I are the classical (PDX) fishbones*



TAE modes suppressed in some discharges

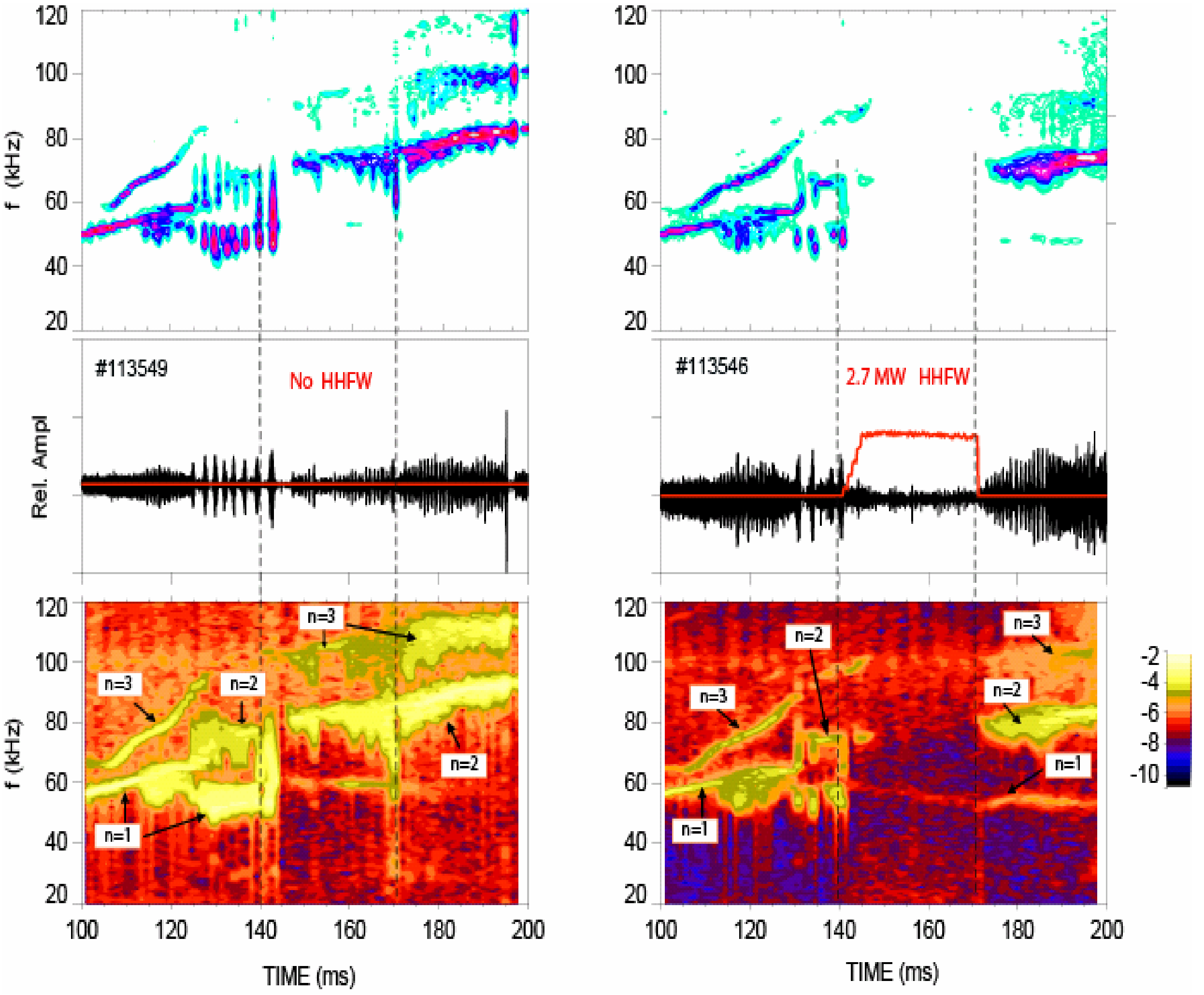
- Suppression clearly visible in this example with 60keV B+C beams:

  - Contour plot of Mirnov signal (top row)

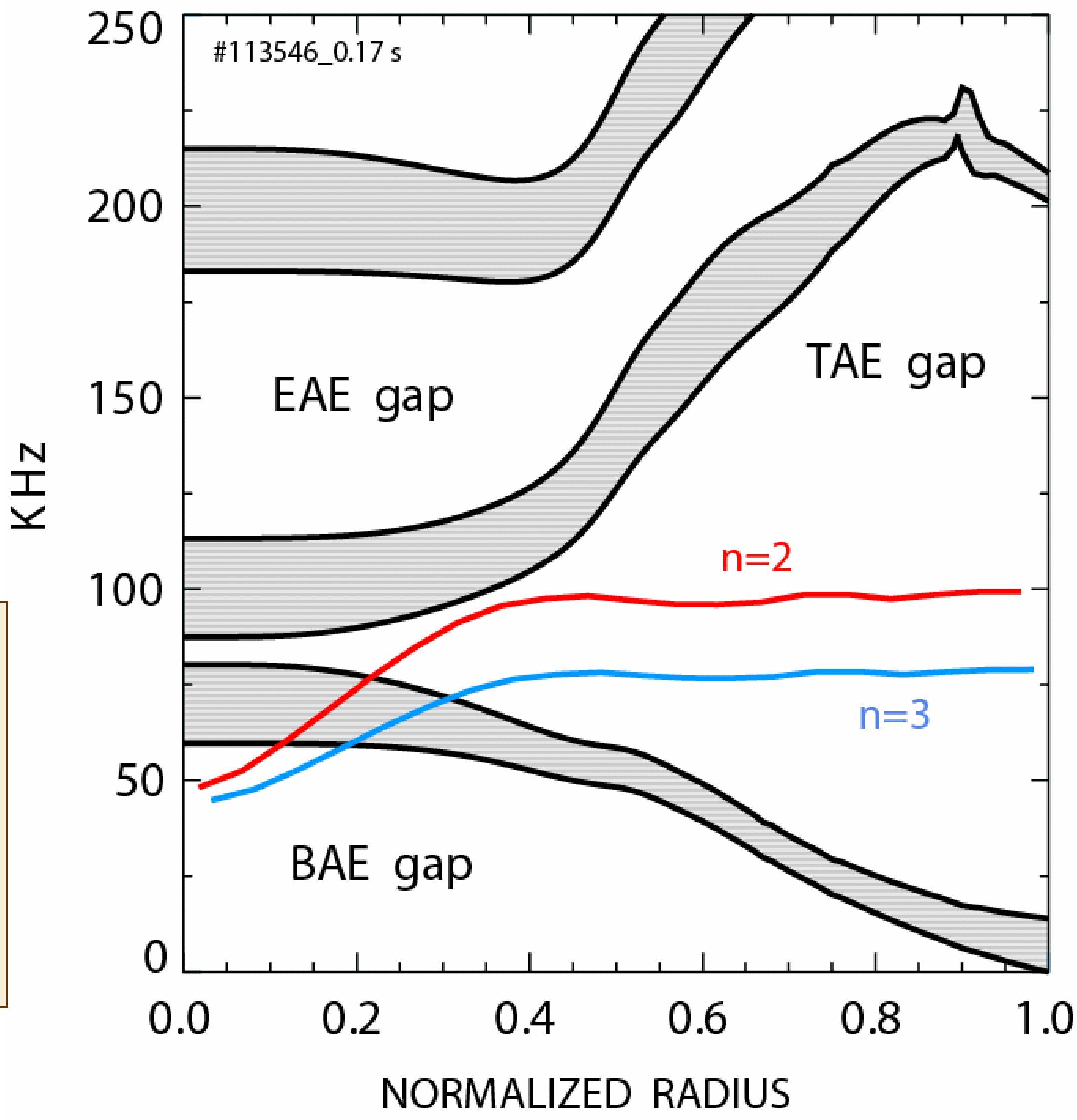
  - Mirnov signal amplitude (middle row)

  - Cross power spectrum of two toroidally located Mirnov coils (bottom row)

Mode numbers for some of the modes are shown.

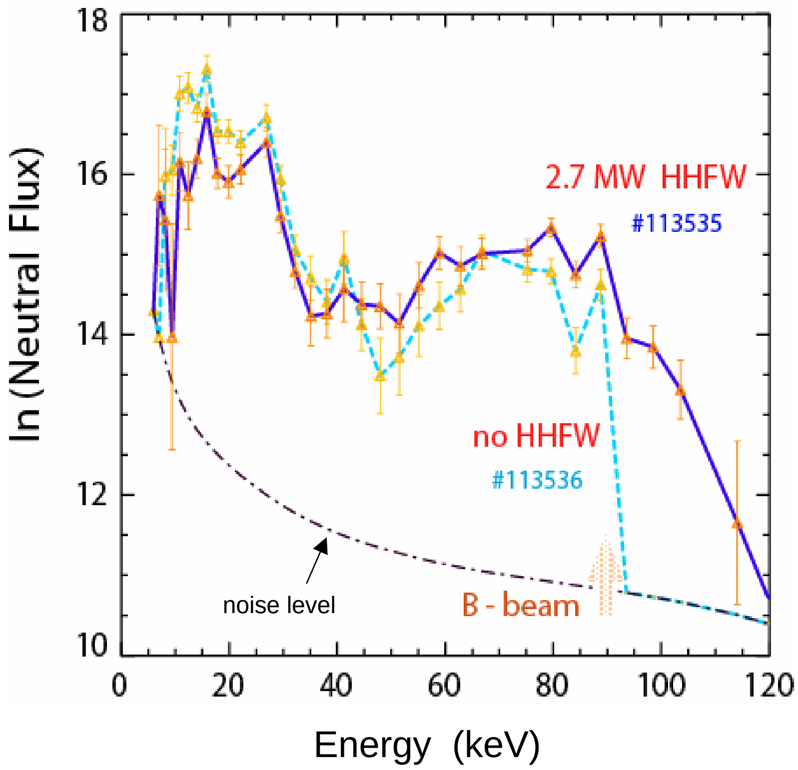


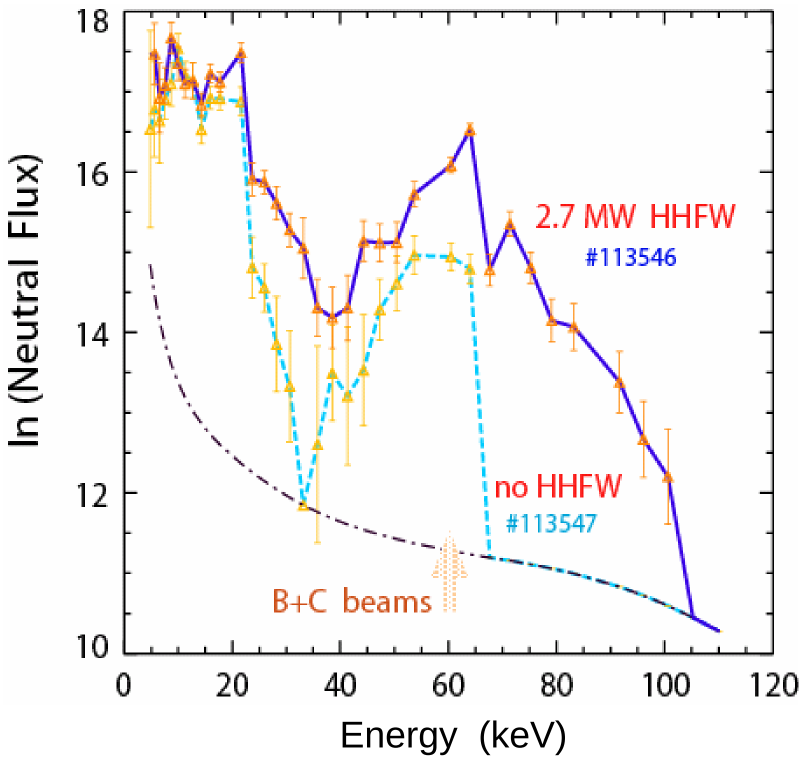
NSTX has wide TAE and BAE gaps



- Alfven gap structure calculated with the CONT code
- TAE modes with n=2 and n=3 shown
- Plasma rotation estimated from charge exchange recombination measurement in a different discharge

HHFW accelerates beam-ions above injection energy

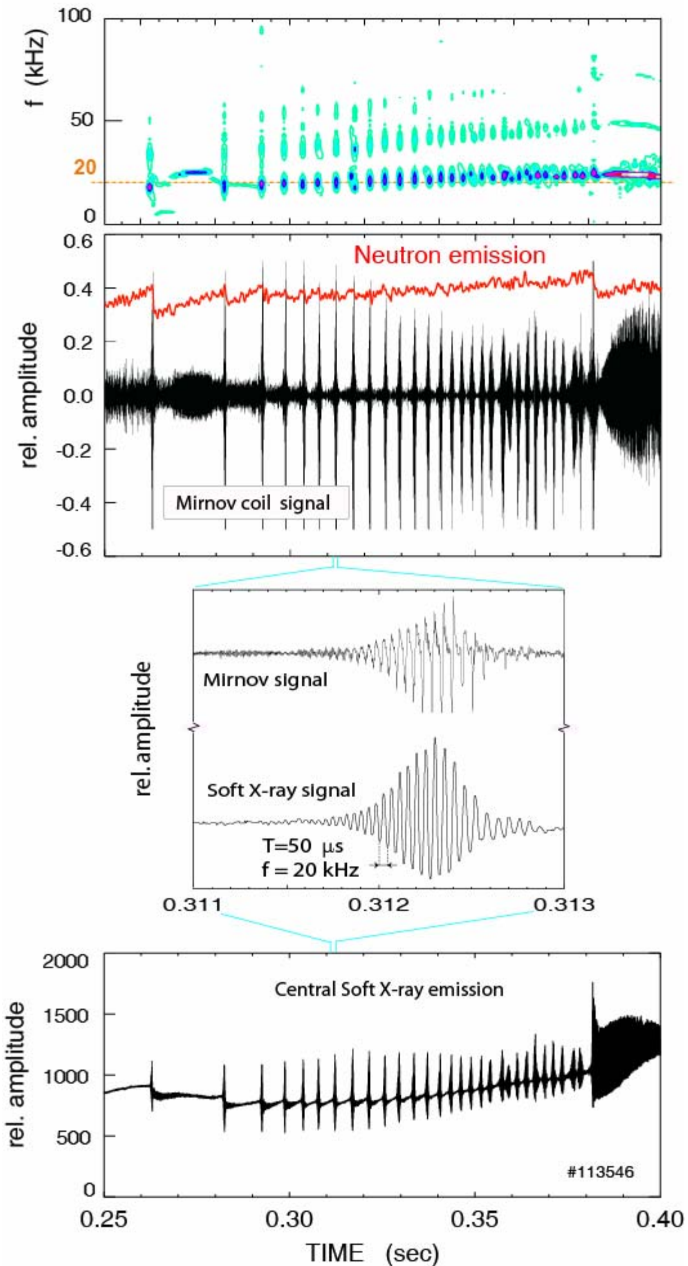




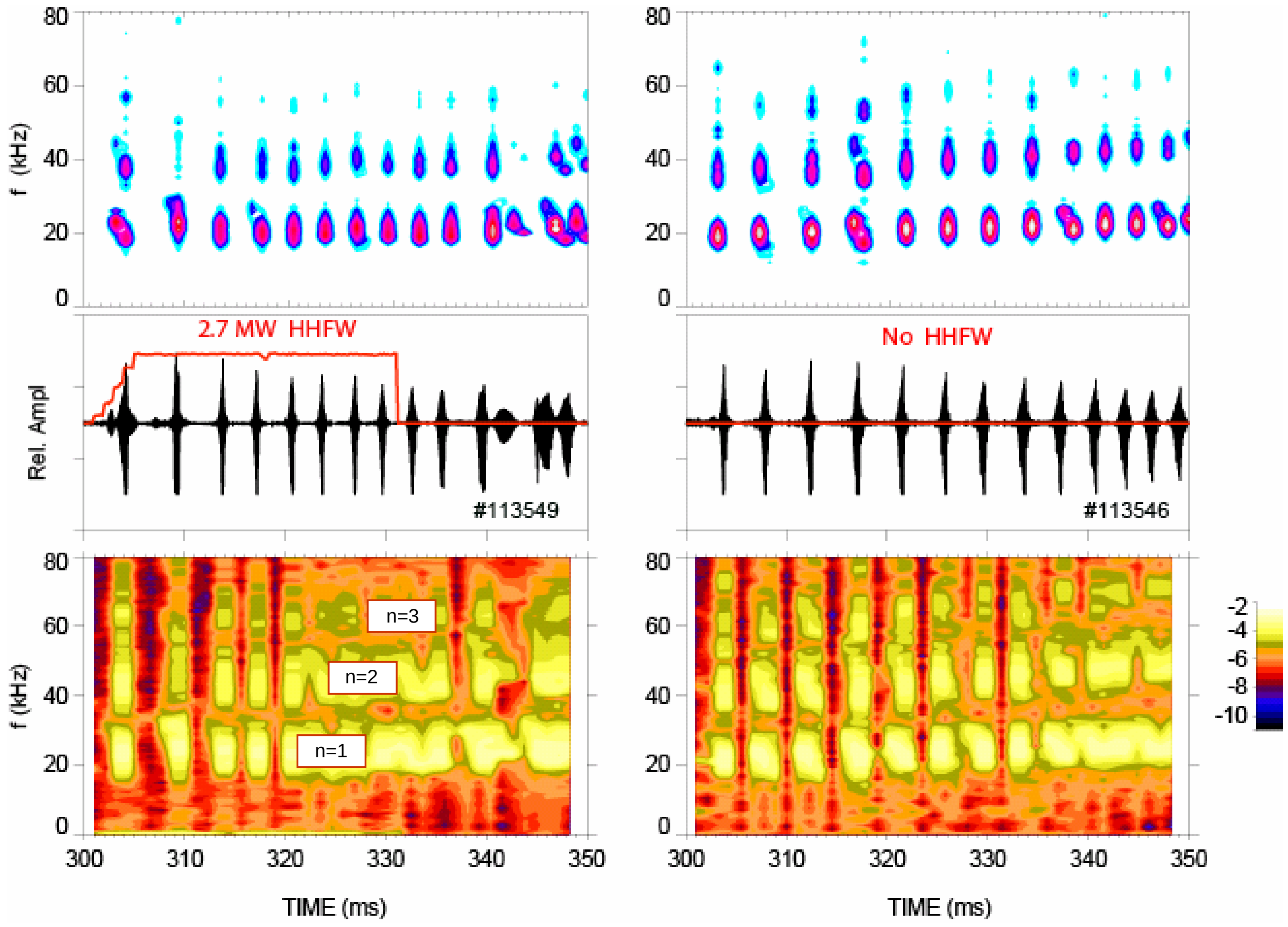
- Neutral particle fluxes were measured at the end of the 30ms HHFW heating pulse
- HHFW heating preferentially accelerates beam ions in the perpendicular direction

Signatures of Type II fishbone activity

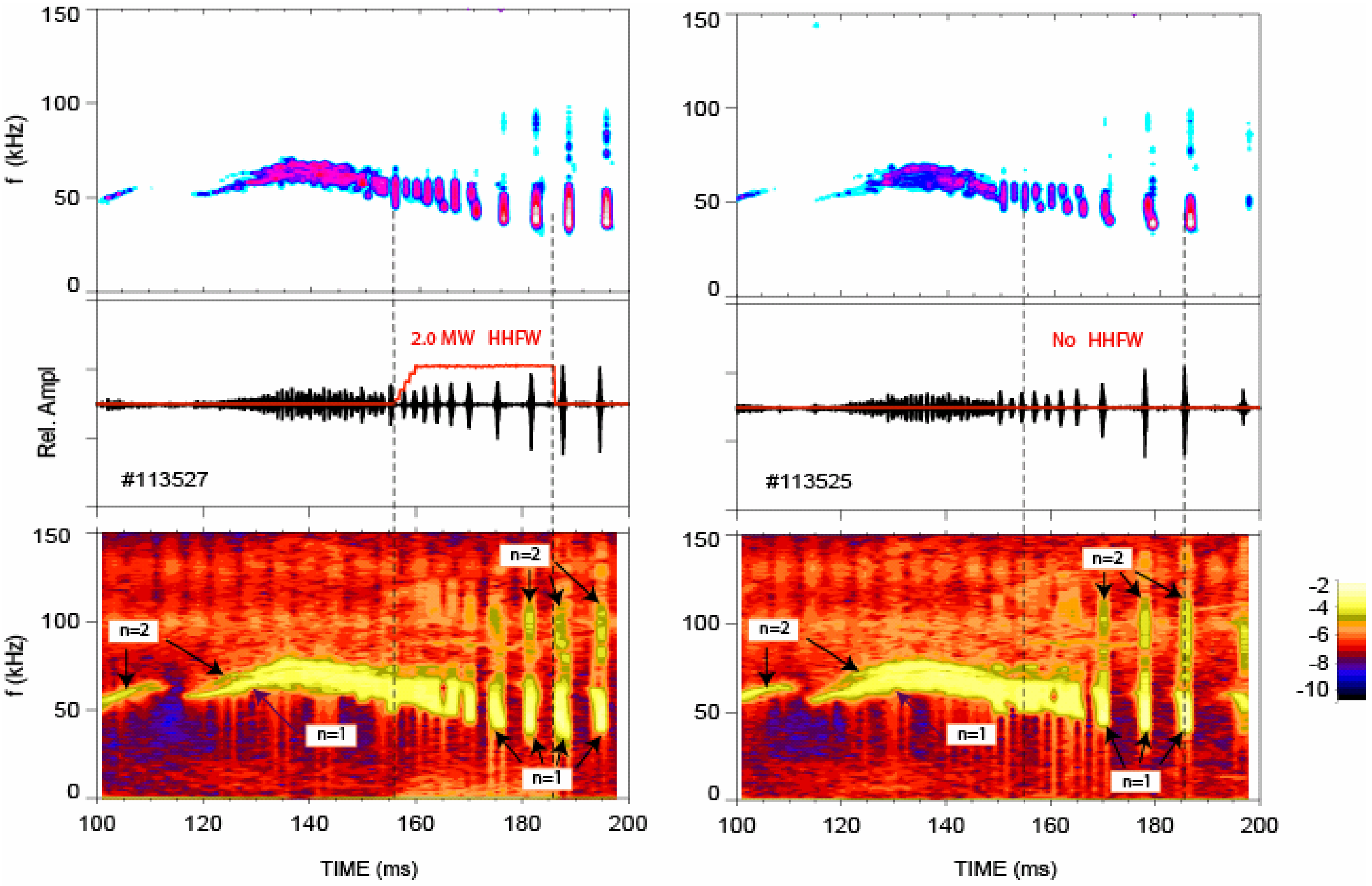
- Frequency in the 20 kHz range
- Neutron drops up to 25%
- Burst duration ~1ms
- Bursts separated by ~5ms
- Occur when $q_o \rightarrow 1$
- Strong in the plasma core



HHFW heating does not affect Type II fishbones

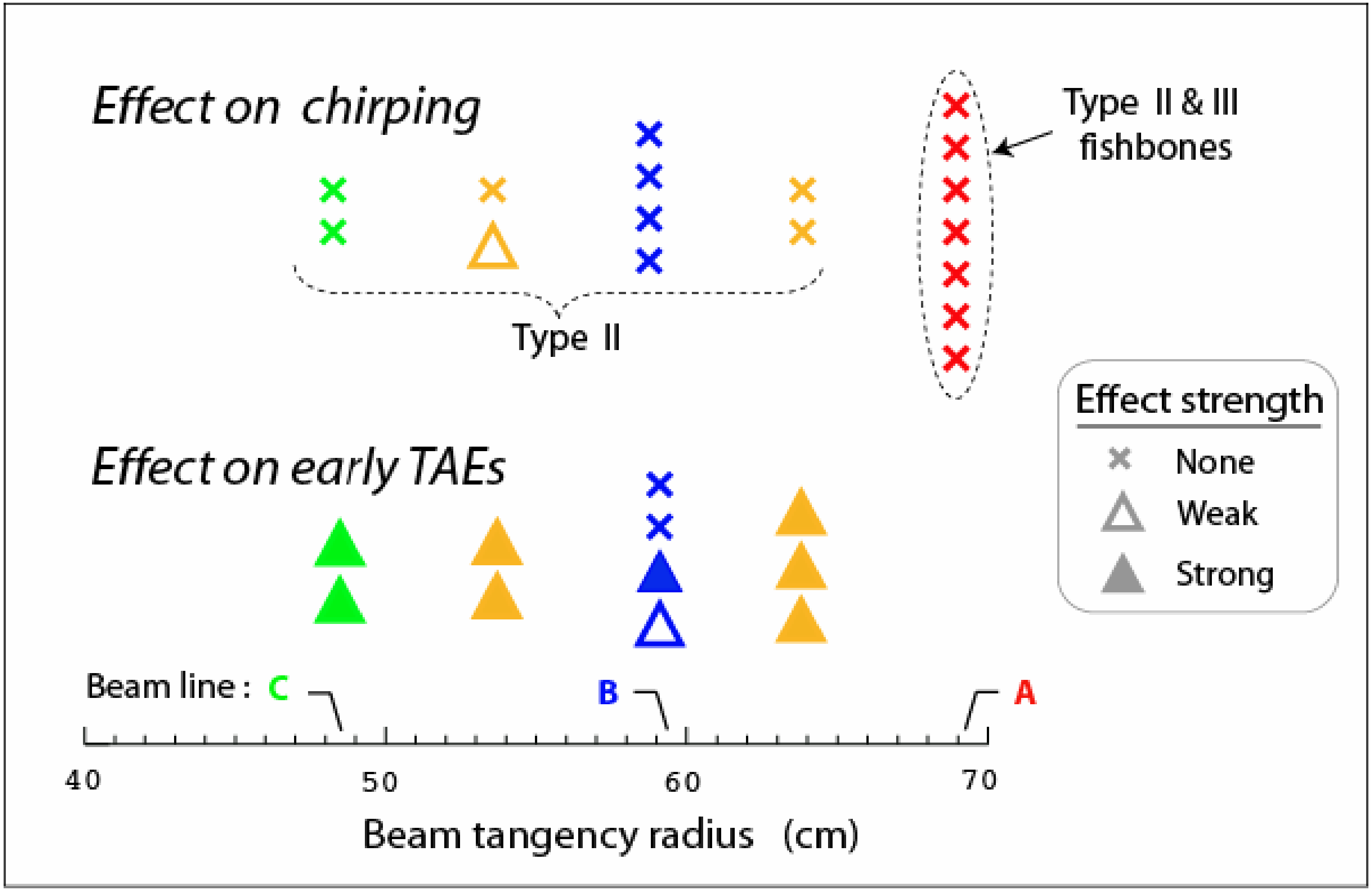


HHFW heating does not affect Type III fishbones

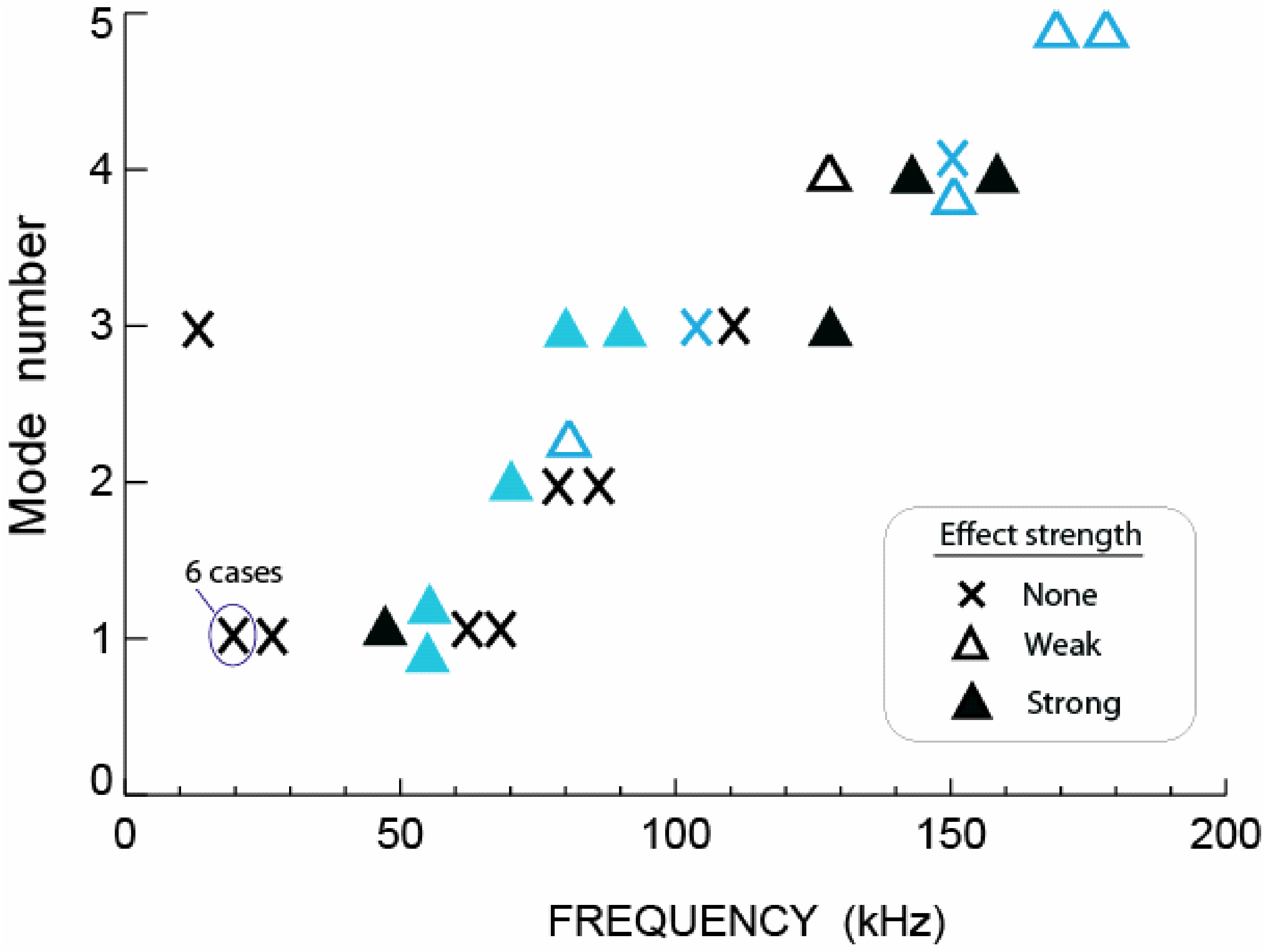


- Type III fishbones observed early in the discharges heated with 90keV beam-line **A**
- Have frequency in the TAE region; occur when $q_0 > 1$; typically n=1,2
- Probably same type of instability as TAE, but with different saturation mechanism

Effect of beam R_{tan} on the observed modes



Observed mode suppression depends weakly on mode number and frequency



Surprising experimental result:

- Although the goal was to suppress the chirping modes, the HHFW heating did not affect them at all. Instead, early TAE modes were suppressed; the most strongly suppressed modes were in plasmas heated with low energy (60keV) beams with large perpendicular component.

- Fishbones / chirps occur in all discharges with all beam combinations; they are not affected by the HHFW heating.

- Strong Type III chirping modes occur early in discharges where beam-ions have large tangential component (90keV beam source A); HHFW does not affect them. They might be the same type of mode as TAEs, but with different saturation mechanism.

- Steady frequency modes in the TAE band are partially stabilized by the HHFW heating. The effect develops on a 1-10ms timescale.

Why it didn’t work (1)

Possible Semi-Empirical Explanations:

- **The early instabilities (during current ramp-up) are not that strong, thus modest changes in the beam distribution function by HHFW alter their nonlinear saturation. This is not the case with the later, stronger chirping instabilities which are harder to suppress.**

- **TAEs are driven by passing particles: by moving some of the passing particle into trapped orbits, the perpendicular heating reduces the fast ion drive.**

- **Chirping modes are driven by trapped beam ions, so perpendicular heating enhances the drive instead of suppressing it.**

Why it didn't work (2)

HHFW power was adequate !

- In the Dipole experiment 1kW of Electron Cyclotron Heating (ECH) formed the fast-electron population, and only ~40W of ECH was sufficient to suppress the chirping.

- In this experiment the HHFW power was higher than the beam power that created the fast-ion population!

- Berk estimates that the required energy diffusion is:

$$D_E > 10^5 \ (\text{keV})^2 \ / \ \text{s}$$

Estimates based on NPA data indicate that in the experiment:

$$D_E \sim \mathcal{O}(10^7) \ (\text{keV})^2 \ / \ \text{s}$$

Why it didn’t work   (3)

Phase Space Misalignment of HHFW with Fast Ions that drive the Instabilities ?

- In the Maslovsky experiment no suppression was observed when the RF heating was misaligned spatially …
- … but in this experiment, HHFW heats broadly in space and energy [1]
- Need to understand the instability mode structure and wave-particle resonance.

[1] A.L Rosenberg *et al*,, Phys. Plasmas **11** (2004) 2441

Why it didn’t work (4)

Berk-Breizman theory inapplicable?

- The Berk-Breizman theory is a generic model of nonlinear dynamics which has successfully explained many phenomena (pitchfork splitting, steady mode saturation, chirping suppression in the Maslovsky experiment, etc) …
- … but it is a simplified one-dimensional model of a complex wave-particle dynamics.