Turbulent suppression of coherent chirping behavior in ST40

Nucl. Fusion. **63**, 036018 (2023)

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in collaboration with

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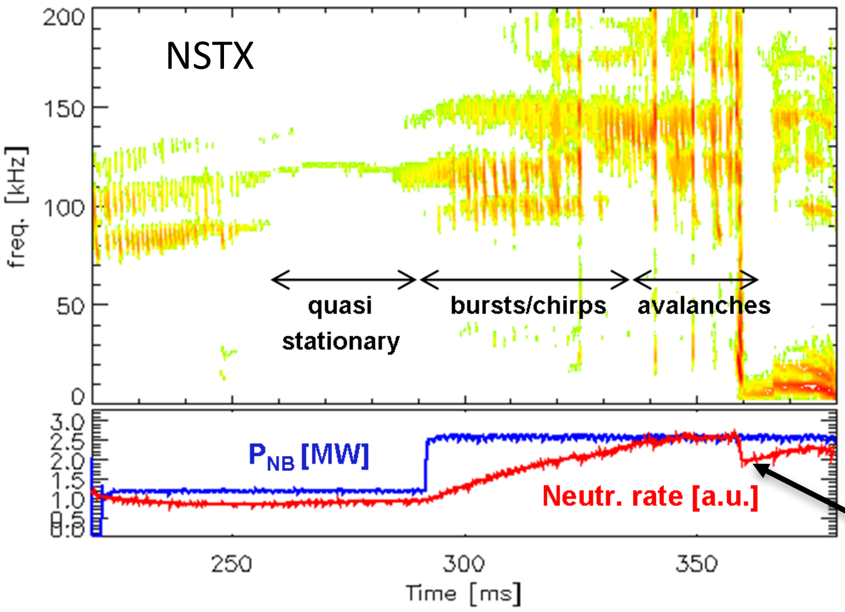
Fast ions in ST40

- Currently in operation: 1 MW 25 keV and 1 MW 55 keV neutral beams
- 3rd 1MW 55 keV NBI planned
- All beams are launched from the midplane and are tangential, co-injected with the plasma current
- Two 1 MW gyrotrons planned

→ Temperatures of the order of 10 keV have been demonstrated in recent experimental campaigns

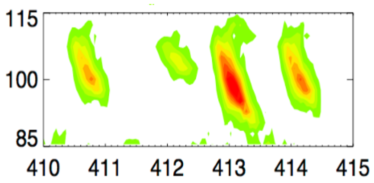
M. Gryaznevich, "*Experiments on ST40 at high magnetic field*", Nucl. Fusion **62** (2022) 042008

Alfvén waves can exhibit a range of bifurcations upon their interaction with fast ions



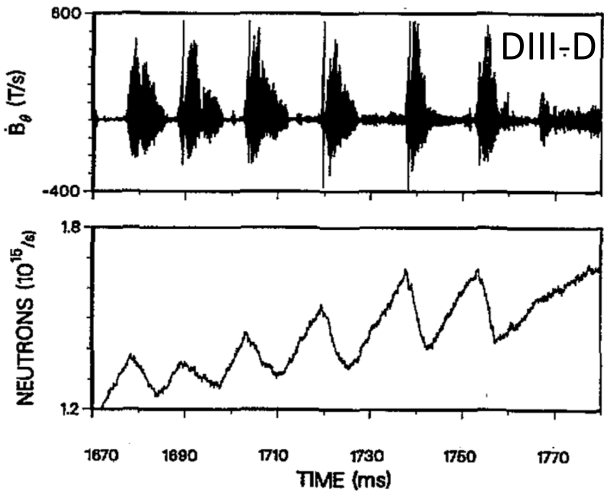
Podestà *et al*, *Nucl. Fusion* **51** 063035 (2011)

Chirping is a gateway to avalanches



30-40% of confined ions get lost

Each chirp induces fast ion losses



Heidbrink, *Plasma Phys. Control. Fusion* **37** 937 (1995)

Micro-turbulence has been put forward as an explanation as to why chirping is common in spherical tokamaks and rare in conventional tokamaks Duarte *et al*, *Nucl. Fusion* **57** 054001 (2017)

A criterion for the likelihood of chirping onset in tokamaks

Starting point: the evolution equation for mode amplitude A near marginal stability:

$$\frac{dA(t)}{dt} = (\gamma_L - \gamma_d)\, A(t) - \int_0^{t/2} d\tau \int_0^{t-2\tau} d\tau_1 \tau^2 e^{-\hat{\nu}_{stoch}^3 \tau^2 (2\tau/3+\tau_1) + i\hat{\nu}_{drag}^2 \tau(\tau+\tau_1)} \mathcal{O}\left(A^3\right)$$

stabilizing

destabilizing (makes integral sign flip)

Berk, Breizman and Pekker, PRL 1996
Lilley, Breizman and Sharapov, PRL 2009

Blow up of A in a finite time-> system enters a strong nonlinear phase (chirping likely)

Chirping criterion:

$$Crt = \frac{1}{N} \sum_{j,\sigma_\parallel} \int dP_\varphi \int d\mu \frac{|V_{n,j}|^4}{\omega_\theta \nu_{drag}^4} \left|\frac{\partial \Omega_j}{\partial I}\right| \frac{\partial f}{\partial I} Int\left(\frac{\nu_{stoch}}{\nu_{drag}}\right)$$

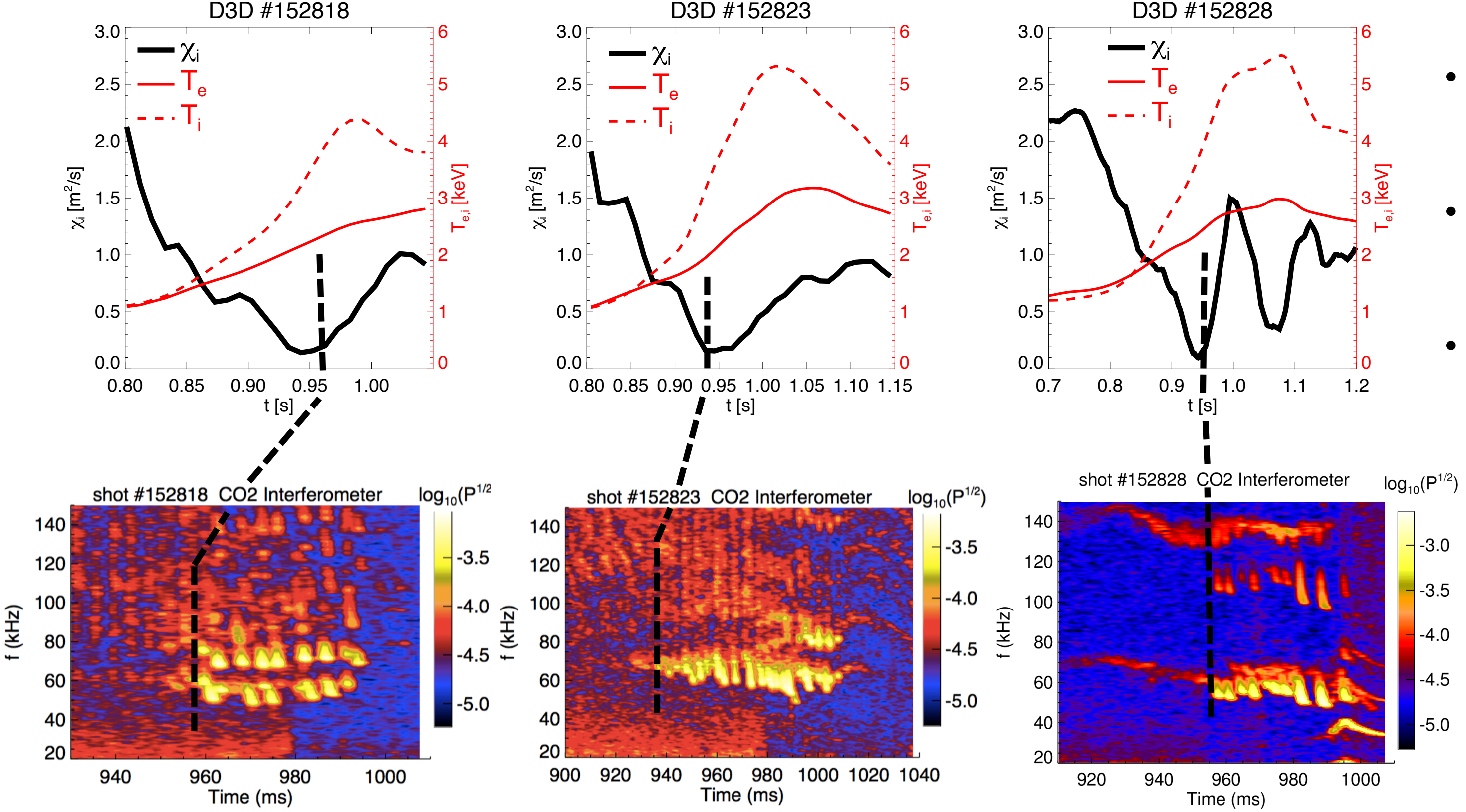
>0: fixed-frequency solution likely
<0: chirping likely to occur

(nonlinear prediction from linear physics elements->incorporated into the linear NOVA-K code)

The criterion ($Crt \gtrless 0$) predicts that micro-turbulence should be key in determining the likely nonlinear character of a mode, e.g., fixed-frequency or chirping

Duarte *et al*, *Nucl. Fusion* **57** 054001 (2017)

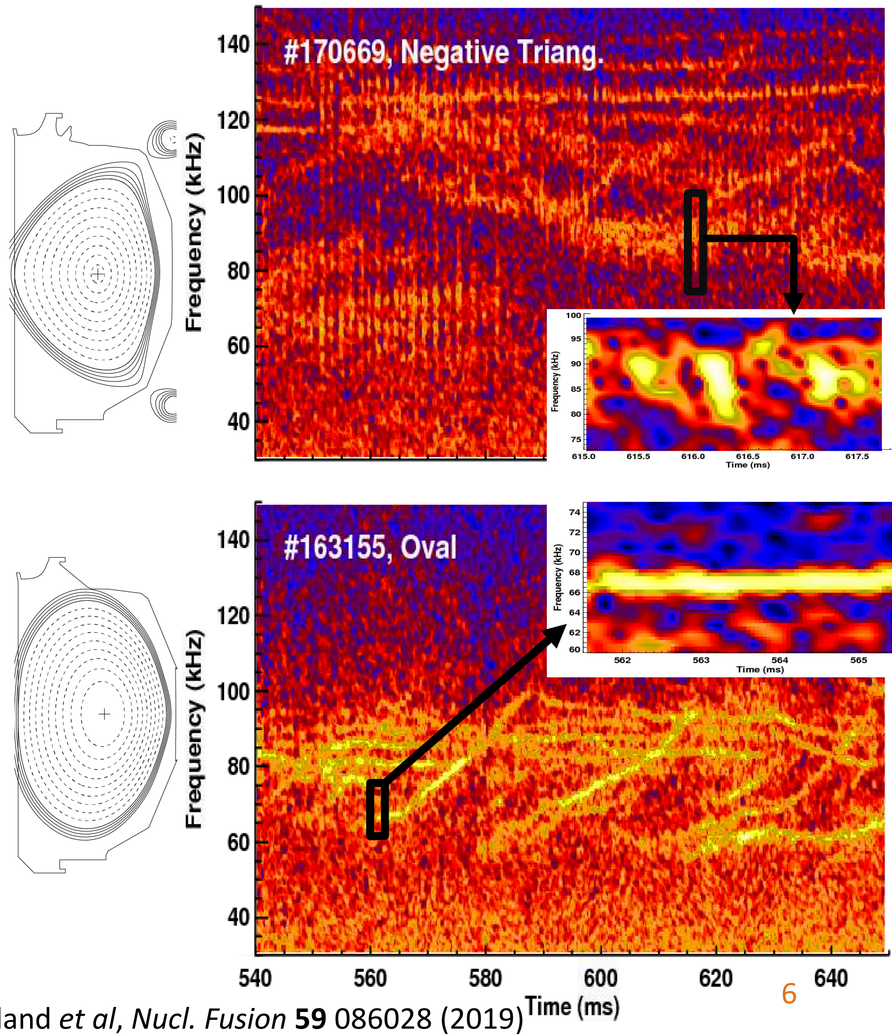
Correlation between chirping onset and a marked reduction of the turbulent activity in DIII-D



- Diffusivity drop due to L→H mode transition
- Strong rotation shear was observed
- This observation motivated DIII-D experiments to be designed to further test the hypothesis of low turbulence associated with chirping

Duarte *et al*, *Nucl. Fusion* **57** 054001 (2017)

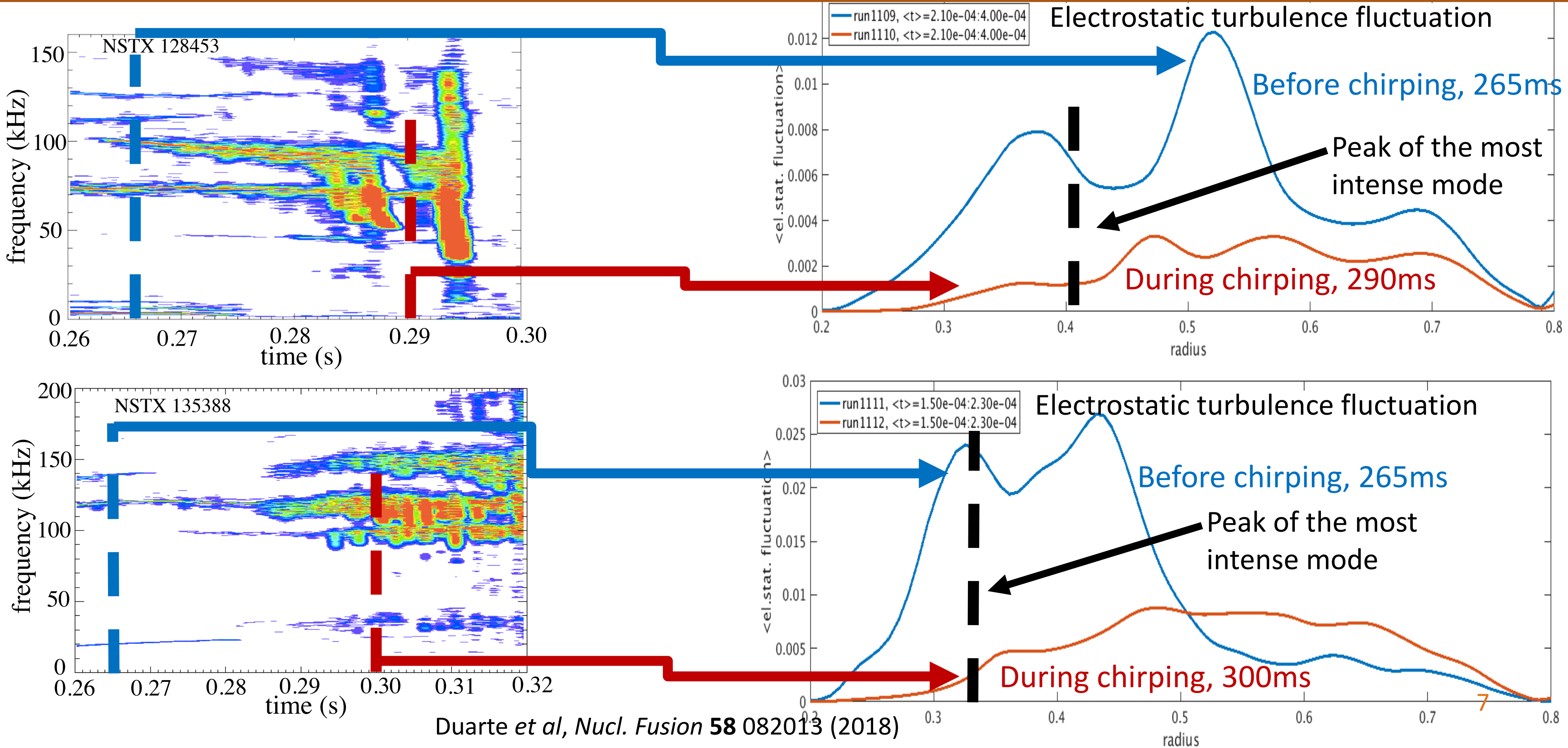
Dedicated experiments showed that chirping is more prevalent in negative triangularity DIII-D shots



Transport coefficients calculated by TRANSP are 2-3 times lower in negative triangularity, as compared to the the usual positive/oval triangularity

Van Zeeland *et al*, *Nucl. Fusion* **59** 086028 (2019)

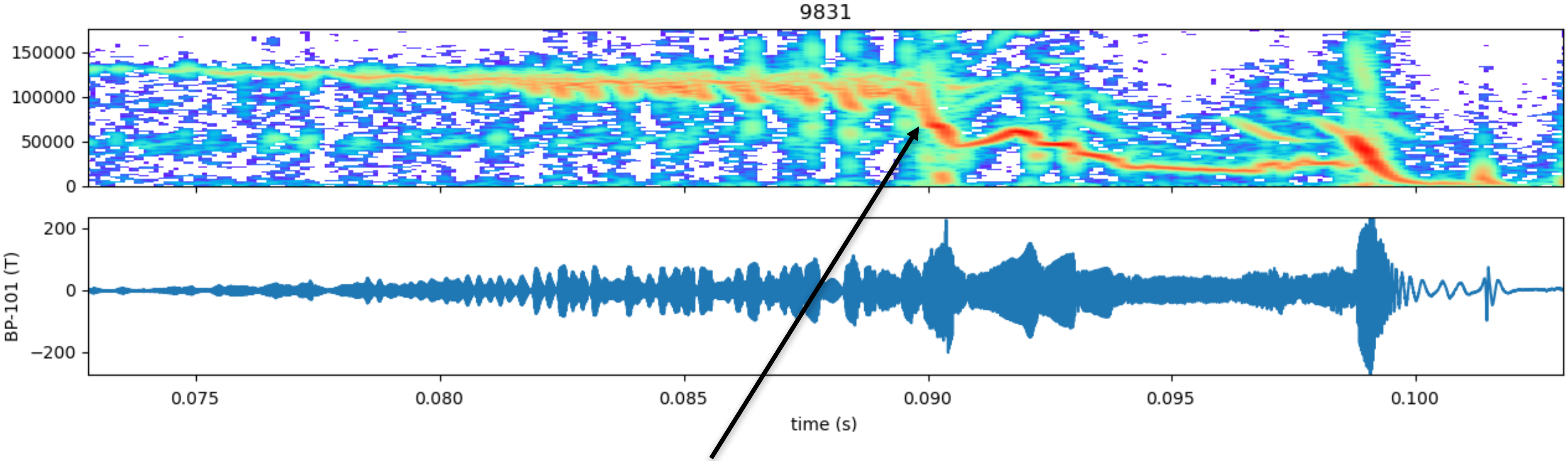
GTS global gyrokinetic analyses show turbulence reduction for rare NSTX Alfvénic transitions from fixed-frequency to chirping



Duarte *et al*, *Nucl. Fusion* **58** 082013 (2018)

ST discharge 9831

NOVA/NOVA-K[1] indicates that the most unstable modes are found to be core-localized n=1 beta-induced acoustic Alfvén eigenmodes (BAAE)

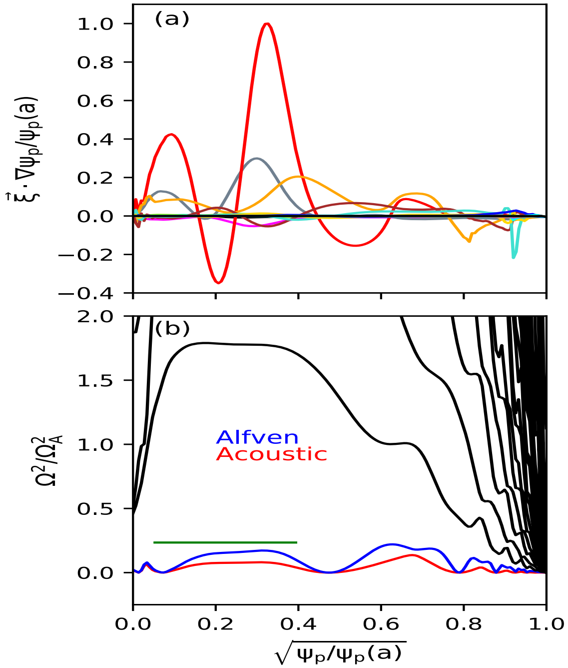


Reminiscent of NSTX(-U) avalanches preceded by chirping

[1]Cheng, *Phys. Rep.* **211** 1 (1992); Gorelenkov, *Phys. Plasmas* **6** 2802 (1999)

Eigenstructure and fast ion distribution function in ST40 #9831 at 85ms

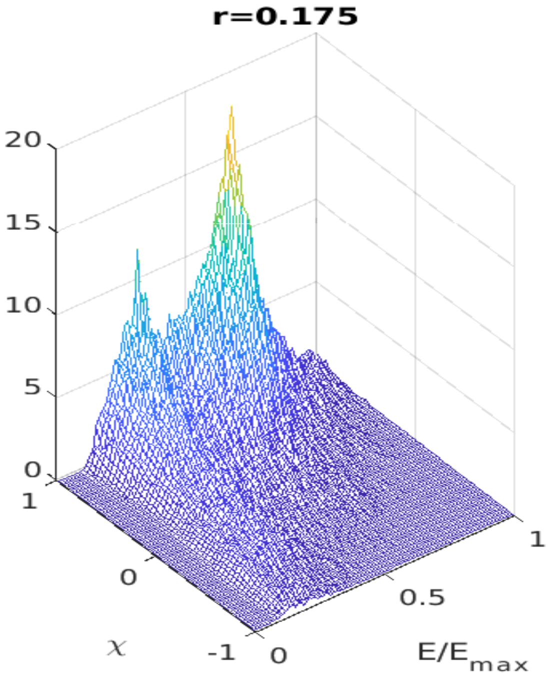
NOVA

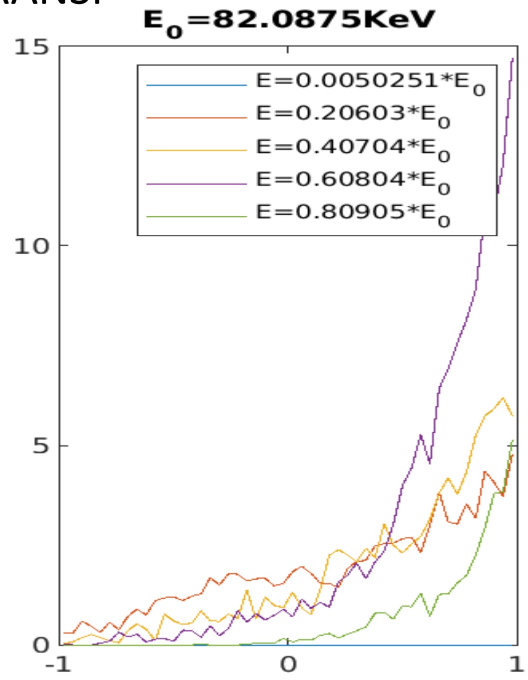


Mode resides in the BAAE gap

Gorelenkov et al, PLA'07

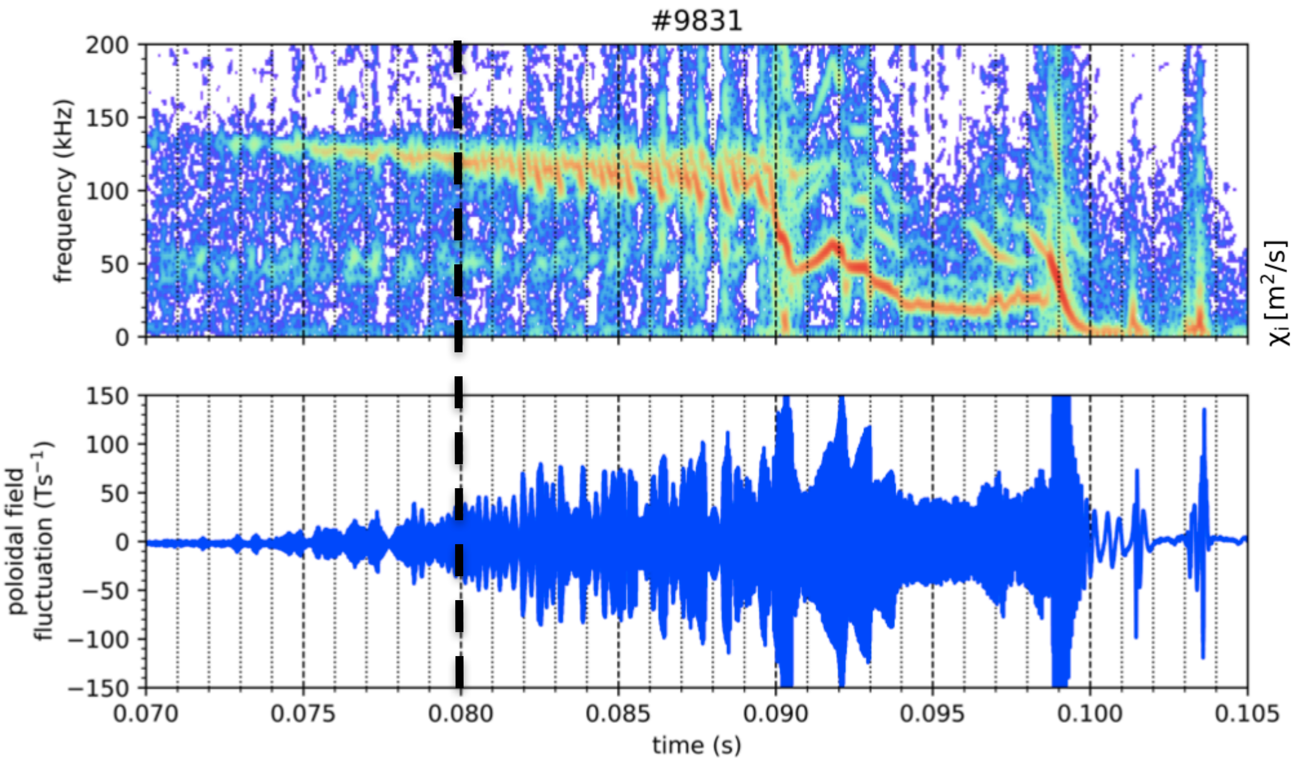
NUBEAM/TRANSP

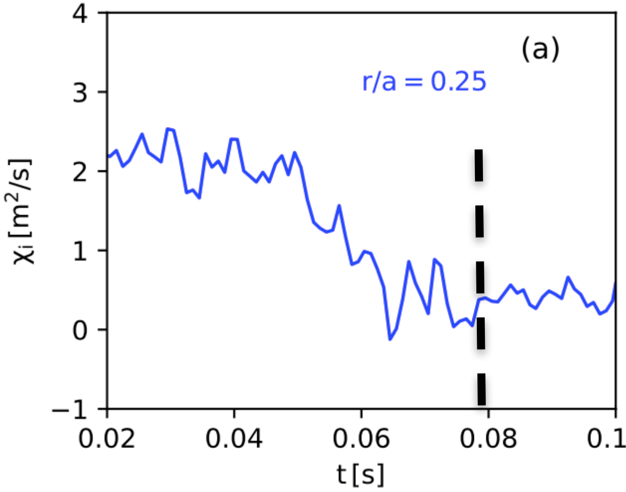




An integrated data analysis approach was used to constrain several quantities based on the available measurements

The steady-to-chirping frequency transition correlates with a marked drop in the turbulent activity: #9831





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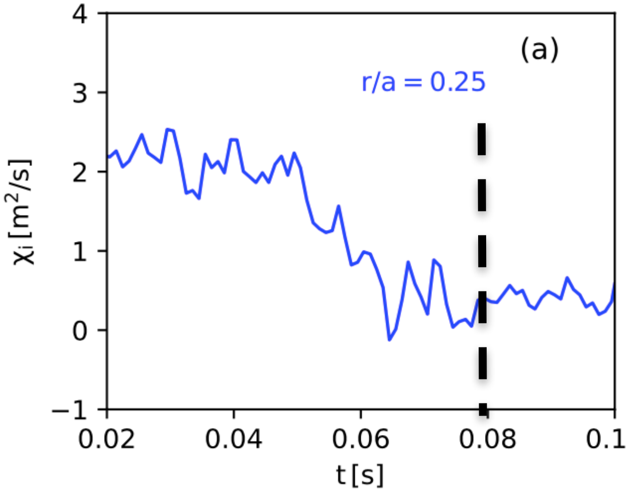
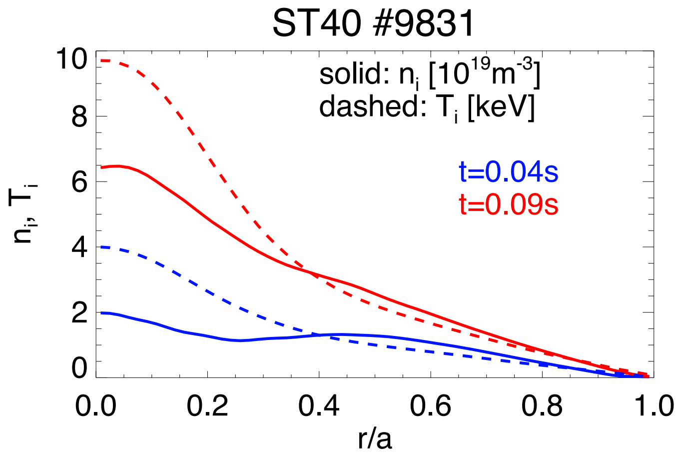
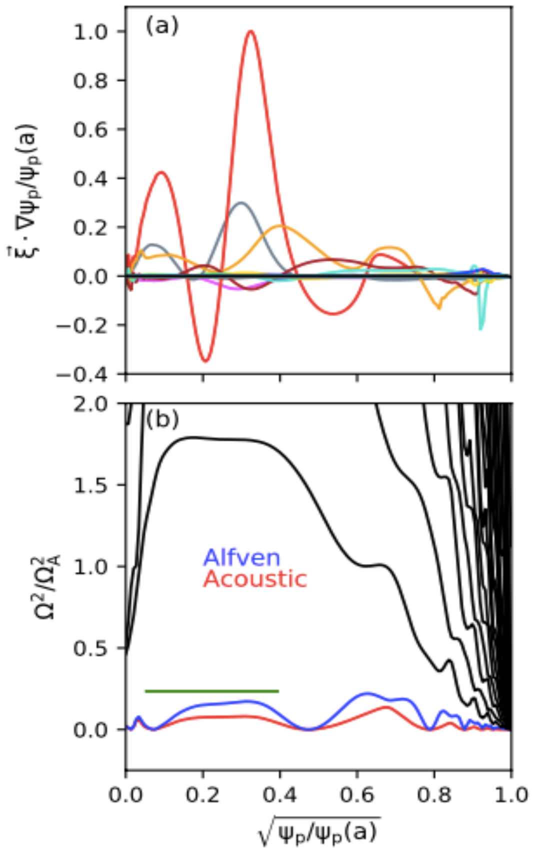


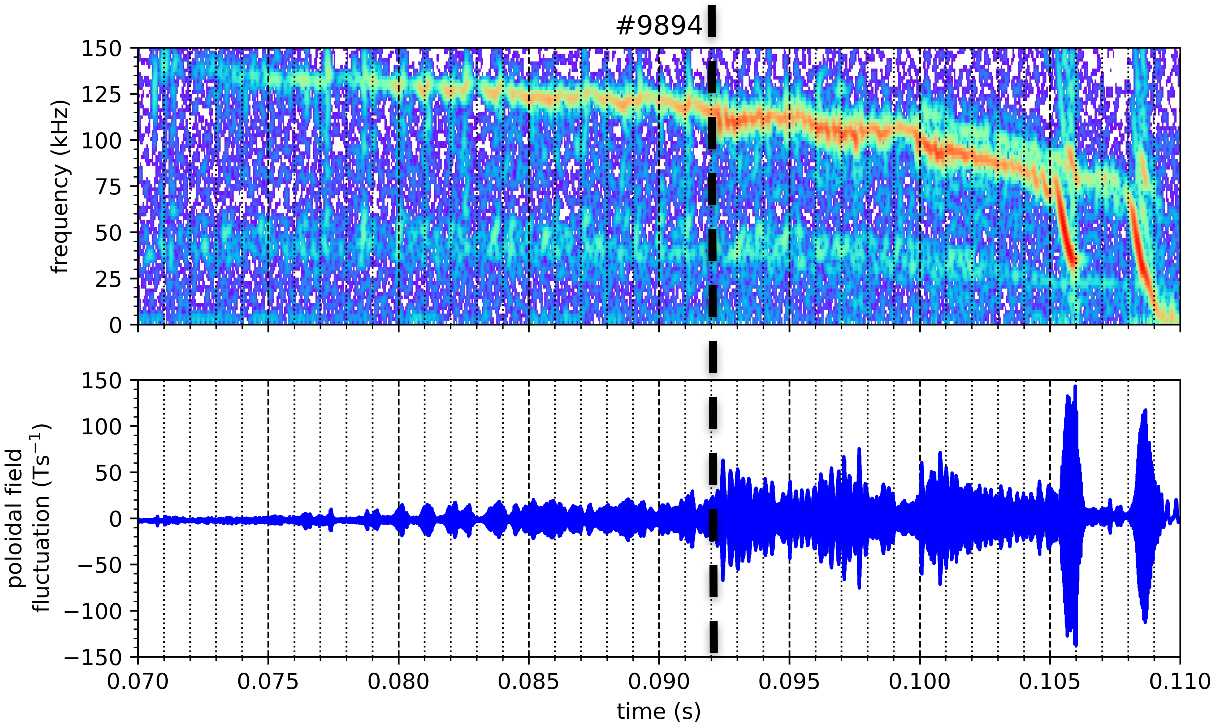


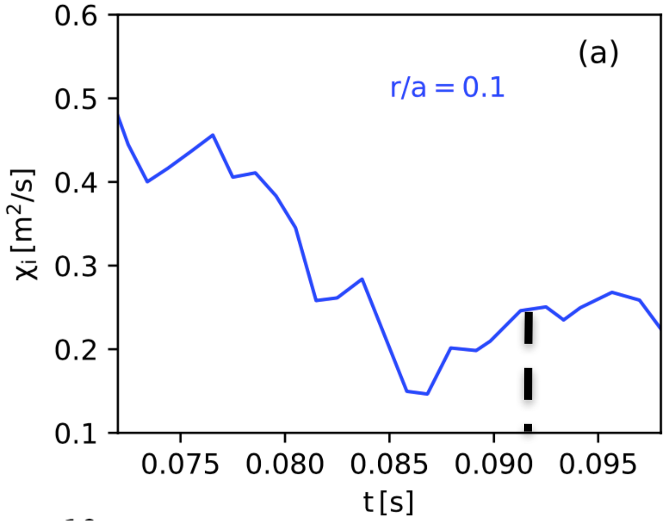


The strength of the turbulent spectrum drops by a factor of 5 before the transition to chirping:

- The initially flat density gradient becomes steep and decreases the ITG drive associated with $\eta_i=|\text{grad} \log T_i|/|\text{grad} \log n_i|$
- The chirping criterion, as evaluated by NOVA-K, indicates that chirping is predicted to occur for $\chi_i<0.8 m^2/s$, at the peak of the eigenstructure

Another example of chirping onset correlation with a marked drop of turbulent activity: #9894





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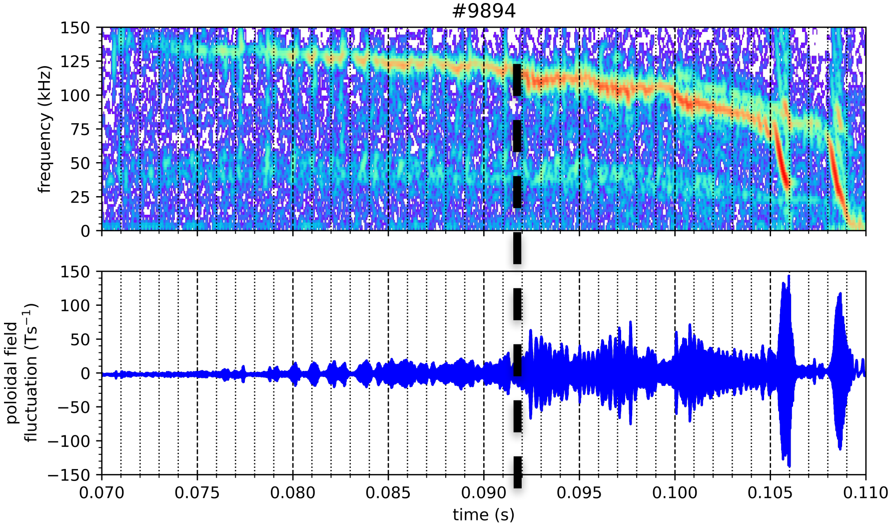
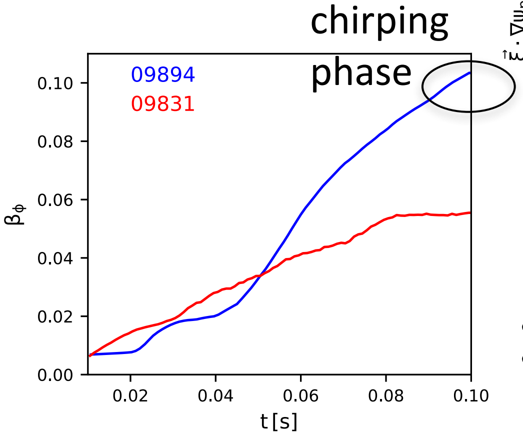
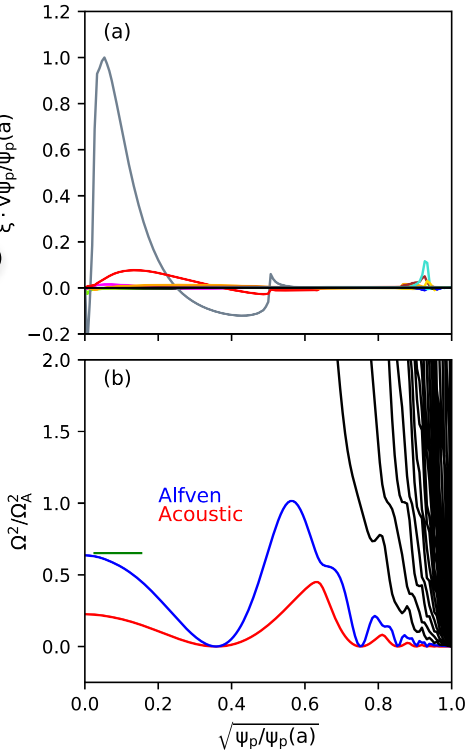






Chirping likely emerges due to plasma beta effect on turbulent suppression

Conclusions

- TRANSP and NOVA/NOVA-K analysis has been performed on high B_t, high T_i ST40 discharges, with two tangential NBIs at 25kEV and 55keV, with 1MW each. An integrated data analysis approach was used to constrain several quantities based on the available measurements.

- Anomalous transport was found to dominate over neoclassical transport on the ion scale.

- The most unstable modes appear to be n=1 BAAEs (with mixed acoustic and Alfvénic polarization), as identified by the NOVA and NOVA-K codes.

- Chirping behavior in ST40 has been inhibited by micro-turbulent scattering on fast ions - interpreted in terms of the suppression of coherent phase-space structures that support chirping.

Limitations of the current modeling

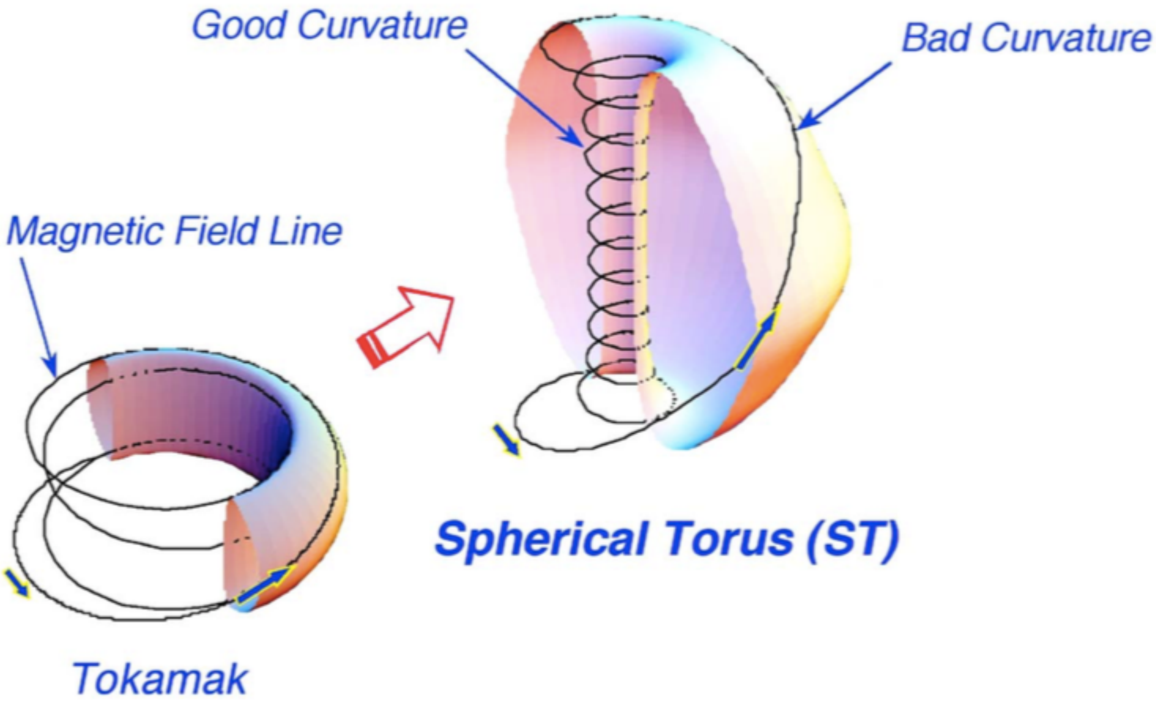
- Changes in temperature and wave amplitude has an effect on the damping and can also be linked with changes in the nonlinear character of Alfvénic waves.

- Turbulence drive was inferred from extrapolated temperature and density profiles.

- Stability of the BAAEs need to be more systematically addressed: non-perturbative effects important?

→ Upcoming campaigns with enhanced diagnostic capabilities will allow us to make more conclusive statements to better inform/predict experiments.

Backup slides

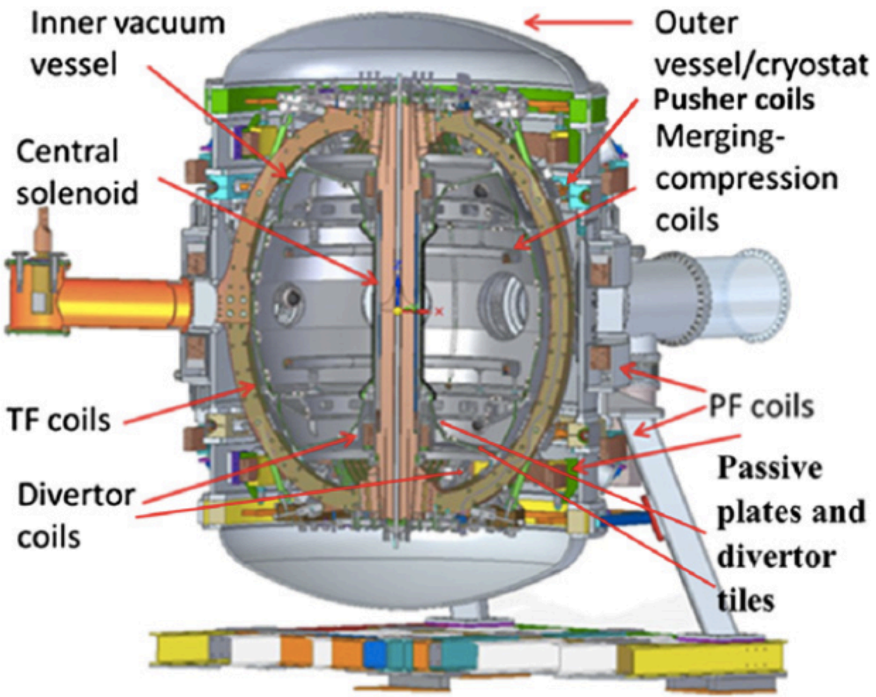

Good Curvature
Bad Curvature
Magnetic Field Line
Spherical Torus (ST)
Tokamak

ST40: high field spherical tokamak built and operated by Tokamak Energy, in the UK

Combines the high beta of spherical tokamaks with high toroidal field, using high temperature superconducting coils, with the goal of maximizing the fusion power scaling ~$\beta^2 B_t^4 V$

Design parameters:

- R = 0.4–0.6m,
- R/a=1.6–1.8,
- elongation k=2.5
- I_p=2MA,
- B_t =3T,
- pulse duration ~1–2 sec



M. Gryaznevich, "*Experiments on ST40 at high magnetic field*", Nucl. Fusion **62** (2022) 042008