Observation and interpretation of tornado modes coupled to near-axis Alfvén cascade eigenmodes in JET sawtoothing plasmas

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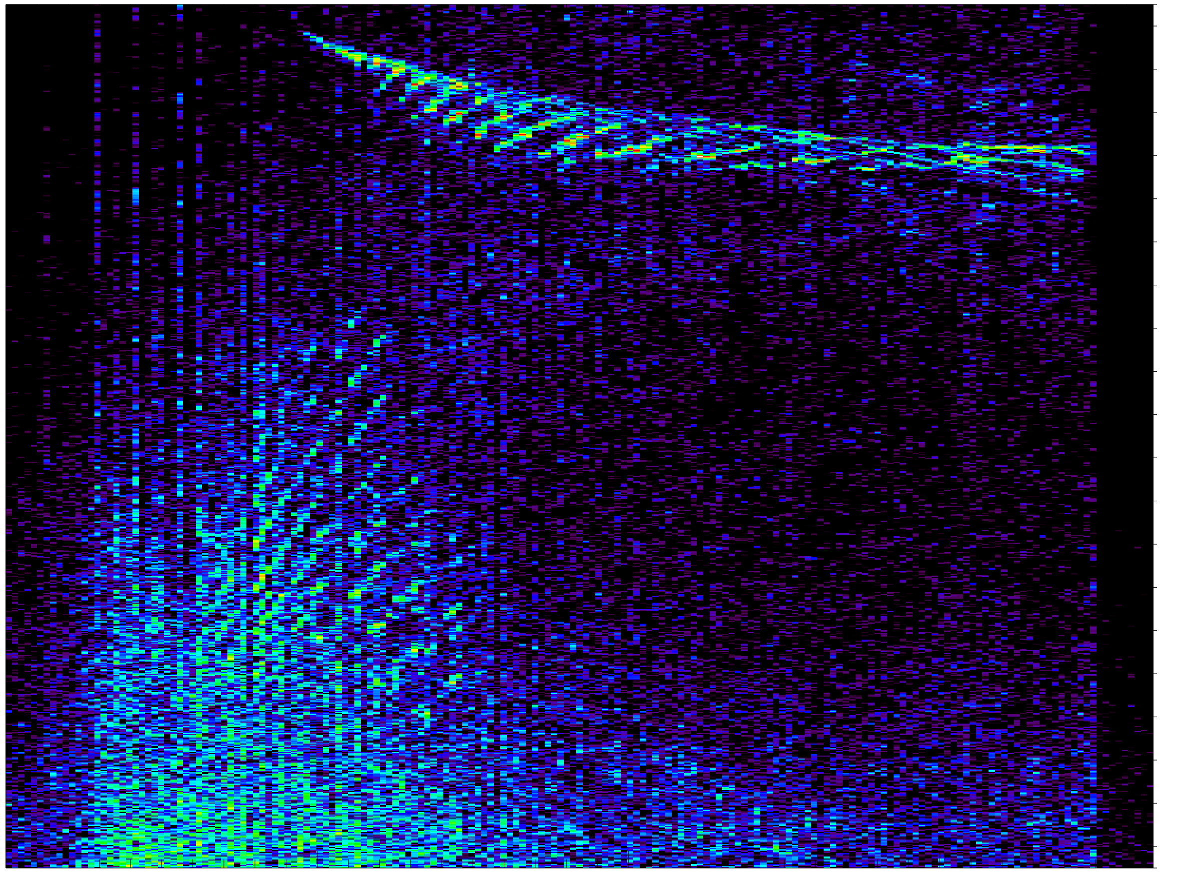

GTM meeting

28/05/2021

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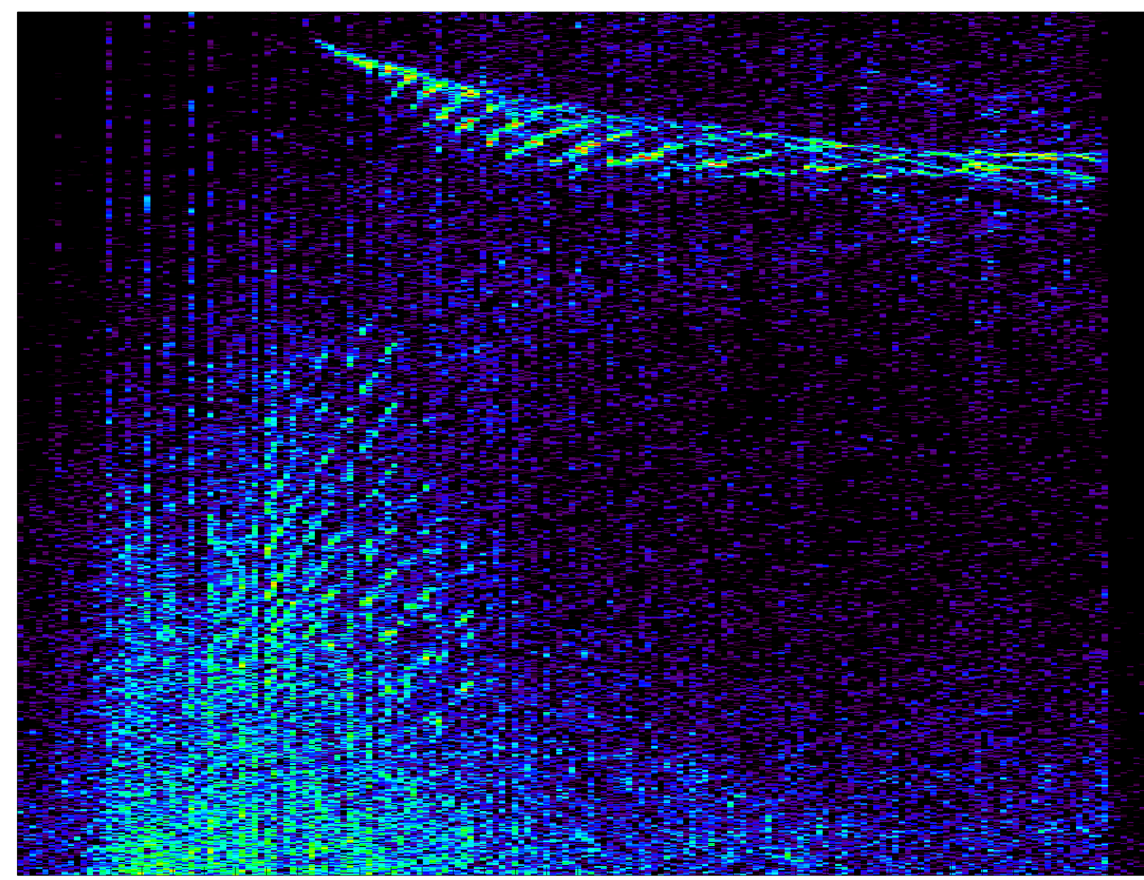

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Motivation

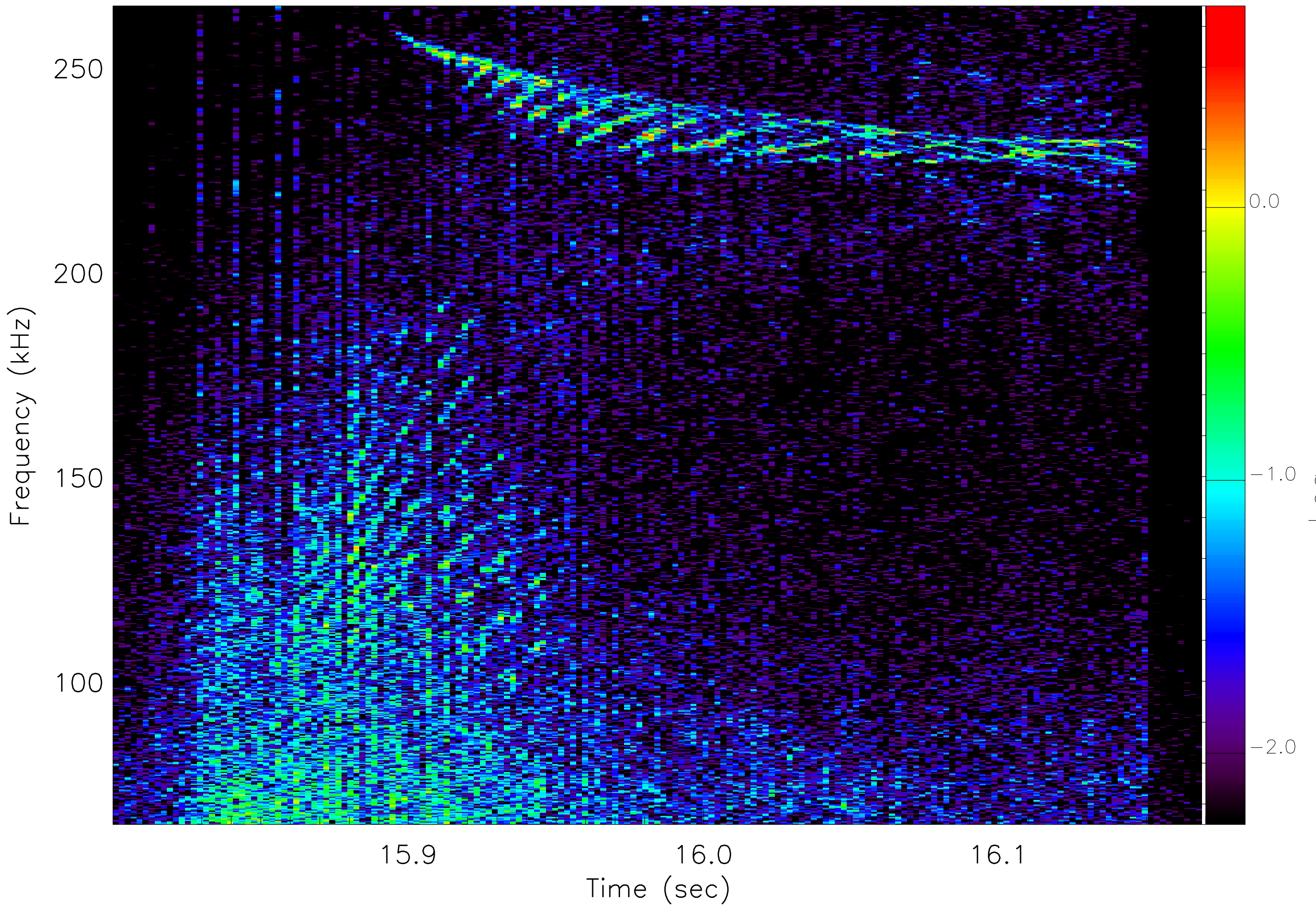
Two types of modes seemingly coupled:

- Upward frequency sweeping modes in the range 100-200 kHz
- Modes within the frequency range 225-250 kHz with some frequency modulation

1st type resembles Alfvén Cascades (ACs)

2nd type was previously identified as tornado modes*

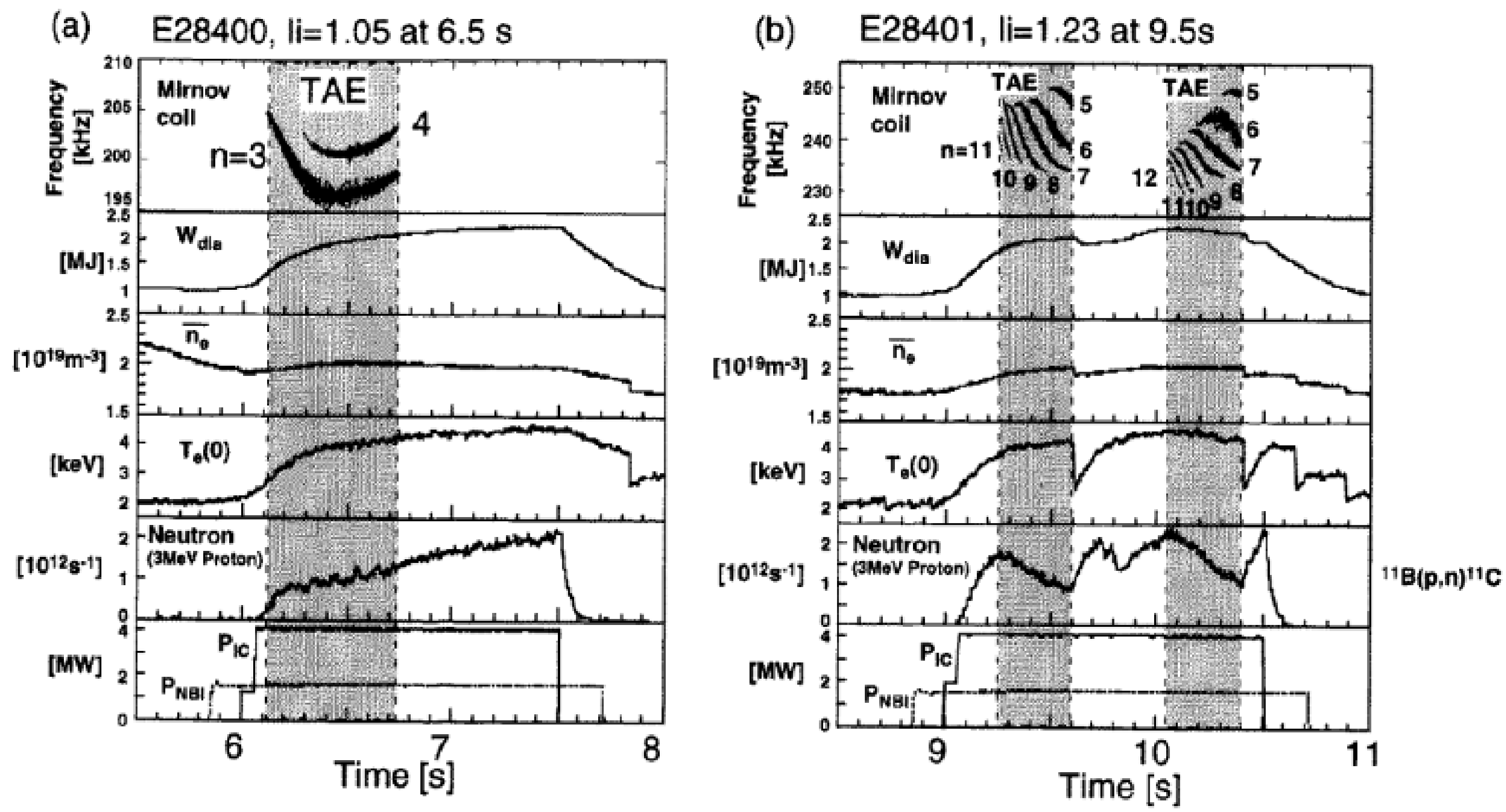
Applicability to MHD spectroscopy of post-sawtooth dynamics?



*P. Sandquist, S. E. Sharapov, M. Lisak, T. Johnson, Phys. of Plasmas 14, 122506 (2007)

Tornado Modes Preceding Sawtooth Crashes

First reported by the JT-60U Team[1]



Called “Tornado” because of non-Alfvénic frequency sweeping (not ~$B/\rho^{1/2}$)

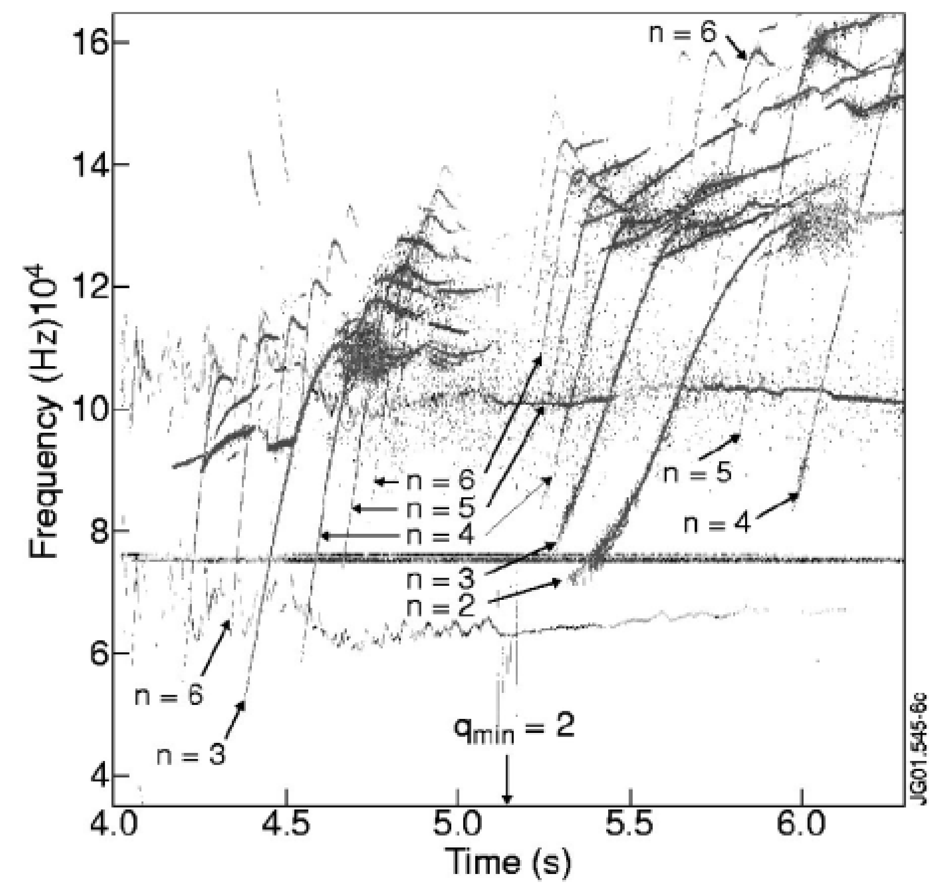
Identified as TAE inside the q=1 radius, with the “twist” frequency caused by the proximity to magnetic axis[2]

[1]M.Saigusa et al., PPCF 40 (1998) 1647

[2]G.Kramer, S.Sharapov et al., Phys. Rev. Lett. 87 92 (2004) 015001

The "Alfvén Cascade" Modes in Reversed Shear Discharges

First observed in JT-60U negative shear plasmas[1]



Observed then in JET, DIII-D, ASDEX-Upgrade, C-MOD, MAST, NSTX, TCV…

Interpreted as Eigenmodes residing at maximum points of Alfvén continuum caused by the zero magnetic shear[2,3]

ACs are usually associated with non-monotonic q(r)-profiles. However, the possibility of AC existence in plasmas with monotonic but very flat q-profiles was predicted in [B.Breizman et al., Phys. of Plasmas 10 (2003) 3549]

[1]Y.Kusama et al., PPCF 38 (1998) 1215

[2]H.Berk et al., Phys. Rev. Lett. 87 (2001) 185002

[3]S.Sharapov et al., Phys. of Plasmas 9 (2002) 2027

Outline

- Experimental conditions and observations
- Identification of the modes
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  - Resonances and orbits contributing to mode drive along its evolution
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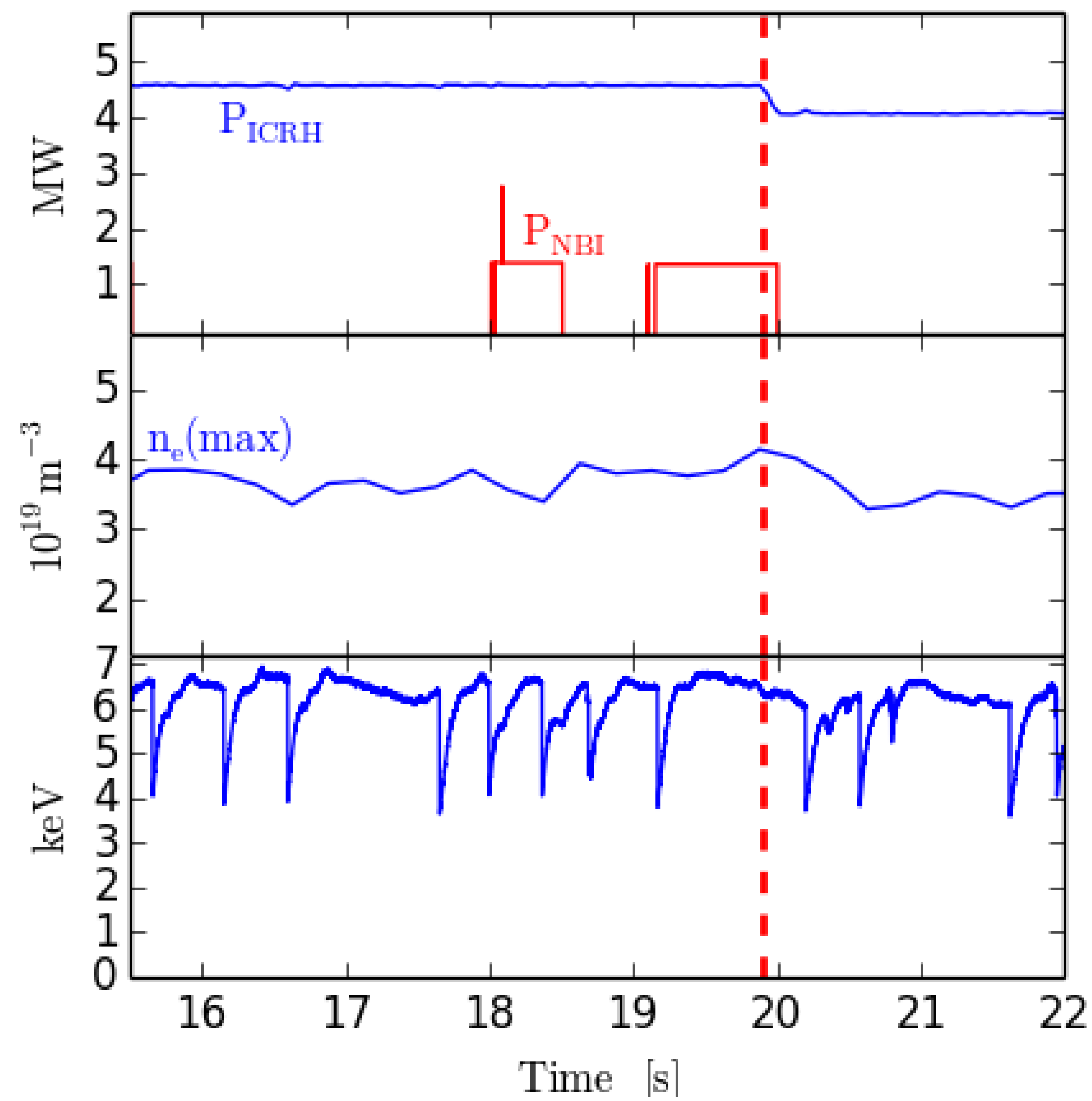
Experimental conditions

Auxiliary plasma heating was on-axis ICRH of hydrogen minority (n_H/n_e=2.5%) with flat power waveform

Diagnostic NBI blips necessary for MSE measurements crucial for reconstruction of q-profile close to the axis

Density approximately constant; temperature evolution indicates sawtooth oscillation



JET machine parameters: 2.7 T magnetic field, 2 MA plasma current

P. Sandquist, S. E. Sharapov, M. Lisak, T. Johnson, Phys. of Plasmas 14, 122506 (2007)

Observation of near-axis coupled AC type and tornado modes

Tornado modes are TAEs and so they are associated with specific $q_{n,m}=(m-1/2)/n$

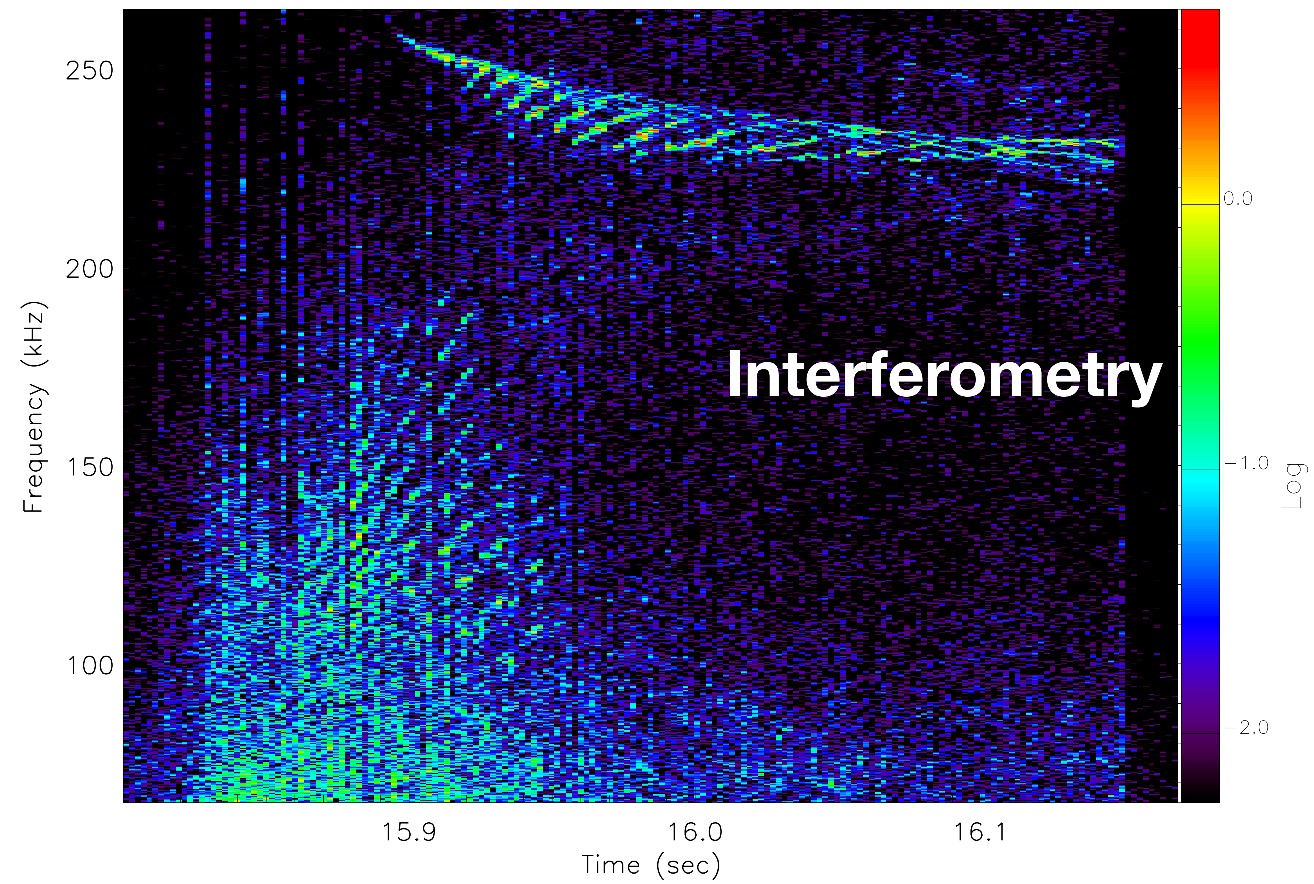
We are between sawteeth so q_0 is close to unity but gradually decreasing in time, and the modes have m=n

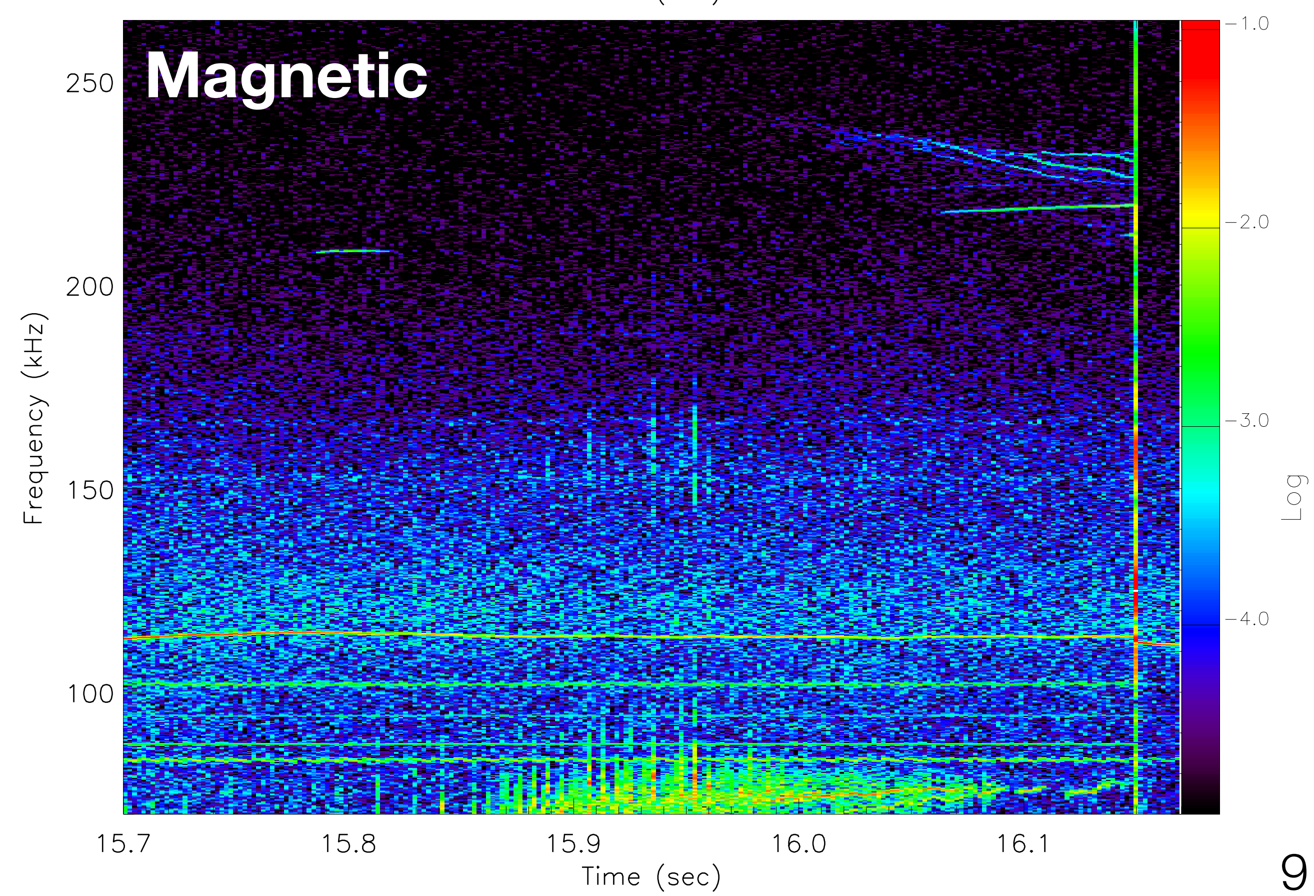
As the q-profile decreases q_0 crosses $q_n=(n-1/2)/n$ and the corresponding tornado mode is then allowed to exist, which explains why they appear one by one from high to low toroidal mode numbers

ACs and tornado modes are observed in interferometry diagnostics but not in magnetics which are peripheral

↓

Modes very close to magnetic axis





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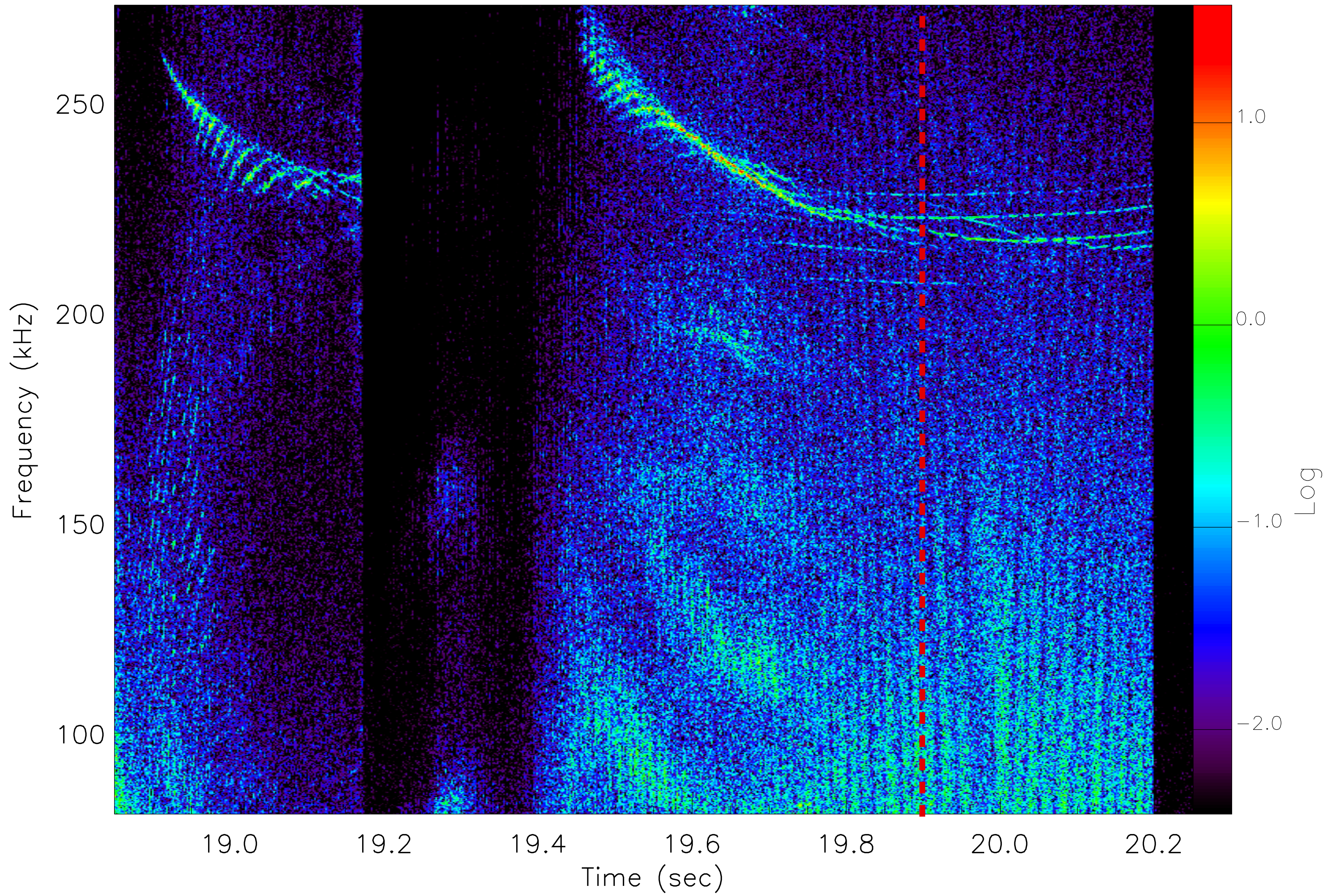
Retrace back from late stage tornado



Starting point in final stage of tornado modes → Retrace back plasma evolution → Establish connection between ACs and tornado modes

Rescaling q_0 to mimic post-sawtooth plasma evolution

Before sawtooth crash $q_0<1$, crash raises q_0, then it gradually decreases

We have EFIT equilibrium reconstruction with MSE measurements refined with HELENA for t=19.9s

Equilibrium reconstructed q-profile is rescaled to reproduce plasma evolution after sawtooth crash

Raise q_0 → Move backwards in time

For each step (i.e. for each q_0) MHD code MISHKA is used to scan for the existence of modes close to the axis

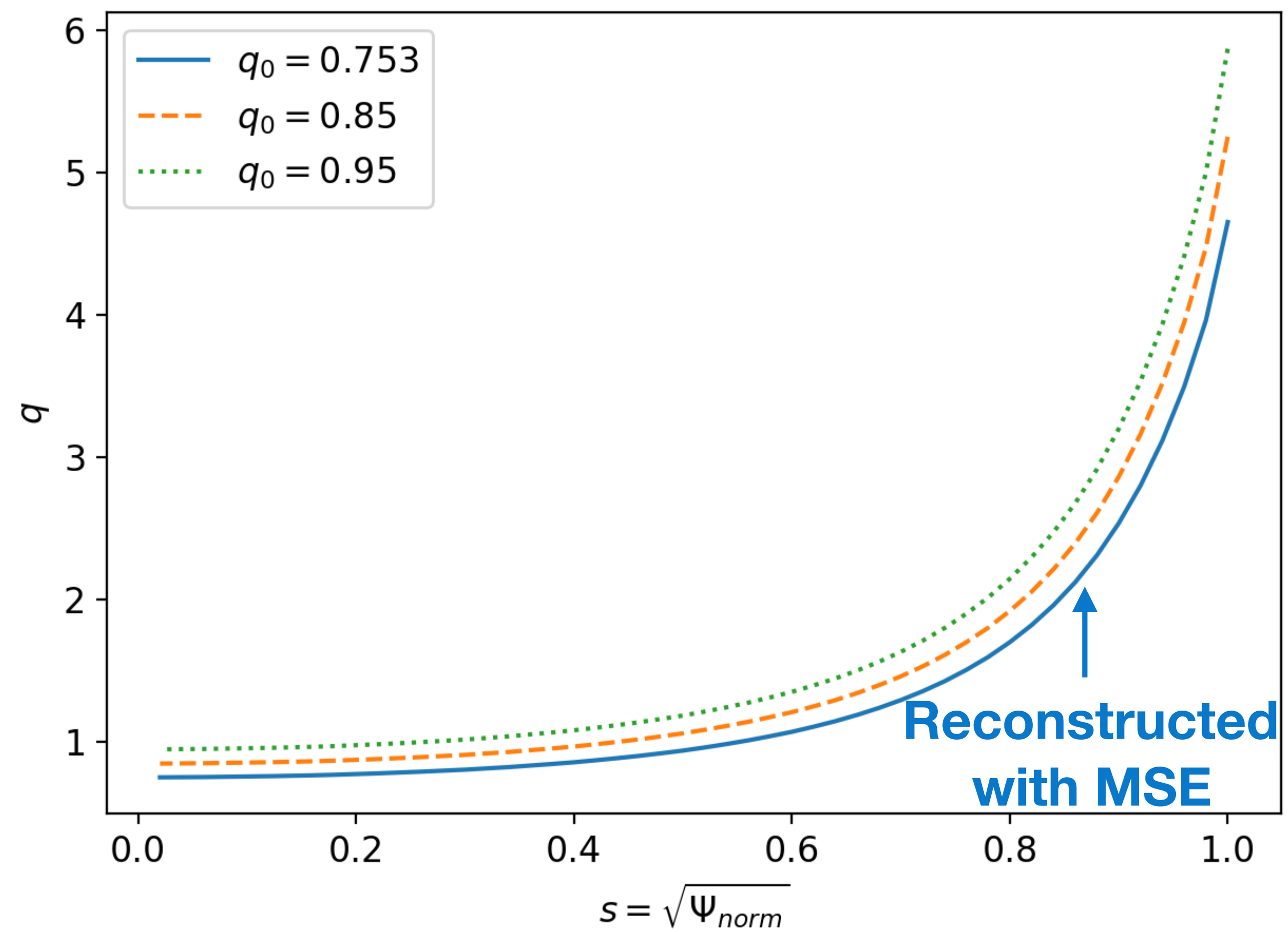
Near-axis cascades in very flat q-profile

q-profile is very flat near the axis but nonetheless monotonic

ACs are usually connected to shear reversal; however, they can be allowed in the right conditions if q-profile is sufficiently flat*

Tornado modes: TAEs inside q=1**

AC modes: near-axis, flat q cascades



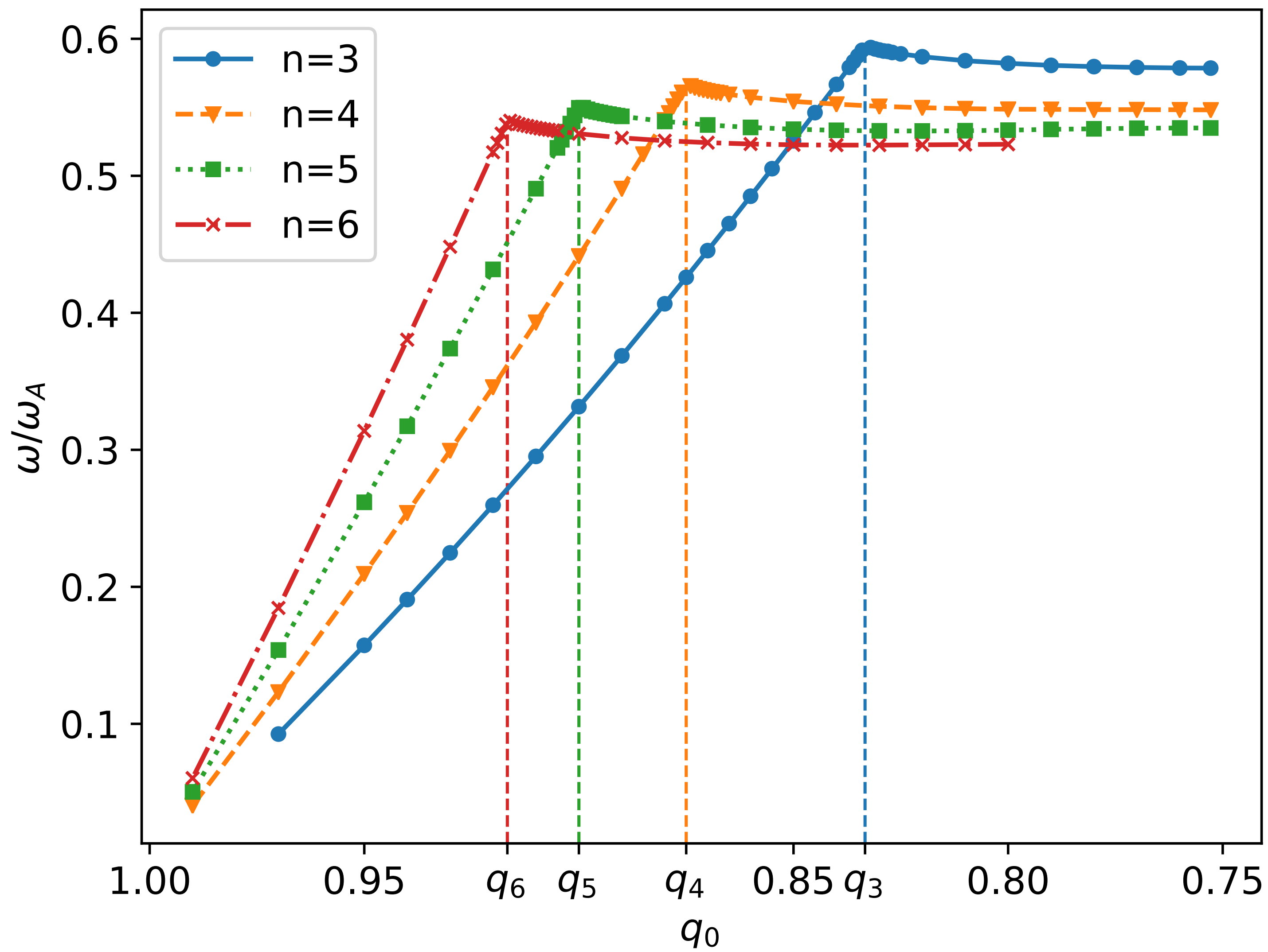
*B. N. Breizman, H. L. Berk, M. S. Pekker, S. D. Pinches, and S. E. Sharapov, Phys. of Plasmas 10, 3649 (2003)
**T. Gassner et al., Phys. of Plasmas 19, 032115 (2012)

AC→tornado transition occurs at $q_0=(n-1/2)/n$

All modes have the same evolution

1^{st} stage: grand cascade with higher n modes sweeping faster in frequency*

2^{nd} stage: tornado mode



For mode with toroidal mode number n the transition point occurs at $q_0=q_n=(n-1/2)/n$

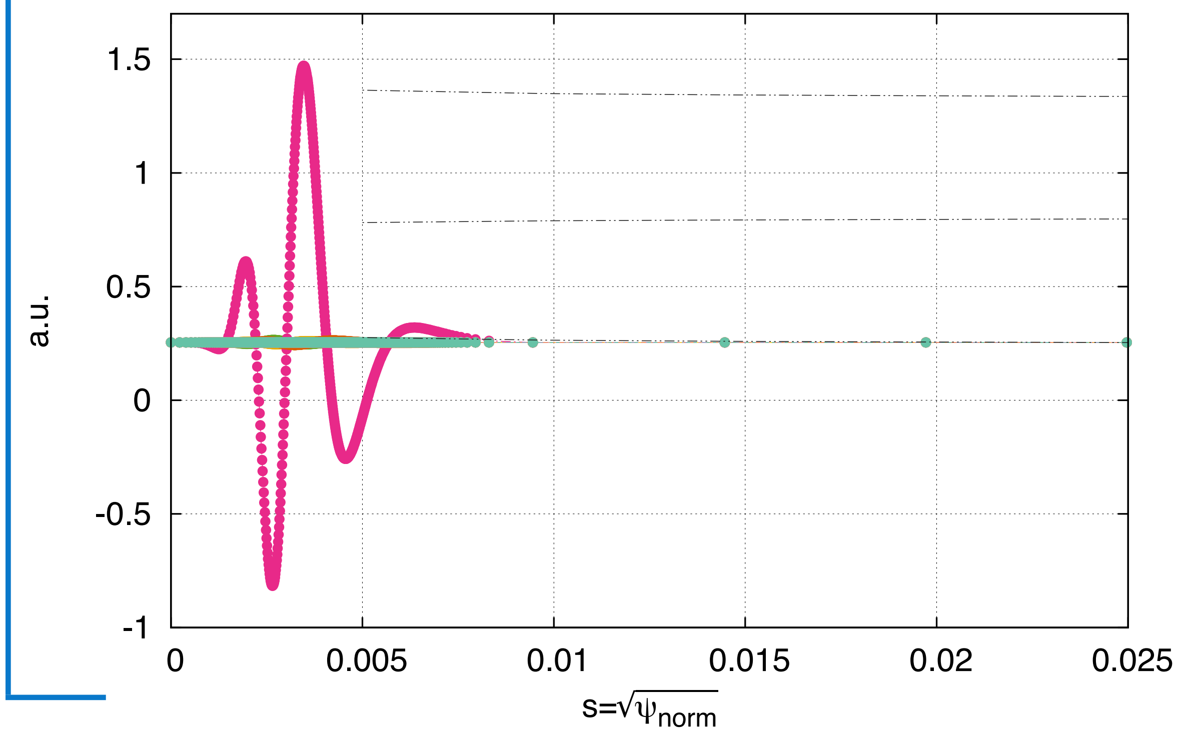
MHD spectroscopy of q-profile evolution after sawtooth crash: $q_6=0.917$; $q_5=0.9$; $q_4=0.875$; $q_3=0.833$

*H. L. Berk, D. N. Borba, B. N. Breizman, S. D. Pinches, and S. E. Sharapov, Phys. Rev. Lett. 87, 185002 (2001)

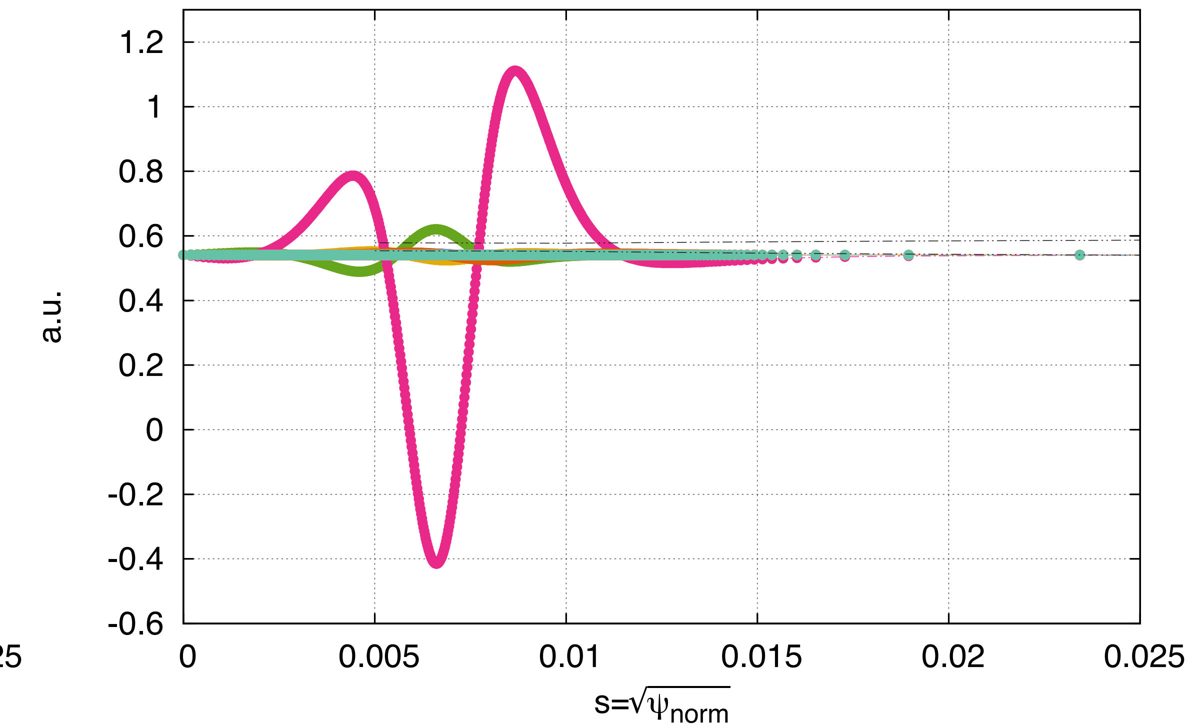
Highly localised AC, tornado modes larger radial extent

n=4:

AC

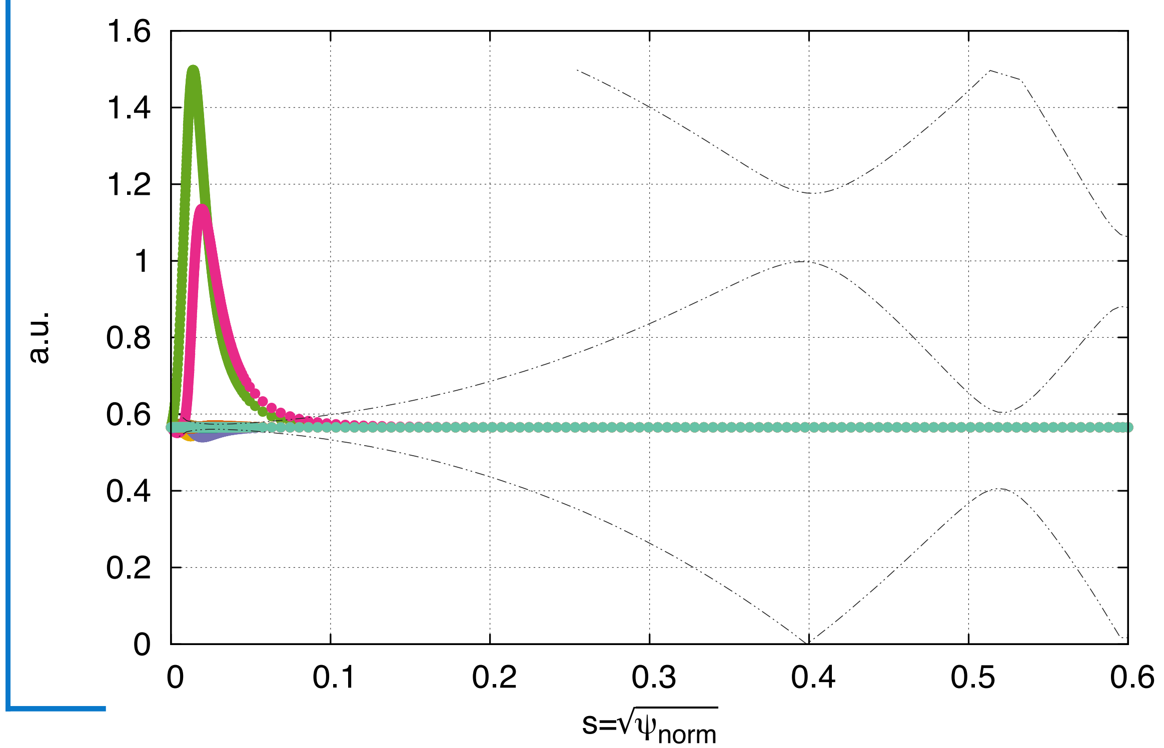


(a) $q_0 = 0.94,\ \omega/\omega_A = 0.254$

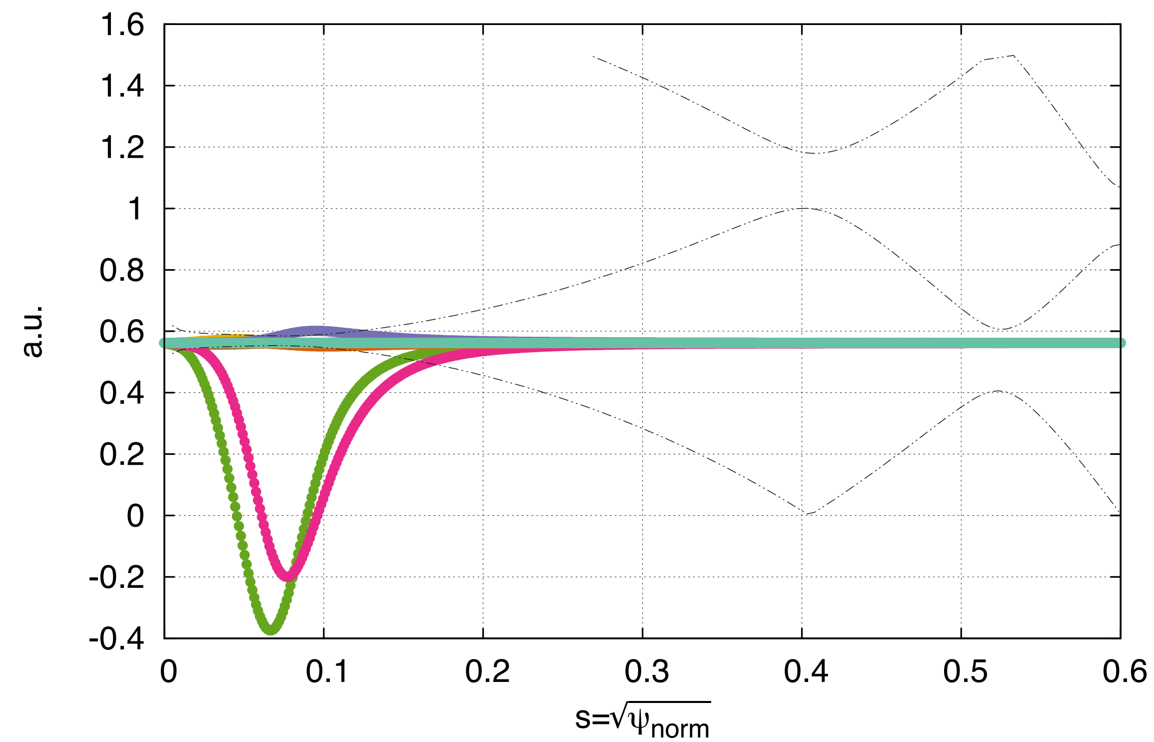


(b) $q_0 = 0.88,\ \omega/\omega_A = 0.541$

Tornado



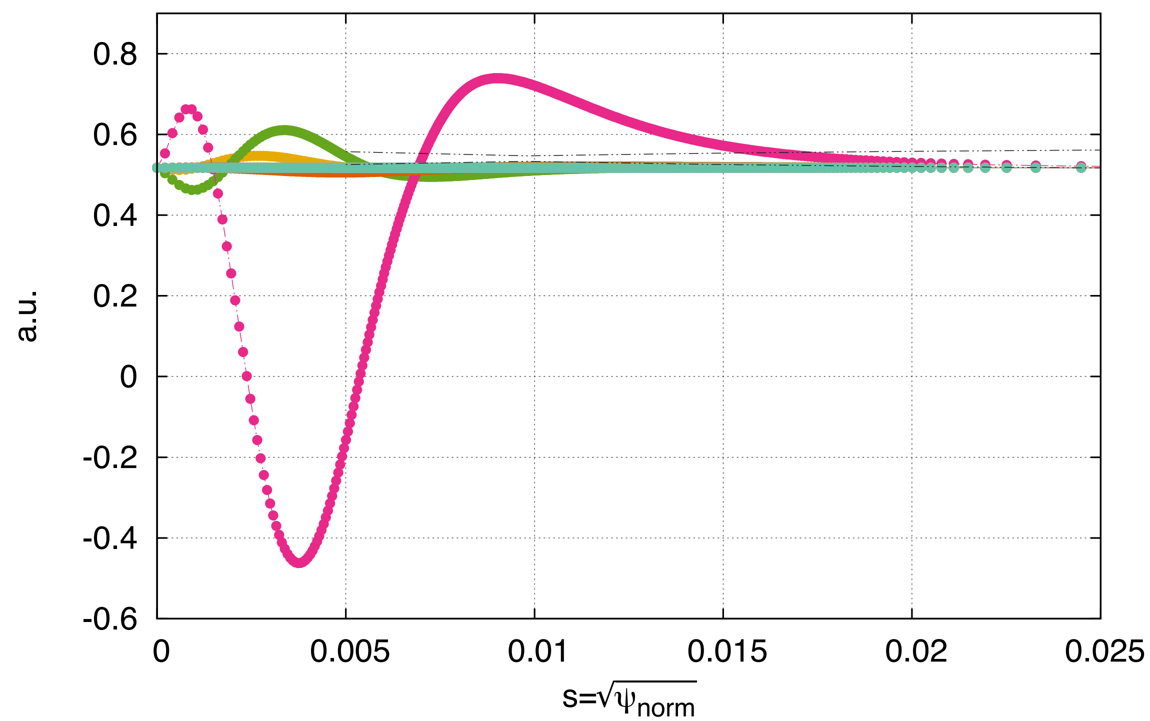
(c) $q_0 = 0.874,\ \omega/\omega_A = 0.566$



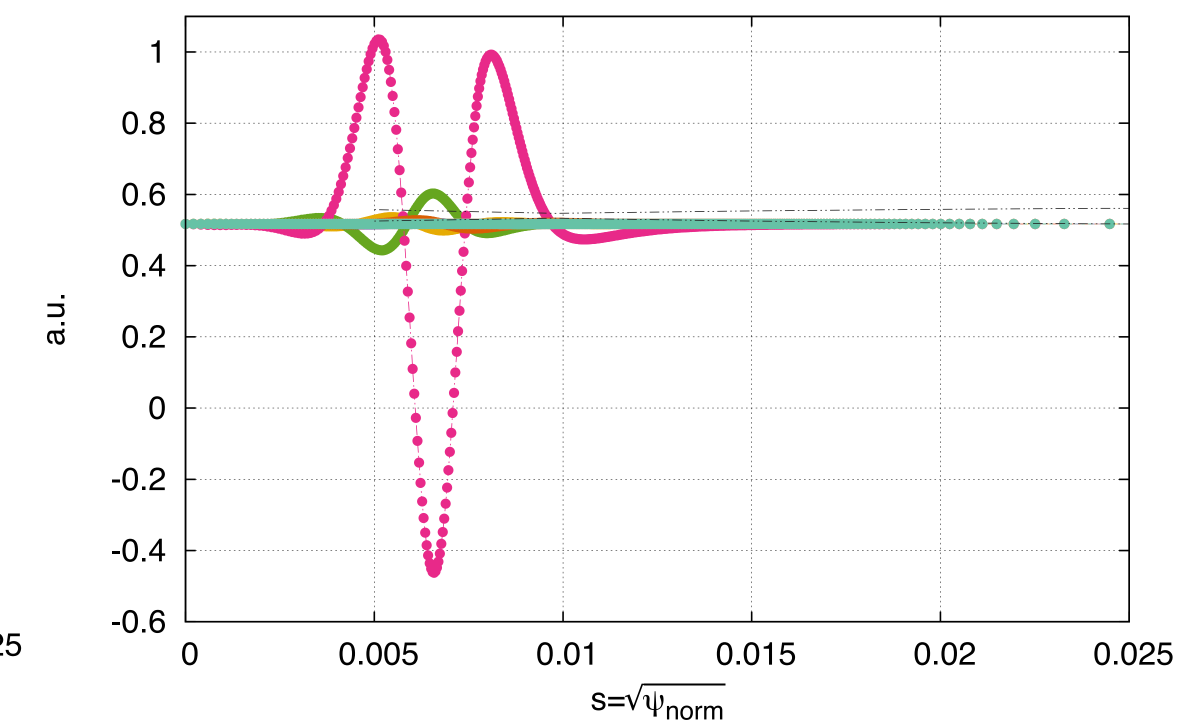
(d) $q_0 = 0.87,\ \omega/\omega_A = 0.562$

Multiple radial wavenumber modes exist in same “potential well”

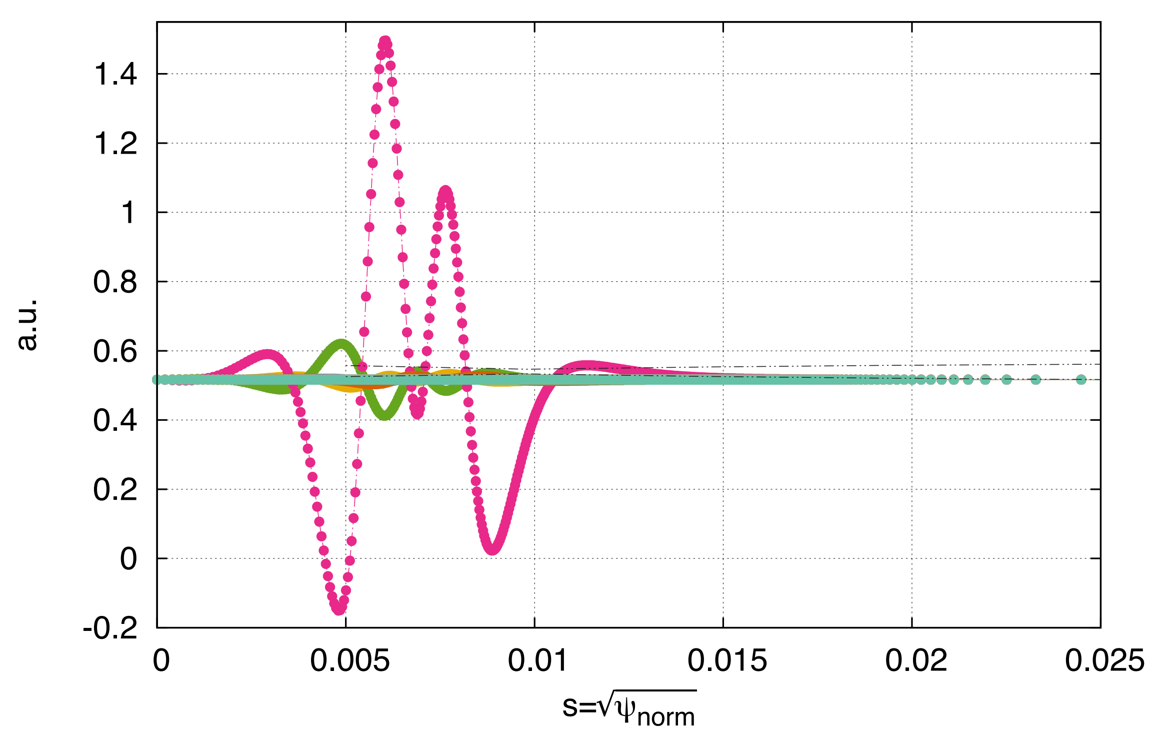
n=6 ACs



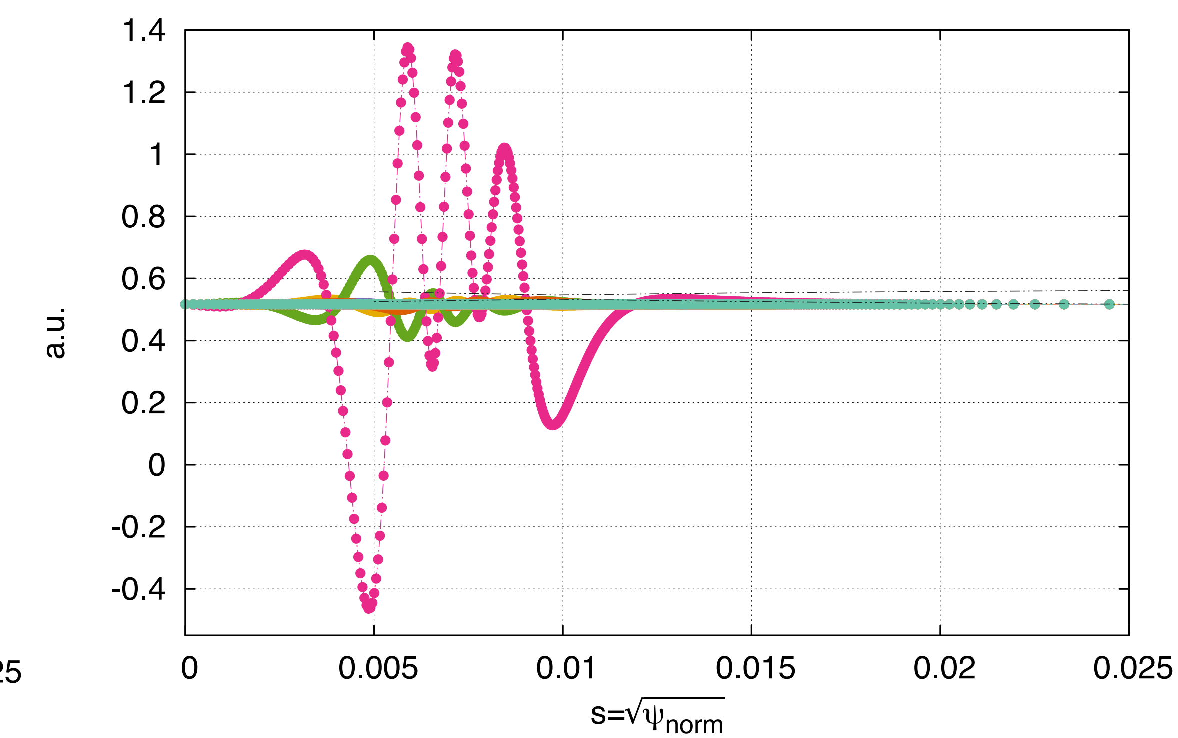
(a) $\omega/\omega_A = 0.5172$



(b) $\omega/\omega_A = 0.5170$



(c) $\omega/\omega_A = 0.5165$



(d) $\omega/\omega_A = 0.5163$

*B. N. Breizman, H. L. Berk, M. S. Pekker, S. D. Pinches, and S. E. Sharapov, Phys. Plasmas 10, 3649 (2003)

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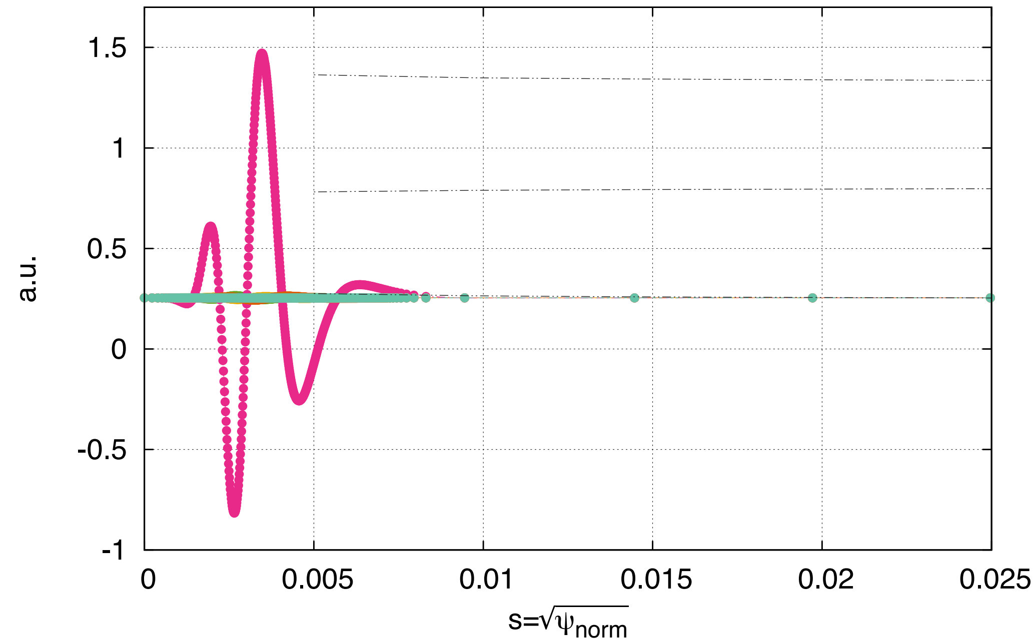
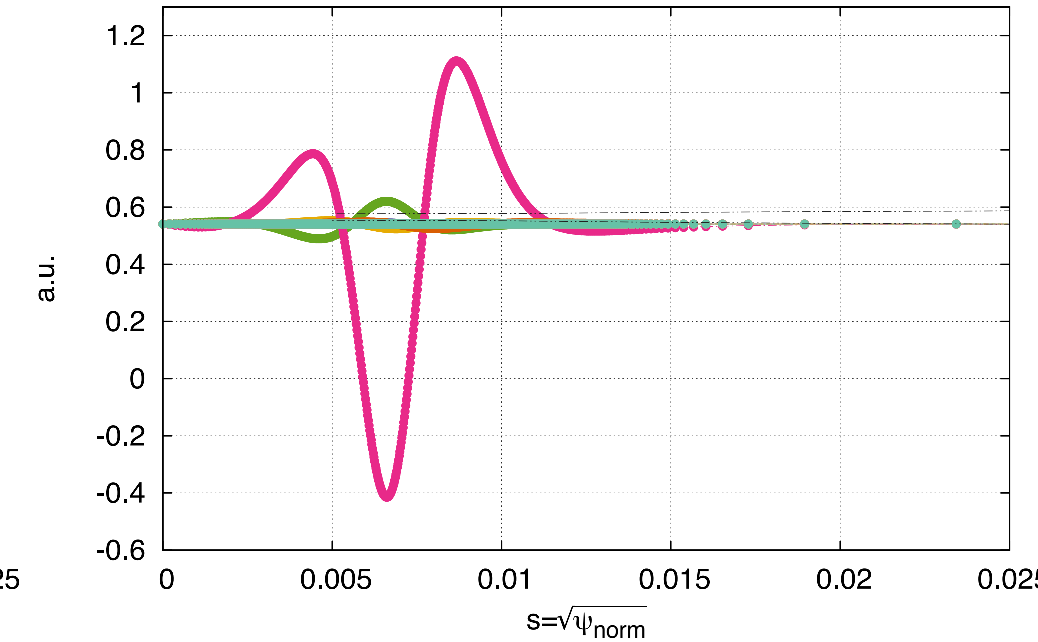
Assess energetic hydrogen minority drive of n=4 mode

n=4



(a) $q_0 = 0.94,\ \omega/\omega_A = 0.254$

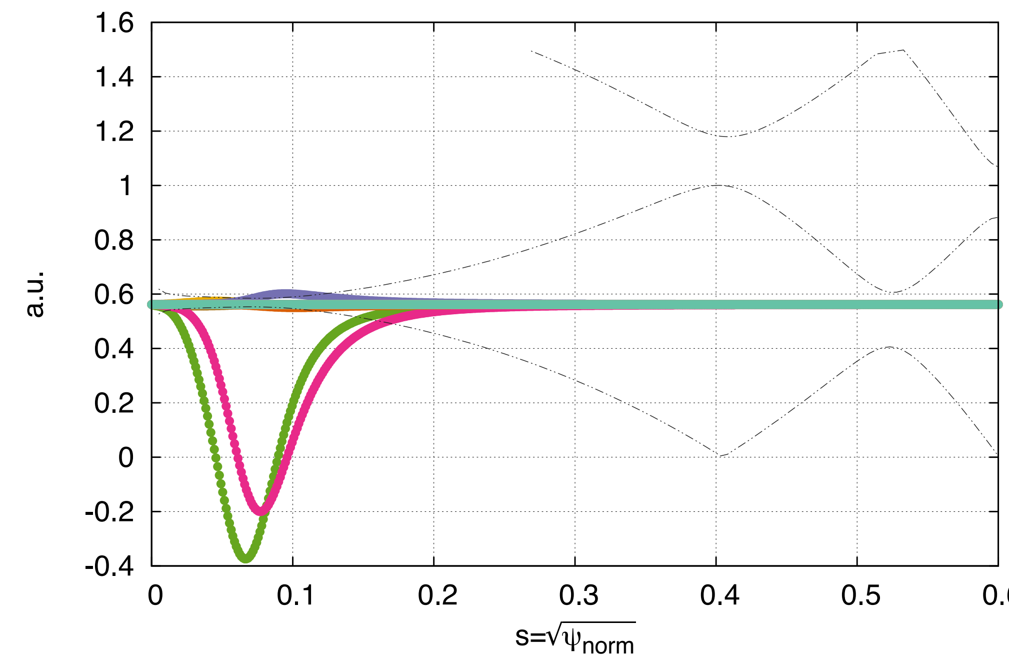


(b) $q_0 = 0.88,\ \omega/\omega_A = 0.541$

Ion orbits are characterised by the constants of motion (E, P_ϕ, Λ), $P_\phi = Ze\Psi + v_{\parallel} R B_\phi / B_0$, $\Lambda = \mu B_0 / E$

Energetic ion population*:

- single $\Lambda = 0.96$
- Maxwellian distribution with temperature peaked on-axis of 527 keV
- radial density profile $\rho = \rho_0 (1 - \Psi_{norm})^2$

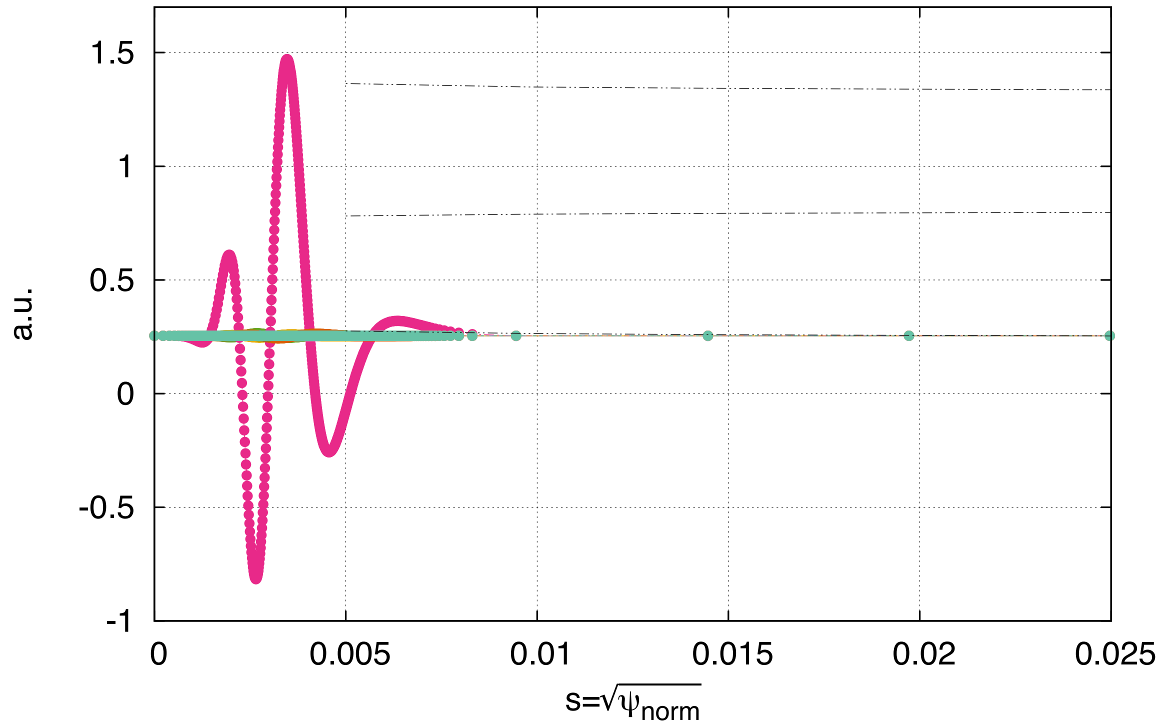


(d) $q_0 = 0.87,\ \omega/\omega_A = 0.562$

Drive of n=4 mode is calculated with CASTOR-k at three steps of mode evolution

*P. Sandquist, S. E. Sharapov, M. Lisak, T. Johnson, Phys. Plasmas 14, 122506 (2007)

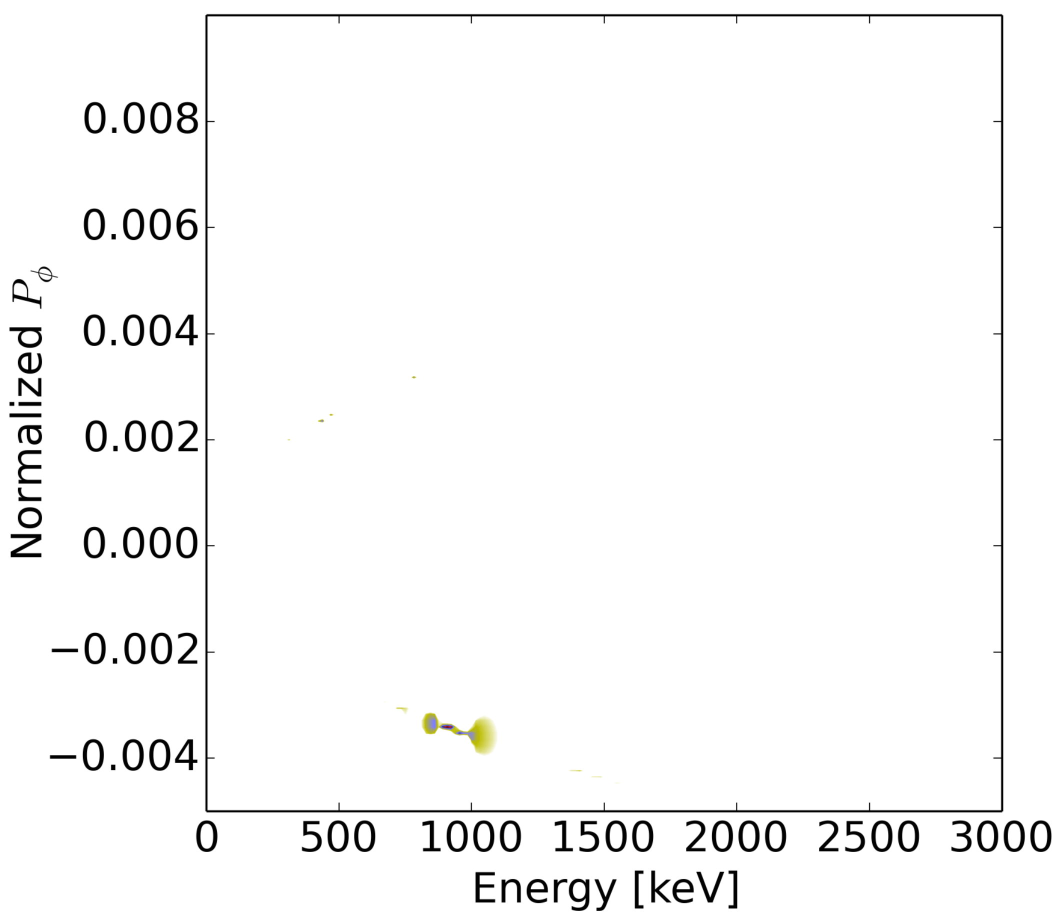
Low frequency cascade interacts with single, very narrow resonance

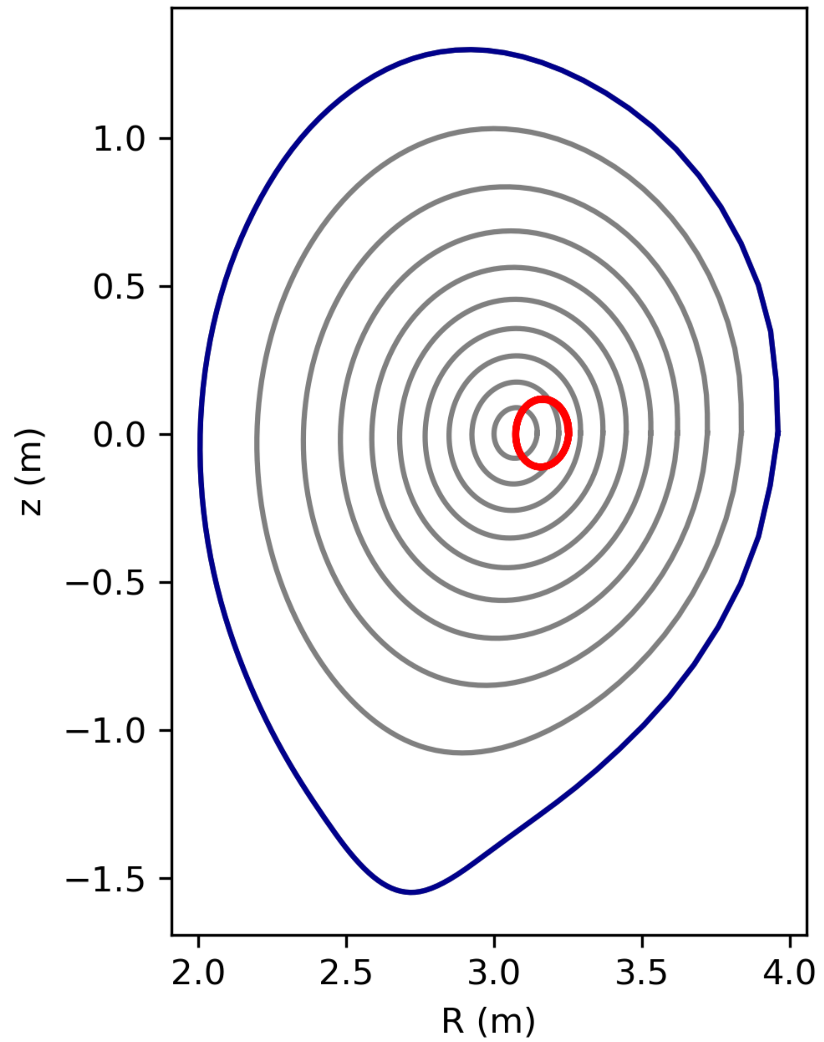


ω/ω_A=0.254 → f≈92kHz

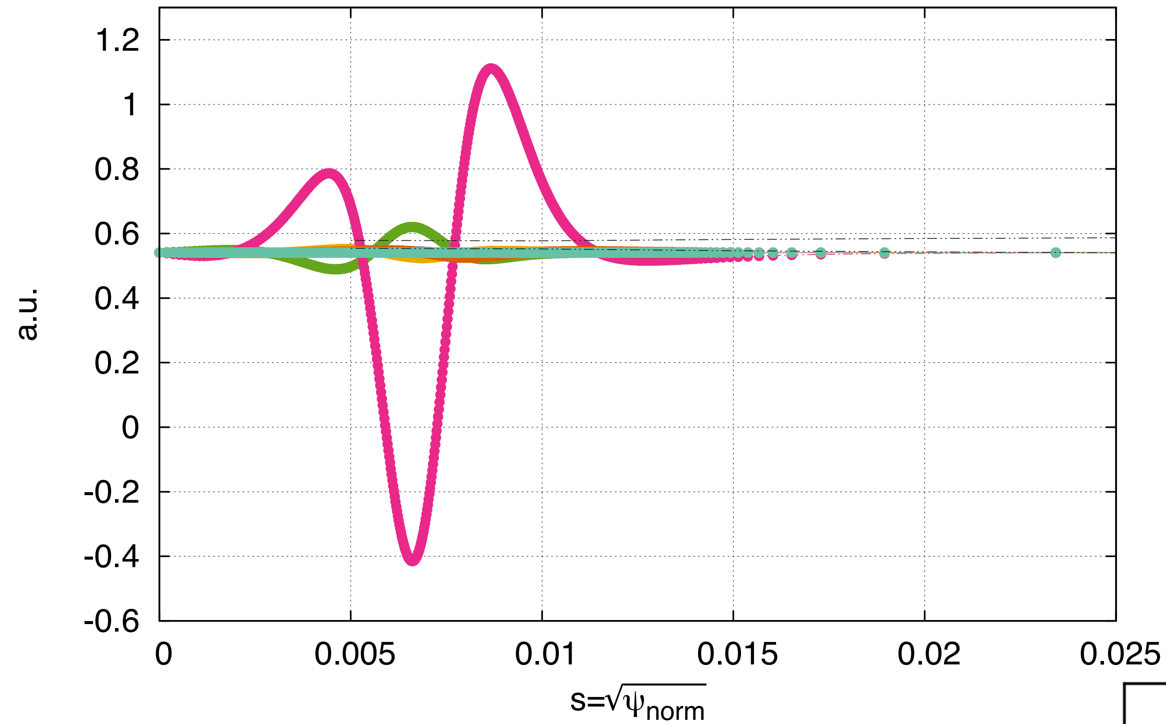
Single relevant interaction in a very narrow resonance

Corresponding orbit is non-standard and close to the axis





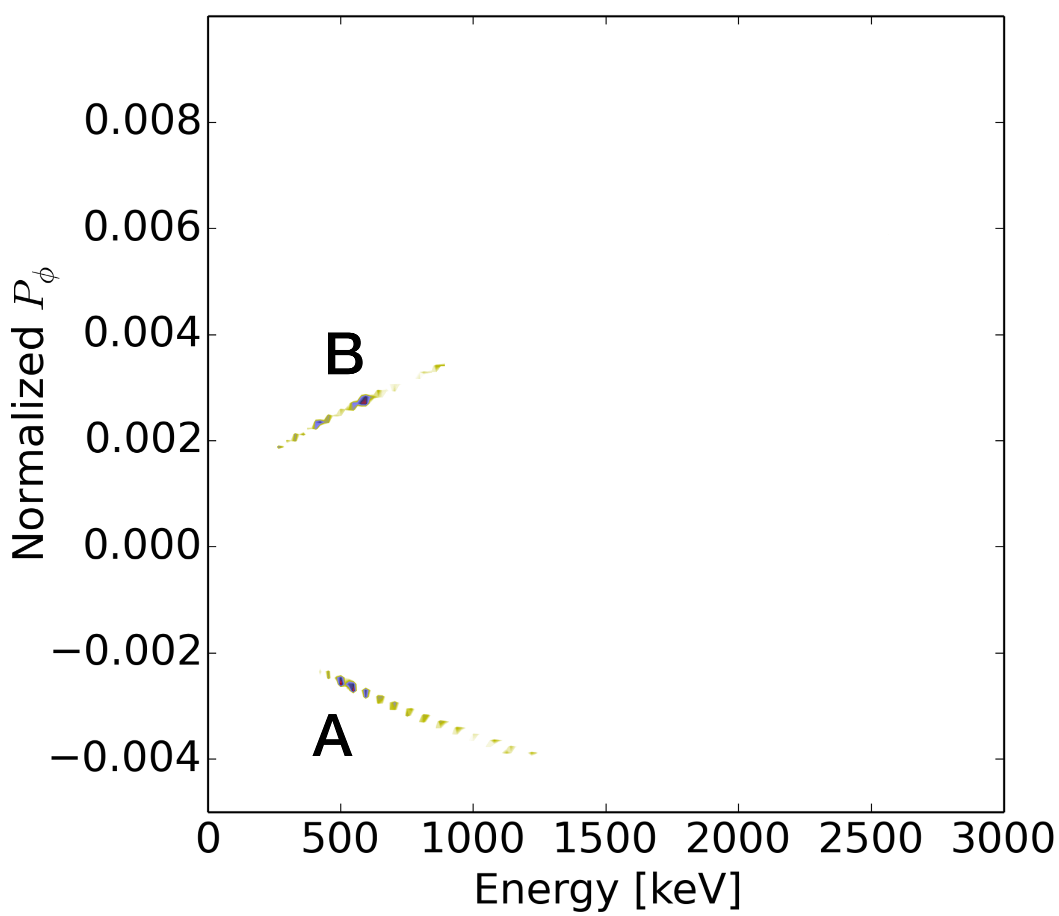
High frequency cascade interacts with two very narrow resonances

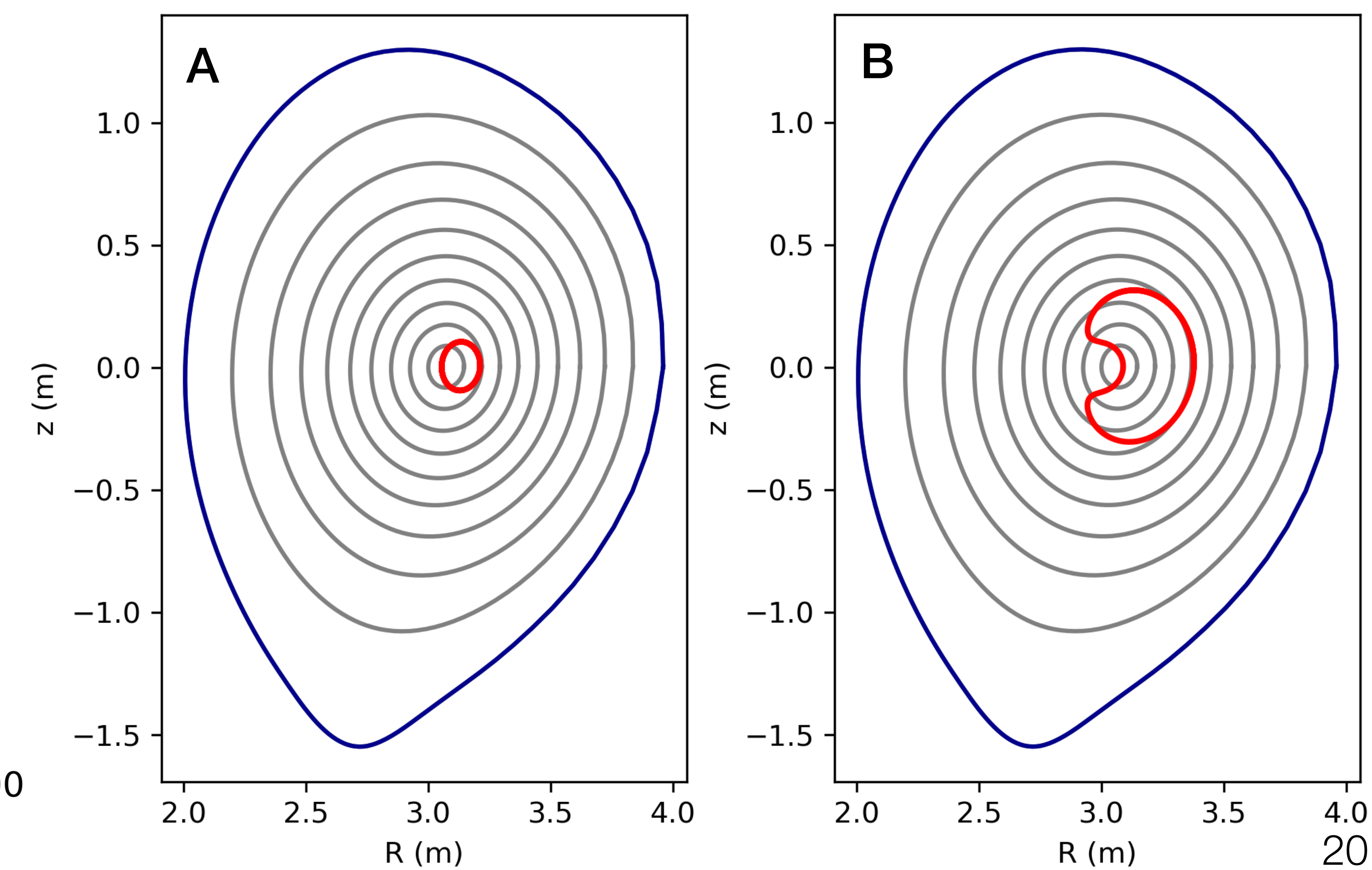


ω/ω_A=0.541 → f≈195kHz

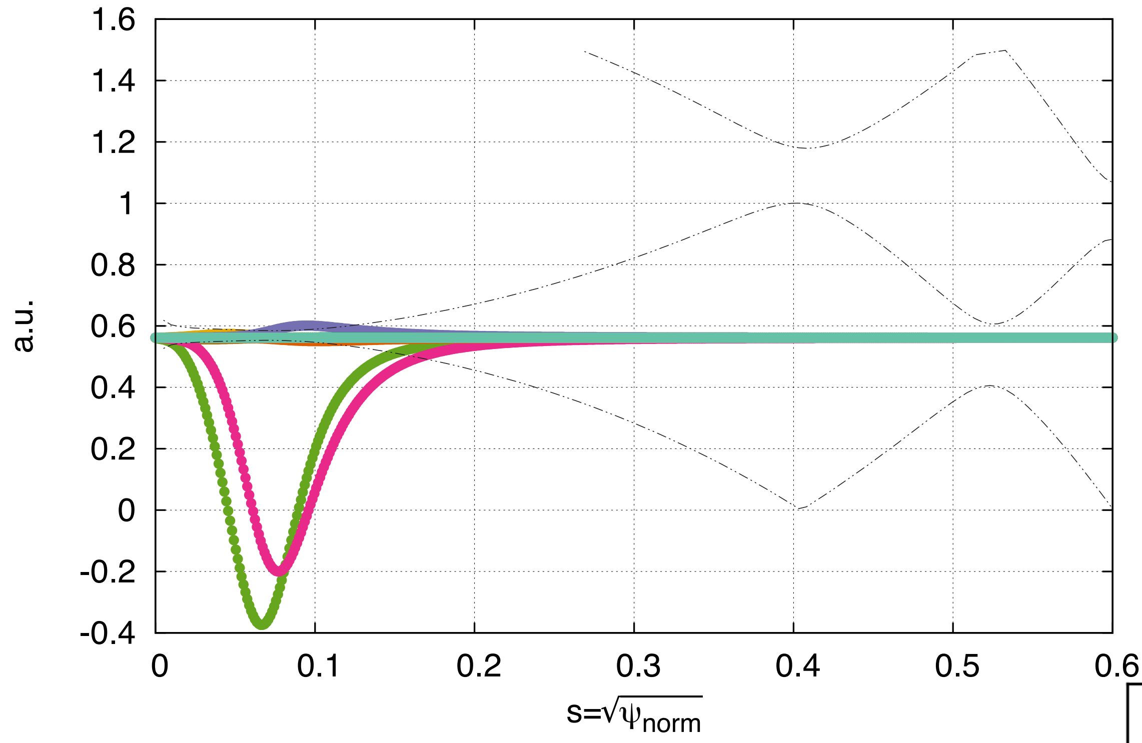
Two relevant interactions in very narrow resonances

Corresponding orbits are non-standard and close to the axis





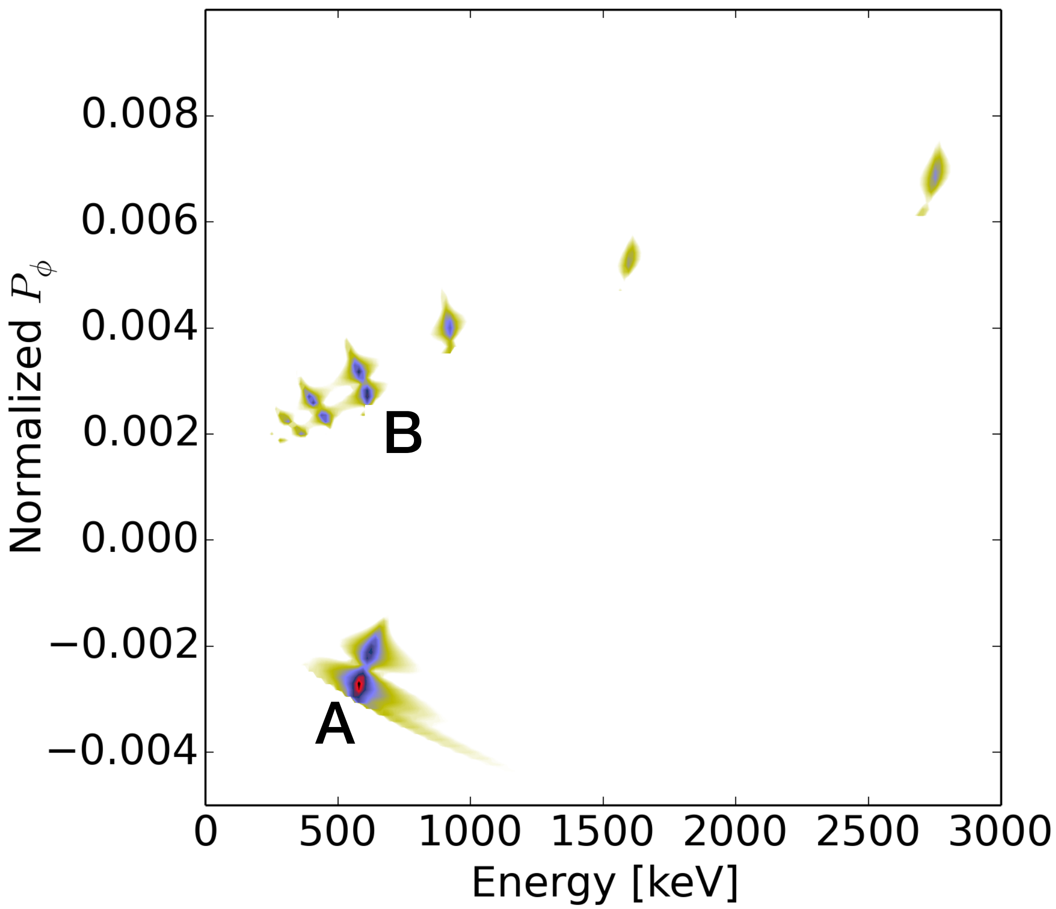
Tornado mode interacts with two broader resonances

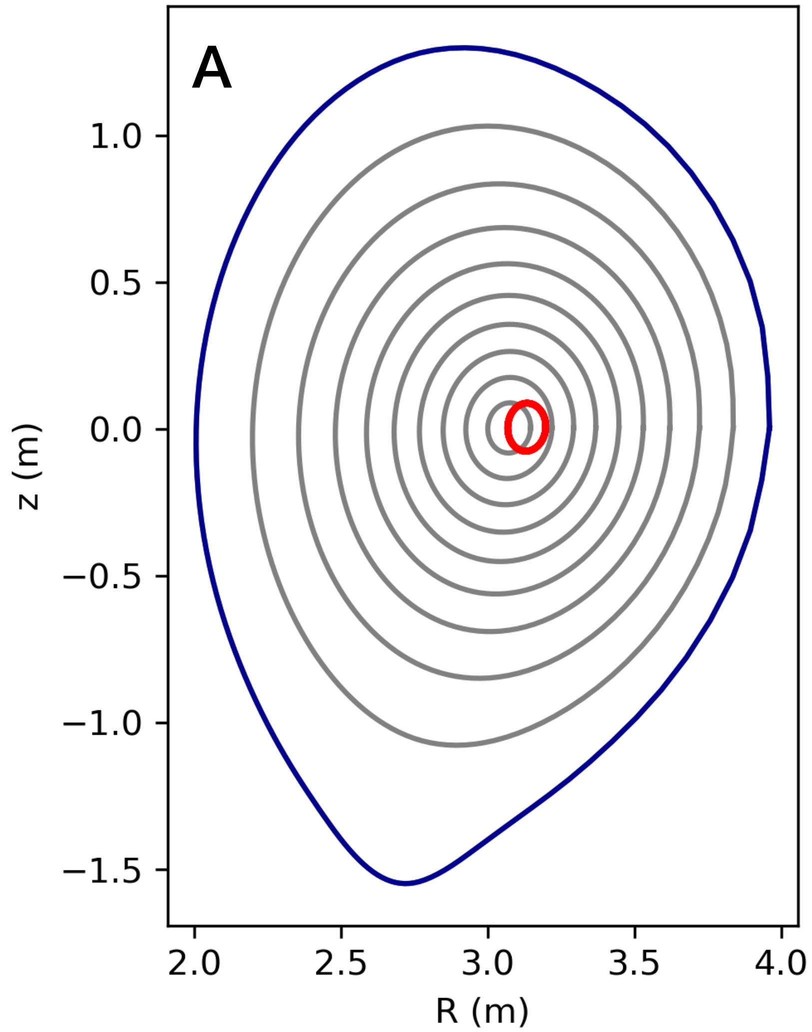


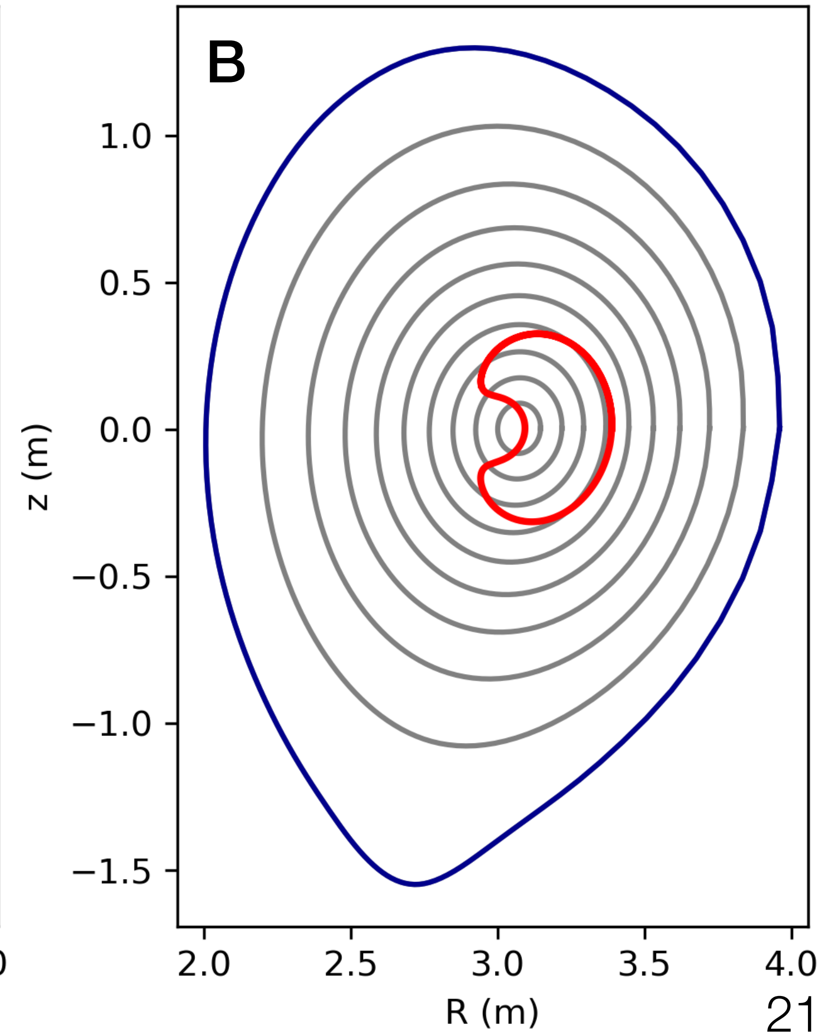
ω/ω_A=0.562 → f≈203kHz

Two relevant interactions in broader resonances

Corresponding orbits are non-standard and close to the axis







Energetic minority drives the mode

Mode Type	q_0	ω/ω_A	γ/ω (%)
Low frequency AC	0.94	0.254	0.196
High frequency AC	0.88	0.541	0.0168
Tornado	0.87	0.562	3.07

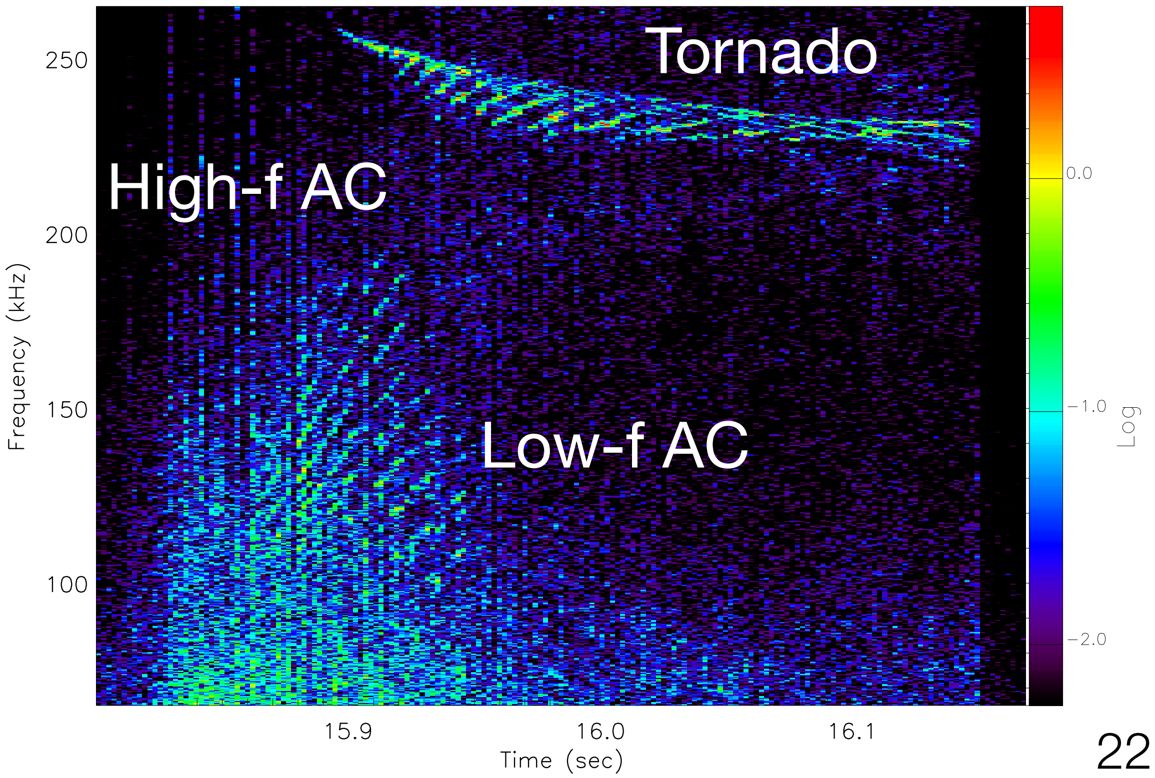
Intermediate drive in low frequency AC phase

Drive is weaker in high frequency AC phase

Drive is stronger during tornado phase

Mode experiences drive throughout its evolution

Lower drive in high frequency AC may explain why a gap is observed between ACs and tornado modes



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Conclusions

We have numerically reproduced mode evolution from the base of grand cascade to TAE frequency range followed by transition to tornado mode

Fast upward sweeping modes were identified as highly localised near-axis AC made possible due to the very flat q-profile

AC → tornado mode transition occurs when $q_0=q_n=(n-1/2)/n$, which we propose to be used as an MHD spectroscopy technique to track q-profile evolution post-sawtooth crash. Only magnetics data is sufficient.

Throughout plasma evolution the mode is excited by energetic minority species, though high frequency AC phase experiences weaker drive which may explain gap between ACs and tornado modes observed in diagnostics