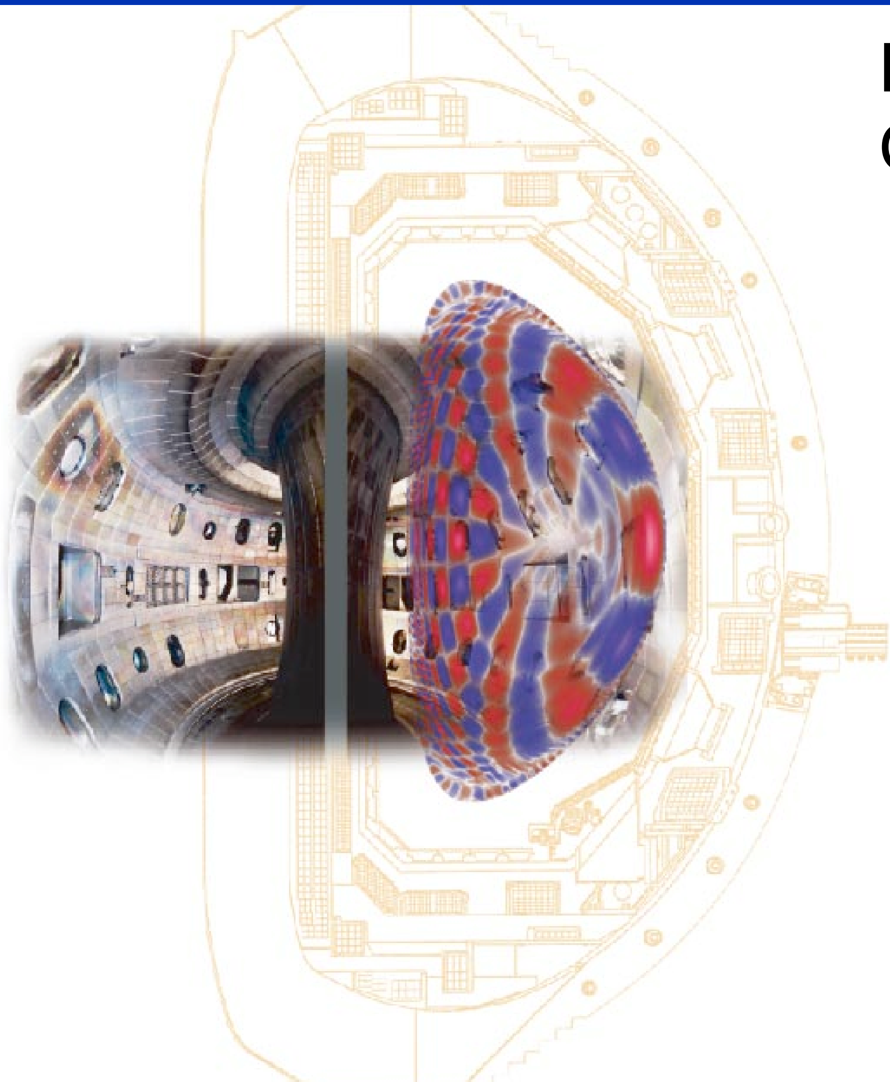
Interpretation of Core Localized Alfvén Eigenmodes in DIII−D and JET Reversed Magnetic Shear Plasmas



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Good progress has been made on the validation of reversed shear Alfvén eigenmode theory theory against new experimental data

- Validation of the NOVA−K code for normal shear scenarios has been successful

N.N. Gorelenkov et al. Phys. Plasmas 11 (2004) 2586

- We want to validate the NOVA−K code also for Advanced Tokamak (AT) regimes so that we can make reliable predictions for AT regimes on ITER

Advanced Tokamak scenarios use non−monotonic magnetic shear configurations

- Such a benchmarking has become possible because of new measurements of Reversed Shear Alfvén Eigenmodes (RSAE) on DIII−D and JET

RSAEs are able to enhance fast−ion transport and degrade the plasma performance

Good progress has been made on the validation of RSAE theory against new experimental data

- Many core−localized modes are observed in JET and DIII−D AT regimes with similar characteristics
- Modeling with NOVA−K allows the identification of RSAEs in AT regimes
  - NOVA−K is able to reproduce the frequency of low−n modes observed on JET
  - The localization of high−n modes on DIII−D is corroborated with NOVA−K calculations
- High−n toroidal mode numbers are inferred for core localized RSAEs in DIII−D from their Doppler shifts
- Investigate the RSAE stability with the NOVA−K code and obtain some first results for AT regimes

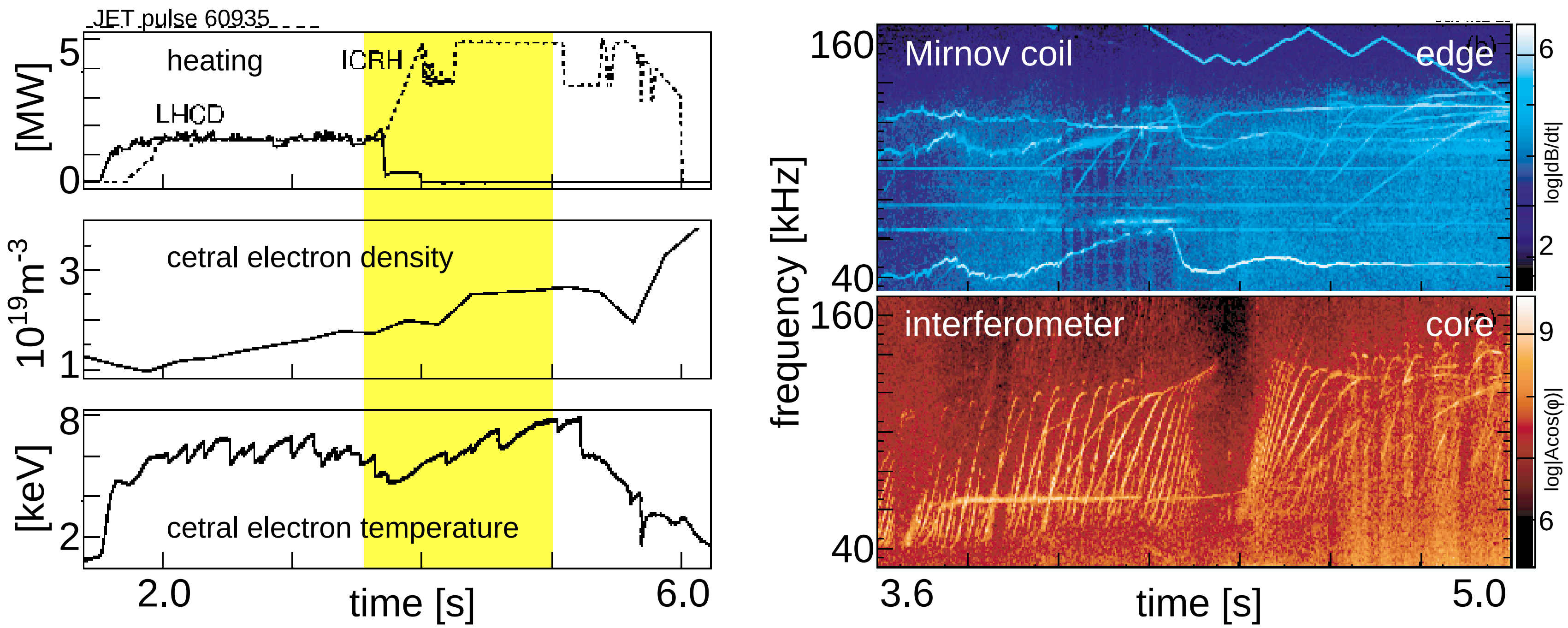
Many core–localized modes

are observed in JET and DIII–D

AT regimes

with similar characteristics

A multitude of modes is observed in ICRF heated plasmas on JET

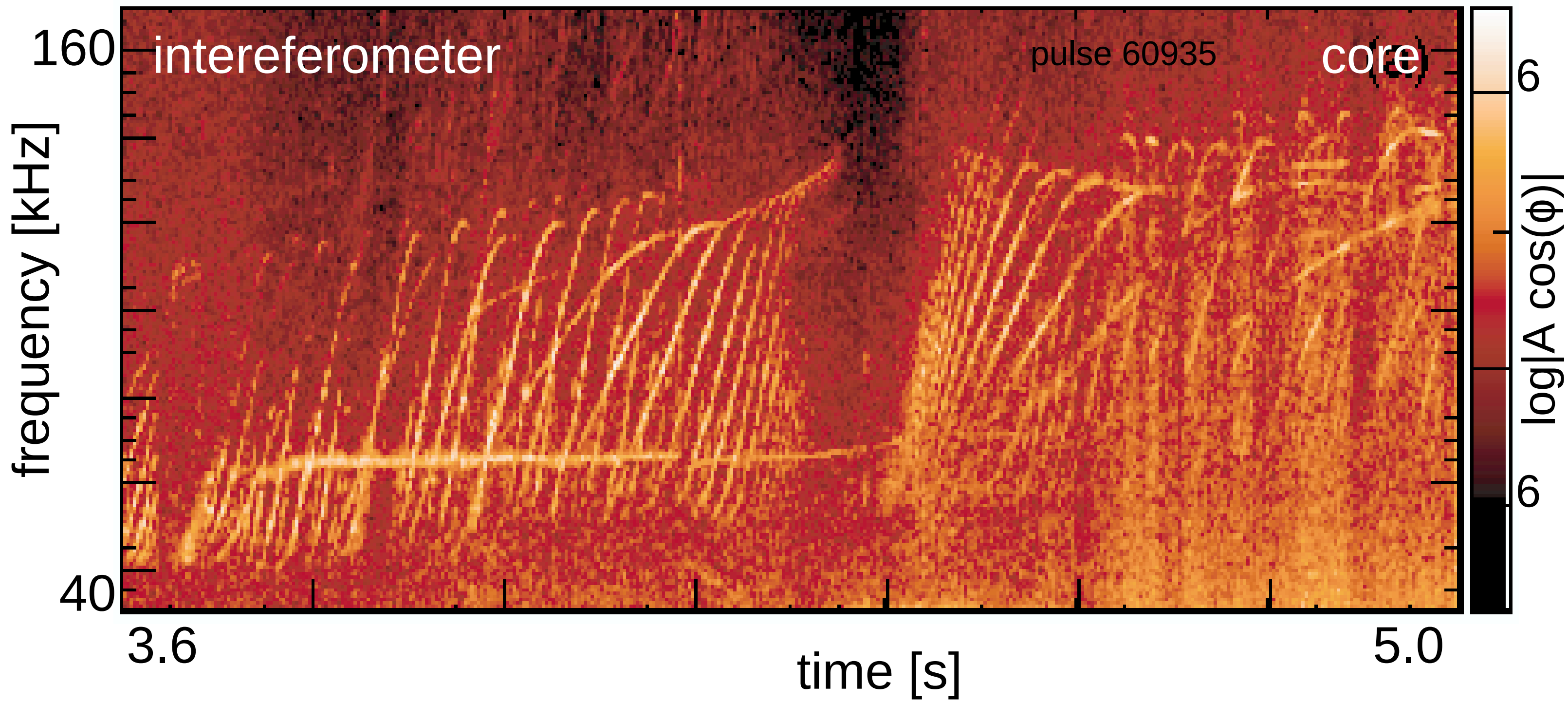


- Reversed shear is created with a combination of LHCD and ICRH
  - no momentum input so very low toroidal plasma rotation

Modes measured from the start of the main ICRH heating (yellow box)
  - A wealth of modes is observed on the microwave interferometer
  - Only a few of those modes appear in the Mirnov coil signal

S.E. Sharapov et al. Phys. Rev. Lett. 93 (2004) 165001

The modes are characterized by frequency chirping

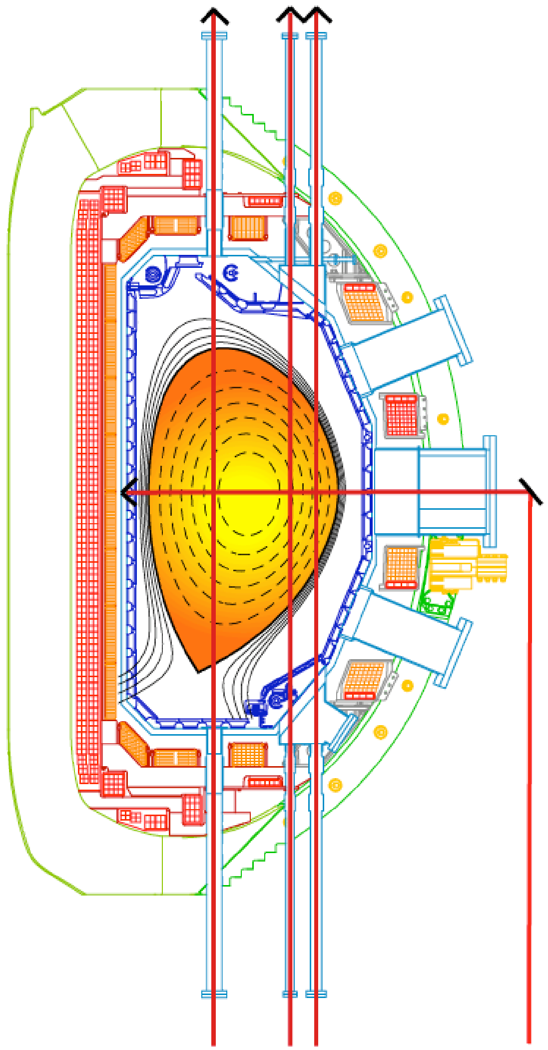


- The observed modes are characterized by:
  - frequency chirping on a 10 to 500 ms time scale
  - localized in the plasma core

These modes were called "Alfvén cascades" in JET

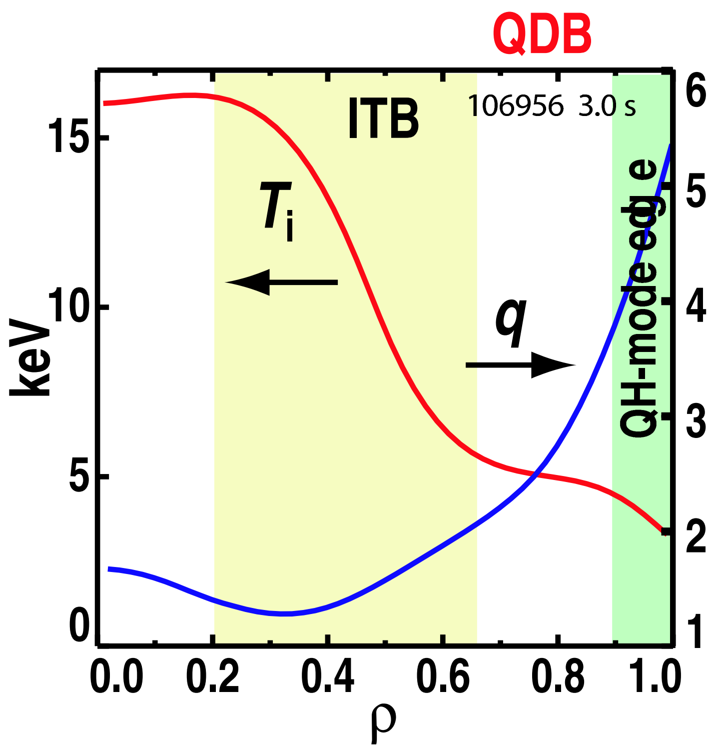
Many of the fluctuation diagnostics on DIII−D have enabled new measurements of core−localized modes

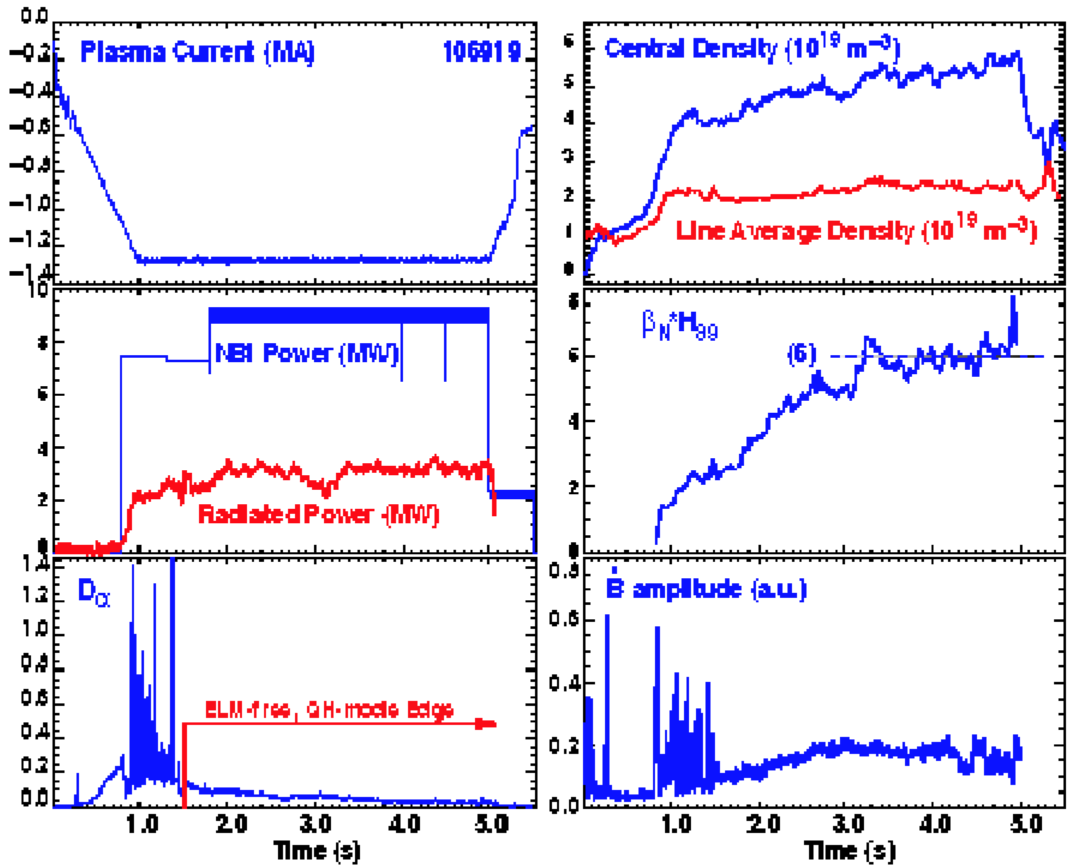
- Beam−emission spectroscopy (BES) provides measurements of radial localized density fluctuations band width: 0.5 MHz
- Four chord CO_2 interferometer provides measurements of line integrated density fluctuations band width: < 1.6 MHz
- Far infrared scattering (FIR) provides measurements of line integrated low−k ($k<1\ cm^{-1}$) density fluctuations band width: ~10 MHz
- q−profiles are measured with the Motional Stark Effect (MSE) diagnostic



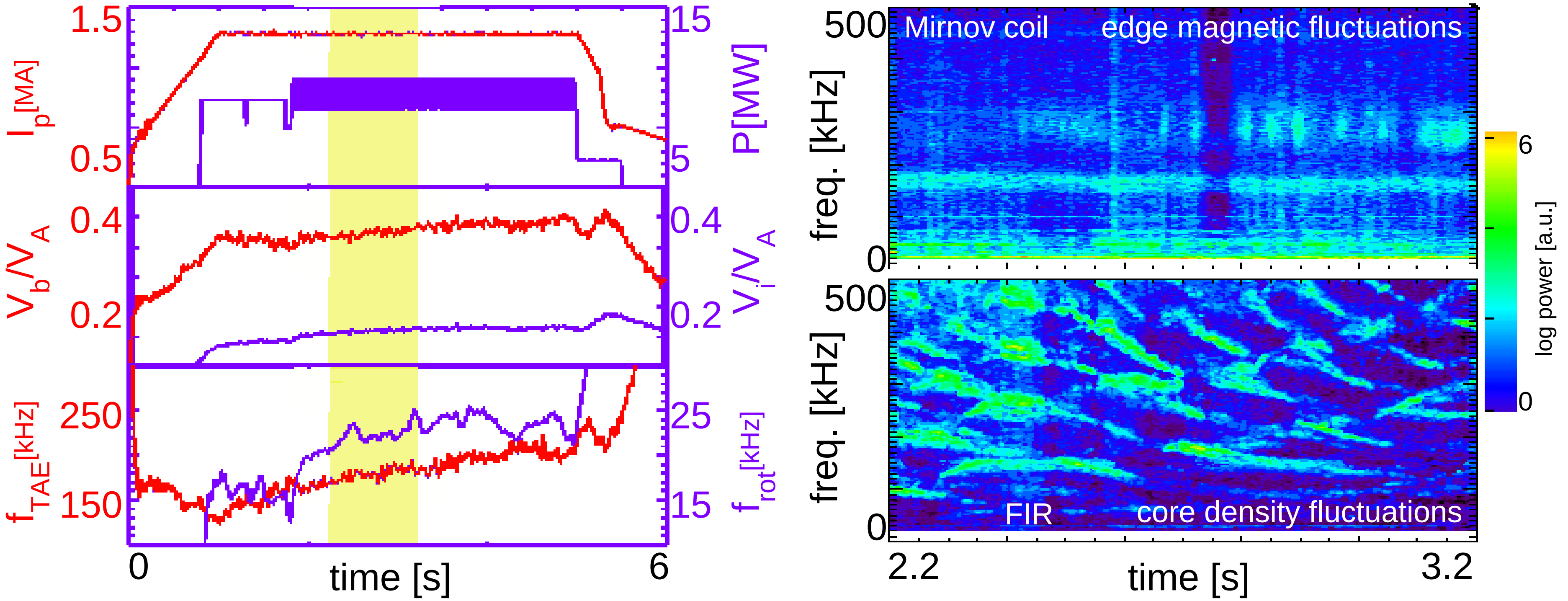
Quiescent Double Barrier plasmas combine ELM−free edge plasma (QH−mode) with core transport barrier (ITB)

- Sustained ITB plasmas with performance above conventional H−mode
- Obtained with counter−NBI





Core−localized frequency chirping modes are also observed on DIII−D



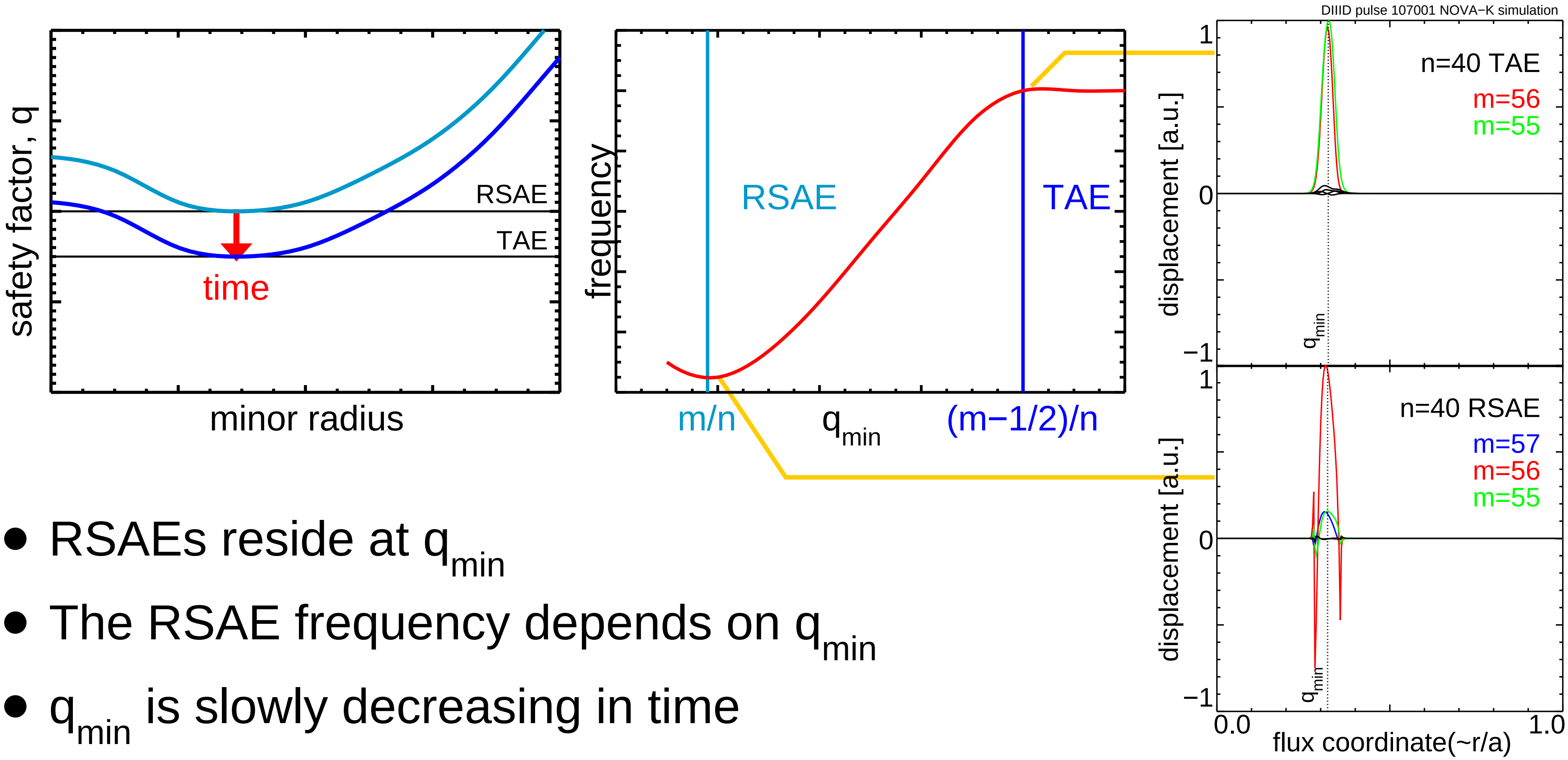
- Reversed shear is created with a neutral beam injection (NBI)
  - NBI is not balanced which leads to rapid toroidal plasma rotation
- Modes measured during the steady state phase (yellow box)
  - Many modes are observed on the far infrared scattering system
  - None of those modes appear in the Mirnov coil signal

Modeling with NOVA−K allows the identification of RSAEs in AT regimes

NOVA−K is used to identify RSAEs in JET and DIII−D

- NOVA−K uses ideal MHD theory to calculate eigenmodes of tokamak plasma
- Kinetic extensions are used for the stability analysis:
  - ion and electron Landau, electron collisional, continuum, radiative damping
  - non−adiabatic fast−ion response
- Input to NOVA−K:
  - full plasma geometry
  - experimental profiles (pressure, q, density, temperatures)
  - toroidal mode numbers
- Output from NOVA−K:
  - Spectrum of eigenfrequencies of the modes
  - Radial structure of the eigenmodes
  - damping and growth rates of the modes

RSAEs reside at q_{min} and evolve when q_{min} changes



- RSAEs reside at q_{min}
- The RSAE frequency depends on q_{min}
- q_{min} is slowly decreasing in time
- RSAE frequency chirps up to the TAE frequency

$$\omega_A = K_{\parallel} V_A = \frac{(m - n\,q)}{q\,R} V_A$$

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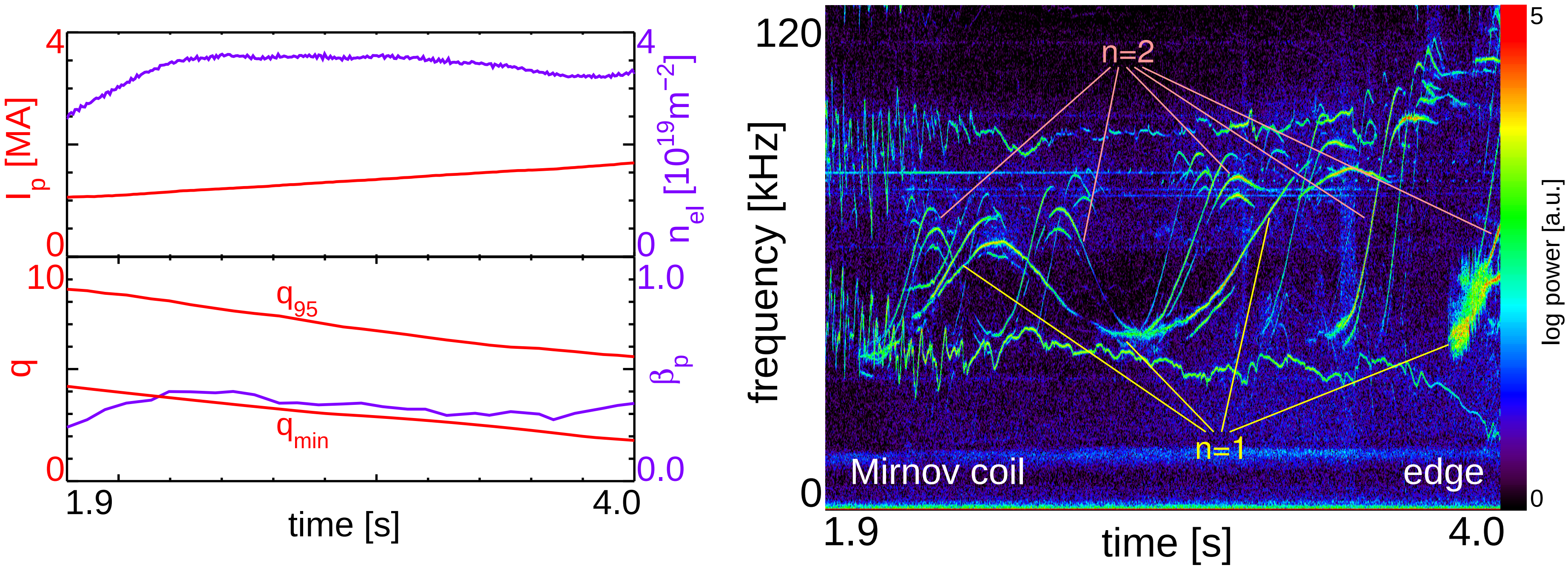
NOVA–K is able to reproduce the frequency of low–n modes observed on JET

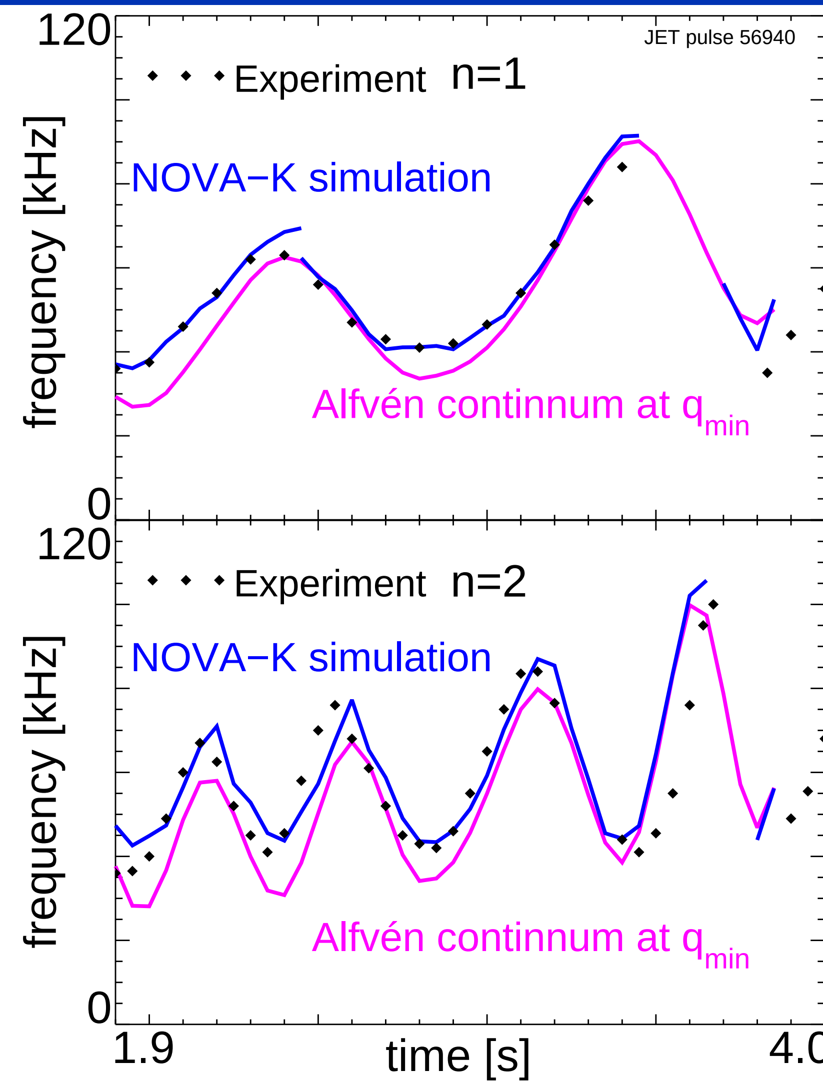
RSAEs are observed on Mirnov coils in JET



- Toroidal mode numbers are determined unambiguously from Mirnov coil data during the current ramp−up phase
- off−axis LHCD and ICRH create the reversed magnetic shear
- minimum of the q−profile is decreasing

Simulated frequency agrees very well with experiment

- The NOVA−K simulated frequency agrees very well with the measured n=1 and n=2 RSAE frequency
- The mode frequency follows the Alfvén continuum at q_{min}
- Coupling to the geodesic acoustic mode included



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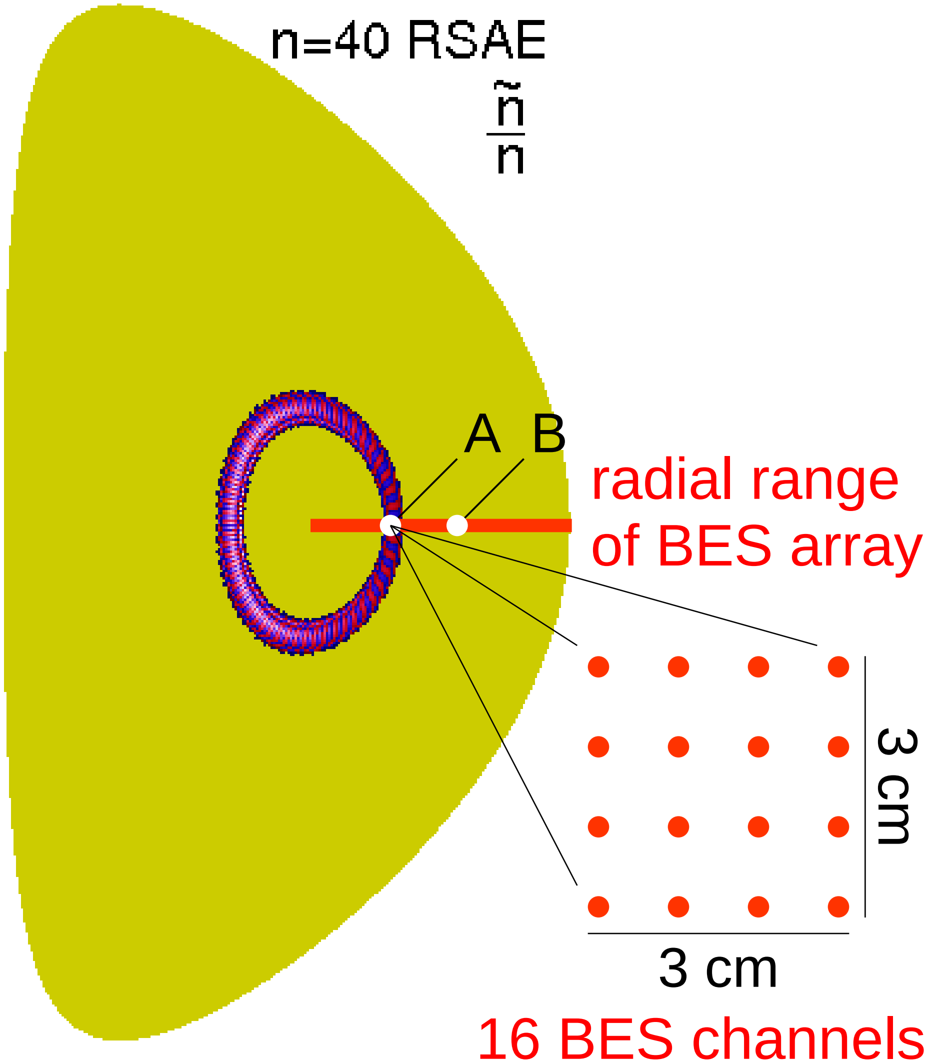
The localization of

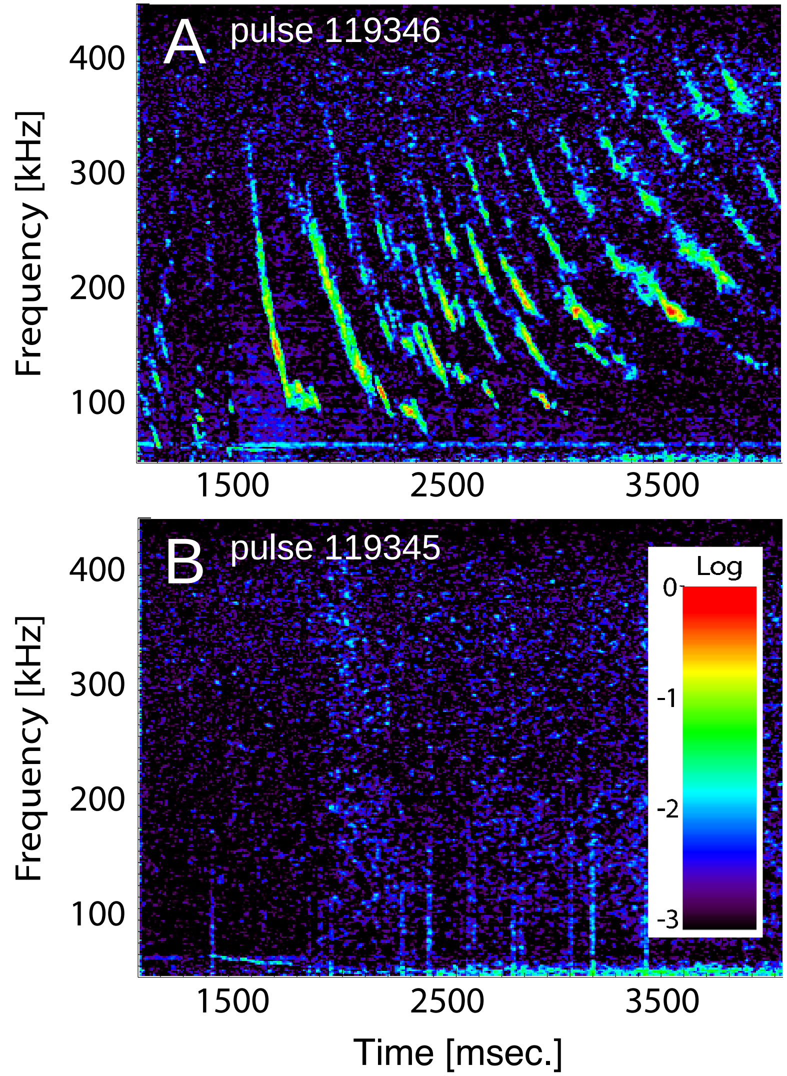
high–n modes on DIII–D

is corroborated with

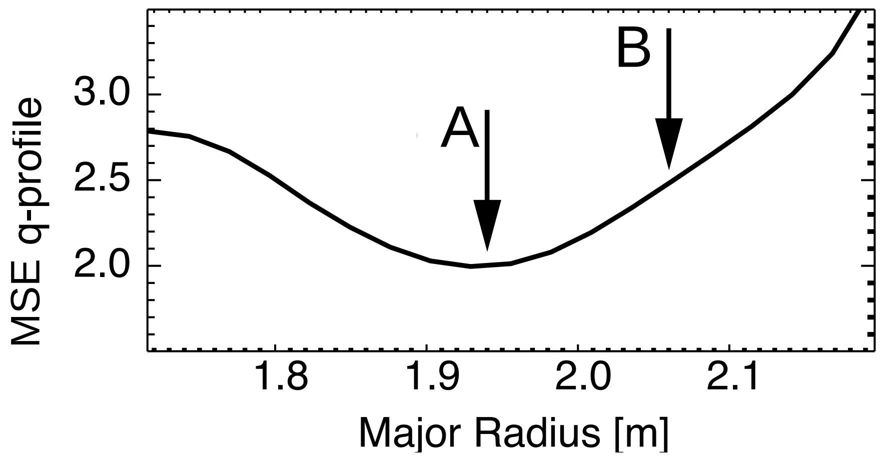
NOVA–K calculations

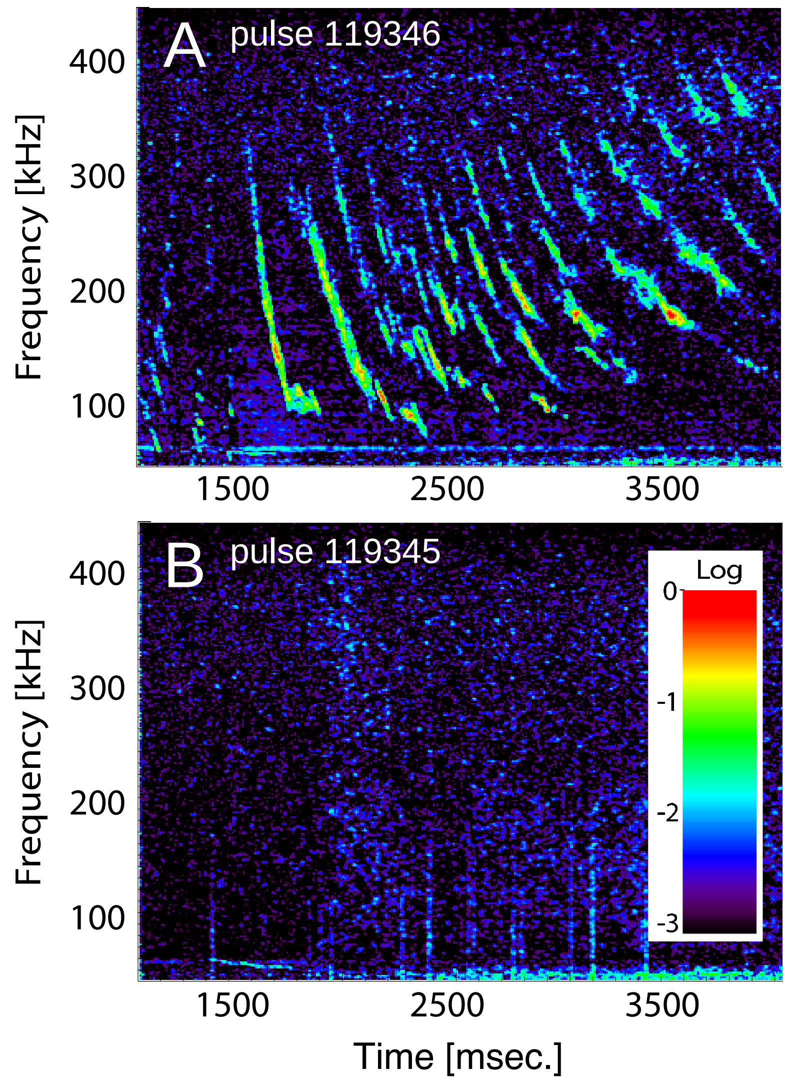
BES observes highly localized RSAEs





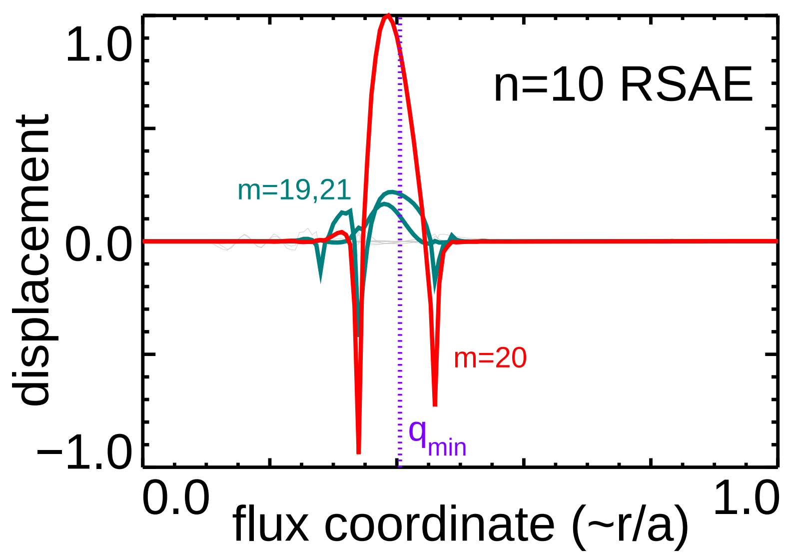
BES density fluctuations are localized near q_{min}

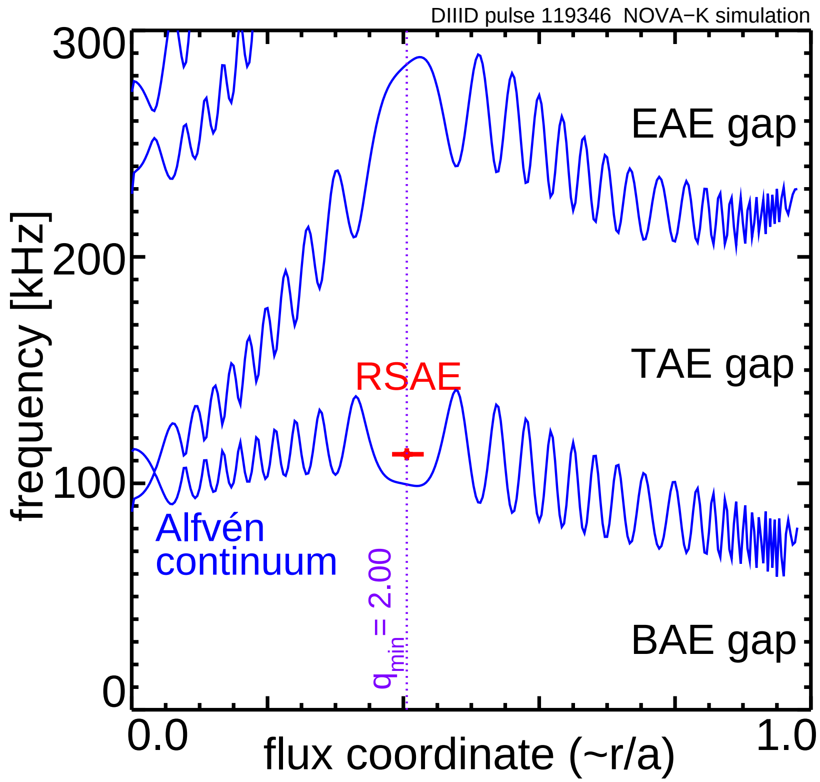




- MSE measurements reveal that density fluctuations are highly localized near q_{min}
- The position of q_{min} does not change in time
  only its value decreases in time

NOVA−K confirms that RSAEs are localized at q_{min}





- In the NOVA−K simulations it is found that RSAEs are localized at q_{min}
- The localization increases with n

The localization of the modes found in the DIII−D experiments is compatible with the localization for RSAEs found with NOVA−K

High−n toroidal mode numbers are inferred for core localized RSAEs in DIII−D from their Doppler shifts

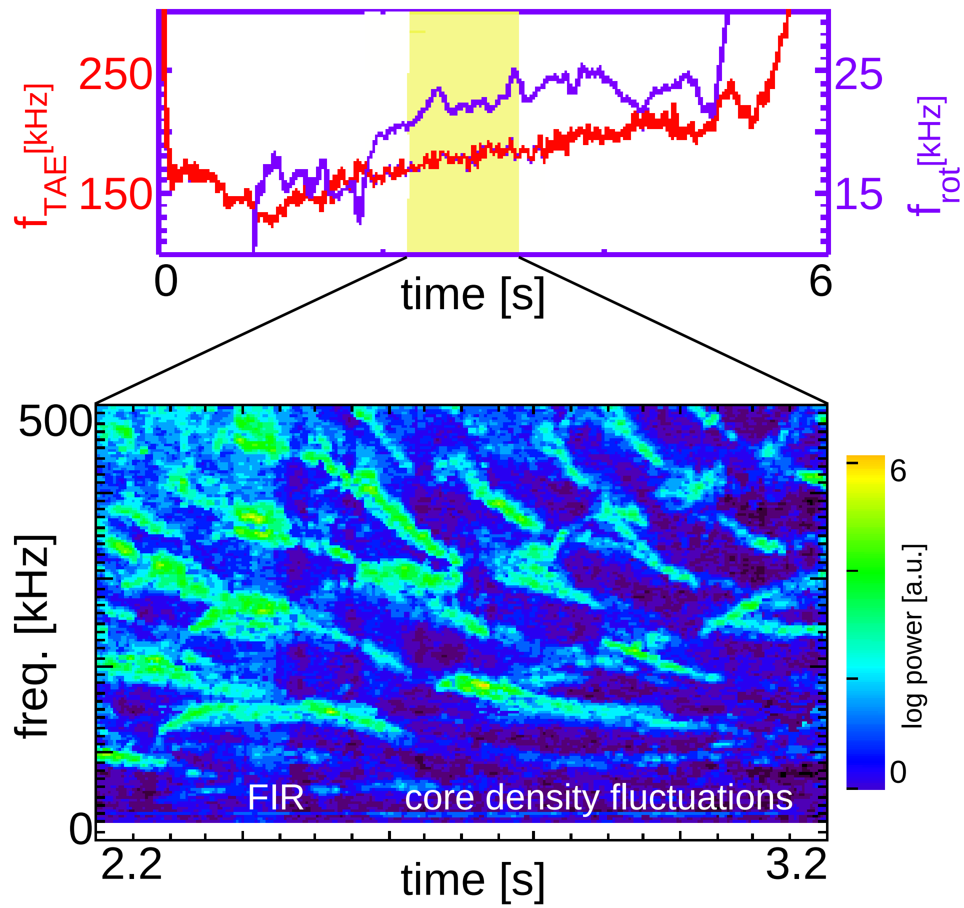
For high−n modes the Doppler shift is the main contributor to the observed frequency

- Measurements of the toroidal plasma velocity show that the plasma is rotating at about
  23 kHz

- This is more than 10% of the Alfvén velocity

- The Doppler shift is
  $n * f_{Dop}$

n toroidal mode number
f_{Dop} toroidal rotation frequency



Rapid counter rotation changes the direction of the frequency chirp for high−n modes

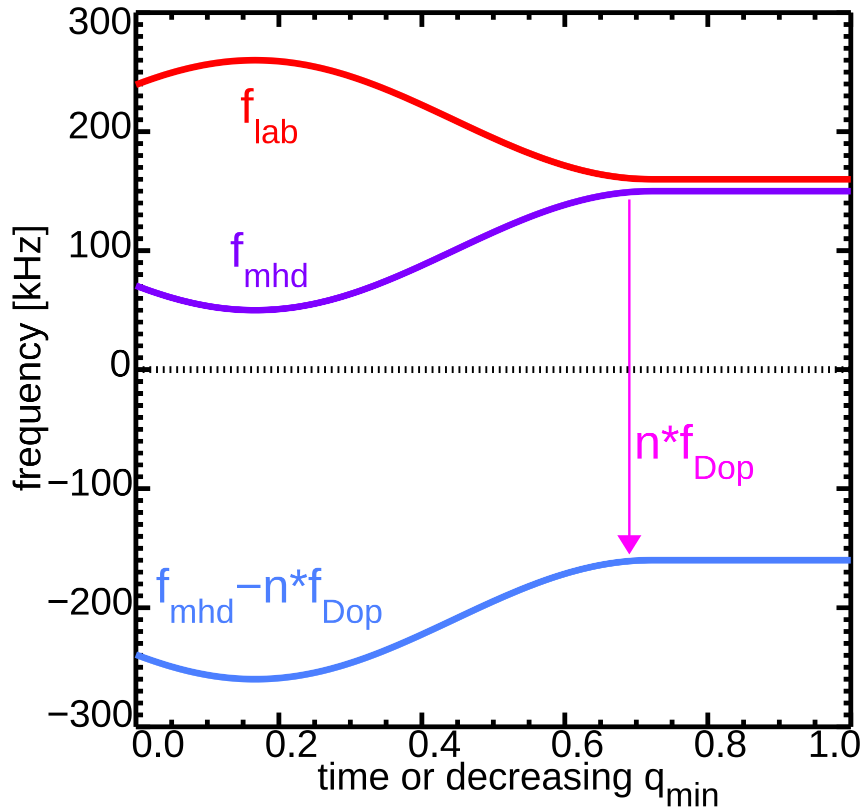
Theory: modes chirp up from minimum RSAE to TAE frequency
Experiment: frequency chirps down

This apparent down chirp is due to the large plasma rotation

1. frequency in plasma frame: mode chirps up

2. frequency in laboratory frame: $f_{lab} = | f_{mhd} - n{*}f_{Dop} |$

- In the current DIII−D experiments mode propagation is opposite to the plasma rotation



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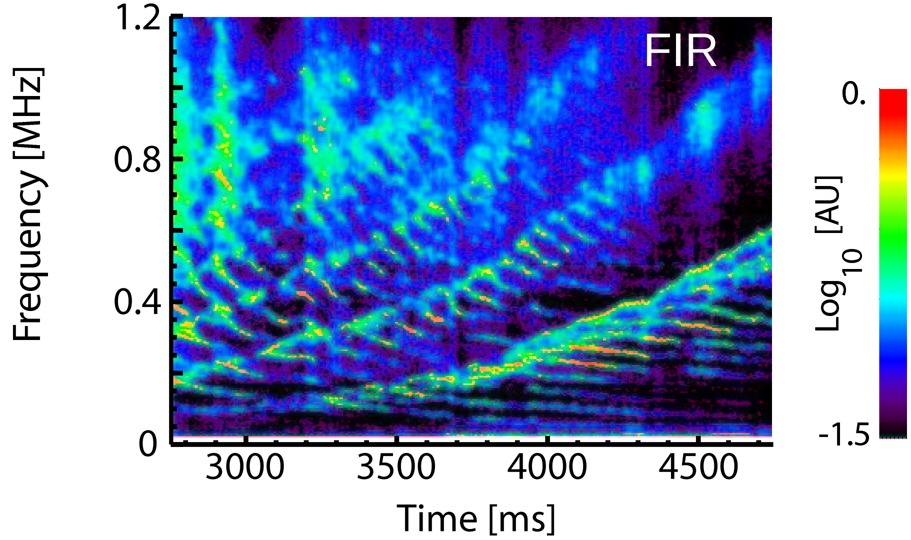
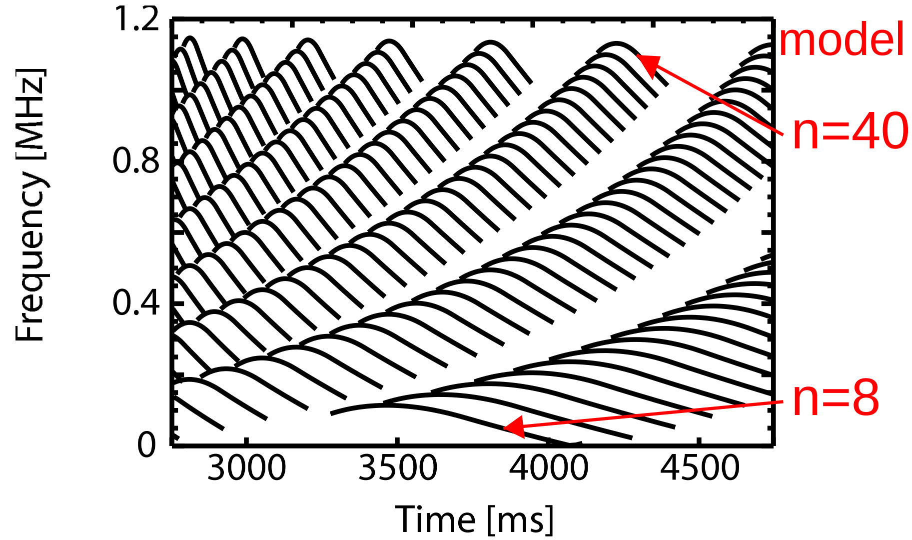
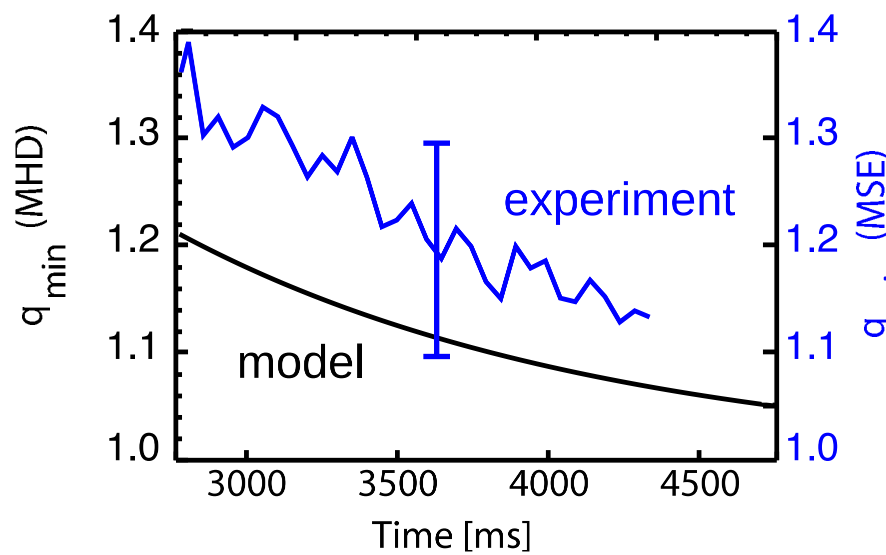
Frequency evolution is accurately reproduced from the RSAE model and the Doppler shift





- Bands of modes appear due to plasma rotation
- Comparison between experiment and simulation reveals modes with mode numbers up to n=40



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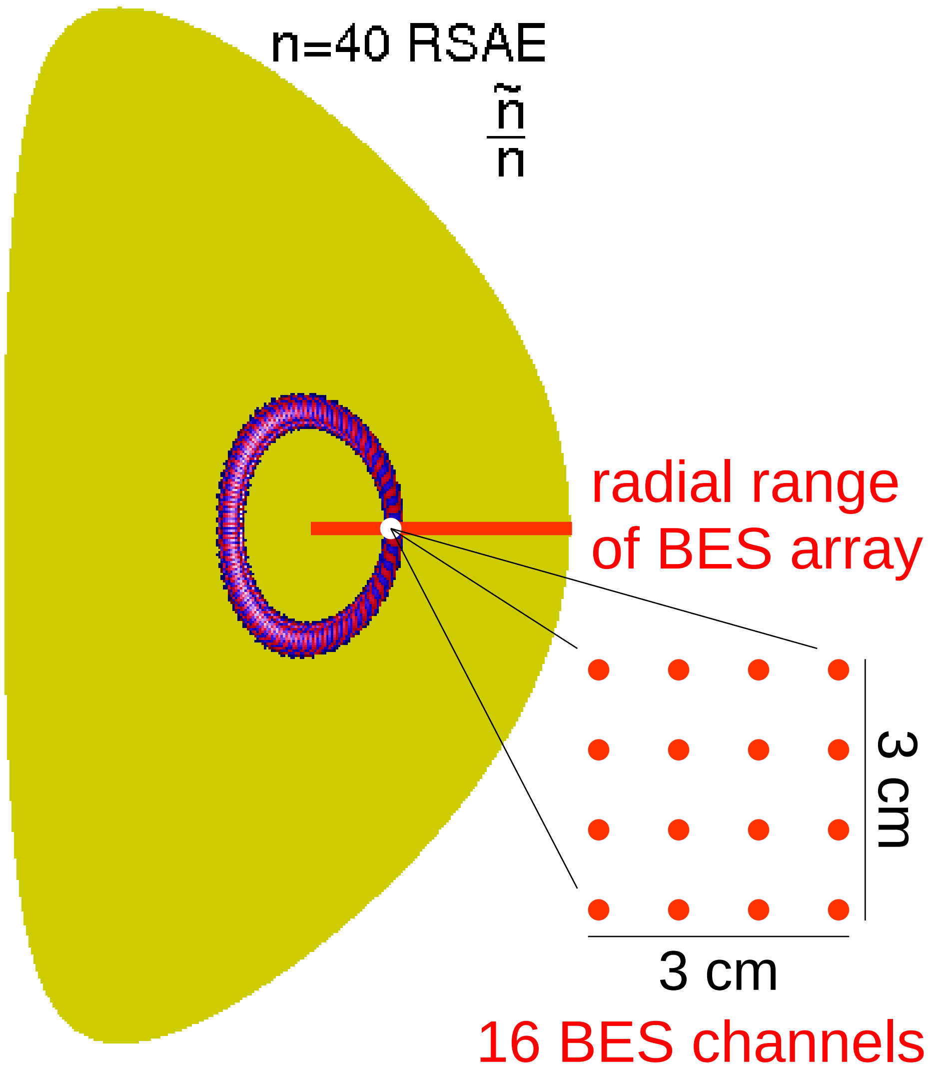
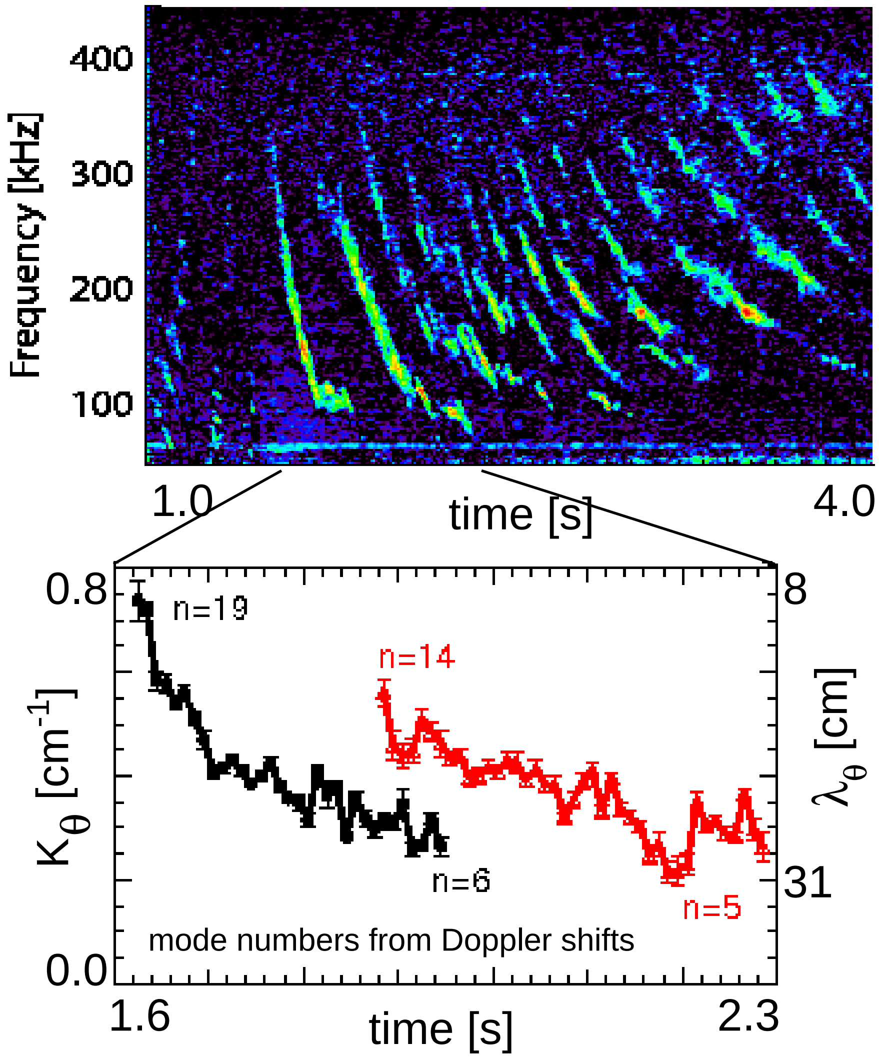
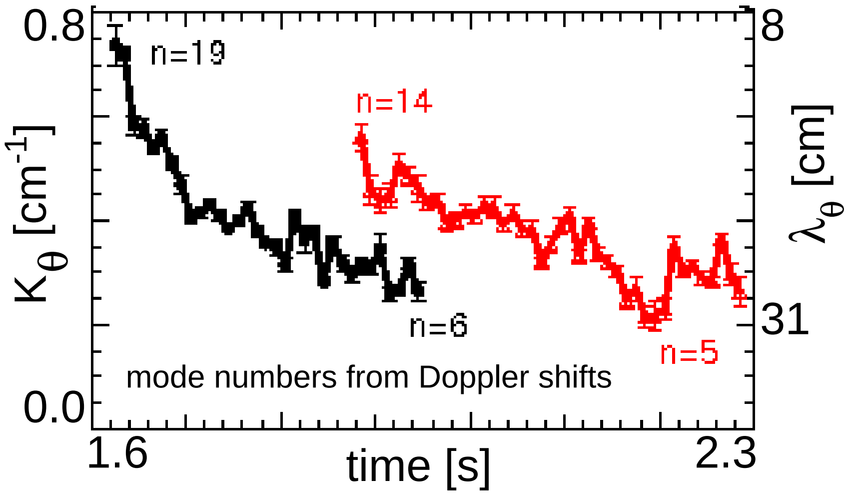
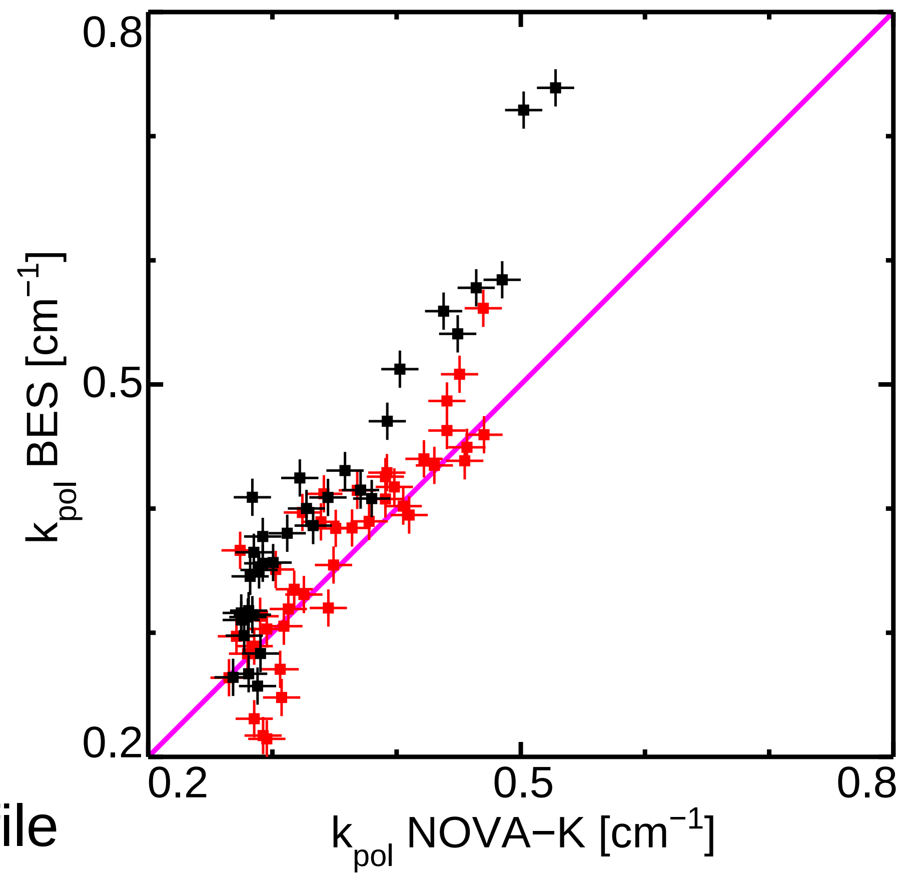
The high toroidal mode numbers are confirmed from poloidal wave number measurements





BES and MSE measurements in combination with NOVA−K gives poloidal and toroidal mode numbers





- NOVA−K shows: k_θ varies with distance in poloidal direction
- BES and NOVA−K k_θ agree well
- NOVA−K uses experimental q−profile q−profile from MSE, so:
  - Poloidal and toroidal mode numbers are known for core−localized RSAEs

Investigate the RSAE stability with the NOVA−K code

first results for AT regimes

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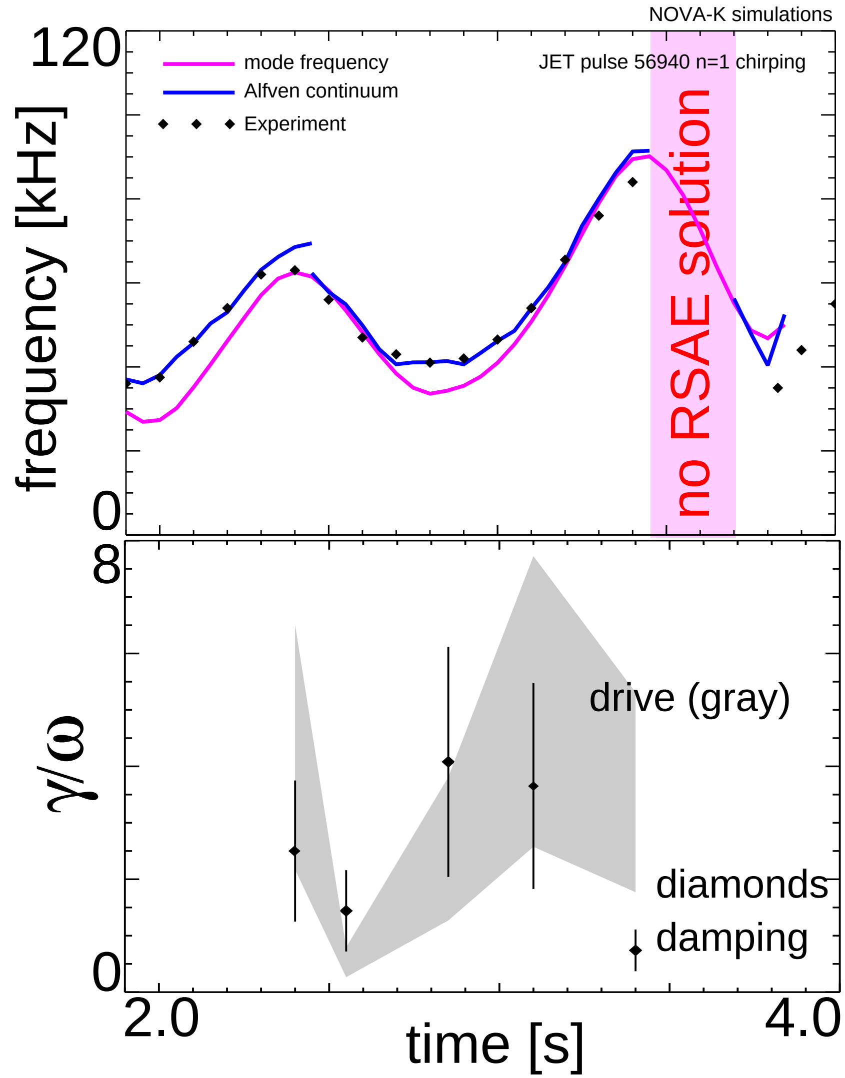
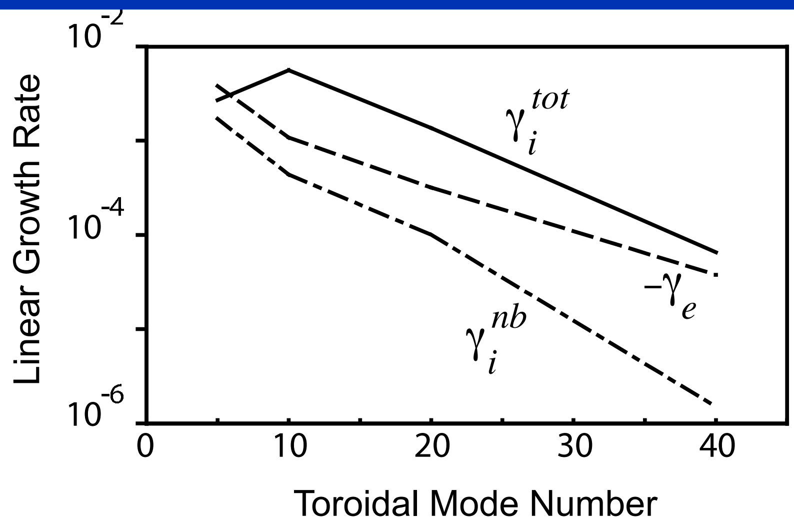
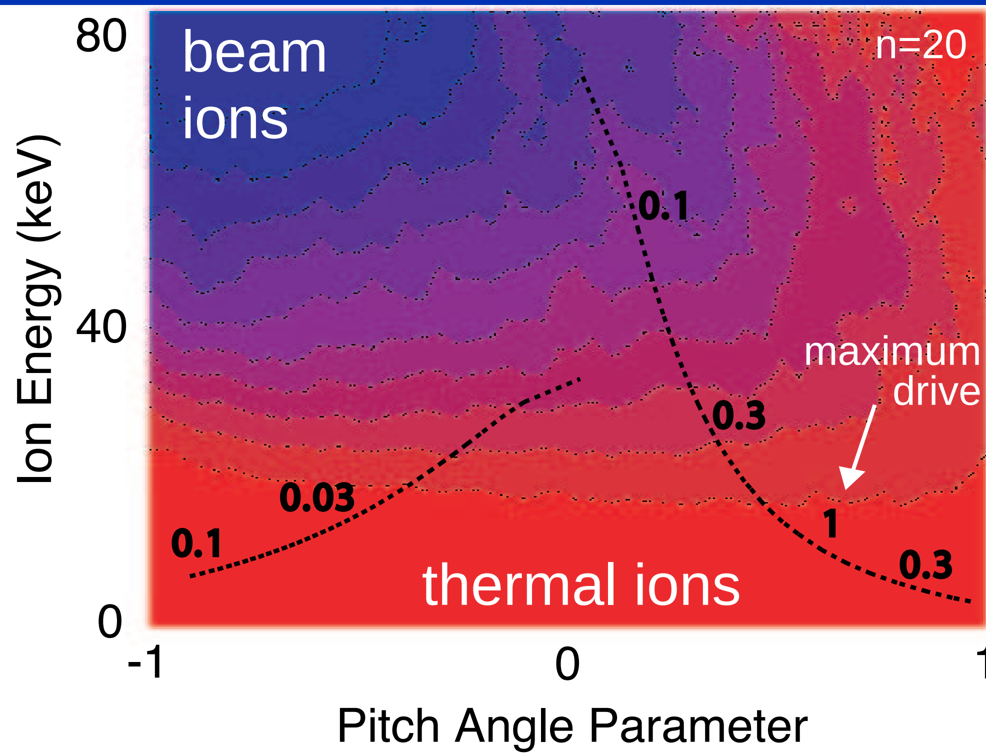
ICRH generated ions excite RSAEs on JET

- The RSAEs in JET are driven unstable by ICRH ions
  ion tail temperature ~140 keV
- Drive and damping vary with mode evolution
- TAE stabilization mechanisms:
  Landau damping
  radiative damping
- RSAE stabilization mechanism:
  continuum damping



NOVA−K suggests that RSAEs interact strongly with thermal ions in DIII−D





γ_i^{tot} drive of all the ions
γ_i^{nb} drive of beam ions only
$-\gamma_e$ damping, mainly thermal electrons

- NBI is insufficient to drive the RSAEs
- The dominant resonances that excite the RSAEs in DIII−D are in the tail of the thermal ion distribution
- The main damping mechanism is electron Landau damping

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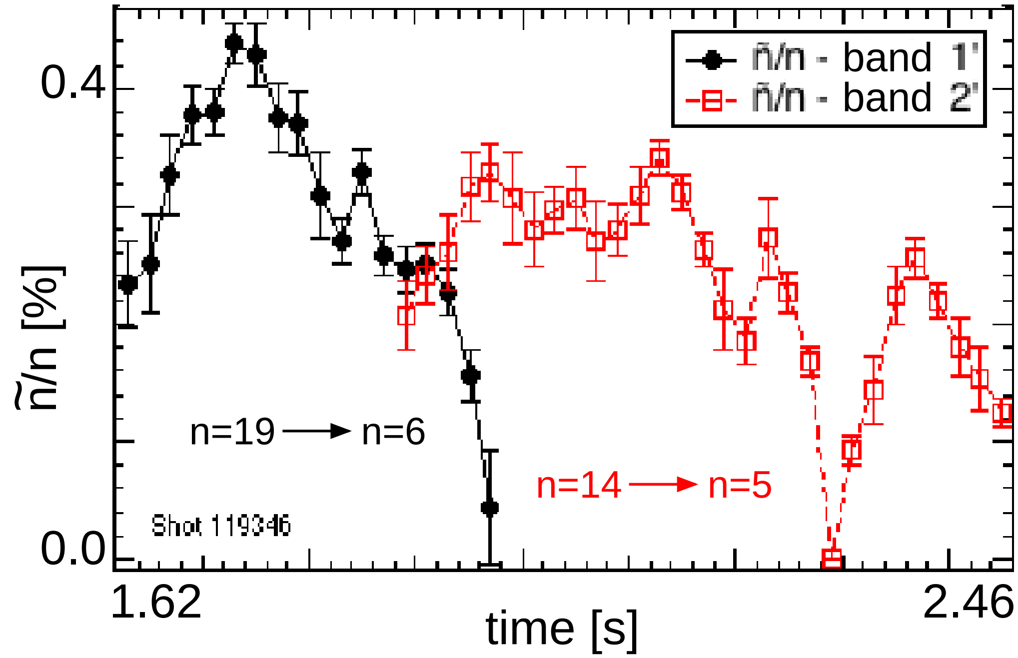
RSAE induced fast−ion transport can be studied because fluctuation levels and mode structures are known

- BES measures saturated density fluctuation levels

  for a single RSAE:
  $\tilde{n}/n = 0.3\%$

- It then follows from NOVA−K that for a single RSAE:

  $\tilde{B}/B = 0.03–0.06\%$



- The next step is to model fast−ion transport induced by the RSAEs
  - the mode structures are known
  - the fluctuation levels are known

- The next challenge for theory development is to explain the observed mode saturation levels

Summary and outlook

- New measurements of core localized RSAEs on DIII−D and JET have enabled a detailed comparison with theory
- These RSAEs have been studied validate the NOVA−K code
  - reproducing the observed RSAE frequencies
  - calculating the observed mode localization
  - giving reasonable growth and damping rates
- NOVA−K suggests that a major contribution to the drive of the RSAEs in DIII−D comes from thermal ions
- This improved understanding leads to more reliable extrapolations for advanced tokamak scenarios on ITER
- The next challenges are to improve the stability analysis and the non−linear mode saturation mechanisms for predicting fast ion losses