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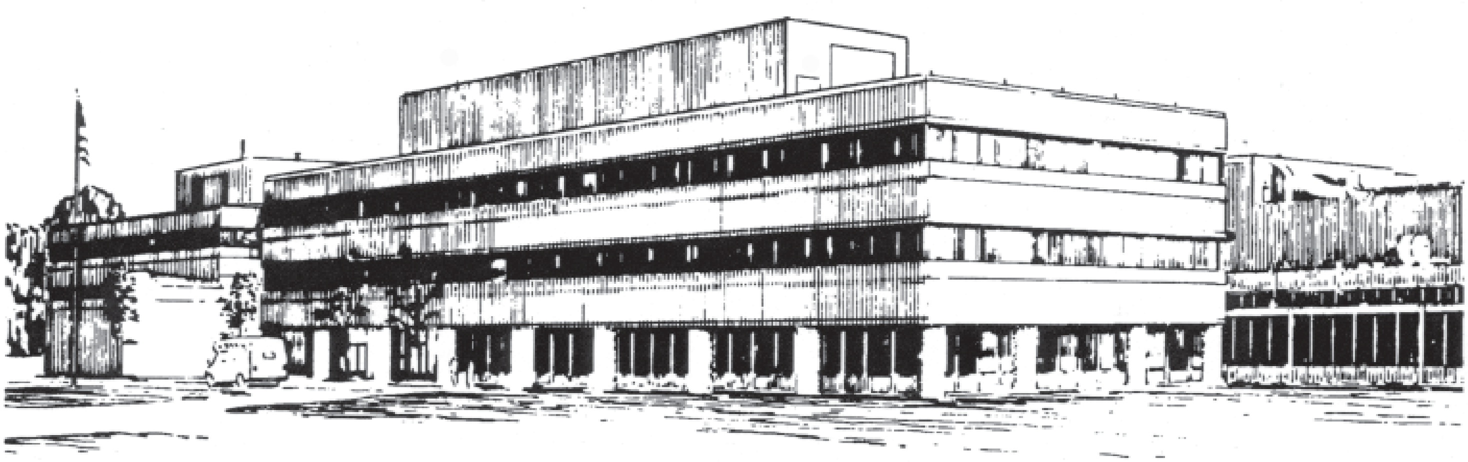
PRINCETON PLASMA PHYSICS LABORATORY



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A New Interpretation of Alpha-Particle-Driven Instabilities in Deuterium-Tritium Experiments on the Tokamak Fusion Test Reactor

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Abstract

The original description of alpha particle driven instabilities in the Tokamak Fusion Test Reactor (TFTR) in terms of Toroidal Alfvén Eigenmodes (TAEs) remained inconsistent with three fundamental characteristics of the observations: (i) the variation of the mode frequency with toroidal mode number, (ii) the chirping of the mode frequency for a given toroidal mode number, and (iii) the anti-ballooning density perturbation of the modes. It is now shown that these characteristics can be explained by observing that cylindrical-like modes can exist in the weak magnetic shear region of the plasma that then make a transition to TAEs as the central safety factor decreases in time.

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In a magnetic confinement fusion reactor, the nuclear interaction of deuterium and tritium (D-T) releases a large quantity of energy in the form of 14 MeV neutrons and 3.5 MeV alpha particles. The neutrons escape from the magnetic field and are captured by a lithium blanket used to generate electricity and breed tritium. The alpha particles are confined by the magnetic field, imparting their energy to the D-T plasma and thus sustaining the thermonuclear burn. The 3.5 MeV alpha particles are far more energetic than the thermal ions and their birth velocity is sufficient to excite Alfvén instabilities. The Alfvén modes perturb the alpha particle orbits and may even expel alpha particles before they deposit their energy to the plasma. In addition, the premature loss of alpha particles may cause damage to plasma-facing components. These concerns motivate the study of alpha particle driven instabilities as one of the key scientific objectives of the fusion program.

Deuterium-tritium experiments on the Tokamak Fusion Test Reactor (TFTR) provided the very first opportunity to investigate the excitation of Alfvén waves by fusion alpha particles under reactor relevant conditions [1, 2]. The original observation of alpha particle driven instabilities in TFTR was reported as evidence for the existence of alpha-particle-driven Toroidal Alfven Eigenmodes (TAEs) [3]. TAEs are resonant cavity modes in the toroidal plasma residing within frequency gaps in the shear Alfvén continuum spectrum and they were predicted to be susceptible to excitation by fusion alpha particles [4].

Figure 1 shows data for a typical TFTR D-T discharge in which high frequency magnetic oscillations were observed in the after glow of the discharge. The afterglow is the period of time following the termination of intense neutral beam heating. These oscillations were observed in discharges where the penetration of the inductively driven current into the plasma core was delayed by preheating the plasma during the period where the current is ramping up [5]. The delayed current penetration creates regions of weak central magnetic shear, which is anticipated to occur in future steady state fusion reactors with large non-inductive current drive. The mode frequencies observed on external magnetic probes were consistent with theoretical calculations for TAEs. However, internal measurements of the same modes exhibited anomalies in frequency and mode structure that were in conflict with TAE theory and these anomalies remained unreconciled until now. Here we report the reconciliation.

The frequency anomalies in the TFTR data can be seen in Figure 2 which shows the temporal evolution of the mode frequency with time as observed on external magnetic probes (red) and internal reflectometer measurements (blue). The external magnetic measurements are performed with a simple pick-up loop located on the outer midplane of the toroidal device. The internal reflectometer signals are obtained from the change of the phase of a microwave beam reflecting from the core of the plasma [6]. Fluctuations in the plasma density are revealed by phase changes on the reflected waves, much like an interferometer measures changes in the refractive index of a transparent medium [7]. The magnetic signals (red) measured outside the plasma clearly peak around the TAE frequency as indicated in Fig. 2. However, the core reflectometer signals (blue) indicate that the modes originally emerge at lower frequencies in the plasma core and then chirp up to the TAE range of frequency where they are observed on the magnetic probes. This frequency shifting character is a property of all the TFTR D-T shots that exhibited Alfvénic activity driven solely by alpha particles and which require the special current profile preparation described above. The data indicates that the spatial structure of the mode is evolving in time from a core localized to a global (radially extended) mode as the TAE frequency is approached. As indicated in Fig. 2, the central safety factor gradually decreases during this period as the toroidal plasma current continues to penetrate into the core. Although Fig. 2 shows that the external magnetic signals peak in amplitude around the TAE frequency, the frequency at the early onset of the mode activity can be significantly lower than the TAE frequency. Within the context of TAE theory, the modes should have a far smaller frequency variation in the core of the discharge where the central safety factor is roughly uniform. An attempt to maintain a TAE based explanation with the assumption that frequency may change due to steep density gradients in the plasma profile, temporal changes in time or from plasma flow effects, are incompatible with the data. The core density has a flat profile, the density is rather steady in time (less that a 5% variation) and the plasma flow is small.

It should be noted that the frequency at which the external magnetic measurements peak in amplitude shows good agreement with standard TAE theory. On the other hand, the dominant mode activity in the core of the discharge measured with the reflectometer is quite unlike TAEs and this data suggests a complexity in the mode activity that cannot be encompassed by TAE theory alone. In particular the evolution of the mode frequency from internal oscillations (blue) toward the TAE frequency detected by external magnetic signals (red) is reminiscent of the chirping behavior of so-called Alfvén Cascades observed in JET and JT-60U plasmas with reverse and weak central magnetic shear [8,9]. Here we shall also refer to the chirping phase of the modes in TFTR as Cascade modes. Originally an explanation of the Alfvén Cascades was attributed to a non-perturbative contribution of energetic particles that was needed to set the mode and produce only up-chirping behavior as the central q-value decreases [10]. However, numerical calculations show that ideal MHD theory in toroidal geometry can produce such behavior as well [11-14] and an analytic theory that describes the contribution from both effects has been developed [15]. In contrast to the strongly reversed magnetic shear discharges in JET and JT-60U where similar modes were identified, the TFTR discharges considered here have a nearly flat q-profile in an extended region of the central plasma cross section (see Fig. 1d and note that the small depression in the reconstructed experimental q-profile is not statistically significant). In TFTR the partial pressure of alpha particles is quite small so that we expect that the toroidal MHD contribution sets the mode rather than the non-perturbative energetic particle contribution, which shall be ignored in this paper.

Both the CASTOR [16] and the NOVA-K [17, 18] codes were used to study the frequency behavior of the Cascade modes observed in TFTR and their transition to the TAE with the relevant plasma parameters and profiles obtained from the analysis of the TFTR data. A comparison of the numerical results with the TFTR data is shown in Fig. 2. The CASTOR and NOVA-K solutions are in good agreement. When q_0 is too large for TAEs to appear ($q_0 > (m - 1/2)/n$ for given m and n values) the Cascade modes are found. The calculations show that Cascade modes in TFTR consist of one dominant poloidal harmonic (a characteristic of Cascade modes away from the TAE gap) with mode number $m=2n$ and are localized in the central weak magnetic shear region of the discharge where the alpha particle drive is greatest. We see in the figure that the Cascade mode frequency increases rapidly with decreasing q_0 until the mode frequency enters the TAE gap. At this point the Cascade mode transforms into the TAE by coupling to the additional poloidal harmonic $m=2n-1$. When q_0 decreases further the TAE becomes more global and is eventually damped. The transition from the core localized Cascade mode to the more radially extended TAE is consistent with the observation of an increase in edge magnetic signals as the mode frequency enters the TAE range of frequency as shown in Fig. 2.

The density perturbation associated with the mode has two main contributions, which in the equatorial plane is given by,

$$\frac{\delta\rho}{\rho} = -\nabla\cdot\xi - \xi\cdot\frac{\nabla\rho}{\rho} \cong -\left(\frac{2\hat{\mathbf{R}}}{R^2} + \frac{\hat{\mathbf{n}}}{L_\rho}\right)\cdot\xi \qquad (1)$$

where the approximation in Eq. (1) is written in the low plasma beta limit, ξ is the magnetic field line displacement, $\vec{n}$ is the density unity vector normal to the magnetic surface, ρ is the plasma density, R is the major radius and L_ρ is the density scale length. In the following we compare the magnitude of the density perturbation on the low and high field side of the magnetic axis and thus the phase of ξ is not important. The second term in brackets in Eq.(1), the convective term, is symmetric about the magnetic axis whereas the first term, the compressional term, is antisymmetric leading to partial cancellation of the density fluctuation level on the low field side. Note that the density scale length is comparable to the major radius in these TFTR D-T discharges. As a result, the compressional term is of the same order as the convective term. The symmetry of the density perturbation is therefore expected to be strongly anti-ballooning even though the magnetic perturbation is symmetric about the magnetic axis for a cylindrical-like mode.

These observations are used in Fig. 3 to show a resolution of an apparent anomaly in the TFTR data concerning the purely anti-ballooning structure of the lowest frequency $n=2$ mode as observed on the phase response of the core reflectometer diagnostic. The outstanding feature of this data is the near total absence of mode activity on the low field side of the magnetic axis despite the fact that the magnetic structure of the mode is essentially cylindrical. The NOVA-K calculation of the perturbed density exhibits a striking agreement with the reflectometer response for the $n=2$ eigenmode. This agreement indicates that the asymmetry of the density perturbation results from cancellation of the compressional and convective contributions to the perturbed density on the low-field side of the magnetic axis (see Eq. (1)).

The transition from a core localized cylindrical mode to a more global TAE is shown in Fig. 4. In this figure we see the radial mode structure of the density fluctuations taken with the reflectometer at two different times during the n=4 mode activity observed on magnetic probes (Fig. 4a). The first time is during the period when the signal begins to appear on the external magnetic probes but is of very low amplitude. The second time is taken at the peak of the observed magnetic mode activity. At the first time, the internal reflectometer measurements (Fig. 4b) indicate slightly anti-ballooning density fluctuation even though the magnetic structure tends to be ballooning. The difference is again due to the effect of the compressional term discussed above. However, at the later time the density amplitude is diminished on the high-field side relative to the low-field side. Figure 4c shows for comparison the radial profile for the density eigenmode for the two cases corresponding to the Cascade-TAE mode transition (early in time) and the TAE (later in time) obtained with NOVA-K for the same plasma profiles used in Fig. 3. Observe that the expected change in the symmetry of the density fluctuation level (in Fig. 4c) is entirely consistent with the experimental change in symmetry of the mode data (Fig 4b). This transition also confirms the in-phase coupling of the $m=2n-1$ with the $m=2n$ poloidal components that is needed to produce the outward ballooning structure expected for TAEs. Note also that the mode structure at the peak of the magnetic signal is more oscillatory and radially extended. This shows that the mode structure becomes more global and couples better to the plasma boundary as the mode frequency enters the toroidicity induced gap in the Alfvén continuum. Further the relative increase in the magnetic signal compared to the reflectometer signal during the frequency chirp in Fig.2 is consistent with the simulation of the mode structure near the TAE frequency.

In conclusion, during the times when the Cascade modes are present and when the transition is made to the TAE mode, the theory and calculations for the radial structure and frequency of the modes are in very good agreement with the experimental data obtained on TFTR.

We are now left to ponder the implications of this new understanding for fusion reactors. It is important to note that the dominant modes observed in the TFTR experiments are Cascade modes. TAEs were observed only after the appearance of the Cascade modes and they were rapidly damped in amplitude after the transition from the Cascade to the TAE. This may be due to the more radially extended nature of the TAE which can enhance its damping by coupling to the periphery of the discharge where there are few alpha particles. The Cascade modes should be especially important for the advanced Tokamak reactor concept which requires high levels of off-axis non-inductive current drive leading to broad regions of weak magnetic shear. If the alpha particle birth population is sufficiently extended to encompass the region of weak magnetic shear, then Cascade modes are likely to emerge. Careful analysis of the stability, non-linear growth and coupling of multiple Cascade modes needs to be assessed in present scale experiments in order to predict their behavior in a burning plasma.

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Figure Captions

Figure 1

Time history of the central alpha particle pressure (a) with the neutral beam heating duration also indicated. The central plasma pressure is shown in (b) for comparison. The time history of the magnetic fluctuations is indicated in (c) where a range of toroidal mode numbers are observed in succession from n=5 to n=2. The experimentally reconstructed q-profile is shown by the solid curve in (d) where the weak central magnetic shear is indicated by the flatness of q-profile in the core. A centrally flat q=profile used in the calculations discussed below is shown by the dashed curve. The plasma has the following machine parameters: major radius 252 cm, plasma toroidal current 2.0 MA, Toroidal magnetic field 5.3 T.

Figure 2

Contour plot of edge magnetic measurements (red) and core density fluctuations using an X-mode reflectometer (blue) for the discharge in Figure 1. The reflectometer measurements are located at a normalized minor radius of –0.3. Also indicated is the range of expected mode frequencies for TAEs and the range of mode frequency expected for Cascade modes. Rectangles indicate CASTOR code calculations of the mode frequency expected for Cascade modes using the measured plasma equilibrium and evolving the central safety factor over a narrow range near q=2.

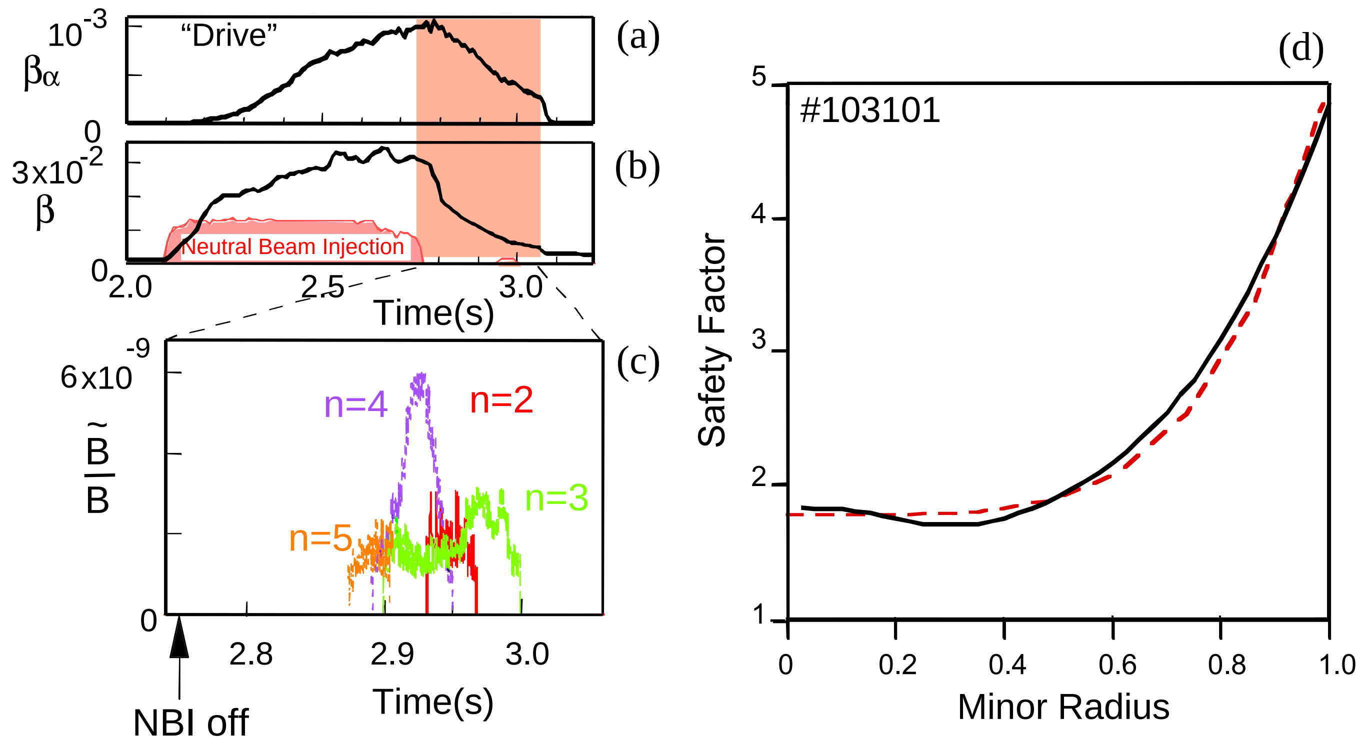
Figure 3

Measured radial structure of density fluctuations (a) for the n=2 mode in Figure 2 compared to the theoretically expected radial mode structure for the n=2 Cascade mode according to the NOVA-K code. In (b) the magnetic fluctuation level $|\delta B/B|$ from

NOVA-K is also shown, indicating the cylindrical nature of the mode from the near equal amplitude on the high and low field side of the magnetic axis.

Figure 4

Time evolution of edge magnetic fluctuations for the n=4 mode in Figure 2 (a). The radial density fluctuation profile using the reflectometer diagnostic is shown in (b) early (left) and later (right) in time, and radial density eigenmode expected for the n=4 Cascade mode (left) and TAE (right) in (c).



(a)
"Drive"
10^{-3}
β_α
(b)
3×10^{-2}
β
Neutral Beam Injection
2.0
2.5
3.0
Time(s)
(c)
6×10^{-9}
$\tilde{B}/B$
n=4
n=2
n=3
n=5
2.8
2.9
3.0
Time(s)
NBI off
(d)
#103101
Safety Factor
Minor Radius

Fig. 1

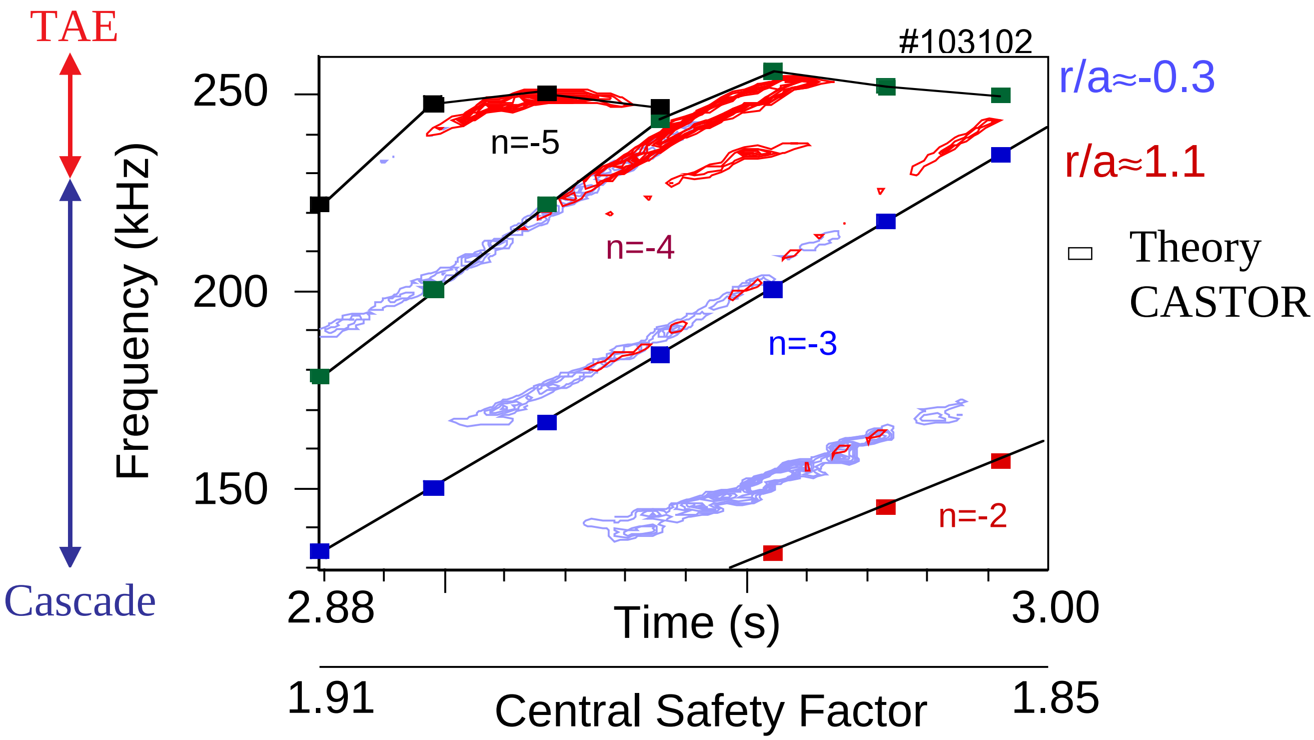
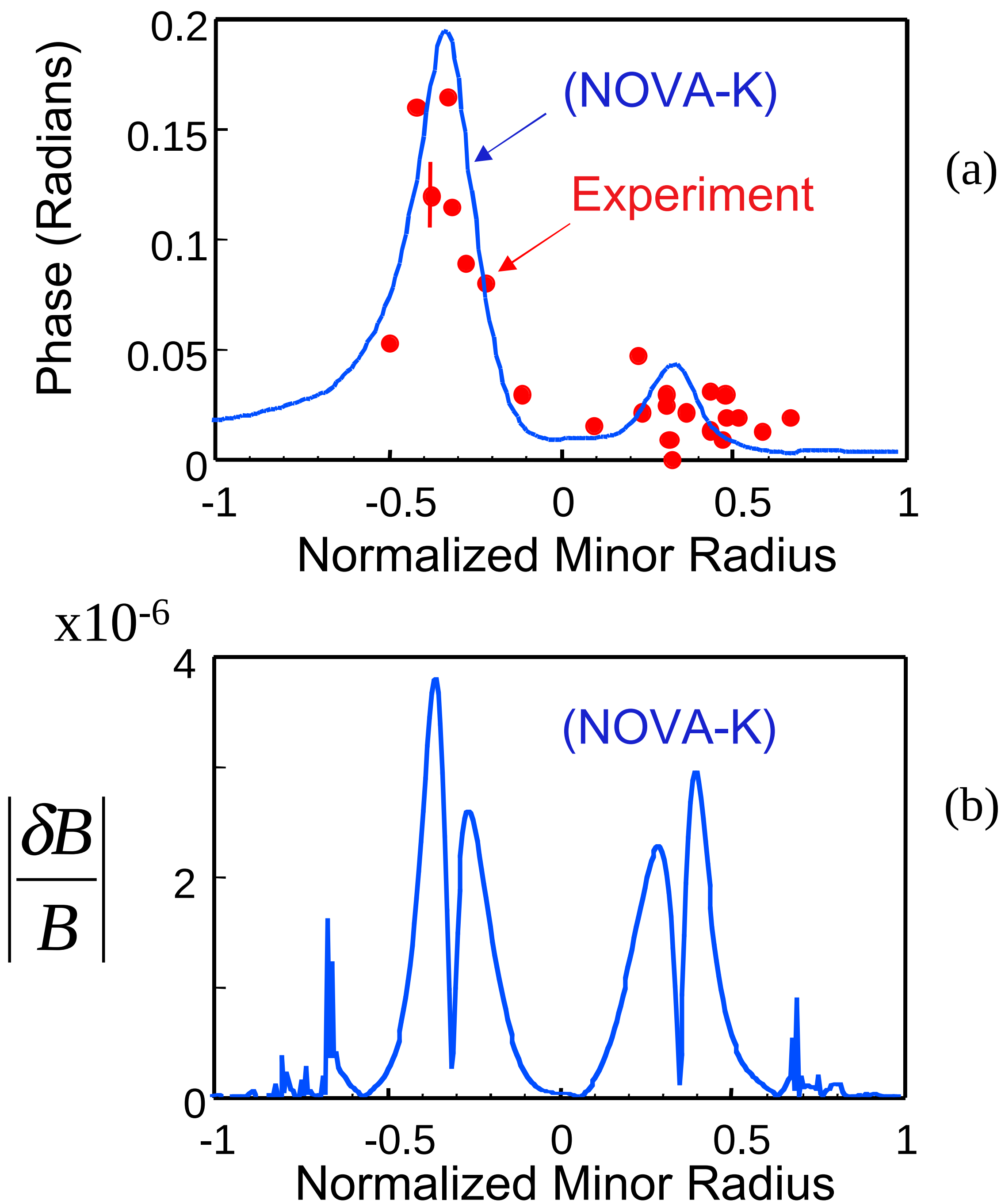

TAE
Cascade
#103102
250
200
150
Frequency (kHz)
n=-5
n=-4
n=-3
n=-2
r/a≈-0.3
r/a≈1.1
Theory
CASTOR
2.88
Time (s)
3.00
1.91
Central Safety Factor
1.85

Fig. 2



Phase (Radians)
0.2
0.15
0.1
0.05
0
(NOVA-K)
Experiment
-1
-0.5
0
0.5
1
Normalized Minor Radius
(a)
x10-6
4
2
0
(NOVA-K)
-1
-0.5
0
0.5
1
Normalized Minor Radius
(b)

Fig. 3

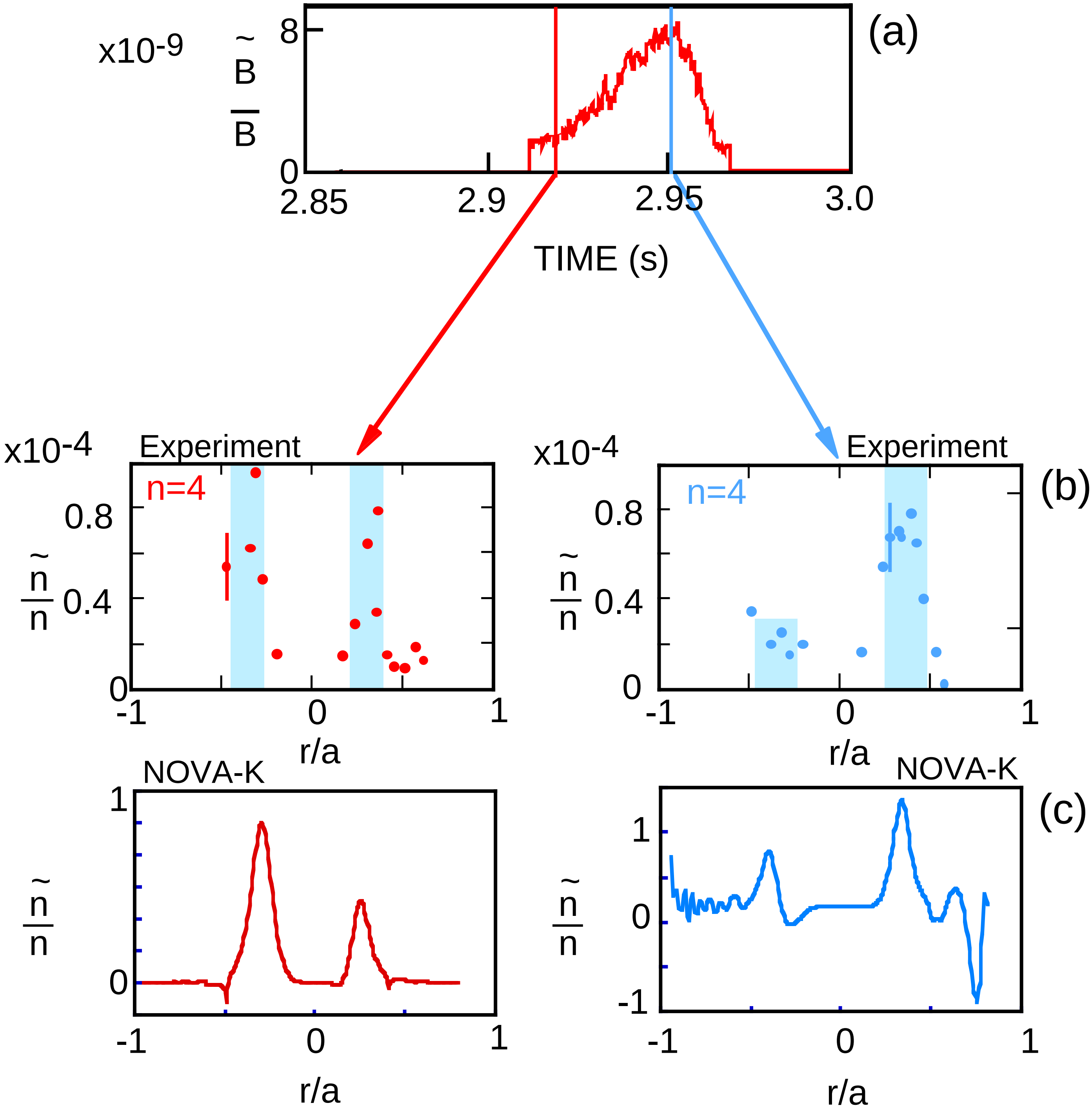

x10-9
~B/B
8
0
(a)
2.85
2.9
2.95
3.0
TIME (s)
x10-4
Experiment
n=4
0.8
~n/n 0.4
0
-1
0
1
r/a
x10-4
Experiment
n=4
(b)
0.8
0.4
0
-1
0
1
r/a
NOVA-K
1
0
-1
0
1
r/a
NOVA-K
(c)
1
0
-1
-1
0
1
r/a

Fig. 4

External Distribution

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