Isotope mass scaling of AE damping rates in the JET tokamak plasmas*

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Abstract

The damping of radially extended Alfvén Eigenmodes in tokamak plasmas is investigated in JET discharges with different ion mass. The comparison of damping measurements with predictions of a gyro-kinetic model indicates that mode conversion into kinetic Alfvén Waves is the dominant damping mechanism for Alfvén Eigenmodes in the plasma core.

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In fusion grade D-T plasmas, alpha particles (α's) resonate with Alfvén waves as they slow down by colliding with plasma electrons and ions and can drive the waves unstable if sufficient free energy is embedded in their pressure gradient. In toroidal confinement devices such as tokamaks, the coupling of different poloidal Fourier harmonics leads to the formation of global standing waves, named Alfvén Eigenmodes (AEs) [1]. If AEs are driven unstable and reach relatively large amplitudes, they can significantly affect the alpha particle orbits and consequently the ignition process [2].

The linear stability of AEs is studied systematically on JET by measuring the plasma response to small perturbations imposed by an external antenna [3]. This method provides direct, independent measurements of the AE damping produced by the background plasma and of the drive generated by super-Alfvénic fast particles, such as α's generated by fusion reactions or ions energized by additional heating [4].

Various mechanisms have been invoked for the damping of AEs in a tokamak plasma. In general, energy may be absorbed by the plasma ions or electrons via Landau damping, i.e. non collisional wave-particle interaction, either directly with the global AE wave field [5] or with the mode-converted kinetic Alfvén waves (kAWs). Fluid models estimate mode conversion at the resonance layer of the shear Alfvén wave or in its proximity using *ad hoc* descriptions of energy tunneling to kAWs in the form of *continuum damping* [6] and *radiative damping* [7]. However, since the mode conversion efficiency and the associated energy exchange depend on the precise global field structure of both the AEs and the kAWs, within the shear Alfvén wave gaps as well as outside, a full toroidal gyro-kinetic description of the plasma is necessary [8].

Such model reproduces the strong damping observed for low toroidal mode number AEs as a magnetic divertor is switched on to create an X-point in the plasma, with damping rates up to $\gamma/\omega_{damp} \sim 15\%$ for $|n| < 3$ [4]. The enhanced absorption in the presence of a large edge magnetic shear is due to a strong radial localization of the AE wave field which increases the perpendicular wavenumber, allowing efficient mode conversion to kAWs. This effect can stabilize AEs extending to the plasma edge, which could generate fast particle transport throughout the plasma cross section [9].

In this Letter we investigate a new AE damping mechanism, based upon mode conversion of AEs into kAWs in the plasma core and related to the presence of a region of low magnetic shear close to the magnetic axis where the local aspect ratio is large. The importance of this mechanism resides in the fact that, for most reactor relevant scenarios, AEs that are potentially driven unstable by α's generally have a finite amplitude in the central region of the plasma where α's are generated by fusion reactions.

To validate the interpretation of this new AE damping scheme, a series of discharges with similar equilibria and different ion masses have been analyzed. Damping rates for low-n

AEs are measured and compared with those calculated using the gyro-kinetic model PENN [10]. To experimentally distinguish the core damping mechanisms from mode conversion at the plasma edge, the comparison is undertaken at a time in the discharge well before the divertor phase is approached, i.e. before the edge damping becomes significant.

In the local approximation, the frequency and the electron Landau damping rate of the shear Alfvén wave can be cast in forms that easily show respectively a direct and an inverse dependence on the square root of the plasma effective mass

$$\omega = k_{\|} v_A \propto A_{eff}^{-1/2} \tag{1}$$

$$\gamma/\omega_{damp} = (\pi/4)^{1/2} (m_e/m_i)^{1/2} k_{\perp}^2 v_s v_A/\Omega_i^2 \exp(-v_A^2/v_{the}^2) \quad \propto A_{eff}^{1/2} \; \textit{(for } v_{thi} < v_A < v_{the}\textit{)} \qquad (2).$$

Here v_{thi} and v_{the} are the ion and electron thermal speeds, v_s is the sound speed and Ω_i is the ion cyclotron angular frequency. Full toroidal calculations based on the fluid shear-Alfvén model, such as LION [11] or NOVA-K [12] predict global mode structures, hence $k_{\perp}$ and $k_{\|}$ that are independent of the plasma mass. The local scaling from (1) and (2) therefore applies in general to all AEs computed using the fluid model.

However, as a finite ion gyro-radius induces a dispersion across the magnetic field, the expression defining the frequency of the kinetic Alfvén waves differs from (1) [13]

$$\omega = k_{\|} v_A [1 + k_{\perp}^2 \rho_i^2 (3/4 + T_e/T_i)]^{1/2} \qquad (3).$$

The small parameter $k_{\perp}\rho_i$ introduces a more complex dependence of the damping rate on the plasma mass, which can only be accounted for by using a gyro-kinetic model for the wave fields providing a full toroidal description of the mode conversion process.

In the experiment, n = 1 toroidicity induced AEs (TAEs) are preferentially driven by two toroidally opposed antennas of the four JET saddle coils, energized with opposite phases. Synchronous detection is used in combination with the external exciter to extract the AE driven signal from the noise in a number of channels, including 16 magnetic probes at the plasma edge and various internal diagnostic channels such as O- and X-mode reflectometer, ECE heterodyne radiation detectors and soft X-ray cameras. As the current path in the saddle coils is not entirely symmetric, phase measurements of the magnetic fluctuation signals are operated to identify the launched spectrum.

A digital real time control system, linking the AE resonance detection to the AE wave source, operated as a voltage controlled oscillator, is used to track the individual AE resonances throughout the JET discharges. Resonances associated with TAEs are found at frequencies that follow closely the initial guess corresponding to the shear Alfvén gap center

$$f_{TAE} = v_A/2qR \qquad (4),$$

which follows from Eq. (1) with $k_{\|} = 1/(2qR)$. Here v_A is the Alfvén speed, R the tokamak major radius and q the safety factor at the gap location. A procedure to fit the measured plasma transfer function around the AE resonance with a complex polynomial fraction is then applied to the different channels to extract the different residues, i.e. the amplitudes of the eigenmode at the different probe locations, and the common complex pole, which contains the frequency and damping of the mode [4]. The amplitudes of the driven magnetic fluctuations at the edge, $\delta B/B \sim 10^{-7}$, constitute a negligible perturbation to the plasma.

The chosen equilibrium configuration corresponds to the *hot ion H-mode* JET plasma regime, characterized by a monotonic safety factor profile q(r) and q(0) ~ 1 [14]. The maximum fusion power and fusion power gain were obtained using this scenario [15]. The isotope plasma composition is varied from pure hydrogen to almost pure tritium by gas injection, with values of the effective plasma ion mass, $A_{eff} = (\Sigma_j n_j m_j)/\Sigma_j n_j$, ranging from $A_{eff} = 1$ to $A_{eff} = 2.8$. Special care was taken in these experiments to reproduce very similar plasma background conditions with the goal of identifying the electron heating effect of fusion produced alpha particles [16].

Figure 1 shows the reconstructed equilibrium profiles of ion and electron temperatures, density, q and magnetic shear (shear = r/q dq/dr) at a particular time for one of these discharges, composed of a 50:50 deuterium-tritium mixture. The profiles are obtained in the limiter phase of the discharge and therefore are suitable for a comparison with the theory. Note the small value of the magnetic shear in the central region of the plasma.

The corresponding n = 1 TAE eigenfunction computed by the gyro-kinetic code PENN is shown in Fig. 2, together with the calculated radial profile of the integrated power absorption of the mode. It appears clearly that most of the damping of the driven TAE takes place in the very central part of the plasma radial profile, where the shear is weaker than the inverse aspect ratio, r/R, for r/a < 0.1 [8]. In this region the TAE is converted into a kAW, which in turn is absorbed by electron Landau damping, giving in this case a damping rate of $\gamma/\omega_{damp} \sim 1$ %. The damping rate is calculated in the model from the ratio of the total absorbed power to the stored power, $\gamma/\omega_{damp} = P/(\omega W)$ [11, 17]. Similar wave patterns and consequently similar wave absorption profiles are found to characterize the whole series of discharges considered herein.

In Fig. 3 we represent the experimental data and the theoretical results from the PENN code in terms of frequencies and damping rates normalized to f_{TAE} (with q = 1.5) and to the formula for electron Landau damping (3) [18], both calculated for H plasmas. In the normalization of the damping rates, the value of $k_\perp = 100$ m^{-1} is chosen, consistently with the experimental observations. Points from the fluid plasma model are also included; in this case the damping rates have been artificially multiplied by a factor of 25 for visualization purposes.

In addition to predicting the right magnitude of the TAE damping rates, the results of the PENN code follow the observed scaling with the plasma ion mass. By artificially removing mode conversion in the core, for r/a < 0.1, the damping rate is underestimated by an order of magnitude. Similarly, Fig. 3 shows that fluid models predict a different scaling of the damping with the ion mass from that observed in the data, and underestimate the damping of these global, externally driven TAEs by a factor of about 25.

For this comparison, the PENN plasma model does not include the trapped electron population. Although the interaction takes place with a wave of relatively slow phase velocity, $v_A \ll v_{the}$, neglecting trapped electrons does not significantly affect the results for two reasons. First, in the central region of the tokamak, the number of trapped particles is small compared to that of circulating particles. Second, the damping rate due to mode conversion depends on conversion efficiency, which in turn is related to the wave linear properties, and not on the details of interaction between the mode converted kAW and the electrons.

We conclude that the damping mechanism of AEs via mode conversion to kAWs in the core, predicted by the gyro-kinetic code PENN and visible in the calculated eigenfunction and absorbed power profile shown in Fig. 2, is consistent with the experimental data. This damping mechanism is of interest for future reactor relevant experiments both in terms of the order of magnitude of its associated damping rate, $\gamma/\omega_{damp} \sim 1\%$, which is sufficient to stabilize a variety of α-driven AE instabilities, and of its radial location, in the plasma core where modes can be driven by fusion generated α's.

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Figure Captions

Fig. 1 Reconstructed equilibrium profiles of safety factor q and magnetic shear (r/q dq/dr) (top), and ion and electron temperatures and density (bottom), for JET D-T discharge #42979 at t = 50.12. This time corresponds to the limiter phase of the discharge (the plasma is started at t = 40 s and the divertor coils are switched on around t = 51.5 s) and has been fixed for the comparison with the theory for the series of similar shots considered in Fig. 3. Here and in Fig. 2 the radial variable $s = (\Psi_{pol})^{1/2}$, where Ψ_{pol} is normalized the poloidal magnetic flux, roughly corresponds to the normalized radial position r/a.

Fig. 2 Structure of an externally driven n = 1 TAE calculated by the PENN code for the same discharge and time slice shown in Fig. 1, in terms of the normal electric field. The radial profile of the absorbed power indicates that the damping takes place in the plasma core.

Fig. 3 Measured (o) and computed (*) effect of the ion mass on the n = 1 TAE frequency (top) and damping (bottom). $A_{eff} = \Sigma_i n_i A_i / \Sigma_i n_i$ is measured from edge spectroscopy. Note that the γ/ω_{damp} calculated from fluid models (◊) has been multiplied by 25.

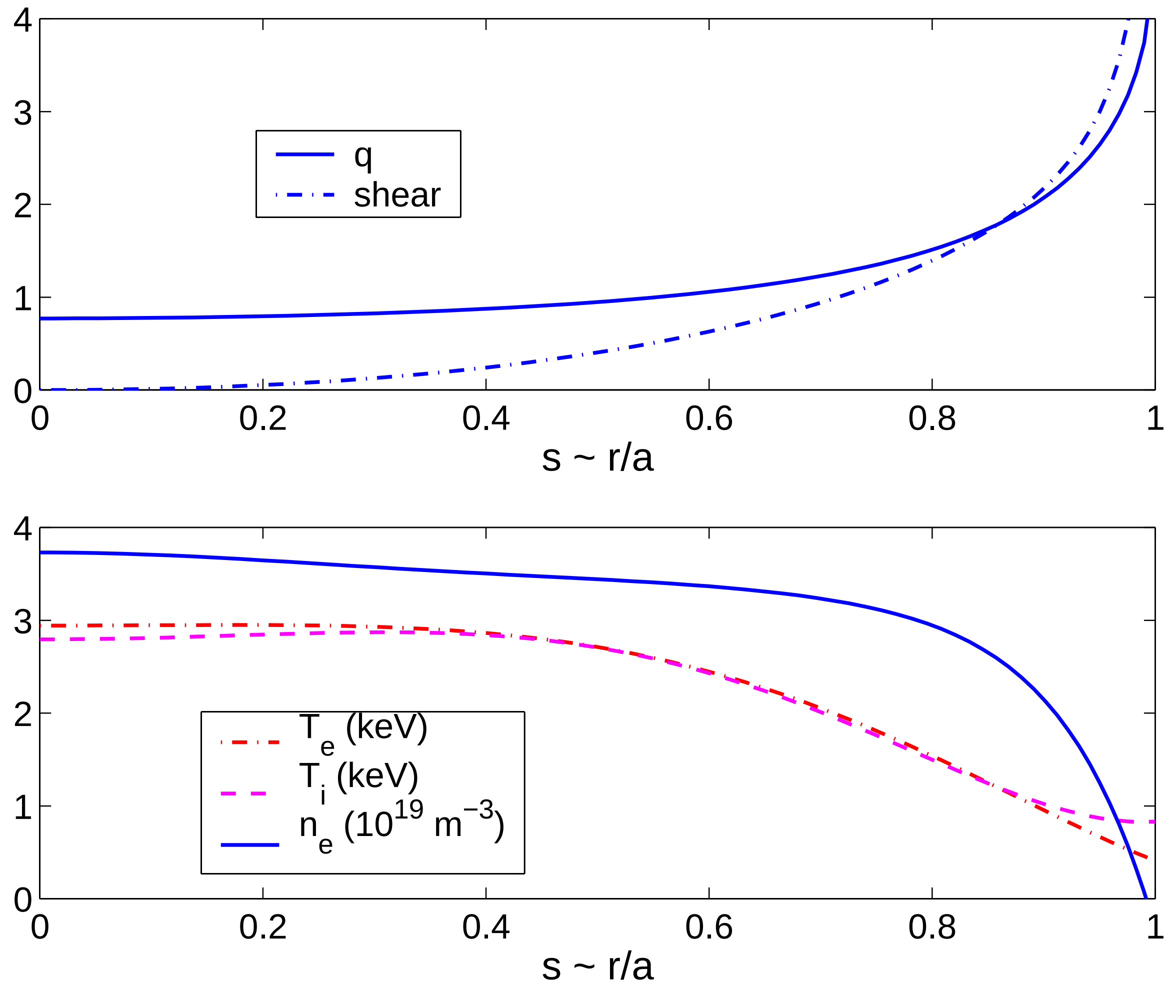
4
3
2
1
0
0
0.2
0.4
0.6
0.8
1
s ~ r/a
q
shear
4
3
2
1
0
0
0.2
0.4
0.6
0.8
1
s ~ r/a
T_e (keV)
T_i (keV)
n_e (10^{19} m^{-3})

Figure 1

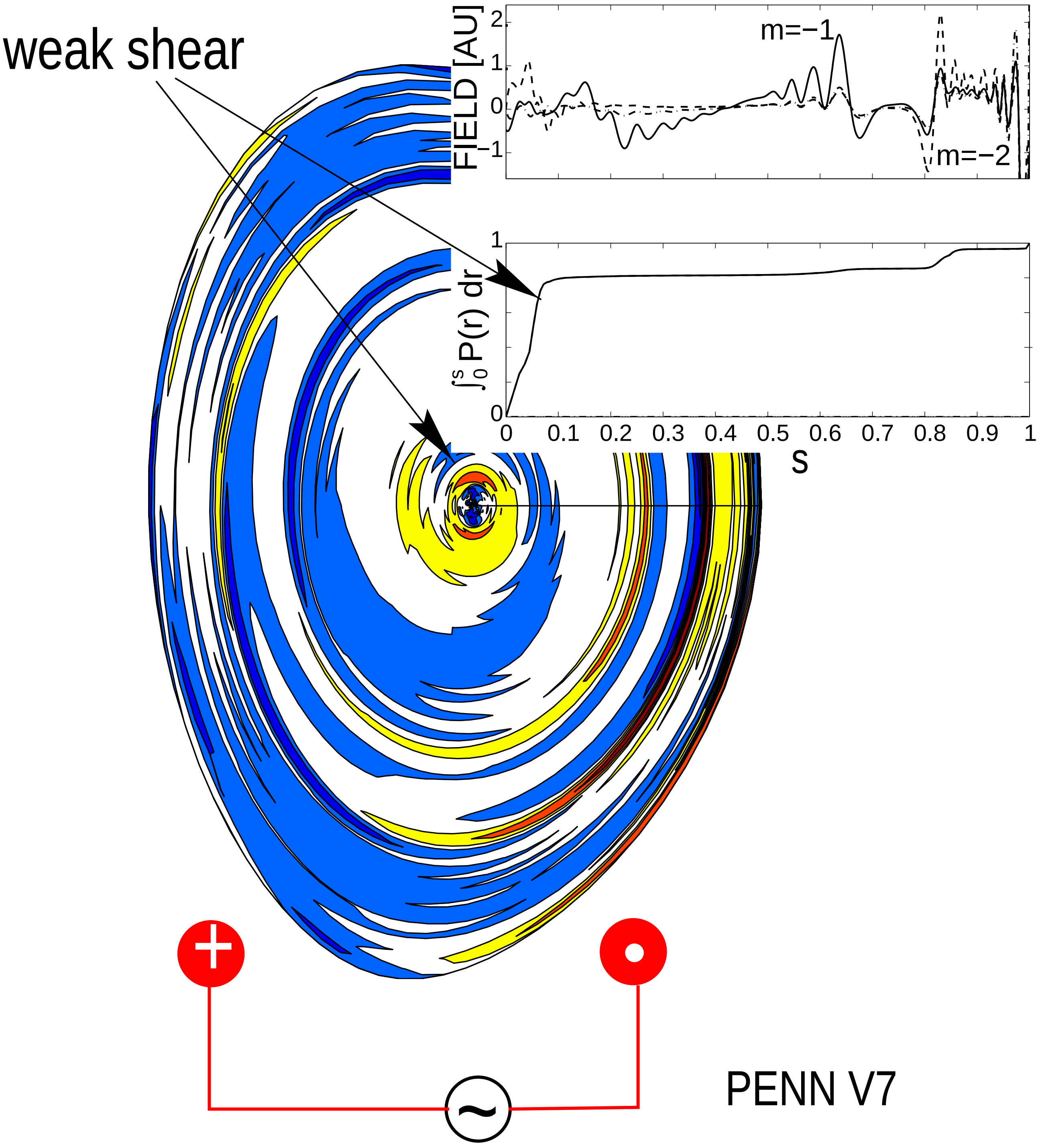
weak shear
FIELD [AU]
2
1
0
−1
m=−1
m=−2
∫₀ˢ P(r) dr
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
s
~
PENN V7

Figure 2

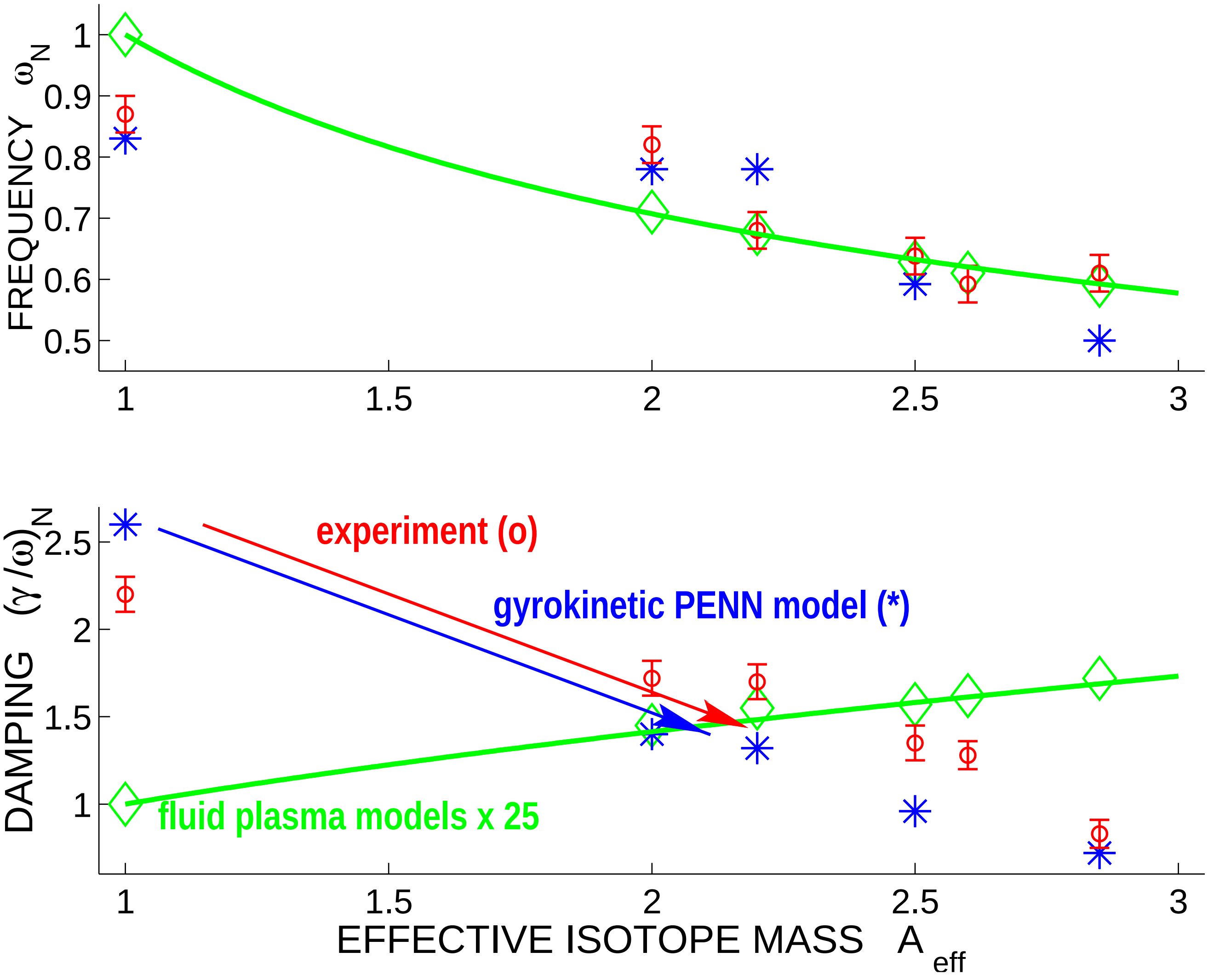
FREQUENCY ω_N
1
0.9
0.8
0.7
0.6
0.5
1
1.5
2
2.5
3
DAMPING $(\gamma/\omega)_N$
2.5
2
1.5
1
experiment (o)
gyrokinetic PENN model (*)
fluid plasma models x 25
1
1.5
2
2.5
3
EFFECTIVE ISOTOPE MASS A_{eff}

Figure 3