Keeping Fusion Plasmas Hot

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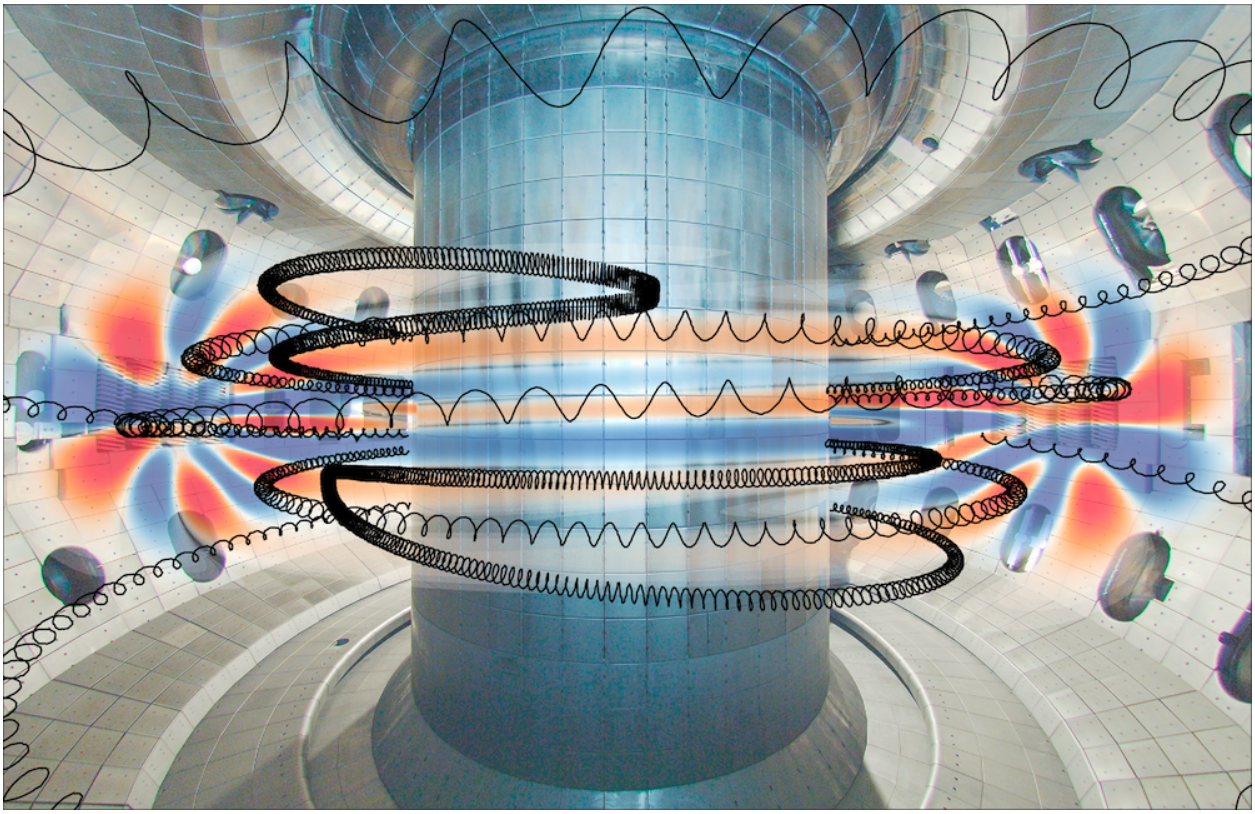
Proposed Cover Graphic



Energetic ion transport in the DIII-D tokamak (the center post diameter is 2.2 m). An energetic ion orbit resulting from neutral beam injection is shown as the black trace. The red and blue contours represent a synthetic image of a plasma wave (e.g., the density perturbation of an Alfvén eigenmode) that perturbs the ion orbit and causes it to impact the outer wall on the right, which happens to correspond to the location of the energetic ion loss detector diagnostic system. (Photo courtesy S. Allen)

Main Article

The development of controlled nuclear fusion is an ongoing international endeavor combining advanced engineering and physics, yet some of the fundamental challenges can be addressed in terms of an electromagnetic wave pushing around a single ion. Tokamak fusion experiments confine an ionized gas (otherwise known as a plasma, the state of matter of over 99% of the visible universe) using magnetic fields in a toroidal solenoid configuration. Interactions between ions and plasma waves increase transport of the particles across the magnetic field, and this mechanism is important to understand because fusion-produced charged particles must be well confined in order to achieve and maintain a plasma that is self-heated by the reactions.

The fusing of light nuclei is the largest energy density process readily available to humanity, and this energy is released without carbon-based emissions or large amounts of radioactive waste. The production of electricity from fusion energy is highly desirable, especially in the context of global population growth. The majority of the worldwide effort to create a viable fusion energy device focuses on the nuclear process with the largest cross-section, the fusing of deuterium and tritium to produce an alpha particle (helium nucleus) and a neutron,

$$D + T \rightarrow {}^4\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV}) \tag{1}$$

where the hydrogen isotope deuterium is plentiful in sea water, and tritium is produced by allowing the fusion neutron to impact a lithium blanket. The alpha particle is more energetic than the background plasma and, so long as it is confined, it heats the plasma to maintain thermonuclear temperatures.

Recent experiments, combining new diagnostic and simulation capability, provide comprehensive detail to the study of wave-induced ion transport in high-temperature, magnetically confined plasmas. The result is an improved understanding of the sensitive phase dependencies that dictate interactions between plasma waves and charged particles. Fundamentally, these processes occur outside of laboratory experiments and exist over an enormous range of spatial scales including plasmas that span the galaxy.

In order to describe the situation encountered in these fusion plasmas, it is necessary to elucidate the geometry of the toroidal magnetic confinement system known as the tokamak (from the Russian "toroidal'naya kamera s magnitnymi katushkami," meaning *toroidal chamber with magnetic coils*). Figure 1 shows a generalized representation of tokamak geometry. This a pure plasma physics representation in which we see the toroidal (i.e., the long way around the torus) plasma shape and ion orbits, but none of the corresponding electromagnet coils or vacuum vessel. In the $R\phi z$-coordinate system, the applied toroidal magnetic field, B_ϕ, is along the ϕ-direction and a poloidal magnetic field, B_p, is produced by toroidal plasma current.

Example ion orbits are shown in Fig. 1 (characteristics of the orbits are the same for electrons). Finer scale structure includes the gyro-orbit of the ion around the local magnetic field, while larger scale drifts occur due to other forces such as that caused by the gradient in the magnetic field. These represent the two main classes of orbit trajectory: passing and trapped. Passing orbits circulate toroidally around the plasma, closely (but not exactly) following the nearest magnetic flux isosurface.

Trapped orbits originate due to the $1/R$ dependence of the magnetic field magnitude in this toroidal solenoid. One consequence of that magnitude variation is that ions experience an increasing (decreasing) magnetic field as they pass to smaller (larger) values of R. Trapped ion orbits are understood by considering that the magnetic moment of an ion is an adiabatic invariant when the confining magnetic field changes on time and length scales that are considerably longer than the gyro-orbit of the ion.

The magnetic moment is,

$$\mu = \frac{\frac{1}{2} m_i v_\perp^2}{B} \tag{2}$$

where m_i is the ion mass and $v_\perp$ is its velocity in the direction perpendicular to the total magnetic field. When an ion moves into a region of increasing magnetic field, the perpendicular velocity will

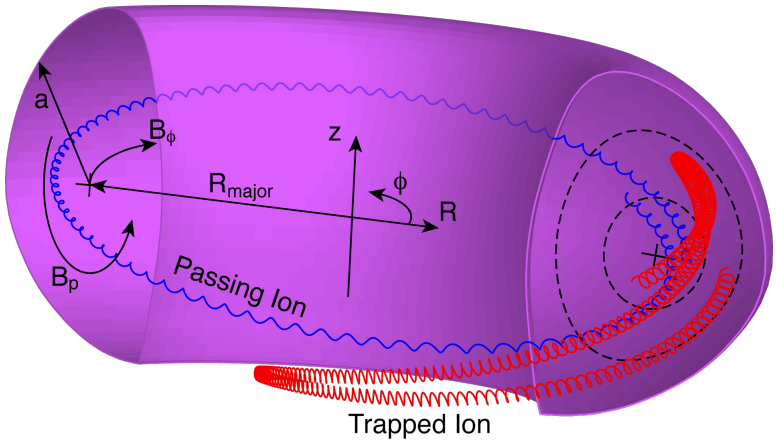


Figure 1: Generalized geometry of a tokamak plasma with example ion orbits. In the $R\phi z$-coordinate system, the applied toroidal magnetic field, B_ϕ, is along (or anti-parallel to, in this case) the ϕ-direction. A poloidal magnetic field, B_p, is produced by toroidal plasma current. The dashed lines represent isosurfaces of toroidal magnetic flux, with the purple plasma boundary representing the outermost isosurface beyond which the magnetic field lines intersect the tokamak walls and the plasma is unconfined. Two example ion orbits illustrate the cases of a passing (blue trace) and trapped (red trace) character.

increase such that μ remains constant. The magnetic field does no work on the ion, therefore the total ion energy remains constant and this requires that the velocity parallel to the magnetic field, $v_\parallel$, must decrease. Eventually, $v_\parallel = 0$ and the ion travels no further in that direction. These ions will traverse back and forth, tracing out a banana-shaped path in the Rz-plane and earning their common designation as "banana orbits."

Kicking ions

Now consider these ions passing through an electromagnetic plasma wave. A charged particle passing through this wave experiences a "kick" that depends upon the average phase between the wave and the orbital motion. In general, both the plasma wave properties (e.g., frequency, spatial structure, and polarization) and particle orbital properties determine the interaction. Figure 2 shows a relatively simple case known as "cyclotron resonance." This example begins with an ion gyrating about a background magnetic field. The energy exchanged in one orbit (whether it is a single gyro-orbit or one complete orbit through the wave, the following expression remains valid) of an ion with velocity $\vec{v}_{\text{ion}}$ is $\int_{\text{orbit}} \vec{F} \cdot \vec{v}_{\text{ion}}\, dt = \int_{\text{orbit}} q\vec{E} \cdot \vec{v}_{\text{ion}}\, dt$, where $\vec{F} = q\vec{E}$ is the force on an ion of charge, q, due to the electric field, $\vec{E}$, of the wave.

In Fig. 2(a), an ion with velocity $\vec{v}_{\text{ion}}$ gyrates about a magnetic field $\vec{B}$. The ion circles the magnetic field at its gyrofrequency f_{gyro}. At any moment, the position within the gyro-orbit is described by a phase angle θ_i with respect to $\vec{B}$. This is the gyrophase of the ion. Adjacent to this ion is a circularly polarized electromagnetic wave for which θ_E represents an analogous phase angle describing the orientation of the electric field vector at a moment in time.

Three specific scenarios in which an ion approaches an electromagnetic wave are depicted in Fig. 2(b). We purposely set the gyrofrequency of the ion and the oscillation frequency of the

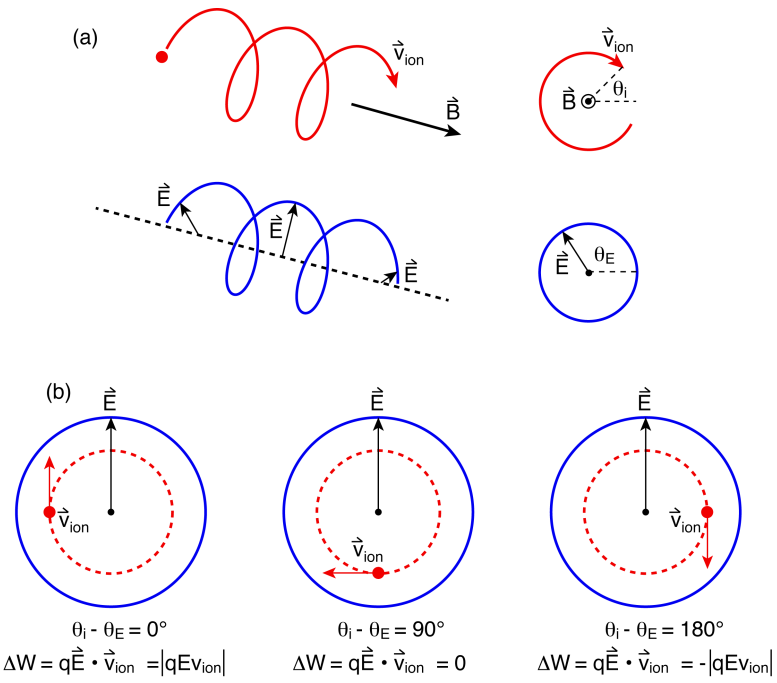


Figure 2: Depiction of the net energy change for an ion interacting with an electromagnetic wave. (a) An ion oscillates about a magnetic field $\vec{B}$ with a gyrophase θ_i. This is analogous to a circularly polarized electromagnetic wave in which the oscillation of the electric field vector $\vec{E}$ can be described in terms of its phase angle θ_E. The oscillation frequencies are equal in this example, i.e., $f_{\text{gyro}} = f_E$. (b) The energy change of the ion, due to the electric field of the wave, is determined according to the phase angle difference. A phase difference of 0° (180°) increases (decreases) the ion energy, while a 90° phase difference results in no energy change because the ion velocity and wave electric field remain always perpendicular, i.e., $q\vec{E} \cdot \vec{v}_{\text{ion}} = 0$.

wave equal, and assume that the wave is driven by some external source. The initial moment of overlap between the ion and the wave then determines the phase difference throughout their interaction. The energy exchange is determined by integrating $\vec{F} \cdot \vec{v}_{\text{ion}} = q\vec{E} \cdot \vec{v}_{\text{ion}}$ during their overlap. Three specific cases are shown in Fig. 2(c). When the phase difference is zero, then the wave always exerts a force on the ion that is parallel to its velocity and as a result the ion gains energy proportional to $\Delta W = qEv_{\text{ion}}$. An initial phase difference of 90° means that the integrand ($q\vec{E} \cdot \vec{v}_{\text{ion}}$, where in this case $\vec{E} \perp \vec{v}_{\text{ion}}$) is always zero and there is no energy exchanged between the ion and the wave. The final extreme result is observed when the phase difference is 180°, resulting in a reduction of the ion energy. This represents the concept of wave-particle resonance, which occurs when the phase differences are preserved throughout the interaction. This phase difference allows some resonance conditions to maximize the energy transfer between the particles and the waves.

Plucking magnetic field lines

A ubiquitous plasma wave is the Alfvén wave, named after Hannes Alfvén, who was awarded the Nobel Prize for his work in developing the field of plasma physics (at the time this was the study of conducting fluids, or magnetohydrodynamics, and it included research in liquid metals as well as

plasmas) [1]. Alfvén waves are transverse electromagnetic waves that can be found in any plasma in the presence of a magnetic field. Consider a magnetic field line to be equivalent to a guitar string, perturbing this field line in a direction transverse to itself, i.e., plucking the string, will cause an Alfvén wave to propagate. The speed at which an Alfvén wave propagates along a magnetic field line is also calculated in fashion similar to the situation encountered for a wave on a string, with the magnetic field amplitude being equivalent to the tension in the string, and the plasma mass density being equivalent to the string's mass density.

Plasma waves can either be purposely applied, or occur naturally. Injecting electromagnetic waves at frequencies that match the gyration frequency is used in industry to heat electrons for plasma processing [2], and in fusion experiments to heat electrons and ions to thermonuclear temperatures. In nature, cyclotron resonance with Alfvén waves plays an important role in heating the solar corona [3].

A special class of Alfvén wave, the Alfvén eigenmode, exists in tokamaks due to the finite plasma boundaries and periodic boundary conditions imposed by the toroidal geometry and magnetic field profile. This geometry results in the plasma's index of refraction also being periodic. In a fiber optic cable, a periodic index of refraction results in Bragg reflection, which causes some wavelengths of light to exist as standing waves inside the fiber without actually propagating through it. Alfvén eigenmodes exist in equivalent wavelength band gaps in the tokamak and there is an incredibly diverse range of different types according to the particulars of the plasma parameters [4].

In a tokamak reactor, the fusion-produced alpha particles resulting from the use of deuterium and tritium are born with an energy of 3.5 MeV (5.6×10^{-13} J, where standard plasma physics notation uses electron-Volts for both energy and temperature) in a background thermal plasma featuring a temperature up to 50 keV (5.8×10^8 K). The fusion alpha population in those devices can drive Alfvén eigenmodes. Research tokamaks do not generally use tritium because of the expense, though there have been a few cases in the past (and near future) in which deuterium-tritium plasmas were studied. Typical tokamak plasmas primarily use deuterium as the working gas, and employ many different heating methods to reach the many thousand electron-Volt temperatures of interest for experiments. The heating methods of neutral beam or radio frequency wave injection generate energetic ions in the plasma, and these energetic ions can also excite Alfvén eigenmodes. A neutral beam injects high energy neutral particles into the plasma (e.g., energies up to 1 MeV), but these neutrals ionize quickly and become energetic ions. Some energetic ions transfer energy to a wave and cause it to increase in amplitude, while others take energy from the wave, and yet others may experience a small energy exchange but a significant orbit perturbation as they transition from a passing orbit to trapped.

Located near the ample deuterium reserves of the Pacific Ocean in San Diego, California, the DIII-D National Fusion Facility is home to the DIII-D tokamak [5]. Experiments in this medium size tokamak (central toroidal magnetic field of $B_\phi = 2.1$ T, $R_{\text{major}} = 1.7$ m, and $a = 0.7$ m) can produce Alfvén eigenmodes using neutral beams that provide up to 20 MW of heating power through the injection of deuterium at a typical energy of 80 keV.

The Alfvén eigenmodes produce measurable fluctuations in magnetic field, electron density, and plasma potential and temperature. These fluctuations are detected by an array of diagnostic systems, and results from a particularly powerful temperature imaging system are shown in Fig. 3.

This system measures the cyclotron emission of electrons (which is the temperature dependent quantity) across a wide two-dimensional space of the plasma cross-section. Importantly, the two-dimensional measurement set allows for rigorous comparison with the theoretically expected wave structures. For the field of plasma physics, this represents an exciting advance as plasma fluctuation diagnostics have evolved from simple time series measurements, to one-dimensional profiles along R_{major}, to the two-dimensional capabilities of present day.

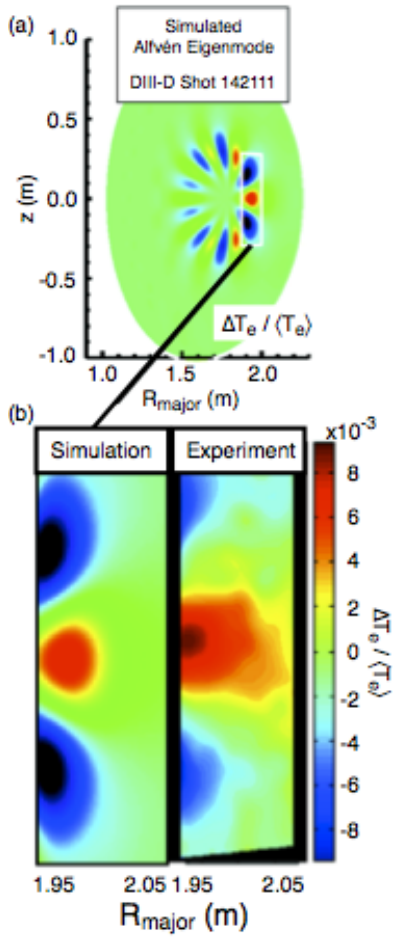


Figure 3: Measurements and simulation of an Alfvén eigenmode in a tokamak experiment. (a) Simulated electron temperature fluctuation pattern of an Alfvén eigenmode calculated by the NOVA code [C.Z. Cheng, Phys. Rep. **211**, 1 (1992)] in DIII-D shot 142111. (b) Zoomed-in view comparing the simulated and measured structure of the wave including the amplitude of its temperature fluctuations. (Adapted from B.J. Tobias, et al., Phys. Rev. Lett. **106**, 075003 (2011).)

Simulations are advancing to keep pace with the increasing fidelity of experimental results. The simulation of Fig. 3 produces an expected Alfvén eigenmode based on experimentally-determined inputs. These inputs include plasma properties such as the magnetic equilibrium profile, allowing for the determination of all the wavelength band gaps in which the eigenmodes may be excited. Increasingly, simulations are moving to include details of the energetic ion distribution and the resulting transport, an important output used in extrapolations to ever more reactor-relevant tokamaks.

A tale of loss

Combining these diagnostic and simulation capabilities has been necessary to understand cases of energetic ion loss in DIII-D in terms of the phase relationship between the ions and the individual Alfvén eigenmodes. Ions resulting from neutral beam injection drive a large population of Alfvén eigenmodes, as indicated by the set of coherent features in the electron density spectrogram of Fig. 4(a). The density measurement is made by a mid-infrared laser interferometer which measures the line-integrated fluctuations in the plasma index of refraction caused by wave induced electron density fluctuations.

Another diagnostic system measures the energetic ions that are lost to the outer wall, and some of the Alfvén eigenmode frequencies are apparent as seen in Fig. 4(b). In this experiment, the loss flux includes a set of coherent frequencies that match some of the Alfvén eigenmode frequencies, and these coherent losses are only observed during the injection of neutral beam #1 [6]. While other beams inject throughout the entire time of this plasma, the use of the beam #1 always correlates with the coherent losses.

This scenario emerges due to the unique phase relationship between a subset of the Alfvén eigenmodes and those ions originating from neutral beam #1. The duration of the beam (20 ms) exceeds the period of the Alfvén eigenmode (8.5 μs) and, therefore, its injected particles sample the full range of possible wave phases. Some of these phase relationships result in the ion being pushed outward and eventually lost to the wall. Others results in the ion being pushed inward, and the combination of all the phase differences results in the energetic ion loss signal fluctuating at the wave frequency. A theoretical description of this short-lived, highly-perturbative, resonant interaction is given by Zhang and colleagues [7].

A graphical depiction for one such ion-wave resonance is shown in Fig. 4(c) for the 117 kHz wave that is highlighted by the green rectangle in Figs. 4(a,b). Three contours of the wave represent its normalized electron temperature oscillation. These contours are taken in the Rz-plane of the tokamak for which the mode structure is evolved self-consistently according to the toroidal position. Each contour also represents the time evolution of the wave, where the elapsed time is set according to the time of flight of the energetic ion whose orbit is also shown. The ion begins in one of the yellow nodes of the wave at time $t = 0.00$ μs. The ion will stay in the region of this wave node throughout its entire time of physically overlapping with the wave. Essentially, the phase angle difference between the two is constant and the resonance allows the wave to push the ion in a particular direction.

Is this about ITER?

Energetic ion effects are studied in present day tokamaks because the physics understanding gained directly translates to future devices that more closely approach the parameters needed for a reactor. The next step in magnetic confinement fusion is taking shape in the form of ITER [8], which will be the first tokamak that produces many times more fusion power than it consumes. ITER will be a burning plasma tokamak, i.e., after reaching fusion temperature, the fusion alphas will maintain the plasma at that temperature. Will these alphas also produce Alfvén waves that push them out of ITER before they deposit appreciable energy to the thermal plasma?

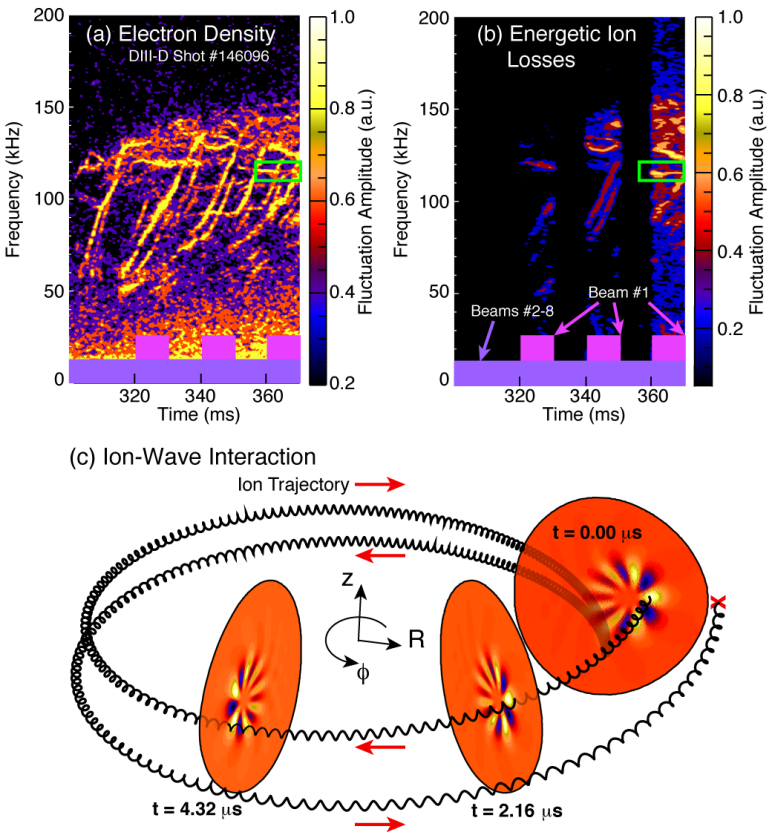


Figure 4: Observations and modeling of energetic ion losses in the DIII-D tokamak. (a) A spectrogram of electron density fluctuations across the entire plasma identifies a dense zoo of coherent fluctuations known as Alfvén eigenmodes. These include both the fixed frequency features, and also those that demonstrate an upward frequency sweep as time progresses. (b) Energetic ion losses are measured at the outer tokamak wall, but coherent features matching the wave frequencies only appear during injection of neutral beam #1, even though combinations of the other beams are injecting throughout this entire time. (c) The coherent losses occur because that neutral beam injects particles such that they ionize with a particular phase angle relationship with respect to the Alfvén eigenmodes. In this panel, normalized electron temperature fluctuations of the 117 kHz eigenmode [enclosed by the green rectangles in panels (a) and (b)] are shown in cross-sections where each contour evolves the wave structure in space and time. A single ion trajectory is shown with its spatiotemporal position in the same reference as the wave. This ion is in resonance with the wave as indicated by the fact that it passes along the same lobe of the wave at all points of interaction, i.e., the phase difference between the ion and the wave is constant. This particular ion is a trapped orbit that features a bounce point behind the first contour and eventually makes it way out of the tokamak to the loss detector system indicated by the red ×.

ITER is one of the greatest engineering endeavors of all time. Its challenge mirrors that of another incredible engineering feat, the Apollo mission. Whereas the Apollo mission sought to send humanity out into the greater universe, ITER seeks to bring that universe, in the form of a star, to Earth. The peak total rated thrust of the Saturn V rocket was 3.3×10^7 N; the structure containing the central magnet of ITER is designed to withstand 6.0×10^7 N. At a temperature above 20 keV, ITER's plasma will be an order of magnitude hotter than the center of the Sun (2.3×10^8

K compared to 1.5×10^7 K). Existing tokamaks are also capable of surpassing solar temperatures, but ITER will be the first to maintain such a state, heated by fusion alpha particles, for minutes or hours.

Figure 5 provides perspective for ITER's unique scale, while also highlighting its familiar physics, by showing its Rz-plane cross section alongside those of three present day tokamaks. Each contour represents the temperature fluctuation pattern of one kind of Alfvén eigenmode. These modes are measured in the NSTX [9], DIII-D [10], and JET [11] tokamaks, and that understanding is used to predict their behavior in ITER [12].

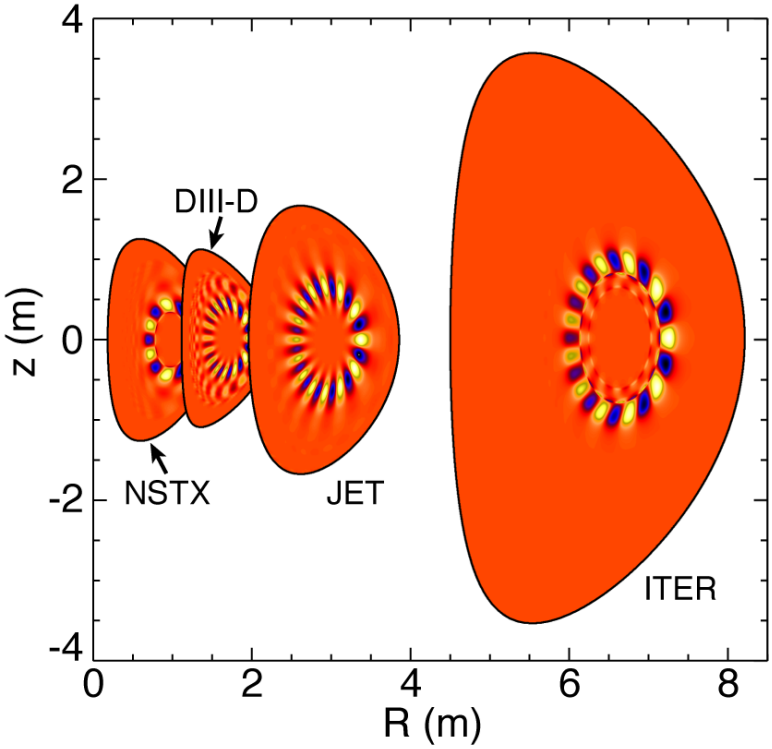


Figure 5: Plasma cross-sections from a set of present day tokamaks alongside the projected ITER scale. The color contours represent the normalized temperature fluctuations corresponding to an Alfvén eigenmode. For NSTX [9], DIII-D [10], and JET [11], these modes are measured and their fundamental structure is well understood. Such experiments lead to the formulation of expectations for how fusion alpha particles (and neutral beams with an energy of 1 MeV) may produce similar waves in ITER [12]. Studying these physics issues in multiple tokamaks is necessary to improve predictive models that are applied to ITER, which, as the Figure shows, is a tokamak on a scale beyond anything previously built.

A strong foundation

The concept of a charged particle orbit phase averaging over a wave field is foundational in plasma physics, with broad applicability to both natural and laboratory plasmas. The most powerful theoretical descriptions of the plasma state utilize averages over orbital motion. Often the processes of greatest interest – such as spatial transport or loss of energy from the system – occur over a timescale that is long compared to the orbital motion. By carefully averaging over fast timescales,

theories known as "gyrokinetics" reduce the dimensionality of the system yet retain the phase-averaged effects associated with the rapid orbital motion [13]. This reduction in dimensionality enables realistic simulations of wave-particle phenomena in fusion devices and natural plasmas.

Theories of the scattering of cosmic rays by galactic magnetic fields incorporate the same physics [14]. High energy cosmic rays orbit through the galaxy, interacting with packets of magnetic fluctuations produced by Alfvén waves. Owing to phase-averaging, wave packets with wavelengths that are small compared to the orbital radius have little effect. The deflections are greatest when the gyration radius of the cosmic ray is comparable in size with an Alfvén wave packet. This process is analogous to the tokamak experiment, but on a galactic scale.

Back in the laboratory, an experiment performed in a plasma with a linear magnetic field configuration, the Large Plasma Device at UCLA [15], illustrates this fundamental phase-averaging process (Fig. 6) by systematically varying the wave structures and ion orbit scales. In one set of experiments, ions of fixed gyro-orbit size are shot past plasma waves of differing scales. When the wavelength is much smaller than the gyro-orbit, then the particle transport, or kick, decreases because the ion averages over the wave fields. In a separate set of experiments, the scale of the plasma wave is held fixed while the ion orbit is scanned to considerably larger scale. Here, too, the resulting ion transport decreases. This is a fundamental plasma behavior that is also observed in periodic magnetic configurations [16]. A key consideration is the wavelength of the mode relative to the orbital motion. Modes with very short wavelengths have little effect: the particle "sees" rapid changes in phase that average out. In most circumstances, the exchange of energy and momentum are maximized when the wavelength and orbital size are comparable.

The electromagnetic dance

Sensitive phase dependencies dictate the interactions between electromagnetic waves and charged particles in magnetically confined plasmas. Of particular relevance to nuclear fusion, Alfvén eigenmodes produced in tokamaks have the potential to increase energetic ion transport beyond levels that would allow net energy output. Experiments are driving improvements in cutting edge simulations that predict plasma behavior in basic plasmas, astrophysical plasmas, and ITER-scale fusion plasmas. Understanding processes that expel high energy ions in existing tokamaks leads to the development of pathways to avoid them in next-step devices. For example, seemingly small changes to the magnetic equilibrium of a tokamak (possibly achieved through the injection of waves at the electron cyclotron frequency) can significantly alter the band gaps of the Alfvén eigenmodes and reduce their transport effects without great changes to the thermal plasma.

As with all scientific work, the development of controlled nuclear fusion improves our physics understanding of the greater world in ways initially unforeseen. While this electromagnetic dance is an important issue for fusion energy development, the ion and the wave are unaware of our plans, and their behaviors are indicative of physics processes that occur throughout the known universe.

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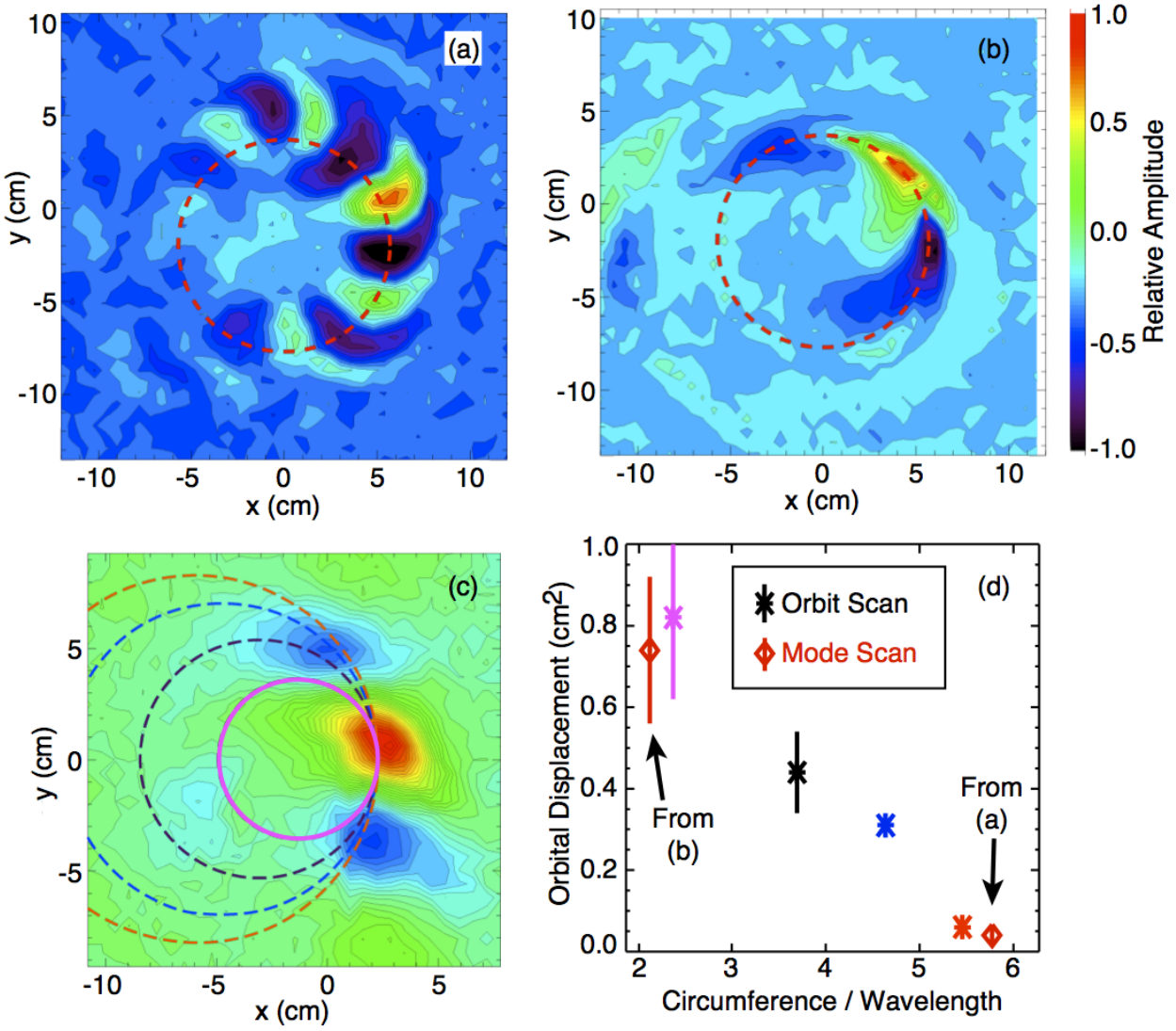

Figure 6: Experimental results from the Large Plasma Device at UCLA illustrate the ability of particles to phase-average over the fluctuations associated with a plasma wave. A collimated, mono-energetic beam of high-energy ions is launched in a uniform solenoidal magnetic field. These ions are depicted schematically as circles indicating their gyro-orbits. Electrostatic fluctuations, represented by the color contours, are produced by creating plasma pressure gradients (e.g., using a physical object to create a sharp density perturbation), then as the ions traverse these fluctuations their deflected trajectories are measured. In one version of the experiment, panels (a,b), the orbit size (red dashed circle) is held constant but the wave structure is varied. Another version, panel (c), varies the orbit size while fixing the wave structure. Both experiments show, panel (d), that the orbital deflections (colors matching the orbit size in the other panels) are greatest as the mode structure and orbit size become comparable.