plasma disperses.[3,4]

Figure 1 captures the first few seconds in the evolution of a single trail detected 12 July 2005. The thin streak is the front edge of the plasma created during the few hundred milliseconds the meteor takes to plow through the lower thermosphere. Behind the ionization front, hot gas and electrons flow too smoothly for radio waves to coherently reflect changes in the dielectric constant, so the signal vanishes. But plasma instabilities driven by the density gradient and by complex electric fields set up between magnetized electrons and collisionally demagnetized ions quickly give rise to turbulence and irregular clumps of plasma that align along Earth's magnetic field.

Peru's JRO sits directly on the geomagnetic equator. Its radar points nearly perpendicular to the field lines, so the scattering cross section is optimal for detecting that blobby aftermath. Also important for observations, JRO's antennas can be partitioned into a phased array capable of interferometry. By beating the phase of one radar channel against another, the team measured not just the position of each part of a plasma trail over time but also its bearing. To get the velocities, they fit the slope of the phase differences between the channels as a function of time.

The interferometry measurements allowed the researchers to build a complete vector profile of the horizontal wind speeds at different altitudes with a spatial resolution less than a few hundred meters—comparable to that from rocket tracer experiments. The profile can also be derived repeatedly on a nearly continuous basis. During the hours before dawn when Earth runs headlong into meteors, JRO detects one every half second or so. Figure 2 shows the proof-of-principle plots of wind vectors constructed from data of many meteors intercepted over several minutes one night in 2005.

Remarkably, Oppenheim's team waited nearly four years before analyzing its interferometry data. "Plasma instabilities were on my mind, not winds," Oppenheim confesses. "I never guessed that the changes in phase from what is mostly turbulence would be as clean as they turned out to be."

Mark Wilson

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Resonant radio waves rotate tokamak plasma

An experiment at MIT's Alcator tokamak has demonstrated a technique that could make fusion plasma easier to confine.

In its original and still-unrealized conception, a tokamak traps steadily fusing plasma within a helical magnetic field that winds around, and delimits, a bagel-shaped confinement vessel nested inside a metal chamber.

Two components create the helical field: a toroidal component, which arises from ring-shaped magnets positioned at regular intervals around the chamber, and a poloidal component, which arises from the circulation of the plasma's fast electrons and slower ions.

Confinement can never be perfect because Coulomb collisions cause electrons and ions to drift across magnetic field lines.

In the mid-1990s, plasma physicists began to realize that a range of instabilities could be mitigated if the current-carrying plasma were made to rotate inside the chamber. The stabilization would be more effective if the rotation had shear, for then it could tear apart nascent eddies before they grew to burst-out size.

Experiments at various tokamaks around the world found that plasmas rotate in response to the various methods used to heat them. That finding is not perhaps surprising. At tokamaks, fusion temperatures are reached by irradiating the plasma with energetic beams of neutral particles or with radio waves.

Without any deliberate rotation-inducing intervention, Alcator plasmas rotate at speeds of about 10 km/s. Now, a team from MIT led by Yijun Lin and John Rice has demonstrated a method for spinning a plasma twice as fast.[1] The method relies on transferring momentum from VHF radio waves via a resonance to minority helium-3 ions seeded in the plasma.

Exactly how the waves rotate the plasma is unclear. Nor do the MIT researchers know how much stability the waves bestow. Even so, the method looks promising for helping to stabilize ITER, which in a few years' time will become the world's biggest tokamak.

Heating plasma

An operational run at a current research tokamak or a future tokamak-based power station begins with the injection of fuel at high vacuum into the chamber. Because of its favorable cross section, a mixture of deuterium and tritium is the likely choice for tokamak reactors. For tokamak experiments, deuterium is typically used.

Despite starting off at room temperature, the fuel contains a modest fraction of free electrons. When a huge electromagnet at the center of the chamber is switched on, the free electrons in the plasma respond like the conduction electrons in the secondary coil of a transformer: They flow. The magnetic field corrals the electrons well enough that they slam into neutral ions, setting off an avalanche of ionization and setting up the so-called plasma current, which gives rise to the poloidal confinement field.

The collisions that ionize the plasma also heat it—to about 10 million K. At that temperature, the plasma's electrical conductivity is about the same as copper's. Attempts to further heat the plasma stall because the plasma's conductance rises with temperature as $T^{3/2}$.

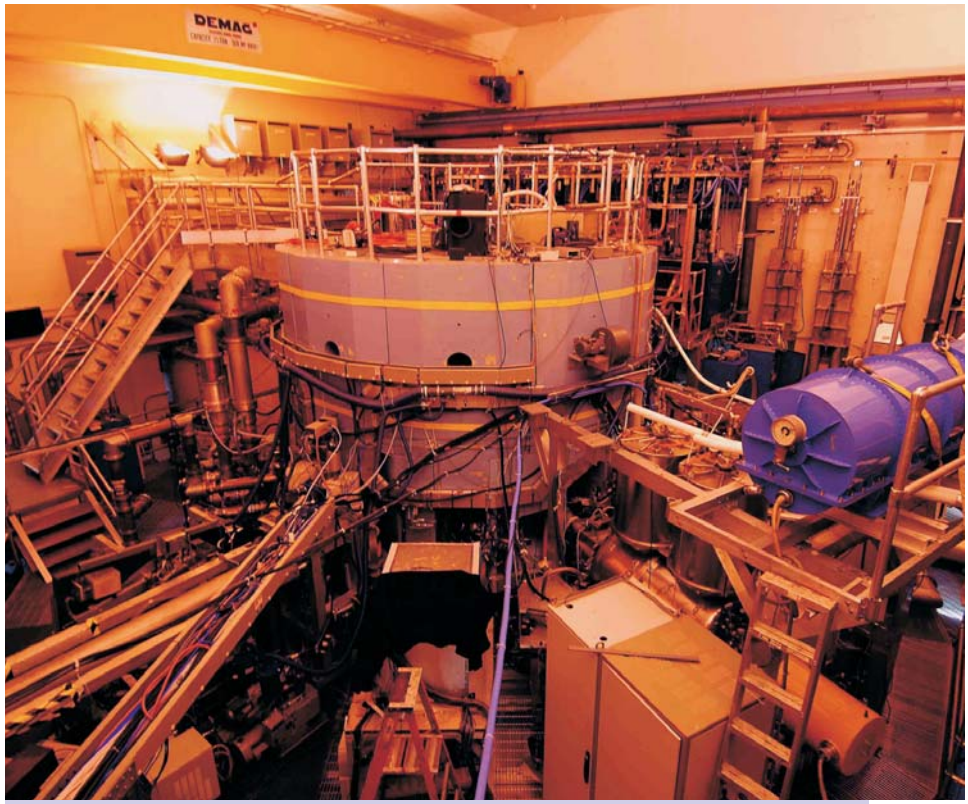
That dependence is unfortunate, because an additional order of magnitude in temperature is needed to ignite the fuel and sustain fusion. To supply the extra heat, two principal methods are employed. The first is to fire into the plasma a high-energy beam of neutral atoms. Being neutral, the atoms are not deflected by the confining magnetic field. But once they penetrate the plasma, they collide with electrons, become ionized, and give up their energy. It was with neutral-beam injection that two tokamaks—JET outside Oxford, England, and TFTR outside Princeton, New Jersey—achieved fusion temperatures in the 1990s.

The other method is to irradiate the plasma with radio or microwaves. Energy transfer occurs at one of three principal resonant bands: ion cyclotron

(~100 MHz), electron cyclotron (~100 GHz), and an intermediate frequency called the lower hybrid band (~5 GHz).

Once the 200-MK fusion temperature is reached, energetic byproducts of fusion act as heat sources. In the case of D–T fuel, 3.5-MeV alpha particles heat the plasma, whereas the other byproduct, 14-MeV neutrons, escapes. If the neutrons are caught in a blanket, their energy can ultimately be converted to electrical energy using a conventional steam-powered generator. Steep gradients in the plasma's pressure and density provide enough free energy to drive as much as 80% of the plasma current; microwaves of particle beams can provide the remaining 20%.

No tokamak has ever reached the so-called burning plasma regime, in which the plasma heats itself. Scaling laws derived from past and present tokamaks imply that an ITER-sized device will reach the burning plasma regime. But to sustain that regime—and maybe just to attain it—plasma instabilities must be suppressed. That's where rotation might come into play.



The fusion chamber at MIT's Alcator tokamak is located inside the gray, hot-tub-shaped, concrete-clad structure.

Ion cyclotron mode conversion

Rotating a plasma is akin to stirring soup: You need a spoon and energy. Lin, Rice, and their colleagues seeded their deuterium fuel with a small admixture of helium-3 ions to serve as a spoon. For the stirring energy, they used radio waves tuned to the helium ions' cyclotron resonance, which, for Alcator's 5-tesla magnetic field, is around 50 MHz.

Because of their significantly different mass-to-charge ratio, the $^3He^{2+}$ ions can be in resonance with the waves when the majority D^+ are not. And because the magnetic field has a gradient, the frequency of the radiation can be adjusted to resonate with $^3He^{2+}$ ions at specific locations in the plasma.

The ability to target the radiation is crucial. Where the waves' momentum ends up and whether it's dissipated before it can rotate the plasma depend on which of several magnetohydrodynamic processes the waves trigger. And that depends on local conditions. The theoretical picture is incomplete, but the MIT researchers believe their input waves are converted into another type of wave that entrains the $^3He^{2+}$ ions, which then impart some of their momentum to the D^+ ions.

Another minority species, argon, provides the diagnostic for measuring flow. Under the temperatures and pressure that prevail in Alcator, argon is stripped of all but one or two of its electrons. The spectra of hydrogen- and helium-like Ar ions are characterized so well that departures from their rest-frame values serve as accurate Doppler probes of motion. Line widths probe temperature.

The MIT team tested a range of minority concentrations and found that a 10% admixture of ^3He provides the biggest rotational boost—from 10 km/s to 70 km/s using 3 MW of VHF power.

Proving that rotation does indeed suppress turbulence requires probing the velocity field on small scales. That goal awaits future experiments, but the MIT team did find indirect evidence. In general, turbulence mixes momenta and flattens gradients. Line widths indicate that the temperature gradient of the optimally seeded plasma was steeper than that of an otherwise similar plasma.

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physics update

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Statistically speaking, Indus script is a language. The Indus Valley civilization, in what is now eastern Pakistan and northwestern India, flourished circa 2500–1900 BCE. To this day its writing, as in the figure, has not been deciphered. Indeed, scholars are unsure if the Indus script represents a language. Other, superficially similar ancient texts are thought to be either rigidly prescribed strings, such as a hierarchical list of deities, or nonlinguistic strings in which order is unimportant. Now computer scientist Rajesh Rao (University of Washington) and colleagues from several Indian institutions have studied the correlations of neighboring tokens (symbols or words) with a statistical tool—the conditional entropy—that reliably distinguishes natural languages from token strings in which the ordering is rigid or unimportant. The Indus script, they conclude, has the structure of a language. Like the conventional entropy, the conditional entropy involves the logarithm of a probability—in this case the conditional probability that a specified token appears, given its