# Everything is plasma

A plasma is what you get if you heat matter until it breaks apart into a gas of charged particles. It is, perhaps, the ultimate many-body system, as long-range interactions make possible countless patterns of collective dynamics. Plasma physics is an enormous sub-field of physics, with physical plasmas existing in anything from metals to the Earth's upper atmosphere to the interiors of stars. All of interstellar space is plasma. To a first approximation, one might say, everything is plasma.

The articles in this Insight on fusion research illustrate a common theme in plasma physics — the key to most progress lies in understanding instabilities, or the myriad ways that plasmas do unexpected things. In principle, achieving controlled fusion should be easy — just heat a contained plasma of fusionable material such as hydrogen to extreme temperature, enough to make fusion reactions likely, and then hold it there for a while. Current programmes mostly work with plasmas mixing deuterium and tritium, as the reaction cross-section is much larger than for ordinary hydrogen. Even so, success remains elusive. Reading this issue is to take a tour through a veritable zoo of ways in which plasma refuses to stay in the tidy symmetric and ordered states that would make fusion a reality.

Efforts in inertial confinement fusion attempt to heat a plasma to ignition temperature by compressing it using intense laser pulses, either directly, laser-on-plasma, or indirectly, by first using the laser light to produce a bath of X-rays, which then hit the target. The inertia of the plasma itself, in this case, is used to keep the plasma confined. Good enough compression would produce ignition, and research has made impressive achievements: temperatures in the tens of millions of degrees Celsius in plasmas under pressures of a hundred billion atmospheres. Yet a host of instabilities get in the way.

On page 435 Betti and Hurricane describe the prominent ones — principally the ablative Rayleigh–Taylor instability, which tends to destroy the spherical symmetry of the imploding plasma, limiting the resulting temperature and pressure achieved. The Rayleigh–Taylor instability is what happens when a layer of heavy liquid rests atop a lighter one, and fluctuations along the layer, driven by gravity, grow into penetrating fingers of the heavier fluid, leading to intense mixing. In the fusion setting, it is the light-ablated plasma driving compression of the denser core plasma. Alongside the Rayleigh–Taylor instability, laser plasma instabilities — caused by direct resonant interactions of the laser with plasma modes — also play a role in limiting the conditions achieved.

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Understanding these instabilities has given researchers the means to defeat them, at least partially, either by engineering the plasma to make the instability less explosive, or by reducing the seed fluctuations on which it acts. For the Rayleigh–Taylor instability, the engineering has come through tuning the characteristics of the laser pulses themselves. These pulses have a structure, taking three or four steps up to peak power within their typical 10 ns lifetime. The first step — known as the foot — strongly influences the growth rate of the Rayleigh–Taylor instability. High-foot experiments have reduced Rayleigh–Taylor growth significantly, although this involves a trade-off, as the implosion results in somewhat lower overall compression.

An analogous story holds for magnetic confinement fusion, which aims to confine the plasma in magnetic bottles of typically toroidal geometries. In the tokamak design, the magnetic field lines form a helical path around the toroid, and guide plasma particles to spiral around these lines, thereby (mostly) remaining trapped and away from the physical walls of the container. Again, sufficient heating — either with radio-frequency waves or through injected neutral beams — should drive the plasma towards ignition. Here too research has made steady progress, routinely producing plasmas with temperatures of 100 million degrees Celsius, holding them for several seconds, and nearly achieving the break-even point where energy produced from fusion surpasses that needed to heat the plasma. Yet instabilities here also get in the way of ultimate success.

In this case, as Ongena *et al.* describe on page 398, key instabilities issue from the fluid-like behaviour of the plasma within the magnetic trap. To a good approximation, the hot plasma inside a tokamak acts like an electrically conducting fluid, as described by the equations for ideal magnetohydrodynamics. If the plasma pressure isn't too large, the plasma can circulate in a stable equilibrium in which the force the magnetic field exerts on plasma currents balances that due to the gradients of plasma pressure. But instabilities creep in if the plasma pressure gets too large — specifically, if the average pressure exceeds a few per cent of the pressure associated with the magnetic field. One of the most important of these is the kink instability, in which the core plasma loses symmetry and shifts from the toroidal centre. It can result in abrupt 'disruptions' in which the plasma current drops in less than a tenth of a second.

As in inertial confinement fusion, researchers have made good headway in understanding these and other instabilities, and so learned a little about how to suppress them, or at least weaken their effects. For example, external coils can be used to control and steer magnetic-field configurations identified with instabilities once they've begun to grow. As Ongena and colleagues note, however, all of this may become a good deal more complicated in future devices such as ITER, due to its increased size, and the influence of true heating within the plasma, which may well kick up further instabilities not yet envisaged. Each new instability discovered is a set-back, yet also a necessary step along the way to better understanding and ultimate success.

These projects — and the many other schemes under development to achieve fusion in less traditional designs — illustrate how much basic physics pours out of difficult but ambitious engineering projects. Fusion aims to re-create on Earth the power source that fuels the stars, yet without the aid of extreme gravity. Success will no doubt come, eventually, offering humanity a virtually unlimited source of cleaner energy. The achievement will be a historic scientific success, and set the stage for a perhaps even larger challenge — seeing if humanity can learn to use that energy wisely. ❐

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