AIP

PHYSICS
TODAY

Magnetically Confined Fusion Breaks a Pressure Barrier FREE

If plasmas can be held at higher pressures, the potential fusion power output is significantly greater.

Barbara Goss Levi

Physics Today **54** (9), 18–20 (2001);
https://doi.org/10.1063/1.1420500

and superconductivity coexist at the same temperature and pressure, but in different atomic planes.

Says Cambridge University's Peter Littlewood: "There's a lot of evidence that magnetic fluctuations of various kinds are promoting superconductivity and so, rather than being just an isolated phenomenon, it's beginning to look like something rather generic."

CHARLES DAY

References

1. S. S. Saxena et al., *Nature* **406**, 587 (2000).
2. C. Pfleiderer et al., *Nature* **412**, 58 (2001).
3. K. B. Blagoev, J. R. Engelbrecht, K. S. Bedell, *Philos. Mag. Lett.* **78**, 169 (1998).
4. D. J. Singh, I. I. Mazin, http://arXiv.org/abs/cond-mat/0107610.
5. K. B. Blagoev, J. R. Engelbrecht, K. S. Bedell, *Phys. Rev. Lett.* **82**, 133 (1999).
6. T. R. Kirkpatrick, D. Belitz, T. Vojta, R. Narayanan, http://arXiv.org/abs/cond-mat/0105627.
7. K. Shimizu et al., *Nature* **412**, 316 (2001).

Magnetically Confined Fusion Breaks a Pressure Barrier

If magnetically confined plasmas are to burn, producing energy by the fusion of light atomic nuclei, they must operate at high pressures, or more precisely at a high β, where β is the ratio of the plasma pressure to the magnetic-field pressure. Having a high β is crucial because the fusion power density varies as the square of the numerator, while the device's costs and complexity increase with the denominator.

> If plasmas can be held at higher pressures, the potential fusion power output is significantly greater.

Throughout the 1990s, experiments conducted on tokamaks—popular, toroidally shaped magnetic "containers"—suggested that the achievable value of β was confined below a certain limit, although some runs showed that the plasma pressures could rise slightly above this limit, at least transiently. Now, researchers working at the General Atomics (GA) DIII-D tokamak in San Diego, California, have shown that, by rotating the plasma about an axis through the center of the torus and applying feedback to correct for imperfections in the magnetic field, they can attain a value of β that is twice the previous limit and close to the maximum one can expect for an ideal device. Stewart Prager of the University of Wisconsin views the work as a "beautiful experiment showing how you can surpass a fundamental limit."

The DIII-D National Magnetic Fusion Facility is operated by GA for the Department of Energy. The research team came from GA, the Princeton Plasma Physics Laboratory, and Columbia University. Larry Johnson of PPPL announced the new results at the European Physical Society Conference on Controlled Fusion and Plasma Physics held in June in Madeira, Portugal.[1]

The success of the rotation strategy was good news for all those working on magnetic confinement schemes that are subject to similar kinds of pressure limits. Those schemes include spherical toruses (see PHYSICS TODAY, May 1999, page 19), advanced tokamaks, and reversed-field pinch configurations. The new results help validate the decision of many designers to build the capability of rotating a plasma into many new devices.

Masa Ono of the PPPL's National Spherical Torus Experiment, which began operation in 1999, said his team plans to try rotating their plasma in about a year. Researchers at another new spherical torus, MAST, at the Culham Science Center in the UK, are just starting to explore the limits on β in their device. While designed to have a higher β value than the DIII-D tokamak, spherical toruses are at an earlier proof-of-principle stage.

The impact of the new work on stellarators is less clear because these devices have three-dimensional magnetic field configurations; they have no symmetric coordinate in their physical shape, and hence no natural direction of undamped rotation. However, a medium-scale stellarator experiment being proposed for PPPL is quasi-axisymmetric in a certain coordinate system and should allow rotation similar to that in a tokamak.

Kink instabilities

In a tokamak, coils are wound around a doughnut-shaped form to create a toroidal magnetic field, with field lines describing circular paths within the torus. A current inside the plasma then generates a poloidal field that wraps the short way around the torus, producing a net helical magnetic field that

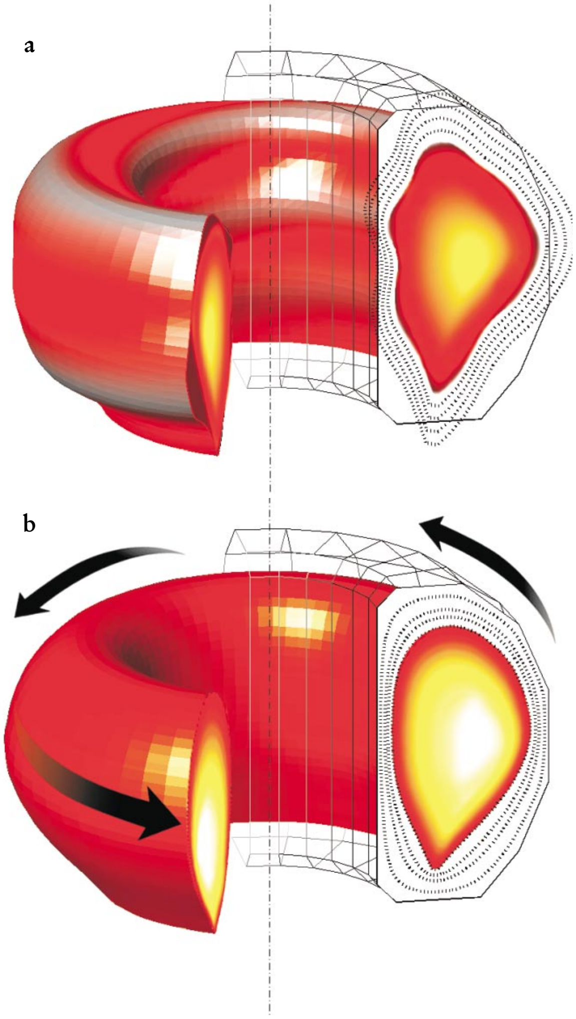

FIGURE 1. PLASMA pressure profile is stabilized by rotation and feedback. Red is lower pressure; white and yellow higher pressure. (**a**) Irregularities (exaggerated by a factor of 10) appear at the edges of the profile once the pressure is raised above the point where instabilities set in. (**b**) During rotation, magnetic fields from feedback coils push back on the distortions, smoothing the profile and allowing the stabilizing rotations to continue. (Figure courtesy of General Atomics.)

confines the plasma.

The upper limit on β is determined by the onset of instabilities—that is, distortions in the density profile of the plasma. The most troublesome instabilities in a tokamak are the "kink" modes, in which the plasma develops helical bulges; it then contacts the walls of the chamber and cools quickly because of the influx of material produced by interaction of the hot plasma with the wall.

The limiting pressures dictated by these instabilities were analyzed in the early 1980s by two groups of theorists, who used calculations based on ideal magnetohydrodynamics.[2,3] Although those groups used different approaches, both predicted that β would follow a certain scaling law, varying directly with the plasma current and inversely with the toroidal magnetic field and its linear cross sectional dimension. Experiments since then have largely followed this scaling law, with a constant of proportionality, known as the normalized β, or β_N, that falls close to the value of 2.8 predicted by Francis Troyon and his coworkers at the Ecole Polytechnique Fédérale de Lausanne in Switzerland.[2]

The value of β_N that appears in the scaling law is also known as the "no-wall" limit because the theories assumed free boundary conditions. In reality, all magnetic fusion devices have walls. If such walls were perfect superconductors, they could suppress instabilities by resisting the associated changes in magnetic field, and one could get to a higher pressure before the instabilities arose. By assuming such ideal boundary conditions, Alan Turnbull of GA and colleagues calculated the limit on β_N with an ideal wall, finding it to be about twice the no-wall value.[4]

The resistive walls in most tokamaks can also suppress the instabilities, but only for a limited time—the time for wall currents to decay. After that, the instabilities are free to grow once more. The slowly growing instability is called the resistive wall mode, and its existence was confirmed at the DIII-D facility.[5] Most devices to date have not managed to get much beyond the no-wall pressure limit.

Strategies to stabilize the plasma

How then, experimenters asked, could they tame the instabilities enough to reach a higher β_N? One possibility is to apply feedback to correct for deviations in the magnetic field caused by the instabilities. That's essentially playing the role of a superconducting wall. Andrea Garofalo (Columbia), who is a member of the team that produced the recent DIII-D results, pointed out that feedback schemes are feasible because the resistive walls slow the growth time of instabilities from the microsecond to the millisecond range, just enough for a feedback system to detect and correct them. The DIII-D device is uniquely equipped with such feedback coils, but still the task is daunting.

Another route to higher β_N is to spin up the plasma. Rotation should have the effect of continually refreshing the image currents in the wall, making it more like a superconductor. Although many theorists had looked at that idea, a particularly thorough treatment in 1994 suggested that rotation at a high enough speed could stabilize the plasma.[6]

The DIII-D experimenters tested this prediction. They got the torque required to spin up the plasma from the high-energy beams of deuterium atoms that are sent tangentially into the plasma to heat it. The linear speeds of rotation can get as high as 300 km/s. With such fast rotation, the pressure was indeed above the no-wall limit, but not for long. Too soon, the rotations died out, to the team's surprise and disappointment.

The DIII-D researchers showed that the rotational braking resulted from tiny imperfections in the magnetic field, which are amplified by the plasma.[7] These imperfections are at the 1 gauss level, or 1 part in 20 000 of the toroidal field. The researchers decided to try a feedback scheme to suppress them. Using pickup coils both outside and, more recently, inside, the tokamak chamber, the DIII-D team sensed any perturbations in the field, both in the toroidal

B-Decay Experiments Show Clear Violation of *CP* Symmetry

In March, back-to-back papers in *Physical Review Letters* reported the measurement of *CP* symmetry violation in the decay of neutral B mesons by groups in Japan and California.[1,2] (See PHYSICS TODAY, May 2001, page 17.) Now the word "measurement" has been replaced by "observation" in the titles of two new back-to-back reports[3,4] by these same groups in the 27 August *Physical Review Letters.* That is to say, with a lot more data and improved event reconstruction, the BaBar collaboration at SLAC and the Belle collaboration at KEK in Japan have at last produced the first compelling evidence of *CP* violation in any system other than the neutral K mesons.

The evidence for *CP* violation in the BaBar and Belle experiments is summarized by a nonvanishing value for the measured parameter sin 2β. In March, each collaboration reported that its measured sin 2β was about 1.7 standard deviations above zero. That was encouraging, but not yet convincing.

Now that each experiment has created more than 30 million $B\bar{B}$ pairs in its asymmetric electron–positron collider, the evidence for *CP* violation in B decays is quite compelling. BaBar reports a sin 2β of 0.59 ± 0.15, four standard deviations from zero. With essentially the same quoted uncertainty, Belle reports an even larger *CP* violation, namely sin $2\beta = 0.99$.

If one combines the two results without worrying about the marginally uncomfortable discrepancy between them, one gets a world average of 0.79 ± 0.1. That's in good agreement with the sin $2\beta = 0.7 \pm 0.2$ predicted without much precision by the standard model of particle theory. As the experimental errors continue to shrink with the accumulation of data over the next few years, so will the uncertainty of the theoretical prediction, which actually depends on ongoing worldwide measurements of related but less exotic processes.

So now, 37 years after the unanticipated discovery of a small amplitude for *CP* violation in neutral-kaon decay, we have at last a second arena in which to study this important phenomenon. But the very attribute that suits neutral B mesons so well to this study—namely, the almost maximal value of sin 2β—is not an unmixed blessing. A phenomenon so generously favored by the standard model makes it difficult to glimpse any small nonstandard mechanism that might guide us toward a more encompassing theory. Therefore Belle and BaBar are also seeking to measure smaller *CP*-violating parameters related to rare B decay modes, in an effort to find small departures from standard-model predictions. BERTRAM SCHWARZSCHILD

References

1. A. Abashian et al. (Belle collaboration), *Phys. Rev. Lett.* **86**, 2509 (2001).
2. B. Aubert et al. (BaBar collaboration), *Phys. Rev. Lett.* **86**, 2515 (2001).
3. B. Aubert et al. (BaBar collaboration), *Phys. Rev. Lett.* **87**, 091801 (2001).
4. K. Abe et al. (Belle collaboration), *Phys. Rev. Lett.* **87**, 091802 (2001).

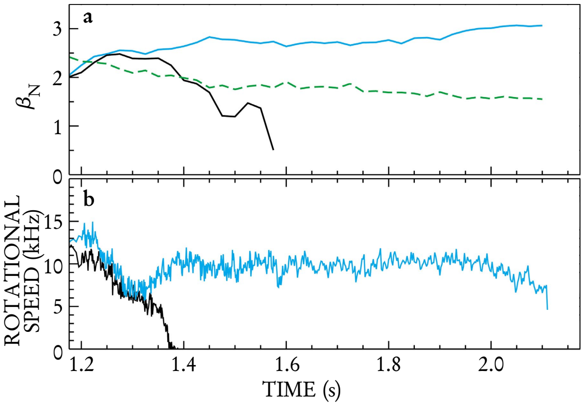

Figure 2. Pressures are higher and rotation lasts longer when magnetic-field feedback corrections are applied to a spinning plasma. (**a**) When feedback is applied (blue curve), the normalized beta β_N rises to twice its no-wall limit (green), whereas it drops to zero without feedback (black). (**b**) The plasma rotates at a nearly steady rate (blue) with feedback; but spins down without it (black). (Adapted from ref. 1.)

and the poloidal directions. These signals activated three pairs of external coils, which applied corrective fields that essentially pushed the plasma back into shape whenever it tried to bulge outward. Figure 1 shows an exaggerated view of the impact of the feedback loops.

In the set of experiments reported in Madeira, the DIII-D team preprogrammed a set of corrections for the active coils based on the feedback required in previous runs. The behavior was essentially the same as with active feedback.

Figure 2 summarizes the results of the rotating-plasma experiment. Early in the run (not shown), the plasma is formed and heated; around 1.2 s, its pressure has built up to just about the stability limit. Feedback is turned on at 1.3 s. The top panel shows that β_N then rises to about twice the no-wall limit. As Richard Buttery of Culham points out, this value is much closer to the upper limit for an ideal conducting wall. So the GA-PPPL-Columbia team has found a way to span the gap between the two limits. The plasma, which had exceeded the no-wall pressure limit for only 0.2 s with no feedback, remains stable at pressures significantly above the no-wall limit for a full second with feedback. In other cases, the plasma has remained stable at high pressure for almost two seconds. Ron Stambaugh, DIII-D program director, asserts that this time is "enormously long compared to the 10–100 μs growth times of instabilities without a conducting wall."

More work ahead

Stambaugh told us that, for the recent work, the device was not set to operate at its peak values for the no-wall limit; the research was more easily conducted at lower values of β_N. Full exploitation of this result requires moving toward higher values. He and his coworkers have already begun such experiments and find essentially the same result: The feedback corrections maintain the rotation and improve stability against pressure-limiting kink modes. They also plan to try to use magnetic-field feedback alone, without rotation, to exceed the no-wall limit. Such research should provide important information for devices whose plasmas cannot be as readily rotated, such as some of the larger devices envisioned for the future.

Barbara Goss Levi

References

1. L. C. Johnson, et al., http://www.cfn.ist.utl.pt/EPS2001/fin/pdf/P4.008.pdf.
2. F. Troyon, R. Gruber, H. Saurenmann, S. Semenzato, S. Succi, *Plasma Phys. Controlled Fusion* **26**, 209 (1984).
3. A. Sykes, M. F. Turner, S. Patel, *Controlled Fusion and Plasma Physics*, Proc. 11th European Conf., Aachen, 1983, S. Methfessel, ed., European Physical Society, Petit-Lancy, Switzerland (1983), Vol. 7D, Part II, p. 363.
4. A. D. Turnbull et al., *Nucl. Fusion* **38**, 1467 (1998).
5. A. M. Garofalo et al., *Phys. Rev. Lett.* **82**, 3811 (1999).
6. A.Bondeson, D. J. Ward, *Phys. Rev. Lett.* **72**, 2709 (1994).
7. A. H. Boozer, *Phys. Rev. Lett.* **86**, 5059 (2001). ■

Element 118 Bows Out

In the spring of 1999, scientists at the Lawrence Berkeley National Laboratory were excited to find[1] three events whose decay chains bore the imprint of the heaviest artificially created isotope to date, with atomic number $Z = 118$ (see Physics Today, August 1999, page 17). In subsequent runs, however, the Berkeley team has not seen any more events like those on which it based its claim, and searches for element 118 have also come up dry at the Laboratory for Heavy Ion Research (GSI) in Darmstadt, Germany; at the RIKEN Accelerator Research Facility in Wako, Japan; and at the GANIL accelerator in Caen, France. The Berkeley experimenters have now submitted a comment to *Physical Review Letters* retracting their published claim.

Group leader Kenneth Gregorich told us that he and his coworkers still don't understand what happened, and they are working to ferret out the problem. In the meantime, Gregorich said, "There's been quite a bit of experimental and theoretical work based on our 1999 data, so that we felt we needed to get the word out." The heavy-ion researchers to whom we spoke congratulate the Berkeley researchers for being straightforward about the misidentification, unfortunate though it was.

The experiment that produced the errant three events was one of the first to be conducted on a gas-filled separator that had been newly installed at the Lawrence Berkeley laboratory. By now, the experimenters there have had two years of experience on the facility, and their procedures and computer codes have naturally evolved. When the subsequent experiments failed to turn up evidence of the earlier decay chains, the group went back to the original data. Analyzing the old data in several independent ways, they did not see the three chains. They are now trying to figure out why the chains showed up in the earlier analysis.

The Berkeley researchers were trying to form the isotope ^{293}118 by the fusion reaction of krypton-86 nuclei impinging on a lead-208 target. Many heavy-ion researchers had discounted the possibility of seeing such a heavy isotope; the synthesis of elements with Z up to 112 had suggested that the fusion cross sections would decrease with atomic number to the point where element 118 would be undetectable. But a theoretical calculation at the time projected a higher production rate for this particular reaction, with a magic projectile, ^{86}Kr, incident on a doubly magic ^{208}Pb target.

Experiments at Berkeley, GSI, RIKEN, and GANIL suggest that the production rates for element 118 on their machines are less than one atom per week. To continue to hunt, Gregorich said, "will take either lots more patience or more sensitive technology."

Barbara Goss Levi

Reference

1. V. Ninov et al., *Phys. Rev. Lett.* **83**, 1104 (1999).