UP THE SCALE WITH Tokamaks

They've climbed a long way since they started in the mid-1960s at the Kurchatov Institute in Moscow. At the top of the slope could be a working fusion reactor.

BY DIETRICK E. THOMSEN

The wind bloweth where it listeth. A thermonuclear plasma is an ionized gas and thus different from terrestrial winds, which are electrically neutral gases. Yet it could readily be said that a thermonuclear plasma bloweth where it listeth, and it usually listeth right out of any apparatus that physicists may have devised in an attempt to hold it.

That's the problem in controlled thermonuclear research: The plasma must be contained at least for long enough for enough fusions to happen so that a practically useful amount of energy comes out. At the same time the plasma must be heated to the ignition temperature proper for the fusion reaction.

Achieving these conditions has proved extremely difficult, much more difficult than many physicists thought it would be when the attempt began about 35 years ago. The public image of the field suffered when the early optimism that had seemed quite well founded at the time was later belied.

In the last few years a new optimism has grown up. It is less theoretical and more cautious and restrained than the earlier enthusiasm, but it centers on a belief that someday there really will be a working fusion reactor.

Speaker after speaker at the recent meeting in New York of the Division of Plasma Physics of the American Physical Society described how his or her particular approach would "scale up" to a reactor. One after another, they stressed the engineering and technical advantages of their designs for a reactor. Ten or 15 years ago such talk would have been the equivalent of picking the flavor of your pie in the sky. Of course no one expects a reactor next year; the most optimistic speak of the middle 1990s. What is significant to those who know the history of the field is that as 1990 approaches, that date does not seem to be receding into the dimmer future.

Because of its history plasma physics is a more empirical science than most. This circumstance has spawned a multitude of approaches to the basic problem. Historically, the magnetic confinement devices came first. A plasma is an electrically conducting fluid, and so a magnetic field should be able to confine a plasma according to the classical theory of conducting fluids that dates from the middle nineteenth century. Only it didn't. The early devices did not work according to classical theory. This was a severe setback and forced the retraction of many early predictions according to which there should have been a working fusion reactor some time ago. A couple of decades of painstaking experiment with gradually changing devices and gradually changing theory brought the present situation and developed, among other things, the class of devices known as tokamaks, which many physicists think contain the germ of the future fusion reactor.

A tokamak is a toroidal or doughnut-shaped vacuum chamber in which the plasma is to be held. The magnetic fields to hold it are generated by coils wrapped around the doughnut to provide forces across the thickness of the doughnut (poloidal field) and around the circle (toroidal field). The term tokamak is made of the first syllables of the Russian words for "toroidal magnetic chamber." Since their invention in the Soviet Union about 15 years ago, tokamaks have proliferated all over the world.

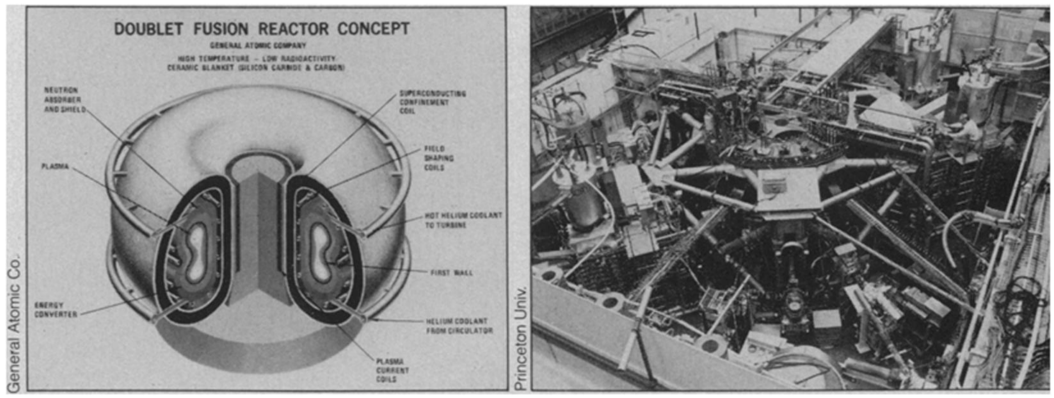
In recent years tokamak watchers in the United States have been giving particular attention to the results of experiments in one toroid—the Alcator at Massachusetts Institute of Technology. According to J. A. Schmidt of Princeton University, who was invited to review the subject for the meeting, the results of Alcator experiments up to 1978 led to a particularly attractive "scaling law."

A scaling law predicts how plasma confinement should improve as various parameters are changed: the ratio between the thickness of the doughnut and the radius of the doughnut, the strengths of the two magnetic fields, the density of particles in the plasma, etc. Schmidt says that recent experiments in several tokamaks (Alcator C, which is the reconstruction of the original MIT Alcator, the ISX-B at Oak Ridge National Laboratory, the Princeton Large Torus at Princeton, Doublet III at General Atomic in San Diego, and others) show that the Alcator scaling law generally works. There are anomalies; there are places where the experiment yields three or four times what theory predicts. These things have to be thought about, but it seems that this kind of scaling is a feasible approach to the design of an ultimate fusion reactor or what is of more immediate interest — a large international tokamak experiment to be called INTOR.

Alcator scaling is related to what is called neoclassical plasma theory. This is the classical theory of electrically conducting fluids modified by what actually happens in a plasma—and modified again and again. Neoclassical plasma theory is not as elegantly and precisely predictive as, for example, the Weinberg-Salam theory is for particle physicists or Newtonian dynamics for the people who calculate spaceprobe trajectories. Neoclassical plasma theory is continually being checked against experiment.

One of the important checks is the study of instabilities. An instability is anything that can disrupt a plasma — some field configuration or resonance that produces an unwanted motion in the plasma and that can grow by feedback until it disrupts confinement by literally driving the plasma up against the wall of the vacuum chamber. B. A. Carreras of Oak Ridge reported on experiments examining the class of magnetohydrodynamic instabilities in the ISX-B tokamak. He and his coworkers observed the formation and growth of "magnetic islands," a form of perturbation of the magnetic field. The shapes of the wave patterns in these perturbations agreed well with the standard magnetohydrodynamic theory, but the correlations between instability activity and plasma confinement predicted by theory failed to appear.

One of the original selling points of the tokamak was that it is self-heating. To get fusion, a plasma must be heated as well as confined. The ignition temperature is expected to be around 100 million degrees. Because of the shape of the tokamak and the configuration of its magnetic fields, an electric current is induced to flow through the plasma in the toroidal direction, that



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Part of every fusion experiment is thinking how it might make a working reactor. Above left is the reactor concept for the Doublet tokamak. The Princeton Large Torus (above right) is almost hidden by auxiliary metalwork. Some of it is experimental instrumentation, but what is structural could cause problems for reactor engineering.

is, around the loop. It was expected that resistance to this current would be enough to heat the plasma.

Resistance heats, but generally not enough; auxiliary means of heating are necessary. The older and more widespread of these is neutral beam heating. This consists of shooting several beams of neutral atoms into the plasma. They have to be neutral so that they can get across the magnetic field. When they get into the plasma, they heat it by the gaseous equivalent of friction. The atoms are also ionized and so add to the density of the plasma, another desirable factor. An alternative method of heating is the passage of radio waves through the plasma to heat it much the way a microwave oven heats frozen food. This radiofrequency heating has scored some experimental successes and has some engineering advantages (SN: 6/23/79, p. 410), but it has not yet reached the high temperatures of neutral beams.

Neutral beam heating is thus under experiment at most tokamak facilities, often to test different aspects of its activity. One of the questions is whether injection of the neutral beams tangential to the plane of the torus is more advantageous than injection perpendicular to that plane. Engineering considerations might make perpendicular injection more desirable.

Perpendicular injection has been tested at Princeton in the PDX tokamak and compared to tangential injection in the Princeton Large Torus. According to R. J. Hawryluk of Princeton, the experiments started out because people "wondered whether something was wrong with perpendicular injection." The results suggest that nothing was wrong with it. When they had made certain adjustments in the interior arrangements of the tokamak, Hawryluk and colleagues found the plasma was heated much better than the earlier results that had led them to wonder about perpendicular injection. "One can correctly predict the central ion temperature on a neoclassical basis," Hawryluk says. And he makes the comparison: "Using nearly the same assumptions, one can predict the temperature in the PLT using tangential injection." Therefore, the two are not that different.

Another problem is that neutral beam injection introduces impurities that may interfere with the desired action of the plasma; no matter how hard you try, things get into the beam. The question is whether injection of the neutral beam with or contrary to the plasma current is better for encouraging the natural sweeping of those impurities out of the plasma. Experiments were done in the ISX-B at Oak Ridge in which impurities were deliberately injected in both directions to see which were swept more easily. Oak Ridge's R. C. Isler reports that injection in the same direction can sweep the impurities out, as some new theoretical formulations had predicted.

The foregoing are some examples of the many things that must be investigated and the many theoretical adjustments that must be made as physicists scale tokamaks up to a possible fusion reactor. Meanwhile, tokamaks are being scaled down to a possible fusion reactor. There are now a series of experiments being done known as "compact tori."

Compact tori, according to James H. Hammer of the Lawrence Livermore National Laboratory, who reviewed them at the meeting, are small masses of plasma that are induced to arrange themselves in tori and to generate their own confining magnetic fields by the action of electric currents within themselves. Thus they are small, and they lack the magnetic coils and other metal work of a large torus. The lack of coils is an engineering advantage when it comes to getting energy out. Their smallness is an economic advantage for applications that need small amounts of power. A conventional tokamak would produce a power plant for a large interconnection.

There are about half a dozen ways to produce compact tori, Hammer says. Experiment has shown that they will form and maintain themselves for a time. Whether they will last long enough or get dense enough or hot enough to produce useful fusion energy is a question that needs a lot of work, but sooner or later it seems a big torus or a little one is likely to make a power plant, maybe even by 1995. ☐