

Therefore a 1.7 m long regenerator target, designed to convert a few percent of the K_L^0 mesons coherently to K_S^0 , is inserted into one of the two beams at the beginning of the decay region. To minimize biases due to unintended asymmetries in the beams or detectors, the regenerator is flipped back and forth between the two beams once a minute. Downstream of the vacuum decay volume, $\pi^+\pi^-$ pairs are analyzed by a spectrometer magnet bracketed between tracking drift chambers. (See the photo on page 18.)

Further downstream is KTeV's most crucial new element—an array of 3100 blocks of crystalline cesium iodide scintillator, each one 50 cm deep and attached to its own photomultiplier tube. This is the electromagnetic calorimeter that records the positions and energies of the two gammas into which each π^0 decays within a micron of its birth. For both the neutral and charged pions one must, of course, be able to recognize and then discard the CP -allowed decays of the K_L^0 to three pions (or to a pion and two leptons).

From a global fit to almost 10 million two-pion decays recorded by KTeV in 1996 and 1997, the collaboration arrives at

$$\text{Re}(\epsilon'/\epsilon) = (28.0 \pm 4.1) \times 10^{-4},$$

almost seven standard deviations from

zero. Statistical and systematic uncertainties contribute about equally to the quoted error. This first KTeV announcement is based on less than a quarter of the data that the collaboration already has in hand, and a new run is scheduled to begin in a few months.

"This firmly establishes the existence of direct CP violation in a decay process," Winstein told us. "So now we can be sure that superweak processes, if there are such things, can't be the whole story." But whether the standard model is the whole story is not quite clear yet. The measured value of $\text{Re}(\epsilon'/\epsilon)$ is somewhat higher than the theoretical estimates, most of which favor a value somewhat less than 10^{-3} .

"We, ourselves, were surprised at how big ϵ' turned out to be," Winstein recalls. "To keep from being unconsciously biased by the theoretical expectations, we hid the final result from ourselves by means of a secret offset until the data analysis and the evaluation of systematic errors were finished." Luis Alvarez used to advocate such blind analyses, to avoid what he called "intellectual phase lock."

The Fermilab group freely admits that the new result is closer to the old CERN results, albeit with smaller uncertainties, than to its own 1993 result. Indeed, shortly after KTeV announced

its result, Konrad Kleinknecht (University of Mainz), a leader of the CERN collaboration, congratulated the Fermilab group, not without a touch of sarcasm, for its "brilliant confirmation of our 1988 observation of this new symmetry violation." The CERN group expects to report its own new results in a few months.

Also to be heard from before year's end is the group studying CP -violating kaon decays by a quite different technique at the new Frascati " ϕ factory" in Italy. The machine is an e^+e^- storage-ring collider designed to create, in abundance, the ϕ meson, a bound state of the strange quark and its antiquark that decays mostly into kaon pairs. Also expected soon are first results from the new "B factories" in the US and Japan. (See PHYSICS TODAY, January 1999, page 22.) B mesons, bound states of the heavy bottom quark and its antiquark, are expected to open important new vistas on CP violation.

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Spherical Torus May Improve Tokamak Cost and Performance

After the tokamak approach became fashionable three decades ago, other approaches to magnetic fusion were left withering on the vine or cut off at the roots. In the last few years, however, US participation in the International Thermonuclear Experimental Reactor (still being pursued by Europe, Japan, and Russia) has been cancelled, and Department of Energy funding for magnetic fusion suffered a major reduction. "The cost of developing tokamak-based fusion systems may be too expensive," according to Rob Goldston, director of the Princeton Plasma Physics Laboratory (PPPL). Fusion scientists both in the US and abroad have once again begun to explore the potential of other concepts. They have revived some old ideas and developed some new ideas, which build on the progress gained from tokamak studies.

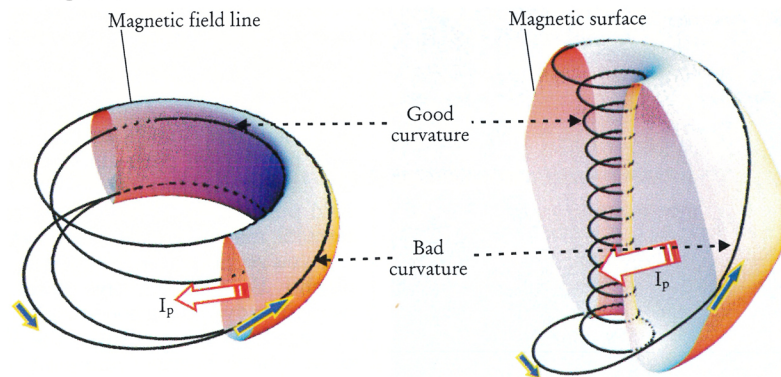
Alternative approaches to magnetic fusion are moving ahead in many labs. One leading approach, the spherical torus, will be tested at two new facilities, just starting up at Princeton and Culham.

A conventional tokamak is shaped like a torus. It has both a strong toroidal field the long way around the torus and a weaker poloidal field the short way around. The poloidal field that surrounds the plasma is generated by a strong current in the plasma itself.

If you just shrink the hole of the tokamak to a very small, but nonzero size, while maintaining a toroidal field strong enough to stabilize the plasma (thus decreasing the aspect ratio, which is the ratio of the major radius to the minor radius), you get the spherical torus (ST). An ST has produced values of β —the ratio of plasma pressure to magnetic pressure—as high as 40%, three times the value achieved by conventional tokamaks.

In the last few months, two new ST facilities have produced their first plasmas—the Mega-Amp Spherical

SPHERICAL TORUS (right) is designed to have a much higher safety factor than the advanced tokamak design (left) because the ST maximizes good curvature of the field lines. The plasma current is shown as I_p . (Figure courtesy of Martin Peng, PPPL.)



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Tokamak (MAST) at the Culham Science Centre in the UK and the National Spherical Torus Experiment (NSTX) at PPPL.

In 1986, Martin Peng and Dennis Strickler (then both at Oak Ridge National Laboratory) suggested producing an ST by putting a vertical conducting rod (to generate a toroidal field) in the middle of a spheromak. (If you eliminate the torus hole entirely, you get a compact toroid, such as the spheromak.) The ST would maximize the length of the stable field lines, explains Peng. If field lines are curved away from the plasma, they would produce unstable plasma. The magnetic surfaces of an ST (see the figure on page 19) combine short field lines of "bad curvature" and high-pitch angle relative to the horizontal plane toward the outer plasma edge with long field lines of "good curvature" and low-pitch angle toward the inner plasma edge. If you were to count the number of times the magnetic field lines go around toroidally for each poloidal circumnavigation, a number known as the safety factor, it becomes 12. Such a high value is aimed at reducing instabilities.

With very high values of β , says Peng, you could expect higher plasma pressure and thus higher fusion power density while requiring lower magnetic field. The lower magnetic field implies lower cost. Magnetohydrodynamic calculations showed that by reducing the aspect ratio from the tokamak (typically 3-5) to 1.3-1.5, the value for β in the center could approach 100%. Says Peng, "At that time, people thought you would need superconducting magnets in the middle of the doughnut and shielding to protect against neutrons. I never believed that. I felt we shouldn't let an engineering approach get in the way of the real goal—very high β and very good confinement."

In 1987, groups at the University of Heidelberg and at Flinders in Australia, and in 1990 at the University of Manchester Institute of Science and Technology produced spherical tokamak plasmas.

The first high-temperature plasma in a spherical tokamak was produced at Culham in its Small Tight Aspect Ratio Tokamak (START). It was built as a prototype by Alan Sykes, Derek Robinson, and Tom Todd and assembled from spare parts dating back to the days of the Zeta (the first reversed field pinch) facility. (If you reduce the toroidal magnetic field by a factor of ten you've produced a reversed field pinch.) By 1992-93, says Sykes, "We were already getting good results." Encouraged by those results, the European Atomic Energy Community (EURATOM) and the UK agreed to split

the cost of building the next generation spherical torus, MAST. Meanwhile, General Atomic's Doublet IIID tokamak (with an aspect ratio of 3) had reached β of 12.6%, and "about 18 months ago, START reached β of 40% by using neutral beam heating," says Sykes, confirming theoretical predictions, although the plasma lasted only about 30 ms.

Now Culham has commissioned MAST, which produced first plasma last December. Then the experimenters encountered a bit of difficulty with one of its main coils. Culham's William Morris expects that operation will resume in the fall, after the faulty coil has been rewound. By that time the first neutral beam injector is expected to be available for plasma heating.

It was the high β achieved at Culham that convinced DOE in 1996 to build NSTX as part of its restructured magnetic fusion program, which was to emphasize innovative approaches. DOE considers NSTX to be a "proof of principle" experiment, one stage beyond START, which DOE considered to be a "concept exploration" experiment.

NSTX and MAST are complementary machines, both roughly the same size and both expected to produce sizable plasma currents lasting as much as several seconds. NSTX will produce 1 MA, and MAST will produce 2 MA. MAST isn't intended to sustain 2 MA for many seconds, Morris explains; the longer pulses will be at lower currents. The relatively low magnetic field of half a tesla in each facility makes possible simplified and flexible designs that ought to ease repairs and upgrades.

MAST will be heated primarily by neutral beams, using equipment lent by Oak Ridge, but there will be additional 60 GHz microwave heating.

NSTX cost DOE \$23.8 million but the facility takes advantage of existing equipment at PPPL valued at \$100 million, says Peng. In July, NSTX is expected to begin doing research. NSTX will concentrate first on radio-frequency heating and helicity injection (helicity is a measure of how knotted the magnetic field lines are). About a year later, PPPL will mount a powerful neutral-beam system on NSTX for experimentation. Says Goldston, "In the future, we have to eliminate the solenoid. Tokamak results first from the Tokamak Fusion Test Reactor [now shut down] at PPPL and then from a number of other experiments around the world have demonstrated the existence of the self-sustaining 'bootstrap' current, which will make it possible ultimately to eliminate the solenoid in the torus hole."

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