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Four new tokamaks will each try for a finite power output

The new generation of tokamak devices now being born is expected to produce a small net fusion power output. In Europe the site for the Joint European Torus has finally been selected after two years of wrangling among the members of the European Economic Community. The $210-million JET is to be built at the Culham Laboratory, near Oxford, England. In the US, ground-breaking ceremonies for the $239-million Tokamak Fusion Test Reactor were recently held at the Princeton Plasma Physics Laboratory. In Japan, construction of components is underway for the JT-60 device, to be built in a suburb of Tokyo still to be selected. The Soviet Union plans to build the largest member of the new tokamak generation, T-20, at a cost of about $500 million. The Soviets will emphasize a capability for breeding tritium and fissile materials in T-20, which might operate in the late 1980's. The other three are to operate earlier.

All but the Japanese device will be capable of burning deuterium and tritium; that is, they will have the shielding and special handling equipment necessary. All but T-20 use water-cooled copper coils rather than the superconducting magnets anticipated for reactors. Auxiliary heating for all four devices will be done by neutral-beam injection; all four devices have the option to use rf power, too. They all have the goal of doing basic

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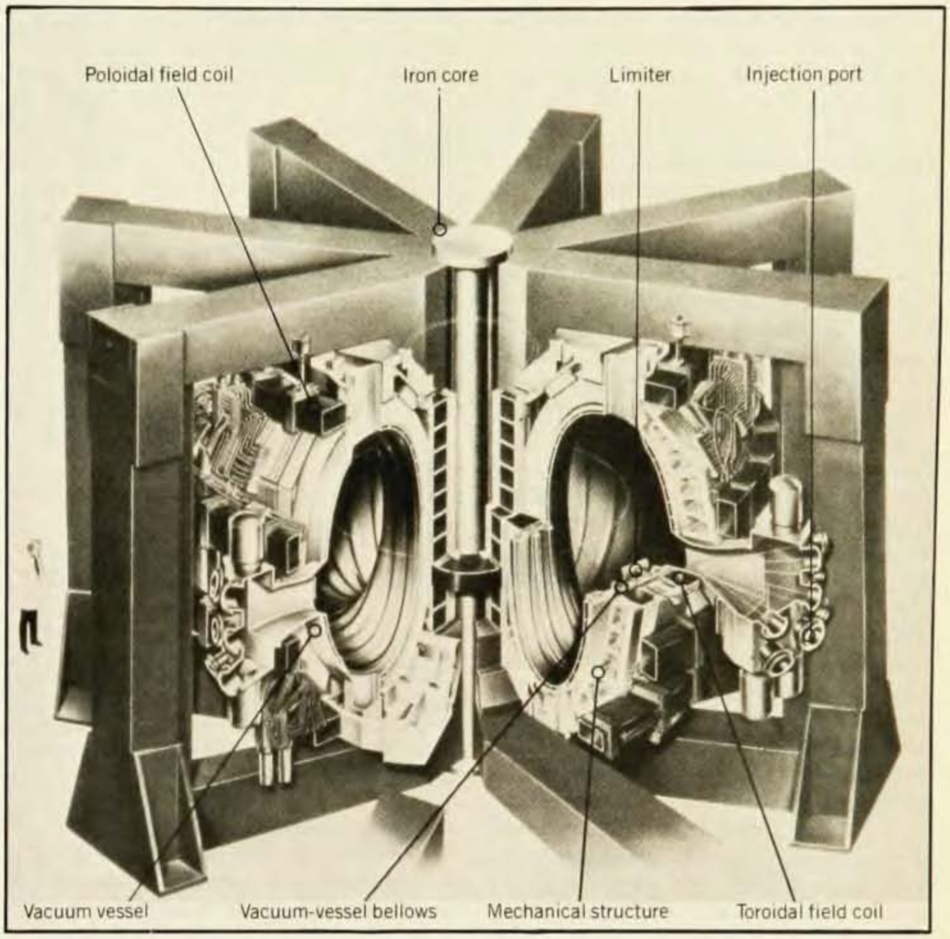

Joint European Torus, which is to be built at Culham, has a vertically elongated D-shaped plasma. It can be operated with a fixed plasma shape or by compression of a reduced size plasma.

Anisotropy in blackbody radiation shows Earth's motion

Soon after the 3-K cosmic blackbody radiation was discovered, many wondered how isotropic the all-pervading radiation in fact was. Now a Princeton group reports that the radiation is isotropic to within 1 part in 1000 and a Berkeley group reports isotropy to 1 part in 3000. Furthermore, they both observe the motion of the Earth with respect to the radiation, so that one can tell how fast the Earth (or the Milky Way) is moving with respect to distant matter in the universe.

In 1967 David Wilkinson (Princeton) and R. Bruce Partridge (Haverford College) did a ground-based experiment that showed isotropy to 1 part in 1000 but with limited sky coverage. Two years later Edward Conklin (National Radio Astronomy and Ionosphere Center), working on a mountaintop, reported detecting anisotropy. However, because he was working at relatively low frequency (8 GHz), he had trouble with synchrotron radiation from our galaxy. In 1971 Paul Henry, then a graduate student at Princeton, used a balloon-borne radiometer at 10 GHz and reported some indication of anositropy, too.

Over the past couple of years the important advance has been to go to higher frequencies and get above atmospheric water vapor. Higher frequencies are advantageous because the spectral intensity of galactic synchrotron radiation falls off approximately inversely as frequency while at the same time the blackbody radiation increases as the square of the frequency in the Rayleigh–Jeans region. However, at high frequency the water vapor in the atmosphere becomes a severe problem. Both the new experiments go to high frequency and high altitude, the Princeton device in a balloon and the Berkeley device in a U-2 aircraft.

In the Princeton experiments, two wavelengths have been used—3 cm and 1.5 cm. The horns are 180 deg apart in azimuth. The apparatus is rotated continuously around the tether of the balloon. The balloon is launched in the evening and stays up all night (about ten hours), so that the apparatus scans a helix going across the sky. Each flight scans 35% of versity of Texas), have repeatedly discussed peculiar motion of the local supercluster (the Virgo cluster and galaxies around it). He concluded that we were moving sideways—that the local group has one component of velocity towards the Virgo cluster and another component perpendicular to it, as could result from a general rotation of the disc-like supercluster. This result was obtained from the systematics of the red shifts of several hundred galaxies. At the time, many were skeptical. But new analyses—the latest was reported by de Vaucouleurs at an International Astronomical Union symposium in Talinn, Estonia last September—have consistently confirmed the motion of the local group in the general direction of Virgo with a velocity of 350 ± 50 km/sec.

The Princeton and Berkeley results are 50 deg away from Virgo, in general agreement with de Vaucouleurs's result. We are moving away from the Virgo cluster roughly in accordance with the general expansion of the universe, but because the local supercluster has so much mass, our motion away from it is somewhat slowed down. But the sideways velocity is a mystery. One natural explanation is that we were born with that velocity. That would require that in the big bang our velocity was relativistic, which Peebles feels is absurd. So the mystery remains, unless it reflects a general rotation of the local supercluster. Theorists in the USSR, in particular L. M. Ozernoy (Lebedev Institute in Moscow), have speculated that the general rotation might be a relic of some primeval turbulence. —GBL

Reference

1. G. F. Smoot, M. V. Gorenstein, R. A. Muller, Phys. Rev. Lett. 39, 898 (1977).

Two-level atom shows photon antibunching

What happens to a two-level atom in an intense laser field? The system resembles the hydrogen atom in its relative simplicity, but only in the last couple of years have experiments shed much light on its behavior. Intensity-dependent resonant light scattering has been studied in two-level atoms by looking at the spectrum and more recently, by observing the time development of fluorescence—photon antibunching. Such scattering is one of the few electromagnetic phenomena that apparently cannot be described by semiclassical arguments; a quantum field theoretical approach appears essential.

In 1956 R. Hanbury Brown (then at Jodrell Bank) and R. Q. Twiss (then at Services Electronics Research Laboratory, Baldock, England) had observed that photons in a monochromatic light beam arrived in clumps or bunches. Although some persons said that photon bunching occurred simply because of Bose—Einstein statistics, Roy Glauber (Harvard University) argued that such statistics are more permissive and that the observed bunching was in fact caused by the chaotic excitation of the light beam. Besides seeing bunching, he said, it should be possible with suitable excitations to observe antibunching, a tendency for photons to stay away from each other—to be anticorrelated over short time intervals. The distribution of relative arrival times could have a hole near $t = 0$. As t increased, the probability would increase for a subsequent photon to arrive at the detector.

Antibunching. A number of groups suggested that photon antibunching could be observed in the light scattered by a two-level atom placed in an intense laser field. The theory of antibunching was worked out over the past couple of years by a former student of Glauber's, Benjamin Mollow (University of Massachusetts, Boston), by H. J. Carmichael and Daniel F. Walls (another former student of Glauber's) of the University of Waikato, Hamilton, New Zealand, by H. J. Kimble and Leonard Mandel (University of Rochester) and by Claude Cohen-Tannoudji (Collège de France, Paris).

Kimble, Mandel and Mario Dagenais (University of Rochester) then set out to do the appropriate experiment, using a setup resembling that used by other workers to study resonance fluorescence spectra from two-level atoms in an intense laser field. Sodium atoms in a low-density atomic beam are excited by a light beam from a tunable dye laser, aimed perpendicular to the atomic beam. To eliminate competing magnetic sublevels, the Rochester team used optical prepumping. The dipole selection rules allowed a single sublevel to be isolated. The resonance fluorescence is emitted at right angles to both the atomic and laser beams and then enters a microscope objective. Next the light is divided by a half-silvered mirror and imaged onto two photomultiplier tubes. Finally the time intervals between photon arrivals are measured and correlated. The dye laser frequency is stabilized to 1 part in 10^9 to compensate for drift. Perpendicularity of the two beams was good to 1 milliradian. Mandel estimates that he and his collaborators use an atomic beam of such low density that only one or two atoms were in the volume of observation at any one time.

The Rochester group recently reported[1] the observation of antibunching. In their paper, they point out that finding photon antibunching is rather direct evidence for an atom undergoing a quantum jump. Once having emitted a photon, the atom is unable to radiate again immediately after having made a quantum jump back to the lower state. Of course these two concepts, they note, are inextricably connected, but it has been difficult in the past to observe this behavior.

The spectrum of light scattered by a two-level system in an intense laser field was considered by many theorists. Among these was Mollow, who was the first (1969) to predict the correct shape of a three-peaked spectrum symmetrical about the laser frequency, that is, a peak in the middle with satellite lines having mirror symmetry. Later an elegant physical interpretation based on spontaneous emission noise radiated in a rotating coordinate system was given by Cohen-Tannoudji and his collaborators.

In 1973 Felix Shuda, Carlos R. Stroud Jr and Michael Hercher (University of Rochester) found a three-peaked spectrum that confirmed the predictions of quantum theory and disproved predictions of neoclassical theory. They were unable to confirm the detailed predictions of Mollow. Herbert Walther (University of Munich) did a similar experiment; recently he observed photon antibunching, too. In 1975 Frederick Wu, Robert Grove and Shaoul Ezekiel (MIT) observed a spectrum with sufficient precision to confirm Mollow's predictions.

In the MIT experiment, as in the later work of Mandel and his collaborators, one produces a two-level atom by optical pumping (as worked out by Joseph Abate of Rochester in 1974). Within the interaction region, a uniform laser field from a tunable dye laser is applied and held at the atomic resonance. Then the spectrum of the fluorescence is analyzed with a scanning Fabry–Perot interferometer. The experiment is repeated for off-resonance excitation. —GBL

Reference

1. H. J. Kimble, M. Dagenais, L. Mandel, Phys. Rev. Lett. 39, 691 (1977).

Four new tokamaks

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physics experiments to develop design information on which a future experimental power reactor would be based. The table summarizes design features of the four devices.

JET. When an international design team started work at Culham in 1973, Culham's director, R. S. Pease said, "There is going to be a glorious international minuet to decide the site for JET." Pease was undoubtedly prescient: It took two years after the design study was completed in 1975 for the European Economic Community to decide on a site. Initially, six possibilities were considered: Ispra in Italy, Mol in Belgium, Cadarache in France, Jülich and Garching in Germany, and Culham. Eventually, the final choice was between Garching and Culham. In the meantime, about one-third of the design team had left the JET project for other jobs.

The JET design, developed under the

direction of Paul Rebut, has a vertically elongated (D-shaped) plasma; the plasma is much larger than that of TFTR. By using a noncircular plasma, theoretically one can maintain a higher β (ratio of plasma pressure to applied magnetic-field pressure). To achieve a given plasma density and temperature, if β is higher, a weaker toroidal magnetic field can be applied. If the noncircular shape turns out to be practical, tokamaks can be made larger for the same amount of money.

JET can be operated with a fixed plasma shape or by compression of a reduced size plasma. In both modes, it can be operated with a circular or D-shaped cross-sectional plasma.

The JET experimental program will include the study of: plasma processes and scaling laws into regions close to those needed in a fusion reactor, behavior of energetic alpha particles produced in D–T reactions, methods of heating plasma to ignition temperature (at which energy released in fusion would sustain the plasma), and interaction of the plasma with the torus walls (which produces impurities).

Even before the site for JET had been selected, some prototypes of important components had already been constructed. The facility at Culham is expected to be finished in 1983.

According to Harold Furth (who is head of the experimental division at the Princeton Plasma Physics Laboratory), JET is optimized for experiments turning out well—for no serious impurity problems showing up. If there is only a small energy loss from impurities, he went on, JET probably has a better chance than TFTR of reaching an $n\tau$ of 10^{14} cm^{-3} sec, where n is the particle density and τ is the confinement time. Furth notes that with a two-component plasma (a plasma consisting of an energetic ion component and a bulk plasma component, which will be produced in all four large tokamaks by neutral-beam injection), one can reach breakeven (input neutral-beam power equal to power produced by fusion reactions) with an $n\tau$ of 10^{13} cm^{-3} sec and a temperature of 5–10 keV.

TFTR is an extrapolated version of the Princeton Large Torus. With PLT, Princeton learned how to make 600-kA discharges. With TFTR, Furth says, they will learn to make 1-2.5–MA discharges. From PLT, Princeton is gaining experience with neutral-beam injection. PLT has two 40-keV beams and this spring will get two more, raising the total beam power to 3 MW. TFTR is to have four 120-keV beams at 20 MW plus 12 MW in lower-energy beam components. In experiments that have just begun, the Princeton experimenters are for the first time applying substantially more power from the neutral beams than is produced with ohmic self-heating of the tokamak discharge. From these experiments, they expect to learn the true temperature dependence of tokamak confinement. These experiments should give a clue to whether $n\tau$ will be 10^{13} or 10^{14} in TFTR.

A second major study will be to explore the theory that radiation from partly stripped impurity ions will be the critical limitation on energy confinement in TFTR-sized tokamaks. PLT results thus far tend to support this idea, Furth said, but also point to the improvements that can be achieved by an appropriate choice of substance for the limiter, the first piece of material that the plasma touches. The shaping of the temperature profile at the plasma edge is also critically important, he said. If the impurity problem turns out to be sufficiently severe, tokamak reactors may have to use a magnetic divertor, a device that bounds the plasma with a magnetic separatrix. Experiments with divertors are to be done at several laboratories. Princeton, for example, will start experiments with a new device, the Poloidal Divertor, this fall.

When TFTR starts operating (scheduled for the beginning of 1982), the first phase of operation will be aimed at producing hot, dense reactor-grade plasmas and optimizing their confinement. For this purpose TFTR will have a heating power density several times greater than that of the other large tokamaks, Furth told us. Initially deuterium and hydrogen will be the working gases (rather than tritium) so as to minimize neutron activation. About a year later, operations with deuterium-tritium mixtures will start, to generate large alpha-particle and neutron yields for fusion plasma experiments. The power density of 3.5-MeV alpha-particle production is expected to be comparable to that in a power reactor. Although $n\tau$ is expected to be smaller than 3×10^{14} cm^{-3} sec, so that ignition will not occur, the alpha particles are expected to make a substantial contribution to the plasma heating. Eventually TFTR is expected to produce 20 MW or more for a few tenths of a second, a power output equal to that of the neutral beams to be used for heating the plasma.

Because tritium is radioactive, the designers of TFTR are paying special attention to the safety of tritium storage and handling. Tritium is stored in multiple thick-walled steel cylinders as a solid in combination with uranium. A very small amount of tritium is converted to a gas by electrical heating—just enough for an operational pulse of TFTR.

JT-60 is to be built near Tokyo, on a site still to be selected. Its first coils were recently ordered, and it is scheduled for completion in 1981. Unlike the other three large tokamaks, JT-60 will not be capable of burning deuterium and tritium. Its major distinguishing feature is that it will have a magnetic limiter and divertor for shaping plasma profiles during the current build-up stage and for controlling interactions between the plasma and walls during the discharge. A fast, movable mechanical limiter will also be provided to allow operation without the magnetic limiter. JT-60 is to have a noncircular vacuum vessel, but elongated in the horizontal direction, not the vertical, to allow the study of a poloidal magnetic divertor. The JT-60 design favors impurity control rather than maximization of the plasma beta capability.

T-20 is still in the conceptual design stage at the Kurchatov Institute in Moscow, and its construction has not yet been approved. It is scheduled to operate in the late 1980's. T-20 is to have a noncircular vacuum chamber (elongated vertically), and a divertor is under consideration. In the near-term, the Soviet fusion program is emphasizing fusion as a means for breeding fuel. In the long-term, however, the emphasis is on a pure fusion reactor. T-20 plans to use superconducting magnets because the pulse length is much longer than the other devices (up to 100 sec).

T-20 provides four locations for the placement of blanket modules. One type does not contain any material for breeding. A second type of module can contain ore for the breeding of fissionable material or the fissionable material itself.

Meanwhile, Kurchatov is building the T-10M, which is roughly the size of the Kurchatov T-10 and Princeton's PLT. Unlike these devices, however, T-10M will have superconducting Nb_3Sn toroidal field coils (to be made at Kurchatov) to produce magnetic fields up to 50 kG. T-10M will be capable of using auxiliary heating, such as neutral beams and rf heating. It is scheduled to operate in 1981.

—GBL□

Comparison of large tokamaks

	JET	TFTR	JT-60	T-20
Plasma major radius (m)	2.96	2.48	3	4–5
Plasma minor radius (m)	1.25 (horizontal)	0.85	0.95	1–1.5
Elongation ratio	1.68	1.0	~1	1.6
Plasma current (MA)	3.8–4.8	2.5–3.0	3.3	3–4
Auxiliary heating power (MW)				
Neutral beams	10–25	32 and 20	20	50–100
rf	10–25	—	15	—
Toroidal magnetic field (kG)	27.7–34.5	52	45	60
DT neutrons/pulse	$\sim 10^{20}$	$\sim 4 \times 10^{18}$	none	$\sim 2 \times 10^{21}$