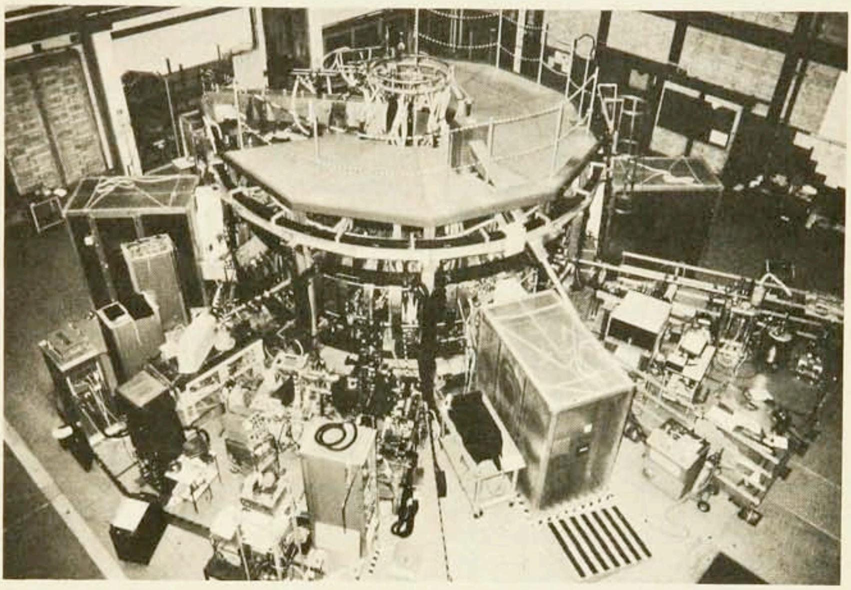
search & discovery

Garching shows stellarators may be good after all

Stellarators appear to be back in business. After a series of consistently disappointing results in the 1960's, Lyman Spitzer's scheme for plasma confinement in a toroidal fusion device was generally abandoned in the last decade by American magnetic-confinement researchers, in favor of the more promising tokamak concept.

But now a group at the Max Planck Institute for Plasma Physics in Garching, near Munich, seems to have demonstrated the equilibrium and confinement capability of the basic stellarator configuration. Günther Grieger, Hermann Renner and their colleagues reported last month at the biennial International Conference on Plasma Physics and Controlled Nuclear Fusion in Brussels that their "Wendelstein VIIA" stellarator had successfully confined a plasma by external magnetic field coils alone—without requiring a circulation current in the plasma itself. Their stellarator not only maintained plasma confinement but also exhibited a fourfold improvement in energy confinement time when its ohmic heating current was shut off in favor of neutral-beam heating and a poloidal magnetic field generated by the helical coils characteristic of the stellarator design.

The revitalization of the stellarator scheme quickens the prospect of a toroidal fusion reactor that can operate in a steady-state mode without external power input.



The Wendelstein VII A stellarator at Garching (near Munich) has demonstrated the equilibrium and confinement capability of the stellarator configuration in the absence of any ohmic plasma current, with helical magnetic coils. The three large rectangular enclosures house three of the four high-energy neutral-beam injectors that heat the toroidal plasma.

In toroidal fusion reactors, the basic toroidal magnetic field is not sufficient to confine the plasma. The confining field must have a poloidal component, adding a helical twist to the primary toroidal field. The tokamak achieves this poloidal field component by inducing a toroidally circulating current in the plasma. The ohmic heating generated by this plasma current also helps to raise the temperature of the plasma toward the 10 keV needed for deuterium–tritium ignition.

The stellarator configuration, first attempted at Princeton in the 1950's, relies on helical coils wound around the torus rather than the ohmic plasma current to provide the necessary twist in the toroidal field. In the ensuing decade, stellarators of increasing size were built at Princeton and elsewhere—but they exhibited a puzzling and disheartening trend. First of all, one couldn't get the plasma very hot; the stellarators of that generation never exceed a plasma temperature of 200 eV. Furthermore, in contrast to the expectation of classical theory, the plasma confinement in these devices got worse with increasing plasma temperature. When it began to appear in the late 1960's that the early Russian tokamaks were producing much higher temperatures and pressures, Princeton converted its "Model C," the largest stellarator of its generation, into a tokamak.

With hindsight developed by extensive experience with tokamaks, it now appears that the problem with the early stellarators was not intrinsic to the stellarator concept. There is a magnetohydrodynamic limit to the current density a toroidal plasma can sustain without becoming unstable. The larger the "aspect ratio" (major/minor radius) of the torus, the lower is this limit on the ohmic current. Even though the stellarator does not require an ohmic current to twist the confining magnetic field, all stellarators use ohmic heating to raise the plasma temperature in the initial phase.

Harold Furth of Princeton told us that the striking improvements observed with the advent of tokamaks were largely attributable to their better (smaller) aspect ratios. They could be made much fatter than stellarators, because they were not encumbered by an extra layer of helical windings. With an aspect ratio of 20:1, the Model C was "simply too skinny," Furth explained, to support enough ohmic-heating current. When the helical stellarator windings were removed in 1969 for its metamorphosis to a tokamak, the Model C could be fattened by almost a factor of three, with a corresponding improvement in temperature and confinement.

The Garching group, by now well aware of the virtues of a small aspect ratio, tried to build the Wendelstein-VII with an aspect ratio significantly

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smaller than 20:1. But the magnetic stresses on the helical coils in the proposed "fat" configuration turned out to be so high that they would have required considerable mechanical buttressing. To avoid the consequent construction delay, the minor radius of the plasma had to be reduced to 10 cm. With a major radius of 2 meters, the Wendelstein VIIA is thus left with an aspect ratio no better than that of the old Model C (though with twice the plasma radius).

But nowadays the aspect ratio is no longer crucial for the achievement of high temperatures. Because it has become clear that tokamaks cannot achieve ignition temperatures by ohmic heating alone, neutral-beam injection has been developed in recent years as an additional source of plasma heating in tokamaks. The Wendelstein VIIA is the first stellarator that incorporates high-power neutral-beam injection. With this second heat source providing up to a megawatt of input power, the plasma current can be shut off after the initial ohmic-heating phase. With the complex stellarator windings making access difficult, it was no mean trick to inject the neutral beam into the plasma at a favorable angle. Although neutral-beam injection has made it possible to operate a stellarator with good confinement even at large aspect ratios, the 20:1 geometry of the Wendelstein VIIA may limit its β (plasma pressure/magnetic field pressure) to about half a percent. The higher pressures and densities necessary for a practical reactor would ultimately require a smaller aspect ratio.

The earlier stellarator project at Princeton having been named "Matterhorn," Grieger and his colleagues called their undertaking Wendelstein, after a modest Alpine foothill outside Munich—a deliberate act of humility. Unlike the racetrack-shaped Model C, the Wendelstein VIIA torus is circular. This avoids the special coils that were necessary in the Model C to smooth the transition between curved and straight sections. These transitional fields are believed by some to have contributed to the poor performance of the earlier machine.

Although the Wendelstein VIIA is significantly smaller than the current generation of large tokamaks, it and its counterparts in the Soviet Union, Britain and Japan have been doing at least as well as tokamaks of comparable size for several years now—without neutral-beam injection. Operating only with ohmic heating, these machines have shown very good values of the confinement parameter (density $\times$ energy confinement time), which now appears to be exhibiting the same favorable scaling behavior as one sees for tokamaks, with respect to temperature, density and size. This improved performance is the cumulative result of numerous small refinements of the stellerator design.

Furthermore, the helical stellarator field appears to prevent the rapid plasma breakup that can occur in tokamaks near the critical ohmic current density. (Such a violent plasma disruption could severely damage a reactor.) All this has generated considerable new enthusiasm for the stellarator concept around the world. But until the recent Garching results, no-one has been able to maintain a plasma of significant pressure in a pure stellarator mode—with the ohmic heating turned off.

Shutting off the ohmic heating has in the past always resulted in the loss of plasma confinement in the stellarator. Last fall, even after they had managed to squeeze their high-power neutral beam into the Wendelstein VIIA, the Garching group found that their plasma invariably got lost in a magnetohydrodynamic resonance as they attempted to reduce the plasma current to zero. But they have now found the trick. Instead of keeping the current in the helical stellarator coils constant as they turn down the plasma current, they gradually increase the helical current in a manner that just compensates for the loss of the plasma current. By keeping the poloidal magnetic field component approximately constant in this way during the transition, so that the offending resonant surface is kept out of the plasma, they find that confinement is maintained as the system goes over to the pure stellarator mode.

In the stellarator mode, with heating provided only by the neutral-beam injection, and the poloidal field component coming only from the helical windings, the energy confinement time of the plasma improves by a factor of four. The confinement time in the Wendelstein VIIA increases from about 5 msec in the ohmic-heating phase to 20 msec in its pure stellarator phase. With a plasma density of 10^{14} cm^{-3}, this represents a confinement parameter of 2×10^{12} sec/cm^3—at least five times as high as attained by tokamaks of comparable size. Of course the plasma temperature achieved in the Garching stellarator is only 700 eV, an order of magnitude below what has been obtained in the Princeton PLT tokamak, with a plasma volume ten times that of the Wendelstein VIIA.

The most attractive feature of the stellarator concept as against tokamaks is that a stellarator reactor would operate in a steady-state mode. Because the plasma current in tokamaks must be induced by the transformer action of external induction coils, it can only operate in a pulsed mode. Even

AGS Celebrates Twentieth Anniversary

Brookhaven celebrated the twentieth anniversary of the Alternating Gradient Synchrotron in May. John Blewett, Ernest Courant (Brookhaven) and Kjell Johnsen (CERN) reminisced about designing and building the machine. Some of the speakers recalled the great physics discoveries made at the AGS. Melvin Schwartz (Stanford) talked about finding the muon neutrino and a "residual level of junk" events that were probably neutral currents. Val Fitch described the discovery of CP violation (an experiment approved on the basis of a two-page proposal with no detailed background calculations). Nicholas Samios (Brookhaven) reviewed the bubble-chamber program, which over the two decades yielded 40 million pictures, including the first Ω^- and the first charmed baryon. Samuel Ting (MIT) described the experiments leading to the J/ψ, which led to a new high-energy era with charm, beauty and other gracious qualities.

The speakers, photographed at the meeting, are (from left): Johnsen, Samios, Fitch, Schwartz, Ting, Courant and Blewett.

though the duration of the pulses in a tokamak reactor would be of the order of an hour, the lack of steady-state equilibrium presents a host of engineering problems. The time variation of heat load, for example, would exacerbate thermal fatigue in the reactor. In a pulsed machine one has to make provision for stresses and other parameters that are constantly varying in time. The attractiveness of steady-state fusion reactors has led a number of groups to begin looking into the possibility of a tokamak with an rf-driven ohmic plasma current.

But even such a steady-state tokamak would require continuous power input. T. K. Chu, a long-time partisan of stellarators at Princeton, told us that the stellarator is unique among magnetic-confinement concepts. It is the only scheme yet suggested, he believes, that promises a fusion reactor that would require no power input after it reaches ignition. Once the deuterium–tritium plasma starts to "burn," the neutral-beam injection could be shut off. (One does of course have to maintain steady confining currents in the external windings.)

Chu, Furth and their Princeton colleagues, Christiane Ludescher, John Johnson and Katherine Weimer, are currently addressing one of the less attractive features of stellarators. Tokamaks and stellarators both require a second set of external coils in addition to the windings that provide the primary toroidal confinement field. (For tokamaks this second set provides the induction that drives the plasma current.) The resulting elaborate systems of external windings make it difficult (if not impossible) to build either of these devices by modular construction—a serious drawback to the proliferation of practical reactors. Developing an earlier idea of Stephan Rehker and Horst Wobing at Garching, Chu and his colleagues are designing a simplified stellarator configuration, in which the poloidal field comes not from an extra set of coils but from a careful distortion of the primary coils. Instead of being simply circular, and thus providing only a toroidal field component, they would be warped into something resembling the periphery of a potato chip. But, Chu cautions, they would not be perfectly stacked "like 'new-fangled' potato chips." To provide the desired helical twist in the confining field, the warp in each coil is rotated from that of its neighbor by a small poloidal angle. The trick is to provide an adequate poloidal field without warping the coils so much that they cannot withstand the severe magnetic stresses to which they are subjected.

The Garching success does not mean that we should now drop everything else in favor of stellarators, Furth stresses. The importance of the Wendelstein VIIA result, he told us, is that we now have two approaches that appear to be adequate. We are no longer rigidly tied to the tokamak as the only toroidal scheme that works. "My hope is that from somewhere in the tokamak–stellarator continuum there will emerge a steady-state toroidal reactor." —BMS

SIS diodes for radio astronomy

As radioastronomers continue to push their observations to shorter wavelengths and fainter signals, their progress is impeded by a lack of sufficiently sensitive millimeter-wave receivers capable of operating at frequencies above 100 GHz. But now a spinoff from Josephson-junction fabrication technology appears to be coming to the rescue. New metallurgical and lithographic techniques developed for Josephson-effect computers are permitting the construction of superconducting diode junctions that promise to function as high-frequency photon detectors and heterodyne mixers near the theoretical limits of sensitivity.

Paul Richards and Ten-ming Shen at Berkeley, working with Richard Harris and Francis Lloyd at the National Bureau of Standards (Boulder), have recently produced superconductor–insulator–superconductor (SIS) quasi-particle tunnel junctions that performed at 36 GHz as heterodyne mixers with a noise level near the uncertainty-principle limit,[1] and as direct photon detectors with quantum efficiency close to unity.[2]

Gerald Dolan, Thomas Phillips and David Woody have achieved 115-GHz heterodyne mixing with SIS junctions they developed at Bell Labs.[3] Having tested their SIS mixers by observing the 2.6 mm-line of interstellar carbon monoxide, Phillips and Woody (now at Caltech) plan to install such diodes at the focal points of the three radio telescopes that will constitute Caltech's new Owens Valley millimeter-wave interferometer.

Quasi-particle tunneling across a barrier between superconductors, unlike Josephson tunneling, involves single rather than Cooper-paired electrons. If sufficient energy (the "superconducting energy gap") is provided, a superconducting Cooper pair can break up into two quasi-free electrons. If the oxide layer that serves as the insulating barrier between identical superconductors at an SIS junction is sufficiently thin (a few tens of angstroms), such quasi-particles can tunnel through the barrier when a voltage bias corresponding to twice the energy gap is applied.

The onset of this quasi-particle tunneling current at the critical bias voltage is extremely sudden. The corresponding sharp corner in the characteristic current–voltage (I–V) response curve for such diodes has been called "the strongest nonlinearity in nature." Such a highly nonlinear I–V curve is precisely what one wants for the heterodyne mixer of a millimeter-wave receiver.

Heterodyne receivers. Just as in an ordinary radio receiver, the heterodyne mixer receives simultaneous input from the signal to be detected and from a "local oscillator" of comparable frequency. Because of the mixer's nonlinear response, its output includes a Fourier component corresponding to the difference between the signal and local-oscillator frequencies—a beat frequency. This "intermediate frequency," being much lower than the original millimeter-wave frequency, is much easier to amplify and rectify in the later stages of the receiver. The more nonlinear the mixer, the stronger is the output at the desired intermediate frequency. The SIS diode approximates the ideal mixer—a switch whose resistance shuttles between zero and infinity every cycle of the local oscillator.

To function at millimeter-wave frequencies, such a superconducting junction must have an extremely small capacitance, and consequently a very small active area—on the order of a square micron. Quasi-particle tunneling at superconducting junctions had in fact been discovered in 1960 by Ivar Giaever at General Electric, but people did not begin seriously to consider SIS junctions for millimeter-wave receivers until recent technological developments made possible the production of reliable SIS junctions of sufficiently small area.

The superconducting junction required for a successful 100-GHz SIS mixer is very much like those one needs to make in large quantities for a Josephson-effect computer (see PHYSICS TODAY, June 1978, page 17). Several industrial labs have therefore lavished attention in recent years on the technological problems involved in fabricating such junctions. By 1975, Phillips told us, new electron-beam lithographic methods at Bell Labs were good enough to interest him in the possibility of using insulating oxide junctions no more than a square micron in area between superconducting layers, produced by thin-film deposition techniques. Dolan has subsequently developed lithographic techniques at Bell