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 'newfangled' 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

Labs for producing SIS junctions of even smaller area (a few tenths of a square micron).

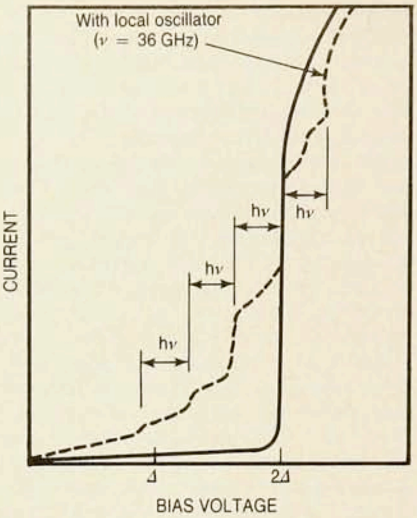
The lithography required for the small junction area is not the only technical problem. Because the oxide barrier must be only about 20-Å thick, small imperfections protruding from the superconducting metal surfaces can easily puncture and short-circuit it. Thermal cycling will cause the formation of needle-like crystals on many superconducting surfaces. By 1977 a suitable lead alloy was available, and both groups began to work on SIS diodes for millimeter-wave radioastronomy. The SIS junctions used by the Berkeley–NBS collaboration are fabricated by Harris and Lloyd at NBS, using optical lithography.

The Heisenberg uncertainty principle puts a limit on the accuracy with which one can measure the number of incident photons in a heterodyne receiver or any similar instrument that measures both the phase and intensity of the photon field. Expressed in terms of receiver noise temperature, the quantum noise limit is given by the $h\nu/k$, the photon energy divided by the Boltzmann constant. At 36 GHz this minimum noise temperature is 1.7 K. In May, Richards and his colleagues reported that they had operated an SIS heterodyne mixer at 36 GHz in the laboratory, with a noise temperature of 1.5 ± 2 K, consistent with the Heisenberg limit.

Phillips told us that the quietest operation his group had achieved with their SIS mixers at 115 GHz was 60 K, an order of magnitude above the photon noise limit (5 K) at that frequency. While the Berkeley–NBS group is primarily concerned with understanding and optimizing these tunnel junctions in the laboratory, the Caltech group is trying to do radioastronomy with them as soon as possible. For Earthbound millimeter-wave astronomy, atmospheric and other background noise contribute about 100 K, making it uninteresting to push receivers much below that noise level. For satellite-based millimeter-wave astronomy, Richards told us, one will want receivers near the quantum noise limit.

Richards and Jack Welsh of the Berkeley Radio Astronomy Laboratory hope to have an SIS mixer operating at 115 GHz on the University of California's Hat Creek millimeter-wave interferometer early next year.

The noise temperature of the full receiver must include the noise contribution of the intermediate-frequency amplifier. The best amplifiers at intermediate frequencies (below 1.5 GHz) have noise temperatures as low as 10 K, but their contribution to the overall receiver noise temperature decreases as the conversion efficiency of the mixer increases. The classical theory of mixers states that the conversion efficiency of a heterodyne mixer (intermediate-frequency power out/signal power in) can never exceed unity. But the Berkeley–NBS group has observed a purely quantum effect that violates this classical limit; their SIS junctions exhibit mixer gain.



Current–voltage curve for Berkeley–NBS SIS diode. Without a local oscillator, the solid curve shows a sudden rise when bias voltage (times electron charge) equals twice the superconducting energy gap, Δ. With a local oscillator, the dashed curve shows $h\nu$ steps, showing photon-assisted tunneling.

The practical importance of observing heterodyne mixer gain in SIS junctions, Richards told us, is that it may ultimately reduce the noise contribution of the intermediate-frequency amplifier to a level comparable with the quantum limit of the mixer noise—essentially by reducing the amount of work this amplifier has to do. But the observation of mixer gain also served to verify the quantum theory of photon-assisted quasiparticle tunneling in SIS junctions in the presence of radiation, as developed by John Tucker[4] of the Aerospace Corporation. Redoing the classical mixer theory in the quantum limit, Tucker predicted that photon-assisted tunneling (where local-oscillator photons contribute to quasiparticle tunneling before the critical voltage bias is reached) would result in conversion efficiency greater than unity.

The Berkeley–NBS group has also observed photon-assisted tunneling with SIS junctions functioning as direct (non-heterodyne) photon detectors. In the direct mode, with no local oscillator, the SIS diode produces a dc output proportional to the power of the input signal. Because this mode simply attempts to count photons without measuring phases, the uncertainty principle specifies no lower noise limit. The group found that their SIS detector noise was attributable entirely to the "shot noise" of the minuscule bias current, that is to say the Poisson statistics of the discrete electrons making up this current. Richards told us that in the direct photon-detection mode, their SIS diodes exhibited a quantum efficiency near unity—one electron out for every photon in. High quantum-efficiency photon detectors already exist in the infrared and visible regions. But the SIS promises to be the first such detector available to astronomers at millimeter wavelengths. Direct detectors are useful in this region for measuring continuous spectra (for example blackbody radiation), but heterodyne techniques, offering narrower bandwidths, are better suited for detecting individual atomic or molecular lines.

Rival devices. The workhorse of microwave radioastronomy over the past decade has been the Schottky-barrier diode, at whose semiconductor–metal junction a potential barrier is formed by an electron-depletion layer in the semiconductor, But at room temperature, even the best of these devices is quite noisy—with noise temperatures of about 500 K. Noise reduction to 100 K at 100 GHz has been achieved with Schottky diodes cooled to 20 K, but further reduction is limited by the shot noise from linear tunneling at low temperatures. The operation of the Schottky diode depends on thermionic emission over the top rather than tunneling through the barrier. The resulting thermionic I–V curve is only weakly nonlinear, requiring much more local-oscillator power for heterodyning than does an SIS mixer.

In the "super-Schottky" diode, where the normal metal layer is replaced by a superconductor, quasi-particle tunneling provides the desired highly nonlinear I-V curve, as it does for the SIS. But the super-Schottky diode suffers from an excessively high RC time constant, making it difficult to operate at high frequencies. The difficulty of fabricating a super-Schottky junction of sufficiently small capacitance compounds the problem of the high series resistance introduced by the semiconductor layer.

Phillips has for years been doing millimeter and even sub-millimeter-wave astrophysics with a bolometer at liquid-helium temperature, capable of operating at frequencies as high as 500 GHz (a wavelength of 0.6 mm). His bolometer is a very simple InSb semiconductor device, which functions as a heterodyne mixer when its carrier electrons absorb incident radiation directly from the signal and local oscillator, with a resulting oscillatory variation of carrier mobility at the intermediate frequency.

Phillips and his colleagues have recently demonstrated the usefulness of their bolometer at sub-millimeter frequencies, by making the first interstellar observation[5] of the ground-state fine-structure line of atomic carbon (492 GHz), with a bolometer receiver aboard the NASA Kuiper Airborne Observatory. But the bolometer mixer suffers at present from an excessively narrow bandwith. With a bandwidth of only 1 MHz, the InSb bolometer requires several observations to measure a single Doppler-broadened spectral line from an interstellar molecular cloud. This narrow bandwidth also slows down the search for spectral lines whose wavelengths are not well known.

Before settling on SIS quasi-particle tunnel junctions, Richards had tried for years to harness Josephson pair tunneling for radioastronomy. He and other workers pursuing this goal have found the Josephson effect too uncontrollably complex to yield suitable mixers and photon detectors. The next big question, Phillips believes, is whether SIS receivers can successfully function at submillimeter frequencies (greater than 300 GHz). —BMS

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Tokamak ready for engineering test

"The Panel is pleased to record its view that the taxpayers are receiving their money's worth ... While the US magnetic-fusion program represents only about a third of the worldwide effort, the US has become its unquestioned leader. As a result of this progress, the US is now ready to embark on the next step ... exploration of the engineering feasibility of fusion power."

These encouraging words are to be found in the introduction of the Fusion Review Panel's report submitted in June to DOE's Energy Research Advisory Board. The Panel, headed by Solomon Buchsbaum of Bell Labs, cautions that the report is to be regarded as preliminary until ERAB acts on it at its next meeting, 18–22 August. The preliminary report was made public to solicit outside comment. Last February Edward Frieman, DOE Director of Energy Research, had asked Buchsbaum, as chairman of ERAB, to convene a panel to review the Department's magnetic-fusion program. The Panel was to consider "the judicious choice of the next major steps to be undertaken in proceeding from the current generation of experimental devices toward demonstration of economic fusion production."

After four months of meetings and visits to principal laboratories, the Panel concluded that recent progress in plasma confinement justifies confidence that "energy breakeven is near." The demonstration of breakeven (fusion power output equal to power input) is expected in at least one of the large tokamaks currently under construction—for example,the Tokamak Fusion Test Reactor at Princeton. Tokamak confinement, the Panel concludes, is sufficiently well understood that one can now make a realistic extrapolation to ignited plasmas. A plasma is said to be ignited when the fusion reaction supplies sufficient heat to maintain itself. The report expresses confidence that a device containing an ignited plasma can be built and successfully operated.

But the state of our knowledge is not yet adequate to determine an optimal plasma or field configuration for a working reactor, the Panel believes. "Nor can we be sure today that a safe, environmentally acceptable, economically attractive fusion reactor can be built and operated."

Recommendations. Their findings have led the Panel to a number of recommendations:

▶ Fusion engineering. The Panel concurs with the consensus it finds in the magnetic-fusion community that a tokamak engineering facility of some sort should be built "forthwith." This device, which would serve as the focus of a broad program of engineering experimentation and analysis, should contain a burning, perhaps even an ignited, plasma. A plasma is described as burning when it reaches energy breakeven.

But the Panel expresses "misgivings about the ETF, as it has been presented to us." This Engineering Test Facility is currently under conceptual development by a multidisciplinary group at Oak Ridge. A magnetic-fusion bill now before Congress, drafted by Rep. Mike McCormack (D-Wash), envisions the completion of such an ETF by1987. (See PHYSICS TODAY, May 1980, page 114.)

The Panel finds the ETF, as envisioned by the Oak Ridge group, "too ambitious. Specifically, we question the role envisioned for the ETF . . . .to bridge the gap ... to the knowledge required to design [demonstration power reactors]. In our view the number of steps between such a test facility and a commercial reactor cannot now be specified." The desire to use the ETF as the ultimate testing facility for materials and engineering design parameters, the Panel feels, results in excessively "stressful requirements"—very high neutron fluxes, low component downtime, long burn times. As a result, "the complexity, cost and risk of failure are high."

Nevertheless, with present knowledge and what we will soon learn from the tokamaks now under construction, the Panel feels that a device containing an ignited deuterium–tritium plasma can be built. In this connection they urge that Princeton's TFTR "be exploited as early as possible."

Instead of the ETF as currently conceived, the Panel proposes a more modest device, which it calls the "Fusion Engineering Device." This FED should be built during this decade at a cost not exceeding about one billion (current) dollars. It should nonetheless provide an ignited, or at least a burning plasma. Among the technological questions this device should address are problems of operator and public safety.

The Report proposes that DOE establish a Center for Fusion Engineering to coordinate a broad program of investigation in all areas pertinent to reactor engineering—for example, tritium handling and breeding, heat removal, rf power supplies, remote maintenance, fuel injection and "first-wall" technology. Major funding increases for this engineering program would not be needed till about 1983-84, by which time TFTR data should be available to help guide the design details of the Fusion Engineering Device.

▶ Fusion physics. In parallel with the engineering program, the Panel stresses the need for continuing basic investigations of fusion confinement in tokamaks, mirrors and alternative devices. "Such work is indispensable ... and should be shielded from encroachment by the FED. No operating funds [for such] experimentation should be diverted to construction."The Panel calls for DOE to undertake a "vigorous advanced tokamak research program experimentation to study physics issues ... " At present no such plans extend beyond the TFTR.

To make the tokamak attractive as a reactor, the report suggests, progress must be made toward steady-state (rather than pulsed) plasma-current drive, and more convenient plasma heating. One must better understand and control wall interactions, impurity behavior in long pulses, and plasma disruptions.

On a more basic level, an understanding of anomalous electron ther-