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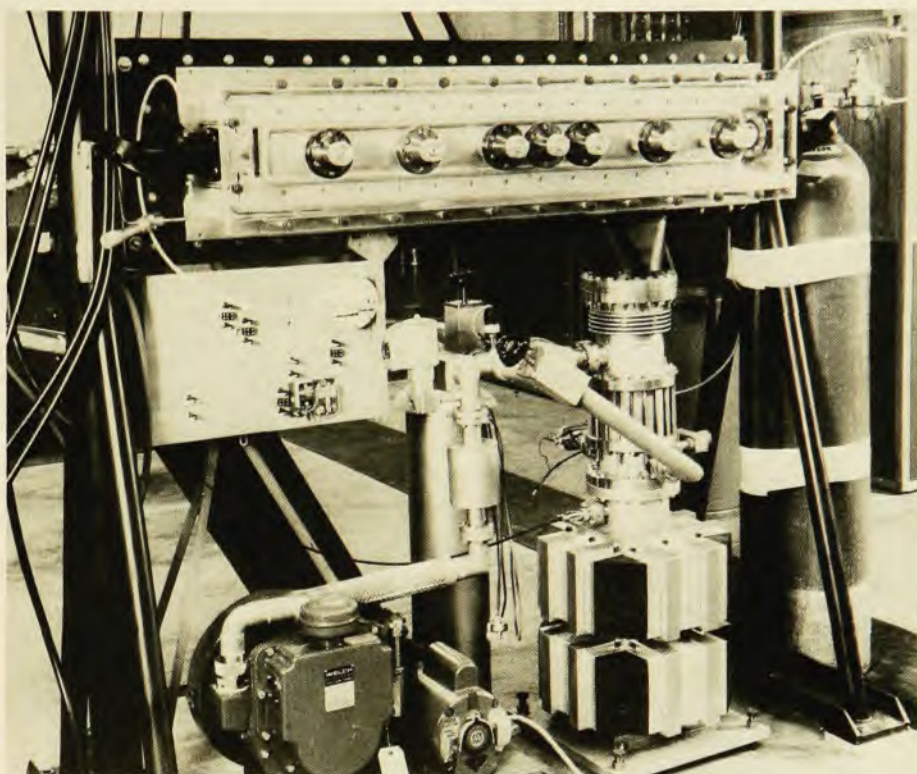
More laser power with electron-beam control

Our best hope for an ultrahigh-power laser with good beam quality appears to lie with molecular gas-discharge devices. The development of these lasers has so far been limited by the difficulty of maintaining stable discharge conditions and by the impossibility of producing a design scalable in all its parameters—size, pressure, and so on. That is, a certain discharge device that runs well cannot in general be rebuilt twice the size for increased power. Now at least three groups in the US and one in Russia are experimenting with devices embodying electron-beam-controlled discharges to solve some of these problems.

One of the basic difficulties of an ordinary discharge laser stems from the dual role expected of the free electrons in the plasma. They must move through the discharge under the influence of the applied electric field, producing new electron-ion pairs by collision to offset the losses by volume recombination and ambipolar diffusion to the walls. If the electric field is too low the electron concentration falls off and the discharge "goes out." (With too high a pressure, on the other hand, the discharge grows until it becomes an arc.) Simultaneously these same electrons must excite gas molecules by collision to populate the upper laser state and bring about the inversion required for lasing conditions. The trouble is that the electron temperatures required for these two jobs are in general not the same—the laser works best at one value of electron temperature and the discharge may be stable only at a different value, if at all. The new approach lies in the separation of these functions—an externally produced high-energy electron beam fired into the laser region maintains the discharge, by the production of relatively low-energy secondary electrons that carry the current across the discharge field and excite the laser levels. In an alternative scheme the secondary electrons are used to excite the molecules directly, without an applied field.

A group at Avco-Everett Research Laboratories has built two machines using an electron beam; both are pulsed carbon-dioxide lasers, and the larger one

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Electron-beam-controlled amplifier for a carbon-dioxide laser system at Los Alamos Scientific Laboratory. This is one stage of a planned four-stage laser amplifier, which is expected to have an output of 1000 joules per 1-nanosec pulse when driven by a TEA laser.

Neutron stars grow magnetic whiskers

It is generally agreed that neutron stars or pulsars have enormous magnetic fields at their surface—in the range 10^{12} – 10^{13} gauss. Mal Ruderman of Columbia University has considered (*Phys. Rev. Lett.* 27, 1306, 1971) what happens to ordinary matter in such fields. He concludes that the surface of the neutron star is not a gas but condensed matter arranged in whiskers of atoms. "Neutron stars have hair," he explains.

Previous work had considered what happens to an atom or a molecule in such huge fields. The atoms became much tighter bound and much smaller.

In the picture that has developed of a neutron star, the star has a solid crust

caused by high density below its surface. The surface itself, though, was generally believed to be a gas. With almost zero pressure on the matter at the surface, but temperatures of perhaps millions of degrees, it was expected that the surface would resemble the gaseous atmosphere of the earth, gradually tailing off in density although with only 10^{-6} the scale height.

Ruderman's unexpected result was that even at zero pressure, the matter holds together very strongly. For iron, which is a likely constituent of the surface, there would be a binding energy per atom of 10–20 kV. In normal matter the binding energy per atom is typically an electron volt. So even at zero pres-

sure the surface would be very dense and like normal condensed matter would have a sharp edge, a discontinuity.

Ruderman finds that the most stable structures at these high densities are short chains of atoms—what Ruderman likes to call “magnetic hair.” Each whisker is a one-dimensional lattice of atoms bound by electrons free to move back and forth along all the atoms, but only parallel to the magnetic-field line. Perpendicular to the magnetic-field lines the electrons are held in place, mainly by the magnetic field rather than by Coulomb forces. The chains of atoms stick together, resembling a package of spaghetti.

The density of the matter on the surface is about 10^4 gm/cm³, its precise value depending on whether it is made of hydrogen, iron or something else, Ruderman says. Heating a normal substance to a few thousand degrees tends to vaporize it. But the surface of the neutron star has such strong binding energies that even if you heat it to a few million degrees (the highest temperature expected to be found in a neutron star), it will not vaporize. Whether the condensed material is a solid or a liquid depends upon its temperature.

How deep do the whiskers go? Ruderman thinks only a few centimeters below the surface, until the pressure increases sufficiently for them to merge into the near isotropic solid crust.

The surface is like a one-dimensional metal, being an extremely good electrical conductor in one dimension (along the magnetic field), and a poor one perpendicular to the magnetic field, Ruderman says.

If a rotating magnetic neutron star has an ionized gaseous surface, the very strong electric fields at its surface would pull plasma out of the star until the outer region is filled with a corotating magnetosphere. Such a picture of a pulsar was put forth by Peter Goldreich and William Julian (Cal Tech) and others.

On the other hand, if the neutron star is like a big rotating solid iron magnet, the outer region does not fill with plasma until the electric fields on the outside are big enough to pull electrons and ions out of the surface. Because of its considerable work function, Ruderman says, you would have to spin an ordinary iron magnet so fast that it would break apart before the electric field would be strong enough even to pull out the electrons from its surface. To remove ions would be even more difficult.

In Ruderman's picture the surface of the neutron star will have a work function of order a kilovolt. In the slower pulsars, with periods longer than a second, the electric fields caused by the rotation are the same order of magnitude as the calculated electric fields required to get an appreciable field-emission electron current coming out of the

surface. It's not clear, Ruderman says, whether the slower pulsars will have sufficient electric field on the outside to continue to pull electrons out of the surface. If they don't, presumably you will no longer be able to observe radio emission from the pulsar.

So far no one had observed any pulsars with periods above a few seconds, although one would expect that such pulsars would have evolved from the faster pulsars over the course of time. Ruderman is not prepared, however, to say that his mechanism is responsible for their nonobservability. —GBL

Electron-beam lasers

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produces 2000 joules per pulse. A device at Los Alamos is being built not as a laser but rather as an amplifier for a large laser system; it will have a single-pass gain factor of 100–200 per meter per stage and consist of four stages. At IBM Research Laboratories (Yorktown Heights) a molecular-hydrogen laser based on the alternative scheme in which an external electron beam functions both as ionizer and energy source has produced Lyman-band stimulated emission at around 1600 Å. And a group at the Lebedev Physics Institute in Moscow is using the technique in a high-pressure xenon laser, for which an unusually high efficiency (close to 100%) is theoretically possible.

The three US groups reported progress at the 24th Annual Gaseous Electronics conference, held in Gainesville, Fla. last October; the Russian work was reported

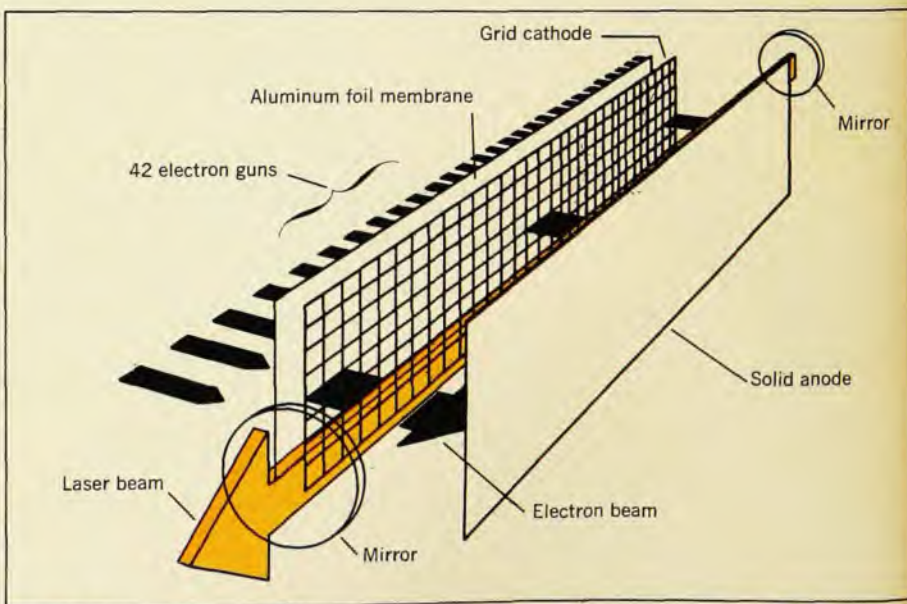
at the Laser-Matter Interaction Conference in Hull, UK, in September.

The Avco-Everett group (Jack Daugherty, Evan Pugh, David Ahouse and Diarmaid Douglas-Hamilton) are working with atmospheric-pressure CO₂ lasers. First they built a relatively small one to prove the method; it worked well, yielding 4–5 joules per pulse from a helium-nitrogen-CO₂ mixture in the proportions 3:2:1. Then they scaled up to a large one, which yields an impressive output of 50 joules/liter or 2000 joules/pulse. This kind of laser is normally pulsed because, when the discharge heats the gas, the lower laser state fills up and so destroys the inversion condition. The laser can either be allowed to switch itself off at this point or the initiating electron-beam pulse can be cut off earlier. The larger Avco machine runs with a 20-microsec pulse length.

Electrons to initiate and control the discharge come from a row of 42 guns, which produce a total of 40 amps of emission current. Between the laser discharge region (at 1 atm pressure) and the electron guns (in vacuum) is a 0.001-inch aluminum foil. At 130-keV energy the electron beam passes easily through this foil into the discharge region, where a pair of electrodes sustains an electric field (3–6 kV/cm) transverse to the axis of the device.

The measured efficiency of this laser is 20–25%, and the gain is 4–5% per cm.

The remarkably good homogeneity of an electron-beam-controlled discharge is shown by optical interferograms of the Avco device (made with a small ruby laser); they show uniformity of the discharge region to $\frac{1}{20}$ of a wavelength at 10.6 microns.



Carbon-dioxide laser at Avco-Everett Research Laboratories, shown very schematically. A discharge in the working gas (a helium-nitrogen-CO₂ mixture at 1-atm pressure) is initiated and maintained by electrons from a row of 42 electron guns. Laser output is 2000 joules per 20-microsec pulse.

With a transverse flow system such a laser could presumably be made to run continuously, and because it is scalable in all dimensions extremely high output could be obtained. The limit is probably set by eventual electrical breakdown of the gas mixture by the laser radiation itself, which might occur at high energy densities.

The Los Alamos devices are amplifiers for short pulses, not laser oscillators, but they also use an electron-beam-controlled discharge. Charles Fenstermacher, Murlin Nutter, Wallace Leland and Keith Boyer reported to the Gainesville meeting on their gain measurements at 10.6-micron wavelength in a 5-atmosphere mixture of He, N₂ and CO₂ in various proportions.

The Los Alamos amplifier system will be driven by a TEA ("Transversely Excited Atmospheric pressure") CO₂ laser that delivers 1 millijoule per pulse in 1-nanosec pulses. With four stages of amplification the output energy is expected to be 1000 joules, still in 1-nanosec pulses. The first stages of the device are being checked out and achievement of 1000-joule nanosec output is expected within the year.

"Our device," Fenstermacher told us, "is essentially a short pulse, single-shot arrangement. The pumping time to build up inversion in the CO₂ levels is typically 5 to 10 microseconds; so you pump for this length of time with the external electron beam, storing energy in the laser levels. Then you hit the amplifier with the short pulse from the TEA laser to dump the energy. There's no way you could get that amount of energy [1000 joules] into the machine in one nanosecond."

The laser development effort at LASL forms part of a larger program to study fusion feasibility. The large laser system will be used to investigate plasma absorption and energy transfer processes in appropriate target materials. Similar studies have been underway with glass lasers for some time (see, for example, PHYSICS TODAY, November 1968, page 57, for a description of the work at the Lebedev Institute). But Fenstermacher believes that glass lasers will reach their energy limit below the breakeven point for laser-induced fusion.

IBM's laser, reported at Gainesville by Rod Hodgson and Russell Dreyfus, also has electron-beam excitation but differs from the others in that no electric field is applied to the discharge to sweep electron-ion pairs through the gas. This hydrogen laser uses a commercial electron-beam generator as its energy source. A 3-nanosec pulse of 400-keV electrons, total current about 10⁴ amps, is confined by an axial magnetic field and fired down a 1.5-meter tube containing 10-100 torr of hydrogen. These electrons either ionize the gas molecules or excite vacuum-uv levels by collision, and they can make many such collisions

before they degrade to thermal energies. Explaining the device to us, Hodgson said: "When a discharge produces breakdown in the gas, the impedance drops and it is difficult to get much more power into it. On the other hand, most of the electron-beam energy can be used efficiently."

At the Lebedev Institute, Nikolai Basov's group is experimenting with electron-beam controlled atmospheric-pressure CO₂ lasers too. But they are also working with a new high-pressure (several atmospheres) xenon laser on the same principle as the Avco device. Xenon lasers are interesting because of their high efficiency compared to CO₂. The higher-energy laser level is one of the bound molecular excited electronic states (Xe₂*), and the lower level is the repulsive ground state of molecular Xe₂. This Xe₂ ground state is so close in ener-

gy to the ground state of Xe that the upward transition, Xe to Xe₂*, is only a little more energetic than the downward one, Xe₂* to Xe₂. This can be thought of as a "pseudo-two-level" system. If efficiency is defined as:

$$\frac{\text{photo quantum energy}}{\text{electron excitation energy}}$$

the ratio for xenon is close to 90%. Basov's group has already measured an efficiency of 50% at 1600 Å. In CO₂ on the other hand, we have a true three-level system in which the transition from the ground state to the upper level, 0.25 eV, is considerably greater than the downward transition to the lower laser level, 0.1 eV. Theoretical efficiency is therefore 0.10/0.25 = 40%. Experimentally measured efficiencies of CO₂ lasers are about 25% at best. —JTS

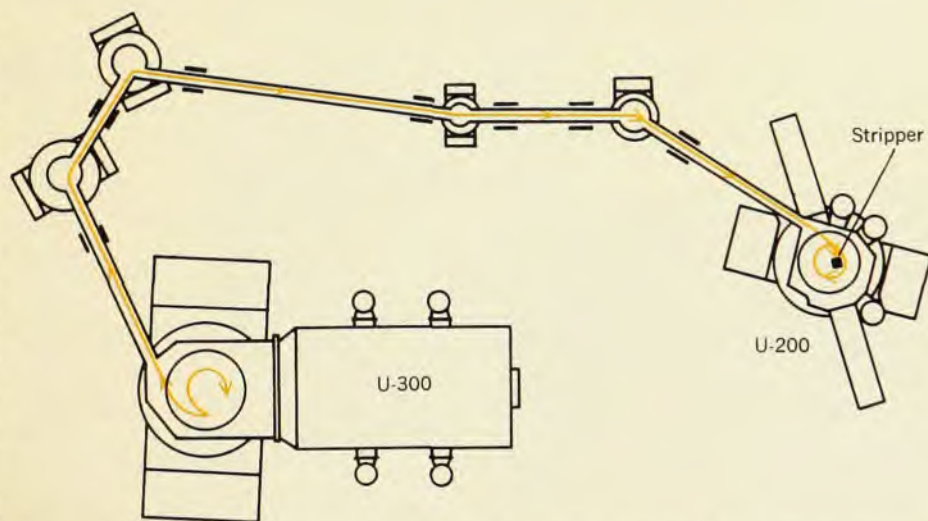
Dubna cyclotrons paired to accelerate xenon

Xenon ions have been accelerated to 7 MeV/nucleon or a total energy of 925 MeV, an energy sufficient to surmount the Coulomb barrier in any known nucleus. The xenon ions, with Z of 54, are expected to be very effective in the attempt to make supertransuranic elements near the island of stability.

To produce the xenon ions, Georgi Flerov and his collaborators at the Joint Institute for Nuclear Physics in Dubna hooked two cyclotrons together. The experiment was described late in October by Ivo Zvara of Dubna at the Argonne transplutonium-elements conference and at the Oak Ridge International Conference on Multiply Charged Heavy Ion Sources and Accelerating Systems.

The experiment was done with the U-300, a 3-meter-diameter cyclotron completed in 1960 and the U-200, a 2-meter cyclotron that was converted three years ago to sector focusing. The two machines, about 70 meters apart, were connected. In the center of the U-300 the Dubna group put an ion source that made (Xe¹³²)⁸⁺. The ions were then accelerated to 0.9 MeV/nucleon; the beam had an intensity of 3 × 10¹² particles/sec.

In the center of the U-200 the experimenters put an aluminum foil, 0.5-microns thick. The xenon was stripped in that foil to +28. Then the (Xe¹³²)²⁸⁺ was accelerated to near final radius. The intensity was 3 × 10⁹ particles/sec. The beam was not extracted



Acceleration of xenon ions at Joint Institute for Nuclear Physics in Dubna. The U-300 and U-200 cyclotrons are connected by a 70-meter transport system that includes a change of elevation as well as numerous bends. So far the (Xe¹³²)²⁸⁺ beam energy is somewhat less than 7 MeV/nucleon at an intensity of 3 × 10⁹ particles/sec. For (Xe¹³⁶)³⁰⁺, full energy of 7 MeV/nucleon has been obtained with an intensity of 3 × 10⁸ particles/sec.