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Sixty Million Degrees

by Dr. Derek Boyd

It got very hot this summer. Perhaps the hottest place in the United States was inside a hollow steel doughnut at the Forrestal Campus of Princeton University. Within that doughnut some hydrogen gas was heated to a record sixty million degrees on the Celsius scale.

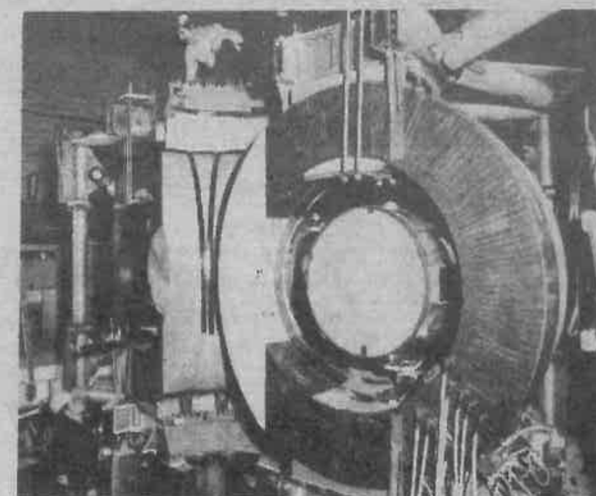
Quickly the news spread around the world. Here the Washington Post carried its page one report below banner headlines. Walter Cronkite told us that scientists at a laboratory of the Department of Energy had succeeded in heating to record temperatures a plasma in a device called a Tokamak. Some of those scientists came from the Department of Physics and Astromony at the University of Maryland in College Park.

To explain how this came about and what really happened, let us go back to that incredibly hot gas in the steel doughnut. At first all the air inside the doughnut is pumped out by four large pumps. Only about one trillionth of the air manages to elude the pumps and remain within the vacuum chamber, which is the doughnut's proper name. Unfortunately, a lot of oxygen and water vapor remains stuck to the inside surface of the steel vacuum cham-

electrons stripped off by the effect of a rapidly varying electrical current in a coil wrapped around the vacuum chamber. Massive generators then drive a huge electrical current through the gas. In about a tenth of a second the current rises to half a million amperes.

As the current rises, beginning with those few electrons torn from the hydrogen atoms, the gas is heated. When it is heated, more electrons boil off from their , until virtually every atom is broken apart and the hydrogen gas has become hydrogen plasma. The temperature soars up, driven by the electrical current. For the electrons, it quickly rises to seven million degrees in the first tenth of a second; then more slowly, until in four tenths of a second the electrons' temperature is twenty-five million degrees. The cores of the hydrogen atoms from which the electrons were stripped, called hydrogen ions, are also heated by the electrical current and at four tenths of a second they have reached ten million degrees. Now the most dramatic part of the experiment is about to begin.

But first it is necessary to digress so that what is happening and will happen can be understood. The



One half of PLT during assembly. The large magnet surrounds the vacuum chamber within which the plasma temperature reached sixty million degrees.

In a Tokamak, the electrical current flowing through the plasma has a double role. It heats the plasma and produces the twist in the magnetic field necessary to hold the plasma in place. If we want to heat the plasms to a higher temperature, all we have to do is to increase the current. The plasma gets hotter and the magnetic field twists a bit more, but disaster lies on this path. There is a limit to the perber. These gases are removed by a black magic recipe devised by Bob Taylor, who is now at UCLA. Finally, a thin layer of the metal titanium is deposited on the interior surface and it forms a very sticky layer on which gas atoms are trapped. This whole elaborate business is necessary, because part of the trick in this great success, was keeping the hydrogen plasma very pure.

Now the experiment which lasts one second is ready to begin. A valve opens and a flow of pure hydrogen gas enters the vacuum chamber. When the density of hydrogen has reached its proper value, about one millionth of the density of the Earth's atmosphere, some of the hydrogen atoms have their

vacuum chamber nestles inside a large magnet powered by giant generators housed in an adjoining room. This magnet produces a magnetic field one hundred thousand times as strong as that which surrounds the Earth. The magnetic field lines of this magnetic field go round the vacuum chamber in the same direction as the electrical current which flows through the plasma. The electrical current also produces a magnetic field and the two magnetic fields add together to produce a twisted, helical magnetic field which loops around inside the machine. This twisted magnetic field holds the plasma away from the steel vacuum chamber and enables the experimenters to heat the plasma while the steel stays cool.

missible twist, and once it is exceeded the plasma flies out to hit the steel walls, causing massive cooling and an avalanche of metal atoms which contaminate the plasma with impurities. Even if disaster is avoided, as the current is increased we enter a regime of dimishing returns, where increases in the current produce less and less heating. Because we will never be able to make the plasma as hot as we want with the electrical current, we must find an additional source of heating and that is why four large guns are attached to the Tokamak.

These are very special guns from the frontier of technological development. They tower over the Tokamak and they do not shoot bullets, but hydro-

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gen atoms. Tremendous streams of highly energetic hydrogen atoms pour out of the nozzles of these guns. Steel plates, if placed in their path evaporate and buckle in the huge energy flux carried by the streams of atoms. The four guns can inject into the plasma twice as much energy as the electrical current. With some luck we could expect a large increase in the plasma temperature.

Now we can rejoin the plasma at four tenths of a second into the experiment. The electrons are at twenty-five million degrees and the ions are at ten million degrees. An electrical pulse flies to the guns from . electronic timer. Two million watts of power streams from the guns into the plasma. As the hydrogen atoms fly into the plasma their electrons are stripped off. Their ionic centers go crashing on, colliding with the plasma electrons, losing their energy of directed motion and passing this energy to the electrons and raising their temperature by doing so. Up, up goes the temperature from twenty-five million, past thirty-five, and on to over forty million degrees. When the ionic centers of the injected atoms have slowed down as a result of their collisions with the plasma electrons, they begin to collide with the plasma ions to whom they give the great majority of their streaming energy. Driven on the power of those four guns, the ion temperature soars upwards, doubling to twenty million, through forty million and reaching up to sixty million degrees and hanging there for a tenth of a second, then dropping again when the guns are shut off. Four tenths of a second later the plasma current is cut off and the experiment is over. In three hundred and sixty seconds the cycle can begin again.

Among the thirty physicists taking data during these experiments were Derek Boyd, Fred Stauffer and Graeme Tait. from the Department of Physics and Astronomy at Maryland. Their apparatus is specially constructed to measure the temperature of the plasma electrons continuously during the one second of the plasma experiment. Only recently have the techniques for doing this been developed by the Maryland group and another group in England led by Alan Costley.

Because the plasma electrons are in a strong magnetic field they emit light of very long wavelength, ten thousand times the wavelength of the light to which our eyes are sensitive. Happily, the intensity of this light, called cyclotron radiation, is proportional to the electron temperature, and so by following the intensity of this light in time, the history of the electron temperature can be obtained. There are very few sensitive detectors of light with such a long wavelength and even these require exotic conditions if they are to operate well. The detectors are kept in liquid helium and pumps are used to reduce the gas pressure above the liquid helium so that it evaporates and cools down to two degrees above absolute zero; two degrees above the lowest temperature than can exist in the Universe. The cyclotron radiation takes a wonderful journey. It is generated in the plasma where the temperature in forty million degrees and is absorbed by a detector which is only two degrees above the coldest temperature in the Universe.

The Tokamak at the Princeton Plasma Physics Laboratory is one of the largest devices of its type in the world. The plasma cross sectional area is seven square feet and the loop of plasma is twenty-five feet long. It is called the Princeton Large Torus (PLT) and is one of a sequence of machines of steadily increasing size, in which scientists have tried and will try to produce plasmas suitable for a fusion reactor.

A fusion reactor will be a remarkable machine in which there is an incredible fire. The temperature of the fiery plasma will be over one hundred million degrees and because of this high temperature, reactions will take place that usually occur at the centers of stars. Hydrogen ions will fuse together to form helium and in the process release large amounts of energy. This is true solar energy in that it is the energy produced by the same mechanism that generates energy in our sun.

The energy produced in the fusion reactor will be converted into electricity and the reactor will use hydrogen taken from seawater as a fuel. One gallon of seawater will be able to produce as much energy as three hundred gallons of oil. There is enough water in the sea to provide our energy requirements for hundreds of millions of years.

This summer a giant step was taken towards producing the plasma required for a fusion reactor. The guns that produced the energetic streams of hydrogen atoms were proven to be effective devices for heating a plasma. About half of the ultimately required temperature was reached and, most importantly, the behavior of the plasma in PLT is expected to be very similar to that anticipated in a reactor and looks very promising. It was a hot summer and a happy one.