Diagnostics for fusion experiments

Elaborate measurements are needed to document the power balance in fusion plasmas. The new era of experiments above "breakeven" will require diagnostic techniques as yet undeveloped.

Charles B. Wharton

Impressive advances have been reported in controlled fusion experiments during the past four years. Both open and closed confinement systems have performed up to expectations, rekindling the old optimism that has lain nearly dormant for 15 years. As a result, breakeven experiments are being proposed, designed and built in several laboratories.

But "breakeven" does not mean that when the installation is completed, the engineers will be able to plug the input cord into the output socket and get the machine to run by itself. What it does mean is that some very well-conceived and executed diagnostics measurements will document a power balance and find it not to be negative. This power balance must include every conceivable energy input and energy loss, and the inferred heating rates and cooling rates must be compatible with the equilibrium temperatures and particle densities actually achieved. Thus, the perceived progress relies very heavily on diagnostics, using techniques ranging from the most basic to the most highly sophisticated.

Over the years a substantial catalog of usable techniques has been developed, addressed to understanding the properties of plasmas in various configurations. That is the main subject of this article. But as we face the new era of fusion-level experiments, we are finding many measurement shortcomings. To fill these gaps will require some diagnostic techniques that have not yet been developed, much less reduced to reliable practice. We thus must discuss not only the present, but also the future diagnostic requirements for fusion experiments. Many of the techniques reported here were discussed in detail at the Varenna Course on Diagnostics for Fusion Experiments in 1978, and I will be relying on the proceedings of that course[1] for many of my references.

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An example is the requirement to measure the magnitude and variations of magnetic field inside the dense, hot plasma without disturbing the reacting particles or destroying the measuring instrument. Probes and molecular beams have been used to good advantage in many types of plasmas, but these instruments will be out of the question in fusion devices. The situation thus is that we do not yet have a direct, reliable method to measure the magnetic field in space and time in a magnetic-confinement fusion plasma. (See the article by Nicol Peacock in reference 1.)

In a slightly better status are methods to measure plasma potential and the spatial distributions of particle density and temperature. Some of the techniques presently employed will continue to be useful, but considerable room for innovation and development remains. And even the present instruments that can be applied directly to future fusion experiments may require "hardening" so they can survive in the high-energy flux levels, which also will include nuclear emissions that were absent at lower levels. (See John Osher in reference 1.)

Diagnostics is now a sizable component of a fusion experiment, as is exemplified by the neutron counter at the Princeton Large Torus shown in figure 1—a device that uses seven tons of paraffin and Li_2CO_3.

Magnetic-confinement fusion

The present generation of experimental systems for magnetic confinement of plasma have similar diagnostics requirements, in spite of the dissimilar geometries and magnetic field configurations. The plasma dimensions are of order one meter, which is several ion gyroradii across; the particle densities are 10^{12} to 10^{14} cm^{-3} and plasma temperatures range up to a few keV. An example of a typical array of diagnostic instruments is sketched in figure 2. The installation is the 2XIIB magnetic mirror at Lawrence Livermore Laboratory, which has "open" confinement geometry. Nearly all of the diagnostic instruments indicated can also be applied to "closed" confinement systems, of which the tokamak is an example. The exceptions are those sampling the component of plasma entering or escaping along magnetic field lines in the end regions. These instruments intercept some plasma, and in closed geometry would thus introduce perturbations that are ordinarily not tolerable.

By tradition the phrase "plasma diagnostics" is reserved for measurements that do not in themselves appreciably change the state of the system.[2] The modifier "appreciably" leaves latitude in how much perturbation can be allowed. At low plasma temperatures, such as in gas discharges, MHD power experiments, and so on, the insertion of probes into the plasma center is possible and justifiable, with the result that the magnetic field, the particle density and temperature, streaming current densities, diamagnetism, and high-frequency fluctuations and waves can all be measured directly, with spatial resolution. But at higher particle temperatures internal probes are ruled out for two reasons. The first and most obvious is damage to the probe, often catastrophic. A side effect of this damage is contamination of the plasma by evaporated material from the probe. Both of these effects lead to energy drains from the plasma. But diagnostically more important, although perhaps less apparent, is the "shadow" along magnetic lines cast by the probe. A hot plasma has a low collision frequency, and therefore poor particle transport across the magnetic field. The cross-sectional area swept out by the probe is thus felt over a disproportionately large volume, rendering valid conclusions difficult. Even if the probe does not burn up, the data are questionable. We are faced then with making *external* measurements, often discouragingly indirect ones.

Langmuir probes, an old-time favorite for density and temperature measure-

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ments in gas discharges, are highly perturbing in a collisionless plasma. Radar, another old-time favorite, offers one alternative solution.

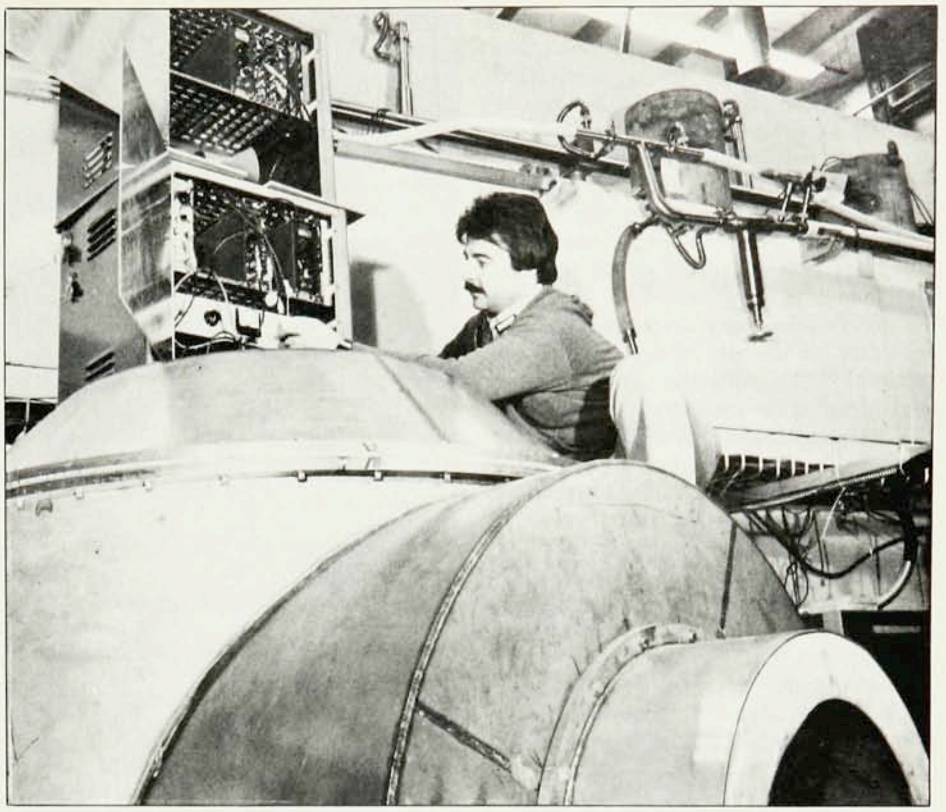
Plasma density

Electromagnetic waves suffer attenuation and phase shift as they propagate through a plasma, and measurements of these quantities can be related directly to plasma density and temperature. The techniques of microwave diagnostics[2] have been developed to a high degree, and have become standard in many laboratories. An interferometer is used to determine the complex refractive index and its spatial distribution. The index decreases as the density increases, finally reaching zero at plasma frequency "cutoff." The maximum density measurable is proportional to the square of the frequency.

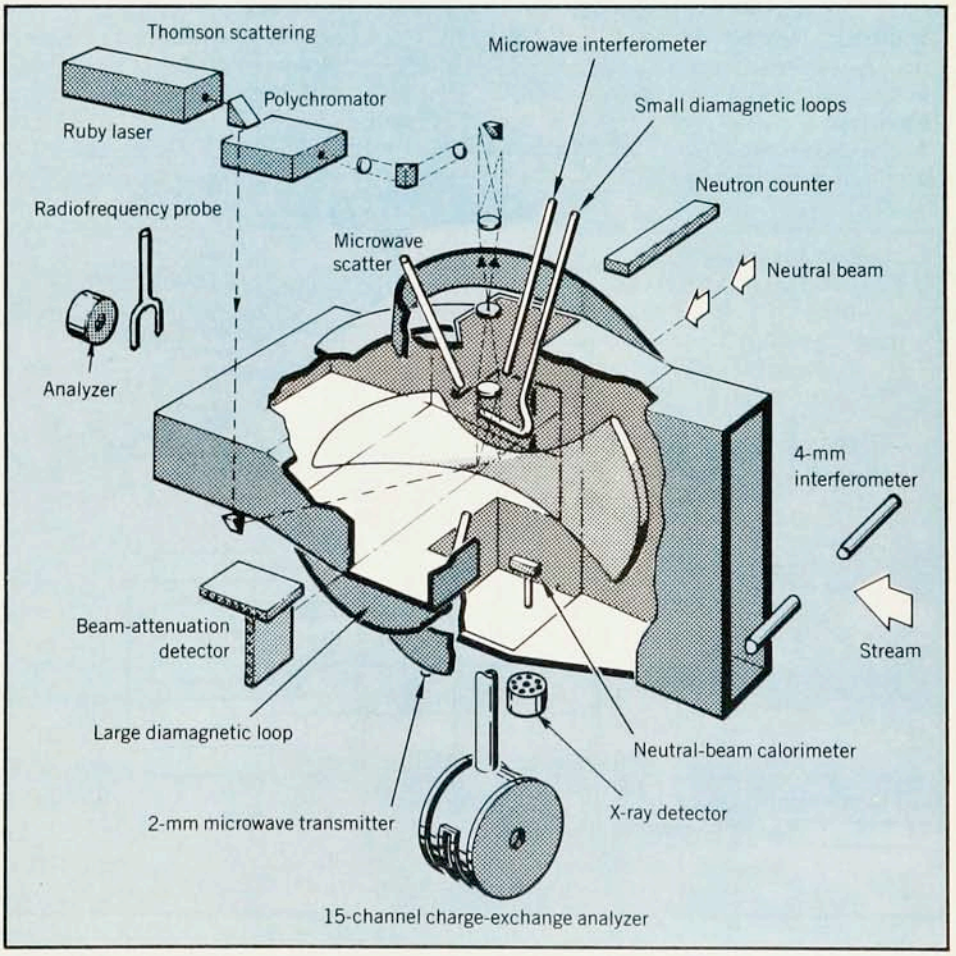
Figure 3 is a photograph of my first microwave interferometer, applied to measuring the density of plasma produced by a titanium hydride source in 1954. The principles employed have not changed much since that time. But the applications have, and methods of data collection and analysis have become so sophisticated that complete information on electron collision frequency, density and spatial distribution, as functions of time, are available within seconds after a machine operational cycle. The experimentalist is thus able to fold these data into his decision for specifying parameters for the succeeding shots. Microwave systems at several wavelengths are indicated in figure 2.

Extensions of these microwave methods into the infrared raise the measurable densities from $10^{14}\ \mathrm{cm}^{-3}$ to $10^{16}\ \mathrm{cm}^{-3}$, the conditions found in some pinch experiments. Figure 4 shows diagramatically a multi-channel laser interferometer arranged to measure dense plasma profiles at the Los Alamos Scientific Laboratory.[1,3] The indium arsenide detectors have fast amplifiers, with outputs split into sine and cosine components to show unambiguously whether the phase shift is positive or negative—that is, whether the density is increasing or decreasing. Digitization of data from such a system permits rapid analysis, but ordinarily leads to some loss of time resolution and speed. The wave techniques measure electron density; the ion density is inferred assuming charge neutrality. If there are two energy distributions of electrons or ions, their proportions must be determined by other means.

Plasma density fluctuations, both macro and micro, cause scattering of waves. The scattering properties depend primarily upon the relationship of the wavelength of the wave to the scale size of fluctuations, somewhat analogously to Bragg scattering.[1,2] In plasmas there are both statistical, thermal fluctuations (from which temperatures may be in-



Neutron counter employed with PLT tokamak. The large chamber is the collimator containing 7 tons of paraffin with Li_2CO_3. The detectors are a He^3 ionization chamber and a NE213 plastic scintillator. (Courtesy J. Strachan, Princeton Plasma Physics Laboratory.) Figure 1

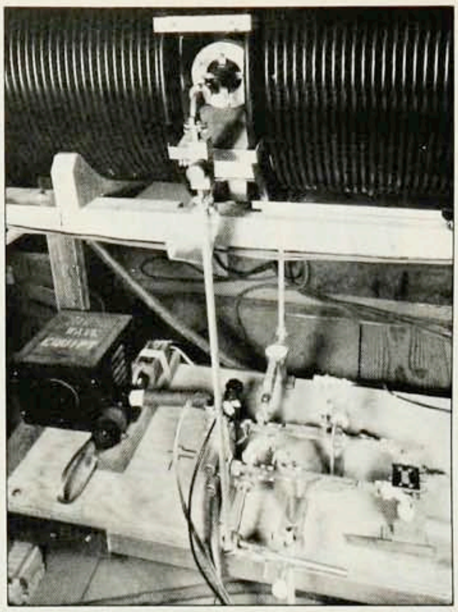


Array of diagnostics instruments applied to the Livermore 2XIIB magnetic mirror. Most instruments are equally useful with other magnetic confinement experiments such as tokamaks and stellarators. (Courtesy Lawrence Livermore Laboratory.) Figure 2 ferred) and collective fluctuations due to instabilities. The microwave scattering apparatus indicated in figure 2 is intended to monitor the amplitude, scale size and location of drift-cyclotron instabilities, which are particularly serious for magnetic mirrors. These instabilities can be controlled by various procedures, and it is important to be able to observe the process. The scattering of electromagnetic waves is from electrons. But even ion instabilities cause scattering, because the more mobile electrons follow the ion space-charge variations. Electron fluctuations may be coherent or turbulent.

When the incident wavelength is much shorter than the fluctuation scale size, the scattering is from individual electrons, and the amplitude is proportional to electron density. This process is called Thomson scattering. Optical wavelengths are required for usual plasma conditions, and ruby lasers are the most common sources. Thomson scattering at 90° is indicated in figure 2, but its application in that experiment is for measuring the electron temperature, which we will discuss later.

Neutral-particle beams also can give information about the plasma density. A neutral beam suffers attenuation proportional to the density as it passes through a magnetized plasma. This decrease in transmitted beam current is caused primarily by three effects:

- atomic (beam) scattering collisions with neutral particles,
- ionization of the beam atoms by plasma electrons, and
- charge exchange between the beam atoms and plasma ions.



K-band microwave interferometer. The first microwave diagnostics experiment at Lawrence Livermore Laboratory, viewing the plasma produced by a titanium hydride source in 1954. (Photo courtesy LLL.) Figure 3

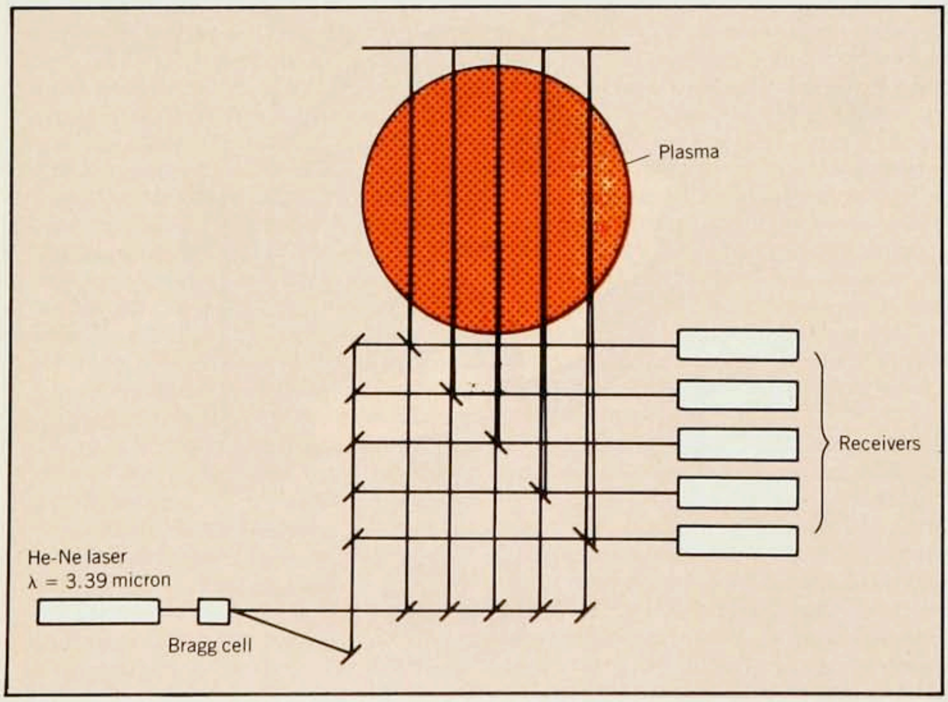
A high temperature plasma is nearly fully ionized, so that the first effect is relatively unimportant. Ionization by electron impact is most important for electron temperatures between 50 and 1000 eV, which is right in the range encountered in fusion experiments. Charge exchange cross sections are of two types, resonant and nonresonant. Resonant processes involve like atoms and ions, such as $H + H^+$, or $D_2 + D_2^+$. The cross sections for these interactions are large for all ion energies, falling off somewhat above 10 or 20 keV. Cross sections for nonresonant charge exchange (between unlike atoms and ions) have a broad maximum for ion energies between 200 eV and 20 keV, which again is within the range for fusion experiments. Thus, both the second and third beam-attenuation processes, electron ionization and charge exchange, must be taken account of; the total attenuation is the integral sum of each effect over the spatial distributions of energy and density along the beam path. An additional complication for data reduction is that one needs to know the kind of ions present.

The 13-channel neutral-beam detector array shown in figure 2 permits a profile to be determined each shot. But because four quantities and their spatial distributions are involved, it is necessary to coordinate these data with those from other diagnostic measurements. Fortunately, for large, high-temperature fusion experiments, with a nonresonant atomic beam one can obtain a situation where electron impact ionization accounts for nearly all beam attenuation, thus simplifying the data analysis.

The inverse of attenuation experiments is also possible—that is, detecting the secondary particles made by collisions. In a strong magnetic field this technique is difficult except with very heavy beam atoms. Tellurium has been much used because it has discrete and widely separated ionization states, easy to detect and analyze.

Lithium and barium are also popular, but for another reason; these atoms fluoresce when illuminated by a dye-tunable laser, or when excited by electron impact. Their progress through the plasma is thus optically observable.

Harold Eubank has given an excellent review of beam probing in reference 1.

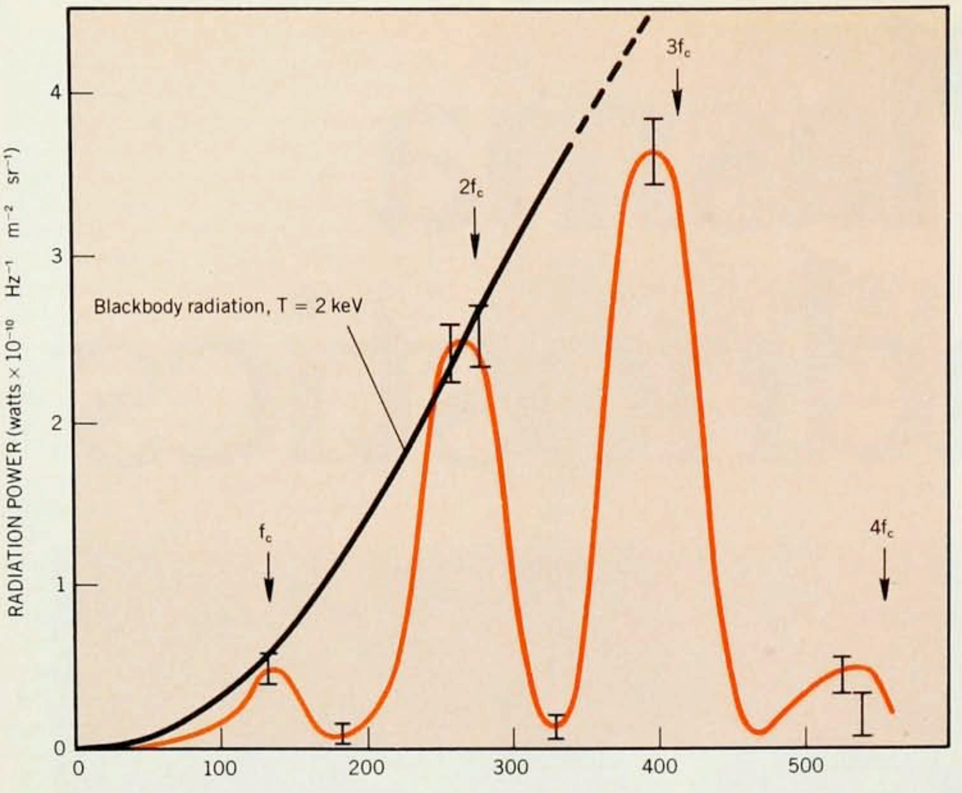


Five channel laser interferometer for plasma density measurements. The heterodyne quadrature detectors indicate unambiguously whether density is increasing or decreasing. The application is for density profiles on the LASL ZT-S reversed-field pinch. (Courtesy A. R. Jacobson and W. Quinn, Los Alamos Scientific Laboratory). Figure 4

Electron temperature

Energetic plasma electrons give evidence of their presence by radiating, by Doppler-shifting scattered waves and by producing diamagnetism. Any of these effects may be used for diagnostics.

Cyclotron radiation, also called "magnetic bremsstrahlung" or "synchrotron radiation," is produced when high-velocity electrons spiral around magnetic field lines. The emitted single-particle radiation occurs at the electron cyclotron frequency $\omega_c = eB/m$ and its harmonics, with an intensity proportional to the number and energy of fast electrons. This phenomenon would make a straightforward diagnostic method if it were not for the collective effects of the plasma. But the polarization of a dense plasma may shield the radiation at the fundamental frequency ω_c so completely that only signals at $2\omega_c$ or higher frequencies can escape. The signals that do escape are very faint, having power densities of picowatts/cm^2.



Cyclotron harmonic radiation data from the TFR tokamak at Fontenay-aux Roses. Calculated radiation for a blackbody at $T = 2$ keV is plotted for comparison. The receiving system was a Michelson interferometer with a Putley detector. (Data obtained from R. Cano[2]). Figure 5

ture. The data shown in figure 5 agree well with the theory for extraordinary wave radiation at low densities.

The microwave superheterodyne receiver has been the customary detector for cyclotron radiation; it is very sensitive, has fast response time and is in the appropriate frequency range for kilogauss magnetic fields. But recent experiments have fields of several tesla, requiring sensitive, wideband receivers at millimeter and submillimeter wavelengths. This can be seen from the frequency scale in figure 5; the magnetic field for those data was 5 tesla.

Fortunately there has been an exciting breakthrough recently in the development of Schottky-barrier diodes, increasing their sensitivity tremendously (see Session A of reference 3). Radiation measurements are now possible at wavelengths down to the far infrared, with response times of less than a microsecond. What is needed now is a breakthrough in their cost, which is still very high.

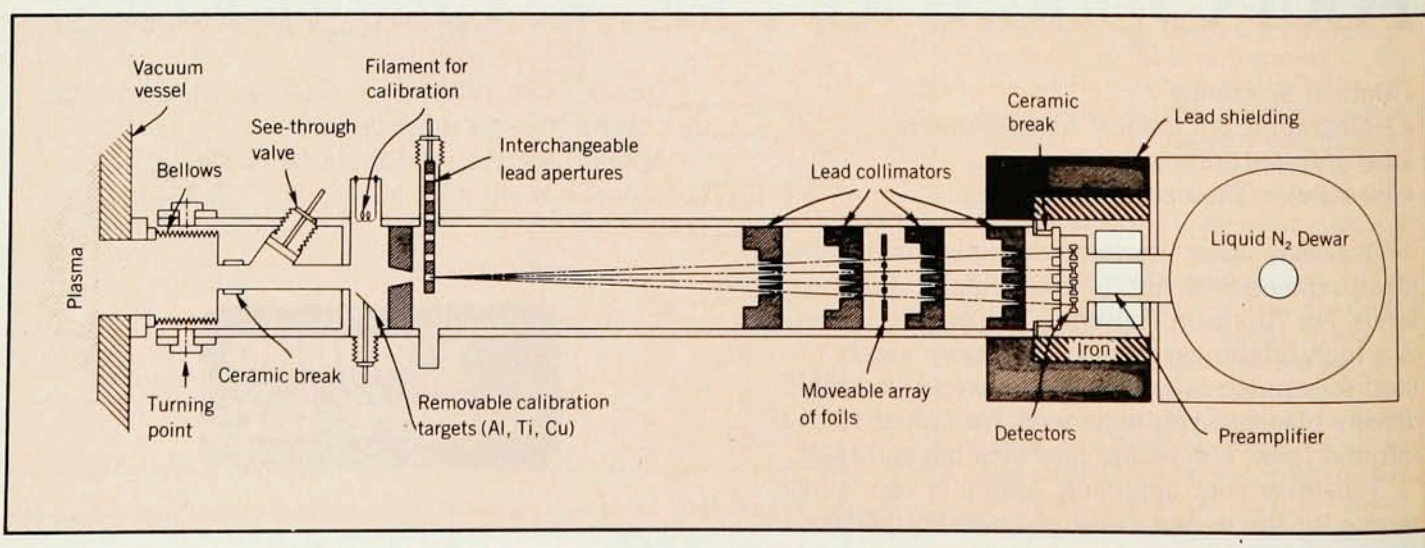
The principle of temperature measurement by Thomson scattering is very simple; measure the Doppler spread in frequency of light re-radiated by electrons. An illuminated electron oscillates in the electromagnetic field of the incident radiation. If it is moving toward the detector its re-radiation will be blue-shifted in proportion to its velocity. If moving away there will be an analogous red shift. A thermal distribution of velocities will give a gaussian frequency dependence to the re-radiated (scattered) emission. The spectral width is proportional to temperature.

Because the Thomson cross section is very small, successful scattering measurements require intense radiating sources and sensitive scattered-wave detectors, about state-of-the-art for both sources and detectors.

Referring again to figure 2, we see a 10-joule ruby laser source and a polychromator–photomultiplier detector.

Fortunately the theory to account for plasma effects has been worked out in detail by several workers (see I. Fidone *et al.* in reference 1 for a review), so that the method may be applied especially to tokamaks—yielding electron temperatures that are consistent with other determinations (see R. Cano[1] and V. Arunasalam *et al.*[3]). Effects of runaway electrons, even when they are highly relativistic, can be accounted for, because they move along magnetic lines. But nonthermal distributions or even mild instabilities may distort the spectrum badly. In fact, a highly anisotropic distribution may lead to strong radiation at harmonic numbers of 20 or higher, at superthermal intensities.[2]

Figure 5 shows the spectrum of radiation emitted by a tokamak having a thermal electron distribution, with plasma frequency ω_p less than ω_c. The calculated curve for blackbody radiation shows that the plasma radiates as a blackbody at ω_c and its second and third harmonics, but as a transparent medium at other frequencies. The intensity at higher harmonics depends upon the ratio of plasma frequency to cyclotron frequency and upon the electron tempera-



Soft x-ray analyzer used with PLT. Absorbers of beryllium or aluminum may be used to reject low energy x rays and to prevent pulse pile-up. The output goes to a pulse-height analyzer and computer. (Courtesy of S. von Goeler, Princeton Plasma Physics Laboratory). Figure 6

There are two additional polychromators not shown, permitting a profile of electron temperature. This 90° scattering system is typical of many in service, each having its specialized features. For example, the Princeton PLT tokamak has a large diameter, and so one needs many sampling points to get an adequate profile. The viewing system has a wide-angle lens focussed on a flat array of light pipes, each of which is focussed onto one spot of the slit of a Littrow spectrometer. The spectrometer is viewed by a micromesh channel-plate intensifier. The tradeoff for the wideangle viewing feature is a large f-number (giving low sensitivity), so that densities above 10^{13} cm^{-3} are required to give detectable signals (see Dirk Dimock in reference 1).

To measure temperatures at lower densities one can, in principle, go to longer wavelengths (for example, the 10.6 micron CO_2 laser), but the optics are not as convenient and the dispersive detectors not as sensitive as at 6943 Å.

Higher temperatures produce greater broadening, thus less light intensity in a given wavelength band of the polychromator. A system that measures 100 eV electron temperatures at a density of 10^{13} cm^{-3} would therefore require a density of 10^{15} cm^{-3} if the temperature were 10 keV. The largest aperture (smallest f-number) possible is thus advantageous, assuming that the direct plasma light is tolerable.

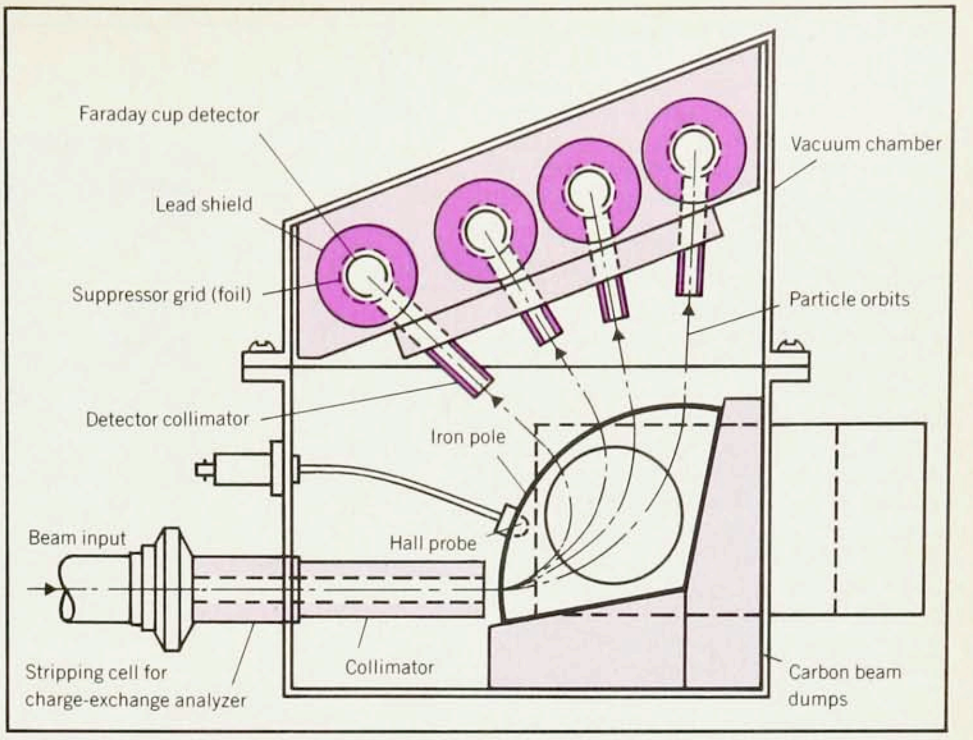
Continuum radiation measurements in the soft x-ray energy range ($h\nu$ between 1 and 20 keV) provide still another method to deduce the electron temperature T_e. The slope of the continuum spectrum, in the absence of line radiation, yields $(T_e)^{1/2}$ directly. The intensity of this bremsstrahlung unfortunately is very sensitive to the nuclear number Z of ions in the plasma, which must be determined to obtain valid conclusions.

Low-Z impurities, such as carbon and oxygen, have transitions below 1 keV, so that a "dirty" discharge (vacuum walls covered with contaminants) does not generally produce line radiation; the slope of a plot of intensity versus photon energy gives fairly good data for electron temperature. After the walls have been extensively cleaned and a low background pressure is obtained, the continuum levels will be low and line radiation will then be visible. For example, in the Princeton Large Torus the plasma bombards the limiter and walls, producing Kα lines of chromium at 5 keV, iron at 6.5 keV, nickel at 7.5 keV and so on, as well as tungsten and molybdenum in the 8 to 15 keV range. Great care must be used to find a region in the spectrum that is representative of continuum radiation, and thus directly yields electron temperature (see Schwick von Goeler in reference 1).

This diagnostic method is also a sensitive indicator of impurities, which cause a large loss of energy by radiation. In early PLT experiments the energy radiated away in the ultrasoft x-ray spectrum (100–1000 eV), due to bombardment of the limiter accounted for nearly all of the ohmic heating input power. Tungsten and iron radiation caused most of the loss, so extensive studies of these spectra have been made (see Heinz Knoepfel in reference 1 and Einar Hinnov also in reference 1). One of the requirements that tokamaks (or any closed systems) must meet before they can achieve reactor conditions is to lower the "effective Z" of contaminants, that is to eliminate the loss due to impurity radiation. The soft x-ray diagnostic is a major tool in monitoring this progress. Open confinement systems, such as magnetic mirrors, have an intrinsic self-cleaning operation, relaxing the requirement to lower the Z_{eff}. Thus, soft x-ray systems have not assumed as large importance there as with tokamaks.

One type of detecting apparatus uses lithium-drifted silicon detectors cooled by liquid nitrogen. These are followed by fast amplifiers and a pulse-height analysis system. Single photons are counted, which requires careful shielding from high energy x rays and foil attenuators to prevent pileup, as well as assist in energy analysis.

The collimating and detecting system shown in figure 6 has been developed at Princeton to detect and analyze x rays in the range 1–20 keV. The detectors are lithium-drifted silicon, in which protons create electron-hole pairs generating a charge pulse proportional to the photon energy. The output goes to a pulse height analyzer and finally to a PDP 10 computer.



Four-channel magnetic analyzer for energy determination of charge-exchange neutrals. Pole faces inside vacuum chamber are shaped to provide focus normal to the deflection plane. (Courtesy Laboratory of Plasma Studies, Cornell University). Figure 7

A second type of system resembles that of figure 6, but each collimating aperture has a different thickness absorber, and PIN diodes or other integrating detectors are used. Energy analysis is obtained from absorption.

Ion temperature

The old standby for measurements of ion temperature is the analysis of energetic neutral atoms formed by charge exchange of plasma ions with a neutral background gas. As ion temperatures become higher there are also nuclear reactions, whose products can be analyzed. And there is the diamagnetic effect due to the ion's magnetic moment.

Let us start with charge exchange. Energetic neutral particles, born when plasma ions exchange electrons with background gas, are able to escape the confinement region readily. A sampling of these atoms may be intercepted, reionized and analyzed by an energy analyzer such as sketched in figure 7. From this process the plasma ion energy distribution can be inferred.

The procedure of analysis is straightforward, but is complicated by the large number of steps between hot ion and data point. A number of reviews and case studies have been published on the subject (see Eubank and Brusati in reference 1, and my paper in reference 4), so we can restrict our discussion here to the highlights.

At the beginning of the chain is the charge exchange. Cross sections are well known for a wide variety of atomic and molecular species, but in the actual experiment the identity of both the ions and background gas is sometimes uncertain. Further, a hot plasma "burns out" the neutral gas that bathes it, so that there is a deficiency of target atoms inside, just where this diagnostic technique needs them. And in a fusion plasma it is not permissible to have any neutral gas at all around the plasma.

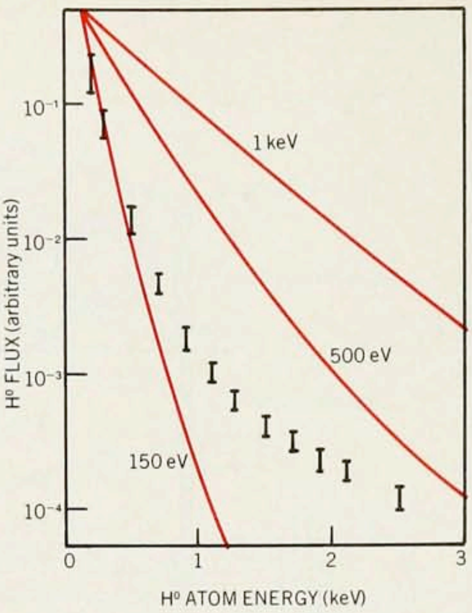
Fortunately for diagnostics, energetic neutral atom beams have recently been developed with fluxes large enough to provide the target atoms, without cooling the plasma. (In fact, neutral beams used to heat the plasma can also serve the diagnostics function; see Osher's paper in reference 1.) The characteristics of the beam may be specified by the experimenter to be compatible with the measurement. As a demonstration, consider a 5-keV H^0 beam passing through a 500-eV H^+ plasma at 90° to the magnetic field; it will generate analyzable charge-exchange neutrals at the same rate as a cold H_2 gas with 20 times the density. The reason is that H^+ has a resonant cross section with H^0, but not with H_2. Furthermore, the charge exchange with the beam heats the plasma, while the gas would cool it.

The second link in the diagnostics chain is to reionize the neutral atoms. The simplest method is stripping in a gas cell. The process is very inefficient, decreasing steeply at low energies. Oxygen has about the largest stripping cross section, but is poison in closed confinement systems, leading many experimenters to use helium in a gas cell isolated from the confinement chamber by huge vacuum pumps.

The third link is the analysis. The best arrangement is that shown in figure 2, which has multichannel analysis in both momentum and energy. This procedure gives energy and charge-to-mass ratio, thus showing also the charge state and species. In pulsed experiments it is possible to observe the time-of-flight, giving still another piece of data.

The final step is the detection. Faraday cups are shown in figure 7, a system that is usable only for large fluxes of charge-exchange atoms. Small fluxes require the greater sensitivity given by systems such as scintillator-photomultipliers, Channeltrons or the ion-electron multiplier Daly system,[4] which has an equivalent gain of about 10^7.

Figure 8 shows some results I obtained from the PULSATOR tokamak at the Institute for Plasma Physics, Garching, Germany in 1974. The system employed had a combination of magnetic and electrostatic deflection (momentum and energy resolution) and a Daly detector. The PULSATOR mode of operation was near the conditions for disruptive instability. The high energy tail evident in figure 8 became much more exaggerated 5 to 10 milliseconds before a disruption occurred, with 10 to 15% of the ions achieving energies of a kilovolt or more by the time



Neutral analyzer data for PULSATOR tokamak. Colored lines show calculated values assuming Maxwellian ion-energy distributions. (Data from C. Wharton[4]). Figure 8

the disruption became evident on the current and voltage diagnostics.

The ion temperature is obtained from the slope of the data curve. The results of figure 8 are evidently non-Maxwellian; so no "temperature" can be specified, only an energy distribution. Tokamaks and mirror machines heated by intense neutral beam sources also have non-Maxwellian distributions due to the ionization of the fast beam particles. Their distributions also resemble figure 8, but the spectrum extends out to more than 15 keV.

The nuclear reactions that become apparent when D^+ ion temperatures exceed a few keV provide another diagnostic tool; the rates of neutron production achieved are not yet health hazards, but they do provide information on ion temperature and density.

The thermonuclear reactions anticipated in a fusion experiment are D(d,n)T, D(d,p)He^3, T(d,n)He^4, and He^3(d,p)He^4, where, for example, the notation D(d,n)T means $D + D \rightarrow n + T$. When runaway electrons (in a tokamak) are present they may also make neutrons from (γ,n) reactions on walls, limiters, and so on. Electron energies above 10 MeV are required. All reaction products have energies in the MeV range; we are dealing with prompt, not thermal neutrons. The cross sections are all steep functions of energy at the ion temperatures obtainable, which means that a high-energy tail can make a disproportionately large contribution to neutron production. This effect is especially evident in experiments heated by high-energy neutral deuterium beams (10- to 60-keV particles), in which case the neutron spectrum usually is characteristic of beam–target, rather than thermonuclear conditions (see Eubank's third paper in reference 1.) Thus, neutron diagnostics cannot stand alone, but must be supplemented by input on spatial density distribution and relative ion energy spectrum. Then the method becomes a valuable indicator of the ion temperature.

For usual experimental conditions fast-neutron counting with good energy resolution has advantages over slow-neutron counting, since the ion temperature can be read right from the data.

The neutron detecting apparatus shown in figure 1 counts individual fast neutrons in a He^3 ionization chamber, followed by a pulse-height analyzer. The Li^6 in the Li_2CO_3-paraffin collimator nonradiatively absorbs thermal neutrons. The apparatus was mounted adjacent to the Princeton PLT so that it could be rotated to view neutrons either in the same direction as the injected neutral heating beam or in the opposite direction. If there is no difference in signals it is taken as evidence for thermonuclear neutrons.

Inertial-confinement fusion

An alternative approach to fusion, using rapid pellet compression, has been shown to produce thermonuclear reactions.[5] No attempt at long-term containment is made; the density and temperature are rapidly made high enough that reactions occur before the pellet can disassemble. The diagnostic requirements are thus much different than for magnetic confinement experiments. Here we must deal with picosecond time scales, micron dimensions, terawatt power levels and solid-state densities at kilovolt temperatures—a whole different world.

Several excellent reviews have appeared recently (see, for example, Lamar Coleman in reference 1 and C. Stickley[5]) pointing out the encouraging progress being made in laser–pellet fusion. The chief advances have been in three areas: laser development, target design and sophisticated diagnostics.

Targets have been mostly glass microballoons, filled with a high-pressure deuterium–tritium mixture. The short laser pulse heats the glass, causing it to push material outward and to explode inward, compressing the fuel to high temperatures. The target diagnostics for the "exploding-pusher" pellet are soft x-ray detectors, neutron cameras and alpha-particle detectors. The soft x-ray detector shown in figure 6 could be used here, except that the sensitive diodes would have to be replaced by less sensitive, but faster detectors. But computer simulations have shown that exploding-pusher pellets cannot achieve high enough gain to reach the Lawson criterion, requiring a new design.

A recent design is a multi-shell "ablative-compression" pellet, which improves the fusion performance but makes the diagnostics more difficult. The electron temperature is lower, decreasing the x

rays, and the compression is larger, making the small object to be viewed still smaller.

A number of important new diagnostic instruments have been developed recently in support of the Livermore Shiva–Nova project. Among the latest additions are instruments that perform time-resolved x-ray imaging, permitting the experimenter to follow details of pellet compression. The resolution goals, now partly realized, are one micron in space and one picosecond in time. At the heart of these systems is a very fast streak camera, viewing a magnified x-ray image of the pellet. Magnification for such a microscope is obtained by grazing-incidence mirrors. Double-reflection curved mirrors (Kirkpatrick–Baez) give magnification up to 3 or 4, with multiplexing into four channels, each having a different absorption filter. A hyperboloid–ellipsoid reflecting pair (Wolter system) gives magnification up to 22 at a large object distance. An alternate magnification system uses a gold Fresnel zone plate, which exposes shadowgraphs that are later viewed with laser light to reconstruct a magnified image, or are scanned and processed by computer to yield multicolor images. Pinhole cameras, Bragg crystals and holographic interferometry are also used to follow the pellet compression to micron dimensions. Coleman has published an extensive catalog (in reference 1) of diagnostic instruments in use with the Livermore Shiva–Nova experiment.

Pellets may also be compressed to fusion conditions not only by laser beams but also by beams of electrons or ions. Because such systems are available with much greater stored energies than laser systems, it is possible to use pellets that are 10 to 100 times as large. This relaxes the picoseconds to nanoseconds, and the microns to millimeters, but still leaves solid-state densities at multi-keV temperatures. Rapid advances in particle-beam fusion systems have occurred in the last few years, particularly at Sandia Laboratories in Albuquerque and the Kurchatov Institute in Moscow, with important advances also at several universities and other laboratories. The prospects for fusion look encouraging.

The diagnostics for electron-beam pellet experiments are still at a very rudimentary stage in comparison to those developed for laser fusion, partly because of the smaller budget, but also because the need for exotic instruments is not yet as great. Considerable information can be obtained from voltage and current monitors, calorimetry, flash x-radiography and x-ray dose analysis.

These requirements are also true for ion-beam pellet experiments, which are just now taking on major importance. A big difference for ion-beam pellet compression is the much reduced x-ray generation. This effect is a great advantage for the reaction processes, since the bremsstrahlung loss in both laser and electron-beam pellet fusion is enormous. But the lack of x rays denies the diagnostician all of the beautiful x-ray techniques already developed for pellet studies. Instead, the use of neutron, alpha-particle and prompt-gamma-ray detectors, nuclear activation and active imaging will be required (see my papers in references 1 and 4).

Nuclear activation is particularly important for ion-beam diagnostics. The high-current beams cannot propagate unless they are neutralized by electrons. Current monitors thus do not read the true ion current. Secondly, there may be more than one specie of ions, for example H^+ accompanying a desired D^+ beam. Protons activate carbon C^{12} (p, γ)N^{13} at 457 keV, while deuterons activate C^{12} (d,n)N^{13} at 328 keV. By viewing the gammas and neutrons it is possible to distinguish which ions are present in the beam. Convenient distinct thresholds up to 10 MeV exist, allowing fairly unambiguous ion-beam energy and current diagnostics.

Active imaging by flash x-ray shadowgraphs will become more important as pellet-compression experiments progress. A 10–100 picosecond electron-beam pulse incident on a 100-micron tungsten sphere can produce an intense diverging x-ray beam that casts a magnified shadow of the pellet. The low level of x rays generated by the ion beam itself makes this method attractive for ion beams but less so for electron beam or laser compression.

Active imaging by ultraviolet holography, for example with the 2660 Å laser line, will also be a useful technique, and much of the extensive hardware developed for laser pellet fusion can be adapted directly, with some of the tolerances relaxed because of the slower timescales and larger pellets used with ion beams.

Ion-beam fusion is an area of great potentialities, but one in which much further development is needed, both in the compression experiments and in the diagnostics.

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