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A GRIDDED IONIZATION CHAMBER FOR DETECTION OF
X-RAY WAVE ACTIVITY IN TOKAMAK PLASMAS

By

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A Gridded Ionization Chamber for Detection of X-Ray Wave Activity in Tokamak Plasmas

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ABSTRACT

In order to carry out X-ray observations of magnetohydrodynamic wave activity of the plasma during DD and DT (deuterium-beam-heated deuterium and tritium plasmas, respectively) operation of the Tokamak Fusion Test Reactor (TFTR), we will need detectors not susceptible to nuclear radiation damage. We have investigated the use of gridded ionization chambers as fast non-damageable X-ray detectors. A prototype chamber is described, which was tested on the PDX tokamak. These tests and laboratory tests with a pulsed X-ray source suggest that the detector has sufficient sensitivity and speed for the required measurements.

INTRODUCTION

Soft X-ray emission from a tokamak plasma gives information about plasma position, magnetohydrodynamic activity, disruptions, location of rational-safety-factor surfaces, and favorable confinement conditions.¹⁻⁶ Typically one observes emission by viewing the plasma through a narrow slot aperture, with an array of X-ray detectors. The diagnostic apparatus, which consists of the slot and detector array, is essentially a one-dimensional slot-hole imaging camera. Each detector measures chordally-integrated and wavelength-

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integrated X-ray emission along a narrow ray bundle neighboring some chord of the plasma minor radius. X rays of interest typically fall in the energy range of .5-20 keV.

Silicon surface-barrier diodes are, at present, excellent detectors for this diagnostic. But in the future, as deuterium-tritium gas mixtures are used and plasma temperatures enter the reactor regime, above 5 keV hard gamma and neutron radiation will destroy surface-barrier diodes. Because line-of-sight viewing of the plasma will be required, a path for hard radiation into the detector will exist. Optical throughput to the detector (the product of detector area and solid angle of view) must be large enough to allow the detector to monitor changes of X-ray signal in a time scale of a few microseconds. To satisfy this requirement and simultaneously permit observation of all chords of the plasma minor cross section, the X-ray imaging array must be near the tokamak. Although shielding can be installed to prevent damage of the silicon detectors during DD operation, the shielding is insufficient to prevent detector damage during DT operation because of the higher fluxes of more penetrating 14-MeV neutrons.

For this reason we have investigated the gridded ionization chamber as a detector of X-ray wave activity. Such a chamber is not easily damaged by radiation. It is, however, less sensitive than a diode of the same area, because of the larger photoionization energy needed to create an electron-ion pair (25 to 30 eV in many fill gases, compared to 3.6 eV in silicon). This disadvantage may be partially compensated for by using a larger chamber area. Another disadvantage is that the requirement for a mechanically reliable window between the tokamak plasma and the ion chamber fill gas means that low energy X rays will be cut off by the window. Nevertheless, the advantage of non-damageability can still be sufficient to make the chamber attractive, even if it is of lower sensitivity.

The use of a grid to provide fast response by an ionization chamber was first described by Frisch.⁷ Subsequently, Bunemann, Cranshaw, and Harvey⁸ presented detailed calculations of grid behavior and measurements of chamber behavior when used for alpha-particle pulse counting. In contrast to these investigators, who used a gridded chamber for ion-pulse counting, we use such a chamber to observe rapidly varying continuous X-ray signals. To monitor MHD activity during plasma disruptions, our chamber must respond to fluctuations at frequencies of several hundred kilo-Hz. To achieve this, a grid and a gas fill of high electron mobility are needed.

We describe here a small chamber which was tested on the PDX tokamak, as a prototype for wave-array detector chambers considered for use during D-D operation of the TFTR tokamak.

DESCRIPTION OF THE CHAMBER

The chamber consists of plane-parallel cathode, grid and electron-collecting anode electrodes, a grounded electrode support plate lying behind the anode, and a beryllium entrance window, oriented perpendicularly to the electrodes and located in front of the cathode-grid space (Figs. 1 and 2). The fill gas is a 90% Argon - 10% CH₄ mixture (P-10) at 1 atmosphere pressure. X rays enter the chamber in a direction parallel to the electrodes, into the space between the grid and the cathode. The anode, lying near ground potential, returns current to ground through a low-impedance dc-coupled current amplifier. The amplifier current has only a collected-electron component. Charge-displacement currents due to positive-ion motions do not appear because the anode is electrostatically shielded from the grid-cathode space.

A theory of the grid shielding action has been given by Bunemann, Cranshaw, and Harvey.⁸ Detailed designs for parallel-wire grids which simultaneously provide both shielding and efficient electron collection are presented there. For our chamber it was found convenient to make the grid of electroformed copper mesh rather than parallel wires. Commercially available 110 holes/inch mesh, manufactured by Buckbee-Mears corporation, was used.

A thick-ribbed support plate supports the cathode, grid and anode electrodes by means of machinable-glass (Macor) spacing insulators and provides stiffness against excitation of microphonic vibrations during the tokamak pulse. The chamber electrode feedthroughs are Ceramaseal coaxial BNC and SHV ceramic feedthroughs welded into a Conflat flange which forms the rear chamber wall. Since all chamber walls and the window are of metal and are at ground potential, the chamber is shielded electrostatically.

The chamber window is a 13 μ m-thick beryllium disc, lying in a cylindrical recess in the chamber front wall. On the external side it is contacted by a viton O-ring gasket, backed by a conical pressure ring; on the inner side it is pressed against the rim of a metal frame machined into the chamber end wall, which defines the window aperture. The external ring presses against the gasket, which forms a corner seal with the chamber wall. The window aperture consists of three slots 1/8" x 1/2" running parallel to the electrodes.

The grid-cathode spacing is .600"; the grid-anode spacing is .170". The chamber is operated at -1200 V cathode voltage, -500 V grid voltage to ground. The anode returns to ground through the low impedance current amplifier.

GENERAL CHAMBER DESIGN CONSIDERATIONS

In order that the chamber current be linear in intensity, for a given X-ray spectral distribution, the chamber is operated as a drift chamber, that is, without charge multiplication due to the chamber electric field, and with little accumulation of space charge between the electrodes. X rays not absorbed in the entrance window and which penetrate past an initial gas layer where the electric field is not yet normal to the cathode plane (an effective dead layer) are absorbed in the fill gas, and produce primary photoelectrons. The primary photoelectrons are slowed down, again in the fill gas, and produce pairs of positive ions and secondary-ionization electrons. The secondary electrons drift through the grid, are collected at the anode, and return to ground potential through a current amplifier. Ions drifting to the cathode do not induce displacement currents on the anode because the grid provides electrostatic shielding. For best electron transmission through the grid, the electric field in the grid-anode space is larger than in the grid-cathode space. If necessary, for radiation shielding, the current amplifier can be located at some distance from the chamber and coupled to the chamber via coaxial cable. The cable capacitance is kept small enough to allow adequate frequency response.

To give fast chamber response, a fill gas is used which has high electron mobility and does not attach electrons to form negative ions.

The maximum drift time of an electron across the chamber is

$$t_{\text{drift}} = d_{\text{ag}}/(v_d)_{\text{ag}} + d_{\text{gc}}/(v_d)_{\text{gc}}, \quad (1)$$

where d_{ag} and d_{gc} are the anode-to-grid and grid-to-cathode spacings and $(v_d)_{\text{ag}}$ and $(v_d)_{\text{gc}}$ are the corresponding electron drift speeds, and $v_d = v_d(E/P)$.

The chamber fill gas is selected so that it has appropriate X-ray absorption for the range of X-ray energies to be monitored and has sufficiently short electron-drift time to allow the desired high frequency chamber response to time-varying X-ray intensity. Suitable candidate gas fills are the rare gases mixed with methane, acetylene, carbon tetra-fluoride, or carbon dioxide. Detailed studies of fast gas mixtures and measurements of drift speed v_d versus electric field divided by pressure E/P have been made for a variety of mixtures of these gases by Christophoru, McCorkle, Maxey and Carter.⁹⁻¹⁰ Measurements of v_d versus E/P have been made for argon-methane and argon-CO₂ mixes by English and Hanna.¹¹ For our puposes we desire a gas fill at atmospheric pressure and an electron drift speed > 2 cm/ μ -sec. A number of gas fills can satisfy this requirement; we must, however, select the fill so as to have the proper X-ray absorption over the X-ray photon energy range desired for the chamber. The X rays must be hard enough to penetrate the dead layer near the entrance window, but they must also be soft enough to have appreciable probability of absorption within the column of fill gas.

Let $\mu = \mu(h\nu)$ be the attenuation coefficient in the fill gas for photoabsorption of photons of energy $h\nu$. In the range of energy of photons contributing to the chamber current the photoabsorption cross section of the fill gas molecules is appreciably larger than the photon scattering cross section, and we may estimate the fraction of photons which penetrate at least to a depth x into the chamber as $\exp(-x\mu)$. In general, μ depends strongly on the type of gas and photon energy and is a discontinuous function of photon energy.

We estimate the fraction of photons which enter the chamber gas and are absorbed between depths x_1 and x_2 , P_{abs} , to be

$$P_{\text{abs}} = \exp(-x_1\mu) - \exp(-x_2\mu) . \quad (2)$$

This function becomes small when μ becomes either very large or very small, and has a maximum value equal to

$$(P_{\text{abs}})_{\text{max}} = \left(\frac{x_2}{x_1} \right)^{\left(\frac{-x_1}{x_2 - x_1} \right)} - \left(\frac{x_2}{x_1} \right)^{\left(\frac{-x_2}{x_2 - x_1} \right)} \quad (3)$$

when

$$\mu = [\ln(x_2/x_1)]/(x_2 - x_1) . \quad (4)$$

Equation (3) is graphed in Fig. 3. The fill-gas absorption efficiency P_{abs} has been calculated on this simple model for two chambers: for the chamber which was tested on the PDX tokamak ($x_1 = 2$ cm, $x_2 = 6$ cm), and for a longer chamber proposed for use on the TFTR tokamak ($x_1 = 0.8$ cm, $x_2 = 15$ cm); a 1-atmosphere 10% CH_4 - 90% Ar fill is assumed (Fig. 4). The absorption constants are obtained from the compilation of soft X-ray absorption cross sections by Veigle, Briggs, Bates, Henry, and Bracewell.¹² The calculation indicates that the longer chamber should have markedly improved sensitivity for photons between 10 and 30 keV energy. By extending the grid-anode region towards the window, chamber sensitivity to X rays below 2 keV energy should also be improved. The low-energy response of the chamber will, however, be primarily determined by window absorption, which depends upon the window

thickness and material, and this, in turn, will be limited by considerations of ruggedness, since we require that the chamber operate reliably in an essentially inaccessible location. We note that our P-10 gas fill is not necessarily optimal, and other gas-fill mixtures may provide more uniform and more sensitive response over selected portions of the X-ray spectrum without sacrifice of speed. We have not yet, however, verified such mixtures experimentally.

We note finally that the ion chamber current should not be adversely affected by the ohmic heating and poloidal magnetic fields of the tokamak. At fill pressures near one atmosphere, the mean electron drift motion is not markedly perturbed by $\mathbf{j} \times \mathbf{B}$ forces because the electron-molecule collision frequency is very high compared to the electron gyro-frequency.

EXPERIMENTAL TESTS

The chamber was tested initially to verify that its response was due only to the electron component of chamber current by placing an Am^{241} alpha emitter inside the chamber and observing the output-current pulse shape. Single pulses were observed, with microsecond rise time and widths approximately 3 microseconds. No delayed secondary pulse was observed which might correspond to a delayed ion-component.

The chamber was then tested for rise-time response to a pulsed beam of X rays. A Kevex K-5020SPD X-ray source using a type K-5020TPS power supply was used. When driven with a 4 volt square-wave voltage signal these units can drive a pulsed electron beam at voltages up to 50 kV, currents up to 2 mA and frequencies exceeding 1 MHz. The actual rise time of the pulse is ~ 100 ns. The ion chamber was examined for fast pulse response over a wide range of X-ray energies and intensities.

In response to pulsed X-ray excitation, the amplified chamber-current rise time was not greater than 1.5 μ -sec. In our measurements it was limited by the speed of the available high-gain current amplifier, rather than the chamber itself. (This was verified by replacing the chamber with a fast-response silicon diode detector.) The chamber response (Fig. 5) was fast enough for our application.

In order to observe X-ray emission from the PDX tokamak, we mounted the chamber and a silicon surface-barrier diode of $1/8$ " by 1" active area, which was used as a comparison detector, side by side at one end of a 1 meter long fiber-epoxy tube. The other end of the tube was mounted at the 75 μ m thick beryllium X-ray window of the tokamak. A 5 mm thick lead plate with a 15 mm by 75 mm rectangular slot defined the entrance aperture. For each detector, the solid angle of view was defined by that slot and by the active detector area. Helium gas was flowed through the tube to eliminate atmospheric X-ray absorption between the tokamak and the ion-chamber window (Fig. 6). X-ray emission was observed along a central tokamak chord, by both the ion chamber and the surface-barrier detector, for plasma discharges having a central electron temperature in the range 800 to 900 eV. The current responses of the two detectors followed one another closely, that is, they were identical up to a constant scale factor proportional to the relative sensitivities of the two detectors. The surface-barrier diode's output current was fifteen times larger than that of the ion chamber. Oscilloscope traces showing an example of the response of the two types of detectors during individual tokamak pulses appear in Fig. 7. Good agreement is observed between the two detectors.

In order to determine whether the ion chamber would be suitable for operation in a neutron environment during D-D operation of the TFTR machine, neutron irradiation tests were performed. The chamber was first taken to the

nuclear reactor at the Brookhaven National Laboratory and exposed to a flux of mainly thermal neutrons. Ion chamber current was measured during the exposure, and a value of chamber current divided by neutron flux of 6.5×10^{-9} nanoampere per neutron-cm⁻² -sec⁻¹ was observed. This sensitivity is generally compatible with operation of a chamber during the D-D phase of TFTR operation, without excessive induced noise current due to irradiation by the thermal component of the expected neutron flux.

The chamber was also exposed to a flux of D-D neutrons at the Princeton University neutron irradiation test cell, to see whether D-D neutrons might produce chamber-current pulses of magnitude high enough to interfere with chamber X-ray detection. Initial measurements indicate that this is not the case, but more extensive measurements must still be taken to verify this claim.

Measurements also were made of the response of the chamber to gamma rays. A response of 3.3×10^{-9} rA per gamma ray cm⁻² sec⁻¹ was observed for Cs¹³⁷ gamma rays having an energy of .662 MeV. All together the response measurements indicate that the ionization chamber, when surrounded by modest neutron and gamma-ray shielding (except for an entrance collimator to transmit X-rays), can make X-ray measurements with good signal-to-background during D-D operation of TFTR.

DISCUSSION

A gridded ionization chamber was constructed which was able to observe fast magnetohydrodynamic wave activity of 800 eV plasma discharges in the PDX tokamak. The response time of the chamber is short enough to observe MHD activity during plasma disruptions. It appears likely that the sensitivity and spectral uniformity of response of such a chamber may be improved

significantly by simple means, such as lengthening the gas cell, reducing the dead-field space at the front of the chamber, and tailoring the gas mixture, without essential sacrifice of speed. Such a chamber is intrinsically able to survive neutron exposure without damage.

For use in the Tokamak Fusion Test Reactor such chambers must be stacked in arrays, so that not only the hot plasma viewed along the central chord across the machine, but also the cooler plasma viewed along chords grazing near the plasma edge can be observed.

Also, the first window, located on the machine just behind the entrance-aperture slot to the diagnostic, must be substantial enough to withstand heating due to ultraviolet, particle, and soft X-ray bombardment. The chamber arrays windows must be strong and reliable enough to maintain vacuum integrity under operational conditions. Thermal loading on the chamber windows is not in itself a problem, and the space between the machine and chamber windows would be evacuated. The requirements for window integrity limit the minimum window thickness which can be used and, in turn, necessarily limit the response of the diagnostic for low energy photons. It is clear that hard-sealed (for example, brazed) chamber windows will be required, and appropriate window fabrication techniques will have to be used.

The above requirements and limitations, though formidable, still allow the use of ion chambers. The chambers of drift mobility type, rather than proportional multiplication type, can be closely stacked in a common gas envelope without mutual interaction. The trade-off between window strength and integrity on one hand and loss of sensitivity to low energy photons on the other hand may, in fact, be favorable when or takes into consideration the high temperature plasmas to be encountered in the later stages of TFTR operation. Further development of such chambers appears desirable because

they appear attractive as an alternative to the radiation-damageable silicon detectors now in use on tokamaks.

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FIGURE CAPTIONS

- Fig. 1 Schematic drawing of the gridded ion chamber.
- Fig. 2 a) The disassembled chamber.
b) The electrode structure.
- Fig. 3 Fractional photon absorption in the chamber; dependence on X-ray attenuation coefficient and minimum and maximum absorption depths.
- Fig. 4 Computed fractional absorption of photons in the fill gas (P-10 gas fill; window loss not included). a) Present chamber. b) Longer chamber anticipated for TFTR use.
- Fig. 5 Amplified chamber response to a pulsed, electron-beam-driven X-ray source. Lower trace - electron beam current versus time. Upper trace - ion chamber response. (Both traces 1 μ -sec/cm.)
- Fig. 6 Test arrangement on PDX tokamak to compare ion chamber response with surface-barrier diode detector response: a) torus, b) slotted Be window, c) plasma, d) Pb plate with aperture slot, e) helium-filled tube, f) diode detector, g) ion chamber, h) amplifiers.
- Fig. 7 Observed PDX X-ray signal versus time during several tokamak shots. Upper trace - surface-barrier-detector. Lower trace - gridded ion chamber. (Amplifier gain is 10X higher for chamber.)

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Fig. 1

Fig. 2a

Fig. 2b

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Fig. 3

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Fig. 4

Fig. 5

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Fig. 6

Fig. 7