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LOW-ENERGY X-RAY EMISSION FROM
MAGNETIC-FUSION PLASMAS

BY

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ABSTRACT

Complex, transient, spatially inhomogeneous tokamak plasmas require careful diagnosis. As the reactor regime is approached, soft X rays become more important as a versatile diagnostic tool and an energy-loss mechanism. Continuum emission provides a measure of electron temperature and light impurity content. Impurity lines serve as a probe for ion and electron temperature, impurity behavior, and radiative cooling. The entire spectrum yields vital information on instabilities and disruptions. The importance of impurities is illustrated by the extensive efforts toward understanding impurity production, effects, and control. Minute heavy impurity concentrations can prevent reactor ignition. Si(Li) - detector arrays give a broad overview of continuum and line X-ray emission (0.3 - 50 keV) with moderate energy (200 eV) and time (50 ms) resolution. Bragg crystal and grating spectrometers provide detailed information on impurity lines with moderate to excellent ($E/\Delta E = 100 - 23,000$) resolving power and 1 - 50 ms time resolution. Imaging detector arrays measure rapid ($\sim 10 \mu s$) fluctuations due to MHD instabilities and probe impurity behavior and radiative cooling. Future tokamaks require more diagnostic channels to avoid spatial scanning, higher throughput for fast, single-shot diagnosis, increased spectral

information per sample period via fast scanning or use of multi-element detectors with dispersive elements, and radiation shielding and hardening of detectors.

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I. INTRODUCTION

Controlled Fusion offers the hope of an essentially unlimited supply of energy with fuel available to all nations [1]. Diagnostics instrumentation plays an important role in controlled-fusion research [2-5]. It serves as the "eyes" and "ears" of the experimental physicist, enabling him to monitor his progress in the quest for attaining optimal conditions for fusion. The transient plasma of most of today's fusion-research devices and the large number and complexity of important interacting physical processes demand measurement of several physical parameters with good temporal and spatial resolution. As plasma temperatures become higher, the electromagnetic spectrum emitted by the plasma shifts toward shorter wavelengths, and X rays become more important both as a source of radiative power loss and as a means of making diagnostic measurements [6]. Several types of instruments have been developed over the years to probe fusion plasmas by measuring various properties of the X-ray emission [3-30]. A necessary part of these developments has been the contribution of expertise by scientists in many areas, such as solid state, nuclear, and atomic physics, astrophysics, crystallography, electronics, etc. These instruments permit measurement of a variety of important plasma parameters. These include electron [8,37,45] and ion [22] temperatures, density [31], plasma equilibrium and stability [23,24], plasma position, and plasma rotation [6]. Other parameters inferred from X rays relate to impurities and include radiative energy loss [10,32-35], concentration [6,8,10] and motion [36], charge-state distribution [21,37], wavelengths of emission lines [38-42], and atomic physics parameters such as cross sections for excitation, ionization, and recombination [43,44,46,47].

This paper is a review of X-ray diagnostic techniques and apparatus, used in magnetic confinement fusion experiments, involving measurement of X-ray emission in both the low energy or ultrasoft X-ray (USX) region (0.1 to 1 keV) and the soft X-ray region (SX) (1 - 10 keV). This extended range is addressed because some instruments operate in both regions and others are applicable to both ranges but have historically operated in the SX region due to the greater complexity required for USX operation. The low energy or USX range, however, is particularly important because the emission in this region is often a significant fraction of the energy loss in tokamaks [10,32-35]. Although various types of magnetic confinement devices exist and some are addressed in the paper, the bulk of the work reported involves tokamaks.

This paper focuses on describing magnetic fusion energy (MFE) X-ray diagnostics to scientists who may not be involved in or have intimate knowledge of MFE. Review information on basic principles of MFE are presented without going into detail. The tokamak is used as an example although some X-ray diagnostic work from other MFE devices is presented. An effort is made to illustrate what the diagnostic needs and problem areas are so that researchers in other fields can understand how they might contribute to the diagnostic effort. In Section II we review the basic principles of the tokamak. Section III emphasizes the importance of impurities. This importance is supported by (a) the extensive work done toward studying impurities, their effects, and their control, and (b) a summary of some specific impurity effects. In Section IV the mechanisms for X-ray production in plasmas and properties of this emission are reviewed. Section V describes the major X-ray diagnostic instruments used on tokamaks. The purpose, principle of operation, and characteristics of each instrument are summarized. Examples of data are presented and discussed briefly. Section VI describes some problems with

present X-ray diagnostics, some improvements planned for the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory (PPPL), and further development that would benefit the fusion program.

II. THE TOKAMAK

At Princeton two tokamaks, the Princeton Large Torus (PLT) and Poloidal Divertor Experiment (PDX) are operating presently. A third larger machine, the Tokamak Fusion Test Reactor (TFTR) [56], will begin operation in 1982. The major goal of TFTR is to achieve "breakeven" (fusion power out = heating power in) in deuterium-beam-heated tritium plasma (DT operation). Several other tokamaks are in operation at other laboratories in the United States and in other countries. These include the Alcator tokamaks at MIT, ISX-B (Impurity Studies Experiment) at Oak Ridge, Doublet III at General Atomic, DITE at Culham, U.K., TFR at Fontenay aux Roses, France, and others in Italy, Germany, Japan, the U.S.S.R., etc.

The tokamak has been reviewed in several papers [1,48-55]. A brief description follows. The basic components are shown schematically in Fig. 1. A hydrogen-isotope plasma characterized by major radius R (130 cm for PLT, 265 cm for TFTR) and minor radius $r=a$ (40 cm for PLT, 85 cm for TFTR) is created and heated in a toroidal vacuum vessel. A strong, static magnetic field B_T (1 - 10 T, depending on the type of tokamak and the regime of operation being studied) is superposed throughout the vacuum vessel by external toroidal field (TF) coils. The basic purpose of B_T is to confine the plasma ions and electrons by constraining them to move in helical orbits about the field lines. A transient toroidal current I_p is then induced in the conducting plasma by transformer action. This current usually has a quasi-steady "flat top" value of several hundred kiloamperes for a period of several

hundred milliseconds. A time-varying vertical magnetic field induced by ohmic heating (OH) windings around the toroidal direction generates the toroidal current, which heats the plasma via resistive or "ohmic" heating to a high temperature. In addition, the current produces a poloidal magnetic field (PF) around the smaller cross section of the torus. The net effect of the TF and PF is a helical magnetic field as illustrated. This field is characterized not only by the net field strength, but also its rotational transform ι . This transform is the poloidal angle a field line traverses during one toroidal circuit around the tokamak. It is this helical or torsional property of the field lines which gives the tokamak its equilibrium and stability characteristics. A parameter more commonly used than ι is the "safety factor" $q = 2\pi/\iota$, which depends on r , B_T , I_p , and major radius R . The value of q varies with minor radius r , and has a strong bearing on the stability properties of the plasma.

The plasma is characterized basically by the temperature of the electrons (T_e) and ions (T_i), typically one to several keV, and electron density n_e (typical peak value $1-10 \times 10^{13} \text{ cm}^{-3}$). These parameters typically have large values near the center of the minor cross section, and decrease to small values near the limiter (a metal aperture which defines the plasma diameter) as illustrated in Fig. 2. Also important are the particle and energy confinement times for ions, τ_i and τ_{Ei} , and electrons, τ_e and τ_{Ee} . The basic goal of the tokamak is to heat the plasma so that the colliding ions can overcome the repulsive Coulomb barrier (to permit fusion), and to provide sufficient density and confinement for a sustained burn, i.e., heat input from fusion reaction products > power losses from plasma. The temperature required for the easiest fusion reaction to attain, that of deuterium and tritium, is about 10 keV or 10^8 degrees K (1 eV = 11,600 K). The required density n and

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confinement time τ are specified by the Lawson criterion, $n\tau \approx 10^{14} \text{ cm}^{-3} \text{ sec}$ [57]. Working contrary to achievement of these goals are several power-loss mechanisms and other processes which tend to cool and destabilize the plasma and prevent attainment of high temperature, high density, and good confinement [51,58]. Power-loss mechanisms include radiation, ionization, charge-exchange losses (a hot ion is neutralized by capturing an electron from a cold neutral atom, and is no longer confined), conduction, and convection. Because of the large thermal and density gradients possible and the profound effect gradients can have on cross field transport of energy and particles, spatially resolved measurements, of T_e , n_e , I_p , impurity concentration and all other quantities of interest are of great importance.

Because temperatures achievable by ohmic heating are limited to 3-4 keV, [51] several auxiliary heating schemes are in use. Injection of intense beams (up to 3 MW of power) of 40-keV neutral deuterium (D^0) atoms into the PLT tokamak [32,59,60] has raised the ion temperature from 1 to 7 keV. Recently, the ion temperature in PDX was increased from 1 to 5.8 keV by 7 MW of neutral-beam power. Neutral-beam injection experiments have been done on other tokamaks [61-63]. Heating by absorption of radio-frequency (RF) electromagnetic radiation at several resonance frequencies characteristic of the plasma (like a microwave oven) has been successfully tested [32,64]. Adiabatic compression is another successful auxiliary heating technique.

III. IMPURITIES

In addition to the working gas, traces of impurity ions inevitably enter the plasma. These include oxygen and carbon in the 1-10% range (relative to n_e) and smaller quantities (.03-1%) of wall and limiter materials (Fe, Cr, Ni, Ti, and Mo) [65]. Tungsten (W) was also used for limiters in earlier times.

These impurities can have profound effects, some deleterious and some beneficial, on the plasma. The importance of these effects is indicated by the extensive experimental [66-100] and theoretical [101-118] efforts by many groups and individuals toward understanding impurity transport and impurity effects on the plasma, impurity production mechanisms, and toward developing schemes for reducing impurity influx and removing impurities from the plasma. Recipes for removal of adsorbed oxygen and carbon from the vacuum-vessel wall [119] are used for all tokamaks. Titanium is evaporated onto walls to cover up adsorbed oxygen [58]. Special low Z limiters have replaced high Z materials to avoid the deleterious effects of high Z impurities in the plasma [58]. Impurity studies and control has been a major emphasis in the PLT research program [58,60]. The PDX experiment was constructed to study, among other effects, removal of impurities by a magnetic divertor [50]. The ISX-A tokamak was constructed to do impurity studies and, in particular, to test a concept for preventing impurities from flowing to the center of the plasma [99,101]. Theoretical models of impurity transport are used to help interpret experimental data [62,102,105,111]. Calculations of radiative power loss have been done for many impurity ions. These results indicate that a W density of .01% of n_e can prevent ignition of DT plasma in a tokamak reactor [107]. Because of the importance of impurity effects and because a major emphasis of X-ray diagnostics is measurement of impurity radiation and behavior, we give here a brief review of this subject.

As an impurity atom enters a tokamak plasma it is ionized by electron impact to successively higher charge states until a balance is reached between ionization and recombination [6,112,113], assuming steady-state conditions. Under these equilibrium conditions a distribution of charge states exists (Fig. 3). This distribution can be altered by motion of ions from hot to

cooler regions, or vice-versa, in tokamaks. The most probable charge state typically has an ionization potential approximately 1-2 times T_e . The distribution is usually narrow, with 4 or 5 ionization stages existing at any particular temperature. Thus, in a tokamak, whose temperature varies significantly with radius (Fig. 2), the distribution progresses continuously from low degrees of ionization at the periphery to higher stages at the center. A given charge state tends to cluster in a shell of several centimeters radius. Low Z impurities such as C and O tend to be fully stripped at the center, whereas high Z ions are only partially stripped.

These impurities affect the plasma in several ways. They cool the plasma by causing power to be radiated away via bremsstrahlung, radiative recombination, and line emission (Fig. 4) [6,52,107]. This cooling can be deleterious in the plasma center, which we are trying to heat. Or radiation cooling of the periphery of a reactor by low Z impurities can be beneficial; low edge temperatures tend to reduce the influx of higher Z wall impurities, presumably by reducing sputtering [32]. The low Z impurities are relatively benign in the center, as far as energy loss is concerned, since fully stripped ions produce no line radiation. High Z impurities in the center can radiate profusely because they have several bound electrons which can be excited [10,33,34,62,80]. Several people have been involved in calculations of radiation power from plasmas [87,106-108,110].

Also, impurities increase the plasma resistivity and can change the plasma-current radial distribution, thereby affecting stability [109,120]. Low Z impurities are usually the worst offenders here since high Z impurities are typically not present in sufficient quantities to affect the plasma resistivity significantly. As impurity content increases, the range of stable operating conditions diminishes; the onset of degraded confinement and disruptive instabilities occurs at lower density and plasma current [120].

A third harmful effect of impurities is dilution of the reacting fuel ions. The overall effect of impurities is often described in terms of their contribution to the effective charge

$$Z_{\text{eff}} = \sum_i \frac{n_i Z_i^2}{n_e} \quad , \quad (1)$$

where the summation is over charge states Z_i of all ions of density n_i . For a burning plasma the reaction rate of fusion power for fixed n_e and T_i is reduced by a factor

$$f = \left(\frac{Z_i - Z_{\text{eff}}}{Z_i - 1} \right)^2 \quad , \quad (2)$$

for a single impurity of charge Z_i , relative to an impurity-free plasma. For a 3% fully stripped C contamination, we get $Z_{\text{eff}} = 2$ and $f = .64$ which corresponds to a 50% increase in the cost of electricity [120].

Impurities can also reduce the penetration of neutral beams used for auxiliary heating due to the large cross section for electron capture by highly stripped impurities from deuterium.

IV. X-RAY EMISSION CHARACTERISTICS

The X-ray emission spectrum from tokamaks consists of a continuum with characteristic peaks superimposed. The continuum has two components resulting from electron-ion collisions:

- (1) free-free (ff) bremsstrahlung on hydrogen isotopes and impurity ions,
and
- (2) free-bound (fb) recombination of electrons with impurity ions.

The dependence of the continuum intensity on atomic and plasma parameters has been treated in detail [6,8]. For our purposes it is sufficient to note that the bremsstrahlung emission is

$$\left(\frac{\Delta W}{\Delta k}\right)_{ff} \propto n_e \sum_i n_i Z_{i,ff}^2 \exp(-k/T_e) , \quad (3)$$

where ΔW is the radiated power per cm^3 into the photon energy interval Δk , n_e and n_i the electron and ion density, $Z_{i,ff}$ the ion charge relevant for free-free transitions ($\approx$ nuclear charge), k the photon energy, and T_e the electron temperature. For recombination radiation in the energy range above the ionization potential of the recombining ion, we can write

$$\left(\frac{\Delta W}{\Delta k}\right)_{fb} = \left(\frac{\Delta W}{\Delta k}\right)_{ff} (\gamma_i - 1) , \quad (4)$$

because fb and ff radiation have the same spectral shape. The parameter γ_i is the enhancement of the continuum radiation over bremsstrahlung due to the recombination radiation. The dependence of the line radiation spectrum on impurity content, atomic physics, and plasma parameters has also been treated in detail for some impurities [118,121].

Examples of typical X-ray emission spectra from the PDX tokamak and the EBT device at Oak Ridge National Laboratory, respectively, are shown in Figs. 5 and 6. Absolute measurements of some impurity line intensities in the USX region have been given [92]. The volume emissivity of photons varies strongly with energy and impurity concentration. Typical values may range from near $10^{15} \text{ cm}^{-3} \text{ sec}^{-1}$ for the Ni XXV 118Å line [92] to $10^{13} \text{ cm}^{-3} \text{ sec}^{-1} \text{ keV}^{-1}$ and $10^9 \text{ cm}^{-3} \text{ sec}^{-1} \text{ keV}^{-1}$ for the continuum at 1 and 10 keV, respectively, for a plasma

with $T_e = 1$ keV and $n_e = 5 \times 10^{13} \text{ cm}^{-3}$. We see that line and continuum intensities can vary by many orders of magnitude over the spectral range of interest. Thus X-ray diagnostics must cover a wide dynamic range. We make three general observations:

- (1) The continuum spectrum has an exponential dependence on photon energy. The slope on a semilogarithmic plot is $-1/T_e$. Using this we can measure T_e from the continuum spectrum.
- (2) The intensity of the continuum depends on the relevant ion charge Z_i as $n_i Z_i^2$. Thus a relatively small ion fraction n_i can produce a relatively large contribution since Z_i^2 is typically large.
- (3) The enhancement factor γ_i is typically ~ 10 for clean discharges [8, 15] but under some circumstances can be as large as ~ 1000 [15,36]. This factor depends strongly on the ionization stage of an impurity ion [6]. Thus for a quantitative evaluation of the continuum, the ion densities and charge-state distributions must be known.

II. X-RAY DIAGNOSTIC INSTRUMENTS

There are several types of X-ray diagnostics used for tokamak research. Each has its own purpose based on its characteristics. These include: (1) energy range, (2) energy resolution, (3) time resolution, and (4) spatial resolution.

In the following sections some of these instruments will be described. Their principles, geometry, mode of operation, characteristics, and examples

of data with some interpretation will be presented. The grazing incidence diffraction-grating spectrometer, traditionally considered a vacuum-ultraviolet (VUV) instrument, will be included since important work in the low energy X-ray region has been done using this instrument.

Briefly the instruments to be described and their basic characteristics are as follows:

- (1) Pulse-Height Analyzer (PHA) - wide spectral range, moderate time and energy resolution, and moderate spatial resolution.
- (2) X-ray Crystal Spectrometer (XCS) - Narrow spectral range, very good energy resolution, and moderate time and spatial resolution.
- (3) X-ray Imaging System (XIS) - broad spectral range, crude energy resolution, very good time resolution, and good spatial resolution.
- (4) Rotating Crystal Spectrometer (RCS) - moderate spectral range, good energy resolution, moderate to good time resolution, and moderate spatial resolution.
- (5) Grazing Incidence Spectrometer and Monochromator (GISMO) - broad spectral range, good time resolution, good to very good energy resolution, and good spatial resolution.
- (6) Other Instruments with various characteristics.

The diagnostic names, acronyms, and instrument descriptions to follow are characteristic of instruments used at PPPL in the X-ray group and UV, visible spectroscopy group. Similar types of diagnostics, however, are used at many other laboratories.

A. PULSE HEIGHT ANALYZER

The Pulse-Height Analyzer (PHA) X-ray diagnostic is a very useful and versatile instrument. It is used on many present day tokamaks [6,13,15,17, 18, 30, 123] and other fusion experiments [122]. It provides a broad overview of the X-ray emission and yields temporally and spatially resolved measurements of T_e from the slope of the continuum, high and low Z impurity concentration (from respectively, impurity line intensities and enhancement of the continuum over bremsstrahlung via recombination), and information on non-Maxwellian features of the electron-velocity distribution [6]. Sample PHA spectra have been shown in Fig. 5. The X-ray energy range at PPPL has historically been limited to 1-30 keV because of beryllium vacuum windows and thin lithium-drifted silicon or Si(Li) detectors. Recently, however, the PHA on PDX has been extended to the sub-kilovolt region by implementation of a windowless Si(Li) detector. This type of detector has already been in use at other laboratories [122]. Figure 7 illustrates the principle of the PHA [6]. The PHA may consist of one pivotable tube (for spatial scanning) or several tubes to view several regions of the plasma simultaneously. In each tube a set of collimators directs the X rays to one or more Si(Li) detectors. Multi-detectors are used to improve the time resolution and statistics by increasing the net count rate of the system. The main technical limitation here is pulse pile-up at high rates [6,14] (two pulses arriving simultaneously at the detector are additive and register as one pulse at

higher energy). The effects of pulse pile-up are exacerbated by the exponentially decreasing continuum spectrum. A few piled-up low energy pulses, due to high intensity, can cause a relatively large distortion of the spectrum at higher energy where the count rate is much lower. The PHA minimizes this problem by constraining, by means of absorber foils and apertures, each of several detectors to focus on a portion of the total spectrum. The low-energy detector has a thin foil to pass low energy radiation and a small aperture to reduce the count rate to an acceptable range. Higher energy channels have successively thicker foils and larger apertures to equalize count rate. From the partial spectra from each detector the computer synthesizes a single total spectrum by

- (a) correcting each spectrum for its absorber and aperture size,
- (b) discarding the higher energy portions which may be susceptible to pile-up distortion, and
- (c) overlaying the separate spectra (mathematically) on a common scale.

Four composite spectra measured from four different chords of the PDX tokamak are displayed in Fig 5. The energy resolution of the PHA must be ~ 200 eV FWHM at 6 keV to permit separation of $K\alpha$ impurity peaks from Fe, Cr, and Ni. These peaks are shifted toward higher energy, relative to the $K\alpha_{1,2}$ peaks, and broadened because of the distribution of emitting charge states [21]. Good energy resolution is also important to permit separation of peaks from the continuum so that undistorted regions of the continuum are available for T_e determination. To obtain time resolution, sixteen or more spectra are taken during a single 1-second discharge. This time resolution is limited at present to about 50 ms by (a) the need for reasonable statistics in a spectrum, (b) count-rate limitations of the detectors at the required energy resolution, and (c) the maximum number of detectors which can reasonably be

used in one PHA tube. The PHA on PLT has four detectors [6,9], PDX has three detectors per tube for each of five tubes [30], and the TFTR PHA will have eight tubes each with six detectors [125]. Any improvement in the time resolution such as by improvement of pulse-pileup rejection, development of higher transconductance FET's [126] etc., would be welcomed.

Figure 6 is a nice spectrum from the 5-detector Si(Li) array on EBT showing a prominent Al $K\alpha$ peak [122]. The continuum slope indicates a T_e value of 850 eV.

B. THE X-RAY CRYSTAL SPECTROMETER

Crystal spectrometers have been used for detailed investigations of impurity line radiation in both the soft X-ray region (SX) and the ultra-soft X-ray (USX) region. Wavelength scanning (point by point) flat crystal spectrometers and curved crystal multiwavelength polychrometers will be treated in this section. A newly developed dynamically rotating flat crystal spectrometer will be described in a separate section.

Shot-to-shot scanning of X-ray spectra using flat crystal spectrometers has been used both on θ -pinches for measurement of impurities [127] and for investigation of temperature diagnostics by measurement of dielectronic-recombination line intensities [45], and on tokamaks for separation of $K\alpha$ radiation from different charge states of Fe [128], for investigation of oxygen K and Fe L spectra in the region .5-1 keV [6], and for measurement of Mo and Cl emission [82]. Curved crystal spectrometers which are much superior to the scanning flat crystal instruments have been developed recently. These have much higher intensity and are equipped with a position sensitive detector which allows simultaneous measurement of an entire spectrum, avoiding the problems associated with shot-to-shot reproducibility [21]. While these

instruments have so far been used only in the SX region, the principle is capable of extension to the USX region, although complications exist. These include: (1) operation in vacuum, (2) use of thin window or windowless detectors, and (3) more severe limitations on resolution because of the relatively broad ($E/\Delta E \sim 2000$) crystal rocking curves.

The multiwavelength Johann curved crystal spectrometer, recently dubbed X-ray Crystal Spectrometer (XCS), was first used on tokamaks (PLT) with film recording [129] for investigation of Fe K α spectra. Subsequently, an improved version with time-dependent readout using a position-sensitive multiwire proportional counter was developed [21]. The principle of operation of this XCS is illustrated in Fig. 8. Also shown is a crystal mounted in a jig used for bending and holding it to a cylindrical shape. X rays from the plasma pass through a vacuum tight beryllium window into tubes filled with helium to minimize X-ray attenuation. X rays of different wavelengths (e.g., λ_1 and λ_2) from different parts of the plasma are diffracted according to the Bragg relation $n\lambda = 2d \sin\theta$ (n = order, λ = wavelength, d = spacing of crystal lattice planes, θ = Bragg angle) and focussed to corresponding points on the Rowland circle of radius R . The range of wavelengths or energies which can be covered during a single integration period is determined by the crystal angular dispersion, the detector length l , and the crystal-to-detector distance $R \sin\theta$,

$$\frac{\Delta E}{E} = \frac{l}{R \sin\theta} \cot\theta \quad . \quad (5)$$

The energy resolution is determined by the position resolution of the detector, the distance from crystal to detector, and the crystal rocking-curve width.

The XCS was first used on PLT to study the charge-state distribution of Fe XVIII - Fe XXV ions [21]. A knowledge of this distribution is important for (a) absolute measurement of Fe concentration from the Fe peak of the PHA spectrum (since excitation rate varies with charge state), (b) realistic studies of transport of Fe ions, and (c) verification of theoretical excitation and recombination rates. As the central electron temperature T_e (d) increases the iron is ionized to a higher charge state, and the spectrum shifts to higher energies (Fig. 9).

For these measurements an XCS with $R \approx 5m$, $E/\Delta E \approx 1700$, and using a Ge (220) crystal was used. The spatial resolution of the proportional counter was .4 mm. To obtain time resolution of ~ 50 ms, 16 spectra can be recorded during a 1 second discharge, although data from several similar discharges may have to be added for reasonable statistics.

More recently the XCS on PLT was greatly improved by substitution of an α -quartz (2243) crystal with $R = 3.33$ m to provide a resolving power $E/\Delta E = 15000$. An Fe spectrum measured with this spectrometer is shown in Fig.10 [22,37]. The peaks shown include resonance lines of Fe XXIII - Fe XXV (β , q , w , respectively), forbidden (z) and intercombination (x,y) lines of Fe XXV, and lithium-like satellites excited mostly via dielectronic recombination.

This ultra-high resolution XCS was developed mainly to measure ion temperature T_i by Doppler broadening of the Fe XXV helium-like resonance line w . A similar high resolution ($E/\Delta E = 23000$) XCS using an α -quartz (2023) crystal has been installed on the PDX tokamak at PPPL for T_i measurements and other investigations using X rays from highly ionized titanium ions. As shown in Fig. 11 this spectrometer has measured ion temperature increases from ~ 1.0 to 5.8 keV resulting from ~ 7 MW of NBI heating. This figure shows the time

history of T_i as inferred from Voigt-function fits to the Doppler broadened titanium XXI 1s-2p resonance line.

Detailed studies of intensity ratios of various peaks indicated in Fig. 10, relative to line w, as a function of T_e and n_e have demonstrated several other useful aspects of the high-resolution spectra. These include measurement of T_e from the ratio I_j/I_w , the departure of Fe charge states from ionization equilibrium, dielectronic recombination rates, and impurity transport rates. Theoretical work by Gabriel and coworkers was used as a basis for some of these measurements [37]. The TFR Group has recently reported similar studies in the USX region for oxygen ions [124].

A different type of high resolution crystal spectrometer using the design of von Hamos and a resistive-anode position sensitive proportional counter has recently become operational on the Alcator C tokamak at MIT [130]. Measurements of Cl and S K spectra have been reported. A higher resolution version has just been implemented for ion-temperature determination [131].

The importance of the XCS for T_i measurement increases for larger, higher density future tokamak plasmas. Other T_i measurement techniques will become severely limited for reactor plasmas [5].

C. THE X-RAY IMAGING SYSTEMS

Development of the technique used for the X-ray Imaging Systems (XIS) has revolutionized the study of magnetohydrodynamic (MHD) plasma instabilities or fluctuations in tokamaks. Use of this technique of measuring x ray fluctuations in tokamaks has been actively pursued at many laboratories since about 1972 [23-27, 132-138] when "sawtooth oscillations" were discovered in the intensity of X-ray emission from the ST tokamak, as measured by a two-detector system [132]. Because of the profound effect (deleterious in some cases and

beneficial in others) the various modes of oscillation can have on plasma particle and energy confinement, MFE theorists and experimentalists have devoted much effort to measurement and interpretation of these fluctuations [23-27,132-139]. In addition, the XIS has been extremely useful in characterizing the effects of impurity radiation on tokamak behavior and understanding the behavior and means of controlling impurities [10]. Various investigators have also used the XIS technique on tokamaks to measure plasma toroidal rotation [6], electron heat conductivity [140], and dielectronic recombination coefficients of impurity ions [47]. A further use is measurement of plasma position.

The principle of the XIS is illustrated in Fig. 12. It is essentially a slot hole X-ray camera. An array of X-ray detectors views the plasma through a slot, permitting measurement of the line integrated X-ray intensity from several chords of the plasma. This X-ray intensity is modulated by rapid density and temperature variations which accompany the propagation of waves or fluctuations through the plasma. The detectors are typically silicon surface-barrier or PIN diodes, operated in current mode. The X-ray energy range of sensitivity of the diodes is usually limited to greater than .1 keV by absorption in a gold contact layer, typically $40 \mu\text{g}/\text{cm}^2$, and a SiO_2 dead layer, typically $7 \mu\text{g}/\text{cm}^2$, on the surface of the detector. The transmission of these layers is given in Ref. [6]. The high-energy efficiency depends on the effective thickness of the detector. Rough estimates of the spectral composition of the radiation are obtained by inserting absorber foils into the X-ray path. Reference [6] shows the transmission factor for various foils used on the PLT XIS.

The time scale for fluctuations in tokamaks ranges from the millisecond to the microsecond range. Typical currents generated in the detectors range

from a few nanoamperes to tens of microamperes. Thus the current in the detectors must be amplified by low noise, wide band amplifiers. Typical noise levels are .3 nA rms for a 500 kHz bandwidth [6]. The current is recorded by transient digitizers at rates of a few kHz to 1 MHz or stored on magnetic tape for later analysis. On PLT the digitizing rate is switchable during the plasma shot, in order to permit measurement of details of fast phenomena such as disruptions.

Figure 13 shows typical data from several detectors of the imaging array on PDX during a portion of a discharge. Graphed is detector current or line integrated X-ray emissivity as a function of time. The stars indicate both chord radius and the zero intensity level for that chord. An $m=1$ oscillation of the plasma column about its equilibrium position occurs, where m refers to the mode number of a Fourier expansion of the displacement in the poloidal angle ϕ . From these data we can also construct the time dependence of the radial emissivity profiles as shown in Fig. 14. These particular $m=1$ oscillations were caused by neutral beam heating.

Emission in the ultra-soft X-ray (USX) range ($0.1 < E < 1$ keV) is often a significant energy-loss mechanism and an excellent medium for monitoring particle transport and magnetic field evolution. A detailed presentation of the use of the broadband XIS arrays for studying the USX with good spatial (~ 1 cm) and temporal (~ 1 ms - 1 μ s) resolution has been given by Eames [10]. Several interesting and significant phenomena have been observed. For example rf heating at the ion cyclotron frequency (ICRH) resulted in a factor of 2.5 increase in the influx of both Fe and deuterium into the plasma, with little change in confinement time ($\tau \approx 40$ ms). With neutral beam injection in the direction opposite to the plasma current, evidence was noted of an increase in both the tungsten flux and its concentration at the center of the plasma. The

power-emission density at the center of the discharge was a very large 2 W/cm^3 just before a disruption occurred. The tungsten concentration, relative to n_e , was four times larger at the center than at one half the minor radius.

Another unusual observation was inverted "sawtooth" oscillations in the USX emission. While the soft X-ray (SX) emission ($E \sim 1 \text{ keV}$) decreases at the center, the USX radiation increases. Sawtooth oscillations are explained as a cyclic process in which the plasma is preferentially heated in the center causing the soft X-ray emissivity to slowly rise and the current to redistribute to a more peaked profile [23,26]. At some point MHD or microstability processes become unstable, and the peak collapses or flattens, the energy being rapidly transported outwards. This causes a sudden drop in soft X-ray emission near the center where the temperature drops and a sudden rise in emission at large radii where the heat is deposited.

A puzzling observation was that of so-called "implosive" disruptions [10]. During the more common "explosive" disruptions both the USX and the SX (Fig. 15) emissions decrease rapidly at the center and increase at the edges. This is suggestive of a movement of the plasma outward from the center, hence, the name "explosive." During "implosive" disruptions, while the SX emission exhibits the usual behavior, the USX emission increases at all radii (Fig. 16). The increase at the center is suggestive of movement of the plasma toward the center, from which the term "implosive" derives. Also observed during the implosive disruption are an asymmetric soft X-ray flash lasting for 10-20 μs and a simultaneous doubling of the USX emission over the plasma cross section in 10 μs . The soft X-ray flash is believed to be due to conversion of magnetic energy into kinetic energy. The doubling of the USX emission over such a short time scale was somewhat difficult to explain. A tentative explanation is enhanced oxygen radiation [10].

D. THE ROTATING CRYSTAL AND GRAZING INCIDENCE

SPECTROMETERS

The recent development of the Rotating Crystal Spectrometer (RCS) [10,141] at PPL has caused a tremendous increase in the volume of high resolution USX data measurable from tokamaks, as compared to grazing-incidence grating spectrometers. The small size, light weight, and relative simplicity of construction of the RCS all represent significant improvements in versatility and in suitability as a multichordal instrument for tokamak measurements. Even so, the RCS is by no means a replacement for the grazing-incidence grating monochromator and spectrometer (GISMO) which has been used for decades for high resolution spectrometry of MFE plasma. Rather, the two instruments are complementary, with GISMO extending to longer wavelength and providing absolute intensity measurements. GISMO is compared with the RCS here only because the two instruments partially overlap in spectral range and are used for similar purposes.

The RCS can scan the entire spectrum from 500 eV to 2 keV with good energy resolution ($E/\Delta E = 400$) twenty times during a tokamak discharge, giving a time resolution of 50 ms. Alternatively, the RCS crystal can be fixed at one setting to provide very good time resolution for one spectral point. The GISMO-type instrument using film instead requires twenty discharges to cover the range 200-1000 eV. Using photoelectric readout the GISMO can measure the intensity at only two points of the entire spectrum during one discharge, so that many discharges would be required to scan the entire spectrum. The RCS, however, may present some problems with regard to absolute calibration since its detector, a series of microchannel plates, has rapid variations in efficiency as the angle of incidence of the radiation is varied.

The RCS is shown in Fig. 17. A Soller collimator limits the angular divergence of the radiation from the plasma to roughly .1 degree. A set of absorber foils of 1 μm parylene and .6 μm Al reduces background due to intense radiation at wavelengths longer than 26Å [141]. The radiation is Bragg diffracted from a TAP or AdP plane crystal and detected by a set of four Chevron microchannel plates (MCP) arranged on a semicircle. The front surface of each MCP pair has a MgF_2 coating to enhance its sensitivity to soft X rays. The signal output consists of current to the collector plates. In order to obtain spectra the crystal is rotated, typically at 10 revolutions per second, and the collector current is measured as a function of time. The energy calibration, i.e., the Bragg angle, is determined by interrupting the light from an LED to a photodetector by a slotted disk which rotates synchronously with the crystal.

Figure 18 shows output traces during a plasma shot recorded with a transient analyzer. Traces (a) show the signal from the photodetector, which is produced by the slotted disk interrupting the light beam from the LED. One of the slots has been covered to provide a reference for angle determination. Figure 18b shows the current to the collector plates of the MCP. Spectra are produced alternately by the TAP and the AdP crystal. The spectra with higher intensity are from the TAP crystal, which spans the wavelength region 10-17 Å where the iron L radiation is located. The two lower spectra show iron L lines on an expanded time scale early and late in the discharge. During the early times Fe XVII lines are dominant ($t = 109-110$ ms). Later all Fe charge states are present ($t = 309-310$ ms). Figure 19 shows an Fe L spectrum late during a PLT discharge. Peak identifications were made from identifications of prominent Fe L lines in solar flare and laser plasmas [10,141]. Another spectrum from an oxygen-rich discharge is shown in

Fig. 20. By tilting the RCS about a pivot point, chordal profiles of X-ray emission can be measured. Figure 21 shows such profiles of several major iron L transitions for different charge-states.

The grazing incidence diffraction grating spectrometer and monochromator has long been used as a standard diagnostic for monitoring radiation from tokamak plasmas, both in the low energy X-ray region and at lower energies ($E < .1$ keV). These instruments are commercially available and are described in the literature [29]. Both photographic (broadband, time-integrated) and photoelectric (one or two narrow wavelength regions, time-resolved) detection have been used [63,79,80].

Comparison of photographic spectra from ORMAK with theoretical calculations for emission from tungsten XXXI-XXXV identified W $\Delta n=0$ transitions as the source of intense pseudo-continua in the 40-70 Å region [80]. Similar pseudo-continua near 50 Å and other bands at longer wavelength have also been observed in the Japanese tokamak DIVA [34,35,94]. These continua are evidently largely due to thousands of unresolved $\Delta n=0$ transitions involving the 4d electrons of several charge states of tungsten. In ORMAK [80] and PLT [33], these bands of radiation often accounted for 40-80% of the radiated power and led to or contributed toward undesirable effects such as poor confinement and hollow temperature profiles (cool central plasma). It was possible to reduce the tungsten content through cooling of the plasma edge by adding small amounts of neon or oxygen, or by appropriate programming of the hydrogen influx. These experiments identifying tungsten as a malefactor, and further experiments with tungsten limiters replaced by low Z limiters of stainless steel and carbon (which yielded much more favorable plasma behavior), led to the policy at PPPL [58] and ORNL of excluding high Z materials from the interior of tokamaks.

Grazing incident spectrometers are routinely used to monitor the OV⁺ and OVIII radiation at 21.6Å and 18.96Å, respectively. An interesting rapid increase in intensity of the OVIII 1021 line from ORMAK coincident with neutral beam injection has been interpreted to be the result of charge transfer from hydrogen (whose density is increased significantly by the beams) to O⁷⁺ ions in excited states [63]. Anomalously high (relative to excitation by electrons) intensities of the 115.8-Å line of O⁵⁺ and the 81.9-Å line of O⁶⁺ in ISX-A have been attributed to excitation via charge transfer from hydrogen atoms into excited states of Oⁿ⁺ [79].

E. OTHER X-RAY DIAGNOSTICS

The filter-detector scheme has long been used for measurements of X rays from plasmas [3,7]. A major defect of this method for temperature measurement is the uncertainty of interpretation and interference from impurity radiation.

The gas proportional counter has also been used for tokamak X-ray spectroscopy [142]. The energy resolution is poor making it difficult to separate K_α peaks from Fe, Cr, and Ni. The gas scintillation proportional counter (GSPC) [143], however, has better resolution, although not as good as the Si(Li), and high rate capability. Because of its radiation-damage resistance, it may be good for reactor-plasma T_e measurement where good energy resolution is not so critical. Photoelectron spectroscopy has been used to deduce the carbon content in the center of the T-4 tokamak [67] following electron capture by CVII from hydrogen. This technique may have further application.

VI. FUTURE DEVELOPMENTS

The controlled fusion research program has always suffered from insufficient information on plasma behavior. Designing instrumentation to provide ideal unambiguous data has always been an elusive goal. Often two or more schemes are developed to measure one plasma property, and neither method is fully adequate, e.g., T_e , T_i , n_e , $I_p(r)$. In addition the research effort has often suffered from a shortage of money, manpower, time, and particularly physicists and engineers with the appropriate expertise to develop optimal diagnostics. The trend at PPPL recently has been more toward either hiring specialists in particular areas of physics relevant to the development of needed diagnostics, or tapping the pool of expertise external to the fusion program through cooperative development efforts, subcontracts, DOE sponsored contracts to outside laboratories, etc. Such collaborative efforts are certainly beneficial to the fusion effort and are probably beneficial, for various reasons, to the external parties involved. The MFE X-ray diagnostics program has several areas where improvements in instrumentation and techniques and new creative ideas for measurements would be welcomed. In the following paragraphs I will discuss some improvements in X-ray instrumentation that are desirable, some of which are currently being developed for TFTR.

In former times when tokamaks were smaller and diagnostics budgets were leaner than today, many experiments required shot-to-shot adjustment of spatial view or time windows to get adequate spatial or temporal information, or accumulation of data over several shots to get usable statistics. In view of the magnitude, cost, importance, and more urgent nature of future fusion experiments such as TFTR and MFTF-B, such arduous, time-consuming approaches are no longer practical. This is especially true for operation of full tritium plasmas in TFTR (the crucial experiments), since the maximum number of

such discharges is 4000 and is limited by the allowable tritium inventory on site and neutron activation. Thus the hope for TFTR X-ray diagnostics and others, is to have several spatial channels and to improve throughput in each channel so that statistically significant data can be recorded during each shot with suitable spatial and temporal resolution.

Much of the development required for TFTR X-ray diagnostics is associated with the increased radiation levels expected during neutral beam injection (NBI) heating as compared to present-day tokamaks. For 45 MW (beam power) DD plasmas a 2.5-MeV neutron flux density of 10^{11} neutrons/cm²/sec is expected near the tokamak for a 1 second pulse. For DT plasmas a flux density of 6×10^{13} 14-MeV neutrons/cm²/sec is predicted. These neutron intensities can quickly damage solid-state detectors. The neutrons and concomitant secondary gamma rays from the tokamak structure and concrete walls can generate background noise levels in detectors which completely mask the X-ray signals. Thus all X-ray diagnostics are being redesigned to include extensive neutron and gamma-ray shielding and collimation to maximize the signal to noise ratio. For the XIS, fast gridded ionization chambers are being developed because of their resistance to radiation damage, to replace the easily damaged silicon surface barrier detectors.

The TFTR PHA will view more (8-12) radial chords than previously for PLT (1-chord) and PDX (5-chords). To accommodate the larger range of T_e , and thus intensity, and to improve time resolution, a combination of more detectors per channel (6 vs 3 or 4) and faster electronics is being implemented. One germanium detector per channel will be added since higher energy X rays will be produced by the higher temperature plasmas. Since overall reliability decreases as the number of detectors increases, and a vacuum failure is potentially more serious, detector passivation techniques

will be developed to improve the probability for detector survival under adverse conditions. Fourteen-MeV neutrons can generate large pulses (up to 11 MeV) in Si(Li) detectors. Special precautions must be taken in the design of electronics to prevent saturation or overloading by these pulses. The amount of remote control, monitoring, and testing is being increased due to the higher degree of complexity and sophistication and the reduced accessibility of the diagnostics. Tokamak diagnostics have always had to be more reliable and automatic than laboratory instruments because of remote operation and limited accessibility. This will be even more true for TFTR.

Some further improvements planned for the TFTR XIS are more detectors, an infrared-emitting diode for system testing and comparison of detector responses, a remotely movable standard detector for calibration of fixed detectors during operation, division of the amplifier into two modules with the first (preamplifier) directly on the detector feedthrough to reduce electrical pickup and minimize input capacitance, and a wider range of gains in the electronics. Because of the tremendous data-generating capacity of the XIS when digitization rates up to 500 kHz are used (240 detectors $\times$ 5 $\times$ 10⁵ words/detector/sec), mass-storage techniques have been investigated. A scheme using FM multiplexing was devised to store data from up to 320 detectors at 500 kHz bandwidth on a 42-track high speed analog tape recorder. Up to 100 shots per reel could be stored for later playback and digitization.

Developments for the TFTR XCS include improving time resolution by means of higher X-ray fluxes at the detector. This will be achieved by (1) using lower Z seed impurities, such as argon, which radiate higher photon fluxes and produce usable signals at lower T_e (this enables us also to make measurements further from the plasma center where T_e is lower), (2) increasing the crystal and detector size, and (3) choosing crystals with higher reflectivity. To

accommodate higher X-ray intensity, faster detectors and electronics are being developed. The larger dynamic range provided by these improvements will be important for TFTR since the temperature excursion during a discharge (and thus the range of X-ray flux) will be large due to intensive neutral beam, rf, and compression heating.

Grating monochromators are being converted to polychromators by use of multi-element detectors such as the intensified Reticon photodiode array [145].

There is need for further improvement of X-ray diagnostics both for near future experiments such as TFTR and for future reactors. The need for higher count rates has been mentioned. Shielding and collimation will just prevent damage to the PHA Si(Li) detectors over the life of TFTR ($\sim 10^{10}$ neutrons/cm²). Reactors, however, will have much higher duty cycles. Thus the detectors will have to either withstand neutron fluences two orders of magnitude higher than present Si(Li) detectors can, or be exposed to the reactor only for brief periods to make a measurement. A possible replacement detector is the gas scintillation proportional counter [143]. Improvement of reflectivity and resolution of multilayer synthetic crystals would make them attractive for extension of the rotating crystal spectrometer to longer wavelength. The present design of the TFTR X-ray imaging array (XIS) makes it suitable for operation with DD plasmas only. Use of the ionization chamber only hardens the system for DT survival; in DT operation background noise levels from radiation will render the system inoperable. For a DT-operational XIS further development must be done. The detectors must be moved further from the plasma and more extensively shielded. In addition reflective X-ray optics, such as grazing incident mirrors or Bragg crystals will probably have to be used to permit removal of the detector from direct view of the neutron-

emitting plasma. One candidate for an improved detector for both the XIS (radiation resistance) and the XCS (high count rate, good position resolution) is the microchannel plate preceded by a high efficiency X-ray photocathode. Solid photocathodes are not suitable. Porous photocathodes of CsI have demonstrated high efficiency [144]. Further work must be done, however, to answer questions about their reliability, construction, degradation with use, efficiency, etc.

VII. SUMMARY

The Tokamak is a major contender for demonstration of controlled fusion as an eventual power source. X-ray diagnostics are an important part of the experimental effort. These instruments permit measurement of plasma conditions from various aspects of the continuum and line radiation due largely to impurities in the plasma. Soft X-ray diagnostics range from (a) instruments with moderate energy and time resolution, which provide an overview of the soft X-ray emission and a measure of electron temperature and impurity concentration, to (b) those with very good energy resolution and moderate time resolution, which measure ion temperature, impurity charge-state distributions, low energy impurity radiative power and other parameters, from details of impurity spectral line profiles, to (c) instruments which view many spatial chords simultaneously with very fast time response but crude spectral resolution to monitor low energy impurity radiation and fast fluctuations in X-ray emission due to MHD instabilities.

Development required for near future tritium-burning tokamaks includes shielding and collimation of neutrons and gamma rays, development of radiation-hard detector substitutes in some cases, and improvement of instrumental throughput. Problem areas are limited count rate for detectors

and electronics, high response to background radiation, low crystal reflectivity, and broad crystal rocking curves in the low energy X-ray region. For reactors, radiation damage susceptibility will preclude use of all solid-state detectors for direct view of the plasma; substitute measurement schemes must be developed.

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FIGURE CAPTIONS

- Fig. 1 Schematic illustrating principles of tokamak operation. (#753361)
- Fig. 2 Sample electron temperature and density profile from PLT measured by Thomson scattering. (#809052)
- Fig. 3 Fractional abundance of several charge states of Ar vs. electron temperature for coronal equilibrium. (#783804)
- Fig. 4 Comparison of the radiative power loss for a variety of impurities. (#772499)
- Fig. 5 PHA X-ray spectra from four chords of PDX at $r = 0, 12, 16,$ and 24 cm. Temperature profiles at several times, deduced from X-ray continua, are shown in inset. (#793687)
- Fig. 6 X-ray spectrum from the EBT device measured by an array of Si(Li) detectors. (Ref. 122).
- Fig. 7 Schematic of the multi-detector PHA system installed on PLT. (#773872).
- Fig. 8 Schematic of the Johann X-ray Crystal Spectrometer used on PLT and PDX. (#773846)

Fig. 9 Sample Fe $K\alpha$ spectra at different electron temperatures illustrate the shift to higher ionization states as temperature increases. (#7733660)

Fig. 10 Sample ultra-high resolution Fe $K\alpha$ spectrum from PLT. The resonance line w of Fe XXV at $1.85\text{\AA}$ is used for Doppler ion-temperature measurement. (#793023)

Fig. 11 The ion Temperature in PDX derived from Doppler broadening of the Ti XXI $2.61\text{\AA}$ line during a neutral-beam heated discharge. (#81X2151)

Fig. 12 Schematic of X-ray imaging system using an array of silicon surface-barrier detectors, as used on PLT. (#796219)

Fig. 13 X-ray emissivity vs. time for several chords from PDX, showing an $m=1$ oscillation. Stars indicate chord radius and zero level of emissivity. (#806858)

Fig. 14 Radial profiles of X-ray emissivity vs. time for the $m=1$ oscillation of Fig. 13. (#806833)

Fig. 15 Soft X-ray traces vs. time from imaging system on PLT showing an explosive disruption at 305.2 ms. (#793050)

Fig. 16 Implosive type of disruption of 514 ms as measured by ultra soft X-ray imaging system on PLT. (#793049)

Fig. 17 Schematic of the rotating crystal spectrometer installed on PLT and photograph of the crystal and detector assembly. (#809045)

Fig. 18 Output from rotating crystal spectrometer with 3 different time scales. (a) Timing pulses generated when a slot in the rotating disk passes the LED. (b) Microchannel plate output obtained as the crystal rotates. (#809056)

Fig. 19 Iron L spectrum measured with the rotating crystal spectrometer. (#806747)

Fig. 20 Oxygen K spectrum from PLT discharge with high oxygen level. (#809110)

Fig. 21 Chord integrated intensity profiles of several iron-L transitions for different charge states, measured by the rotating crystal spectrometer. (#806748)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

ELECTRONICS

Fig. 7

CURVED - CRYSTAL SPECTROMETER

Fig. 8

Fig. 9

Fig. 10

Fig. 11

PLT/PDX X-RAY WAVE DETECTOR SYSTEM

Fig. 12

Fig. 13

PDX SHOT 25821

Fig. 14

I

H I H

H I H

I I I

I I I

I I I

I I I

I I I

I I I

H I H

H I H

Fig. 15

— H —
 — I —
 H H H
 H H I
 H H I
 I H I
 I H I
 H I H
 I H I

Fig. 16

Fig. 17

Fig. 18

Fig. 10

Fig. 21