**Wall Power Measurements of Impurity
Radiation in ORMAK**

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MASTER

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ABSTRACT

Time- and space-resolved measurements of the power loss to the liner of the Oak Ridge Tokamak (ORMAK) indicate that a large fraction ($\sim 60\%$) of the electron power input is lost to the wall, rather than to the limiter. This fraction is relatively constant over a wide range of input powers (ohmic heating plus neutral beam injection) and plasma conditions and for most of the discharge duration. Most of this energy loss is due to impurity radiation from an emission profile having a mean radius about a third that of the limiter radius and is time-correlated with gross plasma fluctuations, internal disruptions, and related spectroscopic impurity signals. In gas puffing experiments resulting in higher densities, the ratio of radiative power to the electron density continually falls as density increases during the course of the discharge.

1. INTRODUCTION

Impurity radiation is a substantial part of the electron energy loss in present tokamak experiments [1-4]. An accurate measurement of the magnitude, time behavior, and spatial distribution of the radiative energy loss is necessary in order to understand the electron energy losses in a tokamak and scaling of these losses with plasma parameters. Previous estimates of the impurity radiation loss have been based on summing over spectroscopic line intensities [5, 6] or on the total energy flux to the wall, inferred from bolometric measurements [7-10].

The technique we describe employs a pyroelectric detector [11, 12] which measures the instantaneous power incident on the detector rather than the accumulated incident energy. This permits both a more sensitive measurement of instantaneous power and a better time resolution than bolometric measurements with signal differentiation. Spatial information on the radiating volume is obtained by varying the radial position (and hence the acceptance angle) of the detector and comparing the signal amplitude variation obtained with that calculated for various radial distributions of the plasma radiation.

In the sections which follow, we describe (1) the physical basis of the measurement and the calculation of the total power lost to the wall, (2) the scaling of this power with input power for a wide range of input powers and plasma parameters, (3) the variation of the wall power flux with gas puffing, and (4) the detailed correlation of the power signal

with other impurity and instability signals for internally disruptive and grossly disruptive discharges.

2. THE MEASUREMENT AND ITS INTERPRETATION

The Oak Ridge Tokamak (ORMAK) [13] and some of the main studies conducted with it [1, 14] have been described elsewhere. For this discussion, the pertinent ORMAK parameters are major radius $R = 80$ cm, minor (limiter) radius $a_l = 23$ cm, liner (wall) radius $a_w = 25.5$ cm, toroidal field $B_t = 10$ –26 kG, plasma current $I = 60$ –175 kA, central chord-averaged electron density $\bar{n}_e = 1$ –6 $\times 10^{13}$ cm $^{-3}$, and input power $P = 100$ –1000 kW. The experiments to be discussed were conducted with ohmically heated hydrogen plasmas supplemented in some cases with up to 350 kW of H^0 beam injection.

The measurement of the wall power is based on a thin (40- μ m), 3-mm-diam, LiTaO $_3$ pyroelectric element [15], the output current of which is proportional to the instantaneous incident power because the pyroelectric (polarization) current generated is proportional to the time rate of change of the temperature of the sensitive element. The constant of proportionality is essentially independent of detector temperature rise (<0.15%/°C). The inherently fast time response of the detector is limited to $\gtrsim 100$ μ s by the current amplifier used rather than by the thermal time constants (~ 400 ms) associated with the pyroelectric element.

Power detection efficiency of the detector is approximately unity both for particles and for radiation from the visible ($>5000\text{-}\text{\AA}$) into the x-ray ($\sim 1\text{-}\text{\AA}$) region; the detector reflectivity is negligible over the photon energy range for which significant transport of energy to the wall is expected in ORMAK. Absolute power calibration of the detector with 10- to 20-keV H^0 beams and a HeNe laser ($6328\text{ }\text{\AA}$) gives the same value as the manufacturer's calibration [15] to within $\sim 5\%$. In addition, the detector does not respond to a relatively high current ($\sim 1\text{ }\mu\text{A}$) but low voltage (a few volts) electron beam with little relative power (much less than the 20-mW/cm^2 detection threshold). By comparison, the threshold for polarization currents detected is $\sim 10^{-9}\text{ A}$, so the detector responds only to incident power and not to current. Also, if the $100\text{-}\mu\text{s}$ time response of the 10^{-7} A/V current amplifier is sacrificed, an improvement of up to two orders of magnitude in detection sensitivity can be obtained by using higher gain current amplifiers.

The detector does not distinguish between particle and radiated power fluxes. However, for the plasma parameters studied (except for the injection cases discussed later), the power input to the ions was much less than the ohmic power input, P_{OH} , varying from $\sim 5\%$ to 20% of P_{OH} , so that the wall power signal represents the electron power losses. This fact plus direct measurements and model calculations of the charge-exchange flux indicate that charge-exchange losses are but a small part of the detected signal. In addition, the detected signal remains constant as the detector is moved 2 cm radially outward from the liner

wall ($r > a_w$), indicating that the detected power is not carried by charged particles. This is as expected, since the toroidal field in the shadow of the limiter should prevent these particles from reaching the walls and thus the detector. Therefore, we conclude that the detected power is mainly due to impurity radiation in the plasma volume.

The detector response to a typical ORMAK discharge is shown in Fig. 1 along with the behavior of the main plasma parameters. For this discharge $I = 120$ kA, $B_T = 18$ kG [limiter safety factor $q(a_\ell) = 5$], and $\bar{n}_e = 2.3 \times 10^{13} \text{ cm}^{-3}$. Except for the time correlation studies discussed later, only the quasi-steady-state behavior (typically at ~ 45 ms) is considered here.

Estimates of the spatial distribution of the plasma radiation are obtained by varying the distance from the detector to the liner, x , from one discharge to another, thereby changing the plasma volume seen by the detector through a fixed liner aperture. This arrangement is illustrated in Fig. 2 along with two extreme representations of the emitting volume: a small central core (I) and a thin surface layer (II). In order to unfold the detector signal vs probe distance data, $P_{\text{det}}(x)$, we assume various models for the radial distribution of the emitting plasma and choose that distribution which gives a calculated $P_{\text{det}}(x)$ closest to that measured. For all distributions, the signal is approximately constant for small detector-to-liner distances, where the probe aperture rather than the liner aperture determines the detector's acceptance angle (out to detector position 2 in Fig. 2). This approximate constancy

arises because for a given distance $s = a_w - r + x$ from the detector to an emitting element at radius r , the emitting volume seen by the detector varies as s^2 but the fraction of that radiation detected varies as $1/s^2$. At larger x (>2 cm or beyond position 2 in Fig. 2), the falloff of $P_{\text{det}}(x)$ depends on the fraction of the radiating volume within the acceptance angle formed by the detector and the liner aperture.

Figure 3 shows some typical $P_{\text{det}}(x)$ data obtained for the plasma conditions shown in Fig. 1 at $t = 45$ ms. Also shown are three curves with values calculated based on the assumption of a uniform power density in an emitting shell characterized by a mean radius r_m and thickness Δr . The calculated curves have been normalized to give the minimum rms percentage error, ϵ_{rms} , between the data and the calculated $P_{\text{det}}(x)$; the normalization constant along with the detector power calibration and viewing geometry then give the absolute power flux. The three curves in Fig. 3 show a "best fit" to the data (curve 2, $r_m = 7$ cm, $\Delta r = 12$ cm, $\epsilon_{\text{rms}} = 8\%$) and two "poor fits," a small central core extending over the central quarter of the plasma (curve 1, $\epsilon_{\text{rms}} = 18\%$) and a shell extending over the outer half of the plasma radius (curve 3, $\epsilon_{\text{rms}} = 31\%$).

The relative uncertainty in the fitting procedure can be seen from Fig. 4, which is a plot of the rms percentage error for different allowable combinations of r_m and Δr . Results obtained through this procedure indicate that the most probable mean position r_m of the radiating volume is centered at 7-9 cm, not only for the 120-kA discharge of Fig. 1 but also over a wide range of plasma parameters. These comparisons are

sensitive to the mean position r_m of the emitting volume, but not to its thickness Δr (as demonstrated in Fig. 4) and hence not to the exact form of the radial distribution. More refined estimates of the radial distribution could not be made on ORMAK but will be carried out on the Impurity Study Experiment (ISX) [16] with an array of highly collimated pyroelectric detectors.

The actual $P_{det}(x)$ calculation takes into account the extent of the plasma in the toroidal direction (perpendicular to the plane of Fig. 2) and the angle of incidence of the power flux at the detector. The radiating volume is taken to be cylindrical rather than toroidal, thus overestimating the wall power by $\sim 10\%$ for reasonable source distributions. A single detector was used, located on the outside of the torus 90° from the limiter, and the wall power flux was assumed to be uniform over the liner area. Support for this last assumption is derived from previous measurements [17] which used a toroidal array of liner thermocouples and indicated a variation of less than 10% in wall power around the torus. Although information is lacking on the poloidal wall power distribution, this too was assumed to be uniform. Finally, wall reflection of the radiation was neglected because this should be unimportant [18] for the energy range ($\lambda \sim 10\text{--}200 \text{ \AA}$) for which significant wall energy flux is expected in ORMAK.

Although it is possible to obtain information on the mean radius of the radiating distribution from the procedure just discussed and illustrated in Figs 3 and 4, little use is made of this capability. Instead,

the discussion focuses on the variation of the total wall power with input power and with its time dependence (on different time scales) correlated with other plasma parameters.

3. STEADY-STATE WALL POWER SCALING

The relation between the wall power losses and the ohmic power input was determined for a wide range of power inputs and plasma parameters. In this study, the parameters I , B_T , and $\bar{n}_e$ were each varied about the base parameter set [19]. The individual ranges covered were as follows: the "I scan" was from 62 to 175 kA [$q(a_\ell)$ varied from 11.6 to 4.1, with $B_T = 21.5$ kG], the " B_T scan" was from 15.6 to 24.1 kG [$q(a_\ell)$ varied from 4.2 to 6.6, with $I = 120$ kA], and the " $\bar{n}_e$ scan" was from 1.2 to $2.7 \times 10^{13} \text{ cm}^{-3}$ [$q(a_\ell) = 5$]. In another sequence ("constant q "), the initial hydrogen filling pressure (5×10^{-4} torr) and $q(a_\ell) = 5$ were held constant as the plasma current was varied from 68 kA to 175 kA ($B_T = 9.5$ kG to 26 kG), producing a density ($\bar{n}_e$) variation from $9 \times 10^{12} \text{ cm}^{-3}$ to $2.7 \times 10^{13} \text{ cm}^{-3}$; a central electron temperature [$T_e(0)$] variation from 600 eV to 1500 eV; and an input power (P_{OH}) variation from 200 kW to 500 kW.

Wall power data for these sequences and data for some gas puffing experiments (discussed in detail in Section 4) are shown in Fig. 5. For all cases, there is an approximately linear relation between P_{wall} and P_{OH} , with only slight systematic trends in the ratio P_{wall}/P_{OH} for the

different parameter scans. For example, $P_{\text{wall}}/P_{\text{OH}}$ increases from 52% to 60% as I increases from 68 kA to 175 kA in the constant q sequence but decreases from 70% to 62% as I increases from 80 kA to 174 kA in the I scan series of experiments. Also, there is a general increase in $P_{\text{wall}}/P_{\text{OH}}$ (from 58% to 75%) as $q(a_\ell)$ is varied from 4.1 to 11.6 for both the I scan and the B_T scan data. Despite these small but apparently systematic differences, the main conclusion from these studies is that a large, relatively constant fraction ($P_{\text{wall}}/P_{\text{OH}} \approx 60\%$) of the input ohmic power is lost to the wall as radiation over a wide range of input powers and plasma parameters.

This conclusion still holds when a substantial part of the electron power input comes from neutral beam injection. The addition of up to 350 kW of H^0 beam injection extends the total power input in this scaling study to 1 MW. There is a clear distinction between the fraction of the total input power lost to the wall in discharges preceded by oxygen discharge cleaning (the usual condition in this study) and the fraction lost in those preceded by hydrogen discharge cleaning. In the first case [1], the ohmic power input dominates the injection power input and the ion power input is a small fraction of the total power input. Under these circumstances, the same fraction ($\sim 60\%$) of the power is lost to the walls as in the ohmic heating study (also with oxygen discharge cleaning) shown in Fig. 5.

However, in the second case (i.e., hydrogen discharge cleaning and higher injection power), the ion power input is usually not a small

fraction of the total power, and typically only 40% of the total power input is detected as wall power. When the wall power is compared with the electron power input, however, the same fraction (i.e., ~60%) is still obtained. Because the impurity radiation with high power neutral beam injection ($P_{inj} \approx 3 \times P_{OH}$) increases only in proportion to the added electron power input ($\sim 0.5 P_{inj}$), we conclude that there is no evidence for disproportionate impurity influx or losses specific to injection. Also, the detector signal remains a measure of mainly radiative power flux, even with neutral beam injection.

Thus, approximately the same fraction of the electron power input is lost to the wall independent of the plasma parameters and the power input over the wide range studied. In addition, apparently a much smaller fraction of the ion input power is detected on the walls. Measurements of the absolute charge-exchange flux also indicate that only a small fraction of the ion power input is lost to the walls via charge exchange, even with large ion power inputs from intensive neutral beam injection.

The approximately constant proportionality between total electron input power and P_{wall} for varying power input is also observed in the course of a discharge evolution, as shown in Fig. 6. In this case, 340 kW of H^0 beam injection (of which roughly half goes to the electrons) was added to ~100 kW of ohmic heating power, causing an increase in electron power input and electron heating [20] and in the impurity

radiation losses to the wall. There is also a corresponding increase in the impurity radiation seen spectroscopically, also shown in Fig. 6. These signals are representative of the behavior of O^{6+} (21.6 Å) and a segment of continuum thought to be closely spaced lines of tungsten (20.1 Å).

The estimates of ~60% of the total input power going to the wall are supported by calorimetric measurements made with a radially movable point limiter [21, 17] and with an array of wall thermocouples [17]. These measurements showed only 5-6% of the ohmic heating power on the point limiter when it was inserted 7 cm inside the fixed limiter position for discharges with $I = 80-95$ kA and $B_T = 17$ kG. In addition, in a different set of experiments (with $I = 100-130$ kA, $B_T = 15$ kG), the array of thermocouples showed ~70% of the input power going to the walls. This conclusion, that most of the power goes to the walls and not to the limiter, is similar to that found on the TFR [2] and more recently on PLT [4], T-10 [20], and DITE [3] but is in distinct contrast to the observations on smaller devices such as T-3 [7], ST [23], and ATC [8], which suggest that a larger fraction of the input is lost to the limiter. On the other hand, indications [17] are that $P_{\text{wall}}/P_{\text{INPUT}}$ increases systematically with increasing minor radius up to a plateau which includes values of $P_{\text{wall}}/P_{\text{INPUT}}$ of 65-90% for PLT [4],

4. VARIATION OF WALL POWER WITH GAS PUFFING

The use of additional hydrogen gas puffing to increase the plasma density in ORMAK leads to discharge time behavior which depends on the density range achieved. For lower density [$\bar{n}_e$ (peak) $< 4 \times 10^{13} \text{ cm}^{-3}$] discharges obtained with gas puffing, the detector signal closely follows the plasma density, as shown in Fig. 7 for $t > 10 \text{ ms}$ into the discharge. In this case, the plasma current and voltage (and hence the ohmic power input) are approximately constant, as is the electron temperature. This direct proportionality of the radiation signal to the plasma density may indicate a relatively constant impurity density. For higher plasma densities ($\bar{n}_e \gtrsim 4 \times 10^{13} \text{ cm}^{-3}$) obtained at higher current ($I \sim 175 \text{ kA}$), the wall power signal is nearly constant in time as the plasma density more than doubles. The power loss per plasma particle decreases as the density increases, although the electron temperature again remains relatively unchanged. This may indicate a reduction in the impurity density at the higher plasma density.

Still higher density is obtained with gas puffing at 175 kA of plasma current by the addition of neutral beam injection, as shown in Fig. 8. In this case, the impurity radiation loss actually decreases, along with the total input power to the electrons, as the density increases. Again, there is a rough proportionality between the wall power losses and the total electron power input. Here the electron temperature increases as a result of injection heating, however, and any interpretation in terms of impurity density is even more suspect than

the rough indications discussed above. However, supporting these interpretations is the vacuum ultraviolet (VUV) spectroscopic observation that the intensity at 50 Å falls even more rapidly as the density rises. For these discharges, most of the impurity radiation seen spectroscopically is in narrow band continua in the range of 20-70 Å from tungsten radiation [24]. Also, another indicator of light impurity (oxygen) density, Z_{eff} , falls as the density rises, perhaps indicating a dilution effect.

5. TIME BEHAVIOR OF THE WALL POWER FLUX FOR UNSTABLE DISCHARGES

In addition to the gross power measurements for quasi-steady-state or slowly varying conditions (as discussed in the preceding sections), the detector also gives detailed information on the plasma behavior in unstable discharges, since instantaneous rather than time-integrated power is measured. Two examples are discussed in terms of the correlation of the wall power flux with other instability signals: (1) multiple minor disruptions and (2) large internal disruptions ("sawtooth oscillations").

Figures 9-11 show an example of an unstable discharge exhibiting repeated gross disruptions. The behavior of the macroscopic plasma parameters (wall power, electron density, discharge loop voltage, and plasma current) is shown in Fig. 9, and the instability (envelope of the $m = 2$, $\dot{B}_\theta$ oscillations) and spectroscopic signals (CIII, 4650 Å; OVI, 1032 Å; and H_β , 4860 Å) are shown in Fig. 10. The large initial peak in

the detector signal is correlated with H_β and impurity light intensities and with the $\dot{B}_\theta$ signal. This peak reflects factors such as the initial ionization and plasma-wall interaction, and it falls as the discharge column position becomes well stabilized and confinement improves. Each plasma interaction with the wall brings in additional impurities, as evidenced by the spikes in the CIII and OVI light intensities. The relative time sequence of these signals is better illustrated on the expanded time scale shown in Fig. 11.

In general, the physical processes leading to a disruptive instability are varied and complex, and no one discharge, including that of Figs. 9-11, should be taken as a typical example of the phenomenon. For this particular discharge, as shown in Fig. 10, the first evidence of a disturbance is a rise in the amplitude of the $m = 2 \dot{B}_\theta$ oscillations beginning at ~ 37 ms into the discharge. From the expanded time scale of Fig. 11, we see that at the onset of the disruption there is an outward plasma shift, a decrease in electron density and loop voltage, and increases in wall power flux and CIII, H_β , and OVI line intensities, all of which occur essentially simultaneously. Peaks of the plasma shift, the wall power signal, the OVI intensity, and the $\dot{B}_\theta$ envelope all occur ~ 0.5 ms later than the peaks of the H_β and CIII lines and the minimum $\bar{n}_e$ and loop voltage. Apparently the disruption arising from the $m = 2$ instability drives plasma to the wall, producing an increase in the neutral gas (H_β) and impurity (CIII and OVI) influxes. The OVI peak (ionization potential of ~ 138 eV) occurs at a higher electron temperature

(assumed to be ~ 40 eV [6] or a few centimeters inside the limiter radius), and its ~ 0.5 ms time delay is not understood, but could be due to a number of reasons, including an inward flow of oxygen or changes in electron temperature and density profiles. During these relatively small disruptions, power flow to the liner sharply increases as the plasma moves outward. The area under each peak in Fig. 11 indicates an additional energy loss of ~ 250 J as a result of each disturbance. The plasma density and wall power then recover on a time scale of ~ 8 ms.

In addition to large macroscopic plasma disturbances, tokamak plasmas can undergo large amplitude internal disruptions while exhibiting only small amplitude MHD $\dot{B}_\theta$ oscillations on external magnetic loop probes. Corresponding fluctuations are found to be superimposed on signals from the pyroelectric wall power monitor. Figure 12 shows the detector signal for a discharge which exhibited large amplitude soft x-ray "sawtooth" oscillations [25, 26]. The period of these relaxation oscillations is the same as that seen on soft x-ray emissions and has the fast increase characteristic of energy flow outside the $q = 1$ surface, rather than that of the plasma core. The amplitude of the sawtooth riding on the detector trace is $\sim 6\%$ of the total signal. This supports measurements with the PIN diode array which indicate that these oscillations are not the dominant factor in the total power flow in ORMAK [1].

6. CONCLUSIONS

A pyroelectric detector has been used to make time-resolved measurements of plasma power losses to the walls in ORMAK. A large and relatively constant fraction (~60%) of the electron power is lost to the liner wall as impurity radiation over a wide range of plasma parameters, both with ohmic heating alone and with neutral beam injection. There appears to be no increase in the fraction of power lost to the wall when injection is added, and at higher densities obtained with injection plus gas puffing, the radiative loss actually decreases as density increases. Detailed time studies, made possible by the fast response of the pyroelectric detector, show fluctuations in wall power losses to be well correlated with those in VUV impurity radiation and various plasma parameters. This is especially apparent in neutral beam injection and gas puffing experiments and for discharges which suffer gross disruptions. Finally, internal disruptions and charge-exchange losses do not play a major role in the direct transport of energy from the plasma to the wall in ORMAK.

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FIGURE CAPTIONS

Fig. 1. Time history of the plasma parameters for a typical ORMAK discharge: plasma current (I), loop voltage (V), central chord-averaged electron density ($\bar{n}_e$), and pyroelectric detector signal (P_{wall}).

Fig. 2. The detector measurement geometry showing two extreme representations (I and II) for the plasma radiation. As the detector moves radially from position 1 to position 3, the detected signal changes in response to the changing acceptance angle and the radial distribution of the source.

Fig. 3. Variation of signal with detector-to-liner distance for the plasma conditions shown in Fig. 1. The circles are data points at 45 ms for the 120-kA discharge. The curves 1, 2, and 3 are calculated for different assumed radial source distributions characterized by a mean radius r_m and thickness Δr .

Fig. 4. Variation of the rms percentage error between the data of Fig. 3 and normalized curves calculated for a cylindrical radiating shell characterized by mean radius r_m and thickness Δr . The points 1, 2, and 3 correspond to curves 1, 2, and 3 in Fig. 3.

Fig. 5. Approximate linearity between the steady-state ($t = 45$ ms) wall power estimate and the ohmic power input for the different experiments described in the text.

Fig. 6. The increase of wall power, total power input to electrons, and VUV spectroscopic signals as a result of neutral beam injection. Signals for impurity radiation at 21.6 Å (O^{6+} + continuum) and 20.1 Å (continuum) are indicated.

Fig. 7. Correlation between the wall power signal and the line-averaged electron density for hydrogen gas puffing in a low density ($\bar{n}_e = 2.5 \times 10^{13} \text{ cm}^{-3}$), low current ($I = 100 \text{ kA}$) hydrogen discharge.

Fig. 8. Reduction of radiative power loss as a result of hydrogen gas puffing (G.P.) with injection in a 175-kA hydrogen discharge.

Fig. 9. Correlation of wall power signal with other gross plasma parameters for a 120-kA, 18-kG, $\bar{n}_e \approx 3 \times 10^{13} \text{ cm}^{-3}$ discharge exhibiting repeated external disruptions.

Fig. 10. Relation between an MHD instability signal (envelope of poloidal $\dot{B}_\theta$ oscillations) and various spectroscopic signals related to impurities (CIII, OVI) and to neutral hydrogen for the discharge shown in Fig. 9.

Fig. 11. Time relationship of wall power signal to the different gross plasma parameter signals and the impurity and instability related signals shown in Figs 9 and 10 on an expanded time scale (44-68 ms).

Fig. 12. Response of the wall power signal to a regular, large amplitude, long period sawtooth oscillation (internal disruptions) in the plasma interior. The lower trace is an expansion (1 ms/division, 0.04 V/division) of the intensified portion of the upper trace (10 ms/division, 0.4 V/division).

ORNL-DWG 77-8849

Fig. 1

ORNL-DWG 76-4290R

Fig. 2

ORNL - DWG 77-8850

Fig. 3

Fig. 4

Fig. 5

ORNL/DWG/FED-77568R

Fig. 6

ORNL/DWG/FED-771003

Fig. 7

ORNL/DWG/FED-77567

$I = 175 \text{ kA}$, $B_T = 26 \text{ kG}$
(350 kW-INJ.) + (GAS PUFF)

Fig. 8

ORNL-DWG 77-8853

Fig. 9

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Fig. 10

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Fig. 11

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Fig. 12

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