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**THE ARGONNE PLASMA ENGINEERING
EXPERIMENT (APEX) TOKAMAK**

by

**J. H. Norem, L. J. Balka, E. E. Kulovitz,
S. R. Magill, D. G. McGhee,
A. Moretti, and W. F. Praeg**

FUSION POWER PROGRAM

**Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439**

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ABSTRACT

The Argonne Plasma Engineering Experiment (APEX) Tokamak was designed to provide hot plasmas for reactor-relevant experiments with rf heating (current drive) and plasma wall experiments, principally in-situ low-Z wall coating and maintenance. The device, sized to produce energetic plasmas at minimum cost, is small ($R = 51$ cm, $r = 15$ cm) but capable of high currents (100 kA) and long pulse durations (100 ms). A design using an iron central core with no return legs, pure tension tapewound toroidal field coils, digital radial position control, and UHV vacuum technology was used. Diagnostics include monochrometers, x-ray detectors, and a microwave interferometer and radiometer for density and temperature measurements. Stable 100 ms shots were produced with electron temperatures in the range 500-1000 eV. Initial results included studies of thermal desorption and recoating of wall materials.

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I. INTRODUCTION

This paper describes the design and operation of the Argonne Plasma Engineering Experiment (APEX) tokamak. This machine was designed to provide a high performance plasma at a minimum cost, thus combining, to some extent, the high current densities, long pulse duration, and flexibility of operation of large, multipurpose machines,¹ with the low cost of small machines.² The APEX tokamak was designed specifically for studies in plasma-wall interactions and RF heating and current drive, and some tradeoffs were made in order to optimize the device for this purpose. The general design, however, should be quite applicable to other uses and could be fairly easily scaled up or down to fit available power supplies and needs. Special features of this design included use of the self-centering force of the toroidal field (TF) coils to simplify the mechanical design of the coils and digital equilibrium field (EF) control.

II. DESIGN CONSTRAINTS

For ohmically-heated discharges, the maximum operating temperature is a function of the machine major radius R , minor radius a , and safety factor q . The dependence of this temperature on machine parameters can be found by setting the ohmic heating power ($I_p^2 R_p$) equal to the radiated power $V_p n_p T / \tau_E$, where I_p , R_p , V_p , and n_p are the plasma current, resistance, volume, and average density. Using the relations for Spitzer resistivity $R_p \approx R/a^2 T^{3/2}$, energy confinement time, $\tau_E \propto na^2$, and maximum current, $I_p \propto B_{\text{poloidal}} = B_T R / q$, where B_T is the toroidal field and q is the safety factor (roughly 3.5 for stable discharges), the maximum plasma temperature scales like

$$T_{\text{max}} \propto (B_T / R)^{0.8} \quad (1)$$

For a given geometry, this reduces to $T_{\text{max}} \propto I^{0.8}$. This relation has been confirmed experimentally in studies using Alcator, PLT, ORMAK,³ and other devices.⁴ The plasma density scaling has been shown by Murakami to follow the relation

$$\langle n_p \rangle_{\max} = (B_T/R) \quad (2)$$

for all ohmically-heated machines. Thus, the hottest, densest plasmas are obtained with high toroidal fields in small machines. Small devices also have an advantage when auxiliary heating is used. Solving the relation $P_{\text{aux}} = P_{\text{loss}}$ for temperature gives the result⁵

$$T_{\max} \propto P_{\text{aux}}/R \quad (3)$$

This relation can also be interpreted as a statement that larger perturbations on plasma behavior can be obtained at least cost in smaller machines, which is useful when considering costing tests of RF or other auxiliary heating and current drive schemes.

The most important machine parameter for the study of plasma-wall interactions (other than vacuum base pressure, which should be less than 5×10^{-8} torr) seems to be the plasma edge temperature. This temperature is limited, however, by the mechanical properties of the wall material (evaporation) and by sputtering yields. It can be shown that the maximum temperature of the edge plasma must be below $T_e \approx 100$ eV if a stable plasma is produced with heavy wall materials (Fe, Ti, etc.).⁶ This temperature can be achieved in very modest machines over small areas.

The pulse length requirement relevant to plasma wall interactions can be determined from the requirement that the plasma should be in equilibrium with the walls. Since the impurity equilibration time has been measured in Alcator to be roughly three energy confinement times τ_E ,⁷ the desired pulse length is roughly given by the relation

$$\text{discharge length} \gg \text{equilibration time} \approx 3 \tau_E.$$

For APEX, $\tau_E \approx 5$ -15 ms, and we have assumed a pulse length of 100 ms. Larger machines would require much longer pulses, since $\tau_E \propto a^2$.

The lower limit to the allowable major radius is given by the flux required through the center of the Ohmic Heating (OH) transformer. This flux must be equal to the sum of the plasma inductance and resistive losses

$$\phi \approx L_p I_p + V_h \Delta t, \quad (4)$$

assuming a holding voltage of V_h is required for time Δt . With $I_p = 100$ kA, $L_p = 1$ μ H, $V_h = 2$ V, and $\Delta t = 0.1$ sec, $\phi \sim 0.3$ V-sec. Using an iron core, which limits the OH field to 1.8 T, requires that the center solenoid be 0.2 m in radius, if the field is reversed. The lower limit on the toroidal field is given by the requirement of $B_t > 1$ T for electron cyclotron temperature measurement (see Sec. 7.4).

Cost scaling can be approximated by comparing machines of different sizes using $(R^3 B^2)$, a parameter that is roughly proportional to stored magnetic energy in the toroidal field system.⁸ These costs are somewhat difficult to compare and we have made some attempt to identify machine cost exclusive of major power supplies and diagnostics. In general, it seems possible to fit costs by the relation

$$\text{Machine cost (\$M)} = (R^3(m) B_T^2(T))^{3/4} \quad (5)$$

for all tokamaks. The annual operating budget must also be considered, and the total machine cost should probably enter in as

$$(\text{construction cost}/\text{operating lifetime})/(\text{annual operating budget})$$

with the ratio commonly being about 0.5.

Since both performance and economy of ohmically-heated devices decrease rapidly with size, it is highly desirable to keep the machine dimensions as small as practicable; the magnetic and mechanical structures were designed to accomplish this. The essential features of this design are shown in Figs. 1 and 2 and Table 1.

III. MAGNETIC DESIGN

The TF coil system was designed to produce 25 kG from 12.5 kA at $R = 50$ cm. This was accomplished with 20 coils of 25 turns each. Each turn was composed of four sheets 10.16 cm wide by 0.158 cm thick, giving a total area of 6.4 cm². Turns were insulated from each other with mylar sheets 0.038 cm thick. The 25 turns were wound continuously on a bobbin so that the overall shape closely approximated a constant tension D. Water cooling packages were attached to the edges of the coils and insulated by mylar 0.013 cm thick. A cross section of the coil (Fig. 3) shows the windings, cooling packages, and the outer fiberglass epoxy coating. The coils were tapered with a milling machine before the final potting was done. These coils can contain fields of up to 50 kG without noticeable deformation.

Figure 1. The APEX tokamak before diagnostic and experimental equipment was added.

Figure 2. The APEX tokamak showing the laminated iron central core, toroidal and poloidal field coils, and structure.

Table 1. APEX Parameters

Major Radius	51.5 cm
Minor Radius	14.5 cm
Toroidal Magnetic Field (max)	20-25 kG
Plasma Current (max)	110 kA
Pulse Length (max)	0.1 - 0.15 sec
TF System	
Power Supply	700 V, 10 kA Mercury Arc Rectifier
Turns	20 coils (25 turns each), 500 total
Inductance	50 mH
Resistance	52 m Ω
Type	Water-cooled, tapewound, pure tension D
OH System	
Turns	$2 \times (17 + 9 + 3)$, 58 total
Volt Seconds	0.45 W at 1.7 T
Inductance	4.7 mH
Resistance	8 m Ω
Power Supply Requirements	(80V, 3 kA) and (190V, 3 kA)
Laminated Iron Core	$A \approx 0.1362 \text{ m}^2$, $h \approx 1.52 \text{ m}$, 0.0355 cm laminations
EF System	
Turns	$2 \times (8 + 8)$, 32 total
Inductance	550 μH
Resistance	41 m Ω
Power Supply Requirements	(80V, 1100 A)
dI_{EF}/dt	42 kA/sec
Vacuum System	
Size	$A \approx 6 \text{ m}^2$, $V \approx 0.4 \text{ m}^3$
Pump	Welch, TurboTorr, 1500 ℓ/sec
Base Pressure	$5 - 7 \cdot 10^{-8} \text{ torr}$
Total Port Area	4200 cm^2

OUTER SECTION

INNER SECTION

Figure 3. Cross section of the TF coil. Copper sheets were separated by 0.038 cm turn-to-turn insulation and water cooling plates were bonded to the coil edges.

In order to operate with existing (225 kW, 3 kA) power supplies, an iron core design was selected. The iron core served a number of purposes: (1) reduction of OH power supply requirements due to reduction in stored energy (8 kJ vs. 77 kJ); (2) reduction in EF requirements due to the stabilizing force produced by image currents; and (3) mechanical support of the TF coil system.

Only the center of the iron transformer was used. This provides a low reluctance (stored energy) at a reasonable cost without obstructing access. The OH coils were also designed to produce the desired number of volt seconds in the transformer core without obstructing access to the plasma in the horizontal and vertical plane. The initial coil design was done with the computer program TRIM.⁹ Coil ratios and positions were determined to produce a high order null in the center of the vacuum chamber. Results are shown in Fig. 4. By using a three-coil geometry, it was possible to insure that $B = dB/dR = d^2B/dR^2 = 0$, within the accuracy of the calculations. During assembly, this coil geometry was tested in position (without the vacuum chamber) and minor trimming of the vertical position of the coils produced an area with $|B_{OH}| < 5G$, 20 cm in diameter under startup conditions ($I_{OH} = 2400 A$). It was verified experimentally that the error field was much more sensitive to the position of the inner (small R) OH coil, which tended to change the field by an additive constant. The middle coil position was least sensitive, and the outer coil position tended to alter dB/dR (Fig. 5).

The EF coil system was designed to provide a centering force to restrain the outward motion of the plasma. Due to the presence of the iron core, much of this force was provided by the interactions with image currents in the core (Fig. 6). As shown by Mukhovatov and Shafranov,¹⁰ the attractive force is a strong function of the ratio of the core radius and the plasma radius R_c/R_p . Radial stability is easiest to maintain when both the force and the ratio R_c/R_p are as small as possible. Most machines operate with $R_c/R_p \approx 0.3$, and serious stability problems were encountered in TFR where R_c/R_p is equal to 0.5.¹¹ In APEX, this ratio is 0.40, however, some additional safety was provided due to the rather short length of the central core and the high magnetic reluctance of the TF coil system, due to eddy currents produced in the inner leg of the TF coils.

The EF coil system consisted of four coils composed of 20 cables mounted near the outer and inner OH coils. This geometry produced a low mutual inductance between both the OH and plasma currents, simplifying the power supply requirements. The field produced is shown in Fig. 7.

Figure 4. The ohmic heating field coil system, which used the iron core and three external coils to produce the central OH flux while providing a high order null at the plasma position.

Figure 5. Measured OH field errors at the plasma position. The upper plots show the sensitivity of the field errors to the coil positions and the lower plot shows the final result.

Figure 6. The poloidal field geometry induced by a plasma current.

Figure 7. The equilibrium field (EF) geometry showing the separatrix passing through the plasma.

In air core tokamaks, it is possible to achieve vertical stability due to the inward curvature of the equilibrium field lines. With iron core machines, the primary component of the equilibrium field is produced by image currents in the central core. Since these image currents follow the plasma, no vertical stability is produced. Additional complications are due to iron plates in the floor, which introduce error fields (Fig. 8) and radial components of the TF coils, due to coil interconnections. The solution to these problems was a coil producing a small (10 G) radial field component through the plasma. This coil was wound in place with compensated clockwise and counterclockwise turns attached to the outer OH/EF coil.

IV. MECHANICAL STRUCTURE

Mechanically, the machine consists of a vacuum chamber threaded through 20 toroidal field coils, and surrounded by 6 OH/EF coils. The central cylindrical transformer core contributes both magnetically and structurally to the design of the device.

The transformer core is composed of 16 blocks of laminated grain-oriented silicon steel. Sheets 0.0355 cm thick were bonded into blocks $8.25 \times 8.25 \times 75.2$ cm, and these blocks were stacked inside a fiberglass cylinder using mylar insulation. A roughly circular cross section was produced by sawing some blocks diagonally to fit in the corners. The blocks of each core quadrant were arranged such that azimuthal symmetry of the flux in air (including leakage fluxes) was obtained. A solid unit was produced by sealing the cylinder, evacuating it, and filling the voids with epoxy. The cylinder had flats machined on the outer surface to contact the inner nose of the magnets.

The primary requirements of the structural design were support of the weight of the device and the electromagnetic stresses during operation. The strongest electromagnetic force was due to the $\vec{I}_{TF} \times \vec{B}_{TF}$ force. This was compensated by winding a pure tension shape to the toroidal field coils and supporting the coils against the central cylinder. The tipping moment due to $\vec{I}_{TF} \times (\vec{B}_p + \vec{B}_{EF})$ was supported by frictional forces of the toroidal field coils against the central cylinder and also by wedges (see Fig. 2) producing frictional forces between the coils. The TF coils were also locked together at the top and bottom by means of half rings of G10. These rings also supported the vacuum chamber halves. Thus, the machine could be fairly

Figure 8. The poloidal field pattern induced by the plasma current in the presence of iron floor plates.

easily disassembled (two man-days) by moving the poloidal field coils out of the way (up or down), unbolting the vacuum chamber halves, and sliding the two halves (TF coils and vacuum chamber) apart. The vacuum chamber could then be threaded out of the TF coils for replacement or modification. The construction of a torque frame was considered, but the strain in the mechanical system induced by operation was not great enough to require this.

The mechanical support structure (Fig. 1) was made from aluminum channel and pipe, with some additional components of G10 fiberglass. Most joints were made with 1/2-13 stainless steel bolts, and care was taken to insure that metal-to-metal joints were insulated to prevent currents being driven in the structure. The vacuum chamber, constructed by Huntington Mechanical Laboratory, had a major radius of 51 cm and a minor radius of 15 cm. All flanges were conflat UHV compatible. Two extensions with ports 30 cm high and 10 cm wide were used for pumping and experiments, and numerous other ports and vacuum interlocks were provided for a variety of possible applications. The chamber was pumped with a Welch Turbotorr 1500 liter/sec pump backed by a 53 cfm mechanical pump. Base pressures of $5-8 \times 10^{-8}$ torr were recorded routinely. Total port area was 4200 cm².

The voltage break, to prevent currents being induced in the vacuum chamber, consisted of a 0.635 cm Viton o-ring, setting in a slight recess machined in one of the large conflat rings. The o-ring was supported on the inside by an Alumina (Al₂O₃) coated stainless steel ring, slightly larger than the inside diameter of the vacuum chamber. The flanges and bolts were insulated by means of polyimide tape and G10 washers. Since the vacuum chamber surface was concentric with the plasma edge, no limiter was used.

Two systems were used to inject various gases into the APEX device. The working gases H₂ and D₂ were supplied for wall conditioning and plasma discharges, and various impurity gases were supplied for testing and diagnostic purposes. The H₂ and D₂ gases were of research purity (99.999%) and were transported through stainless steel regulators, valves, and fittings. This system was baked at 150°C, leak-checked, and roughed-down about once a week. Gas purity was also kept high by the use of a Resource Systems Palladium purifier, one-half liter per minute. The gas puffer injection valve used was a Veeco PV-10 controlled by a programmable step generator valve controller. This system normally supplied ~1 m torr of H₂ or D₂ gas at preset intervals.

The impurity gases available for injection were O_2 , N_2 , CH_4 , He, and A. The transport system was also stainless steel, and was roughed-down prior to each use or change of impurity gas. A separate holding chamber was available prior to injection for determining the exact amount of impurity gas supplied. The puffer valve was also a Veeco PV-10 and was controlled by a manual switch. The complete vacuum system is shown in Fig. 9.

V. POWER SUPPLIES

The toroidal field system utilizes a phase-controlled Westinghouse Mercury Arc Rectifier power supply, pulsed off a 13.2 kV line, capable of 700 V and 10 kA, with an effective source impedance of 20 m Ω . Protective circuitry were added to sense ground faults in the TF coil system. The supply has operated reliably.

The OH/EF system shown in Fig. 10 was designed to use existing 255 kW power supplies. Thyristor (SCR) phase-control and logic-control produce the wave forms shown in Fig. 11. The plasma is produced by turning on PS1 and ramping the current in the OH coil up to 2100-3000 A. Thyristor S1 is then turned off, forcing the current to discharge into resistors R1 and R2. A large loop voltage is thus produced, which causes avalanche breakdown of the gas, starting a plasma current. After 0.7 ms, thyristor S3 is turned on, shorting R2, thereby increasing the L/R decay time. When the voltage across the coil has decreased to 150 V, thyristor S2 is turned on, enabling PS2 to reverse the current in the OH coil and driving it for over 100 ms to a maximum value of 3000 A. The current and voltage produced in the OH system are shown in Fig. 11. The OH system operated at a 58:1 transformer ratio, thus, the voltage at the plasma was initially 50 V, dropping to 2 V in 20 ms and staying at a constant 2 V for 100 ms.

When the plasma is initiated, the equilibrium field coil system uses a capacitor bank to raise the current quickly to a fixed value (~ 300 A) in 700 μ s using a quarter cycle of an LC oscillation. The current is maintained at the maximum of the sine wave by gating the dc to dc converter on after 700 μ s. The dc to dc converter is powered by PS1 (used to initially charge up the OH coil). The dc to dc converter of Fig. 10 can be thought of as a pair of switches, one switch being SCR pair A and AA, while the other is SCR pair B and BB, a

Figure 9. The vacuum system.

Figure 11. The current and voltage wave forms produced in the OH and EF coils.

resonant circuit made up of the transformer (TC), capacitor (CC), and a full wave rectifier made up of diodes D1 and D2. The converter's load is the EF coils shown as L_L and R_L in Fig. 10. When one of the two SCR pairs is turned on, current flows in the transformer primary charging CC until the SCRs are back-biased by the voltage on CC and commutate. At that time, the other SCR pair can be turned on, allowing current to flow in the reverse direction. This cycle is repeated, supplying an ac current source for the transformer primary. The secondary of the transformer is rectified, supplying the load with dc power that has a maximum possible ripple frequency equal to the clock frequency. The maximum ripple frequency is ultimately determined by the leakage inductance of the transformer, the capacitance of CC, the load current, and the load inductance. Eddy current shielding of the vacuum chamber ($\tau \sim 100 \mu\text{s}$) prevents most of this ripple from affecting the plasma. This 12.5 kHz converter is designed to deliver currents of 1100 A and voltages of 0-100 V. A bypass capacitor CA is used to cancel the power supply and wiring inductance of the dc source. The leakage inductance of the transformer is kept low, minimizing converter losses as the resonant circuit is just under-damped to allow the thyristors to commutate properly, but not allowing large growth in the circuit as the load current is increased and the charging frequency increases.

The control logic for the EF system is shown in Fig. 12. A sense signal from the saddle coil (Sec. 7) is used to gate clock pulses into an up-down counter. This counter is then used to set a digital-to-analog converter. The SCRs of the dc to dc converter are energized whenever the current sensed by the I_{EF} shunt is less than that demanded by the analog level. The alternate pairs of SCRs are energized by a flip-flop when a clock pulse occurs. Additional constraints for the SCR operation have been incorporated into the low-level logic, preventing shorts and other malfunctions. Figure 13 shows the operation of this system.

VI. DATA ACQUISITION SYSTEM

The Data Acquisition System is based on a DEC LSI/11 microcomputer, with CAMAC interfaces to analog input data, a Plessey floppy disc drive, and a Versatec printer/plotter output. Analog data was digitized by a LeCroy 8212 Data Logger and 2249A Analog-to-Digital Converter. Digital data was stored

Figure 12. The control circuit for the EF system. Plasma position (radial velocity) is sensed by a saddle coil. The input signal is used to gate an up/down counter, which is compared with the EF current and used to gate the dc to dc converter on and off.

Figure 13. Operation of the radial feedback system showing (a) equilibrium field coil current, (b) voltage on the digital-to-analog converter, (c) saddle coil signal, (d) plasma position, (e) plasma current, and (f) loop voltage. These data are shown in the form presented by the data acquisition system.

using Kinetic Systems 3615 CAMAC scalars. About 10 ms before the start of every pulse, a LAM pulse would be sent to the CAMAC system to start data collection. Data acquisition continued until the data logger memory was full (~ 200 ms). After each shot, the data logger memory would be read out and the data would be stored on floppy disc files and plotted on the printer. In general, 12 quantities were plotted, including plasma current and voltage, and plasma measurements. A total of 32 analog and six digital channels were available.

VII. DIAGNOSTIC SYSTEMS

Selection of individual diagnostics were made on the basis of their usefulness in determination of plasma parameters most needed in the study of plasma-wall interactions, as well as for the understanding of basic tokamak parameters. Both passive and active diagnostics were used. The electrical environment necessitated the need for careful ground loop elimination and the use of special hardware such as optical couplers and isolation amplifiers. Table 2 is a list of diagnostic systems and purpose for their selection on the APEX device. In this section, a review of the individual diagnostic types will be given in varying detail.

A. MAGNETIC DIAGNOSTICS

Basic plasma parameters, such as plasma current, voltage, and position, are monitored in the APEX device, as in other tokamaks, by various kinds of magnetic flux loops. A Rogowsky coil positioned around the outside of the vacuum vessel is used to measure the total plasma current. An estimate of the one-turn plasma voltage is made by an externally-mounted flux loop positioned on the outside wall of the chamber. Plasma position is determined by several methods and is used as the starting point in the EF feedback control system, as described in Sec. V. Both horizontal (or radial) and vertical plasma position are monitored by a set of four small poloidal flux coils externally located on a cross section of the vacuum vessel and oriented at 45° from the horizontal or vertical axis. Appropriate combinations of the four flux loops yields horizontal and vertical plasma position after dividing the total plasma current contribution measured by the Rogowsky coil. Using this system, plasma position can be determined to roughly ± 0.5 cm. A sine/cosine coil

Table 2. APEX Plasma Diagnostics

Diagnostic	Purpose
Magnetic Diagnostics	
Rogowsky Coil	total plasma current (I_p)
Voltage Loop	plasma loop voltage (V_L)
Plasma Position Coils	plasma position (horizontal and vertical)
Saddle Coil	plasma position (horizontal)
Cosine Coil	plasma position (horizontal or vertical)
Visible and UV Spectroscopy	
H β Monochrometer	H β line radiation (4861 Å)
VUV Monochrometer	line radiation from 2500–5000 Å
Photomultiplier Array	six selected regions (band-pass filters)
Laser Fluorescence	plasma impurities
X-Ray Spectroscopy	
Soft X-Ray Photodiode	soft x-ray $\rightarrow$ far UV radiation (200 $\rightarrow$ 1200 Å)
X-Ray Surface Barrier Detectors	average electron temperature ($\bar{T}_e$)
Microwave Diagnostics	
Microwave Interferometer	average electron density ($\bar{n}_e$)
Microwave Radiometer	radial and temporal T_e profiles
Vacuum Diagnostics	
Ion Gauges	machine base pressure
Residual Gas Analyzer	gas composition in machine
Probes	
Swept Langmuir Probe	T_e and n_e of edge plasma

is also used to monitor vertical plasma position.¹² Constant applied horizontal magnetic field (B_H) is adjusted as needed to keep the plasma vertically centered. Finally, a saddle coil, externally mounted to exactly fit the contour of the circular vacuum vessel, is used to monitor horizontal position and provide an incident signal to the EF feedback control system. Construction of this coil was done in a poloidal flux conserving configuration or "bow tie" shape. The coil senses the degree to which the poloidal flux is concentric with the vacuum chamber.

B. VISIBLE AND UV SPECTROSCOPY

Two monochrometers are presently used to monitor plasma radiation in the visible range. A tunable Beckman DU-19 monochrometer with a quartz prism is set to monitor H_β emission, primarily during startup and shutdown disruptions. Also, a tunable Jarrel-Ash Seya-Namioka grating monochrometer was used to monitor selected visible and UV impurity lines with $\sim 5 \text{ \AA}$ resolution. An array of six filtered photomultiplier tubes is also used to monitor impurities such as: Mo I (550.6 nm), O I (615.6 nm), H_α (656.3 nm), and others. Bandpass filters are used with bandwidths (FWHM) of $\sim 6 \text{ nm}$.

A laser fluorescence spectroscopy (LFS) system diagnostic designed and constructed by D. Gruen, C. Young, and M. Pellin of ANL's Chemistry Division is also used. The LFS diagnostic is a versatile system that can be used to study many aspects of tokamak impurity problems. This device produces time, space, and velocity resolved measurements of impurity atom or ion densities. The laser itself consists of an Argon-ion laser incident to a cw ring dye laser with an output power of 200-700 mW in the visible range. This system is described in more detail elsewhere.¹³

C. X-RAY SPECTROSCOPY

A relative indication of impurity levels in the APEX device can be measured by the response of a vacuum photodiode detector. This metal diode, usually operated at some negative bias voltage, detects radiation in the range of 200-1200 $\text{\AA}$ via photoelectron emission. The relative level of the signal is proportional to impurity radiation losses and is an indication of machine cleanliness.¹⁴

Electron temperature distributions are measured by means of x-ray detectors and a microwave radiometer. The soft x-ray bremsstrahlung spectrum characteristic of a plasma in quasi-equilibrium state is a strong function of the electron temperature. As long as impurity line radiation does not dominate this spectrum, it can be used to measure the average electron temperature along the line of sight into the plasma. The filter method, as suggested by Jahoda et al.,¹⁵ and analyzed in detail by Smeulders,¹⁶ is also used. In this case, filtered surface barrier detectors are used for the measurement. Properties of surface barrier detectors as they apply to x-ray measurements are given in Ref. 17. The filters used are of thin (0.0025 to 0.025 cm), pure beryllium foil (99.7%) obtained from A. D. Mackay, Inc. Ratios of signal observed through four separate filtered detectors are calculated to reveal the average electron temperature. The analysis of Smeulders shows that the filter method should be quite reliable in the range $400 \text{ eV} < T_e < 900 \text{ eV}$ with most of the impurities commonly present. Although absolute detector calibration is not needed for calculations of signal ratios, detectors must be calibrated to give similar response for equal incident radiation. This was done by varying the applied negative bias to each detector. This applied bias in the range $-11 \rightarrow -14 \text{ V}$ reduces noise level as well as providing calibration settings.

D. MICROWAVE DIAGNOSTICS

The standard diagnostic for measurements of electron density is the microwave interferometer. The APEX interferometer uses a 2 mm ordinary mode wave propagating along a vertical chord through the center of the plasma to measure line averaged electron density. Although traditional "zebra stripe" displays can be observed, a digital phase display circuit developed at the Princeton Plasma Physics Laboratory¹⁸ is used for direct $\bar{n}_e$ display by the data acquisition computer.

A swept-heterodyne microwave radiometer, developed by Cano,¹⁹ is also used to deduce radial and temporal profiles of the electron temperature by measuring plasma electron cyclotron emission. Since cyclotron frequency is a function of position in the plasma, the swept frequency radiometer can monitor temperatures across the plasma volume using the relation

$$P_{rf} = kT(R)\Delta f(1 - \exp(-\tau))$$

where:

kT = the temperature in eV,

Δf = the bandwidth of the detector, and

τ = a measure of the blackness of the plasma.

To accurately determine electron temperatures, the plasma must radiate as a blackbody at the frequencies of interest. For tokamaks of small cross-sectional area such as APEX, however, theoretical calculations predict that blackbody conditions are not met for all modes under all conditions²⁰ (see Fig. 14). In practice, reflections from the walls of a circular cross section machine will significantly increase propagation paths. A quartz lens focusing the microwave horn on the center of the chamber utilizes the radial symmetry of the chamber to increase reflections in the horn. The horn thus samples a small vertical region of the plasma due to the radial symmetry of the chamber. A large region of the plasma is sampled horizontally due to defocusing of rays in the horizontal plane. Since the ordinary mode is not blackbody, it is desirable to observe cyclotron radiation at the second harmonic extraordinary mode, with toroidal field values less than ~ 12 kG. A reference signal from a local oscillator is mixed with the cyclotron emission from the plasma with the resultant beat frequency signal being detected by an intermediate frequency (IF) receiver and amplifier. The receiver bandwidth, Δf , determines how closely the two signals are matched and thus the resolution of the system. The receiver bandwidth of the IF amplifier used in the APEX microwave radiometer, ~ 250 MHz, when translated into spatial coordinates in the plasma, yields a resolution of ~ 2.5 mm.

Figure 15 is a block diagram of the experimental setup for the microwave radiometer. The 4 mm cyclotron radiation is transported through WR-15 waveguide to an instrument rack. A backward-wave oscillator (BWO) made by Siemens provides the reference signal and can be tuned to frequencies in the range of 50-75 GHz. Tuning is accomplished by the Alfred 650 ramp generator. The power supply for the BWO and Alfred 650 is a Micro-Now 703C. This oscillator combination can be operated in a fixed frequency mode or can be swept between any two frequencies in the range of the BWO. The sweep time can be as short as 4 ms. A leveling circuit controls the power output of the reference signal to keep it constant over all frequencies. The signal then passes through a variable attenuator and is coupled to the mixer by a 6 db broadband directional

Figure 14. Optical thickness τ as a function of cyclotron emission frequency for ordinary and extraordinary modes for APEX parameters. Black-body conditions are met if $\tau \gg 1$.

Figure 15. Basic components of the swept heterodyne microwave radiometer. The system produces signals proportional to power, detected power, and frequency.

coupler. A Hughes diode mixer mixes the signals via a heterodyne process mentioned previously. The resulting signal, which is proportional to the electron temperature, is amplified by the Q-Bit IF amplifier and sent to the data acquisition system. The radiometer system was calibrated by means of a noise source (C.P. Clare and Co., TP 164), which was substituted in place of the detection horn. This source gave a 1.50 ± 0.25 mV signal corresponding to 1 eV plasma temperature. The linearity of the amplifier and diode system was checked by means of an RF signal generator.

E. VACUUM DIAGNOSTICS

Two Granville-Phillips nude ion gauges are used to measure machine base pressure in the range $5-8 \times 10^{-8}$ torr. An Inficon IQ 200 quadrupole mass analyzer displays partial pressures of individual mass peaks. This unit was mounted similarly to the vacuum pump on the opposite side of the machine in order to monitor constituents accessible to the vacuum pump.

F. PROBES

A swept Langmuir-type probe, based on a similar design used at MIT,²¹ has been installed to measure electron temperature and density at the plasma limiter (vacuum vessel wall). The applied sawtooth bias (from -100 $\rightarrow$ +100 V and period of 2 ms) should provide good time resolution during discharges and will yield both a temperature and a density value for each half period.

Neutron activation was also used to study the motion of impurities in the plasma edge region. This system was able to detect impurity deposition at a level 8×10^{-3} monolayers/shot. This system is reported in a separate paper.²²

VIII. OPERATION AND RESULTS

Successful results from tokamak plasma discharges are dependent on vacuum chamber wall conditioning. As a consequence, APEX operation consisted of two phases: (1) wall conditioning techniques; and (2) ohmically-heated plasma discharges.

A. VACUUM CHAMBER WALL CONDITIONING

One of the first methods used was baking of the vacuum chamber. The entire chamber was wrapped in heater tape and insulating material and allowed to bake at $\sim 150^{\circ}\text{C}$ for approximately 24 hours. This technique was useful in lowering the base pressure of the machine by a factor of two, but did not, by itself, alter the discharges significantly.

The main operating method used was Taylor discharge cleaning.²³ In this pulsed technique, ~ 1 m torr H_2 or D_2 gas was puffed into a 2 kG ramped toroidal field. The partially ionized discharge was initiated by coupling a 1.5 kW, 3 kHz sine wave through the OH coils. A pulse length of ~ 120 ms with a repetition rate of one pulse every four seconds was used. This low energy discharge was used to remove loosely bound ions and atoms, mainly oxygen and carbon compounds, from the chamber walls. Oxygen is removed as H_2O or D_2O , and carbon compounds are removed as H_zC_y or D_zC_y , depending on the working gas used. A measure of the effectiveness of this discharge cleaning method for removing oxygen is shown in Fig. 16.

Another method used primarily during the early stages of APEX operation was a steady-state hydrogen glow discharge. A constant H_2 gas pressure of 10-20 microns was maintained in the chamber while an electrode charged to 500 V initiated the discharge. This procedure was terminated when metallic coatings were observed on the optical windows.

Titanium gettering was installed but not used, as acceptable discharges were obtained without it. This technique might be required for high purity discharges.

B. TOKAMAK DISCHARGE RESULTS

The APEX tokamak was normally operated one eight-hour period per day, five days per week. The first three to four hours during each running period were devoted to vacuum chamber wall conditioning using the Taylor discharge cleaning method, as previously described. Most of the remainder of the time consisted of tokamak operation and modifications. The working gas used for these operations was ~ 1 m torr H_2 or D_2 per discharge. The TF coils were normally run at 4000-6000 A, which produced an 8-12 kG field at the center of the vacuum chamber for ~ 110 ms. The OH coils were operated in the range

Figure 16. Water pressure produced during Taylor discharge cleaning and after a one-week shutdown.

2100-2400 A, providing a flux-swing of ~ 0.31 - 0.35 V-sec. Plasma discharges were initiated at a rate of about one pulse per minute. Since electron population from ion gauge filament emission was sufficient to initiate the discharge, no pre-ionization was necessary.

Some plasma parameters measured during a typical discharge are shown in Fig. 17. These discharges were used for calibration and operation of a laser fluorescence system¹³ which detected impurity densities with a threshold of roughly 10^{11} atoms of Zr per cm^3 . Thus, irregular termination of the discharge or position oscillations were required in order to raise the impurity density above the detection threshold. Peak plasma current was typically 45-55 kA in discharges 80-100 ms long. Discharges were terminated at a known time by turning off the EF coils, forcing the plasma into the LFS probe at the outer vacuum chamber wall. The microwave radiometer recorded T_e measurements at a position $r/a \sim 0.5$. Swept operation of this device (as described in Sec. 7.4) also was available and could provide radial and temporal T_e profiles. X-ray measurements were used to determine T_e at the center of the plasma. The comparatively large uncertainty in these measurements is due to the uncertainty in the magnitude of the higher energy component $E > 10$ keV and to line radiation. Much of this error (15-20%) could be eliminated by more exact computer modeling and better data collection techniques. Other parameters shown are the loop voltage (V_L), electron density (n_e), and plasma radial position as measured by the saddle coil. Calculations from typical discharges yielded a value for Z_{eff} of ~ 5 and a safety factor (q) at the plasma edge of ~ 3.4 . Continued operation and tuning is likely to bring significant improvements in Z_{eff} , plasma current, and plasma temperature.

IX. CONCLUSIONS

A number of conclusions can be drawn from the operation of this machine. The primary problems in obtaining long, stable discharges were involved with error fields and cleanliness of the machine vacuum system.² Error fields, primarily due to the interconnection of the TF coils, required cancellation before the plasma would stay in the center of the machine. Vacuum requirements for good operation include; (1) base pressures in the 10^{-8} range; (2) a palladium leak filter on the input gas; and (3) some sort of surface treatment technique such as Taylor discharge cleaning.

Figure 17. Parameters of a typical shot used to test the laser fluorescence system.

The overall performance of this machine was fairly close to its design limits, and it ran repeatably and reliably. The diagnostics indicated that plasmas capable of reactor-relevant experiments were produced, and initial experiments measuring thermal desorption using radioactive tracers and laser fluorescence were concluded.

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