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Recent Results from Tokamak Divertor Plasma Measurements

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New diagnostics have been developed to address key divertor physics questions, including: target plate heat flux reduction by radiation, basic edge transport issues, and plasma wall interactions (PWI) such as erosion. A system of diagnostics measures the target plate heat flux (imaging IR thermography) and particle flux (probes, pressure and Penning gauges, and visible emission arrays). Recently, T_e , n_e , and P_e (electron pressure) have been measured in 2-D with divertor Thomson Scattering. During radiative divertor operation T_e is less than 2 eV, indicating that new atomic processes are important. Langmuir probes measure higher T_e in some cases. In addition, the measured P_e near the separatrix at the target plate is lower than the midplane pressure, implying radial momentum transport. Bolometer arrays, inverted with reconstruction algorithms, provide the 2-D core and divertor radiation profiles. Spectroscopic measurements identify the radiating species and provide information on impurity transport; both absolute chordal measurements and tomographic reconstructions of images are used. Either intrinsic carbon or an inert species (e.g., injected Ne) are usually observed, and absolute particle inventories are obtained. Computer codes are both benchmarked with the experimental data and provide important consistency checks. Several techniques are used to measure fundamental plasma transport and fluctuations, including probes and reflectometry. PWI issues are studied with in-situ coupons and insertable samples (DiMES). Representative divertor results from DIII-D with references to results on other tokamaks will be presented.

I. INTRODUCTION

Current designs of future tokamaks (e.g., ITER¹), which are based on current experimental results and modeling, indicate several critical physics issues in the divertor design, including: 1) Heat flux and erosion at the divertor plate, and 2) particle control by the divertor, involving He exhaust, core density control, and control of neutrals. The development of new, novel diagnostics to measure plasma parameters in the edge of the core plasma (i.e., the scrape-off layer, or SOL) and the divertor of tokamaks has significantly advanced our understanding of the important physics mechanisms, thereby allowing us to optimize the solutions.

Detailed plasma measurements of T_e , n_e , T_i and n_i (impurities) at the plasma midplane and core are routine, and experiments are now adding similar measurements in the divertor. Detailed comparisons of fundamental data with computational codes provides a consistency check on the database and helps identify the relevant physical processes. The small footprint of the power loss observed on the divertor plate results from the fact that the parallel transport along the magnetic field lines is much greater than the perpendicular, cross-field transport. Experiments have been carried out to increase the radial width by ergodizing the field-line geometry². Most experiments, however, have focused on spreading the heat flux over a wider area with radiation. Heat flux reductions by factors of five have been achieved with D₂ and impurity (e.g., neon) puffing³. At the same time, the core plasma must not be substantially degraded. Estimates for ITER indicate that there must be divertor impurity enrichment ($\xi_{div} \equiv c_i^{div}/c_i^{core}$, where c is the concentration) of nearly three for efficient operation. New impurity diagnostics are currently being used to understand the physics of impurity transport and entrainment. In particular, experiments and new diagnostics are focused on whether ion flow in the SOL⁴ or the divertor density⁵ can be used to increase ξ_{div} .

We present here an overview of recent divertor physics results, with emphasis on DIII-D. A detailed review of results from all tokamaks is beyond the scope of the discussion; rather, we will use DIII-D as a representative example and include references to results from other machines. Excellent overviews are available for several diverted tokamaks: C-MOD⁶, JET⁷, ASDEX-U⁸. In Section II we describe basic SOL and divertor measurements, followed by Section III where experiments with divertor heat flux reduction by D₂ puffing are described. Impurity puffing experiments are described in Section IV, and comparisons with calculational models are described in Section V. Surface measurements of erosion and redeposition are summarized in Section VI, followed by a summary and a discussion of diagnostic needs for new measurements.

II. SOL AND DIVERTOR DIAGNOSTIC OVERVIEW

An overview of the DIII-D SOL diagnostic set is shown in Fig. 1a, along with a typical lower-single-null (LSN) diverted plasma shape. DIII-D can be operated either in a single- (SN) or double- (DN) configuration, but the divertor diagnostics are optimized for the lower divertor. The divertor plasma can be moved (keeping the core plasma nearly fixed) so that the distance from the outer strike point to the He-cooled divertor cryopump is varied. This in turn varies the particle exhaust, and can be used to either vary the plasma density or to keep the plasma density fixed as the gas puffing rate is varied (for "pump and puff" impurity entrainment experiments). Fig. 1b shows the details of the lower divertor diagnostics. In unpumped discharges, we sweep the divertor plasma across the diagnostics and thereby obtain 2-D profiles of the plasma quantities (e.g., T_e , n_e , and impurity emissions). As discussed above, we are interested in measurements of the SOL parameters at the "upstream" or midplane location and the "downstream" or divertor plate location. In addition,

measurements of ξ_{div} require both divertor and core plasma measurements. The diagnostic instruments in both regions are summarized in Table I; references to descriptions of the diagnostic and relevant results are included in the table. "Primary" diagnostics refer to the most general measurement technique, and analysis is relatively straightforward. The "other" techniques are either more specialized, are used for confirmation, or require more extensive interpretation and modeling. Fundamental measurements of fluctuations and transport in the divertor and SOL are obtained from probes^{9,10} and a reflectometer, these results are presented elsewhere¹¹⁻¹⁴.

The helium-cooled cryopump in the divertor (Fig. 1a and 1b) has a measured D₂ pumping speed of 30,000 l/s at 2 m Torr. The pressure in the pumping plenum is measured by a fast ionization gauge¹⁵. Pumping rates in ELMing H-mode (EHM) are typically 40 TI/s¹⁶, which is larger than the beam fueling rate of 10-20 TI/s. The particle balance indicates that the remainder is particle removal from the wall.¹⁷ Pumping, along with careful control of error fields¹⁸, has enabled us to reduce the core density to $\sim 1 \times 10^{19} \text{ m}^{-3}$. Density control is particularly important for efficient non-inductive current drive techniques on tokamaks. The cryopump can also be used to exhaust helium when a layer of argon is deposited on the pump. Helium exhaust is an important issue for future tokamaks and reactors (a byproduct of the fusion reaction). The pumping speed for helium immediately after depositing the argon layer is 18,000 l/s, which decreases during the discharge as the argon layer is covered with D₂. Core He transport and exhaust was studied using both helium gas puffing and helium neutral beam^{19,20}. We obtained the favorable result that the helium exhaust rate from the plasma was limited by the exhaust efficiency of the pump, not the core helium transport. The ratio of the effective particle confinement time to the energy confinement time, $\tau_{\text{He}}^*/\tau_E$ was ~ 11 , which is the desirable range for machines

such as ITER.

We will now examine typical H-mode results on DIII-D. The time histories of several signals from a neutral-beam heated H-mode discharge where D₂ was injected at 2000 ms to reduce the divertor heat flux are shown in Fig. 2. The neutral beam heating power, D₂ gas flow rate, lower divertor peak heat flux (from IRTV), divertor H α photodiode (PHD), ion-saturation current (from a divertor plate Langmuir probe near the separatrix^{21,22}), pump exhaust (computed from a gauge in the pumping plenum), and core density are shown. The sharp rise in the PHD signal and the pump exhaust at 2000 ms is due to the increase D₂ injection, and the divertor peak heat flux is sharply reduced. The ion current to the divertor plate is dramatically reduced. The large spikes in the PHD signal are Edge Localized Modes (ELMs)²³. In the next section, we will examine in detail the two distinct regimes shown in this discharge: 1) ELMing H-mode (EHM-before 2000ms) and 2) the period during heat flux reduction, normally called the Partially Detached Divertor Regime²⁴⁻²⁶ (PDD-after 2000 ms). The term PDD comes from the fact that the ion current near the separatrix is decreased, but away from the separatrix it is unchanged or increases.

III. BASIC SOL AND DIVERTOR MEASUREMENTS (Comparison of ELMing H-mode EHM and Partially Detached Divertor-PDD)

The two phases shown in Fig 2. have been studied in detail by sweeping the x-point across the plasma diagnostics. In most cases, we find only modest changes in parameters due to the sweep. In Fig. 3 we compare the radiated power measurements from tomographic reconstructions of the two 24-channel bolometer cameras in the two regimes (Fig. 3a-EHM, Fig. 3b.-PDD). The radiation is more intense on the inside for EHM, and more intense on the outside for the PDD. In Fig. 3c, the divertor plate heat flux derived from IRTV temperature measurements²⁷ show an in-out asymmetry in EHM (solid, open curve), corresponding to the

asymmetry in the radiation. The heat flux is reduced in the PDD (filled curve); we typically see reductions of a factor of 3-5 in the peak heat flux. Quantitative comparisons of the two data indicate that the decrease in the integrated divertor heat flux nearly equals the increase in the radiated power. Furthermore, if we sum up the power from the bolometers and the IRTV's (other cameras measure the upper divertor and the centerpost of the machine), we can account for typically more than 85% of in the input power²⁸.

Fig. 4 shows that the measured T_e distribution from the Divertor Thomson Scattering (DTS)²⁹ decreases dramatically from the EHM (Fig. 4a) to the PDD (Fig. 4b). We typically measure T_e in the 1-2 eV range over a large extent of the divertor during the PDD. These temperatures are lower than expected, and indicate that several new atomic processes in the divertor may be important, including volume recombination. In addition, the electron pressure decreases at the divertor plate. We measure the total pressure at the plasma midplane by the core Thomson Scattering array(n_e and T_e) and the CER array (T_i). In the divertor, we measure the electron pressure and must assume that the ion pressure is equal. We observe reasonable (factor of 2) pressure balance along the field lines in ohmic, L-mode, and EHM. In the PDD mode, we observe significant reductions in the pressure near the separatrix at the divertor plate (more than an order of magnitude). Models have shown that this can be caused by radial momentum transport by neutrals³⁰. On field lines away from the separatrix, we usually measure pressure balance along the field line, or slight increases near the divertor plate. The relationship between the radiation distribution and the pressure drop is currently an active area of both experimental and computational work.

It is also important to understand the species responsible for the radiation in the EHM and PDD regimes. We have used visible and EUV spectroscopy to

determine that carbon and deuterium are the main radiating species. Shown in Fig. 5a (top) is an inversion of CIII emissions at $\sim 4647\text{\AA}$ from the tangential TV array for a PDD discharge. The data has been inverted³¹ using a matrix technique that assumes toroidal asymmetry. We have obtained similar data for other ionization states of carbon and deuterium $D\alpha$. While these data provide valuable information on the spatial distribution of the radiation, it is difficult to obtain quantitative results from these data because of the highly nonlinear relationship between the emission and T_e . Therefore, we use an EUV spectrograph (Divertor SPRED)³² that has been calibrated at the National Institute of Science and Technology (NIST) to determine the line-integrated brightness of resonance transitions in the EUV (100-1150 $\text{\AA}$). The Divertor SPRED views the divertor plasma from the top of the machine. Shown in Fig. 5b (bottom) are spatial profiles of emission lines from several ionization states of carbon and deuterium. Except for CIV, these are resonance transitions (ground and metastable) for the particular ionization state. We have compared the carbon and deuterium radiated power obtained from the Divertor SPRED measurements with the total radiation from the bolometer, and we obtain good agreement. However, the specie that radiates the most and has the largest uncertainty is CIV. Presently, we are expanding the wavelength coverage of the Divertor SPRED to measure the CIV resonance lines ($\sim 1550\text{ \AA}$) and Deuterium $Ly\alpha$ (1216 $\text{\AA}$). In the future, we also plan add other instruments to obtain 2-D information about the UV radiation.

IV. DIVERTOR HEAT FLUX REDUCTION WITH NEON AND ARGON PUFFING

We have also reduced the peak divertor heat flux by injecting neon into the plasma. Unlike the D_2 puffing case which radiates predominantly in the divertor, the bolometer inversion in Fig. 6 shows that the neon radiation is divided between a mantle around the plasma core and a concentrated region near the x-point.

Reduction in the peak divertor heat flux of factors of >5 are obtained. However, the increased core radiation often changes the ELM activity, which in turn changes the core density behavior. Feedback control has been used on the ASDEX-Upgrade device to maintain the plasma in a stable type III ELM condition³³. The impurity gas flow is controlled by the radiated power from a set of bolometer channels that are representative of the total radiated power. The deuterium gas flow is controlled by pressure measurements in the divertor-pumping region. From these experiments, they conclude that the divertor neutral flux is important in determining the amount of impurity enrichment in the pumping plenum.

Experiments on DIII-D with trace argon injection⁴ have indicated that the injection of D₂ at the plasma midplane along with pumping in the divertor can influence the impurity enrichment in the pumping plenum. We have continued these "puff and pump" experiments with neon and nitrogen. Comparisons have been made both with- and without- midplane D₂ puffing and active puffing. As shown in Fig. 1b, we have a unique diagnostic system to measure impurity transport in the core and divertor plasmas. The core CER measures the fully stripped absolute neon density; here we rely on calculations of the neutral beam penetration and accurate atomic cross-sections. In the pumping plenum, a Penning Gauge³⁴ measures the partial pressures of deuterium, neon, and argon. This gauge has been calibrated in-situ by puffing various mixtures of gases (without plasma). In the divertor, the Divertor SPRED measures the line-integrated brightness of ground-state and metastable transitions in NeIII through Ne VIII. To obtain divertor neon inventories, we must estimate the spatial profile (i.e., the length of the emission along the SPRED viewing chord) of the neon from 2-D bolometer profiles. In addition, we can vary the field-of-view of the Divertor SPRED to include the whole divertor region. However, line-integrated concentrations can be compared directly in cases with- and without-

"puff and pump" to discern if there are changes in divertor concentrations (assuming there are not significant changes in the lengths in these two cases and the contribution by the core is small).

The present status of these measurements is that if we compare cases with- and without- "puff and pump" see substantial changes in the *plenum* neon enrichment³⁴ ($\xi_{\text{plenum}} \equiv c_i^{\text{plenum}} / c_i^{\text{core}}$, where c is the concentration obtained from the Penning Gauge in the plenum and the CER in the core) but only modest changes in the *divertor* neon enrichment ($\xi_{\text{plenum}} \equiv c_i^{\text{divertor}} / c_i^{\text{core}}$, where c is the concentration obtained in the divertor with the Divertor SPRED and the CER in the core). We also observe different neon time decays from the three regions, indicating that a detailed multi-region model with different time constants is necessary. These time-constants are reduced when "puff and pump" is turned on. In addition, the measured neon in these three regions is significantly less than the amount of injected neon. Estimates show that some of the neon inventory may be temporarily held up in the wall³⁴. Further checks of diagnostic calibrations and atomic-physics cross-sections are in progress. As optimization of the divertor enrichment is necessary for future successful radiative divertor operation, this is currently an active area of divertor physics research.

V. CALCULATIONAL MODELS PROVIDE IMPORTANT DIAGNOSTIC CHECKS

We compare the SOL data set with calculational models both to determine the important physics mechanisms and to find inconsistencies in the data. Detailed comparisons of the DIII-D data have been made with the UEDGE fluid code^{35,36} and the DEGAS Monte-Carlo neutral transport code. The UEDGE code uses the measured density and temperature profiles at the plasma midplane as inputs, and then calculates the edge profiles in the SOL from the midplane down to the divertor plate.

The calculated IRTV signal at the divertor plate from the UEDGE code agrees well with the data: the peak heat flux is within a factor of two, and the total heat flux agrees to ~30%. We also observe fairly good qualitative agreement between the calculated 2-D T_e distribution from UEDGE and that measured by DTS during the EHM portion of the discharge. We feel that better agreement can be obtained with more sophisticated impurity models, which are present in the code but are under development.

The UEDGE calculations of T_e have consistently been less than that derived from Langmuir probe measurements at the plate. The new Divertor Thomson Scattering (DTS) data indicates lower temperatures which are more consistent with the modeling. In addition, new hydrogen reaction rates have recently been implemented in UEDGE, which has brought the code in even better agreement with the DTS T_e measurements. At present, the largest discrepancy between the UEDGE modeling and the data is that UEDGE underestimates the deuterium emission in the "private flux space" (the triangular region below the x-point) region (there is good agreement at the strike points). We are using data from the tangential TV, a vertically-viewing TV, and the fast ionization gauges to investigate this discrepancy.

The UEDGE fluid equations are solved on a non-orthogonal grid, so we can calculate recycling from complicated divertor structures. UEDGE calculations of the background plasma have been used with DEGAS to calculate the neutral transport in complicated slot divertor geometries. Calculations show that the new DIII-D Radiative Divertor Project (RDP) will reduce the integrated core ionization source by nearly an order of magnitude. The model also showed that if the baffles were too wide, neutrals would leak around the baffle and provide a neutral source near the outer midplane. If the baffles were too narrow, recycling off the structures was close enough to penetrate into the core plasma. An optimum width and baffle shape was

determined from the calculations, and we using these to guide the construction of the RDP for DIII-D. We are able to change the baffle shape and height in the RDP, and comparison of these data with the models will further test our understanding of the relevant physics concepts. This understanding is crucial for the design of future tokamak divertors.

VI. SURFACE MEASUREMENTS

Understanding the interaction of the plasma with surfaces in the tokamak is another important goal of divertor and SOL measurements. It is well known that surface conditioning techniques such as discharge cleaning and boronization improve plasma performance. Both in-situ and removable samples have been used to understand these techniques. On DIII-D, an insertable probe called the Divertor Material Evaluation Studies (DiMES) has been used both for in-situ analysis and to expose samples. As shown in Fig. 1a, it is located in the center of the bottom divertor plate. Colorimetry techniques³⁷ were used to measure the erosion and redeposition of materials in the divertor. The thickness of in-situ thin films was measured by their spectral response. Insertable samples were analyzed by several techniques, including Rutherford Backscattering (RBS) These results agree well with models of erosion and redeposition^{38,39}. These results are guiding the selection of materials for tokamak divertors. Currently, DIII-D has all-carbon walls, but metal walls are used on other machines (e.g., molybdenum on C-Mod).

VII. FUTURE DIRECTIONS--NEW DIAGNOSTICS AND DATA

Significant developments have occurred in both divertor diagnostics and analysis. Several experiments are focused on reducing the divertor heat flux and erosion of the target plate by radiation. We are starting to gain an understanding of

the physics in the SOL, and detailed computational models have been developed. Data on SOL and divertor impurity transport is being obtained and compared with models. Erosion and redeposition of materials in the divertor, including in-situ studies, have been done.

Nevertheless, there are still several critical questions that are unanswered. A major question is the effectiveness of a SOL ion flow in entraining the impurities in the divertor. Direct measurements of ion flow in the SOL would greatly improve this understanding. While we have chord-integrated measurements of the divertor EUV radiation, 2-D imaging of the resonance lines would provide more details to compare with models and would also allow more accurate measurements of the divertor impurity inventory. Some divertor ion temperature measurements have been done by spectral line analysis. Detailed 2-D T_i profiles, including measurements very close to the plate are desired for comparisons with models. There is also evidence of non-Maxwellian electron temperature distributions.

Continued development of diagnostic techniques, divertor structures, and experiments is necessary to achieve the ultimate goal of understanding the physics of the divertor and SOL plasma. This accumulated physics knowledge will most likely reside in a benchmarked computational model. A general understanding of the SOL physics has wide applicability both inside and outside the fusion program. For the fusion program, this understanding will allow us to design efficient tokamak divertors that can handle the heat flux, will have good survivability (e.g. low erosion and can survive disruptions), and will improve the core tokamak confinement.

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Table I

"Upstream" Measurements - Midplane SOL and Core		
Physical Quantity	"Primary" Diagnostic	Other Diagnostics
Midplane SOL & Core T_e	Core Thomson Scattering	Scanning Probe ^{9,10}
Midplane SOL & Core T_i	CER	
Midplane SOL & Core n_e	Thomson Scattering	Interferometers Scanning Probes
Midplane SOL & Core n_i	CER, EUV Spectrograph	
Core Radiation Profile	Imaging Bolometer ⁴⁰	
SOL Fluctuations	Scanning Probe	
Divertor and Pump		
Physical Quantity	"Primary" Diagnostic	Other Diagnostics
Divertor n_e	Divertor Thomson ²⁹	Plate & Moveable Probes Divertor Interferometer
Divertor T_e	Divertor Thomson	Plate & Moveable Probes Divertor Spectroscopy
Divertor Radiation Profile	Imaging Bolometer ⁴⁰	
Divertor Heat Flux	IR Thermography ²⁷	Divertor Probes ²¹
Divertor Particle Flux	Divertor Probes ²¹	
Divertor n_i	UV SPRED (calib.) ³² Visible line monitors Tangential TV ³¹	
Pump Exhaust	"ASDEX" Ion Gauge ¹⁵	
Exhaust Composition	Penning Gauge ²⁰	
Divertor Fluctuations	Divertor Refractometer	

FIGURE CAPTIONS

Fig. 1a(left) A cross-sectional view of the DIII-D tokamak showing the bolometer views, the midplane SOL diagnostics, and the divertor cryopump.

Fig. 1b(right) The locations of the divertor diagnostics in the lower divertor on DIII-D. The eight measurement locations for the Divertor Thomson Scattering, the EUV spectrograph, and the Tangential TV are shown.

Fig. 2. A representative discharge that shows the Elming H-mode (EHM) (before 2000 ms). The D₂ gas puff is increased at 2000 ms, resulting in a reduction in the divertor heat and particle fluxes. This is called the Partially Detached Divertor (PDD) mode.

Fig. 3. The inverted bolometer data for (a-top) the EHM before gas puffing, and the (b-middle) PDD regime during gas puffing. The IRTV (c-bottom) shows the reduction in the divertor heat flux (open-before puffing, filled-after puffing).

Fig. 4. The Divertor Thomson Scattering T_e data during the EHM (a-top) and the PDD (b-bottom). Note the dramatic reduction in the T_e with gas puffing; much of the divertor region has T_e less than 2 eV.

Fig. 5. The inverted 2-D distribution of CIII from the Tangential TV (a-top) during PDD operation. The profiles from the EUV SPRED (b-bottom) obtained by sweeping the x-point are used to obtain quantitative measurements of the divertor impurity densities.

Fig. 6. The inverted bolometer distribution for neon puffing. The radiation is divided between a mantle around the plasma core and localized emission near the divertor.

Fig. 1

- Gas Flow
~200 T-I/s
(Divertor)

- Heat Flux
Reduction

- ELMs
Change

- Separatrix
Ion Flux
Decreases

- Pump
Exhaust

- Density
Constant

Fig. 3