Nuclear Materials and Energy 000 (2016) 1–9

Contents lists available at ScienceDirect

Nuclear Materials and Energy

journal homepage: www.elsevier.com/locate/nme

High-field side scrape-off layer investigation: Plasma profiles and impurity screening behavior in near-double-null configurations

B. LaBombard[a,*], A.Q. Kuang[a], D. Brunner[a], I. Faust[a], R. Mumgaard[a], M.L. Reinke[b], J.L. Terry[a], J.W. Hughes[a], J. Walk[a], M. Chilenski[a], Y. Lin[a], E. Marmar[a], G. Wallace[a], D. Whyte[a], S. Wolfe[a], S. Wukitch[a]

[a] *MIT Plasma Science and Fusion Center, 175 Albany St., Cambridge, MA 02139, USA*
[b] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Alcator C-Mod
Impurity screening
Double null
High field side scrape-off layer

ABSTRACT

New experiments on Alcator C-Mod reveal that the favorable impurity screening characteristics of the high-field side (HFS) scrape-off layer (SOL), previously reported for single null geometries, is retained in double null configurations, despite the formation of an extremely thin SOL. In balanced double-null, nitrogen injected locally into the HFS SOL is better screened by a factor of 2.5 compared to the same injection into the low field side (LFS) SOL. This result is insensitive to plasma current and Greenwald fraction. Nitrogen injected into the HFS SOL is not as well screened (only a factor of 1.5 improvement over LFS) in *unbalanced* double-null discharges, when the primary divertor is in the direction of $B\times\nabla B$. In this configuration, impurity 'plume' emission patterns indicate that an opposing $E\times B$ drift competes with the parallel impurity flow to the divertor. In balanced double-null plasmas, the dispersal pattern exhibits a dominant $E\times B$ motion. Unbalanced discharges with the primary divertor *opposite* the direction of $B\times\nabla B$ exhibit *excellent* HFS screening characteristics – a factor of 5 enhancement compared to LFS. These data support the idea that future tokamaks should locate all RF actuators and close-fitting wall structures on the HFS and employ near-double-null magnetic topologies, both to precisely control plasma conditions at the antenna/plasma interface and to maximally mitigate the impact of local impurity sources arising from plasma-material interactions.

1. Introduction

Fluctuation-induced cross-field transport in the high-field side (HFS) scrape-off layer (SOL) is extremely low compared to the low-field side (LFS) [1]. Consequently, in double-null configurations, HFS density and temperature profiles are very sharp and, unlike the LFS, there are no density 'shoulders' that extend out to impact first wall components, including RF actuators. In single-null configurations, this HFS/LFS transport asymmetry drives strong parallel plasma flows, which poloidally through the SOL of the plasma from LFS to HFS. The HFS SOL also exhibits very strong impurity screening behavior in single-null configurations. Previous experiments have shown that it takes an order-of-magnitude larger injection rate of nitrogen (N) at the HFS midplane compared to the LFS midplane to produce the same core N content [2]. The lack of interchange turbulence on the 'good curvature' side of the torus is believed to be at least partly responsible for both of these features in the HFS SOL – the very sharp density and temperature profiles in double-null configurations and a reduced level of impurity cross-field diffusion, as implied by the excellent N screening properties. Lacking plasma turbulence on the HFS, one might expect that neoclassical transport governs the profiles, particularly in balanced double-null configurations. In this regard, it is interesting to consider how narrow HFS profiles might relate to narrow heat flux footprints found at the divertor target plates [3]. Neoclassical ion drift effects have been invoked to explain the width of the observed divertor heat flux footprints in single-null plasmas, their inverse scaling with poloidal magnetic field strength and relative insensitivity to major radius of the device [4]. Measurements of HFS profiles and an examination of dependencies on plasma conditions are therefore of interest.

Moreover, it has been proposed [5] that future tokamaks should be designed to take advantage of these remarkable characteristics

---

* Corresponding author.
E-mail address: labombard@psfc.mit.edu (B. LaBombard).

http://dx.doi.org/10.1016/j.nme.2016.10.006

Please cite this article as: B. LaBombard et al., High-field side scrape-off layer investigation: Plasma profiles and impurity screening behavior in near-double-null configurations, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.10.006

of the HFS SOL to solve plasma-material interaction and steady state plasma sustainment challenges – relocate all RF actuators and close-fitting wall structures to the HFS and provide a large plasma-wall gap for structures on the LFS. Near-double-null magnetic topologies can be used to provide precise external control of upper/lower x-point flux-balance and HFS plasma-wall gap. In this way, plasma conditions at the HFS antenna/plasma interface could be tailored – even dynamically, in response to real-time measurements – both to optimize wave coupling and to minimize the level of plasma-material interactions. In addition, if the favorable HFS screening characteristics seen in single-null discharges also applied to near-double null configurations, the impact of impurities generated from plasma-wall interactions (possibly now controlled and reduced) would be further mitigated. These ideas are particularly compelling because theory and simulations indicate that RF wave accessibility and damping may be dramatically improved with HFS launch: lower hybrid waves can penetrate to mid minor radius (critical for current profile control) and a 40% or more increase in current drive efficiency may be obtained [6–9] (critical for reducing circulating power and obtaining net electricity production from fusion). In addition, there is a host of other potential benefits: energetic particle loads, ELM heat pulses and runaway electron damage on launch structures may be practically eliminated; neutron fluxes to RF launch structures may be minimized, particularly for locations above or below the inner midplane, which is synergistic with optimization of LHCD ray trajectories; thin, quiescent SOL minimizes undesirable interactions with SOL (e.g., wave scattering, collisional absorption, parametric decay instabilities); low plasma recycling fluxes lead to low neutral pressures and increased RF voltage limits. High field side ion cyclotron RF heating systems would also benefit from these attributes as well as exploit highly favorable wave physics [10], such as 100% first pass absorption of fast waves via mode conversion.

Motivated by this vision, the Alcator C-Mod team is presently investigating key aspects of HFS SOL physics in more detail: (1) Does the previously observed HFS impurity screening behavior extend to balanced double-null conditions where strong parallel flows to the divertor become relatively stagnant and the SOL profiles become very narrow? Could it be that such effects enhance HFS impurity penetration to the point where near balanced double null is a *disadvantage* with regard to core plasma impurity control? (2) How do the 'near SOL' profiles compare, HFS vs. LFS, particularly in balanced double-null? What does this information say about the physics that sets the near SOL widths?

This paper presents a snapshot of results from an ongoing investigation. The data presented here were obtained during Alcator C-Mod's 2015 run campaign in which HFS/LFS nitrogen screening characteristics of L-mode discharges were studied. The investigation will be extended to include H-mode and I-mode discharges before the end of Alcator C-Mod's final operation in 2016.

Sections 2–4 describe the experimental arrangement, the technique used to quantify the screening and nitrogen impurity ion source profile estimates. Section 5 presents experimental results for a range of magnetic equilibria, spanning upper-single null, balanced double null and lower-single null. Section 6 presents impurity 'plume' observations, which provide insight on the mechanisms that control impurity screening in the HFS SOL. High spatial resolution profile measurements, HFS and LFS, for balanced double-null plasmas at three values of plasma current are presented in Section 7. These examine the HFS-LFS mapping of the 'narrow feature' seen near the last-closed flux surface (LCFS). Section 8 discusses the principle findings of this work and its implications.

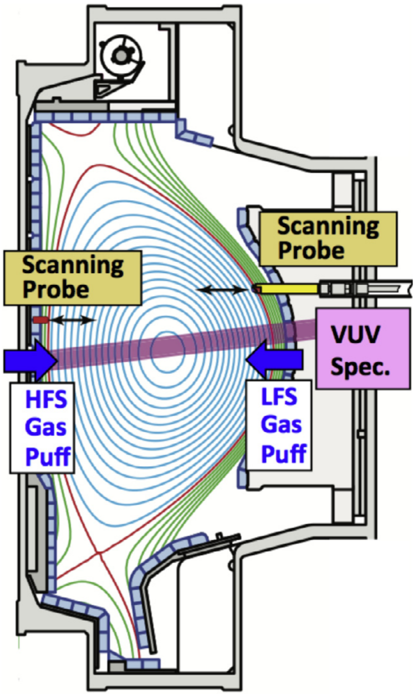

Fig. 1. Arrangement of HFS and LFS scanning probes, capillary 'gas puff' injectors, and the viewing chord for a vacuum ultraviolet spectrometer.

2. Experimental arrangement

Alcator C-Mod [11] is ideally suited for exploring HFS/LFS SOL profiles and impurity screening physics, employing an excellent plasma diagnostics suite that includes scanning probes and capillary gas injectors located on both the HFS and LFS midplanes (Fig. 1), a vacuum ultraviolet (VUV) spectrometer to monitor core plasma impurity emission (Fig. 1). In addition, visible light cameras (Figs. 7, 8) and a poloidally resolved, UV enhanced photodiode array (Fig. 9) are used to monitor nitrogen line emission from impurity 'plumes' that arise from local gas injections.

The two Langmuir-Mach scanning probes employ a four-electrode, high heat flux, pyramidal geometry [12]. These systems provide high-resolution profile measurements of density, electron temperature and parallel plasma flow up to and slightly inside the last closed flux surface (LCFS). Data from the HFS scanning probe electrodes (5 cm above the inner midplane) are obtained by fitting current-voltage characteristics generated by a 2 kHz triangular voltage sweep [1]. The LFS scanning probe (11 cm above outer midplane) employs a 'mirror Langmuir probe' (MLP) bias system [13, 14], producing measurements of density, electron temperature and parallel plasma flow at 1.1 MHz. For the plasmas reported here, nitrogen gas was introduced at HFS or LFS midplane locations via a capillary injection system [15]. An X-ray Extended Ultraviolet Spectrometer (XEUS) [16] with a central viewing chord (see Fig. 1) was used to monitor the brightness of NVI and NVII line emission over the spectral bands of 2.85–2.98 nm and 2.45–2.52 nm respectively. These signals are taken as a relative measure of the concentrations of N^{5+} and N^{6+} in the plasma core for otherwise identical discharges in which location and/or magnitude of the nitrogen gas puff is changed.

Calibrated nitrogen injections were performed on 45 L-mode plasmas (5.4 T, $B \times \nabla B$ towards lower x-point), spanning a variation in magnetic x-point balance (Fig. 2) at fixed current and density, a factor of two variation in plasma current (0.55, 0.8, 1.1 MA) at fixed Greenwald fraction (i.e., line-averaged density normalized to the Greenwald density [17]) and factor of two variation in Green-

Please cite this article as: B. LaBombard et al., High-field side scrape-off layer investigation: Plasma profiles and impurity screening behavior in near-double-null configurations, Nuclear Materials and Energy (2016), http://dx.doi.org/10.1016/j.nme.2016.10.006